The external beam monochromatisation system in the 2·4 m isochronous cyclotron at the Kurchatov Atomic Energy Institute

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ABSTRACT

The results of calculations for the external beam monochromatisation system for the 2·4 m cyclotron at the Kurchatov Atomic Energy Institute are given. In this system an energy spread compensation of the beam by an rf voltage on the debuncher is used. A special mirror-symmetrical achromatic magnetic system provides a momentum separation of the beam. An improvement of energy spread from ±0·2% to 0·02% is expected. The methods of stabilisation and fine control in the system are discussed.

1. INTRODUCTION

There is the possibility of a considerable decrease in the energy spread of cyclotron beams without any loss of intensity if one uses the method developed earlier for linear accelerators. This method is considered a basic one in the Isochronous Cyclotron Laboratory Design at the Kurchatov Atomic Energy Institute.[1–3]

2. RF ENERGY SPREAD COMPENSATION BASED ON THE LONGITUDINAL MOMENTUM SEPARATION OF PARTICLES

Rf compensation is widely used in proton linear accelerators. An additional resonator (so called debuncher) with the same wave length λ as that of the accelerator is placed at a distance L from the linear accelerator.

At the maximum momentum spread of the particles in the linear accelerator $\pm\Delta p_m/p_o$ at the flight length L, a longitudinal momentum separation takes place because of the difference in velocities. The maximum phase shift is:

$$\phi_m = \frac{2\pi L}{\gamma^2\beta\lambda} \times \frac{\Delta p_m}{p_o} \tag{1}$$

where $$\gamma^2 = \frac{1}{1-\beta^2}$$

The debuncher is phase in such a manner that the particles with a momentum $p_o + \Delta p$ are decelerated and those with a momentum $p_o - \Delta p$ are accelerated and thus partial energy spread compensation occurs. Used in this way however direct rf compensation of the cyclotron beam is impracticable.

The longitudinal momentum separation of the particles arises not only because of the difference in velocities in the process of straight drift but also because of the difference in axial trajectories for particles of different momenta in the magneto-optical bending systems.[4] It turns out that the application of the

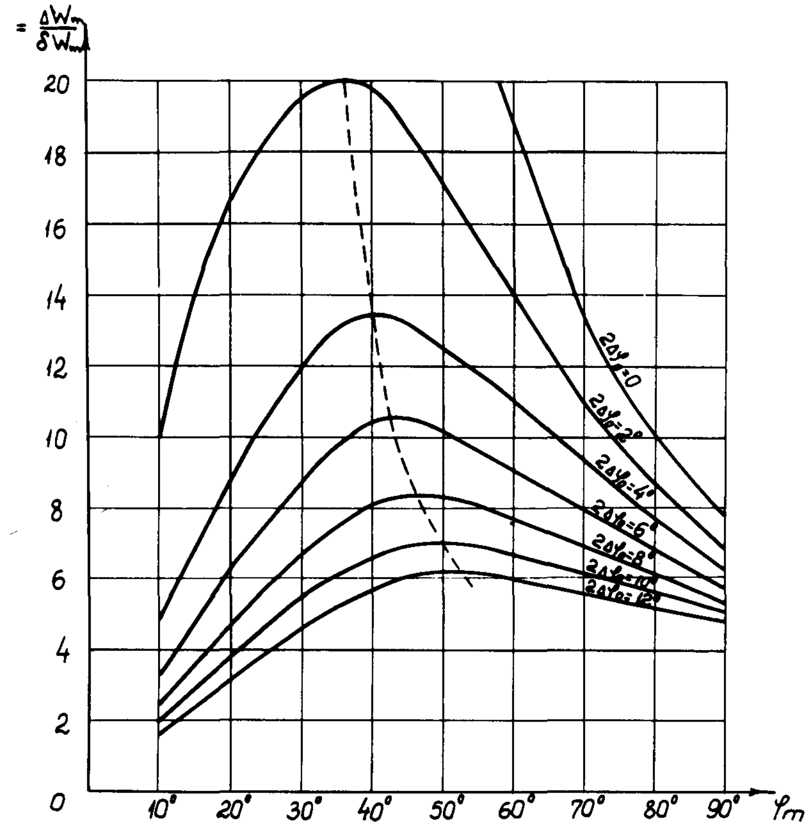

Fig. 1. Dependence of the energy spread improvement coefficient on φ_m at different $2\Delta\varphi_o$

method to be described permits a considerable reduction in the size of the monochromatisation system for the cyclotron beam.[2]

