ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Report on
THE DESIGN STUDY OF INTERSECTING STORAGE RINGS (ISR)
FOR THE CERN PROTON SYNCHROTRON

by

The CERN Study Group on New Accelerators

GENEVA
FOREWORD

Discussions on what new accelerators should be built in Europe have been going on for several years among experimental physicists and accelerator experts. To carry this process further the Director General of CERN, with the help of the Scientific Policy Committee, in January 1963 invited a number of representative European workers in high energy physics to meet at CERN to form the European Committee on Future Accelerators. The object of the meeting was to initiate the preparation of a programme for high energy physics installations for Europe in the next decade. The Committee set up a working party under the chairmanship of Professor Amaldi which, after considerable study, submitted a Report in May 1963 to the European Committee. Both the European Committee and the CERN Scientific Policy Committee endorsed the conclusions of the report and asked that it be submitted to the CERN Council as the basis for future accelerator planning in Europe.

The conclusions are set out in full in Appendix A to the present report; the most important for future international action is the first section:

"I. In the region of highest energies the programme of accelerator construction ("the summit programme") should include both

(a) the construction of a pair of storage rings for operation in association with the existing CERN-PS;

(b) the construction of a new proton accelerator of a very high energy.

"Both these projects should have high priority. Provided authorization could be obtained by the end of 1964 the storage rings could be completed by 1970 and would make possible at a comparatively early date a programme
of highly significant physics in an energy region not accessible by any other means in the foreseeable future. Owing however to the reasons set out below the storage rings while representing a very important part of the programme could never in themselves form an acceptable alternative to a high energy proton synchrotron."

Technical studies on both the storage rings and a high energy proton synchrotron have been pursued in CERN since 1961 by the special Study Group on New Accelerators. The present report gives the results of three years work of this group - now 55 strong - on the storage rings, in the form of a design study for the complete project including detailed time and cost estimates for construction. The design and estimates have been thoroughly revised since a preliminary version was submitted to the Amaldi Working Party a year ago, but do not differ from the latter in essentials. It is now in such a state that further work should be on more detailed engineering design of components, which requires extensive model studies as part of the actual construction. The design study in its present form should, however, give all the elements necessary for the basic decisions authorising the construction to be taken. It is, to give a comparison, in a much more advanced state than was the design of the CERN-PS when approved by the Council at the end of 1953.

The time schedule and annual cost estimates given in Chapter XIV are made on the hypothesis that a decision to construct the storage rings can be made in December 1964. A different date will, of course, alter both the time scale and annual estimates. The latter are given at the cost levels ruling in the 1964 CERN budget, and will be affected by cost variations in future.

A preliminary design for the other project which makes up the "summit programme" for Europe, the 300 GeV proton synchrotron, was also submitted to the Amaldi Working Party last year. It will be revised in a similar way and made available in due time.
The present report is issued both in English and French versions. Because of the detailed and often novel technical matter contained in it, it should be borne in mind that the original language of the report (apart from Chapter XII) was English.

The names of the Study Group members who have carried out this work are given in Appendix B. We are grateful to many other people both inside and outside CERN for discussions and help on particular problems, and to the technical and administrative staff without whom neither could the work have been done, nor the report prepared.

Kjell Johnsen

Geneva, 12th May, 1964

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I. INTRODUCTION

When carrying out experiments with ordinary accelerators one normally analyses the products of a collision between a primary or secondary particle from the accelerator with a stationary particle in a target. If the rest mass of the bombarding particle is \( m_1 \), its total energy \( E_1 \) and the rest mass of the stationary particle is \( m_2 \), the total available energy in the centre-of-mass system is

\[
E_{CM} = c^2 \sqrt{\frac{m_1^2 + m_2^2 + 2m_1 m_2 \gamma_1}{m_1 + m_2 + 2m_1 m_2 \gamma_1}} \quad (I.1)
\]

where as usual

\[
\gamma = \frac{E}{mc^2} \quad (I.2)
\]

If the two colliding particles have the same rest mass \( m \) we get the simpler formula

\[
E_{CM} = m c^2 \sqrt{\frac{2 + 2\gamma}{2\gamma}} \quad (I.3) \quad \text{(for } \gamma \gg 1) \quad (I.4)
\]

The available energy therefore only goes as the square root of the energy of the accelerator, making it necessary to have rather large steps in accelerator energy in order to get significant steps in the centre-of-mass energy.
If one could arrange for the two colliding particles to move against each other, the situation would be different. If, for instance, a particle of rest mass \( m_1 \) and energy \( E_1 \) makes a head-on collision with a particle of rest mass \( m_2 \) and energy \( E_2 \) the available energy becomes

\[
E_{CM} = c^2 \sqrt{m_1^2 + m_2^2 + 2 m_1 m_2 \gamma_1 \gamma_2 (1 + \beta_1 \beta_2)}
\]

(1.5)

The importance of this is best seen if we make the simplifying assumption that both particles are relativistic, in which case we have

\[
E_{CM} \approx 2 \sqrt{E_1 E_2}
\]

which is equivalent to bombarding a particle \( m_2 \) in a stationary target with a particle \( m_1 \) with an energy

\[
E_{eq} \approx m_1 c^2 \left[ 2 \gamma_1 \gamma_2 - \frac{1}{2} \left( \frac{m_1}{m_2} + \frac{m_2}{m_1} \right) \right]
\]

(1.6)

These formulae can also be modified to the case of the particles meeting at a small angle \( \alpha \). In order to have simple formulae we shall only do this for the case of two identical particles with the same energy. We then have instead of (1.5) the formula

\[
E_{CM} = 2E \sqrt{1 - \beta^2 \sin^2 (\alpha/2)} \quad (1.5a)
\]

\[
\approx 2E \cos (\alpha/2) \quad \text{(for } \gamma \gg 1)\]

which is equivalent to bombarding a stationary target with an energy of

\[
E_{eq} = mc^2 \left[ 2 \gamma^2 \cos^2 (\alpha/2) - 1 \right]
\]

(1.6a)
The only way of making use of this possibility is to shoot two beams against each other. If for instance two beams of 25 GeV collide, the available energy is 50 GeV, corresponding to an equivalent energy of 1500 GeV. If, on the contrary, a 25 GeV beam bombards a stationary target, only 7 GeV is available. This illustrates the advantage that colliding beams offer. The main disadvantage is the very low density of a particle beam compared with that of a stationary target, and very intense particle beams are needed in order to make colliding beam experiments feasible at all. We shall discuss this in some detail later in the report.

It is difficult to find who first proposed colliding beam experiments. The first publication seems to be one by Kerst et al. (1956). They proposed to stack successive pulses in an FFAG accelerator to obtain the intensity required to make colliding beam experiments feasible. With two such accelerators having a common section one could make two beams intersect. The detailed theoretical treatment of the stacking process, which was an essential part of the idea of Kerst et al., was published a little later in the same year by Symon and Sessler (1956a).

Lichtenberg et al. (1956) and O'Neill (1956) proposed to use storage rings instead of two FFAG accelerators for making colliding beams.

Although it is many years since the basic idea was proposed no intersecting beam device for protons has been built. This is due to the fact that it is only in recent years that proton accelerators of sufficient intensity and energy to make such a device interesting have become available. The only accelerators to which it is worth while adding storage rings at present are the CERN-PS and the Brookhaven AGS.

The situation for electrons is different, since in order to reach centre-of-mass energies of the order of 1 GeV with one electron at rest, the bombarding energy required would be beyond feasibility (~1000 GeV). Also radiation
damping makes it possible to accumulate very high beam density. Several electron storage ring projects are under construction. We can mention e⁻·e⁻ rings for 500 MeV electrons at Stanford (constructed and run in collaboration with Princeton University), two electron-positron rings at Frascati (ADA for 250 MeV, ADONE for 1500 MeV), electron-positron rings at Novosibirsk and Orsay (700 and 400 MeV resp.) and electron-electron rings (100 MeV) at Kharkov. There are further a few beam stacking devices mainly for trying out the principle. Among these is a 2 MeV electron ring at CERN.

CERN took up this idea in 1957 when the Accelerator Research Group was formed under Schoch. At this time two new accelerator ideas looked promising, the Budker idea based on plasma physics, and the intersecting beam idea. The work on the Budker scheme was discontinued at CERN after a few years, as the preliminary results were not promising and the scheme, even if feasible, was limited in application. The intersecting beam idea, on the other hand, increased in importance as the CERN-PS came into operation, yielding intensities that would make 25 GeV intersecting beams feasible. It was this development that also made CERN switch from the original plans of an FFAG electron accelerator with stacking facilities to a storage ring model. This model is now operating.

The Accelerator Research Division started work on proton storage rings in 1960, and presented the first preliminary results to the Scientific Policy Committee in spring 1961 (Hesward et al. 1961). The result of the preliminary study was sufficiently encouraging for it to be decided that a design study for such rings should be included in the programme of the Study Group established by the CERN Council in December 1961.

In this report will be presented the results and conclusions arrived at by this Study Group regarding the possible storage rings for the CERN-PS. It is the result of a joint effort of a number of CERN staff and visitors. A list of the people who have made substantial contributions to the Study is given in an appendix (Appendix B).

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II. WORKING PRINCIPLE AND EXPECTED PERFORMANCE

Fig. II.1 shows a sketch of the CERN-PS with two intersecting storage rings. The particles are accelerated in the synchrotron to their final energy. A fast ejection system then takes out all the particles in one revolution and puts them into a beam transport system, and a fast injection system puts the particles into one or the other of the two storage rings, where they are picked up by the radio-frequency system and brought into the stacking region (near the middle of the vacuum chamber). Each time the synchrotron has brought a new pulse up to full energy, the process is repeated, and the pulses are stacked side by side in the longitudinal phase plane of the storage rings.

Each pulse occupies a very small fraction of the longitudinal phase plane available in the vacuum chamber of the storage rings. One can therefore build up very high beam intensities (in ordinary space) near the middle of the vacuum chambers.

The two storage rings can have different centres in which case they can have a common tangential interaction region or they can cross each other at two points. We have decided in favour of the concentric arrangement, shown in Fig. II.1, as proposed by Woods and O'Neil (1958). The rings are two slightly distorted circles that cross each other in eight places, all of which can in principle be used for colliding beam experiments. The basis for this choice will be discussed later.

In proton storage rings, where there is only a negligible radiation loss, the intensity to which one can build up a beam is limited by the phase space available compared with the phase space occupied by the beam in the synchrotron. Since the stacking process is in the longitudinal phase plane \((\Delta p, \phi)\) and since coupling between transverse and longitudinal oscillations can be neglected, we only have to consider the \(\Delta p, \phi\) phase plane. We then afterwards have to add the space needed for betatron oscillations.
The particles ejected from the synchrotron have a certain phase space density in the bunches. Calculations have been made to find how efficiently one can transfer these bunches into the storage rings (Swenson 1961). The main conclusion to be drawn from these computations is that the beam can in principle be transferred with very little reduction in phase space density if the total number of stacked pulses is large, say of the order of hundred or more. However, in practice the beam transfer process will have certain imperfections that are not easy to estimate accurately. We assume for performance estimates that the final phase space density in the storage rings is half that of the bunches at the end of acceleration in the synchrotron.

The number of stacked particles within a given momentum bite $\Delta p$ is

$$N_s = \eta \rho_0 2\pi M_{SR} \Delta p$$

(II.1)

where $\eta$ is the stacking efficiency (which from the remarks above will be put equal to 0.5 in subsequent numerical calculations) $\rho_0$ is the phase space density in the PS bunches and $M_{SR}$ is the ratio between the RF frequency and the revolution frequency in the storage ring.

If one is interested in the maximum possible number of stacked particles one inserts the maximum acceptable momentum spread $\Delta p_s$ within the stack, which with the parameters to be discussed later in this report will be about $\Delta p_s/p \lessapprox 2\%$.

The CERN-PS has delivered $9 \times 10^{11}$ p/p in 20 bunches each of a momentum spread $\Delta p = \pm 6.7$ MeV/c, and phase-width $\Delta \theta = \pm 1/4$ radian, measured with respect to the radio frequency, as its maximum performance. We assume that what has been maximum performance up to the present will become standard performance by the time the storage rings are ready. This then gives

$$\rho_0 = 8.5 \times 10^3 \text{ protons/eV/c}.$$
With the storage ring parameters given later in this report \( N_{SR} = 30 \) and we get as numerical estimate

\[
N_s = 0.8 \times 10^6 \Delta p
\]

where \( \Delta p \) is measured in eV/c.

Let us, for example, assume that we want to work with a momentum definition of \( 2^\circ/\text{c} \) full width at 25 GeV/c. This would give as the number of stacked particles

\[
N_s = 4 \times 10^{13}
\]

which means that at least 44 pulses need to be stacked in each ring (with the CPS performance as assumed above), probably somewhat more in order to be able to scrape off the less densely populated tails of the stack.

The maximum number of particles that can be stacked within the maximum momentum spread accepted by the aperture we find by inserting \( \Delta p/p = 0.02 \) in eq. (II.2), which gives

\[
N_{s \text{ max}} = 4 \times 10^{14}
\]

which is equivalent to about 20 A circulating current.

We shall assume that the cross section of the beam in the interaction region is rectangular with a width \( b \) and a height \( h \), and that the angle between the two beams is \( \alpha \). The interaction volume in each intersection region is then

\[
V = b^2 h / \sin \alpha
\]
The height of the beam is determined by the properties of the beam coming from the CPS and to some extent by the parameters of the storage rings. This height is later in this report estimated to \( h = 1 \) cm. The width of the beam is partly given by the same properties as those governing \( h \) and partly by the space needed to accommodate a certain momentum spread. If one makes use of the full stacking possibility within the available aperture one gets from calculations later in this report \( b = 6 \text{ cm} \). The crossing angle will be \( 15^\circ \) and the maximum interaction volume becomes

\[
V = 140 \text{ cm}^3
\]

Within this volume one has a good knowledge of the momentum distribution of the two beams, which reduces the disadvantage of the large momentum spread.

It is possible to incorporate in the design provision for making a localized contraction of the beam (Terwilliger 1959). When maximum use is being made of this possibility, the beam width is mainly determined by the betatron oscillations. In this case one can assume \( b = 1 \) cm and one gets the interaction volume

\[
V = 4 \text{ cm}^3
\]

which is about the minimum interaction volume one can get even in cases when very little momentum spread has been stacked (few pulses). With the Terwilliger scheme applied there is a random distribution of the momentum within this volume, and this is one of the disadvantages of the scheme.

The total interaction rate is approximately given by (see e.g. Jones 1959 and Middelkoop and Schoch 1963)

\[
N_{IR} = \frac{c \delta}{h \tan \frac{\theta}{2}} \left( \frac{N_s}{2\pi R} \right)^2
\] (II.4)
where we have assumed that the two rings are identically filled with \( N_s \) particles in each, \( v \) is the particle velocity, \( \delta \) is the cross section of the reaction under consideration and \( R \) is the mean radius of a ring.

One should notice that this formula does not contain the width of the beam, which means that the application of the Terwilliger scheme does not change the interaction rate in the interacting volume.

However, as seen from eq. (II.1) \( N_s \) is proportional to \( \Delta p \), which means that the interaction rate is proportional to the square of the acceptable momentum spread. (Acceptable may either mean what is acceptable to the machine, i.e. \( 2^\circ/\text{o} \), or to the experiment in question, which may be much smaller).

The radius of the storage rings will be 150 m. This together with the figures arrived at above gives the following interaction rates per intersection region as a function of relative momentum bite

\[
N_{IR} \sim 10^{34} \left( \frac{\Delta p}{p} \right)^2 \delta \text{ interactions/sec}
\]

where \( \delta \) is the cross section in \( \text{cm}^2 \) of the interaction to be studied. This interaction rate can also be expressed in somewhat different terms as one interaction per second, per microbarn at one per cent momentum spread. The total cross section of a p-p collision is \( 4 \times 10^{-26} \text{ cm}^2 \), and the expected total interaction rates in an interaction region are therefore

\[
N_{IR \text{ total}} \sim \begin{cases} 1.6 \times 10^3 \text{ interactions/sec with } \Delta p/p = 2^\circ/\text{o} \\ 1.6 \times 10^5 \text{ interactions/sec with } \Delta p/p = 2^\circ/\text{o} \end{cases}
\]
III. THE EXPERIMENTAL PROGRAMME FOR INTERSECTING STORAGE RINGS AND ITS IMPLEMENTATION

1. Introduction

As it has been pointed out in chapter I, the proposed intersecting storage rings for colliding beam experiments would open the energy range up to 50 GeV in the centre-of-mass system, which, using conventional experimental techniques, would require an accelerator of energy 1300 GeV. Since the proposed device would permit the study of proton-proton reactions only - with possibilities of later extensions to proton-antiproton, proton-deuteron and deuteron-deuteron reactions - it can certainly not take the place of accelerators of higher energies for experiments requiring beams of short-lived particles such as pions, kaons and hyperons. It would, however, represent a unique tool for an exploratory search for whatever clues might be hidden in the range of very high energies that will promote our understanding of elementary particles.

Principal problems in this line of research accessible with this tool are:

- The existence of new particles which are too heavy to be produced by present accelerators. Conjectures based on missing numbers of so far successful group theoretical classifications of particles (SU_3 group classification), and the fact that the heavy boson supposed to mediate the weak interaction processes has not yet been observed, support the expectation that such heavy particles might exist.

The stacking of a limited number of antiprotons in a storage ring could be envisaged. The interaction rate for p- \bar{p} interactions would be a factor of 10^8 lower than for p-p interactions. Later, it might also be feasible to accelerate deuterons in the PS and stack them in the storage rings to enable the investigation of high-energy n-p and n-n interactions.
The existence of highly excited states of baryons and the nature of "fireballs" observed in cosmic-ray-produced "jets".

Reactions with high momentum transfer, related to the question of a nucleon core.

Extension of our knowledge on total and elastic cross sections for p-p (and possibly for p-\bar{p}) interactions to very high energies, in relation with theorems on their asymptotic properties (Pomeranchuk theorems).

The problems of whether and how colliding beam experiments would be feasible, taking into consideration the particular conditions which are very different from those around beams, targets, and detectors in conventional experiments, have been given thought outside and inside CERN during the past few years. Two study meetings of experts had been organized to discuss these problems (1962 Working Party Meeting at CERN on Experimental Use of Proton Storage Rings, and 1963 Summer Study at Brookhaven National Laboratory on Storage Rings, Accelerators and Experimentation at Super-High Energies). General ideas for possible experimental techniques evolved and estimates of possible precision and rates of data collection in specific experiments have been worked out. These are reviewed in the present chapter. It will appear that instrumentation specially adapted to the new technique will be required and will have to be developed in parallel with the design and construction of the ISR.

In addition to the possibilities of colliding beam experiments offered by intersecting storage rings, they would provide a number of interesting supplementary advantages for normal 25 GeV experimentation, to be outlined at the end of this chapter.

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2. The Experimental Programme

The following part of a high energy research programme could be carried out using storage rings. We list these topics in three groups. Groups I and II concern p-p interactions, Group III concerns experiments using other particles. For the experiments of Group I the additional CM energy obtainable using storage rings represents a decisive advantage. The second group includes experiments which could be carried out using storage rings but for which the higher available CM energy is less important or for which the experimental difficulties are considerable.

Group I

1. Measurement of total p-p cross section as a function of energy up to 1300 GeV (laboratory energy equivalent).

2. Measurement of differential p-p elastic cross section for a range of equivalent energies up to 1300 GeV and of (four momentum transfer)$^2$ up to about 1 (GeV/c)$^2$.


4. Study of full details of the p-p interaction process at the highest available energy with particular attention to the rôle of excited baryons, "fireballs" etc. and to collisions involving a high transverse momentum transfer.

Group II

5. Search for new particles and resonances in p-p collisions, including the intermediate vector boson.

6. Search for examples of the breakdown of existing conservation laws (such as associated production) in very high energy interactions.

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Group III

7. Repetition of experiments 1 - 4 using p-d and d-d collisions in an attempt to derive the features of n-p and n-n scattering and interactions at very high energy.

8. Measurements of total p-p cross section as a function of energy.

These experiments involve two main classes of experimental arrangement. In experiments 1 - 3 one is interested particularly in processes involving small angles with the incident proton beam. (We shall refer to these subsequently as class A experiments). Either there are very few particles in the final state or one is not interested in its details. The experimental equipment is for the most part disposed close to the two colliding beams, well down-stream from the interaction region.

In experiments 4 - 6 on the other hand a much more detailed study is needed of individual particles emitted from the interactions and observation cannot be restricted to small angles with the incident beam. The detection devices will surround the whole experimental region. We refer to these subsequently as class B experiments.

3. General Remarks on Experimentation with Storage Rings

In experiments with high energy accelerators it is usually possible to achieve a considerable measure of separation between the accelerator and its associated problems on the one hand and the experimental equipment to be employed with it on the other. In experiments using intersecting beams, however, it is much more difficult to make a sharp separation between the storage ring structure and the experimental apparatus. It is of great importance therefore that plans for the experimentation with storage rings should be worked out in considerable detail together with the final design of the rings, so that
experimental requirements can play their proper part in influencing the design of the rings.

Essential features such as straight sections of adequate length near the intersecting regions, to permit the identification of the particles produced in the interactions, and provision for breaking the ring near intersecting regions to accommodate experimental set-ups have been incorporated in the present design. Further requirements on the design are that the disposal of adequate magnetic fields, both transverse and longitudinal, around parts of the intersecting region in order to facilitate particle identification, should not lead to serious difficulties.

4. Experiments requiring Measurements at Small Angles to the Circulating Beams

We consider first the experiments requiring mainly measurements of the particles emitted at small angles to the circulating beams and which we have called class A experiments.

Let \( p_{\text{lab}}, p_{\text{cm}} \) be the laboratory and CM moments of a proton colliding with a stationary proton. Then

\[
p_{\text{lab}} \approx \frac{2p_{\text{cm}}}{M_o} p_{\text{cm}} \quad (M_o = \text{mass of proton}) \quad (\text{III.1})
\]

Since in any scattering event the transverse momenta are the same in the two systems

\[
\Theta_{\text{cm}} \approx \left( \frac{2p_{\text{cm}}}{M_o} \right) \Theta_{\text{lab}} \quad (\text{III.2})
\]

where \( \Theta_{\text{lab}}, \Theta_{\text{cm}} \) are the scattering angle in the two systems. For \( p_{\text{cm}} = 25 \text{ GeV/c} \),

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\theta_{cm} = 53.3 \theta_{lab} \quad \text{so that, for the same energy in the CM system, the angles to be measured in scattering experiments with colliding beams are 50 times larger and the momenta 50 times smaller. Or, expressed in another way the difficulty of carrying out experiments of this kind using colliding beams at an equivalent laboratory energy of 1300 GeV is about the same as for a similar experiment at 25 GeV using a conventional accelerator (Terwilliger 1963).}

This advantage has to be balanced against the inconveniences introduced by the necessity of working near the interaction region where the magnets of the storage ring may get in the way and also by the greatly reduced collision rate in comparison with that possible using a conventional accelerator.

We consider now in more detail how specific experiments of this class could be carried out.

4.1. Measurements of the p-p total cross section

Fig. III.1 shows a schematic arrangement proposed by de Raad (1962 b) for the measurement of p-p total cross sections using intersecting beams. \( S_1, S_2, S_1' \) and \( S_2' \) are 80 cm diameter counters placed at 0.6 and 6 m from the interaction region. A special vacuum chamber of diameter 5 cm passes through holes in the counters. Secondaries from colliding beam events which pass through the hole in \( S_1, S_1' \) will be counted by \( S_2, S_2' \) unless their emission angle is smaller than 5 mrad. The outputs \( (S_1 + S_2) \) and \( (S_1' + S_2') \) are in parallel and a coincidence between \( (S_1 + S_2) \) and \( (S_1' + S_2') \) is considered as a colliding beam event. By making measurements with holes of different sizes in the counters one can in principle extrapolate to \( \theta = 0 \) to obtain the true number of interactions.
To reduce the range of this extrapolation an arrangement proposed by Jones (1963) could be used. This arrangement, shown in Fig. III.2 measures specifically the elastic scattering at very small angles but since the contribution to the total cross section at such small angles is almost entirely due to elastic scattering it can be used to improve the estimate of the total cross section also.

Two matrices, each consisting of a 5 x 10 array of solid state or scintillation counters, with individual counters having dimensions 2 mm x 2 mm are mounted so that they can be brought to within 1 cm of the centre of the circulating beam at positions in each of the two beams one quarter of a betatron wavelength ($\lambda$) down-stream from the intersecting region. At this position a proton scatters through an angle $\Theta$ is displaced by an amount $x = \Theta \beta \lambda$ where $\beta$ is a factor between 1 and 2, which can be calculated from the detailed orbit parameters. This relation would need correction for the finite size of the counters and for the size and angular spread of the circulating beam but it clearly provides a mean of extending the cross-section measurements down to small angles.

The number of colliding beam events per second, extrapolated to zero scattering angle, $N_{bb}(0)$ can be written

$$N_{bb}(0) = \int_{-\sqrt{2}h}^{\sqrt{2}h} \frac{N_{t1}(z) N_{t2}(z)}{(2\pi R)^2} \cdot \frac{c \sigma}{\tan \frac{\alpha}{2}} \, dz \quad (III.3)$$

where $N_{t1}(z)dz$, $N_{t2}(z)dz$ are the total number of protons between $z$ and $z + dz$ independent of their radial position in the two ISR, $h$ = beam height, $\alpha$ = crossing angle of the beam, $c$ = velocity of light and $\sigma$ = total p-p cross section.
The measurement of the vertical density distribution across the beam may give rise to difficulties. De Raad has proposed to do this by inserting a thick target from above or below into the beam after the coincidence measurements have been completed, measuring the surviving beam current as a function of target position.

Background due to beam-gas collisions should be automatically distinguished from beam-beam collisions by the requirements of a coincidence in $(S_1 + S_2)$ and $(S'_1 + S'_2)$.

4.2. Measurement of the p-p elastic scattering cross section

Experimental arrangements for studying p-p elastic scattering with a pair of ISR have been discussed by Jones and De Raad (1962), De Raad (1962 b), Jones (1963), and Terwilliger (1963).

Fig. V.3 indicates schematically the trajectories of scattered protons emerging from the intersecting region. Fig. III.3 shows the arrangement envisaged. Protons, after scattering, pass through a thin window in the appropriately shaped vacuum chamber and through a pair of spark chambers separated by 2 m, enabling the scattering angle, $\theta$, to be determined to an accuracy of $\pm 0.1$ mradian.

In order to permit the determination of the momentum of the scattered protons, the magnet units adjacent to the region of intersection are replaced by bending magnets with uniform field, plus a set of quadrupole lenses. The bending magnets extend laterally to subtend the required range of scattering angles. Momentum can be measured to an accuracy of $0.2^\circ /o$, the direction of the proton after scattering being determined by a second set of spark chambers.

The very high accuracy of angular and momentum measurements makes possible a very good discrimination against inelastic events. For example for the inelastic event

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\[ p + p \rightarrow p + N^* \rightarrow p + \pi^0 \]

where \( N^* \) has a mass of 1.5 GeV, the fraction of \( N^* \) decay angle for which this particular event could be confused with an elastic \( p-p \) event is less than \( 10^{-3} \). Almost every inelastic event can be identified.

To make fullest use of the angular and momentum resolution inherent in this experiment the energy spread in the circulating beams and their angular spread must be comparably small. This implies a limitation in the size of the stacked beam. For a stacked beam of 1 Ampere corresponding to the stacking of 40 machine pulses a momentum spread of 0.1 per cent and an angular spread of 0.3 mrad can be envisaged.

Terwilliger has discussed the carrying out of this experiment under these conditions and has shown that one can obtain appreciable counting rates with an acceptably small background, out to a scattering angle of 30 milliradians. The estimates of counting rates are based on an extrapolation of the behaviour of elastic cross-sections observed up to about 8 GeV total energy in the centre-of-mass system. At the smallest scattering angles (\(<10\) milliradians) it would be necessary to use counter arrays similar to those of Fig. III.2 to detect the scattered protons, rather than spark chambers. Also, to increase the solid angle available at a given scattering angle it would be desirable to use specially designed quadrupole magnets in the ISR structure next to the intersecting region. Fig. III.4 illustrates a quadrupole with open median plane designed by De Raad to provide maximum solid angles for the scattered beams.

Counting rates of the order of 1 elastic scattering event per second are expected at a scattering angle of 10 mrad, and inside an angular interval of \( \pm 1 \) mrad and a solid angle interval of a few times \( 10^{-5} \) stered. The rate falls off to about \( 10^{-3} \) counts per second in the same angular interval at 30 mrad.
At larger scattering angles in order to obtain a practicable counting rate it will be necessary to increase the available solid angle of the scattered beams and to increase the circulating current. In fact by relaxing the beam momentum resolution requirement to ±1 per cent the beam current could be increased to 10 Amperes, increasing the detection rate 100 times. Elastic scattering could then be measured up to about 40 mrad (corresponding to a value of $(\text{four momentum transfer})^2 = 1 \left(\frac{\text{GeV}}{c}\right)^2$).

For increasing the solid angle, Jones (1963) has proposed the use of an air-cored magnetic field of magnitude $\frac{2 \times 10^4}{R}$ gauss where $R$ (in cm) is the radial distance from the beam axis. This field would be produced in the manner shown in Fig. III.5. Current runs along the beam pipe for 5 metres, starting 5 metres from the target. The return path is arranged to form four coils as shown in the figure, the whole producing an azimuthal magnetic field. This arrangement of magnetic field would not perturb the circulating beam.

Arrangements like those described above for elastic p-p scattering could clearly be adapted to the study of small angle inelastic scattering.

Interfering background is due first to protons scattered elastically from residual gas; these are very similar to elastically scattered colliding beam protons, and at a pressure of $10^{-9}$ to $10^{-10}$ torr in the vacuum chamber, the flux is comparable. Coincidence of both scattered colliding beam protons discriminates easily, however, against elastically scattered background protons.

The background due to inelastic reactions with residual gas nuclei is more important. At $10^{-10}$ torr in the vacuum chamber sections containing the interaction regions, and with 1 A beam current, the background flux passing through spark chambers of 100 cm radius about the beam axis is $\sim 2 \times 10^5$ per second. Assuming a sensitive time for the spark chambers of 0.5 µs, a spurious track would appear only once in every ten recorded events. Furthermore, with $5 \times 10^{-9}$ s time resolution for the triggering coincidence, the fraction of accidental coincidences would be $10^{-3}$.
If the beam intensity is raised to 10 A, or if the pressure is \(10^{-9}\) torr instead of \(10^{-10}\) torr, background tracks and accidental coincidences go up by a factor of 10 and become more perturbing.

5. Experiments Involving Identification of Secondary Products

We consider now experiments of class B, involving the identification of secondary products of p-p interactions.

On the basis of cosmic ray data and of data using presently available machines, Cocconi, Koester and Perkins (1961) have given expressions for the longitudinal and transverse momentum distributions of secondary particles from high energy p-p interactions. Using these expressions Fig. III.6 shows for the collision of two protons each of energy 25 GeV the energy distribution of secondary particles emitted at various angles to the incident beam direction (Burhop 1963). It is seen that most of the secondary particles have a momentum of 1 GeV/c or less. This is a region in which considerable experience has already been obtained in particle identification. Further, the mean emission angle of the secondaries is about 20°. Fig. III.7 shows similarly the expected energy and angular distribution of the beam particles after interaction.

A study of the details of the processes occurring in p-p interactions requires the identification of a large proportion of the secondary particles. We consider now the extent to which it appears practicable to make such identification.

5.1. Identification of Charged Secondary Particles

We discuss in turn some different types of physical measurements that can be made on the secondary and beam particles after interaction and the information that can be obtained from them. They rely in general on the use
of spark chamber or counter detection. Bubble chambers are unlikely to have much application to colliding beam experiments owing to their long sensitive time and the difficulty of distinguishing beam interactions from interactions with the residual gas.

5.1.1. Curvature of Particle Trajectories in a Magnetic Field

The paths of secondary particles can be defined by a set of spark chambers placed in a magnetic field around the interaction region. Many possible dispositions of such chambers can be envisaged. One arrangement is shown in Fig. III.8 in which S represents a series of circular spark chambers, 2 m radius, placed 50 cm apart. If a magnetic field of 16000 gauss can be set up around the interaction region it should be possible to determine the momentum of almost all secondaries emitted at angles greater than $5^\circ$ to the beam direction to an accuracy of better than 1 per cent. In most cases a very much greater accuracy should be realisable. This will be the case whether the magnetic field direction is transverse to the beam direction or parallel to it. Indeed a magnetic field of strength 6000 gauss would be sufficient for most secondaries.

For the scattered beam particles, however, which in general will have a momentum of 20 GeV/c or greater after scattering the longitudinal field arrangement would not give useful momentum determinations. In this case it would be better to rely on the extension of the storage ring bending magnets nearest the interaction region for momentum determinations as illustrated in Fig. V.3.
5.1.2. Rate of Energy Loss of Secondaries in Degrader

Another parameter which is often used to assist in the identification of charged particles is the energy loss of the particles in a degrader of suitable thickness. A degrader in the form of a sheet of uranium 1 cm in thickness followed by another set of spark chambers in a magnetic field to measure the degraded particle momenta would enable the identification of about half the secondary particles emitted. Such a method has the disadvantage, however, of requiring the extension of the magnetic field for a distance of 4 or 5 metres down the beam in either direction from the intersecting region.

5.1.3. Time of Flight Measurements of Secondary Particles

A more practicable method of secondary particle identification employs a combination of the time of flight measurements with the magnetic stiffness measurements discussed in par. 5.1.1. Fig. III.9 shows the flight time for $\pi$ and $K$ mesons and protons of different momenta over a four metre path. Identification of these particles should clearly be possible up to momenta of about 1 GeV/c. In Fig. III.8 C$_1$ to C$_4$ represents a series of divided arrays of scintillation counters which could be used for such time of flight measurements. If each of the scintillators were divided into 50 sections it appears feasible to identify by this method about 60 per cent of the charged secondaries emitted from the interaction. If they could be replaced by matrices of much smaller counters the efficiency of identification could be increased considerably.

5.1.4. Velocity Measurement of Secondary Particles using Cerenkov Detectors

To identify secondary particles emitted with momenta above 300 MeV/c (mostly at an angle less than 30° with the beam direction) the use of Cerenkov
detection seems attractive. At 800 MeV/c the velocities, \( \beta \), of protons, K mesons and \( \pi \) mesons are respectively 0.65, 0.85 and 0.98. At 1.4 GeV/c the corresponding velocities are 0.83, 0.94 and 0.995. A Čerenkov detector containing a medium of refractive index 1.06 (CO\(_2\) at 150 atmospheres pressure) would enable \( \pi \) mesons to be distinguished from K mesons and protons at momenta up to 1.4 GeV/c and protons from \( \pi \) and K mesons up to momenta above 2 GeV/c.

If a Čerenkov angle detector like the Čerenkov chamber suggested by Roberts (1960) capable of recording a number of particles of different velocities moving simultaneously through the detector with a range of incident angles could be developed it should be possible to identify secondaries of momentum up to 3.5 GeV/c.

The problem of identifying the scattered beam particles using such a Čerenkov detector in addition to magnetic stiffness measurements is more difficult, however. For a momentum of 25 GeV/c the quantity \((1 - \beta)\) has values \(0.15 \times 10^{-4}\), \(1.9 \times 10^{-4}\) and \(6.7 \times 10^{-4}\) for \(\pi\), K and p respectively. A gas Čerenkov detector about 7 metres long and capable of an angular resolution of 3 mrad and a Čerenkov angle of 2° should just enable the identification of these particles so that one can conclude that identification of even the scattered beam particles may eventually be practicable. In Fig. III.8 CC represent Čerenkov detectors.

5.2. Detection of Photons

The heavy plates proposed above (section 5.1.2) might be useful, even if the momentum loss method of charged particle identification is not employed, to detect photons and to measure their energy. Such plates of uranium, 4 radiation lengths thick, should make it possible to detect photons with 96.5 percent efficiency. If in addition a cylinder of similar thickness and two metres radius were placed round the colliding region together with a
cylindrical spark chamber it should be possible to detect more than 90 per cent of the photons from $\pi^0$ decays. If in addition it were possible to make estimates of the photon energies by studying the development of the photon-electron cascade they produce it would be possible to determine the direction and momentum of the $\pi^0$ mesons from which they originate. Estimates of photon energies in this way have only statistical validity, however.

5.3. Detection of Strange Particles

The non accessibility of the interaction region is a serious disadvantage of colliding beams from the point of view of the observation of short-lived particles. Approximately 80 per cent of the hyperons produced will decay before they leave the interaction region. It may be possible to detect $\Lambda^0$ (and also $K^0$ mesons) decaying via charged modes from invariant mass measurements of their secondary products. This will not in general be possible for the charged particle decays in which a neutral particle is usually emitted.

5.4. Detection of short-lived Isobars

An understanding of p-p interactions requires not only a knowledge of the long-lived secondary products but also of the directional and momentum distribution of any short-lived isobars in the decay of which they are produced. To detect such isobars it will be necessary to calculate invariant mass distributions of groups of secondary particles. This may be feasible for groups of charged particles. The identification of such isobars involving neutral secondary particles will be very difficult, however. Also the multiplicity of secondaries is generally so high that it will be difficult to detect true peaks due to coordinated groups of secondaries above the background of "noise" provided by groups of unrelated particles. Indeed it may prove possible only to make such studies on the simplest types of events with low multiplicity.
5.5. Identification of Events of Special Type

Suitable selection systems will undoubtedly need to be incorporated to select events of a specially interesting type. Since the expected interaction rate for a set of storage rings containing the maximum expected proton current (20 Amps) will be about $10^5$ particles per second, there would be no point in continuing to accumulate such indiscriminate data over a long period.

One special class of events of great interest involves collisions of large momentum transfer. Collisions of this kind should be characterized by the appearance of one or more particles with a large transverse momentum. Such cases could be selected if a longitudinal magnetic field geometry is used. For example in the geometry of Fig. III.8, with a longitudinal magnetic field of strength 6000 gauss over a 2 metre radius, a particle of momentum 3 GeV/c from the interaction region will emerge from the field region at an angle of 13.5° to the radial direction. Particles moving at a smaller angle than this could then be selected by the cylindrical arrays of scintillator counters, C₅, C₆, C₇ and the spark chambers triggered on such events.

Other selection systems could be envisaged aimed to look at events where all the secondary particles are emitted at small angles to the incident directions, corresponding to peripheral collisions, or where a small number of secondaries are emitted in the way to be expected if they originated from the decay of a known isobar.

Van Hove (1962) had estimated that if the intermediate boson were very heavy, its production cross section in p-p collisions could be as high as $10^{-29}$ cm$^2$. O'Neill has discussed an experiment for detecting the intermediate vector boson in p-p interactions in intersecting proton storage rings. The arrangement proposed is shown in Fig. III.10. The signature O'Neill proposes for W production is the muon produced in a large proportion of W decay. These muons have to be distinguished, however, from those due to π-μ decay.

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He proposes therefore to use a heavy magnetized iron shield 3 m thick between the interaction region and a set of spark chambers to stop all muons of energy less than 3 GeV. If the W particle has a very large mass (5 - 15 proton masses), the decay muons from it would in general have an energy greater than 3 GeV. Such muons would be recorded in both the inner acoustic spark chambers and the outer thick plate spark chambers. The only background would be due to muons from the decay of π mesons with transverse momentum greater than 3 GeV/c and these are expected to be rare. It may be argued that if the W mass is less than 5 GeV the decay muons would not emerge. In that case, however, the experiment is in any case unlikely to yield a positive result since the production cross section would be expected to be too small, the production cross section in p-p collisions varying very rapidly with W mass.

