CENTER REGION DESIGN OF THE CYCLOTRON C400 FOR HADRON THERAPY

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Abstract

A superconducting cyclotron C400 able to accelerate carbon ions up to 400 MeV/amu and H2+ up to 260 MeV/amu has been designed at IBA (Belgium) in collaboration with JINR (Russia).

The ions extracted from the source and transported with the axial line are bent into the median plane of the cyclotron by a spiral inflector. The optimal design of the inflector and cyclotron center for acceleration of the ion beams in the 4th RF harmonic mode was investigated. A computer model of the dee geometry with the inflector and inflector housing was created. The 3D magnetic field map and 3D electric field map were used for beam dynamics simulations. Results of the beam tracking are presented.

INFLECTOR

For the C400 center it will be necessary to use a number of pillars reducing the transit time and slits for phase selection. As the first step, it is necessary to determine the accelerated equilibrium orbit with the analytical presentation of the accelerating field.

The cyclotron RF system will operate with a frequency about 75 MHz. The Kilpatrick sparking criterion for high frequencies gives Es = 100 kV/cm. The maximum electric field in the first accelerating gap was chosen to be 130 kV/cm taking into account that electric field is perpendicular to the magnetic field. The accelerating gap size was chosen to be 6mm, thus the maximum voltage may be 80 kV at the center of the cyclotron. It is necessary to have about 6 mm from the grounded housing of the inflector to the dees.

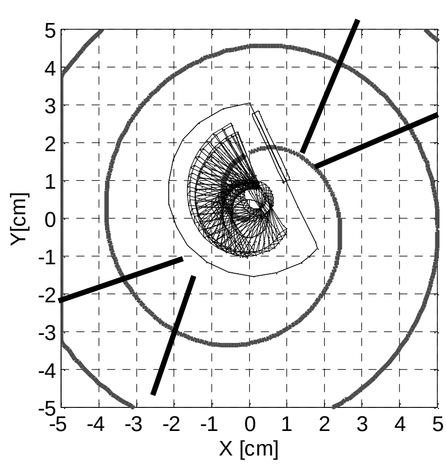

Figure 1: Equilibrium accelerated orbit with the analytical orbit through the inflector (a = 26.3 mm k′ = 0.3).

An equilibrium accelerated orbit through the inflector and the central region was calculated (see Fig. 1). Black lines show possible positions of the dees. From the figure it is clear that the central region of the cyclotron is very tight.

The main parameters of the inflector were chosen such as to make it possible to place the inflector housing and the dees far enough from each other and to place reference particle as close to the equilibrium orbit as possible.

Ion energy per charge was 25 keV/Z. The electric field of the inflector was chosen to be 20 kV/cm. Thus, the height of the inflector (electric radius) is equal to 2.5 cm. The gap between the electrodes was taken to be 6 mm. The aspect ratio between the width and the spacing of the electrodes was taken to be 2 to avoid the fringe field effect. Computer models of the inflector with different tilt parameters were developed. The inflector was placed in the grounded housing. The distance between the grounded housing and the twisted electrodes was 0.5 cm. A computer model of the spiral inflector with the housing is presented in Fig. 2.

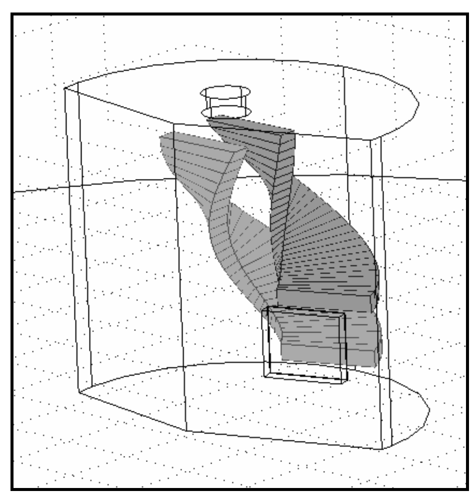

Figure 2: Spiral inflector.

CENTRAL REGION

The principal requirements to the central region design are:

- Acceleration of the beam in a well-centered orbit with respect to the geometrical center.
- Fine tune electric vertical focusing.

A model of the dee geometry at the cyclotron center with the inflector housing was developed. Dee tips have a vertical aperture 1.2 cm in the first turn and 2 cm in the second and other turns (see Fig.3). In the first turn the gaps were delimited with pillars reducing the transit time. The azimuth extension between the middles of the accelerating gaps was chosen to be 45 deg. The electric field simulation of the central region was performed.

