NOVEL TECHNIQUES AND CHALLENGES IN HADRON THERAPY

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Abstract

Whilst particle therapy has stepped into the clinical environment hospitals with moderate patient numbers only do not meet the business plan requirements of multi-vault facilities. Consequently the technology suppliers have started the development of single room installations as well as scalable facilities having moderate footprints. The desirable compactness may be achieved by introducing superconducting accelerator- and beamline-technology in order to increasing the bending radii and thus the building dimensions.

INTRODUCTION

Radiotherapy is a major pillar in the fight against cancer. About 50% of the patients undergo some kind of radiation-based treatment potentially combined with surgery or chemotherapy. Hadron beams combine advantageous ballistic properties with clinical efficacy and are expected to offer improved local control rates in about 15% of the treatments. During the last two decades about 50 proton-only, carbon-only or combined proton-carbon facilities were installed worldwide and have treated more than a 100.000 patients[1]. Typically these facilities were installed at large clinical centers and their multi-vault layout is capable of handling a high patient throughput. These major investments trigger business plans that require patient numbers higher than a thousand per year. Optimizing the workflows and especially the dose delivery process is a must. Nowadays active beam scanning [2, 3] allows for fully tumour-conformal dose delivery and particle accelerators can offer libraries of scanning-ready pencil beams with variable energy, beam spot sizes and intensities to the treatment planners. Today facility design starts at the patient vault where intensity-modulated dose delivery is combined with image guidance. The accelerator technology is capable of adapting to the deduced clinical requirements.

SINGLE ROOM DESIGNS

Conventional radiotherapy systems typically rotate the accelerator, beamline and nozzle around the patient that is immobilized in a supine position. So far the dimensions of particle therapy accelerator systems didn't allow to follow that pattern. As single room solutions were strongly requested by hospitals during the last decade high-field the super-conducting synchro-cyclotron became a candidate to be the basis of extremely compact facilities.

The Mevion S250® Proton Therapy System [4] has recently achieved USFDA 510(k) clearance and the first clinical implementation exists in St. Louis. The heart of this single room design is a Ni3Sn-based superconducting 9 Tesla synchro-cyclotron (see figure 1).

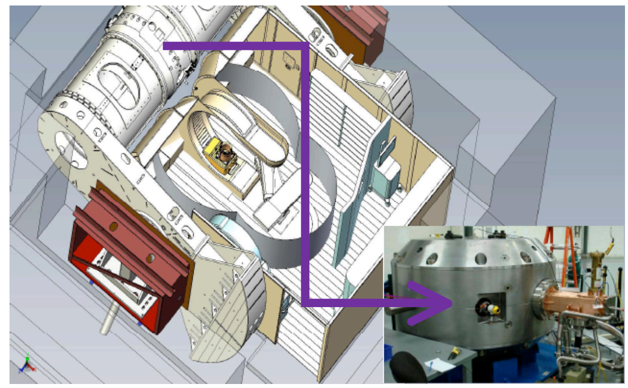

Figure 1: The Mevion S250® Proton Therapy System is based on a 9T, Nb3Sn, synchro-cyclotron that rotates closely around the patient.

For the sake of compactness the accelerator is placed very close to the patient. Consequently the range adaption needed to treat shallow locations is achieved by a degrader which represents a relevant target for neutron production just in front of the patient.

IBA's [5] Proteus One® design still relys on a conventional cyclotron followed by an energy selection stage and a gantry with in-built imaging devices. The footprint of this design covers a relevently larger area compared to Mevion's device on the other hand side it comprises a strict separation of the beam production and the dose delivery system. The latter is an implementation of the beam scanning method allowing for the powerful intenstiy-modulated dose delivery approach which is about to become a standard modality in external beam radiotherapy.

Varian Medical Systems [6] presented a very compact single room solution based on a synchro-cyclotron which is mounted on a gantry. This approach allows for active dose delivery and the avoidance of beam contaminations.

TWO ROOM DESIGNS

Single room facilities are facing unavoidable idle times of the beam production systems whenever patients are immobilized, positioned and image-guidance takes place. Clinical sites having patient referral sufficiently large to load two vaults may profit from this alternating operation mode and the cost-benefit ratio can be expected to be attractive.

The Radiance 330® system designed by ProTom uses an extremely compact linac-synchrotron arrangement to realize a two room facility [7]. Due to the nature of a synchrotron energy- and focus-variation of the pencil-beams required by the scanning beam dose delivery method is in-built.

