Stage 1: Design & Tracking

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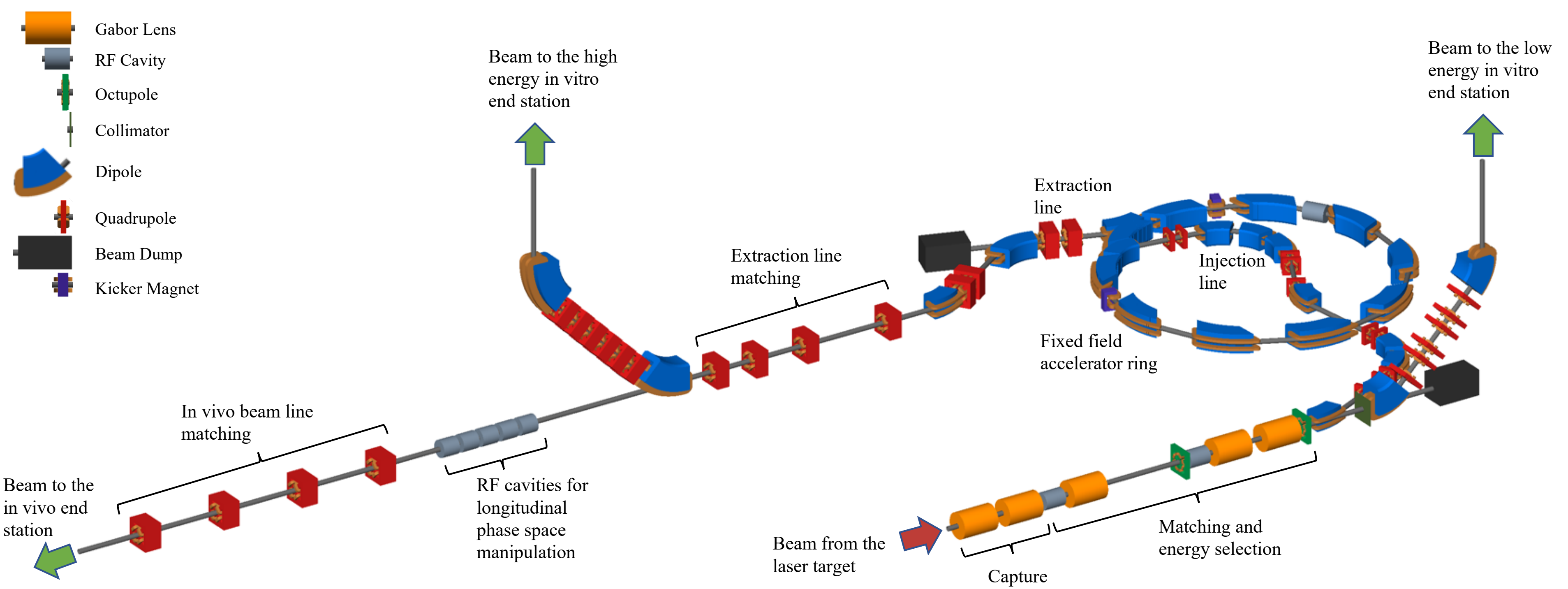
LhARA Collaboration Meeting

27th April 2022

Outline

1. Stage 1 overview
2. Stage 1 performance evaluation with MC simulations
3. Deliverable Dose Estimation
4. Stage 2 injection line performance

