COMPARISON OF SUPERCONDUCTING 230 MeV/u SYNCHRO- AND ISOCHRONOUS CYCLOTRON DESIGNS FOR THERAPY WITH CYCLINACS*

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Abstract

This work presents new superconducting compact cyclotron designs for injection in CABOTO, a linac delivering C^{6+}/H_2^+ beams for proton and carbon ion therapy. Two designs are compared in an industrial perspective under the same design constraints and methods: a synchrocyclotron and an isochronous cyclotron, both at the highest possible magnetic field and with an output energy of 230 MeV/u. The SC design features a central magnetic field of 5 T, an axisymmetric pole and a resonant extraction. The IC design features a 3.2 T central magnetic field, four sectors and elliptical pole gaps in the hills and in the valleys.

TERA'S CABOTO LINAC

The cyclinac is a combination of a fast-cycling cyclotron and a high-frequency linac [1]. It presents a unique feature, compared to the cyclotrons and synchrotrons for ion beam therapy. The linac makes it possible to change the beam energy without absorbers and at high repetition rate, paving the way to the treatment of moving tumors. The linac CABOTO accelerates short beam pulses (1.5 μs) of C^{6+}/H_2^+ pulsed at high repetition rate (300 Hz) up to 400 MeV/u [2].

These particular beam characteristics require specialized ion sources of the EBIS type [3-4] and the cyclotron injector should be as green (low consumption) and light (small weight) as possible, as well as reliable and industrially viable. For the determination of the most adapted injector solution, a linac input energy of 230 MeV/u was chosen, as it allows the use of the cyclotron as a stand-alone accelerator for proton therapy. However, existing compact (as opposed to separated-sector) cyclotrons can only reach up to 200 MeV/u (K1200 of Michigan State University) and the 300 MeV/u SCENT [5] and 400 MeV/u C400 [6] designs have not yet been constructed.

Therefore, new superconducting cyclotron designs have been produced: a synchrocyclotron (SC) [7] and an isochronous cyclotron (IC).

FINAL DESIGN PARAMETERS

All the main parameters of the designs are summarized in Table 1.

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DESIGN METHODS AND CONSTRAINTS

The same constraints were applied to the two cyclotron designs. The underlying philosophy of the designs was to use simplified models, in order to avoid the precise but complex and time-consuming process of three-dimensional modelling. This involved the use of dedicated programs (ALANEW, FIDER, ORBLA, NAJO and CANAL), adapted from previous work [8-9].

Table 1: Comparison of the Two Design Parameters

	IC	SC
q/A	1/2	
Output Energy	230 MeV/u (kinetic)	
Central Field	3.2 T	5.0 T
Pole Type	4 Sectors	Axisymmetric
Pole Radius	1.2 m	1.1 m
Total Current/Coil	1.1 MA.turns	1.9 MA.turns
Ion Sources	At least 2 (external)	
RF cavities	2 (h=4)	1 (h=1)
RF	98 MHz	38-30 MHz
Voltage at Injection	70 kV peak	28 kV peak
Voltage at Ejection	120 kV peak	28 kV peak
RF Power Supply	100 kW	30 kW
Ejection Method	ED	Bump + ED
Yoke Diameter/Height	4.75/2.9 m	4.6/3.3 m
Iron Weight	310 tons	330 tons

First of all, the charge-over-mass ratio (q/A) of the beam was set to 1/2, thus neglecting the 0.8% difference between $^{12}C^{6+}$ and H_2^+.

The cyclotron magnet was modelled using OPERA2D (Vector Fields Ltd). Because of axial symmetry, this approach is exact for the SC. However, for the IC, the azimuthal geometry had to be taken into account by introducing stacking factors. This method can be used to estimate the magnet weight and was found to produce results compatible with existing superconducting cyclotrons and designs by experienced groups [4]. The 3D geometry was approximated using ALANEW and FIDER, which derive the flutter from a given pole profile and introduce the sector spiralling required for focusing. Taking into consideration the safety from quenches and mechanical viability, a limit of 40 A/mm^2 was imposed to the superconducting coil and 10 cm free space was left around the coil. The stray magnetic field outside the cyclotron was limited to 50 mT (at 1 mm distance) by imposing the maximum of the magnetic field modulus at the edge of the iron yoke to be 2.0 T.

Beam optics were studied using the program ORBLA and multi-particle tracking (to study ejection) was performed using NAJO, which allows the superposition of additional electric and magnetic fields to the median plane (MP) magnetic field, given by ALANEW or OPERA. The field produced by the magnetic channel was computed using the program CANAL.

