Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

ION OPTICAL STUDIES OF EXTRACTION TRANSPORT AND ANALYSIS SYSTEMS FOR 240 CM CYCLOTRON

V.N.Barkovsky, Ju.G.Basargin, R.N.Litunovsky, O.A.Minjaev, A.V.Popov, A.V.Stepanov

Scientific Research Institute for Electrophysical Apparatus, Leningrad, U.S.S.R.

Abstract

High demands (for example [1]) claimed to beam quality of modern cyclotrons force to solve on the whole the problems of extraction and transport of particles. In 240 cm cyclotron design [2] six experimental rooms with total area of about 1000m^2 are provided. The ion optics of this installation has been described earlier in the paper on Frascati conference[3]. In the present paper some results of electronic computer calculations of the extraction and transport systems' parameters are given. A brief description of secondary particle analyzers is also given.

Beam Extraction System (Fig.1).

The initial deflection is carried out by 30° electrostatic deflector, placed in the "valley". The last equilibrium orbit has average radius 105÷107 cm. The deflector aperture is 7 mm and the septum thickness is 0.8 mm. In case of 100 MeV protons the field gradient is 120 Kv/cm.

At the radial betatron oscillation frequency ν_r =1.125 (extraction from isochronous orbit) 58% of circulating beam passes the deflector at $\pm 6\cdot 10^{-3}$ inhomogeneity in energy; when ν_r =0.5, the effectiveness increases up to 72% and energy spread decreases to $\pm 3\cdot 10^{-3}$. It was assumed, that for the 100 MeV protons the energy gain per turn is ≤200 Kev and horizontal emittance of circulating beam is 120mmmrad (coherent oscillations are absent).

Three identic sections of special deflecting winding (Fig.1) are symmetrically placed along the equilibrium orbit (one section inside the dee). The length of each section is 35°. Each section consists of two coils with 20 mm vertical distance between them. The winding does not give resonance azimuth disturbance of the magnetic field.

The section behind the deflector operates as magnetic channel, which decreases the main field on 1000 gauss. Beam aperture is not limited by the winding.

Internal part of the winding has the equilibrium orbit form and creates a sharp field drop (averaged along the orbit radial gradient is about 100 gauss/cm). This gives the possibility without any essential phase slip to accelerate ions to the orbit with ν_r =0.5. In such regime it is necessary to compensate carefully the magnetic field disturbances of the first harmonic type.

At 107° distance from the deflector entrance in the middle of the "valley" a 25 cm long magnetic channel with positive gradient 400 gauss/cm is mounted. On the 165° azimuth the beam enters the uniform field magnet M_0, correcting the direction of the extracted beam at changing the energy or the type of accelerated ions. This magnet also has "quadrupole" winding with separate power supply.

On the basis of magnetic field modelling data deflected reference ray coordinates and transfer matrix elements were calculated. These matrices are at the end of the fringe-field

$$M_x\ (165^\circ) = \begin{pmatrix} 0.872 & 779.0 & 836.0 \\ 0.00540 & 5.97 & 7.04 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_z\ (165^\circ) = \begin{pmatrix} -2.18 & -120.0 \\ 0.00332 & -0.276 \end{pmatrix}$$

where M_x operates on the column vector [x(cm), x' (radians), Δp/p] and M_z operates on [z(cm), z' (radians)].

If we assume, that at deflector entrance the particles on horizontal phase plane are distributed inside the canonical ellipse with half-axes $X_{0\,max}$ and $X'_{0\,max}$, then beam halfwidth is $X=\tilde{X}+|a_{13}\Delta p/p|$ where $\tilde{X}=\sqrt{a_{11}^2X_{0\,max}^2+a_{12}^2X'^2_{0\,max}}$

The same for vertical movement

$$\tilde{Z}=\sqrt{b_{11}^2Z_{0\,max}^2+b_{12}^2Z'^2_{0\,max}}$$

where a_{ik} , b_{ik} - appropriate elements of matrices M_x and M_z.

