# Medical Accelerators in BDSIM

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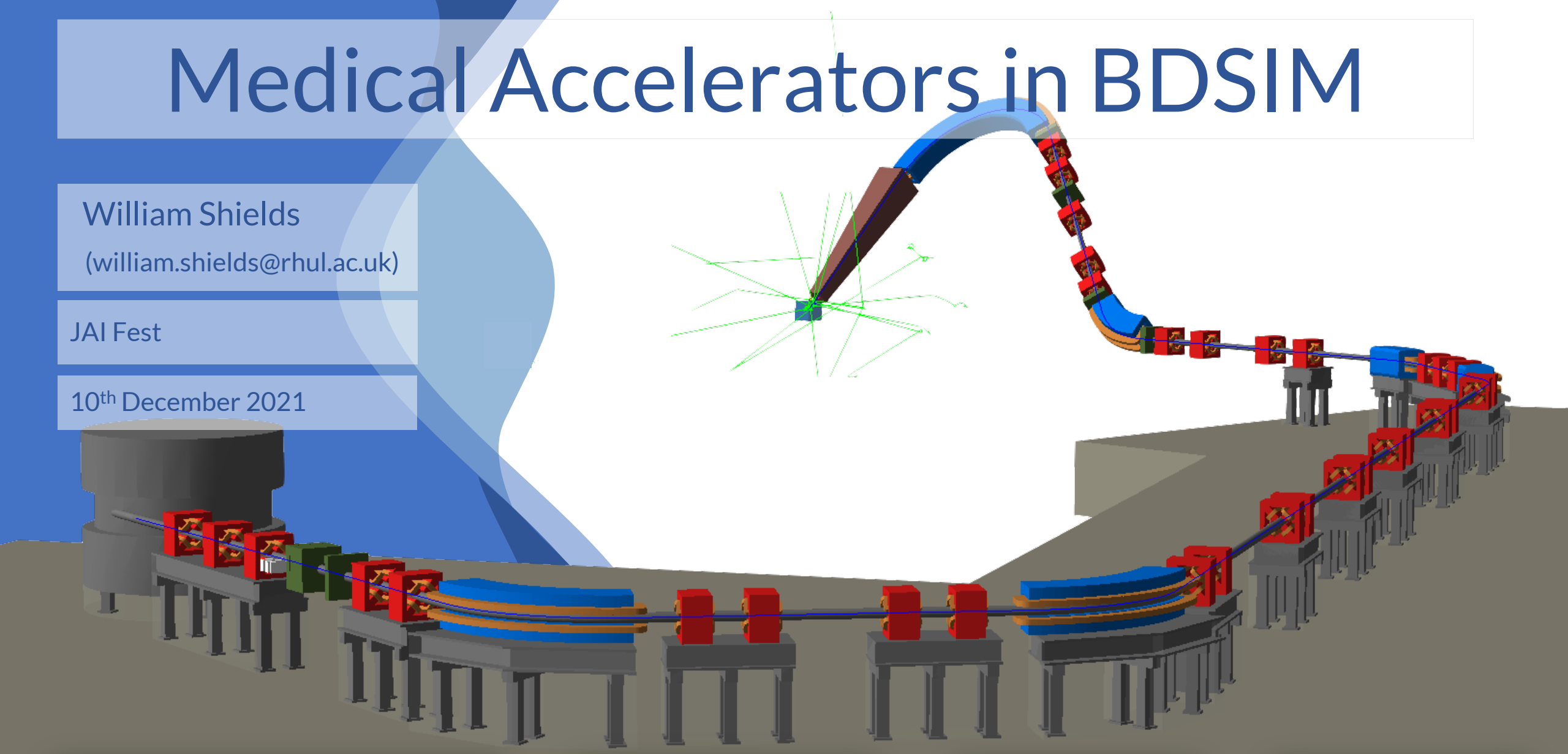
JAI Fest

10th December 2021



John Adams Institute for Accelerator Science

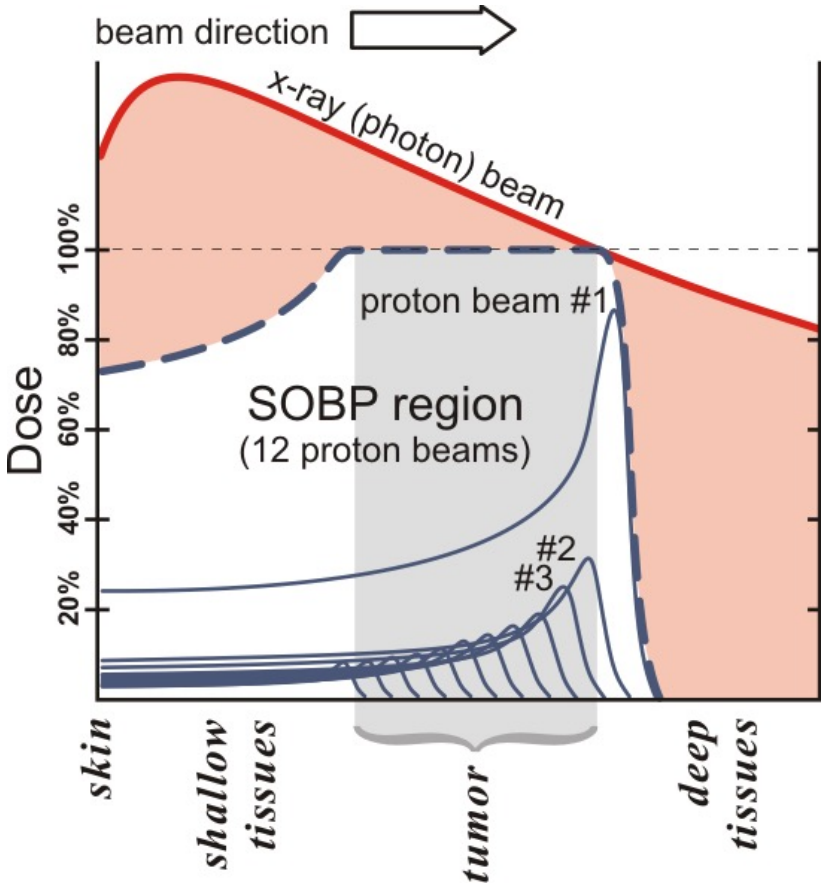
BDSIM

CCAP Centre for the Clinical Application of Particles

ROYAL HOLLOWAY UNIVERSITY OF LONDON

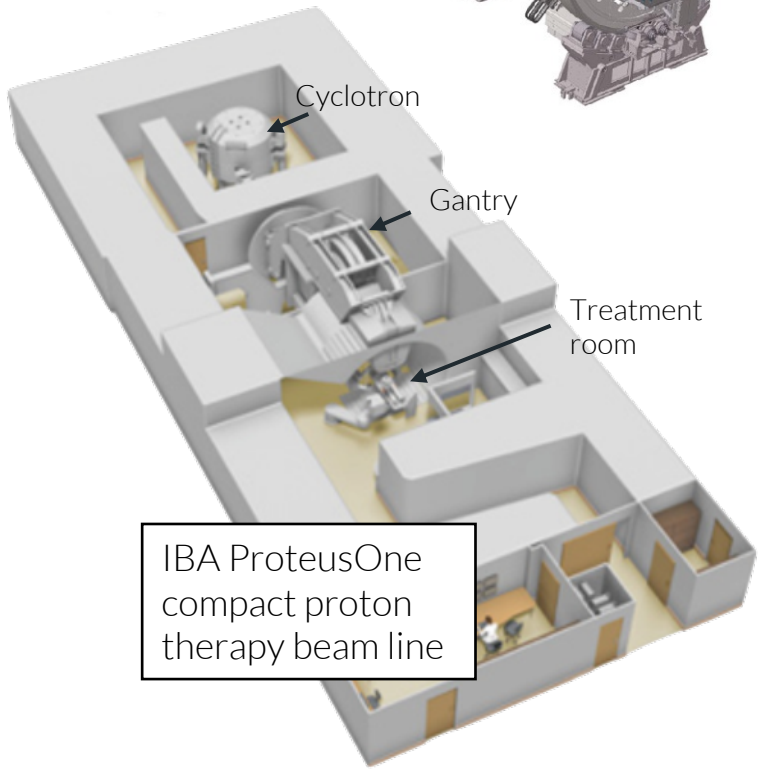
# Proton Therapy: Concept

- 70-250 MeV protons to deliver a dose at a precise depth – the Bragg peak.
- Depth dependant on particle energy.
  - Control position of the dose delivered to the patient.




- Spread Out Bragg Peak (SOBP): multiple beams with different energies.
  - Uniform dose across the tumour.
  - Reduced dose to the surrounding healthy tissue.
- Beams commonly delivered through gantries that rotate around patients.
- Multi-room facilities as beam lines from a fixed energy cyclotron.
- Compact single-room solutions.


Centre for Proton Therapy, PSI

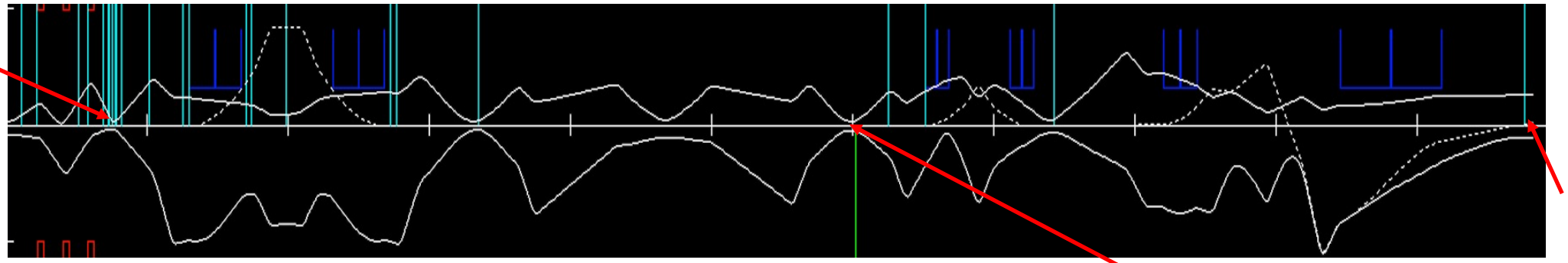



IBA ProteusOne compact proton therapy beam line

# Proton Therapy: Gantry Modelling

- Modelling used to understand & improve accelerator performance.
  - Particle tracking: MADX, PTC, TRANSPORT, Sixtrack, OPAL, etc.
  - Typically no particle-matter interactions – can limit the validity of optics model.

