LhARA Stage 1 as a Proton Source

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On behalf of the LhARA Collaboration

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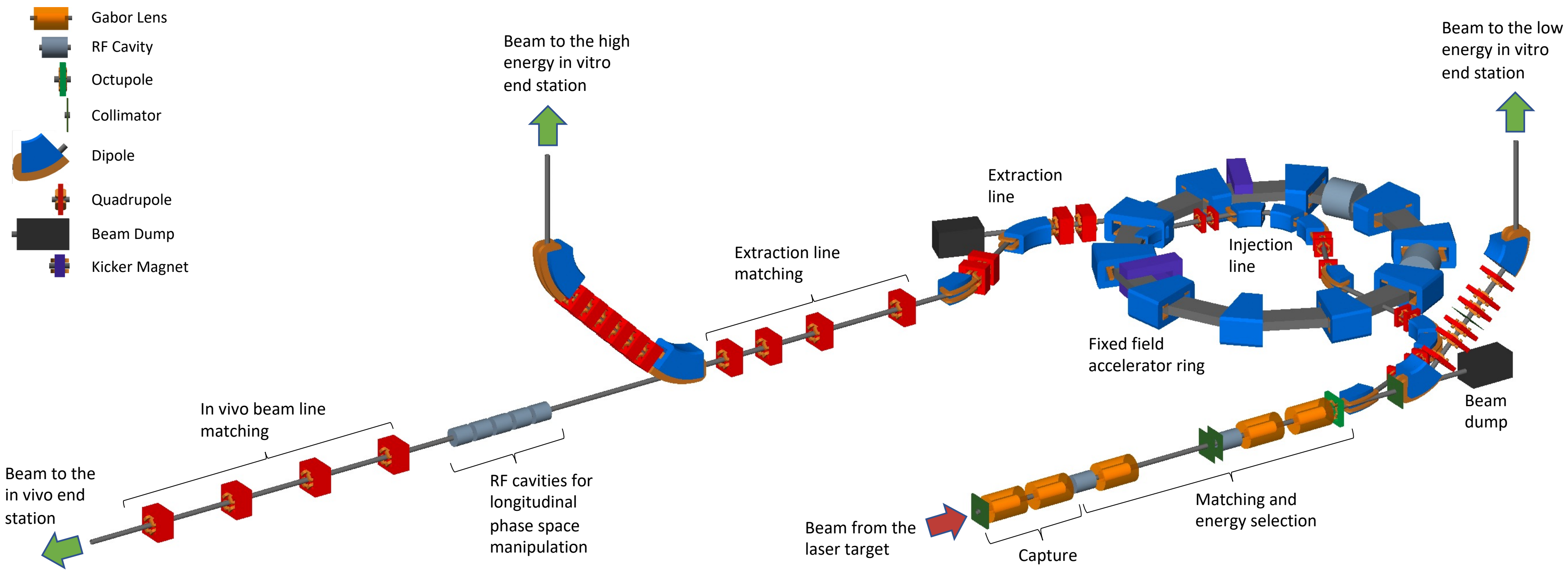
ISIS2/LhARA Common Themes Meeting

1st June 2023

Introduction

- LhARA Overview
- Baseline design
- Beam generation
- FFA injection
- Recent progress
- Future work

LhARA Overview



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

LhARA baseline design technical note:
https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-11-LhARA-Design-Baseline.pdf

LhARA performance summary arXiv:2006.00493

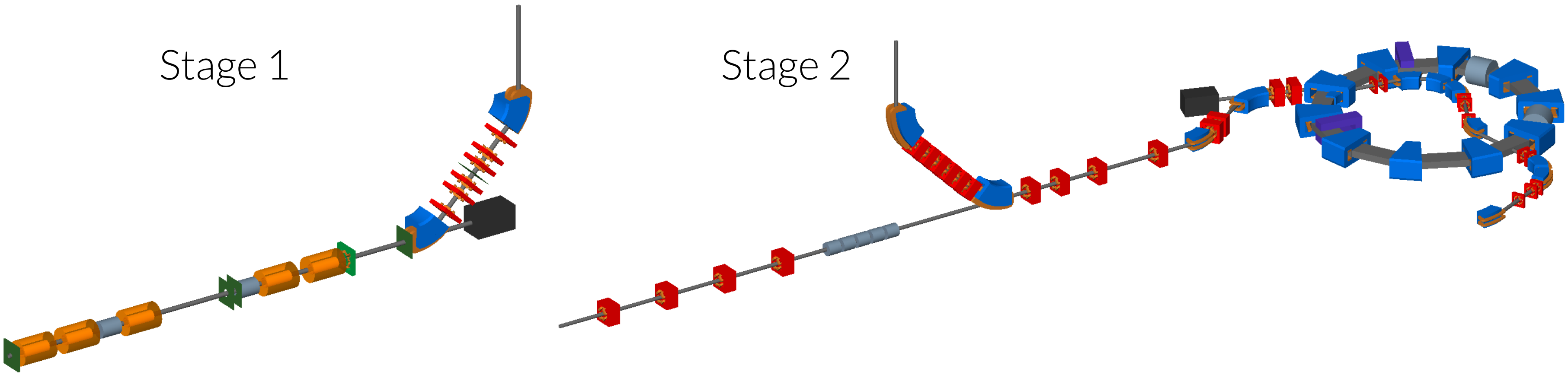
	12 MeV Protons	15 MeV Protons	127 MeV Protons	33.4 MeV/u Carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

