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STUDY OF THE MODIFIED RESONANCE EXTRACTION METHOD FROM A RELATIVISTIC CYCLOTRON

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(presented by V.V.Kolga)

The highly effective extraction of accelerated particles from a relativistic cyclotron (RC) is one of the basic problems since the successful use of the RC a high energy physics instrument and its normal employment are possible only when practically all the particles are extracted from the chamber and external targets are used.

The most effective methods for beam extraction from cyclic accelerators having constant magnetic fields are based on resonance coupling between azimuthal and radial degrees of freedom of the accelerated particle at the given radius.

In this case it is necessary to provide conditions of the absence of coupling with axial oscillations of particles.

The spiral structure of the magnetic field of the RC causes internal nonlinear resonance at the frequency of radial oscillations $Q_r=N/q$, where N is the number of spirals, q is an integral (the resonance order). With N=8 the nonlinear resonance of the 4-th order ($Q_r = 2$) corresponds to about 820 MeV. The Oak Ridge Mc² cyclotron design (USA)[1] envisages the use of the nonlinear resonance $Q_r=8/4$ to construct the extraction system with a 95% efficiency obtained with the electron analogue of this accelerator.

The final RC energy is 700 MeV according to the conversion design of the Dubna synchrocyclotron[2]. In this case $Q_r = 1.8$ and the direct use of the resonance extraction is impossible.

A new method has been proposed in ref.[3] by means of which radial oscillation frequency at the given radius can be changed (±) to a necessary value, for instance, up to two, axial oscillation frequency being unchanged. Therefore strict dependence of radial oscillation frequency upon energy at the given radius taking place in isochronous cyclotrons is avoided. The modified resonance extraction becomes possible in a wide range of limit energies.

The present paper describes further development of the modified resonance extraction method related to the 700 MeV relativistic cyclotron.

2. An additional harmonic having the periodicity N/2 is introduced to the magnetic field structure at a radius corresponding to the given energy to vary radial oscillation frequency at this energy of accelerated particles . The magnetic field in the median plane is

$$H_z(r,\varphi) = H(r)\left\{1+\varepsilon_1 \sin\left(\frac{r}{\lambda} - N\varphi\right) + \varepsilon_2 \sin\left(\frac{r}{2\lambda} - \frac{N}{2}\varphi + \delta\right)\right\}, \qquad (1)$$

where H(r) is the average magnetic field, ε_1 is the amplitude of the basic focusing harmonic, ε_2 is the amplitude of the additional harmonic, δ is the phase of the harmonic with respect to the basic one, $2\pi\lambda$ is the radial step of the main structure of the magnetic field.

Suppose that N is even and $\varepsilon_2 \ll \varepsilon_1$.

As is shown in ref.[3] the equation of free radial oscillations in the magnetic field (I) can be exressed sufficiently accurately in the form

$$\rho'' + \left[A_2 + B_{12}\cos\phi + B_{22}\sin\phi\right]\rho = 0, \qquad (2)$$

where

$$A_2 = Q_{r0}^2 - \frac{\varepsilon_2^2 R^2}{2\lambda^2(N^2-4-4n)}\left[1 - \frac{15\varepsilon_1 R\cos 2\delta}{4\lambda(N^2-4-4n)}\right],$$

$$B_{12} = \frac{\varepsilon_2 R}{2\lambda}\left[1 - \frac{17\varepsilon_1 R}{4\lambda(N^2-4-4n)}\right]\cos\delta,$$

$$B_{2r} = -\frac{\varepsilon_2 R}{2\lambda}\left[1 + \frac{17\varepsilon_1 R}{4\lambda(N^2-4-4n)}\right]\sin\delta,$$

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Q_{ro} is the radial oscillation frequency with $\mathcal{E}_2=0$, $n = (E/E_0)^2-1$ is the index of the average magnetic field,

$$R = \frac{\rho c}{eH(R)}, \quad \phi = \frac{R}{2\lambda} - \frac{N}{2}\varphi .$$

