DESIGN STUDY OF MEDICAL CYCLOTRON SCENT300

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Abstract

The study of the Superconducting Cyclotron named SCENT300 [1] was carried out by the accelerator R&D team of Laboratori Nazionali del Sud (LNS-INFN) of Catania in collaboration with the University of Catania and supported by IBA (Belgium).

Combining the compactness of a superconducting cyclotron, with the advantage of this kind of machine as its continuous beam and its very good current control, the accelerator R&D group of LNS, by its ten-year of experience with this kind of machine, has developed a concept for a multiparticle therapy cyclotron which is described in the following report.

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.

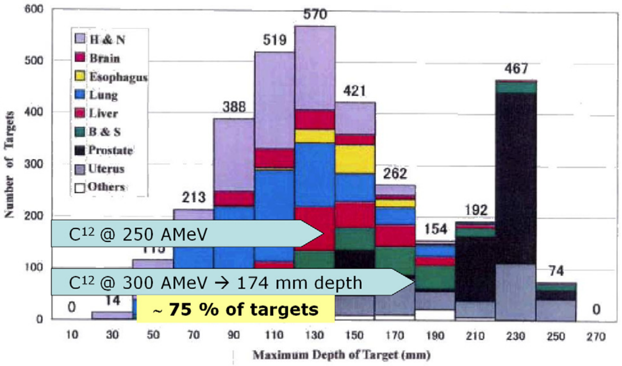

Figure 1 : the plot shows the number of targets (for different tumours highlighted on the left square) as function of the depth inside the human body. The arrows indicate the depth limits of the carbon beams at two different energy. These data are provided by HIMAC (Japan) concerning the treated patients from 1995 to 2001 [2].

Today IBA and INFN are involved to study the possibility to use the cyclotron accelerator to get both the protons and the carbon ions for the therapy. IBA in collaboration with JINR laboratories, is carrying out the project of C400, a compact cyclotron able to accelerate the carbon ions up to the energy of 400 AMeV and protons up to 270 AMeV [3]. The INFN is accomplishing the design study of a superconducting cyclotron to deliver 300AMeV of carbon ions and protons of 260 AMeV [4]. The choice to get the energy of 300 AMeVfor the carbon ions is due to the higher number of tumours reachable inside the human body using the carbon beams, as shown in the Figure 1. On the other hand the extraction energy of protons of 260 AMeV, guarantees to treat the whole targets.

MAIN PARAMETERS

SCENT300 is a four-fold symmetry superconducting cyclotron optimized to accelerate both the fully stripped carbon ion and the H_2^+ with a charge to mass ratio of 0,5 for the hadrontherapy application. The carbon beam is extracted at the maximum energy of 300 AMeV by two electrostatic deflectors (ED) and a set of passive magnetic channels. The ionised hydrogen molecule H_2^+ is extracted at the inner radius of 122 cm, by the stripping process at the energy of 260 AMeV, delivering the proton beam with the same energy, by a different extraction channel through the iron yoke.

Table 1: Main Parameters of SCENT300

Parameters	**Values**
Particles	H_2^+, $^{12}C^{6+}$
Injection Energy	25 AKeV
Extraction Energy	$^{12}C^{6+}$ @ 300 AMeV, H_2^+ @260 MeV
K bending	1200 MeV
Number of Sectors	4
Pole Radius	132.5 cm
Mean Magnetic Field	3.15 tesla ÷ 4.2 tesla
Peak Magnetic Field	4.95 tesla
Injection scheme	Axial + external ion sources
Extraction	Carbon by 2 ED, H_2^+ by stripping
Size	Diameter= 5 m, Height= 3 m
Weight	~ 350 tons
Coils	2 superconductors
Max Current density	47 amp/mm^2
Energy Stored	35 MJ
Number of Cavities	4
Operating RF harmonic	4
RF frequency	~ 98 MHz
Estimated power losses	50 kW/cavity

The machine is a relatively compact cyclotron (5 m in diameter) and most of operating parameters, as the operating RF frequency are fixed (see Table 1).

MAGNETIC FIELD DESIGN

The study was carried out by an intensive use of FEM code in order to get a full parameterization and a better accuracy for the magnetic fields calculation.

