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ENHANCING HADRON THERAPY THROUGH OMA

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Abstract

Continued research into the optimization of medical accelerators is urgently required to assure the best possible cancer care for patients. This is one of the central aims of the OMA (Optimization of Medical Accelerators) project, which received 4 M€ of funding from the European Commission within the Horizon 2020 program. A consortium of universities, research and clinical facilities, as well as partners from industry carry out an interdisciplinary R&D program across three closely interlinked scientific work packages. The three work packages address the development of novel beam imaging and diagnostics systems, treatment optimization including innovative schemes for beam delivery and enhanced biological and physical models in Monte Carlo codes, as well as R&D into clinical facility design and optimization. These studies aim to ensure optimum patient treatment along with maximum efficiency. This paper presents selected research highlights from two of the three work packages and discusses the impact on hadron therapy facilities around the world.

INTRODUCTION

Cancer is a major social problem, and it is the main cause of death between the ages 45-65 years. In the treatment of cancer, radio therapy (RT) plays an essential role. RT with hadrons (protons and light ions), due to their unique physical and radiobiological properties, offers several advantages over photons for specific cancer types. In particular, they penetrate the patient with minimal diffusion, they deposit maximum energy at the end of their range, and they can be shaped as narrow focused and scanned pencil beams of variable penetration depth. 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.

OMA is a European research and training network, funded within the Marie Sklodowska Curie Actions [1]. The project's R&D program ranges from life sciences (oncology, cell and micro biology and medical imaging) to physics and accelerator sciences, mathematics IT and engineering. Therefore, it is ideally suited for an innovative training of early stage researchers. By closely linking all the above research areas, OMA will provide an interdisciplinary education to its Fellows. This will equip them with solid knowledge in research areas adjacent to their core research field, as well as with business competences and give them a great basis for a career in research.

RESEARCH

OMA's main scientific and technological objectives are split into three closely interlinked work packages, as outlined before. The following sections summarize research progress made in selected project since the start of the network on 1 February 2016.

Beam Imaging and Diagnostics

Fundamental to any accelerator system, beam diagnostics are especially necessary in clinical radiotherapy facilities to monitor and evaluate the delivery of the beam to ensure safe but high quality treatment. Typically, ionization chambers (IC) are placed within the treatment head and intercept the beam before it exits through the nozzle, providing an online measurement of dose during operation. Protons will undergo interactions throughout their path, resulting in a slight degradation to the beam. A minimally destructive method of monitoring is ideally desired for this task. One such candidate is the VErtex LOcator (VELO) detector, originally used for the LHCb experiment at CERN. It consists of position sensitive, opposing silicon sensors surrounding a central aperture. This advantageous semi-circular design allows for intensity measurements of the beam 'halo', without any interception to the core of the beam. Using this technology, the QUASAR Group at the Cockcroft Institute and the University of Liverpool are developing an online beam monitor for quality assurance in medical accelerators. Several modifications were necessary for the novel repurpose of these detectors and currently the system is being optimized for integration into the 60MeV eye proton therapy beam at Clatterbridge Cancer Centre (CCC), UK. At present, the beam monitor exists as a standalone system, however, only the VELO hybrid sensors with dual azimuthal and radial geometry across 2048 silicon micro strips, are as their original LHCb state [2]. For migration out of the LHC environment, performance at full functionality and successful integration into CCC required specific amendment to conditions and restrictions within a defined area (integration zone). This warranted changes to the readout electronics, external synchronization of triggering and purpose built sensor shrouds, motorized translational stage, dedicated air flow and cooling system, inclusion of a faraday cup and dedicated VETRA data acquisition software [3]. In addition to these technological adaptations, simulation studies are also an important consideration in assessing the performance and capabilities of the beam monitor.

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In collaboration with the University College London, preliminary simulations were performed by OMA Fellow Jacinta Yap based at the University of Liverpool/Cockcroft Institute with the Monte Carlo simulation toolkit Geant4, using a detailed model of the CCC treatment beamline, see Fig. 1 [4].

