CURRENT LIMIT IN THE COMPACT CYCLOTRON WITH EXTERNAL INJECTION

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Abstract

We are developing the compact H^- 1.75MeV Cyclotron with the vertical external injection using the spiral inflector. At the process of the beam dynamics computer simulation we have found the limit of the beam intensity which is near 2.5mA.

PARAMETERS OF THE CYCLOTRON

Main cyclotron parameters are shown in the following table.

Type of ion	H^-
Injection energy (keV)	30
Average magnetic field (T)	0.64
Number of sectors	4
Sector azimuth angle (°)	10-30
Betatron axial frequency ν_z	0.3- 0.8
Number of dees	2
Angular span of dees (°)	45
RF voltage (kV)	60
Orbital frequency (MHz)	9.76
Harmonic number	4

For betatron frequency ν_z =0.3 the critical beam current [1] is near 1.5mA and its limit when ν_z is decreasing to zero by the space charge influence [2] is near 10mA.

CODE DESCRIPTION

Code PHASCOL [3] has been adopted for the particle dynamic computations in the cyclotron. Full differential equations describing the particle dynamics in an electromagnetic field of cyclotron are integrated inside the PHASCOL taking into account the space charge.

RESULTS OF COMPUTATIONS

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In the first stage of computations we examined the conditions of ideally injected beam. We wanted to answer a question: is it possible, in principle, to accelerate 5 mA current in the cyclotron, without worrying in this case how this current would be injected into a central region?

The effects, which appear in the line of injection, were considered partially at this point of calculations. We took into account only the effects induced by a buncher and did not take the influence of inflector on the injected beam quality. It is well known that an action of spiral inflector on the beam leads to some negative factors:

1. Large axial divergence of the beam.
2. Increase in the phase width of bunch.
3. Miss of the beam in an accelerated equilibrium orbit.

Selection of the beam initial parameters was carried out taking into account minimal bunch phase width ensured by the buncher action depending on the beam intensity. A set of 5000 particles was chosen around an accelerated equilibrium orbit at radius 5.6 cm (Figure 1).

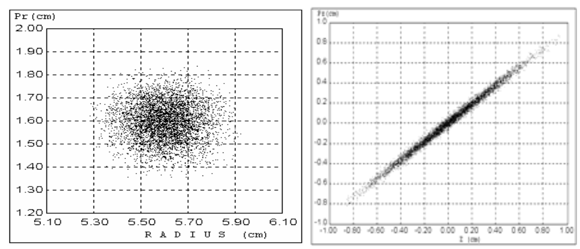

Figure 1: Initial parameters of ideally injected beam with I=5 mA. Emittances $\varepsilon_r = \varepsilon_z$ =125 π mm.mrad, energy W=30±6 keV, phase length $\Delta\varphi$=15*4=60°RF.

Figure 2 shows a layout of the cyclotron with the trajectories of 5000 particles at initial beam intensities 0 and 5mA.

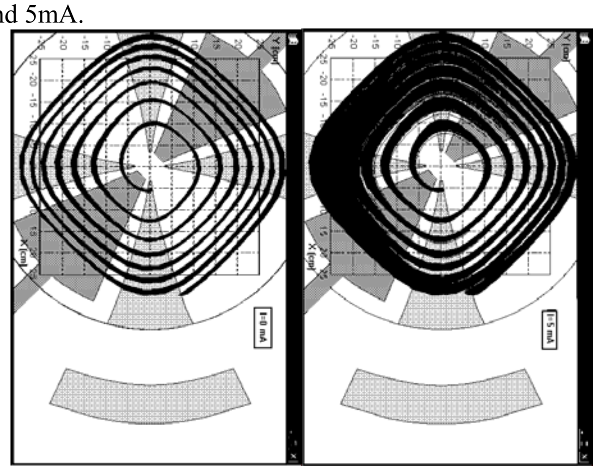

Figure 2: Particle trajectories at different initial current. To the left I=0 mA, to the right I=5 mA.

Axial particle motion is shown in Figure 3. Approximately 15% of the beam with initial current 5 mA were lost on the dees plates during first 2 turns (dee aperture is 3 cm).

