SIMULATION AND DESIGN OF THE COMPACT SUPERCONDUCTING CYCLOTRON C400 FOR HADRON THERAPY

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Abstract

Carbon therapy is most effective method to treat the resistant tumors. A compact superconducting isochronous cyclotron C400 has been designed by IBA-JINR collaboration. This cyclotron will be used for radiotherapy with proton, helium and carbon ions. The $^{12}C^{6+}$and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/amu and will be extracted by electrostatic deflector, H_2^+ ions will be accelerated to the energy 265 MeV/amu and protons will be extracted by stripping. The magnet yoke has a diameter of 6.6 m, the total weight of the magnet is about 700 t. The designed magnetic field corresponds to 4.5 T in the hills and 2.45 T in the valleys. Superconducting coils will be enclosed in a cryostat; all other parts will be warm. Three external ion sources will be mounted on the switching magnet on the injection line located bellow of the cyclotron. The main parameters of the cyclotron, its design, the current status of development work on the cyclotron systems and simulations of beam dynamic will be presented.

INTRODUCTION

Today, cancer is the second highest cause of death in developed countries. Its treatment still presents a real challenge. Protons and light ions allow depositing the radiation dose more precisely in a cancer tumor, reducing greatly the amount of dose received by healthy tissue surrounding the tumor with respect to electrons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams have an extra advantage in radiation therapy: they have a different biological interaction with cells and are very effective even against some type of cancerous cells which resist to usual radiations. That is why the last years have seen increasing interest in particle therapy based on $^{12}C^{6+}$ ions. A C400 dedicated Carbon/Proton therapy cyclotron [1-4] (Fig. 1) has been designed by IBA-JINR collaboration.

Over the last 15 years IBA has designed and equipped over half of the clinical-based Proton Therapy (PT) facilities in the world. The new C400 cyclotron is derived from the design of the current PT C235 cyclotron and will be used for radiotherapy with proton, helium or carbon ions. The $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to the energy 400 MeV/amu and extracted by an electrostatic deflector, H_2^+ ions will be accelerated to the energy 265 MeV/amu and extracted by stripping. All other ions with Q/M = 0.5, which can be produced in reasonable amount by current ECR ion sources can be accelerated as well as for research purposes with unspecified intensity.

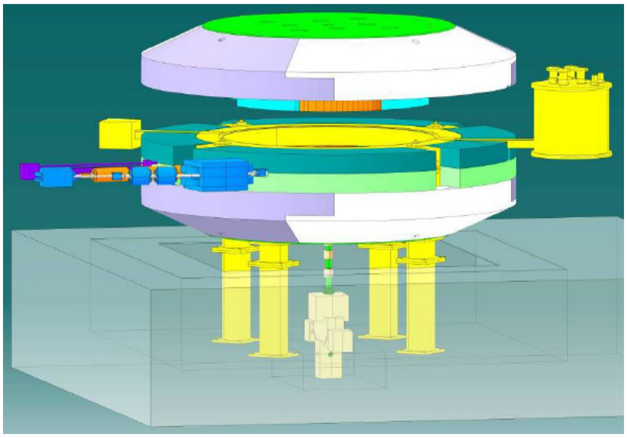

Figure 1: Common view of C400 cyclotron

Table 1: Main parameters of the C400 Cyclotron

General properties	
accelerated particles	H_2^+, $^{4}He^{2+}$, $^{6}Li^{3+}$, $^{10}B^{5+}$, $^{12}C^{6+}$
Injection energy	25 keV/Z
final energy of ions, protons	400 MeV/amu 265 MeV
extraction efficiency	~70 % (by deflector)
number of turns	~1700
Magnetic system	
total weight	700 tons
outer diameter	6.6 m
height	3.4 m
pole radius	1.87 m
valley depth	60 cm
bending limit	K = 1600
hill field	4.5 T
valley field	2.45 T
RF system	
radial dimension	187 cm
vertical dimension	116 cm
frequency	75 MHz
operation	4 harmonic
number of dees	2
dee voltage: center extraction	80 kV 170 kV

The C400 design was based on the main cyclotron characteristics: compact design similar to the existing IBA C235 cyclotron; fixed energy, fixed field and fixed

RF frequency (small RF frequency change 0.6% for H_2^+ regime set up); bending limit K=1600; accelerated particles H_2^+, $^4He^{2+}$, $^6Li^{3+}$, $^{10}B^{5+}$ and $^{12}C^{6+}$; superconducting coils enclosed in cryostat, all other parts are warm; axial injection using a spiral inflector; extraction of carbon beam with an electrostatic deflector; extraction of H_2^+ beam by stripping. All operating parameters of the C400 cyclotron are fixed now (Table 1).