The minimum requirements to satisfy for the magnetic field design, are the following:

- Vertical and radial beam dynamic stability ($Q_r>0$; $Q_z > 0$);
- Isochronism $|\Delta\omega/\omega| < 1\cdot10^{-4}$ in order to keep the phase slip calculated in static mode, within accepTable values $|\Delta\varphi| < 20$ deg;
- Minimization of the current density of the coils to keep right margins of reliability and safety of the cryogenic systems;
- Minimization of harmful effects on the beam quality due to the resonances crossing;

The main magnetic field was refined in order to deliver the fully stripped Carbon ions up to the maximum energy of 300 AMeV. A special care was done to the bring the last orbit accelerated as close as possible to the edge of the pole in order to make easier the extraction process by the ED.

The average magnetic field varies from the value of 3.15 tesla at the injection up to 4.2 tesla at the extraction radius of 129.5 cm. The 4 fold symmetry and the spiral shape of the sectors (82 deg of maximum spiral angle) provide the needed axial focusing of the beam.

To validate the properties of the magnetic field, the preliminary analysis of the beam dynamic in static mode was done by means of dedicated code. The first calculations were done, setting two different values of constant voltage: 70 kV and 120 kV in order to check the phase behaviour, being the effective voltage included within these values. In the plot shown in Figure 2, it can see that the phase value, thanks to the good isochronization, oscillates within a range of ±10 RF deg.

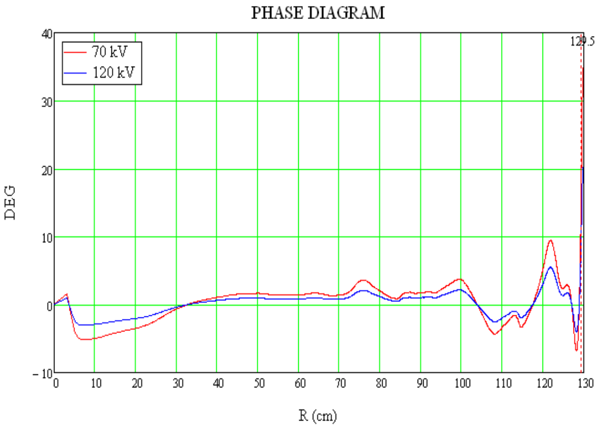

Figure 2: Two different phase behaviours depending on the voltage value set for the calculation in static mode.

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. Ions at the energy of 25 AkeV 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.

An optimal configuration could be able to transport a beam emittance of 30 π mm mrad in phase shift of 20 RF deg to the acceleration region with a few millimetres of off-center and a good vertical focusing.

The accelerating structure consists of a set of specially-shaped electrodes attached to the Dees of the cavities: the position and size of each RF electrodes and of ground are optimized to accelerate the beam along a well centered path with a reasonable energy gain of the beam (see Figure 3). The Dees have been shaped using all the available space between two different magnet hills and reaching the maximum angular amplitude, but in the first 5 cm from the machine centre, where the beam trajectory covers the first turn, the Dee tips and electrodes have to be inserted along the reference trajectory, in order to provide the vertical focusing. The introduction of two channels for each Dee improves the effect of the accelerating electric field and confines it close the gaps.

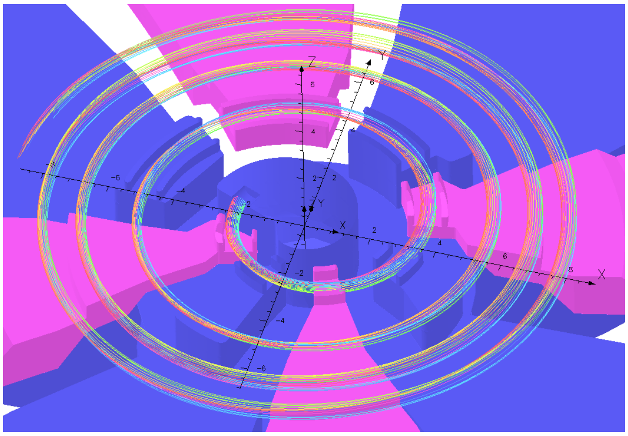

Figure 3: the figure shows the central region configuration. The dee-electrodes are highlighted in magenta, while the ground surfaces in blue. A set of particle trajectories from the housing (where the inflector is located) to first turns.