- Typical technique: run tracking codes, inspect machine optics, and identify regions of interest.
  - Develop independent Monte Carlo simulations as required in a toolchain.




- Single-room compact solutions require more detailed simulation.
  - Tight coupling of beam characteristics, beam losses, and shielding.
  - Needs simultaneous consideration: only achievable with start-to-end Monte-Carlo beam line modelling.

# BDSIM

- Beam Delivery Simulation (BDSIM):
  - Open-source code for Monte Carlo particle tracking through 3D models of accelerators.
- Combines Geant4's geometry & particle-matter interaction physics with accelerator tracking routines.
- Specific developments added and validated for medical beam line modelling.
  - Tracking routines, variance reduction, scoring, degrader, etc.

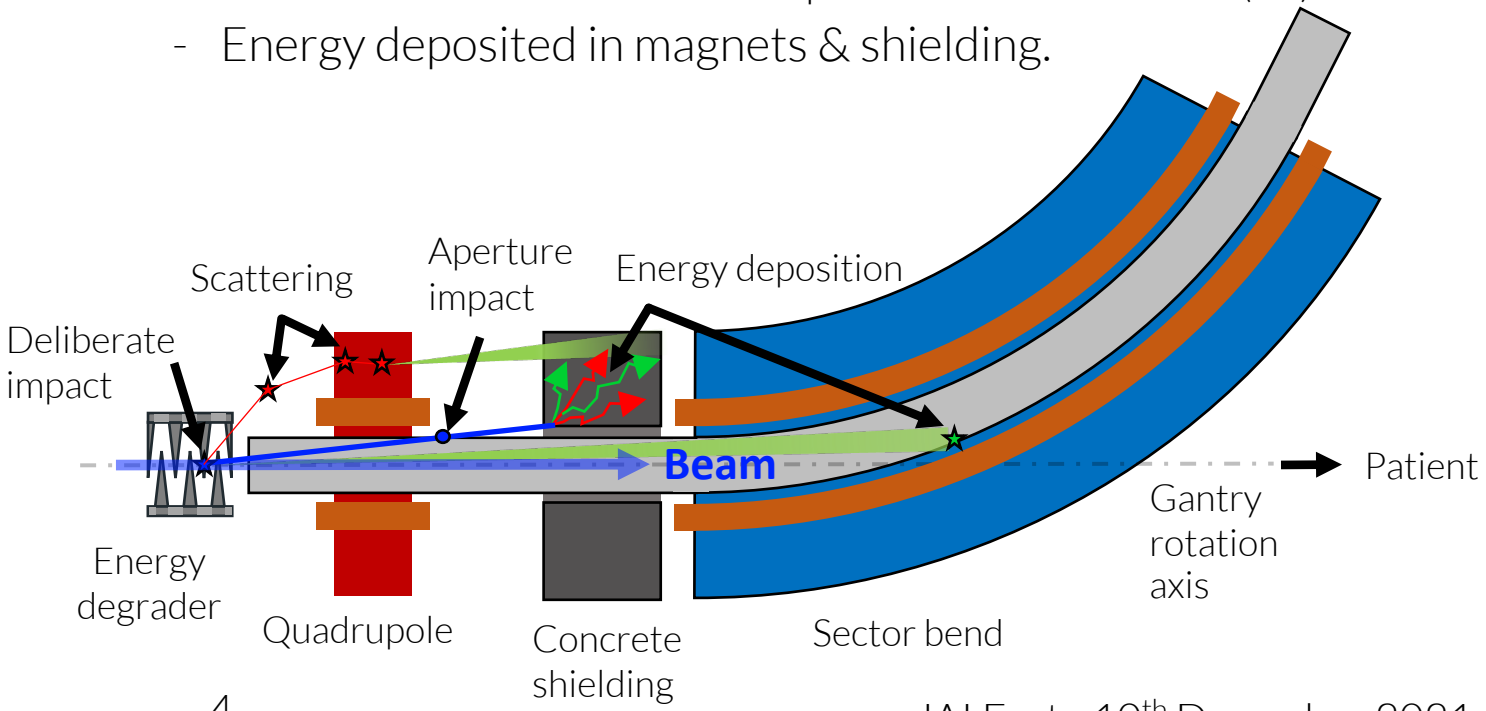
BDSIM Beam Delivery Simulation

GEANT4 A SIMULATION TOOLKIT

BDSIM Paper: Computer Physics Communications (252), July 2020, 107200

BDSIM Manual: http://www.pp.rhul.ac.uk/bdsim/

- Model energy deposition throughout a particle accelerator.
- Example:
  - Protons deliberately collide with an energy degrader & scatter.
    - Aperture hits downstream.
  - Secondary particles continue propagating.
    - Scatter off accelerator components & environment (air).
  - Energy deposited in magnets & shielding.



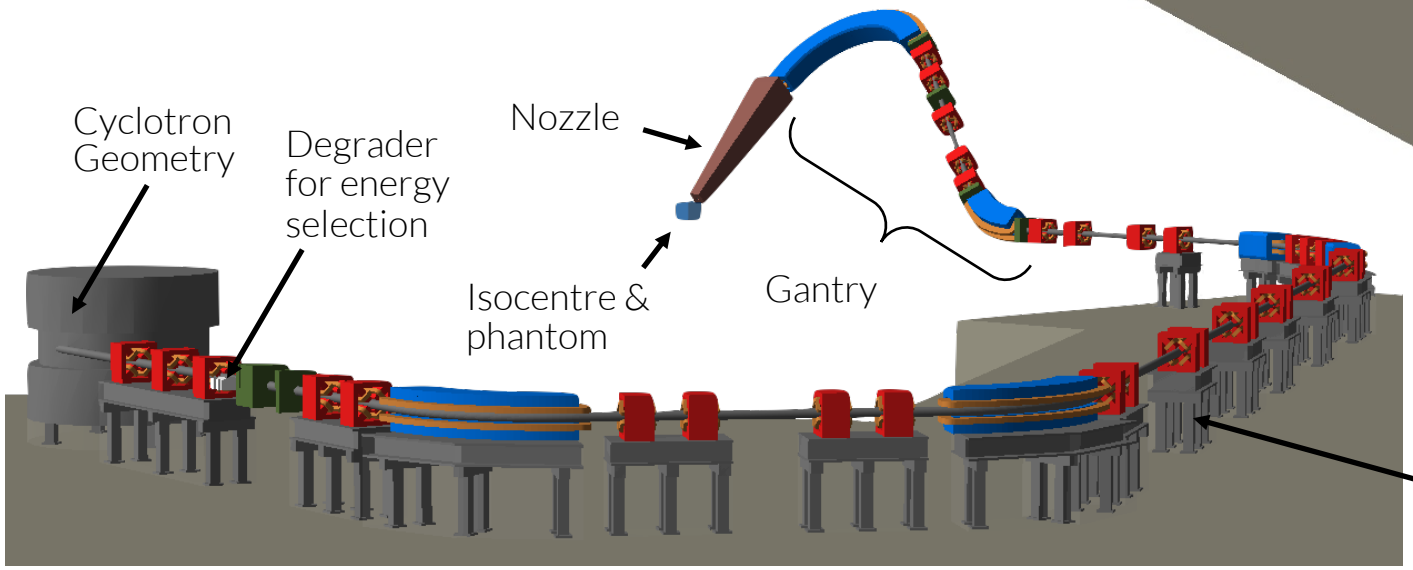
# BDSIM Medical Studies

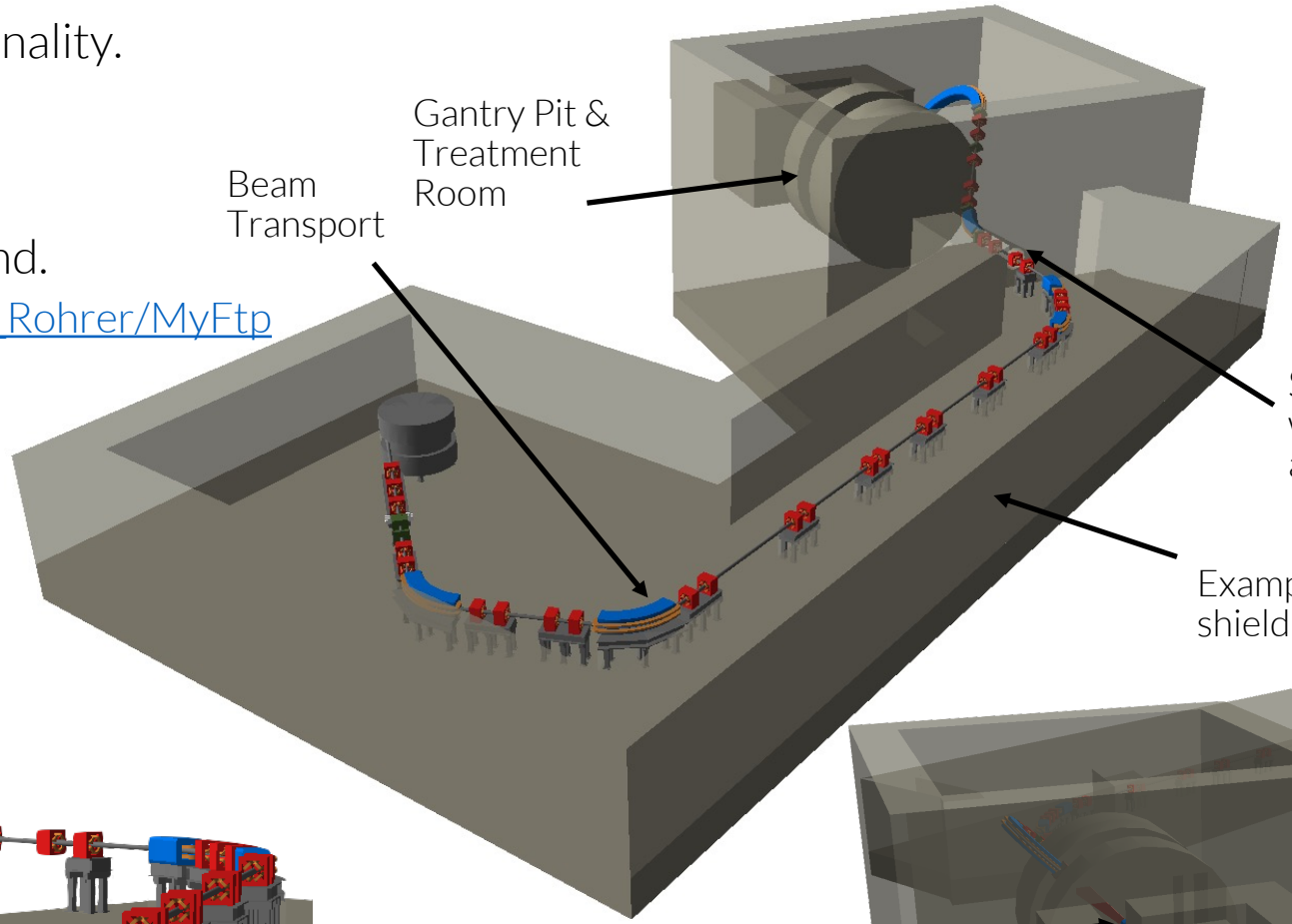
- RHUL In-House Model
  - Demonstrate BDSIM's medical capabilities
- IBA & ULB
  - ProteusOne
  - ProteusPlus
- CCAP
  - Design of proposed UK radiobiology research facility
- MedAustron
  - Nozzle & collimation studies
- PSI
  - Isotope production beam line, gantry 2 & 3 simulations
- Huddersfield/Manchester
  - Beam scraping diagnostic tool to measure beam energy & energy spread
- Clatterbridge
  - Ocular proton therapy beam line (UCL/Liverpool)

