SYNCHROCYCLOTRON PRELIMINARY DESIGN FOR A DUAL HADRONTHERAPY CENTER*

A. Garonna[#], EPFL, Lausanne, Switzerland and TERA Foundation, Geneva, Switzerland

Abstract

The Italian research foundation TERA has proposed an innovative accelerator solution, called "Cyclinac" [1], dedicated to hadrontherapy, the technique of tumor radiotherapy which employs ion beams, in particular protons and carbon ions. It is composed of a fixed-energy cyclotron injecting into a variable-energy linac. This paper describes the preliminary design of a dedicated superconducting synchrocyclotron providing fast cycling (400 Hz) beams of 230 MeV/u C^{6+} and H_2^+ ($K_{bending} = 920$ MeV).

INTRODUCTION

Hadrontherapy and its Accelerators

Hadronterapy with carbon ions is moving from research in physics facilities to clinical routine in hospital-based centers [2]. This pressures the particle accelerator research and industrial communities to provide reliable, precise, flexible, simple to operate and modular solutions, with reduced investment and running costs. All the existing and under construction carbon therapy centers are based on synchrotrons: 20 m diameter accelerators, providing 1 Hz repetition rate variable energy 70-430 MeV/u beams and consuming at least 2 MW power. On the contrary, most of the proton therapy centers are cyclotron-based and need to degrade the beam to lower energies with an Energy Selection System (ESS). TERA proposes a fast pulsed accelerator composed of: a cyclotron providing compact acceleration of C^{6+} / H_2^+ up to 70-230 MeV/u and a high-gradient, high-frequency Cell Coupled Linac providing the second acceleration up to 430 MeV/u. The beam energy can be adjusted from pulse to pulse by modulating the power injected in the linac modules. This accelerator is suited for optimal irradiation of tumors with the most modern techniques of 4D active spreading of the dose. This cyclinac is a commercially interesting solution because of its size (linac length of 20 m) and the limited power consumption (600 kW).

Initial Acceleration

In a cyclinac, the output energy of the cyclotron is a compromise between the size of the cyclotron magnet and the length of the linac. In this study, a large energy has been chosen: 230 MeV/u. Since the cyclotron can accelerate all q/A =½ particles (i.e. C^{6+} and H_2^+), the output beam can be used for standard 70-230 MeV proton therapy (with an appropriate ESS) and carbon ion therapy of superficial tumors (11 cm range in water).

A synchrocyclotron was chosen because: it can be pulsed at the repetition rate of the linac (400 Hz), it has attractive construction and operating costs (compact magnet and low power consumption) and its beam characteristics are well adapted to medical treatment (low current and fast repetition rate). Although this kind of accelerator dates back to the early cyclotron research at Berkeley, it has recently regained interest for its potential application to proton therapy [3,4].

MAGNETIC FIELD

The synchrocyclotron is a weak focusing machine: vertical and radial betatron tunes ν_Z and ν_R are controlled by a field index *n* between 0 and 1 (see Eq. 1-2).

The absence of the Thomas focusing valleys and hills and spiraling, typical of isochronous cyclotrons, allows particle focusing even at very high vertical magnetic fields B. This makes computer modeling simpler and less time-consuming than for isochronous cyclotron magnets, as the magnetic field is axially symmetric.

$$n = -\frac{R}{B} \cdot \frac{dB}{dR} \qquad (1)$$

$$\upsilon_R = \sqrt{1-n} \quad ; \quad \upsilon_Z = \sqrt{n} \qquad (2)$$

Requirements

A 5 T central field is chosen to reduce the magnet dimensions and the vertical betatron tune is set at an average value of 0.14 (see Fig.1).

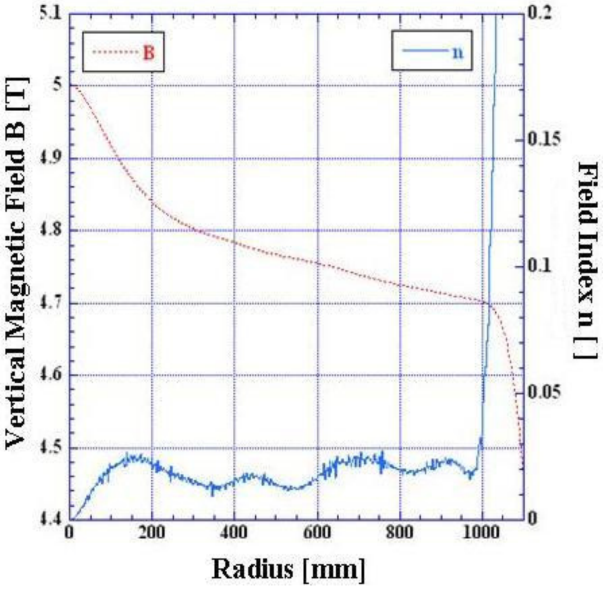

Figure 1: Median Plane Vertical Magnetic Field Profile.

