CURRENT STATUS OF THE IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

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Abstract

A compact superconducting isochronous cyclotron C400 has been designed at IBA (Belgium) in collaboration with JINR (Dubna). This cyclotron will be used for radiotherapy with proton, helium or carbon ions. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to the energy of 400 MeV/amu and extracted by electrostatic deflector, H_2^+ ions will be accelerated to the energy 265 MeV/amu and extracted by stripping. We describe the parameters of the cyclotron, the current status of development work on the cyclotron systems. Reports on the status of the C400 project have been given regularly. Therefore, we will focus on the progress which has been achieved since recent reports at the Cyclotron 2007 [1] and EPAC 2006 [2] conferences.

INTRODUCTION

Over the last 15 years IBA has designed and equipped over half of the clinical-based Proton Therapy facilities in the world. The new C400 cyclotron is based on the design of the current Proton Therapy C235 cyclotron.

Most of the operating parameters of the C400 cyclotron are fixed. It is relatively small (6.6 m in diameter) and cost effective. 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 less scattering and straggling of carbon ions in the degrader.

The key parameters of the 400 MeV/amu superconducting cyclotron are listed in Table 1.

Table 1: Main parameters of the C400 cyclotron

General properties	
accelerated particles	H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
Injection energy	25 keV/Z
final energy of ions, protons	400 MeV/amu 265 MeV/amu
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	4th harmonic
number of dees	2
dee voltage: center extraction	80 kV 170 kV

INJECTION

Three external ion sources are mounted on the switching magnet on the injection line located below of the cyclotron (see Fig. 1). $^{12}C^{6+}$ are produced by a high performance ECR, alphas are also produced by the ECR source, while H_2^+ are produced by a multicusp ion 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 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 can be not more than two minutes, as long as the time needed to retune the beam transport line between different treatment rooms.

Focusing in the channel 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 simulation of the ion beam transportation has been made. The maximum magnetic field induction of the solenoids does not exceed 2 kG. The maximum quadrupole lens gradient does not exceed 25 G/cm. For all types of ions the beam diameters at the entrance of the spiral inflector are less then 2 mm. Therefore the particle losses in the inflector will be absent.

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.

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

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accelerating gaps was chosen to be 45 deg. The electric field simulation of the central region was performed.
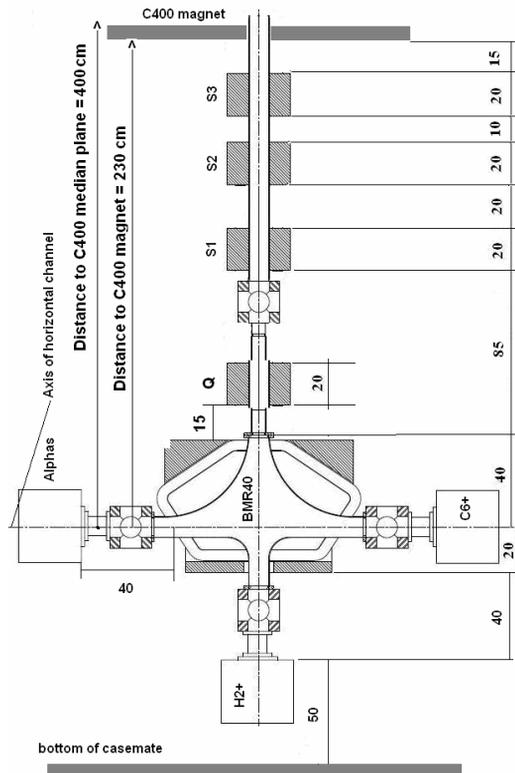
Figure 1: Scheme of the injection beam line.

The electric field in the inflector was chosen to be 20 kV/cm. Thus, the height of the inflector (electric radius) is 2.5 cm. The gap between 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.

Beam dynamics simulations were made for particles with initial distributions in transverse phase planes obtained from the axial injection line simulation.

