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The Magnetic Deflector of the Buenos Aires 180-cm Synchrocyclotron Beam

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The magnetic deflector system of the Buenos Aires 180-cm synchrocyclotron beam consists of a regenerator (previously reported) and a critical magnetic channel. The channel was built starting on the maximum of the radial oscillation and following a trajectory given by $\rho = 83.5 + 10\alpha^{11/4}$ (in cm), where (ρ,α) are polar coordinates with origin at the center of the machine and α is measured from the maximum of the radial oscillation. Alternating gradient magnetic fields were used in order to keep the beam parallel up to the magnetic quadrupoles. Thus the vertical divergence of the beam is vanishingly small and the radial divergence is 1/200. With the complete assembly in place 20% of the circulating beam is thrown by the regenerator into the magnetic channel, and its transmission is 10%. The over-all extraction efficiency is therefore 2%.

I. INTRODUCTION

A BEAM deflector system was previously described[1] consisting of a regenerator, an 80-kv/cm electrostatic deflector, and a magnetic channel. The electrostatic deflector was particularly unstable when the beam was circulating in the machine. The outcoming beam showed no radial divergence but it was strongly divergent in the vertical direction (25°). Evidence for this was obtained by means of an autoradiograph on photographic paper at the ion source air-lock gate. The vertical size of the beam was 17 cm there.

It was then decided to deflect the beam with a magnetic channel with adequate focusing action. Here we describe how we obtained the necessary information about the regenerated beam, and the criteria that governed the construction of the magnetic channel. We feel that it is a critical assembly because of the peculiar geometrical conditions of the medium energy machine for which it was built.

II. REGENERATED BEAM CHARACTERISTICS

Knowledge of the following characteristics was judged necessary for our purpose: the radial gain relation, the position of the nodal points with respect to the regenerator position, and the maximum radial oscillation amplitude obtainable in the machine. The radial gain relation measurement usually proves, at the same time, that the precession of the beam is stopped by regenerator action.[2]

The target used for the radial gain measurement is drawn in Fig. 1(a). It was made of aluminum and its purpose was to obtain the "shadow" cast by an obstacle. The obstacle is 1 and its shadow is 1′. The beam can pass through perforation 2 and hits the target on 2′. Figure 1(b) is an autoradiograph of the target. Call r_n and r_{n+1} the radial oscillation amplitudes of successive turns of the beam. The radial gain relation is given by r_{n+1}/r_n and was found to be 1.3 according to the autoradiograph, under the assumption that the synchronous orbit radius is 77 cm for the regenerated particles.

