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Experimental facilities of the CERN Proton Synchrotron / Citron,

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From Carmen Vasini <vasini@sif.it>

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Carmen Vasini

Experimental Facilities of the CERN Proton Synchrotron.

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The purpose of this lecture is to describe the building layout and provision for experiments which are planned for the CERN proton synchrotron. The general design of this machine has been considered by many people, and the plans proposed are the result of much discussion between members of the CERN P S group and the CERN architect, Dr STEIGER of Zürich. The shielding calculations were made by Professor GENTNER and Dr CITRON in Freiburg, and Dr CITRON has since considered in detail various arrangements for targets and ejection of beams which will be described later in this lecture. I should also say that we have tried to keep in mind all the time that the machine is to be used for nuclear Physics, and that we are anxious to receive, and use, any criticism or suggestions from people with experience in using large machines, or who think that some kinds of experiments are not properly provided for.

When planning for a machine which will not be in full use for seven years or more, and for an energy ten times greater than that obtainable now, the main difficulty is, of course, one's ignorance of the course of physics in the intervening time, and of what will be the focus of interest when the machine actually works. There are, however, a few general considerations one can find from past experience which help in deciding what to include or leave out, and which we have tried to satisfy in our plans.

a) If a machine is to have a useful life of, say, ten years, the vast majority of the experiments done on it will not be of the kind which stimulated the desire for the machine before it was built, the qualitative, exciting work which discovers new particles and wins Nobel Prizes; the machine must also be

(*) Lecture given by Dr HINE

designed for the hundreds of experiments which are done to explore systematically the whole range of energies and nuclear properties and which are essential for proper testing of theories

b) Past experience shows that machines usually fail in these latter types of experiments because of lack of intensity, which may, for example, rule out multiple scattering experiments, or which may prevent adequate analysis and collimation of the wanted particles to reduce backgrounds; because of lack of facilities to observe some energies or kinds of particles at all; and because of lack of experimental space round the machine, both close to the orbit and behind shielding walls

c) With a good machine, the demand to use it can be so high that the machine should be running most of the time, so the shielding must be adequate for some people to be preparing their apparatus near the machine while other people are doing experiments, and also the targets must be arranged so that as many experiments as possible can run simultaneously, even if requiring different energies and intensities

Before I describe how we have tried to meet these requirements in the CERN machine, I will have to recall some facts and figures about the machine, and about nuclear events at these energies. The machine is designed to give protons up to 25 GeV kinetic energy, with the possibility of getting somewhat higher if the behaviour of the magnets permits. The output is in pulses once every five seconds, whose duration might vary between 2 μ s, if all the protons suddenly hit a thick target, and perhaps some tens of milliseconds if more elaborate target arrangements are successful. The beam current we shall actually obtain is less accurately predictable, but if figures which could reasonably be aimed at, of a 1 mA injected beam with 20 % capture and acceleration efficiency, are realized, then there would be $6 \cdot 10^9$ protons per pulse after acceleration, or a flux of about 10^9 per second. This is the figure on which our shielding calculations are based, though we have space in general for more shielding if it is later found necessary.

Nuclear Physics information for shielding and target design has been collected by Dr CITRON in several CERN reports, both from published cosmic ray data, and from information found with the Brookhaven Cosmotron; the latter is of course for energies of about 2 GeV, but if extrapolated sensibly it agrees reasonably with the cosmic ray results. In the 25 GeV region it seems binding of nucleons in the target atoms can be neglected, that being all events treated as nucleon-nucleon collisions, and that the total cross section for nuclear events is rather less than the geometric nuclear cross-section.

