CYCLINACS: NOVEL FAST-CYCLING ACCELERATORS FOR HADRONTHERAPY

Ugo Amaldi,
University of Milano Bicocca and TERA Foundation, Via Puccini 11, Novara, Italy

Abstract

A cyclinac is a high-gradient linac which, driven by a large-current cyclotron, produces the low hadron currents needed for tumour treatments.. For about 15 years TERA has been developing high-frequencies (3 GHz) and thus high-gradient structures. This paper introduces these novel fast-cycling accelerators, illustrates their advantages with respect to cyclotrons and synchrotrons - in particular for the treatment of moving organs - and describes two applications: IDRA for protontherapy and CABOTO for carbon ion therapy.

INTRODUCTION

Hadrontherapy, the technique of tumour radiotherapy which employs beams of the heavy particles made of quarks and called "hadrons", is developing very rapidly. In 2007 turn key protontherapy centres are produced by five companies and "dual" centres – featuring both proton and carbon ion beams – are offered by four companies. The accelerators for protontherapy are 4-5 metre diameter cyclotrons, both at room temperatures and superconducting, and 6-8 metre diameter synchrotrons, while for carbon ion therapy only 20-25 metre diameter synchrotrons are in use. Recently IBA has put on the market, but not yet built, a 6 meter diameter 400 MeV/u superconducting cyclotron which weighs 600 tons.

This paper describes fast-cycling accelerators producing hadron beams with time and amplitude structures better adapted to the treatment of moving organs than the ones from cyclotrons and synchrotrons.

The work described in this report started out in 1993 with a paper that I presented at the Como 'First International Symposium on Hadrontherapy' [1]. This proposal concerned a 30 MeV cyclotron and a proton linac running at the same 3 GHz used by the electron linacs employed in conventional radiotherapy. This would imply high gradients and thus a relative short accelerator.

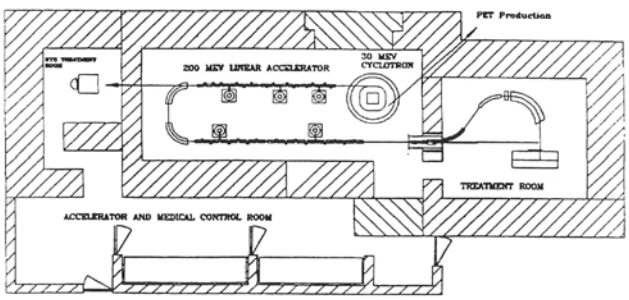

Figure 1: The first sketch of what was later called a "cyclinac" was based on a 30 MeV commercial cyclotron used also for the production of radiopharmaceuticals [2].

In Ref. [1] it is written: "A preliminary solution foresees the use of a 30 MeV cyclotron as an injector, with other options under study. The plan is to complete the study of such a compact linac by the end of 1994 in collaboration with K. Crandall". The study soon branched out in two approaches described in the "Green Book" [3].

Firstly, due to the stringent mechanical requirements needed to construct a linac capable of accelerating 30 MeV protons ($\beta = 0.25$), it was decided that the first linac Side Coupled Linac (SCL) would be designed for a 62 MeV input energy, having in mind in particular the Clatterbridge cyclotron. The results of the optimization where presented by Mario Weiss and Ken Crandall in 1994 [4]. Since then M. Weiss has been the leader of the project LIBO (LInac BOoster). Shortly later Riccardo Zennaro joined as responsible of the design and the RF tests of the accelerating structures.

Secondly, an "all-linac solution" was studied by Luigi Picardi et al., which is based on a new Side Coupled Drift Tube Linac below 62 MeV followed by LIBO for larger energies. This is the "TOP project" of ENEA and ISS.[5].

In 1998 a collaboration was set up among TERA, CERN (E. Rosso, B. Szelezs et al.), the University and INFN of Milan (C. De Martinis et al.) and the University and INFN of Naples (V. Vaccaro et al.) to build and test the double-module LIBO which at present is on display at the CERN Microcosm. The 1.3 m long prototype is composed of four accelerating 'tanks'. During the tests the design gradient (15.7 MV/m) was easily reached with the nominal 4 MW peak power The acceleration tests performed in Catania with a 62 MeV beam extracted from the LNS cyclotron were fully satisfactory [6].