The LhARA Accelerator

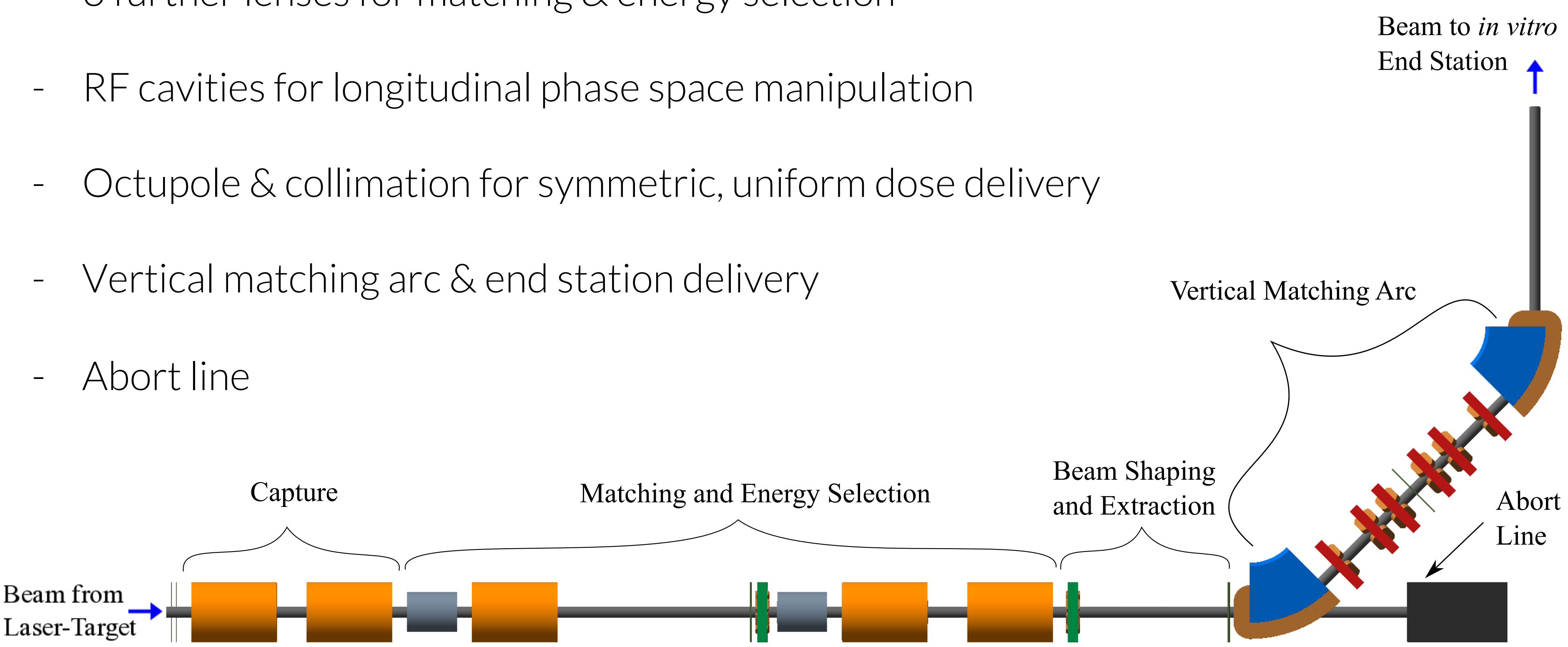


Pre-conceptual design report (pre-CDR) publication:
[Aymar, G. et al, Frontiers in Physics, (8), September 2020, 567738]

Full pre-CDR Technical Note:
[https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf]

Stage 1 Overview

- Beam:
  - Up to 15 MeV protons & ions
- 2 Gabor lenses in the capture section
- 3 further lenses for matching & energy selection
- RF cavities for longitudinal phase space manipulation
- Octupole & collimation for symmetric, uniform dose delivery
- Vertical matching arc & end station delivery
- Abort line



Stage 1 Design Parameters

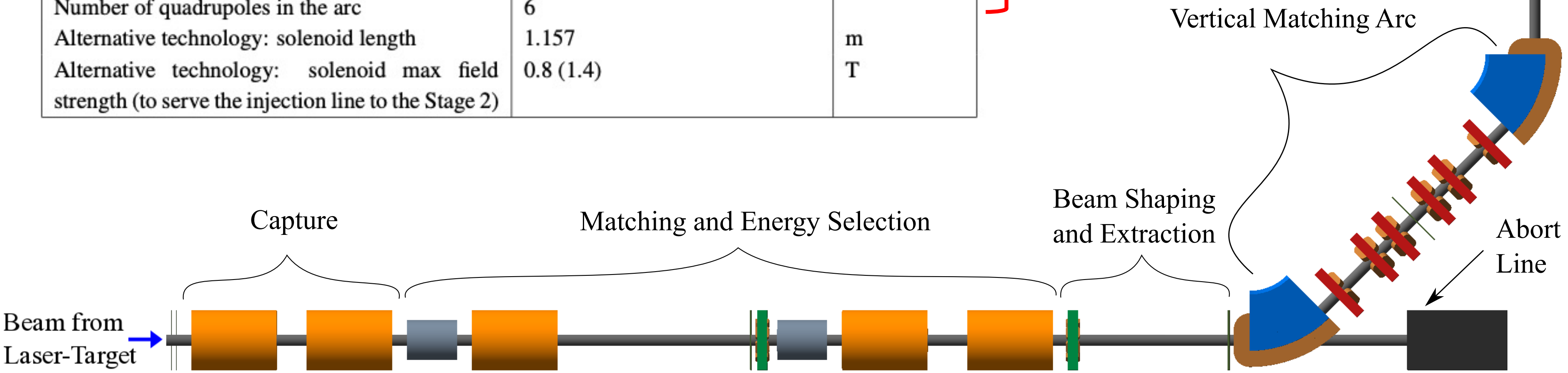
Proton and ion capture		
Beam divergence to be captured	50	mrad
Gabor lens effective length	0.857	m
Gabor lens length (end-flange to end-flange)	1.157	m
Gabor lens cathode radius	0.0365	m
Gabor lens maximum voltage	65	kV
Number of Gabor lenses	2	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength	1.3	T

Gabor Lenses

Alternative: solenoids

Stage 1 beam transport: matching & energy selection, beam delivery to low energy end station		
Number of Gabor lenses	3	
Number of re–bunching cavities	2	
Number of collimators for energy selection	1	
Arc bending angle	90	Degrees
Number of bending magnets	2	
Number of quadrupoles in the arc	6	
Alternative technology: solenoid length	1.157	m
Alternative technology: solenoid max field strength (to serve the injection line to the Stage 2)	0.8 (1.4)	T