When a 25 GeV proton enters a thick target, the final result is always a

star, usually before the proton has lost more than one or two percent of its energy. The star particles, in an average case will amount to about

$$\left. \begin{array}{l} 6 \text{ charged mesons} \\ 2 \text{ neutral mesons} \end{array} \right\} \text{top energy } 6 \text{ GeV}$$

$$\begin{array}{l} 2 \text{ neutrons } > 1 \text{ GeV} \\ 2 \text{ neutrons } > 1 \text{ GeV} \\ 26 \text{ neutrons } < 1 \text{ GeV} \\ 2 \text{ protons } > 1 \text{ GeV} \\ 26 \text{ protons } < 1 \text{ GeV} \end{array}$$

On its way through the target the proton will undergo a certain amount of scattering from both electromagnetic and nuclear forces, including the effects of diffraction, and may also turn into a neutron in a charge exchange process before finally forming a star.

If the target is really thick, that is part of a shielding wall, the more energetic of the star particles can make another generation of small stars. Further thickness of shield gives exponential absorption of the degraded radiation. The absorption length of about 200 g/cm² can be derived by suitable modification of cosmic ray absorption data for the atmosphere. The result of these calculations, which are given in detail in Dr CITRON's reports, and in the Report of the A.G. Synchrotron Conference in Geneva, are that a thickness of 5.5 metres of Barytes loaded concrete is necessary to shield workers against the full beam intensity.

The total attenuation factor of such a wall is about 10⁴, so it is clear that if the intensity of particle beams into the experimental hall is more than one ten thousandth of the main beam in the machine, it may not be possible for people to work near unshielded experimental apparatus with the beam on.

This fact, with our requirement, stated earlier, that the machine must be able to run nearly continuously without affecting assembly and testing of apparatus, is one of the reasons we have experimental space both inside and outside the magnet ring (Fig. 1).

The length of the hall outside the ring was chosen to allow room for experiments to be set up at several points along the beams of highest energy which run diagonally across the hall, and also to allow time for a reasonable fraction of the highest energy π -mesons to decay to μ -mesons inside the hall. The width of the outside hall, and the size of the hall inside the ring give, we hope, enough room for the apparatus to stretch out at right angles to the direction of the main beams, or to the main shielding wall.

The other parts of the building, the workshops, laboratories and offices, are physically as close as they can be to the experimental area, but are shielded from the radiation in the outside hall by a subsidiary shielding wall 2 metres

thick and 5 metres high, running across the main hall and outside across the end of the control room wing (Fig 1)

Fig 1 CERN Proton Synchrotron

With this building and shielding layout we hope we can satisfy all the principles outlined above: the layout is flexible, with room for experiments either close to the magnets or behind the main walls. Targets can be seen from all angles, both in the inside and outside experimental areas. The shield is demountable if necessary, and the floor will carry any amount of extra shielding if, for example it, is needed for a high intensity ejected beam. The whole floor area is free from obstructing pillars, and is spanned by overlapping 20 ton cranes.

The best kind of output from a particle accelerator is of course one where all the circulating beam is extracted with good geometry over a long period of time, to improve counting efficiency and re-

duce background: unfortunately this has not been achieved in any circular high energy machine, and we must first consider the behaviour and yields of targets introduced into the circulating beam. After that the possible use of a Piccioni type ejector scheme will be discussed, but although this seems promising it cannot be regarded as a replacement for more conventional internal targets before it has been tried practically.

To help in evaluating methods of using internal targets, necessary physical data for some target material, and the effect on the proton motion in passing through a target of one nuclear mean free path thickness are given in Table I.

The column «shift of closed orbit» gives the inward radial displacement of the closed orbit in the proposed CERN Machine due to the loss of energy in one passage through the target. The «mean scattering angle» is that due to coulomb forces, and the last column is the amplitude of betatron oscillations produced by the protons being scattered through the mean angle.