---

*Work supported by A.D.A.M. SA, Geneva, Switzerland

[#] Adriano.Garonna@cern.ch

A safe margin from the Walkinshaw resonance (field index of 0.2) is taken at the pole edge, as this constitutes a practical acceleration limit for synchrocyclotrons. For transportation, the iron pieces of the magnet should not exceed 5 m. Based on staff protection regulations and the experience at the Catania K800 [5], the stray field should not exceed 1 mT at 10 m from the cyclotron center (radially) and 50 mT at 1 m from the yoke edge (vertically).

Two-Dimensional Model

The magnetostatic module of Finite Element Method code OPERA2D [6] was used for this task. It has to be noted that at 5 T central field value, contributions from the coil and from the pole have equal importance. The coil of 43.5 A/mm^2 current density is positioned to provide a flat radial field profile. Its shape also ensures stable compressive coil radial stress from the magnetic field [7]. The magnet gap is ± 5 cm, to leave space for the accelerating cavity. The pole geometry is optimized to provide the required radial field decrease. The 4 Million A.turns of the coils make the yoke 4.7 m in diameter and 3.3 m in height for a total weight of 300 tons (see Fig.2).

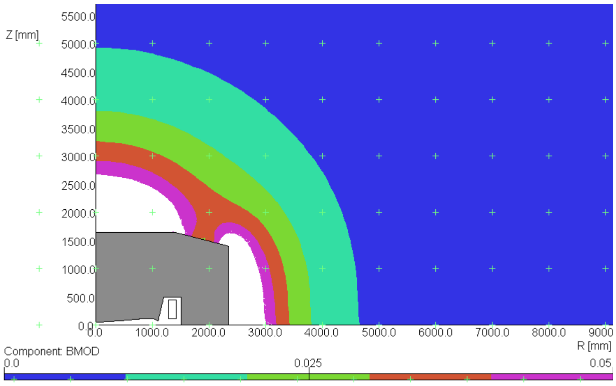

Figure 2: Stray Field in 2D Model (10-50 mT).

INJECTION AND EXTRACTION

This design brings about challenges linked to the high central magnetic field and to the low acceleration voltage, which produce small radial gains per turn.

Pulsed Ion Source

The usual synchrotron choice of an Electron Cyclotron Resonance source producing C^{4+} ions is replaced by the use of a compact commercial Electron Beam Ion Source [8] producing fully-stripped carbon ions at 24 keV/u pulsed at high repetition rate. The beam produced has a low emittance and minimal impurities (lower than 1%). For use in a cyclinac, the source output should be at least $1 \cdot 10^8$ ions per 1.5 µs pulse at 400 Hz.

Axial Injection

The injection beam line consists of a dipole magnet filtering q/A=½ particles, focusing elements and a buncher tuned to the cyclotron injection Radiofrequency (RF). The ions are injected axially through a spiral inflector. Various geometries for the central region are presently being compared in terms of feasibility and ion losses on the 1st turn. Indeed, the small magnetic and large electric radii (9 and 40 mm respectively) result in a strongly spiraled beam trajectory, which the inflector electrodes have to follow. In addition, the radial gain on the first turn is only 3 mm and orbit off-centering should be kept within a few mm.

Resonant Extraction

The natural radial gain per turn at final energies is only 50 µm. The multi-particle tracking code NAJO [9] was used to simulate the particle orbits. A first harmonic positive magnetic perturbation of about 0.02 T and 7.5° azimuthal width produces a coherent radial betatron oscillation boosting the radial gain per turn to 0.4 mm (see Fig. 3), while avoiding beam vertical blow-up (vertical beam half-width lower than 5 mm).

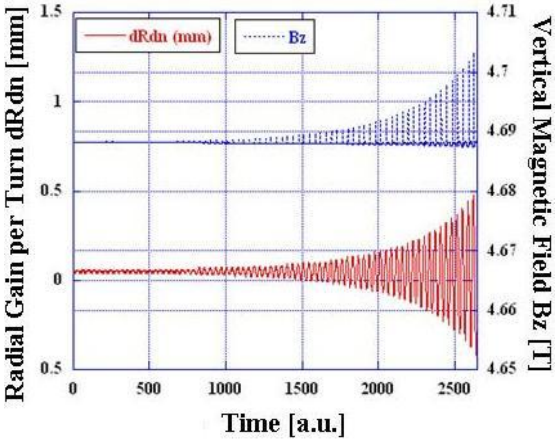

Figure 3: Effect of the magnetic perturbation on the radial gain per turn.

This allows introducing an electrostatic deflector (with a 0.1 mm septum width and a 14 MV/m electric field). After 90°, the radius and radial divergence of the trajectory grow by respectively 1.2 cm and 10 mrad compared to the previous turn (see Fig. 4). The beam exits the pole with 75 % efficiency.

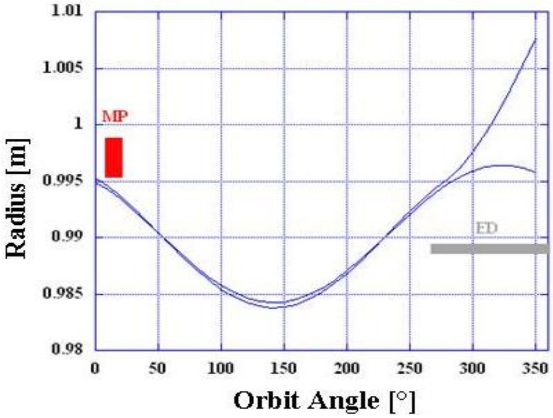

Figure 4: Last two orbit turns, with the Magnetic Perturbation (MP) and Electrostatic Deflector (ED).