Other beam line elements

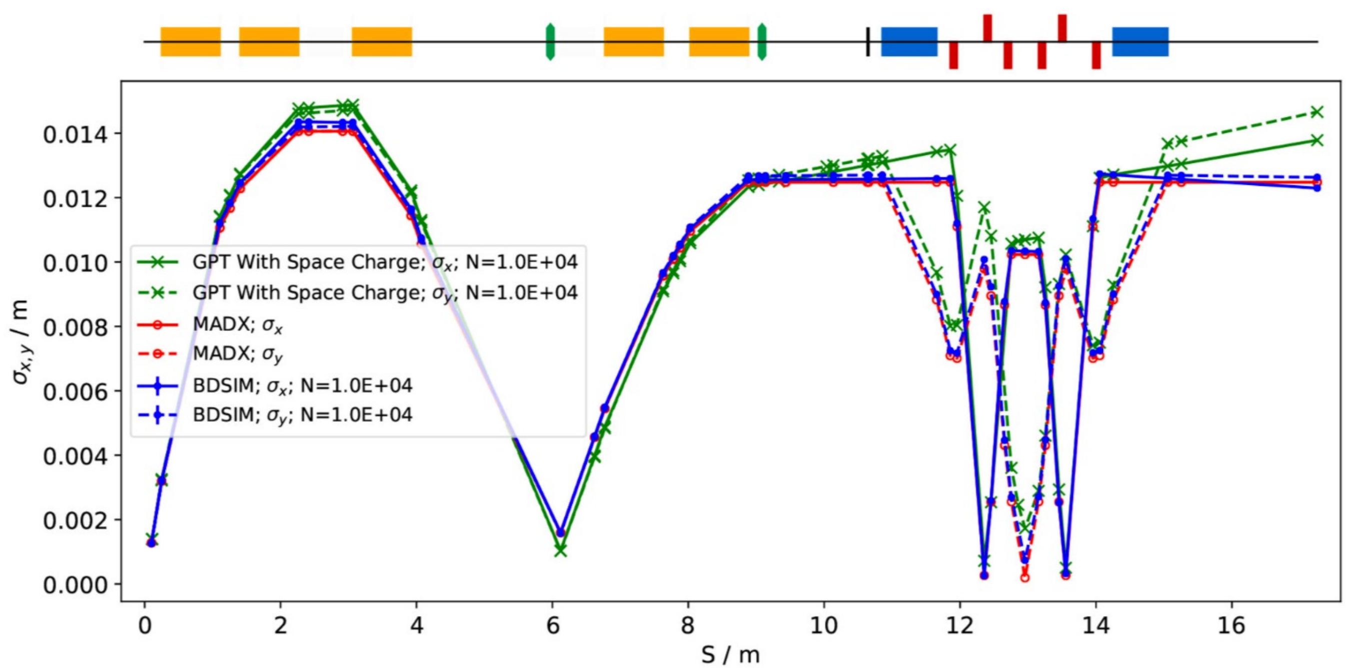


Particle Tracking

- MADX: Initial design
- Hybrid Monte Carlo strategy:
  - BDSIM: Accelerator tracking + particle-matter interactions (Geant4)
  - GPT: Particle tracking + space charge forces
- Gabor lenses modelled as equivalent strength solenoids
- Low energy contaminants between S=0-5cm
  - S=5-10 cm modelled with space charge
- Excellent tracking agreement between tracking codes
  - Idealised beam
- Small space-charge induced emittance growth

Beam Delivery Simulation

General Particle Tracer (GPT)

