CERN 70-6
300 GeV Accelerator
Laboratory Department
26 February 1970

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

DESIGN STUDIES FOR A LARGE PROTON SYNCHROTRON
AND ITS LABORATORY

J.B. Adams and E.J.N. Wilson

G E N E V A
1970

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1. Introduction

During the second part of 1969, a study was made of some basic designs for a large proton synchrotron for the proposed new CERN Laboratory. The first design study for such a machine was made during 1963 under the direction of Prof. K. Johnsen and was published in a design report issued in 1964 (CERN/563, Vol. I and II, November 1964). The main requirements for that study were that the maximum energy of the machine should be 300 GeV and the circulating beam intensity should be as high as possible, aiming at 10^{13} protons per second. The design put forward proposed a combined-function lattice (bending and focusing of the accelerating protons in the same magnet unit) using a C type magnet design, previously adopted for the existing CERN and Brookhaven 30 GeV machines, giving about 1.2 T maximum magnetic field at the equilibrium orbit. Subsequently, in 1968, an American Group under Prof. R.R. Wilson, issued a design report* on a 200-400 GeV machine which was adopted as the basis of the accelerator for the new American laboratory at N.A.L., Batavia, near Chicago. This design proposed a separated-function lattice (bending and focusing of the accelerating protons in different magnet units) using an H type magnet design capable of reaching over 1.8 T on the equilibrium orbit in the bending magnets. The N.A.L. design introduced the idea of an extendible energy machine previously put forward by a group at L.R.L., Berkeley, California (Nucl. Inst. and Methods, 54 (1967) 223-228). It was proposed to begin research operation at the 200 GeV energy level and subsequently to increase the energy to 400 GeV or more by the addition of extra magnet power supplies and radio-frequency accelerating units. Comparisons between the CERN and N.A.L. designs were widely discussed in Europe during 1968 and early 1969 and also the prospect of employing new accelerator technologies such as super-conducting magnets, electron ring accelerators

*National Accelerator Laboratory, Design Report, July 1968.

(also known as Collective Ion Accelerators or Smokatrons) and cybernetic control systems. A commentary on these ideas and developments since 1963 was written in mid-1969 (CERN/869, June 1969) in which it was noted that the cost of a machine following the 1964 CERN design was very similar to that of a machine following the 1968 N.A.L. design and that the new technologies, particularly the use of super-conducting magnets or electron ring accelerators were hardly feasible at that time for very large accelerator projects although in the future they might well become practical and economic possibilities.

Several questions were raised by the June 1969 commentary which required further study; for example, a more precise cost comparison was needed, based on identical performance specifications, between the type of machine proposed by CERN in 1964 and that proposed by N.A.L. in 1968, and the concept of an extendible energy machine needed further exploration. There was also the question of new technologies which, although perhaps impractical for the time being for a very large accelerator, might become available during its construction or later on during its development. These and other questions have been the subject of the work now described which was undertaken by the "300 GeV Machine Committee" composed of representatives of the main national accelerator laboratories of Europe and staff of CERN, Meyrin.

Before describing the work in detail it is relevant to look back at the development of the existing large accelerator laboratories and their machines in the expectation that whatever is important in designing a new machine and a new laboratory should already be foreshadowed by the experience in similar institutions. There are three such laboratories with proton synchrotrons above 25 GeV energy, namely, CERN, Meyrin; B.N.L., Brookhaven and the Institute for High-Energy Physics at Serpukhov. The latter is only just coming into full operation and between the other two laboratories there is a common experience. Since the authors are most familiar with CERN, Meyrin, the experience of that laboratory is used for example and analysis.

2. The Experience of CERN, Meyrin

a) Investment analysis

A way of getting a general appreciation of an institution is to see how its investments have been made over the years of its existence. Figure I shows the annual expenditure of CERN, Meyrin since its beginning in 1953, broken down into three main categories; expenditure on Services (administration, site services, etc.), on Research and Operations and on Buildings and Equipment for the laboratory and the accelerators. There was a peak of expenditure during the initial construction of the laboratory and its 28 GeV proton synchrotron which levelled off towards the end of this construction period in 1960. This was followed by a steady increase in annual budgets during the subsequent period of research use of the facilities. Between 1965 and 1970 a second large construction programme of Intersecting Storage Rings and major improvements to the proton synchrotron caused a second peak in annual expenditure. Figure II shows the cumulative expenditure at CERN, Meyrin during the same period broken down into the same three categories. From this it can be seen that up to 1960, 79% of the money expended went into providing capital equipment including buildings of which the proton synchrotron was the largest single component costing about 120 MSF. By 1965 capital expenditure on buildings and equipment accounted for 60% of the total cumulative expenditure and even by 1970, after more than 15 years of existence, nearly 60% of all the money invested in CERN had been spent on providing capital equipment including buildings.

There are three points to be noted from this expenditure analysis which affect the planning of a new laboratory and a new large accelerator. The first is that capital expenditure after a few years, certainly after the initial construction period, accounts for well over half the money invested in the laboratory; the second is that after, say, 10 years of operation of the laboratory the initial capital cost of the machine accounts for only a small fraction of the total capital invested in the

laboratory (about 10% in the case of CERN, Meyrin by 1970), and the third is that the initial investment for the construction of the original accelerator is followed by others as major improvements and additions are made to the initial capital installations. The relevance of these points to a new laboratory are the following. Economies in the cost of the original machine, however desirable and necessary in order to limit the initial capital investments, become negligible in relation to the capital invested in the laboratory once it gets underway as a research institution and therefore should not be allowed to limit unduly the performance of the machine on which the entire laboratory depends during its whole working life. Secondly, since the capital investment in such a laboratory after several years of operation is so large a fraction of the total investment every precaution should be taken to ensure that improvements and additions to the experimental facilities, including the accelerator, can be carried out on the same site or adjacent to it in order to make the most economic use of the capital infrastructure that has been built up over the years. It is very expensive to have to create a second laboratory remote from the first in order to extend the experimental facilities. Although this seems unavoidable in the case of the proposed new CERN laboratory because of the very large size of its accelerator any new laboratory site should be large enough to accommodate all foreseen additions and extensions to the initial set of facilities for at least 20 years ahead. Thirdly, considering the cost of the proposed new machine, it can be predicted with reasonable confidence that whatever additions are made to the machine and the laboratory in the future will have to be contained within an expenditure profile which increases slowly and smoothly with time and avoids the high peaks in annual expenditures experienced at CERN, Meyrin. A likely expenditure profile might be a slow annual increase rising from the 260 MSF level at the end of the initial construction period (see the dotted line of Figure I labelled CERN II) towards about 400 MSF p.a. many years later. The effect of this on the forward planning of the proposed new laboratory is to extend the time scales for the future development of the initial facilities so that if the project is started in 1970 and the

initial facilities become fully operational around 1980 the forward planning would extend to the end of this century and the facilities created consequently be used by several generations of European research physicists. The only way substantial additional developments can be made in these circumstances is by deliberately reserving from the annual investments sufficient capital sums to afford them.*

b) Machine development

Although the investment pattern of an existing laboratory is useful to indicate a possible investment in any new laboratory, the particular way an existing machine has been developed is a more precise indicator of future trends. Developments of the CERN 28 GeV proton synchrotron and other similar machines are particularly relevant to any new machine because they show the kind of development consequent on the research use of the facilities and the way the research demands have been met. Generally speaking, the development of accelerating machines over the years since their introduction in the 1930's has followed three main lines. Firstly, there has always been a trend for new machines to have higher energies than their predecessors. Secondly, the circulating beam intensity of each machine has usually been steadily increased during its working life. Thirdly, the output beams from the machines have become more numerous and more sophisticated following the requirements of experiments for beams of higher purity with regard to their particle content and improved momentum resolution. These beam developments have been made possible in their turn by the steady improvements in the circulating beam intensity of the machines.

