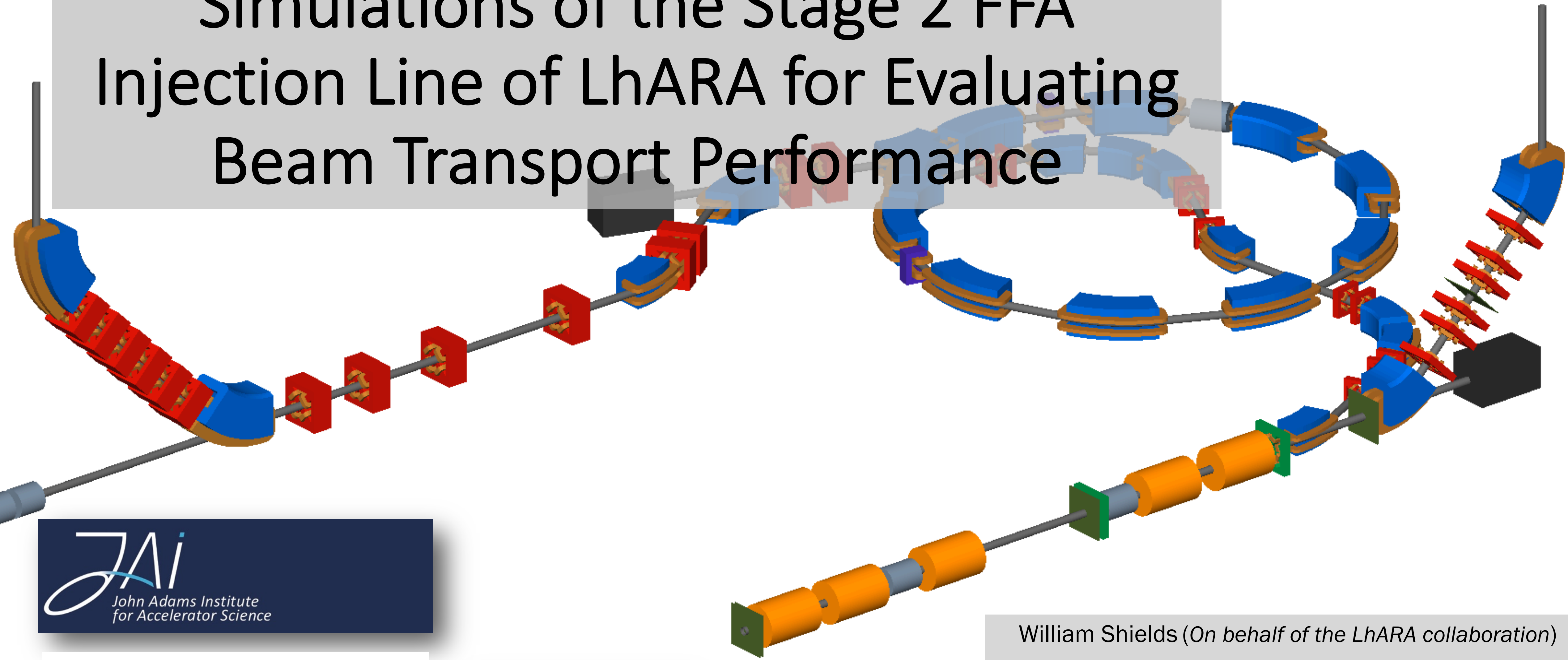
Simulations of the Stage 2 FFA Injection Line of LhARA for Evaluating Beam Transport Performance



John Adams Institute for Accelerator Science

LhARA Laser-hybrid Accelerator for Radiobiological Applications

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IPAC 2021: **THPAB359**

CCAP: Overview

- Centre for the Clinical Application of Particles (CCAP)
  - Multi-disciplinary collaboration of academia, national laboratories, industry, clinical institutes, and accelerator laboratories.