Because of dispersion in the cyclotron magnet fringe-field, the effective horizontal emittance $S_{x\,ef}$ is considerably increased as compared to the emittance

$$S_{x0}=\pi X_{0\,max}X'_{0\,max}$$

at deflector entrance: $S_{x\,ef}=S_{x0}+$

$$+\frac{4\Delta p}{p}\left[(a_{11}a_{23}-a_{21}a_{13})^2X_{0\,max}^2+(a_{12}a_{23}-a_{22}a_{13})^2X'^2_{0\,max}\right]^{1/2}$$

At the extraction from the orbit, where $\nu_r=1.125$, $S_{xo}=15$ mm mrad, but $S_{x\,ef}=180$ mm mrad. In the second regime, when $\nu_r=0.5$, $S_{xo}=30$ mm mrad, $S_{x\,ef}=155$ mm mrad. In the first approximation the dispersion does not influence the vertical emittance which is assumed to be $S_z=\pi\cdot 6\cdot 6\cong 110$mm mrad.

External Ion Optics.(Fig.2).

Beam transport system allows:

1) to direct the preliminary energy analyzed beam on any external target;

2) to eliminate the radiation backround in the operating areas from the analyzing slit by double bending of the beam;

3) to carry out such a regime, when beam quality on targets does not depend on dispersion in deflecting magnetic fields.

The calculations of beam envelopes and dispersion were made. It was assumed, that $S_{xo}=\pi\cdot 2,5\cdot 4=31$ mm mrad, $\Delta p/p=\pm 5\cdot 10^{-3}$, so that at the entrance of magnet Mo, the value $S_{x\,ef}\simeq 440$ mm mrad; vertical emittance, $S_z\cong 110$ mm mrad.

Fig.3 gives the information about beam profile changing (envelopes $\bar{X}$ and $\bar{Z}$) along the central axial trajectory (beginning from deflector entrance) in case of transporting the beam in the area IV. The central ray for particles differing by momentum on $\Delta p/p=+5\cdot 10^{-3}$ is also shown. Magnet Mo and quadrupoles Q_1, Q_2 carry out double focussing of monoenergetic particles in the middle of lens Q_3. The lens doublet Q_4,Q_5 forms very narrow (± 0.5 mm) horizontal waist at the centre of the defining slit C_2. 270° analyzing magnet with inhomogeneous field (n=0.831) refocuses this point at the symmetrically placed centre of the analyzing slit C_3. Dispersion of the cyclotron magnet is added to that of analyzer (its radius is 2 m) and at $\Delta p/p=\pm 5\cdot 10^{-3}$ the dispersion equals ± 12.3 cm in focal plane. At one mm width of the slit C_3, the energy resolution of the analyzer is $8\cdot 10^{-5}$ (not counting aberrations). Lens Q_3 does not almost influence on monoenergetic beam profile, but this lens can change dispersion ray direction. Lenses Q_4, Q_5 focus vertically the beam at the analyzer entrance so, that emittance ellipse is a good match to vertical acceptance ellipse of the analyzer (halfwidth $\bar{Z}$ does not exceed 1,5 cm inside it).

At the entrance and exit of the analyzer the sextupole type field magnets S P_1 and S P_2 (Fig.2) are installed for the compensation of the second order horizontal spherical aberrations.

The analyzed beam is deflected into the corridor by the bending magnet BM_1 and then by means of lenses Q_8, Q_9, Q_{11}, Q_{12} and magnets BM_2 and BM_3 is directed to the area IV, where it is focussed on the target. In the same way the beam can be transported to other areas; we can also direct the analyzed beam to the area I, passing by the corridor (Fig.2).

Fig.3 shows also the focussing functions

$$g_x=\frac{R_k^2}{\rho^2}+\frac{\partial B_z}{\partial x}\frac{R_k}{\bar{B}_k}; \qquad g_z=-\frac{\partial B_z}{\partial x}\frac{R_k}{\bar{B}_k},$$

where ρ - curvature radius of the central trajectory;

$\bar{B}k$ - average field on the radius Rk of the last cyclotron orbit;

$\frac{\partial B_z}{\partial x}$ - magnetic field gradient on the central trajectory.