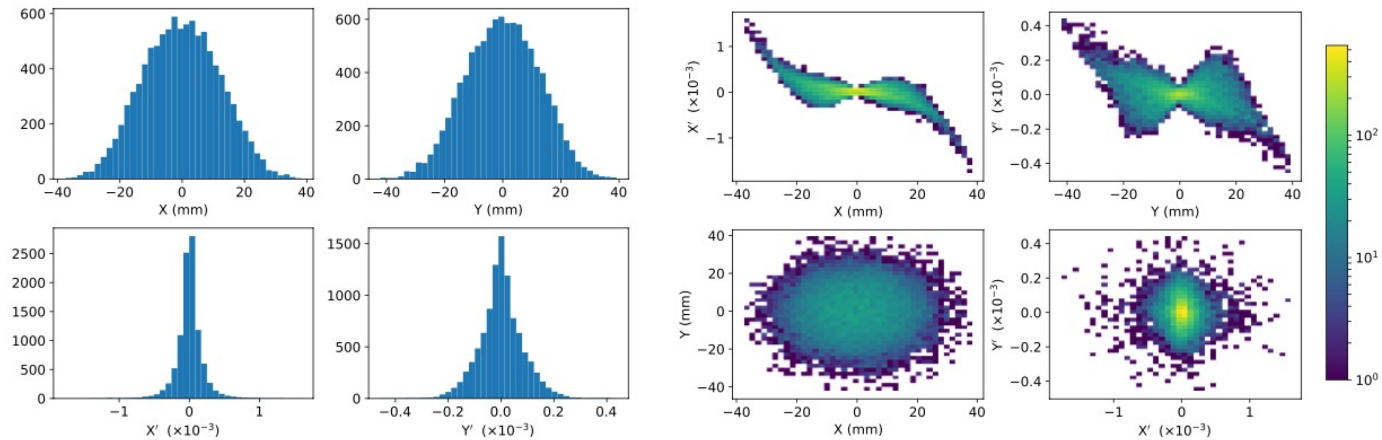


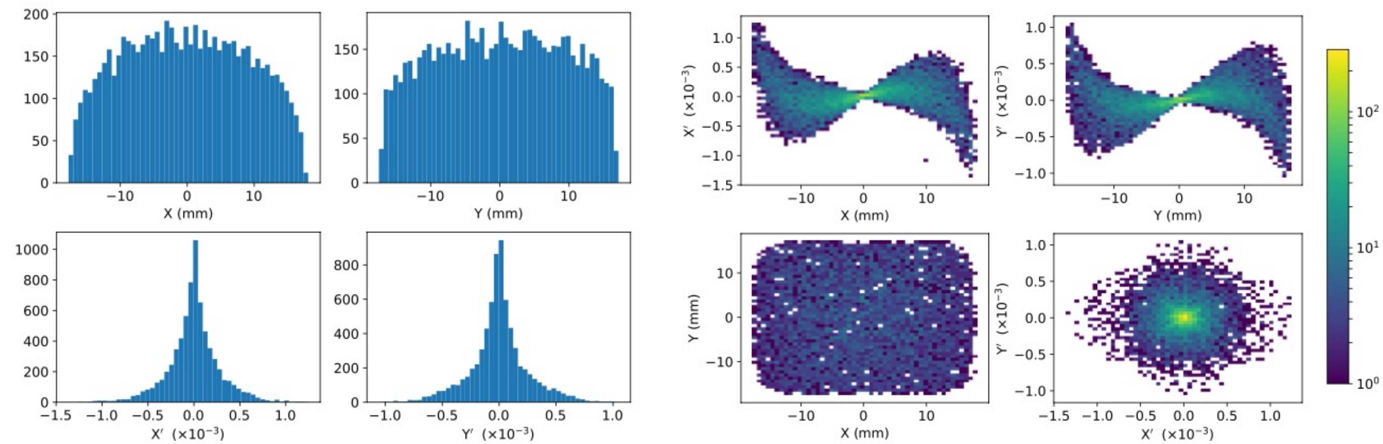
Beam Phase Space

- Phase space aberration arises in Gabor lenses / solenoids

- Octupoles & collimation improves beam uniformity

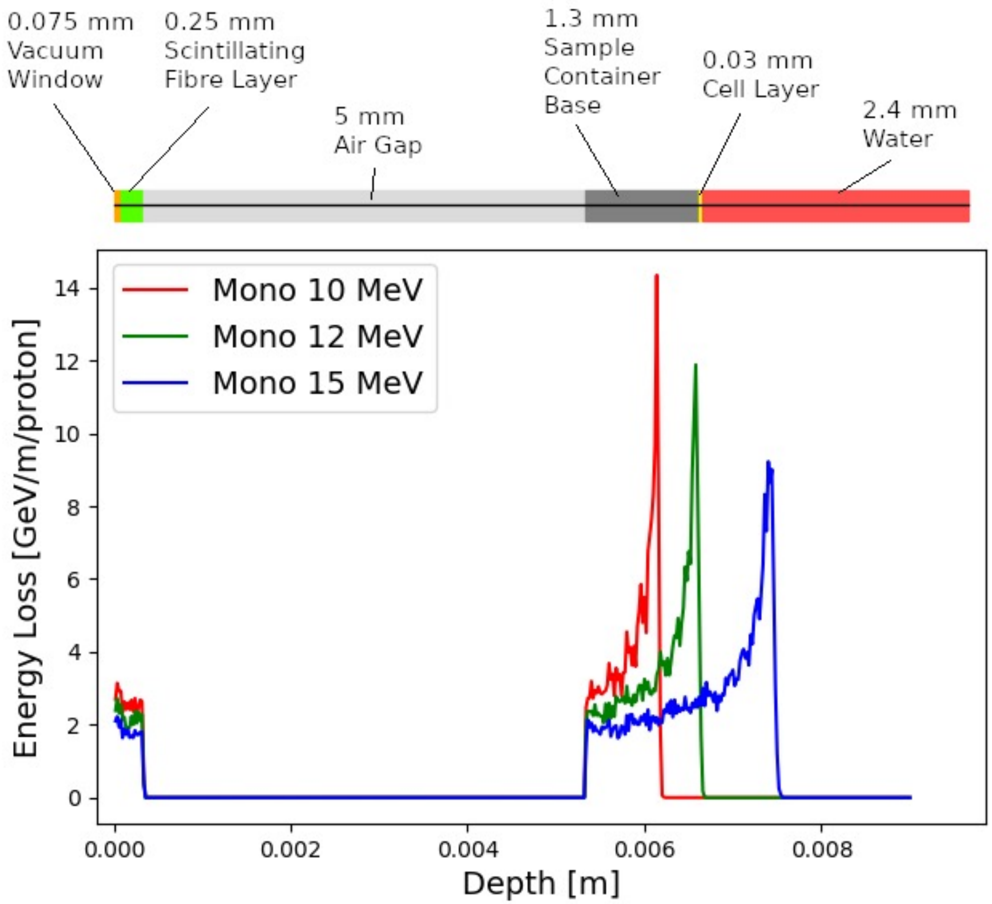
- ~30% reduction in transmission – collimator settings to be optimised.





Deliverable Dose Estimation

- BDSIM energy deposition in end station target materials (H.T. Lau, IC).
- Monoenergetic idealised beams
  - Radiobiological effects from different Bragg curve regions
- 12 MeV beam closest Bragg peak to the cell layer
  - Total energy deposited in the cell layer was 9.63×10^{-6} Gy
  - 5.16 Gy for full 10^{9} proton bunch



- Equivalent water phantom volume simulated at Bragg peak depths
- 15 MeV proton beam - average dose rate of 128 Gy/s
  - 10 Hz repetition rate

