DESIGN STUDIES OF THE COMPACT SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

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Abstract

The last years have seen increasing interest in particle therapy based on $^{12}C^{6+}$ ions. In order to respond to this market situation, a C400 dedicated Carbon/Proton therapy cyclotron has been designed at IBA (Belgium) in collaboration with the JINR (Dubna) [1]. An overview of the current status of the design of the C400 cyclotron able to deliver ion beams with a charge to mass ratio of 1/2 is given. This cyclotron is based on the design of the current PT (proton therapy) C235 cyclotron and 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 400 MeV/u and extracted by an electrostatic deflector, H_2^+ ions will be accelerated to the energy 260MeV and extracted by stripping. Computer modeling results for the axial injection system, magnetic system, inflector and center design are given. Results of simulations of the ion beam injection, acceleration and extraction are presented.

BASIC DESIGN CONCEPT

The C400 cyclotron is a relatively simple machine, with most of the operating parameters fixed. It is relatively small (6.06 m in diameter) and cost effective. As a CW machine, 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. However, 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 present status of the C400 design may be summarized as follows:

- the isochronous magnetic field with adequate focusing characteristics and optimized extraction is obtained by computer simulation with the 3D TOSCA code;
- beam dynamic simulations have been done with multiparticle tracking codes for the acceleration and extraction regions;
- axial injection design and beam dynamic tracking in the injection line have been performed;
- inflector and central region is currently being designed;
- RF cavity design by the CST Microwave Studio is underway;
- ion losses due to residual gas interaction have been calculated.

The main parameters of the 400MeV/u superconducting cyclotron are listed in Table 1.

Table 1.

General properties	
type	compact isochronous
accelerated particles	H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
ion sources	ECR, ECR, multicusp
injection	axial with spiral inflector
final energy of ions, protons	400 MeV/u 260 MeV/u
extracted ions, protons	by deflector by stripping
extraction efficiency	80 %
number of turns	1300 - 1500
Magnetic system	
total weight	700 tons
outer diameter	6.06 m
height	2.76 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	190 cm
vertical dimension	117 cm
frequency	75 MHz
operation	4^{th} harmonic
number of dees	2
dee voltage: center extraction	 100 kV 200 kV

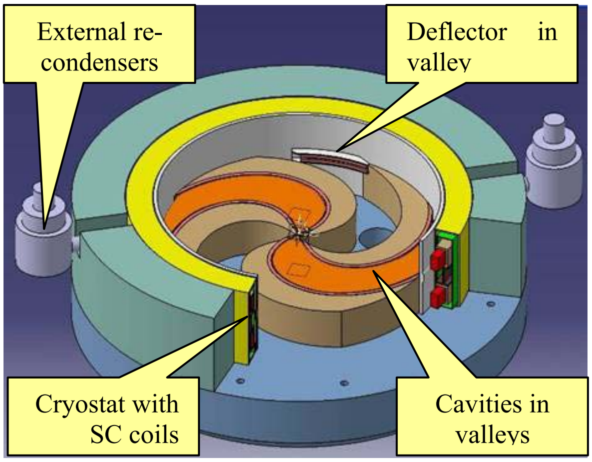

Figure 1: Artist's view of the median plane in the 400MeV/u Carbon/Proton superconducting cyclotron.

INJECTION AND ION SOURCES

Three external ions sources are mounted on the switching magnet on top of the cyclotron (see Fig. 2). $^{12}C^{6+}$ 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. If needed, an additional ion source could be used to produce $^6Li^{3+}$. In order to allow a quick change between ion species, all three ion sources are kept in operation. The selection of the beam is made by the switching magnet. 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 3 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.

The beam is injected in the cyclotron by an axial injection system [2] and is bent into the median plane with a spiral inflector (see Fig. 3).

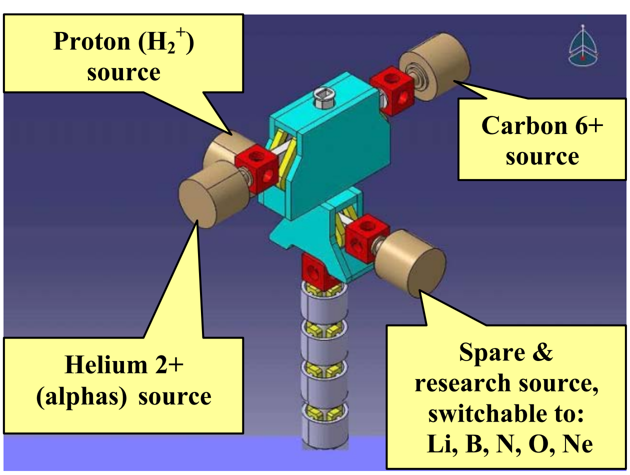

Figure 2: Injection line and ion sources.

The length of the vertical part of the injection channel is about 4 m from the carbon ECR axis to the median plane of the C400 cyclotron. The focusing of the beam is produced by the switching magnet BM90 and the quadruplet Q1-Q4 (see Fig. 2). The quadruplet is used for matching the optical functions (2 alpha- and 2 beta-functions) with the acceptance of the cyclotron inflector. For all types of ions the beam envelopes at the entrance of the spiral inflector do not exceed 2 mm. Therefore the particle losses in the inflector are absent.

CENTER REGION DESIGN

The center region was calculated on the basis of the model calculation of the magnetic field.

