DESIGN STUDIES OF THE 300 AMeV SUPERCONDUCTING CYCLOTRON FOR HADRONTHERAPY

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Abstract

The design study of a compact superconducting cyclotron for hadrontherapy being carried out at Laboratori Nazionali del Sud (LNS), Catania. This machine is able to accelerate light ions with a charge to mass ratio of 0,5 to a maximum energy of 300 AMeV. Light ions like Carbon will be extracted by electrostatic deflectors. The range of ^{12}C at 300AMeV is 174 mm in water and it is enough to treat all the tumours of the head and neck district. The machine accelerates also the ionised hydrogen molecule H_2^+ to 250 AMeV, which is exracted by stripping, giving a proton beam with an energy of 250 AMeV. The range in water of proton beam with this energy being 370 mm, allowing the treatments of the whole tumours. The main parameters of the cyclotron and the main beam dynamics features will be presented.

INTRODUCTION

Beams of hadrons, such as protons and carbon ions, offer an important advantage over traditional radiotherapy: minimum damage to healthy tissue around a tumour. While dedicated facilities based on the proton therapy are well established around the world, most of the hadron-therapy ones are currently in operation at large particle-physics laboratories. In Europe, two dedicated facilities are under construction (CNAO in Italy and HIT in Germany) and many projects based on light ion therapy are at different stages of the approval and financing path [1]. These centres are based on synchrotron accelerators, due to the high energy of light ions (400 AMeV for ^{12}C) needed to reach the whole deep-seated tumours. But according to the distribution of the number of world wide treated patients vs target depth [2], it is possible to use a low beam energy in 50-70% of cases. In the case of treatment with carbon ions, an energy of 300 AMeV is required to treat most of the tumours. These lower energies are achievable with cyclotron accelerators which present some advantages as compared to a synchrotron in terms of cost and compactness. Moreover, the cyclotron continuous beam and its better current control are two crucial features allowing the optimization of the new active scanning method used to deliver the right dose to the target. To combine the advantages of a superconducting cyclotron with the goal of providing light ions and protons, the accelerator R&D group of LNS has developed a concept for a multiparticle therapy cyclotron which is described in the following report.

MAIN PARAMETERS

The cyclotron under study is a four sector compact machine with a diameter of 5 m, height of 3 m and a weight of 340 tons. The magnet is energised by a pair of superconducting coils symmetrically placed above and below the median plane. These coils operate with a current density of 41 Amp/mm^2. This machine, whose K value was fixed at 1200 MeV is designed to accelerate two ion types: the fully stripped carbon ion $^{12}C^{6+}$, which is extracted at the maximum energy by means of two electrostatic deflectors placed at the extraction radius of 130 cm; and the ionised molecule of hydrogen H_2^+ being extracted by stripping at the radius of 120 cm, that provides a proton beam of 250 MeV. The maximum average magnetic field at the extraction is 4.2 tesla. Four RF cavities operating at the fixed frequency of 97 MHz accelerate the ions with a peak voltage of 120 KV. Table 1 summarizes the parameters of the cyclotron.

Table 1: Main Specifications

Parameters	Values
Particles	H_2^+, $^{12}C^{6+}$
Injection energy	25 AKeV
Extraction Energy	$^{12}C^{6+}$ @ 300 AMeV protons @ 250 AMeV
K bending	1200 MeV
Number of sectors	4
Extraction radius	130 cm
Hill gap	50 mm
Main size	5 m x 3 m
Weight	350 tons
Coils	A pair SC
Nominal current	950 amp
Current density	41 amp/mm^2
Number of cavities	4
Operating frequency	97 MHz, 4th harmonic
RF power	60-70 kW per cavity
Extraction Systems	Electrostatic deflectors Stripping process

MAGNETIC FIELD DESIGN

The magnetic circuit of the cyclotron has been designed using the dedicated FEM code TOSCA by Vector Fields.

The poles are shaped with four spiral sectors in order to ensure an adequate axial beam stability. The maximum angle of the magnetic spiral reaches 80 deg. The average magnetic field varies from 3,2 tesla at the center of the machine, up to 4,2 tesla at the extraction radius. This radius was fixed to be 1,3 m to extract the light ion beam at the final energy of 300 AMeV.

