BASIC CHARACTERISTICS OF AN ISOCHRONOUS CYCLOTRON WITH VARIABLE ENERGY OF PARTICLES

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1. INTRODUCTION

At the Scientific Research Institute of Electrical Physics Equipment imeni D. V. Efremov work is in progress on the development of a 2.4-meter cyclotron with a spatial variation of the magnetic field. This cyclotron is designed for the acceleration of particles with Z/A from 0.125 up to 1 over a very wide range of energies. The proton energy domain would cover the 7.5--100 MeV region. The device is designed for the production of relatively large ion currents; it will permit carrying out experiments with beams incident on internal and external targets.

Below we list the basic characteristics of the cyclotron.

The range of energy variations, MeV:	
protons	7,5—100
deuterons	5—60
α-particles	10—120
nitrogen ions	10—145
The diameter of the electromagnet pole pieces	2400 мм
Magnetic structure	Three-sector, slightly helical
Gaps, mm:	
at the 'hill'	230
in the 'valley'	960
Range of magnetic field variation at the center	4000—17 000 Oe
Number of auxiliary windings:	
'valley'	3×2
concentric	12×2
'harmonic'	12×2
The overall power of the electromagnet power supply	2800 kW
The weight of the electromagnet	720 tons
The resonant system frequency domain	5—22 Mc
The amplitude of the accelerating voltage on the dee	125 kV
Aperture at the dees	50 мм
The hf power across the load	600 kW
The current stability across the winding	$2 \cdot 10^{-5}$
Current stability in the auxiliary windings	10^{-4}
The frequency stability of the accelerating voltage	10^{-5}
Amplitude stability of the accelerating voltage	10^{-3}

2. SHORT DESCRIPTION OF THE DEVICE

General Layout. Figure 1 shows the layout of the cyclotron in its entirety. After being deflected, the beam is directed into the commuting magnet which allows aiming the beam at targets located in three experimental halls. Hall I is earmarked for target irradiation by very intensive beams. Hall II may be utilized for physical experiments based on neutron time-of-flight measurements. Hall III receives the beam after crossing the electromagnetic monochromator which makes possible accurate experiments in nuclear spectroscopy.

