OPTIMIZATION OF MEDICAL ACCELERATORS WITHIN THE OMA PROJECT*

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Abstract

Although significant progress has been made in the use of particle beams for cancer treatment, an extensive research and development program is still needed to maximize the healthcare benefits from these therapies. The Optimization of Medical Accelerators (OMA) is the aim of a new European Network. OMA joins universities, research centers and clinical facilities with industry partners to address the challenges in treatment facility design and optimization, numerical simulations for the development of advanced treatment schemes, and in beam imaging and treatment monitoring. This paper gives an overview of the OMA research and training program and presents initial results from three selected projects.

INTRODUCTION

In 1946 R.R. Wilson introduced the idea of using heavy charged particles in cancer therapy. In his seminal paper [1] he pointed out the distinct difference in depth dose profile between photons and heavy charged particles: While photons deposit their energy along the beam path in an exponentially decreasing manner, heavy charged particles like protons and ions show little interaction when they first enter the target and deposit the dominant portion of their energy only close to the end of their range. This leads to an inverse dose profile, exhibiting a well-defined peak of energy deposition (the Bragg Peak). The depth of the Bragg Peak in the target can be selected precisely by choosing the initial energy of the particles. This allows for a significant reduction of dose delivered outside the primary target volume and leads to substantial sparing of normal tissue and nearby organs at risk. The field of particle therapy has steadily developed over the last 6 decades, first in physics laboratories, and starting in the late 90's in dedicated clinical installations. By March 2013 about 110,000 people had received treatment with particle beams, the vast majority having been treated with protons and around 15,000 patients with heavier ions (helium, carbon, neon, and argon). The latter are considered superior in specific applications since they not only display an increase in physical dose in the Bragg peak, but also an enhanced relative biological efficiency (RBE) as compared to protons and photons. This could make ions the preferred choice for treating radio-resistant tumors and tumors very close to critical organs. Proton- and ion therapy is now spreading rapidly to the clinical realm. There are currently 43 particle therapy facilities in operation around the world and many more are in the proposal and design stage. The most advanced work has been performed in Japan and Germany, where a strong effort has been mounted to study the clinical use of carbon ions. Research in Europe, particularly at GSI, Germany and PSI, Switzerland must be considered outstanding. Initial work concentrated predominantly on cancers in the head and neck region using the excellent precision of carbon ions to treat these cancers very successfully [2]. Also, intensive research on the biological effectiveness of carbon ions in clinical situations was carried out and experiments, as well as Monte Carlo based models including biological effectiveness in the treatment planning process were realized [3]. This work has directly led to the establishing of the Heavy Ion Treatment center HIT in Heidelberg, Germany [4]. HIT started patient treatment in November 2009 and continues basic research on carbon ion therapy in parallel to patient treatments. Several other centers offering carbon ion and proton therapy are under construction or in different stages of development across Europe, e.g. five proton therapy centers are being built in the UK, one more has been commissioned in Marburg, Germany and the Medaustron facility has also started patient treatment recently. The OMA network presently consists of 14 beneficiary partners (three from industry, six universities, three research centers and 2 clinical facilities), as well as of 17 associated and adjunct partners, 8 of which are from industry.

RESEARCH

Continuing research into the optimization of medical accelerators is urgently required to assure the best possible cancer care for patients and this is one of the central aims of OMA [5]. The network's main scientific and technological objectives are split into three closely interlinked work packages (WPs):

- Development of novel beam imaging and diagnostics systems;
- Studies into treatment optimization including innovative schemes for beam delivery and enhanced biological and physical models in Monte Carlo codes;
- R&D into clinical facility design and optimization to ensure optimum patient treatment along with maximum efficiency.

The following paragraphs give three examples of R&D results already obtained by Fellows within the network.

Superconducting Gantry Design for Proton Tomography

The precise dose delivery achievable with proton-based radiotherapy requires accurate treatment planning to obtain the greatest benefit. Presently, margins defined

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around treatment plan volumes are greater than they might be; these margins account for uncertainties in translating densities from CT scans. Proton CT (pCT) may reduce this error by directly measuring proton stopping via the loss of energy as protons pass completely through an imaged structure. Whilst head-and-neck and paediatric pCT is within the energy reach of current 230- 250 MeV proton therapy machines such as cyclotrons, full adult pCT will require up to 350 MeV protons to maintain the Bragg peak beyond the imaged patient. OMA Fellow Ewa Oponowicz based at the University of Manchester/ Cockcroft Institute is developing solutions to obtain 330 MeV protons using either FFAG or cyclinac approaches, constructing a prototype linac to be tested later in 2017. She has started to examine a compact gantry design to achieve that [6].

