SIMULATION OF EXTRACTION MAGNETIC ELEMENTS FOR C400 SUPERCONDUCTING CYCLOTRON

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Abstract

The superconducting cyclotron (C400) is under design at IBA (Belgium) [1, 2]. The cyclotron will be able to accelerate $12C^{+6}$ and $2H^{+}$ ions up to the energy 400 MeV/nucleon and protons with the energy close to 260 MeV. The basic technical design line for the cyclotron extraction system uses passive magnetic correctors. By computer simulation with the 2D (POISSON) and 3D (TOSCA, MERMAID and MAFCOD) codes the principal design parameters of the extraction magnetic elements were estimated and their magnetic field maps were simulated. The field maps obtained are used for dynamic simulation of the extracted beam.

INTRODUCTION

The cyclotron has a compact-type superconducting magnet [2] with a pole of radius 187 cm. The basic layout and specifications of the extraction elements were determined by numerical analysis of the extraction trajectories [3]. The possibilities of extraction of carbon ions by means of electrostatic deflector (E=140 kV/cm) and protons by means of 2H+ ion stripping as well as precise alignment of these beams at ~3 m from the cyclotron just in front of the energy degrader were studied. The plan view of the carbon ion extraction trajectory and extraction channel is shown in Fig.1. Table 1 shows the specifications of the extraction elements.

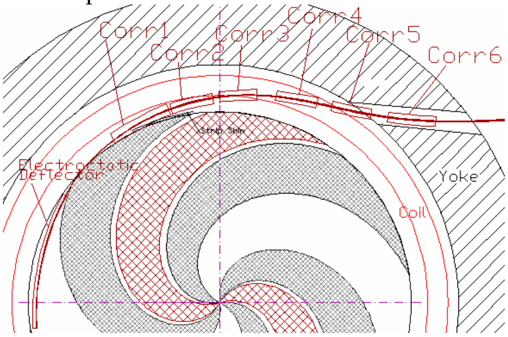

Figure 1: Schematic layout of the extraction elements and carbon ion trajectory

Table 1: Specification of the extraction elements

Element	φ_1°	φ_2°	Aperture (mm)	E (kV/cm)	dB/dx (T/m)
Deflector	262	305	3	140	-
Corrector 1	327	345	20	-	4
Corrector 2	346	359	15	-	20
Corrector 3,4	360	370	20	-	±22
Corrector 5	375	399	25	-	-6
Corrector 6	402	410	25	-	12

The basic idea in the extraction magnetic channel design was to use passive iron correctors. This choice was made after studying the magnetic field of the electromagnetic quadrupole in a strong external field. The simulation of this configuration demonstrated that the quadrupole magnet lost its effectiveness and created a strong unwanted magnetic field perturbation. A three bars design was used for each corrector. The choice of the corrector bar geometry was provided by the MAFCOD code [7] which can simulate the magnetic field from the system of uniformly magnetized iron bars. As the C400 magnetic correctors are in a rather high external magnetic field, this assumption is to be right. This assumption was proved by 3D model simulations. The assumption of the uniform magnetization was proved for the external fields not less then 1 T. For the lower level of the external magnetic field the 3D models were used.

CORRECTOR 1

Corrector 1 was designed by minimizing the volume of iron as its influence on the magnetic field perturbation at the cyclotron beam acceleration region is maximal. The cross-section of the corrector iron bars and its magnetic field and gradient are shown in Fig.2. The magnetic field perturbation in the cyclotron working region is shown in Fig.3. The corrector magnetic field map was simulated by the MAFCOD code. For crosschecking of the simulation accuracy the TOSCA code [5] was used. Figure 4 shows the TOSCA model of the cyclotron magnetic system near the sector edge region with the corrector iron plate. The results of magnetic field simulations for the corrector plate by the MAFCOD and TOSCA code are presented in Fig.5.