The trend towards higher energies, illustrated in Figure III over several decades, has mainly been accomplished by the successive invention of new types of machines rather than by the continuous development of one particular type of machine. The almost straight line curve of the

*This prediction may seem improbable in view of the rapid expansion in the annual budgets of CERN, Meyrin after 1961. However, it is estimated that about the same number of researchers will use the 300 GeV machine as at present use CERN, Meyrin and therefore, apart from the greater expense of the machine and certain large experimental equipment the capital infrastructure of CERN II will be similar to that of CERN, Meyrin. The equilibrium annual budgets of CERN II should therefore not be more than about 50% higher than those of CERN, Meyrin after the peak caused by the construction of the ISR and other improvements to the PS machine.

logarithm of energy against years shown in Figure III from 1930 to 1960 is actually the envelope of many curves representing the evolution of different types of machines, each of which reached a maximum exploitable energy set by practical design limitations or by economic considerations. Thus the original Cockcroft-Walton machines gave way to cyclotrons which subsequently were replaced by synchro-cyclotrons and later by synchrotrons, firstly the constant-gradient type of which the Cosmotron and Bevatron are examples, and secondly the alternating-gradient type of which the CERN, Brookhaven and Serpukhov machines are the largest examples. After 1960 the curve of the alternating-gradient synchrotrons is clearly showing the effect of limitations similar to those which have affected all previous machine types with the new Serpukhov machine, the future N.A.L. machine and the proposed CERN machine continuing an upward energy trend but at a lower energy increase with time which appears to be levelling off at about 1000 GeV energy. The straight line curve of log energy with time is continued after 1960 by the intersecting storage rings (I.S.R.) which give centre-of-mass reaction energies equivalent to machines of very high primary particle energies and at the moment, in the absence of new ideas for cheaper machines permitting much higher primary energies, intersecting storage rings seem the only practical and economic way of continuing the original slope of the energy versus time curve. However, storage rings are not themselves accelerators but must be fed by accelerators. Thus the CERN I.S.R. is fed by the existing CERN 28 GeV proton synchrotron and any higher energy storage rings depend on new accelerators such as the Serpukhov and N.A.L. machines and the proposed new CERN machine. The relevance of this energy trend analysis to any new machine is twofold. Firstly, there is a possibility that storage rings may in time be an addition to the facilities originally constructed at a new laboratory and secondly, if the curves of Figure III are any guide, and the use of them at the present time is of course very speculative, the time when this might take place is probably around 1990-2000 which is not inconsistent with the result of the investment analysis for additions and improvements to the original facilities of a new laboratory. Whether or not storage

rings are added, or indeed whether the upward trend in energy with time continues in the future, depends on many factors such as the needs and relevance of high-energy physics research many years ahead and the financial support it enjoys at that time. There is no law of nature which says that the future must continue the past over decades in time and it certainly cannot be assumed in the planning.

A new trend which is illustrated in Figure III and which has been touched upon in the introduction to this report is the notion of extendible energy machines, that is to say machines whose maximum energy starts at a certain level and later on, by way of additional equipment investments, can be increased to a higher energy. The N.A.L. machine, for example, is planned to start at 200 GeV and later on can be developed to reach 400 GeV or more. This trend is consistent with the deduction from the investment analysis that the capital facilities of a laboratory, which account for well over half the total investment, should be used to the maximum or, in other words, the ability to increase the energy of an accelerator once built on a particular laboratory site can postpone the building of a new laboratory with a larger machine for many years, perhaps a decade, and hence economise in overall investment by the extended use of the existing capital infrastructure. It is also consistent with the common experience that the scientific infrastructure of a laboratory, that is to say, the "human" capital of research scientists, engineers and technicians carefully built up over many years which, together with the equipment capital, determines the real scientific value of a laboratory, takes time and money to establish and once established should be exploited as long as possible.

The trend towards increasing the circulating beam intensity of large accelerators is a fairly recent phenomenon. There was a time, not so long ago, when the late Prof. E.O. Lawrence illustrated his lectures with a slide showing a healthy upward trend in the peak energies of successive machines and a depressing downward trend in their mean intensities and he took a gloomy delight in extrapolating future machines up to cosmic ray energies and down to cosmic ray

intensities. This downward trend in intensity was reversed with the introduction of alternating-gradient proton synchrotrons which in the examples at CERN, Meyrin and Brookhaven have more than equalled the intensities of the previous large accelerators such as the Cosmotron and Bevatron and, when the present machine improvement programmes are completed, will exceed their intensities by about an order of magnitude. The way this has come about is relevant to any new machine and therefore merits a detailed examination.

Figure IV shows the increase in intensity of the CERN 28 GeV machine since its first operation. During the design stage of this machine it was considered sufficient to plan that its intensity would be about the same as that of its immediate predecessor, the Cosmotron, which at the time was running at about 10^9 protons/pulse. Due to the phase-lock idea used in the radio-frequency system for accelerating the protons, invented during the course of construction of the CERN machine and employed on that machine for the first time, there was almost no loss of protons from injection into the machine up to its full energy and, soon after first switching-on, the circulating beam intensity reached was about 10^{10} protons/pulse. Within the first year of operation the intensity was increased by another order of magnitude and over the subsequent ten years yet another order of magnitude increase in intensity was achieved so that at the present time the machine runs at over 10^{12} protons/pulse. When the present improvement programme is completed in 1972, with the addition of a booster synchrotron injector, the intensity should increase by yet another order of magnitude to 10^{13} protons/pulse.

One reason why such extraordinary improvements by several orders of magnitude could be made in the circulating beam intensity of the CERN machine, which are paralleled by similar intensity increases in its sister machine at Brookhaven, is that the size of the vacuum chamber was deliberately made more than sufficient to contain the calculated dimensions of the circulating beam of accelerating protons. Figure V shows for the

vertical direction the size of the vacuum chamber and the beam dimensions near the injection energy. The circulating beam dimensions in the vertical direction are due to the emittance of the beam injected into the synchrotron and the errors due to the inevitable inhomogeneities in the machine, particularly in its magnets. At start-up in 1960, the injected beam emittance gave a beam size of about 10 mm vertical half-height and the errors added a further 10 mm. Thus the beam occupied about 20 mm of the vertical half-aperture of the vacuum chamber leaving an unfilled space of about 10 mm between the beam and the vacuum chamber wall. This 'safety-factor' greatly facilitated the speed with which the machine could be brought into operation although nowadays it might be considered rather a luxury. During the first four years of the operation of the machine, during which the intensity was increased mainly by improvements to the Linac injector, the errors increased in the machine due to experimental apparatus being set up in its vicinity and to a gradual misalignment of the machine magnets in the course of running. However, these error increases could be tolerated without correction since only the 'safety-factor' was reduced. About 1964 further improvements in the injection intensity from the Linac increased the beam emittance to the point that corrections had to be applied to reduce the errors. By 1969-70 the errors had been reduced to about half those originally encountered when the machine was first put into operation thus allowing a beam emittance corresponding to over 10^{12} protons/pulse and the 'safety-factor' had virtually disappeared. Happily by this time the knowledge and skills derived from ten years operation of the machine made a 'safety-factor' no longer essential. For a new machine design this experience suggests that a 'safety-factor' could be dispensed with and that progressive reduction of the errors due to inhomogeneities by a sophisticated beam control system could be assumed with some confidence. A similar argument applies to the horizontal dimensions of the beam and vacuum chamber where synchrotron oscillation amplitudes must be taken into consideration in the beam dimensions in addition to misalignment errors and beam emittance, although in this dimension the demands of the ejection system may limit the reductions in aperture that can be made.