6. Magnetic Field Arrangements for Colliding Beam Experiments

The analysis of the secondary products from colliding beam interactions requires large magnetic fields over a considerable volume in the neighbourhood of the interacting region. These have to be designed in such a way that perturbations in the motion of the stored particle beams are either avoided or compensated. If a transverse magnetic field is used it must be arranged so that the lines of force are vertical. This will then have the effect of moving the interacting region along the direction of the beams. They will still intersect but at a different position. A transverse horizontal magnetic field could have the effect of pushing the beams apart vertically so that they would fail to intersect. Magnets for producing a vertical field in the interaction region, with the return flux used for compensating the effect on the colliding beam orbits, have been suggested and discussed by Jones (1959), O'Neill (1959), De Raad (1962 a), and Resegotti (1962).
It has been pointed out above that from the point of view of selecting a large momentum transfer a longitudinal analysing magnetic field would have advantages over a transverse field. Such a field would have less effect on the beam dynamics of the stored beam. The focusing effect of such a field would need to be compensated, however.

Various schemes have been proposed for the production of the necessary strong magnetic fields in the neighbourhood of the intersecting region while keeping the field in the region of the beam at a small value. Fig. III.11 illustrates some of these possibilities.

The very large fields involved will require massive conductors and the dissipation of many megawatts of power. Since these conditions may well interfere with the experimental arrangements for particle detection it appears that cryogenic magnets may have considerable application in colliding beam experiments.

7. Use of Storage Rings as improved Facilities of the CERN-PS

The provision of storage rings will increase the facilities of the CPS for experiments with 25 GeV protons. They cannot, of course, increase the integrated proton current available but simply by providing more experimental areas they will facilitate the setting-up of a greater number of experiments.

They will also make possible a greater variety of experiments, since the effect of storage rings is to provide intense currents of high energy protons with a 100 per cent duty factor. Counting experiments involving the search for rare processes may not be practicable using a machine with poor duty factor since the accidental coincidence rate is proportional to the square of the current in the pulse while the effect being sought is proportional to the current itself. With the high duty factor possible with storage rings, however, it may be possible greatly to increase the integrated current
over a limited time, while keeping the integrated square of the current below an acceptable maximum.

Even for visual devices such as bubble chambers, experiments using storage rings may have advantages. During normal operation with the CPS, the bubble chamber is recycled at a rate equal to the pulse repetition rate of the machine. This may not be the optimum rate of operation, however. In fact bubble chambers with considerably increased cycling rate are forthcoming. With storage ring operation the bubble chamber could be recycled at a rate determined by the characteristics of the bubble chamber itself, a small prescribed fraction of the stored current being extracted for each cycle of the bubble chamber.

Alternatively the whole of the stored beam could be used for one bubble chamber cycle. This would be of great advantage in studying processes of very small cross section such as neutrino interactions in hydrogen or deuterium. One of the key experiments in neutrino physics is the study of neutrino interactions in hydrogen. With available hydrogen bubble chambers and the existing neutrino (or antineutrino) flux the maximum expected rate of neutrino interactions would be about 1 event per day. To observe this event it would be necessary to take 30,000 bubble chamber pictures. If, however, neutrinos were produced from the decay of pions produced when the whole circulating proton current, obtained by stacking 700 pulses from the CPS, was stopped on a thick target it should be possible to observe 1 neutrino interaction in hydrogen in each 40 pictures. Of course, such an arrangement would not increase the interaction rate but it would greatly reduce the labour associated with the experiment.

Finally, storage rings might be used to advantage in connection with a programme for raising the intensity of the CPS to $10^{13}$ particles per pulse permitting more favorable shielding arrangements and better facilities for slow extraction under conditions of higher intensity.
IV. ORBIT PARAMETERS

1. Introduction

No proton storage rings have so far been built. In fixing parameters we have therefore not been able to extrapolate from any earlier construction. The parameters have had to be evaluated in the main from basic principles although the general experience gained on the CPS has been of great help. Several sets of parameters have been worked out and presented in various internal reports. The present chapter gives the analysis and considerations that have led to the basic parameters on which the actual design has been based.

2. Basic Choices for the ISR Magnet Structure

In order to exploit fully the advantages of the concentric arrangement there should be at least 6 interaction regions. Since the circumference increases with increasing number of interaction regions N, we shall only consider \( N = 6 \) and \( N = 8 \). The number of superperiods is then 3 or 4. The Q-values for the horizontal and vertical betatron oscillations that should be avoided in a machine with \( S \) superperiods are given by the relation

\[
n Q = p S \quad (IV.1)
\]

where \( n \) and \( p \) are integers.

We shall restrict ourselves to Q-values between 6 and 9. Taking \( n = 2 \) we find that the stopbands due to the superperiodicity occur at \( Q = 6, 7.5 \) and 9 for \( N = 6 \) and at \( Q = 6, 8 \) and 10 for \( N = 8 \). To minimize the wiggles on the closed orbit and betatron oscillations the Q-values should be chosen about halfway between the stopbands but, of course, always avoiding integral and half-integral values. Additional Q-values forbidden by \( n = 3 \) and \( n = 4 \)
(quadratic and cubic resonances) are $Q = 6.75$ and 8.25 for $N = 6$ and $Q = 6.67$ for $N = 8$. The quadratic resonances for $N = 6$ leave only the possibilities $Q = 6.25$, 7.25, 7.75 and 8.75, all of which are rather close to the stopbands of the superperiod. For $N = 8$ we can choose between $Q = 7.25$ and $Q = 8.75$ which are both nearly in the middle between stopbands. Therefore we shall restrict ourselves to ISR with $N = 8$. For reasons discussed later in this report we consider $Q = 8.75$ the most suitable value.

The number of periods $M$ of ISR with $Q = 7.25$ or $Q = 8.75$ should be somewhere between 45 and 60 to obtain a phase advance per period between $\pi/3$ and $\pi/4$. The smaller values are to be preferred since they yield smaller gradients and longer straight sections. $M$ must also be a multiple of 4 since there are 4 superperiods. Furthermore it must be possible to subdivide a superperiod conveniently into an inner and an outer arc.

This subdivision is closely related to the angle $\psi$ at which the two ISR intersect. It should be large to avoid mutual interference of the ISR and for convenient experimentation. It should be small to keep the average radius $R$ of the ISR down and the interaction rate $N_{ir}$ up, which is given by equation (II.4).

We call half a period a basic building brick. There are $N_1$ of them in the outer arc and $N_2$ in the inner arc, the bending angle in the brick is $\varphi$. Then we have for 4 superperiods:

$$90^\circ = \varphi \left( N_1 + N_2 \right) \quad (IV.2)$$

$$\psi = \varphi/2 \left( N_1 - N_2 \right). \quad (IV.3)$$

Combining these formulae and writing $N = N_1 + N_2$ we have:

$$N_1 = \frac{45 + \psi}{90} N \quad \quad N_2 = \frac{45 - \psi}{90} N \quad (IV.4)$$
Obviously $N_1$ and $N_2$ must be positive integers and $0 < N_2 < N_1 < N$. Thus $\frac{45 - \psi}{90}$ lies between zero and one half, and must be a rational fraction, say $p/g$. Trying the smallest numbers for $p$ and $g$ one can obtain Tab. IV.1 where only cases with $45 < M < 60$ are given.

In order to present the numerology in a systematic way some cases have been included where the small value of the ratio $N_1/N_2$ leads to an impractically high average diameter of the machine. We feel that a reasonable compromise between the various considerations is $M = 48$ and $\psi = 15^\circ$.

Tab. IV.1. Intersection Angles, Basic Brick and Period Numbers

<table>
<thead>
<tr>
<th>p/g</th>
<th>$\psi$</th>
<th>$N_1$</th>
<th>$N_2$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/3$</td>
<td>15°</td>
<td>16</td>
<td>8</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>20</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>$1/4$</td>
<td>22.5°</td>
<td>18</td>
<td>6</td>
<td>48</td>
</tr>
<tr>
<td>$1/5$</td>
<td>27°</td>
<td>24</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>$2/5$</td>
<td>9°</td>
<td>18</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>$1/6$</td>
<td>30°</td>
<td>20</td>
<td>4</td>
<td>48</td>
</tr>
<tr>
<td>$1/7$</td>
<td>32.1°</td>
<td>24</td>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>$2/7$</td>
<td>19.3°</td>
<td>20</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>$3/7$</td>
<td>6.4°</td>
<td>16</td>
<td>12</td>
<td>56</td>
</tr>
<tr>
<td>$5/12$</td>
<td>7.5°</td>
<td>14</td>
<td>10</td>
<td>48</td>
</tr>
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<td>18</td>
<td>8</td>
<td>52</td>
</tr>
<tr>
<td>$5/13$</td>
<td>10.4°</td>
<td>16</td>
<td>10</td>
<td>52</td>
</tr>
</tbody>
</table>

The magnet structure of the ISR is different from that of the CPS because the ISR must have much longer field free sections for experimental purposes and – as a consequence of their concentric arrangement – different average radii in the inner and outer arcs. Another difference with the CPS is that
in an accelerator the energy spread of the protons is small and the aperture requirements are mainly determined by the injected beam size and closed orbit deviations due to magnet imperfections, whereas in a storage ring the beam is injected with a high energy and a small beam diameter. Most of the horizontal aperture which is a few times larger than the vertical aperture is required for the energy spread in the stacked beam and the injector itself. Thus the aperture requirements are chiefly determined by the betatron amplitude function in an accelerator, and by the momentum compaction function in a storage ring.

Changes in the magnet periodicity along the circumference may lead to azimuthal variations of the betatron oscillation amplitude and the momentum compaction function, in addition to the regular strong focusing wiggle which is always present. In general one finds that by a suitable choice of parameters the azimuthal variation of either the betatron oscillations or the momentum compaction function can be suppressed but that it is not possible to eliminate both.

We shall be particularly interested in matching the momentum compaction function \( \alpha_p \) since it determines the width of the stacked beam in ISR. We define it by

\[
\Delta r(s) = \alpha_p(s) \frac{\Delta p}{p}, \tag{IV.5}
\]

where \( s \) is the distance along the orbit, thus \( \alpha_p(s) \) has the dimension of a length.

In the middle of an F and a D sector the closed orbits for all momenta are parallel to the central orbit. We can therefore interrupt the regular machine lattice at these positions and insert straight sections of arbitrary length without changing the momentum compaction function. This makes it
possible to obtain the long straight sections for colliding beam experiments and a variable mean radius by simply choosing different spacing between the magnet units if a FOFDOD structure is chosen, or by inserting mid-F and mid-D straight sections of appropriate lengths in an otherwise FODO structure.

Let us now consider the influence of this procedure on the betatron oscillations. The focusing properties of an alternating gradient structure are completely determined by specifying how the amplitude function $\beta$, defined by Courant and Snyder (1958) varies around the circumference. The betatron oscillations are given by

$$ x = a \beta^{1/2} \sin \left[ \int \frac{ds}{\beta + \delta} \right] \quad \text{(IV.6)} $$

where $s$ is the distance along the orbit and $\delta$ an arbitrary phase angle. The beam width is therefore everywhere proportional to $\beta^{1/2}$. Relative maxima and minima of $\beta$ occur in the middle of all F and D sectors.

If straight sections of length $L$ are regularly inserted into a structure at $N$ places around the circumference, the change in $Q$-value is in a first order approximation for small $L$:

$$ \Delta Q = NL \frac{(1 + \sqrt{4(d\beta/ds)^2})}{4\pi \beta} \quad \text{(IV.7)} $$

where $\beta$ is the value of the amplitude function at the place of the insertion and $d\beta/ds$ is its azimuthal derivative at the same position. The amplitude function will now fluctuate around the circumference and its maximum increase will be in the same approximation:

$$ \left( \frac{\Delta \beta}{\beta} \right)_{\text{max}} = \frac{L}{2\beta \sin \frac{2\pi Q}{N}} \left(1 + \sqrt{4(d\beta/ds)^2}\right) \quad \text{(IV.9)} $$
In a typical alternating gradient structure \( \frac{d\beta}{ds} \) vanishes in the middle of \( F \) and \( D \) sectors, it is of the order of four between \( F \) and \( D \) sectors. Equations (IV.7) and (IV.9) thus show that the betatron amplitude functions and the \( Q \)-values are much less disturbed by straight sections inserted mid-\( F \) or mid-\( D \) than by straight sections inserted between \( F \) and \( D \) sectors. Therefore the positions of the long straight sections chosen on the basis of matching the momentum compactions function are also preferable since they cause the smaller disturbance of the betatron amplitude functions and the \( Q \)-values.

3. **Comparison of the various ISR Magnet Structures**

Three distinct types of magnet structures have been considered for the ISR: the split focusing and bending (sfb) structure, the FOFOOD structure and the FODO structure.

It may be noted that our method of inserting long straight sections implies that the inner arcs always resemble a FOFOOD structure, so that the characteristic differences between the two last types only show up in the outer arcs. In the following paragraphs we list some of their inherent properties and the important relative advantages and disadvantages of the three structures, and then present a motivation for choosing the FODOtype.

3.1. **Inherent Properties of the various ISR Magnet Structures**

The various structures should be compared under the following aspects:

i) Accessibility of the magnet gap

ii) magnetic field gradients

iii) betatron oscillation amplitudes, momentum compaction factors

iv) insertion of correcting elements

v) sensitivity to magnet position errors

vi) cost

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In the following a short discussion is given of how the various magnet structures under consideration influence these aspects.

3.1.1. Accessibility of the Magnet Gap

As will be seen from chapter IX very strict vacuum requirements have to be imposed on the storage rings. This requires, among other things, that considerations of simplicity in the vacuum chamber design become very important and influence considerably the design of other components of the ISR.

One important feature of an ultra high vacuum chamber is that it must have very thick and rigid flanges at the junctions between the chamber sections. The flange size excludes the possibility of pushing the vacuum chamber sections azimuthally through magnets whose aperture fits rather closely around the vacuum chamber.

With an sfb structure, therefore, the quadrupoles must be split in their median planes to give access to the vacuum chamber, which can easily be placed between the magnet poles radially.

With a POPOD structure where the units are made of an open and a closed sector, as in the CPS, the chamber must be made in two pieces with a junction in a gap between F and D sectors. The half chamber for the closed sector may be pushed in azimuthally if equipment in the straight sections is removed. This would be a major operation and would cause severe difficulties. It would only be considered acceptable if there were other overriding reasons in the choice of this structure.

The easiest structure from the point of view of vacuum chamber accessibility is FODO. If one decides to make only open magnet units the vacuum chamber can be taken out radially without any difficulty.
3.1.2. Magnetic Field Gradients

Regarding the magnetic field gradients FODO and sfb structures are certainly more efficient than FOFDOD structures since they have these gradients in the centres of F and D sections and not right at their edges. As a consequence the gradients in a FODO structure are roughly 3/4 of those in the corresponding FOFDOD structure. For the same field on the equilibrium orbit this increases the height of the minimum gap and thus reduces the saturation effects there.

Because of this fact less poleface winding current will be needed for their correction.

3.1.3. Betatron Oscillation Amplitudes, Momentum Compaction Factors

Tab. IV.2 shows the orbit parameters of a FOFDOD and a FODO structure with approximately equal lengths of the interaction regions.

<table>
<thead>
<tr>
<th>Tab. IV.2</th>
<th>FOFDOD</th>
<th>FODO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta(H)_{\text{max}}$</td>
<td>34.2</td>
<td>38.0</td>
</tr>
<tr>
<td>$\beta(V)_{\text{max}}$</td>
<td>43.2</td>
<td>53.0</td>
</tr>
<tr>
<td>$\beta(V)_{\text{IR}}$</td>
<td>13.4</td>
<td>13.6</td>
</tr>
<tr>
<td>$\alpha(p)$</td>
<td>2.20</td>
<td>2.26</td>
</tr>
</tbody>
</table>

The momentum compaction and the vertical $\beta$-functions at the intersections are approximately equal, whereas the maximum betatron amplitudes are $7\%$ bigger horizontally and $11\%$ bigger vertically in the FODO structure.

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3.1.4. Correcting Elements

Obviously the sf6 structure does not need any correcting quadrupoles. This flexibility in the choice of the Q-values was one of the reasons for proposing it. The straight sections available in FOFDOD structures are just the right places for installing correcting quadrupoles, this is why FOFDOD structures have been used in the CPS and the AGS. In a FODO structure such mid-F or mid-D straight sections are only available in the inner arcs. There it must be checked if an adequate correction can be obtained with such a small number of quadrupoles or if other methods of correction must be used.

We believe that poleface windings on the magnet units can carry also enough current for changing their gradient. A more detailed analysis which will be presented in chapter V has shown that the linear current densities, necessary in a FOFDOD structure for correcting saturation alone, and in a FODO structure for correcting saturation and changing the gradient in the worst combination, are roughly equal.

For higher order corrections there is no big difference between the various structures since the number of mid-F and mid-D straight sections available for sextupoles is approximately equal. They can only be inserted in the inner arc. This fact is obvious in the FODO and sf6 structures since there are no mid-F or mid-D straight sections in the outer arcs of these structures. For the FOFDOD structure computations show that the number of correcting quadrupoles cannot be reduced sufficiently to provide space for sextupoles without causing serious perturbations of the betatron behaviour.

3.1.5. Sensitivity to Magnet Position Errors

Magnet position errors are due to random errors in the alignment of the magnet units and due to ground movements. Considering random alignment errors first the following can be said:
FOFDOD structures made of \( \frac{1}{2} F \frac{1}{2} D \) units as in the CPS are less sensitive to parallel displacements than FODO and sfb structures. They are, however, more sensitive to rotations of the units around their mid points. Since a priori there is no reason why one of these types of misalignments should be more frequent than the other, no marked differences are to be expected in the sensitivity of various structures to random alignment errors.

The validity of this statement is slightly modified by the fact that FOFOD structures are in practice less sensitive to rotations than FODO structures are to parallel displacements, because the position of the magnet units is measured by means of reference marks at their ends. However, this difference is largely balanced by the inherently higher gradient of a FOFOD structure.

Ground instabilities, on the other hand, lead in general to magnet position errors with wavelengths much longer than the magnet units. Thus also from this point of view the detailed layout of the magnet structure has no importance.

### 3.1.6. Cost

An economic study has shown that the cost of the sfb magnet with its power supply and the power consumption costs are respectively 1.4 and 1.7 times higher than for a structure with gradient magnets. This results from the fact that in an sfb structure quite appreciable magnetic fields are generated somewhere just to be compensated elsewhere.

### 3.2. Motivation for the Choice of a FODO Structure

The sfb structure can be discarded for economic reasons. One is therefore left with the choice between FODO and FOFOD structures. The cost, insertion of sextupoles and the sensitivity to magnet position errors do not provide important
arguments in favour of one or the other of these. Simplicity of quadrupole correction and betatron amplitudes favour FOXDODO, accessibility and gradient favour FODO. Of these the betatron amplitudes are of minor importance since they only are a 10\% effect. As has been mentioned earlier, the lower gradient in the FODO structure makes up for the simplicity of the quadrupole correction. Thus only accessibility of the magnet gap remains the important issue in the choice. As already mentioned, under otherwise fairly equal conditions one would certainly favour the choice that would provide the simplest vacuum system design. These considerations have led us to choose the FODO structure.

4. Orbit Parameters of a FODO Structure

4.1. Layout of the FODO Structure

The structure chosen has 48 periods, thus 12 periods in one superperiod. These 12 periods are arranged in 7 compact periods, forming the central part of the outer arc, and 5 expanded periods such that the intersections take place near the centre of the two extreme expanded periods. This is shown in Fig. V.2.

In the present design the average radius of the whole ring has been chosen as 150 m. The average radius of the compact lattice is 102 m, that of the expanded lattice 218 m, and the intersection points are on a circle of 148.5 m radius. In the final design these numbers will have to be modified slightly such that the circumference of the injection orbit in the ISR is exactly 1.5 times the circumference of the ejection orbit in the CPS. This ejection orbit is not yet accurately fixed.

The long straight sections are all mid-F since this is necessary for the interaction regions. As eq. (II.4) shows, the interaction rate is inversely proportional to the beam height. Therefore one wants a small beam height.
which is obtained in mid-F. Having made this choice, one also makes the remaining long straight sections mid-F in order to avoid unnecessary perturbations of the machine periodicity.

From this point of view there need not be any mid-D straight sections in the inner arc. This is even advantageous since it yields the longest interaction regions with minimum disturbance of the machine periodicity. Some space, however, is necessary for mid-D sextupoles. We intend to use these, together with mid-F sextupoles in the long straight sections, for adjusting the radial dependence of the Q-values.

On the basis of these arguments we have inserted fairly short mid-D straight sections in the inner three periods of the inner arc but not in the periods containing the interaction regions.

Although the intersection regions are the more useful for experiments the longer they are, a practical upper limit for their length is set by the fact that the vertical $\beta$-function starts rising steeply above a certain value.

In our design the length of the interaction regions is near to the beginning of that rise. The lengths of the remaining three mid-F straight sections were then chosen such as to minimize the maximum value of the vertical $\beta$-function.

The main parameters of our FODO structure are given in Tab. IV.3. Most of the computations were performed taking fringes field effects into account as will be discussed later.

4.2. Magnetic Field and Gradient

The average length of the magnet units is fixed by considering the field on the equilibrium orbit and the maximum total energy of the protons which should, of course, correspond to the maximum energy available from the CPS, namely 28 GeV.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total energy</td>
<td>$E_{\text{max}}$ = 28 GeV</td>
</tr>
<tr>
<td>Peak field on central orbit</td>
<td>$B_{c\text{ max}}$ = 1.2 T</td>
</tr>
<tr>
<td>Magnetic radius</td>
<td>$\rho$ = 79.2 m</td>
</tr>
<tr>
<td>Average radius</td>
<td>$R$ = 150 m</td>
</tr>
<tr>
<td>Profile parameter in F units</td>
<td>$(n/\rho)_F$ = -3.14 m$^{-1}$</td>
</tr>
<tr>
<td>Number of periods</td>
<td>$(n/\rho)_D$ = 3.05 m$^{-1}$</td>
</tr>
<tr>
<td>Number of superperiods</td>
<td>M = 48</td>
</tr>
<tr>
<td>Number of intersections</td>
<td>S = 4</td>
</tr>
<tr>
<td>Q-value</td>
<td>8</td>
</tr>
<tr>
<td>Transition energy</td>
<td>$\gamma_t$ = 9.1</td>
</tr>
<tr>
<td>Maximum $\beta$ horizontally</td>
<td>$\beta(\beta)_{\text{max}}$ = 38.0 m</td>
</tr>
<tr>
<td>$\beta$ vertically</td>
<td>$\beta(\beta)_{\text{max}}$ = 53.0 m</td>
</tr>
<tr>
<td>Average $\beta$ horizontally</td>
<td>$\beta(\beta)_{\text{av}}$ = 20.8 m</td>
</tr>
<tr>
<td>$\beta$ vertically</td>
<td>$\beta(\beta)_{\text{av}}$ = 23.1 m</td>
</tr>
<tr>
<td>Mid-F momentum compaction function</td>
<td>$\alpha_p(F)$ = 2.26 m</td>
</tr>
<tr>
<td>Length of magnet units in outer arc</td>
<td>$\alpha_p(D)$ = 1.51 m</td>
</tr>
<tr>
<td>5.03 m</td>
<td></td>
</tr>
<tr>
<td>2.44 m</td>
<td></td>
</tr>
<tr>
<td>Space between two half units in outer arc</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Length of straight section between core edges</td>
<td>$a_0$ = 1.63 m</td>
</tr>
<tr>
<td>$a_1$</td>
<td>16.78 m</td>
</tr>
<tr>
<td>$a_2$</td>
<td>1.00 m</td>
</tr>
<tr>
<td>$a_3$</td>
<td>13.28 m</td>
</tr>
<tr>
<td>$a_4$</td>
<td>2.00 m</td>
</tr>
<tr>
<td>$a_5$</td>
<td>10.94 m</td>
</tr>
<tr>
<td>$a_6$</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Horizontal aperture</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Vertical aperture</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Gap height at centre line</td>
<td>0.10 m</td>
</tr>
</tbody>
</table>

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The maximum value of the magnetic field is subject to serious limitations. Whereas in an accelerator like the CPS a few centimetres of good field at top energy are sufficient, in the ISR the field must be correct across the whole aperture, thus a much better correction is required. The fact that the magnet operates d.c. does not ease the situation since heating of the poleface windings limits the possibility of correction. We have therefore chosen a maximum magnetic field on the equilibrium orbit of approximately 1.2 T. (1 T = 1 Wb/m²).

The bending radius is then \( \rho = 79.2 \) m and, if there are 4 units per period, the length of a unit is \( L_u = 2.59 \) m.

The information gathered so far can be used to compute approximately the magnetic field gradient in the units. We use the following formula valid for \( Q \ll M \):

\[
Q = \frac{\pi}{2} \sqrt{\frac{\rho}{M}} \left| \frac{n}{\rho} \right| \sqrt{\frac{R}{\rho}} \frac{R_{\text{FODO}}}{\rho} (3 \frac{R_{\text{FODO}}}{\rho} - 2) \quad (\text{IV.10})
\]

Here \( R_{\text{FODO}}/\rho \) is a partial circumference factor for straight sections inserted in a FODO manner. Inserting numbers yields:

\[
\left| \frac{n}{\rho} \right| \approx 3.1 \text{ m}^{-1} \quad (\text{IV.11})
\]

To compensate for the unbalanced centrifugal force in the horizontal plane and for the difference in total mid-F and mid-D straight section length the horizontal and vertical focusing strength must be different if both \( Q \)-values are to be equal. In the CPS this has been achieved by slightly different lengths of F and D units but equal profile parameters.

Since we shall incorporate a different sextupole component into the pole profile of F and D units there is no technical advantage in designing them for the same gradient. Then the lengths of corresponding F and D units can be made equal and we are left with units of only two different lengths: long units for the outer arc and short units for the inner arc.
4.3. The $\alpha$ and $\beta$ Functions and their Optimization

In this chapter we shall discuss the influence of changes in the structure layout, and thus provide some justification for our choice.

Fig. IV.1 shows how the horizontal and vertical $\beta$-functions vary along half a superperiod of the proposed structure.

4.3.1. Variations of the Length of the Interaction Regions

Tab. IV.4 shows the maxima of $\beta(H)$ and $\beta(V)$ for various lengths of the interaction regions. In the computations it was assumed that $\Delta a_4 = \Delta a_6 = -2/3 \Delta a_2$, i.e. the length gained or lost in the interaction regions was equally distributed among the remaining long mid-$F$ straight sections.

There is rather little variation in the $\beta$-functions towards shorter interaction regions, but there is a steep rise in $\beta(V)$ if one lengthens the interaction regions beyond the value chosen. However, the figures given should be regarded with some caution since they were only carefully optimized for the interaction region length chosen.

<table>
<thead>
<tr>
<th>$a_2$ [m]</th>
<th>$\beta(H)_{\text{max}}$ [m]</th>
<th>$\beta(V)_{\text{max}}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.78</td>
<td>36.5</td>
<td>52.0</td>
</tr>
<tr>
<td>14.78</td>
<td>36.9</td>
<td>50.4</td>
</tr>
<tr>
<td>15.78</td>
<td>37.4</td>
<td>49.0</td>
</tr>
<tr>
<td>16.78</td>
<td>38.0</td>
<td>53.0</td>
</tr>
<tr>
<td>17.78</td>
<td>38.7</td>
<td>58.4</td>
</tr>
<tr>
<td>18.78</td>
<td>-39.5</td>
<td>63.9</td>
</tr>
</tbody>
</table>
4.3.2. Variation of the inner three mid-F Straight Sections

A variation of the lengths of the inner three mid-F straight sections changes the heights of the various vertical $\beta$-maxima such that for a certain length a minimum occurs since two peaks have equal heights. This is shown in Fig. IV.2 which was computed with the assumption $\Delta a_4 = -\frac{1}{2} \Delta a_6$, all other straight sections having their design values.

4.3.3. Variation of the Q-value

Since the mismatch of the betatron oscillations in our structure leads to a stopband at $Q = 8$ its effects were computed. The resulting $\beta$-functions are plotted in Fig. IV.3. Their variation in the working diamond from $Q = 8.5$ to 9 is rather small.

4.3.4. Different Choices of the Q-values

We have explained earlier that the superperiodicity of the ISR structure leaves the choice between $Q = 7.25$ and $Q = 8.75$. If one does not make horizontal and vertical Q-values equal from the beginning one can choose between the four combinations given in Tab. IV.5.

<p>| Tab. IV.5. Orbit Parameters for various Choices of Q |</p>
<table>
<thead>
<tr>
<th>Q(H)</th>
<th>Q(V)</th>
<th>$\beta$(H) [m]</th>
<th>$\beta$(V) [m]</th>
<th>$\alpha_p$(F) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.75</td>
<td>8.75</td>
<td>38.0</td>
<td>53.0</td>
<td>2.26</td>
</tr>
<tr>
<td>8.75</td>
<td>7.25</td>
<td>37.2</td>
<td>92.4</td>
<td>2.23</td>
</tr>
<tr>
<td>7.25</td>
<td>8.75</td>
<td>38.9</td>
<td>49.3</td>
<td>3.20</td>
</tr>
<tr>
<td>7.25</td>
<td>7.25</td>
<td>38.4</td>
<td>85.1</td>
<td>3.15</td>
</tr>
</tbody>
</table>
The maximum $\beta$-values given here are for straight section lengths as given in Tab. IV.3. From these results we conclude that $Q(V) = 7.25$ is excluded since it has such a high $\beta(V)$. To support this we give in Figs IV.4 and IV.5 the maximum $\beta$-values as functions of the straight section $a_0$ which is the only degree of freedom left in our structure. It is obvious that the variation of the $\beta$'s in these figures is very small.

We thus have to choose between $Q(H) = 8.75$ and $Q(H) = 7.25$ both with $Q(V) = 8.75$. Tab. IV.5 shows that both have practically identical betatron amplitudes. However, the inherently bigger momentum compaction function of a structure with $Q(H) = 7.25$ makes it less attractive than that with $Q(H) = 8.75$. This is especially relevant since computations show that the gradients for the two structures differ by only $10\%$ whereas their momentum compaction functions differ by almost $50\%$. Most of the aperture in the ISR is used by the width of the stacked beam and the injection which are proportional to $a_p$. Therefore the necessary relative increase of the width of the good field region for $Q(H) = 7.25$ is higher than the relative decrease in gradient. Thus the magnet for $Q(H) = 7.25$ would be more difficult and certainly more expensive. A further argument against $Q(H) = 7.25$ is the linear coupling resonance occurring at $Q(H) + Q(V) = 16$. For these reasons we have chosen $Q(H) = Q(V) = 8.75$.

4.4. Influence of Field, Gradient and Position Errors

4.4.1. Systematic Errors

If the gradients of the F and D sectors have systematic errors $\delta G_F$ and $\delta G_D$ respectively the changes in the $Q$-values are
\[ \delta Q(H) = 17.5 \frac{\delta G_F}{G_F} - 8.9 \frac{\delta G_D}{G_D} \]  

\[ \delta Q(V) = -13.5 \frac{\delta G_F}{G_F} + 26.2 \frac{\delta G_D}{G_D} \]  

(IV.12)

Systematic errors \( \delta L \) in the lengths of the magnet units change the Q-values by the following amounts:

\[ \delta Q(H) = 5.0 \delta L_F - 5.5 \delta L_D \]

\[ \delta Q(V) = -8.1 \delta L_F + 7.3 \delta L_D \]  

(IV.13)

4.4.2. Random Errors

The short magnet units are made of single blocks and the long units of two blocks placed on a common girder. There are reference marks on each end of the units. With the assumption that the magnet position errors are distributed at random with an r.m.s. value \( \delta \), the maximum distortion \( Y_{98}(\delta) \) in either plane that will not be exceeded in 98% of the machines built with these errors can be computed. We use the following generalization of the well-known formula of Courant and Snyder (1958) for our structure with \( N_1 \) long and \( N_2 \) short units:

\[
Y_{98}(\delta) = \frac{2\pi}{|\sin \pi Q|} \left| n \rho \right| \sqrt{ \frac{\beta_{av} \beta_{max}}{2(N_1 + N_2/2)}} \left| \frac{4N_1 + N_2}{4N_1 + 2N_2} \right|^\delta
\]  

(IV.14)
In this expression we used the fact that the long units are twice as long as the short ones. The factor 2 in the denominator of the first square root occurs since there are two reference marks on each unit.

Inserting figures into (IV.14) yields:

\[ X_{98}(\delta) = 525 \]
\[ Z_{98}(\delta) = 625 \]  

(IV.14 a)

The following three effects contribute to magnet position errors:

i) r.m.s. position errors of the reference marks on the magnet units with respect to the equilibrium orbit \( \delta_1 \)

ii) r.m.s. alignment errors of the reference marks in the tunnel \( \delta_2 \)

iii) r.m.s. ground movement amplitudes \( \delta_3 \)

In the following these errors are assumed to be statistically independent.

R.m.s. field errors \( \delta B/B \) in all magnets distort the horizontal closed orbit by the following amount:

\[ X_{98}(\delta B) = 17 \delta B/B \]  

(IV.14 b)

Random errors in the field gradient \( \delta G/G \) introduce shifts in the \( Q \)-values \( \Delta Q \), stopbands at integral and half integral \( Q \)-values of width \( \delta Q \), and extra wiggle on the betatron amplitude functions \( \Delta \beta /\beta \). Inserting numbers into formulae given by Courant and Snyder (1958) yields the following values:

\[ \Delta Q = 2.6 \delta G/G \]
\[ \delta Q = 5.2 \delta G/G \]
\[ (\frac{\Delta \beta}{\beta})_{\text{max}} = 5.2 \delta G/G \]  

(IV.15)

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At a distance $X_o$ from the equilibrium orbit these gradients errors lead to field errors $\delta B/B$ which are given by:

$$\delta B/B = (n/\rho) X_o \delta G/G$$  \hspace{1cm} (IV.16)

In the CPS $\delta G/G$ was approximately $10^{-3}$. If one assumes the same value for the ISR magnets all effects (IV.15) are practically negligible. Also the field error (IV.16) at the edges of the vacuum chamber is small compared with that assumed in Tab. IV.9 for the field errors on the equilibrium orbit.

4.5. Influence of localized Corrections

As mentioned earlier we plan to adjust the $Q$-values by poleface windings on the magnet units, and the slopes $\partial Q/\partial p$ by separate sextupoles placed in the inner arcs only. This choice is not immediately obvious, in fact it is equally logical to use the poleface windings for sextupole correction and to adjust the $Q$-values with separate quadrupoles.

In the following sections we shall give some numerical justification for our choice.

4.5.1. Quadrupole Correction

Tab. IV.6 shows the quadrupole strength $C$ and the orbit parameters if the $Q$-values are changed by $\Delta Q = \pm 0.25$ using two quadrupole pairs in each inner arc at the positions marked $S_1$ and $S_2$ in Fig. V.1. The nominal orbit parameters are given for comparison.

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Tab. IV.6. Separate Quadrupole Correction

| Q(H) = Q(V) | 9.000 | 8.750 | 8.500 |
| Cₚ | -0.0156 | 0 | 0.0146 m⁻¹ |
| Cᵥ | 0.0155 | 0 | -0.0142 m⁻¹ |
| β(H)ₘₐₓ | 44.3 | 38.0 | 59.0 m |
| β(V)ₘₐₓ | 56.4 | 53.0 | 81.4 m |
| αₚ(S)ₘₐₓ | 2.35 | 2.26 | 2.65 m |

It is obvious from Tab. IV.6 that the quadrupoles introduce quite large extra wiggles, especially in the vertical amplitude function.

Fig. IV.3 already shows that these extra wiggles must be much less important if the Q-values are adjusted by poleface windings. Tab. IV.7 gives the numbers.

Tab. IV.7. Q-changes with Poleface Windings

| Q(H) = Q(V) | 9.000 | 8.750 | 8.500 |
| β(H)ₘₐₓ | 38.7 | 38.0 | 38.6 m |
| β(V)ₘₐₓ | 52.9 | 53.0 | 58.1 m |
| αₚ(S)ₘₐₓ | 2.15 | 2.26 | 2.38 m |

4.5.2. Sextupole Correction

To fix numbers for the amount of correction by the sextupoles we have chosen the following set:

\[ \Delta Q(H) = 4 \Delta p/p \]  \hspace{1cm} (IV.17)

\[ \Delta Q(V) = 6 \Delta p/p \]

These changes are achieved with the following sextupole strengths:
\[ C_F = -0.125 \text{ m}^{-2} \]
\[ C_B = 0.221 \text{ m}^{-2} \]  

(IV.18)

The programme we are using for our computations considers only the linear betatron oscillations. It handles sextupoles and other non-linear elements by computing their gradient on the closed orbit for particles with the momentum error in question. Therefore, in our approximation, the betatron oscillations are not changed by sextupoles on the equilibrium orbit, they are, however, changed for particles with $\Delta p/p \neq 0$.

So far, all betatron amplitude functions were given on the equilibrium orbit. To show the influence of the sextupoles it is necessary to include the whole momentum bite that the stacked beam is likely to occupy at any given moment. It will be shown later that this is $(\Delta p/p) \leq 0.02$.

In Tab. IV.8 we give the maximum values for the maximum of the betatron amplitude functions occurring within $(\Delta p/p) \leq 0.02$ and the maximum distances $\alpha_p(\pm)$ and $\alpha_p(\mp)$ of the closed orbits for $\Delta p/p = \pm 0.02$ from the equilibrium orbit for three different arrangements:

i) The constant $Q$ structure (including the end effects and the sextupole profile on the magnet units to be discussed in section 5) without sextupoles,

ii) the same structure with two pairs of sextupoles with the strength given by (IV.18) in the positions marked $S_1$ and $S_2$ in Fig. V.1 in each inner arc,

iii) the same structure as for i) with the sextupole profile on the magnet units changed such as to get the same value for $\frac{\partial Q}{\partial p}$ as for ii).

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4.5.3. Conclusions for the Choice of the Correction Methods

From a comparison of the betatron amplitude functions given in Tabs. IV.6 and IV.7 for quadrupole correction with separate quadrupoles and poleface windings it becomes clear that it is impracticable to adjust the Q-values with such a small number of quadrupoles. Tab. IV.8 shows that the perturbations in the betatron amplitude functions and in the closed orbits are practically negligible for both kinds of sextupole correction.

Therefore we have decided to adjust the Q-values with poleface windings and to change the values of $\Delta Q/bp$ by separate sextupoles.

4.6. Requirements for Poleface Windings

As seen from section 4.5.1 we have not foreseen any separate quadrupoles for adjusting Q-values within the diamond. Instead, we plan to use the poleface windings of the magnet units. How and why this is possible will be discussed later in chapter V. Here we only list the necessary gradient changes:

$$\Delta C_F = -0.292 \Delta Q(H) - 0.099 \Delta Q(V) \quad [T/m] \quad (IV.19)$$

$$\Delta C_D = 0.146 \Delta Q(H) + 0.189 \Delta Q(V) \quad [T/m]$$

Thus for changing Q across the whole diamond ($\Delta Q(H) = \Delta Q(V) = \pm 0.25$) the following gradient changes are necessary:
\[ \Delta g_F = \pm 0.0978 \quad [T/m] \]
\[ \Delta g_D = \pm 0.0838 \quad [T/m] \quad \text{(IV.20)} \]

5. The required Field Distribution

For a start we have looked at an ideal machine built with curved magnet units of 2.59 m length. Their field drops to zero abruptly at the ends, which are perpendicular to the equilibrium orbit. We used a computer programme for strong focusing rings written by Van der Meer to obtain the following profile parameters:

\[ \frac{(n/\rho)}{F_{id}} = -3.050 \quad \text{m}^{-1} \]
\[ \frac{(n/\rho)}{D_{id}} = 2.959 \quad \text{m}^{-1} \quad \text{(IV.21)} \]

However, in a physical magnet the field does not drop to zero abruptly at the ends due to the fringe field. A useful concept for the description of these effects are effective lengths of the fringing regions. We define two of them, that for field \( L_B(r) \)

\[ L_B(r) = \frac{1}{B(r, \theta_u)} \int_{\theta_u}^{\theta_o} B(r, \theta) \, d\theta - L \quad \text{(IV.22)} \]

and that for gradient \( L_G(r) \)

\[ L_G(r) = \frac{1}{(\partial B/\partial r)_{r, \theta_u}} \int_{\theta_u}^{\theta_o} (\partial B/\partial r)_{r, \theta} \, d\theta - L \quad \text{(IV.23)} \]
where $\Theta_u$ is an azimuthal position in the unit where $B(r, \Theta)$ does not depend on $\Theta$, $\Theta_o$ is an azimuthal position far outside the magnet gap, and $L$ is the azimuthal distance from $\Theta_u$ to the end of the yoke.

