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ADVANCES IN DIAGNOSTICS FOR MEDICAL ACCELERATORS*

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Abstract

The Optimization of Medical Accelerators (OMA) is the aim of a new pan-European project. As one of the largest initiatives of its kind, OMA joins more than 30 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 beam imaging and treatment monitoring. This paper starts with an overview of the project's research into beam diagnostics and imaging. It then presents specific research outcomes from investigations into applying detector technologies originally developed for high energy physics experiments (VELO and Medipix) for medical applications; identification of optimum detector configurations and materials for high resolution spectrometers for proton therapy and radiography; ultra-low-charge beam current monitors. Finally, it summarizes the interdisciplinary training program that OMA provides to its 15 Fellows, as well as the wider medical accelerator community.

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 in the OMA diagnostics work package.

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

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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 [6], 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. 1. More details about the design of the monitor are included in [7].

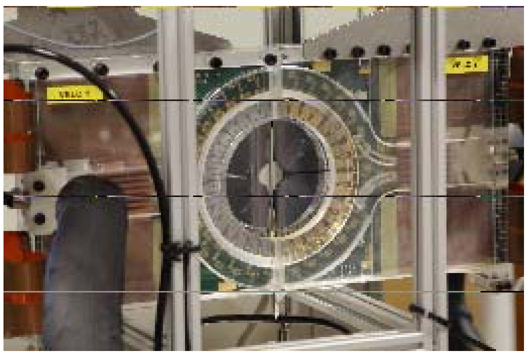

Figure 1: Photograph of the VELO detector that will be used as online beam monitor for quality assurance.

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.

Proton Energy and Range Measurement

The goal of the project of Laurent Kelleter is the transfer of specific technology developed for high energy physics experiments at UCL for use in making precision measurements at clinical proton beam therapy (PBT) facilities. This research programme has grown out of the efforts to support the new proton beam therapy centres in the UK, but strong international collaborations have been forged — particularly with OMA partners — that provide wider opportunities for use of the detectors under development. This project seeks to address a number of challenges in providing effective treatment with proton therapy. Chief amongst these is to improve the systems used for patient imaging. 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 tumour volume to be monitored. However, the increased localisation of proton dose delivery requires a corresponding increase in imaging resolution, exposing the limits of traditional CT imaging. In addition, X-ray CT images do not provide information on the proton-specific absorption characteristics of tissue surrounding the treatment volume.

An alternative is to use protons for imaging: an energy is chosen such that the protons do not stop within the body of the patient but pass through to be detected. Using the same proton beam for both imaging and treatment ensures the patient does not have to be moved between imaging and treatment: in addition, the anatomical information acquired from the imaging does not have to be adjusted from a different imaging modality. A conceptual proton Computed Tomography (pCT) system consists of a series of tracking layers upstream and downstream of the patient, with some method of measuring the final energy of the diagnostic protons.

Figure 2: SuperNEMO OM, showing bare plastic scintillator block (left) and wrapped block with PMT (right).

Preliminary simulations of the detector response were carried out in GEANT4. These showed the anticipated response of the SuperNEMO [9] Optical Module (OM) shown in Fig. 2 in response to the 60 MeV clinical proton beam at the Clatterbridge Cancer Centre (CCC), the only clinical proton therapy facility currently operating in the UK. These simulations indicated a stopping distance remarkably close to that of water — 30.2 mm for PVT plastic as opposed to 30.5 mm in water — supporting the suggestion that the plastic scintillator could replace other water-equivalent materials (such as PMMA plastic) when making a WEPL measurement. The simulations also indicated an energy resolution of 0.6% σ at 60 MeV, below the target resolution of 1% σ. These simulations have since been

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confirmed in measurements at CCC. More measurements have also been taken at CCC to better understand the results. In addition, OMA partner Medaustron provided the opportunity for the UCL group to make first energy resolution measurements with their calorimeter at energies between 60 MeV and 252 MeV for the first time. Results are being analysed and look very promising.