LhARA Overview

- Multi stage:

Stage 1

Stage 2



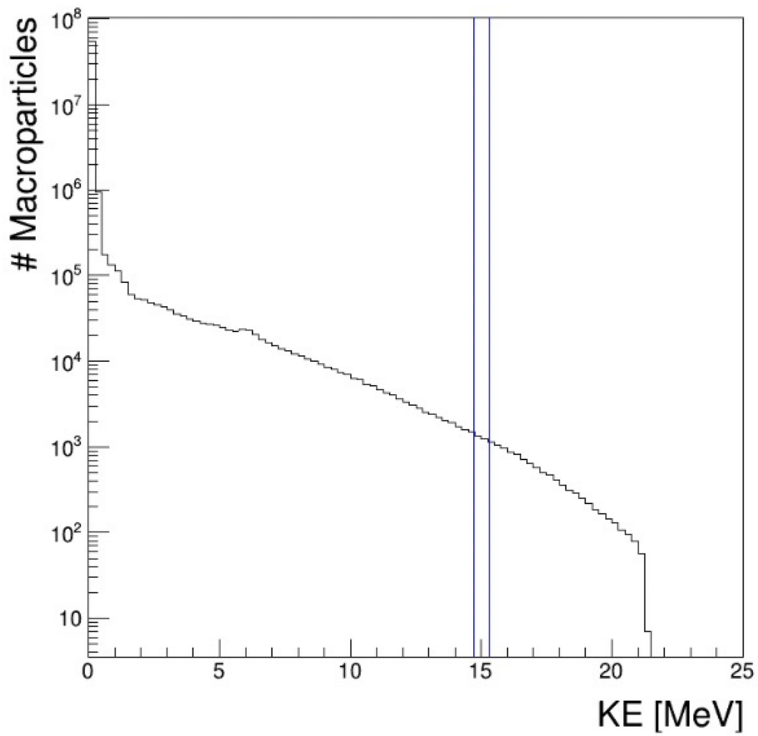
- Design & validate the LhARA accelerator
    - Performance evaluation
- Monte Carlo particle tracking
    - Hybrid strategy:
        - Madx
        - BDSIM
        - GPT

- Status:
    - Full stage 1 model
    - Injection line
    - Stage 2 high energy lines

- FFA ring design ongoing
    - See Jaroslaw's talk

LhARA Beam Generation

- Laser-driven target normal sheath acceleration (TNSA)
  - 10 GV/m - up to 40 MeV/u.
  - 100 TW laser provides suitable proton flux at LhARA energies
  - Broad quasi-thermal particle spectrum