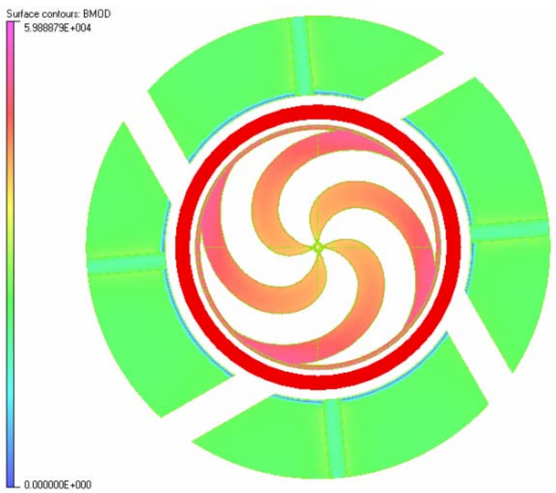

Figure 1: Top view of the magnetic field in the hills and the yoke.

The azimuthally varying magnetic field was shaped to provide a minimum vertical focusing frequency of 0.2, and to avoid the crossing of harmful resonances as Q_r=4/3, as shown in fig.2.

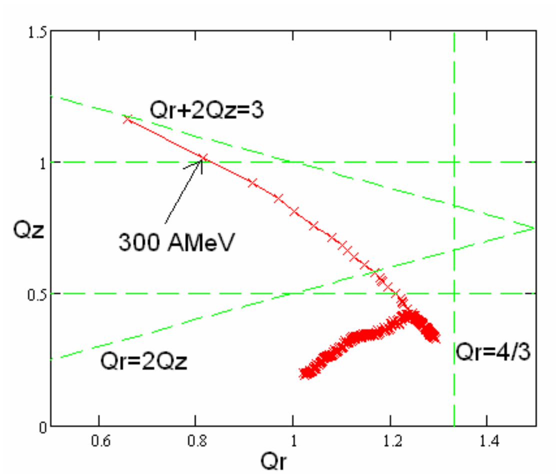

Figure 2: Working point diagram of the cyclotron. The main dangerous resonance are shown as dashed green line.

Despite the charge to mass ratio of both ion species accelerated ($^{12}C^{6+}$ and H_2^+) is similar Q/A~0,5, the isochronous magnetic field has to be changed of ~0.35% to guarantee an acceptable phase varying during the acceleration. The fine tuning of the magnetic field is made by means of a number of trim rods positioned inside the hills. In order to reduce the number of these pistons, we are considering to use an additional coil of small size, operating at room temperature and placed inside the iron yoke, which compensates the main difference in terms of magnetic field needed to accelerated the two beams.

RF SYSTEM DESCRIPTION

The RF system, working in the fourth harmonic, is based on four cavities operating at 97 MHz. These cavities, copper made and water cooled, are entirely installed inside the free valley regions. The multistem cavity configuration [4] needed to reach the high resonant frequency, found out by means of 3D electromagnetic codes. The aim is to obtain a cavity with a voltage distribution going from 70 kV in the injection region to a peak value of 120 kV in the extraction region, and a low power consumption (60-70 kW per cavity). The cavities operate at the phase, and the power is fed by an inductive coupler for each cavity. A trimmer capacitor per cavity will be used for the fine tuning of the resonant frequency. The RF system is powered by four amplifiers.

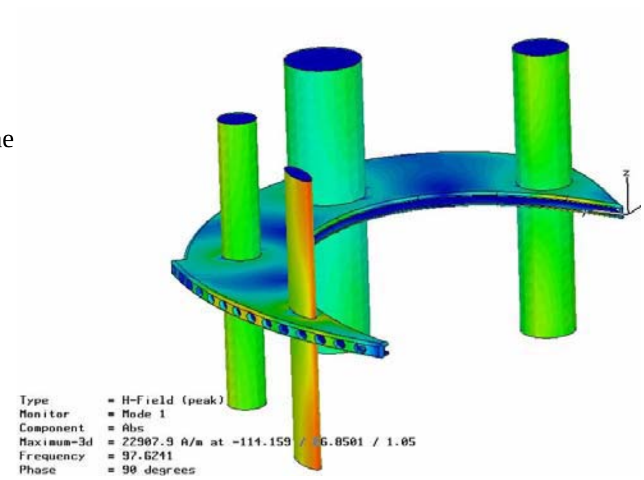

Figure 3: Current distribution on the complex DEE-stems of one cavity. As shown, four stems are expected to get the resonant frequency of 97 MHz. Due to the high value of voltage (120 KV) at the extraction region, the power dissipation on the outer stem becomes higher.

INJECTION AND CENTRAL REGION DESIGN

The proposed cyclotron will be equipped with an external ECR ion source producing both H_2^+ and fully stripped Carbon ions. A solution with two separated sources to reduce the switching time between proton and carbon treatment is also considered [5]. Ions are delivered axially, through an injection line, into the machine, where an electrostatic inflector, operating with an electric field of 23 KV/cm, bends the beam by 90 deg from its axial path to the cyclotron median plane. The advantage to minimise the size of the cyclotron using an high magnetic field has as a drawback the difficulty to design a very compact central region, because of the low injection energy of the beams (25AKeV).

