AXIAL INJECTION BEAM-LINE OF C400 CYCLOTRON FOR HADRON THERAPY

N. Kazarinov†, V.Aleksandrov, V. Shevtsov
Joint Institute for Nuclear Research, 6, Joliot-Curie, 141980, Dubna, Russia
Y. Jongen
IBA, Chemin du Cyclotron 3, B-1348 Louvain-la-Neuve, Belgium

Abstract

The axial injection beam-line of the C400 cyclotron for hadron therapy is presented. The influence of the strong magnetic field from the cyclotron on particles dynamics is taking into account during simulation. The effect of the beam space charge neutralization due to residual gas in the beam-line on parameters of the injected beam is evaluated.

INTRODUCTION

The axial injection system is the part of cyclotron C400 for Hadron therapy developing by IBA (Louvain-la-Neuve, Belgium) [1] in collaboration with JINR (Dubna, Russia). It is designed for acceleration of three species of ions: carbon $^{12}C^{6+}$, helium $^{4}He^{2+}$ and hydrogen $^{2}H^{1+}$. System of injection allows the transportation of $^{12}C^{6+}$, $^{4}He^{2+}$, and $^{2}H^{1+}$ ion beams from ion sources to median plane of cyclotron with 100% efficiency.

STRUCTURE OF INJECTION CHANNEL

General layout of the axial injection system is shown in Fig. 1.

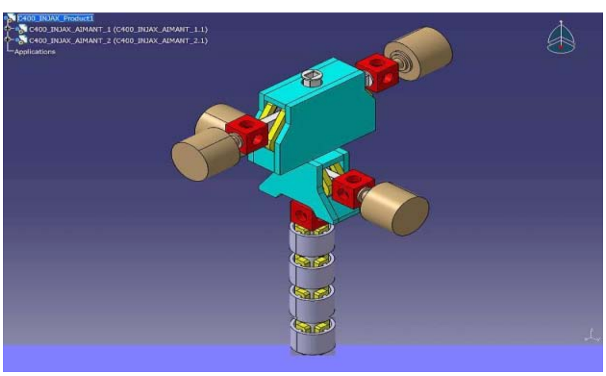

Figure 1: View of axial injection channel.

The ion source injects directly into the switching magnet, which is also used as a charge state analyzing magnet. 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. 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 just after the second magnet. The first magnet (BMR40), 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 (BMR20), to be used for the alpha and for the $^{2}H^{1+}$ ion source does not need a very high resolution, and has a bending radius of 20 cm.

At the exit of the second magnet 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 beam matched with acceptance of the spiral inflector of the cyclotron.

The length of the vertical part of injection channel is about 4 m from the carbon ECR axis to the median plane of the cyclotron C400.

The time to change species can be not more than two minutes to retune the beam transport line between different treatment rooms.

INITIAL BEAM DATA AND AXIAL MAGNETIC FIELD

The main parameters of ion beams used in calculations contains in Table 1.

Table 1: Main beam parameters

Ion energy, keV / Z	25
"Carbon" beam current, eμA	1202
^{12}**C**$^{6+}$ ion beam current, eμA	1
Emittance, π mm·mrad	30
Beam radius, cm	0.5
He^{1+} ion beam current, eμA	200
^{4}**He**$^{2+}$ ion beam current, eμA	20
Emittance, π mm·mrad	50
Beam radius, cm	0.3
^{2}**H**$^{1+}$ ion beam current, eμA	20
Emittance, π mm·mrad	60
Beam radius, cm	0.3

The main particularity in design study of the axial injection system is presence of a strong magnetic field in vertical part of channel (see Fig.2, red line).

† nyk@lnr.jinr.ru

 1-4244-0917-9/07/$25.00

The cyclotron magnetic field in the dipole magnets region (z=0÷90cm) must be suppressed up to acceptable value (≤ 10 Gauss). The possibility of cyclotron magnetic field suppression was studied with the help of 2D and 3D model [2].

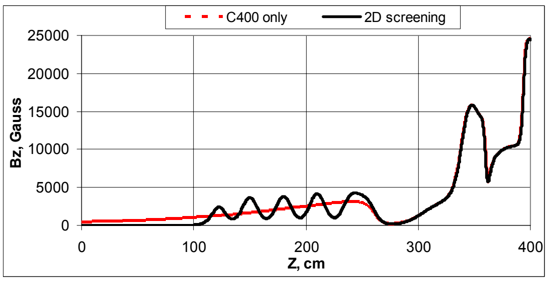

Figure 2: C400 cyclotron magnetic field distribution.

The distribution of the longitudinal magnetic field in the presence of the screen calculated by using POISSON code [3] is shown in Fig.2 (solid line). In the region of quadruplet magnetic induction is about 5000 Gauss. For reducing of the strong coupling in the longitudinal magnetic field the quadrupoles must be turned around the longitudinal axes on suitable angles (tilted lenses).

