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A Superconducting Cyclotron as a primary accelerator for exotic beam facilities

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Abstract A four sector compact superconducting cyclotron for light ion beams with a maximum energy of 250 MeV/amu has been studied. This cyclotron is mainly designed to accelerate H_2^+ ions to be extracted by stripping. Ions like C, O or Ne can also be accelerated and extracted by stripping. Extraction by stripping allows to overcome many problems, especially if a certain beam intensity is requested. The preliminary design model of the magnet circuit has been accomplished with the 3D electromagnetic code OPERA [4]. The design of the main coils and of the cryostat has been investigated, too. The features of beam dynamics of this cyclotron, including extraction trajectories, will be presented. Several fields of application have been envisaged for this cyclotron, namely nuclear physics, therapy treatment, interdisciplinary research and radioisotope production using low or medium intensity beams.

Key words cyclotron • ions • medical • superconducting

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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 LNS 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 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. Such a method requires a large separation between successive turns for reaching the highest extraction efficiency, which is achieved building machines with a large average radius and making the energy gain per turn as high as possible. 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 [1].

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).

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 magnetostatic 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. 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 [3]. It was observed that absolute results of 3D simulations and measurements differ by 1% at the 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.

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 is shown in Table 1.

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 $K_{FOC} = 500$ and to maintain the magnetic field at acceptable values.

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 (see Fig. 1). A parametric model of the cyclotron has been built, and an iterative process has been realized in order to optimize automatically several parameters of the machine like sectors width, hill and valley gaps, spiral angle to fulfill the beam requirements, like the isochronous

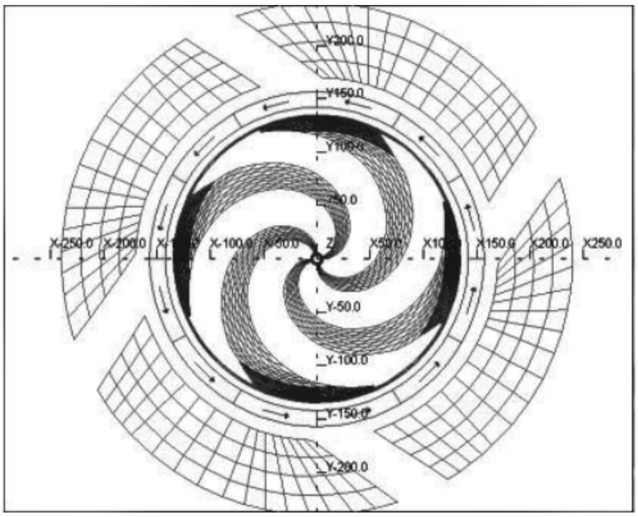

Fig. 1. Layout of the final model of the cyclotron (top view) simulated.

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 spiral angle	73 deg
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	2 pairs
Internal radius of the coils	1420 mm
Size coil α	150 × 178 mm^2
Size coil β	150 × 150 mm^2
Maximum current density	46 A/mm^2
Maximum nominal current	1800 A

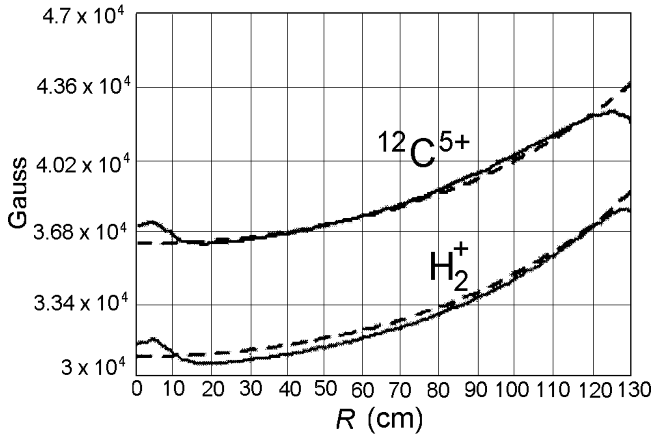

Fig. 2. Average magnetic field for H_2^+ at 250 MeV/amu and $^{12}C^{5+}$ at 210 MeV/amu.

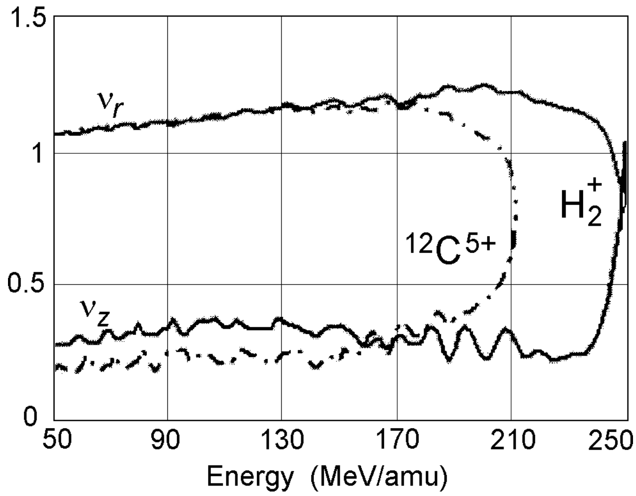

Fig. 3. Focusing tunes for both beams: solid line for H_2^+ and dashed line for $^{12}C^{5+}$.

