STUDY OF A NEW SUPERCONDUCTING CYCLOTRON TO PRODUCE 250 A MEV – 50 KW LIGHT ION BEAMS

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Abstract

A four sector compact superconducting cyclotron able to deliver ion beams with power in the range 20 –100 kW has been studied. This cyclotron is mainly designed to accelerate ions like H_2^+ and $^{12}C^{5+}$ ($Q/A \approx 0.5$) to be extracted by stripping. The maximum energy achievable is 250 MeV/amu for protons and 210 MeV/amu for C ions. This cyclotron can be a useful primary driver to produce radioactive ion beams. Thanks to the extraction by stripping, two simultaneous beams can be extracted. The preliminary design model of the magnetic circuit has been accomplished with the 3D electromagnetic code OPERA ver 8.10 [1].

1 INTRODUCTION

Accelerators of medium power (10-50 kW) are suitable drivers of facilities to produce radioactive ion beams. Therefore a widespread interest has arisen around them. At L.N.S. the EXCYT project is in progress [2]. This project is based on a Superconducting Cyclotron to be used as a primary accelerator to produce radioactive beams to be accelerated by a Tandem accelerator. One main limitation of the project is the primary beam intensity deliverable by the present cyclotron. The EXCYT facility could be significantly upgraded if a primary beam with a 20 – 40 times higher power would be available. For this reason we are investigating on the design of a new superconducting cyclotron able to deliver a beam power of about 50 kW.

Extraction is the critical feature for a cyclotron of this kind, since it is generally performed by electrostatic deflectors. To be an efficient process, this extraction method requires well separated turns, which is achieved with a big radius of the machine and a high accelerating voltage. Both these features make the cyclotron expensive.

Following the design of commercial cyclotrons often used to produce radioisotopes, we propose to overcome the limitations set by electrostatic extraction by using extraction by stripping [3].

Here we present a cyclotron able to accelerate H_2^+ up to 250 MeV/amu. The same cyclotron could accelerate light ions like $^{12}C^{5+}$, to be extracted by stripping and in general light ion beams with charge state q_{ac}=Z-1, Z being the charge of the nucleus (Z=6-10).

2 RESULTS FROM 3D SIMULATIONS

To increase our experience on 3D electromagnetic simulations, and to have some estimate on the accuracy level of the simulations, the Superconducting Cyclotron operating at LNS, Catania, has been simulated by TOSCA, the magneto-static module of OPERA 3D. The simulation of the cyclotron for the whole operating diagram has been done introducing the magnetic configuration with as many details as possible. Computational limitations, finite boundary conditions, and material property variations are all possible limitations on the accuracy of the model. A considerable effort was put into refining the computer calculations to obtain reproducible convergence to very high accuracy. Average magnetic fields and flutter values simulated for different values of the coil current were compared with the corresponding parameters extracted from high accuracy field measurements [4].

It was observed that absolute results of 3D simulations and measurements differ by 1 % maximum, depending on the field level. This discrepancy is generated by variations between the B-H curves for different materials and also by some geometrical difference between the model and the real cyclotron. Further studies will be accomplished to find a complex model allowing to obtain a better agreement throughout different operating points of the Superconducting Cyclotron.

3 MAIN PARAMETERS OF THE CYCLOTRON

The study of the cyclotron has started from the main parameters of the K1200 cyclotron operating in the Michigan State University, USA, and we have modified them to design a new machine, whose characteristics are shown in table 1.

Table 1: Cyclotron parameters

parameters	values
K bending	1600
K focusing	500
Number of sector	4
Extraction radius	1300 mm
Yoke radius	2400 mm
Minimum hill gap	74 mm
Maximum average field	4.2 T
Number of dees	4
RF range	86.4 – 90.4 MHz
operating harmonic	4
peak voltage	100 kV
Number of coils	4

The main differences are the number of sectors and the radius size. As compared to the K1200 cyclotron, the larger radius allows at the same time to increase the flutter, so as to achieve a $K_{FOC} \geq 500$ and to maintain the magnetic field at acceptable values.

3.1 Magnet design

The main characteristics, i.e. spiral angle, sector width and other important parameters of the machine have been preliminarily calculated by analytical approach applying a simple first-order formalism and assuming the uniform iron saturation. Several changes of the preliminary model have been made using the 3D electromagnetic code OPERA. The number of sectors has been fixed to be four in order to avoid the dangerous radial resonance (π-stop band) in view of an eventual upgrading the maximum energy up to 300 MeV/amu for H_2^+.

