THE EXTERNAL PROTON BEAM AT THE COSMOTRON

G. B. COLLINS

Brookhaven National Laboratory, Upton (N.Y.)

The method used of extracting protons from the circulating beam of a proton synchrotron was conceived of independently by Piccioni et al. and by Wright.

The preliminary experiments, modification of the Cosmotron and final adjustments were done by O. Piccioni, R. L. Cool, S. L. Ridgway, G. Friedlander and D. A. Kassner.

Fig. 1 is a schematic drawing of the Cosmotron showing the position of the equipment associated with the external proton beam. The internal proton beam after it has reached full energy, is made to spiral in against a target. In passing through this target enough energy is lost through ionization to reduce the proton's radius of curvature so that on the next revolution it enters the gap of an electromagnet M where a reverse direction field deflects it outward by about 6°.

These protons emerge from the port P between magnetic shims which reduce their angular dispersion and enter a strong focusing pair F which removes stigmatism and focuses the protons at a point outside the shielding S.

The objective, naturally, is to extract the largest possible fraction of the circulating beam and focus it into the smallest possible area, preferably without introducing excessive angular divergence or additional energy spread. The problem divides itself into two parts:

1. Causing a large fraction of the circulating beam to enter the aperture of the deflecting magnet.

2. Providing magnetic focusing, the total effect of which is to act as a lens system which forms a good image of the aperture of the deflecting magnet outside the radiation shield.

Fig. 1. Diagram of external proton beam.
These problems will now be considered in order.

Fig. 2 shows the form of the jump target and its lip. The circulating proton beam of the Cosmotron at full energy has a cross section of about 2.5 cm. in height by 7.5 cm. in width. When the accelerating R. F. is turned off the protons spiral in toward the lip at about .0025 cm. per revolution. Multiple traversals of this lip by the protons finally cause them to traverse the jump target once. The energy lost then is about 8 Mev and causes an average displacement inward on the next turn of 4 inches.

It is important to minimize the effect of horizontal and vertical betatron oscillations which exist originally in the circulating beam and which are induced by transitions through the lip and jump target. It is helpful to consider first the effect of the lip and then the effect of the jump target separately on these horizontal and vertical oscillations.

The first action of the lip is to remove most of the amplitude of horizontal betatron oscillations. This results from the fact that when a given proton first traverses the lip the phase of its horizontal betatron oscillations is such that the displacement in the equilibrium orbit of the proton reduces the amplitude of oscillations in the horizontal plane. The displacement in the equilibrium orbit \( \Delta R \) is:

\[
\Delta R = R/(1 - n) \cdot \Delta p/p \quad \ldots \quad (1)
\]

where \( \Delta p \) is the momentum lost in traversing the lip. After 10 to 20 more revolutions the phase of the horizontal oscillations is such that the proton again passes through the lip and again the amplitude is reduced. Ultimately the equilibrium orbit is displaced to a point inside the proton’s position and then for the first time the actual position of the proton is displaced to a smaller radius. The displacement of the proton \( \Delta r \) is:

\[
\Delta r = \Delta R \left[ 1 - \cos \left[ 1.1 (1-n)^{1/2} \varphi \right] \right] \quad \ldots \quad (2)
\]

where \( \varphi \) is the azimuthal angle measured from the target. This displacement is sufficient to cause the proton on the next turn to traverse the jump target. Thus the lip removes most of the amplitude of the horizontal betatron oscillations and causes the protons to pass through the jump target. The lip does very little to the vertical betatron oscillations.

One turn after passing through the jump target the protons are again displaced by about 4 inches to a smaller radius as given by \( (2) \). At the same time horizontal oscillations are induced as a result of multiple Coulomb scattering and fluctuations in energy loss (Landau effect). The original vertical oscillations present in the circulating beam are enhanced by multiple Coulomb scattering.

The equation of motion for horizontal betatron oscillations is:

\[
y = \Delta R \cos \left[ 1.1 (1-n)^{1/2} \varphi \right] + \frac{\alpha R}{1.1(1-n)^{1/2}} \sin \left[ 1.1(1-n)^{1/2} \varphi \right]
\]

and for vertical oscillations

\[
z = (\alpha + \beta)R/1.1 n^{1/2} \cdot \sin \left( 1.1 n^{1/2} \varphi \right)
\]

where \( \alpha \) is the initial scattering angle and \( \beta \) the angle in the vertical plane due to vertical betatron oscillations.