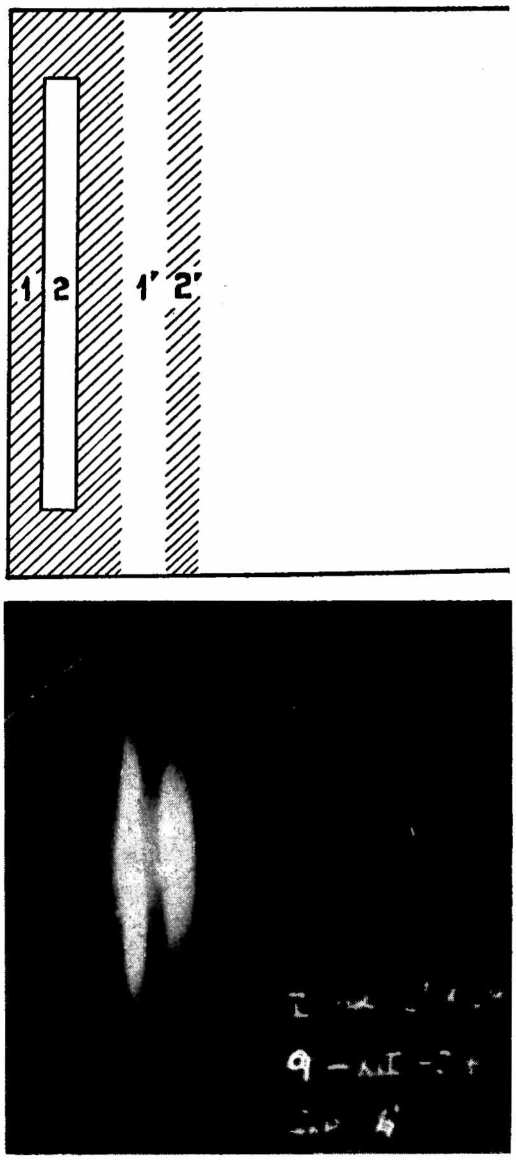
The location of the nodal points was determined by the measurement of beam current as a function of radius at several angles with respect to the regenerator. For this purpose a target moving slowly outwards with constant velocity was used The first nodal point was found to be located at an angle of 45° measured from the regenerator in the direction of the beam circulation (see Fig. 2). At the same time it was possible to confirm that the synchronous orbit of the regenerated beam was 77 cm. The maximum radius attained by the regenerated beam was found to be 84.5 cm, whereas the radius where the beam would spiral out by itself is 91.5 cm. It is the radius where the radial restoring force vanishes, and it can be obtained on the *BR* curve (Fig. 3) as follows: It can be shown that the *BR* value (*B* is the magnetic field and *R* is the radius) equals the value corresponding to the synchronous extraction orbit, in our case 77 cm. The current as a function of radius showed an abrupt cutoff. This is due to the geometry of the machine and to the size of the dee that clips the beam down at 84.5-cm radius, for the positions of the regenerator compatible with the direction of the extracted beam (Fig. 15). A larger dee would permit the regenerated beam to reach larger radii. The maximum separation between successive turns of the regenerated beam is obtained at 90° from the nodal point, at 84.5-cm radius it is 1.7 cm according to the measured value of the radial gain relation. Instead, at 30° from the nodal point, the maximum separation between regenerated orbits is 0.85 cm at 79.3-cm radius. The last figure was calculated by approximating the radial oscillation as a sine function of the azimuthal angle.

III. EXTRACTION OF THE REGENERATED BEAM

Due to the geometrical conditions of the machine it is not possible to extract the regenerated beam with the

[1] S. Mayo, C. A. Heras, and J. Rosenblatt, Nuclear Instr. 2, 9 (1958).
[2] Some of these characteristics could be calculated from the measured values of the regenerator field, but the synchrocyclotron itself was considered to be the best computer.

action of the regenerator alone, as was done for example in the 184-in. synchrocyclotron of the Lawrence Radiation Laboratory.[3] In that case the magnetic channel simply provided the necessary focusing action for the emergent beam (radial focusing), and therefore it was located far enough from the circulating beam as to disturb it the least,



(a)

(b)

FIG. 1. (a) Target for the radial gain measurement. The regions 1 and 2 yield regions 1′ and 2′ in "shadow" and illuminated, respectively; (b) autoradiograph of the target showing the regions indicated in (a).

compatible with its focusing action. In our case the channel ought to convey the beam at least to a radius of 91.5 cm; it should act on particles still bound by the magnetic field of the machine. It was decided that the optimum place to start the beam deflection was at 90° from the nodal point,

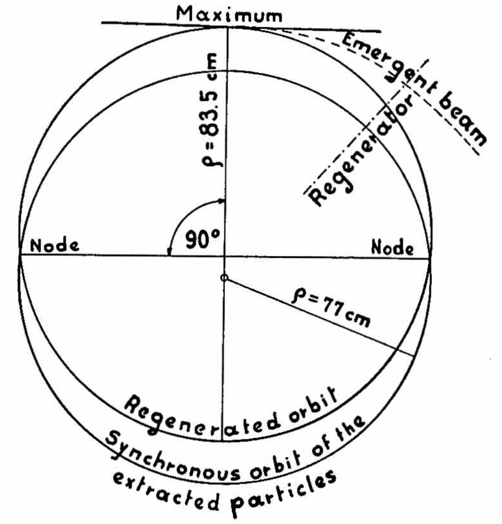


FIG. 2. Diagram showing the relative position of the regenerator and the nodal points of the radial oscillation.

that is, the point where the radius of the regenerated beam is 84.5 cm. Two reasons favor this selection: First, the separation of successive orbits is a maximum there; second, it is the most distant place from the nonregenerated circulating beam.

