CYCLOTRONS OF THE JINR LABORATORY OF NUCLEAR PROBLEMS

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Research on the cyclotron method of acceleration has resently been performed at the Laboratory of Nuclear Problems in the framework of two projects; the 40 MeV proton isochronous cyclotron[1] and the 800 MeV cyclotron with a maximum beam intensity[2].

The principal aim of the first project is to develope and construct an isochronous cyclotron on the basis of the existing U-120 cyclotron built 10-15 years ago.

At the present time the U-120 cyclotron is obsolete and needs to be modernizated. In the project of the former cyclotron the electromagnet and some, auxiliary systems remain unchanged. Practically the former building of the accelerator with its experimental and auxiliary rooms also remainds unchanged. The choice of the final parameters and some main characteristics of the new cyclotron is based on requirement that the former electromagnet be used. Preliminary calculations and experiments using the models of the magnetic and RF accelerating systems permitted determination of all basic characteristics of the accelerator listed in Table I.

Accelerated particles	Protons	Deuterons	α-particles	He_3^{+2}
Maximum energy (MeV)	39.5	20.0	40.0	50.0
Minimum energy (MeV)	13.0	8.7	17.4	17.0
Radius of extraction(cm)	51	51	51	51
Max.value of magn.field induction(T)	1.8	1.8	1.8	1.8
Min.value of magn.field induction(T)	1.0	1.0	1.0	1.0
Max.value of RF (MHZ)	26	13.6	13.6	26
Min.value of RF (MHZ)	15	8.8	8.8	8.8

A four spiral structure of the magnetic field (Archimedes' spiral) has been chosen[3-5]. The angle width of the spiral shimms, a gap between them and the height of the shimms can be changed as a function of radius in order to provide the appropriate law for magnetic field variation and an average value of magnetic field induction over the whole range of the fields. The general view of a chamber cover with the system of spiral shimms is shown in Fig.1.

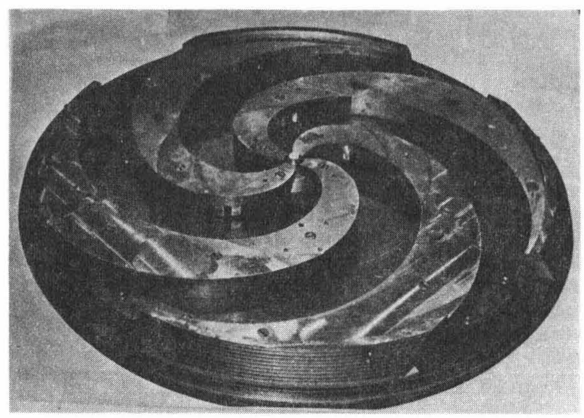

Fig.1. A chamber cover with the system of spiral shimms

The average magnetic field is corrected by means of a system of 18 concerntric water-cooled coils. Their location along the radial line is shown in Fig. 2[6]. The total power consumed by the correcting coils amounts to 80 kW for some values of

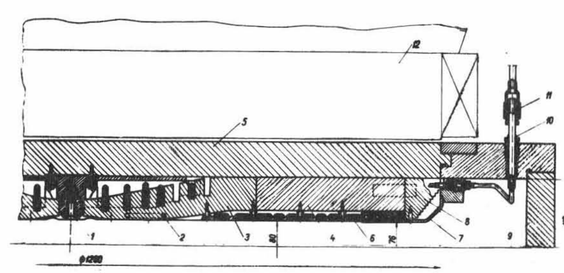

Fig.2. A pole disc with spiral shimms and the system of the trim-coils

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average field. This is 50% of the power supply of the main coil of the electromagnet. The RF accelerating system with a 180° dee and with a rectangular-section resonant line is operated in the frequency range from 8.8 to 27 MHZ by means of moving panels and trimmers. Figs. 3 and 4 show the resonant system schematically.

