COMPUTATION OF BEAM DYNAMICS WITH SPACE CHARGE IN COMPACT CYCLOTRON ON ENERGY ~ 1.8 MEV

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Abstract

A project of isochronous 4-fold compact type cyclotron to the energy of the H^- ions ~1.8MeV with an intensity of about several milliamperes is developed in the JINR. An external source of ions and axial line of injection with spiral inflector is assumed to be used in the cyclotron. The results of calculations of the beam dynamics taking into account the effects of space charge are examined beginning from an exit of inflector. The final parameters of beam - transverse emittances, energy spread, and value of maximal accessible intensity of the beam are given.

PARAMETERS OF THE CYCLOTRON

Main cyclotron parameters are shown in the following table.

Type of ion	H^-
Injection energy (keV)	30
Extraction energy (MeV)	1.8
Average magnetic field (T)	0.64
Number of sectors	4
Number of dees	2
Betatron frequencies ν_r , ν_z	1.1, 0.85
Angular span of dees (°)	45
RF voltage (kV)	60
Orbital frequency (MHz)	9.76
Harmonic number	4

CODE DESCRIPTION

Code PHASCOL [1] 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.

We have used two ways for the computation of beam electric field: (I) - method of direct summation of the Coulomb's field created by each macroparticle (PTP method) and (II) - method of fast Fourier's transform (PIC method). PIC method assumes a calculation of beam electric field on a 3D grid that covers bunch. Both methods gave close results, but the second method worked faster, if the number of macroparticles composed several thousand. Therefore we have used mainly PIC method in the calculations.

RESULTS OF COMPUTATIONS

Ideally Injected Beam

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. 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.

At this moment we assumed that the spiral inflector did not have these negative qualities and that it could transfer beam into the required region of phase space in the center of cyclotron.

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).

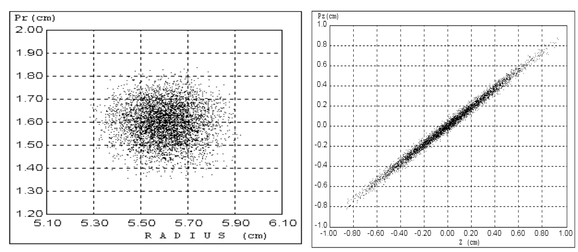

Figure 1: Initial parameters of ideally injected beam with I=5 mA. Emittances $\varepsilon r = \varepsilon z = 125\ \pi$ mm.mrad, energy W=30±6 keV, phase length $\Delta\varphi$=15*4=60°RF.

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

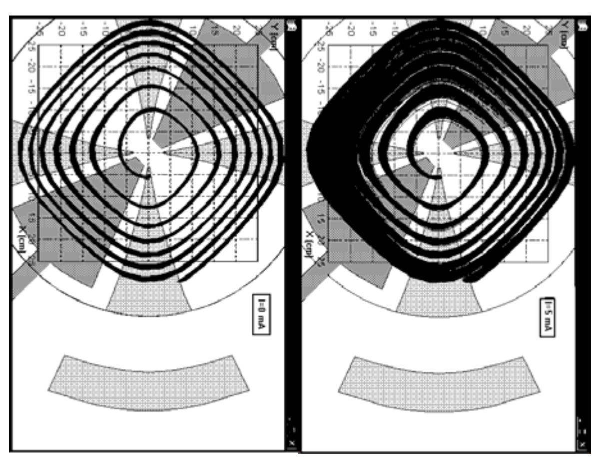

Figure 2: Particle trajectories at different initial current. To the left I=0 mA, to the right I=5 mA

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).

