BEAM DIAGNOSTICS FOR MEDICAL ACCELERATORS*

C.P. Welsch#, Cockcroft Institute and The University of Liverpool, UK
on behalf of the OMA Consortium

Abstract

The Optimization of Medical Accelerators (OMA) is the aim of a new European Training Network that has received 4 ME of funding within the Horizon 2020 Programme of the European Union. 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 beam imaging and treatment monitoring. This paper presents an overview of the network's research into beam diagnostics and imaging. This includes investigations into applying detector technologies originally developed for high energy physics experiments (such as VELO, Medipix) for medical applications; integration of prompt gamma cameras in the clinical workflow; identification of optimum detector configurations and materials for high resolution spectrometers for proton therapy and radiography; ultra-low charge beam current monitors and diagnostics for cell studies using proton beams. 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;

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675265.
#c.p.welsch@liverpool.ac.uk

ISBN 978-3-95450-177-9

- R&D into clinical facility design and optimization to ensure optimum patient treatment along with maximum efficiency.

The following paragraphs outline the research program targeting advanced beam diagnostics for medical accelerators.

Online Beam Monitoring

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 WP target the development of beyond state-of-the-art diagnostics that will provide more detailed and complete information about the beam. Individual projects provide mutually complementary information and will be exploited in parallel to achieve full beam characterization. Results from all projects in this WP will be taken into account for the treatment optimizations carried out in WP3 and benefit the facility and beam line design studies in WP4.

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 University of Liverpool/Cockcroft Institute will use the VELO detector to design, build up and test a stand-alone monitor for online beam monitoring in medical accelerators and link it to an overall diagnostics concept with other Fellows working on facility design and optimization. The Fellow will improve and enhance a stand-alone version of the VELO detector as shown in Fig. 1 [8].

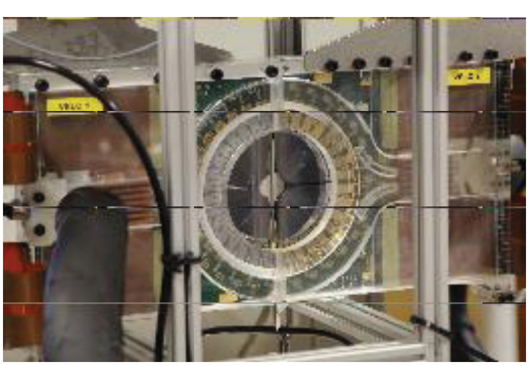

Figure 1: Photograph of the VELO detector that will be used as online beam monitor for quality assurance.

This will include optimizing a local positioning, control, ventilation (with dry air) and cooling system. Extensive measurements will then be carried out to establish a halo-dose correlation data base for different machine settings. This data will then be used for benchmarking Monte Carlo simulations against real data and contribute to enhanced treatment models in WP3.

High-speed Radiation Detection Platform

Another promising detector technology that was originally developed for high energy physics applications and has already found widespread medical applications is the Medipix family of detectors [9]. 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 based 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. 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. As part of this project a dedicated software for a PC-based readout system will be designed with high speed data processing and analysis. The Fellow will also study the interaction of particles with matter and charge collection in different sensors, realize MC simulations of various detector geometries and combine these with a verification of the detector efficiency for different particle species. This has enormous potential for integration at various locations in the main accelerator and treatment beam lines and efficient integration will be considered with the other Fellows in this WP and work carried out by those studying facility optimization.

Imaging Solutions for a Prompt Gamma Camera

An early career researcher at IBA will develop software tools to perform and test the various new treatment workflows made possible by a ‘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 [10]. Currently, ionization chambers are the most commonly used detector type for beam intensity

ISBN 978-3-95450-177-9

measurement. However, they use thin foils which are passed by the beam and decrease the beam's quality by scattering. This Fellow will work on the development of dedicated software tools that are necessary to perform and test the various new treatment workflows made possible by the camera, using the iMagX platform developed by IBA [11]. Measured data will be compared with the delivered spots by means of irradiation logs without synchronization with the scanning controller, feedback on the penetration depth provided by the camera will be combined with feedback on the entrance point of the beam by optical means. Expected profiles will be simulated in multiple error scenarios with CERN and benchmarked against real data from measurements done across the OMA network.

RF-based Measurement of Ultra Low Charges

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 ESR4 will develop a sensitive RF-based current monitor for fully non-interceptive beam current measurement and connect this to ESR1 studies. To mitigate this problem a Fellow at PSI will develop a sensitive RF-based current monitor for fully non-interceptive beam current measurement and connect this to studies at Liverpool University. The work will target the measurement of beam currents as low as 0.3 nA. The design will be based on previous developments at the host [13], but will also take into account developments at other institutes through secondments. A prototype will be used for scans at PROSCAN and fully characterized during the 2nd year in the project.