IV. MAGNETIC DEFLECTOR DESIGN

It is obvious that to extract the beam it is necessary to lower the magnetic field. One could suppose a certain field depression and calculate the corresponding beam path. Otherwise one can set a trajectory for the beam and calculate the necessary field along it. The second-mentioned alternative was the one employed to solve the extraction problem.

The starting point of the calculation is the value of the product B_0R_0, where B_0 is the value of the magnetic field at the synchronous orbit of radius R_0 where the regenerative action starts. This product is usually called the mag-

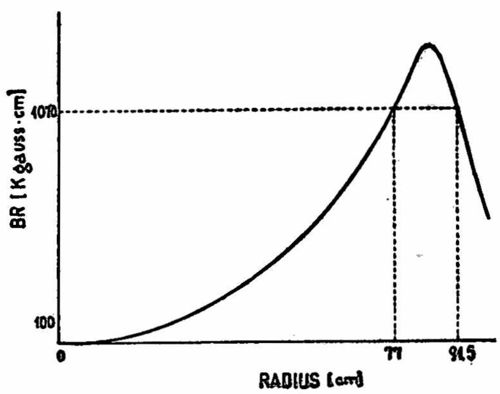


FIG. 3. Determination of the radius where the radial restoring force vanishes for particles corresponding to the synchronous orbit of radius R_0.

[3] W. F. Stubbins, E. Kelly, J. T. Vale, and K. Crowe, Bull. Am. Phys. Soc. Ser. II 2, 382 (1957).

netic rigidity of the particle. In the particular case of the Buenos Aires synchrocyclotron $B_0R_0 = 1070$ kilogauss-cm. The emergent beam trajectory was set to be a spiral, using plane polar coordinates with origin at the center of the machine (ρ,α). The equation can be written as

$$\rho = \rho_0 + k\alpha^m. \tag{1}$$

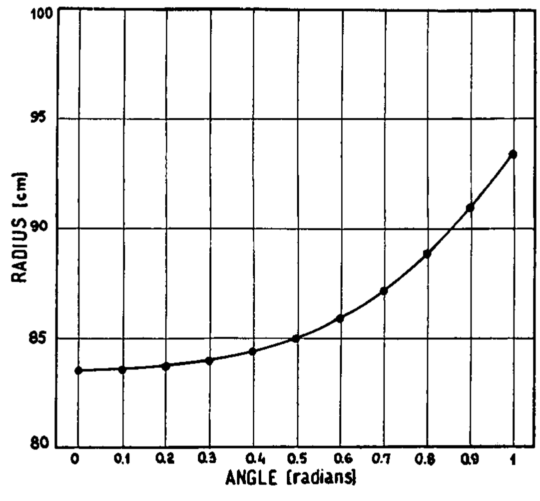


FIG. 4. Plot of the function $\rho = 83.5 + 10\alpha^{11/4}$.