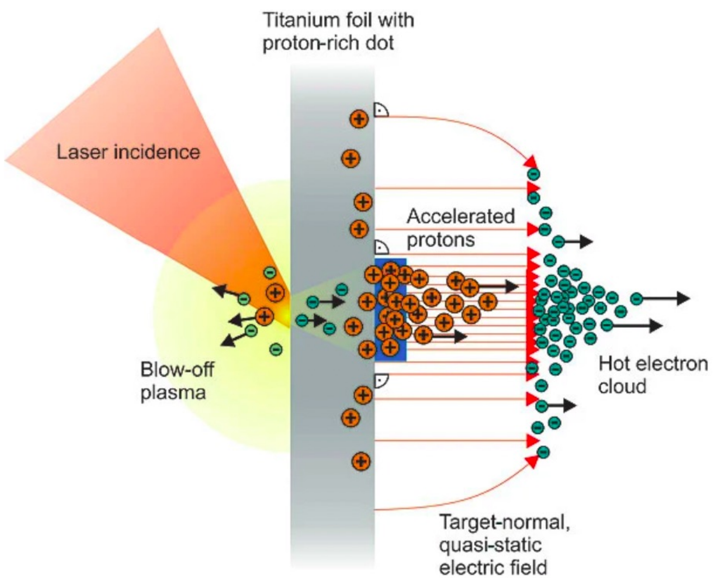
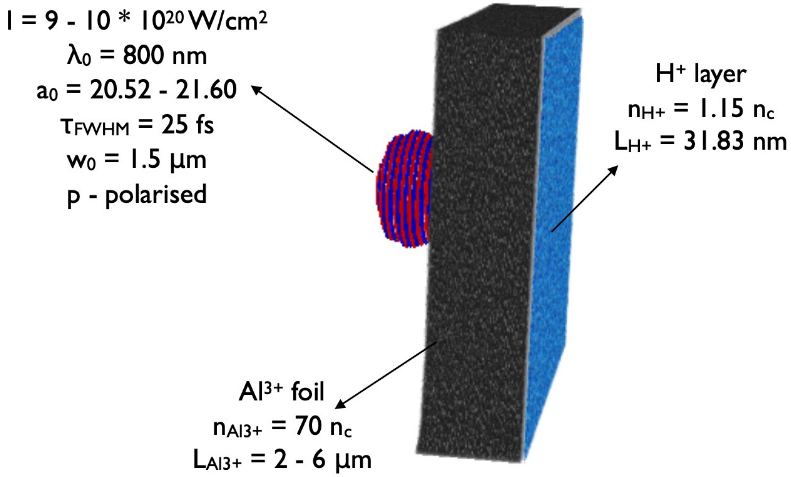


Figure: Schematic diagram of the TNSA process from Schwoerer [1].

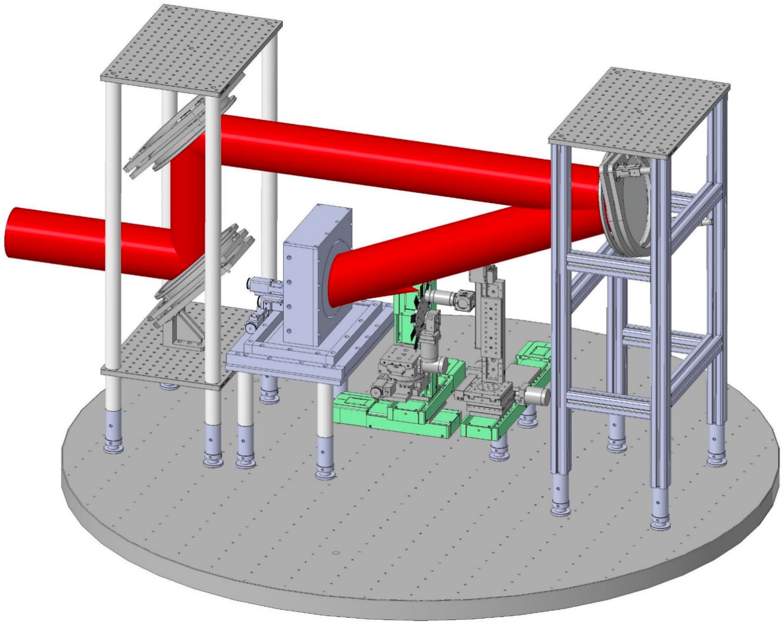
- High bunch charge – 10^9 protons at 15 MeV
- Low transverse emittance (< 10^{-2} mm-mrad)
- Reduced space-charge effects
  - ~ Neutral charge from low energy contaminants

LhARA Beam Generation

- High intensity laser driven ion sources:
  - High instantaneous dose rate - 10-40 ns bunches
  - 10 Hz repetition rate
  - Triggerable; arbitrary pulse structure

