DESIGN STUDY OF THE AXIAL INJECTION SYSTEM OF C400 CYCLOTRON

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Abstract

The axial injection system is the part of cyclotron C400 for Hadron therapy developing IBA (Louvain-la-Neuve, Belgium) [1] in collaboration with JINR (Dubna, Russia). It is designed for transportation of three species of ions: carbon $^{12}C^{6+}$, helium $^{4}He^{2+}$ and hydrogen $^{2}H^{1+}$ into the median plane of cyclotron. Results of simulations of the ion beam injection and parameters of this beam transportation line are presented.

STRUCTURE OF INJECTION CHANNEL

General type of the axial injection system is shown in Fig. 1. 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 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 $^{2}H^{1+}$ ion source does not need a very high resolution, and has a bending radius of 20 cm.

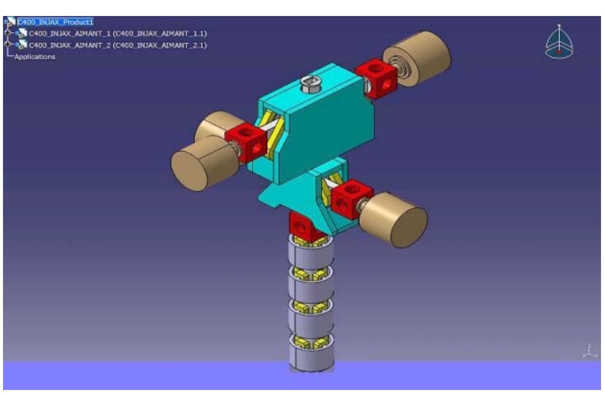

Figure 1: View of axial injection channel

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	300
Beam radius, cm	0.5
Beam divergence	0
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
Beam divergence	0
^{2}**H**$^{1+}$ ion beam current, eμA	20
Emittance, π mm·mrad	60
Beam radius, cm	0.3
Beam divergence	0

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).

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 model. The geometry and positions of steel screens reduced magnetic induction up to required values (see Fig.3) was calculated by using POISSON code [2].

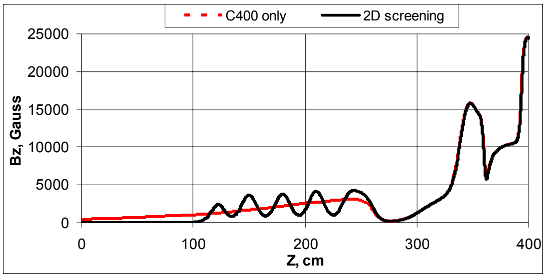

Figure 2: C400 cyclotron magnetic field distribution

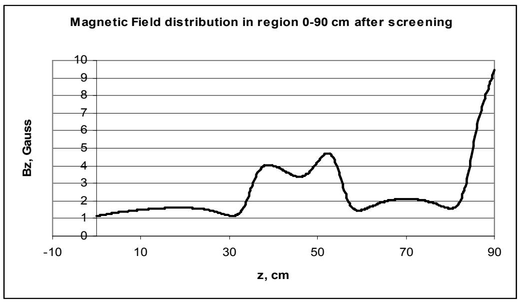

Figure 3: Magnetic field in the region of BM90 with screening

Calculations have shown that 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[3]). New version of this program is based on the computation algorithm of the transfer matrix in the presence of self-field of the intense charge particle beam [4]. In the presence of longitudinal magnetic field when quadrupole gradients are equal to zero the algorithm offered in this work predicts the conservation of emittances in two independent 2D subspaces of the whole four-dimensional phase space. System of differential equations for moments doesn't contain the first derivative of magnetic field on the longitudinal coordinate.

Fitting of lenses gradients was produced within the framework of the moment method. 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 was used the simplex 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 distribution for each ion source was taken into account. 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.

Carbon beam spectrum (charge state distribution), particle trajectories, beam envelopes and ion distributions in phase planes at entrance of spiral inflector for carbon $^{12}C^{6+}$ are shown in Fig.4 - Fig.7 respectively.

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.

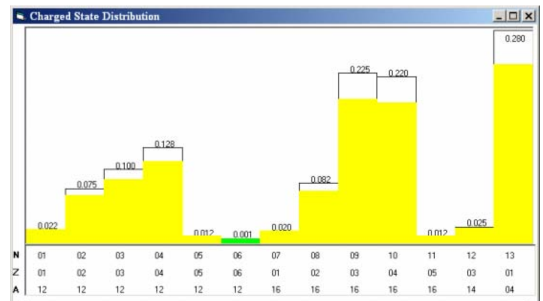

Figure 4: Carbon beam spectrum (charged state distribution):
N – ordinal number; Z – ion charge, A – ion mass

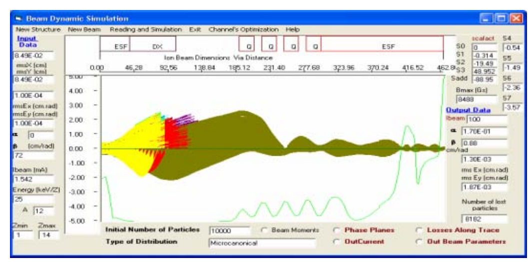

Figure 5: Results of macro particle simulation for $^{12}C^{6+}$. Green line shows distribution of magnetic field

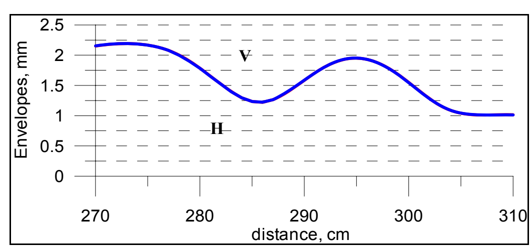

Figure 6: Beam envelopes of $^{12}C^{6+}$ near inflector

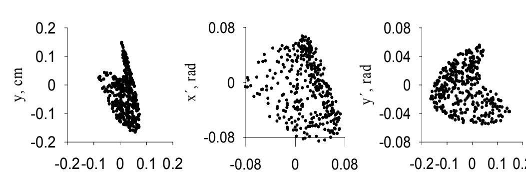

Figure 7: $^{12}C^{6+}$ ions distributions in phase planes at entrance of spiral inflector

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**

From Table 2 one can see that maximal value of gradients not exceed 300 G and tilt angles independent on the ion sort.

CONCLUSION

The magnetic induction in the dipole magnets region has been suppressed up to acceptable value ≤ 10 Gauss. This has been done for 2D model of the vertical part of the injection channel.

Gradients of the quadrupole lenses have been fitted for all types of ions ($^{12}C^{6+}$, $^{4}He^{2+}$, and $^{2}H^{1+}$).

For reducing of the coupling in the longitudinal magnetic field the quadrupoles are turned around the longitudinal axes on required angles (tilted lenses).

The rotation angle of the quadrupoles lenses should be found only at initial stage of operation only for one sort of injected ion (for example carbon).

These rotation angles are the same for all other type of the ions with mass-to-charge ratio equal 2 and should not be changed during routing operation.

For all types of ions the beam envelopes inside the spiral inflector are not exceed 2 mm. Therefore the particle losses in the inflector will be absent.

The maximum gradient in quadrupole lens is about 300 G/cm.

The offered focusing scheme of a beam does not demand bulky system of shielding of quadrupole lenses.

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.

REFERENCES

[1] W. Kleeven et al, XXXIV European Cyclotron Progress Meeting, Belgrade, Serbia and Montenegro, 2005, http://www.tesla-sc.org/ecpm/ecpm.htm.

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