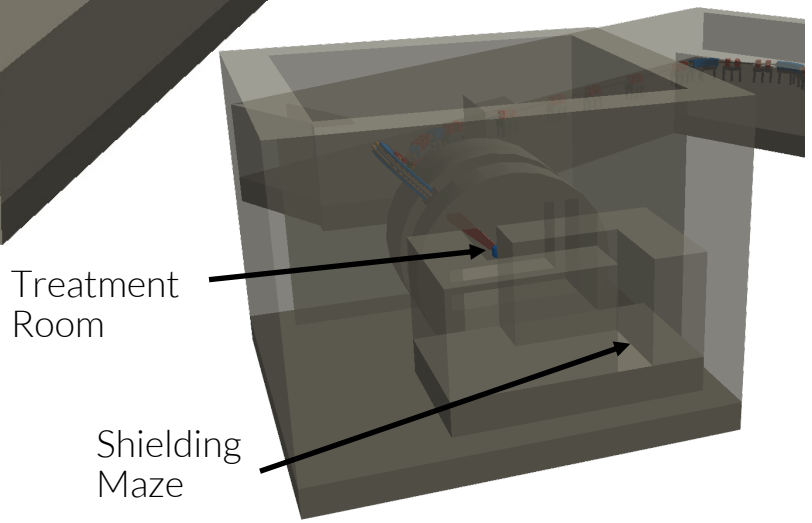
# BDSIM In-House Model

- Model for demonstrating BDSIM's medical functionality.
  - Overcome limitations of traditional tracking codes.
- Publication to be submitted imminently.
- Gantry 2 from Paul Scherrer Institute in Switzerland.
  - Lattice publicly available: http://aea.web.psi.ch/Urs_Rohrer/MyFtp
  - Conceptual design – different from real machine.

- Since added geometry for shielding, magnet supports, cyclotron, nozzle, & water phantom.



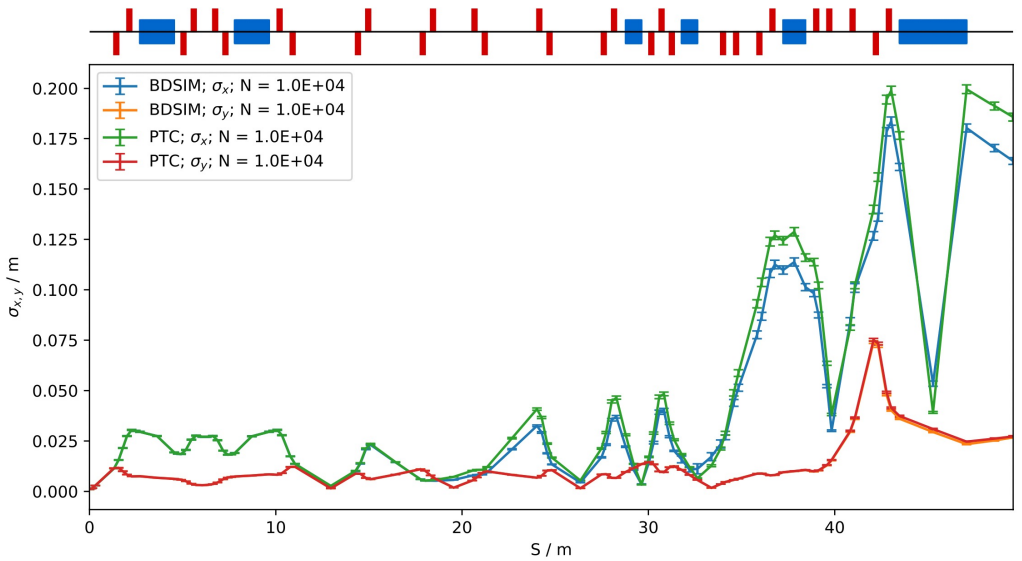



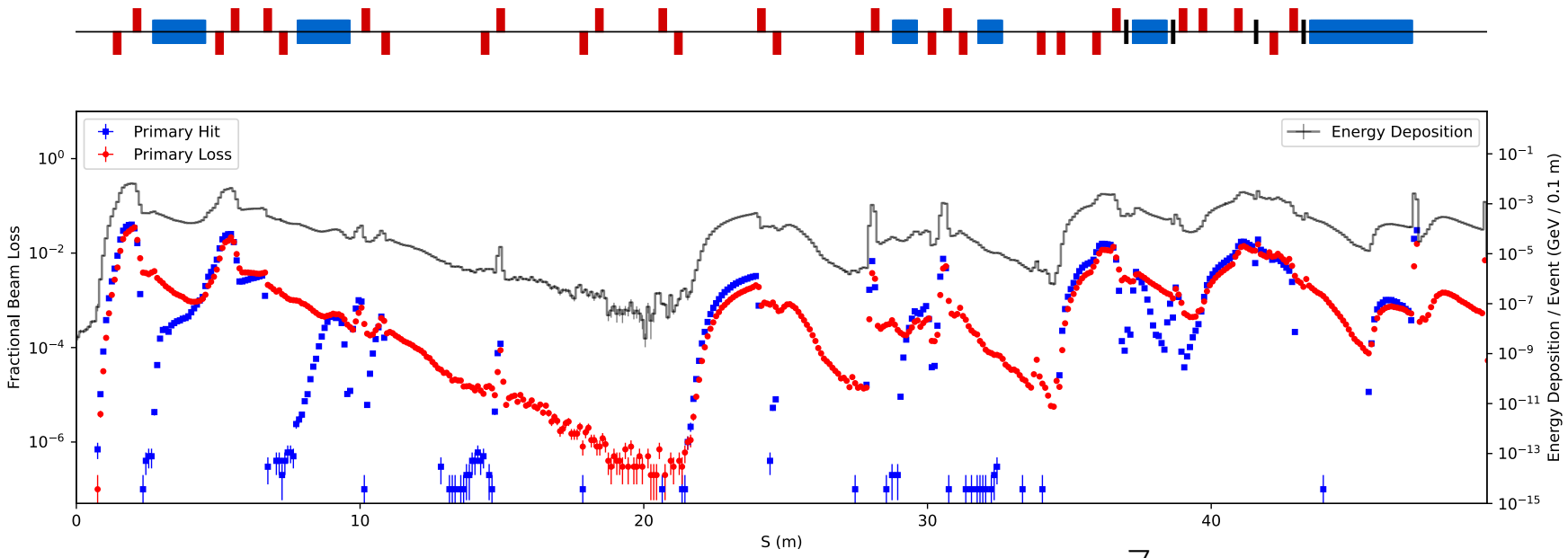



# Optics & Losses

- Reasonable agreement seen with PTC.
  - Difference due to losses.
  - Wide aperture model – 3.75 cm nominal aperture.

- Optics validation of many machines in BDSIM.
  - Medical & beyond.