Semi-Realistic Beam

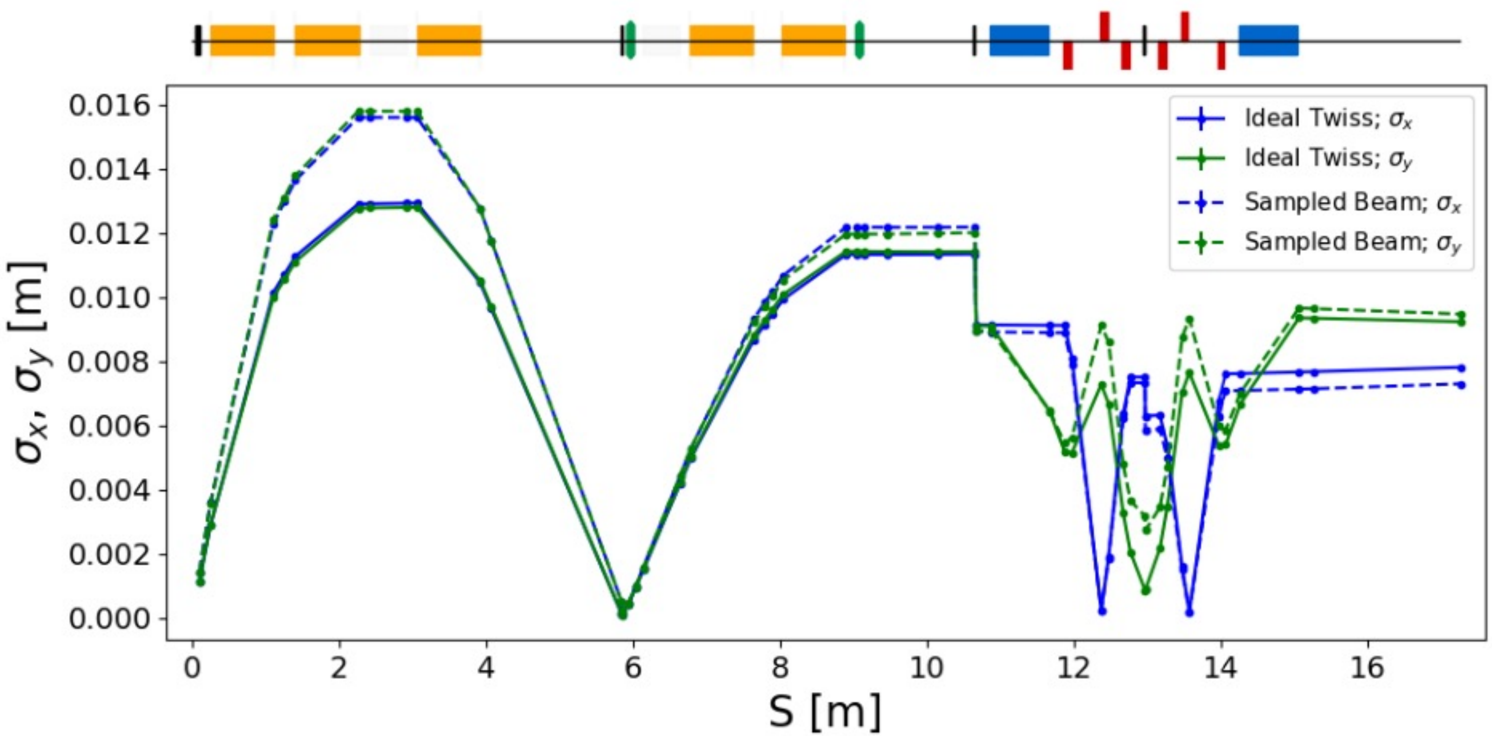
- Sampled beam from laser-target interaction simulation in Smilei (PIC code)
  - 3D distribution approximated from 2D simulation output

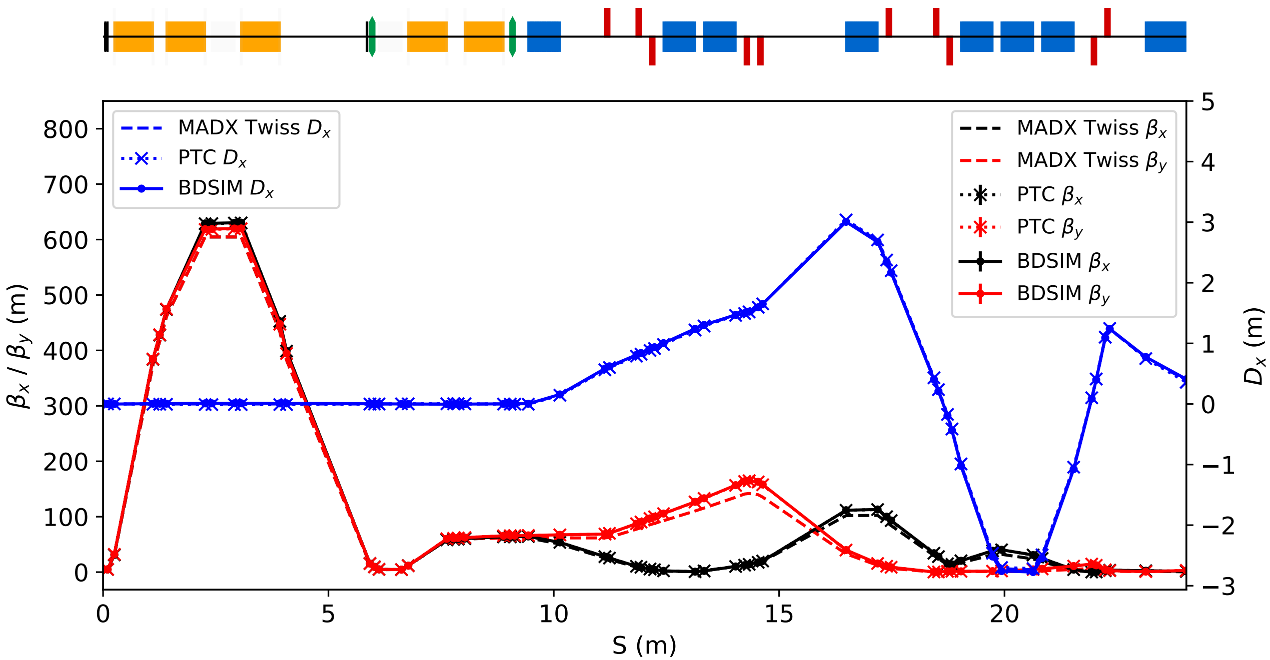
- Momentum cleaning collimator before first Gabor lens
  - Removal of low energy particles