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 multi-stem cavity configuration [5] 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.

In a general cavity structure, the stems give the main contribution on the inductance of the cavity and give mechanical stability being the connection between the dee and the liner. As regards the cavities we expect to use in SCENT300, in order to attain the high resonant frequency, we have been forced to insert at least three stems. Thus, we have chosen to have higher electrode voltages on the inner and outer extremities and to keep a lower voltage in most of the DEE, in order to optimise the shunt impedance. By applying the above-described method, we have obtained the resonator shown in Fig # The large central stem (low inductance) concentrates the currents coming from most of the electrode, while the two lateral ones (high inductance) resonate with the much smaller capacitances of the DEE extremities.

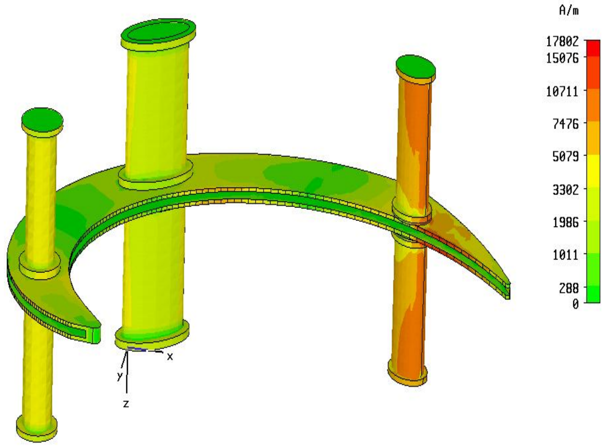

Figure 4: the three stems configuration of a single cavity without the liner is shown. The current density on the surfaces of the DEE and stems is also plotted. The peak value is 142 A/cm.

BEAM DYNAMIC STUDY

In the following section the beam dynamic of Carbon ions taking into account the acceleration effects on the beam envelop, is discussed. The working diagram of the machine is shown in figure 6.

As first step, we verified the accelerated equilibrium orbit AEO of a single particle, in order to check the phase slip using the varying voltage profile. The starting conditions for the AEO, i.e. the radius, the radial momentum and the phase are given by the equilibrium orbit data. From the dynamic calculations, a very small excursion of phase is reached. The maximum value corresponds to 44.4 deg at 303.4 AMeV (130.42 cm of radius). The energy gain varies from 0.2 AMeV/turn to 0.47 AMeV/trun, being almost 1100 turns needed to get the final energy.

The beam envelop behaviour during the acceleration is analyzed. The transverse beam dynamic on phase space (r,r') and (z,z') is carried out. Two values of radial amplitude A_r of displacement from the AEO have been studied: +0.1 cm and +0.2 cm.

The twice crossing of the dangerous structural resonance $Q_r=4/3$, respectively at 120.6 cm (246 AMeV) and 127.9 cm (293 AMeV), does not cause a significant growth of the beam size with an initial amplitude $A_r=0.1$ cm. The harmful effect instead is quite evident on the radial envelop of particles delivered with the initial amplitude of 0.2 cm, as shown in Figure 5.

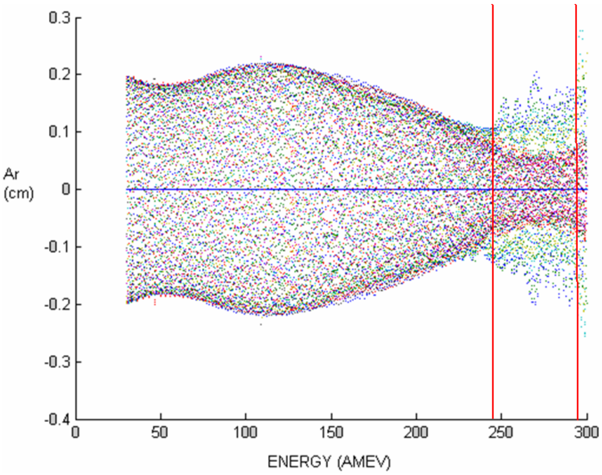

Figure 5: Radial beam envelop versus energy of the accelerated orbit with Ar=0.2 cm of initial amplitude. The effect of the crossing of the Qr=4/3 (signed by the red lines) on the size of the beam is evident.