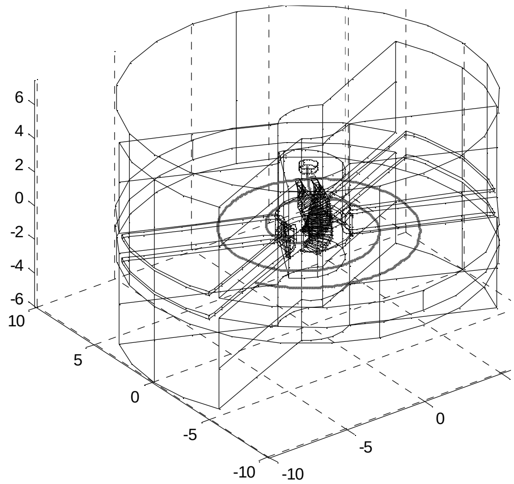

Figure 3: Center region model.

BEAM DYNAMICS SIMULATION

Final results of simulation of the continuous beam with accelerating voltage about 80 kV are presented. The mean magnetic field against the radius is shown in Fig. 4. One can see that the value of the bump in the central region is about 200 G. At the end of our simulation (R = 8 cm) the mean magnetic field is isochronous.

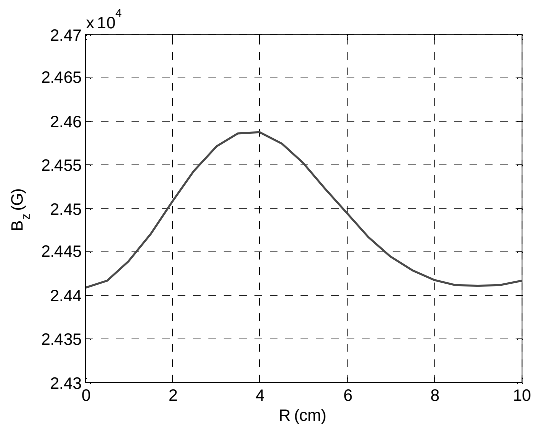

Figure 4: Mean magnetic field in the center region.

We simulated continuous beam motion through the inflector without a tilt and in the center region to R = 8 cm. For this purpose 1818 particles with initial distributions obtained from simulation of the beam motion through the axial injection line at the point z = 4.5 cm were taken. Motion of this slice was calculated for a half of the RF oscillation period. All coordinates with a z step corresponding to 10° RF were taken as initial values for the simulation of continuous beam motion. Most of the pictures (Figs. 7 – 9) are given for small number of particles (3458) for better visualization. Initial bunch distributions in the X-Y, Y-Z planes (blue dots) are presented in Figs. 5, 6, green dots are particles involved in acceleration with radial amplitudes less than 0.3 cm, red dots are particles involved in acceleration with radial amplitudes less than 0.2 cm.

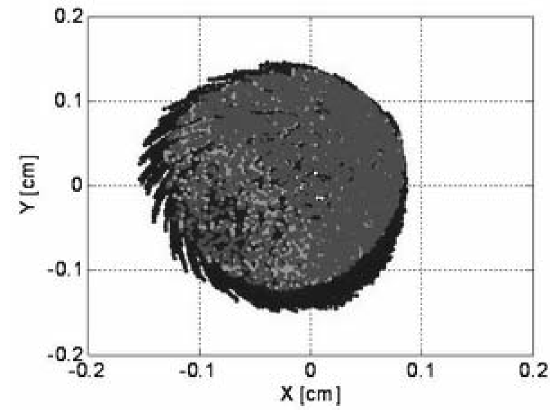

Figure 5: Initial bunch distributions in the transverse plane.

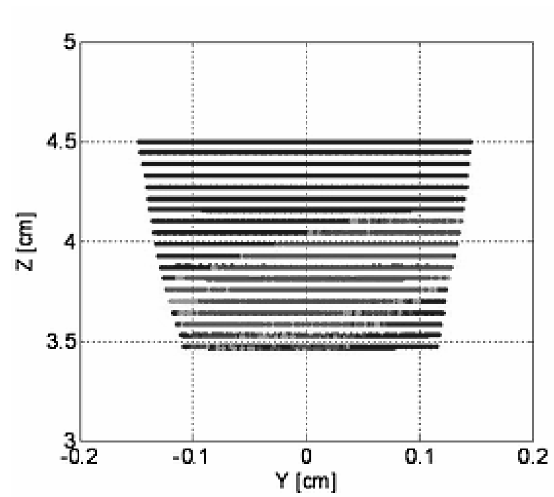

Figure 6: Initial bunch distributions in the Z-Y plane.

Axial motion was restricted by the vertical aperture of 1.2 cm at the very center and 2 cm in the second and further turns.

49% of calculated ions were left inside the vertical aperture, many of them had a big amplitude of radial oscillation. From beam dynamics simulations in the accelerating region we know that the amplitude of radial oscillation must be smaller than 4mm to avoid intolerable increase of amplitudes of betatrone oscillations induced by resonances. To reduce the amplitude of the radial oscillation a phase selection slit was established at the azimuth 0° at the radii 3.4 – 3.8 cm bounding the first turn. The azimuth for phase slit was chosen at the point of maximum width of the beam in the radial direction. As a result, about 20% of the calculated ions passed through the slit. Fig. 7 presents amplitudes of radial betatron oscillations of these ions. It is seen that particles have amplitudes less than 4 mm.

