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EXPERIMENTAL RESEARCH OF THE CLOSED ORBIT EXPANSION EFFECT IN THE STRONG FOCUSING CYCLOTRON

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Summary

The theoretical and experimental study of beam extraction method using the closed orbit expansion effect is described. The steep slope of the magnetic field variation magnitude is used to change the momentum compaction factor into the limit radial area. The orbit separation is found by computing the dynamical equations, since the behaviour of the betatron oscillation frequencies and the beam phase are investigated in this radial region. The experimental study of the effect is carried out with the ring cyclotron electron model, which is a strong focusing eight sector isochronous cyclotron. Calculated orbit separation in the extraction area is about 2÷4 cm. The magnet system which is to obtain the proper gradient of the magnetic field variation and the magnet measurement results are described. The measured value of the orbit separation equals 4 cm. At the same time the space between two orbits without current (free of particles) is about 2 cm and the full current on the separated orbit is equal to that before separation.

The theoretically predicted beam phase shift is found to be equal to 30÷40°.

The obtained results confirm the possibility of the 100% beam extraction from the accelerator with space magnetic field variation.

I. Introduction

The basic problem in the design and construction of cyclic accelerators is a 100% beam extraction efficiency from the accelerator chamber. This problem is important for the meson facilities in the 1 GeV energy range and the 1 mA current range due to the accelerated beam power which exceeds 1 MW [1] in this case.

The theoretical consideration of this problem has shown that all the methods of beam extraction based on free oscillation excitation cannot provide the full orbit separation. Thus, beam losses are inevitable due to finite barrier thickness.

The necessity of solving this problem made us search for methods neglecting the conventional excitation of free oscillations as well as the achievement of full separation emittance at the full radius without the noticeable emittance distortion. It has been established that the method satisfying these conditions is based on closed orbit expansion at full acceleration radii [2].

The results of experimental and theoretical studies of this effect obtained by means of the electron model of the JINR strong focusing cyclotron are the subject of our paper [3].

II. Theoretical Basis and the Dynamical Calculations

The magnetic field variation (ϵ) results in the change of the mean radius (R) of the closed orbit for the particle momentum p, which is characterized by the parameter λ.

The mean radius R can be found from the expression

$$p = eB(R)R\lambda, \tag{1}$$

where $B(R)$ is the mean value of the magnetic field induction with the radius R, while

$$\lambda = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{\epsilon^2}{2N^2}\left(\frac{3}{2} + n + \frac{R}{\epsilon}\frac{d\epsilon}{dR}\right)} \tag{2}$$

$n = \dfrac{R\,dB}{B\,dR}$, $\epsilon = \dfrac{B_N}{B(R)}$, N is the periodicity of the magnetic field structure. The coefficient of closed orbit expansion is obtained directly from (1)

$$\eta = \frac{p}{L}\,\frac{dL}{dp} = \frac{1}{1 + n + \frac{R}{\lambda}\frac{d\lambda}{dR}}\,. \tag{3}$$

The radial step of the closed orbit with the energy gain ΔE is, respectively,

$$\frac{\Delta R}{R} = \eta\frac{\Delta p}{p} = \eta\frac{\Delta E}{\beta^2 E}\,. \tag{4}$$

As follows from (3) it is possible to control the coefficient of the closed orbit expansion by changing magnetic field variation.

The condition

$$1 + n + \frac{R}{\lambda}\frac{d\lambda}{dR} = 0 \tag{5}$$

determines the sign of η dividing the magnet structure into two classes: one having positive and the other one having negative η. A typical plot of expansion coefficient dependence obtained with the characteristics of the electron model magnetic field with a proper variation law is shown in Fig. 1.