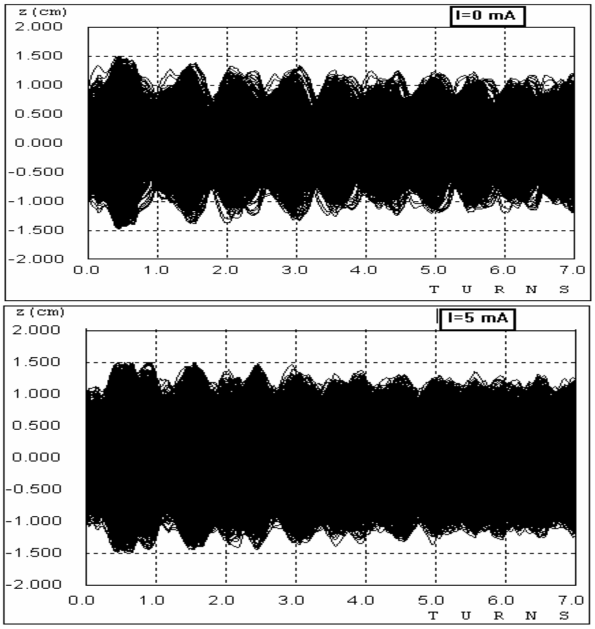

Figure 3: Axial trajectories at different initial current. Above I=0 mA, below I=5 mA.

Some conclusions were made on the base of computations for ideally injected beam:

• the focusing properties of the cyclotron magnetic field make it possible to accelerate beam with the current approximately 5 mA.

• radial width of beam with current 4.3 mA on the last turn equals 18-25 mm depending on azimuth;

• final root-mean-square (±2σ) emittances of beam are following :ε_r=170 π mm.mrad, ε_z =130 π mm.mrad.

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At the second stage of calculations we used the more realistic initial conditions [4], which corresponded to the passage of the beam through the injection line ended by the inflector. Selection of the beam initial parameters was done in a range 1-20 mA. As an example, in Figure 4 one can see position of 2000 macroparticles inside 6D phase volume at injection current 5 mA. Here we can see an increase in the particle density as the result of acting the buncher, and the axial divergence of beam, which reaches ~300 mrad. The energy spread of the injected beam (± 10%) is determined by the space charge and buncher action. Motion of the particles in injection line is shown in Figure 5 for two beam intensities 1 and 10 mA.

The calculations of acceleration were performed in two regimes:

1. With three radial diaphragms (width ΔR=20 mm) installed inside the dees on the first turn.
2. Without radial diaphragms.

Three types of losses were simulated in the calculations. Particle was removed from the computations if:

1. Axial coordinate of particle was greater than half of vertical aperture (Z>15 mm).
2. Particle did not pass the window of diaphragm.
3. Particle went to the center of cyclotron because of bad phase motion.

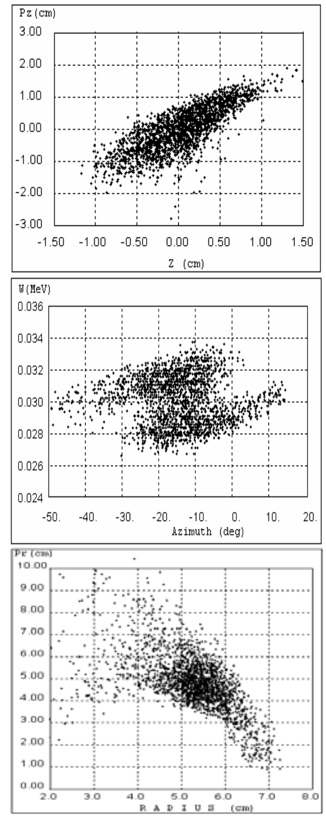

Figure 4: Initial position of 2000 particles on three phase planes. Above –axial plane, below -radial plane, in center - (azimuth-energy) plane (I=5 mA).

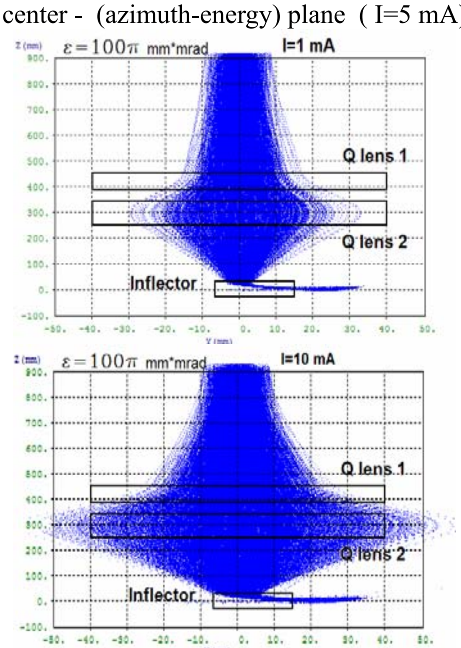

Figure 5: Ion trajectories in injection line.

Computations have shown (Figure 6) that axial losses were greater in 2 – 4 times than radial ones. There are two main reasons of axial losses: large initial beam axial divergence and bad RF phase for a part of the beam when it passes through the 1-st accelerating gap. The last occurs due to large phase width of the bunch.

