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V 35

Mixed fields of range-shifted and pristine bragg peaks are safe and improve sparing of collateral OARs in PBS proton therapy

Agnieszka Wilk-Kohlbrecher, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, Agnieszka.Wilk-Kohlbrecher@psi.ch
Rosalind Perrin, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, rosalind.perrin@psi.ch
Nanta Fachouri, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, nanta.fachouri@psi.ch
Vasilis Rompokos, Radiotherapy Department, University College Hospital, London, Vereinigtes Königreich, vasilis.rompokos@uclh.nhs.uk
Francesca Albertini, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, francesca.albertini@psi.ch
David Oxley, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, david.oxley@psi.ch
Sairos Safai, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, sairos.safai@psi.ch
Damien Charles Weber, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, damien.weber@psi.ch
Alessandra Bolsi, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, alessandra.bolsi@psi.ch
Tony Lomax, Center for Proton Therapy , Paul Scherrer Institute, Villigen-PSI, Schweiz, tony.lomax@psi.ch

Purpose: Treating shallow tumors with Pencil Beam Scanned (PBS) proton therapy typically requires a range-shifting pre-absorber to deliver pencil beams at ranges <4 cm. Such absorbers however degrade the lateral profile of the beam by widening the penumbra. For this reason, Gantry-2 at PSI supports two pre-absorber modes, **field-specific** (a pre-absorber of 4.1 cm water-equivalent thickness being in/out for the full field delivery), or **Bragg-Peak (BP)-specific** (the afore-mentioned pre-absorber being inserted automatically during delivery **only** for BPs with range <4 cm). In this work we show the potential clinical advantage in a planning study, and report on clinical commissioning measurements of mixed fields.
Methods: Different clinical patient plans, originally planned and delivered with **field-specific** pre-absorption, have been re-planned retrospectively using the **BP-specific** approach, and the resulting dose metrics for PTVs and OARs compared to those of the clinically applied plan. In parallel we measured BP-specific-mode fields to investigate the dosimetric effect of mixing range-shifted and pristine BPs with different lateral penumbrae, both absolute depth-dose, and spatially-resolved relative dose using a wedge phantom and a CCD camera-scintillating screen device.
Results: The planning study demonstrated that field- and BP- specific pre-absorption provide comparable target coverage and homogeneity, while the BP-specific approach substantially reduces the planned fields' lateral penumbrae (by ~2 mm). OAR D2 doses could be reduced (by 1-11 GyRBE) when using BP-specific pre-absorption. Absolute dose measurements in water of the field- compared to BP- specific modes were within 2.3% at all depths. Field flatness measurements from CCD images under the wedge phantom were all within 2.0%.
Conclusion: We demonstrated that automatic insertion of the pre-absorber only for low range BPs improves plan quality. Clinical commissioning of this mode showed that the mode is safe for application to patients, and will become the default mode for treatment plans at our centre.

V 36

Improving the lateral fall-off for proton pencil beam scanning

Carla Winterhalter, Paul Scherrer Institute, Villigen PSI, Schweiz, carla.winterhalter@psi.ch
Sairos Safai, Paul Scherrer Institute, Villigen PSI, Schweiz, sairos.safai@psi.ch
David Oxley, Paul Scherrer Institute, Villigen PSI, Schweiz, david.oxley@psi.ch
Damien Charles Weber, Paul Scherrer Institute, Villigen PSI, Schweiz, damien.weber@psi.ch
Tony Lomax, Paul Scherrer Institute, Villigen PSI, Schweiz, tony.lomax@psi.ch

