FEASIBILITY STUDY OF A HIGH-GRADIENT LINAC FOR HADRONTHERAPY*

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Abstract

Compact, reliable and little consuming accelerators are needed for tumour treatment with ions. TERA proposes CABOTO (CArbon BOoster for Therapy in Oncology), a linac which boosts the energy of $^{12}C^{6+}$ ions and H_2^+ molecules coming from a cyclotron. The linac is divided into several modules. The beam energy can be varied in steps of about 1 MeV/u without using absorbers by acting on the power that feeds the different modules of the linac. This work presents the structure design of a 5.7 GHz high repetition rate Side-Coupled Linac for a cyclinac, that accelerates carbon ions from 150 up to 400 MeV/u in about 25 meters. The beam dynamics and the energy selection system are also discussed.

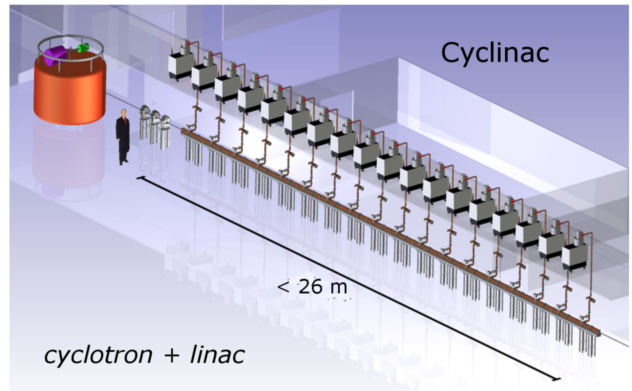

Figure 1: Artist's view of a cyclinac for hadrontherapy.

INTRODUCTION

A dedicated accelerator for hadrontherapy should be compact, reliable and little consuming, and should provide the best possible treatment modality and deliver an appropriate beam for treating patients with hadrons. A proton beam energy between 60 and 230 MeV and a carbon beam energy between 110 and 430 MeV/u, corresponding to a 3 to 32 cm range in water-equivalent tissue, are needed for hadrontherapy. A good energy selection system, preferably without absorbers, is required to avoid beam quality degradation and activation of accelerator and nozzle components. A small energy spread (0.3-0.4% FWHM) is needed to profit of the rapid fall-off of the Bragg peak. A fast variation of the energy corresponding to a 0.5 mm range precision is required to accurately cover the target. If the beam repetition rate is in the range of 100-400 Hz, the beam pulse can be synchronised with moving organs and cold spots can be corrected by painting several times the tumour volume within the same treatment session (the so-called multipainting technique). A beam with enough current is desired to reduce the duration of the treatment. The minimum dose rate is equal to 2 GyE/min in a 1 liter target [1].

In this context, TERA Foundation proposes the "cyclinac", a dedicated accelerator complex for hadrontherapy, composed of a high repetition rate high-frequency linac which boosts the hadrons previously accelerated by a cyclotron [2]. A sketch of the cyclotron is shown in Fig. 1.

CABOTO is a copper standing-wave Side-Coupled Linac operating at 5.7 GHz. It receives a C^{6+} beam previously accelerated in a cyclotron and boosts its particle energy from 150 up to 400 MeV/u. The carbon ions of 400 MeV/u reach a depth of 28 cm in water, necessary to treat deep-seated tumours. The linac is divided in different sections called units. Each unit is fed by its own klystron of 12 MW peak power.

The division of the linac into independently fed units allows a rapid (1-2 ms) and continuous beam energy variation. No absorbers are needed for scanning the tumour in depth. The beam energy can be changed from pulse to pulse by acting on the power that feeds the linac units. This characteristic, together with the high repetition rate at which the machine can be operated (300 Hz), makes the cyclinac suitable to apply the 3D spot scanning technique with multipainting, which combined with an active 3D feedback system, is the most adapted for treating moving organs.