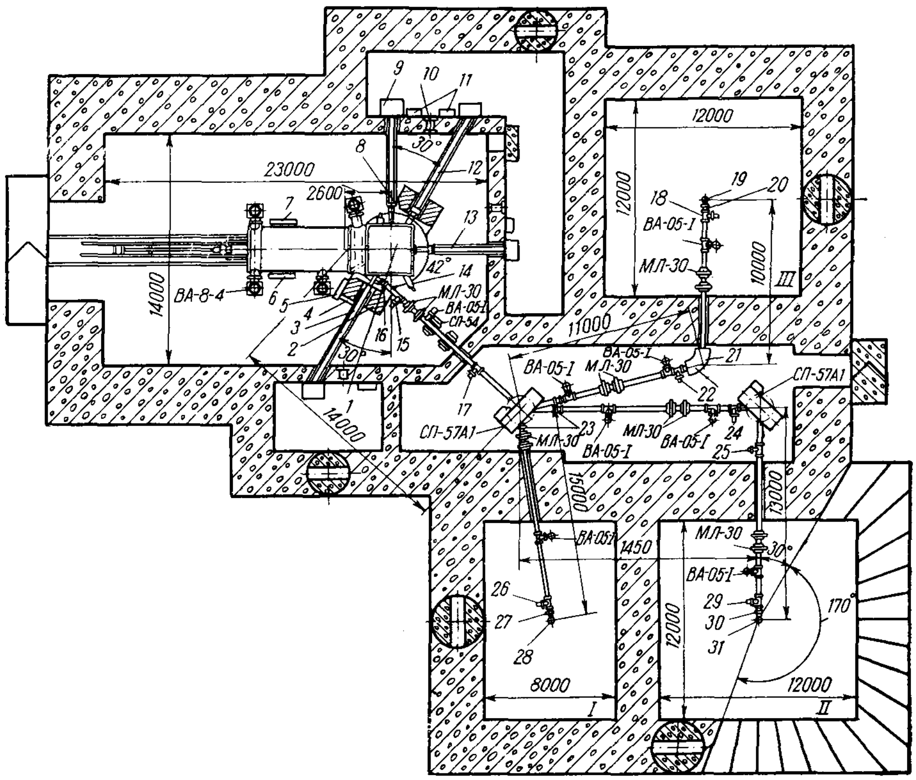

Figure 1. Layout of the cyclotron:

1 -- Accelerating chamber; 2 -- basic electromagnet; 3 -- powered sampler No 4; 4 -- panel No 2; 5 -- panel No 1; 6 -- panel No 4; 7 -- panel No 3; 8 -- powered ion source with remote control; 9 -- shield; 10 -- observation window; 11 -- control desk; 12 -- powered sampler No 3; 13 -- powered sampler No 5; 14 -- sampler No 2; 15 -- sampler No 1; 16, 20, 23, 27, 30 -- slide valves; 17, 22, 24 -- sampler No 4; 18, 26, 29 -- sampler No 5; 19, 28, 31 -- target; 21 -- monochromator; 25 -- collimator.

The ionic-optical system for channeling, focusing, and commutation of the beam consists of six pairs of quadrupole lenses, two identical rotating electromagnets, the monochromator electromagnet, and two small electromagnets for vertical correction of the beam.

Electromagnet. The electromagnet has a Ш-shaped magnetic circuit with the gap oriented horizontally. The maximum weight of the movable section is 50 tons. The pole surfaces carry sector plates whose thickness is independent of the radius. The "valley" windings, which magnify the depth of the field variation along the azimuth, are located within the sectors. The power fed to these "valley" windings is 1000 kW. The magnetic field distribution along the radius is corrected by 12 pairs of independently fed concentric coils. The correction of the azimuthal field distribution is carried out by four pairs of "harmonic" windings located within each "valley." This means that the power supply of the electromagnet consists of 26 independent sources of variable power.

Resonant System. The system consists of a quarter-wave coaxial line terminating in a 180-degree dee. The resonance system was modeled full size. Retuning of the resonant frequency is achieved by remote shifting of the shorting plate without disturbing the vacuum. The accuracy of the frequency adjustment is ±(5--18) kc. The continuous hf adjustment is carried out by means of two trimmers capable of changing the frequency by 2--4 percent. The hf generator is capacitatively coupled to the resonant system. The dee with its coupling rod can be shifted in the vertical and horizontal planes and along its axes remotely without disturbing the vacuum.

Accelerating Chamber. The chamber consists of two sections: the high vacuum part which can be taken out of the magnetic gap together with the resonant line and the preliminary vacuum section which is in two parts, mounted on the magnetic poles. Concentric windings are located at the outer side of the thin disc placed at the boundary of the high and low vacuum sections. The terminals of the "harmonic" and concentric windings are in the fore-vacuum section. The gap between the inner plate surfaces is 185 mm, the gap between the dee and the plate is 45 mm (the dee voltage is 125 kV).

The chamber contains remotely controlled measuring probes and targets for internal beam operations. The location of the ion source can likewise be adjusted by remote control, and, in addition, one can exchange cathodes or the entire source without disturbing the vacuum. The beam extraction system elements are located in the other half of the chamber away from the dee. The evacuation proceeds through the tank of the resonant system. There are four oil-vapor pumps with semiconductor traps; the capacity of the pumps is 5000 ℓ/sec.