It can be seen that a target thick enough to absorb most of the incident protons is large and unwieldy if made of a light element, and that the resulting large emitting area of the target will result in low particle fluxes into exper-

imental apparatus This performance can be compared with that of a very thin foil target, where the energy loss is perhaps 50 keV rather than 200 MeV

TABLE I

Material	Nuclear Mean free Path		Energy loss in one m f p		Shift of closed orbit cm	Mean Scattering Angle in one m f p		Amplitude of free oscillations cm
	g/cm ²	cm	MeV	%		radians	degrees	
H ₂	35	500	140	0.56	1.6	0.58 · 10 ⁻³	0.033	1.2
Li	50	94	145	0.57	1.6	0.70 · 10 ⁻³	0.040	1.4
H ₂ O	77	77	154	0.62	1.8	1.16 · 10 ⁻³	0.067	2.3
Al	105	39	210	0.84	2.4	1.7 · 10 ⁻³	0.097	3.4
Pb	206	18	412	1.65	4.7	4.75 · 10 ⁻³	0.27	9.4

In this case, if the target is pushed into the beam after the magnetic field has stopped rising, the energy loss in one passage through the target is made up by energy gain from the radio frequency accelerators during the next revolution. Some small phase oscillations may be set up as a result, but the amplitude of the corresponding radial oscillation is of the order of a few millimeters. Otherwise the proton will continue to revolve in the machine neither gaining nor losing energy until it makes a nuclear collision in the target foil. During this time small angle scattering will have built up free oscillations to about the amount given in the last column of Table I, as the angle of scatter is the same whether the proton makes one transit through a thick target or many transits through the same total thickness of foil. As can be seen from the Table, the resulting oscillation can be comfortably held in the vacuum chamber for all but very heavy targets, and for light elements it is small enough to allow a total target thickness of two mean free paths, in which time almost all the protons will have caused a nuclear event.

There is one source of loss in this way of using targets, that if an appreciable nuclear scattering or a charge exchange occurs, the proton will be lost from the circulating beam and will not cause a star. In a single thick target, of course, these processes do not interfere with the final fate of the proton. This loss of star production is, however, a gain if one wants to use the scattered protons or the charge exchange neutrons, and this use of thin targets is the most efficient way of producing them. The proportion of protons which will undergo a serious scattering, or turn into neutrons is difficult to estimate from existing data, but taking some Brookhaven information (Quarterly and Annual Progress Reports, 1953) on the tracks of 2.2 GeV protons from the Cosmotron in photographic plates, and on neutron and proton cross-sections, it might be that about one fifth of the protons are significantly scattered, and that of these

a fraction, probably between one quarter and one tenth, will lose their charge and appear as neutrons

Several advantages follow from the use of very thin targets in this manner:

a) The duration of the bombardment is longer than if a thick target is used, and can be controlled fairly easily, by varying either the thickness of the foil, or its shape and cross sectional area. In using this latter method, the target would be a small disc or even a piece of wire, whose thickness is still kept about 50 keV, but whose area is so small that only a fraction of the particles in the beam hit it on each revolution, so that more revolutions are needed before every proton has been absorbed.

If the energy loss per traversal is 50 keV, and the total loss, from Table I, is 200 MeV, the whole process will last about 4000 revolutions, or 8 milliseconds. By using a target with small cross section area this could perhaps be increased to 1/10 second, which would be very satisfactory from the nuclear physicist's point of view. During such a time the magnetic field and hence the proton energy might change by a few percent, but this would not be objectionable in most cases.

b) This system will work equally well if the 50 keV foil is split up into several thinner foils, and put at different places round the circumference. Thus, by choosing foil materials, thicknesses and areas, several experiments can be run simultaneously with different intensities and types of reaction, provided they can all put up with the same proton energy.

c) With such small targets the ease of handling is greatly increased, and they could be moved in and out of the beam very rapidly. Further, materials only obtainable in small quantities can be used, and it might be possible to use a liquid hydrogen target in the form of a thin wall tube a few mm in diameter with the hydrogen flowing through it.

d) Targets with small cross-section area form sources with low acceptance, (the product of size and angular divergence), which are much easier to use with lenses to transfer large fluxes of particles into counter systems or cloud chambers some distance away. This point will be elaborated later on.

