SCENT300, A SUPERCONDUCTING CYCLOTRON FOR HADRONTHERAPY

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Abstract

SCENT300 is a superconducting cyclotron for hadrontherapy. It can deliver carbon and proton beam at energy of 300 and 260 AMeV respectively. The main parameters of the cyclotron and the main beam dynamics features will be presented. The results from mechanical simulations and the RF system description are also shown here.

INTRODUCTION

The design study of a compact superconducting cyclotron for hadrontherapy is being almost completed by the Accelerator R&D team of the Laboratori Nazionali del Sud (LNS) in collaboration with the University of Catania. This machine was optimized to accelerate both the fully stripped Carbon ion and the H_2^+ with a charge to mass ratio of 0,5. The Carbon beam is extracted by electrostatic deflectors (ED) at the maximum energy of 300 AMeV. 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 a proton beam with the same energy.

The motivations that leaded the design guidelines of SCENT300 have been widely explained in the previous papers [1]. The SCENT300 cyclotron is a relatively compact machine (5 m in diameter) with most of operating parameters fixed (see table 1).

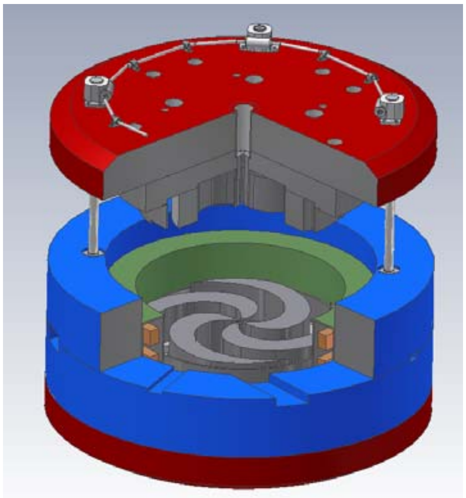

Figure 1: layout of the SCENT300 accelerator.

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
Mean Magnetic Field	3.2 tesla ÷ 4.2 tesla
Max. Magnetic Field	4.95 tesla
Injection scheme	Axial + external ion sources
Extraction	Carbon by 2 ED, H_2^+ by stripping
Size	ϕ= 5 m , Height= 3 m
Weight	≤ 350 tons
Coils	2 superconductors
Energy Stored	35 MJ

MAGNETIC FIELD DESIGN

The magnetic field was designed by means of 3D and 2D dedicated FEM codes [2,3] and refined in order to deliver the Carbon ion up to the energy of 300 AMeV at the extraction radius of 129 cm. 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 ~0.7% to guarantee an acceptable isochronism during the acceleration. A pair of additional room temperature coils placed symmetrically respect to the median plane, on the top and bottom of the cyclotron yoke, allow to perform this small field tuning. These conductors (with a small re-setting of the main coils) provide the small magnetic field contribution (few tenths of gauss) and the right form factor of the field along the radius, needed to accelerate both the beams.

Special care was done to the isochronous field design in order to keep within acceptable values (±20deg) the phase excursion of the beam during the acceleration. The need to get a very accurate isochronism, according to the formula:

$$\Delta\varphi \propto 2\pi \cdot \frac{\Delta B}{B} \cdot h \cdot n$$

h: harmonic mode, 4 in our case
n: number of turns, ~ 1000
ΔB/B: isochronism field difference

causes the crossing of some resonance as shown in the working diagram in fig. 2. The cross of the two resonances Q_z=0.5 and Q_r–$2Q_z$=0 takes place during the last turns and it comes in a fast way without damaging the beam. Otherwise the effects on the beam dynamic of the multi cross through the $3Q_r$=4 and Q_r– Q_z=1 resonances, have been subjected to accurate studies whose results are shown below.

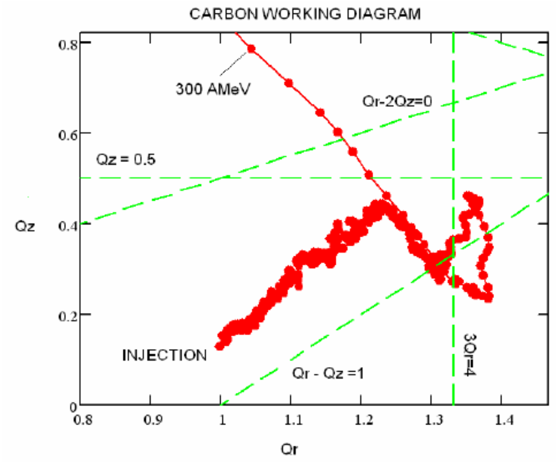

Figure 2: Working point diagram of the cyclotron. The main dangerous resonance are shown as dashed green line.