MAGNET SYSTEM

The magnet yoke diameter is 6.6 m. The total weight of the magnet is about 700 t. The main coil current is 1.2 MA.

Superconducting coils will be enclosed in a cryostat, all other parts are warm.

The main parameters of the cyclotron magnetic system were estimated and optimized by computer simulation with the 3D TOSCA code.

The required isochronous magnetic field was shaped by azimuth profiling of the sectors. 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 to 15 mm from the pole edge. Keeping the last orbit as close as possible to the pole edge facilitates extraction.

The optimized sector geometry provides vertical focusing $v_z \sim 0.4$ in the acceleration and extraction

regions (see Fig. 2). Special attention was paid to avoiding dangerous resonances. Detailed dynamics simulations were performed to be sure that resonances crossed during acceleration did not cause significant harmful effect to the beam [3].

The number of turns is expected to be about 1700.
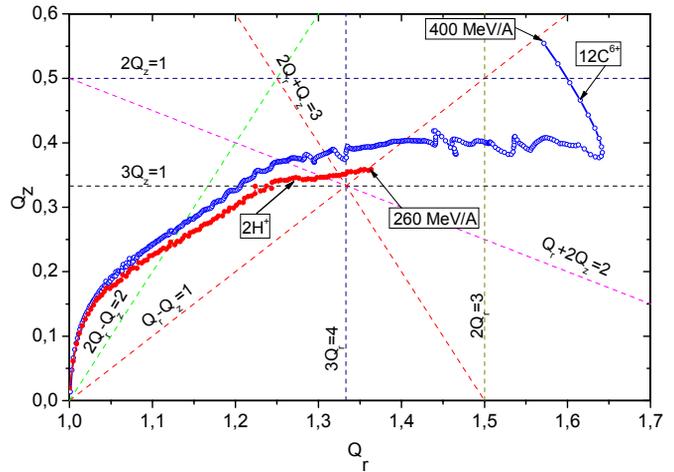
Figure 2: Working diagram of the cyclotron.

ACCELERATING SYSTEM

Acceleration of the beam will occur at the fourth harmonic of the revolution 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 of the C400 cyclotron was developed in the Microwave Studio. The depth of the valley permits accommodation of the cavity with total height 116cm. The vertical dee aperture was equal to 2 cm. The accelerating gap was 6 mm at the center and 40 mm in the extraction region. The distance between the dee and the back side of the cavity was 45 mm. The azimuth extension of the cavity (between the middles of the accelerating gaps) was 45 deg up to the radius 170 cm. The cavities have a spiral shape similar to the shape of the sectors. We inserted four stems with different transversal dimensions in the model and investigated different positions of the stems to ensure increasing voltage along the radius. The thickness of the dee was 20 mm. Edges of the dees are 10 mm wide. Based on the 2D electric field simulations we chose the optimal form of the dee edges. RF heating simulation was performed to determine the cooling system layout.

Each cavity will be excited with the RF generator through a coupling loop (which should be rotated azimuthally within small limits. For precise resonator adjustment, a tuner (piston) will be provided at radii compatible with the holes in the yoke.

Average losses will be 63 kW. Each cavity will be powered by a 75 MHz, 100 kW tetrode-based amplifier (as used in the current C235 cyclotron).

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EXTRACTION

Extraction of protons is supposed to be done by means of the stripping foil.

It was found that 320 MeV is the minimal attainable energy of protons which can be extracted during 1-turn after the stripping foil and 265 MeV is the minimal energy of protons for 2-turn extraction. The latter variant was chosen as optimal one because the energy of the 2-turn extracted protons is essentially closer to the normally used energy for the proton beam treatment.

It is possible to extract the carbon beam by means of one electrostatic deflector (which is located in valley between sectors) with a 140 kV/cm field inside. The septum of the deflector was located at the radius 179.7 cm for tracking simulation. The extraction efficiency was 73% for the septum with increased $0.1 - 2$ mm thickness along its length**.**

The extraction of the carbon and proton beams by the separate channels and their further alignment by the bending magnets outside the cyclotron was chosen as the acceptable variant. The passive magnetic elements (correctors) are supposed to be used inside the cyclotron and the active current elements (quadrupole lenses and bending magnets) outside the yoke.

