

## INJECTION SYSTEM OF THE COMPACT CYCLOTRON

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### Abstract

Compact Cyclotron will be equipped with the external ion source. Since the injection system will transport space charge dominated, high-intensity beams, the injection energy must be as high as practically achievable (limited by the voltage holding capability spiral inflector). Ions energy from ion source will be equal 30 keV.

The injection system consists of a double-drift beam bunching system, a spiral inflector, beam analysis diagnostics, focusing and adjustment elements.

The design and optics characteristics for the injection line (buncher-quadrupole doublet-inflector) are described and the results of the computer simulations taking into account space charge effects are presented.

The injection axis is vertical, while the cyclotron's acceleration plane is horizontal.

### BEAM DYNAMIC COMPUTER SIMULATIONS

Numeric simulations are carried out for 500 particles using code for calculation of particle dynamics by integration of differential equations in Cartesian coordinate system written in MATLAB. Direct Coulomb particle-to-particle method is used to take into account space-charge effects. 3D electrostatic field calculations are performed for particle motion simulation through the inflector. 3D magnetostatic calculations of the quadrupole doublet are also made. Calculated electric and magnetic field maps are used for beam dynamic simulations.

First of all particle dynamic modelling in buncher and inflector is carried out. Finally the beam motion in different variants of injection line (including focusing elements, buncher and inflector) is simulated.

### THE AXIAL BUNCHER

To guarantee 100% beam bunching efficiency beam-bunching system should use an ideal saw-tooth waveform. However, a high-power, high frequency saw-tooth wave generator is expensive and quite difficult to realize in practice. Generally, bunchers use sinusoidal waveform generators with a few higher order harmonics.

In our simulations we use a double-drift buncher design (the buncher gap is 5 mm and the distance between 2 gaps is  $3/2\beta\lambda$  (92 mm)) with sinusoidal waveform. The main advantages of sinusoidal bunching system are simplicity in structure and low cost. Initial transversal emittances were equal to  $5 \times 20 = 100 \pi$  mm mrad, initial phase extension –  $360^\circ$  RF. Voltage amplitude on the sinusoidal buncher was 1500 B, providing focus location from buncher – 40 cm.

Fig. 1 and Fig. 2 demonstrate beam bunch creation along z-axis after sinusoidal buncher ( $z = 0$  corresponds to the beginning of the first accelerating gap). Figure 1 –

without space charge effects, Fig. 2 – taking into account space charge effects (DC beam intensity  $I = 5$  mA).

Number of particles in one histogram bin corresponds to number of particles within bunch width  $36^\circ$ RF thus one can estimate efficiency of the buncher.

Sinusoidal buncher efficiency totals 60% for  $I = 0$  mA and about 50% for  $I = 5$  mA (bunching efficiency is the ratio of the number of particles within the bunch width ( $60^\circ$ RF) to the total number of particles in an rf cycle). Energy spread induced by sinusoidal buncher is equal to  $\pm 3$  keV. Such energy spread is required to compensate Coulomb forces in space charge dominated beam.

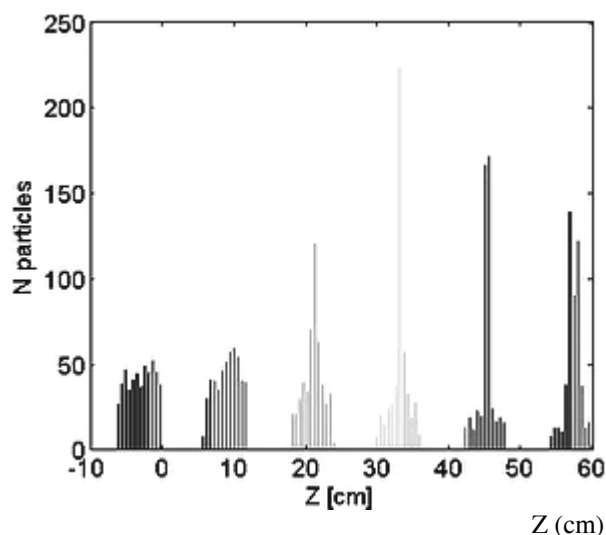


Figure 1: Sinusoidal buncher, without space charge effects, (number of particles in one histogram bin corresponds to the number of particles within bunch width  $30^\circ$ RF).