H.T. Lau, IPAC 2021: WEPAB139

- Early discrepancy mitigated by downstream collimator (S=6m).

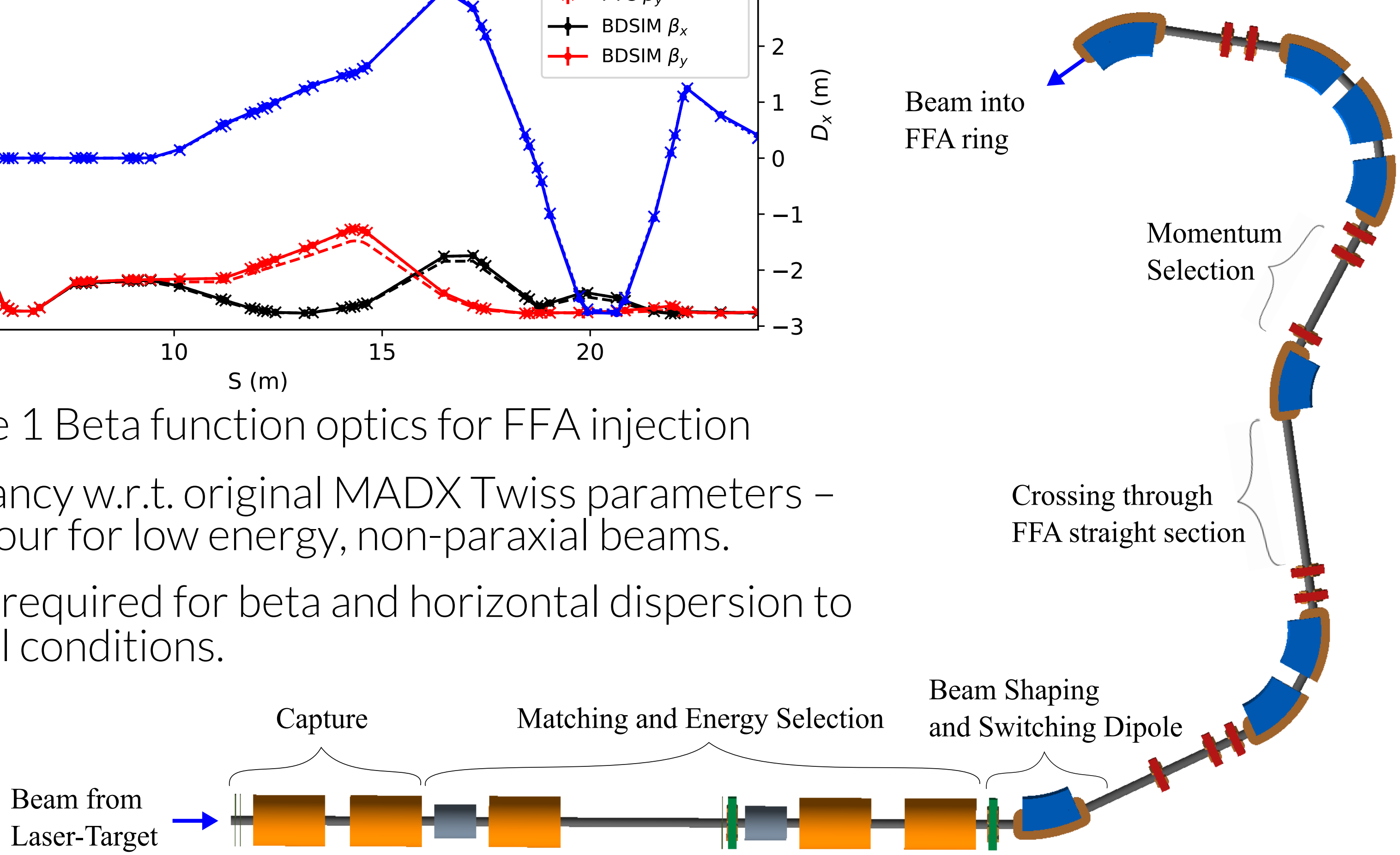
- Ongoing optimisation studies.