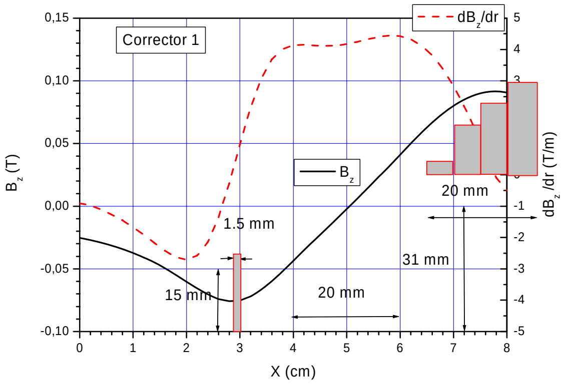

Figure 2: Transverse dependence of the magnetic field response for corrector 1

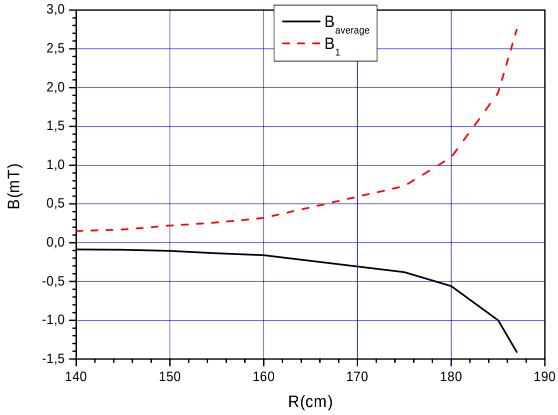

Figure 3: Perturbation of the magnetic field for the working region of the cyclotron

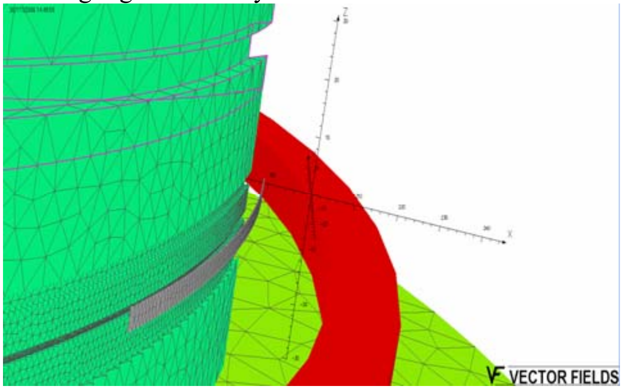

Figure 4: TOSCA model with the corrector plate

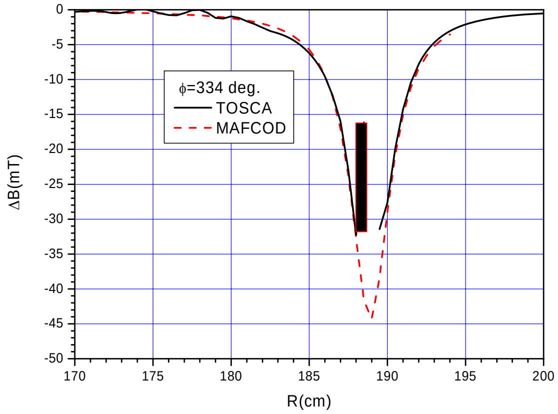

Figure 5: Magnetic field response for the corrector plate, φ=334º

CORRECTORS 2-4

Correctors 2, 3 and 4 have approximately the same parameters and are installed in a rather high cyclotron fringe magnetic field (1.2-2 T). These correctors have the same design. The cross-section of corrector 4 iron bars and the corrector magnetic field is shown in Fig.6. As the end part of corrector 4 is in the fringe field ~1.2 T, the checking of this field magnetization ability for corrector 4 was realized by a 2D POISSON model (Fig.7). The effect of the magnetization field in this model was provided by the current coil. The magnetic field gradient for corrector 4 weakly depends (Fig.8) on the external field level (2 – 1.2 T).