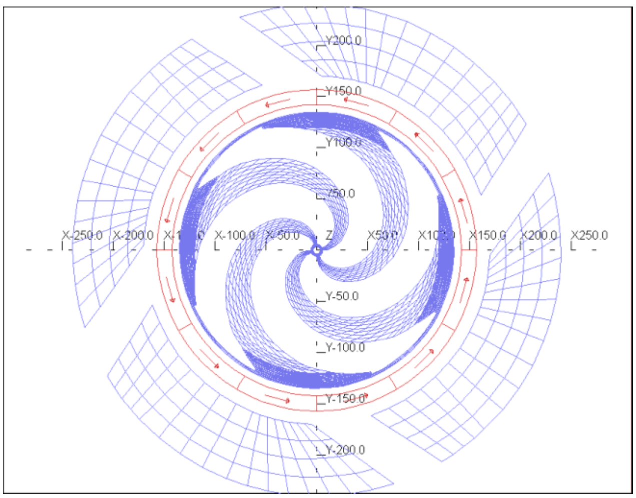

Figure 1 :Layout of the spiral sectors and holes for extraction by stripping.

A parametric model of the cyclotron has been built, and an iterative process has been realised in order to optimize automatically several parameters of the machine like width sectors, hill and valley gaps, spiral angle to fulfil the beam requirements, like the isochronous field and vertical focusing. Figure 2 shows the parametrization process of the model. The sector width varies from 25 deg at the center of machine up to 40 deg at extraction radius. The maximum gap height of the valley has been fixed to 45 cm and an iron shim of 10 cm high has been introduced up to 90 cm of radius to better shape the isochronous field. Four holes have been located at the center of the valleys (70 cm from the center and 29 cm of diameter) to lodge the RF cavity stems.

A large gap (80 mm) between the poles has been provided for eventual beam growth in the vertical plane and allows to introduce the trim coils system. An adequate shimming of the hill gaps at the extraction region should ensure a good vertical focusing. Difference in gap height at the minimum and maximum radius is about 6 mm. Decreasing the hill gaps at the last centimetres of the pole, the spiral constant can be reduced, which is advantageous also from the RF point of view.

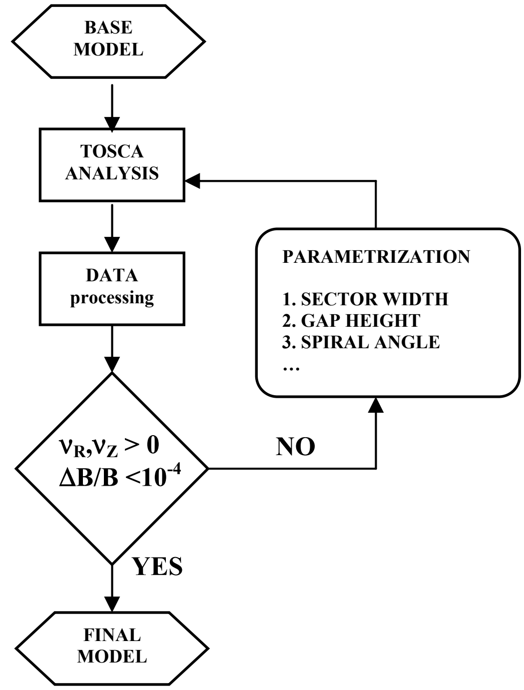

Figure 2: Scheme of optimization process.

3.2 Main coils

Two pairs (α and β) of superconducting coils, symmetrically placed above and below the median plane, are supposed to generate the isochronous fields for H_2^+ and $^{12}C^{5+}$ beams. The position, geometry and currents of the coils have been optimized with a process similar to the above mentioned one, to cover the whole range of energy. A big vertical space (200 mm) between the coils is requested to permit access to the cyclotron median plane for the beam stripper, the extraction elements and the beam diagnostic probe.

Table 2: Main parameters of the superconducting coils.

parameters	α	β
R_{int}	1420 mm	1420 mm
ΔR	150 mm	150 mm
h_{min}	100 mm	330 mm
Δh	178 mm	150 mm
J for H_2^+	46.6 A/mm^2	10 A/mm^2
J for $^{12}C^{5+}$	40 A/mm^2	40 A/mm^2

4 BEAM SPECIFICATIONS

The design of the machine model has been done to accelerate H_2^+ molecules up to 250 MeV/amu and $^{12}C^{5+}$ ions up to 210 MeV/amu, corresponding, respectively, to a maximum average field at extraction radius of 3.8 tesla and 4.2 tesla. Figure 3 shows the isochronous field for both ion species. The dashed line shows the calculated isochronous field, while the solid line is the result of the simulations obtained with the main coils. Fine tuning of the fields should be obtained by using trim coils system whose fields are estimated to be less than a few hundreds of gauss.