Something can be said about the angular distribution of the particles leaving the machine. The high energy neutrons and protons come mainly from the scattering and charge exchange mentioned above, and these are essentially two body elastic processes. In that case the variation of energy with angle of scatter is a known function. In our case, for 25 GeV protons, whose total energy in centre of mass space is 3.8 times rest mass, the energy is given by

$$E = \frac{25}{1 + (3.8 \operatorname{tg} \theta)^2} \text{ GeV}$$

This gives energies of 22.6, 17.2, 12.3 GeV at 5°, 10°, 15°

The yield from a process which is isotropic in centre of mass space, which might be roughly true of some of the scattering, is given by

$$N(\theta) \propto \frac{1}{\cos^3 \theta (1 + (3.8 \tan^2 \theta))^2}$$

This shows half intensity at about 10°. For charge exchange, the process is known to occur predominantly at small angles in the centre-of-mass space, with a half width of about 22° both at 400 MeV and at 2 GeV, and if this holds at higher energies, the corresponding angle in the Laboratory will be about 2.5° for half intensity and 5° for one tenth.

Diffraction scattering occurs at even smaller angles, possibly with a half width of $\sim 30'$, so that these protons are unfortunately too much scattered to remain trapped in the machine, but not enough to get clear of it before the fringing field of the next magnet unit disturbs them.

The fastest particles which come out of the stars are the π -mesons, and a few fast protons and neutrons, which cannot easily be distinguished from them in photographic plates. The angular distribution of such particles from cosmic ray created stars have been measured (CAMERINI, LOCK, PERKINS) and the yield curve is predominantly in the forward direction. The energy is not a unique function of angle, but the energy distribution of the π mesons in centre of mass space is known to extend up to about 800 MeV from cosmion experiments, and this upper limit does not seem to depend much on energy of the proton creating the star. The corresponding upper limit of energy in laboratory space, and the yield, at various angles are given in Table II.

TABLE II

Angle in Laboratory Space	Meson/sterad per proton	Upper limit of Energy (kinetic) for 800 MeV in C.M. space
0°	12	6.0 GeV
5°	10	5.6 "
10°	7	4.4 "
15°	5	3.2 "
20°	3	2.3 "
30°	1.5	1.3 "
60°	0.5	330 MeV
90°	0.25	90 "
180°	0.2	20 "

In addition to the charged π -mesons, there will be also perhaps one third that number of neutral π -mesons, which decay within a few centimetres into a pair of high energy photons, which will go in essentially the same direction as the parent meson. Thus as well as the charged meson distribution given above there will be a similarly distributed flux of photons, of about one half the intensity, and whose upper energy limit is about one half the figures in the last column of Table II.

The other, lower energy, particles from the stars are distributed more isotropically, especially those with energies only of the order of 10 MeV, which will be by far the most common particles leaving the targets at angles of 90° or more.

It would be unwise to expect to find any other types of particles at a useful distance from the machine, as the lifetimes of most mesons are too short for flight paths of more than a few centimetres. There does seem to be some evidence that the τ -meson's lifetime might be as long as 10^{-8} s, so an energetic meson of this kind might survive a flight of 20 metres, allowing for the effect of time dilatation. This would still not be able to reach the far side of the main shield, but could be detected in apparatus in the inner target areas.

The possibility of observing the various classes of particles that have been discussed can be seen in Fig 2, which shows the possible positions of targets

Fig 2 - Target arrangements

i

in the straight sections between the magnet units, and the ranges of angle over which each target can be seen, either from the outside or inside experimental hall. Obstruction to emerging particles from the iron return yoke of

the magnet is avoided to a great extent by arranging the magnet units in groups of three, with the yokes alternately outside and inside the proton orbit

Some of the low angle beams of π -mesons are shown emerging not from the target, but further down the following magnet unit. It seems possible, to judge from some tracing of trajectories, to allow this to happen, and to use the magnets to do some energy analysis, and to bend the beams, especially those of π^+ -mesons on the inside of the ring, so that they hit the shielding wall at a greater angle than otherwise. There is space between the magnets and the shield for other extra bending or analysing magnets. These may have to be quite large and heavy, since it needs a magnet about 5 metres long to deflect a 5 GeV meson through 30° .