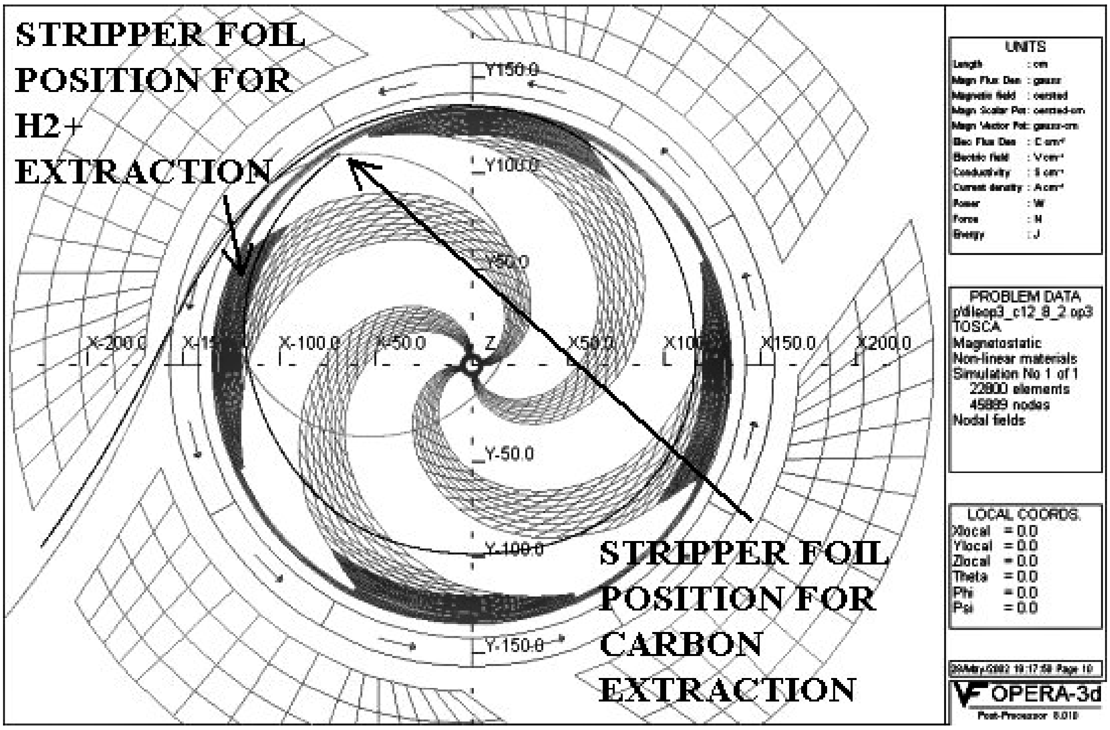

Fig. 4. Trajectories of extraction by stripping for H_2^+ and $^{12}C^{5+}$.

field and vertical focusing. The sector width varies from 25 deg at the centre 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 were 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 was provided for possible 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.

Two pairs (α and β) of superconducting coils (see Table 1), symmetrically placed above and below the median plane, are supposed to generate the isochronous fields for light ion beams. The position, geometry and currents of the coils have been optimized with a process similar to the above mentioned to cover the whole range of energy. A big vertical space (200 mm) between the coils is requested to allow access to the cyclotron median plane for the beam stripper, the extraction elements and the beam diagnostic probe.

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 an extraction radius of 3.8 tesla and 4.2 tesla. Figure 2 shows the isochronous field for both ion species. 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 gausses.

The beam dynamic properties have been studied by the code GENSPE1, which calculates the equilibrium orbits. In Fig. 3, the vertical and radial focusing frequencies are plotted for both the ion types *vs*. energy. The preliminary trajectories of extraction by stripping have been traced for H_2^+ and $^{12}C^{5+}$ ions (see Fig. 4).

Conclusions

First modelling and calculations concerning a 250 MeV/amu – 50 kW cyclotron have been performed. The detailed interpretations of the results and further detail modelling is in progress. Further electromagnetic studies concerning the central region and the RF system requirements will be done. We are studying the possibility to develop, from the main parameters of this machine, a cyclotron dedicated for medical applications. Such machine should be able to accelerate light ions with Q/A = 0.5 at 250 MeV/amu allowing to cover a large range of tumor treatments.

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