CENTER REGION DESIGN OF THE SUPERCONDUCTING CYCLOTRON C400

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Abstract

Compact superconducting isochronous cyclotron C400 [1] has been designed at IBA (Belgium) in collaboration with the JINR (Dubna). This cyclotron will be used for radiotherapy with proton, helium or carbon ions. 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 studied. A computer model of the dee tip 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. Comparison between field map created in electrostatic simulation and field map from RF simulation is given. Results of the beam tracking are presented.

C400 CYCLOTRON

The last years have seen increasing interest in the particle therapy based on $^{12}C^{6+}$ ions.

IBA, the world’s industrial leader in equipment of the proton therapy centers, has designed a superconducting C400 cyclotron based on the design of the current Proton Therapy C235 cyclotron.

Most of the operating parameters of the C400 cyclotron are fixed: fixed energy, fixed field and fixed RF frequency (small main field and RF frequency changes are needed for switching species). It is relatively small (6.6 m in diameter) and cost effective.

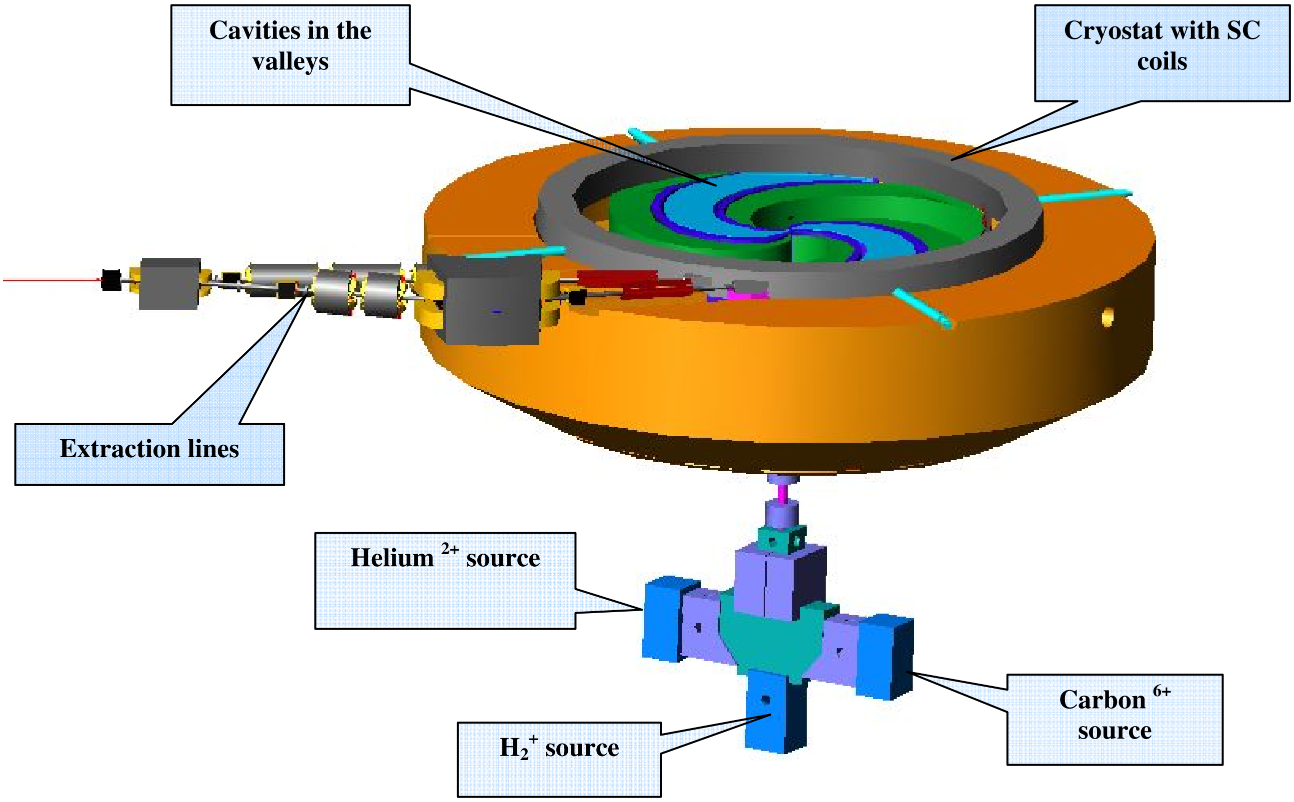

Figure 1: View of the median plane in the C400 superconducting cyclotron.