The principal requirements are:

- a beam should be accelerated in a well-centered orbit with respect to the geometrical center
- fine tune electric vertical focusing
- longitudinal and transversal beam matching.

Ion energy per charge is equal to 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 electrodes was taken to be 8mm. The aspect ratio between the width and the spacing of the electrodes was taken to be equal to 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 model of the spiral inflector with the housing is presented in Fig. 3.

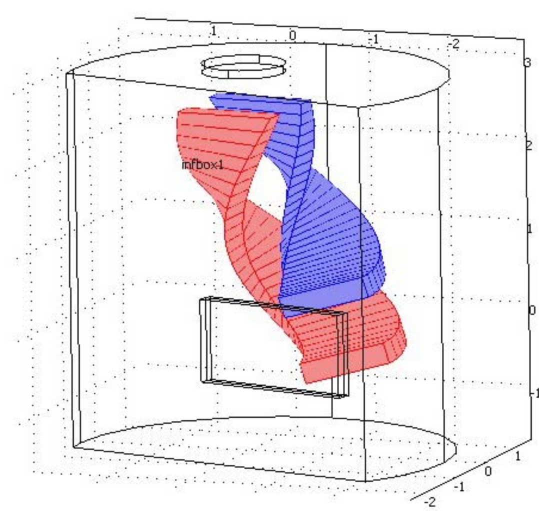

Figure 3: Spiral inflector.

A model of the dees geometry at the cyclotron center with the infector housing was developed. Electric field simulation of the central region was performed. The maximum electric field in the first accelerating gap is 160 kV/cm. Beam dynamic simulations were made for particles with initial distributions in transverse phase planes obtained from the axial injection line simulation. Optimization of the center region design is currently underway.

SOME CHARACTERISTICS OF C400 MAGNET

The main parameters of the cyclotron magnetic system were estimated and optimized by computer simulation with the 3D TOSCA code (pole radius 187 cm, outer diameter 606 cm, valley depth 60 cm, height 276 cm) [3]. The weight of iron was minimized with the stray field kept at an acceptable level. The required isochronous magnetic field was shaped with an accuracy of ±2 mT by axial and azimuth profiling of the sectors and by additional grooves and sector shims. 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 till 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 $\nu_z \sim 0.3$ in the acceleration region. The vertical focusing (ν_z) at the extraction region made as close as possible to 0.5, decreases the vertical beam size and minimizes the median plane effects. Special attention was paid to avoiding dangerous resonances.

CHARACTERISTICS OF THE RF 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 at the fouth harmonic will guarantee maximum acceleration. The dee voltage increases from 100 kV at the center to 200 kV at the extraction region, resulting in an average of 600 kV/turn.

Each dee will be supported by 2 pillars in a half-wave resonator. The vertical dimension of the cavity is 117 cm. The radial dimension is 190 cm. Each cavity is powered by a 75 MHz, 100 kW tetrode-based amplifier (as used in the current C235)

RF cavity simulations using the CST Microwave Studio are underway to optimize geometry, shunt impedance and dee-voltage profile.

ACCELERATION AND EXTRACTION

The acceleration and extraction system will be very similar to the current IBA proton therapy cyclotron. Detailed dynamic simulations were performed to be sure that resonances crossed during acceleration did not cause significant harmful effect to the beam [4]. The number of turns is expected to be about 1300, against 800 in the current proton therapy cyclotron

The extraction uses an electrostatic deflector (uniform electric field 140 kV/cm, gap width 4 mm) and two gradient correctors. 260MeV protons can be extracted with an efficiency close to 100% by stripping H_2^+ (two-turn scheme).

BEAM LOSSES BY RESIDUAL GAS INTERACTIONS

Simulations of ion losses in the cyclotron and in the injection line with water vapor and hydrogen as a residual gas were done.

The vacuum losses in the injection line were estimated using experimental cross section data from [5, 6]. The simulations show that vacuum requirements for the injection system are determined by $^{12}C^{6+}$ ions. Losses will be about 2 % for the residual gas pressure $2*10^{-7}$ torr.

Vacuum requirements in the cyclotron are determined by H_2^+ ion stripping. Unfortunately, data on experimental cross sections for high energy interaction of H_2^+ ions with water vapor are very poor. This is why we tested losses with the classic Bohr theory and the modified Bohr formula used in [7]. In the most pessimistic variant of estimations the losses will not exceed 3 % for the vacuum level 10^{-7} torr (Fig. 4).

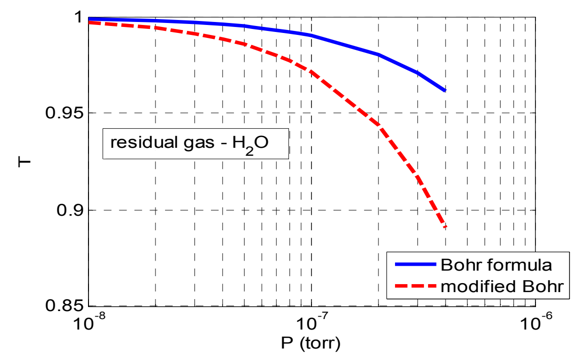

Figure 4: Transmission efficiency of H_2^+ ions for the C400 cyclotron as a function of vacuum pressure.

CONCLUSIONS

The detailed simulations done so far show that the energy range of 400MeV per nucleon (K = 1600) can be achieved with the compact design similar to the existing IBA C235 cyclotron. The C400 cyclotron will also provide a proton therapy beam with energy 260MeV.

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