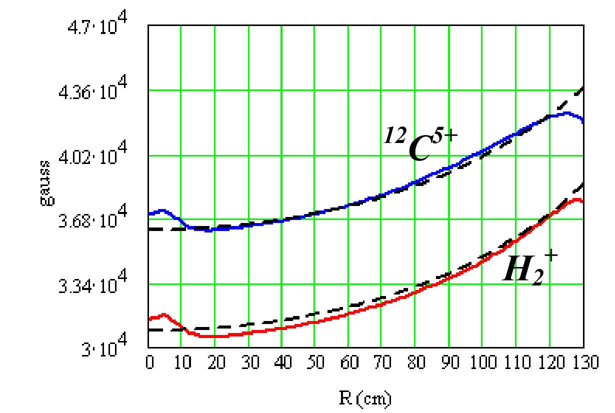

Figure 3: Average field for H_2^+ at 250 MeV/amu and $^{12}C^{5+}$ at 210 MeV/amu

The beam dynamics properties have been studied by the code GENSPE1, which calculate the equilibrium orbits. In figure 4 the vertical and radial focusing frequencies are plotted for both the ion types vs energy.

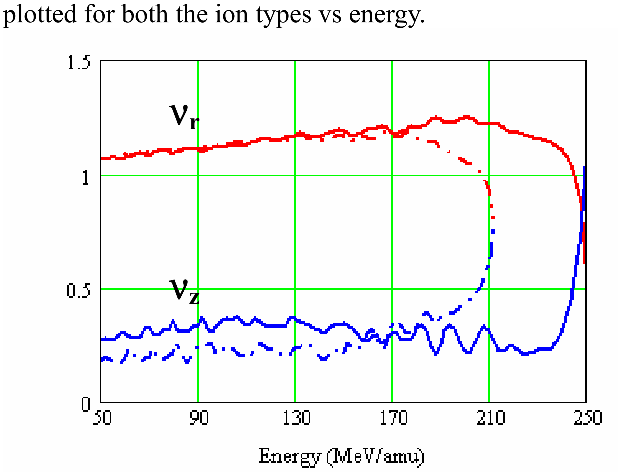

Figure 4 : Focusing tunes for both beams: solid line for H_2^+ and dashed line for $^{12}C^{5+}$.

5 FURTHER STUDY

The cyclotron parameters have been optimised to produce light ions at intermediate energy with high intensity, taking also account of the requirements for the radioactive beams production. We are studying the possibility to extract from the main parameters of this machine to accelerate ions for medical applications. The energies of the beams requested to cover the whole range of proton therapy are between 60 MeV/amu and 300 MeV/amu. For carbon ions an energy of 250 MeV/amu should allow to cover a large range of tumor treatments [5]. Since no high performance is requested for applications of this kind, the cyclotron characteristics should not go close to the maximum possible limit. From a detailed analysis of the fields we have extracted the focusing constant (K_{FOC}) for this machine.

$$\frac{T(r)}{A} \le \frac{Z}{A}\cdot K_{FOC}(r) = \frac{Z}{A}\cdot\frac{q\cdot c\cdot r}{2}\cdot\sqrt{C(r)^2\cdot(1+\tan^2\xi(r))} \qquad \textbf{(1)}$$

where C is the main harmonic derived from the fields, ξ is the magnetic spiral angle. Plotting the focusing index we have:

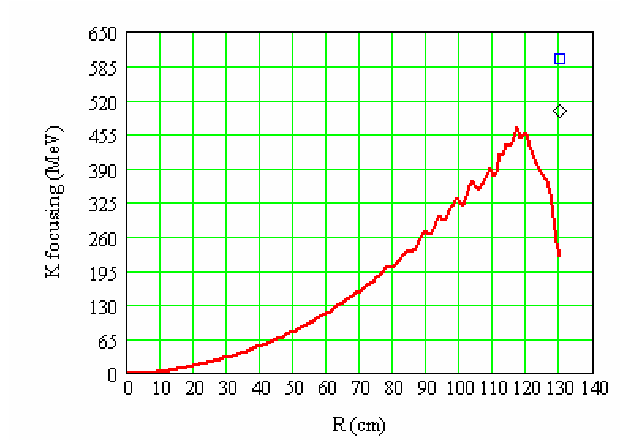

Figure 5: Focusing limit of the cyclotron vs radius of cyclotron, with K_{FOC}=500 (diamond) and K_{FOC}=600 (box).

The solid line shows the upper limit of the machine here described. The decreasing above 120 cm is compensated by negative gradient of the field (this term does not appear in (1)) , resulting in an increase of focusing frequency ν_Z. We think that modifying some parameters (smaller hill gap, different coil geometry…) it is possible to obtain a higher value of K_{FOC} (up to 600) so as to accelerate H_2^+ up to 300 MeV/amu and C ions to 250 MeV/amu.

6 CONCLUSIONS

First modelling and calculations about 250 MeV/amu-50 kW cyclotron have been performed. The detailed interpretations of the results and further detail modelling is in progress. Further electro-magnetic studies concerning the central region design and the RF system requirements will be done. A parallel study has begun aiming to upgrade the energy of the machine in order to optimize the main characteristics to meet the requirements for medical applications

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