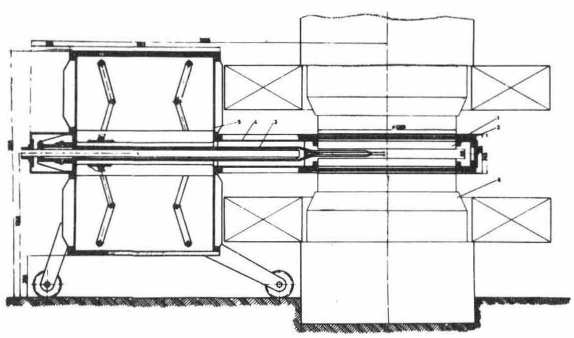

Fig.3. Vertical section of the RF accelerating system

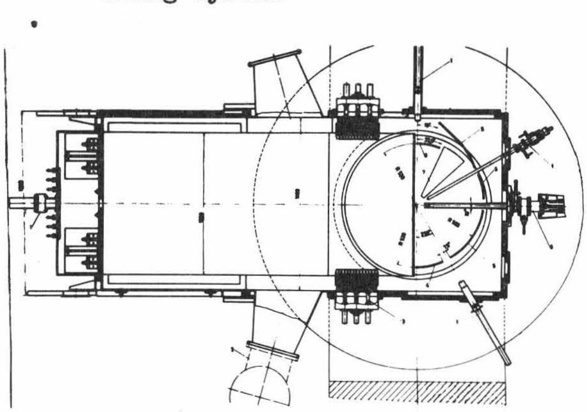

Fig.4. Horizontal section of the cyclotron.

The whole range of frequencies is overlapped only at three positions of the moving panels due to relatively large values of the trimmer capacity (1000 pF). It is expected that the accelerating voltage of about 50 kV will be obtained on the dee. The power supply of the RF generator equals 150-180 kW. As the production of the beams of accelerated ions with an energy spread of about 0.1% is stipulated by the project, some measures have been taken in the generator to increase the stability of the accelerating voltage amplitude[10,11].

The position of the ion source of the closed type with a heated cathode and that of the central optics are regulated depending on the type of accelerated ions and the value of the magnetic field. The slotted puller draws off ions in the given phase interval of accelerating voltage. For a typical mode of operation $\Delta\varphi = 10°$.

The extraction of accelerated ions is carried out by an electrostatic deflector[12,13] divided into three sections (see Fig.5). Each section performs its own functions. The first section has a homogeneous field in its initial part in order to ensure a minimum thickness of a septum.

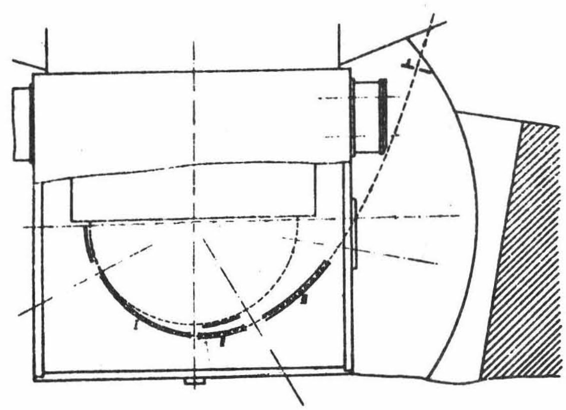

Fig.5. The layout of the extraction system elements.

The rest of the first section as well as the second and third sections have a radial focusing electrostatic field that compensates for radial defocusing forces in a shrply dropping adge magnetic field. The angular widths of the sections are equal to 58°, 23° and 37°, respectively. The maximum electric field intensity does not exceed 80 kV/cm. To throw the beam into the deflector one uses the method of the coherence excitation of radial oscillations by means of two short (20°) areas of the electric fields shapes by an exciter and compensator[14,15]. The exciting field is located in front of the input of the deflector and the compensating field is placed with the azimuthal shift of 100° (in the area of the 2-nd section of the deflector). The purpose of the compensator is to supress the parametric influence of the exciter field upon the beam. By choosing the appropriate value and shape of the fields in both sections practically fully separated orbits were obtained on the extraction radius without considerable distortion of the emittance . When the effective thickness of the input electrode of the first section is equal to 0.5 mm,the losses will not exceed 10% for the radial emittance value of 8 mm•mrad.

In the control system of the cyclotron[17-19], the M-6000 type computer is used, which fulfils the function of the operator's "adviser" during the tuning of the accelerator at the given mode of operation (type of the accelerated ions, the energy limit) and participates in the automatic adjustment of the average magnetic field on the basis of data on the beam phase. The magnetic field is regulated by trim-coils and the current needed for their excitation [20,21] is calculated by the computer.

The magnetic field measurements and the tuning of individual systems of the cyclotron are currently in progress. It is planned to make the complex testing in 1976.

The second project, the construction of isochronous cyclotron designed for proton accelerator up to 800 MeV with a beam intensity of tens and hundreds of milliampers("supercyclotron"), is at the initial stage. By now, only analytical and model investigations are performed to verify the basic preconditions of the project. Recently two initial preconditions have been tested using models. First, it has been shown that at an isochronous cyclotron the configuration of magnetic field can be shaped with tolerancies permitting conservation of isochronism during acceleration for more then 2000 turns[22]. Secondly, at the model of isochronous cyclotron with strong focusing[23] it has been shown that it is possible to accelerate proton beams with an average intensity of about 200-300 mA without beam distortions due to Coulomb repulsion.