With regard to the development in the output beams of large proton synchrotrons the relevance to any new machine design is mainly in the continuous multiplication of beams of secondary particles that has taken place with the existing large machines and the implications of the ever increasing circulating beam intensities. During the design stage of the CERN 28 GeV machine a single experimental hall was foreseen using targets placed inside the machine which allowed several beam lines to be set up outside and inside the machine circumference. Figure VI shows this first hall (North-South Hall). A few years after the start-up of the machine, in 1963, a beam ejection system was developed which together with a new experimental hall (East Hall) allowed another extensive set of beam lines to be set up, some of them feeding a large hydrogen bubble chamber. Later on, in 1968, a neutrino beam line was developed from another ejection system and at present yet another, even larger, experimental hall is being constructed (West Hall) fed by another ejected beam from the CERN machine. Figure VI also shows the intersecting storage rings which are fed from the CERN 28 GeV machine and their associated experimental halls. It is clear that the development of output beams from the CERN machine together with their experimental areas and the intersecting storage rings represent a trend in machine development which must be taken into account in planning a new machine. To a large extent these developments have been dependent on the continuous improvements in the circulating beam intensity of the machine since more beams of greater quality require more circulating beam intensity. These developments have taken place in the ten years since the machine was first brought into operation and, although the time scales are likely to be longer, perhaps doubled, for any new and much larger machine for the reasons already given, the trend is likely to continue. With regard to the ever increasing intensity of the circulating beams in larger proton synchrotrons up to values of 10^{13} protons/pulse a new problem arises due to the high radiation levels produced in the machine itself which both damage the machine components and seriously add to the maintenance problems and hence can adversely affect the machine operating schedules. At these high intensity levels the tendency is to eject the circulating beam onto external targets remote from the machine where the radiation problems can better be dealt with rather than use internal targets which produce

damaging radiation inside the machine. If the beam losses are due to interactions of the circulating beam with internal targets or other localised equipment such as ejection septa intense radiation regions are produced in the machine and it should be remembered that considerably more irradiation is produced by a 300 GeV proton than a 30 GeV proton. Coupled with the high intensity of the circulating beam this implies that in practice only a few percent of the circulating beam can be allowed to interact with localised equipment in the machine and the ejection efficiency must be 95% or higher. Although considerable progress has been made in understanding and improving the efficiency of ejection systems in the last year the circulating beam intensity may well be restricted in a new machine by the ejection efficiencies which can be maintained during actual operating runs. Furthermore the resulting levels of radiation in the machine will, almost certainly, call for remote handling devices for machine maintenance which further complicate operation and add to operating costs. It should also be emphasised that, independent of the ejection efficiency, the problem of irradiation of external targets, where inevitably a much larger fraction of the beam interacts, is very severe and may also limit the maximum intensity which the machine is allowed to produce for some time.

From this experience with the CERN 28 GeV machine, which is closely paralleled by the Brookhaven 33 GeV machine and is already evolving with the Serpukhov 70 GeV machine, a pattern emerges which is likely to persist with new machines of ten times the energy. In summary this pattern is as follows;

- a) Economies in the initial machine cost required by a limited budget for the initial construction should not unduly restrict the performance and development of the machine in the future since these economies become a small fraction of the investment in the laboratory after a few years of operation.

- b) The planning should cover all foreseen additions and improvements to the experimental facilities of the laboratory, including the machine, to avoid having to move to a new site in order to extend the facilities and thus having to recreate the expensive capital infrastructure of the laboratory and its equally valuable scientific infrastructure.
- c) The forward planning for the next generation of accelerators should cover possible developments over a period of 20 years from the first operation of the machine.
- d) An extendible top energy for the machine by a stage by stage process over the years allows a longer use of the expensive capital infrastructure of the laboratory and its scientific infrastructure and should therefore be a positive design aim. If foreseeable new technologies could be incorporated with advantage at some stage of the development of the machine the planning should allow for it. Storage rings give considerable energy extension in the centre-of-mass system for a limited range of experimentation and unless new and much cheaper accelerators are developed in the future, perhaps, for example, the electron-ring accelerator, they offer the only way to the very high reaction energies.
- e) Beam intensity increases by orders of magnitude during the operation phase is part of the evolutionary pattern of recent large proton synchrotrons. Although this pattern may not be extended much further in new and larger machines due to radiation problems the way it has taken place should be exploited to reduce the vacuum chamber dimensions and hence the costs of new machines.
- f) The extensive output beam developments of existing proton synchrotrons indicate a pattern that is likely to be repeated with new and larger machines and must be allowed for in the forward planning and site layouts. Because of radiation problems in the machine ejected beams

of high efficiency with external targets remote from the machine are the likely trend. Site layouts should include the possibility of intersecting storage rings at some later date.

This pattern has been deduced by the methods of "exploratory forecasting*" from the experience with existing large installations. "Normative forecasting"* methods are restricted in this case to assessing the needs of European or other groups of research physicists in the future and the financial resources likely to be made available to satisfy them. Such forecasts have been made by CERN and N.A.L. and were not repeated in this study. Both forecasting methods are subject to considerable errors especially over time scales of several decades. Particularly, the course of physics research is not a smooth function which can be extrapolated with confidence into the future. For example, when CERN, Meyrin was planned bubble chambers had not been invented and computers were esoteric toys used by a few specialists. Even a cursory look at CERN, Meyrin today and the part now played by bubble chambers and computers in its research programmes should humble the most ardent forecaster. Yet some things were foreseen in the CERN, Meyrin planning, particularly for the machine development, which have enabled the CERN 28 GeV accelerator to be steadily and spectacularly improved over the years to the great benefit of the research programmes. If the unforeseen cannot, by definition, be foreseen at least trends deduced from relevant past experience should be taken into serious account in the planning. For the rest, a wise dictum for all planners is to keep open as many options as possible for future developments and never to close an option until the last possible moment when it is absolutely unavoidable. In this way maximum flexibility is maintained at all times in a laboratory and it is flexibility above all that enables the unforeseen development to be taken up quickly and exploited.

*for definitions see "Technological Forecasting in Perspective"
by Erich Jantsch, O.E.C.D. Publication, Paris, 1967.

3. General Requirements for the Proposed New CERN Laboratory

In the preceding section trends deduced from the experience of CERN, Meyrin was examined as a background to the planning of a new laboratory and the design of its machine. In this section other requirements are examined which also determine the form of the laboratory and the machine design.

a) Financial requirements

An obvious limitation on any machine design is the money available to build it which in turn depends on the money available to build the whole laboratory and the allocation within that total sum to the component parts of the laboratory. The first estimate for the proposed new CERN laboratory was carried out by the CERN Study Group in 1964. At the prices applicable in that year the cost breakdown put forward was as follows;

Table I (in millions of Swiss francs)

	<u>Totals</u>	<u>%</u>	<u>Machine</u>	<u>Laboratory</u>	<u>Research</u>
Equipment	801.5	52	646.5	60.0	95.0
Buildings	536.5	34	195.5	170.5	170.0
Services	127.0	6	-	127.0	-
Research Operations	91.0	8	-	-	91.0
Totals	1556.0	100	842.0	357.5	356.5
%	100		54	23	23

From Table I it can be seen that the machine itself accounted for just over half the cost of the laboratory the other half being equally divided between the cost of building and equipping the laboratory and preparing for the initial research programme. The capital invested in

the laboratory and the machine in equipment and buildings accounted for 86% of the total investment. In the case of CERN, Meyrin the corresponding figure for total capital investment during the initial construction phase from 1953 to 1960 was 79%. Subsequent to the CERN Study Group estimates, ECFA (the European Committee for Future Accelerators) in 1967 revised these figures and in the prices applicable in that year arrived at a very similar percentage breakdown as follows;

Table II (in millions of Swiss francs)

<u>Total</u>	<u>Machine</u>	<u>Laboratory</u>	<u>Research</u>
1776	931	431.5	413.5
100%	53%	24%	23%

Later on CERN put forward a reduced estimate for a laboratory with less facilities as follows; (1967 prices)

Table III (in millions of Swiss francs)

<u>Total</u>	<u>Machine</u>	<u>Laboratory</u>	<u>Research</u>
1335	870	270	195
100%	65%	20%	15%

It is clear from a comparison between Table II and III that the main reductions made were in the buildings and the equipment for the laboratory and in the preparations for research, whilst the principal tool of the laboratory and its raison d'être was only marginally affected. This proposal was finally brought up to date in 1969 at the prices applicable in that year as follows;

Table IV (in millions of Swiss francs)

<u>Total</u>	<u>Machine</u>	<u>Laboratory</u>	<u>Research</u>
1431	933	289	209
100%	65%	20%	15%

Thus the money initially available to construct the proposed new CERN laboratory is limited to a ceiling figure of 1431 MSF (1969 prices) and the breakdown given in Table IV indicates a possible allocation to the three components of the laboratory.