The system is achromatic, if its elements are tuned according to the Fig.4. The lenses Q_4, Q_5 make the horizontal trajectories "parallel". The "picture-frame" analyzing magnet has "quadrupole" winding, which changes the value n from 0.831 (this value is provided by gap profile) to 0.352. At n=0.352 the parallel monoenergetic beam is horizontally focussed at the analyzing slit C_3. In this case the regime of lens Q_3 is chosen in such a way, that by means of lens Q_6 the central dispersion ray from the cyclotron can be connected with imaginable dispersion ray, emerging in the opposite direction from magnet BM_1. At the magnet BM_1 exit the horizontal emittance is equal to that at deflector entrance, which is 5÷10 times less than the effective emittance of the extracted beam. Similar to the scheme of Fig.3, the beam is focussed vertically at the analyzing magnet entrance. After magnet BM_1 the beam can be directed in any experimental area. The use of standard achromatic bending systems (magnet-quadrupole - -magnet[4]) maintains on the targets a small value of the horizontal emittance. The variation of analyzing slit C_3 width can change beam momentum spread without deterioration of the beam quality. At $\Delta p/p=\pm 5\cdot 10^{-3}$ dispersion in focal plane equals ± 2.7 cm in regime of Fig.4.

Analyzing magnet aperture is $40\cdot 10$ cm^2. C - shaped magnets BM with uniform field have the aperture $20\cdot 10$ cm^2 and the effective bending radius 160 cm. The quadrupole lens effectife length is 60 cm, gradient - 500 gauss/cm and aperture - 20 and 15 cm.

Secondary Particle Analyzers.

Two secondary particle analyzing magnets, spectrometer and broad-range spectrograph, are supposed to be installed in the arèa I. Vertically mounted 270° magnet with 180 cm bending radius and n=0.831 is used as a spectrometer. Fig.5 shows the trajectories if we assume a point source. We observe double focussing in focal plane and intermediate vertical focus is formed in the middle of sector.The target and the detector are symmetrically placed at the distance of 175 cm between them. At 2 mm analyzing slit width the momentum resolution is 10^{-4} (not counting aberrations). The used solid angle is $4\cdot10^{-3}$ steradian.

The "quadrupole" winding can change the value n to n=0.169. From Fig.6 we can see, that in this case the triple focussing (similar to the Stanford spectrometer [5]) takes place, that allows to record the particles with momentum spread ±5% simultaneously.

The Fowler spectrograph [6]with vertically focussing quadrupole lens at the entrance can be used for the simultaneous recording and analyzing of particles, differing by momentum 2.25 times (such combination (Fig.7) was also proposed in Helsinki University [7]). Trajectory radii are 80÷180 cm; the field in the gap of the magnet with uniform field is up to 12000 gauss. The difference of the 220 cm long focal line from a straight one doesn't exceed 7 mm. At 2 mm target width the momentum resolution is estimated to be equal to $3.7\div4.8\cdot10^{-4}$ (not counting aberrations). Lens length is 30 cm, gradient - 1250 gauss/cm.

In room IV an achromatic channel for ions polarized while scattering at the target is to be installed.

References.

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Note: Presented in Russian by A. V. Stepanov with translation by J. Lewin.

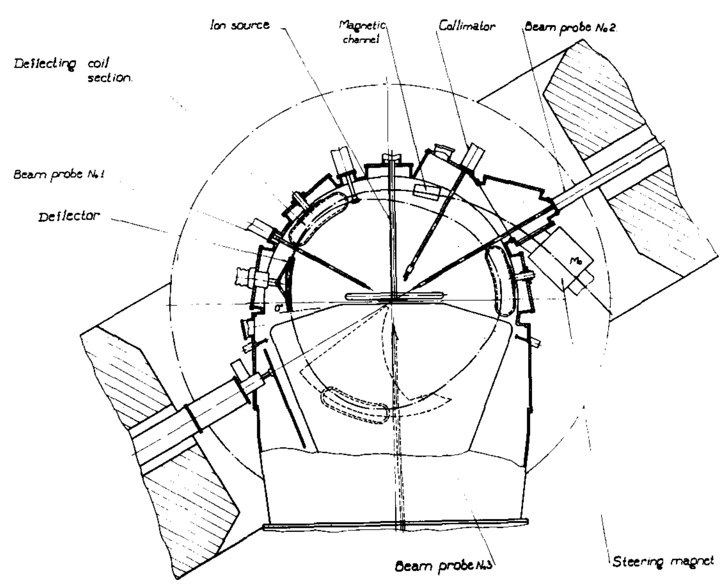

Fig.1. The vacuum chamber.