During the last few years the third problem has been tackled, i.e. beam extraction from the isochronous cyclotron vacuum chamber with losses not exceeding 10^{-4}. The solution of that problem is as important as the proof for the possibility of accelerating particle beams with a current about hundreds of milliampers at in an isochronous cyclotron. In this case the beam power amounts to hundreds of megawatts and even losses as small as 10^{-4} are not admissible, while the present-day methods of extraction by means of a resonant excitation of oscillation are have an efficiency of not more than 80-95%. In 1972, an extraction method was found which is based on closed orbit expansion at full acceleration radii. This method makes it possible to solve the extraction problem with a 100% efficiency.

The effect is based on a considerable dependence of the expansion coefficient of closed orbits $\eta = \frac{p}{L}\frac{dL}{dp}$ on magnetic field variations (L - is a closed orbit length). A mean radius R_{ms} in the magnetic field of a strong-focused cyclotron can be found from the expression:

$$p = eB(R_{ms}) \cdot R_{ms} \cdot \lambda \quad , \qquad (1)$$

where:

$B(R_{ms})$ is a mean value of the magnetic field induction with the radius R_{ms} and

$$\lambda = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\varepsilon}{2N^2} \cdot \left(\frac{3}{2} + n + \frac{\varepsilon}{R_{ms}} \cdot \frac{d\varepsilon}{dR_{ms}}\right)} \qquad (2)$$

$$n = \frac{R_{ms}}{B} \cdot \frac{dB}{dR_{ms}} \; ; \; \mathcal{E} = \frac{B_N}{B(R_{ms})} \; ;$$

where N is the periodicity of the magnetic field structure. The expansion coefficient of the closed orbit is obtained directly from (1) :

$$\eta = \frac{1}{1+n+\frac{R_{ms}}{\lambda} \cdot \frac{d\lambda}{dR_{ms}}} \qquad (3)$$

and in the vicinity of the value : $\frac{R_{ms}}{\lambda} \cdot \frac{d\lambda}{dR_{ms}} \approx -(1+n)$ there is a possibility of a considerable orbit expansion.

In a statical regime the radial step of closed orbits can be increased up to 20-50 times. The dynamic regime of this effect has been investigated by numerical calculations. As a result it is shown that under certain tolerances for the magnetic field amplitude and phase variations in the orbit expansion region the beam emittances are not distorted and the effect of a factor of 20-50 in the radial step is retained.

The experimental verification of the orbit expansion effect was performed in 1974 using the electron model of a ring strong-focused cyclotron. This model was used previously to the mode of accelerating the beams with maximum intensity. The results of preliminary calculations of the orbits expansion with real model parameters in Fig.6 are shown. The mean radius of the last closed orbit is seen to increase by about 3 cm per turn. The axial frequency changes negligibly due to the special law that has been chosen for the magnetic field phase variations in the orbit expansion area.

To provide the appropriate law for the variation of the amplitude and phase of the 8-th magnetic field harmonic, an additional coil has been installed in the electron model which does not distort the mean magnetic field.

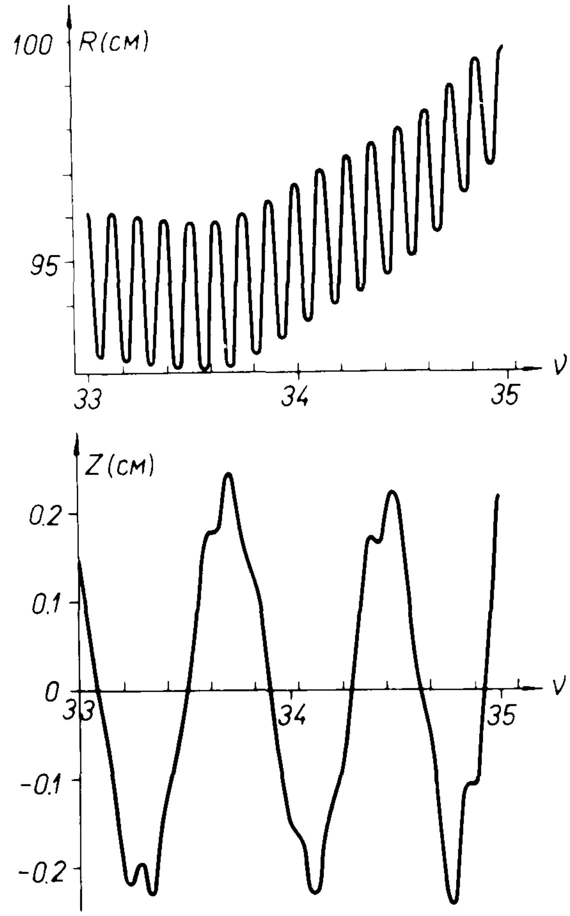

Fig.6. Results of calculations of the beam characteristic in the orbit expansion zone

Fig. 7 shows the general view of the electron model during the assembly of these additional coils. The actual characteristics of the magnetic field obtained after installation of additional coils are shown in Fig. 8 (solid lines).