In general both $L_B$ and $L_G$ are functions of the radial distance $r$ from the equilibrium orbit. They are usually determined from measurements on a magnet model. Since there is not yet such a model for the ISR magnet we have used in our computations the following values derived from the CPS prototype unit measurements by approximate scaling:

$$L_B(0) = 7.58 \text{ cm}$$
$$L_G(0) = 3.15 \text{ cm}$$

$$\frac{\partial L_G}{\partial r}(0) = 0.21$$

These figures apply to a magnetic field $B_o = 0.3$ T. In the computations they were used in the following way:

The core length of the units was chosen such that $L_u$ and two end effects $L_B(0)$ add up to $2.592$ m, thus

$$L_u = 2.592 \text{ m} - 2 L_B(0) \quad \text{(IV.26)}$$

(an air gap approximately equal to $2L_B$ is assumed between the joining half units in the outer arc). We then arrive at the numbers given in Tab. IV.3. The gradient length of units becomes:

$$L_{uG} = L_u + 2 L_G(0) \quad \text{(IV.27)}$$

Since the computer programme used is not aware of a difference between effective lengths for field and for gradient, the figures given by (IV.27) were used to compute the actual profile parameters:

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\[(n/p)_F = -3.141 \text{ m}^{-1}\]
\[(n/p)_D = 3.048 \text{ m}^{-1}\] (IV.28)

\[L_B \text{ and } L_G \text{ are functions of the field on the equilibrium orbit. We computed the influence of independent changes in either of them on the } Q \text{-values. The results are:}\]

\[\delta Q(H) = 3.1 \delta L_G\]
\[\delta Q(V) = 4.4 \delta L_G\] (IV.28 a)
\[\delta Q(H) = -3.3 \delta L_B\]
\[\delta Q(V) = -4.9 \delta L_B\]

These changes are thus of nearly equal magnitude but opposite sign. Since measurements on the CPS prototype magnet unit show that \(L_B\) and \(L_G\) decrease by roughly equal amounts with increasing field level, the \(Q\)-values must also remain approximately constant.

An ideal structure has a momentum dependence of the \(Q\)-values such that \(\Delta Q/Q \approx -\Delta p/p\); the exact numbers for our structure with edges perpendicular to the equilibrium orbit are:

\[\Delta Q(H) = -7.95 \Delta p/p\]
\[\Delta Q(V) = -12.35 \Delta p/p\] (IV.29)

As shown in (IV.25) the effective length of the magnet units changes with radial position. \(F\) units are shorter and \(D\) units are longer for \(r > 0\). One therefore expects that \(Q(H)\) is reduced and \(Q(V)\) is increased for \(r > 0\). The combined momentum and end effects are:

\[\Delta Q(H) = -16.60 \Delta p/p\]
\[\Delta Q(V) = -0.80 \Delta p/p\] (IV.30)
Since the distance from the injection orbit to the bottom of the stack is 36 mm, and the width of the stack is 57 mm in mid-F, the total momentum range occupied by the beam is approximately 40%. The variation of Q(V) from (IV.29) is then almost 0.5, and the variation in Q(H) from (IV.30) exceeds this value. Therefore parts of the stack either cross or come very near to the stopbands at Q = 8.5 and Q = 9 if neither momentum nor end effects are compensated.

Obviously the maximum distance from the adjacent stopbands is obtained for all momenta simultaneously if the Q-values are independent of momentum. The sextupole components in the field distribution necessary to achieve this are:

\[
\begin{align*}
n_F/\rho &= -1.852 \text{ m}^{-2} & n_F/n_F &= 0.589 \text{ m}^{-1} \\
n_D/\rho &= 1.313 \text{ m}^{-2} & n_D/n_D &= 0.431 \text{ m}^{-1}
\end{align*}
\] (IV.31)

The amount of correction is quite substantial. The gradients at the outer edge of the aperture are 60% higher in D units and 90% higher in F units than those at the inner edge of the aperture.

6. Aperture Requirements

6.1. Beam Emittance

We assume that the beam radius in the CPS at a position where \( \beta = 16 \text{ m} \) is 3 mm at 25 GeV and 5 mm at 10 GeV. In the ISR with \( \beta_{\text{max}}(H) = 38.0 \text{ m} \) and \( \beta_{\text{max}}(V) = 53.0 \text{ m} \) the maximum beam radii are:

\[
\begin{align*}
\varphi &= 4.7 \text{ mm and } \varphi' &= 5.4 \text{ mm at 25 GeV} \\
\varphi &= 7.9 \text{ mm and } \varphi &= 9.0 \text{ mm at 10 GeV}
\end{align*}
\] (IV.32)

The radial amplitude of the synchrotron oscillations both in the CPS and the ISR is about 1 mm.

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6.2. Injection Space and Errors

Injection enters into aperture considerations in two ways

i) Field errors in the ejection and injection magnets and radial closed orbit instabilities in the CPS and the ISR displace the centre of the injected beam which then occupies more space than given by its emittance. The amount of displacement due to these errors is estimated in chapter VIII, the figures obtained being:

\[ \Delta x_{\text{inj}} = 5.8 \text{ mm} \]
\[ \Delta y_{\text{inj}} = 4.1 \text{ mm} \]  \hspace{1cm} (IV.33)

Combining (IV.32) and (IV.33) gives the following figures for the maximum width \( w \) and the maximum height \( h \) of the injected beam anywhere around the circumference:

\[ w = 21.0 \text{ mm and } h = 19.0 \text{ mm at 25 GeV} \]  \hspace{1cm} (IV.34)
\[ w = 27.4 \text{ mm and } h = 26.2 \text{ mm at 10 GeV} \]

In the interaction regions the height is the important quantity and it is

\[ h_{\text{IR}} = 9.6 \text{ mm at 25 GeV} \]
\[ h_{\text{IR}} = 13.3 \text{ mm at 10 GeV} \]

ii) Since the injection kicker is operating when there is already a stacked beam in the ISR the kicker stray field must not affect the stack. This sets a lower limit for the distance between the injection orbit and the bottom of the stack. This is estimated in chapter VIII and found to be 36 mm.

5.3. Influence of Random Magnet Errors

We assume r.m.s. errors of the various magnet imperfections given in Tab. IV.9.

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Tab. IV.9. Root Mean Square Magnet Imperfections

<table>
<thead>
<tr>
<th>Imperfection</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position of reference marks with respect to equilibrium orbit</td>
<td>0.1</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Alignment of reference marks in tunnel</td>
<td>0.2</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Ground movements</td>
<td>0.2</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Relative magnetic field error</td>
<td>$5 \times 10^{-4}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Inserting these numbers into (IV.15) and (IV.16) and adding the various closed orbit distortions quadratically yields the following total distortions which will not be exceeded in 98% of all machines:

$$X_{98}(\text{total}) = 18 \text{ mm}$$
$$Z_{98}(\text{total}) = 11 \text{ mm}$$

6.4. Aperture for Stacking

The design momentum spread in the stack is $\delta p/p = 2.5\%$. Thus the maximum width of the stack is $\delta x = \alpha (\text{max}) \delta p/p = 57 \text{ mm}$.

6.5. Vertical Aperture for Multiple Scattering

The dimensions of the beam slowly increase due to multiple scattering with the residual gas. We base the choice of the vertical aperture on the requirement that 95% of the beam should remain inside the aperture after 12 hours operation at a pressure of $10^{-9}$ Torr.

The vertical aperture for the beam must then be 28 mm for a proton energy of 25 GeV.

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6.6. Conclusions for the Aperture

In the following we combine the numbers given in the previous sections to determine the aperture requirements for the ISR. They are based on the beam characteristics at 25 GeV.

A schematic cross section through the ISR vacuum chamber at the position of the kicker magnet is given in Fig. IV.6. The horizontal aperture is made up as follows:

<table>
<thead>
<tr>
<th>Stack width</th>
<th>57 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the injection orbit to the bottom of the stack</td>
<td>36 mm</td>
</tr>
<tr>
<td>Beam size</td>
<td>21 mm</td>
</tr>
<tr>
<td>Closed orbit distortions</td>
<td>36 mm</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>150 mm</strong></td>
</tr>
</tbody>
</table>

Since multiple scattering only affects the edges of the stack and since one can make sufficient horizontal space available by moving the stack into the centre of the vacuum chamber when stacking is finished, no space has been allowed for horizontal multiple scattering.

The vertical aperture is given by the following two contributions:

| Beam size including gas scattering | 28 mm |
| Closed orbit distortions | 22 mm |
| **Total** | **50 mm** |

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7. Special Magnets for Experimental Purposes

7.1. Superpositions of Closed Orbits

A small beam width in some interaction regions, which is desirable for certain types of experiments, can be obtained by superposition of the closed orbits for different momenta there. Terwilliger (1959) has shown that this can be achieved by applying a harmonic gradient perturbation to the magnet structure with a harmonic number close to \( Q \).

In Fig. IV.7 a distribution of Terwilliger quadrupoles \( T_F \) and \( T_D \) is given together with the momentum compaction \( \alpha_p(s) \) over one superperiod. All closed orbits are coincident and parallel to each other in four of the eight intersection regions; in the remaining four the beam width is only slightly reduced. A total number of 24 quadrupoles is used with the following strengths

\[
\begin{align*}
8 \ F \ \text{quadrupoles with } C &= -0.0154 \ m^{-1} \\
8 \ D_1 \" C &= 0.0059 \ m^{-1} \\
8 \ D_2 \" C &= 0.0095 \ m^{-1}
\end{align*}
\] (IV.36)

The Terwilliger scheme has the following effects on the orbit parameters:

Since the average momentum compaction function is unchanged in a first approximation, \( \alpha_p(s) \) is roughly doubled in the D quadrupoles. As the stacked beam intensity is proportional to the ratio of stack-width and maximum momentum compaction, it will be reduced when the Terwilliger scheme is applied. The exact amount of the remaining intensity depends on the operation of the scheme. If it is applied after stacking, the injection aperture can also be used to accommodate the stacked beam, thus allowing for about 80\% of the normal intensity. If the quadrupoles are already excited during stacking, e.g., because of a special small cross section vacuum chamber in the intersection regions, only 50\% of the normal intensity can be accommodated.
The influence on the maximum values of the $\beta$-functions is rather small, about $2^{\circ}/o$ increase in the horizontal and $6^{\circ}/o$ increase in the vertical plane.

7.2. Special Magnet Section for Experiments

The magnet units of the ISR can be used for momentum analysis of particles scattered by small angles if their fields are extended radially downstream the interaction regions. This is somewhat difficult with strong focusing magnets, but very easy in an sfb structure where the field of the bending magnets can be made almost arbitrarily large.

We have therefore investigated the influence of replacing the first half period of the inner arc by an sfb structure in the interaction regions where the beams go towards the centre of the ISR, as shown in Fig. V.3.

The momentum compaction functions $\alpha_p(s)$ are different in sfb and FODO structures. Therefore the insertion of a length of sfb structure introduces a beating of $\alpha_p(s)$ around the circumference of the ISR and thus a reduction of the intensity of the stacked beams.

It is, however, possible to obtain a match of the momentum compaction function in the following way: The distance between the F and D quadrupoles, and thus the length of the bending magnet, is chosen so that $\alpha_p(D)$ is equal in the two structures.

This, of course, increases the mismatch in $\alpha_p(F)$. By exciting small defocusing quadrupoles $Q_m$ and $Q'_m$ at the end of the interaction region towards the outer arcs one can, however, obtain that the closed orbits pass through the F quadrupoles which are made slightly stronger at the correct distance from the equilibrium orbit, as shown in Fig. IV.8.

The maximum values of the $\beta$-functions are only slightly increased by this operation: by about $2^{\circ}/o$ in the horizontal and by about $5^{\circ}/o$ in the vertical planes.
The total length of the sfb insertion is approximately 6.9 m, and the strength of the quadrupoles roughly 0.075 m⁻¹.

8. Performance Limitations

The performance estimates arrived at in chapter II were based on the performance of the CPS as an injector into the ISR and on the phase space available in the ISR for stacking. However, other limitations on currents can be foreseen. These are due to a number of phenomena that have been predicted theoretically or have been observed experimentally, especially in electron stacking devices. We shall in this discussion give a summary of how they can be expected to affect the design and the performance of the ISR.

8.1. The Transverse Space Charge Effect

The frequency of the oscillations of the protons is influenced by the electric and magnetic fields from the beam itself, modified by the image currents and charges in the walls of the vacuum chamber or the magnet. This change of focusing forces can lead to a shift ∆Q in betatron oscillation frequency large enough for one of the normal resonances to be approached.

This kind of disturbance has been the subject of many investigations. One of the most thorough ones has been given recently by Laslett (1963). Since he did not take into account neutralization, which may be important in storage rings, Resegotti (1964) has modified his results to take into account this effect. The transverse space charge effects as treated by Laslett can be divided into two classes. The first one, the so-called single particle effect, is mainly due to the fact that each individual particle makes oscillations with respect to the rest of the beam, seeing a space charge force that varies with its position within the beam. The other class of Q shift insta-
bility is a coherent one coming from the fact that the force on the particles varies with the position of the beam as a whole (the position of the centre of the beam). This is entirely an image effect.

The space charge limits for the two cases, deduced by means of the modified field expressions by Resegotti, are given by the following formulae when we assume no bunching in the stacked beam:

\[ N = \frac{\pi}{2} \frac{b^2 \gamma}{r_p R} \frac{1}{h^2 \epsilon_1 (1 - \eta)} - \frac{2}{\epsilon_2} - \frac{1}{b (a + b)} \bigg( \gamma^{-2} - \eta \bigg) \]

where

- \( \eta \) is the neutralization factor \((< 1)\),
- \( N \) is the total number of particles in the beam,
- \( r \) is the "classical radius" for the particles and may be taken as \( 1.536 \times 10^{-18} \) m for a proton,
- \( R \) is the average radius,
- \( a \) and \( b \) are the radial and vertical semi-axis of the beam cross section (assumed elliptical),
- \( h \) is the half height of the vacuum chamber,
- \( g \) is the half height of the magnet gap,
- \( \beta \) and \( \gamma \) are the usual relativistic coefficients,
- \( \epsilon_1 \) and \( \epsilon_2 \) are the image-force coefficients which are a function of the particular geometric configuration of the vacuum chamber and of the magnet gap respectively.

\( Q_{\nu} \) is the number of betatron oscillations per revolution for a low intensity beam and \( \Delta Q_{\nu} \) is the permitted variation of \( Q_{\nu} \) by space charge forces for single particle stability. The minus sign is due to the fact that when
the denominator is positive, \( \Delta Q_v \) must be taken negative, because then \( Q_v \) is reduced by space charge forces, while the contrary happens when the denominator is negative.

In assuming a numerical value for \( \Delta Q_v \) in this formula, one should take into account Lloyd Smith's (1963) remark that in practice a large blow-up of the beam should occur only when the computed \( Q \)-variation by space charge forces is double the distance from the next integral or half-integral stopband. In fact, a tendency of the beam to increase in diameter is inhibited by the change in integral frequency because of the non-linear character of space charge forces with respect to beam diameter.

b) For stability with respect to a coherent vertical displacement it must be considered that magnetostatic images will refer to the average position of the beam in the chamber, while the variable components of the magnetic field resulting from the coherent oscillations of the beam will be subject to the boundary conditions imposed by the vacuum chamber.

Therefore the space charge limit will be

\[
N = \frac{\pi}{2} \frac{\beta^2}{r_p R} \frac{-2 Q_{vo} \Delta Q_{vc}}{\frac{1}{h^2} \zeta_1 (\gamma^2 - \eta) + \frac{1}{g^2} \epsilon^2 \beta^2} \tag{IV.38}
\]

if the stopband approached is at half an odd integer. If, on the other hand, the stopband approached is integral, the vertical displacement of the beam appearing at a given azimuth from revolution to revolution will become slower and slower and the penetration of the variable magnetic field into the chamber wall will increase, thus adding a positive term to the denominator. If the denominator is already positive, the space charge limit will be decreased, if it is negative, it will be increased.

In the first case the limit tends to
\[
N = \frac{\pi}{2} \frac{\beta^2}{r \rho R} \left[ -\frac{2}{\hbar^2} \zeta_1 (1 - \eta) - \frac{1}{\delta^2} \zeta_2 \right] \text{ (IV.39)}
\]

while for the second case it is only possible to say that it will be larger than given by the first formula.

\(\zeta_1\) and \(\zeta_2\) are image force coefficients, different from \(\varepsilon_1\) and \(\varepsilon_2\), which are also a function of the particular geometric configuration of the vacuum chamber and of the magnet gap respectively.

Expressions for the coefficients are given by Laslett (1963) for several cases of interest and in particular for a vacuum chamber of elliptical cross section and for a wedge-shaped magnet gap.

The above formulae have been applied to the case of the ISR using the parameters presented earlier in this chapter.

Since neutralization may play an important role; we have computed the extreme cases \(\eta = 0\) and \(\eta = 1\). From machine parameters and representative beam dimensions presented earlier in this chapter we find when we assume \(\Delta \zeta_{vs} = \pm 0.5\) and \(\Delta Q_{vc} = \pm 0.25\), that the limit currents with regard to single particle stability in vertical oscillations (case a) above) are:

- for \(\eta = 0\) \(I_{so} = 200\) A
- for \(\eta = 1\) \(I_{sl} = 14\) A

and with regard to coherent vertical displacement of the beam (case b) above):

- for \(\eta = 0\) \(I_{co} = 370\) A
- for \(\eta = 1\) \(I_{cl} = >53\) A

We can see that in this case image effects reduce drastically the conventional space charge limit for a non neutralized beam, which would have been as high as 10 000 A, but they do not make it lower than that of a neu-
lized beam.

This shows that it is important to deneutralize the beam, and clearing electrodes will be inserted in parts of the vacuum chamber for this purpose. If one succeeds in deneutralizing completely there is hope that the space charge limit may be an order of magnitude higher than the estimated stacked beam from present maximum performance of the CPS. This shows that the storage rings will probably be able to make use of any future improvement of the CPS.

8.2. Wall Resistivity Effect

Other kinds of coherent transverse instability have recently been observed in stacked electron beams at MURA and Stanford (O'Neil 1963) and in three proton accelerators: the Bevatron, the Cosmotron (Barton et al. 1963) and the CPS (Hereward 1964). They are characterized by a definite phase relationship between the betatron oscillations of particles in different azimuthal parts of the machine, given by mode-number \( k \), in such a way that the beam at any given azimuth oscillates transversely with a frequency \( |k - Q| F_{\text{rev}} \). Such oscillations may be caused to grow, relatively slowly, by the action of small beam-induced fields associated with the finite resistivity of the vacuum chamber wall (Laslett et al. 1963), but in the CPS case it is believed to be due to the positive ions produced in the residual gas.

We have examined the theory of these processes in the ISR, with the following results:

1) Modes with \( k - Q \) negative are damped by the resistive-wall effect. The positive ions produce a field in anti-damping phase, but this is relatively quite small, so only reduces a little the damping rates that one would calculate from the resistive wall effect alone.
ii) For modes with \( k - Q \) positive the resistive wall effect again dominates and will produce antidamping, with e-folding times of the order of a few hundred microseconds, if the instability is allowed to occur. It can, however, be suppressed by the stabilizing effect of a sufficient spread in the frequencies \( |k - Q| F_{\text{rev}} \), which can be obtained by the use of sextupole lenses, or an equivalent suitable shaping of the magnet pole profile.

Thus the known coherent transverse instabilities do not seem to produce any serious difficulties for the ISR. Processes which we propose to investigate theoretically are the effects of the electrons produced in the residual gas, and coherent transverse oscillation of moments higher than the first in the particle distribution.

8.3. Beam-beam Interaction

When a particle from one beam passes through the other beam this other beam acts like a defocusing lens. The forces come both from the charge and the current, and since the two beams move in nearly opposite directions, the two forces add. The most pessimistic case occurs when the beams are considered completely deneutralized, in which case the total defocusing force is about twice the magnetic force since the particles are nearly relativistic.

Such a lens is highly nonlinear, but to the first approximation, to see whether the effect is serious, it can be assumed linear and its effect can be estimated. Assuming 20 A in a ribbon 6 cm wide and 1 cm high and 25 GeV particles, such an estimate gives a lens strength of \( C \simeq 2 \times 10^{-4} \text{ m}^{-1} \).

Eight such lenses at equal distances around the ring give a Q shift \( \Delta Q \simeq 2 \times 10^{-3} \), which is quite negligible. From this point of view an order of magnitude larger circulating current would be acceptable.
Since the beams may be displaced slightly with respect to each other, there is also a small kicking action. The maximum kick is received by a particle that just scrapes the surface of the other beam. With the beam size and beam intensity assumed above this kick would be at maximum $10^{-6}$ radians, and the resulting closed orbit deviation will be less than 0.1 mm, which is again completely negligible, and one could in fact envisage much larger currents without getting trouble from this effect.

8.4. Negative Mass Instability

Of the particles in a synchrotron beam the ones with the lowest momentum have the highest revolution frequency if one is above the transition energy. This has the effect that the longitudinal repelling forces due to space charge lead to the particles being retarded catching up with those being accelerated, leading to a tendency of azimuthal bunching. This can be unstable if the space charge forces are above a certain limit. This limit depends on the momentum spread of the beam.

This problem has been studied by Nielsen et al. (1959). Applying their theory and the parameters and performance estimate of the ISR we find that there is always enough energy spread for longitudinal stability.

8.5. The Touschek Effect

When the electron storage ring AdA was put into operation the lifetime of the beam showed a strong dependence on the beam intensity (Bernardini et al. 1963). The explanation for this was that when particles in a beam perform betatron oscillations there is a certain probability of collisions between particles in the same beam resulting in a transfer of transverse momentum into longitudinal momentum. This can lead to particles being thrown out of the maintaining buckets, as in electron storage rings. In proton storage

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rings there is no maintaining bucket, but the effect might still in principle lead to an increase in the momentum spread of the stacked beam.

Although this effect has turned out to be very serious for electron storage rings in a certain energy range (like AdA), it has been shown that the effect is negligible for proton storage rings. This difference in seriousness between electron rings and proton rings comes mainly from the much larger beam volume in proton rings and the fact that the momentum distribution in the CM system is much less anisotropic.

8.6. Non Linear Resonances

Because of the absence in proton storage rings of any effect that would cause damping of single particle oscillations\(^{\text{[x]}}\), all effects capable of producing cumulative build-up of such oscillations require careful examination.

Apart from gas scattering – dealt with in ch. IX – fluctuations and perturbations of the guiding field can act in this way under certain conditions.

Resonant build-up of transverse oscillations due to imperfections of the azimuthal distributions of the bending field or of its gradient is avoided by avoiding integral and half integral values of the betatron wave numbers \(Q_\text{H}\) and \(Q_\text{V}\). At intermediate values, obeying relations

\[
n_1 Q_\text{H} + n_2 Q_\text{V} = kS,
\]

where \(S\) is the number of superperiods and \(n_1, n_2, k\) are integers, imperfections of the azimuthal distribution of the sextupole, octupole and higher multipole components of the focusing can, however, produce build-up of betatron

\(^{\text{x]}\) The situation is different for electron storage rings in this respect, where orbit radiation can be used to produce efficient damping of all oscillatory modes.

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oscillations by non-linear resonance. With imperfections resulting from practical manufacturing tolerances, disturbing cumulative build-up occurs only if the working point \((Q_H, Q_V)\) fluctuates and consequently crosses the resonance condition \((E_0, (IV.40))\) a considerable number of times. In each crossing the amplitude of a particle increases or decreases by a small amount, depending on the phase of its oscillation at the instant of crossing. With uncorrelated phases in repeated crossings, an average build-up of the amplitude proportional to the square root of the number of crossings results.

Ripple of the magnetic field, and radial oscillations in the presence of a radio-frequency accelerating field are agents causing the \(Q\)-values of the particles to fluctuate. The build-up effects produced in an AG-synchrotron, such as the CPS, are of no consequence due to the relatively short time the particles are kept in the machine. The effects can be serious, however, in storage rings (Schoch 1963). Assuming manufacturing tolerances as have been obtained for the CPS, and a magnetic field ripple \(\frac{\Delta B}{B} = 10^{-4}\), it would take particles sweeping through a third order (sextupole) resonance approximately 1 minute to get lost. It takes more time for the loss to occur at the higher order resonances, but it will be necessary to control the \(Q\)-values with sufficient accuracy to stay away from at least all the lower order resonances. The particles affected by the loss are those inside a momentum range corresponding to the ripple amplitude (if a non-linear resonance falls into such a range). With \(\frac{\Delta B}{B} = 10^{-4}\), this range would be about \(\frac{\Delta p}{p} = 10^{-4}\) or the equivalent of about 5 injected pulses. Thus tightening the tolerance for magnet ripple reduces the fraction of particles potentially affected by non-linear resonance loss. Any slow drifts of \(B\) have also to be kept within tight tolerances in order to avoid the wiping out of a too wide range of momentum by sweeping it through non-linear resonances.

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V. THE MAGNET SYSTEM

1. General Layout

According to the FODO structure, presented in the previous chapter, the main magnet of each storage ring will consist of 28 long and 40 short radially focusing (F) units and 32 long and 32 short radially defocusing (D) units. The steel cores of the short units will be 244 cm long. The cores of the long units will be made out of 2 cores of the corresponding short units, with a spacing of 150 mm in between, to make the distribution of end effects uniform.

All units will have roughly hyperbolical profiles, as in A.G. synchrotrons, but the profiles in the F and D units will be slightly different, because the compensation of Q dependence on particle momentum requires different field distributions.

The configuration of the return yokes is determined by the requirement of giving free access to the ultrahigh vacuum system. All units will have the return yoke on the high field side of the gap only, in order to have the gap open toward the outside: this shape is known as "open C". The return yokes will thus result to be on the exterior of the orbits in the radially focusing sectors and on the interior in the radially defocusing ones. For the same reasons of gap accessibility the coils will be placed on the poles, away from the plane of the orbit.

The general layout of the main magnet system is presented in Fig. V.1 and one octant of the main magnet is shown at a larger scale in Fig. V.2. The magnet will be equipped with poleface windings for the correction of field distortions due to steel saturation and of end effects at high field. The poleface windings will also be used for adjusting the number of betatron oscillations in the machine.

Backleg windings mounted on couples of adjacent F and D magnets in each ring and powered with individually adjustable currents will be used for cor-
recting radial orbit distortions, while 16 auxiliary radial field magnets, at a distance approximately one quarter betatron oscillation wavelength on each side of the interaction regions, will allow to adjust independently the vertical position of the beam in each interaction region, in order to obtain the maximum number of colliding beam events.

Sextupole lenses will be inserted in 4 of the long straight sections of each inner arc, with the purpose of adjusting the Q dependence on particle momentum.

A set of 24 quadrupoles per ring (Terwilliger quadrupoles) will have the purpose of superposing closed orbits of different momenta in the interaction regions.

A set of 32 quadrupole lenses per ring, with their axes at $45^\circ$ (skew quadrupoles) will permit to decouple vertical and horizontal betatron oscillations.

Four couples of one short F and one short D units per ring, on the inner side of those interaction regions where the beam goes inwards, may be replaced by special groups of 2 quadrupoles with open median plane and one bending magnet with uniform field, for the purpose of experimentation. These special groups are not included in the basic layout of Fig. V.1, but their position is shown in Fig. V.3. The yoko of one of the two units following this special magnet section should be reversed, in order to facilitate experimentation.

The composition of the particle guiding system for each ring is summarized in Table V.1.

2. The Main Magnet

2.1. Pole Profile

The field distribution required in the F and D magnets in order to maintain the chosen value of vertical and radial Q for all particles in the stack can be expressed in terms of the local values of the profile parameters
TABLE V.1.

**Composition of the Particle Guiding System in Each Ring.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Long</th>
<th>Short</th>
</tr>
</thead>
<tbody>
<tr>
<td>F units:</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>D units:</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Radial field magnets</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Torwilliger quadrupoles</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Skew quadrupoles</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Sextupole lenses</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

**Variant:**

- Uniform field magnets: 4
- Open F quadrupoles: 4
- Open D quadrupoles: 4

**Replacing:**

- 4 short F units
- 4 short D units

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\( n/\rho = -C/B_o \), which have to change linearly with radial position:

\[
(n/\rho)_F = (n_o/\rho)_F + (n'/\rho)_F r \quad \text{(V.1)}
\]

\[
(n/\rho)_D = (n_o/\rho)_F + (n'/\rho)_D r \quad \text{(V.2)}
\]

where \( r = 0 \) on the equilibrium orbit.

The values of the coefficients have been given in chapter IV:

\[
(n_o/\rho)_F = -3.141 \text{ m}^{-1} \quad (n/\rho)_F = -1.852 \text{ m}^{-2}
\]

\[
(n_o/\rho)_D = 3.048 \text{ m}^{-1} \quad (n/\rho)_D = 1.313 \text{ m}^{-2}
\]

The above values are only approximate, because they are based on the evaluation of the expected end effects in these magnet units from experimental data of the CPS magnet, by means of approximate scaling criteria. For an accurate calculation, results of measurements on a model will be used. It should be noticed that the required variations of the field gradient across the aperture are far from negligible, since they reach 9 o/o in the F sectors and 6 o/o in the D sectors.

The equations of the equipotential surfaces in the above field distributions are:

\[
\begin{align*}
\text{in the F units:} & \quad z - \frac{n_o F}{\rho} rz - \frac{n'_F}{6\rho} (3 r^2 z - z^3) = \text{const.} \quad \text{(V.3)} \\
\text{in the D units:} & \quad z - \frac{n_o D}{\rho} rz - \frac{n'_D}{6\rho} (3 r^2 z - z^3) = \text{const.} \quad \text{(V.4)}
\end{align*}
\]

The design of the magnet pole is made for the field values at which the permeability of the steel core is very high, so that the pole surface is practically a magnetic equipotential. The possibility of shaping the pole profile to give the correct field distribution at the nominal field of 1.2 T, at which saturation effects start to show up in the pole tips, has been considered, because the correction of field distribution at lower...
field values would require less power than at maximum field. This approach has finally been discarded for the following reasons:

a) The profile chosen with this criterion would be right only for steel of given magnetic characteristics.

b) The correction would be required for operation at all energies below the maximum, while in the case of medium field design the storage rings could operate without corrections up to 23 GeV.

The middle parts of the pole profiles will follow the theoretical equipotentials given by formulae (V.3) and (V.4) while on both sides some adjustments will be required to compensate for the effects of the limited polewidth and for the influence of the coils. The region at the minimum gap and beyond it will be shaped in such a way as to reduce pole saturation.

A preliminary study of the complete profile shape has been made with a computer programme, similar to that developed at DESY (Hardt 1959) and the behaviour at saturation has been estimated on the basis of results from the CPS magnet. A tentative F profile is shown in Fig. V.4. After further refinement, the computed profiles will be built in the first magnet models and the final shapes will be based on measurements and trimming on these models.

A systematic error of 0.1 o/o in the gradient of the magnetic field, corresponds to an error of 1.5 μ/cm on the slope of the profile. Therefore the systematic errors on the profile dimensions may not be permitted to exceed ± 0.01 mm.

2.2. Gap Height and Pole Width

The gap height at the equilibrium orbit is based on the vertical vacuum chamber aperture discussed in the preceding chapter, i.e. 50 mm. It has been assumed that the portions of the vacuum chamber inside the magnet will have just the computed aperture, while enlarged portions, containing deneutralizing electrodes, will be placed only at the ends of each magnet yoke, between the coils, taking advantage of the natural drift of the electrons in the direction perpendicular to the field gradient.
In addition to the aperture, the thickness of the vacuum chamber, with heating elements and thermal insulation, the heat shield and the poleface windings are taken into account, as shown by Fig. V.5. Owing to the neatly hyperbolical shape of the poles, the chamber has most conveniently an oval cross section. In order to maintain the 50 mm height over the whole stack width of 57 mm, the central inner height of this oval vacuum chamber is 52 mm. The oval shape permits the wall thickness to be limited to 3 mm. A space of 6 mm around it is reserved for the heating elements and for the thermal insulation.

A metal heat shield 4 mm thick, with a polished external surface, fitted with cooling water pipes, is foreseen to protect the poleface winding during the bake-out of the chamber. In order to reduce the space requirements, the shield will be used as supporting and cooling structure for the poleface windings. The windings themselves, with their insulation, take 8 mm.

As a result of the above considerations, the magnet gap height at the equilibrium orbit will be 100 mm.

The required radial aperture computed in the previous chapter is 150 mm. Since, however, the sagitta of the circular trajectory, of 79.2 m radius, in the straight magnet sectors, about 2.5 m long, is 10 mm, the total width of the useful field region must be 160 mm.

Profiles computations and comparison with other strong-focusing magnets give confidence that the pole does not need to extend more than 16 cm on the open side of the gap, despite the necessity to make possible the correction over the whole useful width up to the maximum field. On the side of the minimum gap some increase with respect to the half-width of the CPS' magnet will be necessary: a figure of 20 cm has been tentatively assumed. The total polewidth is 360 mm, and the axis of the pole would be displaced by 2 cm with respect to the equilibrium orbit. This is possible with independent F and D units. Model measurements will show if this polewidth can still be reduced.

The return yoke will be given the same width as the pole. In this way the flux density in the yoke is expected to be about 1.6 T for a 1.2 T equili-
brium field, and saturation effects should show up only in the poles.

2.3. Core Construction and Steel Properties

The most economical method to achieve the tight mechanical tolerances required on the pole profile of the magnet core consists probably in punching thin steel sheets with a precision die. As in the construction of the CPS magnet, a thickness between 1 and 2 mm is expected to provide a satisfactory balance between precision of punching, packing factor and cost, although, from the point of view of magnet operation alone, thicker plates could be used.

The cores will preferably be assembled by welding together stacks of laminations, by means of longitudinal strips. Insulation of the lamination surfaces is necessary, but less critical than in the CPS because the magnetic field may be varied only slowly, when the energy of the beam is changed by phase displacement. De-excitation of the magnet with its own time constant will be five times slower than the forced decay of the CPS, and the influence of remanent field variations due to eddy currents will be considerably reduced at field levels of a few kilogauss, which correspond to the minimum expected operating energies. Insulation by surface treatment is proposed and will be tested on the first model. The cores of the short units can be made in one straight piece: the sagitta of the circular orbit over this length is about 1 cm, but the corresponding increase in aperture is largely compensated by the constructional simplifications in the magnet itself, in the poleface windings, and in the vacuum chamber. The cores of the long units will be made by mounting two of the short cores on a common girder, at suitable angle and distance. A spacing of 150 mm should be sufficient to ensure that the bending lengths of all units remain practically equal at all field levels.

The I.S.R. magnet shall normally be operated at rather high fields, and therefore the most desirable magnetic property of the steel for this magnet is a permeability as high as possible at high fields. It can be said, in fact, that the percentage variation of \( n \) at saturation can be correlated to the value of the steel permeability at the maximum flux density that
exists in the steel near the minimum gap. (For two identical magnets, made out of different steel, the same deterioration of the n plateau would occur at field values for which the permeability in the pole tips is the same).

The results of the magnetic measurements, carried out in the course of our investigation of European steel production have shown that some recently developed mild steel sheet, with extremely low carbon content, has of...n permeability values even higher than the steel of the present CPS. Values of $\mu$ up to 2000 have been measured at 1.5 T. These sheets, after annealing, are very soft, hence they might be punched with small punch-to-die clearance, but the details of this process, and in particular the formation of burr, are still to be studied. This material will (probably) be used in the first magnet model.

Some shuffling of the steel sheet over the whole delivery will be necessary, in order to obtain a high uniformity of field and gradient distribution around the machine at high fields, despite the unavoidable spread in permeability in the production. To this effect a good uniformity of the average core density is also important.

2.4 The Magnet Coils

The magnet will be excited by d.c. current in water cooled coils of hollow copper conductor placed on the poles. All coils of one ring will be connected in series, in order to achieve a uniform excitation of the magnets. The position of the coils is determined by the requirements of accessibility of the vacuum system: the clearance between them is 210 mm. The current density has been chosen to minimize the sum of machine cost and of capitalized cost of power and water. The value of $2 A/mm^2$ at 1.2 T has been adopted. Although this density is twice as high as the r.m.s. current density in the aluminium coils of the CPS, these coils will take more space, because their r.m.s. current due to the d.c. operation, is so much higher than in the CPS.
About 100,000 ampereturns will be necessary to create a field of 1.2 T on the equilibrium orbit. This corresponds to a total copper cross section of 50,000 mm². The maximum height of a finished pancake, permitted by the minimum gap through which the coils must be introduced, is about 66 mm. Therefore the height of the copper conductor has been taken to be 56 mm, leaving an adequate space for insulation. Two pancakes per pole are necessary to achieve the required cross section with coils of a reasonable shape: the choice of the number of turns will then be determined by the preferred relation between voltage and current obtained from power supply studies. In order to preserve the possibility of accelerating a stacked beam of reduced section to energies higher than 28 GeV, the power supply has been designed for 120,000 ampereturns, which should give a maximum field of 1.35 T. The preferred type of power supply, namely a phase controlled rectifier set, is best suited for a voltage between 1.5 and 2 kV: a 32 turn winding which corresponds to a maximum current of 3750 A and a voltage of 1875 V has been tentatively adopted. The maximum power dissipation per ring would be 7 MW. In this tentative design each magnet has therefore 4 pancakes, each with 8 turns of 56 x 32 mm² conductor with a hole of 16 mm diameter. Each pancake has 95 m of conductor in the long units and 54 m in the short ones. The pancakes are connected in series electrically, but their water cooling circuits are in parallel in order to reduce water pressure requirements: an adequate water flow for a temperature rise of 20°C at full power will be ensured by a pressure drop of 1.5 kg/cm² in a long pancake. For each ring, the resistance of the magnet circuit at 27°C will be about 0.5Ω, its inductance about 2.7 H, while the water flow for a 20°C temperature rise at 7 MW is 0.085 m³/sec. The magnet parameters are tabulated in Table V.2. The preliminary model is shown in Fig. V.6.

3. The Poleface Windings

3.1. Purpose of the Poleface Windings

The fields distribution in the magnet gap, for a field value of 1.2 T at the equilibrium orbit, will be distorted by saturation of the steel in
## TABLE V.2

**Main Magnet Parameters for One Ring**

<table>
<thead>
<tr>
<th>Number</th>
<th>Core length</th>
<th>Block per core</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short units F</td>
<td>40</td>
<td>2440 mm</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>32</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Long units F</td>
<td>26</td>
<td>5030 mm</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>32</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

- **Block length**
- **Gap height at equilibrium orbit**
- **Profile parameter at equilibrium orbit**
- **Polewidth**
- **Approximate steel weight per finished block**
- **Steel sheet weight required per block**
- **Total steel sheet weight**
- **Copper weight for one short unit**
- **Copper weight for one long unit**
- **Total copper weight**
- **Ampereturns at 1.2 T**
- **Current density at 1.2 T**
- **Maximum ampereturns**
- **Peak field**
- **Number of pancakes per magnet**
- **Number of turns per pancake**
- **Conductor cross section**
- **Hole diameter**
- **Total resistance of the magnet windings**
- **Total inductance (maximum) of the windings**
- **Maximum current**
- **Maximum voltage**
- **Maximum dissipation**

2440 mm
100 mm

\[
\begin{align*}
- & 3.141 \text{ m}^{-1} \text{ in F sectors} \\
& 3.048 \text{ m}^{-1} \text{ in D sectors}
\end{align*}
\]

360 mm
21 tons
26 tons
5000 tons
3.2 tons
5.5 tons
560 tons
100 000
2 A/mm²
120 000
1.35 T
4
8
56 x 32 mm²
16 mm

0.5 Ω
2.7 H
3750 A
1875 V
7.04 MW
the region of the minimum gap. For particles in the vicinity of the equi-
librium orbit, the effect of this distortion could be compensated by quadrupoles
and sextupole magnetic lenses. This method is well adapted to an accelerator,
where the beam diameter at high field is a small fraction of the aperture,
but much less suitable in the Storage Rings, where the full aperture is requi-
red, even at maximum field. We consider it necessary therefore to correct the
field distortion locally, by means of conductors on the pole surfaces. This
increases the magnet aperture, but it saves a considerable amount of straight
section length and therefore reduces the circumference. In fact, it would be
difficult otherwise to maintain the machine within the size permitted by the
presently available site.