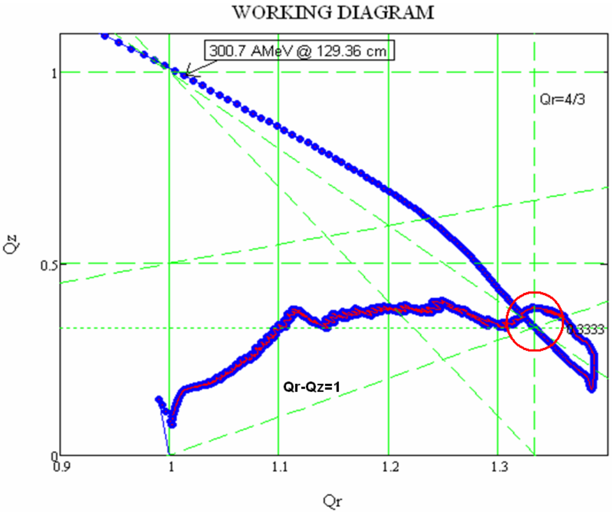

Figure 6: working point diagram of Carbon ion. Lines of most important resonances are shown. The point were the beam passes through 2 dangerous resonances is highlighted.

Despite the first crossing does not get an excessive growth, the second one, even if faster, could become capable to doing harm on the beam quality.

On the other hand, since the beam passes through both the coupling (Qr–Qz=1) and structural (Qr=4/3) resonances at the same point on the working diagram (see Figure 6), it could be possible to introduce a local $B_{1r}(r)$ perturbation (max 10 gauss) in order to reduce the impact on the radial growth at expense of the vertical one.

TRIMMING OF THE MAGNETIC FIELD

The SCENT300 machine is designed to get carbon ions and protons for hadrontherapy use. Despite the charge to mass ratio of both ion species is similar (Q/A= 0.500137 for $^{12}C^{6+}$; Q/A=0.4966345 for H_2^+), the magnetic field has to be changed in order to compensate the de-isochronization due to the mass discrepancies between the two beams.

There are two ways to do that:

- changing only the main magnetic field (+0.78% constant along the radius) and keeping constant the RF cavity frequency;
- changing both the main magnetic field (from 0% at injection to -0.5% at extraction) and the RF cavity frequency of about 0.78%;

The first solution allows simplifying the cavity design but it requires a larger tuning of the magnetic field as shown in Figure 8; the second one requires a small variation of the magnetic field but it needs to design a RF system working at two different frequencies.

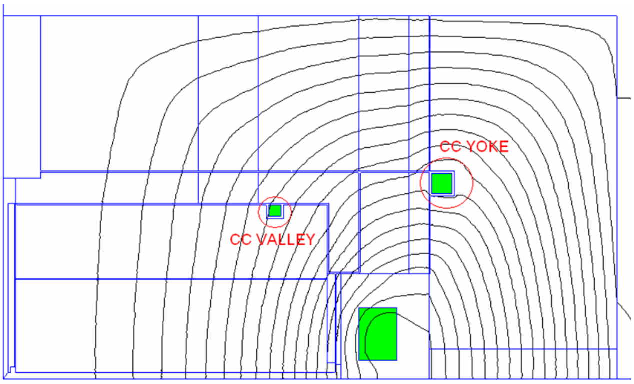

Figure 7: side view of the cyclotron with the coils position highlighted.

We decided to keep constant, within few hundreds of Hertz, the RF frequency, changing the whole magnetic field of almost 0.78%. To do that, in addition to the main coils current setting, we suggest to insert two pair of correction coils (CC) operating at room temperature as shown in Figure 7. The position and the size of the coils were chosen to best fit the needed magnetic field and, at the same time, to minimize the current and the power losses of the resistive coils (see Table 2). The found out solution allows shaping the magnetic field with a precision of ± 3 gauss respect to the ideal one as shown in Figure 8. The small magnetic spread ensures for the H2+ dynamic, a phase excursion within ± 10 RF deg both in static and acceleration mode.

