Beam Extraction from Electron Model by Expansion-Computer Simulation

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The orbit expansion effect in the sector cyclotron seems to be a promising method of beam extraction. An experiment with the electron model of a 8-sector ring cyclotron is now under preparation. The computer simulation of the beam behavior is undertaken and its results are presented. The proper dependence of the main harmonic of the magnetic field on radius is found. The influence of the beam emittance, beam energy spread, flat-top acceleration on the last turn separation is investigated.

The closed orbit expansion effect in the cyclotron [1,2] seems to be a very attractive method for high-efficiency beam extraction. An experiment is now under preparation [3] for the beam extraction from the electron cyclotron. This is why this calculation was fulfilled.

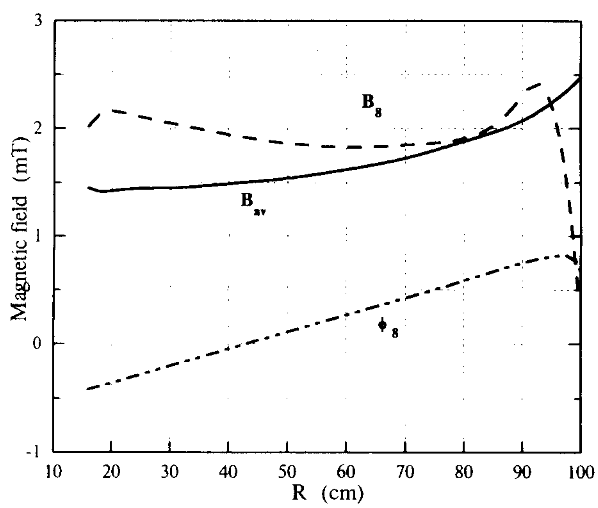

Figure 1. Magnetic field versus the radius.

The magnetic field of the electron model (fig.1) can be described as

$$B = B_{av} + B_N(r)\cos[\phi_N + \frac{r}{\lambda} - N\varphi] \qquad (1)$$

where B_{av} is the average magnetic field, B_N is the main harmonic amplitude, φ_N is the phase of this harmonic, N = 8 is the periodicity of the magnetic field structure. For the magnetic field like this the orbit compaction factor $\alpha = \frac{p}{r}\frac{dr}{dp}$ can be expressed [4] with an accuracy of a few percent as

$$\alpha \approx [1 + n + \frac{1}{2N^2}(s^2 + \varepsilon d)]^{-1} \qquad (2)$$

where $n = \frac{r}{B_{av}}\frac{dB_{av}}{dr}$; $\varepsilon = \frac{B_N}{B_{av}}$

$$s = \frac{r}{B_{av}}\frac{dB_N}{dr}; d = \frac{r^2}{B_{av}}\frac{d^2B_N}{dr^2}$$

If B_N does not depend on the radius, the orbit compaction factor $\alpha = (1+n)^{-1}$. For the magnetic field shown in fig.1 $\alpha \approx$ 0.7 at the 90 cm radius. Hence the turn separation value is 3 mm for the energy gain of 1.5 keV. Introduction of quadratic non-linearity in the main harmonic dependence on the radius (it should be negative for the orbit expansion effect) allows one to increase the turn separation by several times for the same energy gain.

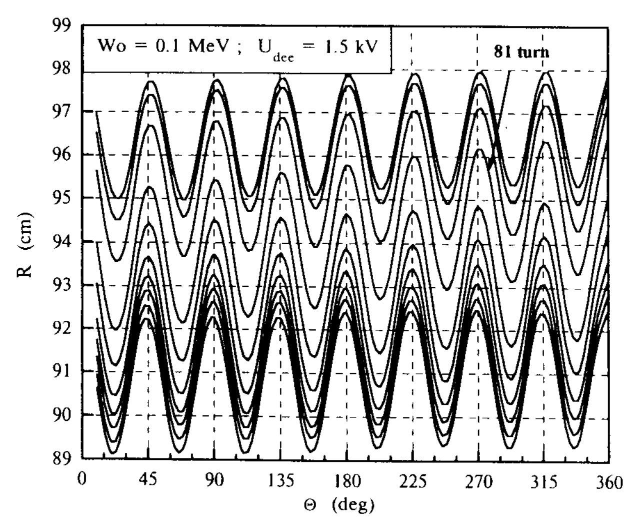

Figure 2. Last 10 turns (turns 75-84) of the central particle.