The efficiency of compensation becomes worse owing to the final phase width of the monoenergetic bunches $2\Delta\varphi_o$ immediately in front of the debuncher and owing to the non-linearity of the sinusoidal rf voltage. The energy spread improvement coefficients $\eta = \Delta W_m / \delta W_m$ vs maximum phase φ_m for different values of $2\Delta\varphi_o$ are shown in Fig. 1. Some magneto-optical transportation systems with a rectilinear axis are similar to the achromatic bending systems in which the length of the monoenergetic bunches and the transverse emittance of a non-monochromatic beam[5, 6] are constant in a linear approximation. In the case of systems with curvilinear axes the longitudinal separation can be characterised by an effective length $\widetilde{L}$

$$\widetilde{L} = L_o - \gamma^2 L^* \qquad (2)$$

where L_o is the length of the system axis between the accelerator and the debuncher, and L^* is the beam dispersion function in the system.[5]

3. DESCRIPTION OF THE ENERGY SPREAD COMPENSATION SYSTEM

The parameters of the system conform to the requirement of the beam monochromatisation in the Y-240 cyclotron[7] with maximum energy protons of 100 MeV. The system is given in Fig. 2. The 4π symmetrical and achromatic bending system and the debuncher T_2 are the basic devices. The flight tube of

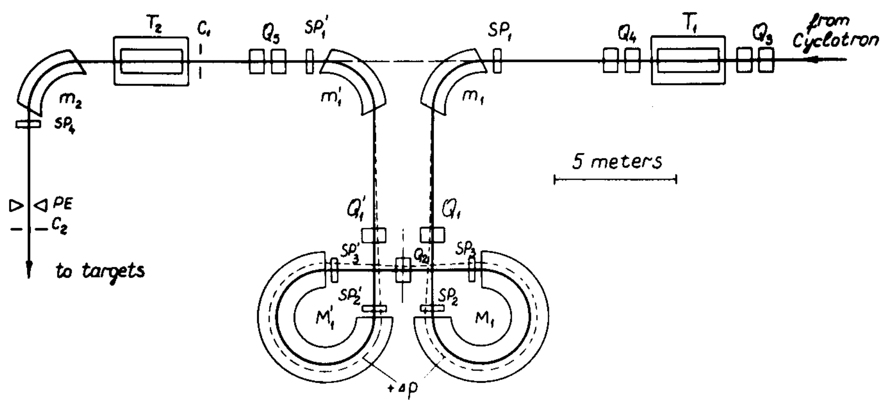

Fig. 2. Monochromatisation system

the debuncher with two accelerating gaps has a length of $\pi r_k = \frac{1}{2} q \beta \lambda$, where r_k is the radius of the last orbit in the cyclotron and q is the harmonic number. Magnets m_1 and m_1' with homogeneous field and with 'edge' vertical focusing ($\epsilon_1 = \epsilon_2 = 26{\cdot}5^\circ$) deflect the beam by 90° each; magnets M and M' with 'gradient' focusing ($\eta = 0{\cdot}831$) deflect the beam by 270° each.

The magnet m produces an initial angular deflection of the dispersive axial trajectory shown in Fig. 2 by a dashed line. A quadrupole lens Q_1 produces defocusing in the horizontal plane thus considerably increasing the angle of the dispersive trajectory. Such a 'drive' results in a large positive value of dispersion D inside the magnets M and M' and correspondingly in a large absolute effective length of the system L. The quadrupole lens Q_2 makes the dispersive trajectory symmetrical and this provides the achromaticity of the system. The magnets M, M' are supposed to be similar to those in a spectrometer.[8]

Protons with an energy of 100 MeV have an effective flight length $\widetilde{L}$ of 860 m; this requires $\varphi_m = 40°$ at $\Delta p_m/p_o = 1 \times 10^{-3}$ and needs a maximum potential of 150 kV at the drift tube of the debuncher.

