OPTIMIZATION OF MEDICAL ACCELERATORS

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Abstract

The Optimization of Medical Accelerators (OMA) is the aim of a new European training 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 advanced treatment schemes, and beam imaging and treatment monitoring. Projects include: compact accelerators for proton beam energy boosting and gantry design; strategies for improving Monte Carlo codes for medical applications and treatment planning; and advanced diagnostics for online beam monitoring. The latter involves RF-based measurements of ultra-low charges and new encoding methodologies for ultra-fast 3D surface scanning. This paper presents an overview of the network's research program and highlights the various challenges across the 3 scientific work packages. It also summarizes the network-wide training program consisting of schools, topical workshops and conferences that will be open to the wider medical and accelerator communities.

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.

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The following paragraphs outline a very broad, yet closely interconnected research program into medical accelerators where OMA Fellows will build up expert knowledge in a number of different fields and combine them to enhance ion beam treatment provision.

Beam Imaging and Diagnostics

Compared to conventional radiotherapy, proton therapy is still a developing technology. While the accelerator systems required to provide a 200-400 MeV proton beams are a mature technology, numerous challenges, both clinical and technical, must be overcome before proton therapy has as sound a clinical footing as e.g. X-ray radiotherapy [6]. Amongst these challenges, effective imaging is of critical importance. All projects in this first WP target the development of beyond state-of-the-art diagnostics that will provide more detailed and complete information about the beam.

The Vertex Locator (VELO) which was developed for the LHCb experiment at CERN [7], is an example of a silicon micro-strip detector positioned around the experiments interaction region. By the use of 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. A Fellow based at the Cockcroft Institute/University of Liverpool will use the VELO detector to design, build up and test a stand-alone monitor for online beam monitoring in medical accelerators, building up on work presented in [8]. Another promising detector technology that was originally developed for high energy physics applications and has already found widespread medical applications is the Medipix [9] family of detectors. These are solid state hybrid X-ray pixel detectors working in photon counting mode and suitable for a wide range of applications including X-ray and particle beam imaging. A Fellow at Amsterdam Scientific Instruments will develop a new type of high-speed hybrid pixelated detector based on the Medipix readout chip and target readout speeds of more than 1 kHz; roughly one order of magnitude faster than the current frame rates of up to 120 Hz.

Comprehensive information about the beam requires its measurement before it enters the patient and after it has left them. In state-of-the-art ion beam delivery schemes the tumor volume is ‘painted’ spot by spot with a so-called ‘pencil beam’ scanned by magnets [10]. Ion therapy offers extremely high precision in beam delivery and hence demands very high accuracy to ensure that the maximum penetration depth coincides with the tumor. Typically 10% of the ions undergo nuclear collisions with nuclei of the patient tissue along their paths, resulting in the instantaneous emission of prompt gamma rays. These are emitted along the ion trajectories, escape the patient and hence give an opportunity to produce an image of the beam inside the patient [11, 12]. A Fellow based at IBA will develop software tools to perform and test the various new treatment workflows made possible by such ‘prompt gamma camera’. To complement information about the beam, it would be highly desirable to monitor its intensity in a parasitical way that does not affect the beam during measurement. Currently, ionization chambers are the most commonly used detector type for beam intensity measurement. However, they use thin foils which are passed by the beam and decrease the beam’s quality by scattering. To mitigate this problem a Fellow at PSI will develop a sensitive RF-based current monitor for fully non-interceptive beam current measurement.

Traditional treatment planning with photons requires multiple patient CT images to build up an effective diagnostic image for patient planning, both before the start of treatment and between fractions, to allow changes in the tumor volume to be monitored. An alternative is to use higher energy protons to image the patient [13]: protons in the 300 MeV range are used to ensure they emerge from the body without significant dose deposition. Using the same proton beam for both imaging and treatment ensures the patient does not have to be moved between imaging and treatment [14]. Individual proton energy measurements at the 1% level are essential for such proton imaging system and would provide valuable quality assurance measurements – a Fellow at the University College London will adapt existing calorimetry technology for the precise measurement of proton energy in a clinical setting. Finally, a Fellow at CNA/University of Seville will investigate into the overall optimization of beam diagnostics for the determination of all essential beam parameters. This includes measurements of the intensity profile at the position where cell samples are placed with radiochromic film, a transmission ionization chamber for dosimetry and proton fluence measurement with CR-39 nuclear track plates, as well as beam energy at the position of the cell samples with silicon detectors. This will provide a framework for cell studies and important information for a critical performance assessment of all diagnostics R&D in this WP.

Treatment Optimization

By combing advanced computer simulations for dose delivery planning with novel treatment schemes and innovative patient scanning systems, OMA strives to further improve one of the technologically most advanced cancer treatment modalities in this second scientific WP.