Since the Storage Rings operate at d.c., the current in the individual
conductors (or sections) of the poleface windings could be separately adjusted
and thus an accurate correction would be possible over the whole aperture
and at all field levels. This flexible correcting system could be used also
for producing arbitrary changes in focusing strength; in particular it is
planned to create in this way a distributed quadrupole correction, and, if nece-
sary, also octupole effects could be introduced.

3.2 Correction of Saturation Effects

The distortions of the field distribution to be expected at saturation
in the magnets of the Storage Rings can be estimated from the measurements
on the CPS magnet by means of approximate scaling laws, assuming that the
cores are made out of steel of equal magnetic characteristics, and forgetting
the linear variation of the gradient introduced in the new profile design.

Since the saturation conditions are typically represented by the field
at the minimum gap, $B_{\text{max}}$, the excitation level can be identified by this field
level. We consider the case of two similar magnets $M_o$ and $M_1$, having nomi-
nal fields $B_o$ and $B_1$ for the same maximum field $B_{\text{max}}$, and power parameters
$(n/p)_o$ and $(n/p)_1$ respectively. The gradient errors at points having the
same field $B_2$ in the two magnets, for the same maximum field, should satisfy
the relations:

\[
\left( \frac{\Delta G}{G_1} \right)_{1, B_2} = \left( \frac{\Delta G}{G_1} \right)_{0, B_2} \tag{V.5}
\]

\[
\left( \frac{dG}{G_1 \, dx} \right)_{1, B_2} = \left( \frac{n/\rho}{(n/\rho)_0} \cdot \frac{B_1}{B_0} \right) \left( \frac{dG}{G_1 \, dx} \right)_{0, B_2} \tag{V.6}
\]

\[
\left( \frac{d^2 G}{G_1 \, dx^2} \right)_{1, B_2} = \left( \frac{n/\rho}{(n/\rho)_0} \right)^2 \cdot \frac{B_1^2}{B_0^2} \left( \frac{d^2 G}{G_1 \, dx^2} \right)_{0, B_2} \tag{V.7}
\]

In the FODO magnet $B_{\text{max}} = 1.65 \, \text{T}$ for $B_1 = 1.2 \, \text{T}$, the corresponding equilibrium field level in the CPS is $B_0 = 1.1 \, \text{T}$. On the curves $n = n(x)$ measured in the open sectors of the CPS at 1.1 T level, the point at which the field is $B_2 = 1.2 \, \text{T}$, i.e., a point displaced by 2.3 cm from the equilibrium orbit towards the minimum gap, must be considered.

Referring to this point as $x = 0$, the $n$ error curve can be approximated by the formula:

\[
\frac{\Delta n}{n} = -0.015 - 0.0028 \, x - 0.00017 \, x^2 \quad (x \text{ in cm}) \tag{V.8}
\]

where the positive direction of the $x$ axis is towards the minimum gap, and therefore the $\frac{\Delta n}{n}$ curve in the FODO magnet, referred to the equilibrium orbit, would be given by

\[
\left( \frac{\Delta n}{n} \right)_{\text{FODO}} = -0.015 - 0.0023 \, x - 0.00012 \, x^2 \quad (x \text{ in cm}) \tag{V.9}
\]

The required current distribution for the correction can then be computed by considering the variation of magnetic potential along the polefaces,
which would produce the expected distortion. It results that in the F unit of the FODO magnet the linear current density should increase from 10 to about 55 A/cm moving along the profile from the open side to the minimum gap, in order to correct the expected distortion at 1.2 T; as shown in Fig. V.7a, curve 1.

It may be noticed for comparison that for a POFDOD magnet, which would have the same profile as the CPS magnet, the error should be taken from the CPS curves at 1.2 T level:

\[
\left( \frac{\Delta n}{n} \right)_{\text{POFDOD}} = -0.020 - 0.0045 x - 0.00035 x^2 \quad \text{(V.10)}
\]

The linear current density for the corresponding correction should increase from 0 to 135 A/cm as shown in Fig. 7b.

The poleface windings will also be used to compensate for the effect of the variations of the equivalent length of the units for field and for gradient at high fields, by introducing such variations in \( n \) as to bring back \( Q (H) \) and \( Q (V) \) to their original values. These "equivalent" variations in \( n \) have been calculated for both the foreseen FODO and POFDOD I.S.R. structures to be only a small fraction of the main \( n \) error. The reasons why these corrections are small are, first, that the radial variation of the equivalent length for gradient is almost entirely compensated also at high fields by the sextupole component introduced in the profile, second, that the effects of the variations of the equivalent lengths for field and for gradient at the equilibrium orbit due to saturation compensate each other to a large extent, with the foreseen arrangement of the half units.

3.3. Adjustment of \( Q \)

It has been shown, in the discussion of particles orbits, that an independent variation of vertical and horizontal \( Q \) values by amounts up to \( \pm 0.25 \) should be obtained by varying the values of the field gradients by independent amounts in the \( F \) and \( D \) units by means of the poleface windings. The required current distribution can be calculated by the same method of the potential
variation along the pole surfaces as for saturation correction.

For the extreme gradient variations necessary in the \( F \) and \( D \) units respectively, i.e.:

\[
\Delta G_F = \pm 0.0940 \text{ T/m} \quad \Delta G_D = \pm 0.0615 \text{ T/m}
\]

the following values of the linear current densities at typical points along the profile are obtained:

\[
\begin{align*}
&x = -12 \text{ cm} \\
&\quad \text{(open side)} \\
&x = 0 \\
&x = +12 \text{ cm} \\
&(\text{min. gap})
\end{align*}
\]

- \( F \) units: \( \pm 88 \text{ A/cm} \) \\
- \( D \) units: \( \pm 79 \text{ A/cm} \)

\[
\begin{align*}
&\pm 36 \text{ A/cm} \\
&\pm 32.5 \text{ A/cm} \\
&\pm 19 \text{ A/cm} \\
&\pm 17.5 \text{ A/cm}
\end{align*}
\]

The current density distributions in the poleface windings of the \( F \) units for extreme \( Q \) variations and for correction at saturation are combined in curves 2 and 3 of Fig. V.7a. By comparison with Fig. V.7b the maximum required linear current density for this combined correction in the FODO magnet appears to be lower than for the correction of saturation alone in the FOFDOD magnet, although the average value may be higher. Therefore the poleface windings of the FODO magnet, which should serve the double purpose of correction at saturation and of quadrupole adjustment, would not take more space than those of the FOFDOD magnet, which would only be needed for saturation, but would dissipate more power.

3.4. Structure of the Poleface Windings

Since our computations of required currents contain several approximations, a safety factor of about 1.5 should be taken on the computed values. The windings are thus tentatively designed for a linear current density of 130 A/cm, waiting for more precise information from measurements of the first magnet model.

The layer of parallel conductors on the pole surface will be made by inserting individually insulated copper bars between ridges or pins fixed to the
copper heat shield, which will hold and locate them precisely. A system of 24 bars of 4 x 8 mm\(^2\), distributed uniformly one per centimetre along the pole on the two sides of the equilibrium orbit is tentatively considered. Each bar could carry up to 128 A with a current density of 4 A/mm\(^2\). The maximum dissipated power of about 1 kW per sheet (in a long unit) would be easily removed by the water cooling system of the heat shield. The return conductors would be collected in two groups, running along the main coils. In order to avoid disturbing the field at the equilibrium orbit, the conductors on each side of it should have their returns on the same side.

An adequate flexibility in adjustment of the correction should be achieved by having 12 independent current loops on each pole: all corresponding loops on the poles of homologous magnet units could be connected in series (upper poles first and lower poles after) giving two groups (F and D) of 12 independent circuits per ring.

Assuming all circuits to be equal and to carry the maximum current of 128 A, and taking into account the resistance of the return windings and of the connections along the ring, the power required in a circuit would be 32 kW at 250 V. The arrangement of the circuits and the ratings of the power supplies shall be considered in more detail at a later stage. For the present estimates, 24 generators, rated at 40 kW, 300 V have been assumed.

The reference voltages for the current regulation of the generators (for the windings on one type of unit) will be produced by adjustable potentiometric division of the two voltages controlled by the field B through function generators, the one corresponding to the chosen Q shift and the second to saturation correction. In this way the correction can be automatically adapted to changes in B during acceleration or deceleration by phase displacement, at least in first approximation. A quick overall adjustment of the quadrupole correction is also possible by manual control of the proportionality constant in the first function generator.
Independent adjustments of local current densities can be made by means of the individual potentiometers.

4. Correcting Magnets

4.1. Sextupole Lenses

The design of the sextupole lenses is based on the requirement to produce approximately half of the momentum dependence of the Q-values, that has been suppressed by the modification of the magnet profile. The sextupole lenses must be placed mid-F and mid-D in order to be able to change independently the momentum dependence for \( Q_v \) and \( Q_H \). Such locations exist only in the inner arcs and therefore only 8 pairs of lenses per ring are possible.

The required strengths, computed in chapter IV, are:

\[
C_F = -0.125 \text{ m}^{-2} \quad C_D = 0.221 \text{ m}^{-2}
\]

The highest of these figures corresponds to \( B''L = 21.2 \text{ T/m} \): the sextupoles will be given a maximum \( B''L \) of 25 \text{ T/m}.

The main characteristics of the sextupole lenses are thus:

- Diameter of the inscribed circle: 200 mm
- Width of the useful field region: 150 mm
- Steel length: 500 mm
- Equivalent length: 585 mm
- Second derivative of the field, \( B'' \): 42.5 \text{ T/m}^2
- Maximum flux density in the poles: 0.7 T
- Required ampereturns per pole: 4500
- Current density in the windings: 5 \text{ A/mm}^2
- Maximum dissipation per lens: 5 kW
- Overall length: 900 mm
- Total weight: \( \sim 2 \text{ tons} \)

A high current density must be chosen because the space for windings is rather limited. Since the sextupoles may have to operate continuously at
full power, the coils must be water cooled. Therefore they will probably have few turns and will require rather large current and low voltage.

The 8 sextupoles mid-F of one ring will be connected in series in one circuit. Two d.c. power supplies of about 50 kW will be required.

4.2. Terwilliger Quadrupoles

The maximum required strength of the quadrupoles to superpose the closed orbits in all intersection regions is:

$$C_p = -0.0154 \text{ m}^{-1}$$

The diameter of the inscribed circle must be 200 mm, in order to give a useful region of 150 mm. The possible overall length of these quadrupoles is limited, because they must fit within the short straight sections between magnet units. A maximum gradient of 10 T/m would be possible, this would make a yoke length of 150 mm sufficient, but the excitation coils would become disproportionately large. It seems preferable to have a steel length of 300 mm, and a gradient of 5 T/m. The main characteristics of these quadrupoles would then be:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the inscribed circle</td>
<td>200 mm</td>
</tr>
<tr>
<td>Width of the useful region</td>
<td>150 mm</td>
</tr>
<tr>
<td>Steel length</td>
<td>300 mm</td>
</tr>
<tr>
<td>Gradient</td>
<td>5 T/m</td>
</tr>
<tr>
<td>Required ampereturns per pole</td>
<td>30 000</td>
</tr>
<tr>
<td>Current density</td>
<td>3 A/mm$^2$</td>
</tr>
<tr>
<td>Dissipation</td>
<td>6 kW</td>
</tr>
<tr>
<td>Overall length</td>
<td>750 mm</td>
</tr>
<tr>
<td>Total weight</td>
<td>1.5 ton</td>
</tr>
</tbody>
</table>

All F Terwilliger quadrupoles in one ring will be connected in series in one circuit, while the 2 sets of quadrupoles D/2 will have two independent circuits. Therefore 3 power supplies of about 50 kW will be required for these quadrupoles.
4.3. Skew Quadrupoles

If in certain parts of the machine, either due to the magnet imperfections or to stray fields, there is a radial gradient of a radial field, the horizontal and vertical betatron oscillations are no longer independent. Experience with the CPS shows that in a machine with $Q_H = Q_V$ the coupling is almost 100% of. The magnet systems that transfer the beam from the CPS to the Storage Rings contain several pulsed horizontal deflecting magnets. Errors in these lead to an increased amplitude of the horizontal betatron oscillations in the I.S.R. To avoid a consequent increase of the vertical betatron oscillations, the two planes must be decoupled by means of skew quadrupoles. A similar argument is valid for the vertical closed orbit, which would depend on the momentum in the presence of a gradient $dB_x/dx$.

The required strength of the skew quadrupoles is difficult to predict, but it seems desirable that their number be large, in order to distribute the correction. Two sets of 16 skew quadrupoles per ring, having the same size and strength as the Terwilliger quadrupoles, have been tentatively considered in the layout of the machine.

They would require two power supplies of about 100 kW.

It might seem attractive to replace the skew quadrupoles by octupoles with additional quadrupole windings as in the CPS, but in this case it would be difficult to maintain a satisfactory quality of the quadrupole field distribution over the whole aperture except at very low fields. Therefore it is preferable to introduce octupole effects, if necessary, by means of the poleface windings in the main magnet.

4.4. Radial-field Magnets and back-leg Windings

Each of the 16 radial-field magnets should be able to displace the closed orbit vertically by 1 cm at the next interaction region, at about a quarter wavelength distance. Therefore its strength should be about 0.06 Tm. The gap
of this magnet must be higher than the width of the vacuum chamber, with its heating system, i.e. about 200 mm. Therefore it is important to reduce the field strength by increasing the length as much as possible, in order to maintain the excitation within reasonable limits. Since these magnets should be independently excited it is desirable that they have small exciting currents in order to reduce the cost of the long connections: since coils of thin conductors cannot be water cooled so efficiently as large bars, a low current density is assumed.

The following parameters result:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap height</td>
<td>200 mm</td>
</tr>
<tr>
<td>Pole width</td>
<td>300 mm</td>
</tr>
<tr>
<td>Steel length</td>
<td>300 mm</td>
</tr>
<tr>
<td>Field</td>
<td>0.2 T</td>
</tr>
<tr>
<td>Ampereturns</td>
<td>32 000</td>
</tr>
<tr>
<td>Current density</td>
<td>2 A/mm²</td>
</tr>
<tr>
<td>Dissipation</td>
<td>2.3 kW</td>
</tr>
<tr>
<td>Overall length</td>
<td>700 mm</td>
</tr>
<tr>
<td>Total weight</td>
<td>2 tons</td>
</tr>
</tbody>
</table>

Sixteen power supplies of about 3 kW should be considered.

It is assumed that the back-leg windings must be able to change the field in the magnets by about 1 o/o, and that 32 of them would be sufficient. Each winding would then require 1000 ampereturns and dissipate about 1 kW, with a current density of 2 A/mm². An equal number of independent power supplies of about 2 kW each should be considered.

5. Special Magnet Sections for Experiments

For small angle scattering experiments, it would be desirable to extend the I.S.R. magnet units downstream of the interaction region in the radial direction, so that their magnetic field can also be used for momentum analysis of scattered particles (De Raad, 1962 b). Since this procedure
is somewhat difficult with strong focusing magnets, it may be interesting to replace four couples of one short $F$ and one short $D$ unit per ring, on the inner side of those interaction regions where the beam goes inwards, by four groups of 2 quadrupoles with open median plane and one special bending magnet with uniform field, as is explained in chapter III, par. 4.2, and shown in Fig. V.3.

The length of the special magnet section is limited by the requirement of matching the betatron oscillations and the momentum compaction of the normal FODO structure, as explained in chapter IV. The distance between the outer ends of the steel cores of the quadrupoles should be equal to 6.9 m. A short quadrupole would be needed on the other side of the long straight section for complete matching.

The useful aperture of these elements has been estimated by De Raad (1962 b) for the case of an elastic scattering experiment. The useful field region of the magnet should extend radially for 600 mm from the orbit on the side of interest, and the gap height should be at least 200 mm. For the quadrupoles, the diameter of the inscribed circle should be about 200 mm, in order to obtain a good field region of 150 mm.

The bending magnet must have a strength of 6.1 T m. The maximum field level up to which the width of the useful field region can be kept constant with a reasonable taper of the pole tips and suitable shims is 1.45 T. Therefore the bending length must be 4.21 m. Taking into account end effects, the required steel length is 4.0 m. In order to have a useful field region 700 mm wide, the steel width at the base of the poles must be 1100 mm. As for the main magnet, the proposed maximum excitation will be 10 o/o higher than that required for the nominal field.

These bending magnets must be C-shaped, with their yokes oriented in such a way that pairs of particles scattered in opposite directions from the interaction region can be observed. Their main parameters can be tentatively listed as follows:
Gap height 200 mm
Radial width of the good field region 700 mm
Pole width 1100 mm
Steel length 4000 mm
Nominal field 1.45 T
Ampereturns at 1.6 T 300 000
Current density $3 \text{ A/mm}^2$
Maximum power dissipation 180 kW
Overall length 4900 mm
Steel weight 220 tons
Coil weight 10 tons

The quadrupoles with open median plane should have the following characteristics:

Nominal strength 0.075 m$^{-1}$
Diameter of the inscribed circle 200 mm
Width of the good field region 150 mm
Steel length 700 mm
Gradient 10 T/m
Required ampereturns per pole 60 000
Current density $3 \text{ A/mm}^2$
Power dissipation 30 kW
Overall length 1200 mm
Steel weight 7 tons
Coil weight 1.8 tons

The small additional matching quadrupoles could be similar to the Terwilliger quadrupoles.
VI. POWER SUPPLY AND COOLING

1. Main Power Supply

1.1. Required Performance

During normal operation of the I.S.R. the magnet will be operated at the same field level from the beginning of the stacking period to the end of the experiment, i.e. completely d.c. operation. However, there is a certain interest in the possibility of acceleration or deceleration of the particles by phase displacement after the stack has been filled. The power supply must consequently be provided with the possibility of making the magnet follow this slow acceleration or deceleration. In general therefore the magnet power supply must be able to produce a magnet operating cycle as indicated in Fig. VII.1 showing the magnetic flux density B as a function of time t.

The precision requirements during the various periods of the cycle can be summarized as follows:

Preparation period

Setting of the correct values for injection. This setting should be reproduced to one part in $10^4$.

Stacking period

The current stability during this period must be better than $10^{-4}$ (long term - one hour say). The peak to peak voltage ripple for frequencies higher than 1 Hz must be less than $2 \times 10^{-4}$ of the instantaneous d.c. voltage.

Acceleration (or deceleration) period

It must be possible to increase or decrease the current linearly at a maximum rate of 5 A/sec. Deviations from the linear rise must not exceed $10^{-3}$ times the instantaneous value.

Storage period

The duration of this period may vary from several hours to several days. The current stability requirements are $10^{-3}$ times the instantaneous

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value, with a reproducibility of one part in $10^3$.

**De-excitation period**

There are no special requirements for this period.

**1.2. Proposed Scheme**

The following parameters are the basis for the present study:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>0.5 ohm</td>
</tr>
<tr>
<td>Time constant</td>
<td>5.5 sec</td>
</tr>
<tr>
<td>Nominal current</td>
<td>3 750 A</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>1 875 V</td>
</tr>
</tbody>
</table>

The diagram in Fig. VI.2 shows the proposed scheme.

A transformer with a variable secondary voltage acts as a coarse regulator. The variable secondary voltage is achieved by a stepping switch, which selects a particular contact on the transformer windings. The electrical arrangement of this transformer is shown in Fig. VI.3.

The secondary winding has for example five output taps, which divide the voltage into five equal step values. In series with each of these steps, two regulation windings can be connected, which are arranged so that they can only be "switched-in" when the coil is not carrying current. The two regulation windings connected in series have the same output voltage as one step of the divided main secondary winding. The regulation windings have several outputs, which may be switched "on-load" by a tap-changer. If the regulation winding is divided into equal steps of 1 o/o of the full main secondary winding voltage it is possible to vary the total output voltage from 10 o/o to 110 o/o of the nominal value, in steps of 1 o/o.

The variable output voltage from the transformer secondary winding is then rectified by a silicon diode and transformer technique, in such a manner as to achieve the desired values of current and voltage.
Since the stepping transformer changes the output voltage in a "step-wise" discontinuous manner, an additional regulation system is needed to cover the gaps between the steps. This can be achieved by using a power supply with a "continuous" variable output, designed to have say, one tenth of the total output power, so as to cover several transformer steps. The supply is composed of an arrangement of silicon thyatrons and transformers. The required reproducibility of the setting of one part in $10^4$ can be reached, if the firing points of the thyatrons can be adjusted to within 5 $\mu$s. A variation of the firing points of 5 ms ($90^\circ$ electrical) covers the full range of the variable power and, since this power is 10 o/o of the total power, 5 $\mu$s variation corresponds to one part in $10^4$.

The precision requirements of $10^{-4}$ in the d.c. current can be reached by using a shunt of say 0.5 m ohm, giving a volt drop of 2 V at a current of 4000 A. When the I.S.R. is powered with the minimum current, say 400 A, the voltage on the shunt is 200 mV. A variation of $10^{-4}$ in the current means a variation of 20 $\mu$V on the shunt. This value can be handled by conventional d.c. chopper amplifiers.

The dissipation in the shunt when the I.S.R. magnet is powered at the maximum current will be of about 8 kW, therefore the shunt has to be water or oil cooled, to maintain its temperature variations within a prescribed range.

The current regulation will be possible because of the 5.5 s time constant of the I.S.R. magnet and the quick-acting regulation loop. The dead time of a controlled 12 phase rectification proper is only 20 ms/12 = 1.6 ms, therefore the total time constant of the regulation can be assumed to be about 20 ms. With these parameters a step variation of say 1 o/o in the mains will give an overswing of 4 $\cdot$ $10^{-5}$ in the magnet current.

The main excitation of the magnets is obtained from a 24-phase system, using diodes which, being uncontrolled, give an inherent harmonic voltage ripple of about 3 o/o peak to peak. A 12 phase silicon controlled rectifier set capable of 10 o/o of the total excitation is added for control purposes and in this set the harmonic voltage ripple will vary from 7 o/o to about 30 o/o.
when the control angle is changed between 0 and 90°. Consequently, the total peak to peak ripple output as a percentage of the full d.c. voltage output will not exceed 3 o/o neither at 600 Hz nor at 1200 Hz. To reduce this to the required value of $2 \times 10^{-4}$ during stacking, a suitable filter is needed.

To reduce the cost of a passive filter composed of an R, L and C network, an additional electronic filter is envisaged.

The passive filter will be split in two parts, one part with a time constant $\tau_1$ of 20 ms the other with a time constant $\tau_2$ of 5 ms. This requirement can be achieved by different parameters if they follow this rule:

$$\tau = \sqrt{L \cdot C} \quad R = 2 \sqrt{\frac{L}{C}} \quad (VI,1)$$

If we choose $L_1 = 5 \text{ mH}$ and $L_2 = 1 \text{ mH}$ we have the following resistors and capacitors

$$C_1 = 80 \text{ mF} \quad C_2 = 25 \text{ mF}$$

$$R_1 = 0.5 \text{ ohm} \quad R_2 = 0.4 \text{ ohm}$$

Since the I.S.R. magnet will be powered with a d.c. voltage it is possible to use electrolytic condensers, which are much cheaper than other condensers. There will be no need to reverse the polarity of this power supply, because the possibility of inverting the current in the magnet for storing antiprotons can be ensured by a system of cross connections. The passive filter will reduce the 600 Hz ripple by a factor 40 and the 1200 Hz ripple by a factor 100. The resulting ripple after the filter will therefore be of the order of $10^{-3}$ for the 600 Hz, and of the order of $3 \times 10^{-4}$ for the 1200 Hz ripple component.

The remaining reduction to $2 \times 10^{-4}$ will be achieved by the electronic

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filter. It should also reduce the harmonics of lower frequency which are almost not reduced by the passive network. The power of the electronic filter is of the order of some VA's if \( L_3 \) is 0.5 mH. At 600 Hz the electronic filter has to push about 1.5 A through the inductance \( L_3 \) to produce 2 V, i.e. about \( 10^{-3} \) times the nominal magnet voltage.

Before fixing the final parameters of the electronic filter and of the passive filter one will have to consider the latest improvements achieved on the performances of the electronic filter already in use at the CPS. This may lead to a reduction in the size of the passive filter.

If some distortion in the mains appears, a 100 Hz ripple will result. This ripple will be little reduced by the d.c. filter, and cannot be compensated by the regulation, which acts only below 50 Hz. In case the resulting ripple exceeds the capability of the electronic filter, an a.c. filter may be foreseen.

In industrial plants, e.g. for aluminium electrolysis and, by this time, even in traction applications, silicon diodes and silicon controlled rectifiers are used with a great success for powers of the same order or even bigger, as the I.S.R. supply power. Therefore, the experience of industry can serve as a base for detailed specifications.

### 2. Auxiliary Power Supplies

#### 2.1. Pole Face Windings Power Supply

The pole face windings will serve two purposes:

a) they will compensate the saturation effects in parts of the iron core,

b) they will enable the operator to create a quadrupole field configuration in the airgap of the main magnet.

Assuming 12 independent circuits for the F units and 12 for the D units, 24 separate supplies per ring are necessary. Therefore, 24 generators will be needed. Their power will be about 40 kW each (300 V and 135 A),
In each circuit, the current has to follow the changes of the main magnet field in a prescribed manner, which is determined by the required quadrupole corrections and by the saturation effects.

The overall precision of the current should be of the order of 1 °/° of the nominal value.

The diagram in Fig. VI.4 shows the proposed electrical arrangement for these power supplies.

The scheme can be explained as follows:

A voltage $U_B$, proportional to the field $B$, is fed into a function generator, which produces a voltage $U_\perp$, proportional to the correction required for saturation at the field level $B$:

$$U_\perp = f_{sat}(U_B)$$

The function generator may be a simple network of diodes and resistors.

The same voltage $U_B$ supplies a linear d.c. amplifier with two outputs of opposite signs:

$$U_2 = -U_3 = k_1 U_B$$

where $k_1$ is adjustable according to the required variation of $Q$.

By means of potentiometers, a different combination of these two corrections can be adjusted for every generator. The summation of the two voltages, $U$ saturation and $U$ quadrupole, gives the reference for the regulation loop of a given generator.

Therefore the current in generator $n$ will follow the equation

$$I_{Gen n} \cdot R_{shunt} = U_{n_{sat}} + U_{n_{quad}}$$

and

$$U_{n_{sat}} = p_{n_{sat}} \cdot U_\perp = p_{n_{sat}} \cdot f(U_B)$$
\[
U_{n_{\text{quad.}}} = U_2 - p_{n_{\text{quad.}}} = (U_2 - U_1) = (1 - 2p_{n_{\text{quad.}}}) k_1 U_B.
\]

The required precision of 1 o/o can be reached also with a d.c. current transformer instead of a shunt. This would improve the reliability of the pole face winding power supply since the regulation part would not be linked to the power equipment.

An adjustable octupole correction could also be added to the present scheme without much change in the circuitry.

2.2. Power Supplies for Correcting Magnets and Lenses

The way in which different types of correcting elements in the magnet system have to be powered, in relation with their specific function, has been indicated in chapter V, section 4. The required power supplies can be listed as follows:

<table>
<thead>
<tr>
<th>Correction Type</th>
<th>Number of power supplies per ring</th>
<th>Individual power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextupole lenses</td>
<td>2</td>
<td>50 kW</td>
</tr>
<tr>
<td>Terwilliger quadrupoles</td>
<td>3</td>
<td>50 kW</td>
</tr>
<tr>
<td>Skew quadrupoles</td>
<td>2</td>
<td>100 kW</td>
</tr>
<tr>
<td>Radial field magnets</td>
<td>16</td>
<td>3 kW</td>
</tr>
<tr>
<td>Back-leg windings</td>
<td>32</td>
<td>2 kW</td>
</tr>
</tbody>
</table>

These power supplies can use d.c. generators or silicon controlled rectifiers. In order for the corrections to follow the changes in the main magnetic field during acceleration or deceleration by phase displacement, the excitation of the generators or the firing phase of the rectifiers will be controlled by a voltage proportional to the main field.

2.3. Possible Power Supplies for Special Magnet Sections

The corresponding components of the four special magnet sections for
experiments in each ring should be powered in series. According to the design in section V.5., the following power supplies per ring would be necessary:

<table>
<thead>
<tr>
<th>Bending magnets</th>
<th>800 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole lenses $Q_1$</td>
<td>150 kW</td>
</tr>
<tr>
<td>&quot; &quot; $Q_2$</td>
<td>150 kW</td>
</tr>
<tr>
<td>&quot; &quot; $Q_4$</td>
<td>30 kW</td>
</tr>
</tbody>
</table>

Since these special elements would replace the strong focusing magnets of the main magnet system, their field and their gradients should match precisely the main field level, despite their different saturation properties. Therefore their power supplies should be equipped with current regulation circuits controlled by the main field through suitable function generators. The required precision in current regulation would be $2 \cdot 10^{-3}$.

Schemes similar to that of the main power supply, consisting of large silicon diode rectifiers, supplied from the main stepping transformer, and of smaller auxiliary silicon thyatrons, for fine regulation, would be used.

2.4. Power Supply for Beam Transfer Elements

In anticipation of the discussion of the beam transfer scheme in chapter VIII section 3, we list here the power requirements for the appropriate elements of the beam transfer system.

<table>
<thead>
<tr>
<th>Number of elements</th>
<th>Total power required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole lenses</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>Horizontal bending magnets</td>
<td>42</td>
</tr>
<tr>
<td>Vertical bending magnets</td>
<td>16</td>
</tr>
</tbody>
</table>

3. Magnet Cooling

A review of the cooling problems arising from the I.S.R. project immediately shows that the various heat dissipating components cannot be treated separately. Only an integrated system will give good overall economics and
will allow the water requirements to be kept to a reasonable level. The term "magnet cooling" in the present sense refers, therefore, to a system which covers not only the I.S.R. magnets but also other items, such as condensing units for air conditioning, experimental magnets, etc. These various components and their particular characteristics are listed in the following table:

<table>
<thead>
<tr>
<th>Items</th>
<th>Component</th>
<th>Total heat dissipation MW</th>
<th>Water to be used</th>
<th>Temperature of cooling water in °C</th>
<th>Current °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I.S.R. Magnet, Pole Face Windings, quadrupoles</td>
<td>18</td>
<td>Demineralized</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>Beam Transfer and Injection System</td>
<td>2</td>
<td>Demineralized</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Air conditioning condensing Units</td>
<td>2</td>
<td>Raw water or water from cooling towers</td>
<td>Condensing Temp. not to exceed 40°C</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Experimental Magnets</td>
<td>20</td>
<td>Demineralized</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

The supply water temperature of 17°C required by item 1, can, at least during summer, only be reached by the use of raw water (at 12°C) or with a heat pump. Partial cooling towers or water-to-air heat exchangers are not excluded, however, in view of the comparatively high return water temperature of 37°C. Items 2 and 4 with their supply water temperature of 30°C fit well into the field of cooling towers or water-to-air heat exchangers with water injection. Cooling towers are also adequate for item 3, at least as long as the refrigerant condensers are of the water cooled type.

There is thus a great variety of possible systems which differ with respect
to water and power consumption, first cost and ease of operation. The basic systems which have been considered are briefly described in the following table. The list starts with the system having the highest cost and the lowest water consumption and ends with the one which is the most favourable with respect to first cost but which has the highest water consumption.

<table>
<thead>
<tr>
<th>System</th>
<th>Mode of Cooling</th>
<th>Approximate water consumption m³/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The total heat is finally rejected in water-to-air heat exchangers. A heat pump is used for partial cooling of item 1</td>
<td>negligible</td>
</tr>
<tr>
<td>2</td>
<td>The total heat is finally rejected in cooling towers. A heat pump is used for partial cooling of item 1</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>No heat pump is used. Raw water is used for partial cooling of item 1, to the extent that this cannot be done by cooling towers. The remaining heat is rejected in cooling towers</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>Cooling towers are used for exp. equipment only. Raw water is used for cooling items 1, 2 and 3 and part of item 4. The remaining heat is rejected in cooling towers</td>
<td>800</td>
</tr>
<tr>
<td>5</td>
<td>All cooling is done with raw water taking into account the different temperature levels required by the various items</td>
<td>1000</td>
</tr>
</tbody>
</table>

System 1 would only be interesting if a negligible quantity of raw water was available. The small quantity needed in summer for injection, when the air dry bulb temperature exceeds the design wet bulb temperature, could be taken from a storage tank. System 2, as a preliminary investigation showed, would enter into the picture at a water price of 0.20 Fr/m³ or higher. It is
very tempting to modify this system in such a way that during the cold and moderate season, when all the cooling can be done with cooling towers, the heat pump is used for heat recovery for space heating. This point is still being studied. Both, system 1 as well as system 2, would need a very careful balancing of investment and capitalized power and water cost.

In the case of systems 4 and 5, a large amount of water (700 and 850 m$^3$/h respectively) would be rejected at a temperature of about 50$^\circ$C. This water, before being drained away, would have to be cooled down to about 30$^\circ$C by being passed once through a natural draft cooling tower.

All the above described systems would meet the thermal requirements equally well. The choice depends on the availability of raw water and on the water and power cost. As the situation looks at present water could be supplied to the future site at a rate of up to 1000 m$^3$/h. The cost at this rate would be about 0.06 Fr/m$^3$. Keeping this in mind, and taking into account the current cost of power one comes to the conclusion that system 4 would represent the most economic solution. This system shall, therefore, be discussed in some detail.

The system is schematically represented in Fig. VI.5. The indicated temperatures apply to full load at extreme summer outside conditions (air wet bulb temperature 21.5$^\circ$C, air dry bulb temperature 30.5$^\circ$C). The unavoidable splitting of circuits is not indicated as this has no influence on the principle of the system. With respect to item 1, for instance, one must therefore imagine that there are three separate secondary circuits instead of only one; the primaries of their heat exchangers are connected in parallel. The indicated temperature levels and capacities of heat exchangers and cooling towers, as well as the raw water rate of 800 m$^3$/h are tentative only. They are the result of a preliminary economic study on the information now available. They are moreover based on the assumption that all heat exchangers would be counter-flow connected. A more refined investigation may eventually bring about certain changes. It is, however, not very likely that these will considerably affect the cost of the system.
It is assumed that raw water would be available at the specified rate and at adequate pressure (min. 3 kg/cm²). If one reads the diagram from right to left, there are first the systems for item 1 and item 2. Their primaries are connected in parallel. The system for item 1 is similar to the one being used for the CPS magnet. A constant water flow rate is maintained in its secondary circuit so that at full load the temperature difference across the magnet reaches 20°C. The mean temperature of 27°C in the magnet is maintained by automatic control of the bypass flow across the heat exchanger. The primary water flow rate can either be kept constant or it can be automatically adapted to the load conditions of items 1 and 4. In the secondary circuit one finds the familiar components: water circulating pump, mechanical filter, demineralizing plant connected across the pump and an expansion tank. The latter, as experience has shown, should be pressurized with nitrogen in order to suppress dissolution of oxygen in the demineralized water. This applies, in fact, to all closed secondary circuits in the system. The system for item 2 is similar but the temperature control is effected directly by regulating the primary water flow admitted to the heat exchanger.

The raw water is then further used for cooling item 3, and for partial cooling of item 4 and it is then led into a buffer tank. If the machine only is in operation, without any experiments being performed, the water arrives there at a temperature of max. 35.5°C. It can then be drained away (via overflow).

When, in addition, experiments are being made, the water may arrive at the buffer tank at a temperature of up to 50°C. In this case, before being drained away, it is pumped into a natural draft cooling tower in which it is cooled down to 30°C or lower.

The rest of the cooling in the system for item 4 is done in a second heat exchanger in conjunction with a cooling tower. This latter must be of the forced or induced draft type to allow a better adaptation to the varying load and atmospheric conditions. For the rest this system looks very much like the one used for item 1. There is a difference, however, with respect to regula-
tion in so far as it is the supply water temperature which is being kept constant. The temperature of the water returning from the experimental magnets depends then on the instantaneous load and water flow rate in the secondary circuit.

The whole cooling system presents technically no difficult or unknown problems. All the components of which it is made up have been tried on the CPS and it is known from experience where the weak points are and what must be done to avoid them.
VII. RADIO FREQUENCY SYSTEM. BEAM OBSERVATION

1. Introduction

The only storage ring parameters relevant to the discussion of the RF system are the average radius, the transition energy and the radial aperture available for stacking - or the corresponding momentum spread. The following values taken from chapter IV will be used for computing numerical examples throughout this chapter.

Mean radius
Transition energy over particle rest energy
Available width for stacking (in mid-focusing sections)
Corresponding fractional momentum spread
Corresponding fractional momentum variation

\[ R : 150 \text{ m} \]
\[ \gamma_t : 9.1 \]
\[ : 6 \text{ cm} \]
\[ (\Delta p/p)_s : 2.5 \% \]
\[ (\Delta p/p)_i : 1.5 \% \]

The purpose of the RF system is to trap the beam that has been transferred from the synchrotron, to accelerate it from the injection orbit to the stacking orbit and to deposit it there. The object is to carry out the whole process with a phase space efficiency (defined as the particle density in phase-space within the stack to that in the injected beam) as close as possible to one, during the time available between subsequent pulses arriving from the synchrotron.

2. Parameters imposed by the Properties of the Synchrotron Injector

Since the storage rings are filled from an existing accelerator with given parameters some of the basic parameters of the storage ring RF system can be fixed at once.

First of all, in order to build up a stacked beam as quickly as possible under all circumstances, it is very desirable that the RF system
is able to complete a full cycle of acceleration and stacking in a time not longer than the CPS cycle time, which is 3 seconds at 25 GeV at present, but might be reduced to 2 s in the course of future development. However, twice this time is permissible, whenever both rings are filled simultaneously, with alternate pulses from the synchrotron.

Secondly, it appears to be safest, and most convenient, to transfer the bunches that are already existing in the CPS directly to the storage ring and to capture them in synchronized buckets by means of a phase lock system. This means that the frequency of the storage ring must be equal to that of the CPS i.e. 9.55 MHz at maximum energy. Since the harmonic number of the CPS is 20 and the average radius of the storage ring is assumed to be 1.5 times larger than that of the CPS, the harmonic number for the storage ring is

\[ h = 30 \]

In addition, the bunches have to be matched to the buckets, i.e. the bunch boundary must correspond to a bucket trajectory. However, this requirement imposes no further restrictions on the storage ring RF system because the bunch can be shaped in the synchrotron, before it is transferred to the storage ring, to match any desired bucket shape.

Since 10 out of 30 storage ring buckets remain unoccupied in this scheme the stacking efficiency can never exceed 2/3 as long as only one CPS pulse is stacked each time. One may improve this, as has been proposed by Johnsén, by holding a first injected pulse, bunched, at the injection orbit by means of the RF system until one can fill the gap by a second pulse from the CPS. However, this shall not be discussed here any further.