In the ECFA estimate of 1967 a detailed breakdown of the machine costs were given. Since the total estimated machine cost at that time was 931 MSF it is very similar to that of Table IV and therefore the ECFA breakdown can be used to indicate probable financial allocations to the component parts of a machine with reduced facilities at prices appropriate to 1969, as follows;

Table V (in millions of Swiss francs)

	<u>Amounts</u>	<u>%</u>
Main Ring	470	50
Injector + Booster	130	14
Installation and Miscellaneous	133	14
Design and Construction Group	200	22
Total Machine Cost	933	100

Thus half the cost of the machine goes into the capital investment items of the Main Ring which include the machine tunnels and their equipment, the magnet system, the accelerating system, vacuum system, etc. A more detailed breakdown of the Main Ring costs is given in the following table;

Table VI (in millions of Swiss francs)

	<u>Amount</u>	<u>% of Machine Cost</u>
Tunnel Complex	179	19
Magnet System	226	24 } 43
R.F. Accelerating System	40	4
Vacuum System	25	3
<hr/>		
Total Main Ring Cost	470	50
<hr/>		

from which it can be seen that over 86% of the expenditure on the Main Ring or 43% of the expenditure on the whole Machine is invested in the Machine tunnel complex and the Magnet system. Clearly then, the magnet system adopted for the machine together with the tunnel complex in which it is housed are by far the most costly items of the machine and the laboratory and if substantial economies are to be made it is these items which need the first examination. Conversely, it is precisely these two items which largely determine the performance of the machine and its flexibility for future development so that economies, if unwisely made, can severely limit the future of the machine and the whole laboratory.

b) Technical requirements

The original specification proposed by ECFA for the 300 GeV CERN machine, which formed the basis of the 1964 CERN Study Group Report, was based on the concept of a fixed-energy machine of 300 GeV giving the highest possible circulating beam intensity, aimed at 10^{13} protons/s. It is obvious that a machine of this kind can be run at lower energy and lower intensity but following the design practice of previous machines it would not be able to run economically at much higher energy and the intensity foreseen was considered an upper limit. This original specification was modified in the reduced laboratory estimate by accepting a lower energy than 300 GeV for the first stage of installation and a

lower circulating beam intensity with the idea that both energy and intensity should be restored to their original values at a later date if and when extra money became available. Thus the concept of a two-stage installation programme developed which was not so dissimilar to that adopted for the N.A.L. 200-400 GeV machine.

4. Some Design Considerations for the Proposed CERN 300 GeV Machine

Since the trends in machine and laboratory development based on experience at CERN, Meyrin and at Brookhaven, analysed in the second section of this report, and the general requirements for the new laboratory and its machine outlined in the third section all seem to point in the same direction towards a machine extendible by stages in energy and intensity with the maximum number of options for future development at each stage, the search for machine designs with these characteristics became the main subject of the present study. Since the Main Ring components account for 50% of the total cost and 70% of the capital investment of the Machine, they were singled out for particular study and of the Main Ring components it was the magnet system in its underground tunnel complex which received the most attention.

It has already been mentioned that the CERN design made in 1964 and the N.A.L. design of 1968 differed in respect of the magnet lattice structure. The CERN design used a combined-function lattice and the N.A.L. design a separated-function lattice. However, the cost of the two machines appeared to be almost the same as far as comparisons could be made, although for several reasons the N.A.L. magnet system was the cheaper. In order to determine whether the cost differences depended on the lattice structure two optimised machines were designed to the same specification, one with a combined-function lattice and the other with a separated-function lattice, and their Main Ring costs were compared. The specification adopted for comparison purposes for the two machine types was as follows;

Table VII

1. Output energy

- a) Economic operating energy, 300 GeV
- b) Energy at maximum magnetic field, 400 GeV

2. Injection energy

- a) Injection energy from Booster synchrotron, 8 GeV

3. Intensity

- a) Design target at 300 GeV, 10^{13} protons/s, cycle time 3.1 s, acceleration time 0.9 s
- b) Less than 10^{13} protons/s at 400 GeV by lengthening the cycle time using the same rate of acceleration as 3 a)

4. Beam emittance

- a) At 8 GeV injection energy, $2\pi \cdot 10^{-6}$ rad.m. (vertical and horizontal)

5. Assumed errors for closed-orbit calculation

- a) Horizontal alignment errors

Survey monuments, 0.2 mm r.m.s.

Magnet unit targets to survey monuments, 0.1 mm r.m.s.

Magnet unit centre line to targets, 0.1 mm r.m.s.

- b) Vertical alignment errors

Magnet unit to unit levelling error, 0.1 mm r.m.s.

Magnet unit centre line to target, 0.1 mm r.m.s.

- c) Bending field errors

$$\begin{aligned}(\Delta B/B)_{\text{rms}} &= 0.5 \cdot 10^{-3} \\ (\Delta L/L)_{\text{rms}} &= 0.5 \cdot 10^{-3}\end{aligned}$$

- d) Rotational errors about the circumferential axis (tilt)

$$\Delta\theta_{\text{rms}} = 0.2 \cdot 10^{-3} \text{ rad}$$

e) Remanent field errors at injection

$$\begin{aligned} (B_{\text{rem}})_{\text{rms}} &= 0.25 \text{ G (vertical component)} \\ &= 0.1 \text{ G (horizontal component)} \end{aligned}$$

6. Field free straight sections

- a) Intermagnet unit gaps, 0.8 m
- b) Short straight sections, a total circumferential length of 612 m
- c) No medium or long straight sections.

Optimisation was carried out by designing and costing several machines and selecting the lowest cost machine of each type. For the separated-function (S.F.) designs an H type magnet was assumed with flat coils above and below the median plane giving a maximum magnetic field of 1.8 T. For the combined-function (C.F.) designs a C type magnet was assumed giving a maximum magnetic field of 1.1 T or 1.3 T depending on the profile parameter (the ratio of the magnetic field gradient to the equilibrium field) and two profile parameters were used in the optimising calculations. The magnetic field values given above were taken to give the same magnetic field errors across the aperture for each magnet type. The magnet unit lengths ranged between 7 and 8 m. Many other less important assumptions were made in the calculations and all were aimed at making the comparison practical and as fair as possible. The principal parameters for the resulting two cost-optimised machines were as follows;

Table VIII

	<u>Combined-function</u>	<u>Separated-function</u>
Mean radius (m)	1209	1037
No. of periods (N)	108	108
No. of bending magnets per period	8	6
No. of short straight sections	216	216
Field at 400 GeV (T)	1.3	1.8
Field at 300 GeV (T)	0.975	1.35
Profile parameter (m^{-1})	2.26	-
Half-aperture vertical (mm)		
F or B I magnets	22.85	26.16
D or B II magnets	29.70	31.05
Half-aperture horizontal (mm)		
F or B I magnets	51.43	50.63
D or B II magnets	38.74	34.38
Approximate stored energy		
at 300 GeV (MJ)	34.7	61.0
at 400 GeV (MJ)	61.7	108.4
Q (for min. stored energy)	24.25	23.75
μ /period (degrees)	81	79

All the machine designs were costed using unit price figures for components derived from recent experience with the CERN intersecting storage ring project and other machines and the costs were calculated using computer programmes developed by staff of the Karlsruhe laboratory, who also carried out the calculations. The two cost-optimised machines of each type whose main parameters are given in Table VIII above are compared in the table below for their Main Ring costs.

Table IX - Main Ring Costs at 300 GeV
(in millions of Swiss francs)

	<u>Combined-function</u>	<u>Separated-function</u>
Magnet costs	129.8	132.2
Magnet Power Supply costs	14.6	23.5
Magnet Cooling System cost	4.8	6.1
Fixed radius costs ⁽¹⁾	61.6	61.6
Radius dependent costs ⁽²⁾	82.6	70.0
Total cost	293.4	293.4

(1) Fixed radius costs include building costs for such items as tunnel entrances, entrance buildings and equipment rooms which are independent of the machine radius. Also included is that part of the R.F. system cost which is radius independent.

(2) Radius dependent costs include costs for such items as the machine tunnel, its air conditioning, electrical installations, drains and peripheral roads, the vacuum system and the remainder of the R.F. accelerating system.

Although the accuracy of the costing calculations cannot be much better than a few % it is clear from Table IX that the result of the comparison is that the type of machine lattice chosen does not affect the total cost of the machine if cost-optimised machines are designed to the same specification.