3. THE RESULTS OF THE MODELING OF THE MAGNETIC FIELD

The modeling of the magnetic field was carried out in two stages. The preliminary modeling was carried out on an electromagnet having pole pieces 342 mm in diameter, and we studied several versions of magnetic systems. On the second model (an electromagnet with a pole piece diameter of 685 mm) we studied in detail the alternative slightly helical structure. The angular extension of each sector changes with radius in a manner analogous to the cyclotron*. Sectors are of equal thickness, making the "shell" gap equal to 65 mm, while the gap in the "valley" is 275 mm. For $H_z(0) = 15$ kOe the number of ampere-turns of the basic coil of the model was 256,000. This coil consumed 100 kW of power.

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*Livingston, R. S., Howard, F. T. Nucl. Instr. Meth., Vol 6, 1, 105, 221 (1960).

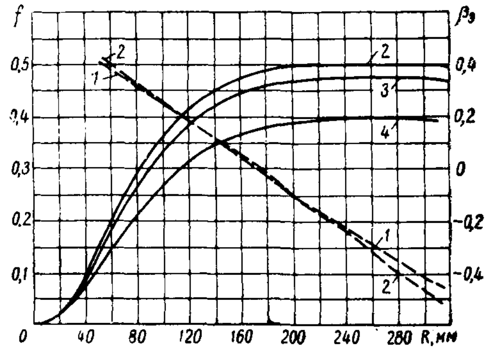

Figure 2. The degree of variation (and phase) of the lowest harmonic (dashed line) as a function of radius. The values of $H_z(0)$:

1 -- 12.1 and 15 kOe; 2 -- 8.3 kOe; 3 -- 12.1 kOe; 4 -- 15 kOe.

Figure 2 shows the degree of variation as a function of radius, f(R)

$$(f(R) = \sqrt{2\,\frac{\langle H^2\rangle - \bar{H}^2}{\bar{H}^2}},$$

where $\langle H^2\rangle$ is the mean square over the azimuth field and the phase $\beta_3(R)$ of the main (third) harmonic. It can be seen from the curves that for a central field $H_z(0)$ = 15 kOe, the degree of the magnetic field variation does not exceed f = 0.4 which is insufficient for the acceleration of protons up to 100 MeV. An increase of the degree of variation was achieved on the model by turning on the "valley" windings consisting of six sections. The number of ampere-turns of each section reached 48,000. The "valley" windings consumed 200 kW of power. The curves in Figure 3 show the dependence of the degree of magnetic field variation along the radius on the particular model used (R = 280 mm corresponding to the limiting acceleration radius) on the current within the "valley" winding for three values of the central field strength. One sees that values f = 0.5--0.6 may be achieved in practice with $H_z(0)$ = = 15 kOe. The curves in Figure 4 present, at $H_z(0)$ = 15 kOe, the relationship f(R) for different polarities of the "valley" windings and also with no current in the same coil.

On the model with the coil diameter of 685 mm, we also measured the magnetic fields due to each of the seven pairs of concentric windings. As an example, we show in Figure 5 the radial dependence of the average over the azimuth fields of the 2nd and 7th winding. These curves were measured at three levels of the basic field. They indicate that with a change in the basic field the action of the concentric coils as well as the distribution of their field also changes.

The dashed curve in Figure 6 corresponds to the calculated relationship $\bar{H}(R)$ needed for an almost isochronous acceleration up

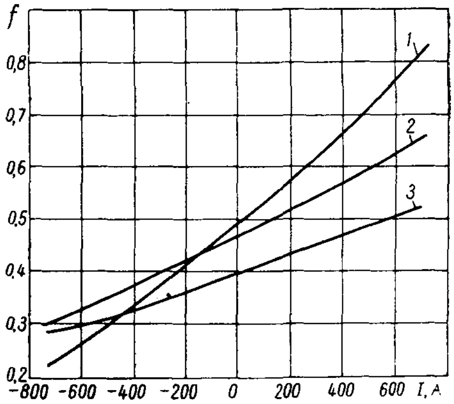

Figure 3. The degree of variation as function of the current in the "valley" coil for various values of central field strength (R = 280 mm), $H_z(0)$:

1 -- 8.3 kOe; 2 -- 12.1 kOe; 3 -- 15 kOe.