Measurement of Ultra-Low Charges

Beam current is the basic quantity of a charged particle beam. Beam current is the first check of accelerator functionality and has to be determined in an absolute manner. It is also important for transmission measurements and to prevent for beam losses [10]. However, due to many varieties of accelerator, this becomes a challenging task from beam diagnostic perspective. Beam current is an intermediary for measuring beam lifetime in storage rings, superconducting linacs and ERLs [11]. For the PROSCAN facility at Paul Scherrer Institut (PSI), interceptive ionization chambers or secondary emission detectors have been used for beam current measurement in the past. However, these degrade the beam quality due to multiple scattering or energy losses. Since this implies a strict regulation of the use of these diagnostic devices during therapy, non-interceptive monitors of the beam current would be highly advantageous for online control. OMA Fellow Sudharsan Srinivasan is in the process of developing a reentrant cavity current monitor. This device works on the principle of an ordinary resonant circuit which consists of an inductor and a capacitor in parallel. Its fundamental mode resonant frequency 145.7 MHz was designed to match the 2nd harmonic of the beam pulse repetition rate, 72.85 MHz.

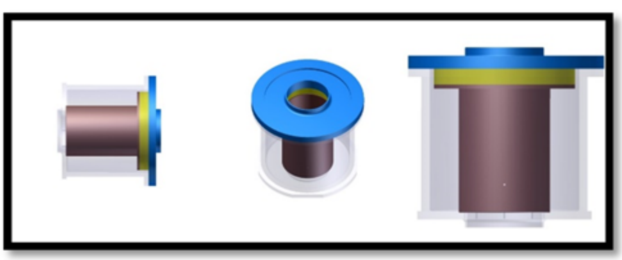

Figure 3: ANSYS HFSS model of the RF current monitor being designed at PSI.

Initial design studies with ANSYS HFSS (High Frequency Structural Simulator) yielded a parametric model which allowed to analyze the monitor properties in detail, see Fig. 3. A prototype is currently being built and will be used for experimental studies in the near future.

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 and experience at another institution. 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. All OMA Fellows joined 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 took part in an international School on the Optimization of Medical Accelerators. This was held at the CNAO Centre in Pavia, Italy in June 2017 and covered beam physics, instrumentation R&D and charged particle beam simulations level [12]. More than 70 researchers participated in this event. 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. Three 2-day Topical Workshops covering two scientific WPs at a time will also 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]. A three-day International Conference will be hosted by the national accelerator center (CNA) in Seville, Spain in the final year of OMA. It will promote all research outcomes 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 2019 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 applications of the technologies concerned.

SUMMARY AND OUTLOOK

In this paper, a general overview of the OMA project, along with selected initial research from the diagnostics and instrumentation work package was given. A brief overview of the broad and interdisciplinary training program was also given. Many more training events are now setup for the OMA Fellows and the wider medical accelerators community and detailed information will be made available via the project website and the quarterly OMA newsletter.

REFERENCES

[1] M. R. Wilson; *Radiology* 47 (1946) 498-491.

[2] D. Schulz-Ertner, *et al.*, *Int. J. Rad. Onc. Biol. Phys.*, 58, (2004), pp. 631–640 and G. Kraft, *Progr. in Particle and Nuclear Physics* 46 (2001).

[3] M. Krämer, *et al.*, *Phys. Med. Biol.* 45 3299 (2000) and T. Elsässer, *et al.*, *Int. J Rad. Onc. Biol. Phys.* 78 (2010), p. 1177–1183.

[4] S.E. Combs, *et al.*, *Radiotherapy and Oncology* 95 (2010), p. 41-44.

[5] OMA Project, `http://www.oma-project.eu`

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-MOPCC01

[6] LHCb VELO Technical Design Report, CERN/LHCC 2001-0011, LHCb TDR 5, Geneva.

[7] T. Cybulski, "Non-invasive Beam Monitor for Medical Accelerators", *PhD thesis*, Liverpool (2017).

[8] R. Schnuerer, J. Yap, *et al.*, "Non-invasive online beam monitor using LHCb VELO", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper THPVA136.

[9] R. Arnold *et al.*, Eur. Phys. J. C 70, 927 43 (2010).

[10] P. Forck, "Pick-Ups for bunched beams," JUAS Archamps, p. 6.

[11] J. C. Denard, "Beam Current Monitors," Notes Work. Accel. Instrumentation, BNL, October, 1989, no. 1, pp. 141–155, 1990.

[12] OMA School on Medical Accelerators, https://indico.cern.ch/event/595518/