Pencil beam scanning (PBS) is widely considered to be the future of proton therapy. However, without collimation, the lateral fall-off for PBS for shallow targets is inferior to passive scattering. The lateral fall-off for uncollimated PBS is depependent on two main parameters – the width of the pencil beam and the ability of the optimisation to laterally enhance field-edge pencil beams (edge-enhancement) such that the fall-off approaches that of a single pencil beam. In turn, the size of the pencil beam depends on energy, the thickness of any material in the beam-path, e.g pre-absorbers, and the air-gap between these and the patient. Here we comprehensively investigate the potential of collimation to improve PBS lateral fall-off taking all these factors into account. For all investigations, mono-energetic, square PBS fields based on PSI Gantry2 commissioning data (ranges 4.15cm-30.70cm) have been simulated in a water phantom, using the TOPAS3.0.p1 Monte Carlo tool. Both fixed (4cm water equivalent) and variable (8x5mm water equivalent, individually insertable range-shifter plates) pre-absorbers have been simulated. Without pre-absorber, collimation alone improves 80-20% penumbras at the Bragg-peak only for ranges up to 10cm (10cm air-gap). Sharpest lateral fall-off is achieved with edge-enhanced collimation (the inclusion of laterally collimated pencil beams into the optimisation) which reduces penumbra from 5.4mm to 2.8mm compared to uncollimated PBS (range 4.15cm, 10cm air-gap). For air-gaps above 5cm, the use of a variable, rather than fixed, pre-absorber reduces the penumbra, for example for the 20cm air-gap from 8.8mm to 6.2mm and further to 5.0mm when combined with edge-enhanced collimation (3.99cm range). Best penumbras were reached with pre-absorption devices placed downstream, rather than upstream, of the collimator. In conclusion, using edge-enhanced collimation, and the best possible arrangement of components, the lateral fall-off for PBS could be substantially improved, leading to less dose to the surrounding healthy tissue.

V 37

Investigation on beam width tolerances for proton and carbon ion pencil beam scanning

Benjamin Ackermann, Medizinphysik, Heidelberg Ion-Beam Therapy Centre (HIT), Heidelberg, Deutschland, benjamin.ackermann@posteo.de
Stephan Brons, Medizinphysik, Heidelberg Ion-Beam Therapy Centre (HIT), Heidelberg, Deutschland, stephan.brons@med.uni-heidelberg.de
Malte Ellerbrock, Medizinphysik, Heidelberg Ion-Beam Therapy Centre (HIT), Heidelberg, Deutschland, malte.ellerbrock@med.uni-heidelberg.de
Oliver Jäkel, Medizinphysik, Heidelberg Ion-Beam Therapy Centre (HIT), Heidelberg, Deutschland, oliver.jaekel@med.uni-heidelberg.de

Beside beam spot position and range, the beam spot width is one of the central parameters for the correct application of ion beam therapy plans utilizing pencil beam scanning techniques. The aim of this work is to investigate the influence of variations of the nominal beam width on the dose distribution of cubic dose volumes, utilized in QA.
Physical absorbed dose is optimized for cubic dose volumes with a spread out bragg peak (SOBP) of 3x3x3 cm^3 using the treatment planning system syngo RT Planning (Siemens, Germany). The nominal dose in the SOBP is 0.5 Gy. The depth in water of the centre of the cubes is 5.0, 12.5 and 20.0 cm, respectively. Plans are recalculated with MATLAB (The MathWorks, United States) with nominal and varied beam width. Dose distributions are analyzed performing a 3D gamma index analysis with criterias of 1mm distance to agreement and 5% dose deviation, normalized to global maximum. The maximum tolerable beam width deviations are determined where all points still show a gamma index < 1.
The maximum tolerable beam width variations for proton and carbon ion plans in medium and large depth are between -12%/+17% and -17%/+25%. The plans in small depth show rather small tolerable deviations with -7%/+10% for protons and -8%/+16% for carbon ions. It is observed, that this is mainly affected by the strong variation of the particle numbers per scan spot in each energy slice, optimized to achieve lateral penumbras as small as possible. Following this observation, we created plans in small depth with the same field size consisting uniform scanned energy slices. Resulting tolerable beam width deviations for these plans are -13%/+13% for protons and -19%/+25% for carbon ions.

V 38

Optimization of a compton camera prototype for particle beam range verification

Silvia Liprandi, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, silvia.liprandi@physik.uni-muenchen.de
Saad Aldawood, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, S.Aldawood@physik.uni-muenchen.de
Tim Binder, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, tim.binder@physik.uni-muenchen.de
Georgios Dedes, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, g.dedes@physik.uni-muenchen.de
Michael Mayerhofer, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, m.mayerhofer@physik.uni-muenchen.de
Akram Mohammadi, Imaging Physics, National Institute of Radiological Sciences, Chiba, Japan, mohammadi.akram@qst.go.jp
Fumihiko Nishikido, Imaging Physics, National Institute of Radiological Sciences, Chiba, Japan, nishikido.fumihiko@qst.go.jp
Sodai Takyu, Imaging Physics, National Institute of Radiological Sciences, Chiba, Japan, takyu.soudai@qst.go.jp
Ingrid Valencia-Lozano, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, Ingrid.Valencia@physik.uni-muenchen.de
Taiga Yamaya, Imaging Physics, National Institute of Radiological Sciences, Chiba, Japan, yamaya.taiga@qst.go.jp
Katia Parodi, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, katia.parodi@physik.uni-muenchen.de
Peter G. Thirolf, Medizinische Physik, Ludwig Maximilians Universitaet Muenchen, Garching, Deutschland, Peter.Thirolf@physik.uni-muenchen.de

