SOME PECULIARITIES OF LONGITUDINAL MOTION OF THE PARTICLES IN AN ISOCHRONOUS CYCLOTRON

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A B S T R A C T

In this paper the results of numerical investigation of transverse motion influence on time duration of the ion bunch in the isochronous cyclotron are reported. The requirements to the control degree of transverse motion parameters at beam extraction from the isochronous radius and from the region with dropping magnetic field are formulated. The ion entry into the additional bunching dee operating at the highest harmonic compared with the accelerating voltage of the main dee has been investigated. In conclusion the results of numerical modelling of the beam acceleration in the ring isochronous cyclotron with double-acceleration system at the beam extraction from radial stability boundary are given.

INTRODUCTION

In some cases very fine stabilization is not required, but there is a limit to time bunch duration. For example, at the cyclotron operation in neutron spectrometer mode (especially at beam dropping on the internal target) time bunch duration and phase motion are the controlled parameters. The same is with the cyclotron operation together with the system of active external beam monochromatization[1], though in this case more accurate control of transverse motion is required. But the connection between longitudinal and transverse motion limits the betatron oscillation amplitude. In the first section founding on the numerical investigations of ion acceleration in the isochronous cyclotron the requirements to the control degree of transverse motion parameters are formulated.

At the cyclotron operation in neutron spectrometer mode the beam bunching by an additional dee, operating at the highest harmonic relative to the main dee voltage can be useful[2]. In the cyclotron with the internal ion source the additional dee can start only from a certain radius accounting for its design. At the dee entry the radial component of the accelerating voltage perturbates the ion motion. In the second section of the paper the main investigation results of the entry into the additional dee are given.

In the reference[3]the possibility of obtaining a small energy spread beam at its extraction from the boundary of radial stability in the ring cyclotron was discussed. It was supposed that acceleration is carried out at one of the curve peaks $\Delta W(\varphi)$, and near the maximum radius the phase band is shifted into the "well". In conclusion it is shown that in this case one can obtain the beam with energy spread about $5\cdot10^{-4}$.

1. The Influence of Transverse Motion on time bunch duration

At "statistical" mode of beam acceleration and extraction with time duration of some degrees it is necessary to limit the connection of transverse and longitudinal motion. To define the degree of transverse motion parameter control a number of numerical calculations has been carried out. The data of magnetic field modelling in Kiev cyclotron for acceleration mode of the protons up to 100 MeV were used[4]. The ion motion in isochronous mode and at the end of acceleration was considered. The acceleration up to 98 MeV is isochronous. In the range of 98÷100 MeV the beam is crossed by the resonances $\nu_z = 0.5$, $\nu_r - 2\nu_z = 0$, $\nu_r = 1$. The extraction from the dropping field region, where $\nu_r = 0.87$, corresponds to 102 MeV.

The maximum phase bunch width increases the effective radial emittance. The particles with the same starting conditions over r-motion but different R.F. phases move over the independent trajectories. The amplitude of the excited radial oscillations to a great extent depends on the accelerating system type. In the cyclotron[4]with a single 180°dee the oscillations are rather small. It is well seen in fig.1, where the particle trajectories with R.F. phases of 0° and ±20° are shown on the phase plane (r, r'). But at the end of acceleration after the zone ν_r =1 the ions move along different trajectories, and so the effective beam extraction is complicated.

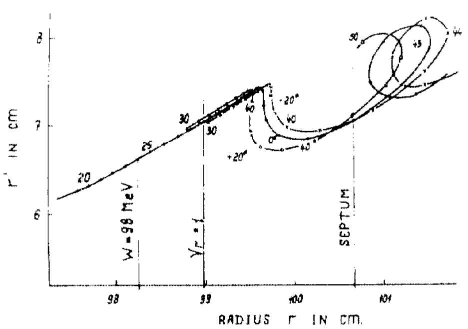

Fig.1. Phase diagram for radial particle motion with R.F.phases 0° and ±20°.

Radial oscillations in turn cause the modulation of the initial phase band. In linear approximation radial oscillations excite phase oscillations with the frequency ν_r . Non-linear character of the magnetic field distribution causes the constant phase drift. In the cyclotron[4] at the isochronous acceleration region (92 MeV - 98 MeV) the constant broadening is approximately equal to 0.0125°/turn for the amplitude of 6 mm. The maximum broadening with oscillations is equal to 1.5°. After passing the zone ν_r =1 the broadening increases and at the end of acceleration can be 3.6° at the same amplitude value.