During these design and cost calculations it was observed that the radius-dependent costs, although about one quarter of the total cost of the Main Ring, do not increase very steeply with radius. Thus the Main Ring cost of the S.F. lattice machine given in Table IX whose radius is 1037 m is 293.4 MSF. Extending the same machine to a radius of 1280 m would only increase its Main Ring cost by 20 MSF. If this extra cost

is recovered by reducing the number of bending magnets in the machine, thus reducing its top energy, the decrease in machine energy to keep the costs the same at the larger radius is 46 GeV or a reduction from 300 GeV to 254 GeV. This observation was checked by calculating in detail a separated-function lattice machine of 1280 m radius and 250 GeV energy and comparing it with the S.F. lattice machine of Table IX. Its Main Ring cost came out to be almost the same as that of the original machine. Thus it appeared that if there was an advantage to be gained in designing machines with larger than optimal radii the energy penalty was not so very great. Such an advantage it was thought might come from the increased options offered by machines of this type for future development particularly towards higher energies. If it was possible, for example, to design an economic machine for 250 GeV initial energy with a certain total circumferential length of bending magnets leaving an equivalent space empty round the ring tunnel then at some later date a second set of bending magnets could be installed and the machine energy doubled to 500 GeV. This idea, which has become to be known as the Missing-Magnet design is an alternative way of designing an extendible energy machine to the N.A.L. proposal of installing all the magnets at the start but underpowering them initially and running the machine at half its maximum possible energy - an idea which has been called the Missing-Power design.

Various magnet lattice structures which allow the number of bending magnets to be increased after the initial installation were put forward in a paper by a group at L.R.L. in 1967 (Nuclear Inst. & Methods, 54 (1967) 223-228 by A.A. Garren, G.R. Lambertson, E.J. Lofgren and L. Smith). An S.F. lattice structure which allows a doubling of the initial energy is shown in Fig. VII. In this design only half the bending magnets are installed initially together with the focusing quadrupole magnets and the machine is aligned accordingly. Later on the other half of the bending magnets are installed and the machine realigned leaving the positions of the focusing magnets and the adjacent equipment in the short straight sections unchanged. The radial displacement (shown as x

in Fig. VII) on realignment is only a few centimetres and can easily be contained within the machine tunnel which would be about 4 m inside diameter. Of course, the focusing quadrupoles must be powerful enough to focus the beam at the higher energy without changing Q.

Several designs of missing-magnet machines have been made and costed but before describing them it is worthwhile to examine the options for future development opened up by this idea and to compare them with those of the missing-power machine design. Figure VIII shows these options. For the missing-magnet machine the initial energy at Stage I is E_1 and the machine is installed with half its bending magnets and half the magnet power supply. There are three options open for future development, all leading to about twice the original energy, i.e. $2E_1$. The obvious option is to install the other half of the bending magnets and the rest of the magnet power supply. A second option is to install the other half of the bending magnets but no more power supplies and to reduce the repetition rate of the machine to reach $2E_1$ with the original power supplies. A third option is to install superconducting magnets, if they are practical and available by that time, in the free spaces round the circumference, leaving the original bending magnets in place but disconnecting them, and reach an energy of $2E_1$ by running the superconducting magnets at twice the original magnetic field level, i.e. at about 4 T which is considered modest for pulsed superconducting magnets of the future. Later on still, at a third stage, the energy could possibly again be doubled to $4E_1$ by removing the original bending magnets and installing a second set of superconducting magnets. This would only be done, of course, if experience with the first set had proved completely successful. If this was not the case the original bending magnets could be repowered and the first option exercised to reach $2E_1$ safely. There is yet another way of reaching $4E_1$ by using the Stage I machine installation as an injector for a superconducting magnet machine built concentrically around the original machine in another tunnel but this is a more expensive option. At the different energy stages of the develop-

ment of the machine intersecting storage rings could be added and the equivalent primary beam energy is noted in the last line of Fig. VIII. Thus the missing-magnet machine offers several options for stage by stage development from its initial energy to four or more times that energy and allows the introduction of new technologies such as superconducting magnets at times when they are likely to be available for such large installations (for example in 10 years' time).

The missing-power machine also offers several options for future development. At Stage I, at an initial energy of E_1 , all the bending and focusing magnets are installed but only part of the power supplies. $2E_1$ can be reached at the second Stage either at reduced repetition rate or by installing the remainder of the power supplies. $4E_1$ can be reached by building a second machine concentrically round the first with superconducting magnets and using the original machine as an injector or, alternatively, by removing from the tunnel, or disconnecting, the original magnets and their associated equipment and replacing them by a superconducting magnet system. Again there are several options open for adding intersecting storage rings. In general the number of options open at each Stage is less with the missing-power machine than with the missing-magnet machine.

It is important to compare the cost of the three development Stages for the missing-magnet and missing-power machines. At Stage I the missing-magnet machine should be cheaper since only half the bending magnets are installed. At Stage II the costs are about the same for the two machines since both machines by then would have all their bending magnets installed and either the full magnet power supplies or part of these supplies depending on the repetition rate used. The cost of the superconducting magnet option at Stage II of the missing-magnet machine is impossible to estimate at present but it is assumed that it would not be taken up unless the costs were comparable with the other Stage II options. At Stage III the missing-magnet machine is cheaper either

because the new superconducting magnet machine costs are the same for each machine but the original missing-magnet machine used as an injector is cheaper or because converting the missing-magnet in its original tunnel with much of the capital equipment remaining is cheaper than building a new superconducting machine in the same tunnel. In general therefore it seems that developing a missing-magnet machine by stages to higher energies is cheaper than developing a missing-power machine.

Development costs for the machine alone, however, are not the only criteria for comparing the two types of extendible energy machines. There is the time taken and the disruption caused in operation in going from one Stage to another which affects the experimental programme by requiring machine shut-down periods while the modifications are being carried out.

To go from Stage I to Stage II of the missing-magnet machine it would be feasible during each of the normal maintenance shut-down periods to bring in a few of the new bending magnets and place them roughly in position without energising them. When they are all in place it would be possible to realign the whole machine during a longer shut-down period of a few months and connect up the magnets to the increased power supply. Thus the interruptions in the experimental programme would be minimal and not much greater than experienced with the normal shut-down periods of existing machines. The same system might be used for the superconducting magnets although the shut-down times for the step by step installation of the magnets would probably be longer.

To go from Stage I to Stage II of the missing-power machine does not involve any modifications to the magnet but only to external power supplies although it would be necessary to add extra R.F. accelerating cavities in the ring tunnel. Alternatively, even less modification is necessary if a longer cycle time and hence less mean intensity is acceptable at the higher energy level. In this case it could even be contemplated to switch

periodically from Stage I energy to Stage II energy with less intensity following the requirements of the experiments. Thus the down-time for modifications and additions should always be shorter for a missing-power machine than a missing-magnet machine although by careful use of the normal shut-down periods this difference could be minimised.

In comparing the missing-magnet and missing-power designs as extendible energy machines it seems that the missing-magnet design offers more options at each stage of development generally at a cheaper cost than the missing-power design but at some greater inconvenience to the research programmes because of longer shut-down times for the conversions. These advantages may not be overwhelming but they seem sufficiently attractive to warrant the inclusion of missing-magnet machine designs along with missing-power and fixed-energy machine designs in the range of choices for any new CERN machine.

5. Comparison of Alternative Machine Designs

Using the general specification of Table VII, designs for fixed energy, missing-power and missing-magnet machines were calculated and costed, the aim being to produce in a simple form a graph of cost versus energy which would clearly show the comparative costs of such machines and using that graph to consider the advantages and disadvantages of these three approaches to the design and development of large proton synchrotrons.

An S.F. fixed-energy machine similar to that of Table VIII when costed gave one point on the fixed-energy machine curve and another was derived from a recalculation of the design made by CERN in 1964. For the missing-magnet machine new designs were made with Stage I energies of 200 and 250 GeV and Stage II energies of 400 and 500 GeV respectively. These designs were costed and gave points on the curve for the missing-

magnet machines. The same designs at their Stage II installation phase (i.e. complete with all bending magnets and power supplies) were used as the basis of the missing-power machines to cover the 200-400 GeV and 250-500 GeV energy ranges, and costed to give a curve for the missing-power machines.