GENERAL PROPERTIES OF CYCLINACS

A generic cyclinac is shown in Fig. 2.

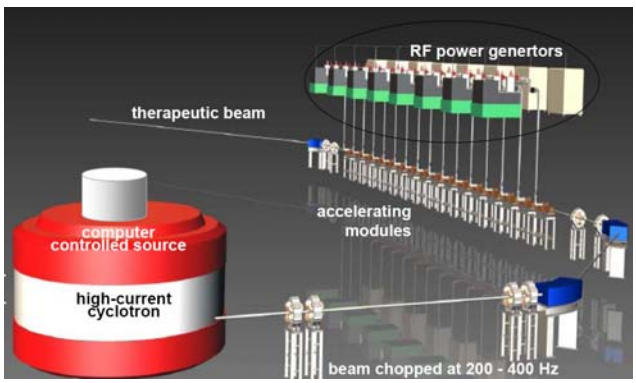

Figure 2: Sketch of a cyclinac. One beam is sent to the linac. Other beams extracted from the cyclotron can be used for medical purposes different from hadrontherapy.

The source is triggered at the repetition rate of the linac and the beam is chopped accordingly, so that a very low current is sent to the linac gallery. This repetition rate (Fig. 3) is chosen having in mind the spot scanning technique developed by PSI [7] in which, to 'paint' the tumour, the Bragg 'spot' is moved transversally with two crossed magnetic fields.

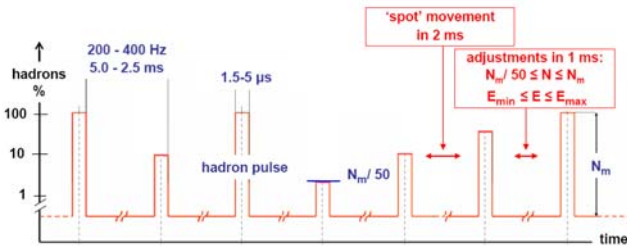

Figure 3: Time and amplitude structures of the therapeutic beam produced by a cyclinac.

The linac produces 1.5-5 μs long "hadron pulses" separated by 5 ms (2.5 ms) when the repetition rate of the klystrons producing the RF power is 200 Hz (400 Hz). Note that the pulsed beam is continuously present, as in a cyclotron.

In the 2.5-5 ms separating two successive pulses, the number of particles to be accelerated in the next "hadron pulse" and to be delivered to the next voxel can be adjusted with a 3% precision - between N_m N_m /50 - by acting on the computer controlled source of the cyclotron.. In parallel the hadron energy can be chosen by acting on the amplitudes of the RF pulses powering the twenty or so accelerating modules. To this end, the number of accelerating cells per module and the strengths of the Permanent Quadrupole Magnets (PMQs) – two per module – are chosen in such a way that a beam of any energy is transported without losses along the linac. To reduce the energy the RF power sent to a contiguous set of accelerating modules – starting from the end of the linac - is set to zero while the power sent to the last active one is continuously varied. Crandall's dynamics programs were used to define the optimal conditions to obtain such an unusual and sophisticated behaviour. Thus, as shown in Fig. 3, the beam energy can be varied at will between the cyclotron energy E_{min} and the maximum project value E_{max}.

As indicated in the last row of Table 1, the beams produced by cyclinacs are more flexible than the beams extracted from cyclotrons and synchrotrons, mainly because in linear accelerators there is no need of complicated injection and extraction systems.