The longitudinal motion influences very little the vertical motion envelope but phase ellipse orientation corresponding to the region occupied by the beam is changed.

The vertical ion motion gives also the time bunch broadening (fig.2). In isochronous acceleration mode phase band broadening is about 3.10^{-3} °/turn (for Z_0= 1 cm). In the dropping field region the broadening can be 2.5° for Z_0=1.4 cm.

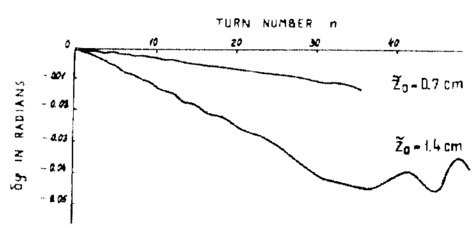

Fig.2. Phase motion for the particles with the zero radial emittance and envelope over the vertical Z_0=0.7 cm and 1.4 cm. Acceleration is isochronous up to n=30 .

At isochronous acceleration mode the coupling of vertical and radial motion is weak. At the end of acceleration, where the field changes quickly, the picture is quite different. Fig.3 shows the evolution of phase beam volume with zero initial radial emittance for the particles distributed inside the ellipse (Z, Z')with initial envelope 1.4cm.

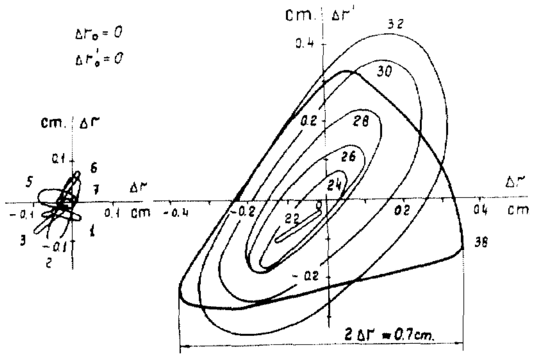

Fig.3
Phase diagrams for radial particle motion. The initial envelope over the vertical is 1.4 cm, over the horizontal is 0 cm. Fig.shows the turn number.

The magnetic field perturbations are absent. At the end of acceleration the radial envelope is equal to 3 mm and the vertical one is reduced to 8 mm.At the radial oscillation amplitudes higher than 5 mm and the first harmonic of the magnetic field higher than 3-4 Gs the beam can be lost at the dees.

At beam extraction from the radius, where $\nu_r < 1$ to keep the high-quality beam at bunch acceleration with phase duration less than 5° the initial envelope of radial oscillations should be not higher than 2-3 mm and that of vertical oscillations should be not higher than 10 mm. The amplitude of the magnetic field first harmonic should be controlled with the accuracy better than 1 Gs. At isochronous acceleration mode for the similar conditions the radial oscillations up to 6 mm are possible.

2. Longitudinal motion at bunching dee entry

In the reference[3] the beam bunching effect in the double accelerating system cyclotron was discussed when phase band is transferred from the "well" on the curve $\Delta W(\varphi)$ to the peak (the main dee and the one operating on the highest harmonic are switched opposite one another, and the voltage amplitudes are approximately equal). In the internal source cyclotron the bunching dee can extend with a certain radius. In this case the particles at the dee entry are influenced by the transverse electric R.F. field. The isochronous cyclotron with axial-symmetric magnetic field was used as a computed model (vertical motion was not considered). The data of the dee electric field measurement on the electrolytic tank are used at calculation.

Transverse R.F. field excites radial oscillations correlating with the phase. It is appeared, that for the initial phase band of $\pm 5^{\circ}$ the amplitude of the additional radial oscillations is equal to 0.6 mm, and for that of $\pm 15^{\circ}$, the amplitude is 1.3 mm. Another effect is the broadening of the initial phase band. Thus, the phase band of $\pm 5^{\circ}$ is increased by 3.5 times and the band of $\pm 15^{\circ}$ is broadened up to 65°.

Apparently, the latter effect can be used for the beam bunching by the additional dee R.F. field at simultaneous dee switching. In this case the subsequent non-isochronous acceleration mode is not necessary. At the ratio of energy gain per turn from the additional and main dees equal to 4-5 the ten-fold bunching can be obtained.

3. The beam dynamics in the ring cyclotron at the beam extraction from the radius, where $\nu_r \to 0$

The main difference of this cyclotron version from the designs[5,6] is the beam extraction near the boundary of radial stability at small energy gain per turn. The double accelerating system [3] provides for sufficiently high energy gain per turn in the main acceleration region.