Finally, the most important parameter which is given by the properties of the CPS beam is the area in phase-space that the bucket must have when it approaches and enters the stacked beam. This area should not be greater than the area of the bunch which the bucket contains.
The phase-space area of a bunch in the CPS at top energy can be roughly determined from the signal observed at a wide band induction electrode. The result is that the area is essentially equal to the theoretical value assuming ideal damping and a full bucket at injection. It follows from this, that the final area of a storage ring bucket when it enters the stack should be equal to the bucket area of the CPS at its injection energy (50 MeV). This area, in a \((\Delta p/m_0 c, \varphi)\) plane – where the phase \(\varphi\) is measured in radians with respect to the accelerating frequency – is

\[
A = 5.5 \times 10^{-3}
\]

Now the area of a stationary bucket is 8 times its half-width in momentum and the area of a moving bucket with stable phase angle \(\varphi_g\) (measured from the zero crossing of the RF wave) is \(\alpha\) times the area of a stationary bucket that has the same RF voltage. The factor \(\alpha\) is given as a function of the parameter \(\Gamma = \sin \varphi_g\) by Symon and Sessler (1956 b).

One finds then, using the theory of Symon and Sessler (1956 a) that the voltage per turn which is needed to form a bucket with area \(A\) is

\[
eV = \frac{E \omega A^2}{128 E \alpha^2} \pi h \xi
\]

(VII.1)

with

\[
\xi = \left| \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \right|
\]

where \(E_0\) is the particle rest energy, \(E\) the total energy and \(\gamma = E/E_0\). The rate of change of momentum is

\[
\frac{\dot{p}}{p} = \frac{A^2 \Gamma h c}{256 \gamma^2 \alpha^2 \beta R}
\]

(VII.2)

where \(\beta c\) is the velocity of a particle. The frequency of phase oscillations becomes

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\[ f_p = \frac{A \hbar \xi c}{32 \pi \alpha \gamma R} \sqrt{\cos \varphi_s} \]  \hspace{1cm} \text{(VII.3)}

The results of eq. (1), (2) and (3) are listed in Table VII.1 for $E = 25 \text{ GeV}$ and different values of $\Gamma$.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>0</th>
<th>0.3</th>
<th>0.5</th>
<th>0.8</th>
<th>0.84</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV</td>
<td>8.4</td>
<td>29</td>
<td>75</td>
<td>850</td>
<td>1500</td>
<td>5000 (eV)</td>
</tr>
<tr>
<td>$\frac{p}{p'}$</td>
<td>0</td>
<td>0.11</td>
<td>0.48</td>
<td>8.7</td>
<td>16</td>
<td>58 $\times 10^{-3}$ (s$^{-1}$)</td>
</tr>
<tr>
<td>$f_p$</td>
<td>1.3</td>
<td>2.4</td>
<td>3.7</td>
<td>10</td>
<td>13</td>
<td>21 (Hz)</td>
</tr>
</tbody>
</table>

3. Non-Repetitive Stacking

It is obvious from Table VII.1 that the rates of change of momentum are too low for carrying every new pulse through the stack and up to its top in the available time, unless values of $\Gamma$ rather close to one are used.

Detailed calculations of stacking efficiency (Swenson 1961) have only been made so far for values of $\Gamma$ not exceeding 0.5, but it is generally assumed that values of $\Gamma$ much larger than this lead to bad stacking efficiencies unless a very large number of pulses is stacked. Although it is true that the number of pulses is, in fact, very large in our case - ideally up to 800 pulses may be stacked in the available aperture - it is felt that it would be unsafe to rely entirely on stacking with $\Gamma$ close to one.

Instead, we prefer to design the RF system in such a way that stacking at $\Gamma = 0.5$ for example is possible, if so desired.

This means that one must deposit every new pulse at the stack bottom by means of a non-repetitive scheme consisting of the following three parts:
1. The particles are captured and accelerated in buckets of large area, yielding a large acceleration rate, for a time $T_1$, until they are close to the stack. As the stack width is growing the time $T_1$ is gradually shortened.

2. The bucket area is then reduced, during a period of time $T_2$, until it fits tightly around the bunch.

3. The bucket — which now has the parameter of one of the columns of Table 1 — is maintained, and the particles are slowly accelerated for a time $T_3$, then the RF is turned off.

The parameters during $T_1$ can be chosen rather freely. Obviously, the time $T_1$ is inversely proportional to the accelerating voltage, $V_1$, during this period, and one is led to choose a rather high voltage. The voltage is, however, limited by economic considerations. Also, the tolerances for programming the voltage and frequency during the slow-down period $T_2$ become too critical if the acceleration rate is chosen too high during $T_1$.

As a good compromise, though a very uncritical one, a voltage of 20 kV and $\Gamma = 0.5$ has been chosen. This leads to a maximum value of $T_1$ of 0.31 s to shift the beam all the way across the available aperture.

The time $T_2$ is governed by the requirement that the reduction of bucket area must be done with very little decrease of phase-space density. An adiabatic change of parameters is the most convenient way of doing this in practice.

The problem of changing bucket parameters adiabatically has been treated — in linear approximation — by Hereward (1960 a). For a process which is conducted in such a way that the fractional change per period of instantaneous phase-oscillation frequency is kept constant during the change it can be shown that the time $T_2$ to change from the initial bucket to the final one is

$$T_2 = \frac{1 + \eta}{2 (1 - \eta)} \left( \frac{1}{\omega_{p2}} - \frac{1}{\omega_{p1}} \right)$$  \hspace{1cm} (VII.4)
where $\omega_{pl}$ is the angular phase-oscillation frequency associated with the initial bucket, $\omega_{p2}$ is that of the final bucket and $\eta$ is a quantity which, under certain assumptions (Hereward 1960 a) may be taken as the phase-space efficiency of the process.

Since $\omega_{pl}$ is much larger than $\omega_{p2}$ in all cases of practical interest, the time $T_2$ is almost independent of the initial conditions. Assumming $\Gamma = 0.5$ and $\eta = 0.9$ one finds $T_2 = 0.41$ s.

There are two reasons why it is necessary to spend a period of time $T_3$ carrying the final buckets a small distance into the stack before they are dropped.

Firstly, the lower edge of the stack will not be exactly sharp. Instead there will be a tail in the distribution through which the pulse should penetrate, before it is deposited. In the absence of good knowledge about the energy distribution at the edge of the stack it is assumed - on the basis of rather qualitative arguments - that it is sufficient to complete the slow-down period $T_2$ about ten ideal pulse widths before the RF turn-off point. The corresponding contribution to the time $T_3$ at $E = 25$ GeV and $\Gamma = 0.5$, is 0.69 s.

Secondly, unavoidable errors in programming the rate of acceleration during the period $T_2$ lead to errors in the location, relative to the stack bottom, where the bucket has reached its final size. Therefore, in order to be certain that the bucket has shrunk to its final size before reaching the stack, one should complete the period $T_2$ a little too early and spend an additional time at the final parameters. If one assumes an error of 2 % in the acceleration rate during $T_2$ and $V_1 = 20$ kV one must allocate a time of 0.14 s for this purpose.

Summing up all times one arrives at a total time of about 1.6 s which still leaves some reserve. One might add another period of time for converting the final bucket into a stationary one and turning the RF off adiabatically. This time would be of the order of magnitude of the inverse phase oscillation frequency at $\Gamma = 0$. PS/4361
For energies lower than 25 GeV it is found that the stacking time decreases at first and then rises again when the transition energy is approached. However, one can come rather close to transition (about 5%) before the stacking time becomes excessive. For energies larger than 25 GeV the stacking time rises slowly, but it does not exceed 1.8 s up to the top energy of 28 GeV.

4. Repetitive Stacking

Repetitive stacking schemes, in which every new pulse is carried through the stack up to its top, become possible if the parameter $\Gamma$ can be made larger than about 0.8 (cf. Table VII.1).

While it was originally believed that high values of $\Gamma$ are excluded, it has been pointed out to us by Symon that stacking schemes involving values of $\Gamma$ close to one are probably permissible because the number of pulses to be stacked is so very large.

Exact computations of energy distributions resulting from stacking a large number of pulses at high $\Gamma$ do not seem to be available but Symon (1963) proposes to use the following rough rule which results from interpolation of known situations at different $\Gamma$ and is expected to be a safe estimate:

The root mean square energy spread at the bottom edge of the stack, caused by the passage of $n$ buckets of given $\Gamma$ is assumed to be equal to, or smaller than, $\sqrt{n}$ times the half-area of a stationary bucket having the same voltage as the actual bucket divided by $2\pi$. Since the average width of the stack is proportional to $n$ and the spread proportional to $\sqrt{n}$, one slowly gains stacking efficiency with increasing $n$.

Assuming $n = 600$ (corresponding to 30 min. stacking at one pulse per 3 s) and $\Gamma = 0.84$, the above rule yields an r.m.s. spread equal to 0.28 times the average width, which appears to be quite acceptable. In any case, full phase-plane density can always be obtained at any place of the
stack if the stacking is carried on long enough and the particles in the tail of the distribution are allowed to be lost.

A stacking scheme of this kind is much simpler than the one considered in the preceding section. In the simplest case one may keep constant voltage and constant rate of change of frequency all the way from injection to the top of the stack where the RF is always switched off at the same point.

With \( \gamma = 0.84 \) and \( E = 25 \text{ GeV} \) it takes 2.5 seconds - somewhat less than the present cycle time of the CPS - to accomplish the maximum required momentum change of 4 \(^\circ\)/o.

It can be seen from eq. (VII.2) that the required time scales with energy as \( \gamma^2/\xi \). As in the case of the non-repetitive scheme, the time decreases at first with decreasing energy and then rises again as the transition energy is approached. The same time as at 25 GeV is again required at an energy 7 \(^\circ\)/o above transition.

Since one has to work close to the threshold value \( \gamma = 1 \) where the bucket disappears small variations in \( \gamma \) will result in large variations of bucket area and close tolerances have to be imposed on the constancy of voltage and rate of change of frequency.

Fortunately, with the given parameters, the requirements are not unreasonable yet: at \( \gamma = 0.84 \) one finds from the figures for \( \alpha(\gamma) \) tabulated by Symon and Sessler (1956 b) that a 1 \(^\circ\)/o change in \( \gamma \) leads to about 6.5 \(^\circ\)/o change in area. Since a given fractional increase of bucket area, occurring before the bucket has reached the stack, is equivalent to a dilution of phase-space density by the same amount one should keep \( \gamma \) constant to about 2 \(^\circ\)/o, for instance, in order to keep a phase space efficiency of 87 \(^\circ\)/o.

Thus, for programmed acceleration, the voltage and the rate of change of frequency should be kept to about 2 \(^\circ\)/o tolerance. If phase lock should be used during part of the process, the corresponding requirement would be a tolerance of 1.8 \(^\circ\) in phase. These tolerances can certainly be kept by a well-designed RF system.
5. Radio Frequency Noise

The CPS, like other large synchrotrons, has a beam control system which locks the phase of the radio frequency to the bunches, so that blow-up of phase oscillations by frequency-modulation noise is largely eliminated. A similar system can be used in the storage ring for trapping and for part of the acceleration. However, when the accelerating buckets approach the stack, the stacked beam becomes more and more modulated by the RF and produces a signal in the pick-up electrode which superimposes itself to that due to the bunches and which may make phase-lock beam-control difficult or impossible. Programmed acceleration must, therefore, be used for part of the process and frequency-modulation noise is a serious problem.

The theory of RF noise has been treated by Hereward and Johnson (1960). If the bucket parameters are kept constant during acceleration - as in the repetitive scheme - and if the FM noise spectrum is constant over a range of modulation frequencies around the phase oscillation frequency, it is found that the mean square amplitude $\Delta \phi^2$, of noise-induced phase oscillation after an acceleration time $t$ is equal to

$$\Delta \phi^2 = 2 \pi \bar{\phi} t \quad (VII.5)$$

The quantity $\bar{\phi}$ is given by

$$\bar{\phi} = \pi \frac{\Delta f^2}{b} \quad (VII.6)$$

where $\Delta f^2$ is the mean square frequency deviation per bandwidth $b$ of modulation frequencies. If one is willing to tolerate a root mean square phase blow-up of 0.1 rad for instance and the acceleration time is 2.5 s, one must make $\bar{\phi} \leq 6.4 \times 10^{-4}$ s$^{-1}$, which corresponds to a root mean square frequency deviation of 0.14 Hz for a bandwidth $b$ of 100 Hz.

In the case of the non-repetitive scheme the situation is even worse, because the change from large to small bucket area during acceleration is found to lead to an increase of the noise-induced blow-up. Indeed, a given
phase amplitude that is induced while the bucket is large and the bunch is wide in momentum and short in phase is increased together with the natural width of the bunch when it is made narrow and long by reducing the bucket area. For the RF programme considered in section 3 one must make
\[ \dot{\phi} \leq 2.3 \times 10^{-4} \text{ s}^{-1} \]
in order to keep the r.m.s. phase blow-up below 0.1 rad.

These requirements are rather tight. Fortunately the design of a low noise RF system is much helped by the fact that only a small frequency range has to be covered. Nevertheless, RF noise is expected to present a problem and an experimental investigation of this point has been started.

So far, only the variable frequency oscillator has been studied. Two models of this oscillator have been built and tested.

The first model is an ordinary LC oscillator whose frequency can be varied from 10 to 20 kHz by means of variable capacity diodes. Its frequency modulation noise has been measured by locking the frequency of one such oscillator to that of a second identical one by means of an automatic phase correction servo-system. This consists of a phase detector measuring the phase difference between the two oscillators and a feedback path from the phase detector output to the input of one of the FM oscillators. The frequency modulation noise can then be measured in terms of the error voltage fed back from the phase detector to the FM oscillator.

A disadvantage of the capacitive diode oscillator is its strongly non-linear modulation curve. Therefore, a second type of oscillator was built whose frequency is controlled, via a servo system, by a linear electronic frequency meter. The noise of this second type of oscillator can be measured simply in terms of the output voltage of the frequency meter.

For both types of oscillators the quantity \( \dot{\phi} \) of eq. (VII.6) was found to be less than \( 5 \times 10^{-5} \text{ s}^{-1} \) which is well below the tolerance.

6. Low Level Electronics

The two stacking schemes that have been discussed should only be considered as typical examples of what one may want to do. Other schemes may
be found advantageous and flexibility must therefore be one of the main design features of any RF system for storage rings.

Precise programming of the RF voltage is required in any case.

In the case of the non-repetitive scheme of section 3 the voltage programme consists of a large and constant voltage during a time $T_1$, a steeply falling voltage during $T_2$ and again a constant but very small voltage during $T_3$. A voltage variation of about a factor 300 must be covered by the programme generator. The transition between the first and the second part of the programme can be controlled by a pulse derived from a measurement of the accelerating frequency. The frequency where the pulse occurs must be changed by a small amount after every stacking cycle.

The moment when the RF is finally turned off may also be determined from a frequency measurement. However, it seems both possible and preferable to derive this time from the signal induced in a pick-up electrode, making use of the fact that the induced signal disappears when the bunches enter the stack.

In the case of the repetitive scheme a constant voltage, switched off when the frequency has reached a fixed predetermined value, may be all that is required.

In order to obtain the required precision it is necessary to tie the voltage across the accelerating gap to the output of the programme generator by means of an automatic gain control servo-system.

At least during part of the accelerating process a frequency programme is required. The rate of change of frequency must follow the RF voltage with about one to two percent precision. It is intended to derive the frequency programme from the voltage programme via an electronic integrator as shown on Fig. VII.1. If the frequency to voltage relationship of the FM oscillator is linear, the stable phase is kept constant. A variation of stable phase is, however, possible by means of a variable attenuator between the programme generator and the integrator.
Only 4.3 kHz frequency variation is needed to shift the beam all the way across the available aperture. Therefore, the final frequency shall be composed out of a fixed frequency $f_0$ (from a very stable quartz oscillator) and a rather low, variable, frequency $f_1$ (e.g. 10 to 14.3 kHz from a wide range FM oscillator) by means of a mixer and filter. All frequency measurements can then be made at the frequency $f_1$ where the required relative precision is reduced by a factor $f_1/f_0$ compared to a measurement at the final frequency.

Larger changes of frequency occur when the mean operating energy and hence the particle velocity is changed. These changes are most conveniently done by adjusting the frequency $f_0$.

Phase lock beam control is needed at least for trapping the bunches arriving from the injector synchrotron and it must be possible to switch from phase lock to programmed acceleration at a suitable moment. This will be done with a system for automatic phase control, similar to the one which is used in the CPS, as shown on Fig. VII.1. The switch for disconnecting the phase lock error signal must be arranged in such a way that no sudden change in phase or frequency can occur when the switch is opened.

The whole proposed RF system is shown schematically on Fig. VII.1.

7. Accelerating Cavities and High Power RF System

The accelerating cavities for each of the two storage rings shall all be located in one long straight section per ring where a free length of 9 m is available (cf. Fig. V.1).

The maximum peak accelerating voltage has been fixed at 20 kV and it must be possible to turn the voltage down to about 75 V in a smooth and well-controlled fashion.

The total frequency swing during stacking is less than one part in a thousand but larger variations of frequency occur when the mean operating energy of the storage ring is changed. For instance, if protons of a
minimum kinetic energy of 5 GeV are stacked the frequency is 1.3% below
the maximum value. Therefore the η-factor of the accelerating cavities
should be kept rather low, so that the variable tuning, if necessary at
all, is made uncritical. Probably, a η-factor of about 150 will be chosen.

The most serious problem for the high power RF system is that of beam-
loading. In order to be safe against beam-cavity interactions the total
voltage induced by the beam in all accelerating cavities should remain small
compared with the minimum accelerating voltage of 75 V. The beam current
produced by \(10^{12}\) protons injected from the CPS is 75 mA. Since the beam
consists of short bunches the RF component of the beam current at the
accelerating frequency is about twice the DC current, i.e. 150 mA. Thus,
if the total beam-induced voltage should remain smaller than one tenth of
the minimum accelerating voltage, the sum of the impedances of all cavities
as seen by the beam must not exceed 50 Ω.

On the other hand, the total shunt impedance presented by the cavities
to the RF power source must be much larger than 50 Ω in order to arrive at
a reasonable power consumption. It is excluded, therefore, that beam loading
is eliminated simply by means of heavy damping of the cavities.

Indeed it is planned to equip each ring with 9 accelerating cavities
of about 1.2 kΩ shunt impedance each, so that the total RF power consumption
for 20 kV per turn will be 18 kW per ring. Each individual cavity will be
powered by a separate 2 kW amplifier so that the RF system remains usable
even if one or two accelerating stations have failed.

The required low impedance on the beam side will be obtained by driving
the cavities from amplifiers with very low output impedances, which must be
obtained by strong negative feedback. This requires the final power tubes
to work in nearly class A condition since maximum transconductance associated
with maximum anode current is required mostly when the RF output is low.
Therefore, the efficiency of the power amplifier must be expected to be
rather low. It is estimated that it will be about 35%, such that the
total DC input power to all power amplifiers of both storage rings will be
about 100 kW.

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Since the beam consists of short bunches the beam current contains higher harmonics of the accelerating frequency up to frequencies as high as 100 or 200 MHz. Therefore, the impedance presented by the cavities to the beam must remain small for these higher frequencies as well as for the accelerating frequency itself. This requirement implies that the cavities are free from higher resonance modes that could make their impedances rise to undesirable values.

8. Beam Observation

The storage rings will be equipped with capacitive induction electrodes for observing the radial and vertical beam-positions and the azimuthal charge distribution, as is standard practice with synchrotron accelerators.

48 stations for observing the transverse beam position will be distributed around the circumference of each ring, as shown in Fig. V.1. Each station contains electrodes for both vertical and horizontal displacement. Since some straight sections into which it would have been desirable to place observation stations are already fully occupied by other equipment or forbidden because of ultra high vacuum requirements a somewhat irregular distribution had to be chosen. However, the distance between neighbouring stations nowhere exceeds one quarter wavelength of the betatron oscillation.

In principle, the induction electrodes and the associated electronic system will be very similar to the corresponding system of the CFS. There are, however, some differences:

In a synchrotron the beam centre is usually kept rather close to the centre of the vacuum chamber. Large deviations from the centre are normally regarded as errors which have to be reduced anyhow and which one may be satisfied to know in sign and rough magnitude only. This is not the case in a storage ring, at least not as far as radial displacement is concerned, and the observation system must yield good precision near the radial aperture limit as well as near the centre. Also, since one attempts to fill the entire aperture, very tight tolerances on closed orbit distortion are
required and a correspondingly good precision of the observation system is desirable. It is believed that an overall precision of ± 1 mm can be obtained. This involves, of course, mechanical positioning of the electrodes with respect to the storage ring magnets within a few tenths of a millimetre.

Finally the electrodes and their vacuum envelope must meet ultra high vacuum requirements and must be bakeable to 300° C.

The proposed construction of a beam observation station is shown in Fig. VII.2. The exact shape of the electrodes themselves has not yet been determined, it will be similar to shapes that have been developed for the CPS. The bandwidth of the electrodes and of the associated electronic system will reach from below the revolution frequency of the beam to above the bunch frequency and the signals induced in the electrodes will be transmitted via coaxial cables directly to the main control room where they can be observed directly, as is standard practice with the CPS and other accelerators, or undergo further treatment.

Two electrodes for observing the azimuthal charge distribution, so called "sum" or "phase" electrodes, are foreseen in each ring. One of them drives the beam control system (cf. Fig. VII.1). The other is connected to a wide band amplifier and permits one to observe the bunch shape during trapping and stacking. These electrodes have the form of simple tubes surrounding the beam. Their vacuum envelope will have similar shape and dimensions as the one shown in Fig. VII.2.

Obviously, neither of the two types of electrodes can be used for observing the unbunched stacked beam. However, the stacked beam can be made "visible" by frequency-modulating the RF voltage in such a way that small empty buckets are moved through the stack (Symon and Sessler 1956 a). The main purpose of this method is to explore the distribution of particle density versus energy within the stack. For example, if empty probing buckets of the same parameters \( V = 75 \, V, \Gamma = 0.5 \) as the ones proposed for non-repetitive stacking are used, the voltage induced in the induction electrode by the local modulation of the stack is about the same as that.
which is normally induced by the injected beam and it takes about a minute to scan through the full stack. The disturbance of the stack produced by the small probing bucket is negligible.

Finally, DC current transducers of the same type as are now being developed for the CERN electron storage ring model will be employed to measure the total stacked beam current, and a system of movable beam-sensing targets as well as fluorescent screens and television cameras may be used as destructive means for measuring beam position and size during running-in periods.
VIII. BEAM TRANSFER AND INJECTION

1. Energy and Frequency Requirements during Beam Transfer

The beam must be transferred from the CPS to the ISR in such a way that a maximum number of protons can be stacked in the energy band determined by the 57 mm stack width of the ISR. Possible RF systems for this purpose have been discussed in chapter VII. At the moment of beam transfer the frequencies of the RF systems in the CPS and ISR must be the same. The ratio of the circumferences of ejection and injection orbits are 1 : 1.5 and therefore the harmonic numbers are 20 and 30 respectively. After a pulse from the CPS has been injected there are 20 full and 10 empty buckets circulating in the ISR. For maximum intensity it would be desirable to fill also the latter before the beam is accelerated towards the stack.

A possible scheme to do this and to avoid any loss of protons would be to place in the beam path between the CPS and ISR a fast switching magnet followed at a distance $\lambda/4$ by a septum magnet. This combination operates in the same way as the fast ejection system of the CPS. The sequence is then as follows. First a complete pulse from the CPS is transferred to ISR a. The second pulse from the CPS is timed in such a way, that it fills the 10 empty buckets of ISR a, but after the first 10 bunches have passed through the switching magnet, the latter is energized and sends the second half of the pulse into ISR b, which then has 10 full and 20 empty buckets. The latter are filled with a third pulse from the CPS. Meanwhile the injected beams are accelerated towards the stack and at the fourth pulse from the CPS the sequence starts to repeat itself.

With an RF voltage of 20 kV (Schnell 1962 and 1963) the bunches in the ISR have an energy spread (determined by the CPS parameters) $\Delta E/E \approx 2 \times 10^{-4}$ and a phase spread $\pm 18^\circ$. The bunches of the second pulse must be properly phased and have the same average energy as the bunches which are already present in the ISR. The phasing is relatively easy, because the RF systems of CPS and ISR are locked together at the moment of beam transfer. Since the velocity of the protons is the same in the CPS and ISR, the frequency determines the mean radius of the orbit in each machine so that equal
energies can only be obtained if the magnetic fields have the correct ratio at the moment of beam transfer. An error in the ratio of the magnetic fields of 4 parts in $10^5$ gives an energy difference which is $10^{-6}$ of the total energy spread in the bunches. To obtain this accuracy the CPS should be operated with a flat top that has a very small slope. The beam must then be ejected when the CPS field passes through the appropriate value.

For the first pulse which is injected into ISR a the tolerances are less severe. If there is a small error in energy the bunch will start a coherent phase oscillation which is damped out by the phase lock feedback loop of the RF system in ISR a. The same applies for the second half of the second pulse which is injected into ISR b. The tolerances on the absolute stabilisation can therefore be relaxed if it is arranged that the ratio between the magnetic fields of ISR a and CPS during the second pulse is the same as during the first pulse, and that the ratio between the magnetic fields of ISR b and CPS during the third pulse is the same as during the second pulse. In that case the precision of a few parts in $10^5$ need only be maintained from one pulse to the next.

It should be noted that if it is considered sufficient to fill only $2/3$ of the ISR circumference, the tolerance on the ratio of the magnetic fields of the ISR and the CPS can be relaxed by a factor of ten.

The mean radial position of the injection orbit is $\Delta r = -41 \text{ mm}$ (injection occurs from the inside of the vacuum chamber) but if we inject with the Terwilliger quadrupoles excited the mean radial position becomes $\Delta r \approx -21 \text{ mm}$ and therefore it must be possible to eject from different mean radii in the CPS. Due to the complicated shape of the orbits in strong focusing machines with magnet imperfections it is difficult to determine very accurately the circumference of the orbits in the CPS and the ISR. If the closed orbit deviations in the ISR turn out to be smaller than has been assumed in Eq. (IV.35) it would be advantageous to choose an injection orbit at a somewhat larger distance from the central orbit than we assume here in order to have a wider and therefore more intense stacked beam.
From these arguments we conclude that the CPS ejection system should be able to eject the protons from all orbits with mean radial positions in the interval $\Delta r = \pm 15$ mm.

2. Ejection from the CPS

The beam is ejected from the CPS by means of a fast ejection system consisting of a fast kicker magnet, followed at a distance $(k + \frac{1}{4}) \lambda$ by a septum magnet. The fast kicker of the present CPS ejection system is installed in straight section 97. A distance $5/4 \lambda$ corresponds to 20 magnet units so that ss17 is the optimum position of the septum magnet. Since this is a short straight section it is necessary to use two septum magnets in series, placed in ss17 and ss18. With a small increase in kicker strength one can also place the septum magnet in ss16, which is long and mid D, or in mid D ss18 which would then be lengthened at the expense of ss17 and ss19. The last two possibilities are seriously being considered by the MPS division in connection with the proton beam ejection for the east area, for which the use of the same fast kicker magnet is intended, and the modifications involved for the present CPS layout of magnets and RF equipment. In both cases the ejected beam has probably to pass through holes in the wall of the linac wing, but these are never very long as can be seen from Fig. VIII.1. Neither of the ejected beams interferes seriously with the linac or CPS injection optics. The thick wall inside which the beam from ss16 crosses the linac beam is made of loose blocks.

Whether the ejection is from ss16 or 18 the beam passes the non-linear stray field of the minimum gap side of an F unit, and this leads to some aberrations. For an ejection trajectory starting in ss16 at $\Delta r = +60$ mm and at an angle of +25 mrad the vertical and horizontal emittance increase by about 20 $\%$ and 40 $\%$ respectively for a beam radius of 3 mm (25 GeV). With a beam radius of 5 mm (10 GeV) the corresponding figures are about 30 $\%$ and 65 $\%$ respectively. From studies of ejection trajectories for the East area it looks feasible, however, to reduce the aberrations by a
careful choice of the ejection trajectory (Áliech 1963), shaping of the stray field or by adding a moderate sextupole component to the gradient of the first beam transport quadrupoles. For the continuation of this chapter we shall assume that the ejection occurs in ss16. Eventual ejection from ss18 will not change any essential argument.

3. Beam Transport System

To focus the beams on their path from the CP3 to the ISR it appears best to use a number of regularly spaced, alternating F and D, quadrupoles. For a given length of beam and a given total length of quadrupoles the smallest value of $\beta_{\text{max}}$ occurs if the quadrupoles are subdivided in such a way that the phase shift per period is $\mu \approx 0.88$. The minimum is very flat and in order to have a somewhat larger quadrupole spacing we have chosen the following parameters:

<table>
<thead>
<tr>
<th>Table VIII.1</th>
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<tbody>
<tr>
<td>Distance between quadrupole centres</td>
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<tr>
<td>Quadrupole strength $C$</td>
</tr>
<tr>
<td>$\mu$</td>
</tr>
<tr>
<td>$\beta_{\text{max}}$</td>
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<tr>
<td>$\beta_{\text{min}}$</td>
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<tr>
<td>Aperture</td>
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</tbody>
</table>

The ejected beam is strongly focused vertically and defocused horizontally by the stray field of unit 16. It has a vertical focus at the downstream end of ss17 and the horizontal dimension has already increased a factor 2 at this place. Therefore it is necessary to place an F quadrupole in ss17. The latter must be pulsed in order to reduce its overall dimensions. The subsequent beam transport quadrupoles are operated dc. To match the vertical and horizontal emittance ellipses of the ejected beam to the acceptance of the beam transport system one needs to have 4 free parameters.
and therefore the currents in the first 4 quadrupoles must be separately adjustable. The same holds for the 4 last quadrupoles before the injectors of the ISR. All other quadrupoles can be excited in series.

After the first two quadrupoles there is a vertical bending magnet $B_{V1}$ which gives a deflection of 10 mrad. The ejected beam then passes about 23 cm above the linac beam, so that they can have separate vacuum pipes and is made horizontal again by $B_{V2}$. We have also foreseen a horizontal steering magnet $B_H$. The fast switching magnet is indicated by $K_s$. There are 3 quadrupoles between $K_s$ and its corresponding septum magnet which is not shown in Fig. VIII.1. After the beams have been separated they are deflected over angles of $10^\circ$ and $60^\circ$ respectively (Fig. II.1) for injection into the ISR. The gap height of the horizontal bending magnets is 30 mm.

Injection into the ISR must necessarily occur in the inner arc since the outer arc has no long straight sections. Moreover the injection trajectories should not limit the possibilities for experimentation in the two interaction regions where they pass rather nearby. In this connection it is convenient that the level of the site adjacent to the CPS, which is available for the ISR is appreciably higher than that of the present CERN site, so that the beam level of the ISR will be at least 10 m higher than that of the CPS. We intend therefore to let the ejected beam continue horizontally at about 30 cm above the CPS level. It passes under the hall for 25 GeV experiments (Fig. II.1) at a sufficient depth to provide adequate shielding and is then deflected upwards over 100 mrad. The injection trajectories pass the interaction regions at 4.8 m below the ISR beam level, which should be sufficient for experiments.

We propose to inject from the inside of the ISR vacuum chamber, rather than from the outside, since it is more advantageous to accelerate than iccelerate during the stacking process. This has the additional advantage that the aberrations in the first F magnet sector are unimportant since the beam passes through its gap on the open side. Finally it gives a somewhat smaller minimum distance between CPS and ISR.
The last part of the injection trajectory is shown in Fig. VIII.2. After a vertical deflection of 63 mrad in V1 and V2 and of 37 mrad in V3 and V4 the beam is again horizontal and then it is made parallel to the ISR orbit in the long straight section by the septum magnets S1 and S2, each of which produces a deflection of 25 mrad. With a length of 2.2 m for each septum magnet the magnetic field has to be 1.06 T for 28 GeV. The latter two are pulsed but all other magnets we have mentioned operate dc. Their currents should be stabilized to one part in $10^4$. The last beam transport quadrupole is also pulsed in order to reduce its outside dimensions so that there is some space left for a possible correcting element of the ISR. A 5 cm diameter hole will be provided in the yoke of the first upstream D unit in order to let the beam pass. The alternative of having the yoke on the outside of the ISR has been rejected since the vacuum chamber has to be accessible through the open side of the gap.

4. Injection into the ISR

We have chosen to place the septum magnets $S_1$ and $S_2$ in $a_6$ and the kicker magnet in $a_4$ downstream of $a_6$. This provides minimum interference between the injection trajectory and the interaction region. Moreover, $\alpha_p$ for the displaced Terwilliger scheme will be near to its maximum at this kicker magnet position, which facilitates injection with the Terwilliger quadrupoles excited.

Minimum kicker strength is obtained by placing the kicker at the downstream end of $a_4$. The betatron phase shift from septum magnet to kicker can then be made 90°. The beta functions for the septum magnet centre are $\beta_s(H) = 19.3$ m and $\beta_s(V) = 17.2$ m while for the kicker centre $\beta_k(H) = 37.1$ m and $\beta_k(V) = 16.6$ m. The relation between kick and displacement at the septum is $a = \sqrt{\beta_k(H) \beta_s(H)} \Psi = 26.8 \Psi$. The mid F radial position of the injection orbit at the septum position is $\Delta r = -48.6$ mm, while it is $-48.0$ mm at the position of the kicker magnet. From the ultra high vacuum point of view it would be convenient to have the septum magnet completely
outside the ISR vacuum chamber and to have some clearance for bake-out. We shall assume therefore that the beam centre is \( \Delta r = -108 \text{ mm} \) in the septum magnet. As shown in Fig. VIII.3 we propose to put a 9.4 mm bump on the injection orbit by means of backleg windings on two ISR magnet units which are half a wavelength apart. The total displacement due to the kicker magnet must then be 50 mm, corresponding to a strength \( B \ell = 0.175 \text{Tm} \) at 28 GeV.

The kicker magnet must have a small stray field, since it should not perturb the stacked beam. We intend therefore to place a movable screen between the kicker magnet and the stack at the moment of injection.

5. Beam Size and Transfer Errors

We assume that the beam radius in the CPS at a position where \( \beta = 16 \text{ m} \) is 3.0 mm at 25 GeV and 5.0 mm at 10 GeV. In the ISR the maximum values of the amplitude function are \( \beta_{\text{max}} (H) = 38.0 \text{ m} \) and \( \beta_{\text{max}} (V) = 53.0 \text{ m} \). This gives as maximum half sizes of the beam \( \hat{\chi} = 4.7 \text{ mm} \) and \( \hat{z} = 5.4 \text{ mm} \) at 25 GeV and \( \hat{\chi} = 7.9 \text{ mm} \) and \( \hat{z} = 9.0 \text{ mm} \) at 10 GeV. The amplitude of the radial synchrotron oscillations in the CPS and ISR is about 0.5 mm at 25 GeV and 1.0 mm at 10 GeV. To this must be added the effect of the bending magnets of the beam transport system between the CPS and ISR. We shall assume that the phase shifts in the beam transport system are chosen in such a way that protons of different energies are injected onto their respective closed orbits, so that this effect does not increase the beam size.

In the horizontal plane the beam transfer errors are mainly due to the pulsed magnets of the CPS ejection system, the fast switching magnet and the ISR injection system. In all these cases we have a kicker magnet and a septum magnet a distance \( \lambda/4 \) apart. If the angular deflections of such a pair have errors corresponding to maximum betatron oscillation amplitudes \( a_K \) and \( a_S \), their combined effect is an amplitude

\[
\Delta \hat{\chi} = \sqrt{a_K^2 + a_S^2}
\]  

(VIII.1)
We shall assume that $2/3$ of the errors in the pulsed magnets is caused by current fluctuations and $1/3$ is caused by field inhomogeneities due to end effects, saturation and imperfections in the construction. The latter $1/3$ will therefore also occur in the vertical plane. We shall assume that stray field aberrations in the CPS and ISR are corrected by shimming and that all dc quadrupoles and bending magnets can be constructed and stabilized so precisely that their errors can be neglected.

We shall now list the various sources of errors in the horizontal plane and calculate the corresponding betatron oscillation amplitude in the ISR at a position where $\beta_{\text{max}}(H) = 38.0$ m. The septum magnet in the CPS is at a place where $\beta = 12$ m and gives a deflection of 25 mrad. The displacement produced by the fast kicker is 30 mm. An error of $\pm 0.1\%$ of the septum magnet and $\pm 2\%$ of the kicker gives $\Delta \hat{x} = 1.3$ mm in the ISR. For the fast switching system which is not subject to space limitations, we shall allow half this error, $\Delta \hat{x} = 0.7$ mm. A radial instability of the closed orbit of $\pm 0.5$ mm in the CPS gives $\Delta \hat{x} = 0.8$ mm in the ISR. A $0.1\%$ error in $S_1 + S_2$ and a $3\%$ error of the injection kicker (allowing for the decay time of its magnetic field) give $\Delta \hat{x} = 2.5$ mm. Finally we allow a $0.5$ mm instability of the closed orbit in the ISR. The sum of all these errors is

$$\Delta \hat{x}_{\text{inj}} = 5.8 \text{ mm} \quad (\text{VIII.2})$$

so that the total horizontal half width of the beam becomes 10.5 mm at 25 GeV and 13.7 mm at 10 GeV.

The vertical errors of the pulsed magnets are taken as $1/3$ of the horizontal errors, so that for $\beta_{\text{max}}(V) = 53$ m we find $\Delta \hat{y} = 1.7$ mm. We take the same c.o. instabilities as horizontally which gives $\Delta \hat{y} = 1.4$ mm. The vertical beam transfer errors are clearly smaller than the horizontal errors, but the question is, how much energy transfer there is from the horizontal plane to the vertical plane due to coupling. This effect is certainly reduced by the skew quadrupoles, but we shall allow somewhat arbitrarily $\Delta \hat{y} = 1.0$ mm for it. The sum of these vertical errors is then
\[ \Delta \hat{z}_{\text{inj}} = 4.1 \text{ mm} \] (VIII.3)

which gives a total half height of 9.5 mm at 25 GeV and 13.1 mm at 10 GeV.

It should be noted that the total injection errors are calculated as the linear sum of the individual errors. It might be argued that a quadratic summation would be more appropriate but since the errors are not all independent, we prefer to present the most pessimistic case.

6. The Kicker Magnet for Injection into the ISR

At the position of the fast kicker magnet \( \beta_k(V) = 16.6 \text{ m} \) and \( \beta_k(H) = 37.1 \text{ m} \). The height of the beam in the fast kicker just after injection is therefore 10.8 mm at 25 GeV and 14.8 mm at 10 GeV. We have chosen a gap height of 15 mm. It is desirable to have the possibility of moving the stacked beam to the centre of the vacuum chamber after the stacking process is finished in order to have sufficient horizontal aperture to accommodate the increased beam size due to multiple scattering. The proposed gap height of the kicker magnet is not sufficient to accommodate the increase in beam height due to gas scattering, but in order to keep the high voltage requirements to a reasonable level, the gap height should be as small as possible.

It would be desirable therefore to mount the kicker magnet in such a way that after the stacking process is finished, it can be displaced radially inward over about 50 mm so that it leaves the ISR aperture entirely free.

During the stacking process, however, the kicker will be in a fixed position. The closed orbit will be made to pass just through the centre of the kicker by distorting the closed orbit with backleg windings and vertical correcting magnets. As a criterion for adjustment, one can use the absence of coherent betatron oscillations of the injected beam.

The horizontal space needed for the beam in the fast kicker just after injection is calculated to be 20.2 mm at 25 GeV and 26.4 mm at 10 GeV. In view of the results of the magnetic field measurements by Bertolotto et al. (1963) on the CPS kicker presently in use for ejection, we want to allow
for a 5 mm radial interval at the open gap side where the field may drop more than 3% while moreover a 1 mm thick conductor will have to be placed at the closed gap side. Since there is, moreover, no stringent reason for not having a comfortable margin on the gap width, we have chosen a gap width of 35 mm.