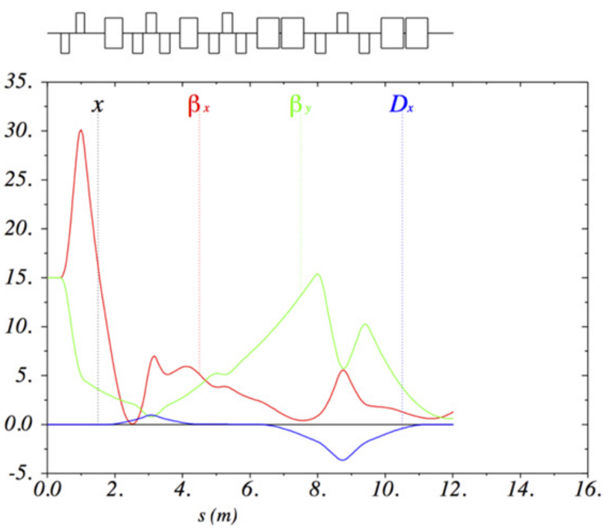

Figure 1: Typical optical functions achievable in a compact pCT gantry design [6].

Whilst compact, normal-conducting gantry designs exist for protons up to 250 MeV with dipole fields up to about 1.8 T, there is not yet a compact design suitable for 330 MeV protons where the maximal beam rigidity increases from 2.43 Tm at 250 MeV to 2.95 Tm. Initial studies by the OMA Fellow are focusing on the optimization of overall beam transport; an example lattice configuration is shown in the above Fig. 1.

LHCb VELO as an Online Beam Monitor

A non-invasive beam current monitor based on the multi-strip LHCb Vertex Locator (VELO) silicon detector has been developed at the Cockcroft Institute/University of Liverpool and first tests have been carried out at the treatment beam line at the Clatterbridge Cancer Centre (CCC), UK. Originally, the VELO detector was designed to track vertices in the LHCb experiment at CERN [7], but first feasibility tests performed at the CCC treatment beam line back in 2010 demonstrated the possibility of non–intrusive beam monitoring. The initial measurements consisted of data taken at several points along the beam line and gave high count rate, high resolution results. It is now planned to relate the proton 'halo' region hit rate, as measured by the VELO detector, with absolute beam current value, determined by a purpose-built Faraday cup. An illustration of the setup is shown in Fig. 2. More details about the design of the monitor are included in [8].

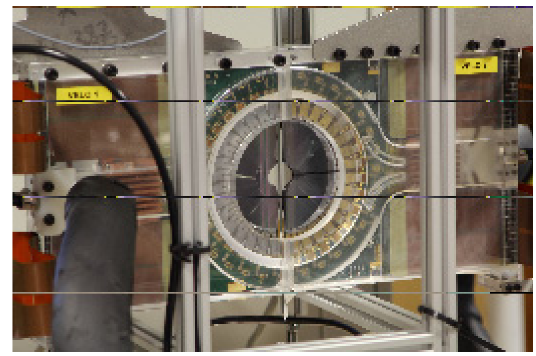

Figure 2: Photograph of the VELO detector that will be used as online beam monitor for quality assurance.

VELO is an example of a silicon micro-strip detector positioned around the experiments interaction region. Using two types of strip geometries the radial and azimuthal coordinates of traversing particles are measured. VELO provides precise measurements of track coordinates which are used to reconstruct the primary collision vertex as well as displaced secondary vertices that are characteristic of B-meson decays. It is hence a promising technology for non-invasive real time beam monitoring applications. Jacinta Yap is an OMA Fellow based at the University of Liverpool/Cockcroft Institute**.** She works closely with QUASAR Group member Roland Schnuerer and both will further the understanding of VELO as an online beam monitor in medical accelerators. Their initial work has focused on building a deeper understanding of the detector's signal linearity through laser-based measurements in a dedicated lab setup. This was then linked to results obtained from measurements with beam [8]. In a next step, Monte Carlo simulations will be used to reproduce and optimize beam transport at CCC. Results will then be benchmarked against experimental data obtained in additional experimental studies.

High Gradient RF Technology for Hadron Therapy Accelerators

Significant progress has been made over the past decade by studies of normal-conducting linear colliders to raise the achievable accelerating gradient from the range of 20-30 MV/m up to 100-120 MV/m. Today, there are several applications which might benefit from the advance in high gradient normal conducting RF technology including linear accelerators for hadron therapy. This accelerator type is of particular interest for medical applications because they can provide a high degree of flexibility for treatment. For example, proton and carbon ion linacs running at 100-400 Hz have the capability of varying the beam energy (and intensity) on very short time scales of only 2.5-10 ms between two consecutive pulses.