The estimates of yields of different kinds of particles we have made can now be combined with the geometry of the targets and shielding to estimate the fluxes of different kinds of particles on the safe side of the shield. No extra focusing is considered at the moment.

a) High energy protons

About 1/10 incident protons scattered with half width 5°

Target distance, from outside shield, 35 metres

Angle of scatter 5°

Energy of scattered proton 22 GeV

Flux emerging from shield $5 \cdot 10^2$ protons/pulse cm^2

b) High energy neutrons

About 1/40 incident protons send neutrons into a beam 2.5° half width, which, of course, can be used at its angle of highest intensity

Target distance 40 metres

Energy of neutrons 25 GeV

Flux emerging from shield $8 \cdot 10^2$ neutrons/pulse cm^2

c) High energy π -mesons

About 6 π mesons/steradian per proton, at 10° to beam

Target distance 20 metres

Energy of mesons 4.4 GeV upper limit

Flux emerging from shield $7 \cdot 10^3$ mesons/pulse cm^2

d) High energy photons

About 4 π^0 mesons/steradian per proton along the tangential direction, with the exchange neutrons

Target distance 40 metres

Energy of photons 3 GeV upper limit

Flux emerging from shield $8 \cdot 10^3$ photons/pulse cm^2

There will be, as well, a large flux of lower energy photons and electrons from cascades in the wall of the channel through the shield

e) Low Energy π mesons

About 0.5 π -mesons/steradian per proton at 60° to the beam

Target distance 10 metres

Energy of mesons 300 MeV upper limit

Flux emerging from shield $2 \cdot 10^3$ mesons/pulse cm^2

f) Low Energy Protons and Neutrons.

About 40 low energy nucleons (< 30 MeV) per proton isotropically distributed

Target distance 10 metres

Flux emerging from shield $1.6 \cdot 10^4$ nucleons/pulse cm^2

These fluxes may or may not be adequate for qualitative experiments; the high energy proton beam would certainly be too intense for a cloud chamber, a few pulse would fully load a photographic plate, the neutron beam would probably be reasonable for cloud chamber work. For work involving scattering, and counter telescopes or analyses of low efficiency these yields would be regarded as far too low for work in the cyclotron energy range. The beams in general contain particles of a wide range of energy, and the backgrounds are very high. Further, it will be difficult to detect short lived particles from the targets in the main proton beam itself, where the targets are inaccessible and the background probably high.

To counter these difficulties, two improvements can be asked for, a high current ejected beam of protons, clean and well collimated, outside the main shield; and some general techniques for improving the efficiency of collecting particles emitted from targets, so that either intensities can be raised, or the same counting rates maintained but with a much smaller circulating beam or thinner targets, and a corresponding reduction in background.

This problem of how to form and transport beams of particles about the laboratory has been greatly eased by the use of the alternating gradient focusing principle, in just the same way as the design of synchrotrons has been. Some special cases can be discussed to show that the use of A.G. lenses and channels for this purpose seems quite practical.

Two conditions should be fulfilled, or at least aimed at, in the design of an economical focusing channel: the focusing and bending forces should be

spread out evenly along the length of the channel, and no part of the channel should have a larger aperture than is needed to carry the beam of particles safely. The first requirement is well known, and easy to demonstrate: the focusing or bending forces are proportional to some electric or magnetic field strength, whereas the stored energy, and cost, are proportional to the square of the field. The field distribution along the particle trajectory which minimizes the cost while keeping the product of field strength and length of focusing regions constant is the uniform distribution.