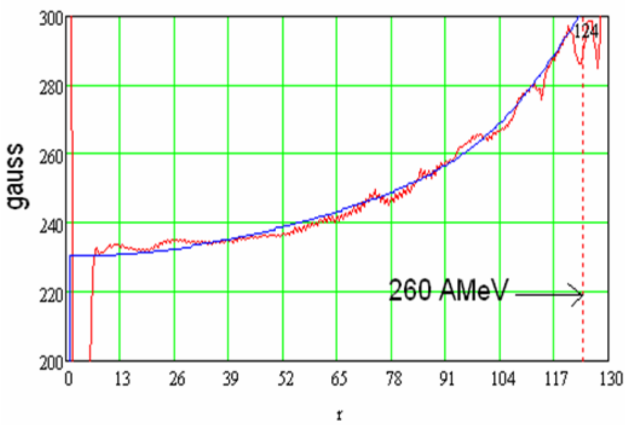

Figure 8: Comparison between the average magnetic field needed to accelerate the H2+ (red line) and the best fit achieved by tuning the main coil current and by adding on two resistive correction coils.

Table 2: Different Coils Setting for C and H_2^+ Acceleration

	MAIN COIL	CC VAL	CC YOKE
SIZE mm^2	150x210	80x80	50x40
C setting A/mm^2	45.86	0	0
H_2^+ setting A/mm^2	45.86+0.53	4	1.1
Power losses kW/coil	SC	3.24	1.32

EXTRACTION STUDIES

The extraction of a fully stripped ion $^{12}C^{6+}$ requires the use of electrostatic deflectors (ED). The choice to install the 4 RF cavities inside the valleys implies to put two electrostatic deflectors (E1 and E2 in Figure 9) in two hills, where the gap is deep enough (5 cm). The electrostatic deflectors operate at 50 kV and the maximum electric field on the gap is 120 kV/cm. 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 260 AMeV as shown in Figure 9. The protons leaves the cyclotron by a single turn without interfere with the central region device and the inner wall of the cryostat. The two beams exit from two different yoke apertures. A set of passive magnetic channels (MP and MC in the figure 9) are needed to make easy the extraction both the carbon and the protons. Such magnetic channels compensate the defocusing effect on the radial plane due to the fall-off of the magnetic field close the outer edge of the poles.

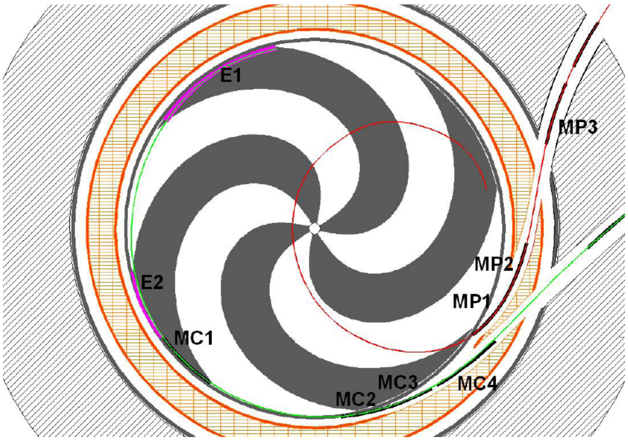

Figure 9: the two extraction path are shown in figure. The red line corresponds to the proton trajectory, and the red one to the carbon beam. The position of the different passive magnetic channels (MP used for the protons and MC for the carbon) is shown.

FINAL CONSIDERATIONS

The magnetic field trimming system is the key point of this cyclotron. Since SCENT300 operates in 4th harmonic mode, the average magnetic field has to match with high precision the isochronous one to accelerate both the ion species. We think that the described system could become useful during the cyclotron commissioning to provide for eventually fine tuning for the Carbon magnetic field too. Indeed some imperfection due to the iron cast and the mechanical assembly has to be taken into account during the building of the machine. Their effect on the magnetic field is seldom negligible and it may require at later stages, extensive modifications could be impractical or difficult, because of the freezing meanwhile of other parameters.

While the use of both superconducting (K250 SC by VARIAN-ACCEL Gmbh) and conventional cyclotrons (C235 RT by IBA) in protontherapy centers is today consolidated, this cyclotron is an interesting option for the facilities dedicated to the treatments of tumours with ions and protons too.

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