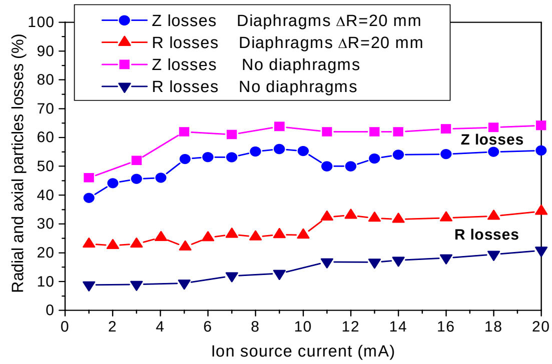

Figure 6: Radial and axial particle losses versus injection current.

Interpretation of the results (Figure 7) shows that beginning from the current of injection 12 mA an increase in the internal current of cyclotron practically stops. At this moment the current of cyclotron reaches approximately 2 mA.

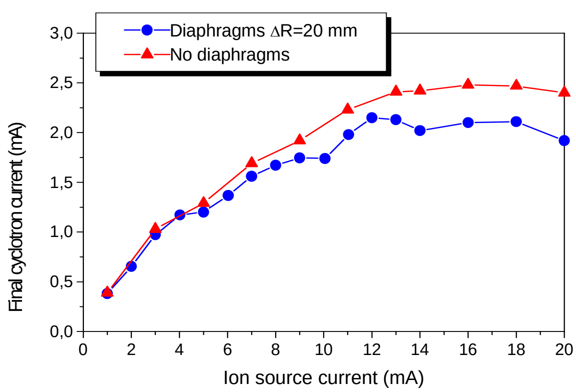

Figure 7: Cyclotron current at the end of acceleration versus injection current.

Remarkable deterioration in the radial beam quality is observed (Figure 8) when injection current becomes greater than 10 mA. The axial emittance of beam weakly depends on intensity, since it is determined mainly by the vertical aperture of dees.

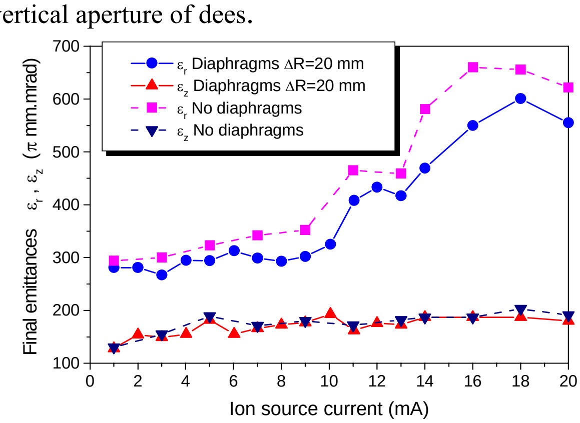

Figure 8: Transverse emittances at the end of acceleration versus injection current.

Our computation results are well matched with the results of TRIUMF [5] (see Fig. 9)..

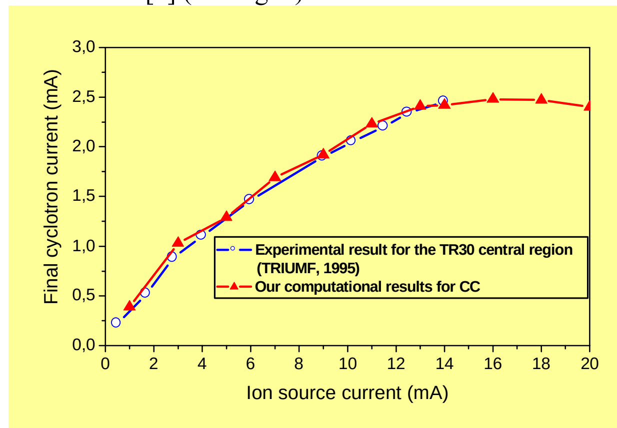

Figure 9: Dependence of the cyclotron beam final current on the injected current.

CONCLUSIONS

We can conclude from our computer simulation of the beam dynamics in the compact cyclotron with external injection that maximal accessible current of cyclotron is 2 mA with the diaphragms ΔR=20 mm and 2.5 mA without the diaphragms.

Particles are lost mainly on the vertical plane because of bad axial motion. Radial (phase) losses are several times less than axial ones.

Noticeable deterioration in the radial quality of cyclotron beam is observed if the current of injection exceeds 10 mA.

Final cyclotron parameters that correspond to injection current 10 mA are: current 1.75 mA; angular divergence of beam ± (15-30)mrad; beam energy spread ± 8%; emittances $\varepsilon_{r,z}$=300, 150 π mm·mrad.

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