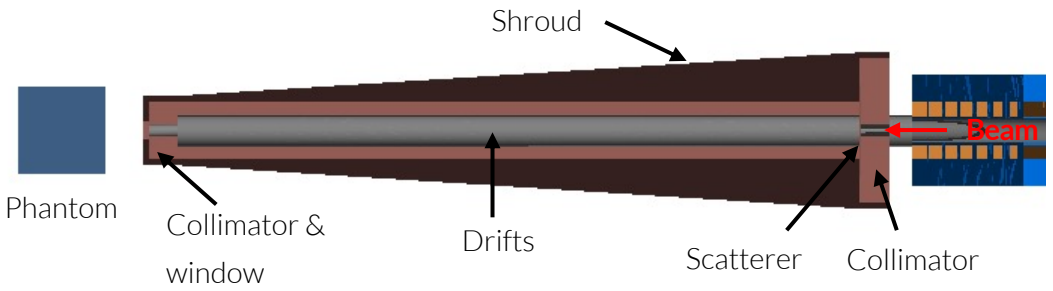


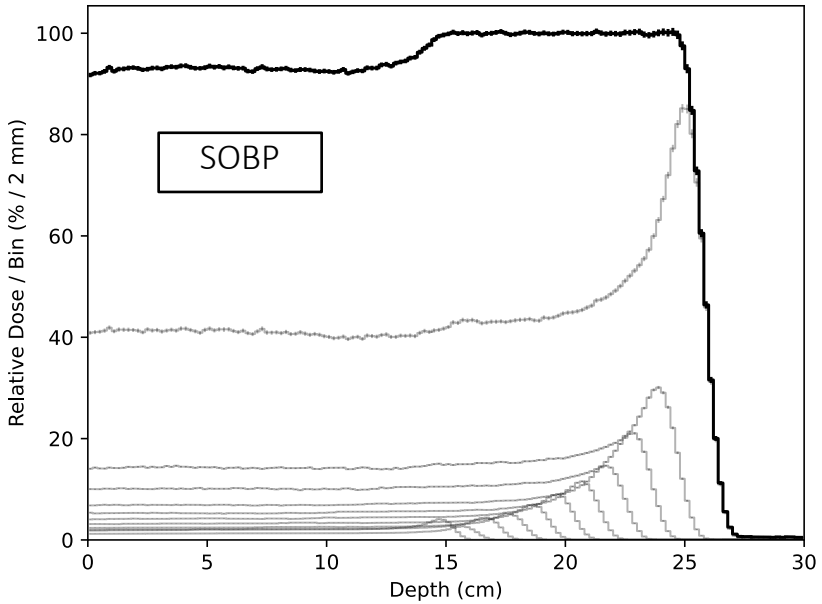



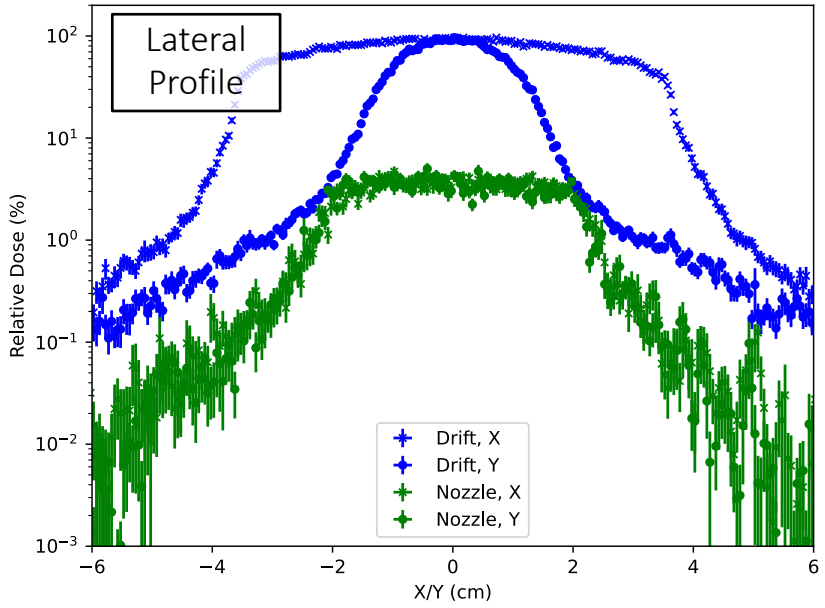

- Hits, losses, and energy deposition seen throughout.
- Machine protection.
- Particularly useful for machines with SC magnets.
  - Ion therapy beam lines.

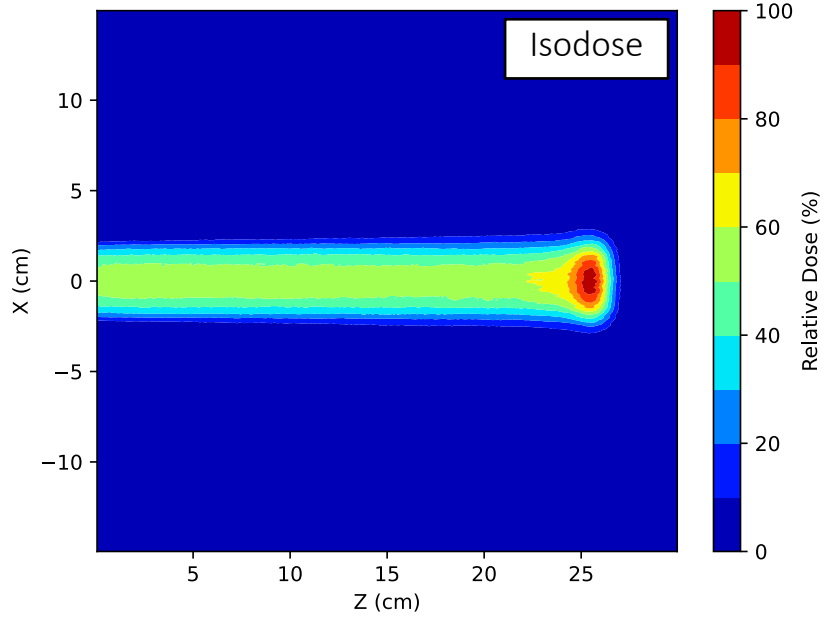
# Nozzle: Dose Formation

- Demonstrate that properties of the delivered dose can be considered whilst modelling the accelerator.
- Single scattering nozzle to improve dose formation.
  - Unsuitable dose with beam shaping elements.
  - Low efficiency – heavy collimation & losses.
- Good depth-dose uniformity, improvement in lateral dose profile.
  - High proximal dose from scatter-induced low energy tail.

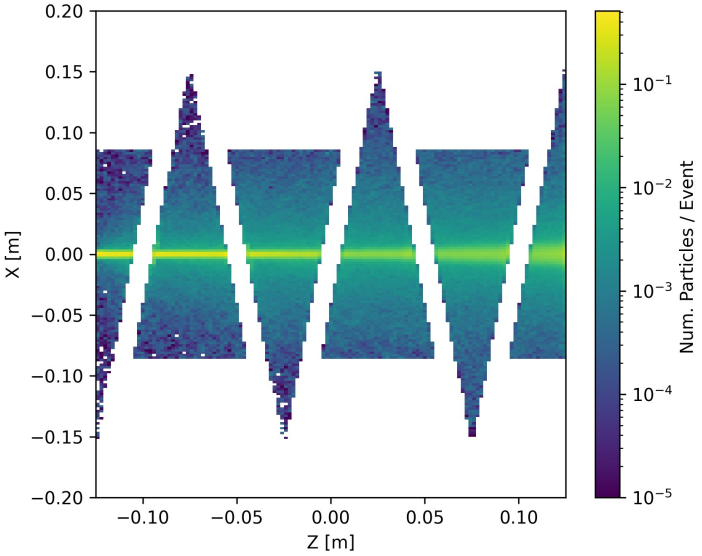


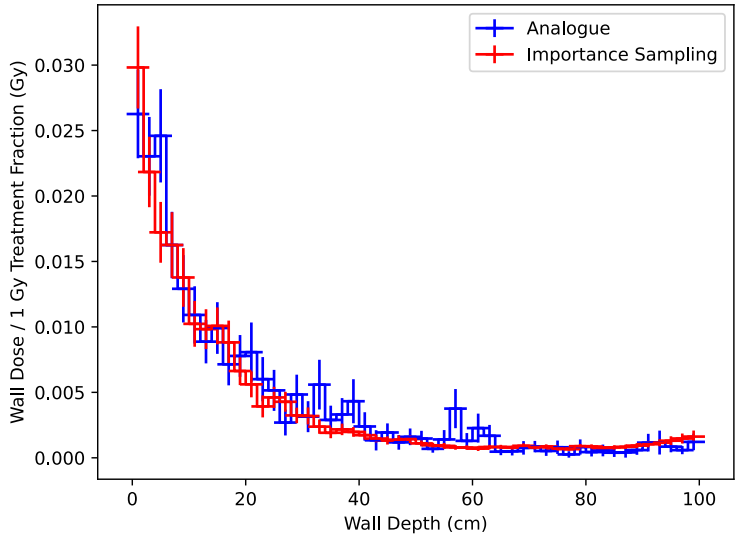



# Other capabilities

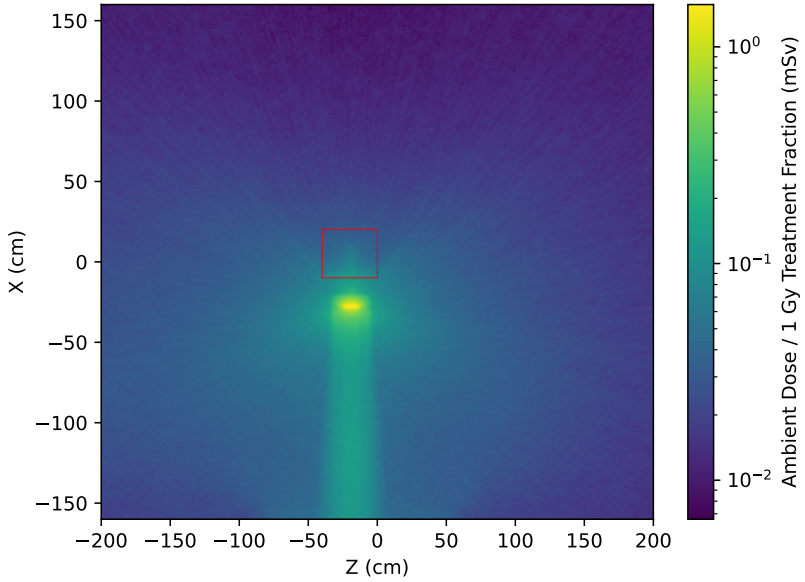


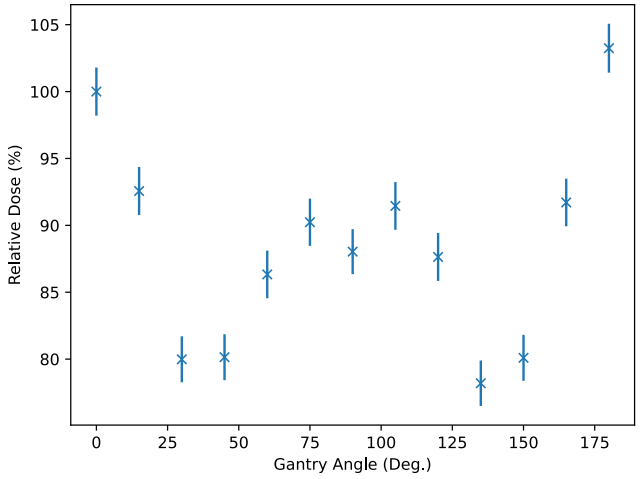

- Beam profiling after the energy degrader.
- Hits and energy deposition in beam line elements.