At beam dynamics investigation the four-sector cyclotron, considered in[6] was used as a model. Fig.4 gives two versions of dependence of the average magnetic field on radius. In the first version the rate of R.F. phase change in the extraction zone is small. But the phase volume occupied by the beam at passing the resonance zone $\nu_r = 4/3$ can be distorted. The calculation results showed that this factor should be considered even at the initial amplitude of radial oscillations of 2 mm. In the second case $d\varphi/dW$ is maximum at the extraction radius. However, the radial motion for the amplitude up to 5 mm

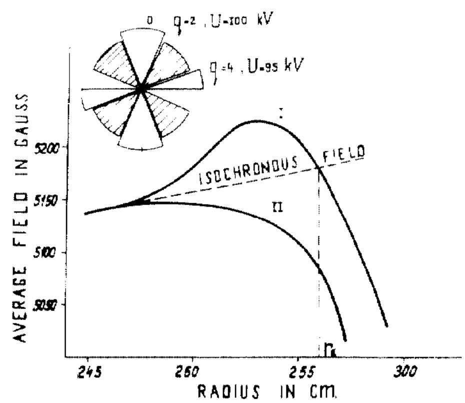

Fig.4. The dependence on the average magnetic field radius. The dotted line is the isochronous field .

is completely stable. Fig.5 shows the dependences of small radial oscillation frequencies, R.F.phase and energy gain per turn on the turn number (the starting was at 72 MeV, the extraction - at 80 MeV).

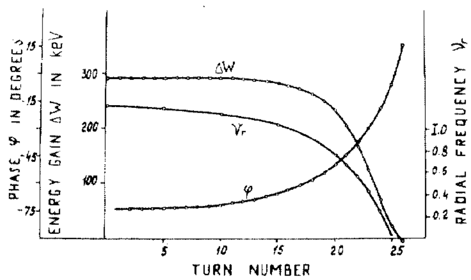

Fig.5. The dependence of the radial oscillation frequencies, R.F. phases and energy gain per turn on the turn number.

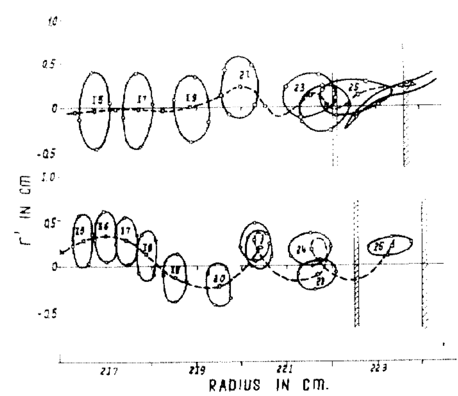

Fig.6. Phase diagrams for radial motion. Top - starting over the equilibrium orbit, the radial oscillation amplitude is 3 mm. Bottom - starting with 3 mm drifting from the equilibrium orbit, the amplitude is 2 mm.

Fig.6 shows the phase diagrams (r, r') of initially monoenergetic beam. In the upper part of the fig. the data for the particles starting along the equilibrium orbit are given as well as for the ions with oscillation amplitude of 3 mm. The results of the lower part of the fig. refer to the case, when the axial trajectory is drifted by 3 mm from the equilibrium orbit and the amplitude is equal to 2 mm. The upper diagram illustrates the extraction mode, when the orbit separation is defined by energy gain per turn. On the 25-th turn the separation is sufficient for the particles with the initial amplitude of 2 mm. The condition in the lower part of the fig. is more favourable for extraction. The orbit separation in this case is defined by energy gain per turn as well as by the orbit precession. The amplitude of coherent oscillations in 3 mm can be excited at the end of acceleration at passing the resonance zone $\nu_r = 1$ by introducing the first harmonic of the magnetic field of about 0.5 Gs.

The energy spread in the beam as a result of instability of R.F. voltage in $\pm 10^{-3}$ over the amplitude and in $\pm 1^{\circ}$ over the phase at the phase band of 20° can be estimated as 32 KeV at halfheight. The initial phase band of 2° corresponds to the phase band of 20° at the extraction. Due to the coupling of transverse and longitudinal motion the additional energy gain in the initial monoenergetic beam with maximum phase volume appears. The spread value depends on the amplitude (linearly) and phase of radial oscillations. The spread in the beam is about 3 KeV at the amplitude of 1 mm. Thus at the initial amplitude of radial oscillations of 2 mm the total energy inhomogeneity is about 5.10^{-4}.

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