AXIAL INJECTION BEAM LINE OF C400 SUPERCONDUCTING CYCLOTRON FOR CARBON THERAPY

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Abstract

The final layout of the axial injection beam line of C400 cyclotron is given.

INTRODUCTION

C400 is compact superconducting isochronous cyclotron for carbon beam therapy designed by IBA, Louvain-La-Neuve (Belgium) in collaboration with JINR, Dubna (Russia) [1]. The cyclotron can accelerate all ions with charge to mass ratio 0.5. Protons are accelerated as single charge $^2H^+$ molecules and extracted by stripping at 270 MeV. All other ions are extracted by an electrostatic deflector at 400 MeV/amu. The main parameters of the C400 cyclotron are contained in Table 1.

Table 1: C400 Main Parameters

Accelerated particles	$^2H^+$, $^4He^{2+}$, $^{12}C^{6+}$
A/Z	2
Energy $^2H^+$/other, MeV/amu	270/400
Pole radius, m	1.87
Magnetic field, valley/hill, T	2.45/4.5
Number of sectors	4
RF frequency, MHz	75
Harmonic number	4
RF voltage, center/extraction, kV	80/170
Number of Dees	2
Ion extraction method $^2H^+$ other	 Stripping foil Electrostatic deflector

General description of the axial injection beam line of C400 cyclotron is given in this report.

BEAM LINE LAYOUT

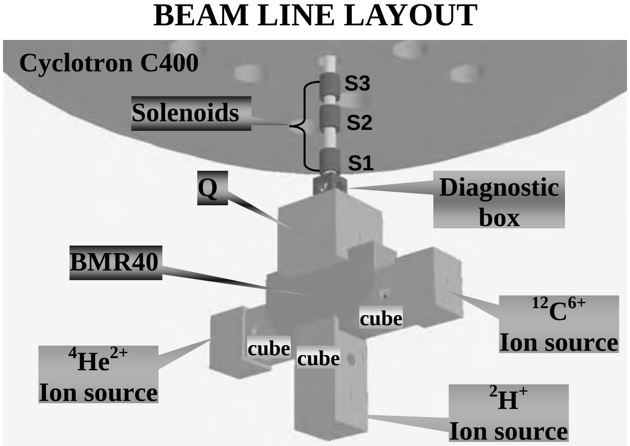

Figure 1: C400 axial injection beam line.

The layout of C400 axial injection beam line is shown in Fig.1. Three external ions sources are mounted on the switching magnet BMR40 located below of the cyclotron. $^{12}C^{6+}$ ions are produced by a high performance 14.5 GHz Electron Cyclotron Resonance ion source, $^4He^{2+}$ are produced by the 2.45 GHz ECR ion source, while $^2H^+$ – by a multicusp ion source. All ion sources have the same extraction voltage 25 kV. 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 injection of carbon and helium ions is produced through the BMR40 magnet with bending radius 40 cm. The $^2H^+$ ion source is placed at the vertical axis of the beam line and the BMR40 magnet is switched off during injection of $^2H^+$ ions.

The ion source exit electrode is located at 40 cm 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. At the exit of the magnet a diagnostic box is placed which includes two pairs of remotely adjusted slits, an insertable beam stop (Faraday cup), and a vacuum pump flange.

Each cube and diagnostic box contains also two pairs steering magnets to have the possibility of a position and angle correction at the entrance of a spiral inflector of the cyclotron. The input face angle of the 90° magnet is selected to focus the beam into the analyzing slits which are located in a cube placed after the magnet.

Focusing in the channel is provided by three solenoid lenses (S1-3), the rotational symmetry of the beam is re-established with the help of quad Q placed just after BMR40 bending magnet. The focusing system adapts the optics to get beam matched with acceptance of the spiral inflector. Between the solenoid S3 and the spiral inflector a bunching system is located. The injection system is designed to achieve at least 25% injection efficiency (the internal beam to ion source). The length of the vertical part of injection channel is about 4 m from the carbon and alfas ECR axis to the median plane of the cyclotron C400.

The main feature in design study of the axial injection system is presence of a strong magnetic field from the C400 cyclotron at places of the beam line elements location. The cyclotron magnetic field suppression by means of iron screens is proposed in [2].

BEAM DYNAMICS SIMULATION

Simulation of beam dynamics in injection channel was fulfilled using the new version of the Multi Component

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Ion Beam code (MCIB04 [3]). It is based on the linear system of equations of motion in the presence of self-field of the intense charge particle beam. These equations are valid in the special coordinate frame [4] coincided with one rotating with Larmour's frequency in the case of the motion in the longitudinal magnetic field. In this case emittances in two independent 2D subspaces of the whole four-dimensional phase space are constant when quadrupole gradients are equal to zero. The system of differential equations doesn't contain the first derivative of magnetic field on the longitudinal coordinate.

