IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zaremba, IBA, Belgium
V. Aleksandrov, A. Glazov, S. Gurskiy, G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, G. Shirkov, E. Syresin, A. Tuzikov, JINR, Russia.

Abstract

Progress of design work on the compact superconducting isochronous cyclotron C400 able to deliver ion beams with a charge to mass ratio of 0.5 is reported. This cyclotron will be used for therapy of cancer using either protons or light ions. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to energy 400 MeV/amu and extracted by the electrostatic deflector, H_2^+ ions will be accelerated to the energy 260MeV and extracted by stripping. Computer modeling results on the axial injection, magnetic, accelerating and extraction systems are given. Design of the main systems of the cyclotron and the present status of beam dynamics studies are summarized. Details are presented in some contributions to this conference.

INTRODUCTION

Today, cancer is the second highest cause of death in developed countries. Its treatment is still a real challenge.

Protons and light ions allow depositing the radiation dose more precisely in a tumor, greatly reducing the amount of the dose received by healthy tissue surrounding the tumor as compared with electrons and photons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams, have an additional advantage in radiation therapy: thanks to their high linear energy transfer, they have a different biological interaction with cells and are very effective even against some types of cancerous cells resistant to usual radiations.

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

BASIC DESIGN CONCEPT

Most of the operating parameters of the C400 cyclotron are fixed. It is relatively small (6.9 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. 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 key parameters of the 400 MeV/amu superconducting cyclotron are listed in Table 1. The view of the cyclotron is presented in Fig. 1.

Table 1: Main parameters of the C400 cyclotron

General properties	
type	compact isochronous
accelerated particles	H_2^+, $^{4}He^{2+}$, ($^{6}Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
ion sources	ECR, ECR, multicusp
injection	axial with spiral inflector
injection energy	25 keV/Z
final energy of ions, protons	400 MeV/amu 260 MeV/amu
extracted ions, protons	by deflector by stripping
extraction efficiency	70 % (by deflector)
number of turns	~1700
Magnetic system	
total weight	660 tons
outer diameter	6.9 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	180 cm
vertical dimension	116 cm
frequency	75 MHz
operation	4^{th} harmonic
number of dees	2
dee voltage: center extraction	 80 kV 200 kV

The present status of the C400 design:

- The isochronous magnetic field with adequate focusing characteristics and optimized extraction is obtained by computer simulation with the 3D TOSCA code.

- Beam dynamics simulations have been done with multiparticle tracking codes for the acceleration and extraction regions.
- Axial injection design and beam dynamics tracking in the injection line have been performed.
- Inflector and central region design and beam dynamics tracking have been performed.
- RF cavity design is currently being performed by the CST Microwave Studio.
- Ion losses due to residual gas interaction have been calculated.

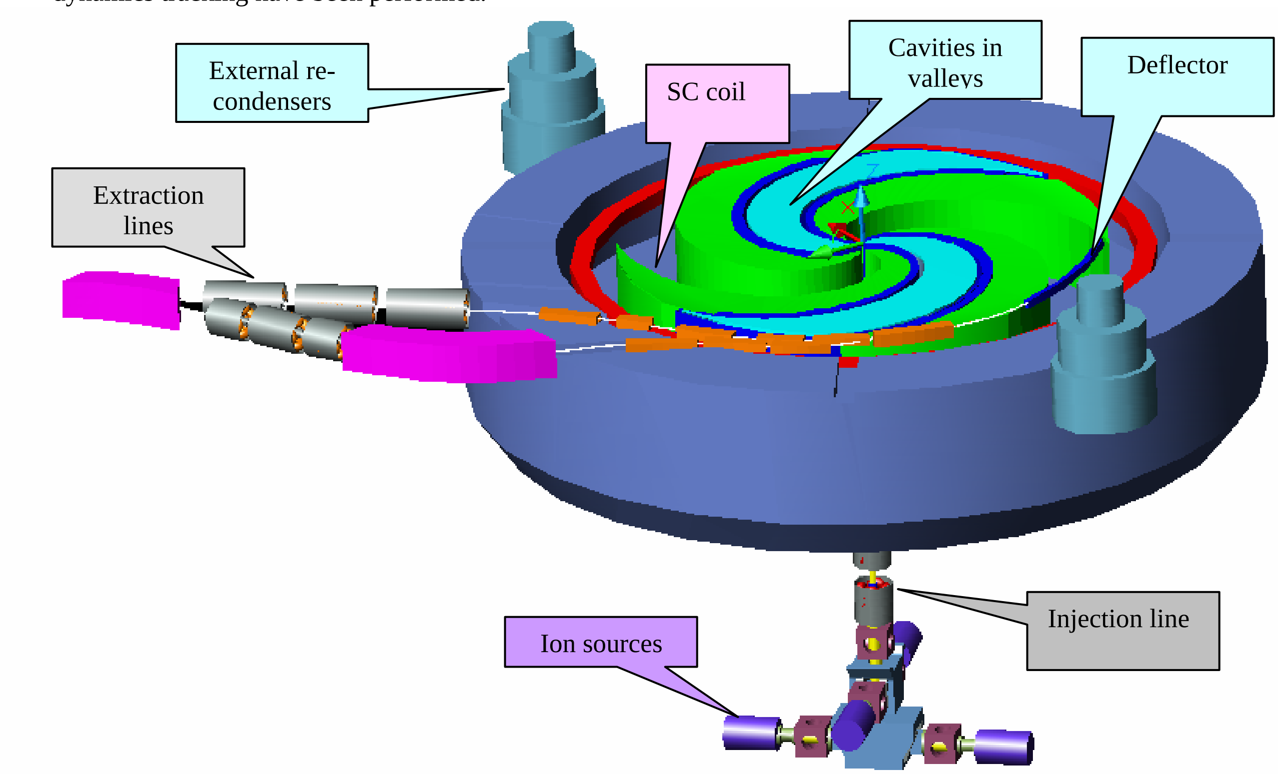

Figure 1: Artist's view of the median plane in the 400 MeV/amu Carbon/Proton superconducting cyclotron.