BEAM DYNAMIC STUDY

The beam dynamic studies were done in collaboration with the JINR of Dubna (Russia) [4]. The aim was to verify the validity of the magnetic field of SCENT300 by means of different codes dedicated to the beam dynamic. The axial motion for a particle starting with a 2 mm off center is shown in fig. 3. The amplitude oscillation is well focused along the acceleration and it is due only to the vertical betatron behavior along the radius.

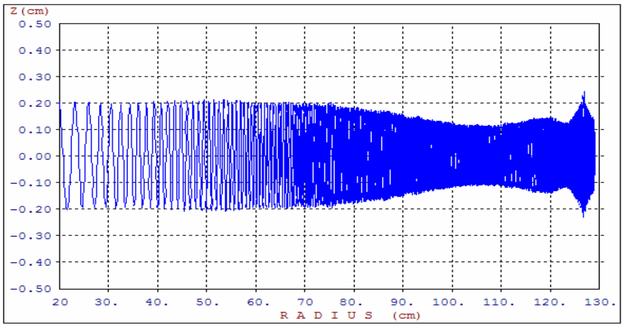

Figure 3: axial motion along the radius.

The effects of the resonance $3Q_r$=4 on the radial amplitude get the value of 2 mm as the maximum initial radial size allowed. Indeed if an initial radial amplitude of 3 mm is chosen, the crossing of the resonance compromises the radial stability as shown in fig.4.

However by using the coupling effects due to the crossing of the Q_r– Q_z=1 resonance, it is possible, by inserting a radial field bump, to reduce the radial amplitude at the expense of the vertical one.

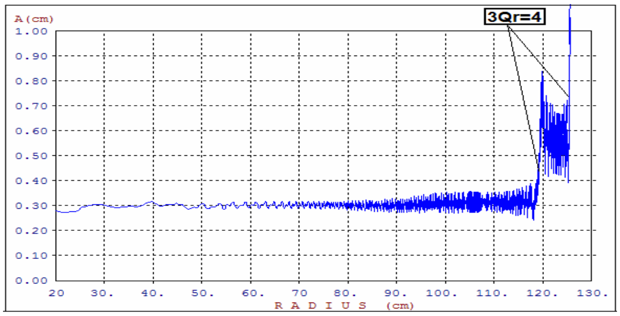

Figure 4: radial amplitude versus the radius. The effect of the structural resonance $3Q_r$=4 crossing, is highlighted.

A set of 1000 particles uniformly distributed inside an eigenellipse with normalised emittance of 2.1 π mm·mrad were accelerated from 30 to 301 AMeV. The emittance value being a 3 times larger than the emittance measured at ECR source. The distortion of the beam bunch begins just after the crossing of the resonance $3Q_r$=4. But the beam size remains acceptable. The vertical bunch is not affected of any distortion also if an emittance 2 times larger is simulated.

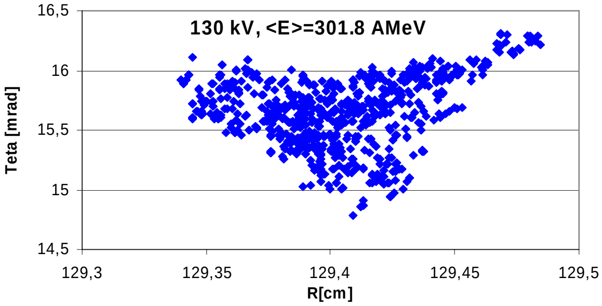

Figure 5: acceleration of 1000 particles from 30 AMeV to 301.7 MeV. Initial normalized emittance being 2.1π mm·mrad.

RF SYSTEM DESIGN

The RF system for the SCENT 300 cyclotron is composed by four resonant cavities operating in the fourth harmonic, at a RF frequency of 99.50 MHz. These cavities, copper made and water cooled, are entirely installed inside the free valley regions and will be powered by four RF amplifiers. The cavity study was performed by means of the 3D electromagnetic code CST MicroWaveStudio [5]. Each cavity is composed by a dee that presents an angular width of 34° and a gap (clearance between the two dee surfaces pointed to the median plane) of 20 mm, designed to reduce the power dissipation and to supply the right energy to the beam.