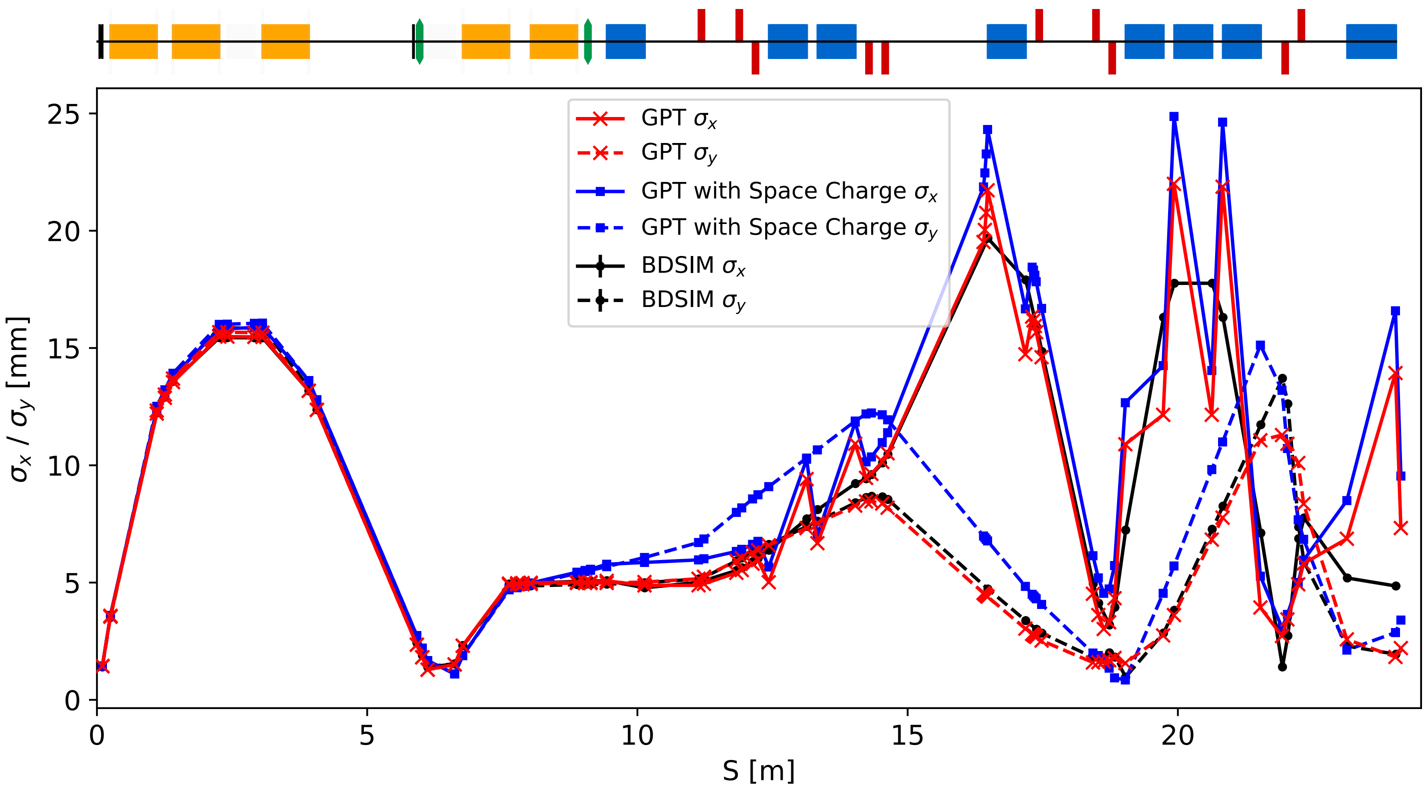


- Excellent agreement between BDSIM and PTC with idealised beam (10k primaries).

- Reduced stage 1 Beta function optics for FFA injection
- 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.



Injection Line Performance

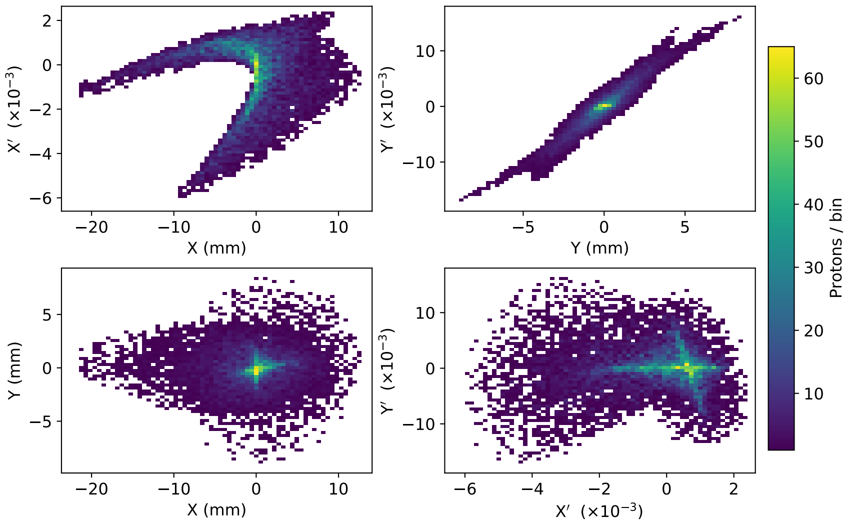


- Beam simulated in GPT with & without space charge.
- Good agreement between BDSIM and GPT without space charge.