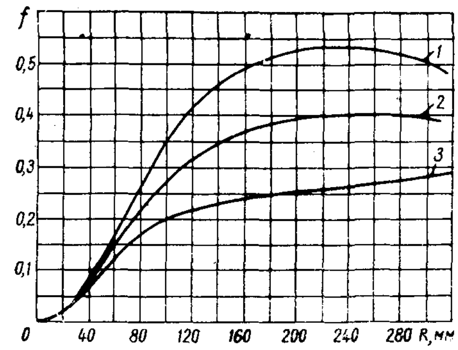

Figure 4. The degree of field variation ($H_z(0)$ = 15 kOe) as function of radius, $I_{val.\ coil}$:

1 -- 720 A; 2 -- 0; 3 -- 720 A.

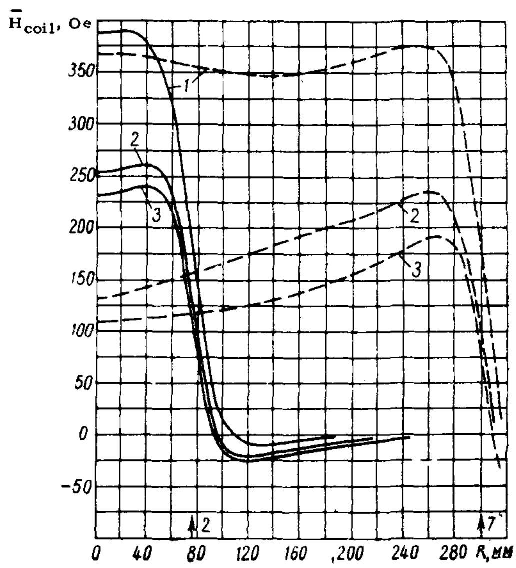

Figure 5. Average magnetic field due to the 2nd (solid line) and 7th (dashed line) concentric coils at various levels of the basic field $H_z(0)$:

1 -- 8.3 kOe; 2 -- 12.1 kOe; 3 -- 15 kOe.

to 100 MeV; the solid line is the $\bar{H}(R)$ corrected by means of the mentioned windings. The solid line is the result of a numerical superposition of the calculated values for the field of each correcting winding. The currents within these windings were calculated on computers following the method of least squares, utilizing the data from magnetic computers.

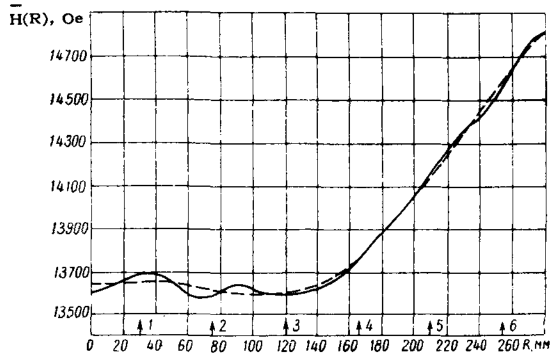

Figure 6. Magnetic field correction by concentric coils (solid line -- the final result; dashed line -- the preliminary one):

Winding	1st	2nd	3rd	4th
Current, A	−2416,4	−3046,8	−488,6	−866,3
Winding	5th	6th	7th	ΔI, of the basic winding
Current, A	−1215,4	−2226,8	−1912,9	+82,3

* * *

Using the 685 mm diameter pole piece electromagnet we are currently adjusting the cyclotron for the spatial variation of the magnetic field. The magnetic field of such a cyclotron is similar to the one described above. The cyclotron will be able to accelerate protons up to 8 MeV, and deuterons up to 4 MeV. It will also be utilized for studies of various alternatives for the extraction of the beam.