Table 1: Properties of the beams of various accelerators

Accelerator	The beam is always present?	The energy is electronically adjusted?	What is the time to vary E_{max}?
Cyclotrons	Yes	No	≥50 ms
Synchrotrons	No	Yes	1 s
Cyclinacs	Yes	Yes	1 ms

The *first question* of Table 1 is relevant when the beams are synchronized with the expiration phase of the irradiated patient. The *second question* is important for the depth scanning of tumours. Cyclotrons require the mechanical movement of absorbers to vary the penetration range, while the electronic control, possible in synchrotrons and cyclinacs, is more reliable, requires less maintenance and does not entail in the Energy Selection System (ESS) the production of neutrons and induced radioactivity. However, in synchrotrons the adjustment takes one second and cannot be used for the 3D feedback system proposed by GSI to treat moving organs and tested by varying the depth with fast moving absorbers [8]. Instead in a cyclinac the variation of the depth of the Bragg 'spot' is even faster that the transverse adjustment (Fig. 3). To profit from this feature to treat longitudinally moving organs it is enough for the transport line and the gantry to have a ± (1.5 - 2)% momentum acceptance, so that the depth can be varied in about one millisecond by ± (10 - 15) mm.

IDRA: A CYCLINAC FOR PROTONS

Along the years many proton proton cyclinacs have been designed which mainly differ for the injection energy. Four cyclotron energies have been studied: 24, 30, 62 and 70 MeV. In 2006 a design based on a 30 MeV linac has been proposed to a group on Italian investors to realize the first facility, which would also be a pilot plant (Fig. 4). P. Pearce has designed an RF system in which 10 klystrons and 20 Fast Ferrite Transformers control the power levels sent to the 20 accelerating modules. Discussions are going on with IBA which is interested in participating in the project as provider of the control system and of all the components except the linac.

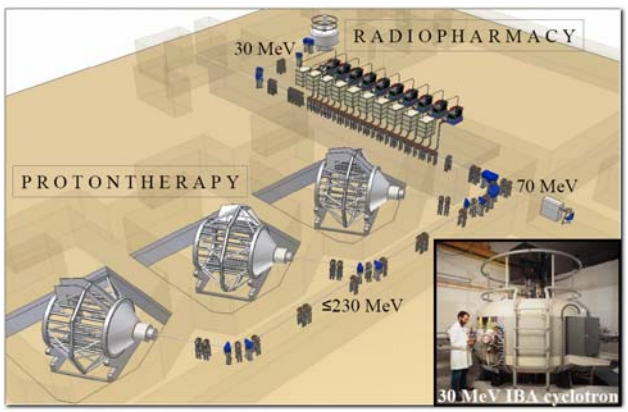

Figure 4: IDRA (Institute for Diagnostic and Radiotherapy) features a 750 mA/30 MeV cyclotron for the production of radiopharmaceuticals, a 18.5 m long and 200 Hz linac, an eye beam line and three gantries.

In the 'spot scanning technique' with N_m =2 10^7 (current ≤ 1 nA) 2 Gy min^{-1} l^{-1} can be delivered to a spherical 1 litre volume (subdivided in 4,028 voxels) by 'painting' each one of them at least 16 times. In fact the combination of 'multipainting' with the GSI 3D feedback system discussed in the previous Section is an optimal approach to the treatment of moving organs.

A CYCLINAC FOR CARBON IONS

The fraction of a continuous beam transmitted by a 200-400 Hz linac having the time structure shown in Fig. 3 is in the range 10^{-5}–10^{-4}. The main point of this paper is that such a minute overall acceptance poses no problem because tumour therapy with protons beams only requires about 1 nA and commercial proton cyclotron produce much more than 100 μA. However the best ECR sources cannot produce more than 10 μA of fully ionized carbon ions and one has to use the most recent Electron Beam Ion Sources (EBIS). For instance, at 400 Hz the new superconducting SC-EBIS by DREEBIT Gmb (Dresden) produces 10 μs long pulses containing more than 5 10^7 C^{+6} ions, a large number indeed [9].

In the design of the carbon cyclinac the 300 MeV/u cyclotron by Luciano Calabretta et al. has been adopted [10]. As shown in Fig. 5, G. Cuttone and L. Calabretta have proposed to build in the Catania 'Cannizzaro Hospital' a centre based on SCENT, the Super Conducting Cyclotron for Exotic Nuclei and Therapy.