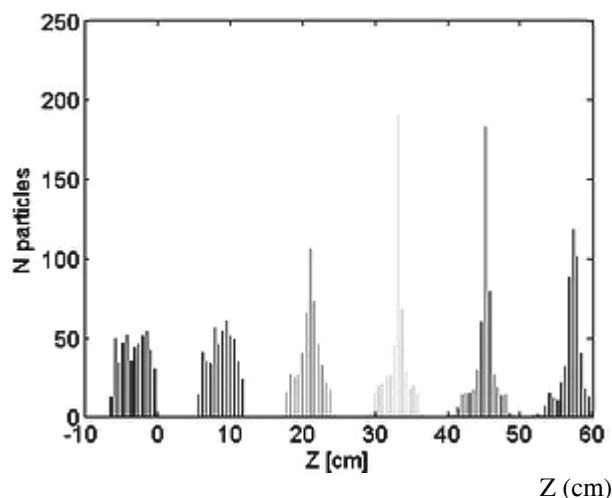


Figure 2: Sinusoidal buncher (taking into account space charge effects).

Fig. 3, 4 show beam energy variation vs time. One can see energy spread narrowing induced by space charge.

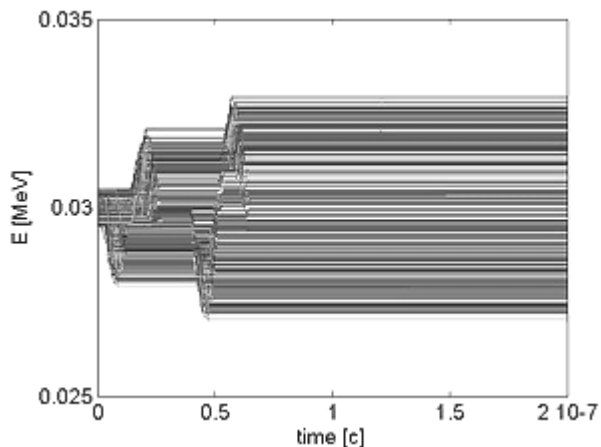


Figure 3: beam energy vs time (without space charge effects).

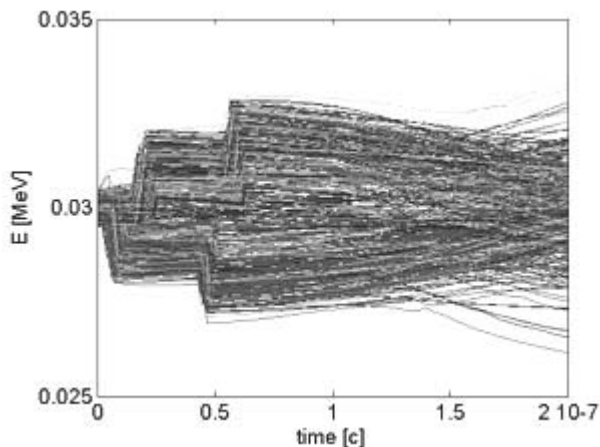


Figure 4: beam energy vs time (taking into account space charge effects).

Thus space charge effects decrease efficiency of the buncher. For a 5 mA unbunched circulating beam, 30 kV injection energy,  $h = 4$  the optimum position for the buncher less than 0.40 m from focus location.

For more accurate results it is necessary to perform 3D-numeric simulation of the buncher gap field to take into account fringe field effects.

### QUADRUPOLE DOUBLET- BUNCHER – INFLECTOR.

Quadrupole doublet is used for injection line focusing. The quadrupole doublet rotation with respect to the inflector ensures an optimal matching capability. Computer model of the inflector is described in [1]. View of the quadrupole doublet computer model is presented in Fig. 5. A layout of the injection system is shown schematically in Fig. 6.