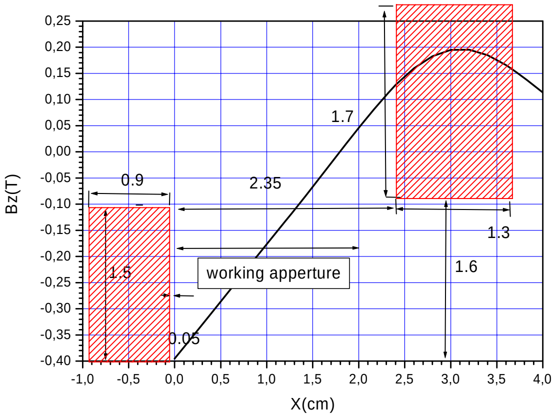

Figure 6: Transverse dependence of the magnetic field response for corrector 4

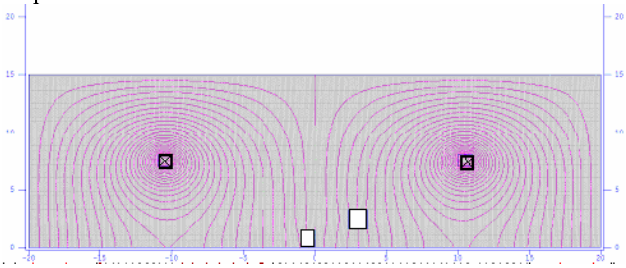

Figure 7: 2D POISSON model for corrector 4

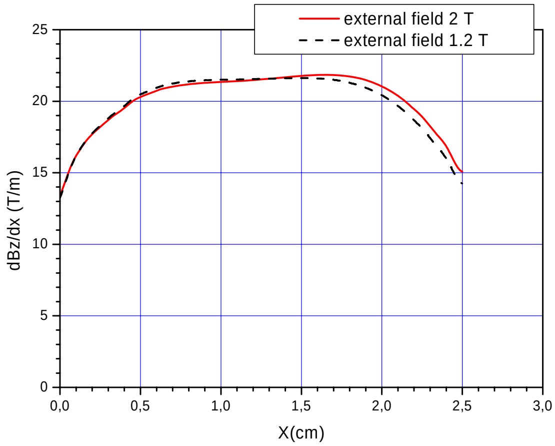

Figure 8: Magnetic field gradient for corrector 4 due to different level of the external magnetic field

CORRECTORS 5-6

Corrector 5 is placed in the fringe magnetic field which is changing linearly in the range ±1.2 T. As the part of the corrector is in a very low external field, the 3D MERMAID code [6] was used. In the test MERMAID model (Fig.9) a piece of conductor was used for the external magnetic field generation. The results of the magnetic field simulation for corrector 5 are presented in Fig.10-11.

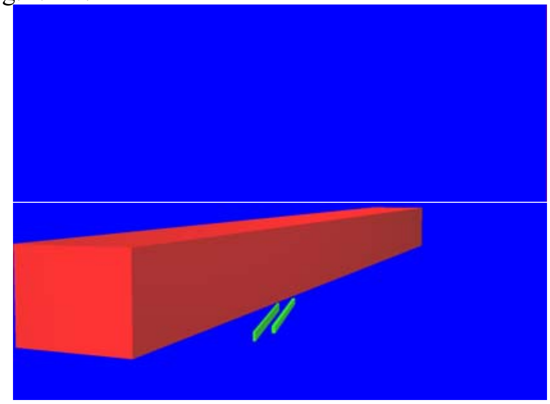

Figure 9: MERMAID code model for the corrector 5 test (3D view)

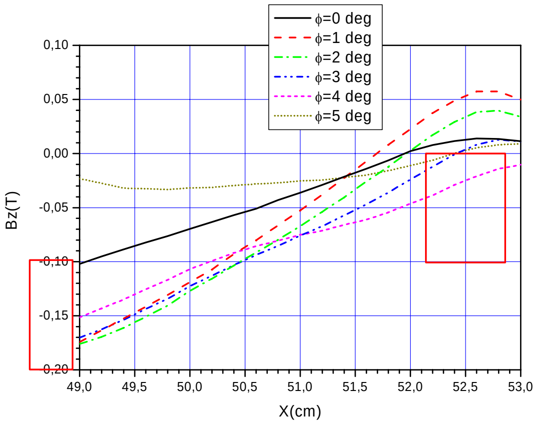

Figure 10: Transverse dependence of the magnetic field response for corrector 5 at different azimuth angles

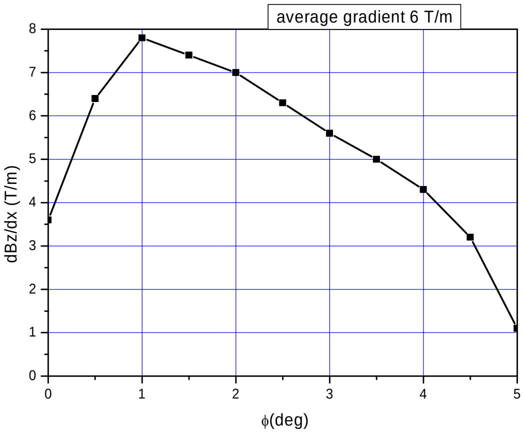

Figure 11: Central magnetic field gradient along corrector 5 (½ length)

The corrector 6 design and magnetic field simulation were done with the MAGCOD and MERMAID code. The cross-section of the corrector iron bars and the corrector magnetic field and gradient are shown in Fig.12 and 13.