- LhARA: Laser-hybrid Accelerator for Radiobiological Applications
  - Design of a proposed novel and flexible research facility capable of delivering proton and ion beams in FLASH doses
  - Multi-stage development for *in vitro* and *in vivo* studies

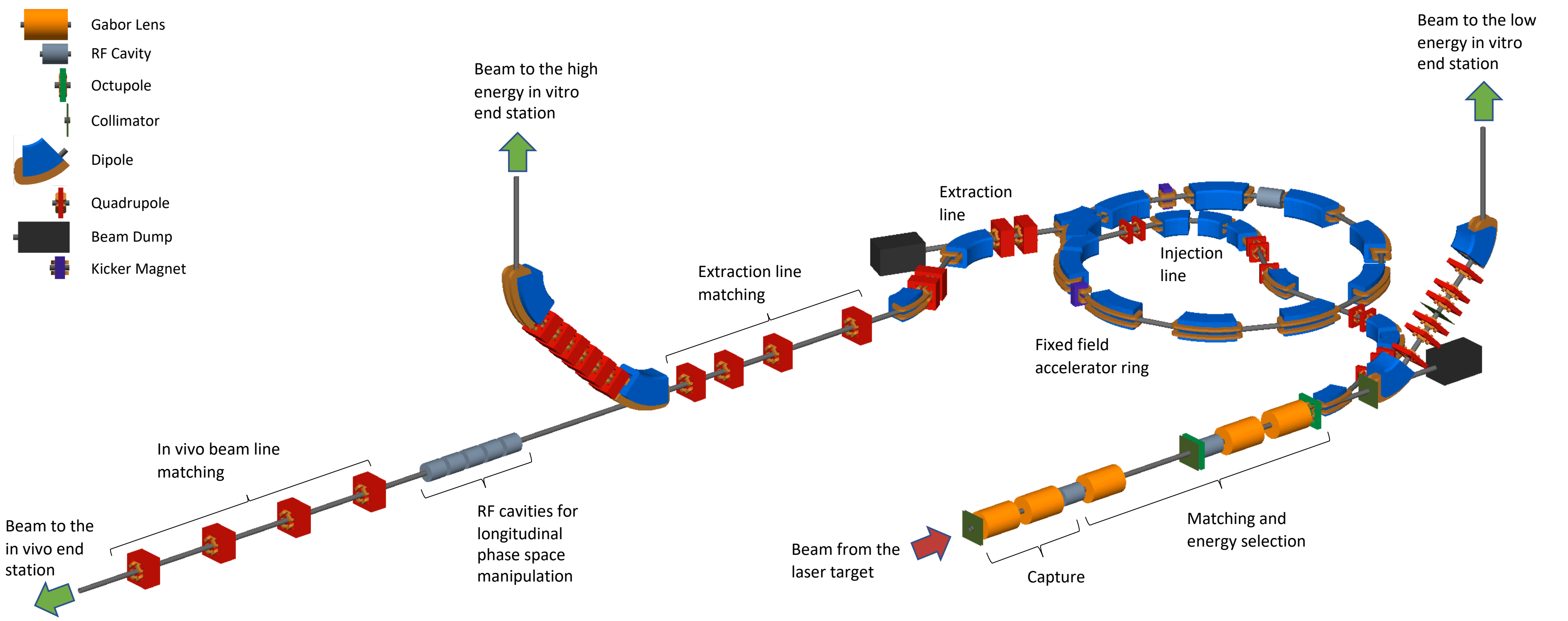
- Develop biophysical understanding of interactions between protons and ions with tissue
  - Create capability to develop new treatment modalities

Imperial College London
Department of Physics
Faculty of Medicine
ICR The Institute of Cancer Research
UKRI Medical Research Council Oxford Institute for Radiation Oncology
University of Oxford
JAI John Adams Institute for Accelerator Science
CCAP Centre for the Clinical Application of Particles
Imperial College Academic Health Science Centre
Cancer Research UK | Imperial Centre
NHS Imperial College Healthcare NHS Trust

Manchester 1824 The University of Manchester
University of Birmingham
Queen's University Belfast
University of Liverpool
Lancaster University
University of Strathclyde Glasgow Department of Physics
UCL Medical Physics & Biomedical Engineering
Royal Holloway University of London
Swansea University Prifysgol Abertawe
University of Birmingham | Positron Imaging Centre
University of Birmingham | Cyclotron Facility
The Cockcroft Institute of Accelerator Science and Technology
LEO Cancer Care
Maxeler Technologies Maximum Performance Computing
Corerain 鲲云科技