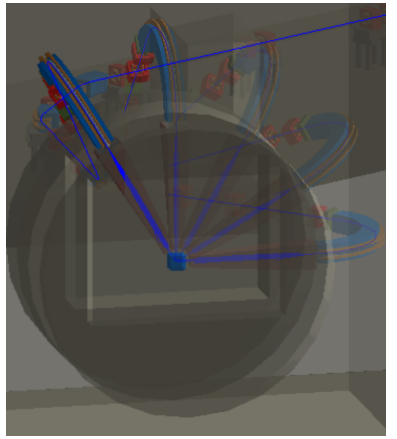



- Variance reduction techniques: importance sampling.
- Neutron dose in a treatment room wall.
- Heavy beam line losses.

- Scoring maps: record integrated quantities.
- Treatment room ambient dose equivalent.
- Per-particle species.



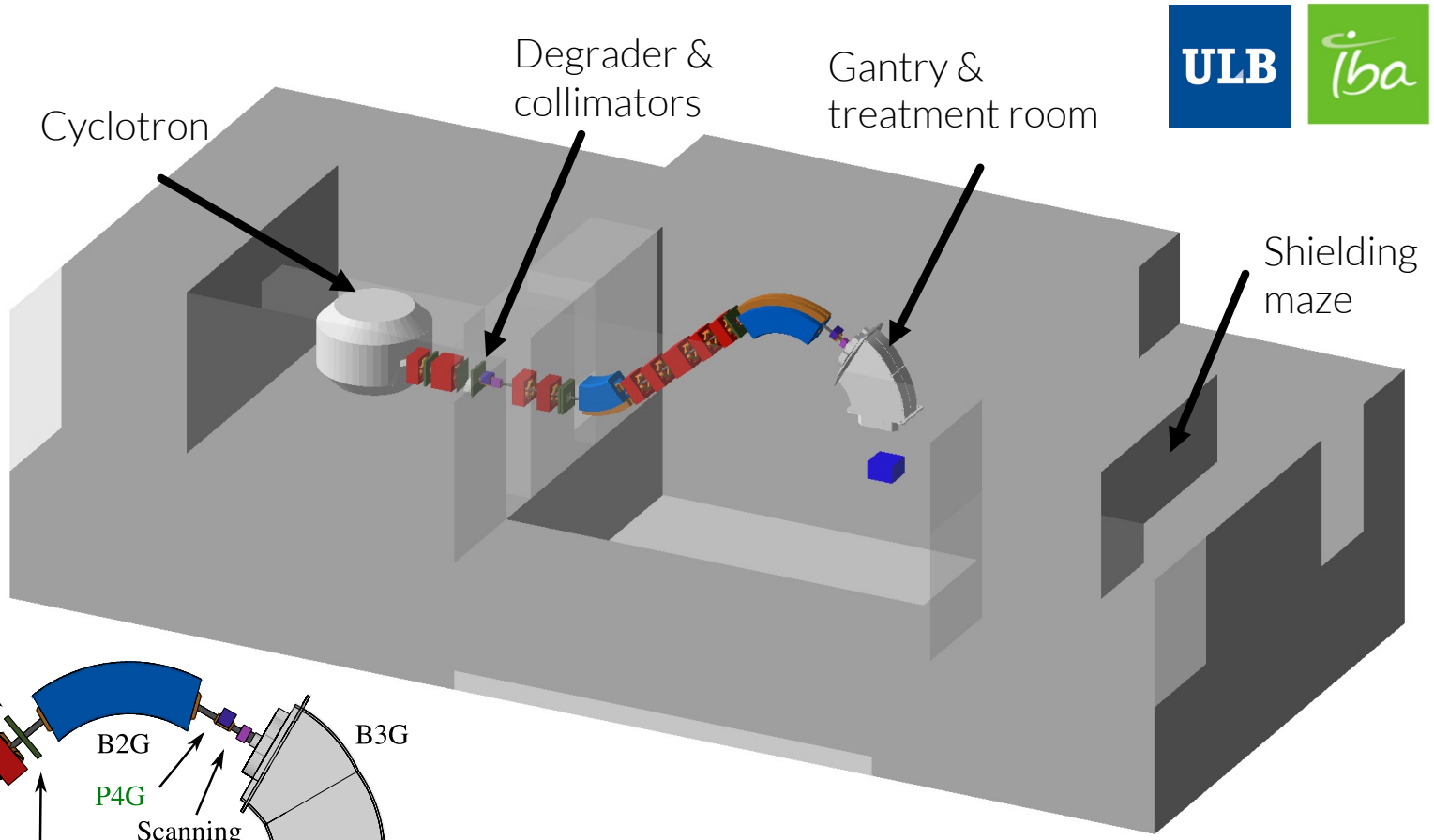



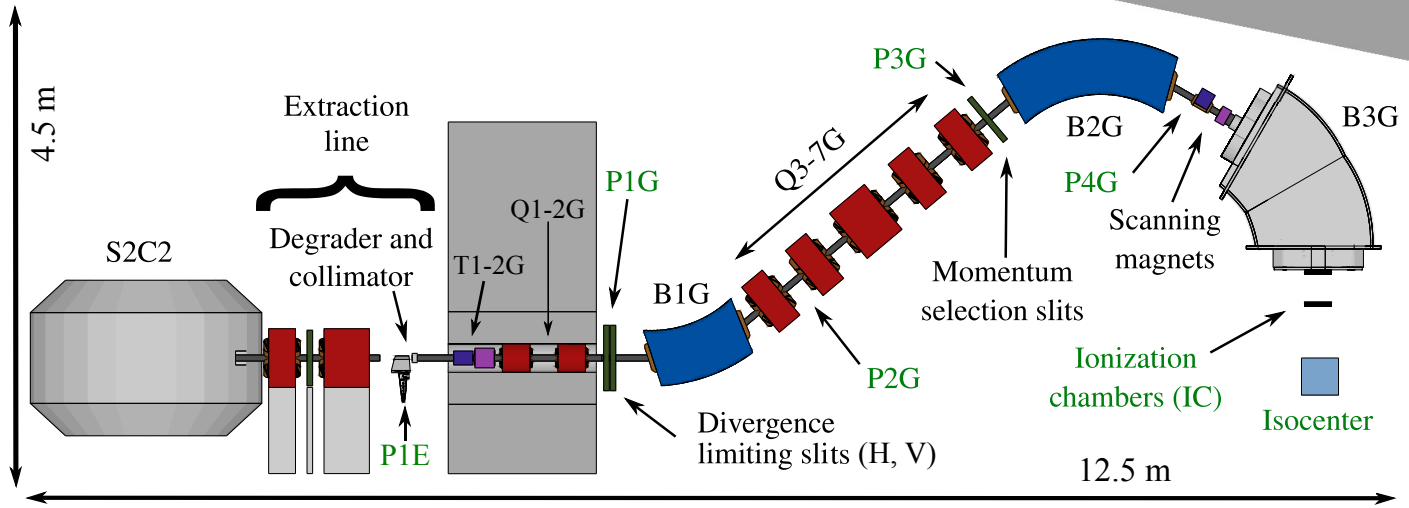



- Vary gantry rotation angle: dose modulation.

# The ProteusOne Model in BDSIM

- Start-to-end simulation of IBA's ProteusOne systems.
- Combination of standard BDSIM geometry & external files (via pyg4ometry).
  - Cyclotron included for modelling losses & dose maps of cyclotron vault.
  - Final dipole converted from CAD model – crucial to include fringes.
  - 3D magnetic field map attached to custom beamline element.