The beam dynamics calculation was done for the following initial conditions: W_0= 0.1 MeV, R_0 = 64.7 cm. The orbits for turns 75÷84 are shown in fig.2. The turn separation between the 80th and the 81st turns (energy W = 0.285 MeV) increased up to 13 mm.

Fig.3 shows dependence of the betatron frequencies on the radius. In the orbit expansion zone the radial betatron frequency significantly decreases, while the vertical one slightly grows. Fig.4 shows the phase of the central particle relative to the accelerating voltage. It is obvious, that the orbit expansion is accompanied by the fast phase shift of about 30°.

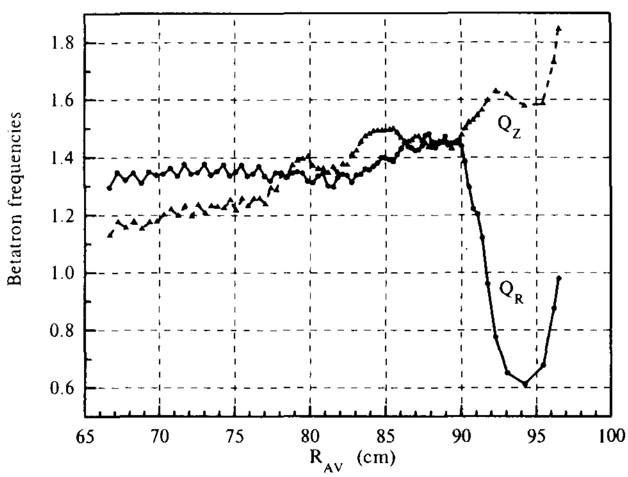

Figure 3. Betatron frequencies versus radius.

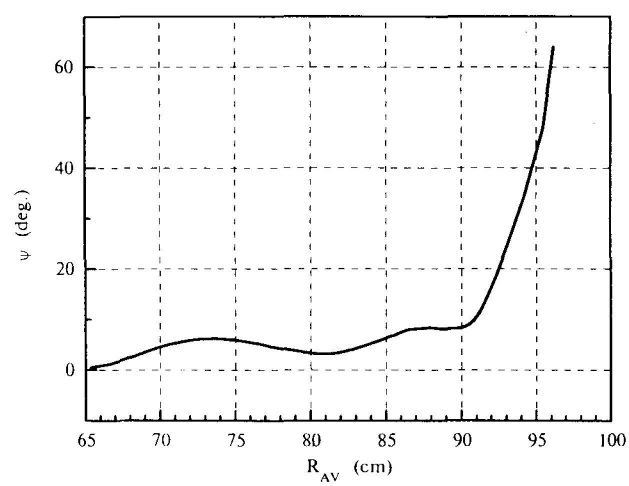

Figure 4. RF phase of the central particle.

For the extraction purpose the separation between the beam radial emittances rather then between the orbits (turns) is interesting. In our calculations the initial emittances were $\varepsilon_r = 12\pi$ mm×mrad, $\varepsilon_z = 30\pi$ mm×mrad. Fig.5 shows the radial and axial emittances in the orbit expansion region. The radial separation about 5 mm between emittances is clearly seen, while the values of the radial and axial emittances did not change.