NHS University Hospitals Birmingham NHS Foundation Trust
NHS The Clatterbridge Cancer Centre NHS Foundation Trust
institut Curie
UKRI Science and Technology Facilities Council
ASTeC
Particle Physics Department
ISIS Neutron and Muon Source
INFN Catania
Central Laser Facility
The Rosalind Franklin Institute
NPL National Physical Laboratory
LhARA Laser-hybrid Accelerator for Radiobiological Applications

LhARA: Overview



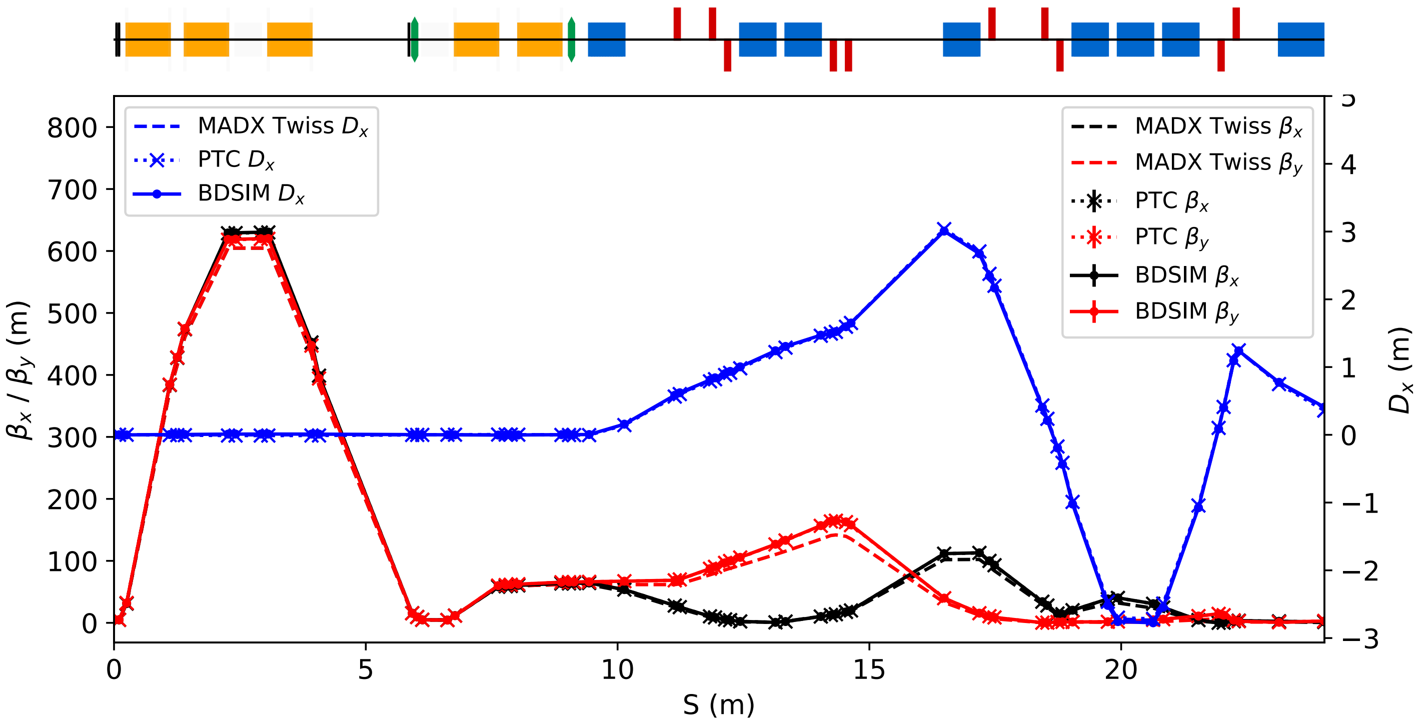
- Laser-target driven source
- Beam capture with Gabor (plasma) lenses
  - Equivalent focusing to solenoids but with a much lower magnetic field.
- Pulse duration as low as 10 ns in an arbitrary pulse structure.