Three stems are required to reach the high resonant frequency and to give a good mechanical stability to the system. The liner shape was designed to reduce the capacitive effect where the electric energy is high: a volume of vacuum was added in the extraction region close to the external stem. The desired voltage distribution from 70 kV in the injection region to a peak value of 125 kV in the extraction region was achieved by moving the stems around their equilibrium position, together with a low power consumption of 65 kW simulated per cavity.

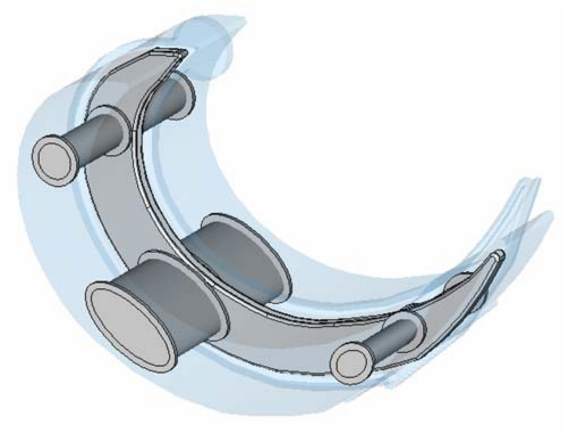

Figure 6: layout of the resonant cavity with 3 stems.

Table 2: Main parameters of the resonant cavity

Parameters	Values
Resonance frequency	~99.5 MHz
Voltage range	70÷125 kV
Quality factor	~7300
Simulated RF power dissipation	65 kW

FORCES AND STRESSES EVALUATION

The magnetic forces acting on the structure of SCENT300 are evaluated by the codes OPERA, FEMM [2,3]. These codes employ the functions which apply the Maxwell Stress Tensor on the surfaces containing the parts over the forces are calculated.

The cyclotron was subdivided in different parts as shown in fig. 7: central plug, central pole cup, sectors or hills, pole caps and ring yoke.

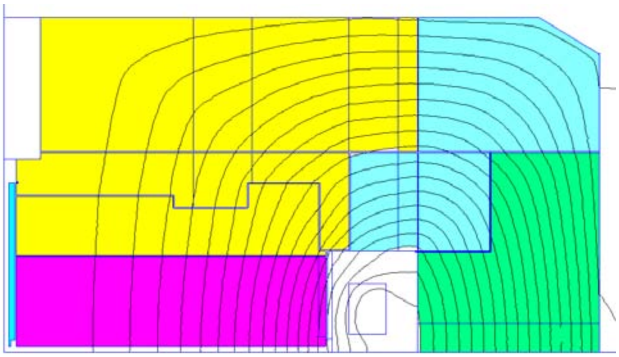

Figure 7: layout of the subdivision of 1/8 of the cyclotron. Each coloured zone corresponds to an independent part.

The forces due to the magnetic field are mainly directed vertically and cause a compression between the poles of the machine of about 2800 tons. The table 3 shows the strength values calculated for each part. The maximum vertical displacement achieved on the structure by applying the forces was calculated by means of ANSYS code [6]. The results show that the maximum stress is 3.8 kg/mm^2 (fig. 8), under the elastic limit of the iron of 12 kg/mm^2. The maximum vertical displacements get the value of 0.33 mm.

Table 3: Values of force on the cyclotron parts.

Parameters	Values
Central plug	-14230 N
Central pole cap	-19.11 MN
Pole cap	-8.79 MN
Ring Yoke	-5.6 MN
Sectors	-2.13 MN

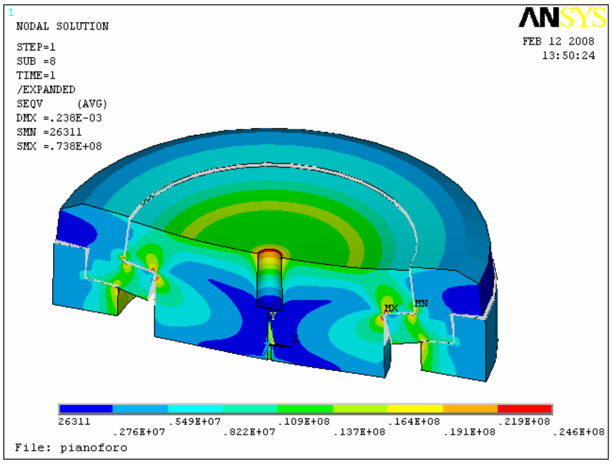

Figure 8: distribution of Von Mises stress on the upper part of the cyclotron (values are in N/m^2).

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