The first condition looks very obvious, but its point is usually obscured by a common way of describing beams of particles simply by their angular

Fig 3

divergence, as though all the particles had come from a point source. If that were so the diverging beams could be made to converge onto an exact point image by a lens, and then the rays could be bent by a diverging lens, placed just before the new focal point into a parallel pencil with as small a diameter as one wished (Fig 3a). Such a pencil beam could then travel indefinitely with no further focusing. The absurdity of this conclusion comes from the neglect of the finite size of the original source of the particles; from any point on the surface of the source comes a whole bundle of diverging rays, and any optical systems which attempt to make a small beam by forming a reduced

size image of the source will at the same time form an image from whose surface the ray divergence is by the same factor larger (Fig 3b)

This is a consequence of a general theorem of wide range, in optics the Helmholtz-Lagrange law, in dynamics Liouville's theorem, which says, in ray-optical terminology, that the product of the radius of a pencil of rays and the incoherent part of the angular divergence (half angle) is a constant along the pencil (Fig 3c). In CERN accelerator work this constant product is called Acceptance; pieces of apparatus, such as counter telescopes or focusing channels, or holes through a shield can all be given an acceptance by drawing the extreme rays which can just pass through them and calculating the radius and angle of divergence of the pencil so formed. The most economical optical system for bringing particles to an experimental apparatus is one where the acceptance of the focusing lenses and apertures etc., are all equal to that of the experiment. If the lenses are properly arranged all the parts of the system will just carry the pencil of rays, and the maximum possible flux of particles will be taken from the target to the experiment. This maximum flux can be calculated by finding the effective angle over which the source emits, from the source size and the acceptance of the experimental apparatus. No knowledge of the intervening channel is necessary.

As an example, the acceptance of the structure in Fig 4a, which might be a counter telescope, or a hole through a shielding wall, or the sensitive region

Fig 4

of a cloud chamber, of length d and radius a , is $\frac{1}{2}(a^2/d)$. If the source, the spot at the target, has radius a_s , and emits a total flux of Φ particles per steradian, then the number N of particles emitted in a pencil of half angle θ is $N = \Phi\pi\theta^2 = \Phi\pi A^2/a_s^2$, where A is the acceptance of the pencil,

and which is determined by the counter geometry. This shows that the flux of particles into the counters can be increased by decreasing the spot size on the target, until the angle at the source becomes too large for practical lenses to handle. If mks units are used the unit of acceptance is the metre radian, with subdivisions mm rad and μ rad. This latter is the same as $1 \text{ mm } 10^{-3} \text{ rad}$, a unit already used for describing the properties of beams from accelerating machines.

For some typical cases, the acceptance might vary from 2 mm rad for a cloud chamber of 40 cm diameter and 8 cm thick sensitive region to 0.1 mm rad for a counter telescope 5 cm diameter and 3 m long. The simple target arrangement with no focusing 30 m from a 20 cm diameter hole in the shield will have an acceptance of 0.03 mm rad for a 1 cm radius target spot, so such a size of shield channel will seriously limit the possible intensity which might be put into these detectors.

A focusing channel, formed from a string of A.G. quadrupole lenses can be made with quite a high acceptance by these standards. The equation of transverse motion for a particle in such a channel is

$$\frac{d^2y}{ds^2} + \left(\frac{e}{p} \frac{\hat{B}}{a_{\text{ch}}} \right) y = 0,$$

where P is the particle's momentum $\left. \begin{array}{l} a_{\text{ch}} \text{ the radius of the channel} \\ \hat{B} \text{ the maximum magnetic field (at radius } a_{\text{ch}}) \end{array} \right\} \text{ mks units}$

Putting $m = (e/p)\hat{B}/a_{\text{ch}}$ the equation has the same form as that for particles in the A.G. Synchrotron, and the theory of that machine can be used to find the acceptance of such a channel. If the channel is designed for highest acceptance A for a particular energy, then

$$A = 0.24 a_{\text{ch}}^2 \sqrt{m} \text{ m rad}$$

For a big channel, for 10 GeV particles, with radius 10 cm and peak field 10^4 gauss, $m = 0.3$ and the acceptance

$$A = 1.35 \cdot 10^{-3} \text{ m rad} = 1.35 \text{ mm rad}$$

This is 45 times as large as the acceptance of the hole in the wall considered above, and as the flux of particles is proportional to A^2 , its use would permit an increase in intensity of two thousand times into a suitably designed piece of apparatus.