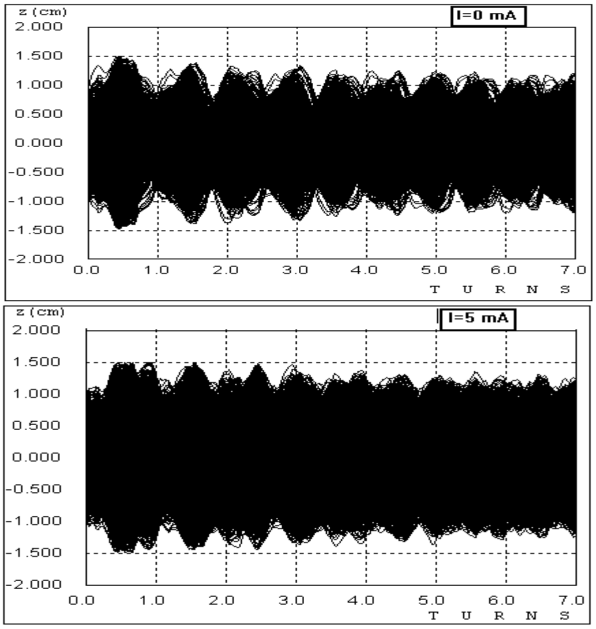

Figure 3: Axial trajectories at different initial current. Above I=0 mA, below I=5 mA.

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 :εr=170 π mm mrad, εz =130 π mm mrad**.**

Not Ideally Injected Beam

At the second stage of calculations we used the more realistic initial conditions [2], 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 200 mrad. The energy spread of the injected beam (± 10%) is determined by the space charge and buncher action.

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.

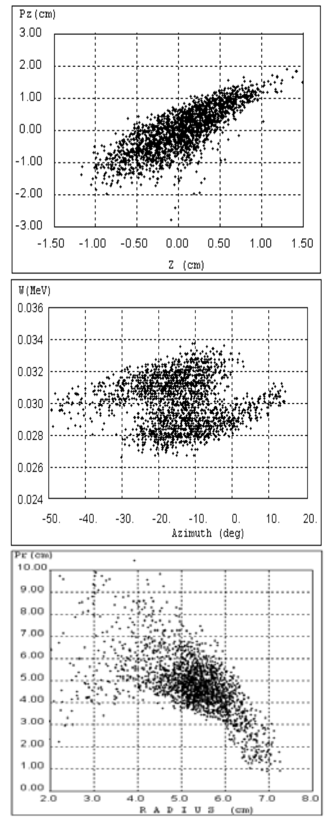

Figure 4: Initial position of 2000 particles on three phase planes. Above –axial plane, below -radial plane, in center - (azimuth-energy) plane (I=5 mA).

Computations have shown (Figure 5) 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.

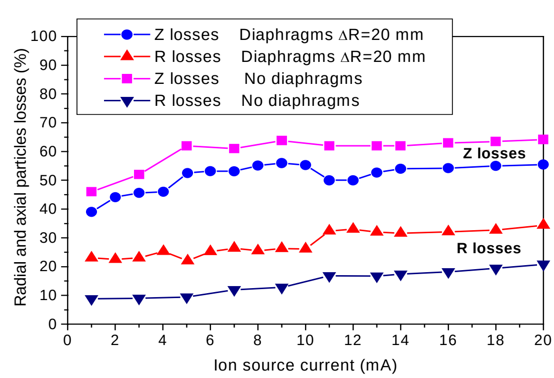

Figure 5: Radial and axial particle losses versus injection current

Interpretation of results (Figure 6) 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.

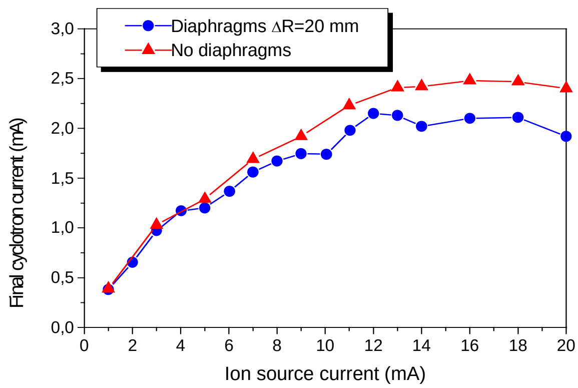

Figure 6: Cyclotron current at the end of acceleration versus injection current

Remarkable deterioration in the radial beam quality is observed (Figure 7) 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.