The magnetic system rigidity in the transverse direction to the closed orbit changes in the region of the coefficient variation. However, the expansion itself occurs during one or two last revolutions at which resonance phenomena have not time to develope. Some negligible variations of free oscillation amplitudes lead to invariant relations between the frequencies:

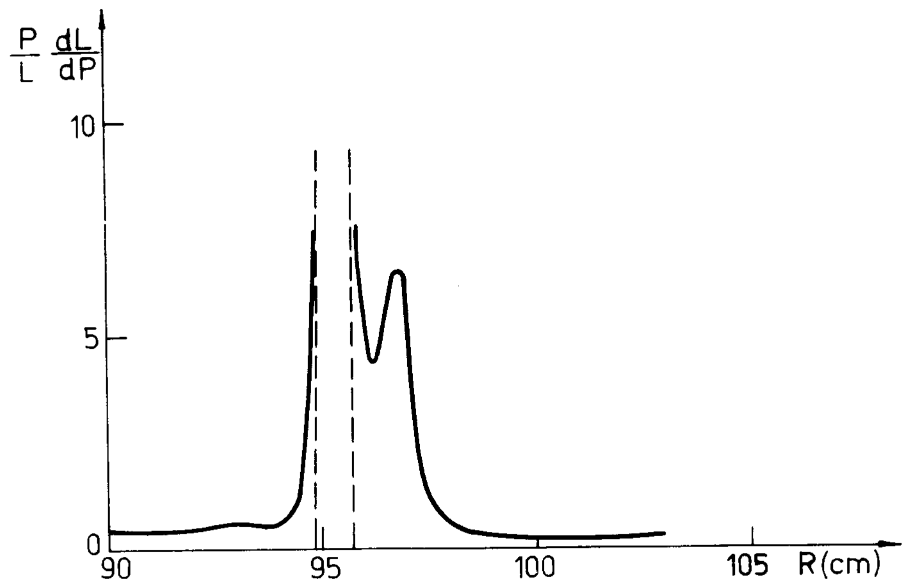

Fig. 1. Dependence of the closed orbit expansion coefficient upon radius.

$$Q_z^2 + Q_r^2 = \text{const.} \qquad (6)$$

Closed orbit expansion is accompanied by the phase shift of the beam centre which is described by the following equation

$$\frac{d\phi}{d\nu} = 2\pi \left(\frac{E_0^2}{E^2} - \eta \right) \frac{eV\cos\phi}{\beta^2 E}, \qquad (7)$$

where $eV\cos\phi$ is the energy gain of the ν-th revolution, E is the full energy. The rapid change of the orbit expansion coefficient (Fig. 1) makes it necessary to consider the dynamic process since the calculation by formulas (4) and (6) is impeded by the discontinuities of the function η.

Dynamical calculations have been performed when the parameters were optimized by numerical calculations of the system of equations in a cylindrical system of coordinates (r, ϕ, z):

$$r'' - \frac{2r'^2}{r} - r = -\frac{e}{p}\left(1 + \frac{r'^2}{r^2} + \frac{z'^2}{r^2}\right)^{1/2} \left[(r^2 + r'^2) B_z - r'z'B_r - rz'B_\phi\right] - \frac{e\epsilon_\phi r' r}{p\beta c}\left(1 + \frac{r'^2}{r^2} + \frac{z'^2}{r^2}\right), \qquad (8)$$

$$z'' - \frac{2r'z'}{r} = \frac{e}{p}\left(1 + \frac{r'^2}{r^2} + \frac{z'^2}{r^2}\right)^{1/2} \left[(r^2 + z'^2) B_r - r'z'B_z - r'zB_\phi\right] - \frac{e\epsilon_\phi z' r}{\beta c p}\left(1 + \frac{r'^2}{r^2} + \frac{z'^2}{r^2}\right),$$

where ϵ_ϕ is the azimuthal component of the electrical field of the accelerating electrode $\pi/2$ long.

A typical picture of particle oscillation in the r and z planes for two last revolutions in the expansion region is shown in Fig. 2.