INJECTION AND ION SOURCES

Three external ions sources are mounted on the switching magnet on the injection line located below 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 $^{6}Li^{3+}$. In order to allow a quick change between ion species, all three ion sources are kept in operation. All species have a charge to mass 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 ion source injects ions directly into the switching magnet, which is also used as a charge state analyzing magnet. The ion source exit electrode is located 40 cm away from the entrance of the magnet (effective field boundary). Between the source insulator and the magnet entrance we provide a cube to connect a vacuum pump and install a removable beam stop to measure the total current extracted from the ion source. The input face angle of the 90° magnet is selected to focus the beam into the analyzing slits which are located in a cube located just after the second magnet. The first magnet to be used for the Carbon ECR source (and perhaps for an optional ion source for lithium) has a bending radius of 40 cm. The second magnet, to be used for the alpha and for the H_2^+ ion sources do not need a very high resolution, and has a bending radius of 20 cm.

At the exit of the second magnet a diagnostic box is placed which will include two pairs of remotely adjusted slits, an insertable beam stop (Faraday cup), and a vacuum pump. The quadruplet of quadrupoles adapts the optics to get the beam matched with the acceptance of the spiral inflector of the cyclotron.

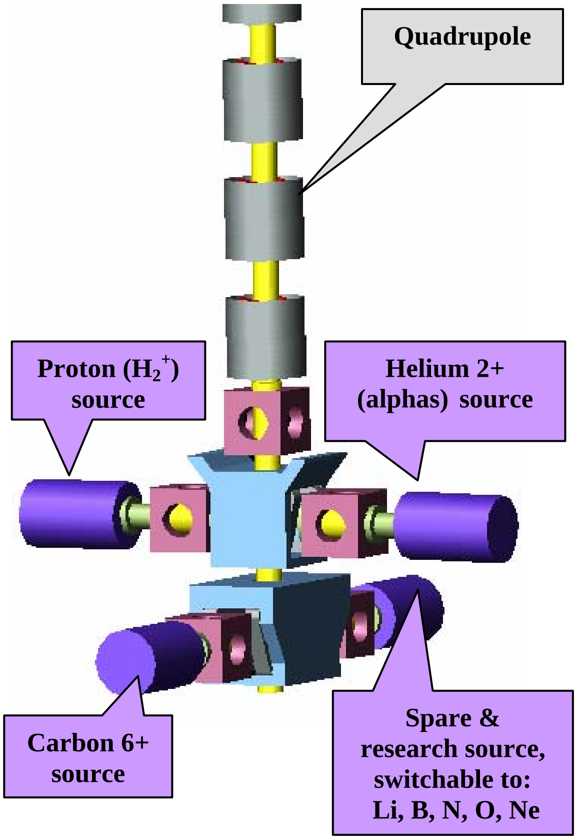

Figure 2: Injection line and ion sources.

The length of the vertical part of the injection channel is about 5 m from the carbon ECR axis to the median plane of the C400 cyclotron. 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 will be absent.

The magnetic induction in the region of the dipole magnets has been suppressed to the acceptable value $\leq$ 10 Gauss. This has been done for the 2D model of the vertical part of the injection channel [1].

Gradients of the quadrupole lenses have been fitted for all types of ions ($^{12}C^{6+}$, $^{4}He^{2+}$, and H_2^+). To reduce the coupling in the longitudinal magnetic field, the quadrupoles are turned around the longitudinal axes by required angles (tilted lenses). The rotation angle of the quadrupole lenses should be found only at the initial stage of operation only for one sort of injected ions (for example carbon). These rotation angles are the same for all other types of the ions with the charge to mass ratio 1/2 and should not be changed during the routine operation. The maximum gradient in the quadrupole lens is about 300 G/cm.

The offered beam focusing scheme does not demand a bulky system of shielding of quadrupole lenses. The system of injection allows transportation of $^{12}C^{6+}$, $^{4}He^{2+}$, and H_2^+ ion beams from ion sources to the median plane of cyclotron with a 100% efficiency.

CENTER REGION DESIGN

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

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 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 computer model of the spiral inflector with the housing is presented in Fig. 3.

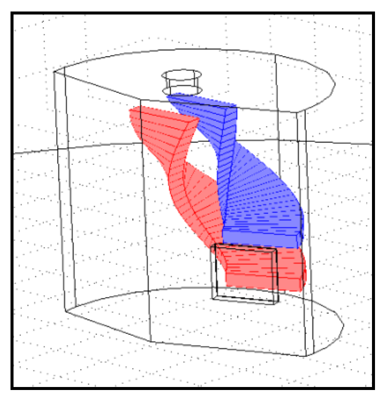

Figure 3: Spiral inflector.

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

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