In order to be able to produce a pulsed magnetic field, the time dependence of which is a square pulse, the kicker magnet will be made as a ferrite loaded transmission line through which a pulse forming network (p.f.n.) will be discharged into a load resistance, all three having the same characteristic impedance in order to avoid reflections of the pulse. The requirements for rise and fall times when the ISR is only being filled for 2/3 of its circumference are easy to satisfy. When the remaining 1/3 of the circumference is also filled by half a pulse from the CPS the rise and fall times of the magnetic field have to be less than the time in between two bunches (∼90 ns) since the protons continue to circulate through the kicker magnet for some time after injection.

The theory of kicker magnets is well known (O'Neill 1959) but for convenience we shall repeat some of the relevant formulae. We consider a kicker magnet with a total length \( l \), that has been subdivided into \( N \) sections, each with a length \( l/N \). All sections are pulsed in parallel. Putting \( w = \text{gap width} \) and \( h = \text{gap height} \), the self inductance per section is

\[
L = \frac{\mu_0 w l}{hN}
\]  

(VIII.4)

For a characteristic impedance \( Z \) the total loading capacity per section is

\[
G = \frac{L}{Z^2} = \frac{\mu_0 w l}{2Z^2 hN}
\]  

(VIII.5)

and the rise time of the magnetic field due to the delay of the electric pulse over the length of a kicker magnet section is

\[
\tau = \sqrt{L \cdot C} = \frac{\mu_0 w l}{Z hN}
\]  

(VIII.6)
For a given charging voltage $V$ of the p.f.n.,

$$I = \frac{V}{2Z} \quad \text{(VIII.7)}$$

and the magnetic field

$$B = \frac{\mu_0 I}{h} = \frac{\mu_0 V}{2h Z} \quad \text{(VIII.8)}$$

The deflection due to the total kicker magnet is then proportional to

$$B_l \frac{\mu_0 V l}{2h Z} = \frac{N V \tau}{2w} \quad \text{(VIII.9)}$$

We are considering a kicker magnet for injection into the ISR with parameters as given in the following table.

**TABLE VIII.2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Total length of magnetic field</td>
<td>$l = 150$ cm</td>
</tr>
<tr>
<td>Number of sections</td>
<td>$N = 6$</td>
</tr>
<tr>
<td>Length per section</td>
<td>$\frac{l}{N} = 25$ cm</td>
</tr>
<tr>
<td>Gap width</td>
<td>$w = 35$ mm</td>
</tr>
<tr>
<td>Gap height</td>
<td>$h = 15$ mm</td>
</tr>
<tr>
<td>Inductance of a kicker section</td>
<td>$L = 0.733 \times 10^{-6}$ H</td>
</tr>
<tr>
<td>Capacitance of a kicker section</td>
<td>$C = 0.374 \times 10^{-8}$ F</td>
</tr>
<tr>
<td>Characteristic impedance</td>
<td>$Z = 14 \Omega$</td>
</tr>
<tr>
<td>Delay per kicker section</td>
<td>$\tau = 52.3$ ns</td>
</tr>
<tr>
<td>Pulse duration for $2/3$ filling of the ISR</td>
<td>$T = 2.05 \mu$s</td>
</tr>
</tbody>
</table>
| " " " 1/3 " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " " 

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Since the kicker has to be placed in the ultra high vacuum, the use of organic insulation material is excluded and the whole system has to be bakeable at temperatures of 300 to 350 °C. Fig. VIII.4 shows the design of a model under construction.

By the use of coaxial high voltage cable as p.f.n. instead of lumped parameter delay lines we hope to obtain rise and fall times of the magnetic field less than 90 ns and with a flat top which is constant to within ± 3 °/o. Also reflections after the pulse have to be suppressed to within this tolerance. The coaxial cable will be discharged by a coaxial spark gap into the kicker magnet and its load resistance.

7. Slow Ejection

Apart from colliding beam experiments, each SR can also be used as a beam stretcher for the CPS. In particular for experiments which make use of the external proton beam, where the counting rates will often be very high, a duty cycle close to unity is of great value. We shall therefore discuss the possibility of slow ejection from the SR, using the theory of resonant extraction that has been developed by Hereward (1961) for the CPS. The only difference is that in the CPS the Q-value is an integer +1/4, whereas in the SR it is an integer −1/4.

The principle of operation is as follows. In one of the mid F straight sections is a non-linear lens, whose quadrupole component increases the Q-value on the central orbit to 9.0. Its sextupole component is such, that Q < 9.0 for Δr > 0. If the beam is a few mm radially outward from the central orbit, it is stable, but if the magnetic guiding field is slowly increased, Δr decreases and the beam gradually becomes unstable. The time at which a proton becomes unstable depends on its energy and betatron oscillation amplitude. The motion of the unstable protons is a forced oscillation, whose amplitude increases approximately exponentially and whose phase depends very little on amplitude. Most of the protons can therefore be made to jump the septum of a magnet, placed at a suitable

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azimuth, which deflects them away from the machine. The rate of spill-out of the protons is determined by the rate of change of the radial position of the proton beam in the non-linear lens. To reduce the quadrupole strength of the latter the SR can be tuned to $Q = 8.875$ with its pole face windings. Using Hereward's figures we then find that the non-linear lens has a quadrupole component of 3.2 T and a sextupole component of 95 T/m at 28 GeV.

The requirements on the septum magnets are on the one hand more severe than in the CPS, since they must operate dc, but on the other hand the SR has very long straight sections. Many arrangements of septum magnets are possible. We shall describe here a layout consisting of three septum magnets, of which the first one has a septum thickness of 1 mm. Hereward has calculated an efficiency of 73% for an ejection magnet in the CPS with a septum thickness of 5 mm. Therefore the ejection scheme discussed here should have an efficiency of about 95%. Proton trajectories are shown in Fig. VIII.5 for the FODOD structure as studied by de Raad (1963). For the FODO structure as considered in this report the situation will be very similar. Proton C, which just grazes the septum would on its next revolution follow trajectory A. Magnet S1, which has a 1 mm septum thickness, is placed at the upstream end of a long straight section and gives a deflection of 0.7 mrad. At the downstream end of the same long straight section the separation between trajectories B and C has increased to 5.5 mm so that we can place there a magnet S2 with a 5 mm thick septum. In the next long straight section the spacing between trajectories B and C has become so large that there is ample space for a strong septum magnet S3 which deflects the protons away from the machine. It is convenient that the ejected beam has a horizontal cross-over inside magnet S3. The main parameters of the septum magnets for 28 GeV protons are given in Table VIII.3. These ratings are moderate and therefore the construction of the septum magnets should not present any special problems.
Table VIII.3

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection angle</td>
<td>0.7 mrad</td>
<td>2.2 mrad</td>
<td>25 mrad</td>
</tr>
<tr>
<td>Length</td>
<td>2 m</td>
<td>2 m</td>
<td>4 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.033 T</td>
<td>0.10 T</td>
<td>0.6 T</td>
</tr>
<tr>
<td>Septum thickness</td>
<td>1 mm</td>
<td>5 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Gap height</td>
<td>15 mm</td>
<td>15 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>Current</td>
<td>400 A</td>
<td>1200 A</td>
<td>2000 A</td>
</tr>
<tr>
<td>Voltage</td>
<td>1.1 V</td>
<td>1.1 V</td>
<td>10 V</td>
</tr>
<tr>
<td>Power</td>
<td>440 W</td>
<td>1.3 kW</td>
<td>20 kW</td>
</tr>
</tbody>
</table>

The main problem in this slow ejection scheme is the stability of the SR magnetic guiding field. The difference in radial positions of the equilibrium orbits where the entire beam is stable and where all protons have been spilled out is about 1 mm. This corresponds to a field difference of 4 parts in $10^4$. If we want to spill out the protons during the 3 s interval in between successive pulses from the CPS, the radial position of the equilibrium orbit must change at a rate corresponding to

$$\frac{1}{B} \frac{dB}{dt} = 1.3 \times 10^{-4} \text{ s}^{-1}$$  \hspace{1cm} (VIII.10)

If the dc magnet voltage $V_{dc}$ has a ripple voltage with instantaneous value $V_r$ superposed on it, and if the magnet has a time constant $\tau$, then this gives rise to a rate of change of the field

$$\frac{1}{B} \frac{dB}{dt} = \frac{1}{\tau} \frac{V_r}{V_{dc}}$$  \hspace{1cm} (VIII.11)

If we allow a $\pm 10\%$ modulation of the spill-out rate and take $\tau = 5.5$ s, the amplitude of the ripple voltage must be smaller than

$$\frac{V_r}{V_{dc}} < 7 \times 10^{-5}$$  \hspace{1cm} (VIII.12)
which is more stringent than the usual requirements for dc magnets.

It is more convenient to keep the magnetic guiding field constant and to change the radial position of the beam in the non-linear lens by means of a programmed bump on the equilibrium orbit, since the long time constant of the SR magnet makes it difficult to produce fast and accurately controlled field variations, in particular to reset the guiding field to its original value after the whole beam has been spilled out and before the next pulse from the CPS is injected. The bump of the equilibrium orbit could be produced by two small magnets or backleg windings, excited from a feedback system which measures the instantaneous intensity of the external proton beam and keeps the spill-out rate constant. If the feedback system has a sufficiently large bandwidth, it might also cancel part of the SR magnet ripple.

As discussed in section 4, the beam is injected near the inside wall of the SR vacuum chamber ($\Delta r = -48$ mm), but for $\Delta r < 0$ the beam is unstable. One solution is to inject with no current in the non-linear lens. After injection the beam is accelerated slightly beyond the central orbit, say $\Delta r = +2$ mm and subsequently the non-linear lens is excited to start the ejection process. Another possibility is to excite the non-linear lens continuously, to keep the equilibrium orbit at $\Delta r = +2$ mm but to give it a -50 mm bump so that it just passes through the centre of the kicker magnet for injection. After injection is finished, the bump is reduced to zero and ejection can start. In both cases one loses a short time (say 0.2 s) just before and just after injection.

The septum magnet S3 is placed in the interaction straight section since this gives the most convenient trajectory for the ejected beam. With the septum magnet layout of Fig. VIII.5, S2 is at the same azimuthal position as the fast kicker magnet for injection, but since S2 is radially at the outside and the kicker magnet at the inside of the vacuum chamber, the two are compatible. Neither do the two other septum magnets interfere with the injection and they can all be stationary. For colliding beam
experiments they must obviously be removed from the SR aperture. If the
ejection system is properly adjusted, only the septum of S1 is hit by protons,
but since this is just $\frac{3}{4} \lambda$ upstream of the interaction region, one can
expect a certain amount of induced radioactivity in the interaction region.

If the whole ejection system is displaced one long straight section
upstream, some difficult deflections of the ejected beam are necessary to
avoid the magnet units of the outer arc of the other SR and the ejection
trajectory would still pass rather close to the interaction straight section
as discussed above.
IX. VACUUM

1. Vacuum Requirements

The average residual gas pressure in the vacuum chamber must be so low that the lifetime against gas scattering is at least one order of magnitude longer than the time necessary for filling up both rings. Hence a lifetime of several hours is required.

The intensity of a circulating proton beam decreases due to collisions with atoms of the residual gas. A collision can cause outright loss by nuclear scattering or by single Coulomb scattering. Multiple small angle Coulomb scattering is responsible for a gradual build-up of betatron oscillation amplitudes.

Let us assume that the residual gas consists of nitrogen or carbon monoxide. The total nuclear cross section for 25 GeV protons on hydrogen is 40 mb. (Ashmore et al. 1960). Taking into account that the cross section for heavier nuclei is less than proportional to the atomic mass, we can take for carbon, nitrogen and oxygen nuclei the approximate average value of 400 mb. With this nuclear cross section one calculates for a pressure of $10^{-9}$ torr a beam loss of 3.2% in 12 hours.

Particle loss due to single Coulomb scattering occurs if a proton is scattered into an angle which is greater than the critical angle. This critical angle is determined by the maximum available vertical half aperture $z_{\text{max}}$,

$$\theta_{\text{crit}} = \frac{\sqrt{2}}{\beta_z} z_{\text{max}}$$  \hspace{1cm} (IX.1)

where $\beta_z$ is the maximum value of the vertical $\beta$-function. The factor $\sqrt{2}$ takes into account the fact that only the projected scattering angle is relevant. For the ISR $\beta_z = 53.0$ m and $z_{\text{max}} = 14$ mm, yielding a critical angle

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of 0.37 milliradian. From these figures one calculates a beam loss of 0.8\% in 12 hours due to single Coulomb scattering.

The calculation of the beam blow-up due to multiple Coulomb scattering leads to the expression

$$\overline{z^2}(t) = \overline{z_0^2} + 6.20 \times 10^{-4} t \text{ (mm}^2\text{)}$$  \hspace{1cm} (IX.2)

where $\overline{z^2}(t)$ is the vertical mean square amplitude after $t$ seconds and $\overline{z_0^2}$ the initial mean square amplitude of the beam. The assumption is always a pressure of $10^{-9}$ torr $N_2$ or CO. The lifetime due to multiple scattering can be estimated in a quite formalistic way, using expression (IX.2) to calculate after what time the root mean square amplitude would reach the maximum possible half-aperture $z_{\text{max}}$. One finds for $z_{\text{max}} = 14$ mm a time of about 2 days. The relative beam losses due to multiple scattering are initially very small, in fact nearly negligible for the first 12 hours, since the initial root mean square amplitude is only about 5 mm.

From lifetime considerations alone a pressure of $10^{-9}$ torr would be largely sufficient for an experiment of 12 hours. There is, however, another consideration which is, as pointed out by De Raad (1963), the decrease of the interaction rate in a colliding beam experiment due to gas scattering. This rate is given by equation (II.4). Due to gas scattering $N_s$ decreases while $h$ increases according to eq. (IX.2). Assuming an initial r.m.s. amplitude of 5 mm and a pressure of $10^{-9}$ torr the amplitude after 12 hours becomes

$$z_{\text{rms}} (12 \text{ h}) = 7.2 \text{ mm.}$$

This is an increase of the beam height by 44\%. With the decrease of $N_s$ by 4.0\% due to nuclear and single scattering, the interaction rate is
altogether decreased by 36º/o. In reality, the decrease in interaction rate must be expected to be a little larger than this due to losses from multiple scattering, although only small during the first 12 hours. The proton losses due to the colliding beam events are negligible. Under these conditions the optimum duty cycle, that is the time between subsequent fillings of the rings, is about 12 hours. An optimum duty cycle is the one which gives the maximum interaction rate averaged over a complete cycle. With increase of the pressure above 10^-9 torr the optimum duty cycle decreases and with it the average interaction rate.

While a pressure of 10^-9 torr is adequate as average pressure along the whole length of the vacuum chamber, a still lower pressure is required in the colliding beam areas, where one wants to observe scattered protons from colliding beam events. The protons scattered on the residual gas due to nuclear interaction or single Coulomb scattering form an undesirable background for those observations. In order to keep the background at a reasonable level the gas pressure in the colliding beam areas should not exceed 10^-10 torr, and for elastic p-p scattering even a pressure of the order of 10^-11 torr is desirable. (See chapter III.4.2).

All pressures quoted so far assume nitrogen or carbon monoxide as residual gas. For other gases one has to take into account the differences in scattering cross sections. Nuclear cross sections are less than proportional to A (A = atomic mass). The Coulomb scattering is proportional to Z^2 (Z = atomic number). As a result hydrogen, which is often the predominant gas in ultrahigh vacuum systems, contributes only by one tenth to nuclear scattering, which is mainly responsible for the background in colliding beam experiments. To the beam build-up due to multiple Coulomb scattering hydrogen contributes only by one fiftieth, hence it can practically be neglected.
2. Design of the Vacuum System

2.1. The Vacuum System of CESAR

The design of the vacuum chamber and of the pumping system can follow in many details the design of the Electron Storage Ring CESAR (Ferger et al. 1963), since the pressure of $10^{-9}$ torr, required for this model, is the same as for the ISR. The main exceptions are the colliding beam areas where a pressure of $10^{-10}$ to $10^{-11}$ torr is demanded.

The vacuum chamber of CESAR is made of stainless steel, argon-arc welded and mounted with metal seals. The chamber is electrolytically polished on the inside and can be baked up to $300^\circ$ C, typically for 48 hours. The main pumping system consists of 8 titanium getter ion pumps of the Penning type, each with 140 $\ell$/s pumping speed, distributed on the circumference of 24 metres. Three turbo-molecular pumps of 140 $\ell$/s pumping speed are used for roughing down the chamber and for pumping during the bake-out when the getter ion pumps are not operating. In normal operation the turbo-molecular pumps are separated from the chamber by means of all-metal valves, so that the chamber with the getter pumps represents a closed system.

The optimum performance of the described system has been demonstrated on a section of the ring of 3 metres length with one pumping station. One week after bake-out an ultimate pressure $10^{-10}$ torr has been obtained at the end of chamber farthest away from the pump, while the pressure at the entrance of the pump was $5 \times 10^{-11}$ torr. These pressures remained stable for 6 weeks, until the experiment was shut down. The specific outgassing rate of the chamber walls could be evaluated; it was found to be $(1 - 3) \times 10^{-9}$ torr litre sec$^{-1}$m$^{-2}$. Two thirds of the residual gas was hydrogen and $\sqrt{3}$ carbon monoxide.

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In the complete vacuum system of CESAR the ultimate pressure could not yet be reached due to leaks in one special chamber section, the DC inflector tank. This has recently been replaced by a completely redesigned tank which has proved to be tight. There is no doubt that the ultimate pressure in CESAR will be below $10^{-9}$ torr. The experiences gained in the overall design as well as in details during the construction and operation of CESAR are very valuable for the design of the vacuum system of the ISR.

2.2. Stainless Steel

The usual material for large ultrahigh vacuum chambers is stainless steel because of its good mechanical properties, easiness to weld and the low gas desorption rate after bake-out. For the ISR in addition a very low magnetic permeability of $\mu = 1.004$ is required. The best match for these requirements, out of a dozen types which have been carefully tested, is stainless steel J 15 BM (Souchet 1962). It has been used for the vacuum chamber of CESAR. This stainless steel has the typical composition:

- chromium: 17.4 %
- nickel: 13.1%
- carbon: 0.014%
- manganese: 0.59%
- silicon: 0.42%

The extremely low carbon content is obtained by vacuum processing and casting. A low carbon content is essential for reliable ultrahigh vacuum welding. Apart from this, vacuum processing reduces the quantity of occluded gas and consequently the final desorption rate. The magnetic permeability of U 15 BM is $\mu = 1.002$ to 1.003. In welds and after mechanical deformation the permeability may be locally increased up to 1.04. This is typical for all types of
stainless steel. The thermal treatment, however, as would be used for mechanical stress release will bring the permeability back to its undisturbed value. Electrolytic polishing, which is primarily used for reducing the gas desorption rate (Souchet 1962, 1963, Ficher et al., 1963), also has the property of restoring the local permeability.

A quantity of about 200 tons of steel will be required for the vacuum chamber of the ISR.

2.3. Vacuum Chamber

The vacuum chamber of the ISR will be composed of separate sections which are joined by means of demountable flange connections with metal gaskets. One type of chamber sections will have the approximate length of the magnet units and an oval cross section (160 mm by 52 mm inner dimensions) which fits into the magnet gap (See chapter V.2.2. and Fig. V.4). The straight sections will partly be occupied by a variety of special chambers, such as pick-up stations, sector valves, inflector or target tanks, RF acceleration stations, etc. The straight sections, or parts of them, where no special chambers are placed, will be cylindrical of 160 mm diameter. All parts of the vacuum chamber will be argon-arc welded and must stand a bake-out temperature of 300°C.

Clearing electrodes for deneutralization of the beam (Chapter IV.8.1) will be placed at both ends of the magnet units between the coils where more vertical clearance is available than in the magnet gap.

The best procedure for cleaning and reducing the outgassing rate for the long magnet chamber sections, which have a constant profile and are inaccessible otherwise, is electrolytic polishing. For complicated chambers in the straight sections "glass ball honing" can be successfully used. This is a procedure similar to the well known "sanding" where the quartz sand
being blown against the surfaces is replaced by very fine glass beads. It has
the advantage, in comparison to electrolytic polishing, that corners and re-
cesses can easily be reached. It will perhaps be possible to combine the two
procedures.

The bake-out makes it necessary to include stainless steel bellows in
some of the chamber sections to compensate for the longitudinal thermal
expansion. The most suitable position for these bellows seems to be at both
ends of the magnet chamber sections. Additional bellows might be necessary in
some of the straight sections where equipment is installed. Such equipment
might be electrostatic pick-up stations, the geometrical positioning of which
is particularly critical.

2.4. Bake-out

A bake-out of the vacuum chamber or of a part of it is necessary after
each time it has been left to atmospheric pressure for a repair or a modifica-
tion.

The bake-out temperature of 300°C has been chosen mainly because this
temperature, maintained for a period of about 48 hours, turned out to be
sufficient for reducing the outgassing rate after the cooling-down to a value
in the range of $10^{-9}$ torr litre sec$^{-1}$ m$^{-2}$. (Fischer et al. 1963).

On CESAR three different types of heating elements for the bake-out of
the vacuum chamber are being used. The sections between the poles of the
bending magnets and quadrupole lenses are heated by flat heating elements,
which are manufactured in a printed-circuit technique and bent over and glued
onto the chamber walls from outside. The same heaters are used for some of
the chambers in straight sections and for the tubings leading to the vacuum
pumps. The getter ion pumps are heated by permanently installed ovens.
Much smaller and demountable ovens are used for some small but complicated
parts of the vacuum chamber, such as the driving mechanisms for movable targets. Other parts, the inflector tanks for instance, are heated by flexible heating tapes, with fibre-glass insulation, wrapped around the chamber. All three types of heaters: flat surface elements, ovens and flexible tapes can be used for the ISR.

There exist other possibilities, e.g. the passing of an electric current through the chamber walls, infra-red quartz lamps inside the chamber or overheated steam. Of these three methods the first one seems practicable for long vacuum chamber sections of simple shape. The other methods may be considered for special sections of the vacuum system.

2.5. Metal Gasket Seals

All chamber sections around the rings will have end flanges of identical size and design so that sections can easily be exchanged or reversed. A male-female flange design would limit the flexibility. Apart from these main chamber flanges, many other flanges of different sizes will be required for pumping ports, electrical feed-throughs, gauges, targets, etc.

Different gasket materials - gold, copper and aluminium - are used in ultrahigh vacuum techniques and a large variety of flange designs are known. There is, however, at present very little agreement among vacuum workers in firms and institutes as to which design is the most reliable, particularly if repeated bake-out is required.

On CESAR all flanges are sealed with gold wire gaskets. Chemically pure gold wire of 1.2 mm thickness is welded into rings of appropriate size and annealed before use. For making a seal the gasket is compressed between the polished faces of two mating flanges by means of bolts, nuts and spring washers. (Fig. IX.1). This sealing technique could also be used for the ISR, however, the reliability is not quite adequate for a system with more than

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two thousand demountable seals of different sizes. One can say that one out of twenty newly made seals develops a leak either before or after bake-out.

A new metal seal technique has recently been developed (Wheeler '1963), called the ConFlat seal, using flat gaskets of 2 mm thickness made of OFHC copper. The flanges are symmetric and have an edge which cuts into the gasket when the bolts are tightened. This edge has one vertical and one conical surface. (Fig. IX.2). The idea is that the sealing part of the metal gasket is captured between three surfaces - the two conical ones and the vertical outer ridge holding the gasket - and not between two parallel surfaces as in the case of the gold wire seal (Fig. IX.1). Being captured between three surfaces the copper encounters a higher resistance against creeping, particularly during the bake-out, and maintains a higher internal pressure, which is essential for a tight seal. It seems, judging from the experiences of independent institutes, that the ConFlat seal is more reliable than the gold wire seal between parallel faces. In addition, ConFlat seals are easier to mount, especially in the case of vertical seals or for an unskilled worker. Almost all seals on the ISR will be vertical and most of the seals will have to be made by unskilled or semi-skilled installation workers under supervision. Moreover, it is impossible to dislocate a ConFlat gasket accidentally. The gasket has also the function of a centering ring for the two mating flanges. ConFlat copper gaskets are more expensive than gold wire gaskets, taking into account that used gold gaskets are returned to the supplier, but on the other hand the handling of large quantities of gold with the necessary book-keeping and controls is unpleasant.

2.6. Sector Valves

If a repair or a modification of a part of the vacuum chamber becomes necessary, one cannot afford to let the whole chamber with a total length of about two kilometres up to atmospheric pressure. One must have a certain
number of sector valves, which allow the separation of a given sector from the rest of the vacuum system. There should be at least four sector valves for each of the eight beam intersection regions, installed at distances of 15 to 20 metres from the intersecting points. The whole vacuum chamber is then sectorized into the eight outer arcs, the eight inner arcs and the eight intersection regions. The sector valves must be bakeable in open and closed state and must have in open state a clearance of 160 mm by 52 mm. The valves must be so tight that either of the two rings can be operated with ultrahigh vacuum while the other one is partly or as a whole let up to air.

Such valves do not exist on the market. From the point of view of mechanical engineering they are probably the most difficult part of the whole vacuum system and will require considerable development work.

2.7. Getter Ion Pumps

Getter ion pumps of the Penning gas discharge type (Hall 1958; Herb 1959), such as those in use as main ultrahigh vacuum pumps on CESAR, perform so well (Fischer 1962, 1963) and have so many advantages over other types of pump for big storage rings that they will be used for the ISR as well.

The main advantage of a getter ion pump is its simplicity. It has no moving parts, no liquids and does not need any kind of maintenance. An oil or mercury diffusion pump for the ISR, for instance, would require a continuously running backing pump, water cooling and a continuous supply of liquid nitrogen for the traps. Furthermore, it would need an automatically operating bakeable shut-off valve on the high-vacuum side and many other automatic safety devices in order to protect the vacuum system or the user against all kinds of failures. None of this is required for getter ion pumps. The only supply is 6 kilovolt dc with practically no power (apart from a short starting period) and the only safety device is an overload circuit breaker in the power supply. Another advantage of a getter ion pump is the fact that its current is proportional to the pressure and that the pump is therefore at the same time a pressure gauge, with an accuracy comparable to that of a Penning gauge (in fact it is a Penning gauge).
Of great importance is the possibility of using a getter ion pump as a leak-detector. This is due to the fact that the pump current is sensitive to the nature of the pumped gas. For leak detection, a pump is connected to a modified power unit which allows the detection of small variations of the pump current and suspicious parts of the chamber are then sprayed with argon or oxygen, in the same way as one does with helium when using a helium leak detector. The sensitivity of this method is inversely proportional to the total pressure. In the range of $10^{-8}$ torr it is about equal to that of a standard helium leak detector. Having as many leak detectors permanently installed on the system as there are pumps will be an invaluable help for the very difficult and time consuming task of leak hunting on the ISR.

2.8. Roughing Pumps

For roughing down the vacuum chamber of the ISR before the getter ion pumps are started, and for pumping during the bake-out, turbomolecular pumps (Becker 1958) could be used. These have been used on CESAR with good success. The only alternative solution we can think of is a mercury diffusion pump with a refrigerator cooled vapour trap. Such a unit would probably be more economic than a turbomolecular pump.

2.9. The Required Number and Pumping Speed of the Pumps

A possible distribution pattern of all pumps on the ISR, except the cryopumps to be discussed in the next section, is shown in Fig. IX.3. The spacing between two getter ion pumps is determined by the conductance of the vacuum chamber and the expected outgassing rate from the chamber walls, besides, of course, that it must follow in one way or another the pattern of the magnet system. The pressure in a tubular vacuum chamber between two pumping stations follows a parabola and the pressure difference between a pumping port and the middle between two pumps is given by
\[ \Delta p = \frac{q U \ell^2}{8 c_0} \]  \hspace{1cm} (IX.3)

where \( q \) is the outgassing rate per square metre, \( U \) the circumference of the chamber section, \( \ell \) the distance between the pumps and \( c_0 \) the molecular conductance of one metre length of the chamber.

The conductance of one metre of the oval vacuum chamber of the ISR for air is 75 \( \ell/s \) and that of the chamber with circular section is 500 \( \ell/s \). Outgassing rates of \( (1-3) \times 10^{-9} \) torr litre sec\(^{-1}\) m\(^{-2}\) have been measured after 300\(^\circ\) C take-out on CESAR. If one takes into account a safety factor, \( 10^{-8} \) torr litre sec\(^{-1}\) m\(^{-2}\) seems to be a reasonable figure for estimates. In the outer arc of the ISR the spacing of the pumps is 6.6 metres (see Fig. IX.3) yielding according to eq. (IX.3) \( \Delta p = 1 \times 10^{-10} \) torr, which is adequate for a working pressure of \( 10^{-9} \) torr. In the same way one finds for a long straight section on the inner arc, where the chamber has a circular section and the spacing is 13.3 metres a pressure "bump" of \( 2 \times 10^{-10} \) torr. The total gas load for each pump in the proposed arrangement would be between \( 3 \times 10^{-8} \) and \( 10^{-7} \) torr litre sec\(^{-1}\), depending on the position and the equipment installed. This would require a pumping speed between 100 and 300 \( \ell/s \) per unit. In the region of \( 10^{-9} \) torr a pump may have a reduced speed, so that altogether a nominal pumping speed of \( 400 \ell/s \) for the standard getter ion pumps seems to be adequate. The ultimate pressure of these pumps must be about \( 3 \times 10^{-10} \) torr. The getter ion pumps shown in Fig. IX.3 near the crossing of the colliding beams, must have a pumping speed about 4 times higher than that of a standard pump, since they must pump all four branches of the crossing. For the roughing pumps a pumping speed of 100 - 200 \( \ell/s \) and an ultimate pressure of \( 10^{-7} \) torr are sufficient.

The total number of pumps required for the ISR according to the arrangement of Fig. IX.3 is:

- 72 roughing pumps
- 216 getter ion pumps of 400 \( \ell/s \) nominal speed
- 8 getter ion pumps of 1600 \( \ell/s \) nominal speed.
2.10. Cryopumping

In contrast to the problems on the vacuum requirements of $10^{-9}$ torr over the greater part of the ISR, for which operational experience on CESAR has provided a very realistic model, there exists no prior information on the problem of how to meet the extreme vacuum requirements for the intersection regions. However, considerations of a general nature have led to the conclusion that some form of cryopumping provides the most feasible method, and probably the only possible method. A working pressure down to $10^{-11}$ torr implies the use of pumps with an ultimate pressure in the $10^{-12}$ torr range. Although such pressures are obtainable without cryopumps it is only with very considerable difficulty and, a vital factor, with a loss of predictable performance and reliability. In most non-cryogenic pumping systems the available pumping speed is falling rapidly and unpredictably in the $10^{-12}$ - $10^{-11}$ torr region, even if it is not actually zero. If, as envisaged, four or possibly five pumps are used at each intersection region of the ISR, then each pump will have to handle between $10^{-8}$ and $10^{-7}$ torr litre sec$^{-1}$. At an operating pressure of $10^{-11}$ torr this implies a pumping speed of $10^3$ to $10^4$ L/s. Such a capacity is large by any standard and it is clear that no conventional pump will suffice. By cryopumping standards, however, such requirements are quite realistic.

In some preliminary experiments, conducted in a stainless steel system of about 40 litre capacity, it has been possible, using a liquid helium cryopump which is commercially available, to obtain a pressure of $\sqrt{3} \times 10^{-2}$ torr. The residual gas as analyzed by a mass spectrometer was almost entirely hydrogen. This pressure could be achieved with reasonable reliability and maintained over a period of several hours without difficulty. In these preliminary investigations neither the cryopump nor the system was of optimum design for the quantitative determination of pumping speeds or saturation effects. However, an order of magnitude calculation indicates values of parameters were compar-
able with those to be expected in the ISR; namely, a gas load in excess of $10^{-9}$ torr $\ell/s$ implying a pumping speed of the order of $10^3$ $\ell/s$.

These results are encouraging because the commercial cryopump used was designed primarily to pump gases other than hydrogen or helium and did not permit the temperature of the pumping surface to be brought lower than $10^0K$. At this temperature all heavier gases can be either cryo-adsorbed or condensed, and hence can be pumped in unlimited quantities. For hydrogen, however, the equilibrium vapour pressure is $\sim 1$ torr at this temperature and the pumping mechanism can only be one of cryo-adsorption. A pump working by this process will have a limited capacity after which it becomes saturated (simply 'covered' with hydrogen) and cease to pump. It is known from the work of Hunt et al. (1961) that the initial pumping efficiency of pumps working on this process of cryo-adsorption can be improved by 'coating' the cold metal surface with several mono layers of a readily condensible gas, e.g. $CO_2$ or $N_2O$. It is also known from the same workers that any hydrogen adsorbed by such cryo-adsorption is released at temperatures below $20^0K$ - this precludes the use of the cheaper (although more hazardous) liquid hydrogen cooled cryo-pump.

Apparatus has been designed and constructed and experiments are now in progress in which, it is hoped, it will be possible to obtain quantitative data under controlled conditions on the performance of cryopumps. In particular the characteristics of cryo-adsorption will be studied to determine the optimum conditions of surface temperature and coverage with respect to the efficiency and saturation effects. Further, the possibility of rejuvenation of the cold surface by re-coating will be studied if saturation appears to be a limiting factor. The possibility of cooling the surface below the temperature of liquid helium, to $\sim 3^0K$, will also be studied. At this temperature it should be possible to condense hydrogen down to its equilibrium vapour pressure of $\sim 10^{-12}$ torr and hence pump it in unlimited quantities. In these experiments
emphasis will be placed upon pumping hydrogen since experience has shown that it is the main component, and the most difficult to pump in cryo-pumped ultra-high vacuum systems.

In deriving the above order of magnitude figures a value for the specific outgassing rate of the stainless steel vacuum chamber of $5 \times 10^{-13}$ Torr $\ell/$sec cm$^2$ has been used. This is a realistic figure which has been obtained in practice (Fischer et al. 1963). Values as low as $5 \times 10^{-16}$ Torr $\ell/$sec cm$^2$ have been claimed in the literature as the result of special outgassing procedures. Such a figure would make the vacuum requirements of the ISR, especially in the intersecting regions, very much easier to obtain. By constructing the intersecting region vacuum chamber of a single welded piece it should be possible to use these refined techniques of outgassing (e.g. very high temperature bake-out or 'electron scrubbing'). It is hoped to explore these possibilities in parallel with the above cryopumping programme.

It would be premature at the present state to give a detailed description of the cryovacuum system of a beam intersection region, not only because our data on cryopumping have still to be completed, but also due to the fact that the vacuum system will depend very much on a specific experiment. It is probable that for every essentially new colliding beam experiment a new cryovacuum system must be designed.

2.11. Vacuum System of the Beam Transfer System

The pressure in the transfer lines must be so low, that the beam blow-up due to multiple scattering during the time of flight of about 1 µs is negligible. Using expression (IX.2) and taking into account that the numerical factor is proportional to the pressure, one finds for $10^{-2}$ Torr an increase of the root mean square amplitude of less than 0.1 mm.
The requirement of a pressure of less than $10^{-2}$ torr leaves us with the choice between several possibilities. One could, for instance, use ordinary two stage rotary pumps. The oil vapour backstreaming from these pumps, however, would be disturbing in the differential pumping system at the ends of both transfer lines where the pressure must be gradually reduced to the pressure in the storage rings of $10^{-9}$ torr. It would be advisable for this solution to inject into the storage rings through a window. The beam blow-up in a window due to multiple scattering can be expressed in analogy to eq. (IX.2) by

$$\overline{z^2}(x) = \overline{z_0^2} + 13.0 \times (\text{mm})^2$$ (IX.4)

where $x$ is the target thickness in g cm$^{-2}$. A beryllium window of 0.1 mm = $1.8 \times 10^{-2}$ g cm$^{-2}$ would increase the root mean square amplitude by 0.5 mm and would, hence, be acceptable.

The principal disadvantage, however, of any type of rotary or diffusion pumps is that these pumps require regular maintenance and automatic safety devices. We prefer, therefore, to equip the transfer lines with essentially the same kind of vacuum system as the main system.

The chamber will be made of stainless steel and metal gaskets will be used. Turbomolecular pumps will rough the system down and getter ion pumps will maintain the pressure in the range of $10^{-6}$ torr. The main differences from the main system will be that no bake-out will be required for the beam transfer lines and furthermore that the conductance of the circular pipes of 40 mm inner diameter is only 7 $\ell$/s. Hence the getter ion pump can be much smaller than for the main system. A possible solution are pumps of 15 $\ell$/s pumping speed spaced with 10 m intervals. Assuming a gas desorption rate from the unbaked stainless steel of $10^{-4}$ torr litre sec$^{-1}$ m$^{-2}$, the gas load per pump will be $10^{-4}$ torr litre sec$^{-1}$ and the equilibrium pressure 2 x $10^{-6}$ torr.

The following total numbers at pumps will be required.

- 70 getter ion pumps of 10 $\ell$/s pumping speed
- 10 molecular pumps of 150 $\ell$/s pumping speed.
X. SHIELDING

1. Introduction

The proposed intersecting storage rings make it possible to perform simultaneously 8 different colliding-beam experiments. In addition they can be used to provide delayed beams of secondary particles by slowly splitting out the injected protons in between successive pulses from the CPS. The most flexible experimental area would therefore be a large annular hall around the ISR, with inner and outer radii of, say, 120 m and 180 m respectively. The ISR would then be shielded with side walls made of concrete blocks and a roof made of concrete beams that could be rearranged so as to suit any specific experiment. Unfortunately such a lay-out requires huge amounts of concrete and is very expensive.

Since, per unit volume, earth shielding is about a factor 30 cheaper than ordinary concrete, one should try to use earth for shielding purposes whenever possible. Burying the ISR in an underground tunnel is the most effective way of achieving this. This solution is in fact imposed by the quality of the ground of the site on which the ISR have to be built. From studies of the structure of the subsoil we have chosen 444 m as the optimum level of the tunnel floor (see chapter XIII.2), in order to be directly on stable molasse along most of the circumference of the ISR. The lowest level of the ground surface around the machine is at about 449 m, while the highest level is at 462 m. A tunnel of 6 m height will therefore have its roof at most one metre above the natural ground surface.

On the other hand, the problem of access to the colliding beam areas has led to the proposal of an excavated road on the 444 m level on the inside of and about concentric with the ISR tunnel as shown in Fig. X.1. In spite of the fact that earth shielding for the side walls cannot slope down steeper than at a rate of 1:2.5 for stability reasons, which implies an earth
volume of 3.5 times that of a concrete shield, earth shielding remains the only economical proposal. This reasoning also applies to the shielding of the colliding beam experimental halls, of which the sizes have been tentatively fixed at a length of 70 m and a width of 25 m for the intersection points where the ISR beams go towards the inside, at a length of 50 m and a width of 25 m for the points where the beams go towards the outside, and with a height inside the halls of 13 m in both cases.

There are only two cases where an argument can be made in favour of a wall and roof shielding consisting of concrete blocks. The first one is a demountable tunnel section at an intersection point, which allows the construction of a colliding beam hall, the size and shape of which can be decided in the future, without an extensive shut-down period for the ISR. This case will not be treated further in this report. The other case, which will be considered here, is that of a demountable shielding around the part of the ISR to be used for conventional target operation, the whole spanned by part of an experimental hall of 50 x 200 m² for the use of secondary beams.

In estimating the required shielding thicknesses, we shall whenever possible extrapolate from the existing information about the radiation level around the CPS instead of basing ourselves on less reliable theoretical calculations. Measurements have been made by the CERN Health Physics Group in order to survey the radiation hazards around the CPS. Although these measurements have perhaps not the desired accuracy for our purpose and more extended measurements will have to be made, they offer already the most reliable starting point for estimating the required shielding thicknesses against nuclear radiation. For the muon background estimates based on the known pion production spectra are made.
2. Biological Requirements

We shall base the shielding design on biological requirements and assume that any detector which needs a lower background has its own special shielding. The maximum permissible dose (mpd) for radiation workers is 2.5 mrem/hr (Rossi 1957).

When a beam of strongly interacting high energy particles passes through a concrete shield its intensity decreases by absorption, but after a few mean free paths each surviving primary particle is accompanied by a large number of lower energy particles, most of which are neutrons from nuclear stars and other processes and the biological effects are mainly due to these degraded particles. The degraded radiation emerging from a thick shield usually consists of a mixture of fast neutrons, slow neutrons and γ-rays.