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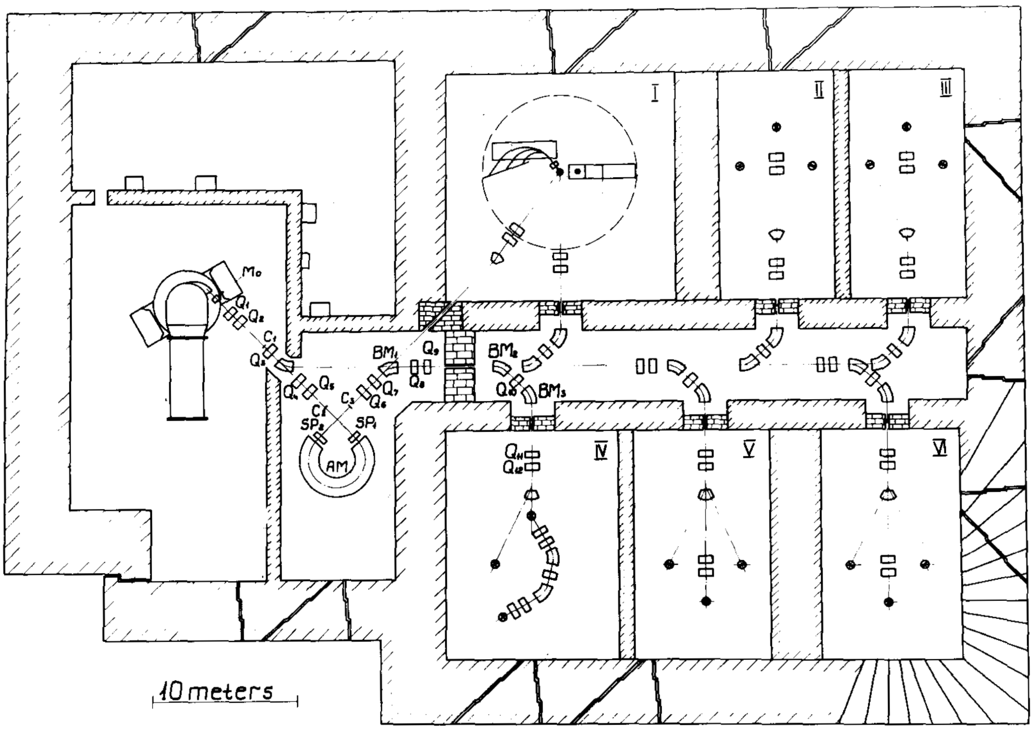

Fig.2. The ion-optics layout

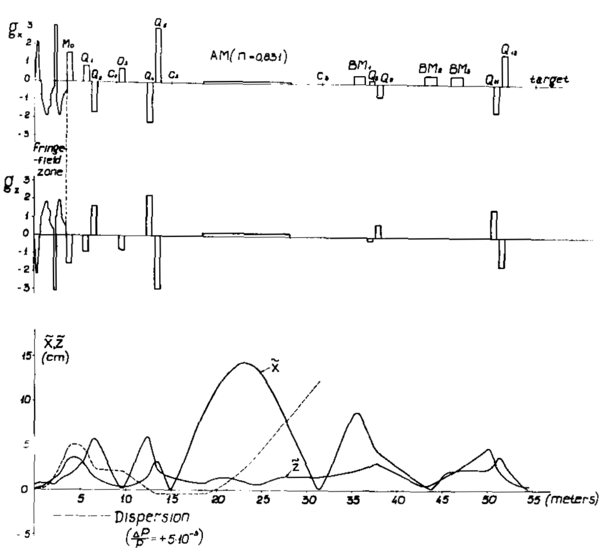

Fig.3. Beam envelopes and dispersion in the case of analyzed particle transport to area IV. Analyzing magnet has n=0,831

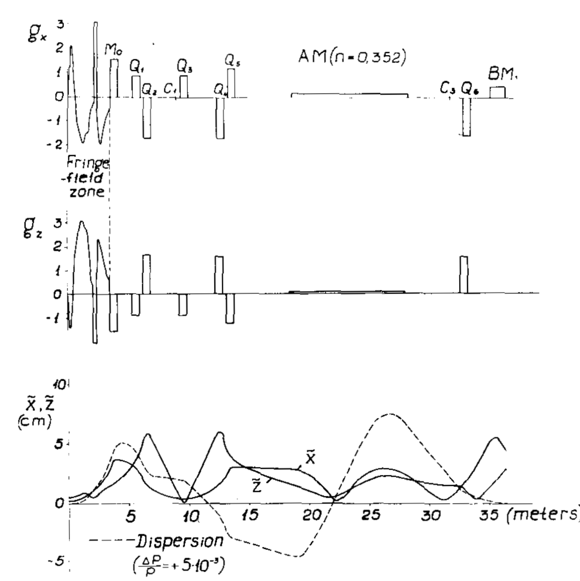

Fig.4. Beam envelopes and dispersion in the case of achromatic transport. Analyzing magnet has n=0,352