Both the missing-magnet and missing-power machines were designed to give less circulating beam mean intensity at their Stage II energy levels than at their Stage I energy levels. At Stage I levels the cycle time assumed was 3.1 s and the acceleration time 0.9 s whereas at Stage II levels the cycle time was lengthened to 4.7 s and the acceleration time extended to 1.8 s to keep the rate of acceleration the same at both Stages. Thus the same R.F. acceleration system would serve at both the Stage I and Stage II energy levels. The reason for this choice was partially to economise on power supply and R.F. acceleration system costs at Stage II but also it recognised that the increase in the secondary particle beam intensities due to an increase by a factor of two in the primary beam energy going from Stage I to Stage II more than compensated for the decrease in secondary beam intensities due to the decrease in mean intensity of the circulating beam of primary particles in the machines at Stage II. It is, of course, the flux of secondary particles from the targets rather than the mean circulating beam intensity which is of importance from the point of view of most of the research experiments.

The main parameters of one missing-magnet machine design (250-500 GeV) selected for costing are given in Table X below, and may be compared with the S.F. fixed-energy machine of Table VIII.

Table X

	<u>S.F. Missing-magnet machine*</u>	
	<u>Stage I</u>	<u>Stage II</u>
	(250 GeV)	(500 GeV)
Mean radius (m)	1280.3	1280.3
No. of periods (N)	102	102
No. of bending magnets per period	4	8
No. of short straight sections	204	204
Field at full energy (T)	1.8	1.8
Half-aperture (vertical) (mm)*		
B I	-	21.92
B II	27.83	27.83
B III	32.15	32.15
B IV	-	33.53
Half-aperture (horizontal) (mm)*		
B I	-	59.48
B II	63.51	63.51
B III	54.44	54.44
B IV	-	37.7
Approximate stored energy (MJ)	88.4	164.1
Q (for min. stored energy)	22.75	22.75
μ /period (degrees)	80.29	80.29

*The lattice periodicity used was Q_F ss BI BII BIII BIV Q_D ss BIV BIII BII BI where Q is a quadrupole, B a bending magnet and ss a short straight section.

The final graph of Main Ring costs versus energy for the three types of machines is reproduced in Figure IX where it can be seen that, within the approximations of costing, the missing-power machines at Stage I lie on a straight line passing through the origin with a slope of 1.4 MSF/GeV, the missing-magnet machines at Stage I lie on another straight line passing through the origin with a slope of 1.2 MSF/GeV and the fixed-energy machines

lie on yet another straight line passing through the origin with a slope of 0.9 MSF/GeV. All these machines are designed for the same beam intensity. It might be expected that at Stage II of the missing-power and missing-magnet machines the points on the graph should lie on a single straight line passing through the origin which is also the line of the fixed-energy machines. This would nearly be so if the mean circulating beam intensity of all three types of machines were the same at their highest energies but as already explained, the cycle times and acceleration rates at the top energies of the missing-power and missing-magnet machines were reduced, which largely accounts for the differences in the costs.

Using the curves of Fig. IX it is possible to compare the machines in a particularly simple way by assuming that a limited sum of money is available for their Main Ring costs - a situation which is very likely to be the case in practice - and for that sum of money to see what energy can be obtained with each machine type. Table XI below gives such a comparison assuming that 300 MSF is allocated for the Main Ring costs covered in the calculations.

Table XI - Equivalent Machines for 300 MSF Main Ring Costs

	<u>Stage I energy</u> <u>(GeV)</u>	<u>Stage II energy</u> <u>(GeV)</u>	<u>Extra cost for*</u> <u>Stage II (MSF)</u>
Fixed-energy machine	340	-	-
Missing-magnet machine	260	520	120
Missing-power machine	220	440	30

*At reduced beam intensity

Table XI brings out very clearly the cost penalties of the machine designs at the Stage I level. If the aim is to build the highest energy and highest intensity machine for the money available there is no question that a fixed-energy machine is the best solution and this is hardly a surprising result. If, however, some reduction of energy is acceptable at Stage I in order to be able to double the Stage I energy later on at

Stage II then the missing-power machine offers a fairly balanced solution. The Stage I energy is 120 GeV lower at Stage I than that of a fixed-energy machine of the same cost and it is possible at Stage II to reach 100 GeV higher energy at a reduced circulating beam intensity at the relatively small extra cost of 30 MSF or 10% of the original investment. In practice it may well be considered more advantageous to spend this extra 30 MSF at Stage I rather than later and so to construct a machine whose circulating beam intensity varies with energy from Stage I to Stage II energy levels. In the nomenclature of this report such a machine would be a "fixed-energy machine" specified in such a way that its energy and mean intensity were related by arbitrary invariants such as the R.F. acceleration system costs or the magnet power supply costs. Such a notion lay behind the machine specification given in Table VII.

If the energy penalty of the missing-power machine is considered too high at Stage I then the missing-magnet machine is a better solution since it starts at only 80 GeV lower energy than the fixed-energy machine at Stage I (i.e. 76% of the energy) and can reach 180 GeV more energy at Stage II for an extra investment of 120 MSF or 40% of the original investment. Also if superconducting magnets become practical and economic in the future there is a Stage III option open for the missing-magnet machine of very much higher energy, perhaps in the 1000 GeV range.

It must be stressed very firmly at this point that the cost calculations leading up to the figures of Table XI although based on the most reliable data available should not be regarded as having a high absolute accuracy. That can only be obtained by very detailed cost estimation of every component part of the Main Ring costs based on industrial prices appertaining at the time. However, it is considered that the relative accuracy of the cost calculations is quite sufficient for comparing different machine types which was the purpose of the study.

One important point which does not come out in the cost calculations presented above is the utilisation of the capital invested in the installations and the running costs of the machine at the different stages of development. Ideally an extendible energy machine should at each energy level use the minimum invested capital and be optimised for the minimum operating cost. This is an ideal difficult to realise in practice although a fixed-energy machine if correctly optimised and operated at its economic design energy should be close to the ideal. A way of expressing departures from the ideal is therefore to look at the capital invested in the machine components at each energy stage which is in excess of that strictly necessary for a fixed-energy machine of the same energy. In the case of the missing-magnet machine the excess capital investment is for the extra circumferential length of the tunnel required for the second half of the bending magnets to reach the Stage II energy and to a smaller extent in the extra aperture required in the bending magnets used for Stage I. From Fig. IX the excess capital for these components and other small component differences amounts to about 75 MSF more than the 215 MSF strictly necessary for a fixed-energy machine of 260 GeV, that is 35% more capital investment. In the case of the missing-power machine the excess capital investment is for the extra circumferential length of the ring tunnel and for half the bending magnets neither of which are strictly necessary for a fixed-energy machine of the Stage I energy. Again from Fig. IX, the excess capital investment is 130 MSF or 60% more than required for a fixed-energy machine of the same energy and is considerably greater in this case than for the missing-magnet machine. From the point of view of the operating costs of the machine the situation is the reverse. The missing-power machine, of course, is the cheapest to run since its magnet, being twice the circumferential length strictly required for the Stage I energy, operates at half the field of a fixed-energy machine and uses about one quarter of the power. The calculated magnet operating cost is 1.2 MSF/annum at Stage I energy (250 GeV). The missing-magnet machine on the other hand operates at the same magnetic field level at Stage I as at Stage II and can therefore be optimised at both levels but the running

cost is higher at Stage I than that of the missing-power machine. It amounts to 2.7 MSF/annum and is similar to that of a fixed-energy machine of 250 GeV energy. From these figures it can be seen that the missing-power machine is heavily overcapitalised at the Stage I level, far more so than the missing-magnet machine but the power costs for operating its magnet system, which to some extent compensate its overcapitalisation, are less than half the missing-magnet machine power costs. Some way of balancing overcapitalisation costs against less running cost is therefore needed to make a proper comparison between the three types of machines. A way of doing this is to use the discounted cash flow method of referring all costs to a single reference date at a certain fixed interest rate, as is carried out, for example, in industrial project calculations. Using this method, taking as the reference date the start-up date of the machine at Stage I energy and an interest rate of 8% per annum, the capital invested during construction is discounted forward at 8% per annum to the start-up date and the annual operating costs (and also later capital investments, for example, for the additions to reach Stage II) are discounted backwards at the same interest rate to the same reference date. The result of such a calculation is shown in Fig. X where the 250-500 GeV missing-power and missing-magnet machines previously studied whose capital investment costs can be obtained from Fig. IX are compared. Thus the capital investments for Stage I (250 GeV energy level) installation of the missing-magnet and missing-power machines which were 292 MSF and 345 MSF respectively, when discounted forward at 8% per annum to the start-up date of the machine become 352 and 415 MSF respectively, allowing for a practical expenditure profile during construction. After start-up, the cumulative annual operating costs reach an asymptotic level after about 20 years since costs in 20 years' time when discounted back to the start-up year have a very small value. The extra capital costs for Stage II are also shown, it being imagined that they are incurred five or ten years after the start-up date. Perhaps the most likely curve to follow in Fig. X is that corresponding to Stage II being completed 10 years after the machine has begun to operate at the Stage I energy. In this case the

economic comparison between the missing-magnet and missing-power machine is given by the following table,