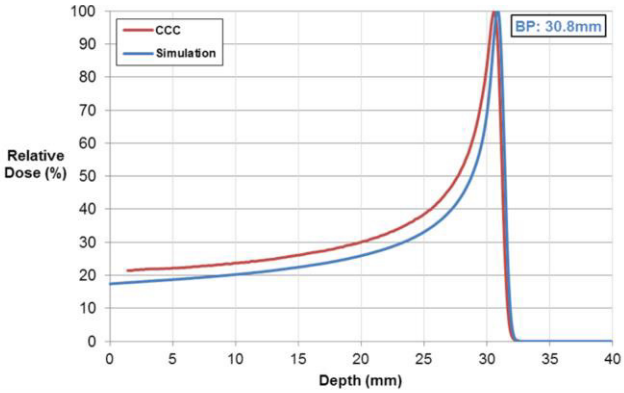

Figure 1**:** Measured and simulated proton beam dose profile at the Clatterbridge Cancer Center**.**

These initial results offer an overview of the general behavior of the beam, originating from the partition wall joining the cyclotron bunker to out past the treatment nozzle. Using this code protons and interactions can be tracked throughout the components of the delivery system and relevant information obtained to examine the beam and halo propagation. A specific focus was given to the designated integration zone where beam profiles and transverse intensity maps have been generated at the anticipated first position of measurement, relevant in assessing the expected distribution of signal and extent of the halo. These form the basis for halo maps; for comparison with VELO measurements, correlation of the halo with the beam core and for conversion to absolute dose during active delivery. However, further development including experimental measurements and additional beam dynamic studies will contribute to validation of the model. Determination of the Twiss functions and a better understanding of the transport of the beam from the accelerator bunker will also follow on from emittance measurements taken by the QUASAR group in 2012 [5]. Lastly, future work will look at beam cell interactions, complex damage and the repair of different cancer cell lines as part of collaboration with North West Cancer Research, UK.

In addition to beam profile and halo measurements, absolute beam intensity is a very important parameter which ideally can be measured during treatment. A non-interceptive beam current monitor has been developed by researchers including Fellow Sudharsan Srinivasan to investigate the measurement possibilities of low-intensity beams down to 1 nA for proton therapy machines without the drawback of interceptive monitors. This works on the principle of a reentrant cavity resonator [6] such that its fundamental mode resonance frequency of 145.7 MHz matches the second harmonic of the pulse repetition rate of the cyclotron beam i.e. 72.85 MHz. The Driven Modal analysis from the simulation tool ANSYS HFSS [7] was used for parametric model development and to optimize design parameters such as e.g. the position of the inductively coupled pick-ups. A ceramic plate has been inserted in the resonator gap to relax the precision required during manufacturing. A test bench has been designed and constructed for the characterization tests of the prototype. The simulation and measurement show good agreement. Deviations in the results are now subject to further analysis. For example, the dielectric constant of the MACOR ceramic is frequency dependent [8] which might cause the value used in the simulation to be different from the dielectric constant of MACOR that is used in the construction of the prototype.

Facility Design and Optimization

Medaustron is a synchrotron-based ion therapy center allowing tumor treatment with protons and light ions, in particular C^{6+}. Commissioning of all fixed lines, two horizontal and one vertical, has been completed for protons. Commissioning of a gantry using C^{6+} is progressing alongside studies into facility upgrade options [9]. In this context, two optimizations of slow extraction are under consideration: RF-channeling [10] and RF Knock Out [11].

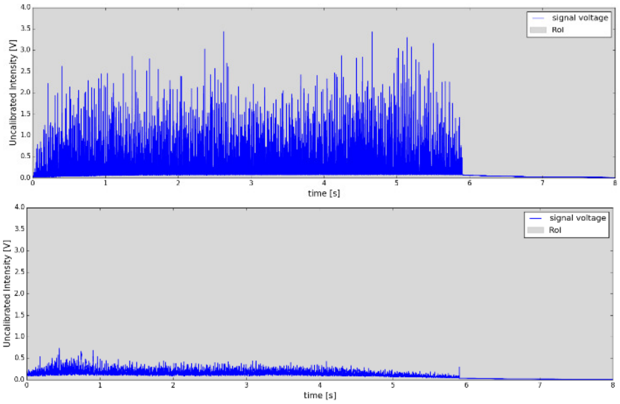

Figure 2: Extracted beam intensity over time, 50 kHz sampling. (top) Reference (bottom) with RF-channelling.

RF-channeling is a front-end acceleration technique that, coupled with the 3^{rd} order resonance driven in momentum by a betatron core, showed a significant spill ripples reduction, fundamental to safely operate the machine at the highest intensities. RF Knock Out is an alternative extraction technique which opens up interesting possibilities for fast beam energy and intensity modulations. Preliminary tests led by OMA Fellow Andrea De Franco, who is based at Medaustron, demonstrated the feasibility of implementation using the plates of an already installed Schottky monitor as a transverse kicker to increase betatron oscillation amplitudes. Focus of the development is now on beam optics optimization, choice of RF signal pattern to feed the exciter with, relevant electronics chain, and main ring low level RF adaptations, see Fig. 2.