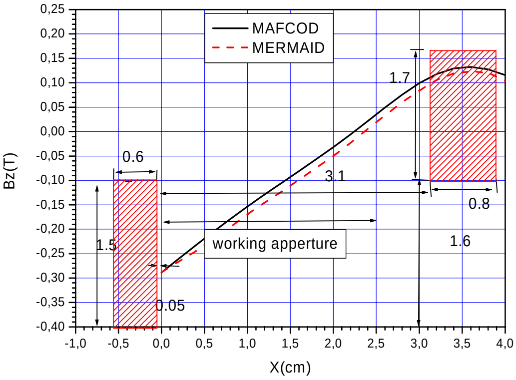

Figure 12: Transverse dependence of the magnetic field response for corrector 6

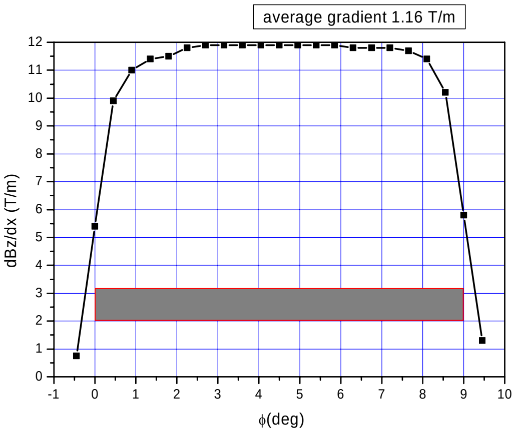

Figure 13: Central magnetic field gradient along corrector 5

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INVESTIGATION OF INTENSE BEAM TRANSPORT ON INJECTION LINE AND INFLECTOR OF COMPACT CYCLOTRON*

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Abstract

In this paper we present a numerical simulation work of high intensity DC beam transport on injection line and inflector of compact cyclotron. A two-dimensional PIC/FFT method is adopted to simulate beam transport on the injection line. In this method, external applied field is dealt with single particle tracking scheme; space charge field is dealt with Particle-Mesh method, and FFT technique is utilized to calculate the space charge forces. A fully three-dimensional model is established for self-consistently simulating the DC beam transport in the spiral inflector, which is developed based upon conventional Particle-Mesh method and includes both space charge effects and image charge effects from the electrodes. Moreover, we developed two object-oriented codes CYCPIC2D (for the injection line) and CYCPIC3D (for inflector). We also present a simulation result of high intensity beam transport in the injection line and inflector of CYCIAE-100 cyclotron.

INTRODUCTION

Along with beam intensity increase in modern cyclotron, space charge force is becoming an important factor which can heavily impact beam's behaviour. PIC method is an efficient macro-particle computer simulation method which is well developed in accelerator community along with the development of computer science during the past decades [1-3].

In compact cyclotron with external ion source, DC particle beam emitted from ion source is injected along the axial beam line and then inflected onto the middle plane of central region using spiral inflector. In order to extract intense beam with high transmission efficiency, it is significant to carry out quantitative simulation study on space charge effects during beam transport on injection line and spiral inflector.

INJECTION LINE

Physical model

The general form of potential solution of 2D Poisson equation of electric field in beam rest frame can be expressed as

$$\phi(x,y)=\frac{1}{2\pi\varepsilon_0}\int G(x,x',y,y')\rho(x',y')dx'dy' \qquad (1)$$

Where (x,y) and (x',y') are the coordinates of target point and source point respectively, $\rho(x',y')$ is the charge density of beam, and $G(x,x',y,y')$ is 2D Green function of open boundary system. The computational domain including all particles is divided into a discrete grid space and the particle charge is deposited onto the grid using a CIC (Cloud-In-Cell) scheme to obtain the charge density of the grid space. Then the potential at the grid nodes can be expressed as

$$\phi_D(x_i,y_j)=\frac{\Delta x\,\Delta y}{2\pi\varepsilon_0}\sum_{m=1}^{Nx}\sum_{n=1}^{Ny}G_D(x_i,x_m,y_j,y_n)\rho_D(x_m,y_n) \qquad (2)$$

Where Δx and Δy are the mesh sizes along x and y directions respectively, and Nx and Ny are the number of nodes along x and y directions respectively.

The space-charge potential on the nodes can be calculated by solving Eq.2 using a FFT based algorithm [4]. Then the electric field is transformed into the lab frame using Lorentz transformation formula and interpolated onto each particle's location to obtain the space charge force on each macro-particle.

To integrate the movement equation of charged particle, symplectic split-operator method is adopted to separate external applied field and space charge field [5].

We implemented above model in an Object-Oriented code CYCPIC2D using FORTRAN 95 language. In our code the longitudinal coordinate is used as the independent variable.

Application

As the first application case, CYCPIC2D was applied to simulate 8mA DC beam transport on the axial injection line of CYCIAE-100 cyclotron, which is under construction at CIAE (Chinese Institute of Atomic Energy). The arrangement of transport elements is O-BS-O-D-O-F-O (BS: magnetic solenoid, D: defocus quadrupole, F: focus quadrupole and O: drift). The parameters of each element were determined by TRACE 3-D [6].

We simulated the beam transport under different neutralized rates. The result was also verified by compared with ORBIT [1] and TRACE-3D. The RMS beam envelopes given by the three codes are shown in Fig.1. The beam envelopes from the three codes agree well with each other in low intensity conditions. CYCPIC2D and ORBIT can still give almost the same results under low neutralized rates, while the result of

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