In practice different values of \( n \) can be obtained by varying the pole face windings and different values of \( \varphi \) can be obtained by locating the jump target at different points around the magnet ring with respect to the deflecting magnet. If values of \( n \) and \( \varphi \) are so chosen that the angle \( [1.1 (1-n)^{1/2} \varphi] \) is an odd multiple of \( \pi \) the displacement of the proton to a smaller \( y \) is a maximum for a given \( \Delta R \) as given by the first term in \( (3) \) and the jump target is imaged at the entrance of the deflecting magnet. If \( [1.1 n^{1/2} \varphi] \) is an integral multiple of \( \pi \) the jump target will be imaged at the entrance of the deflecting magnet simultaneously for vertical betatron oscillations. Unfortunately, for \( \varphi = 2 \pi \) this condition leads to values of \( n \) for which a beam cannot be accelerated. In practice it has been found desirable to make \( \varphi = 2 \pi \) and adjust \( n \) to put a maximum fraction of the deflected protons into the aperture of the deflecting magnet.

The gap in the deflecting magnet is 2.5 cm. vertically and 7.5 cm. horizontally. By bombarding a foil in front of this magnet and measuring its activity at various points it has been found that under favourable circumstances 60% of the circulating beam can be made to enter the gap. The observed distribution can be almost completely explained in terms of variations in the energy lost by protons in the jump target and to a small extent to uncorrected Coulomb scattering. We will now consider that aspect of the problem concerned with focusing the emerging protons into a small area.

A special port was created in the side of the vacuum chamber to permit the exit of the deflected protons. If
no modification was made of the Cosmotron’s fringing field, however, those protons which emerged on the side of the beam near the machine would be deflected in the fringing field more than those on the outside of this beam. A horizontal defocusing would result. This fringing field, however, produces considerable vertical focusing and since these two effects are related, the problem was to alter the shape of the fringing field where the beam emerged to increase the original horizontal focusing at the expense of the original vertical focusing which is excessive. This was done by introducing iron slabs above and below the median plane so that the fringing field was concentrated into a small area and consequently did not diminish in intensity appreciably across the area traversed by the emerging protons.

Some mechanical difficulties were encountered in restraining the large forces exerted on these slabs by the magnetic fields. This problem was solved however. Exposure of x-ray films to the emerging protons showed that a vertical focus existed about 30 cm. from the exit port and that in the horizontal plane the focus was essentially at infinity.

The divergence of the beam and the location of the focal points are such that a strong focusing pair with a 12 inch aperture can focus these protons both vertically and horizontally at any point outside the radiation shield.

This focused beam can be observed on a closed circuit television, the camera of which is directed at a mosaic of sodium iodide crystals through which the proton beam passes. Observing the fluorescent spot facilitates the adjustment of the currents in the strong focusing pair to produce optimum focus.

Measurement of radioactivity produced in an aluminium foil has shown a vertical and horizontal distribution as shown in fig. 3 and fig. 4. Tests made at 2.9, 2.0 and 1.0 Bev show that extraction of about 50% of the circulating beam is possible at these energies.

The quality of the magnetic focusing makes it possible to form what has been called a pencil beam. For this the aperture of the deflecting magnet is reduced by supporting a metal block with a .6 cm. hole in it ahead of its gap. An image of this defining aperture can then be formed with little magnification outside the radiation shield. To achieve a well defined pencil beam scattering along the path must be kept small by reducing the thickness of the metal in the exit port and inserting helium filled plastic bags along the trajectories to reduce air scattering.

It has been possible to contain some $10^7$ protons per pulse within a 0.5 cm. diameter circle. The fraction of stray particles outside this cylinder is about 0.001.

Some remarks about the possible usefulness of this external beam may be in order. There will surely be advantages from the standpoint of convenience of doing experiments although how great this advantage will be is still uncertain. One can get very close to an irradiated target particularly when the pencil beam is used and this feature should be effective in studying particles with lives in the $10^{-9}$ sec. range.

The possibility of using liquid hydrogen targets is perhaps at this time the most outstanding advantage of an external over an internal beam. Finally, one has the possibility of eliminating essentially all background radiation not originating from a bombarded target. This can be done by bringing the beam through a shield without letting it touch the opening and stopping the unused protons at a great distance. With this in mind, a mound of earth has been erected some 500 feet behind the experimental area.
LIST OF REFERENCES