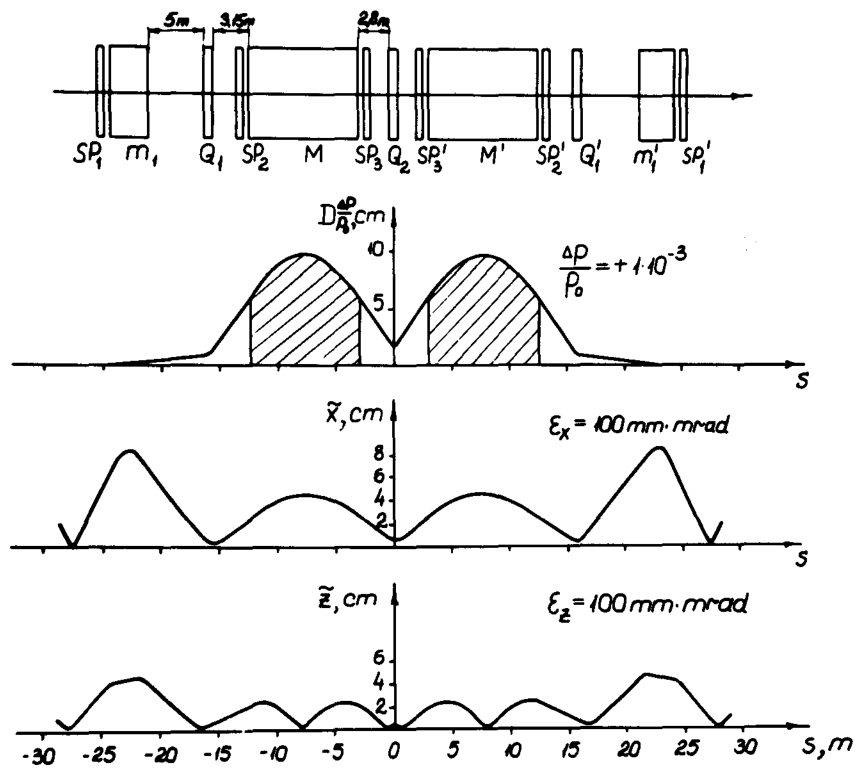

Fig. 3. Dispersive trajectory and beam envelopes

The optical properties of the system are shown in Fig. 3 in a linear approximation. The lengths of the rectilinear paths between the effective boundaries of the bending magnets and the quadrupole lenses are shown. The dispersive trajectory $D\,\Delta p/p_o = 1 \times 10^{-3}$.

Behind the magnet m'_1 a quadrupole pair should focus beams in front of the analysing magnet m_2(Fig.2), with a homogeneous field and with 'edge' vertical focusing ($\epsilon_1 = \epsilon_2 = 31°$). At the slits C_1 and C_2 with a width of 1 mm this magnet analyses the beam energy with an accuracy of 2×10^{-4}. In front of the slit C_2 a probe indicating the beam location is placed. This probe is connected with a system of stabilisation and energy control provided by a drift tube T. Besides this, sextupole magnets SP with rectangular apertures[8] (which are necessary for compensating the aberrations of the longitudinal and transverse movements) are incorporated in the system (Fig. 2).

4. STABILISATION AND FINE ENERGY VARIATION

The beam phase instability in the cyclotron, the debuncher voltage phase instability and the instability of the magnetic fields in the elements of the monochromatisation system lead to a drift of the median beam energy at the outlet of the system.

A block diagram of the system used for stabilisation and fine energy variation over a small range is given in Fig. 4. It omits the adjustment of the cyclotron and the elements shown in Fig. 2, with the exception of the analysing magnet m_2 which is a controlling part of the system.