LhARA design publication [1]:
https://doi.org/10.3389/fphy.2020.567738

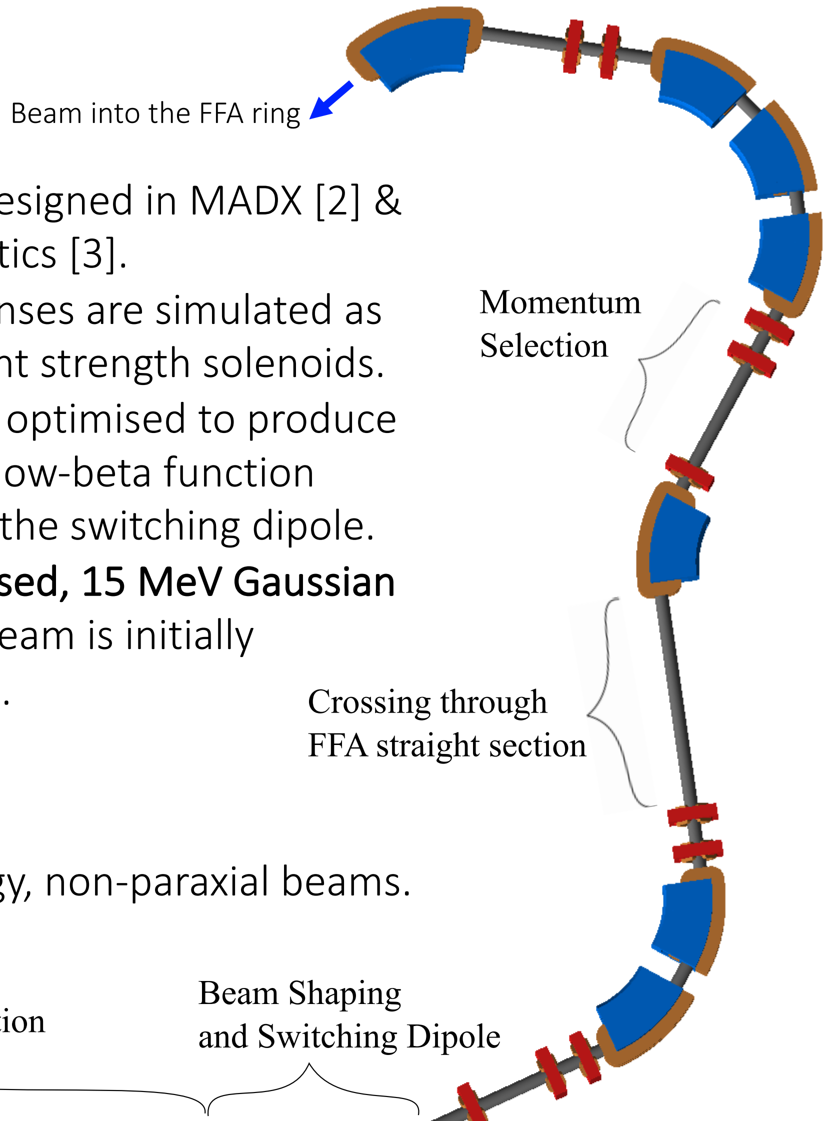
Pre-conceptual design report:
https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

- Stage 1: *In vitro* studies with proton beams up to 15 MeV.
  - RF cavities for longitudinal phase space manipulation.
  - Collimation for momentum selection & cleaning, and beam shaping.
  - Octupoles for dose uniformity.
- Stage 2: Fixed field alternating gradient accelerator.
  - *In vitro* and *in vivo* studies with proton beams up to 127 MeV and ion beams up to 33.4 MeV/u.

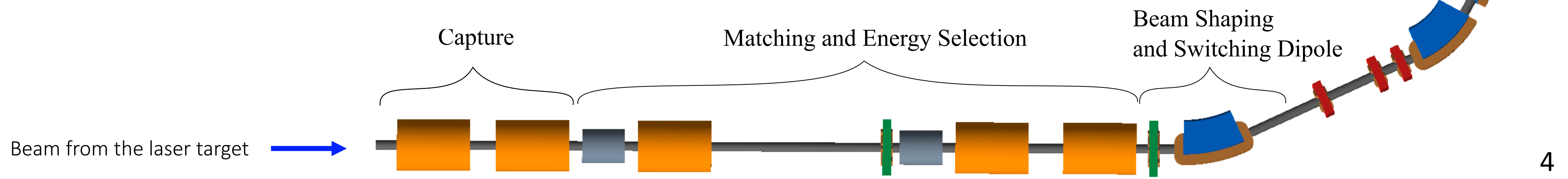
LhARA Injection Line: Optical Verification