IBA's Proteus Nano® concept aims at the reduction of the footprint by distributing the technology over two building floors (see figure 2).

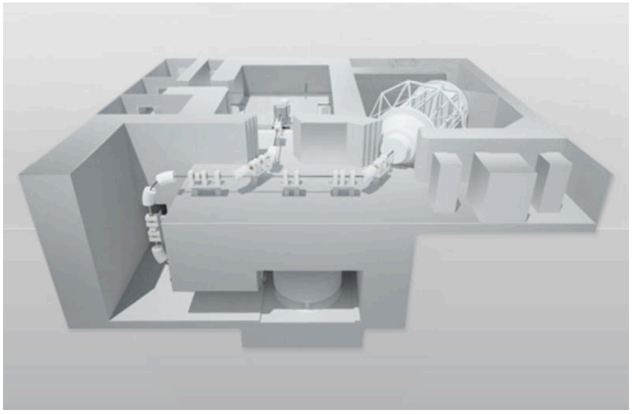

Figure 2: IBA’s Proteus Nano® two-room solution aims at a very compact footprint by distributing the particle accelerator technology over two levels.

HOSPITAL-BASED CARBON FACILITIES

Carbon ion radiotherapy is receiving growing interest in the radio-oncological community. Presently about half a dozen first-generation hospital-based facilities are operated [1]. Typically their scope is twofold: a multitude of clinical trials should be combined with the treatment of large patient numbers in order to broaden the clinical database for this new modality. Frequently the legacy of the particle accelerator labs being involved in the realization of these centers can be identified. In Europe and Japan the reimbursement rates for the treatments challenge the inevitable business plans. Therefore the optimization of every aspect within the treatment process starting at the accelerator to the dose delivery system just in front of the patient is a challenging task.

The Heidelberg Ion Beam Therapy Centre (see figure 3) is the first European particle therapy facility using protons as well as heavier ions to treat deep-seated tumours [8] It is a hospital-based facility being designed to treat up to 1.000 patients per year and to conduct a broad research and development programme in parallel. The Italian National Centre for Hadrontherapy CNAO [9] and centres in Japan at Gunma and Hyogo (see [1]) have started clinical operation during the last years. HIMAC at Chiba has been treating patients using carbon ions for almost a decade but just recently two beamlines utilizing the beamscanning dose delivery where put into operation.

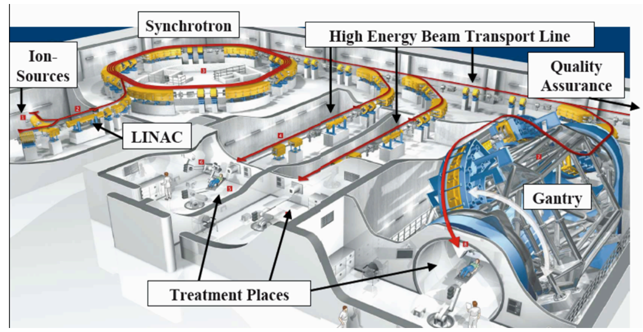

Figure 3: The Heidelberg Ion Beam Therapy Centre HIT.

HIT as well CNAO fully rely on active beam scanning dose delivery, i.e. active energy variation in the synchrotron as well as variable beam intensity and focussing on a cycle-by-cycle basis. The synchrotron and the high-energy beam transport system are used to produce a library of highly focussed pencil-beams. This library covers thousands of beam parameter combinations (ions species, energy levels per ion, intensity steps and spot sizes). It is shared between the accelerator control system and the treatment planning platform. 3D dose delivery is performed using the rasterscanning technology [mss] that steps in depth through stacked iso-energy slices which is a time consuming process as the synchrotron has to be filled, ramped up and down besides the extraction phase which is used to scan the tumour with Braggpeak ions.

The synchrotron operation can be optimized prior to and during beam extraction for the patient treatment. Magnetic field feed-back (B-train) and dynamic spill shaping have the potential to significantly reduce the irradiation duration. In normal, i.e. current-controlled, operation mode stable extraction conditions are reached once the eddy currents in the dipoles have faded. Typically this accounts for a prep phase of 700 ms. Additionally the normalization of the hysteresis in the quadrupoles is done by ramping up to the maximum field. Via introducing a magnetic field feed-back for the dipoles and quads in the synchrotron these time-consuming mitigations are no longer needed: the time saving can be up to 30% can be achieved [10].