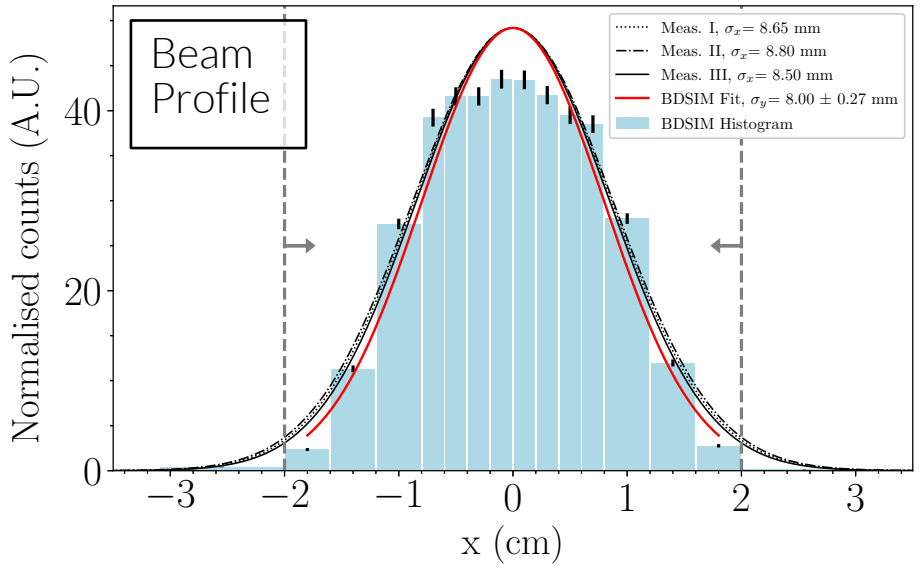



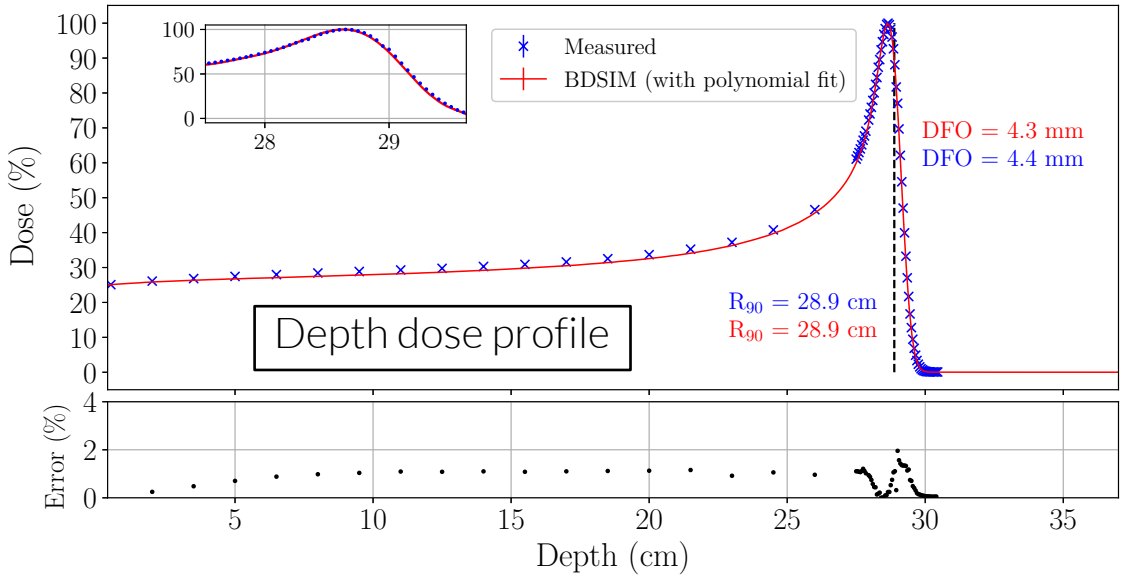

C. Hernalsteens, W. Shields et al, European Physics Letters, (132), December 2020, 50004

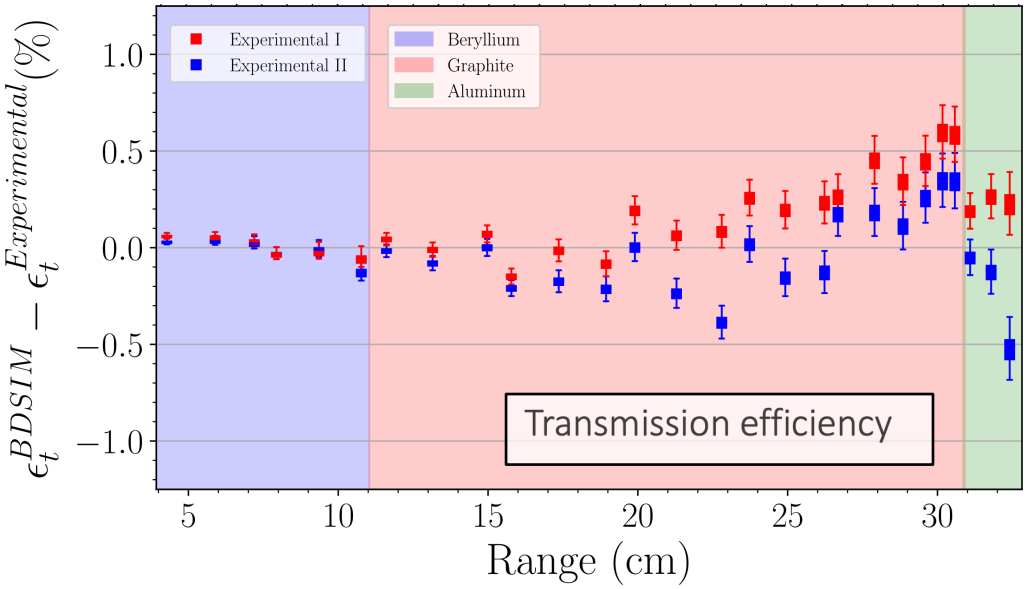
Optics, cyclotron beam profile & losses:
R. Tesse. et al, IPAC2019,

# Experimental Validation

- Excellent agreement between experimental data and simulations.
- Simulated horizontal & vertical beam profile.
- Depth dose profile in water.
  - Range & distal fall-off.
- Total transmission efficiency.
  - Extraction beamline & degrader to isocentre.
  - Multiple ranges to cover all degrader materials.

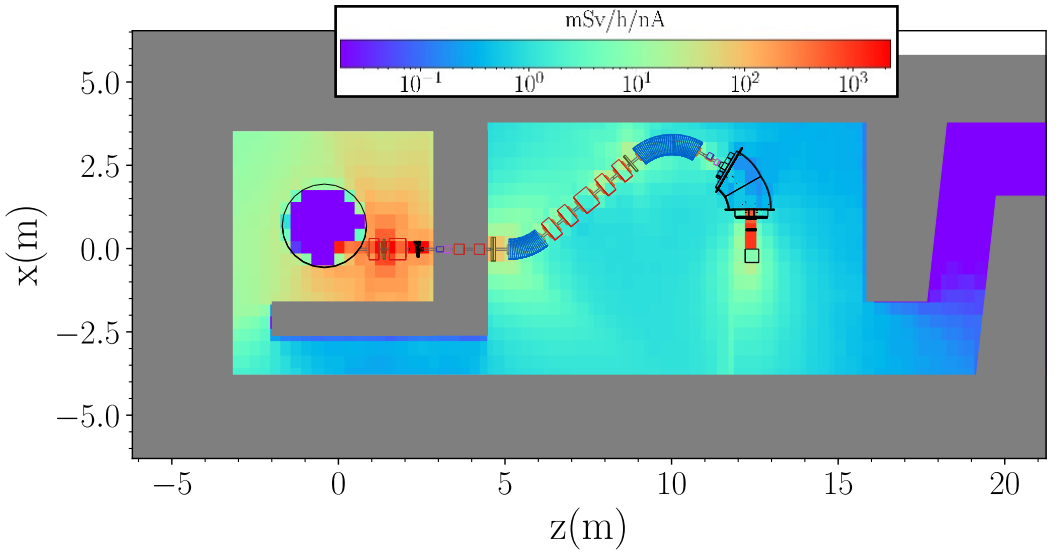


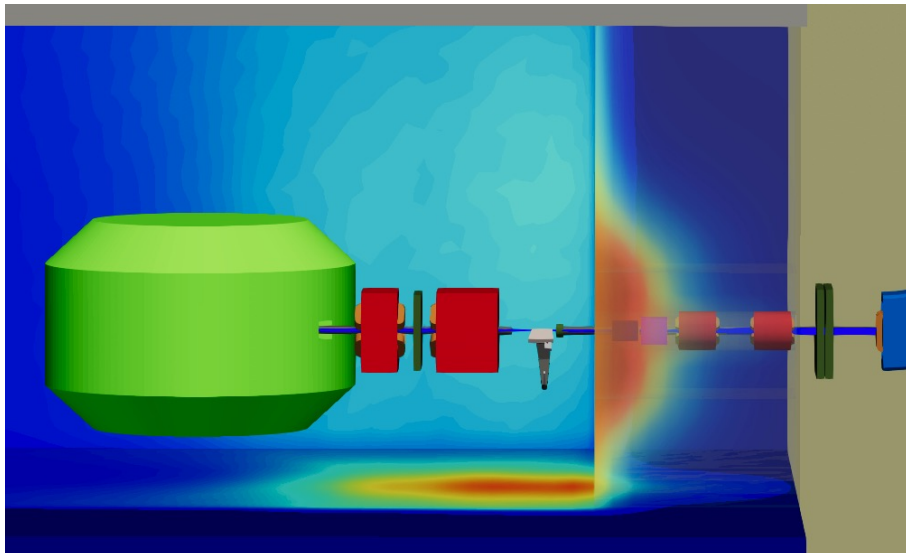
# Other Studies & Developments

- Ambient dose map for activation studies.
  - Ambient dose equivalent scored in the cyclotron vault, treatment room, and the maze.
- Beam transport & degrader losses for 28.65 cm range dose.
  - High cyclotron vault dose: degrader and collimators.
  - Smaller beam transport losses, air gap.
- IPAC paper on ULB-lead developments.



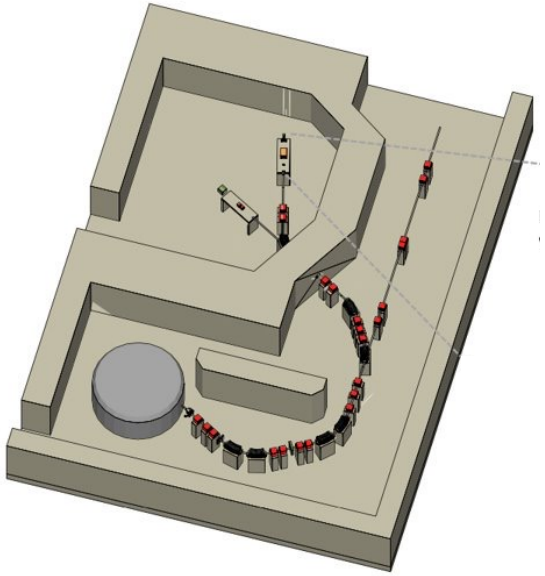

- DICOM files - dose deposition scoring in reconstructed volumes.
- Step toward BDSIM involvement in validation of TPS treatment plans.

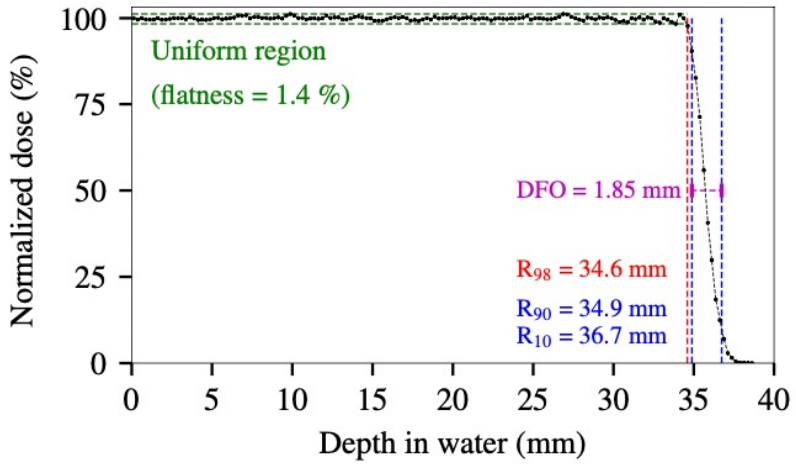
- Shielding activation studies.
  - BDSIM in conjunction with FISPACT-II.
- Development of 4D scoring (3D + energy) – forms FISPACT input.
- Studies ongoing.