Fig. 2 clearly shows the monotonous displacement of the closed orbit which is seen at each period of the

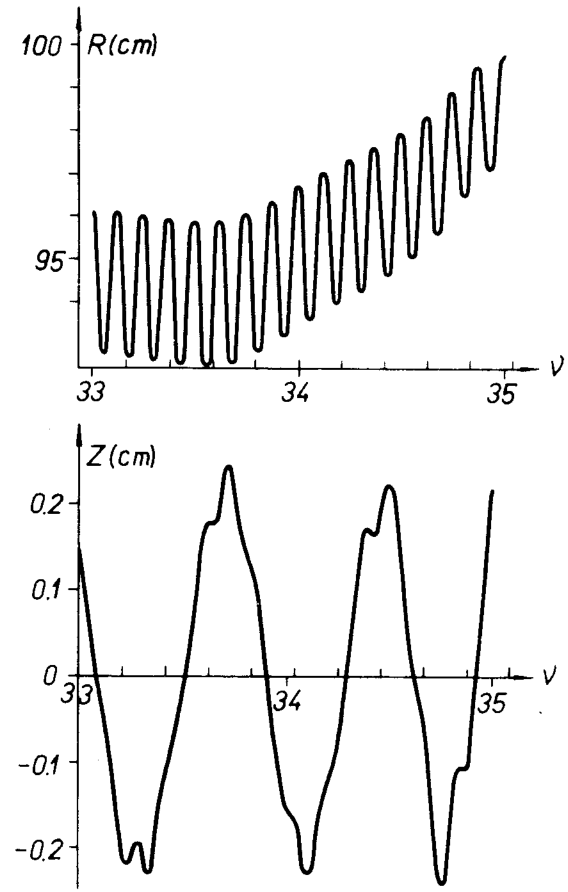

Fig. 2. Effect of closed orbit expansion.

magnetic field structure and results in calculated separation per revolution in the 2-4 cm scale with respect to the chosen observation azimuth.

III. Shaping the Magnetic Field

The required dependence of the amplitude and the phase of the 8th magnetic field harmonic was formed by means of an additional harmonic coil. The coil is a system of two separate conductors symmetric with respect to the median plane. They are located along the radial lines and circumference arcs. For the complete compensation of the mean magnetic field formed with an additional harmonic coil each coil pole is made of two identical branches shifted by a half-period of the system (22.5°) with currents of opposite directions. With removed chamber covers one can see the coils and the mechanism for displacing the Permalloy probe of the measuring device in the radial and azimuthal directions (Fig. 3). Fig. 4 shows the configuration of the additional variation coil remoted from the median plane by 7.05 cm. The required law for the magnetic field induction in the median plane of the orbit expansion region was set by the following expression

$$B_z = B(r) + \sum_N B_N(r) \cos N[\phi - \phi_N(r)], \quad N = 8, 24, \qquad (9)$$

where $\phi_N(r) = r \frac{d\phi}{dr}$ for each harmonic of the field structure. The limit was imposed only for two harmonics in the structure $N = 8$, $N = 24$. The average value of the magnetic field induction along the radius $(B(r))$ corresponded to the isochronism conditions of the closed not expanded orbits. The tolerance for the amplitude of the magnetic field variation did not exceed a few per cent. There were no special requirements for lower harmonics of the magnetic field structure. As a result of the numerical modelling of the expansion effect an additional condition for the phase of the basic harmonic in the expansion region is found: $\phi_8 =$ const.