Fitting of parameters of optical elements was produced within the framework of the moment method. The matching conditions at the entrance of the spiral inflector correspond to the steady state of the beam (without envelopes oscillation) in the uniform magnetic field with magnitude equal to the field in the cyclotron center. The simplex method was used for fitting procedure.

The initial conditions for the moments of ion beams were defined at the exit of the BMR40 bending magnet and were found by macro-particle simulation. Charge state distribution for each ion source was taken into account.

In MCIB04 computer code the neutralization effect was taken into account by changing of a beam current I_b according to

$$I = (1 - f) * I_b \tag{1}$$

where I is effective current of the neutralized beam, f – neutralization factor.

The results obtained by moments method were checked by macro-particle simulations. All methods give a rather good agreement.

Initial Beam Data

The main parameters of ion beams used in calculations contain in Table 2.

Table 2: Main Beam Parameters

Ion source extraction voltage, kV	25
"Carbon" beam current, eμA	1542
$^{12}C^{6+}$ ion beam current, eμA	3
Emittance, π mm·mrad	30
Beam radius, cm	0.17
He^{1+} ion beam current, eμA	50
$^{4}He^{2+}$ ion beam current, eμA	5
Emittance, π mm·mrad	30
Beam radius, cm	0.33
$^{2}H^{1+}$ ion beam current, eμA	5
Emittance, π mm·mrad	30
Beam radius, cm	0.3

The starting point is a waist of the beams located at 40 cm before the BMR40 bending magnet. Final point is the median plane of the cyclotron magnet or entrance of the spiral inflector. Number of macro-particles in PiC simulation is 5000 or 20000.

Carbon and Helium beam spectrum (charge state distribution) are shown in Fig 2.

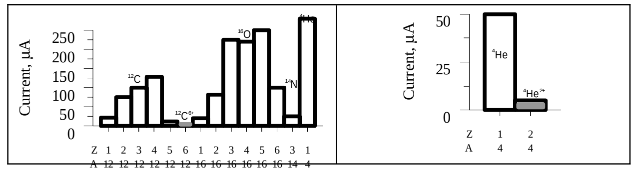


Figure 2:Carbon (left) and Helium (right) beam spectrum

Magnetic Field

The permissible values of the C400 cyclotron magnetic fields (<10 Gauss) are reached everywhere it is required, i.e. at the horizontal part of the beam line, inside the bending magnet BMR40, the quadrupole lens Q and at the places of ion sources location [2]. The plot of the cyclotron magnetic field used in calculations is shown in Fig.3.

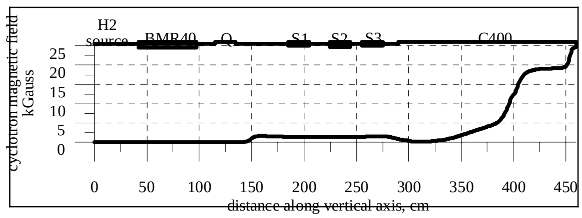


Figure 3: Cyclotron magnetic field

Carbon Beam Line

The Carbon beam have been transported with switched on solenoids S2 and S3. The solenoid S1 is switched off. The simulation has been fulfilled both for full and zero neutralization of the beam current. The envelopes of the $^{12}C^{6+}$ beam are shown in Fig. 4. The distributions of C^{6+} ions in the various phase planes at median plane of the C400 cyclotron are shown in Fig.5,6.

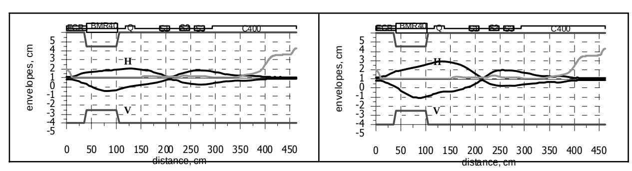
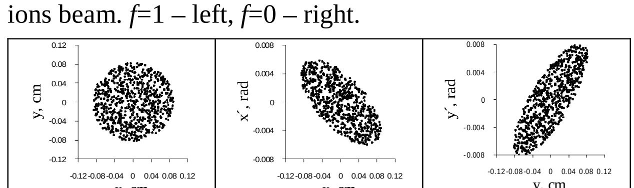
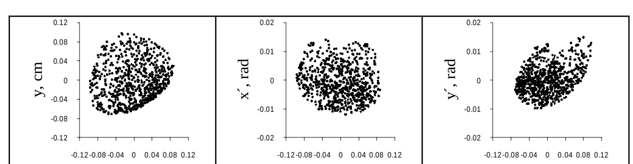


Figure 4: Horizontal (H) and vertical (V) envelopes of C^{6+} ions beam. f=1 – left, f=0 – right.



