COUPLING OF CYCLOTRONS TO LINACS FOR MEDICAL APPLICATIONS

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Abstract

Cyclotron and Linac technologies cover the vast majority of accelerator solutions applied to medicine. Cyclotrons with beams of H^+/H^- around 20 MeV are found for radioisotope production and cyclotrons with beams up to 250 MeV are widely used for protontherapy. Linacs are present in every medium-sized hospital with electron beams up to 20 MeV for radiotherapy and radioimaging. They have also recently become available as commercial products for protontherapy. The coupling of these two strong technologies enables to expand the capabilities of cyclotrons by using linacs as boosters. This opens the way to innovative accelerator systems allowing both radioisotope production and ion beam therapy (cyclinacs), new treatment techniques (high energy protontherapy) and new imaging techniques (proton radiography). This paper provides an overview of the technical challenges linked to coupling cyclotrons to linacs and the various solutions at hand.

INTRODUCTION

Cyclotrons

A list of all existing research and commercial cyclotrons is regularly compiled [1]. The vast majority of cyclotrons have a medical purpose as producers of radioisotopes for medical imaging and therapy. The typical primary beams of H^+/H^- ions are accelerated by normal conducting isochronous cyclotrons with kinetic energies up to 30 MeV. Compared to other accelerator technologies, cyclotrons benefit from their compactness, reliability and efficiency. Nowadays, normal conducting cyclotrons also represent the workhorse in protontherapy [2] with H^+ beams in the 235-250 MeV range. Recently, also superconducting isochronous and synchro-cyclotrons enter the protontherapy world as commercial solutions and their numbers are rapidly increasing.

Linacs

The vast majority of modern radiotherapy apparata is based on 3 GHz electron linacs, which are normal conducting copper standing-wave structures providing electron beams up to 20 MeV. They are so compact (1-2 m length) and light that they are mounted on rotating systems to irradiate the tumors from all possible angles.

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TERA Foundation

For more than 20 years, the TERA foundation has played an active role in the development of accelerator and detector technologies employed in the field of hadrontherapy. Its outputs and staff are, among others, at the core of the Proton Ion Medical Machine Study [3], the CNAO Foundation [4], which has built and operates the Italian hadrontherapy center in Pavia and the company ADAM S.A. (Switzerland), which commercializes protontherapy centers based on linacs. In the field of detectors, TERA developed the Proton Range Telescope [5] installed at CNAO and the BISE (Beam Imaging with Secondary Electrons) [6] detector installed at the 18 MeV cyclotron of Swan Isotopen AG.

TERA's present activities focus on designing novel gantries that make full use of the special properties of the beams produced by hadron linacs, and also research and development in the technologies of linacs for carbon (and helium) ion acceleration [7]. In collaboration with CERN, two lines of development are pursued: a system made of an RFQ followed by three linac structures (called "*all-linac solution*") and the combination of a cyclotron and a linac, a so-called "cyclinac". This combination allows enhancing the advantages of both accelerator types and opens new possibilities in therapy and imaging for radiotherapy centers (ex-novo or based on existing cyclotrons). The main innovations of all the proposed linac systems are the rapid energy variation (at rates in the range 100-400 Hz), the small transverse emittances of the beams and the cost-effectiveness. The related research activities concern pulsed ion sources, high-gradient high-frequency linacs, new concepts for beamlines and gantries, beam tracking tools and full-scale Monte Carlo simulations from the source to the patient.

CYCLINACS

General

The use of linacs for therapy has the advantage of allowing a fast (within a few ms) modulation of the beam output energy. This is a unique feature of a cyclinac, since protontherapy cyclotron systems use degraders for energy variation in the timescale of 100-1000 ms and the synchrotron systems vary the beam energy from cycle to cycle in timescales of 1-2 s. Additionally, the linac beam has a very small transverse emittance (around 0.3 μm rms, normalized) which allows to reduce the aperture (and cost) of the high energy beam transfer line magnets.