α is measured in radians starting at the point of maximum radial oscillation amplitude, i.e., the point where one wishes to start the extraction of the regenerated beam; ρ_0, k, and m are adjustable parameters. We chose $\rho_0 = 83.5$ cm, the distance to the center of the machine of an intermediate orbit between the last one at 84.5-cm radius and the corresponding orbit one turn earlier at 82.8 cm. The necessary magnetic field along the path can be calculated once the curvature radii R_c are known. These are obtained with the well-known formula

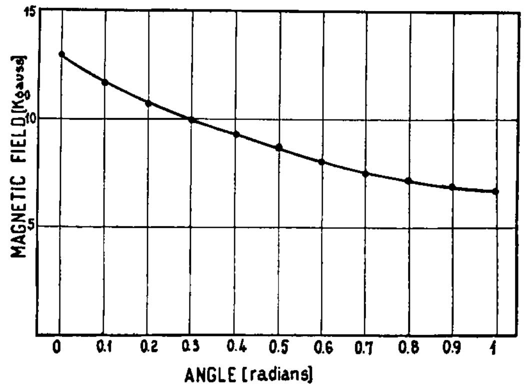


FIG. 5. Magnetic field corresponding to the proposed trajectory.

$$R_c = \frac{(\rho'^2 + \rho^2)^{\frac{3}{2}}}{\rho^2 + 2\rho'^2 - \rho\rho''}, \tag{2}$$

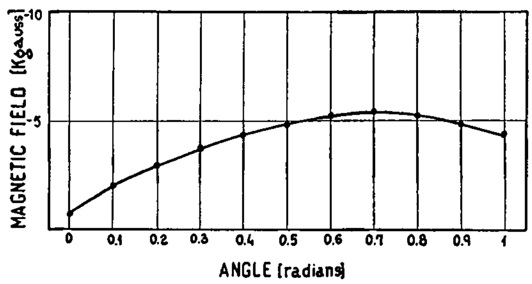


FIG. 6. Magnetic field decrease in the channel.

where the primes indicate derivatives with respect to α. If the initial curvature ($\alpha = 0$) should be $1/\rho_0$, Eq. (2) indicates that $m > 2$. Its value, as well as the value of k, were obtained after a number of trials, taking into account the criterion of least perturbation of the circulating beam. If ρ is given in centimeters, $k = 10$ and $m = 11/4$; thus, the equation of the spiral finally chosen for the extraction is

$$\rho = 83.5 + 10\alpha^{11/4}. \tag{3}$$

Figure 4 is a drawing of the function $\rho(\alpha)$ in the interval of 1 rad. The necessary magnetic field values for the emergent particles are then simply calculated as $B(\alpha) = B_0R_0/R_c(\alpha)$. This function is shown in Fig. 5. The differences with respect to the existing field in the machine are shown in Fig. 6. Next it is necessary to determine the size and shape of iron required to produce the calculated field along the trajectory. For this purpose the interval from 0 to 0.7 rad was divided into six sectors. The principle of least perturbation of the regenerated orbits was used to decide the construction of the first three sectors as "one-wall channels" (see Fig. 7). The field depression is produced by a single piece of iron A, while the pieces B and B′ restore the field value in the region between them to the one existing before, in the absence of A. Between pieces B and A the field shape should provide vertical focusing. The height of the iron is 4 cm because this was the vertical size of the beam. The remaining magnetic channel sectors were conventionally made with two walls of equal size. The channel sectors were mounted in such a way as to permit their radial displacement or to change their direction. Two alternatives were considered concerning the installation of the deflector in

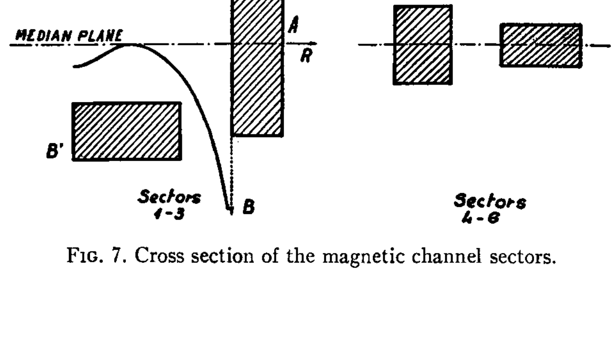


FIG. 7. Cross section of the magnetic channel sectors.