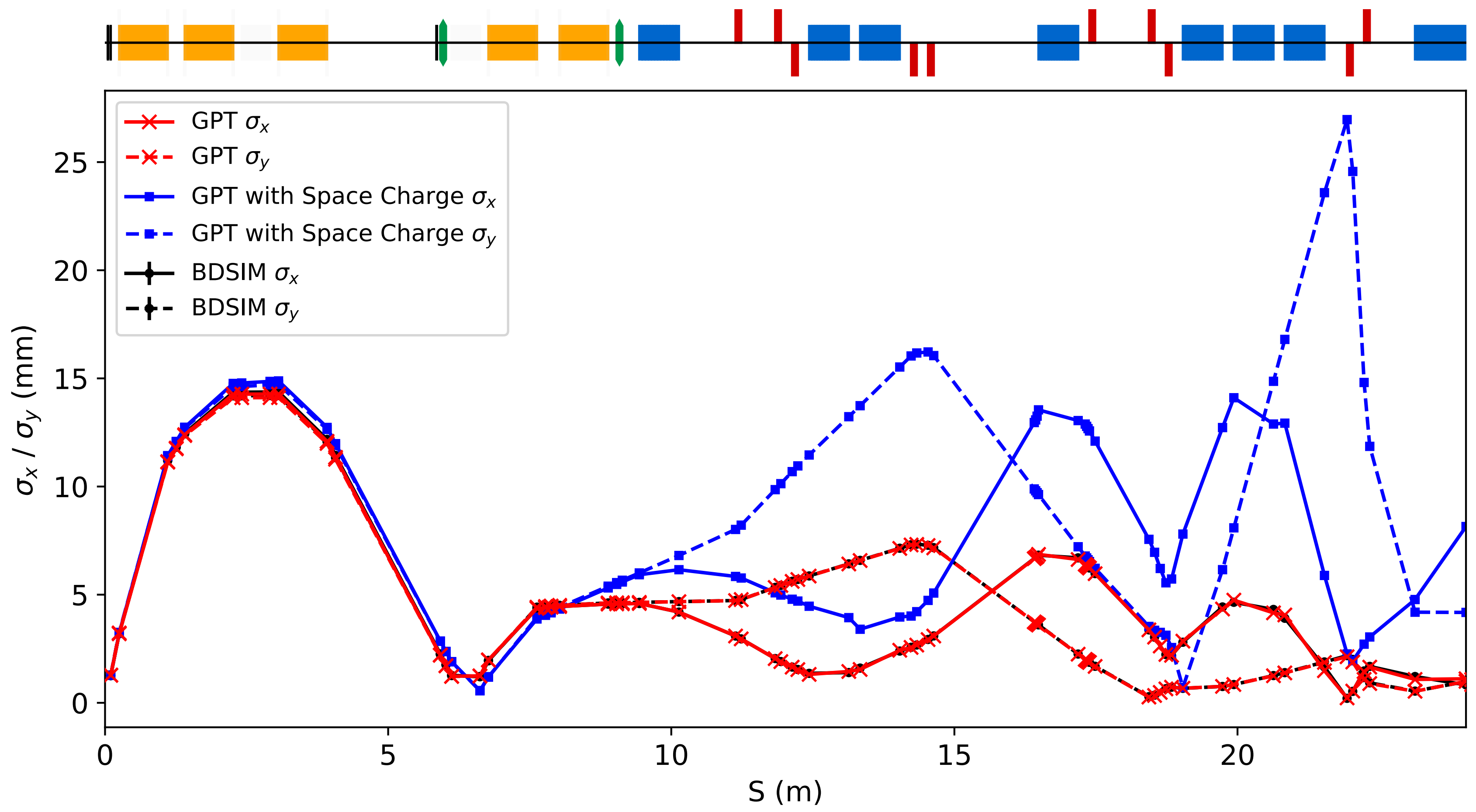
- Lattice designed in MADX [2] & BeamOptics [3].
- Gabor lenses are simulated as equivalent strength solenoids. They are optimised to produce parallel, low-beta function beam at the switching dipole.
- An **idealised, 15 MeV Gaussian** proton beam is initially assumed.