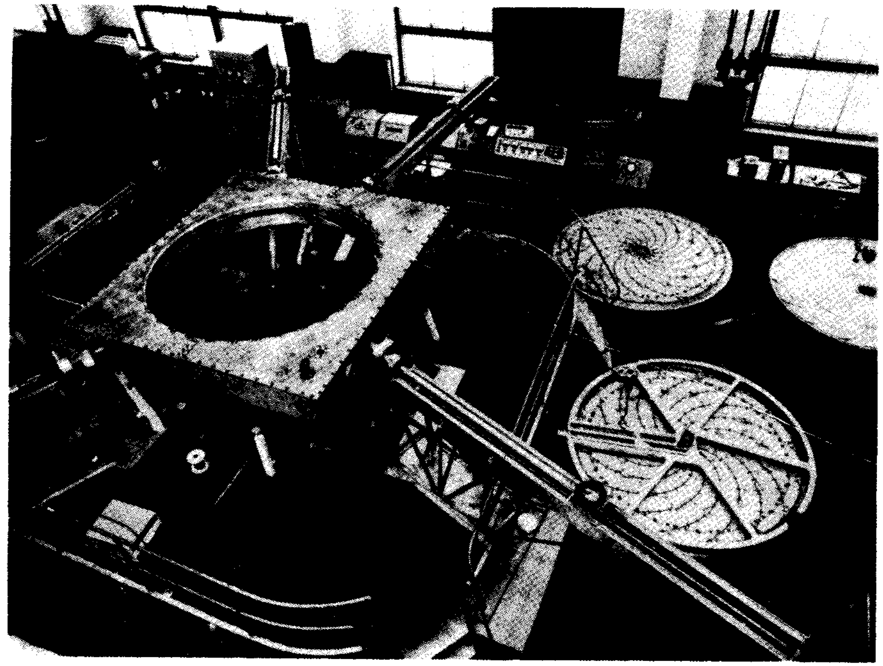

Fig. 3. A general view of the electron model during the assembly of additional coils.

The magnetic field distribution for the given radius was measured with 144 equidistant points along the azimuth with a (0.5÷1) cm step. The data of magnetic measurements were recorded on the punched paper tape and then processed by the computer. The accuracy of the magnetic field measurements performed with a Permalloy probe technique [4] is 2×10^{-3} .

The power supply of the additional harmonic coil has the magnet comparator [5] which allows one to put the current value with an accuracy better than 10^{-4} . The power supplies of other coils have the measuring shunts of the same accuracy [6].

The shaped magnetic field in the region of full radii is shown in Fig. 4. It is seen that the gradient of the 8th field harmonic at R = 97.5 cm is 2.8 Gs/cm and corresponds to the required value, and its phase is close to a constant in the radial region (94-99) cm. The magnetic field parameters before the installation of the additional coil are shown in the same figure by dotted lines.

IV. Experiment

In order to observe experimentally closed orbit expansion five moveable measuring devices were used supplied with differential targets whose collector was projected 2 mm from the grounded screen.

The computer calculations have shown that with a completely compensated first harmonic of the magnetic field the maximal closed orbit separation could be expected on probes No. 3 and 4. The separation value should be 4.5 and 4 cm, respectively. The first observations of the expansion effect have confirmed this conclusion. All the probes containing differential targets have proved orbit separation which could be seen in a noticeable current density modulation with respect to radius.

The effect was observed visually by using a fluorescent target mounted on probe No. 4. When the probe was moved along the radius one could clearly observe a jump of the light spot from the edge of the target to its middle (the

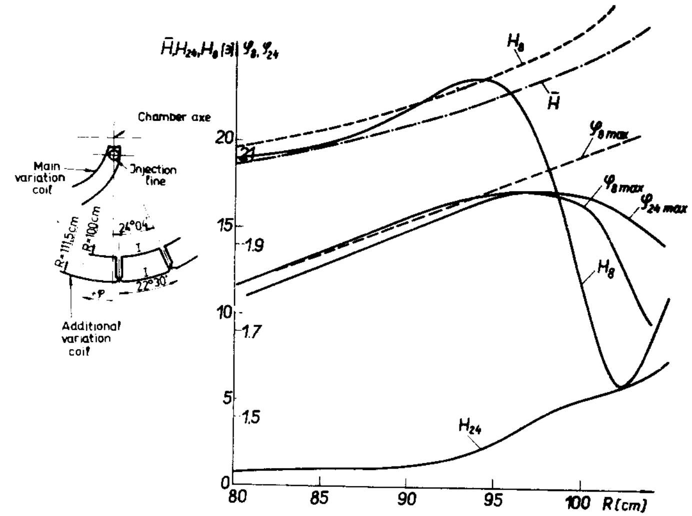

Fig. 4. Basic characteristics of the meagnetic field at full radii.

fluorescent target was 70 mm along the radius), which corresponds to the separation of two adjacent orbits of 3.5 ÷ 4 cm.