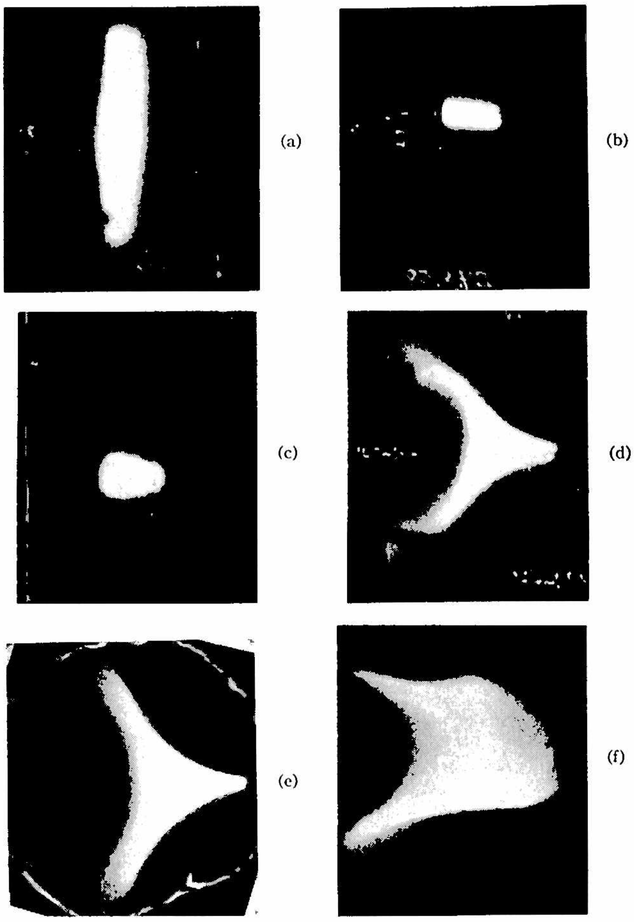


FIG. 8. Cross section (approximate reduction, two-thirds) of the beam obtained with autoradiographs: (a) at the entrance of the channel, (b) at the exit of the third sector, (c) beam lost on the cross section of the internal wall of the fourth sector, (d) beam emerging out of the sixth magnetic sector, (e) beam emerging out of the machine (glass autoradiograph), and (f) beam entering the magnetic quadrupoles (glass autoradiograph). In all cases the machine should be to the left of the reader.

the machine: (1) The complete assembly could be installed and the field restored with the necessary shimming before letting the beam circulate through the channel. (2) Having confidence in the localized nature of the perturbation, one could install the channel sectors without restoring shims, using the beam to determine the optimum position; afterwards, the magnetic field could be restored once and for all.

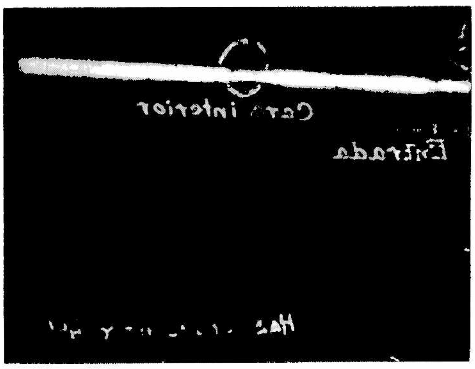


FIG. 9. Autoradiograph of the beam incident on the internal wall of the fourth magnetic sector. The circle encloses a node of the vertical oscillation. (Reduction, three-fifths.)