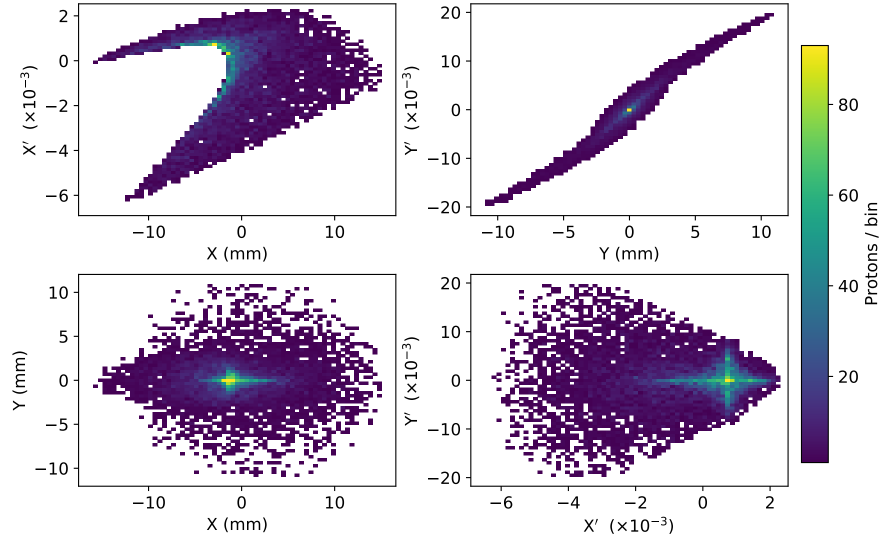
- Emittance growth observed when modelling space charge forces.
  - Final dimensions do not match FFA cell requirements - optimisation is required.

- Horizontal beam size jumps due to GPT output capturing the bunch partially within sector-bend fields
  - Strategy needed to mitigate GPT simulation output control

Gabor Lens Aberration



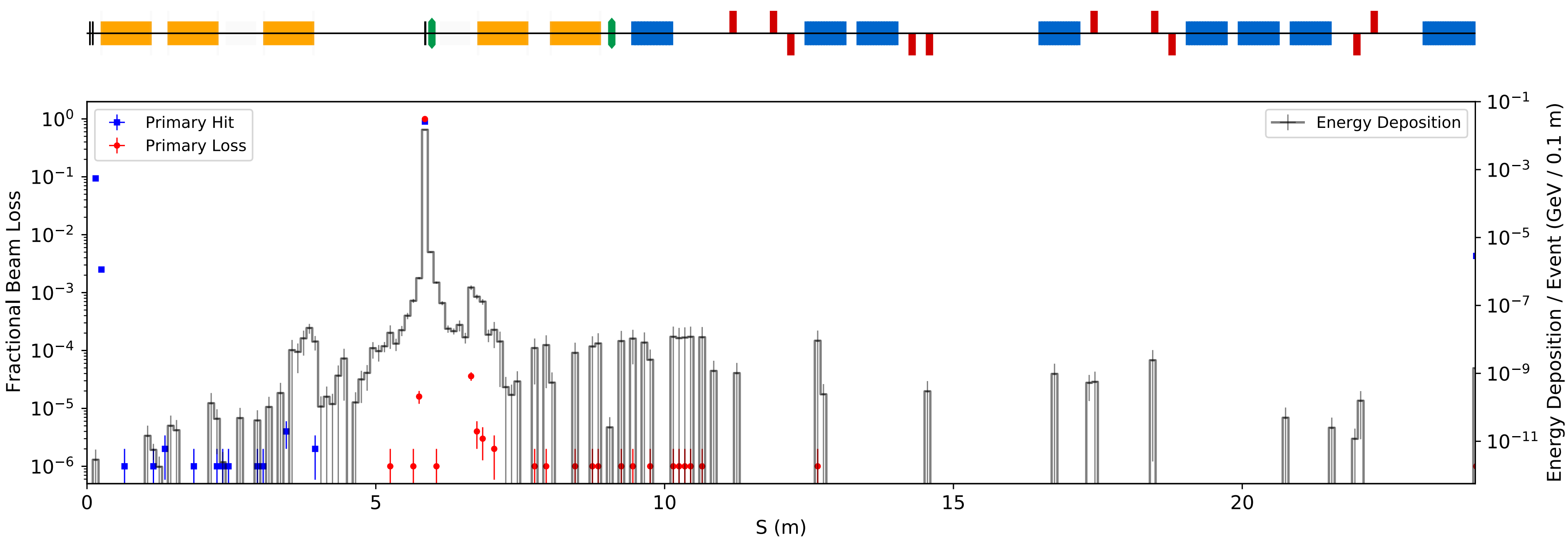
Solenoid



Field map

- Replaced solenoids with limited Gabor lens field map (T. S. Dascalu, IC).
- Minimal impact on optical performance compared to solenoid optics.
- The aberration the result of a solenoid-like field. Possibly unavoidable.
  - Potentially acceptable by FFA ring, but further understanding needed

Losses & Energy Deposition



- Momentum selection collimator aperture radius set to 0.5mm (the settings for stage 1 in vitro energy collimation).
- Heavy losses are observed with < 1% of the beam reaching the FFA septum magnet.
- Energy deposition is mostly restricted to within +/- 2m of the collimator.
- New collimator settings are required for energy selection through the injection line.
    - Beam line transmission must be considered.

Summary

- Successful stage 1 design capable of dose delivery into the FLASH regime.

- Number of validated Monte Carlo models
  - Well supported workflow
  - Ideal functionality for future studies

- Optimisation studies identified
  - Emittance growth due to space charge
  - Collimator settings
  - Transmission efficiency
  - …

Thank you

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