Radial oscillation frequency is determined by the characteristic index of Mathieu equation (2) and can be expressed as:

$$\cos\frac{4\pi}{N}Q_r = \cos\frac{4\pi}{N}\sqrt{A_r} - \frac{4\pi}{N^3}\,\frac{\sin\frac{4\pi}{N}\sqrt{A_r}}{\sqrt{A_r}}\cdot\frac{B_{1r}^2+B_{2r}^2}{1-\frac{16}{N^2}A_r}. \qquad (3)$$

Equation (2) and formula (3) show that radial oscillation frequency is greatly dependent both of $\mathcal{E}_2$ and the phase shift of the N/2 harmonic (δ).

Fig. 1 shows the dependence of Q_r upon δ with $\mathcal{E}_2=0.04$ and 0.03 and the value of the remaining parameters corresponding to the RC design values at the final radius $R_k = 325$ cm. Here are these values: N=8, $\lambda=7.7$, n = 2.05, $\mathcal{E}_1=0.273$, $Q_{ro} = 1.8$.

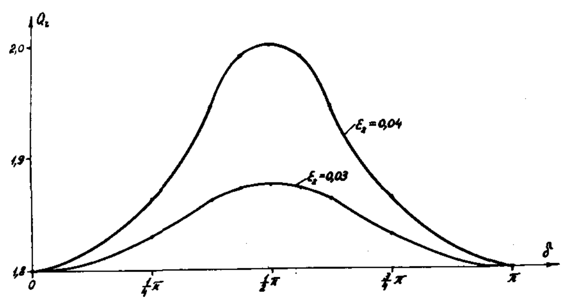

Fig.1. The dependence of Q_r on δ .

As is seen from Fig. 1, with $\delta=\pi/2$ the harmonic having the amplitude $\mathcal{E}_2=0.04$ causes the increase of the radial oscillation frequency up to $Q_r=2$, i.e.particles can be extracted at the nonlinear resonance $Q_r=8/4$ by the resonance method from the 700 MeV RC.

The solid line in Fig.2 is the deradial oscillations upon the amplitude of the 4-th harmonic with $\delta=\pi/2$ for the 700 MeV RC. Cross-hatched are frequency values obtained directly by integrating over the whole system of equations of particle motion on the electronic computer.

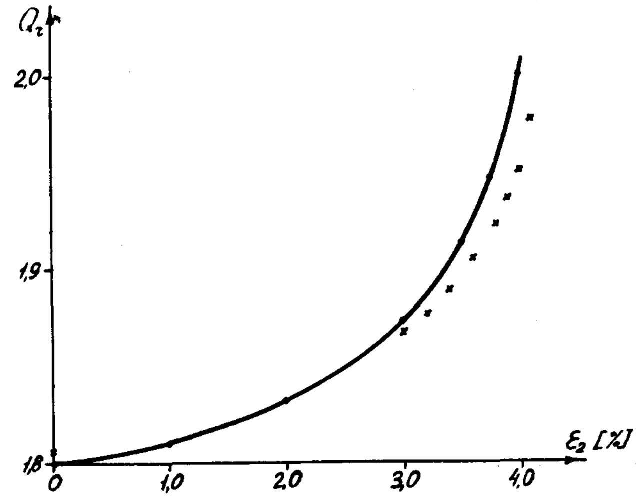

Fig.2. The dependence of Q_r on $\mathcal{E}_2$.

Varying the amplitude of the 4-th harmonic one can change the radius of the nonlinear resonance and control within some limits the extracted beam energy.

The introduction of the N/2 harmonic to the field structure results in additional axial focusing, therefore, the amplitude of the 8-th harmonic should be somewhat reduced to save the constant frequency Q_z, the radial oscillation frequency Q_r being practically not reduced.

Thus, axial and radial oscillation frequencies can be controlled by varying the amplitudes of the N-th and N/2-nd harmonics in the field structure.

3. The actual modified resonance extraction from the 700 MeV RC will require additional units in the magnetic system at final radii.