Measurements made by the CERN Health Physics Group (Baarli 1964 a) indicate the following radiation composition in rem-dose outside the CPS shielding, which is about independent of shielding thickness and target location:

- thermal neutrons: 11 to 12\(^\circ\)/o
- fast neutrons (100 keV - 20 MeV): 50 to 76\(^\circ\)/o
- high energy particles (above 20 MeV): 2 to 25\(^\circ\)/o
- γ-rays + ionization from charged particles: 2 to 19\(^\circ\)/o

Only the number of fast neutrons will be considered in our calculations and it will, therefore, be assumed that the mpd corresponds to a neutron dose rate of 1 mrem/hr. The latter figure is equivalent to 7 fast neutrons /cm\(^2\) s (Rossi 1957). This conservative assumption seems justified as the calculations will be mainly based on the neutron measurements made by the proton recoil counter and long counter which are only sensitive to the neutron energy range of (0.1 - 14) MeV (Baarli 1964 b).
An important part of the background in our case consists of fast muons. We therefore also note (Lindenbaum 1961) that 1 mrem/hr corresponds to 9 minimum ionizing particles/cm$^2$ s.

In calculating shielding thickness we shall aim at the mpd on top of the roof, where people do not normally work, and 0.1 of the mpd in the working areas at both sides of the ISR. We believe that this last figure provides an adequate safety factor against possible errors in our results due to uncertainties in the parameters which enter into the calculation.

3. Sources of Background Radiation

The shielding design should be based on the intensities which might be reached with the CPS in 6 years from now, in order to avoid expensive additions to the shielding after the first period of operation of the ISR. The maximum intensity which one might hope to reach with the CPS with the present 50 MeV linac as injector is

$$N_a = 2 \times 10^{12} \text{ protons/pulse.}$$

This is about 2.5 times the present CPS intensity. If the 50 MeV linac is to be replaced by one of 200 MeV, as is seriously being considered at present, the CPS intensity could go up by another factor of five to

$$N_a = 10^{13} \text{ protons/pulse.}$$

The maximum current expected to be stacked in each of the ISR is

$$N_s = 4 \times 10^{14} \text{ protons (= 20 Amp).}$$

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For the purpose of estimating the shielding thickness however, we shall assume a maximum stacked current of

\[ N_s = 4 \times 10^{15} \text{ protons (} \approx 200 \text{ Amp)}. \]

In spite of this last assumption it will be shown that the required shielding thickness is not determined by the colliding beam experiments but by the use of the ISR to provide dc beams of secondary particles for the orthodox way of experimentation. The shielding calculation for this last case will be based on the injection of \(10^{13}\) protons per pulse into the ISR.

For the purpose of shielding calculations we assume a pressure of \(10^{-8}\) torr in the ISR. In chapter IX is shown that the beam loss due to nuclear interactions is more important than the loss due to the Coulomb scattering. Here are therefore only considered the nuclear interactions which give rise to a beam life of 33 hours, under the assumption that all residual gas is nitrogen and that the total nuclear scattering cross section is 380 mb (Ashmore et al. 1960). The number of protons lost from each SR is then \(3 \times 10^{10}\) protons/s. The radiation from a point target is smeared out over some 40 m along the ISR circumference of 940 m. Therefore the beam loss from both ISR due to gas scattering gives close behind the shielding wall about the same background as a point source of \(3 \times 10^9\) protons/s. Lindenbaum (1961) reports that when the Cosmotron was accelerating \(2 \times 10^9\) protons/s at 3.0 GeV, with barrier shielding, but without roof shielding, the sky-shine radiation level was already 3 mrem/hr which is slightly above the mpd. It appears therefore that even under more ideal conditions than assumed above the ISR are not such clean devices as one might think at first sight.

Suppose that the beam in the ISR is renewed after 24 hours. The injected beam must pass as close as possible to the vacuum chamber wall in order to use effectively the total horizontal aperture. Moreover one may spill,
say, 25\% of the protons from the RF bucket during stacking. Finally the surviving beam after 24 hours must be disposed of before a fresh beam can be stacked. We shall be somewhat generous and assume that during all these manipulations each ISR is allowed to spill out 10\% at any place around its circumference. This gives an extra point source strength of $9 \times 10^9$ protons/s.

Although we may assume that normally one can dispose of the beam in a well shielded place, it might occasionally happen that the beam is lost somewhere else before it can be dumped, due to some minor accident, like vacuum or magnet trouble. These troubles are likely to be associated with an experimental set-up in the interaction region, so that the beams of both ISR would be lost at approximately the same place. This gives rise to a large instantaneous radiation level. Let us assume that the total dose behind the shielding at that moment can be treated as if it were due to a slow loss of the full stacked beams over a period of 4 weeks with 40 working hours per week. This then corresponds to a source strength of $14 \times 10^9$ protons/s.

Adding up we find a total equivalent point source strength of $2.6 \times 10^{10}$ protons/s for the case of colliding beam experimentation with the ISR.

One might argue that these estimates are somewhat exaggerated regarding stored proton intensity and prevailing pressure. However, if the ISR are used for 25 GeV experiments the interaction rate in the target is about $3 \times 10^{12}$ protons/s. A 3\% spill-out at any place (or over some 40 m length) due to injection and targetting together would correspond to a point source strength of $10^{11}$ protons/s. A total spill-out of about 70\% over the whole circumference of the machine is not excessive since the proposed vertical aperture of the ISR is only 52 mm instead of 70 mm for the CPS. This reduces the number of multiple traversals through a target, and thus the target efficiency, and increases the beam loss. On the other hand, it is expected that the machine contamination will prevent the continuous use of
internal targets at the maximum intensity foreseen. This will make imperative the use of fast or slow ejected beams in some $80\%$ of the non-colliding beam experiments, and the internal beam loss may be expected to be reduced to at most $20\%$ during this type of experiments.

We see that the required shielding thickness is determined by conventional target operation, in spite of the somewhat generous beam loss assumptions for the case when the ISR are used for colliding beam experiments. The beam loss estimates outside the target region would be about the same for both situations if the use of the 200 MeV linac was not taken into consideration.

The average beam loss near the injectors under normal working conditions should of course be small compared to that in the targets. However, during the starting up process when the initial attempts are being made to circulate the beam, it is possible that most of the beam might get lost in the injector region, so that it looks desirable to shield it for the full beam intensity.

For shielding design we shall take a point source strength of

$$10^{11} \text{ protons/s per 40 m run of tunnel}$$

$$3 \times 10^{12} \text{ protons/s in the region of the target and the injectors.}$$

4. Shielding against Strongly Interacting Particles

Measurements have been made by the CERN Health Physics Group of the background on top of the CPS tunnel at 7.5 m above an uranium target operating in straight section 82. The beam intensity was $4.1 \times 10^{11}$ protons per burst at 5 s intervals, with a proton energy of 26 GeV. The fast neutron level had a maximum value of 16 neutrons/cm$^2$ s right above the target and gradually decreased to half this value at about 20 m downstream of the target. Other measurements, with other target materials and at different positions,
give similar results. Qualitatively one can explain this behaviour by noting that although most of the secondaries are produced at small angles to the primary beam, they are partially shielded by the steel of the CPS magnet and hit the roof under such small angles, that their effective path in it is several times the perpendicular thickness.

Geibel et al. (1963) have made a theoretical estimate of the target efficiency by a Monte Carlo procedure. Their results indicate that values as high as 70°/o can be expected in case of beryllium targets and up to 40°/o for copper targets. No absolute experimental values are reported by them, however.

Targets with larger Z have more Coulomb scattering and therefore tend to have lower efficiency. We shall assume that in the measurement reported above the target efficiency was 25°/o.

In the following we shall express all shielding thicknesses as equivalent thickness in concrete. The roof thickness of the CPS tunnel is 40 cm of concrete (2.4 g/cm³) plus 3.2 m earth (1.7 g/cm³) which is equivalent to 2.66 m concrete. As derived from the measurements by the Health Physics Group the radiation level on the tunnel roof then is 80 fast neutron/cm² s for a source of 10¹¹ protons/s, which is about ten times the mpd.

It might be argued, that on top of the roof a neutron flux larger than the mpd would be allowed, since access to the roof can be restricted or forbidden when the ISR operate. However, it is well known that the neutrons are scattered back from the air and give rise to a general background radiation (skyshine) which is approximately inversely proportional to the distance from the source (Lindenbaum 1961). The radiation level allowed for the general population is about 44 times smaller than the mpd for radiation workers. Therefore we consider it advisable that the neutron flux on top of the roof does not exceed the mpd. Moreover, it is difficult to add roof shielding at
a later stage, since the roof strength would not be sufficient. Also for this reason we consider it advisable to be somewhat on the conservative side in the choice of the roof thickness.

Since the preliminary accepted height for the ISR beam tunnel is 6 m against 4.5 m for the CPS, the ISR tunnel width 15 m against 6 m for the CPS and since we anticipate a thicker shielding for the ISR than for the present CPS, we shall calculate the roof and inner side wall shielding for a chosen radiation dose at 10 m distance from the beam everywhere around the tunnel while this distance will be taken 12 m for the target and injector regions. The different distances from the beam are accounted for by the inverse \( r^2 \) law, where \( r \) is the distance to the source.

Hence, we allow a level of 7 neutrons/cm\(^2\) \( s \) on top of the roof. The mean free path in concrete for removal of nuclear particles around 1 GeV such as are produced at large angles is 130 g/cm\(^2\). Starting from the measurements of the Health Physics Group we find a roof thickness of 3.7 m concrete for a source of \( 10^{11} \) protons/s and 5.3 m for a source of \( 3 \times 10^{12} \) protons/s.

The inside wall of the shielding is exposed to radiation in much the same way as the roof. To reduce the background to 0.7 neutron/cm\(^2\) \( s \) we need 4.9 m concrete for a source of \( 10^{11} \) protons/s and 6.6 m concrete for a source of \( 3 \times 10^{12} \) protons/s.

For the outside wall the situation is quite different. The average inelasticity of high energy collisions is not more than 50\% so that quite often the primary proton retains most of its energy. The average transverse momentum of the secondaries is about 400 MeV/c. Then there are the elastically scattered protons and the high energy neutrons which are strongly peaked in the forward directions. The majority of these high energy secondaries produced at small angles will hit the outside shielding wall, which must therefore be thicker than the roof and the inner wall. Accurate calculations are difficult in this case, but it will be shown below that the thickness of
the outside shielding wall is mainly determined by the muons. We shall therefore restrict ourselves to an approximate pessimistic calculation of the thickness required for the outside shielding wall to reduce the fast neutron level to 0.1 of the mpd. For the moment we shall neglect the effect of the magnet yokes.

Let us assume that half of the energy of the primary proton is carried away by high energy secondaries which are contained in a cone with half opening angle 2° and that the other half is distributed over low-energy secondaries produced at much larger angles, up to 90°. The latter half is taken care of by the same shielding thickness as we have found for the inner wall, so that we only consider the forward cone. We assume the geometry shown in Fig. X.3. Each high energy secondary of the forward cone develops a nuclear cascade in the shielding wall. If all degraded particles went in the forward direction, their effective path in the concrete would be very long. We take for the removal mean free path at these high energies in concrete 170 g/cm² and assume a fast neutron build-up factor 100 per 25 GeV proton. Finally, we assume that the nuclear cascade in the concrete forms a uniformly filled cone with half opening angle 30°. To reduce the fast neutron background to 0.7 neutron/cm²s, we then need a concrete thickness of 6.3 for a source strength of $10^{11}$ protons/s and 7.6 m for a source of $3 \times 10^{12}$ protons/s.

5. Shielding against Muons

The mean free path for decay of a $\pi$-meson is 55 p metres, where $p$ is the momentum in GeV/c. A 10 GeV/c $\pi$-meson has a 1.8% probability to decay in a flight path of 10 m, so that the high energy muon flux is, roughly speaking, a few per cent of the high energy $\pi$-meson flux. However, the muons are not absorbed by nuclear interactions but are only slowed down due to energy

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loss by ionization. Only those muons are suppressed, whose range is smaller than the shielding thickness.

The energy spectra of \( \pi \)-mesons produced by 25 GeV protons are reasonably well known (Baker et al. 1961, Diddens et al. 1962, Cocconi 1961). For a given \( \pi \)-meson momentum \( p_\pi \) the muon momentum \( p_\mu \) has approximately an equal probability to have any value in between 0.57 \( p_\pi \) and \( p_\pi \). We shall assume therefore that the momentum of all muons is 0.79 times the momentum of the parent \( \pi \)-meson. The momentum of the muon in the rest frame of the \( \pi \)-meson is about 30 MeV/c so that in the laboratory system the muon has essentially the same direction as the \( \pi \)-meson. The angular distribution of the \( \pi \)-mesons is strongly peaked in the forward direction. The most realistic figure for a shielding design is the muon flux, averaged over a suitably chosen area. We have therefore integrated the \( \pi \)-meson spectra over all angles and calculated the total number of muons, per interacting proton, whose momentum exceeds a value \( p_{\text{min}} \), assuming a \( \pi \)-meson decay path of 10 m. The result is shown in Fig. X.2.

The high energy muons are produced approximately tangentially to the ISR, so that they only influence the shielding thickness on the outside of the ISR. The attenuation of the muons depends strongly on the geometry of the shielding and the ISR magnets. If the ISR beam level will be on 445.5 m there will essentially be only a muon problem in the hall for secondary beams from conventional target operation. Since the lowest surface ground level encountered around the ISR is about 449 m (the highest about 462 m), all muons will be stopped in the surrounding earth. We shall therefore treat only the case of the secondary beam hall where a demountable shielding of concrete blocks around the machine is foreseen. The lay-out is shown in Fig. X.3.

We want to determine the shielding thickness necessary to reduce the muon flux to 2.5 muons/cm² s, i.e. 0.1 of the npd, behind the shielding wall at a distance of 50 m from the target. For simplicity we assume that all
muons come from the internal target. For all calculations in this section we shall make the following assumptions:

a) The number of interacting protons is $3 \times 10^{12}$ per s. Half of the $\pi$-mesons are absorbed in the vacuum chamber wall or collimators close to the point of production, so that they do not contribute to the muon flux.

b) The average flight path of the $\pi$-mesons is 10 m. We average the total number of muons as derived from Fig. X.2 over a cone with a half opening angle of 50 mrad and neglect the detailed influence of the magnet stray field.

c) We consider all negative muons and only 50% of the positive muons, since roughly half of the latter will be deflected inward by the downstream magnet units and consequently strike the side walls under small angles, which increases proportionally their path length inside the shielding, and are moreover smeared out over a large length of the shielding wall.

d) The average momentum loss of the muons in collimators, beam transport, downstream magnet yokes, etc. is 3 GeV/c. The equivalent of 2.1 m of steel is needed for this energy loss, if we assume $\frac{dE}{dx} = 1.8$ MeV per g/cm$^2$.

Under those conditions the total number of muons of one sign per interacting proton with $p_\mu > p_{\text{min}}$ for 10 m decay path of the $\pi$-mesons has to be smaller than $1.7 \times 10^{-7}$. Extrapolating the trend of Fig. X.2 we estimate that all muons with momentum smaller than 15 GeV/c have to be stopped. Allowing for an energy loss of 3 GeV in the target area, the shielding in the forward direction has to be sufficient to stop 12 GeV/c muons, which corresponds to $6.7 \times 10^3$ g/cm$^2$ i.e. 8.55 m of steel ($\rho = 7.8$ g/cm$^3$) or 19.0 m of baryte ($\rho = 3.5$ g/cm$^3$). It is obviously advantageous to place the shielding wall
so that it provides maximum path length in the $0^\circ$ direction. On the other hand, if a 5-ton. crane is required in the target area as in the other parts of the ISR tunnel, its shielding has to be constructed as a continuation of that tunnel. With the shielding lay-out as shown in Fig. X.3 a wall thickness of 7.6 m of baryte is sufficient for the required path length in the $0^\circ$ direction. It may be noted that this thickness provides 40 removal mean free paths ($\lambda \approx 170 \text{ g/cm}^2$) for the high energy strongly interacting particles in the forward direction.

For muons which originate upstream from the target we assume a point source strength of $10^{11}$ interacting protons and calculate the shielding thickness at 60 m from the source. The other conditions remaining the same we calculate a path length of 14.3 m of baryte along the appropriate $0^\circ$ production direction. For this a shielding wall thickness of 5.85 m of baryte is required. However, a decrease of beam loss in this region by appropriately placed beam catchers in the ISR could be attempted. Moreover, space requirements in the ISR tunnel upstream from the target may be less stringent so that some additional baryte shielding could be provided near to the ISR inner arc straight sections in order to prevent pion decay and to slow down muons. A wall thickness of 5 m of baryte is therefore proposed for the longest part of the outside shielding wall.

The thickness of the inner wall is chosen as 4.5 m of baryte and that of the roof as 5.3 m of concrete since they are determined by the attenuation of the nuclear cascade as treated in section X.4. The choice of baryte as shielding material for the side walls was made on space considerations. Cost considerations could still lead to the choice of an equivalent thickness in concrete for a large part of the shielding wall in the hall for secondary beam experiments. The fact that this shielding is demountable allows its adaptation to the actual beam intensities injected into the ISR at a given moment.

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6. Conclusions

The following table summarizes the shielding thicknesses for the inner wall and the roof as calculated in section X.4.

<table>
<thead>
<tr>
<th>Source strength</th>
<th>(10^{11}) protons/s per 40 m run of tunnel</th>
<th>(3 \times 10^{12}) protons/s target and injection region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part of shielding</td>
<td>earth</td>
<td>concrete</td>
</tr>
<tr>
<td>Roof (mpd allowed)</td>
<td>5.2 m</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Inside wall (0.1 mpd allowed)</td>
<td>6.9 m</td>
<td>4.9 m</td>
</tr>
<tr>
<td>Outside wall</td>
<td>See section X.5.</td>
<td></td>
</tr>
</tbody>
</table>

For the outside wall no figures are mentioned since the tunnel floor is at least 5 m below the lowest ground surface level, by which automatically an adequate earth shielding is provided. This is not the case for the secondary beam hall. Here the shielding thickness is determined by the required attenuation of the muon flux, as it always is for the outside wall for our primary proton energies. An estimate for the shielding thickness adapted to this particular situation is given in section 5 while the lay-out is shown in Fig. X.3.

As the thickness estimate for the outside and inside shielding walls is based on 0.1 mpd behind the wall in the experimental area and on a maximum CPS intensity which might be a factor 2 higher than realistically can be hoped for, we have a safety factor of 20 against errors resulting from the uncertainties in the experimental data for the parameters on which the calculation is based. It is our opinion that this safety factor is sufficient, but not exaggerated. Better data about the effectiveness of the CPS shielding
could lead to some reduction in this safety factor, thereby reducing the required shielding thicknesses. The accuracy of the estimate for the thickness of the outside wall is limited by the dependence of the muon flux on the lay-out of collimators, beam transport etc. in the target area.

The critical evaluation of the calculation for the roof shielding is complicated by the requirement to have the npd for the general population at the boundary of the CERN site. This dose rate in mrem/hr is 44 x smaller than that for radiation workers. It is difficult to make a reliable estimate for the dose at larger distances which is determined by the sky shine radiation, but preliminary estimates show that this condition is met for the proposed shielding. More extensive measurements on the CPS radiation level at larger distances will have to be made to elucidate this point.
XI. CONTROLS

1. General Remarks

It would seem that, in first approximation and apart from the necessary modernization, the extension of control philosophies and methods used in the CPS, to the ISR would meet the basic requirements.

Although this is true for many aspects of the overall control system, some important differences in certain basic conditions call for corresponding variations in the general conception.

The most important difference is inherent to the operational mode of the ISR. Whereas in the CPS an interruption entailing the loss of the beam lasts as long as the originating fault, in the ISR the loss of the stacked beam, produced by an interruption however short, corresponds to the loss of up to a few operating hours for both machines (the CPS has to refill the ISR) and to the radiation hazard produced by the "dumping" of an intense beam.

The other differences originate from the "size" of the ISR installations, which includes both the geographical extension and the amount of the equipment involved.

As to the geographical extension, the mean distance between a piece of equipment and its remote controls, assumed centrally located, will be approximately twice that encountered in the CPS. This has obviously a direct influence on the length of the interconnections but affects other aspects such as the balance to be found between local and remote controls (to maintain the displacement of personnel within reasonable limits), etc.

As to the amount of the equipment, one can take into account also here a factor two of increase over the CPS equipment.

The three basic differences enumerated so far may lead to a control system probably more elaborate and, in any case, requiring a more detailed analysis than in the CPS at an early stage of the design.
In particular, the possible loss of up to a few hours in both machines for any malfunctioning suggests the use of very reliable methods and components.

This requirement can be met rather efficiently, without the use of sophisticated equipment, if, in addition to transistorized electronics, the maximum possible amount of control circuits is installed outside radiation hazardous areas.

The increased size of the installations with respect to the CPS stresses the importance of:

a) appropriate assessment on whether or not a certain indication or control is necessary in the Main Control Room (MCR),

b) selection and scanning methods to share the same interconnection between a certain number of functions originating far away from the MCR,

c) in connection with b), the use of modern data storage and conversion to assist few people in managing a large complex,

d) the utilization of "GO - NO GO" and in - tolerance - out of tolerance signals whenever possible, for economy reasons,

e) standardization of control inputs and outputs to allow automatic adjustments by means of on-line computer, should the need arise.

No detailed studies on actual possible control circuits have started. We have concentrated mainly on two basic problems, the general layout (Control Rooms, Tunnels, etc.) and the transmission of control signals over the relatively long distances involved.

The first problem has to be considered together with the building layout and may have an influence on it, requiring therefore an early study. The second one may affect the design of all control circuits and therefore has also to be investigated at an early stage.

The remainder of this chapter tries to give a more detailed account on these points.
2. General Layout and Control Rooms

The experience of the CPS and of other large accelerators suggests the adoption of as few as possible Control Rooms permanently manned.

It seems in fact appropriate, since the injection does not introduce a rather complex machine like a Linac, to reduce their number to two:

- Main Control Room (MCR),
- Power Control Room (PCR).

By saying this, we do not exclude, of course, local control stations from where starting-up procedures and/or special studies could be executed. We simply stress that, as from the beginning of normal operation, only these two rooms should need a permanent attendance.

The normal operation of the entire machine should be accomplished, essentially, from the MCR, the PCR taking care of the power and cooling water supplies for the machine magnets and of the substations.

More in detail, the MCR should include:

- information on the operating status of the various machine parts,
- data about primary and secondary beams and their adjustments,
- all necessary equipment for personnel security, including essential radiation monitors.

Malfunction indication should be limited to the ones identifying the equipment involved and its geographical location. No detailed malfunction information should appear in the MCR for which the recovery action cannot be taken from it.

It seems convenient to locate the two Control Rooms next to each other since this gives the following advantages:

- mutual help of the two operating teams in case of necessity,
- sharing of cable tunnels and passages for power and controls.
As to the position of the so obtained CR complex, it must logically be in proximity of:
- the main office and laboratory building (L),
- the Power House (P) and the Cooling Hall (C),
- at least one of the major experimental areas (E1).

The proposed solution can be seen on Fig. XI.1. The Control Rooms and the Power Halls constitute a unique complex. Good liaisons with E1, L and W are ensured by the indicated cat-way, whereas I4 and I5 are easily reached by means of the inner circular road.

Fig. XI.1 also shows the basic tunnel system.

The auxiliary buildings A1 to A8 play an important rôle, as it will be seen in section 2.1. Fig. XI.2 shows possible interconnections between the machine and the control rooms.

In first approximation no control signals need go around the machine tunnel. Control functions from individual pieces of equipment are transmitted to the nearest auxiliary building (A) where they can be conveniently treated, summed-up and sent to the MCR.

1.1. Auxiliary buildings (A1 to A8)

Their main purpose is to locate outside radiation hazardous areas transistorized electronic equipment, special power supplies, local substations, and as many as possible of actual control circuits.

In this way a high degree of flexibility and reliability can be obtained without the use of special equipment and components. In addition, these buildings can serve the purpose of summing-up and/or selecting the signals to and from the CR in order to reduce the number of long interconnections to be provided.

A first tentative list of equipment to be installed there includes:
a) vacuum and bake-out controls,
b) electronics for pick-up electrodes,
c) local substation (for the corresponding ring section and intersection area),
d) control circuit summary and selection,
e) RF power equipment where appropriate (e.g. A 1 and A 8).

These buildings should be sufficiently shielded with respect to the ISR tunnel as to ensure absolutely free access irrespective of the operational conditions. Only in this way is it possible to take full advantage of their introduction in the layout.

2.2. Layout inside the machine

As indicated in Fig. XI.1, the circular tunnel TR under the machine tunnel R makes possible the installation of cables, pipes and other general services for the two rings in a rather convenient way.

Fig. XI.3 shows the cross-section of R and TR, together with zones which are reserved for the various installations.

The space between the two magnet structures must be left free for passage and transport of equipment but some cables and services can be installed on the lateral walls.

Connections between TR and the equipment in R are made possible by suitable apertures in the TR ceiling continued by small trenches obtained in the top part of the supporting slab.

At eight positions around the circumference (Fig. XI.1), chosen in such a way as to preserve the possibility of erecting eventually other colliding beam halls, sections of radial tunnel connect TR with TA and the A buildings. The same radial tunnels can also serve the purpose of collecting cables, installed on the lateral walls of R, for continuation to A buildings.

Under the actual Colliding Beam Halls I 4 and I 5, a second section of radial tunnel completes the system.
2.3. Beam transfer tunnels and liaison CPS - ISR

Equipment in the beam transfer tunnels (TT 1 and 2) can be remotely controlled from the Control Rooms by means of cables installed on a lateral wall of such tunnels and through TP 1.

The same path can be used for CPS - ISR interconnections.

3. Transmission Techniques

To keep the ISR working smoothly and safely, several thousand communication links must be provided between the various sub-systems and the Control Rooms. Although most of the signals are technically simple to transmit (ON/OFF, slow digital data, voice, etc.), the detailed needs are difficult to predict, and one must be ready to accept extensive additions and modifications to the system between the initial starting-up period and later operation. Flexibility and speed of installation are therefore as important requirements on the communication systems as economy and long life.

Although conventional point-to-point wiring will continue to play an important part in the ISR, some of the inherent drawbacks of that technique must be overcome by introducing other and more refined communication methods, based upon multiplex techniques (many signals transmitted by means of the same wire). An analysis of the remote control and telemetry systems in use at the CPS has shown that an accelerator installation puts different requirements on the communication network than do industrial or other professional users of large control systems. The number of information channels (thousands rather than hundreds), the average transmission distance (hundreds of metres rather than many kilometres), and the type of layout (distributed rather than concentrated) are unusual requirements for industrial systems. If to this are added the requirements of low cost as well as extreme flexibility in use, it can be shown that existing multiplex systems are insufficient, and of relatively little direct interest for the ISR.

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The combination of well-known techniques and modern components has, however, made it possible to design new communication systems which can satisfy the specific accelerator requirements. One such system has been developed at CERN, and is now undergoing tests in the CFS. Since the introduction of this system may significantly influence the philosophy of the ISR control design, it is briefly described below.

3.1. The Trunk/Multiplex System (Sagnell 1964)

Fig. XI.4 shows the block-diagram of the system together with the equipment required for one-way, single channel ON/OFF communication. The system achieves a high degree of flexibility by using a single trunk cable as the only link between many pieces of equipment, and by using self-contained multiplex circuits to provide a large number (400) of independent transmission channels. To avoid mutual interference between the different channels, each transmitter/receiver pair operates at its own, crystal-controlled frequency. When the transmitter is in operation, the generated carrier frequency can be detected by the appropriate receiver in any other point along the line, and the resulting relay closure can be made to operate external control circuits.

Unlike other existing remote signalling equipment, the CERN multiplex transmitters and receivers are completely self-contained, and require no additional circuits, power supplies etc. to operate. It is sufficient to connect a transmitter/receiver pair to the same trunk cable to obtain one-way ON/OFF communication. There is therefore no need for careful pre-planning if such a system is employed. Functions can be added and removed, control panels and equipment can be changed and moved without the need for time-consuming cable installations. Furthermore, the multiplex equipment can be recuperated from obsolete equipment and re-used in other projects, thereby further reducing the transmission cost.

The basic multiplex units only transfer ON/OFF signals, which is the most important signal in a remote control system. However, other types of data may also be transmitted by a suitable coding, and units exist for

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transferring analogue voltage values and three-state signals. The present system will therefore cope with the majority of remote control, telemetry and interlock functions needed by an accelerator.

3.2. Possible applications

To clarify the concept outlined above, two out of the numerous possible applications of the multiplex system to the ISR are given here, merely as illustrations.

3.2.1. During the commissioning period it will be necessary to install all along the Transfer Tunnels TT a number of flags, TV screens, etc. in order to define in the best possible way the beam position and shape. Such an equipment, requiring a considerable amount of remote controls and indications, could be drastically reduced once the basic settings would be known. It appears then well justified to install multiplex units instead of point-to-point wiring, since they can be readily removed after use and re-employed somewhere else.

3.2.2. During normal exploitation, an extensive use of the multiplex system between the A buildings and the Control Rooms could also be advantageous. In fact, this would allow rapid re-arrangements of the controls made available to the operating team, according to needs.
XII. SURVEY

The ISR must not be considered as a separate machine but as part of a complex, closely linked to the CPS.

One of the purposes of the survey is to assure the geometrical link between the CPS and the ISR. This work will be described in the first part of this chapter.

The second part will be devoted to the methods to be used to realise the alignment of the 264 magnet units and all the auxiliary devices such as quadrupoles, sextupoles, etc., as well as the elements of the beam transport in the two injection tunnels.

1. Geodetic Link between the CPS and the ISR for the Civil Engineering Work

The rectangular coordinate system of the CPS is defined in an internal CERN report (Gervaise 1962).

The origin of the coordinates is the middle of the line joining the reference pillars $P_1$ and $P_2$ of the CPS. Arbitrarily, and to plan the construction of the ISR, the values of $X = 1000$ m and $Y = 1000$ m were given to this point.

The coordinate system was defined in the following way:

- **X axis**: $P_2 P_1$
- **Y axis**: perpendicular to $P_2 P_1$ in the middle of $P_1 P_2$ in the direction of the centre of the synchrotron.

Outside the CPS there exist two pillars for measurements (see Fig. XII.1), one above the centre $P_0$ of the CPS, and one above $P_6$. (The latter was erected for the purpose of surveying the East Area.) It will be these two pillars which will serve to start the geodetic net for the lay-out of the ISR. In fact the external length between $P_0$ and $P_6$ is known with an accuracy of 0.2 mm and it will be the direction $P_0 P_6$ which will be used as the reference azimuth.

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On the new site it will be necessary to build parallel to the national road No. 84, eleven pillars separated between centres by 50 metres, thus making a base of 500 metres.

The top of these pillars will be at the same level; on their upper surfaces sockets will be fixed with precision holes of 30 mm diameter. The alignment of the holes will be done by means of a theodolite and the distances measured with the special CERN device for length measurements (Gervaise 1964).

The distance \( B_1 B_{11} \) will be known within an accuracy of 0.13 mm. On this base we shall calibrate a geodimeter AGA model 4. (This geodimeter is an instrument for measuring length based on the use of a light beam modulated at 30 MHz.) This will then be used to measure all distances between the other pillars on the site.

Besides these pillars determining the base line \( B_1 B_{11} \), it will be necessary to build along the south border of the site a pillar \( S_2 \) 2.70 m high and a concrete tower \( S_1 \) 12.00 m high, sheltered from the sun.

The extension figure of the base \( P_0 P_6 \) will be determined by the geodetic points \( P_0, P_6, B_2, B_9, S_1 \) and \( S_2 \) (see Fig. XII.1). All the angles will be measured with a theodolite Wild T3 and all the lengths of the sides measured: \( P_0 P_6 \) and \( B_2 B_9 \) with invar wire, and the others with the AGA geodimeter.

All data from the measurements will be used to establish an adjustment programme to be solved by the least squares method (method of variation of coordinates). A complete programme will give directly the values of the coordinates of the points \( B_2, B_9, S_1 \) and \( S_2 \) in the GPS coordinate system.

A coordinate transformation programme will then enable us to obtain the value of these coordinates in the grid system used by the Site and Building Division of CERN.

The position of the points \( S_1 \) and \( S_2 \) was chosen so that during the first step of the construction period, the lines of sight will stay free.
The quadrilateral $B_2B_9S_1S_2$ will serve for the placing of the ISR concrete ring and of the experimental halls; it will permit checking this implantation and provide on demand the points necessary for carrying out the civil engineering work.

Moreover, the points $B_1$ to $B_{11}$, $S_1$ and $S_2$ will be used as reference points for all site lay-out work such as buildings, roads, drains and other canalizations.

The surveyors in charge of these works will not need any traverse longer than 500 metres to do the setting up of all the detail points. They may add a few supplementary net points, such as frontier marks, which present a good guarantee of duration.

The origin of the level of the present CERN site is a bench mark of the cantonal precision levelling net, placed on the building of the Swiss Customs of Meyrin. This will be used for all the work on the new site.

2. Alignment of the Magnet Units inside the Ring

The main difference between the ISR survey and that of the CPS is the absence of radial tunnels. Moreover, the knowledge acquired during the alignment of the 100 magnet units of the CPS and during the control survey regularly made since the initial running-in has shown that the optical measurements are far less precise than the length measurements with invar wires. Since the invar measurements can be done very rapidly, we have decided to perform the horizontal alignment of the ISR magnets by means of length measurements only. The procedure is roughly as follows: A number of reference pillars distributed along the tunnel will be aligned by trilateration and the magnets will then be aligned from these reference pillars, also by trilateration.

2.1. Reference pillars

The reference pillars will be cast in reinforced concrete, isolated from the ring, lying on the molasse at such a depth that an overload on
the floor of the ring will not interfere with their stability.

All their upper surfaces will be at the same level, and they will support crossed-link motion plates with 30 mm diameter bores to be used for all types of measurements.

There will be two rows of pillars, one near the external wall of the ring of the ISR, the other near the internal wall.

The number of pillars is not yet fixed. Two possibilities have been studied with regard to the number of betatron oscillations, namely two rows of 24 pillars (see Fig. XII.2) or two rows of 32 pillars each (see Fig. XII.3). In both cases, the distance between the two rows of pillars will be 12 m.

Both solutions make it possible to use only short invar wires, the longest being 41 metres long. So we avoid the difficulties due to the risk of shock during the transportation of the wires, and also we will stay within such lengths that the influence of the invar flow is much reduced.

All the lengths of the sides of the double polygon with 24 or 32 apexes, as well as the diagonals, will be measured with the special CERN device for length measurements.

In the case of 24 pillars, the wires will be: 12.00 m, 37.53 m, 40.65 m, 40.86 m long, while in the case of 32 pillars, the wires will be: 12.00 m, 28.17 m, 30.52 m, 31.69 m long, all wires having a precision of 0.01 mm.

From the results obtained with the special CERN device, the r.m.s. value for an isolated measurement of a length between 0 and 50 m inside the tunnel is 0.01 mm.

Assuming this value, we computed the maximum error of closure for the polygon as being 0.20 mm and 0.23 mm for the cases of 24 pillars and 32 pillars respectively.

The corrections to be given to the pillar coordinates, after the first set of measurements, will be worked out by a computer. The reference

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plates will then be given the necessary corrections to place them in their theoretical position, then a survey check will be made and the process repeated as necessary.

The levelling will be made with a Wild N3 level, a CERN type lift-tripod and target. The r.m.s. value for levelling in this condition is 0.1 mm.

2.2. Magnet survey

Each magnet unit is situated inside a quadrangle formed by four reference pillars (see Fig. XII.4).

It will be put in the right position by means of invar wire measurements from each of these four pillars. Three measurements are sufficient to define the exact position, the fourth one being a check, permitting the r.m.s. value of the coordinates of each magnet to be worked out. It is expected that with this method the alignment of the magnet units can be done with an r.m.s. error less than 0.2 mm. The levelling will be done by conventional methods with an r.m.s. error of 0.1 mm.

2.3. Calibration of the invar wires

It will be necessary to build an underground, well air-conditioned tunnel, separated from the ISR ring to re-install the calibration base, at present placed in the radial tunnel No. 5 of the CPS.

The present calibration bench is accessible only two days every fortnight, and during machine shut-downs; that is not sufficient for the standardization and development work necessary for the lay-out of the 264 ISR magnet units and all other auxiliary equipment.

Furthermore, by using the new method, the number of invar wires will be considerable; consequently the calibration work will go on almost continuously.
2.4. Beam transport survey in the injection tunnel

Long straight alignments will be done with a laser beam working inside a rough vacuum pipe. The necessary angles will be measured by means of a theodolite and the distances with a special CERN device.

2.5. New techniques for length measurements

The survey group of the AR Division has begun some experiments with a laser to study its possibilities of use. We plan to use the base $B_1 - B_{11}$ (see section 1 ) for alignment experiments with lasers. The laser beam will then be used to indicate a reference line.

Length measurements on the ISR magnets by means of laser beams cannot be done in the open air with the same precision as that of invar wire measurements. Moreover, if it were necessary to equip the pillars, the magnets and all the auxiliary equipment with vacuum pipes, the measurements with invar wires would be far quicker.
XIII. BUILDINGS AND SERVICES

1. General Layout

In the general layout of the ISR (Fig. XIII.1) the following buildings are shown:

- The main ISR tunnel (R) with
- Halls for colliding beam experiments (I4, I5);
- A hall for 25 GeV experiments (E1);
- The tunnels TT1 and TT2 through which the beam is transferred from the CPS to the ISR;
- A divisional workshop W;
- A laboratory building L to house the ISR Division;
- A building complex inside the ring containing the power and cooling installations (P and C) and the Main and Power Control Rooms (MCR and PCR);
- Eight auxiliary buildings (A1 to A8) distributed on the inside around the ring to contain power distribution and control equipment;
- Two similar buildings (A11 and A12) to contain injection power equipment;
- A building (Y) to contain power and control installations for the equipment in the beam transfer tunnels;
- An electrical substation (SW) for the ISR area;
- Cooling Towers (CT) for the experimental equipment to be built for the storage rings;
- A water tower WT with its storage tank;
- A purification plant (PF) for the waste water;
- A tunnel (TS) containing a geodetical calibration bench.

The roads planned are the following:
A main road from the CERN entrance to the ISR complex (during the construction period mainly to be used for building activities);
A connection road to the CPS buildings (at the same time the access road for CERN staff during the construction period);
An access road to the colliding beam halls and the buildings inside the ring.
The figure further shows the system of service tunnels (TP1, TP2, TP3, TA, TR) through which e.g. power and cooling water are brought to the various buildings and through which control cables run between the buildings.

2. Location of the ISR Tunnel

There was not much freedom in the location of the ISR tunnel. Its size is such (as can be seen from Fig. XIII.1) that a displacement to the North, West or South would hardly be possible without crossing the boundaries of the site. It could have been placed nearer to the CFS, but this would have had the following disadvantages:

a) An area, which would naturally be used for CFS extensions (new linac, third experimental area) would be blocked;

b) The ISR buildings (experimental hall, laboratories, offices) would have to be built on the West side of the ring, which would be very inconvenient during the construction period;

c) The beam transfer system would require more bending and therefore be more expensive.

We have therefore chosen the position indicated. This does involve a rather high ground level on top of the ring in the West corner, but this is limited in area.

An important parameter to be fixed was the level of the tunnel.

It was felt from the beginning that an elastic ring support as applied to the CFS would be extremely difficult to realize for the ISR. The shape (2 rings intersecting in 8 places) would be complicated and, moreover, in the interaction regions the presence of this supporting ring would be undesirable, since rather bulky detectors will there be built around the vacuum chamber.