A plan view of both lines is shown in Fig. 3. The system for carbon ion extraction consists of an electrostatic deflector, two passive magnetic correctors MC1, MC2, three quadrupole lenses $CQL1 - 3$ and three steering dipole magnets CSM1-3. The first pair of the steering (in vertical and horizontal direction) magnets is located between the cyclotron and the entrance to the first quadrupole lens CQL1. The third steering (in vertical direction) CSM3 magnet is located between the quadrupole lens CQL3 and the bending magnet BM2. It is assumed that the latter will be used for horizontal steering of the carbon beam.
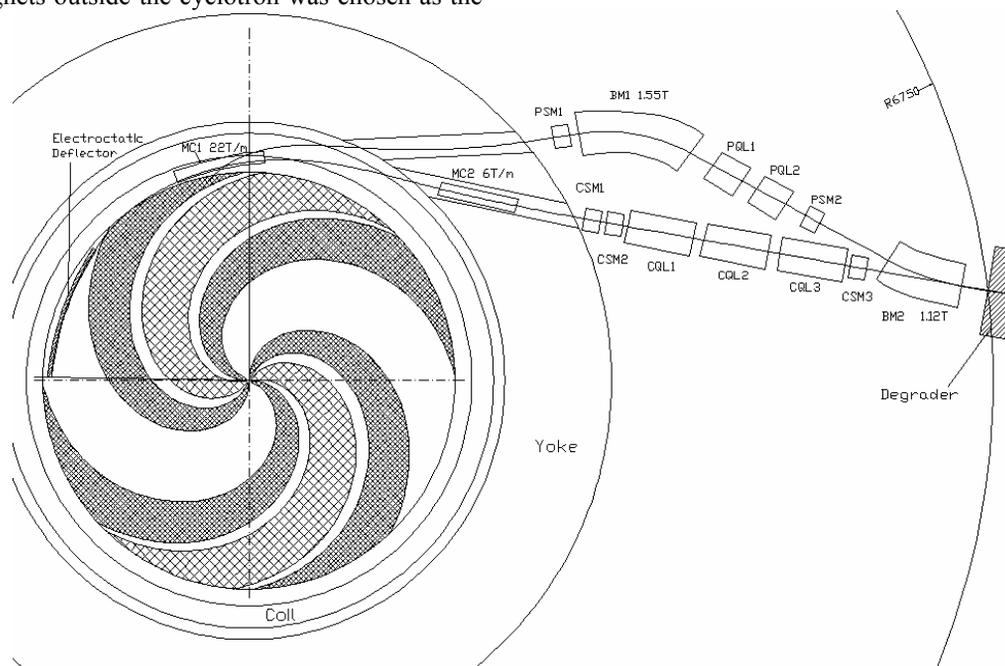
Figure 3: Layout of the cyclotron C400 with two extraction lines.

Modelling of action of the different focusing elements in both carbon and proton extraction systems was carried out to avoid the beams large divergence during the extraction. It is possible to align both beams into one direction just before the energy degrader (6750 mm from the cyclotron center). Both beams have a spot with $\sigma_{x,y}<1$ mm at this point.

CONCLUSIONS

The detailed computer simulations of the beam dynamics and the main systems of C400 cyclotron have been performed. The results of the simulations show that the energy range up to 400 MeV per nucleon (K = 1600) can be achieved with the compact design similar to that of the existing IBA C235 cyclotron. The C400 cyclotron will also provide a proton therapy beam with energy 265 MeV. The project will be ready for the construction in the nearest future.

REFERENCES

[1] Y. Jongen et al., "IBA C400 Cyclotron Project for hadron therapy", in Proc. of Cyclotrons 2007, Italy, p. 151.

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