The second alternative was followed because it seemed to be simpler (the first usually requires a second field correction once the optimum channel orientation is found). Thus, the first three "one-wall" sectors were placed inside the machine with good results. The regenerative action persisted, and a beam vertically focused was obtained out of the channel. The beam height was 40 mm at the entrance and 3 mm at the exit, see Figs. 8(a) and (b). As the fourth sector was placed in the machine the regenerative action disappeared. Nevertheless, it could be restored by moving the regenerator radially inwards. Obviously the positive regenerator field compensated the depression due to the sector inside the machine. This procedure failed with the fifth sector. It was then decided that, in view of the small vertical size of the beam emerging from the first three sectors, it was advisable to change sectors four to six and "tailor" them to the size of the beam. The fourth sector was made 1.5 cm high; it provides some radial focusing. The fifth and sixth sectors are 2 cm high and provide the same type of focusing as the fourth. The "history" of the beam passage through the magnetic channel sectors is shown in Fig. 8. The perturbation produced by the new channel sectors was obviously smaller because it was possible to restore the regenerative action by moving the regenerator radially inwards. In order to obtain the optimum channel orientation the following procedure was followed: The inside walls of the sectors were covered with aluminum foil from which autoradiographs were taken. The blackening of the photographic plates was proportional to the activity of the foil, and the latter was proportional to the intensity of the beam hitting the channel walls. The channel sectors were oriented in such a way as to obtain a slight and equally strong blackening on both walls. Figure 9 shows one of these autoradiographs; it corresponds to the fourth sector and it is interesting to note that one can

FIG. 10. Photograph of the magnetic channel and the regenerator installed in the machine. The channel is without the correcting shims.

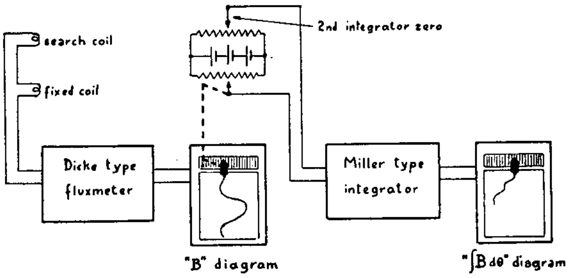


FIG. 11. Block diagram of the magnetic measurement equipment.

observe a vertical node of the beam. Figure 10 is a photograph of the magnetic channel and the regenerator before the restoring shims were placed in front of them.

V. MAGNETIC FIELD CORRECTIONS

It was necessary to perform a magnetic field measurement to determine the value of the perturbation produced by the magnetic channel. A fluxmeter (Dicke[4]) constructed by our Department of Electronics was used to measure the magnetic field. Along different radii the $\int B_z d\theta$ was simultaneously obtained with an electronic integrator of the Miller type. By following a suggestion by P. A. Lenk, the input signal for the integrator was obtained from a potentiometer mounted on a Philips registering voltmeter (used to inscribe the magnetic field variations). The potentiometer terminals were connected to a battery, and the signal was obtained from a contact fixed to the registering carriage. Figure 11 is a block diagram of the magnetic field measurement equipment. An interesting feature is the compensating coil shown there. It is similar to the one used to measure the magnetic field, but is wound in the opposite direction and kept at a fixed place in the field of the machine. Thus one eliminates the field variations not corrected by the electronic magnet current regulator. These variations were important when the integral $\int B_z d\theta$ was small. Figure 12 shows the perturbation due to the channel and the result of the correction. The basic idea was to annul the value of $\int B_z d\theta$, trying at the same time to reduce to a minimum the absolute value of field B_z variations for all values of θ. Figure 13 shows the final field obtained with the regenerator, the channel, and the correcting shims. The net regenerator field can be adequately approximated by

$$F = 2.5r + 0.1r^2 \text{ (kilogauss-deg)}, \quad (4)$$

where $r = \rho - 77$.