RF DESIGN AND LINAC LAYOUT

Cell geometry has been optimized in order to maximize the shunt impedance Z (related to power requirement) while keeping the ratios peak surface electric field over accelerating gradient E_{max}/E_0 and maximum Poynting vector over accelerating gradient S_{max}/E_0 (related with breakdown rate) as small as possible. The RF simulations for this optimization has been performed with POISSON SUPERFISH. A common cell radius has been established for all the cells, independently of the energy for which they were designed, for machining simplification. The bore hole radius has been fixed to 2.5 mm for all cells and quadrupoles, small enough to provide a high shunt

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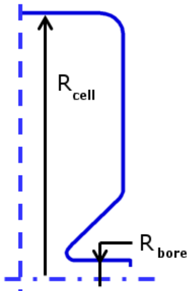
impedance, and so a reduced power requirement, but large enough not to lose too many particles in the transverse plane. In Fig. 2 the optimized cell geometry for particles with 150 MeV/u energy and its corresponding basic electromagnetic quantities are presented.



R_{cell} [mm]	38
R_{bore} [mm]	2.5
Q	8500
Z [MΩ/m]	138
E_{max}/E_0	4.4
S_{max}/E_0 [MW/Vm]	0.012

Figure 2: Optimized cell geometry for 150 MeV/u energy particles and corresponding electromagnetic quantities.

The code DESIGN [3] has been used to design the overall layout of CABOTO. The linac has been divided in 14 units. Each unit consists of 4 tanks. All the tanks have the same number of cells (24 cells/tank) to get a smooth transverse phase advance progression. The transverse focusing of the beam is provided by a set of Permanent Magnetic Quadrupoles (PMQs), alternatively placed in the drift spaces between tanks, in a FODO structure every two tanks. All the quadrupoles are 60 mm long and have a strength of 200 T/m. The synchronous phase is progresively reduced from -16.7 to -11.7 degrees. Fig. 3 (below) shows the synchronous phase variation along the 1296 RF gaps of the structure. Cell length is kept constant for all the cells in a tank to ease machining, leading to phase slippage between the beam and the RF waveform. DESIGN adjusts the synchronous phase to minimize the phase slippage effect. More details about the design can be found in [4].

Total peak RF power for the klystrons is 168 MW. The linac plug power at 300 Hz and 3.2 μs-long pulses is about 500 kW. In order to reduce the linac length to about 25 m, a mean accelerating gradient of 28–30 MV/m is excited in the structure. Accordingly to the results from the high power RF test of the structure prototype for the Frascati photoinjector SPARC energy upgrade [5], the linac could work at higher accelerating gradients without compromising its reliability [6]. Therefore, a new design of CABOTO operating with accelerating gradients of 33–35 MV/m will be done in a future. A collaboration between TERA Foundation and the CLIC RF group of CERN has been established to explore the high-gradient performances of accelerating structures in S and C-band. In particular, a 3 GHz single-cell cavity has been designed, built and high-power tested in 2010 [7]. It will be high-power tested again in fall 2011 and at the beginning of 2012 at CTF2. A set of 5.7 GHz single-cell cavities is at present being tuned and brazed and will be tested in 2012 [8].

BEAM DYNAMICS STUDIES

The beam dynamics has been studied with the code LINAC [3]. Space charge effects are not included due to the small beam intensity. Fig. 3 (above) shows the envelope of a beam that reaches CABOTO acceptance. Fig. 4 presents the energy distribution for different energy beams. The beam delivered by CABOTO presents a long tail which contains all the particles that stay out of the acceleration bucket. These particles will be removed from the beam with a bending magnet and a slit located downstream the linac. The study of such system will be performed in a future.