The magnetic system parameters of the RC technical design have been chosen basing on the calculations and experiments with a magnetic system model having the scale K = 6.087[4]. The unit producing the 4-th harmonic of the magnetic field can be located only in the gaps between spiral shims. At the final radius of the accelerator the above units should produce the amplitude of the 4-th harmonic of the magnetic field $\mathcal{E}_2\approx0.04\div0.06$ having a phase close to $\psi_2 = \frac{r}{2\lambda} + \frac{\pi}{2}$.

The average magnetic field introduced in producing the 4-th harmonic should be such that it could be compensated with the system of circular coils. The calculations have shown that the use of current coils locating in the gaps be-

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tween spiral shims does not result in the required law ε_2 and ψ_2 with increasing the radius.[2] In this connection a system of steel shims having the periodicity N=4 was used to produce the 4-th harmonic. The shim parameters were preliminary determined by calculations performed under the assumtion of their uniform magnetizing[3]. The analysis of these calculations has shown that

a) the necessary value of the shim spirality depends considerably upon their radial range. Thus, in order to have the field parameters λ_2 =15,4 cm the shims should be cut in an Archimedian spiral with λ=10.27 cm, the radial length of shims being R=335-307.5=27.5cm and with λ=7.7 cm, R=332.5÷312.5=20 cm,

b) the dependence of the phase of the field basic harmonic varies aslightly when an additional system of shims is introduced,

c) the employment of shims having azimuthal width of $5^o \div 9^o$ allows to obtain the reuqired dependence of the 4-th harmonic amplitude with $\delta \approx (\frac{5}{8}\pi \div \frac{6}{8}\pi)$

d) in all the above cases the amplitude of the field basic harmonic is reduced by the value exceeding the required one,

e) the azimuthal width of shims producing the 4-th harmonic should be increased with increasing the radius to obtain the required radial distribution of the average field, the amplitude of the 4-th and 8-th harmonics.

The parameters of the shims system shaping the 4-th harmonic have been chosen basing on these calculations. The results of experiments performed with these shims on the magnetic system model are shown in Fig. 3.

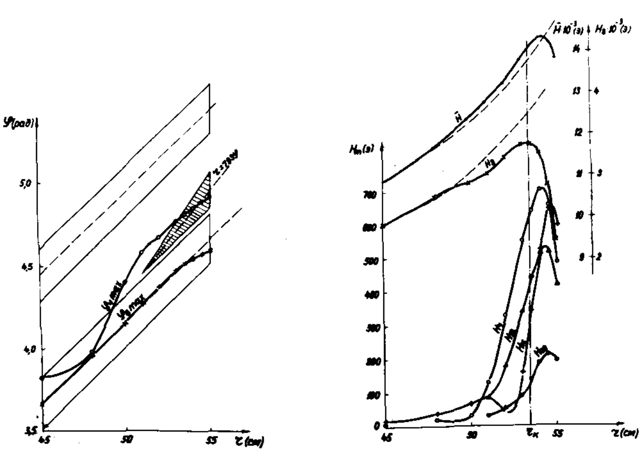

Fig.3. The results of the measurements with a magnet system model.

The left-hand side of the Fig.3 is the lay-out of additional shims with respect to the basic ones and the dependence of the maximum phase of the basic and the 4-th harmonics of the field upon the radius. The right-hand side of the Fig.3 shows the average field, the amplitudes of the 4-th, 8-th and higher harmonics versus the radius.

It is seen that the character of th the distribution amplitude of the 4-th harmonic satisfies the requirements imposed on the system of radial oscillation frequency variation in the narrow region near the final radius of the accelerator. The obtained excess of the average field over the resonance one can be compensated by means of current coils of fine and rude corrections. The reduction of the amplitude of the basic harmonic exceeds the necessary value. Therefore, the obtained value of the 8-th harmonic amplitude should be increased, which can be achieved by slight varying the profile of the spiral shim system.

The above studies show that modified resonance extraction is possible in the 700 MeV RC. All the units of the extraction system including the magnetic channel will be finally designed basing on further theoretical investigations of particle dynamics and the experiments on the magnet system model.

