BEAM INJECTION AND EXTRACTION OF SCENT300, A SUPERCONDUCTING CYCLOTRON FOR HADRONTHERAPY

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Abstract

SCENT300 is a superconducting cyclotron able to deliver proton and carbon beam at 260 and 300 AMeV respectively. The simulations of the beam injection through the central region, the beam extraction through the electrostatic deflector for Carbon beam and by stripper foil for the proton beam are here presented.

INTRODUCTION

Some years ago we presented a study for a 250 AMeV superconducting cyclotron dedicated to hadrontherapy able to deliver both proton and carbon beam [1]. The results of our previous study and the commercial interest of a company suggest us to upgrade the maximum energy up to 300 AMeV increasing the magnetic field and the spiral angle of the hill, maintaining the outer diameter of the machine < 5 m. The higher values of field and of spiral angle pose strict problems to be solved. In particular, the central region becomes more compact and the extraction of proton beam at 260 MeV is not trivial. Here we show how both these problems have been solved.

CENTRAL REGION DESIGN

The beam delivered by an ECR source will be injected axially inside the SCENT cyclotron. A spiral inflector, placed at the centre of cyclotron, will bend the beam from the axial direction to the median plane of the machine. The goals of the central region design study are: to find out the position of the beam coming out from the inflector; to find out the position and size of each RF electrodes and of ground thus to accelerate up a beam that matches an equilibrium orbit having a mean centre coincident to the magnetic centre of the cyclotron. Another additional requirement is to achieve an RF phase acceptance of about 30°.

Design Method

The back-forward integration method was applied: this approach simplifies the optimization process. The starting point was a well centred 3 MeV/A equilibrium orbit at about 16 cm from the machine centre, where the magnetic field is isochronous [2]. Using the analytical formulas that describe the trajectory inside the spiral inflector [3] with some additional empirical corrections derived from our simulated models, the possible exit points from the inflector configurations were found out, Fig. 1. The different positions are available by small variations of the inflector parameters, shown in Table 1. The parameters d, V and K being the gap, the voltage and the angle of tilt of inflectors electrode respectively. The goal of the back-forward integrated trajectory is to match a possible position of the inflector beam exit.

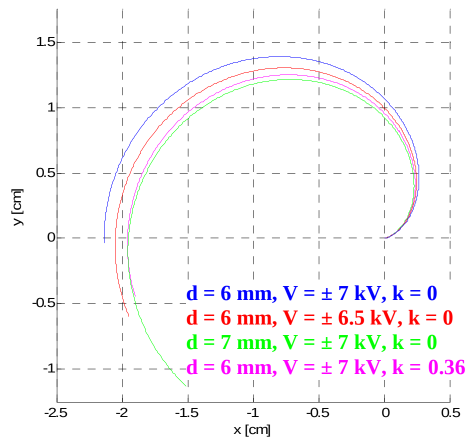

Figure 1: Some examples of reference trajectories through the spiral inflector.

In order to get better the design method, the central region was divided into two parts:

- the inner part, between the space occupied by the inflector and the inner side of the magnet hills;
- the outer part, over 5 cm from the machine centre.

Table 1: Inflector and central region parameters.

Inflector		RF Dee	
Gap [mm]	7	Voltage [kV]	70
Height [mm]	50	E field [kV/cm]	117 ÷ 88
Exit radius [mm]	19	Radial gap [mm]	6 ÷ 8
Voltage [kV]	7	Axial gap [mm]	10 ÷ 20

SCENT300 operates in 4th harmonic mode; for that reason the RF Dee must achieve a width as near as possible to 45° to maximize the energy gain at each accelerating gap. According to the strict constraints due to the iron pole size, due to the copper made RF liner and due to the clearance between the RF Dee and the ground electrode which has to be large enough to prevent discharge, the RF Dee width is in the range 34°÷40°.

The beam decelerated from 3 AMeV to about 300 keV, enters the inner region where it goes along the last turn. Here a two steps optimization procedure starts. First the last turn of the beam trajectory is evaluated assuming an average energy variation of about 29 keV/A in each of the last 9 gaps and drawing back the trajectory of the reference particle to the inflector exit using analytical approximation [4]. This method allows to find the position where to place the Dee tips and Dummy Dee (ground) to perform the final optimization. So 8 channels, shown in Fig. 2, are designed and electrically simulated.

The width of each channel is 8 mm. The final optimization is achieved by the small modification of the inflector parameters (voltage, gap and tilt of electrodes) and of the accelerating gap along the first turn in the inner central region to fit properly the position and the direction of the beam trajectory at the exit of the inflector.