Table XII

(MSF - discounted at 8% p.a. to the start-up date of Stage I)

	<u>Missing-magnet machine</u>	<u>Missing-power machine</u>
Stage I capital cost	352	415
Operation costs for 10 years	17	8
Total	369	423
Stage II capital cost	48	19
Total	417	442
Operating cost for 20 years	14	15
Total	431	457

from which it can be seen that the missing-magnet machine appears to be cheaper at all stages. As has already been pointed out, a fixed-energy machine would be cheaper still at the Stage I energy level and have operating costs similar to the missing-magnet machine but to double its energy 10 years after operation at the Stage I energy would require a capital investment much greater than those of either the missing-magnet or missing-power machines which would bring its final cost at Stage II well above that of the other machines. (This statement assumes that a Stage II modification of a fixed-energy machine would either involve stripping the tunnel of equipment and building in it a superconducting machine or building a superconducting or normal magnet machine in a separate tunnel around the original machine and using the latter as the injector.)

Thus the fixed-energy machine is only the cheapest solution in the short term assuming that it will never be increased in energy at any later date - an assumption which conflicts with the requirements developed in Section 2 above.

6. Other Design Considerations for Improved Flexibility

The previous two sections discussed and compared alternative designs for a large proton synchrotron mainly aimed at flexibility from the point of view of an extendible energy range by means of a stage by stage development programme for the accelerator. The present section discusses ways of achieving other flexibilities for future machine development in intensity and in output beams which are applicable to any of the three types of machines compared in the previous section.

a) Intensity flexibility

In Section 2 the experience of CERN, Meyrin with regard to the development of the intensity of the circulating beam of its 28 GeV accelerator was discussed. This experience, which is similar to that of Brookhaven and more recently Serpukhov, can be used to develop a stage by stage process of increasing the circulating beam intensity of a proton synchrotron and of cheapening its cost.

It can be assumed, with reasonable confidence, that the 'safety factor' built into the apertures of the previous machines will not be tolerated in any new and larger machines if only because the cost of such a 'safety factor' would be prohibitive for a machine ten times the size of the present machines. For the 28 GeV CERN machine the cost penalty of the aperture 'safety factor' was rather small and the flexibility it allowed at the start-up and in the first few years of operation of that machine more than justified the cost. It was an investment deliberately made for future flexibility which has paid off handsomely over the ten

years of operation of the machine and the Meyrin Laboratory. However, the CERN, Meyrin machine now operates essentially without this 'safety factor', as has been noted in Section 2, and a new and larger machine will be expected to start without one by using the previous experience. Nevertheless, it is essential to design into any new machine the ability to improve its intensity over the years and if this should not be done by deliberately introducing a 'safety factor' in the machine aperture other ways of achieving the same result must be examined.

The reason the aperture 'safety factor' has largely disappeared in the CERN 28 GeV machine is that ways have been found to control and reduce the fraction of the vacuum chamber aperture taken up by the beam due to errors in aligning the machine and differences between the units of its magnet. In particular, the methods of controlling and reducing the closed orbit of the machine at injection and during acceleration have improved greatly during the last ten years. Essentially these methods use devices placed at regular intervals round the circumference of the machine to measure the vertical and horizontal closed-orbit deviations from the ideal closed orbit of a perfect machine. If these devices, the beam pick-up electrodes, are spaced so that there are about four per betatron wavelength round the machine their outputs can be combined to yield an accurate record of the closed-orbit deviations throughout the acceleration cycle of the machine and computers can be used to give a continuous analysis of the closed-orbit deviations during operation. Either the computer output can be used as the basis of a manual adjustment of correcting magnet units spaced out round the machine circumference to reduce the closed-orbit deviations in successive steps or, more ambitiously, the computer output can be fed directly to the correcting magnet units and a continuous automatic computer-controlled reduction made in the closed-orbit deviations. The latter is an example of what has been called "cybernetic control" in accelerators, the first application of which was the phase-lock beam control system used in the CERN 28 GeV accelerator to control the radio-frequency acceleration system.

Two methods of cybernetic control of the closed orbit are currently being explored, the 'beam-bump' method and a least square fit procedure but it is not the purpose of this report to describe them in any detail. It is sufficient to point out that both methods, and indeed any cybernetic system of this type, relies for its success on the accuracy with which the beam pick-up electrodes can determine the local positions of the beam round the circumference of the machine and the accuracy with which the correcting units distributed round the machine can operate to alter the beam position. The computer itself and its programmes are usually by far the most accurate part of the whole system. A rough analogy of the situation might be that of a man of high intelligence but imperfect eyesight driving a car with loose steering along a rather narrow lane.

Assuming that during the course of the construction of a new large machine a cybernetic control system for closed-orbit correction is successfully developed and installed, which is a very reasonable assumption in view of progress in the last few years, the question arises how such a system can be employed to give stage by stage beam intensity increases after the first operation of the machine. One possible method which has been investigated during the course of this study is illustrated in Fig. XI. Based on the specification for the machine comparisons given in Table VII and the assumptions about the various magnet errors made in that specification, the space likely, with 98% probability, to be occupied by the beam due to these errors in a typical machine aperture, is 21.5 mm (half-aperture). In the calculations for the machines presented this half-aperture was added to the injected beam dimensions due to its emittance to give the vertical half-aperture of the vacuum chamber and no improvements due to closed-orbit corrections were assumed. The calculations assumed a beam emittance of $2\pi \cdot 10^{-6}$ rad.m. at injection. Thus the required vacuum chamber half height in this example would be 21.5 mm (errors) + 16.4 mm (emittance) = 37.9 mm. However, an emittance of $2\pi \cdot 10^{-6}$ rad.m. is thought to correspond to an accelerated beam intensity of about 3×10^{13} protons/pulse which is the intensity to be

reached by development work some time after the first operation of the machine. It can be argued that on first switching on the machine a much lower intensity would be sufficient since an energy step of a factor ten between the CERN 28 GeV machine and the new machine will take the experimenters several years to assimilate. Furthermore, the radiation problems at the highest intensities will also take time to resolve as will the development of high-efficiency ejection systems. If indeed a lower intensity would be sufficient for a few years the machine design could be based on a step by step intensity increase starting with a pencil beam of low emittance just sufficient to get the beam control system working. The second step would then be an intermediate intensity beam of, say, about 10^{12} protons/pulse ($\pi \cdot 10^{-6}$ rad.m. emittance) achieved by the early use of the beam control system and as that system was improved with experience and other problems such as radiation damage and maintenance were gradually resolved the full beam intensity could be reached in stages. Some allowance could also be made for even higher beam emittances and intensities in the more distant future by further improvements to the beam control system. By this means the vacuum chamber dimensions, instead of being determined by the addition of the beam dimensions at full intensity and the space allowed for the beam dimensions due to the initial errors, would be determined by the space allowance for the beam dimensions due to the initial errors plus only the dimensions of a pencil beam. Thus instead of a vacuum chamber vertical half-height of 37.9 mm only 25.5 mm would be required (21.5 mm (errors) + 4 mm (pencil beam)) and this would considerably reduce the dimensions and cost of the magnet system and reduce its stored energy which is a serious limitation with very large machines. A recalculation of the Main Ring costs of a S.F. Missing-Magnet machine for 250-500 GeV energy, whose principal parameters are listed in Table XIII below, with long straight sections as described in 6 b) below, but with a reduced magnet aperture gave a total cost figure similar to that of the machine described in Table X and the stored energy of its magnet system was reduced by about 60%. Figure XI illustrates this step by step method of increasing the

beam intensity and can be compared with Fig. V which showed the way in which the CERN 28 GeV machine intensity was increased over a ten year period. It can be seen that the experience of the present CERN machine has strongly influenced the approach to this problem.