4. To experimentally study the modified resonance extraction of particles from the RC of the Laboratory of Nuclear Problems the electron analogue of the relativistic cyclotron with the coefficient of the dynamic identity $K_{dyn.}$=3.2 has been designed and is presently aimed at accelerating electrons up to 380 keV ($\beta \approx 0.82$) corresponding to the 700 MeV proton energy. The magnetic field is produced with three systems of current conductors one of which provides the necessary fine correction of the average magnetic field along the radius. The change of the variation depth with radius is achieved by profiling the vertical gap between the conductors. At the final acceleration radius (R_k=101.7 cm) provision is made for a winding producing the 4-th harmonic of a necessary value and a phase to produce the nonlinear resonance Q_r=8/4 at this radius. The magnetic field is 13.7 Oe at the centre. The peaks of the magnetic field with N=8 are varied according to the Archimedian spiral r= 19.3 (cm).

The accelerating system is a 90^o dee operating at the frequency of 38.5 MHz. The voltage over the dee can be varied within a wide range.

Provision is made both for the internal electron source and the external one having the injection energy of

5.5 keV and sufficiently high intensity (some mA).

The general view of the analogue is shown in Fig. 4.

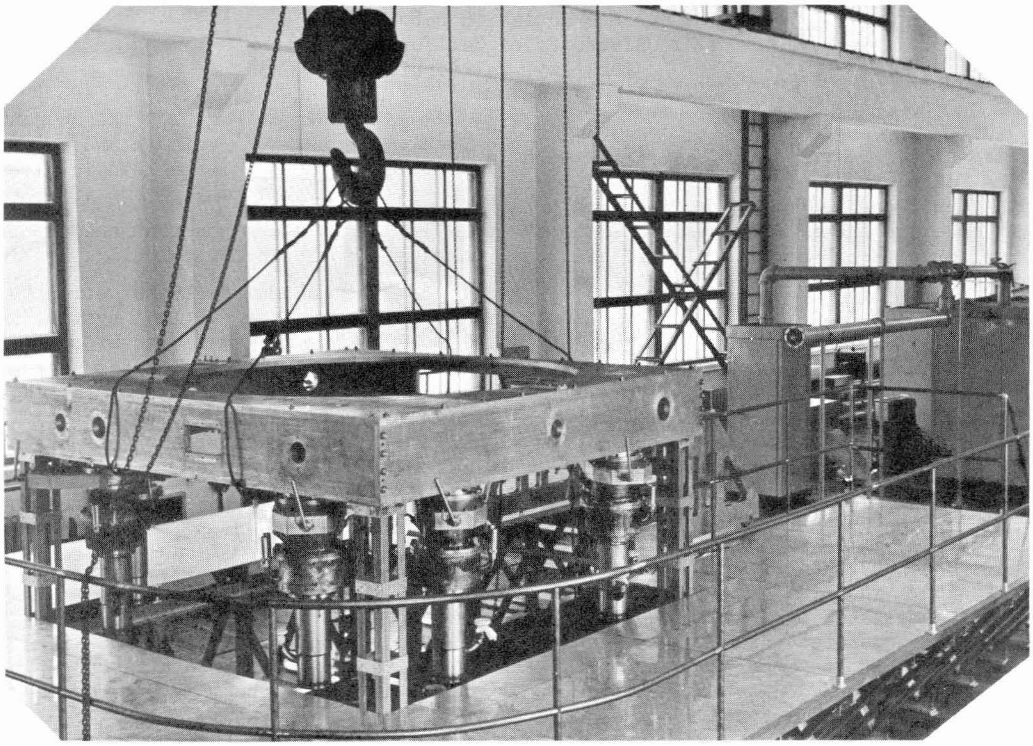

Fig.4. The electron analogue.

Further theoretical and experimental investigations will allow to draw final conclusions on the methods of practical applications and possible efficiency of the modified resonance extraction for the 700 MeV relativistic cyclotron

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