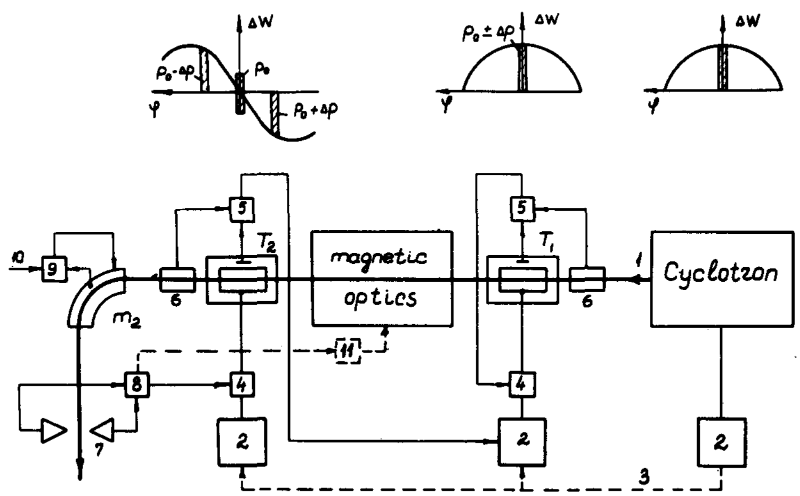

Fig. 4. Block-diagram of the energy variation and stabilisation system.
1 - beam, 2 - rf oscillators, 3 - synchronisation and initial phasing circuits, 4 - phasechangers, 5 - phase detectors, 6 - phase probes, 7 - differential beam displacement probe, 8 - amplifier, 9 - stabilisation and field control circuit using the signal from a nuclear magnetic resonance probe, 10 - control system, 11 - power-supply for the correcting magnets d *and* d'

Instability of the median energy causes a displacement of the beam axis behind the magnet m_2. This displacement is measured with a differential beam position probe. The error is fed to a phase-switcher of the debuncher T_2, which shifts the rf voltage phase in the corresponding direction referred to the centre of the bunch. Changing the field of the magnet m_2 by this feed-back, it is possible to control the energy in a rather narrow range. The phase of the bunch centre can be brought back to the zero position if one changes the energy at the inlet of the system with an additional resonator T_1 (Fig. 2). This can be performed automatically by the second independent feed-back. Limitations on energy variation depend on the voltage at T_1 and on the permissible radial displacement of the axial beam trajectory in the chamber of the magnets M and M'. Curve 1 in Fig. 5 shows a displacement of the axial trajectory from the axis of the system when a median momentum is changed by $\Delta p_v/p_o = 1 \times 10^{-3}$.

A second mode of stabilisation and energy variation has also been discussed for which a signal from a differential beam location probe shifts the bunch phase relative to the rf debuncher voltage. For this purpose it is necessary to vary the effective length $\widetilde{L}$ of the system by magneto-optical methods. In the second mode a signal acts on the power-supplies of short correcting magnets d and d' (Fig. 5). The magnet d disturbs the axial trajectories of particles with a momentum p_0. It is necessary to compensate this disturbance in the second part of the system with a magnet d' to preserve symmetry and achromaticity. The compensation will take place if d and d' are located symmetrically and in