If the energy of the wanted particles were lower A will remain unchanged if $\hat{B}$ is decreased by as much as p the momentum; for 2 GeV particles only 2000 gauss is needed at the edge of the aperture.

For the highest energies, the acceptance needed is lower, as the half angle of the high energy beams does not exceed $1/20$ radian ($2\frac{1}{2}^\circ$), so, for a 1 cm radius target spot, the acceptance is 0.5 mm rad, and a 10 cm radius channel for 25 GeV will need only 3000 gauss at the edge. It is worth noticing that although a channel with the same acceptance could be made with only about 6 cm radius by raising the field at the edge to 10 000 gauss, such a channel would have more stored magnetic energy and cost more. The stored energy per unit length of channel, E_s , is proportional to $a^2 \hat{B}^2$.

Now

$$A^2 \propto a^4 m \propto a^3 \frac{\hat{B}}{p} \propto \frac{a^3 \hat{B}}{(\text{GeV})} \quad \text{for relativistic energies}$$

So

$$a^2 \propto A^{1/3} (\text{GeV})^{2/3} \hat{B}^{-2/3}$$

and

$$E_s \propto A^{1/3} (\text{GeV})^{2/3} \hat{B}^{1/3}$$

An advantage of A.G. channels is that they will not pass particles of low energy. There is a complete cut off at an energy of about half that for maximum acceptance, and a strong fall off for energies much above the chosen value. The energies in the pass band can be varied simply by the level of magnetic field ($\hat{B}/p$ is a constant for a given channel) which gives a convenient way of making a crude monochromator and of reducing background.

The ability of the channel to separate energies can be much increased by adding some uniform bending field to the quadrupole type focusing field in the channel, and arranging the channel on a circular arc rather than on a straight line. Since the bending field occupies a large part of the particles path between the target and the experiment, it is much lower for a given energy resolution than if a conventional bending magnet is used, and the cost and engineering design do not seem to be very worrying.

There is one more problem in the use of these channels, that of injecting the particles into the channel and of guiding them out properly into the experimental apparatus. This can be done by extra lenses at the beginning and end of the channel. The source is imaged onto the entry of the channel, with sufficient magnification to give an image whose size is $1/\sqrt{2}$ the aperture of the channel. The lens aperture is made sufficient to take that angle of beam which gives, with the particular source size, the same acceptance as that of the channel, and the resulting (demagnified) angular divergence of rays from the image at

the entry to the channel uses up the remainder of the aperture (Fig 4b). This condition, in which the apertures needed for the size and angular deviation of the virtual source are equal, can be called the «matched» condition (*). The lenses which are used for this matching process can also be alternating gradient units, though if the magnification needed is not unity, different lengths or m values must be used in the two parts of the lens to get proper focal lengths for the horizontal and vertical directions, as these lenses are in general not astigmatic.

The other way in which the effectiveness of the CERN synchrotron could be increased would be to secure an efficient ejector for the main proton beam. The efficiencies of the plain «hole in the wall», and a good channel, using low angle scattered protons, are of the order $0.3 \cdot 10^{-4}$, $2 \cdot 10^{-3}$ respectively, which leaves a long way to go.

A good ejector should have three qualities:

- a) it should eject a high proportion of the circulating beam;
- b) the ejected beam should have reasonable geometry;
- c) the ejection process should last a long time, at least a millisecond.