The Radiofrequency (RF) design involved the modelling of the resonators as coaxial transmission lines composed of discrete sections of rectangular or cylindrical cross-section with constant characteristic impedance. Analytical calculations used to quantify the impedance for rectangular transmission lines were developed and validated [4] with OPERA and HFSS (Ansoft).

Injection was studied using OPERA3D, allowing also multi-particle tracking and using specific scripts adapted from previous work [10].

MAGNETIC DESIGN

The highest possible central magnetic field was determined for each case. For the SC, the chosen field allows to limit the pole radius to a value similar to the one of IBA's C235 proton therapy cyclotron. For the IC, the limiting factor is the injection.

Pole

The pole of the SC is axially symmetric and features a large vertical aperture and a constant magnetic field index in the acceleration region, producing a constant vertical betatron tune of 0.14. The magnet is shown in Fig. 1.

The IC magnet features 4 sectors with elliptical pole gaps, which limit the total hill axis rotation angle to 85° (similar to that of COMET [11], although higher central magnetic field and output energy are used). This very moderate spiralling simplifies the geometry of the RF cavity, with respect to superconducting IC designs with the typical constant polar gap. The vertical half-gap ranges from 30 to 3 mm in the hill and from 50 to 11 cm in the valley (see Fig. 1). The sector azimuthal width was set constant to 45° for all radii, to maximize the flutter.

Yoke Size

Both designs reach similar iron weights. This is because in the IC, the use of the elliptical profiles minimizes the pole radius and the field needed from the coils. In addition, the isochronous field shape results in a coil position close to the MP and to the pole edge. Vice versa, in the SC, the vertical aperture needed for the Dee results in a large pole radius. In addition, the requirement of a radially decreasing field translates into a coil position far from the pole edge (radially) and/or far from the MP (vertically).

EJECTION

In the SC, the strong magnetic field and low acceleration voltage result in a radial gain per turn of 70 µm in the last turns. This value was increased to 170 µm by exciting the first radial integer betatron resonance with an artificial magnetic perturbation of 0.1 T and 5° azimuthal width. This enabled to introduce an electrostatic deflector (ED) and to eject the beam, while controlling transverse beam size.

In the case of the IC, a simplified ejection with a single ED in a valley with no RF cavity was achieved with negligible beam losses. A magnetic channel of 19 mm and 180 T/m quadrupolar gradient was placed on the beam path at the exit of the hill to compensate the strong negative radial gradient of the magnetic field (characteristic of elliptical pole gaps) and provide vertical focusing. This is shown in Fig. 2.

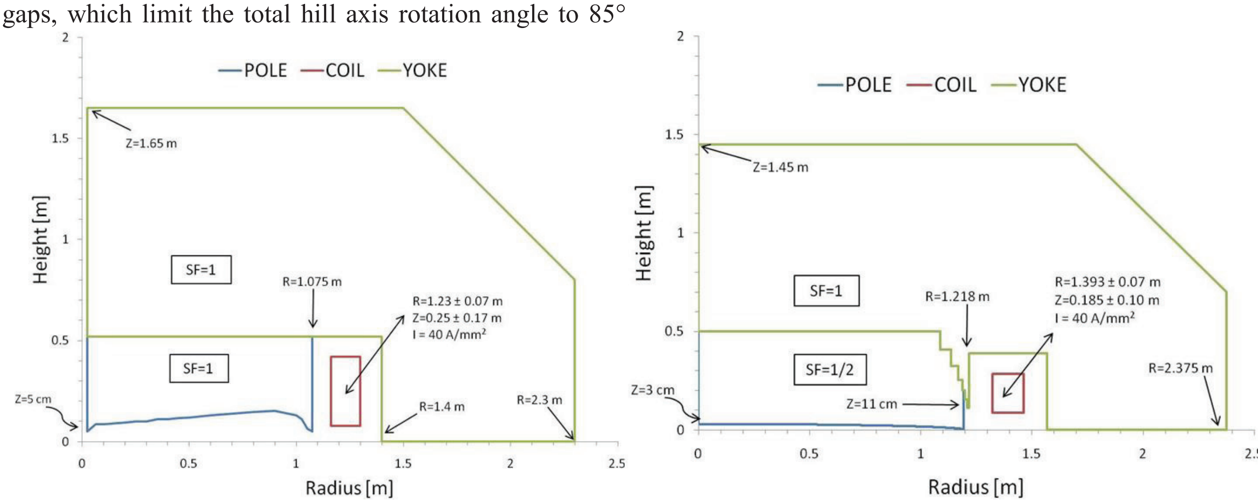

Figure 1: Scheme of the SC (left) and IC (right) Magnet Geometries (SF stands for stacking factor).