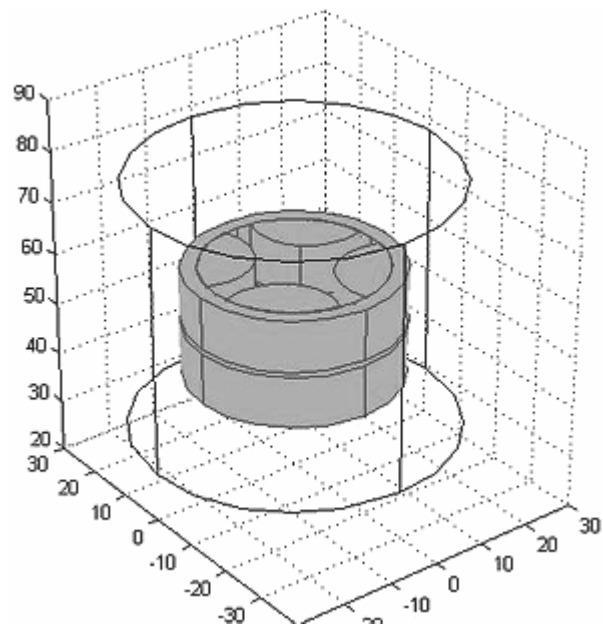


Fig.5: Quadrupole doublet computer model

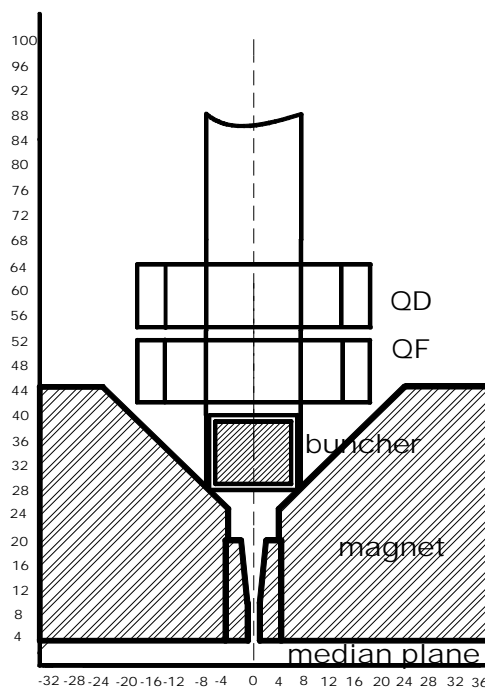


Figure 6: Layout of the injection system.

Quadrupole field gradients less than 30 mT/cm, effective length of the quadrupoles – 10 cm, aperture diameter – 15 cm.

The position for the buncher is 0.4 m from the cyclotron median plane. Beam trajectories in axial injection line are demonstrated in x-z and y-z axis (z – along the injection line) in Fig. 7, Fig. 8.

In Fig. 9 beam axial emittance at the exit from inflector is shown.

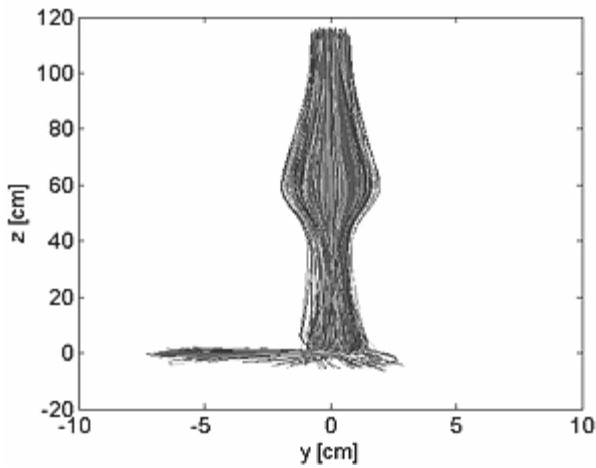


Figure 7: Beam trajectories in axial injection line in Z-Y axis.

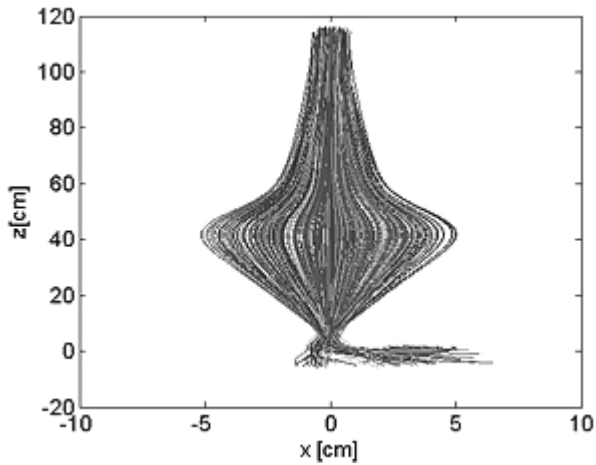


Figure 8: Beam trajectories in axial injection line in Z-X axis.