The required isochronous magnetic field is shaped by axial and azimuth profiling of the sectors. The optimized sector geometry provides vertical focusing Q_z~0.4 in the region of extraction. Four-fold symmetry and spiral sectors with an elliptical gap (120 mm at the center decreasing to 12 mm at the extraction) provide stable beam acceleration up to 10 mm from the pole edge. Keeping the last orbit as close as possible to the pole edge facilitates extraction. Detailed dynamic simulations were performed to be sure that resonances crossed during acceleration did not cause significant harmful effect to the beam. The number of turns is expected to be about 1700.

INJECTION

Three external ions sources are mounted on the switching magnet on the injection line located below of 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 ion sources are at the same potential, so that 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.

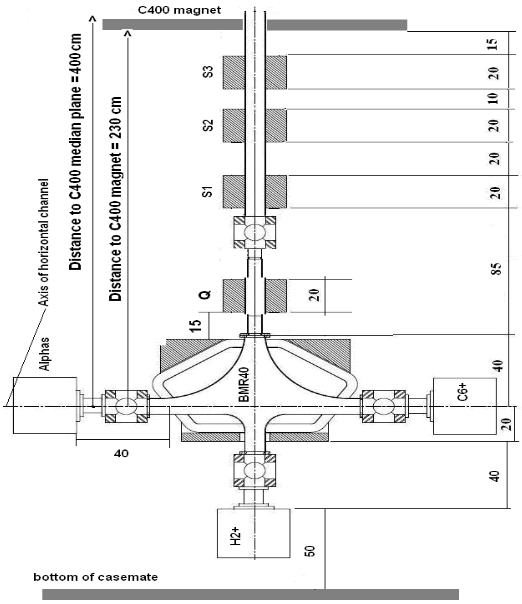

Figure 2: Scheme of the injection beam line.

Focusing in the channel (Fig. 2) is provided by three solenoid lenses (S1 … 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 entrances, one vertical one, and one exit for the ion beams. The bending radius of the magnet BMR40 is equal to 40 cm. The maximum magnetic field corresponds to 0.75 kG, gap height is 70 mm. The maximum magnetic field of the solenoids does not exceed 3 kG, a good field region is of 80 mm. The maximum quadrupole lens gradient does not exceed 100 G/cm.

The big values of the magnetic field from the C400 cyclotron in the region of the horizontal part of the channel and inside the BMR40 and the quadrupole lens require an additional shielding.

The simulation of the ion beam transportation has been made. For all types of ions the beam diameters at the entrance into the spiral inflector are less then 2 mm.

A model of the dee geometry at the cyclotron center with the inflector housing was developed. 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 45 deg. The electric field simulation of the central region was performed. The electric field in the inflector was chosen to be 20 kV/cm. Thus, the height (electric radius) of the inflector (Fig. 3) is 2.5 cm. The gap between electrodes was taken to be 6 mm, tilt parameter is equal to 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.

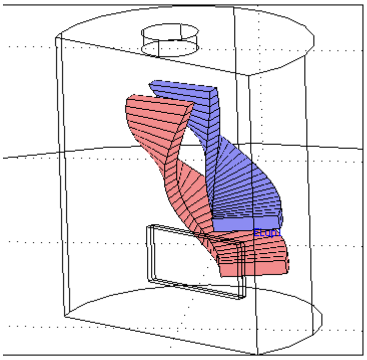

Figure 3: The spiral inflector k′=0.1 E=20 kV/cm.

Beam dynamics simulations were made for particles with initial distributions in transverse phase planes obtained from the axial injection line. The inflector with tilt k′=0.1 can be effectively used for beam intensity modulation. Axial beam motion is given in Figure 4. Figure 5 demonstrates turns in the central region for design voltage U_0 = ±5.82 kV (100% intensity - green lines), for U=0.95U_0 (53% intensity - blue lines) and for U=0.9U_0 (15% intensity - red lines). The voltage 0.89U_0 corresponds to the situation when all beam is lost in the diaphragm (situated on the first antidee - 0.2 mm).

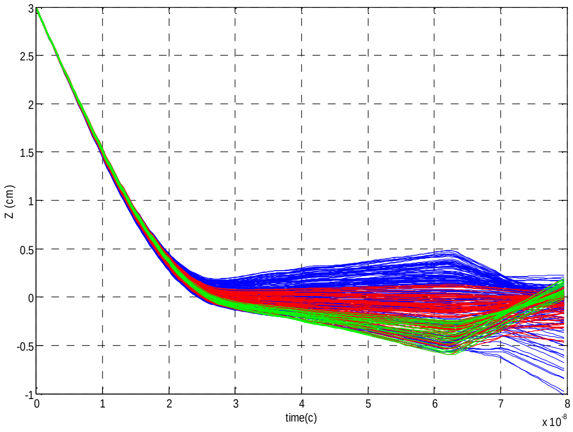

Figure 4: Axial beam motion.