At LMU Munich we are developing a Compton camera for medical imaging. The camera is designed to detect prompt-γ rays induced by nuclear reactions during irradiation of tissue in particle therapy. Our prototype consists of two components: the scatterer is a stack of 6 double-sided silicon strip detectors and enables the tracking of the Compton scattered electrons; the absorber consists of a monolithic $LaBr_3$(Ce) scintillator and registers the energies of the Compton scattered γ-rays. Prompt γ-ray imaging requires the detection of the interaction position and deposited energies in both parts of the Compton camera. The camera has been characterized offline in the laboratory and online at clinical proton beams. Different consolidations and upgrade options are currently being studied: an upgrade of the DSSSD signal processing turned out to be mandatory. ASIC- and non ASIC-based alternatives are presently being evaluated in view of the performance requirements expected for a realistic treatment scenario. Improved shielding (thermally as well as EMP-related) together with an active air-cooling system resulted in a reduction of the DSSSD leakage current by about a factor of 4, helping the lower-energy signals to be registered. $CeBr_3$, comparable in performance to $LaBr_3$(Ce), however not suffering from internal radioactivity background, is being evaluated as an alternative to the present absorber. The concept of a monolithic absorber is being compared to a segmented scintillator (4-layer depth-of-interaction detector) from LYSO. The final goal is to design a versatile detector system from the experience gained with the present prototype and based on a compact and combined signal processing of scatterer and absorber. Such a Compton camera system could be applied for prompt-γ particle beam range monitoring and, in a hybrid geometry with PET detectors, for registering triple photons coincidences from suitable positron emitters ("γ-PET" mode) to exploit the enhanced sensitivity provided in this scenario.

V 39

Comparison of prompt gamma emission for helium and proton beams: a Monte Carlo study

Riccardo Dal Bello, Medical Physics in Radiooncology, DKFZ, Heidelberg, Deutschland, r.dalbello@dkfz.de
Joao Seco, Medical Physics in Radiooncology, DKFZ, Heidelberg, Deutschland, j.seco@dkfz.de

Charged particle radiation therapy relies on the favourable dose distribution of light ions compared to conventional radiotherapy. Among other ion species, Helium-4 beams present advantageous characteristics: reduced lateral and distal spread compared to protons and reduced fragmentation compared to Carbon-12. The finite range of the primary particles potentially allows sparing healthy tissue, which however requires a superior capability in range control. Compared to other range verification techniques such as post-treatment MRI or PET; the Prompt Gamma Imaging (PGI) permits a real-time range monitoring due to the instantaneous (<<ns) emission of the secondary radiation. Time and energy resolved PGI coupled with knowledge of the discrete reactions cross-sections has been proposed for absolute range verification. We aim to optimize the technique for Helium-4 beams. A systematic study should be supported by reliable Monte Carlo simulations. In this work, we adopted the Geant4 simulation toolkit to investigate the performance of different nuclear interaction models. For hadron-therapy applications, the Geant4 collaboration recommends the QGSP_BIC_HP physics lists in which intermediate energy (< 10 GeV) inelastic nuclear interactions are handled by the Binary Cascade Model (BIC), which has been shown to overestimates the experimental PG yield up to 50% for protons. The optimization of the more complex Quantum Molecular Dynamics Model (QMD) provides better results. Since a dedicated optimization for Helium-4 beams is missing, we investigate the performance of customized physics for such beams based on three different inelastic nuclear interaction models: Binary Light Ion Reaction (BICLI), Liege Intranuclear Cascade Model (INCL) and QMD. Our study aims at resolving the intensity of the discrete Gamma lines for different projectile energies towards experimental comparison. The INCL and QMD models reproduce the theoretical expectations better than BICLI. The investigated models show 2 to 4 times higher PG yields for Helium-4 compared to proton beams with the same range.