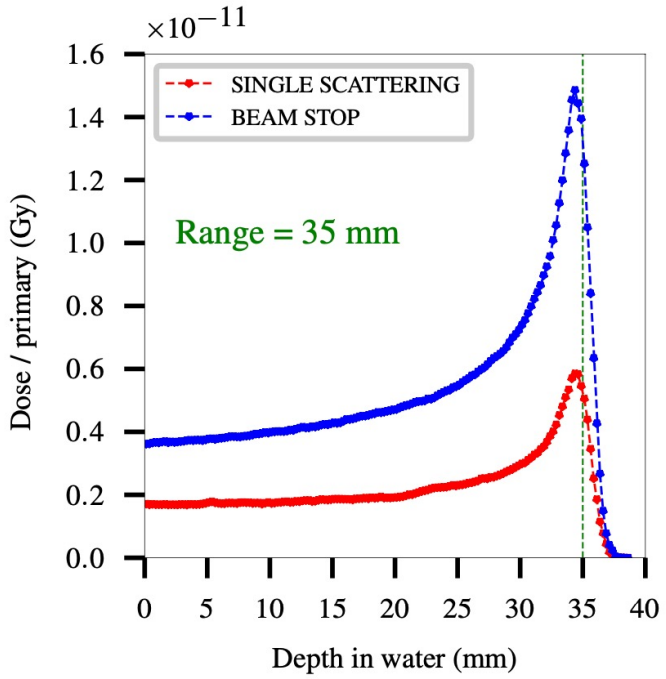


# ProteusPlus Eyeline Optimisation

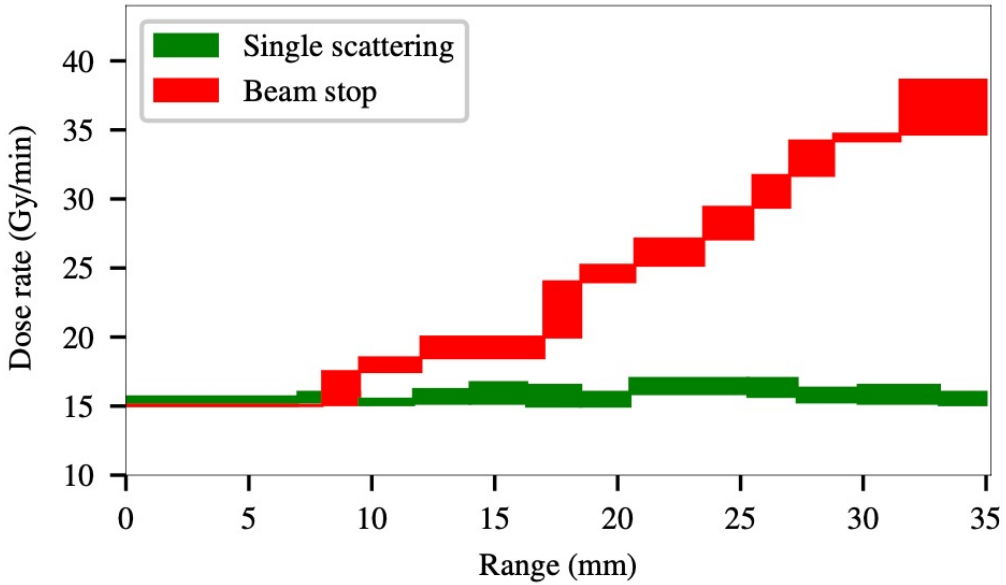
- IBA eye-treatment beamline, part of the Proteus Plus (P+) system.
  - Treatment of ocular tumours (70-105 MeV).
- Publication submitted (E. Gnacadja, ULB).
- Improve deliverable dose rate and depth-dose distal fall-off.
- Optimise energy selection system, optics & nozzle
  - Maintain clinical requirements.






- Options defined providing uniform depth-dose to variety of depths.
  - Maximum dose rates between 15.5 and 17.0 Gy/min.
- Beam stopper added to the nozzle
  - Factor of 3 improvement in deliverable dose.
  - Complete treatment session in under 60 seconds.



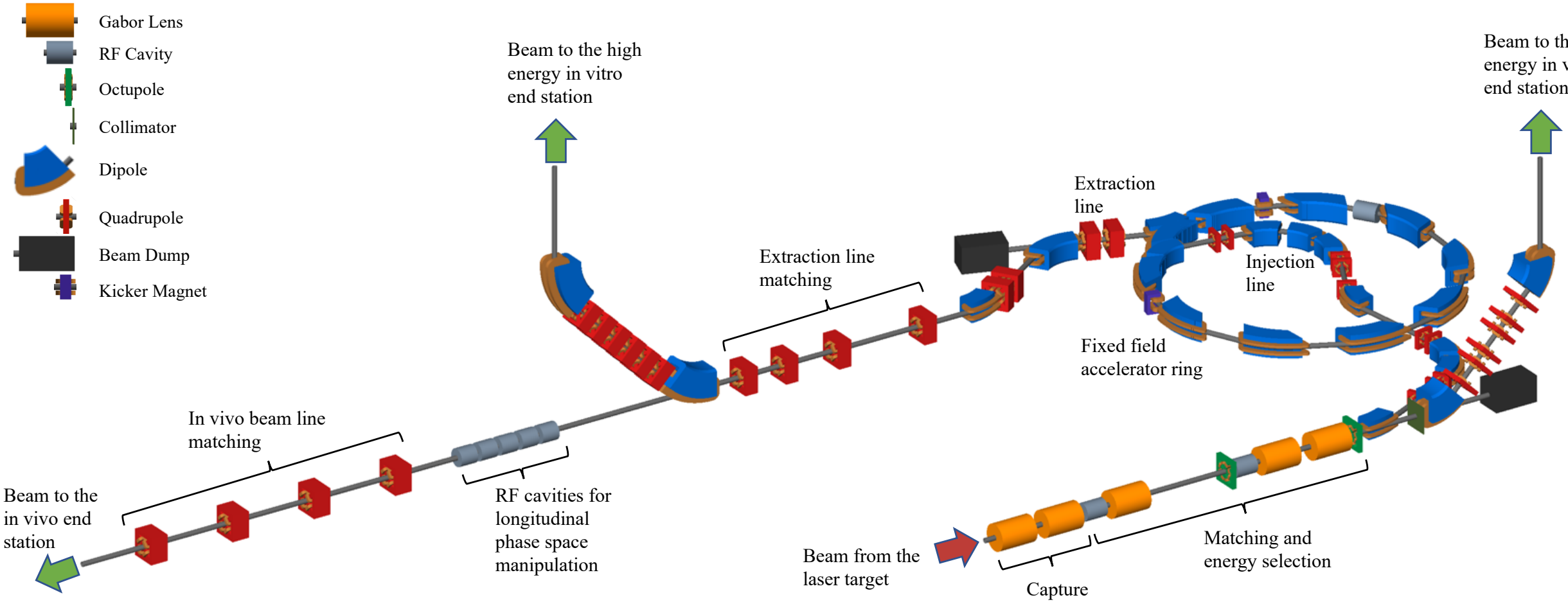
# CCAP: Overview

- Centre for the Clinical Application of Particles (CCAP)
  - Multi-disciplinary collaboration of academia, national laboratories, industry, clinical institutes, and accelerator laboratories
- Design of a proposed facility for cutting edge radiobiology research – LhARA
  - Multi-stage facility capable of delivering proton and ion beams in FLASH doses


- Biophysical understanding of interactions between protons and ions with tissue.
  - Radiobiology program in development.

- Conceptual design complete – working towards technical design.

# CCAP: LhARA




Conceptual design report (CDR) publication:

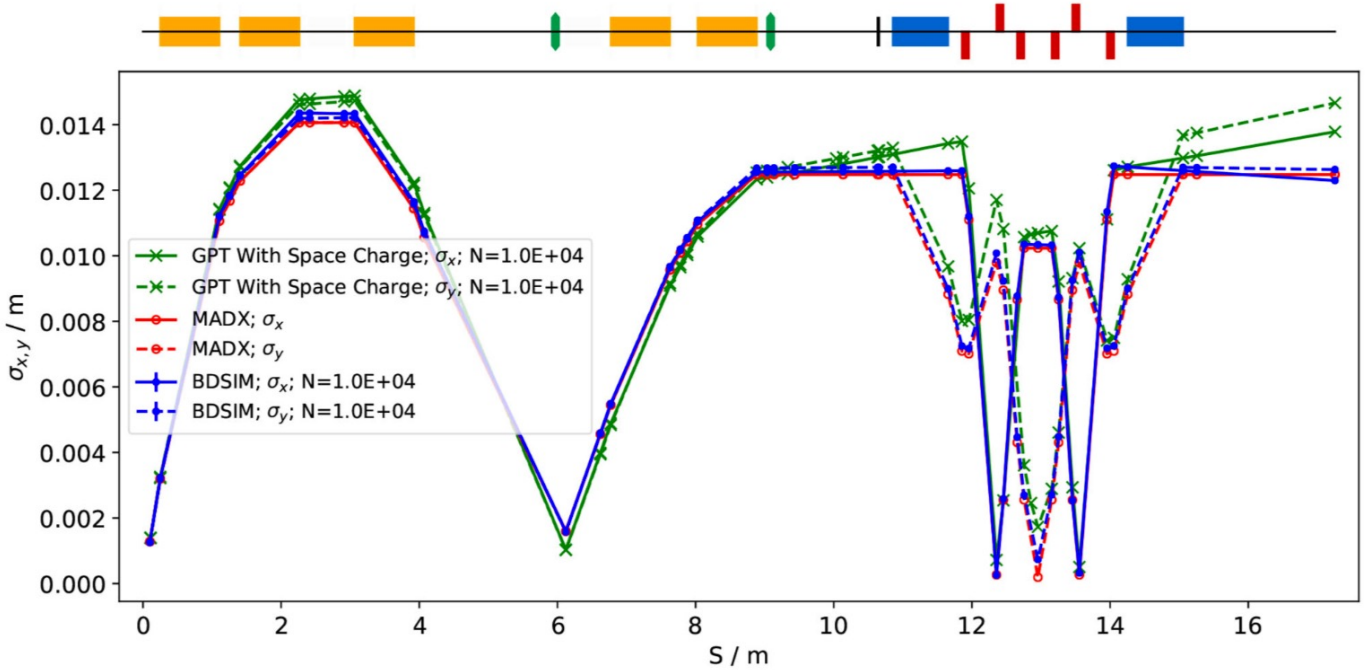
Aymar, G. et al, Frontiers in Physics, (8), September 2020, 567738