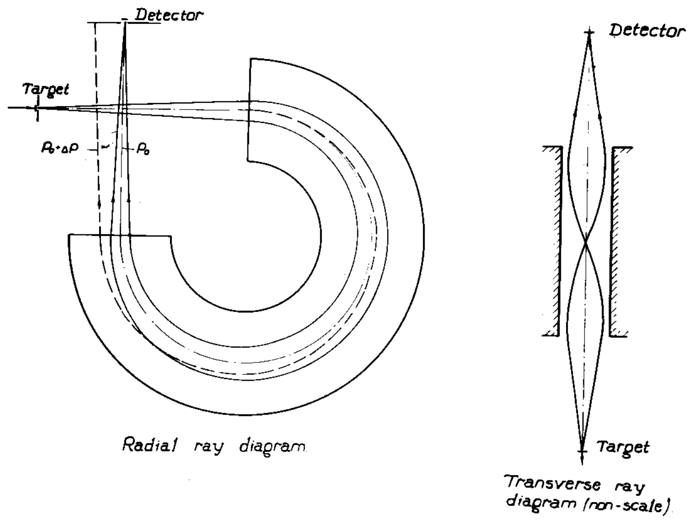

Fig.5. Trajectories in the spectrometer with n = 0,831.

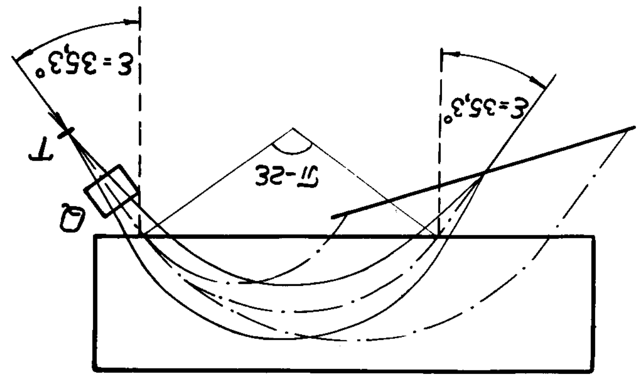

Fig.7. Horizontal plane trajectories for Fowler spectrograph with quadrupole lens.

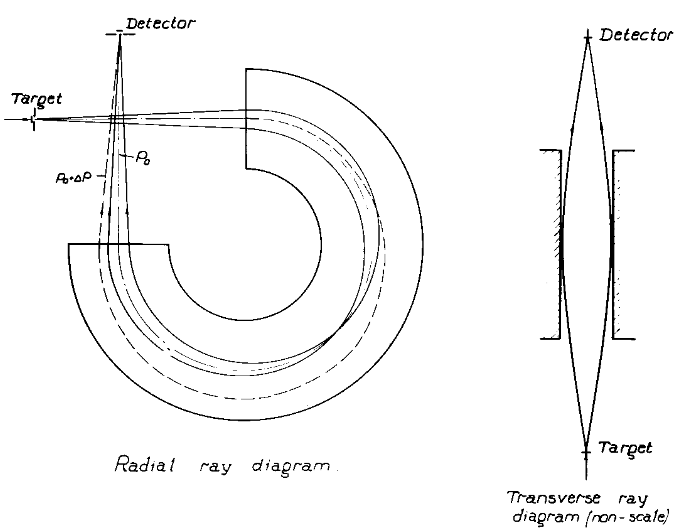

Fig.6. Trajectories in the case of triple focussing (n=0,169).

DISCUSSION

WEGNER: What is your construction schedule?

STEPANOV: The magnet with trim coils is now under construction, nearing completion, and construction has begun on the site in the city of Kiev.

LIVINGOOD: What is the slit width used in attaining 8 x 10^{-5} energy resolution?

STEPANOV: 1 millimeter.

BALL: What is the radius of the curvature of this beam-analyzing magnet?

STEPANOV: 1.8 meters.