b) Long straight sections

The machine designs and their costs so far discussed have ignored the long straight sections which are arranged at regular intervals round the circumference of the machine and required for the injection of the beam of protons into the machine, the ejection of protons from the machine, radio-frequency acceleration units and other devices. The insertion of these long straight sections is to some extent determined by the magnet lattice adopted for the machine and there are several requirements that they must satisfy. In the original 1964 CERN design, which used a combined-function lattice, it was proposed to use twelve Collins-type insertions. The N.A.L. design, which used a separated-function lattice, proposed six long straight sections each derived from replacing one half of the tenth cell of each superperiod (there are 6 superperiods in the complete machine) by a long field-free section matched into the normal magnet lattice at each end by special quadrupoles. Both these systems impose a superperiodicity on the machine by interrupting the normal focusing periodicity and both can make available sufficient space around the circumference of the machine for the equipment mentioned above. During the course of this study another type of insertion was proposed* which does not interrupt the normal focusing periodicity. Essentially the method consists in leaving out the bending magnets of a separated-function lattice over three magnet half periods leaving the normal focusing quadrupoles undisturbed, and repeating this insertion round the circumference to give six long straight sections. The form of this insertion is shown in Fig. XII together with typical beam ejection

*J. Parain - Advantage of S.F. Lattice for beam extraction in a proton synchrotron, Proc. VII Int. Acc. Conf., Yerevan (1969).

elements which would occupy the free spaces so created. The N.A.L. type insertion and this new type can be made interchangeable as regards the overall length and matching to the normal magnet lattice and hence a choice can be made between them later on. In Table XIII below parameters are listed for an S.F. missing-magnet machine which includes six long straight sections of the type shown in Fig. XII each giving a rather generous free space of 105.5 m. The apertures of this machine were determined in the way suggested in Section 6 a) above.

Table XIII - S.F. Missing Magnet Machine with Long Straight Sections

	<u>Stage I</u> <u>(250 GeV)</u>	<u>Stage II</u> <u>(500 GeV)</u>
Mean radius (m)	1456	1456
No. of periods (N)	114	114
No. of bending magnets per period	4	8
No. of short straight sections	228	228
No. of long straight sections	6	6
Free length in a long straight section (m)	105.5	105.5
Field at full energy (T)	1.8	1.8
Half-aperture (vertical) (mm)		
B I	-	17.66
B II	20.80	20.80
B III	24.23	24.23
B IV	-	27.84
Half-aperture (horizontal) (mm)		
B I	-	60.15
B II	51.66	51.66
B III	43.64	43.64
B IV	-	36.47
Approx. stored energy (MJ)	53.0	105.0
Q (for min. stored energy)	27.75	27.75
μ /period (degrees)	87.63	87.63

c) Output beams and site layout flexibility

No detailed designs have been made in this study of the output beams of the new CERN machine beyond those reported in the ECFA Utilization Study*. It is thought, however, that radiation damage and maintenance problems will require the use of high-efficiency ejection systems and targets external to the machine. Thus the layout of the machine on the laboratory site will involve one or more ejected beams coming from the long straight sections around the machine circumference which strike targets remote from the machine which in turn generate secondary particle beams fanning out from the targets at rather small angles. In the preliminary layouts, such as that shown in Fig. XIII, three main beam lines are foreseen whose ejection systems would occupy up to three of the six long straight sections provided round the machine circumference. Another long straight section would be occupied by the injection system from a booster synchrotron and yet another by the radio-frequency acceleration system whose total length can be accommodated in one long straight section. Thus one long straight section would remain which could be used for ejection into a storage ring system at some future date or for other purposes. Two of the output beams are arranged to be about 5 km long and the third about 2 km. It is envisaged to start operation with the shorter beam and progressively develop the others later. Space on the site has been foreseen for storage rings both inside and outside the machine circumference, the outer one of the highest energy lying under the main output beams of the machine which are at ground level. Figure XIII shows a site layout which would provide for all these features covering possible developments of a new laboratory over a period of about 20 years after the start-up of the machine.

*CERN/ECFA 67/16 Vols. I, II, III.

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7. Summary and Conclusions

In the study covered by this report an attempt has been made, using the experience of CERN, Meyrin and that of other similar laboratories, to establish guide lines for the proposed new CERN Laboratory and for its principal research tool, a large proton synchrotron. From these generalities some design requirements have been put forward for the accelerator which have led to specific designs for three different types of machines called the fixed-energy machine, the missing-power machine and the missing-magnet machine. The options for future development of the laboratory opened up by the different types of machines are discussed and their costs compared. Finally other design considerations arising from the need for flexibility for future development are discussed.

The theme which emerges from this study is undoubtedly flexibility for future development with respect to energy, intensity, output beams and laboratory layout and the proposal is put forward of a stage by stage development of the machine and the laboratory initially constructed, covering a period in time up to the end of this century. This flexibility, however, costs money which must be taken from the finances provided for the initial construction cost of the laboratory and the cost of research operations using the Stage I facilities. It cannot be assumed in the planning that the various stages of laboratory and machine development will necessarily follow one another over the years. There are many reasons why the development may be discontinued in the future and therefore each stage of the development of the machine and its laboratory, including the initial stage, must be complete in itself and economic in its use of the capital invested and in operating costs. The economics of any stage of development must not, for example, depend on completing the next stage. Furthermore, the first Stage of the machine and laboratory construction and the preparations for research must not cost more than a ceiling figure of 1431 MSF (1969 costs) which is the present proposal for the initial programme. Although machine energies of

250-500 GeV have been given as examples in this report the matching of the Stage I energy to the money available has yet to be done accurately and will in any case depend on the industrial prices appertaining at the time. These are difficult conditions to satisfy simultaneously since there is always a conflict between the desire for flexibility for the future and the cost of providing that flexibility at the present time. Yet to provide insufficient flexibility or none at all at the beginning is extremely expensive in the long term. If the evolution of physics research were always a smooth progression, planning a new laboratory and its machine over the next three decades would be a far easier process, but it is well known that the course of research can change abruptly and flexibilities now planned can turn out to be pointed in the wrong direction later on and the money spent on providing them, wasted. It is suggested that the twists and turns in the progress of the research programmes can best be followed by a stage by stage development of the machine and its laboratory whereby many options are built into the design and kept open for as long as possible at each stage.

Of the three machine designs discussed in this report the missing-magnet design seems to come closest to satisfying the requirements of a stage by stage machine development with several options open for future development at each stage and a balanced use of invested capital and operating costs at each stage. However, the missing-power machine design is superior in some respects though worse in others, and the fixed-energy machine whilst undoubtedly the best buy at the Stage I energy level is the least flexible of all. Combining some of the virtues of the missing-power machine with those of a fixed-energy machine produces a hybrid whose circulating beam intensity decreases as its energy increases keeping the secondary beam intensities roughly constant whilst providing an increasing range of secondary beam energies as the primary proton energy increases. This variable energy, variable intensity machine may prove an attractive alternative to the missing-magnet machine and is currently under study.

The purpose of this report, apart from describing work done during the studies so far carried out for the proposed new CERN Laboratory is to encourage informed discussion on the different types of machines and the ideas put forward for flexibility for future development of the laboratory and its proton synchrotron.

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Figure I

CERN, MEYRIN

ANNUAL EXPENDITURES AT 1969 PRICES

Figure II

CERN, MEYRIN
CUMULATIVE EXPENDITURES AT 1969 PRICES

Figure III

Figure IV

Figure V

C. P. S.
CERN I

Figure VI

Figure VII

MISSING MAGNET GEOMETRY
(one half period)

Figure VIII

MACHINE DEVELOPMENT OPTIONS

Figure IX

Figure X

Figure XI

Figure XII

S.F. MISSING MAGNET MACHINE

EJECTION ELEMENTS SHOWN

POSSIBLE SITE LAYOUT

CERN, MEYRIN
(on same scale)