For efficient treatment planning and decision for optimum dose delivery schemes, Monte Carlo simulations are a key tool. The FLUKA code [15] is extensively used for hadron therapy and medical applications. The models embedded in the code for atomic and nuclear interactions have already demonstrated their accuracy for clinical applications. Two Fellows at CERN and LMU in Munich will work closely together to further improve the modeling of the emission of secondary radiation for therapy monitoring, including prompt gammas, positrons

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and other charged particles, and thereby providing the required simulation framework for studies across the different WPs. The potential for treating mobile tumors by means of active particle beam scanning depends upon the capability of overcoming a set of technological and methodological issues related to the geometric uncertainties and dosimetric effects caused by motion [16, 17], . The key challenge is the integration of a highly performing motion monitoring technique with an efficient solution for beam in-plane tracking and energy modulation [18]. A Fellow at CNAO will design, implement and experimentally assess such integrated system and related strategies for tumor tracking in active beam scanning particle therapy. 3D scanning to monitor patient movement takes advantage of high-precision, high-resolution pattern projectors. Phase shifting methodology was adopted from interferometry enabling the highest level of accuracy and data density. The projected patterns are of sinusoidal shape and high quality requirements apply for these sinusoidal fringes to solve the corresponding phase reconstruction without artefacts from higher harmonics. For ultra-high-speed 3D scanning, it would be ideal to use the 10-20 kHz switching rate of binary patterns. However, this cannot be achieved directly without losing the sinusoidal brightness distribution in the projection. A trainee based at ViALUX will develop new encoding methodologies that allow for ultra-fast 3D surface scanning.

Facility Design and Optimization

Different software is involved in cancer treatment, ranging from creating a treatment plan, the treatment planning system, the oncological information system, dose delivered monitoring to real time scheduling, event logging and overall quality assurance. Presently, many of these systems have a proprietary interface that cause difficulties in interconnection and maintenance. A second Fellow based at CNAO will create a common software bus using only industry standard protocols that shall enable any software (sub)system to easily interconnect for exchanging workflow information and safe facility operation. Significant progress has been made over the past decade to raise achievable accelerating gradients from 20-30 MV/m to 100-120 MV/m [19]. This promises great benefit for linear accelerators (linacs). These run at 100-400 Hz and have the capability of varying beam energy (and intensity) during the 2.5-10 ms separating two consecutive pulses, hence allowing to ‘multi paint’ a tumor while using a 3D feedback system to deliver the dose to a moving organ by applying a spot scanning technique . A Fellow at CSIC/IFIC will design, construct and power test two novel high-power prototype 3 GHz accelerating structures at 76 MeV (low energy) and 213 MeV (high energy). A Fellow based at MedAustron will study upgrade scenarios for this specific facility to reduce patient treatment time, thus allowing for a larger number of patients to be treated each year. Their work will benefit from the research results from all other Fellows in OMA.

It is well understood that present imaging techniques are insufficiently accurate, in part because there is an implicit conversion needed between the density measure of the imaging technique and that relevant for the protons themselves. Ideally, protons that have sufficient energy both to pass through the patient and to give an accurate residual energy measurement in an appropriate detector would be measured directly. One way to obtain a higher final energy is to use a short section of linear accelerator after the primary proton source. Whilst the transmission efficiency through such a linac is poor (around 8% typically), it would be sufficient to provide the much lower proton dose needed for imaging. A Fellow at the Cockcroft Institute/University of Manchester will study the beam dynamics in such booster linac, the beam delivery gantry and the system layout for delivering proton tomography and other imaging for use at the CHRISTIE and PSI centers.

TRAINING EVENTS

Training within OMA consists of research-led training at the respective host, in combination with local lectures, as well as participation in a network-wide training program that is also open to external participants. This training concept is based on the successful ideas developed within the DITANET, oPAC and LA3NET projects [20-22]. 3 week-long international Schools, open to all OMA Fellows and up to 50 external participants on Monte Carlo Simulations, Medical Accelerators and Particle Therapy will be organized. All Schools will be announced via the project home page [5]. To further 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’. In the last year of the project a 3-day international conference will be organized, with a focus on the novel techniques and technologies developed within the network.

SUMMARY

An overview of the R&D program within the recently approved OMA project was given. The network is a very large European training network and the first that has even been evaluated with a 100% mark. OMA will train 15 early stage researchers over the next four years. The consortium consists of universities, research centers, clinical centers, and industry partners and will also organize a large number of training events. This includes Schools, Topical Workshops, an international conference and various outreach events which will all be open also for participants from outside of the project.

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