On the other hand, there are some technical challenges linked to the design of cyclinacs and corresponding beam-

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lines. Firstly, the transverse and longitudinal characteristics of the beam coming from the cyclotron do not match the small acceptance of the linac. Indeed, the transmission between the cyclotron and the linac is estimated to be less than 10 %. However, hadrontherapy treatments require low particle numbers and this is therefore not a limitation. Secondly, to make advantage of the fast energy modulation of the linac, the downstream beamlines have to minimize the dispersion and fast regulation systems have to be used for the magnets.

Proton Multi-Room Facility

The first cyclinac was proposed in 1994. It is based on a 30 MeV cyclotron, such that by night and weekends, medical radioisotopes not accessible to typical hospital cyclotrons can be produced (see Fig. 1).

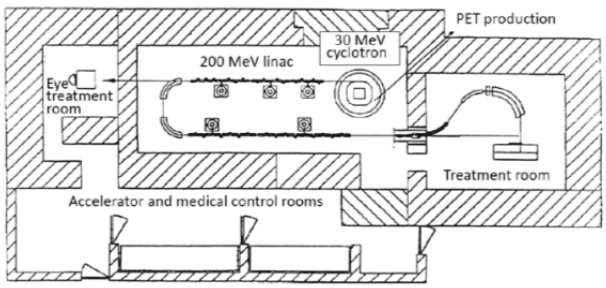

Figure 1: Layout of the first cyclinac [8].

At the end of the 90's, in collaboration with the European Laboratory for Particle Physics (CERN) and the Italian Institute for Nuclear Physics (INFN), TERA built the LI(nac)BO(oster), a 3 GHz Cell Coupled Linac which successfully accelerated a beam coming from a cyclotron from 62 to 74 MeV [9-10]. Various designs for cyclinac-based protontherapy centers have since been proposed [11]. One strong argument for this cyclinac solution is the possibility to combine the production of radioisotopes to the treatment of tumors by using a commercial proton cyclotron.

Dual Proton-Carbon Facility

At the time of writing all dual hadrontherapy centers (for proton and carbon ion treatment) are based on synchrotrons. Given the large beam rigidity required for carbon ion treatments (6.4 Tm), there is still a large margin of improvement in the footprint, cost and complexity of these accelerators. As shown in Fig. 2, in this respect, the cyclinac is a competitive solution.

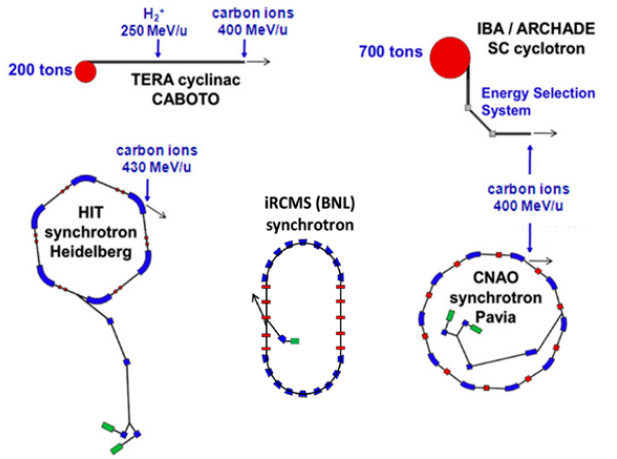

Figure 2: Dimensional Comparison of different accelerator technologies for hadrontherapy.

The linac solution for dual proton and carbon ion centers is called CABOTO [12-13]. The proposed cyclinac is composed of commercial electron beam ion sources producing C^{6+} and H_2^+, a superconducting isochronous cyclotron [14] accelerating them up to 150 MeV/u and a high-gradient 3 GHz linac boosting the energy up to 410 MeV/u. The corresponding produced beam has a 300 Hz repetition rate with pulse lengths of a few µs, as schematized in Fig. 3.