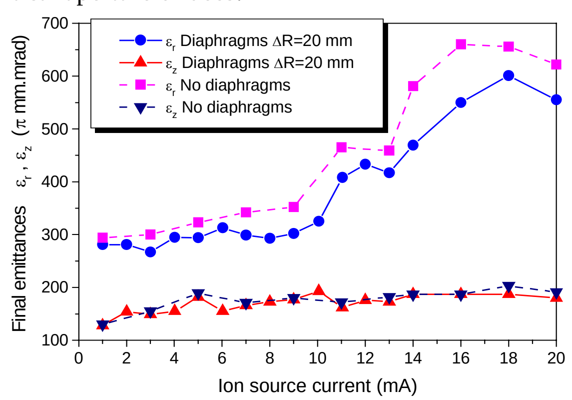

Figure 7: Transverse emittances at the end of acceleration versus injection current

Extraction System

Two types of the system of beam extraction from the cyclotron were examined: on the base of stripping foil and with the aid of the electrostatic deflectors. Since the possibility of guaranteeing the sufficiently long time of the foil life at the beam intensity ~ 2 mA causes doubts, then basic efforts were concentrated during the development of the electrostatic system of extraction.

The system of extraction consists of two deflectors ESD-1 and ESD-2 (Figure 8) with the strength 22 kV/cm of electric field at the center of their aperture. Voltage 60 kV on the high-voltage electrode corresponds to the value of the horizontal aperture of deflectors 2.5 cm. For compensating the beam defocusing in the horizontal plane by the action of edge magnetic field the necessary gradients of electric field in the deflectors ESD-1 and ESD-2 are -4.6 and -12.2 kV/cm^2, respectively.

Electrostatic elements are supplemented with the turning passive magnet MC with the field at the center of its aperture -0.2 T and with a gradient in the horizontal plane 0.02 T/cm.

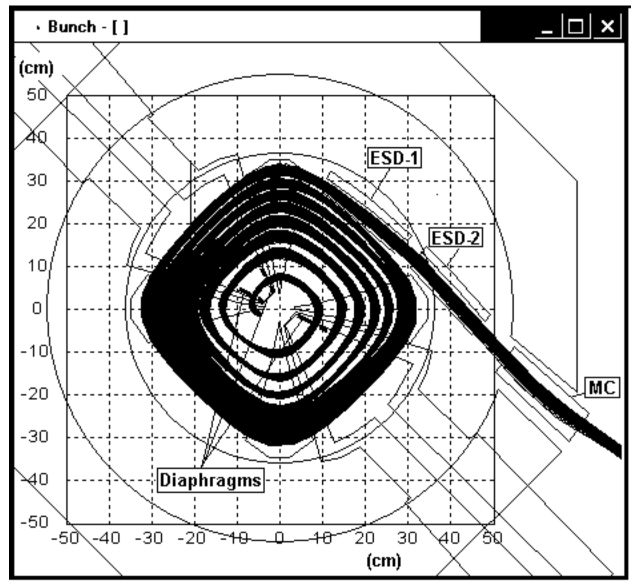

Figure 8: Layout of the cyclotron with particle trajectories. Only particles accelerated to final energy are depicted. Position of the diaphragms and extraction system are drawn schematically.(I=1 mA)

Computations showed that extraction efficiency is ~80%. The basic losses of particles are observed at the entrance into the first deflector of the extraction system. Losses inside the extraction system are insignificant since horizontal size of the beam cross section remains less than deflectors' aperture.

CONCLUSIONS

Maximally 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 the bad axial motion. Radial (phase) losses are several times less than axial ones.

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

Final cyclotron parameters that correspond 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.

REFERENCES

[1] L.M.Onischenko et al, Numerical simulation of space charge effects in the sector cyclotron, Nukleonika, 2003, 48 (Supplement 2), p.45-48.

[2] G.A.Karamysheva, Injection line for the customs cyclotron, this conference.