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This opens manifold avenues for 'multi-paint' tumour targeting using a 3D feedback system to deliver the dose to a moving organ by applying the spot scanning technique. To cover the relevant therapeutical energy range, the accelerator would ideally provide beams in the energy range between 70-230 MeV for protons and 100-400 MeV/nucleon for heavier ions, such as carbon. The design and fabrication of a high-gradient prototype for medical proton linacs has been started by the Knowledge and Transfer (KT) group at CERN, under the project 'High-gradient accelerating structures for proton therapy linacs' [9]. It is planned to carry out test of this structure in a dedicated high gradient laboratory at CSIC/IFIC in Valencia, Spain. OMA Fellow A. Vnuchenko is based at CSIC/IFIC and her project focused on the design, construction and power testing of two novel high-power prototype 3 GHz accelerating structures at 76 MeV (low energy) and 213 MeV (high energy).

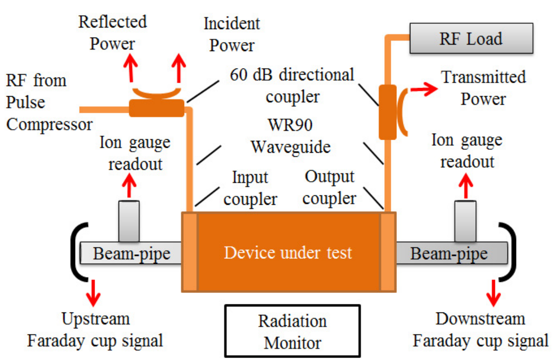

Figure 3: Schematic layout of test stand including various diagnostic systems. The red arrows show the signals that are sent to the NI PXI crate for acquisition and analysis.

The design and status of the CSIC/IFIC facility with a focus on low/high power RF and associated diagnostics, cooling and vacuum requirements, as well as the foreseen data acquisition system are described in more detail in [10]. The RF-lab has a similar configuration to the Xbox-3 test facility at CERN [11]; its diagnostic and control system have been designed to be flexible to allow any possible changes that might be required during structure testing. A schematic layout of the diagnostics systems is shown in the above Fig. 3.

TRAINING

The fundamental core of the OMA training is a dedicated cutting-edge research project for each Fellow at their host institution. The network is then used to provide opportunities for secondments for all Fellows to spend time working at other institutions within the network for hands-on training in specific relevant techniques and for broader experience including different sectors. All Fellows will be in post for 36 months and most of them are registered into a PhD program. This local training will be complemented by a series of network-wide events that include external participation.

International Schools

All OMA Fellows were invited to a researcher skills training at the University of Liverpool in April 2017. This week-long School included for example sessions on project management, presentation skills, communication of research outcomes to diverse audiences, as well as IP rights and knowledge transfer. As an introduction to the field of medical accelerators all recruited OMA Fellows will take part in an international School on the Optimization of Medical Accelerators. This will be held at the CNAO Centre in Pavia, Italy in June 2017 and cover beam physics, instrumentation R&D and charged particle beam simulations at an advanced level [12]. It targets PhD students, Postdocs, as well as experienced researchers and is open also to participants from outside the network. A Monte Carlo School will be held in November 2017 in Munich and an international School on the Optimization of Medical Accelerators at an advanced level will be held in 2019.

Topical Workshops

A series of Topical Workshops will cover all work packages within the network. They will promote knowledge exchange and ensure that all Fellows are exposed at highest possible level to the techniques and methodologies developed in the other WPs. Three 2-day Topical Workshops covering two scientific WPs at a time will be organized. These will cover 'Facility Design Optimization for Patient Treatment', 'Diagnostics for Beam and Patient Monitoring', and 'Accelerator Design & Diagnostics'. Topical Workshops will be held from early in 2018 and will be announced via the project website [5].

Conference on Accelerator Optimization

A three-day International Conference will be hosted by the national accelerator center (CNA) in Seville, Spain in the final year of the OMA project. It will promote all research outcomes of the network and enable the Fellows to engage with other university groups and private companies. The conference will also present an opportunity for follow-up activities between the OMA partners and participating scientists from outside the network and thus serve as a career platform for all Fellows.

A Symposium on 28 June 2017 on Accelerators for Science and Society will be organized at the Liverpool Convention Center as a finale to the outreach activities undertaken during the course of the network. This will present the main project findings in an understandable way for the general public, emphasizing the possible applications of the technologies concerned.

SUMMARY AND OUTLOOK

In this paper, a general overview of the research aims of the OMA project, along with selected initial research results was given. This highlighted the importance of the R&D also for other medical accelerators and associated technologies. A brief overview of the broad and interdisciplinary training program was also given.

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