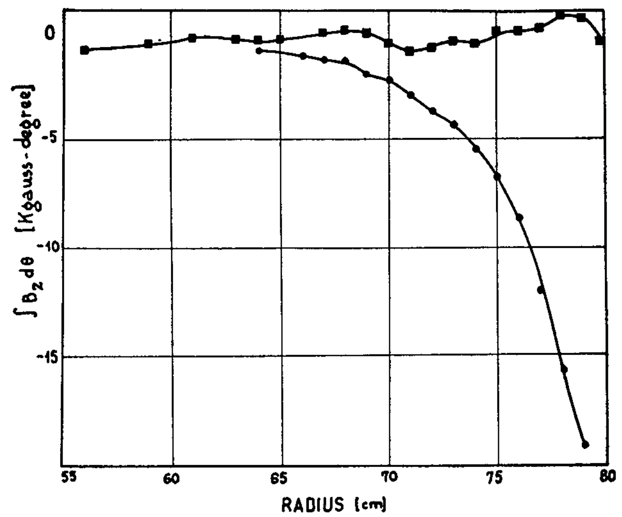


FIG. 12. $\int B_z d\theta$ corresponding to the magnetic field disturbed by the magnetic channel (circles) and to the corrected field (squares).

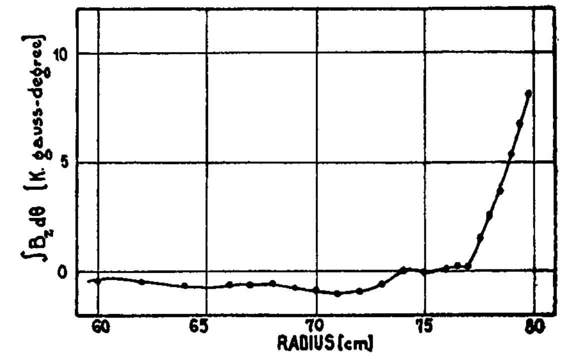


FIG. 13. Final field due to the regenerator, the magnetic channel, and the correcting shims.

VI. BEAM TESTS AND CONVEYANCE INTO THE EXPERIMENTAL AREA

The efficiency measurements were performed using the conventional target at 77-cm radius, a target at the channel entrance, and a Faraday cup at the channel exit. The resulting over-all efficiency was 2%. Twenty percent of the circulating beam is thrown into the channel, and its transmission is 10%. It is worth while to point out that the transmission of the channel was raised from 5 to 10% by properly orienting the last three sectors.

The beam emerging out of the magnetic channel passes behind the structure supporting the regenerator; fixed on the same structure there is a directing iron that centers the

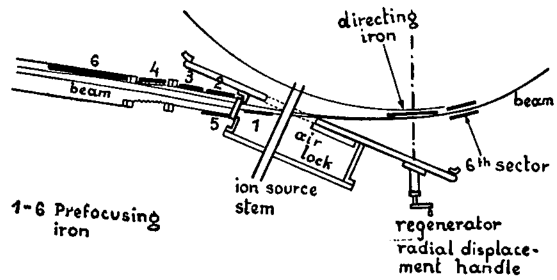


FIG. 14. Geometrical layout of the beam exit apertures and of the directing and prefocusing iron.

[4] R. H. Dicke, Rev. Sci. Instr. 19, 533 (1948).