From these criteria it follows that whatever is used to kick particles out of the focusing region of the machine must have an or all nothing property: if a particle is at all affected it must be given a full size kick and not merely given an oscillation of large amplitude in the synchrotron which will probably lead to its loss rather than its successful ejection. This rules out a simple kicking magnet, whose fringing field has just this trouble: some property if the circulating beam is moved slowly into the magnet gap: slowly, as it must be to satisfy rule c).

Fig 5

The only successful device to date even on paper is that used in the Piccioni type ejector, where the energy loss of a particle in passing through a fairly thick target is used

(*) Note added in proof — This is too simple a discussion of the matching problem. Other methods can be used which do not involve forming images of the source.

to start a large free oscillation about a new equilibrium orbit displaced towards the centre of the machine (Fig 5a). This oscillation is large enough half a wavelength further round the machine to take the particle into a kicking magnet which can now be far enough from the remaining beam of undisturbed particles not to affect it appreciably. The effective «fringing field» of such an «energy losing» target is due to scattering of the particles out of the side of the target before they have passed through and lost the full amount of energy.

From the data in Table I, it is clear that although a heavy element target would be best for high efficiency, since an energy loss corresponding to a closed orbit shift of 2 cm can be obtained by a thickness of less than one half a nuclear mean free path, the amplitude of oscillation caused by the scattering in the target is too large for the vacuum chamber at a point one quarter of a wavelength further round the machine, so a lighter element target about one mean free path long must be used, with only about 30% of the incident protons coming out on the far side. The angular divergence is then quite small, and at the kicking magnet half a wavelength away the particles come to a focus again, so that the magnet aperture needed is only about 1.5×3 cm, to hold the initial width of the beam and the radial spread caused by energy straggling in the target.

A kicking magnet 1 metre long with a field of 20 000 gauss will give enough sideways momentum to the protons to take them clear of the main magnetic

Fig 6

field about one magnet period later, and the kicker can be so placed that the subsequent motion and the fringing fields of the main magnets allow the ejected beams to come out with a very reasonable size and angular

divergence i.e. a reasonable acceptance (Fig 6). The acceptance of the beam in the kicking magnet is about 0.02 mm rad and the aberrations in the subsequent magnetic fields should not increase this beyond 0.1, which is easily handled by lenses and A.G. channels to take the beam across the experimental hall.

To generate a long output pulse it is necessary to move the circulating beam very slowly onto the target. Under practical conditions there is then a considerable loss due to protons being scattered out of the side of the target rather than passing right through. To avoid this, a further, quite thin, target, can be used half a wavelength further back, on the outside of the beam this time, to give a displacement of, say, 2 mm to the protons hitting it, which will

ensure their staying inside the main target for the whole of its thickness. This thin target will not have sufficient scattering in it for its «fringing field» to be serious (Fig. 5*b*).

The movement of the beam onto the targets can be accomplished by a pair of small bending magnets spaced one wavelength apart, as in Fig. 5*c*, which induce and then cancel an oscillation of growing amplitude as the exciting current in the magnet is increased.

The principal losses of protons in this scheme occur in the main target, where perhaps 60-70% will be lost by nuclear collisions, and some further losses from fringing fields. One might however hope for an overall efficiency of 10-20%, which gives a gain in intensity of nearly 1000 over the simple scattering ejector.

This use of focusing channels and ejectors may seem too complicated and expensive, and so it will be for a year or so after the machine starts to operate. In practice, however, within a few years experimentalists are always clamouring for ever higher intensities, and it is usually found possible to get money and staff to build an untried type of machine even in an energy range which is fairly well covered, if its intensity is increased by a factor of several hundreds or more for some types of experiment. As an example, Gt. Britain has started building a proton linear accelerator for 600 MeV even before the cyclotron for a similar energy at Liverpool is fully operative. Viewed in this light, the cost, perhaps a million francs or so, of a set of channels is a very cheap way of staving off of the inevitable day when this proton synchrotron becomes a reason for nuclear physicists avoiding instead of visiting Geneva.