- BDSIM [4] and PTC show **excellent agreement** for the beta function and dispersion.
  - 10000 particles were tracked in BDSIM with an enlarged aperture to minimise losses.
- Slight discrepancy w.r.t. original MADX Twiss parameters – known behaviour for low energy, non-paraxial beams.
- Minor tweaks required for beta and horizontal dispersion to match FFA cell conditions.



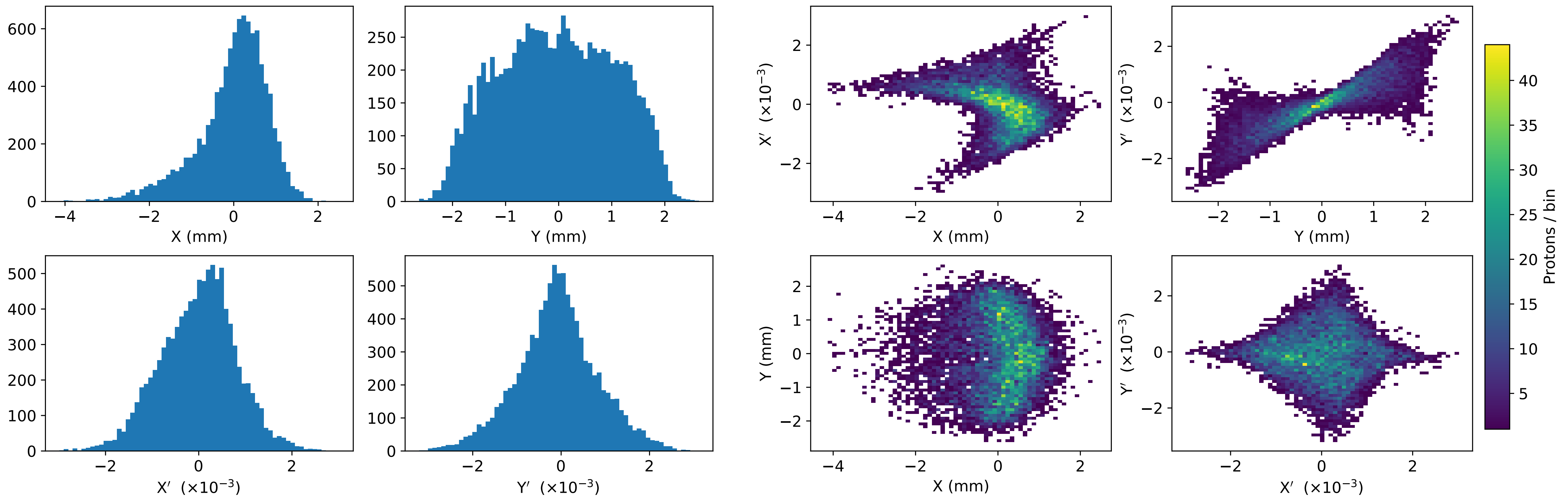
Optical Performance with Space Charge Effects



- Compare BDSIM's tracking to GPT [5] which includes space charge effects.
- BDSIM and GPT show **excellent agreement** when not considering space charge.
- Space charge was simulated with 10000 particles representing a total bunch charge of 10^9 protons. An **initial emittance growth** results in a larger than nominal beam in the capture section.

- A **significant impact** on the downstream optical performance is observed, deviating from the design optics.
- Injection line beam focusing is limited to one dimension, we anticipate **minimal impact** from space charge effects after the switching dipole.
- Further optimisation is needed to improve capture performance.