Plane (x,y)	Plane(x,x′)	Plane(y,y′)

Figure 5: C^{6+} ions distributions, f = 1.



Plane (x,y)	Plane(x,x′)	Plane(y,y′)

Figure 6: C^{6+} ions distributions, f = 0.

The beam envelope inside the spiral inflector is less than 1mm. The proposed optical scheme of the beam line gives the possibility to match Carbon beam for any neutralization of the beam current.

Helium Beam Line

It is proposed to use all three solenoids S1, S2, S3 for Helium beam matching. The envelopes of the $^4He^{2+}$ beam are shown in Fig. 7. The distributions of $^4He^{2+}$ ions in the various phase planes at median plane of the C400 cyclotron are shown in Fig.8.

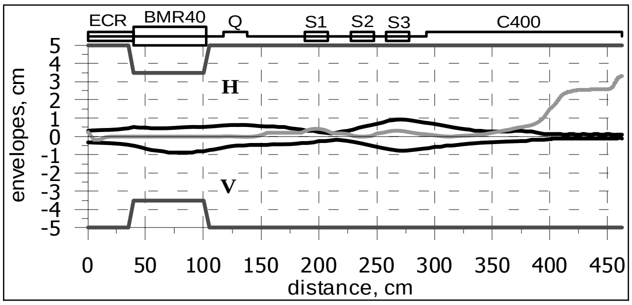


Figure 7: Horizontal (H) and vertical (V) envelopes of He^{2+} ions beam.

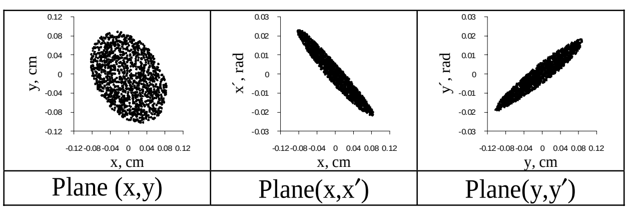


Figure 8: He^{2+} ions distributions.

The helium beam envelopes inside the spiral inflector are less than 1 mm.

Hydrogen Beam Line

During transportation of the Hydrogen beam, bending magnet BMR40 and quadrupole lens Q are switched off. It is proposed to use the solenoids S1 and S3 with switched off solenoid S2 for $^2H^+$ beam matching. The envelopes of the $^2H^+$ beam are shown in Fig. 9. The distributions of $^2H^+$ ions in the various phase planes at median plane of the C400 cyclotron are shown in Fig.10.

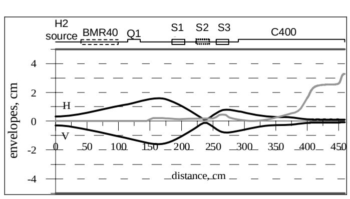


Figure 9: $^2H^+$ ions beam envelopes.

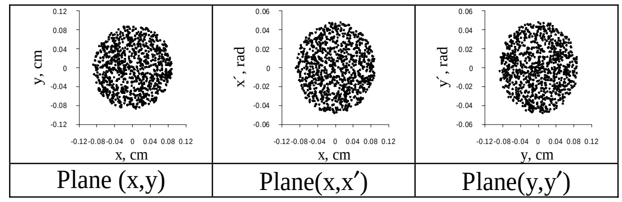


Figure 10: $^2H^+$ ions distributions.

The Hydrogen beam envelopes inside the spiral inflector are less than 1 mm.

CONCLUSION

The proposed C400 axial injection beam line gives the possibility to transport Carbon, Alfas and Hydrogen beams from ion sources to the exit of spiral inflector without beam losses on the wall of vacuum pipe. The proposed optical scheme of the channel allows matching the beam with the acceptance of spiral inflector. In the case of Carbon beam it is valid for any neutralization of the beam current.

The particle distributions of $^{12}C^{6+}$, $^4He^{2+}$ and $^2H^+$ ion beams are defined at the final point of the channel (spiral inflector entrance). For all cases the beam diameter at this point is less then 2 mm. This is sufficient for good beam transmission through the spiral inflector of the cyclotron C400.

The maximum magnetic field induction of the solenoids does not exceed 2 kGauss. The maximum quadrupole lens gradient does not exceed 25 Gauss/cm.

Verifying 3D calculations of beam transport in the axial injection beam line give new parameters of solenoids. The maximum magnetic field induction of the solenoids does not exceed 2.5 kGauss.

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