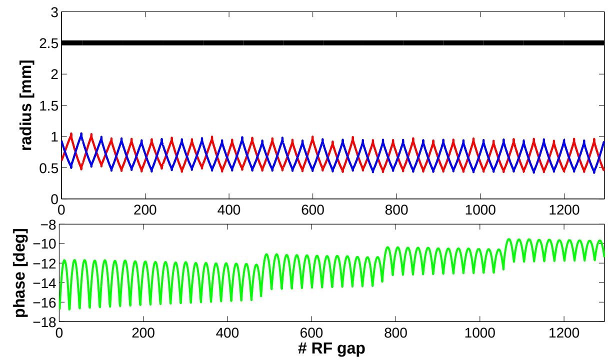


Figure 3: Beam envelope reaching CABOTO acceptance (above) and synchronous phase variation along CABOTO (below). In black, bore hole radius; in red and blue, rms beam size for both transverse planes.

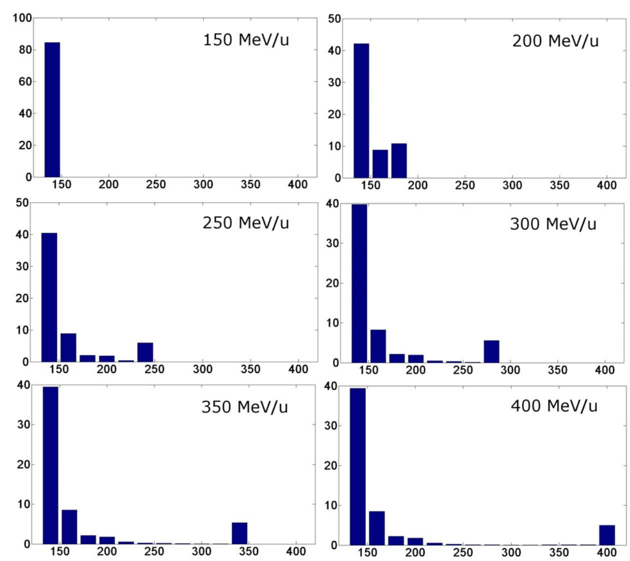


Figure 4: Energy distribution of a beam accelerated by CABOTO to different final energies. The horizontal axes represents the particle energy in MeV/u. The vertical axes is the percentage of particles that have a given energy at the linac exit. A bending magnet and a slit will be used to clean the low energy tail.

Acceptance

So far no cyclotron delivers carbon ions at 150 MeV/u. SCENT300 is a cyclotron that accelerates carbon ion beams up to 300 MeV/u. The carbon ion beam delivered by SCENT300 [9], with normalized emittances of 2.15 and 4.3 mm mrad in the radial and vertical plane, respectively (95% of particles), has been rescaled from 300 MeV/u down to 150 MeV/u. The rescaled SCENT300 beam is shown in Fig. 5.a). Simulations for the present acceptance study use this rescaled beam.

CABOTO presents a small longitudinal acceptance for the typical beam delivered by a cyclotron, since it appears to be almost continuous for the high-frequency linac, as it is shown in Fig. 5.b). Transmission scarcely depends on the beam energy spread dE/E for continuous beams. Almost 40% of the particles are lost at CABOTO entrance due to transverse acceptance. The total transmittance is about 4%. Assuming an output beam intensity of 100 nA from the cyclotron, CABOTO could provide 4 nA with the appropiate energy for hadrontherapy.