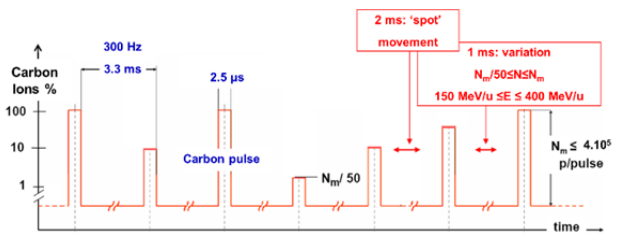

Figure 3: CABOTO Pulsed time structure (for C^{6+}).

The choice of the output energy of the cyclotron (and input energy for the linac) is strongly linked to the clinical aims of the therapy center. Indeed, an energy of 70 MeV/u would allow to use the cyclotron for proton eye tumor treatments and the linac for all deep-seated tumor treatments with both proton and carbon ion beams but would result in a larger and more energy-consuming accelerator. An energy of 230 MeV/u would allow to use the cyclotron as a stand-alone accelerator of H_2^+ molecules for 'standard' protontherapy using degrader systems and only use the linac for carbon ion treatments. This opens the possibility of a staged-approach in the treatment center's investment and treatments. The intermediate energy of 150 MeV/u (corresponding to 5 cm range in water for carbon ions) allows:

- covering the whole spectrum of tumor indications, with a linac-based active beam energy modulation system for carbon ions
- limiting the power consumption and accelerator building surface of the cyclinac

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- reducing the iron weight of the cyclotron to values similar to IBA's C235 cyclotron, the protontherapy workhorse

Proton Single-Room Facility

With the progress of the accelerator technology towards compact and light machines, more and more centers are based on single-room accelerators. This allows reducing the investment cost and multiplying the number of centers in order to cover more uniformly the territory. The equivalent cyclinac solution proposed by TERA is called TULIP (Turning LInac for Protontherapy). It involves mounting the whole linac structure on a rotating gantry [15]. An example is shown in Fig. 4. The RF power transmission is made possible by high power rotating joints developed in collaboration with the CLIC [16] group at CERN.

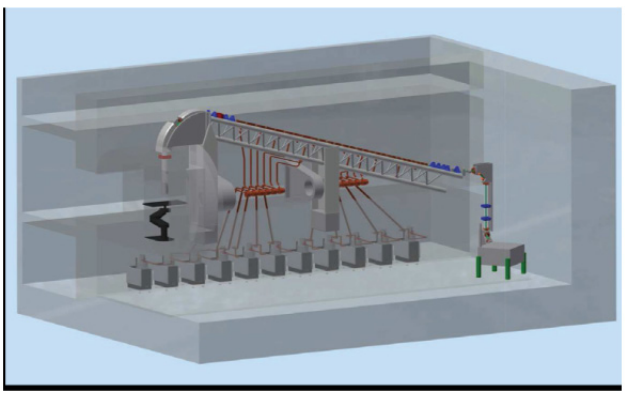

Figure 4: Artistic view of TULIP, based on a commercial 24 MeV cyclotron and 11 m Cell Coupled Linac similar to LIBO.

Proton Linac Booster

To overcome the limitations of modern protontherapy, some novel approaches are under study in the medical physics community. These include MRI-guided proton-therapy, proton imaging, proton tomography and high energy protontherapy [17]. These last two applications require boosting the energy of the clinical proton beams from the currently available 230-250 MeV up to 350 MeV and more. This upgrade would allow the use of passing proton beams both for proton radiography and for the treatment of small tumors that are surrounded by multiple, relatively small critical organs [18-19]. The Paul Scherrer Institut and TERA have designed a booster based on a linac similar to the one of Fig. 4 [20].

CONCLUSION

In conclusion, cyclotrons and linacs constitute the workhorse accelerators in the medical world. Their combination was introduced by the TERA Foundation under the name 'cyclinac'. Despite the technical challenges and limitations coming from this association, cyclinacs open incredible possibilities in the fields of medical imaging and medical therapy as they can vary the beam energy in a few ms without any beam intercepting devices and can in a modular fashion expand the capabilities of existing cyclotron-based centers.

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