The development of low-β high-gradient (HG) accelerating structures is one of the main requirements for implementation of compact and cost-effective linear hadron accelerators. They need to provide particle beams with energies in the range between 70-230 MeV for protons and 100-400 MeV/nucleon for carbon ions. For effective acceleration to higher energies, HG S-band structures are used. An overview of 3 GHz Backward Travelling Wave (BTW) structures currently under test is given in [12]. This accelerating structure is part of the TULIP project [13], a single room facility for proton therapy. The prototype has been designed to accelerate protons with energies of 70 MeV and accelerating gradients up to 50 MV/m.

HG operation of RF cavities is limited by undesired RF breakdowns (BD) as these cause beam losses, cavity surface damages, radiation and vacuum deterioration. The breakdown probability of a given RF structure has to be as low as possible, with a limit of order of 10^{-7} BDs per RF pulse. The main goal of a study carried out by OMA Fellow Anna Vnuchenko at IFIC/CSIC in Valencia, Spain is to define the HG limits of S-band cavities in terms of breakdown rate (BDR). Specifically, she has been testing a structure that includes BD localization within the structure and study of the BD dependence on RF field and pulse parameters [14]. The first high-power test of a BTW structure has been tested on the S-band test facility at CERN. A computer-controlled algorithm was used on the Xboxes to test the structure [15]. Conditioning was carried out by increasing the input power level and pulse width in a controlled manner whilst limiting the BD rate to about $3{\cdot}10^{-5}$ BDs per pulse. Fig. 3 shows results from conditioning. A typical pulse length for medical accelerators is 2.5 µs flat-top with a rise time equal to the filling time of the structure. The next step will be further testing of the structure with longer pulse lengths as this is of significant interest. Threshold detection of reflected signals from the structure and dark current signals, measured from upstream and downstream Faraday cups are used to determine if a BD has occurred.

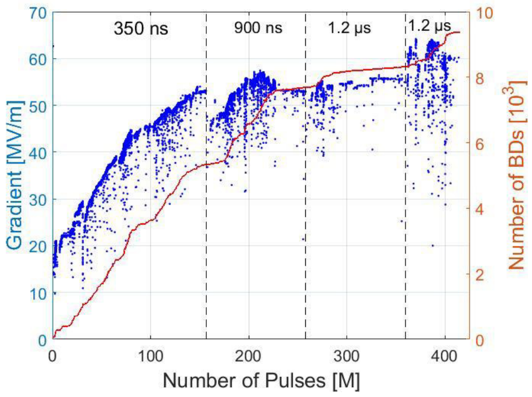

Figure 3: Conditioning history of a BTW prototype.

Data is then analyzed offline to characterize the detailed behavior of the structure. Differences in timing between the transmitted and reflected signals have been used for BD localization. This measurement allows determination of the spatial distribution of the BD along multiple cells of the structure. The results show that BDs are spread along the structure. A structure analysis was also carried out to study dark current. During operation of the structure, field emission currents vary over time. Higher values are observed during initial conditioning due to unavoidable imperfections on the surface. To quantify the quality of the surface of the structure, a power scan measuring the dark current level was performed using a radiation monitor and Faraday cups. A detailed discussion of the results and future plans is given in [14].

TRAINING EVENTS

Training within OMA consists of hands-on workshops via local cutting edge research projects, lectures and seminars provided to the Fellows at their host institution, as well as a network-wide training program that is also open to external participants. This training concept is based on the successful programs developed within the DITANET, oPAC and LA³NET projects [16-18]. The international events help broaden the knowledge and experience of Fellows beyond their core research project and improves their employability. Since project start one researcher skills school, two international schools on medical accelerators (4-9 June 2017 at CNAO, Italy) [19] and Monte Carlo Simulations (6-10 November 2017 at LMU Munich, Germany) [20], as well as one Topical Workshop on Facility Design Optimization for Treatment at PSI in Switzerland [21] have already been held. Presentations from all events are available via the respective indico page.

SUMMARY AND OUTLOOK

OMA is one of the largest Innovative Training Networks within the Marie Sklodowska Curie Actions in the European Union's Horizon2020 program It has received around 4 Million Euro of funding to train 15 Fellows based at institutions across Europe. This paper has given selected examples of initial research progress made across two of the three scientific work packages to highlight the range of studies being made. In addition, the paper has briefly summarized the trainings already offered to the OMA Fellows. There are now two more Topical Workshops planned, one at CERN on 4th and 5th June on Diagnostics for Beam and Patient Monitoring and one on Accelerator Design and Diagnostics later in 2018. An advanced School on Medical Accelerators will be hosted at Medaustron in spring 2019. An outreach Symposium will be held at the ACC in Liverpool on 28 June 2019, and an international conference later in 2019 will round off the events organized for the network's Fellows and the medical and accelerator communities. Information about all events will be made available via the project website [1] and social media.

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