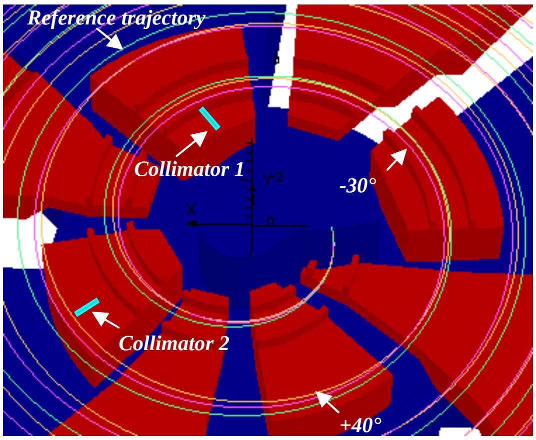

Figure 2: View of the first turns of the trajectories from the inflector and through the electrode channels.

Tools

The two main codes used to design and to simulate the central region were AUTOCAD and OPERA, while MATLAB code was used to develop all the auxiliary software for the data analysis and for the analytical computations concerning the inner central region electrodes. In particular MATLAB was used to create a geometric approximation of the reference trajectory along the first turn. The most useful feature of the developed software is that its output is easily imported in AUTOCAD program. The model of the electrode structure was drawn by AUTOCAD, using the magnet pole model as main constraint for the available space. Some simple modifications were also realized with OPERA modeller functions, for examples the "union" or the "intersection" of different bodies of the model or the "offset" or the "sweep" of some surfaces. The data were easily transferred between the two programs by ACIS file creation.

The electric field of the model was evaluated by OPERA. A specific tool for OPERA to integrate the particles path, using the fields calculated by OPERA itself, was developed too. This new tool was based on the TRACK OPERA command and on the manipulation of the components of the electric field and of the magnetic field; in particular, the electric field components have been modified to take into account the time variation and the particle phase. This method has been improved to work both in OPERA 2D and OPERA 3D.

The numerical analysis of the trajectories, calculated by the new OPERA tool to achieve time-space coordinates, were performed by a dedicated MATLAB code to find out energy gain, phase history, off-centre and the graphical representation of the data, here presented.

Results

The central region of SCENT-300 is quite satisfactory. Three different particles, with phase -75°, -60° and -45° were simulated in the central region configuration. The trajectories were accelerated from the inflector exit to a final energy of 3 MeV/A.

Fig. 3 shows the trajectory of the three particles on the median plane and the position of the curvature centre for the central particle. Fig. 4 and Fig. 5 show a quite uniform

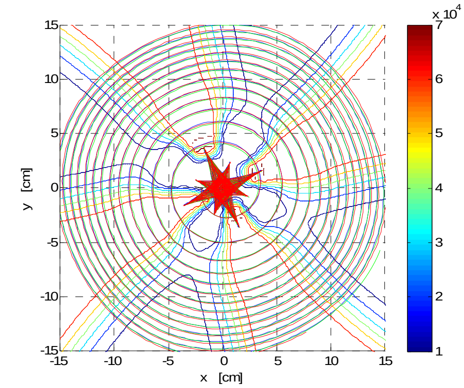

Figure 3: Trajectory of three particles with different phase. The stars like spot are the curvature centres of the trajectories.

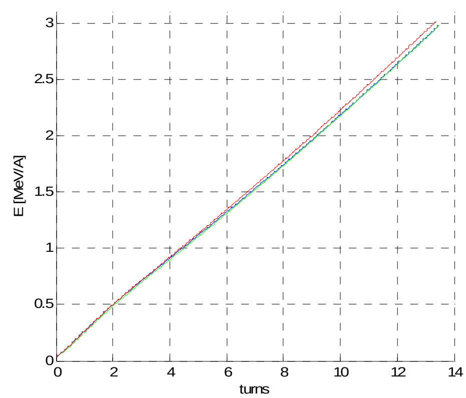

Figure 4: Energy gain in the central region.

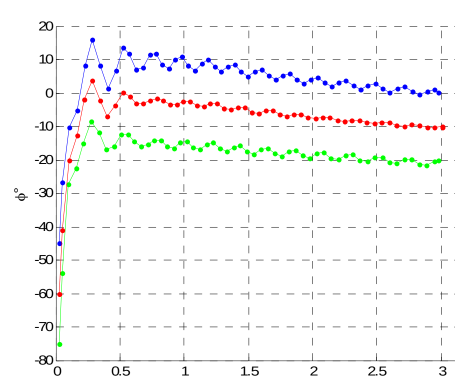

Figure 5: Phase history in the central region.

energy acceleration along the trajectory and the history phase for the 3 particles.

Small variations of the initial parameters allow us to fit the mean centre of the orbits to the magnetic centre of the cyclotron. Two collimators to select the range of the accelerating phase and of the accepted beam emittance will be placed at the positions shown in Fig. 2.