As we were working with particles initially distributed inside a half of the RF oscillation period, the injection efficiency will be 10 %. In other words the central region selects about 36° RF.

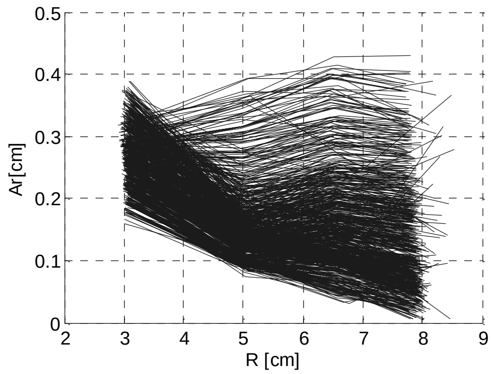

Figure 7: Amplitudes of radial betatron oscillations (one slit).

Figure 8 demonstrates turns of these ions in the central region.

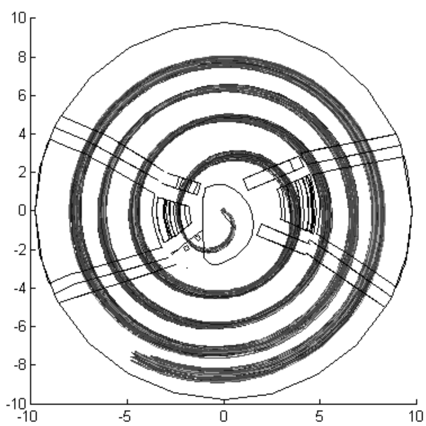

Figure 8: First turns at the center.

Energy of particles during two turns against time is presented in Fig. 9.

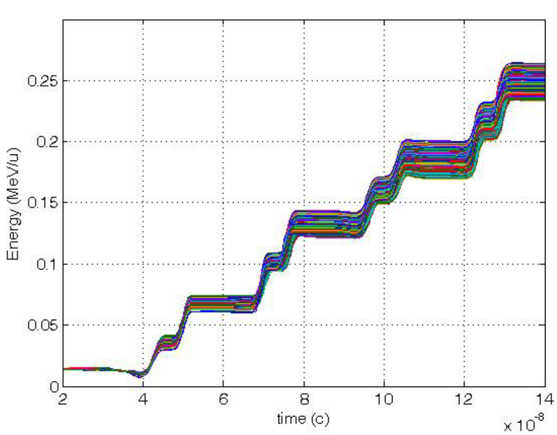

Figure 9: Energy of particles during two turns.

Then the width of the first slit was established at the radii 3.3 – 3.9 cm and the second phase slit was established at the azimuth 0° at the radii 6.5 – 7.0 cm. As a result, the injection efficiency was 12 % for ions with amplitudes of radial betatron oscillations less than 4 mm. In other words, the central region selects about 43° RF.

INTENSITY MODULATION WITH SPIRAL INFLECTOR

We tested the possibility of the beam intensity modulation by changing voltage on the electrodes of the spiral inflector. We simulated ion motion with decreasing voltage. It is necessary to decrease voltage by about 12% to lock the beam. Of course, it is possible to achieve the same result with increasing voltage, but the voltage variation will be greater, about 40%. This is not acceptable for two reasons: 1) the electric field intensity in the inflector can exceed the breakup threshold 2) variation of the radial motion will be greater.

The intensity of the beam against the voltage on the inflector electrodes is presented in Fig. 10.

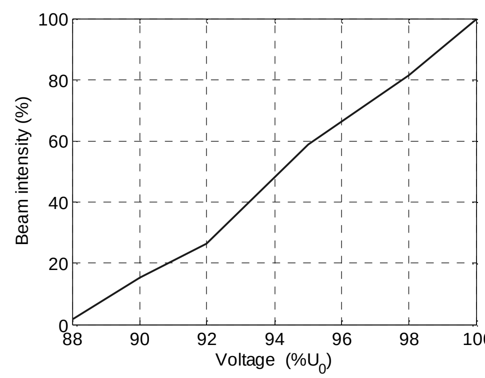

Figure 10: Intensity of the beam against voltage.

It is clear from the simulation that the intensity modulation method has one disadvantage – radial displacement of the beam – but it is smaller than 1 mm.

CONCLUSIONS

The central region of the C400 was designed. It is proposed to use the inflector 2.5 cm height with a gap of 6 mm between electrodes which ensures good centering (less than 1mm).

Continuous beam simulation shows that when we use two phase selection slits, injection efficiency is 12% for ions with amplitudes of radial oscillations less than 0.4 cm.

Axial focusing is provided by electric focusing.

REFERENCES

[1] G.Karamysheva et al., "IBA C400 Cyclotron Project for Hadrontherapy", this conference.