It offers very good beam intensity control for ultra-fast pencil beam scanning (PBS). But it requires an energy selection system (ESS) in order to vary the beam energy. The efficiency of the ESS for carbon is better than for protons due to lower scattering and straggling of carbon ions in the degrader.

INJECTION

Three external ion sources are mounted on the switching magnet on the injection line located below the cyclotron. $^{12}C^{6+}$ are produced by a high-performance ECR at current 3 μA, alphas and H_2^+ are also produced by a simpler ECR source. All species have a Q/M ratio of 1/2 and all ions are extracted at the same voltage 25 kV, so the small retuning of the frequency and a very small magnetic field change achieved by different excitation of 2 parts in the main coil are needed to switch from H_2^+ to alphas or to $^{12}C^{6+}$. We expect that the time to switch species will be not longer than two minutes, like the time needed to retune the beam transport line between different treatment rooms.

Focusing in the channel (Fig. 1) is provided by three solenoid lenses (S1, S2, S3), the rotational symmetry of the beam is reestablished with the help of one quad Q placed just behind the BMR40 bending magnet. The 90º bending magnet has two horizontal and one vertical entrances, and a common exit for all ion beams.

CENTRAL REGION

A model of the dee tip geometry at the cyclotron center with the inflector placed inside the housing was developed [2] (see Fig. 2). Dee tips have the vertical aperture 1.2 cm in the first turn and 2 cm in the second and further turns. 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 45º. The electric field in the inflector was chosen to be 20 kV/cm. Thus, the height (electric radius) of the inflector is 2.5 cm. The gap between the electrodes was taken to be 6 mm, and the tilt parameter is k′ = 0.1. The aspect ratio between the width and the spacing of the electrodes was taken to be 2 to avoid the fringe field effect. The electric field simulation of the central region was performed.

We compared two variants of central region:

a) with pillars around first turn
b) without pillars.

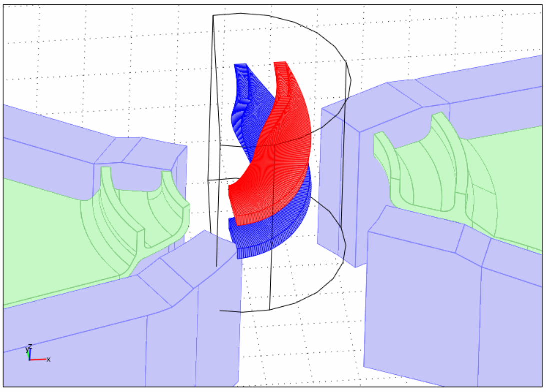

Figure 2: Central region with the spiral inflector model.

The width of the channel around the first turn was equal 1cm. Fig. 3 shows potential distribution of the both variants. Voltage distributions along radius are presented in Fig. 4. The voltage value was obtained by integrating the electric field in the median plane of the resonant cavity. It is seen that pillar increases voltage in the area of the first turn (R = 25 mm) from 55 kV (dashed blue line) to 59 kV (solid red line).

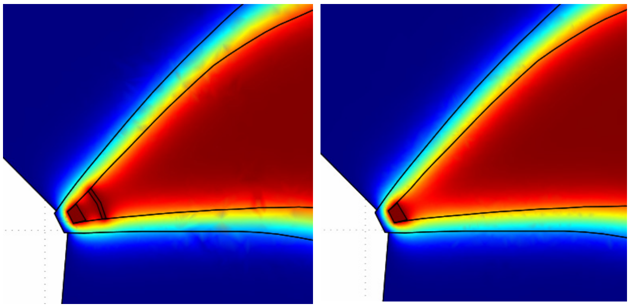

Figure 3: Dee tips with channel (left) and without channel (right).

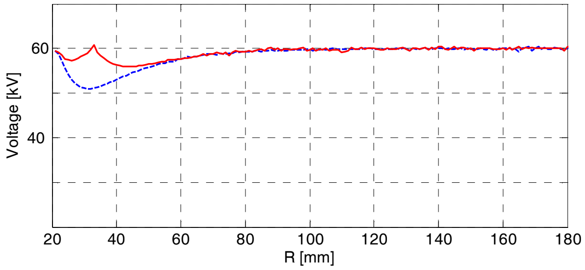

Figure 4: Voltage distribution along radius, red solid line - with channel, blue dashed line-without channel.