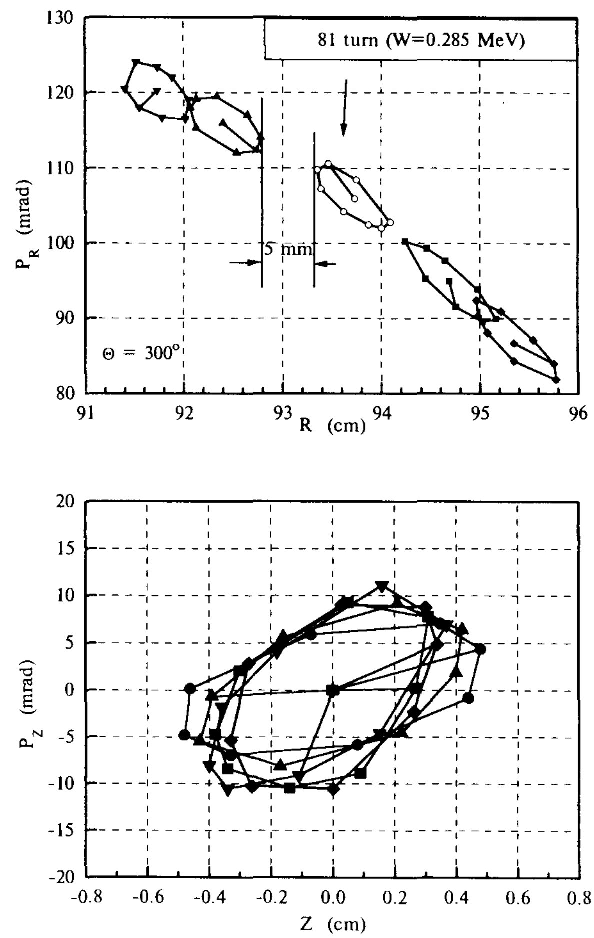

Figure 5. Radial and axial emittances in the orbit expansion zone for the monoenergetic beam.

But this good result immediately disappears if we take into account the beam phase width and the resulting energy spread. For calculations we have chosen the initial beam rf phases from −8.5° to 6.5° (beam phase width 15°). In fig.6 the beam radial emittances are shown (3 emittances with initial phases −8.5°; -1°; 6.5° for each turn). It is evident that separation disappeared.

Then the flat-top acceleration was introduced, which suppressed the energy spread in the beam to $3 \cdot 10^{-3}$ (instead of $7.5 \cdot 10^{-3}$). In this case the turn separation of 3 mm between emittances is restored (fig.7).

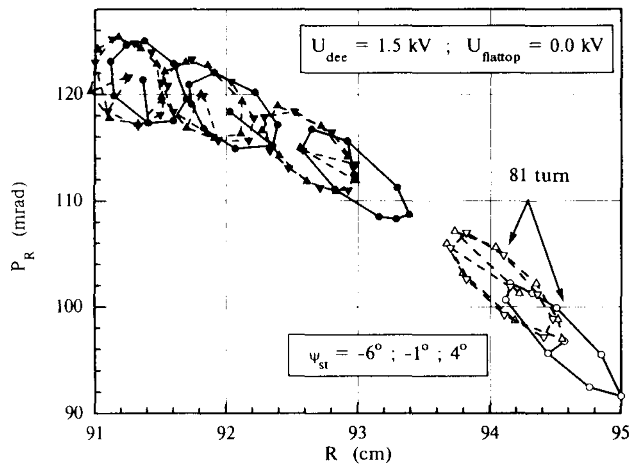

Figure 6. Radial emittances for the beam of phase width15°.

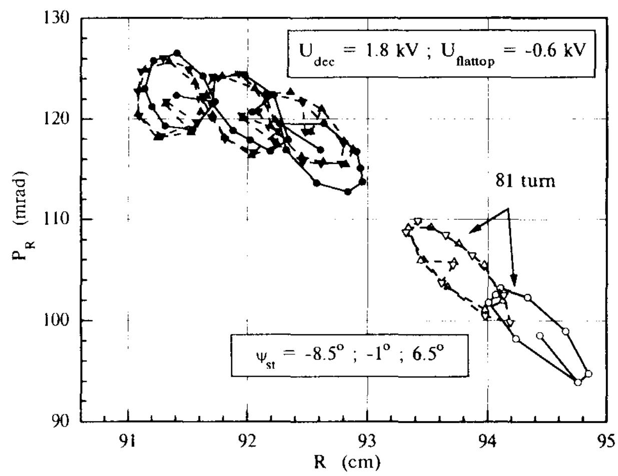

Figure 7. Radial emittances as in fig.6 but with a flat-top.

We intend to carry on our studies of the orbit expansion effect until the limits of its application are found.

References

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[3] A.A. Glazov et al., On the high Efficiency Extraction (~100%) from Sector Cyclotron (at this conference).

[4] O. Borisov, L. Onischenko, Proc. of EPAC'96, Barcelona, v.3, p.2438.