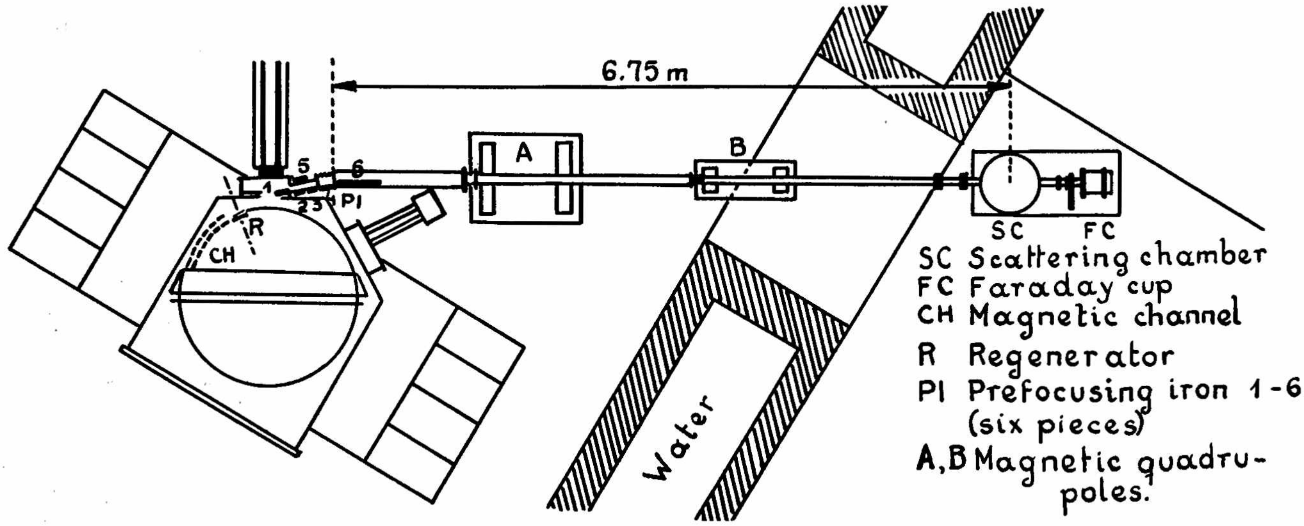


FIG. 15. General view of the external beam facilities.

beam on the ion source air-lock gate. This aperture is unfavorably located with respect to the emergent beam, as is shown in Fig. 14. The stray magnetic field of the machine has a strong defocusing action on the beam. To neutralize this effect six additional magnetic sectors were located along the beam path. They are magnetized by the stray field and with them it was possible to keep the beam almost parallel up to the entrance to the alternating gradient quadrupole lenses, some 2 m from the vacuum tank of the machine (see Fig. 15). The radial divergence was cut down to 17′ of arc (1/200) and the vertical divergence was not measurable.

Two pairs of magnetic quadrupoles provide the necessary focusing of the beam in the experimental area, at 6.75 m from the machine. Numbering the quadrupoles 1, 2, 3, and 4 in the order they are met by the beam, their focusing action for the optimum beam shape and current is as follows: radial, vertical, vertical, and vertical (referred to a parallel beam). The currents through all of them differ. Beam shape autoradiographs were taken by irradiating plain glass. The glass acquires a brown color after a short irradiation time (15 to 30 sec) and reveals very accurately the shape and structure of the beam. Positives can be obtained on photographic paper, just as with conventional negative plates.

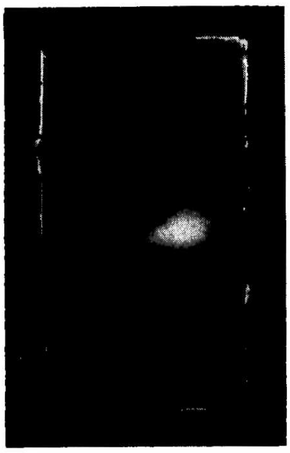


FIG. 16. Glass autoradiograph (no reduction) showing the beam spot on the target in the experimental area. No slits or collimators were used along the beam path.

The extraction work was performed with deuterons. Their energy was found to be 28.1 Mev as reported elsewhere.[5] The beam spot in the experimental area is some 7 mm in diameter and 0.05 μa in intensity. A nice feature of the magnetic deflector assembly is that the regenerator can be displaced radially from the outside, thus permitting an easy optimization of the external beam with regenerator and directing iron position.

VII. ACKNOWLEDGMENTS

We wish to thank the synchrocyclotron technicians J. Garanzini, B. Ietri, M. Professi, and S. Tejero for their able assistance during all phases of our work. We are indebted to electronics engineer P. A. Lenk for his continuing help during the materialization of the project and for many useful discussions.

[5] P. A. Lenk and R. J. Slobodrian, Phys. Rev. 116, 1229 (1959).