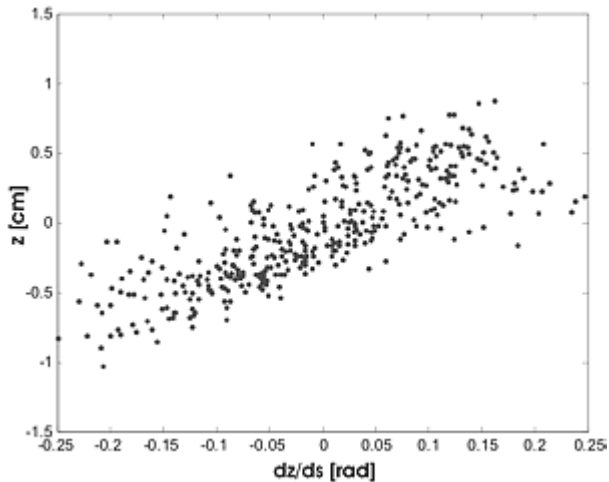


Figure 9: Beam axial emittance at the exit from the inflector.

The beam losses totaled  $\sim 10\%$ . The axial divergence of the beam (see Fig. 8) can cause additional losses in the center of cyclotron. Bunch azimuth distribution in the first accelerating gap is presented in Fig. 10. Efficiency of the

buncher is about 50%. It is necessary to perform additional simulations paying particular attention to the matching between the injection line and the cyclotron central region. Fig. 11 shows beam energy distribution in the first gap. It is clear that accurate estimation of the beam losses in the cyclotron center may be done after realization integrate modelling of the central region.

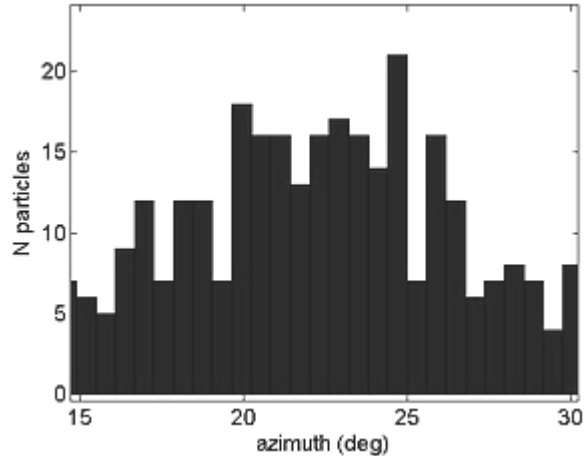


Figure 10: Bunch azimuth distribution in the first accelerating gap.

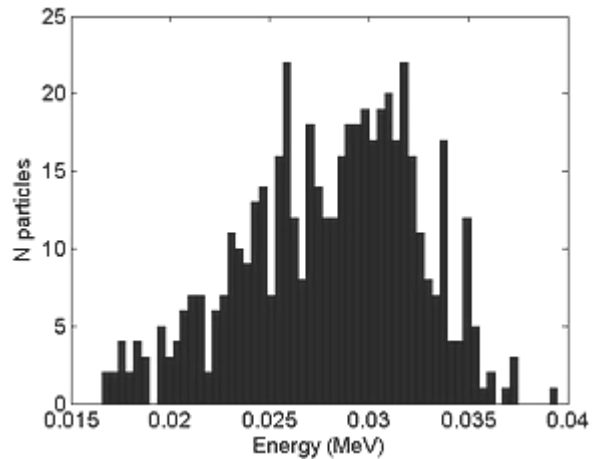


Figure 11: Beam energy distribution in the first gap.

## CONCLUSION

Computer modelling confirmed the possibility of high-intensity beam transmission, bunching and bending from axial to median plane with losses less than 10 % at an injection voltage of 30 KeV (DC beam intensity  $I = 5$  mA). Bunching efficiency is about 50%. Precise estimation of beam losses in the cyclotron center may be done after realization 3D modelling of the central region and computer simulation of beam matching to the acceptance of the cyclotron.

## REFERENCES

1. G.A.Karamysheva, L.M.Onischenko, Spiral inflector for compact cyclotron, this conference.