Beam dynamics simulations in the central region were made for particles with initial distributions in transverse phase planes obtained from the axial injection line. For all types of ions the beam diameters at the entrance into the spiral inflector are smaller than 2 mm.

The mean magnetic field against the radius is shown in Fig. 5. 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.

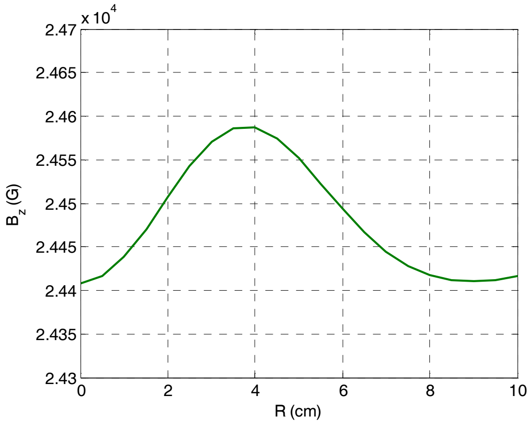

Figure 5: Mean magnetic field in the center region.

In spite of the fact that we have a magnetic field bump in the central region, it does not provide an appreciable magnetic axial focusing, but promotes electric axial focusing which plays the main role during the first turns.

Continuous beam simulation shows that when we use two phase selection slits, the injection efficiency is 12% for ions with amplitudes of radial oscillations smaller than 4 mm. The use of the buncher will increase the beam intensity at least by a factor of two.

We tested the possibility of modulating the beam intensity by changing voltage on the electrodes of the spiral inflector. We simulated ion motion through the inflector with decreasing voltage. It is necessary to decrease voltage by about 12% to lock the beam. It is clear from the simulation that this intensity modulation method has one disadvantage – radial displacement of the beam – but it is smaller than 1 mm.

COMPARISON BETWEEN RF AND ELECTROSTATIC APPROACHES

The geometric model of the double-gap delta cavity housed inside the valley of the magnetic system of the C400 cyclotron was developed. Calculations of the created model were performed using the eigenmode JD lossfree solver (Jacobi Division Method) in the CST MICROWAVE STUDIO [3]. RF cavity simulations are very time consuming therefore we usually used simplified model without pillars in the center, with vertical aperture equal 2 cm for all radii and so on. It is impossible to simulate accelerating field with good accuracy for the exact geometry of the central region from RF simulations. Usually central region model is simulated in electrostatic approach. In order to determine the margin of acceptability of this approach we compared voltage distribution from RF and electrostatic simulations in the central region. Results one can see in Fig.6 where red solid line –from electrostatic simulations and blue dotted line from RF simulations.

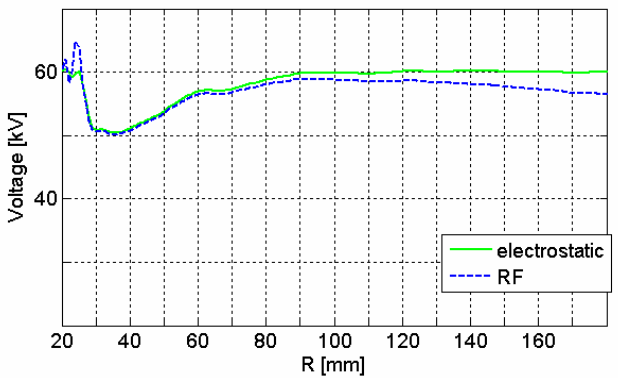

Figure 6: Voltage distribution along radius.

One can conclude that there is no difference in voltage by those approaches up to R = 60 mm. Therefore the best approach for center region design is electrostatic one because only in electrostatic approach it is possible to calculate accelerating field distribution only in the region of interest. RF approach demand modeling of the whole cavity and this is much more time consuming.

CONCLUSION

The central region of the C400 was designed using electrostatic approach in the field simulation. 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.

In spite of the fact that we have a magnetic field bump in the central region axial focusing is provided mainly by electric focusing.

REFERENCES

[1] Y. Jongen, etal.“COMPACT SUPERCONDUCTING CYCLOTRON C400 FOR HADRON THERAPY“, Nuclear Inst. and Methods in Physics Research, A, 2010.

[2] Yves Jongen et al, “Center region design of the cyclotron C400 for hadron therapy”, The 18th International Conference on Cyclotrons and their Applications Cyclotrons 2007, Laboratori Nazionali del Sud, Giardini Naxos, Italy 2007.

[3] CST STUDIO SUITE http://www.cst.com