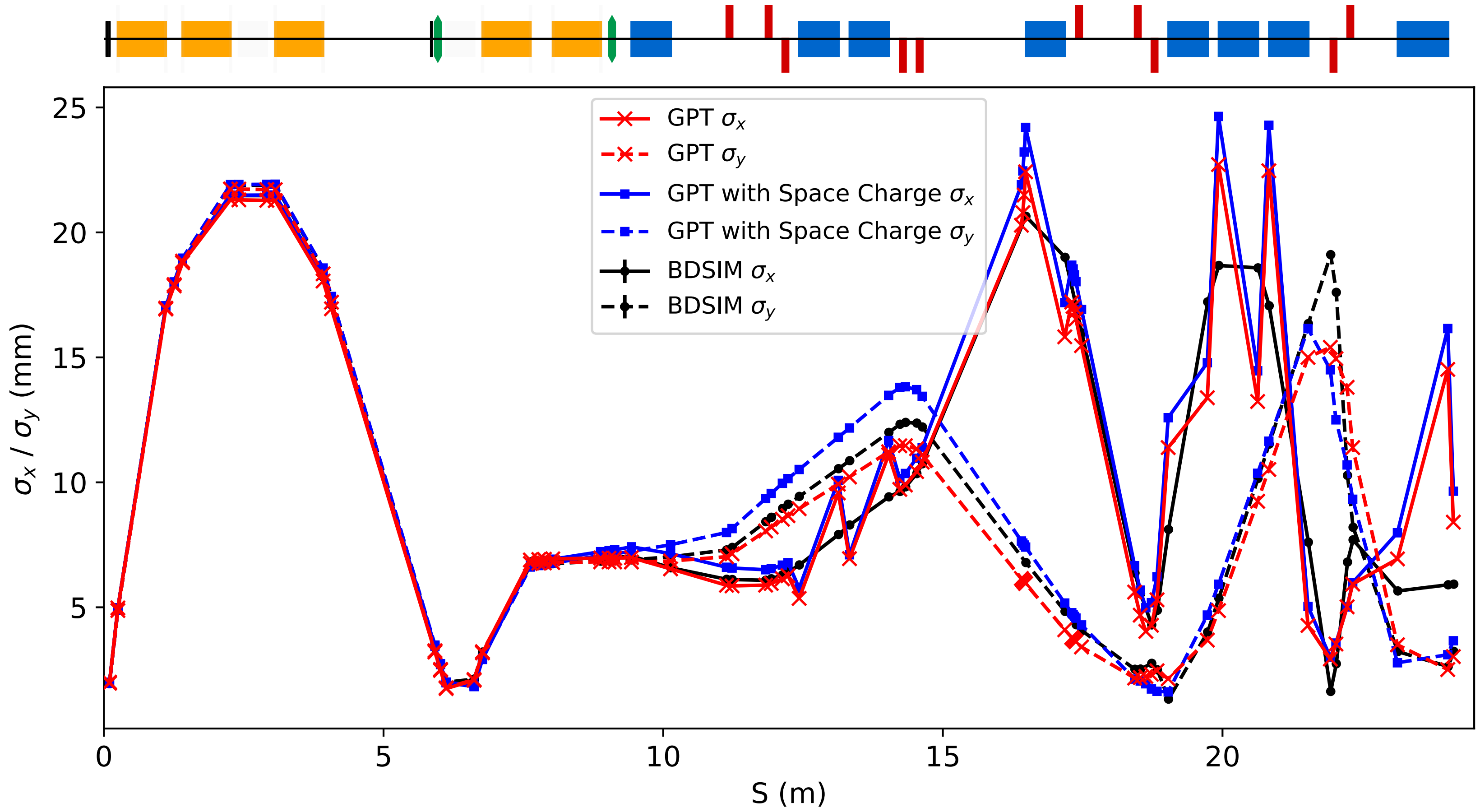
Ideal Beam Phase Space



- **Aberrations** arising in capture section solenoids persist throughout the injection line
  - The same aberrations impact LhARA stage 1 transport performance.

- Solenoids will be replaced by **full electromagnetic simulations** of the Gabor lenses, at which point the aberration and transport performance will be further investigated.

