DESIGN FEATURES OF A 300 AMEV SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

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Abstract

The study of the Superconducting Cyclotron named SCENT300 [1] was carried out by the accelerator R&D team of LNS-INFN of Catania in collaboration with the University of Catania and supported by IBA (Belgium). The new design features concerning the magnetic properties of the machine and the last results about the beam dynamic are presented.

INTRODUCTION

SCENT300 is a 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 apllication. 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.

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).

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

MAGNETIC FIELD IMPROVEMENT

The need to improve the main features of SCENT300 and its performance in terms of extraction efficiency and reliability, brought about the new 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 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. Respect to the previous design, 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 (see fig. 1).
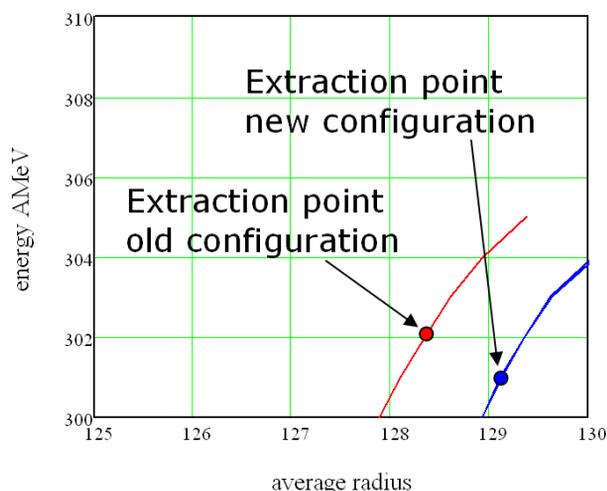
Figure 1: The new magnetic field design allows to extract the carbon ions at the external radius with a gain of 1 cm.

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 fig. 2, it can see that the phase value oscillates within a range of ±10 RF deg.
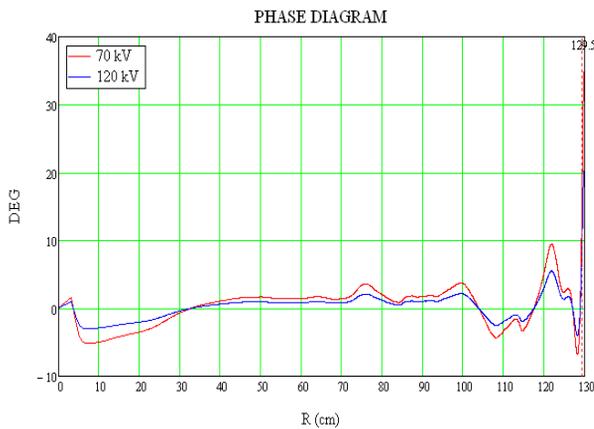
Figure 2: Two different phase behaviours depending on the voltage value set for the calculation in static mode. The good isochronization allows to maintain within acceptable value the phase excursion (±10deg)

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 accelerating system of the cyclotron consists of 4 multi-stems RF cavities operating in 4th harmonic at the fixed frequency of 98 MHz. The average voltage profile along the radius, calculated by simulations, varies from 70 kV at the injection up to 120 kV.

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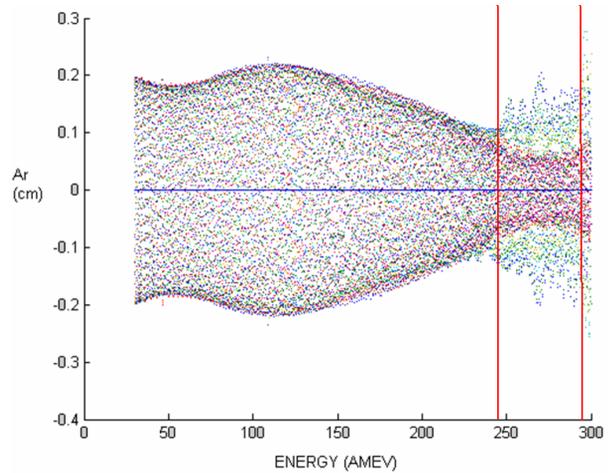
Figure 3: Radial beam envelop versus energy of the accelerated orbit with $A_r=0.2$ cm of initial amplitude. The effect of the crossing of the $Q_r=4/3$ (signed by the red lines) on the size of the beam is evident.