ISBN 978-3-95450-128-1

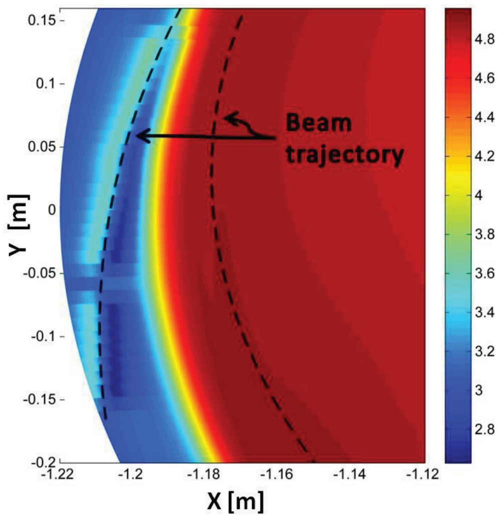

Figure 2: Vertical MP magnetic field (in color) and beam path (in black dashed line) over the last two turns.

INJECTION

A unique design of a spiral inflector was studied for the SC using OPERA3D. This inflector enables beam axial injection at 10 keV/u with negligible beam losses, despite the difficulties linked to the strong magnetic field and low acceleration voltage. The inflector features no tilt angle, a ratio between electric radius and magnetic diameter of 1.4, a small electrode aspect ratio of 1.25 and a central region where the inflector housing was cut to enable beam transmission on the first turn.

A schematic view of the SC inflector is shown in Fig. 3.

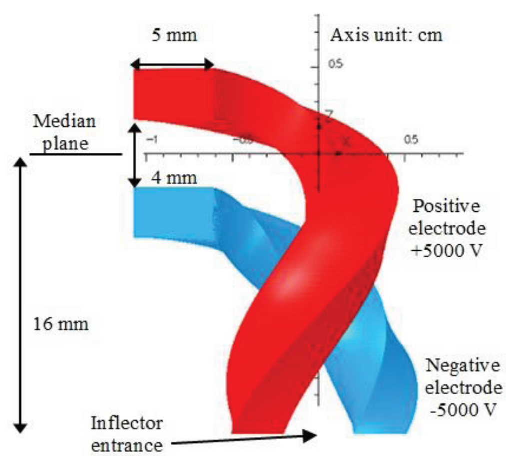

Figure 3: SC inflector (beam injected from below).

In the case of the IC, the inflector would be similar to the one of SCENT [10], although the lower acceleration potentials should be taken into account.

RADIOFREQUENCY

The SC RF system consists of a λ/2 line (see Fig. 4) with a 180° Dee inside the magnet gap and a rotating capacitor (RotCo) modulating the terminal capacitance between 90 and 800 pF. The sparking risk at the RotCo limits the acceleration voltage.

The IC RF cavities were modelled as two non-spiralled vertically symmetric λ/4 lines with a single stem, reaching a quality factor of 7100.

SUMMARY AND DISCUSSION

The study proved the feasibility of both cyclotrons, based on designs using the highest possible central magnetic fields and having the same constraints. These can thus be compared as injectors for CABOTO.

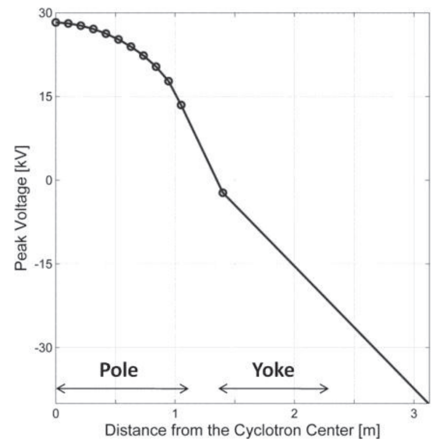

Figure 4: SC inflector (beam injected from below).

Taking into account the cryogenic cooling power of 40 kW, the total installed electrical power is 140 kW for the IC and only half for the SC (RF power consumption of the IC could be reduced by a factor 16 by pulsing the power source). These values are anyhow very minor compared to those of CABOTO (300 kW).

The acceleration and extraction of H_2^+ requires precise corrections to the RF and/or the magnetic field for the IC, because of the small phase acceptance and high precision needed for the magnetic field. This is not the case for the SC, where the tolerances on the magnetic field precision are more relaxed.

All things considered, the IC proves to be a more adapted solution as CABOTO injector for the two most crucial parameters: the overall reliability and the magnet size. Indeed, the reliability of the SC is put to question by the need of a large and fragile RotCo and by the complexity of the injection and ejection systems.

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