Performance with a Laser-Target Sampled Beam



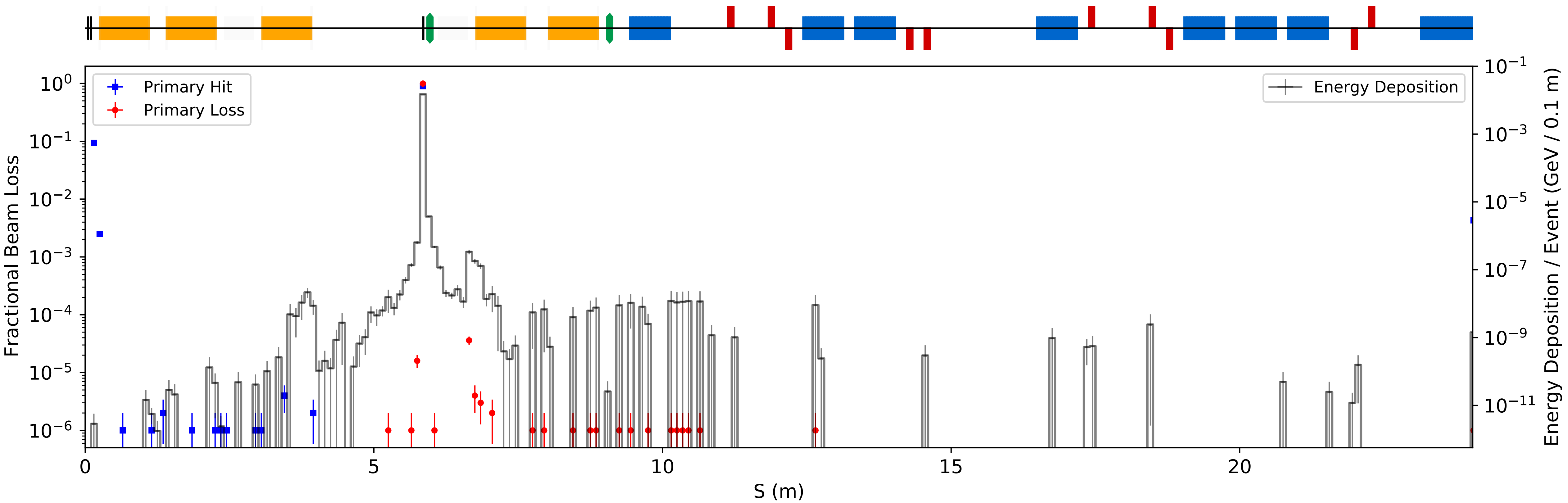
- Semi-realistic beam generated from sampled output of laser-target interaction simulation
  - Particle-in-cell code, Smilei [6].
  - See **WEPAB139** (these proceedings) by Hin Tung Lau for more details.

- Particles outside of the 3.65cm Gabor lens radius were not fully focussed, resulting in a beam halo and subsequent losses.
  - Radius widened to study downstream optical performance.

- Broadly **similar result** obtained with BDSIM & GPT. **Smaller emittance growth** from space charge effects.
  - Final dimensions do not match FFA cell requirements. Further optimisation is therefore required.

- Horizontal beam size jumps are due to a longer temporal profile in GPT snapshots capturing the bunch partially within sector-bend fields.

Laser-Target Sampled Beam: Losses & Energy Deposition



- The beam was simulated in BDSIM with particle-matter interactions and the momentum selection collimator aperture radius set to 0.5mm (the settings for stage 1 *in vitro* energy collimation).
- Due to the aforementioned aberrations in the capture section, **heavy losses** are observed with < 1% of the beam reaching the FFA septum magnet.
- Energy deposition from **primary protons and secondary emissions** is mostly restricted to within +/- 2m of the collimator.
- New collimator settings are required for energy selection through the injection line.
- These losses will be addressed when simulations of the Gabor lenses are available.

Conclusion & References

- LhARA's injection line has been modelled in Monte Carlo simulations to assess optical performance.

- Space charge causes early emittance growth in an ideal beam, resulting in the beam being unmatched to FFA cell parameters.

- A more realistic beam showed less susceptibility to space charge effects, but the final beam parameters require tuning to match the FFA requirements.

- Optimisation of the beam line is required. The combination of space charge effects in GPT and BDSIM's accurate collimation capabilities are suited to optimisation studies going forward.

[1] G. Aymar *et al.*, "Lhara: The laser-hybrid accelerator for radiobiological applications," *Frontiers in Physics*, vol. 8, p. 432, 2020.

[2] CERN, "Mad - methodical accelerator design," 2021.

[3] Y. Chao, "BeamOptics: a Symbolic Platform for Modeling and the Solution of Beam Optics System," tech. rep., CERN, Geneva, Nov 2000.

[4] L. J. Nevay *et al.*, "Bdsim: An accelerator tracking code with particle-matter interactions," *Computer Physics Communications*, p. 107200, 2020.

[5] S. Van der Geer and M. De Loos, "Applications of the general particle tracer code," in *Proc. 5th Eur. Part. Acc. Conf.*, p. 1241, 1996.

[6] J. Derouillat *et al.*, "Smilei : A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation," *Computer Physics Communications*, vol. 222, pp. 351 – 373, 2018.