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 ($Q_r–Q_z=1$) and structural ($Q_r=4/3$) resonances at the same point on the working diagram (see fig. 4), 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 deisochronization due to the mass discrepancies between the two beams.

There are two ways to do that:

1. changing only the main magnetic field (+0.78% constant along the radius) and keeping constant the RF cavity frequency;
2. changing both the main magnetic field (from 0% at injection to -0.5% at extraction) and the RF cavity frequency of about 0.78%;
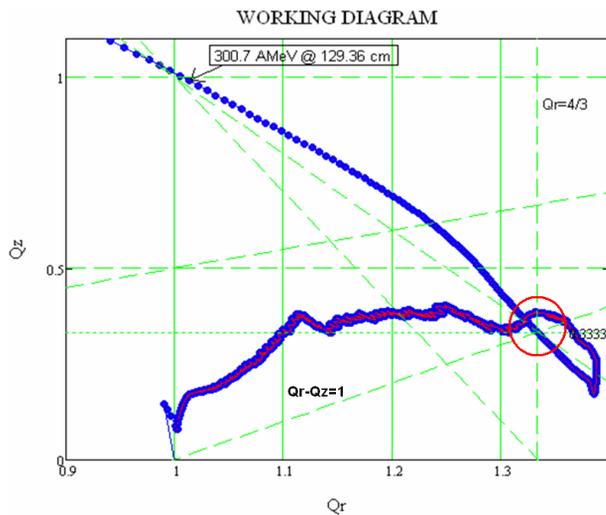
Figure 4: working point diagram of Carbon ion. Lines of most important resonances are shown. The point were the beam passes through 2 dangerous resonances is highlighted.

The first solution allows to simplify the cavity design but it requires a larger tuning of the magnetic field as shown in fig.6; the second one requires a small variation of the magnetic field but it needs to design a RF system working at two different frequency.
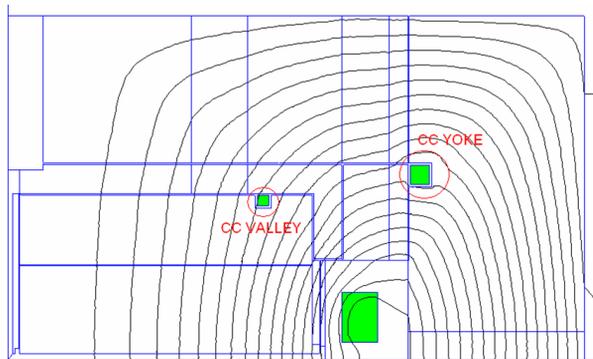
Figure 5: side view of the cyclotron with the coils position highlighted.

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 fig.5. 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 tab. 2). The found out solution allows to shape the magnetic field with a precision of ± 3 gauss respect to the ideal one as shown in fig. 6. The small magnetic spread ensures for the H2+ dynamic, a phase excursion within ± 10 deg both in static and acceleration mode.
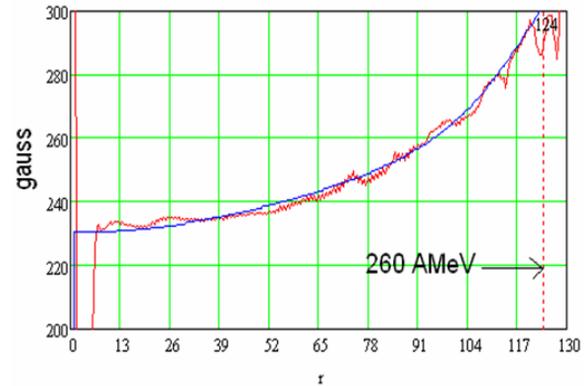
Figure 6: Comparison between the average magnetic field needed to accelerate the H2+ (red line) and the best fit achieved by tuning the main coil current and by adding on two resistive correction coils.

Table 2: Different coils setting for C and H2+ 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

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 construction 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.

REFERENCES

[1] M.Maggiore et al., "SCENT300, a superconducting cyclotron for hadron therapy", EPAC'08, Genova, July 2008, TUPP123, (2008); http://www.JACoW.org.