In order to study the effect in detail a special combined target was mounted on the probe. It is a set of 9 lamelles. The radial size of each of them is 1 mm. The radial size of the last one, mostly remoted from the centre is 18 mm. The lamelles have isolated channels with outputs to a recording device. This target makes it possible to measure, due to proper commutation of channels, the distribution of current density along the radius or the full current. Figure 5a shows two current dependences upon radius measured with the target, i.e., the dependence of the current Δi upon radius fixed with lamelles 1 and 2 ($\Delta R = 2$ mm) and the dependence of the full current I upon radius ($\Delta R = 26$ mm). The above figure shows that orbit separation is 4 cm. The completely current-free region at the given azimuth is 2 cm. The current I of a separate orbit ($R_4 = 99.8$ cm) measured with the integral target equals that before orbit expansion ($R_4 = 94$-96.4 cm) and is 230 μA. This result shows the absence of current losses during closed orbit expansion. The integral of the current distribution function of the separated orbit measured with a differential target

$(\int \frac{\Delta i}{\Delta r} dr)$ is 235 μA. This proves a good experimental accuracy. A barrier of 3 mm radial size was installed in the completely current-free region $R_4 = 98.1$ - 99.8 cm. The displacement of the barrier (within this region) did not affect the value of the full current at $R_4 = 99.9$ cm).

Figure 5b shows an instant distribution of particle density along the vertical axis obtained with a multi-lamelle target. Figure 5b shows also that the expansion is accompanied by some increase of the vertical beam size. Thus, before expansion ($R_4 = 95$ cm) the full width at the distribution basis is 10 mm, while FWHM is 4 mm. After the closed orbit expansion ($R_4 = 100$ cm) the full width at the distribution basis is increased to 14 mm, FWHM is 6 mm.

The effect of closed orbit expansion causes the changes of the phase of the bunch centre of the accelerated beam.

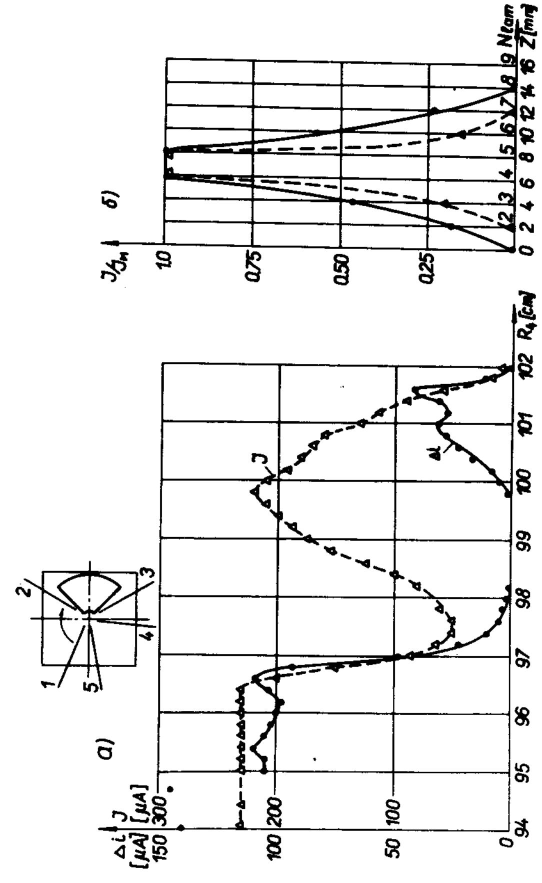

Fig. 5. a) current dependence upon radius Δi is the differential target current ($\Delta R = 2$ mm), J is the integral target current ($\Delta R = 26$ mm), b) instant distribution of current density along the vertical.