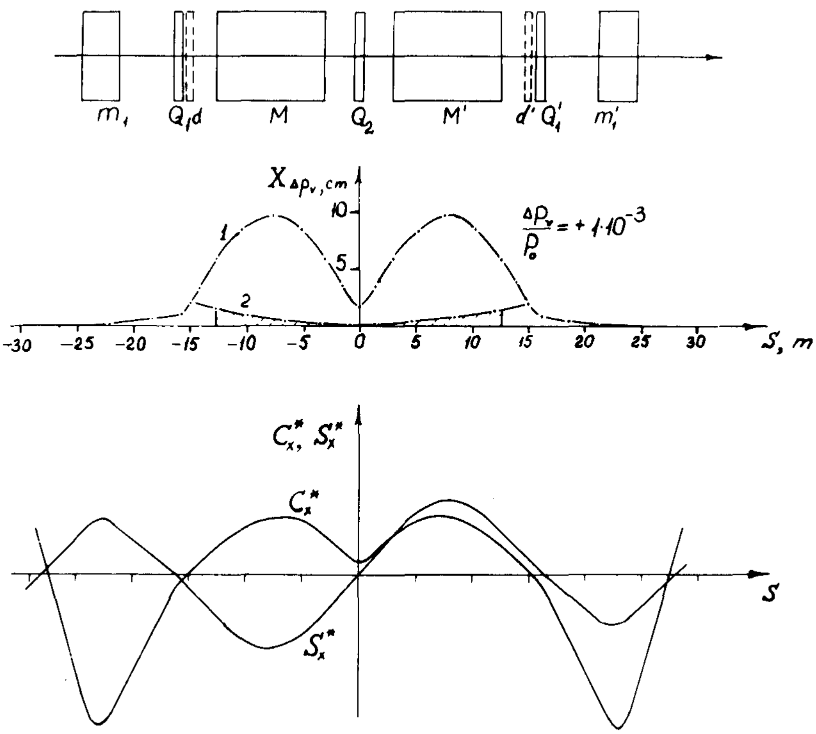

Fig. 5. Displacement of the beam axis in the process of energy control and the main sine-shaped and cosine-shaped trajectories. The shaded area below Curve 2 corresponds to a negative phase displacement compensating a positive displacement along the length from T_1 *to* T_2 *in the second mode of energy control*

such a manner that the cosine shaped main trajectory C_x^* of the horizontal movement[5] crosses the axis of the system half way between these magnets, as shown in Fig. 5.

In the second mode an extension of the energy variation is also provided by changing the rf voltage of the resonator T_1. But in this case the beam axis is displaced from the axis of the system by $X_{\Delta p_v}$ (curve 2, Fig. 5), considerably less than in the first mode. The necessary accuracy of field control in the magnets m_1, m_1', and m_2 is 1×10^{-5}, and in M and M' it is 3×10^{-5}. The necessary accuracy of current control in the quadrupole lenses is 1×10^{-4}.

5. ABERRATIONS IN THE LONGITUDINAL MOVEMENT

The greater the energy spread improvement coefficient determined with the curves in Fig. 1 the less is the phase width $2\Delta\phi_o$ of the monoenergetic bunches at the entrance to the debuncher. However, the bunches are lengthened on their path from the cyclotron deflector to the debuncher. The first order monoenergetic bunch expansion effect in the fringing field of the cyclotron can be compensated by a corresponding shaping of the beam with a 45° bending magnet placed between the cyclotron and the monochromatisation system. Optical effects of higher orders are present, and the Coulomb field of the beam affects the longitudinal motion. But the last effect can be neglected because of the small density of the space charge. A change in the trajectory length in comparison with L_o in the second order is determined by the ratio:

$$\Delta l = \int_0^{L_o} \left[\frac{1}{\rho} (\Delta X_x + \Delta X_z) + \frac{1}{2} (X'^2 + Z'^2) \right] \mathrm{d}S \qquad (3)$$

where $X'(S), Z'(S)$ = angular deflection in linear approximation
$\Delta X_x(S)$ = horizontal aberrations to second order in the median plane of the system
$\Delta X_z(S)$ = horizontal aberrations due to vertical motion.

A partial compensation of the aberration extension can be provided by a selection of the parameters for the two symmetrical pairs of sextupole magnets SP_2, SP_2' and SP_3, SP_3' shown in Fig. 2.

At present some calculations on second order effects are being carried out. Preliminary results show the possibility of beam transmission through the system with a phase band extension of the monoenergetic bunches of no more than 2°.

CONCLUSION

Analysis of the beam monochromatisation system properties shows that it is possible to decrease the energy spread of the beam from 2×10^{-3} to 2×10^{-4} for phase widths of bunches in a cyclotron near to 5°. It can be provided by a precise adjustment of the magneto-optical system of the cyclotron including some correction of the aberration effects. It is necessary to note that the monoenergetic beam will be extended up to a phase width of no less than 85°.

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