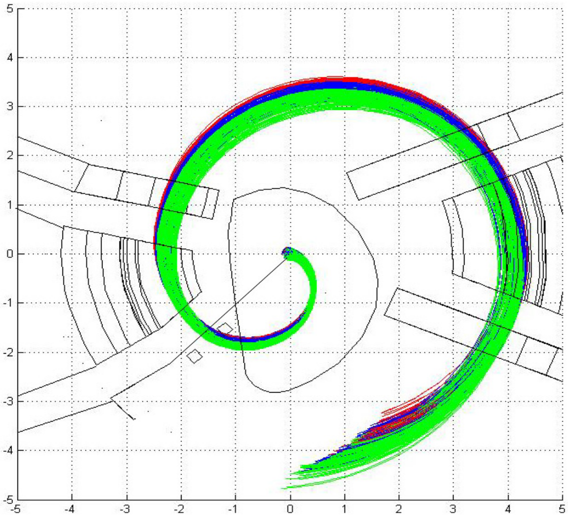

Figure 5: First turns in the center region.

MAGNET SYSTEM

The simulation and design of the C400 magnetic system was based on its main characteristics: four-fold symmetry and spiral sectors; deep-valley concept with RF cavities placed in the valleys; elliptical pole gap is 120 mm at the center decreasing to 12 mm at extraction; accelerate up to 10 mm from the pole edge to facilitate extraction; pole radius is 187 cm; hill field is 4.5 T, valley field is 2.45 T; magnetic induction inside yoke is less 2-2.2 T; the magnet weight is 700 tons and the magnet yoke diameter is 6.6 m; the main coil current is 1.2 MA. The main parameters of the cyclotron magnetic system were estimated and optimized by computer simulation with the 3D TOSCA code (Fig. 6).

The view of the spiral sectors is given in Fig. 6. The sectors are designed by a way with flat top surface and without additional grooves, holes etc. The sectors have following parameters: the initial spiral law with parameter Nλ=77 cm with increasing spiral angle to the final radius with parameter Nλ~55 cm; the sectors azimuth width is varying from 25º in the cyclotron center to 45º at the sectors edge; axial profile is the ellipse with 60/1874 mm semi-axis, at the final radii the ellipse axial profile is cut by the planes at the distance z= ± 6 mm.

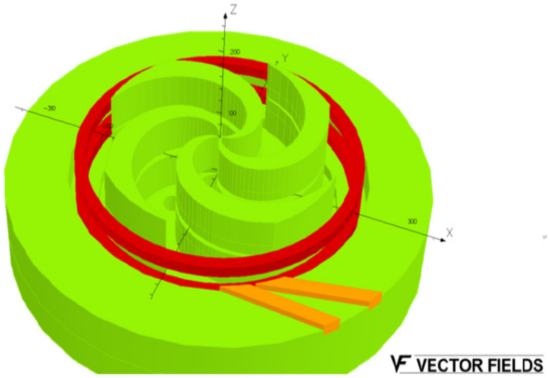

Figure 6: 3D TOSCA simulation of C400 magnetic system.

The accuracy of average magnetic field at shaping simulation is ±10 G in the middle and end region of the beam acceleration. The required isochronous magnetic field was shaped by azimuth profiling of the sectors. The optimized sector geometry provides vertical focusing Q_z~ 0.4 in the extraction region (Fig. 7).

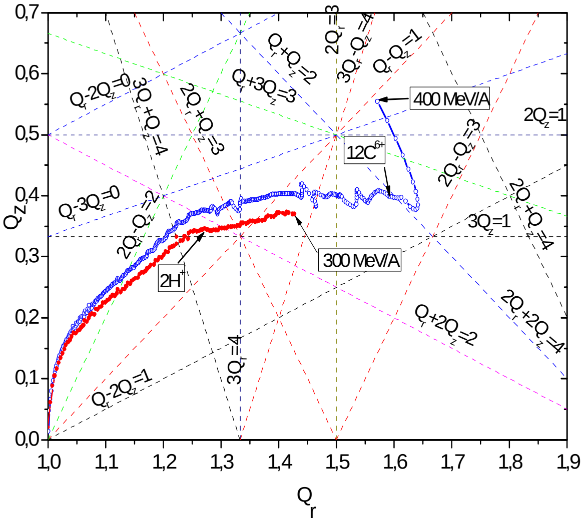

Figure 7: Working diagram of the cyclotron.

ACCELERATING SYSTEM

Acceleration of the beam will occur at the fourth harmonic of the orbital frequency, i.e. at 75 MHz. The acceleration will be obtained through two cavities placed in the opposite valleys. Two 45° dees working at the fourth harmonic will guarantee the maximum acceleration. The dee voltage increases from 80 kV at the center to 170 kV in the extraction region. A geometric model of the double gap delta cavity housed inside the valley of the magnetic system was developed in the Microwave Studio (Fig. 8).