As follows from the dynamical calculations, the beam phase shift is 35-40° in the narrow radial region of 95-100 cm. The phase of the bunch centre was measured with the apparatus [7] which allows one to follow the phase variation with an accuracy not worse than 2°, the accuracy of its absolute value determination being ±4°. Figure 6 shows the phase dependence upon radius from which it is seen that at 85-95 cm radii the phase of the bunch centre becomes constant and is 10-12° smaller than the phase corresponding to the maximal energy gain. Then with orbit expansion it jumps 28°. To compensate phase deviation at 60-80° cm radii no special efforst were made in our experiment. The phase behaviour with respect to radius was confirmed to a good accuracy by the oscillographic measurements. Oscillographic measurements were performed with a Hewlett-Packard 140A sampling oscilloscope an equivalent band of which is 1 GHz with a sensitive vertical deviation of 1 mV/cm, the input resistance being 50 Ohm. The duration of the accelerated beam pulse was measured by means of the oscilloscope. It was (4.5±0.2) nsec at the pulse pedestal and (2.5±0.2) nsec at half width, which corresponds to the azimuthal bunch width of 65° and 36°, respectively. The measurements have shown that pulse duration at orbit expansion does not vary within ±0.2 nsec accuracy (±3°).

The beam orbit after expansion was detected with five probes. The orbit position agrees satisfactorily with the computer calculations.

V. Conclusion

The thoretical and experimental results of studying the closed orbit expansion in space variation magnetic fields show a possibility of a 100% beam extraction from the sector cyclic accelerators. They are as follows:

a) middle energy cyclotron (below 1 GeV) having weak or strong focusing magnetic field structure,

b) ring phasotrons (below 10 GeV) having a periodic magnetic field [8] structure.

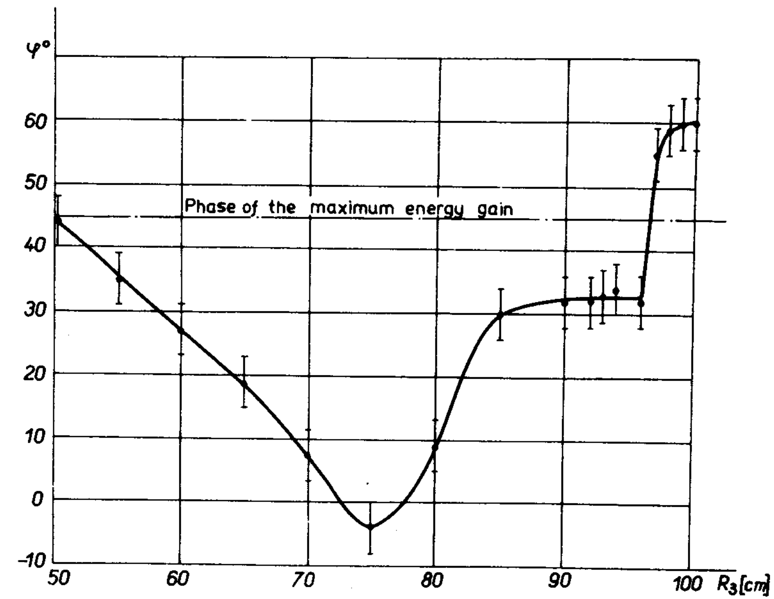

Fig. 6. Dependence of the beam phase upon radius.

The closed orbit expansion cancells out a very important limitation essential for cyclic accelerators of continuous operation due to the requirement of a great energy gain per revolution which is specific for accelerators of SOC type [9]. It allows one to solve the problem of particle acceleration using a small number of accelerating cavities in contrast to high current linear accelerators for the same energies [10].

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