RADIOFREQUENCY SYSTEM

The synchrocyclotron RF operates in first harmonic at a repetition rate of 400 Hz. As the revolution frequency decreases inversely to the relativistic mass of the particle, the RF has to be modulated by 20% from injection to extraction. The λ/2 resonator chosen is composed of a 180° Dee (20 kV peak voltage) in the magnet gap, a rectangular coaxial transmission line through the magnet yoke and a mechanical rotating capacitor (RotCo).

Analytic Model

The Dee is modeled as 6 rectangular coaxial line segments of different characteristic impedances, connected in series (see Fig. 5).

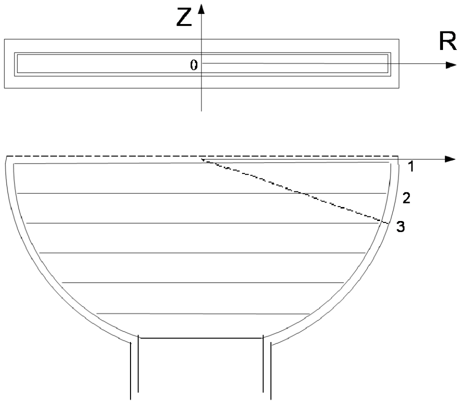

Figure 5: Front and Top view of Dee model: the aperture on the median plane is ± 1 cm.

Starting from a Dee gap capacitance of 60 pF, by the formula on Eq. 3, one can compute the transformation of the impedance Z along some electrical length βl having characteristic impedance Z_0.

$$Z_{i+1} = Z_0 \cdot \frac{Z_i + jZ_0 \tan(\beta l)}{Z_0 + jZ_i \tan(\beta l)} \tag{3}$$

The resonance condition and analytical formulas for wall surface power dissipation were implemented in a MATLAB [10] code to derive the general parameters (see Table 1). The small impedance of the transmission line facilitates the design of the RotCo (lower cyclotron fringe field and lower voltages), while preserving a realistic mechanical geometry.

Table 1: RF System Parameters

Resonant Frequency	**38 MHz**	**31 MHz**
Transmission Line Length and Impedance	2.2 m / 6 Ω	
Voltage on the RotCo	-29 kV	-21 kV
Capacity on the RotCo	90 pF	680 pF
Q-value	2000	1700

As expected, the average power consumption is low (17 kW with a 20 % duty cycle).

Frequency Modulation

The calculated parameters are similar to the specifications of the RotCo used for many years at the Orsay synchrocyclotron [11]. Reducing the gap between rotor and stator by 25 % would increase the capacity range, while respecting the voltage limits.

However, RotCos are large and delicate rotating mechanical structures. Electric sparks between capacitor plates and movable electric connections have often been the source of shutdowns for synchrocyclotrons. A possible improvement is the use of an electronic modulation, as in synchrotrons and FFAGs. The end of the line is loaded with ferrites whose permeability can be tuned by applying a bias magnetic field thus modifying the terminal inductance of the line and its resonant frequency. Also in the case of RotCos, the structure should be carefully shielded from the cyclotron stray field.

ACKNOWLEDGMENTS

I warmly thank André Laisné for his help throughout this interesting and challenging part of my PhD thesis. I am also thankful to Prof. Amaldi and Prof. Rivkin for their guidance and support. Finally, I express my gratitude to S. Meyroneinc and M.-P. Bourgarel for their kind help, and to S. Verdú Andrés for her corrections.

REFERENCES

[1] U. Amaldi et al., "High Frequency Linacs for Hadrontherapy", RAST, Vol. 2 (2009), 111-131.
[2] U. Amaldi et al., "Accelerators for Hadrontherapy: from Lawrence Cyclotrons to Linacs", NIM A, in print.
[3] Wu Xiao Yu, "Conceptual Design and Orbit Dynamics in a 250 MeV Superconducting Synchrocyclotron", MSU PhD Thesis (1990).
[4] T. Antaya, "High-field superconducting synchrocyclotron", Patent, PCT/US2007/001628 (2007).
[5] L. Calabretta, "Preliminary Study of the SCENT Project", Internal Report (2006); http://lnsweb.lns.infn.it/accelerator/RDGroup/Documents/Articles.
[6] OPERA, Vector Fields Ltd.
[7] M. Wilson, "Superconducting Magnets", Oxford Science Publications (1983).
[8] G. Zschornack et al., "Dresden EBIS-SC – A new Generation of Powerful Ion Sources for the Medical Particle Therapy", Proc. Cyc. (2007).
[9] Fortran program from GANIL, modified and kindly given by A. Laisné.
[10] Matlab R2009a, The Mathworks Inc.
[11] A. Laisné, "The Orsay 200 MeV Synchrocyclotron", IEEE TNS, Vol. NS-26, No. 2 (1979).