It was therefore decided to support the magnet directly on the floor of the tunnel. It is obvious that this can only be done in the molasse,
because the moraine is far too unstable. A ground investigation comprising altogether 26 borings of total length 600 m was carried out. The result was the following:

Disregarding the problem of magnet foundation the most economical level for the tunnel floor would be 446 m. (This would take into account only excavation and earth shielding.) A sure level where the ring would rest immediately on the molasse everywhere would be 442 m (see Fig. XIII.2). This would, however, be a very expensive proposition, since the ground level would be high above the tunnel floor and the problem of access roads to the halls would be rather difficult and expensive to solve. A level of 444 m was therefore accepted as a compromise. Concrete fillings will have to be applied in those places where the magnets would not be immediately on the good molasse.

For comparison, the floor level of the CPS is at 432.40 m.

3. The ISR Tunnel

The general layout of the two magnets in the ring building is shown in Fig. V.1. The maximum distance between the two orbits is 9.5 m. Adding sufficient space for the magnet yokes, for survey monuments and room to pass we have arrived at a width of the tunnel of 15 m.

The height of the tunnel was chosen 6 m. We have allowed for lifting facilities for 5 tons and a beam height above the floor of 1.50 m.

The normal cross section of the tunnel is shown in Fig. XI.3. The construction will be performed as follows. First the excavation will be carried out to a depth about 1 m above the planned floor level. The tunnel walls and roof will then be built and the shielding earth put back on top. Then borings inside the tunnel will give the information of how deep the excavation has to be pursued. This will then be done and, where necessary, the concrete filling will be applied. Finally the floor will be constructed independent of the tunnel shell. The advantages of this method are:
a) The ground will settle under the heavy load of the shielding before the floor is cast;

b) The molasse will be protected from the penetration of rain water.

The tunnel will be airconditioned so that the air temperature will stay between 15 and 25°C and the dew point at 10°C. The capacity of the plant, both for heating and cooling, will be 2 MW.

A service tunnel which will run all along the main tunnel under the floor will carry the cables and pipework around. In the interaction regions this service tunnel will run much deeper so as to provide space for 4π detectors around the colliding beams.

4. Halls for Colliding Beam Experiments

The colliding beam experiments will be carried out around the interaction regions and it is planned to enlarge the tunnel appreciably in some of these regions by the construction of so-called colliding beam halls.

There are two types of interaction regions: in four of them the beams go to the inside and in four to the outside of the ring. Because of the magnet layout (longer straight sections to the inside) the first type is considered more suitable for experiments at very small angles, as elastic scattering, and the second type for large angle experiments (e.g. new particles created at very high proton energies). In the first case one can imagine to need a rather long momentum analyser, in the second case a detector built immediately around the interaction region. We have therefore designed the colliding beam hall of the first type to be 70 m long and the other 50 m. Both are 25 m wide and placed asymmetrically, so that more width is available at the side where the beams go. The height of the halls is 9 m under the crane hook.

We have discussed at length how many colliding beam halls should be provided in the beginning. Beside the economical reasons there are two strong arguments for not building all of them at the same time. One does
at the moment not yet know how many 25 GeV halls will be constructed later and one has not yet any experience with colliding beam experiments, so that the "ideal colliding beam hall" may look different from what we think now.

We have made a study of a demountable tunnel, which could, later on, be turned into a colliding beam hall without having to close down the ISR, but this turned out to be very expensive.

We have decided to construct in the beginning one hall of each type as well as one 25 GeV hall built in such a way (Fig. XIII.4) that colliding beam experiments are possible too.

In all interaction regions facilities (access, floor pit, etc.) will be provided to do colliding beam experiments in the available width of the tunnel, and it is expected that a few more halls will be constructed later, involving a close down of the ISR.

The construction of the halls is shown in Fig. XIII.3.

There will be 50 ton cranes in each hall. The floor loading will be 20 t/m² and, in the pits, 40 t/m². A concrete door, in parallel with a labyrinth, will provide access through the shielding. This facility is provided in all interaction regions, a circular access road running all along the inside of the ring. The service tunnel under the main machine tunnel has branches to the walls in all interaction regions and is, moreover, connected to the auxiliary power and control buildings on the inside of the ring.

5. Hall for 25 GeV Experiments

This hall (Fig. XIII.4) will be placed partly across the beam (in Brookhaven fashion) so that the main cranes can be used to build up the shielding walls. Moreover, this design allows colliding beam experiments to be carried out in this hall as well.

In determining the dimensions of the hall it was clear that from the experimental physicists' point of view it would be advantageous to make it as big as possible but there are, of course, economic considerations.

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The size was chosen so that it can house (together with the colliding beam halls) all the parts of the ISR and its measuring equipment (e.g. magnets, vacuum system, beam transport system etc.) at the time of the installation. The height is 14 m under the crane hook and the total height 21 m.

The hall will be provided with two 50-ton cranes. The floor loading will be 20 t/m².

6. Beam Transport Tunnels

The layout and cross section of these tunnels is shown in Fig. XIII.5. They will be at the level of the CPS for the larger part and rise to the ISR level with a slope of 10 °/o.

7. Other Buildings

The building complex placed on the inside of the ring will contain the following parts:

a) The power and cooling halls (P and C) 7 m high and with a total area of 1700 m² which will contain the magnet power supplies and the cooling installations;

b) The control rooms (Main Control Room MCR and Power Control Room PCR) of 600 m² area. Part of the control room area will be used as office space in the beginning.

The control building will be connected to the 25 GeV hall, the workshop and laboratory building by means of a passerelle.

The laboratory building (L) will contain light laboratories and stores, drawing offices and normal offices, with a layout similar to that in the CPS buildings. It will contain 4 floors and a basement and the total floor area will be 4500 m². It will house the ISR Division.

The divisional workshop (W) will have an area of 30 x 60 m² and a height of 13 m (9 m under the crane hook). The general layout is such that the

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divisional workshop can be extended later on with a hall and against this hall more laboratory wings can be constructed (as indicated in dotted lines) e.g. for DD, NP, etc. Eventually these laboratory wings can be connected with more buildings without ground floor.

**Auxiliary buildings** inside the ring and near the beam transfer tunnels (A1 to A8, A11, A12, Y) will house the local substation for machine and experimental halls, the vacuum and vacuum chamber heating controls, equipment for RF and pickup stations and for inflector and beam transfer power supplies. Their total area will be about 2000 m².

8. **General Electricity Distribution**

The general electricity distribution system for the storage rings will be closely related to the existing distribution scheme on the CERN site.

The power will be taken from the new 130/18 kV main substation actually under construction. However, the subdistribution between the Swiss and the French site will not be done in this main substation but by means of an intermediate substation "Jura" to be built near the existing substation "PH" at the main entrance of CERN.

Consequently, this intermediate substation will be used as a main distribution point for the feeder cables for the storage rings.

**Power requirements**

In the following the power requirements are listed item by item (the indicated ratings represent the installed capacities):

- main magnet power supplies
  (including correcting devices) 26 000 kVA
- cooling for main magnet coils 100 "
- RF system 100 "
- vacuum pumps 300 "

*carry over 26 500 kVA*

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carried over 26,500 kVA

- heating of the vacuum chamber 1,000 "
- beam transfer magnet power supplies 2,400 "
- ventilation system 400 "
- lighting in machine tunnel 150 "
- lighting in colliding beam areas 80 "
- auxiliary services in machine tunnel 200 "
- auxiliary services in colliding beam areas 200 "
- total power for experiments 25,000 "
- cooling for experimental magnets 600 "
- air conditioning 500 "

Total 57,030 kVA

Short description of the proposed system

Fig. XIII.6 shows the distribution from the substation "Jura" down to three substations and eight local substations situated near the storage rings.

The main transformers of the ring magnet power supply plant are directly connected to the intermediate substation "Jura" whereas all the other loads will be supplied by the following substations:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Location</th>
<th>Installed Capacity (MVA)</th>
<th>Serves for:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation SP</td>
<td>Storage ring power house (inside the ring)</td>
<td>4</td>
<td>Auxiliaries for ring magnet power supplies, cooling, air conditioning, etc.</td>
</tr>
<tr>
<td>Substation ST</td>
<td>Between CPS and ISR</td>
<td>2.4</td>
<td>Power supplies for beam transfer magnets</td>
</tr>
<tr>
<td>Substation SE 1</td>
<td>Near the 25-GeV Hall</td>
<td>14</td>
<td>Power supplies for experimental magnets in the Internal Target Hall</td>
</tr>
<tr>
<td>Substations AI - A8</td>
<td>Ring service buildings</td>
<td>8 x 0.63 2 x 8</td>
<td>Power supplies for experimental magnets in Colliding Beam Areas, general services in the ring building and the halls, vacuum, RF, ventilation, injection, etc.</td>
</tr>
</tbody>
</table>

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In the present scheme, it is assumed that all the power supplies for experimental magnets would consist of mobile units to be put wherever needed inside the experimental halls or nearby outside.

Power supplies for beam transport or similar magnets, up to about 300 kW, would be connected to 380 V, whereas the track chamber power supplies would be directly connected to 18 kV.
XIV. TIME SCHEDULE, MANPOWER AND COST

1. Time Schedule

The construction schedule is shown in Table XIV.1. This schedule is valid only if the authorization for the project is given by January 1st, 1965.

A delay of one year beyond that date would cause a shift in the programme of about half a year provided that the attitude of the Council towards the project would be positive by January 1st, 1965. Any subsequent delays would be more serious. The shift in programme will then amount to at least the delay and probably more because of the resulting movement of the staff.

From the schedule it is clear that the first nuclear physics experiments on the colliding beams can be expected during 1971, if these experiments have been planned properly and prepared in due time.

2. Staff

Towards the end of the construction period the old PS Division had 50 scientific and 130 technical and administrative staff members working on the accelerator.

At the moment much more experience is available in the existing staff and the ISR has no linear accelerator. On the other hand, it has become clear from our preliminary studies that almost every single item of the ISR will be more difficult than the corresponding item of the CPS. Examples are:

a) **Theory**: The stacking is a new and complicated process. The machine is essentially non linear. Very long straight sections are essential. The lattice structure is more complicated. Collective phenomena have to be taken into account.

b) **Buildings**: The ring tunnel is larger in cross section and diameter and more complicated because of the intersections.
<table>
<thead>
<tr>
<th>TABLE XIV.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tentative Programme Proton Storage Rings</strong></td>
</tr>
<tr>
<td>Main Tunnel and Colliding Beam Halls</td>
</tr>
<tr>
<td>Beam Transfer Tunnels</td>
</tr>
<tr>
<td>25 GeV Hall</td>
</tr>
<tr>
<td>Offices, Laboratories, Workshop</td>
</tr>
<tr>
<td>Central Building and Auxiliary Buildings</td>
</tr>
<tr>
<td>Movable Shielding Blocks</td>
</tr>
<tr>
<td>Magnet System</td>
</tr>
<tr>
<td>Magnet Power and Cooling</td>
</tr>
<tr>
<td>RF System and Beam Observation</td>
</tr>
<tr>
<td>Vacuum System</td>
</tr>
<tr>
<td>Injection and Injection</td>
</tr>
<tr>
<td>Control Cables and Ducts</td>
</tr>
</tbody>
</table>
c) **Magnet system**: Tolerances are tighter and the width over which the field must have an exact non-linear shape is larger. DC operation increases power problems, especially in the pole face windings.

d) **Vacuum system**: The vacuum required is a factor of $10^4$ better than in the CPS.

e) **General technology**: Is complicated very much by the ultra high vacuum requirements.

f) **Size of the project**: The physical size of the ISR is more than twice that of the CPS and this is reflected in the organization and execution of the installation.

We estimate that the staff composition will not be very much different from that of the old PS Division, but the total figure will be higher by about 20%o. When the staff has reached its peak, the composition of the ISR Division will be as follows:

<table>
<thead>
<tr>
<th>Division and Administration</th>
<th>Scientific Staff</th>
<th>Technical and Admin. Staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory and Parameters</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Magnet</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>Magnet Power Supply and Cooling</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Survey</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>RF and Beam Observation</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Vacuum</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>Beam Transfer</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Equipment for Colliding Beam Experiments</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Electrical Engineering and Controls</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>General Engineering. Drawing Office</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Mechanical Workshop. Stores</td>
<td>-</td>
<td>30</td>
</tr>
</tbody>
</table>

Total: 57 163

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These figures do not include installation labour which will be three times as high as for the CPS (see section 3.3c).

From the experience in the PS Division we expect that towards the end of the construction period some of the staff of the magnet group will be switched to work on equipment for colliding beam experiments and strengthen that group considerably.

The way in which this staff will build up over the years is shown in the table below:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Staff in ISR Division by the end of each year</td>
<td>65</td>
<td>100</td>
<td>140</td>
<td>180</td>
<td>210</td>
<td>220</td>
</tr>
</tbody>
</table>

3. Budget

The budget figures given below do not take into account any future increases caused by rising prices, general salary increases, inflation, etc. They are based on cost levels ruling in April 1964.

Wherever possible the estimates for the machine parts have been made by comparison with similar parts of the CPS taking into account a 25% general rise of prices since 1957/58.

The estimates for the buildings, made by the SB Division, are based on layout drawings, or for some minor items where these drawings do not exist, on overall $m^2$ or $m^3$ prices.

3.1. Staff expenses

The total average staff expenses per man year at present range from 23,700 francs (in SB and Administration Division) to 45,000 francs (in the Theory Division). Whereas in divisions like MPS, NPA, TC the average figure is around 32,000 francs, in the Study Group on New Accelerators it is 38,000 francs.

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In the beginning of the project when the proportion of scientific to technical staff is unusually high, the average staff expenses will also be high, but they will diminish in the course of time as more technical staff is employed. We therefore estimate the average staff expenses in the ISR Division to be 38,000 francs in 1965 and to diminish gradually to 32,000 francs in 1970. With the staff build-up given above the total staff expenses during the years 1965-70 are then 27.8 Mfrs.

3.2. General expenses

Under this heading the CERN budget contains items that can neither be considered as capital nor as staff expenses. There is a variety of these items such as: Administrative Expenses, Consultants and Experts, Consumable Goods, Reproduction of Documents, etc.

Extrapolating the experience of the PS Division during the construction time we estimate the General Expenses per man year in the ISR Division to be 3700 francs or altogether 3.2 Mfrs.

However, this sum does not contain General Expenses paid by other divisions or behalf of the ISR Division, e.g. Electricity, Water, or Computing. We shall account for these expenses later on.

3.3. Capital expenses

We can list the following items:

a) Site and Buildings

1) Excavation of moraine and molasse and filling up later on for shielding purposes, Total ground moving 1,000,000 m³

Mfrs

2) 1600 m of tunnels and 1000 m of drains specifically for the ISR

3.5

3) 1600 m of road and a bridge passing to the middle of the ring

1.1

4) Surface flattening, surroundings, etc.

0.9

Total cost of preparatory work

17.8
5) **Ring tunnel**, 820 m long cross section 6 x 15 m. fully equipped with 5 cranes 5 tons each, air conditioning, hydraulic access doors 18.0

6) **One 70 m and one 50 m colliding beam hall**, 25 m wide, fully equipped with 50 ton cranes and hydraulic access doors 6.4

7) **2 Beam transfer tunnels** from the P0 to the ISR 700 m long 2.8

8) **8 Equipment rooms** for the airconditioning and a 70 m long tunnel with the geodetical calibration bench, airconditioned 0.6

**Total cost of ring tunnel complex**

9) **25 GeV experimental hall**, 50 x 200 m² equipped with 50 ton crane and hydraulic entrance door 12.3

10) **Central building** for control rooms, power and cooling hall with passerelle to the laboratory building.
    Total area 2400 m² 3.3

11) **Laboratory building** 4 floors and basement of 900 m² each 2.2

12) **Divisional Workshop** 1800 m² of hall equipped with 50 t crane 1.6

13) **11 auxiliary buildings** for power supplies and controls placed around the ring and near the beam transfer tunnels, about 2000 m² together 1.3

14) **Distribution of power, water, compressed air, telephone etc.** 0.7

**Total cost of these buildings and install.** 21.4

15) **Movable shielding blocks** to be used in the 25 GeV hall and in the colliding beam halls 5.0

**Total cost of Site and Buildings** 72.0
### h) Machine Parts

1. PS Ionizer, beam switch, and 2 injectors, including power supplies and controls 3.5
2. 100 quadrupole lenses for the beam transfer system, 60 cm steel length, 4 cm aperture
   - 42 Horizontal Bending Magnets, 2.5 m steel length, 3 x 15 cm² aperture
   - 16 Vertical Bending Magnets, 2.5 m steel length, 4 x 15 cm² aperture including
     - Model Work and Measuring Equipment 2.2
3. Special Magnets (matching lenses and pulsed magnets near the F3 and the ISR) 1.0
4. Supports for the beam transfer system 0.5
5. Power Supply and Cooling for the Beam Transfer System (2 MW) 2.0
6. Beam observation equipment for the beam transfer 0.2

**Total cost of Beam Transfer Equipment** 9.4

7. RF System: 19 power amplifiers and drivers 1.3
8. 19 Cavities 0.4
9. Power Supplies, controls, cables and low power system 0.8
10. Models 0.5
11. 100 pick up stations with electronic equipment, supports and bake out facilities 1.0
12. Electronics and cabling 0.8
13. Models for beam observation 0.2

**Total cost of RF system and Beam Observation** 5.0

14. Magnet yokes: 10,000 tons of steel 14.0
15. Block making, 390 blocks of 122 x 101 x 250 cm³ 13.5
16. Coils: 1070 single pancakes, total weight 1140 ton 20.8

---

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<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>17) Bus bars: Total weight 100 tons</td>
<td>3.0</td>
</tr>
<tr>
<td>18) Jacks, girders and other fixings. For 264 units</td>
<td>3.0</td>
</tr>
<tr>
<td>19) Pole face windings 780 sheets</td>
<td>3.7</td>
</tr>
<tr>
<td>20) Correcting Elements. 112 quadrupole lenses, 32 sextupole lenses, 32 vertical kickers, backfield windings on 128 units</td>
<td>4.5</td>
</tr>
<tr>
<td>21) Power Supplies including regulation and cables (2x7 MW and about 100 sets in the range 5-400 kW each)</td>
<td>8.0</td>
</tr>
<tr>
<td>22) Magnet Cooling System for about 18 MW total power</td>
<td>3.5</td>
</tr>
<tr>
<td>23) Models</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total cost of Magnet System (including Power Supply and Cooling)</strong></td>
<td><strong>75.0</strong></td>
</tr>
<tr>
<td>24) Vacuum chamber 5 x 16 cm$^2$ elliptical 2000 m total length, complete with bakeout system, bellows and flanges for ultra high vacuum</td>
<td>9.0</td>
</tr>
<tr>
<td>25) Special tanks and valves</td>
<td>4.0</td>
</tr>
<tr>
<td>26) 250 getter ion pumps 400 l/s with power supplies, and 10 getter ion pumps 1600 l/s, controls and bakeout units</td>
<td>5.5</td>
</tr>
<tr>
<td>27) 80 molecular pumping units 150 l/s with ultra high vac. valve and vacuum gauge</td>
<td>2.0</td>
</tr>
<tr>
<td>28) 20 cryopumps 5000 l/s with controls</td>
<td>0.6</td>
</tr>
<tr>
<td>29) 4 refrigerators 80$^0$K and 4 refrigerators 10$^0$K</td>
<td>1.2</td>
</tr>
<tr>
<td>30) 100 Bayard Alpert gauges and magnetron gauges</td>
<td>0.8</td>
</tr>
<tr>
<td>31) Vacuum chamber for beam transfer system. 4 cm Ø tube 700 m total length with bellows and flanges</td>
<td>0.2</td>
</tr>
<tr>
<td>32) 70 getter ion pumps 15 l/s and 10 roughing stations, including gauges and controls</td>
<td>0.5</td>
</tr>
<tr>
<td>33) Research and model work</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Total cost of Vacuum System</strong></td>
<td><strong>25.6</strong></td>
</tr>
<tr>
<td>34) Interaction region equipment, cost of replacing 8 pairs of magnet units by split focusing and bending units to allow momentum analysis</td>
<td>5.0</td>
</tr>
<tr>
<td>35) Other equipment for Nuclear Physics Experiments</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total cost of experimental facilities in interaction regions</strong></td>
<td><strong>10.0</strong></td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>125.0</strong></td>
</tr>
</tbody>
</table>
36) Control Cables and Ducts
37) Main Control Room Equipment
38) Auxiliary control equipment, Power Supplies, TV, etc.
39) Communications and Security

Total cost of General Machine Controls

40) General Power and Cooling Installation in the Ring Building and some smaller items

Total cost of Machine Parts

Total cost

4) Installation Labour

We estimate that 500 man years will be required for the installation of the machine. This labour will be hired temporarily at 12 francs per hour, i.e. a total cost of 125.0 Mfrs.

4) Laboratory equipment and tools

9.3 Mfrs was spent on this item during the construction of the CPS. The estimate for the ISR project is 15.0 Mfrs.

The total capital expense for the ISR Division, including its buildings, is 236 Mfrs.

And the total budget for the ISR Division, including its buildings, staff and divisional general expenses, is 267 Mfrs.

3.4. Services by other divisions of CERN

In addition to the expenses mentioned above, the ISR project will be charged for some work done or material delivered by other divisions of CERN. In some cases this refers to e.g. consumption of electricity, which is normally paid by the SB Division, in other cases it may be work of interest to the ISR project as well as to the existing CERN, when it is assumed that
the ISR project pays only part of the cost; finally there are cases of pure overhead costs (e.g. cost of the Finance Division) which have to be charged in a fair way. We have budgeted for the following items:

a) Commissioning of the new site

In order to make the new land in France suitable as a laboratory site the following work is foreseen: Extension of the network of roads, drains and service tunnels. Installation of the distribution system for power, water, telephone, compressed air, etc. Increase of the power house both for electrical power and heating, and construction of a new electrical substation on the site. Extension of the telephone exchange. Construction of a new water reservoir and a new waste water purification plant. To fence the site. To construct new canteens.

The cost of all this work is estimated at 28.6 Mfrs.

An analysis of the likely division of use of the new facilities and services leads us to charge 16.8 Mfrs to the ISR project.

b) Consumption of Electrical Power, Water, Heating, etc.

The consumption of these items will be metered separately and the ISR project will be charged accordingly by the SB Division, which normally pays for the whole of CERN.

In 1956 these expenses were for the whole of CERN 170,000 francs, in 1957 438,000 francs.

We estimate the total expenses for the ISR Division for 1965-1970 to be 1.5 Mfrs.

c) Design of ISR Buildings and construction supervision by the SB Division

We shall provide the expenses for 100 man years or 2.6 Mfrs.

d) Use of the computers in the DD Division

We provide a total amount of 1 Mfrs for this purpose.
e) Experiments to be carried out in other divisions

These can be e.g. experiments on the CPS or on the Storage Ring Model in the AR Division. We shall provide 0.5 Mfms.

f) General Overheads

We distinguish between two types of overheads - those which are proportional to the number of staff in the ISR Division and those proportional to the area of ISR buildings completed at any time.


For 1964 the first type of overhead was budgeted 8.545 Mfms in total and was related to a (non-service) staff of 1200. The second type was budgeted 10.465 Mfms in total and covered 82,000 m² of building area.

Adding about 10 % for offices for new service staff we arrive at the following overhead formula: Yearly overhead = frs. 8000. - per staff member in the ISR Division and ISR design and supervision staff in the SB Division + frs. 140. - per m² of finished buildings in the ISR project.

With these figures and the construction and staff build up programme the General Overheads for 1965-'70 amount to 22.6 Mfms.

The total expenses for the ISR project via other divisions is 45.0 Mfms, and the total cost of the whole project is 312 Mfms.

3.5. Yearly budgets and summary

The division of the total budget over the years of construction depends not only on the extent to which the programme is followed, but also on commercial terms obtained from the firms. The following distribution is based on a strict adherence to the construction programme and on a 30 % down payment on major machine parts and 10 % on building contracts.
### Table XIV.2. Yearly Budgets in Mfrs for the ISR Project

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Staff Expenses</td>
<td>2.0</td>
<td>2.7</td>
<td>4.2</td>
<td>5.4</td>
<td>6.5</td>
<td>7.0</td>
<td>27.8</td>
</tr>
<tr>
<td>General Expenses</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Preparatory Site and Bld Work</td>
<td>2.3</td>
<td>9.5</td>
<td>5.0</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>17.8</td>
</tr>
<tr>
<td>Ring Tunnel Complex</td>
<td>-</td>
<td>7.0</td>
<td>11.0</td>
<td>9.0</td>
<td>0.8</td>
<td>-</td>
<td>27.8</td>
</tr>
<tr>
<td>Labs, Hall and other Blds</td>
<td>-</td>
<td>10.0</td>
<td>6.5</td>
<td>3.5</td>
<td>1.0</td>
<td>0.4</td>
<td>21.4</td>
</tr>
<tr>
<td>Movable Shielding Blocks</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam Transfer Equipment</td>
<td>0.1</td>
<td>0.5</td>
<td>2.0</td>
<td>2.6</td>
<td>2.2</td>
<td>2.0</td>
<td>9.4</td>
</tr>
<tr>
<td>RF System and Beam Observation</td>
<td>0.1</td>
<td>0.5</td>
<td>1.4</td>
<td>0.8</td>
<td>1.5</td>
<td>0.7</td>
<td>5.0</td>
</tr>
<tr>
<td>Magnet System</td>
<td>0.2</td>
<td>1.3</td>
<td>19.0</td>
<td>20.0</td>
<td>22.0</td>
<td>12.5</td>
<td>75.0</td>
</tr>
<tr>
<td>Vacuum System</td>
<td>0.2</td>
<td>0.9</td>
<td>7.5</td>
<td>6.0</td>
<td>6.0</td>
<td>5.0</td>
<td>25.6</td>
</tr>
<tr>
<td>NP Experimental Equipment</td>
<td>-</td>
<td>0.2</td>
<td>0.4</td>
<td>2.4</td>
<td>2.0</td>
<td>5.0</td>
<td>10.0</td>
</tr>
<tr>
<td>General Machine Controls</td>
<td>-</td>
<td>0.2</td>
<td>0.4</td>
<td>1.4</td>
<td>2.5</td>
<td>3.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Other Items</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Installation Labour</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>5.0</td>
<td>6.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Laboratory Equipment and Tools</td>
<td>0.3</td>
<td>1.1</td>
<td>2.0</td>
<td>4.5</td>
<td>3.5</td>
<td>3.6</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>Total Expenses ISR Div. and its Buildings</strong></td>
<td><strong>5.5</strong></td>
<td><strong>34.2</strong></td>
<td><strong>59.8</strong></td>
<td><strong>58.7</strong></td>
<td><strong>57.2</strong></td>
<td><strong>51.6</strong></td>
<td><strong>267.0</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expenses via Other Divisions</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning of New Site</td>
<td>5.2</td>
<td>5.2</td>
<td>5.7</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>16.8</td>
</tr>
<tr>
<td>Consumption of Power, Heating etc</td>
<td>-</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Building Design Studies and Supervision by SB</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
<td>0.2</td>
<td>0.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Use of Computers in DD</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Experiments in Other Divisions</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>General Overheads</td>
<td>0.6</td>
<td>1.3</td>
<td>2.5</td>
<td>4.6</td>
<td>6.3</td>
<td>7.3</td>
<td>22.6</td>
</tr>
<tr>
<td><strong>Total Expenses via Other Div.</strong></td>
<td><strong>6.4</strong></td>
<td><strong>7.8</strong></td>
<td><strong>9.4</strong></td>
<td><strong>6.2</strong></td>
<td><strong>7.1</strong></td>
<td><strong>8.1</strong></td>
<td><strong>45.0</strong></td>
</tr>
</tbody>
</table>

| **Total Expenses**                      | **11.9** | **42.0** | **69.2** | **64.9** | **64.3** | **59.7** | **312.0** |

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3.6. The scope of the budget

The budget shown is limited to the design and construction of the ISR and its buildings, including the first experimental equipment to demonstrate the proper working of the colliding beam device.

One 25 GeV experimental hall, one 50 m colliding beam hall and one 70 m colliding beam hall are included in the budget, but neither the beam transport systems with power supplies and cooling nor detectors to be used in the 25 GeV hall. When the storage rings become operational both the NP and DD Divisions may be increased, but this is not considered part of the ISR project as such and therefore not budgeted for. These increases must rather be considered as part of the running and exploitation cost, which we estimate to be about 75 Mfrs/year during the first few years after the construction. This estimate is only based on experience on earlier accelerators where it has turned out that the exploitation cost in the early years of operation does not differ much from the yearly construction cost in the most expensive year. How the expenses will go after several years of operation depends entirely on the scientific interest and economic situation at that moment. A slow but gradual increase over several years can be expected.

Finally we want to issue a word of caution. The present estimate is based largely on past experience in the CPS construction. It is, however, known that CERN has often obtained very low prices for machine parts because industry found it worthwhile to get its name attached to this international enterprise. Recent discussions with firms indicate that their spirit is still the same, but it is clear that this is no guarantee for the situation by the time contracts are placed.

Since this budget does not contain any cover for contingencies or unforeseen expenditure the Council may prefer to add a certain amount for this purpose.
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APPENDIX A

1. The Conclusions of the European Committee on Future Accelerators

In the following are presented the full conclusions arrived at by the Amaldi Working Party and endorsed by the European Committee on Future Accelerators:

"I. In the region of highest energies the programme of accelerator construction ("the summit programme") should include both

(a) the construction of a pair of storage rings for operation in association with the existing CERN-PS;

(b) the construction of a new proton accelerator of a very high energy.

"Both these projects should have high priority. Provided authorisation could be obtained by the end of 1964 the storage rings could be completed by 1970 and would make possible at a comparatively early date a programme of highly significant physics in an energy region not accessible by any other means in the foreseeable future. Owing however to the reasons set out below the storage rings while representing a very important part of the programme could never in themselves form an acceptable alternative to a high energy proton synchrotron.

"II. The energy of the proton accelerator should be about 300 GeV provided that the necessary authorisation for its construction can be obtained by the end of 1965 so that the machine could be completed between 1973 and 1975. Its design should provide for injection at a comparatively high energy (6 - 10 GeV) from an intermediate high repetition rate proton synchrotron ("booster") in order greatly to increase the proton current. In comparison with a 150 GeV machine which was also considered it would be a better and more versatile machine and have a longer potential life while for the first ten years after the commencement of construction
the annual budgets of the two machines would be almost the same. The Working Party considered that these advantages outweighed the disadvantage that the time when useful physics could commence would be delayed (by at most 2 years assuming the same date of starting construction). The choice of energy should be reconsidered, however, if for any reason the likely delay in starting physics should turn out to be substantially longer.

"III. The above programme should be supplemented by suitable national or regional accelerator projects in the Member States (the "base of pyramid programme"). This is essential to ensure a balanced programme of research in high energy physics, to make it possible for the University and national laboratories in the Member States to carry out research with the facilities provided by the "summit programme", to continue with or initiate researches in their own laboratories, and to provide an adequate supply of trained physicists and engineers for the many other scientific activities in the Member States.

"IV. In order to provide for a minimum balanced programme of research in high energy physics in addition to the summit programme at least one of each of the following types of machine should be built as national or regional projects.

(a) Low energy (500 - 750 MeV) high current proton accelerator to provide beams of \( \pi \) mesons ("pion factory").

(b) High current machine of energy about 10 GeV to provide intense beams of \( K \) mesons, antiprotons and neutrinos ("kaon factory").

(c) High energy electron accelerator of energy \( \leq 10 \text{ GeV} \).

"Beyond the minimum programme individual countries or regional groups of countries may wish to build other machines, to meet their own special research requirements, for training purposes and to ensure continued effective participation of universities and national institutions in this field.

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"A number of such machines have been proposed by Member States for one or more of the above reasons. The scope and importance of some of these projects may be strongly influenced by the decisions on the summit programme.

"V. Careful attention should be given to the automatic analysis and computing facilities needed to enable proper exploitation of the physics potentialities of the above "summit" and "base of pyramid" programmes. It seems likely that about ten computers of a capacity equal to the largest at present available on the market would be needed, three of which would be located in the central accelerator laboratory.

"VI. The sharing of a few modern accelerators between many universities and national institutes requires that very good communications and transport facilities be made readily available. The provision of adequate housing for visitors must be treated as a normal laboratory service. At the same time the universities should make possible frequent visits of their research staff to other laboratories by appropriate arrangement of their duties.

"VII. The "summit programme" for the large international accelerators is estimated to require an annual outlay of about 450 M. Sw. francs by 1977 while the entire programme is tentatively estimated to involve a gradually increasing annual outlay rising to about 1600 M. Sw. francs by 1977. This represents about 0.07 per cent of the estimated gross national product of all the CERN Member States.

"VIII. It is estimated that by 1977 about 2500 physicists of Ph.D. standing and above, together with 1500 professional engineers, would be involved in the entire programme. It is very difficult to obtain reliable forecasts of professional manpower but from those available it appears that it should be possible to obtain the required numbers of physicists and engineers needed for the programme without undue difficulty and without diverting a disproportionate number of available technical and scientific personnel into this field."
For further information on the basis for these conclusions one may refer to the "Report of the Working Party on the European High Energy Accelerator Programme", CERN Paper FA/WP/23/Rev. 3.

2. Names of people who have attended meetings of the European Committee on Future Accelerators.

- J. Geheniau, Belgium
- J.K. Bøggild, Denmark
- C. Möller
- B. Peters
- A. Berthelot, France
- A. Blanc-Lapierre
- B.P. Gregory
- A. Lagarrigue
- L. Leprince-Ringuet
- F. Perrin
- J. Teillac
- H. Ehrenberg, Federal Republic of Germany
- W. Gentner
- W. Jentschke
- W. Paul
- Ch. Schmelzer
- H. Schopper
- M. Teucher
- Th. Kanellopoulos, Greece
- E. Amaldi (Chairman), Italy
- G. Bernardini
- M. Cini
- M. Conversi
- I.F. Quercia
- G. Salvini
- P.C. Gugelot, Netherlands
- A.H. Wapstra
- S.A. Wouthuysen
- B. Trumpy, Norway
- A. Duran, Spain
- G. Ekspong, Sweden
- G.W. Funke
- G. Källén
J.P. Blaser  Switzerland
P. Scherrer  
J.B. Adams  United Kingdom
C.G. Butler  
J.M. Cassels  
J.C. Gunn  
A.W. Merrison  
T.G. Pickavance  
C.F. Powell  
A. Salam  
D.H. Wilkinson  

E.H.S. Burhop (Secretary)  CERN
G. Cocconi  
S.Aff Dakin  
G. von Dardel  
P. Germain  
H.G. Hereward  
K.G.N. Hine  
K. Johnsen  
L. Kowarski  
P. Lapostolle  
P.C.P. Mollet  
Ch. Peyrou  
P. Preiswerk  
G. Puppi  
C.A. Ramm  
E. Regenstreif  
A. Schoch  
L. Van Hove  
V.F. Weisskopf  
C.J. Zilverschoon  

The following attended one meeting of the Committee:

A.A. Kolomenskij  U.S.S.R.
B. Yablokov  
W.K.H. Panofsky  U.S.A.
N.F. Ramsey  
K.R. Symon  
L. Simons  Finland.

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<table>
<thead>
<tr>
<th>Member</th>
<th>Substitute</th>
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<tbody>
<tr>
<td>Italy</td>
<td>E. Amaldi (Chairman)</td>
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<td>United Kingdom</td>
<td>J.M. Cassels</td>
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<tr>
<td>Scandinavia</td>
<td>G. Ekspong</td>
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<tr>
<td>France</td>
<td>B.P. Gregory</td>
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<tr>
<td>Federal Republic of Germany</td>
<td>W. Paul</td>
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<td>Belgium and Netherlands</td>
<td>S.A. Wouthuysen</td>
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<td>CERN</td>
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<td>J. Geheniau</td>
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The work of the Committee was greatly assisted through technical advice given by the following who attended one or more meetings of the Working Party:

APPENDIX B

The following is a list in alphabetic order of the people who have made contributions to the Design Study of the ISR. The list also shows the main field in which the Study Group members have worked.

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Field</th>
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<tbody>
<tr>
<td>B. Bianchi</td>
<td>(SB Div. CERN): Building Design</td>
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<tr>
<td>E.H.S. Burhop</td>
<td>(Univ. College London): Experimental Programme</td>
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<tr>
<td>R. Calder</td>
<td>(AR Div. CERN): Vacuum</td>
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<tr>
<td>Miss T. Capone</td>
<td>(AR Div. CERN): Shielding</td>
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<tr>
<td>E. Fischer</td>
<td>(AR Div. CERN): Vacuum. SR Model</td>
<td></td>
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<tr>
<td>J. Gervaise</td>
<td>(AR Div. CERN): Survey</td>
<td></td>
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<tr>
<td>B. Godenzi</td>
<td>(ENG Div. CERN): Power Supply</td>
<td></td>
</tr>
<tr>
<td>F. Harris</td>
<td>(AR Div. CERN): Beam Transfer</td>
<td></td>
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<tr>
<td>K. Henrichsen</td>
<td>(AR Div. CERN): Magnet</td>
<td></td>
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<tr>
<td>H.G. Hereward</td>
<td>(MPS/AR Div. CERN): Theory</td>
<td></td>
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<tr>
<td>E. Hugi</td>
<td>(ENG Div. CERN): Cooling</td>
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<tr>
<td>K. Johnsen</td>
<td>(AR Div. CERN): Head of the Design Study Group</td>
<td></td>
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<tr>
<td>E. Jones</td>
<td>(AR Div. CERN): SR Model</td>
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<tr>
<td>L.W. Jones</td>
<td>(CERN/MURA): Experimental Programme</td>
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<tr>
<td>M.J. de Jonge</td>
<td>(AR Div. CERN): Radio Frequency</td>
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<tr>
<td>E. Keil</td>
<td>(AR Div. CERN): Theory</td>
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<tr>
<td>P.T. Kirstein</td>
<td>(AR Div. CERN): SR Model</td>
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<tr>
<td>H. Kozioł</td>
<td>(AR-Div. CERN): SR Model</td>
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<tr>
<td>J. Lozano Campoy</td>
<td>(AR Div. CERN): Vacuum</td>
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<tr>
<td>Ch. Mallet</td>
<td>(SB Div. CERN): Building Design</td>
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R. Mosig  (ENG Div. CERN):  Power Supply
A. Nakach  (Saclay):  Theory
G.K. O'Neill  (Princeton University):  Experimental Programme
M.J. Pentz  (AR Div. CERN):  SR Model
R. Perin  (AR Div. CERN):  Magnet
G. Pluym  (AR Div. CERN):  Magnet
B. de Raad  (AR Div. CERN):  Parameters, Experimental Programme
L. Resegotti  (AR Div. CERN):  Orbit Parameters, Magnet
W. Schnell  (AR Div. CERN):  Radio Frequency, Beam Observation
A. Schoch  (AR Div. CERN):  Theory, Experimental Programme
K.R. Symon  (CERN/MURA):  Theory

The Study Group has further had considerable help both from inside and outside CERN on a more part time basis.
Fig. III.2 - Configuration for studying very small angle elastic scattering with colliding beams
**Fig. III-4.** Quadrupole with open motion plane.
Fig. III 5 - Configuration of axial magnet and spark chambers for large angle elastic scattering with colliding beams
Fig. III 6.

No. of \( \pi \)-mesons of one sign per Gev/c per colliding beam interaction per radian emitted at angle \( \theta \) to incident proton direction

Secondary Momentum (Gev/c)
Fig. III 9.
Fig. III 10 - Configuration for colliding beam neutrino experiment
Fig. III.11a. Longitudinal field produced by two coaxial solenoids such that resultant field cancels in the interaction region A and adds in the space between coils B and C.

Fig. III.11b. Longitudinal field produced by two coils of semi-circular section producing equal and opposite longitudinal fields in the two halves but with fields cancelling at the intersecting region A. (due to G.K. O'Neill)
Fig. III.11a. Configuration proposed by L. J. Jones to produce an isolated field near interaction region for studying products of peripheral interactions.