The rasterscanning dose delivery process deposits a pre-calculated amount of stopping particles at a pattern of rasterpoints. Presently the extracted intensity (spill structure) from the synchrotron is shaped via a static feed-forward concept in the process data generation aiming at an almost rectangular shape. As the intensity of the pencil-beam is sampled at a rate of 100kHz using parallel-plate ionization chambers directly in-front of the patient a feed-back to the RF-knock-out exciter driving the extraction process could be developed. This feed-back mechanism can be used to shape spill structure in a rectangular mode saving about 15% irradiation time. Tailoring the extracted intensity in real-time to the structure of the patient-specific fluence maps potentially saves up to 45% beam-on time [11].

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So far therapy synchrotrons were operated to produce a constant beam energy per cycle. Due to the unavoidable preparation, injection and ramping phases the achievable duty-cycle in typical clinical applications couldn't be above 70%. Recently the extraction of multiple energy levels could be demonstrated at HIMAC [12]. Combining the described optimization concepts will significantly improve the patient throughpu in these first generation carbon ion facilities.

GANTRIES

In proton-only centres typically several gantries are installed. These medical devices can be larger than the accelerator even if an energy selection system is attached (cyclotrons only). For carbon ions the dimensions are even more impressive. The worldwide first implementation of a carbon gantry exists at HIT, Heidelberg. This iso-centric design combines active beam scanning of energy-variable pencil beams with robotic patient positioning and integrated digital x-ray imaging to maximally support intensity-modulated and imageguided treatments.

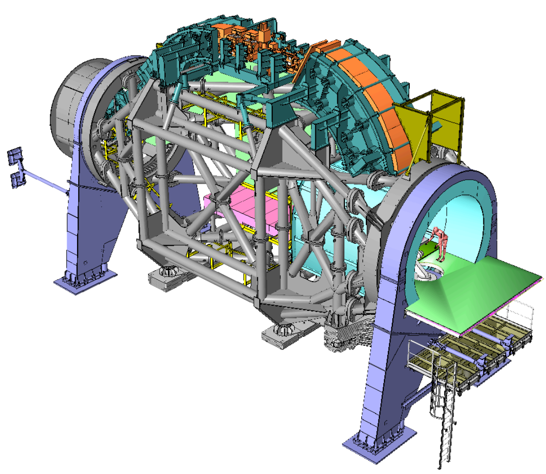

Figure 4: HIT's worldwide first iso-centric scanning ion gantry. This unique device was realized in a cooperation of GSI, Darmstadt, Siemens Medical Solutions, MT Mechatronics and HIT, Heidelberg.

As these rotational beamlines cover large volumes that need to be covered by material capable of stopping fast neutrons emerging from the patients into large solid angles. Typically walls of concrete having thicknesses of about 2m or sandwhich structures are used to shield the staff. The investment intrinsically tied to this radiation protection measure represents a relevant part of the total costs. Introducing super-conducting magnet technology would allow for raising the magnetic field strength and reducing the weight by a factor of 2 to 3. As a consequence the mechanical gantry structure could be realized within a smaller budget and in addition the volume to be covered with shielding walls would shrink dramatically. Obviously this holds true for proton gantries too.

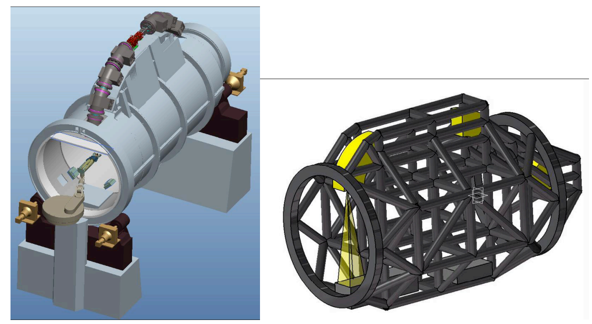

Figure 5: Design studies for iso-centric and super-conducting carbon ion gantries. At NIRS/HIMAC (left) the planned 3T result in a radius of 5.5m whereas the concept presented by IBA/CEA (right) is based on 5.4T magnet design allowing for a very compact radius of 4m only.

Recently more compact carbon gantries are under discussion. Figure 5 shows two design studies building on increased field levels that allow for reduced radii down 4 meters only. At least the device developed at HIMAC can be expected to be realized within the next years.

CONCLUSION AND OUTLOOK

While the first generation of particle therapy technology is in routine operation at several dozens of clinical sites the next facility generation aiming at extreme compactness and improved patient throughput is under development.

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