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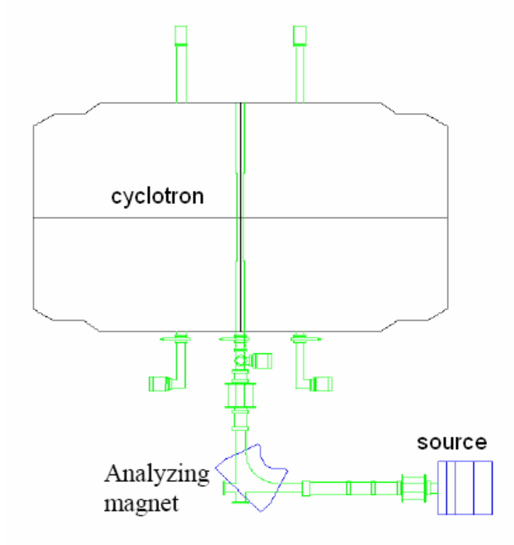

Figure 4: Layout of the injection line with one source.

Concerning the 300 AMeV cyclotron under study the central region operates at 3.2 tesla, with a DEE voltage of 70 kV. An electrode separation of 8 mm limits the electric fields to 88 kV/cm. The electrodes are optimised to guide the beam through the central region leaving it reasonably well centered. A code, mainly developed in Matlab, allowing to design the spiral inflector and the central region was implemented [6].

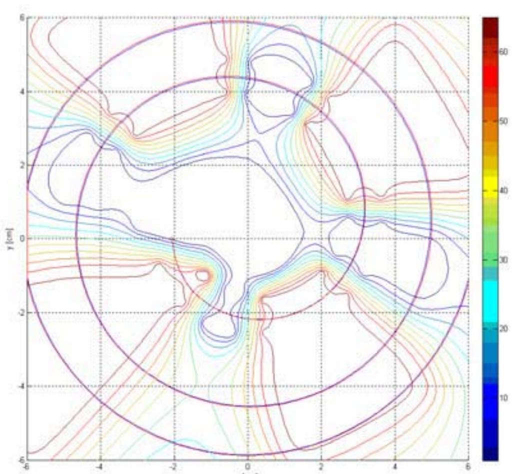

Figure 5: Trajectory of the injected beam for the first turns. The voltage distribution is also shown, reaching the maximum value of 70 kV.

EXTRACTION STUDIES

The extraction of a fully stripped ion $^{12}C^{6+}$ needs the use of electrostatic deflectors (ED). The choice to install the 4 RF cavities inside the valleys implies to put two electrostatic deflectors in two hills, where the gap is deep enough (5 cm). However a system with the ED placed into the cavities, between the accelerating DEE, was studied. This choice makes the extraction process easier, but it increases the power consumption of the RF cavities.

The protons are extracted by stripping of the H_2^+. The carbon foil is positioned at the internal radius of 120-122 cm, in order to intercept the accelerated beam at the energy of 250 AMeV as shown in fig. 6.

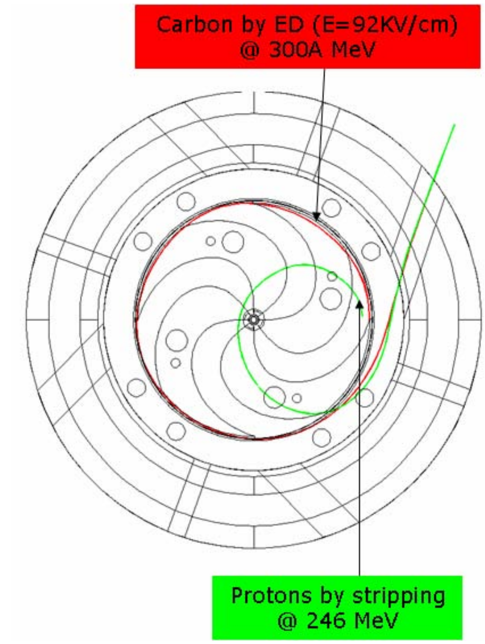

Figure 6: Two different extraction processes.

CONCLUSIONS

While the use of both superconducting (K250 SC by ACCEL Gmbh) and conventional cyclotrons (C235 RT by IBA) in protontherapy centers is consolidated, this cyclotron is an interesting option for the facilities dedicated to the treatments of tumours with ions and protons too. The preliminary design of this machine was carried out. The INFN has signed a technology-transfer deal that will fast-track the commercialization of its know-how in superconducting cyclotrons for hadron-beam cancer therapy.

REFERENCES

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