BEAM DYNAMICS SIMULATION

Simulation of beam dynamics in injection channel was fulfilled using the last version of the Multi Component Ion Beam code (MCIB04[4]).

Fitting of lenses gradients was produced within the framework of the moment method. The initial conditions for the moments of ion beams were defined at the exit of the bending magnet with radius 20 cm (Fig. 1) and were found by macro-particle simulation. Charge state distributions for each ion source (see Fig.3) and beam self-fields were taken into account.

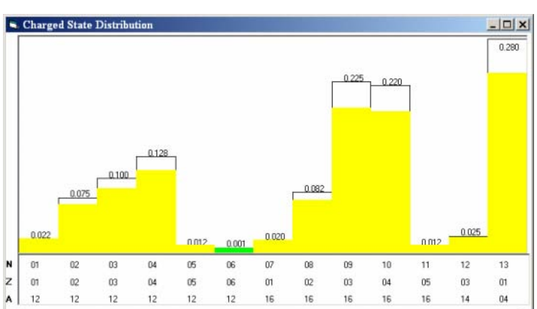

Figure 3: Carbon beam charged state distribution: N – ordinal number; Z – ion charge, A – ion mass.

The matching condition at the entrance of the spiral inflector correspond to the steady state of the beam(beam without envelopes oscillation) in the uniform magnetic field with magnitude to be equal to the field in the cyclotron center. For minimization of functional the simplex method was used.

All results were checked by macro-particle method. For all ion species the results of the macro-particle and moment method simulation ones are in a rather good agreement.

Particle trajectories, ion distributions in phase planes at entrance of spiral inflector for carbon $^{12}C^{6+}$ are shown in Fig.4, 5 respectively.

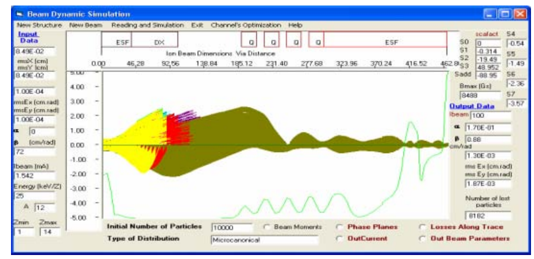

Figure 4: Results of macro particle simulation for $^{12}C^{6+}$. Green line shows distribution of magnetic field.

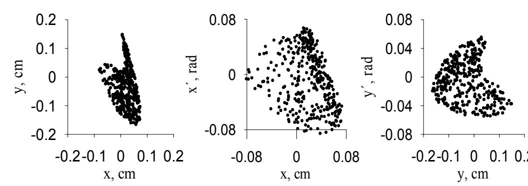

Figure 5: $^{12}C^{6+}$ ions distributions in phase planes at entrance of spiral inflector.

Analogous results were obtained for another two ion species. The matching conditions of the optical functions with the acceptance of the cyclotron inflector were satisfied in all cases.

The quadrupole coefficients of the lenses and the tilt angles for all ion species are contained in the Table 2.

Table 2: Parameters of quadrupole lenses

	Tilt, rad	Quadrupole coefficient K1, m^{-2}			Quadrupole gradient G/cm		
		$^{12}C^{6+}$	$^{4}He^{2+}$	$^{2}H^{1+}$	$^{12}C^{6+}$	$^{4}He^{2+}$	$^{2}H^{1+}$
Q1	**0.55**	**-0.337**	**11.048**	**10.33**	**-1.09**	**35.57**	**33.26**
Q2	**1.50**	**-19.51**	**1.534**	**6.99**	**42.79**	**4.94**	**22.52**
Q3	**2.37**	**49.12**	**21.93**	**11.28**	**158.14**	**70.59**	**36.22**
Q4	**3.57**	**-88.33**	**62.13**	**81.51**	**-284.4**	**200.01**	**262.4**

One can see from Table 2 the maximal value of gradients do not exceed 300 G and tilt angles are independent on the ion sort.

EMITTANCE GROWTH

In the presence of longitudinal magnetic field and zero quadrupole gradients the emittances in two independent 2D subspaces of the whole four-dimensional phase space corresponding to coordinate frame rotated with Larmor frequency around longitudinal axes are constant [5]. For nonzero gradients the results of the simulation show the significant increasing (Fig.6) of the $^{12}C^{6+}$ beam emittances caused by strong coupling due to nonzero longitudinal magnetic field in the quadrupole lenses.