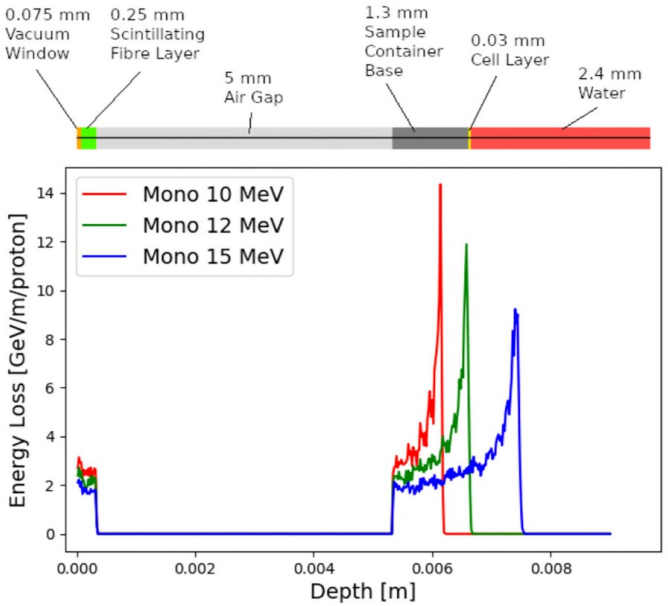
Full CDR Technical Note:

https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

# Stage 1 Performance Evaluation

- Good optical agreement with space charge tracking simulations (GPT).
  - Stage 1 simulated + stage 2 post FFA.
  - Average dose of 128 Gy/s – FLASH capable.
- Bragg peak range simulated in the end station.
- Dose uniformity improved with octupole focusing and collimation.

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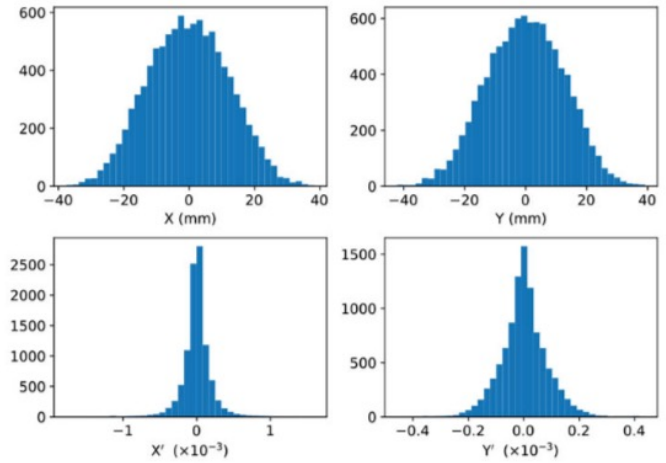


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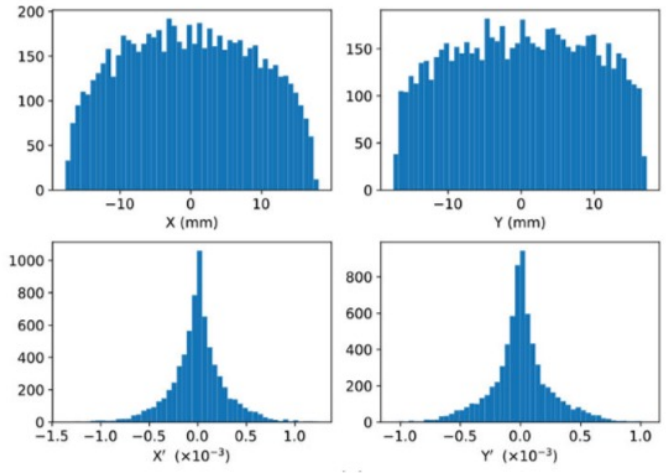
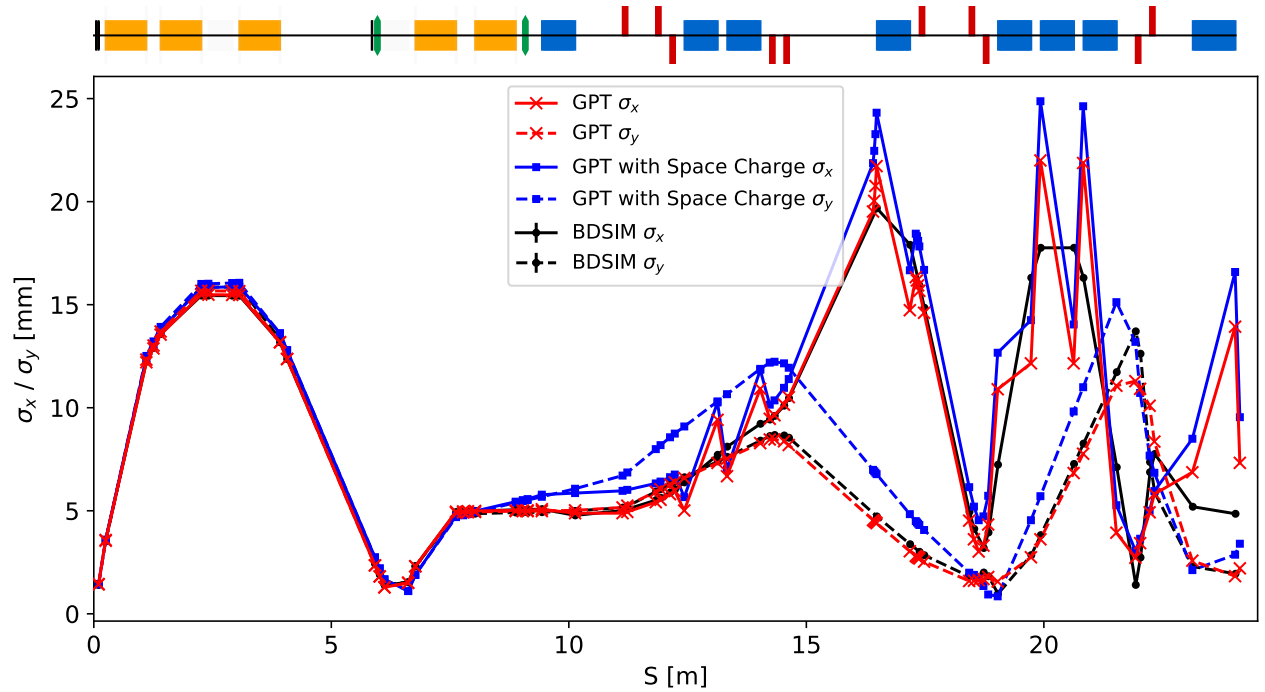
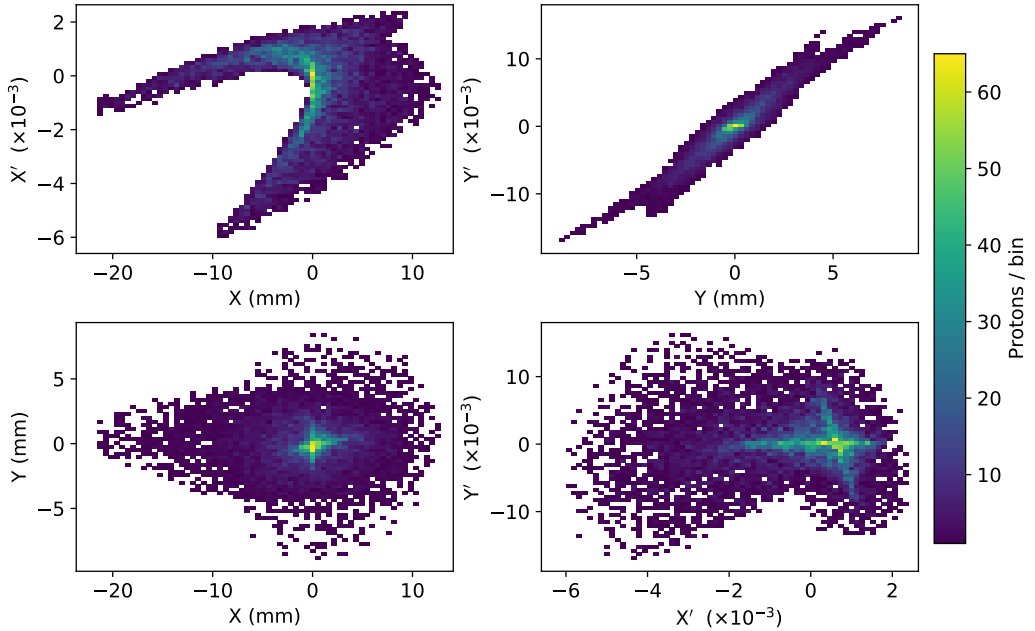


# Stage 2 Injection Line Performance

- Stage 2 FFA injection line modelled (IPAC2021)
- Semi-realistic beam from laser-target interaction simulation (H.T. Lau, IC).
  - Good BDSIM & GPT agreement without space charge.
- Emittance growth observed when modelling space charge.
  - Final dimensions do not match FFA requirements
  - GPT horizontal beam jumps are simulation artefacts




- Phase space aberrations observed, previously seen in stage 1 simulations.
  - Arises in stage 1 solenoids & persists in the injection line.
- Replaced solenoids with 3D Gabor lens EM field map (T. S. Dascalu, IC).
  - Minimal performance impact compared to solenoid optics.
  - Similar phase space observed – unavoidable effect.
  - Potentially acceptable by FFA – studies ongoing.



# Summary

- In-house model:
  - Showcase BDSIM's capabilities.
  - Well developed code, highly suited to modelling proton therapy accelerators.
  - Increasingly used in medical beam line research – academia & industry.
  - Publication submission imminent.

- ULB & IBA:
  - Excellent agreement with experimental data.
  - Successful modelling of 2 of IBA's flagship proton therapy systems.
  - Ongoing studies & developments.

- LhARA:
  - Crucial contribution in LhARA's design performance evaluation.
  - Continued use in design evolution.


# Thank you for listening!

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JAI Fest 2021

10th December