EXTRACTION

To extract the carbon beam at the maximum energy of 300 AMeV a couple of Electrostatic Deflectors, E.D.1 and E.D.2, joint with a set of 3 magnetic channels are used. SCENT allows to deliver also proton beam by the acceleration of the hydrogen molecule H_2^+. This beam is extracted by a stripper process. The H_2^+ beam crosses a stripper foil which breaks the molecule into two protons. This method allows to extract the proton beam with the minimum energy of 260 MeV. To achieve a beam with a variable energy from a fixed energy cyclotron, an energy degrader followed by an Energy Selector System (ESS) is generally used. The efficiency of the ESS depends both on the beam energy extracted from the cyclotron and on the beam energy required for the treatments [5], eg. to decrease a proton beam from 230 MeV to 70 MeV the transmission efficiency is 1÷2%. Thus it is convenient to extract a proton beam with an energy equal to the maximum required for the deepest treatment to minimise the current of the extracted beam and the activation of the degrader target and of the surrounding devices.

Fig. 6 shows the trajectories of carbon beam and proton beam after the crossing of the stripper. The strong precession of the proton trajectory around the centre of the cyclotron brings the orbit outside the pole region. The shielding field of two magnetic channels (MC4,MC5), helps the proton beam to escape from the cyclotron field. Further two magnetic channels (MC6, MC7) are used to focus the proton beam along the extraction trajectory.

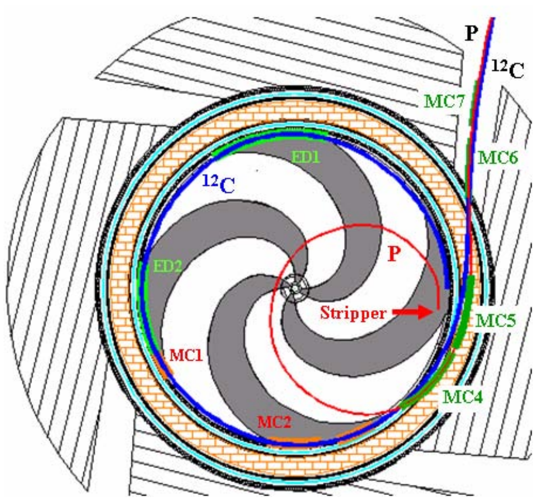

Figure 6: Layout of SCENT300. The trajectories for carbon (blue) and protons (red) extraction, electrostatic deflectors and the magnetic channels are shown.

According to Fig. 7 the carbon beam trajectory crosses near the channels MC4÷MC7, thus the stray field effect due to these channels was included in the simulation of the trajectory of carbon beam. In particular, the channel MC4 stops the carbon beam when MC4 is in the right position to extract the proton beam. Thus this channel is rotated of about 9° towards outer radii to extract the carbon beam.

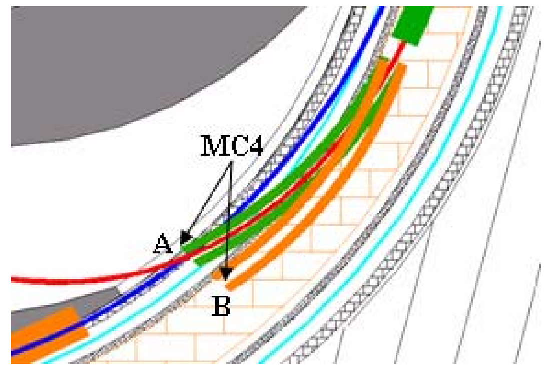

Figure 7: The channel MC4 is moved from position A to B to extract the proton and carbon beam respectively.

An important advantage of this shift is a strong reduction of its stray field on the extraction trajectory and mainly on the accelerated orbit. Moreover the rotated position of MC4 brings it just inside the boundary of the LHe vessel like for the MC5 channel, see Fig. 7. The stray field of the magnetic channel MC1÷MC5 produces a significant first harmonic on the accelerated orbits. Thus a set of compensation bars must be installed to restore the four fold symmetry of the main field. The position B for MC4, see Fig. 7, simplifies quite much the insertion of these compensation bars.

Also the MC6 and MC7 channels need some position adjustments to fit the proper position and fields for both proton and carbon extraction. The beam envelope for both the extraction trajectories were evaluated for a beam with normalised emittance of 0.54 π. This value is about 3 times larger than the emittance of the beam delivered by an ECR source at 25 AkeV. Generally the beam envelope along both the trajectories is smaller than 10 mm. Despite along the proton trajectory an axial beam bump, large up to 24 mm, is present, this is not a serious problem because it is just outside the cryostat region.

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