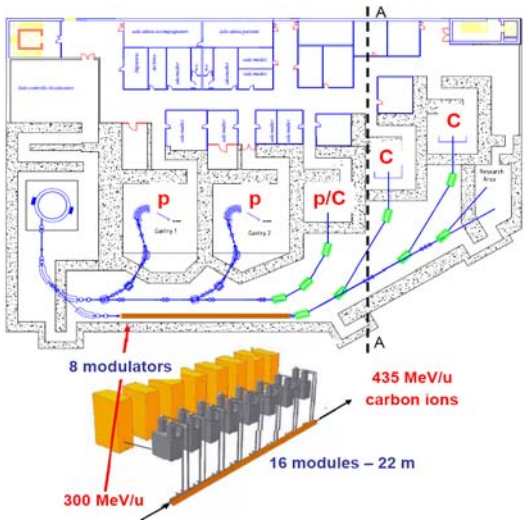

Figure 5: The initial phase of the Catania centre could be the facility for 250 MeV protons and 300 MeV/u carbon ions which is represented at the left of the AA line.

Initially the centre will feature two proton gantries and a room where patients can be treated with a horizontal proton and carbon ion beam. The tumours which can be treated with 300 MeV/u carbon ions are shown in Fig. 6.

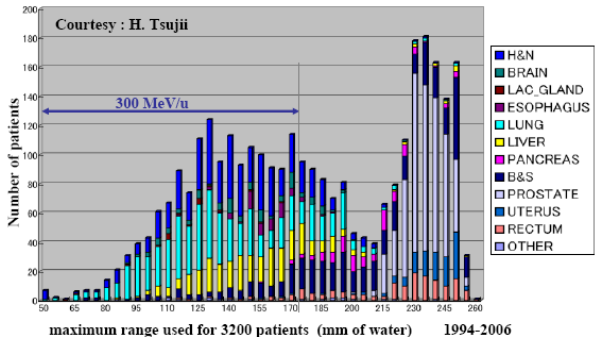

Figure 6: The distribution of the maximum range used at HIMAC (Chiba, Japan) for the 3200 patients treated between 1994 and 2006 is characterized by two peaks.

The percentages of the different tumour sites that have been treated at HIMAC with 300 MeV/u carbon ions are: Head Neck and Brain: 85%; Lung and Liver: 80%; Bone and Soft Tissues sarcomas: ≤ 20%; Pancreas, Prostate, Uterus, and Others: ≤ 3%. The sharp fall-off of the right peak of Fig. 6 indicates that – considering also the large fraction of European fat patients – it would be better to have energies larger than 400 MeV/u, which corresponds to a 260 mm range. For this reason the linac CABOTO (Carbon Booster in Therapy for Oncology) shown in Fig. 5 brings the 300 MeV/u carbon ions to 435 MeV/u.

As shown in Figs. 5, CABOTO can be installed in the same corridor used for transporting the beams, possibly in a later phase of the construction. The linac is made of 16 modules structurally identical to the IDRA ones, but longer. They are powered by 16 klystrons mounted on 8 modulators which run at 400 Hz. The energy and intensity can be varied pulse by pulse, as in any cyclinac (Fig. 3). The carbon pulses are 2.5 μs long and contain at maximum 4 10^5 C^{+6} ions, easily delivered by the EBIS source described above [9]. The linac plug power is about 400 MW, to be added to the 800 MW needed for SCENT.

CABOTO employs all the technologies developed for IDRA. In particular the 'spot scanning technique' will allow, with a maximum number of protons per pulse N_m = 4 10^5 (current ≤ 0.2 nAe) to deliver – to a spherical 1 litre target subdivided in 10,120 voxels – a *flat* 4 Gye min^{-1} l^{-1} effective dose (i.e. on average about 2 Gy min^{-1} l^{-1}). In these conditions each voxel is visited at least 10 times.

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