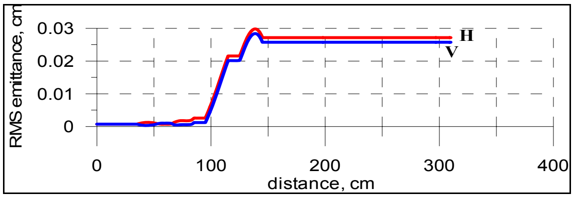

Figure 6. Horizontal (H) and vertical (V) $^{12}C^{6+}$ beam emittances in the rotational frame. Non-tilted lenses.

This leads to increasing of the beam dimensions in the spiral inflector. The beam diameter at the entrance of the inflector is equal to 10 mm.

For reducing of the coupling in the longitudinal magnetic field the quadrupoles have to be turned around the longitudinal axes by required angles (tilted lenses). The direction of the quadrupole rotation coincides with one of the particle in the longitudinal magnetic field. The values of the rotation angle are defined by absence of the coupling in the center of the quadrupole lens. The variation of the tilt of Q3 lens may give the possibility to get the equal emittances for two transverse degrees of freedom. Unlike the previous case the emittance growth is not significant (see Fig.7).

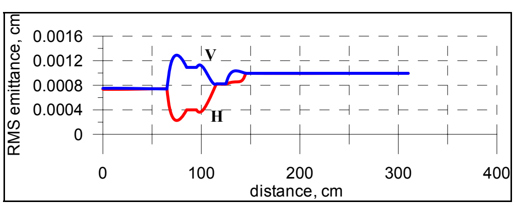

Figure 7: Horizontal (H) and vertical (V) $^{12}C^{6+}$ beam emittances in the rotational frame. Tilted lenses.

As may be seen from the Fig.8 the beam envelopes inside the spiral inflector are equal to 1 mm.

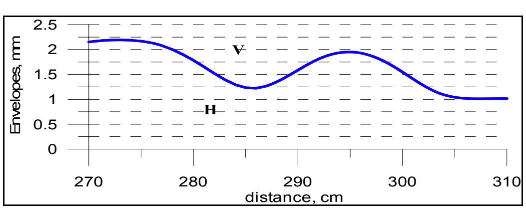

Figure 8: $^{12}C^{6+}$ beam envelopes near inflector.

BEAM NEUTRALIZATION

The influence of beam neutralization on the parameters of the proposed injection system was considered. It was suggested that neutralization to be equal for all ion species and constant in all part of the channel. Numerically the influence of the neutralization reduced the total beam current by factor $(1\text{-}f_N)$.

The simulation show that neutralization of the hydrogen and helium beams up to high degree (f_N =1) does not have essential influence on beam dimensions and divergences and may be compensate by insignificant changes of the quadrupoles gradients.

In the case of carbon ions quadrupole gradients have to be optimized for each neutralization factor. This is explained by big value of the initial beam current. Moreover it was clarified that displacement of beam center of mass is the function of neutralization factor too. The reason of this displacement is common electrostatic action of ions of different species on the beam center of $^{12}C^{6+}$ ions during separation. So the strength of magnetic field in vertical dipole BMR40 was optimized to minimize this displacement. The optimal values of adjustments to magnetic field in vertical dipole BMR40 (nominal value is equal to 805.26 Gauss) are shown in Fig. 9:

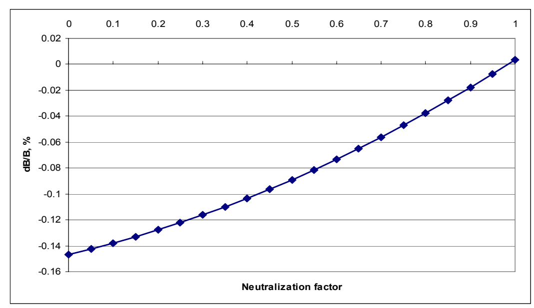

Figure 9: Optimal adjustments to magnetic field via neutralization factor f_N.

REFERENCES

[1] J. Jongen et al, Design studies of the compact superconducting cyclotron fo hadron therapy. In: Proceedings of the EPAC06, 26-30 June, 2006, Edinburgh, Scotland, p.1678.

[2] N. Kazarinov, V. Aleksandrov, V. Shevtsov, A. Tuzikov, J. Jongen et al. Screening of cyclotron magnetic field in C400 axial injection beam-line. These proceedings TUPAN080.

[3] POISSON Program, Los Alamos Acc.Group, LA-UR-87-115,1987.

[4] V. Aleksandrov, N. Kazarinov, V. Shevtsov, Multi-Component Ion Beam code - MCIB04, Proc. XIX Russian Particle Accelerator Conference (RuPAC-2004), Dubna, Russia, 2004, p.201.

[5] N.Yu.Kazarinov. Transfer matrix of linear focusing system in the presence of self-field of intense charged particle beam. In: Proceedings of the EPAC06, 26-30 June, 2006, Edinburgh, Scotland, p.2817.

 1-4244-0917-9/07/$25.00