Calorimeter for Proton Therapy and Radiography

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. Individual proton energy measurements at the 1% level are therefore essential for a proton imaging system.

In addition, an accurate calorimeter would also provide valuable quality assurance measurements of the treatment protons. In order to ensure that treatment is carried out safely, a range of quality assurance (QA) procedures are carried out each day before treatment starts. The majority of this time is spent verifying the Bragg Peak and depth dose curve of several proton beam energies. These energy QA measurements take significant time to set up and adjust for different energies.

A project at UCL seeks to adapt existing calorimetry technology for the precise measurement of proton energy in a clinical setting, see Fig. 2. This technology was developed by the UCL High Energy Physics group for the SuperNEMO experiment [14]. Preliminary calculations indicated that such a SuperNEMO detector could achieve an energy resolution in the region of 1% for clinical proton energies. Early experimental measurements using the 60 MeV clinical proton beam at the Clatterbridge Centre for Oncology demonstrated that the detector performance is as anticipated.

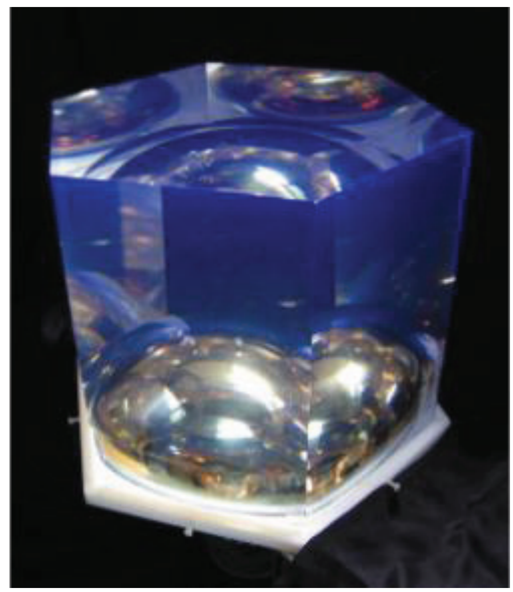

Figure 2: Photograph of detector for calorimeter applications at UCL, UK.

Existing Geant4 simulations will be adapted to optimize detector configuration for proton therapy. The PVT scintillator is already well characterized, reducing the initial effort required. Further measurements will be made with the Clatterbridge proton beam to fully characterize the performance of the detector. This will form the basis of the calorimetry stage for a proton CT system. In addition, this detector will also be used as the basis for a fast energy QA system. This would allow several energies to be measured across the full energy range available at the nozzle in only a few minutes, significantly reducing the time taken to carry out the daily QA.

Radiobiological Effectiveness of Protons

A Fellow at the University of Seville/CNA, Spain will investigate into the overall optimization of beam diagnostics for determination of all essential beam parameters. They will study the radiobiological effects of protons using the CNA facilities. Its 3 MV tandem accelerator and the cyclotron (delivering 18 MeV protons) will provide protons with energy ranges of interest for

ISBN 978-3-95450-177-9

radiobiological studies, irradiating cell samples. Beam diagnostics and dose measurements prior to, during and after irradiation are key to a full understanding: radiochromic film at the position of the cell samples, transmission ionization chambers for dosimetry; and CR-39 nuclear track plates for proton fluence measurements will be used and results analysed with GSI. Silicon detectors will be used at the position of the cell samples to determine proton energies with AMS. Finally the "low-dose hyper-radiosensitivity (LDHRS)" phenomenon [11] will be studied with protons to understand the dependence of LDHRS on the type of radiation and linear energy transfer (LET). This will provide a framework for cell studies and important information for a critical performance assessment of all diagnostics R&D in this WP.

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 [12-14]. 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 in beam diagnostics 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 and most Fellows will start their projects on 1 October 2016. 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.

REFERENCES

[1] 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] Optimization of Medical Accelerators Project, `http://www.oma-project.eu`

[6] J.S. Löffler and M. Durante, *Nature Reviews Clinical Oncology* 10, 411 24 (2013).

[7] The LHCb Collaboration, CERN-LHCC/200029, CERN (2002).

[8] T. Cybulski, *et al.*, "Design and first operation of a silicon-based non-invasive beam monitor", *Proc. of IPAC2014*, Dresden, Germany, paper THPME185.

[9] K.-F. Pfeiffer, *et al., Nucl. Instr. and Meth. A* 509 (2003), p. 340; X. Llopart, M. Campbell, *Nucl. Instr. Meth. A* 509 (2003), p. 157.

[10] J Smeets *et al.*, *Phys. Med. Biol.* 57 (2012) p. 3371–405.

[11] U. Schneider and E. Pedroni, *Medical Physics* 22, 353 (1995).

[12] DITANET, http://www.liv.ac.uk/ditanet

[13] OPAC, http://www.opac-project.eu

[14] LA^{3}NET, http://www.la3net.eu

ISBN 978-3-95450-177-9