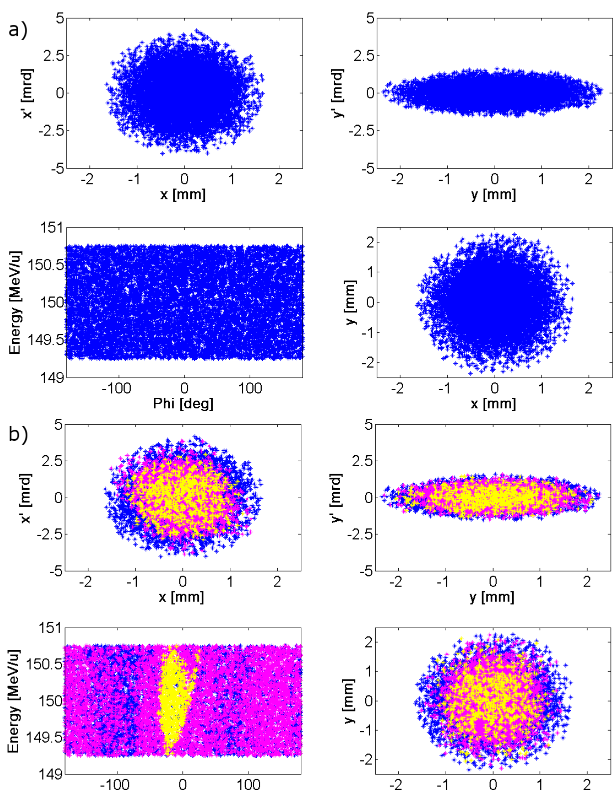


Figure 5: Tracking simulation for CABOTO with a SCENT300-like beam: a) SCENT300-like beam at the entrance of CABOTO; b) In blue, all beam particles; in pink, particles transmitted through the linac; in yellow, those particles transmitted with the appropriate energy.

Beam Energy Modulation

The beam energy can be decreased in steps of about 15 MeV/u from the maximum energy of 400 MeV/u by switching-off the RF power of a given number of units. In order to reduce the energy step down to 1 MeV/u (corresponding to a range step of 2 mm in water-equivalent tissue), one can vary the amplitude and/or phase of the power that feeds the last active unit. The range can be reduced from the maximum range (about 280 mm) in steps of 2 mm by decreasing in steps of 10% the amplitude field in the last active unit. The carbon ion range in water-equivalent tissue presents a linear dependence with the field amplitude in the units, except for the three lowest energy units. Shorter steps in field amplitude or a variation in the power phase are required to get a range step of about 2 mm for low energy beams. The lowest transmittance (2%) is found when a unit is operating with half the field for which it was designed to operate. The energy jitter influence on the beam has to be studied.

SUMMARY

A preliminary design for a compact, reliable, little consuming, 150–400 MeV/u CABOTO-C for a carbon ion therapy cyclinac has been presented.

The linac can also be used to accelerate H_2^+. With the RF power of the second half switched-off, the output beam will produce 250 MeV protons by inserting a thin foil downstream of the linac. Absorbers could be used to get the appropriate proton energy for therapy. The dynamics of a proton beam through CABOTO will be studied in a future.

REFERENCES

[1] S. Verdú-Andrés, “Comparison between RF Linacs and FFAGs for Hadrontherapy”. PARTNER deliverable WP25 (FP7/2007-2013, grant no.215840-2), Geneva, Switzerland (2011).

[2] U. Amaldi et al., “Acc. for Hadrontherapy: From Lawrence Cyclotrons to Linacs”, NIM A 620 (2010) 563-577.

[3] K. Crandall, private communication (2006).

[4] S. Verdú-Andrés, “High Frequency Linac Design”. PARTNER deliverable WP25 (FP7/2007-2013, grant no.215840-2), Geneva, Switzerland (2010).

[5] D. Alesini et al., “High Power Test of a C-band Accelerating Structure Prototype for the Energy Upgrade of the FRASCATI Photoinjector SPARC”, SPARC Tech. Note LNF-INFN, to be published.

[6] A. Degiovanni and S. Verdú-Andrés, “Expected High-Gradient Performances of TERA Accelerating Structures”, TERA Internal Note, Geneva, Switzerland (2011).

[7] S. Verdú-Andrés et al., “High-Gradient Test of a 3 GHz Single-Cell Cavity”, LINAC’10, Tsukuba, THP037 (2010).

[8] A. Degiovanni et al., “TERA High-Gradient Test Program of RF Cavities for Medical Linear Accelerators”, NIM A (2011), in press.

[9] L. Calabretta, private communication (2011).