The orbit expansion effect was discovered immediately after the starting of the accelerator with a new-type magnetic system[25]. Fig.9 shows the beam current dependence upon the beam radius. It indicates that the radial step of the last turn reaches 3 cm. The vertical distribution of the beam current density before and after orbit expansion is also shown in this figure.

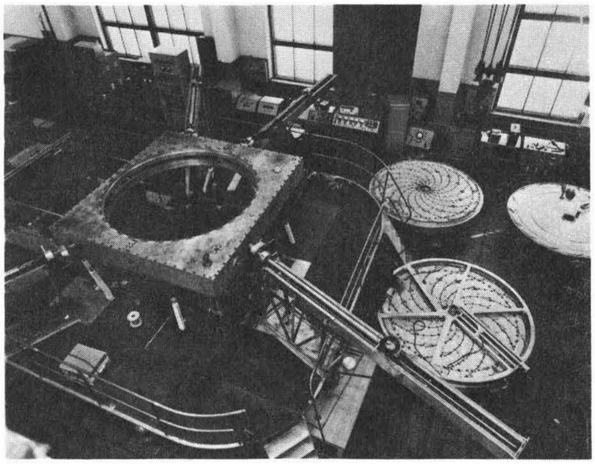

Fig.7. The model of ring cyclotron during the mounting of additional coils

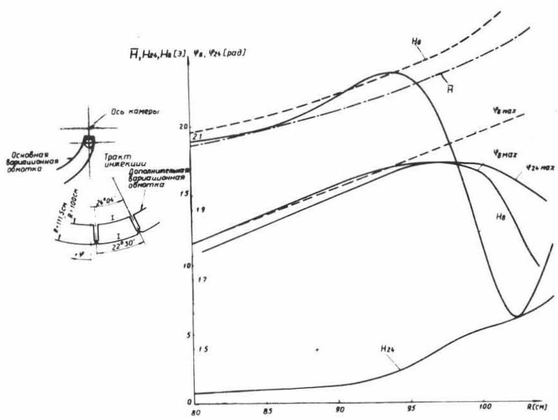

Fig.8. Actual characteristics of the magnetic field

One can see that the expansion effect is accompanied by some increase on the vertical dimention of the beam. Thus, the experiments fully confirm the calculated magnitude of the effect. The subsequent beam extraction from the accelerator chamber with the help of the magnetic channel involves no difficulties. As a result, it one has removed the last fundamental obstacle in using ring isochronous cyclotrons to produce superhigh current proton beams energies up to 800 MeV.

From the point of view of the maximum efficiency, this type of accelerator has obvious advantages as compared with linear accelerators. This situation makes it possible to begin the development of an isochronous cyclotron with beam intensities substantially exceeding the so far achieved level in the near future.

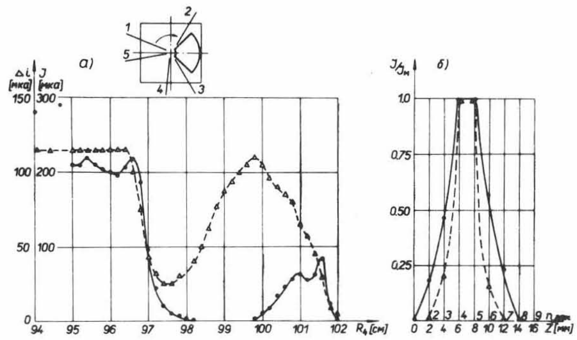

Fig.9. A) The radius dependence of the current in the orbit expansion zone.
I - current on the differential probe
J - current of the integral probe
B) The vertical distribution of the current density. Along the beam before expansion (dashed line) and after it (solid line).

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DISCUSSION

D.J. CLARK: Could you comment on any plans at Dubna for a large heavy-ion cyclotron?

Y.N. DENISOV: Our cyclotrons are designed in the Laboratory of Nuclear Problems, JINR. They are dedicated mostly to the acceleration of p, d, α and ^{3}He.