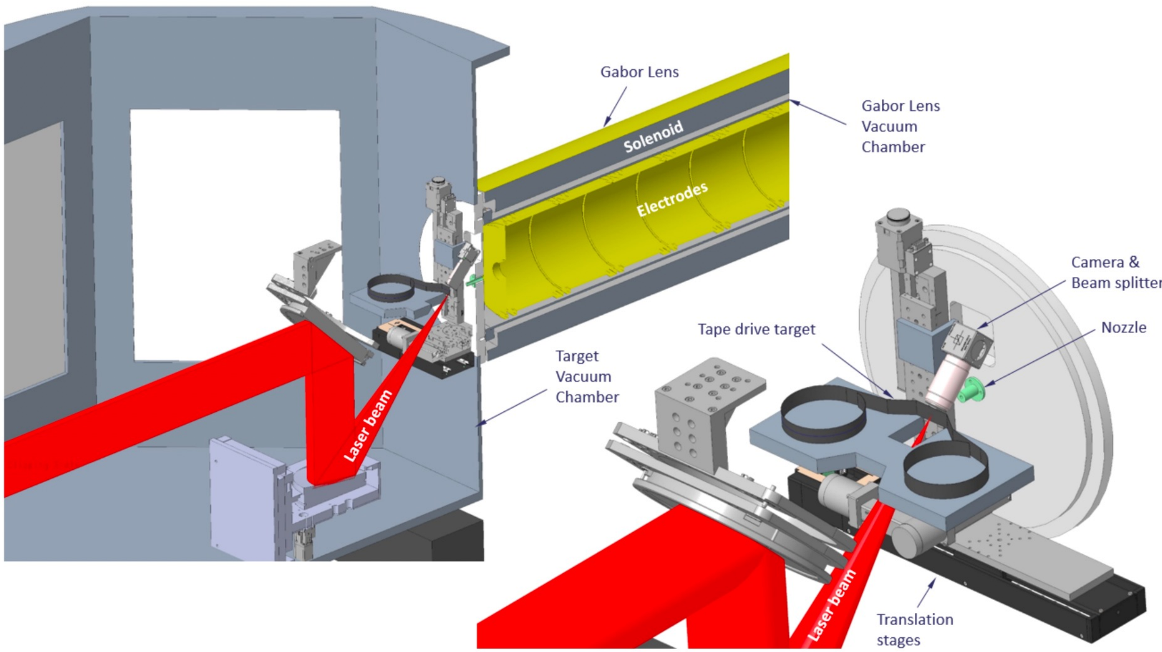


- Proton & ion source prediction
  - 3D TNSA simulations
    - PIC code Osiris
  - SCAPA facility & experimental beam time



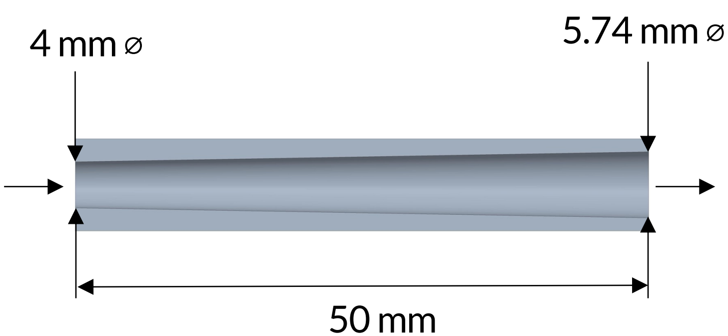
- WP1.2: Identify LhARA facility laser requirements
  - Generation of proton (15 MeV) and carbon (4 MeV/u) beams using existing "tape" targets
  - Understanding of debris & stabilisation schemes

Nozzle & Target Housing



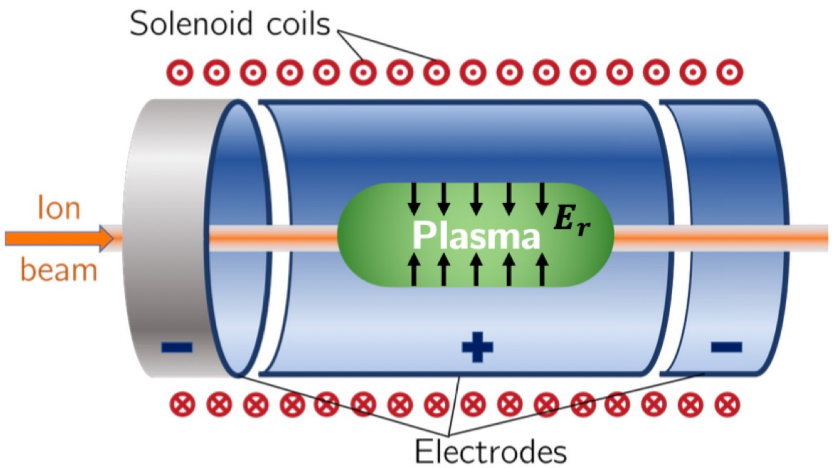
- Ongoing engineering & CAD designs
  - Tight spatial constraints – laser transport, target holder, diagnostics, particle beam profilers, vacuum, …
- Gabor lens target proximity for capture efficiency

- Vacuum nozzle collimation
  - Aperture dictates downstream beam dimensions
- Beam tracking including space-charge forces
- Studies of co-propagating beam to be performed
  - Uncertainty in beam profile & spectrum.



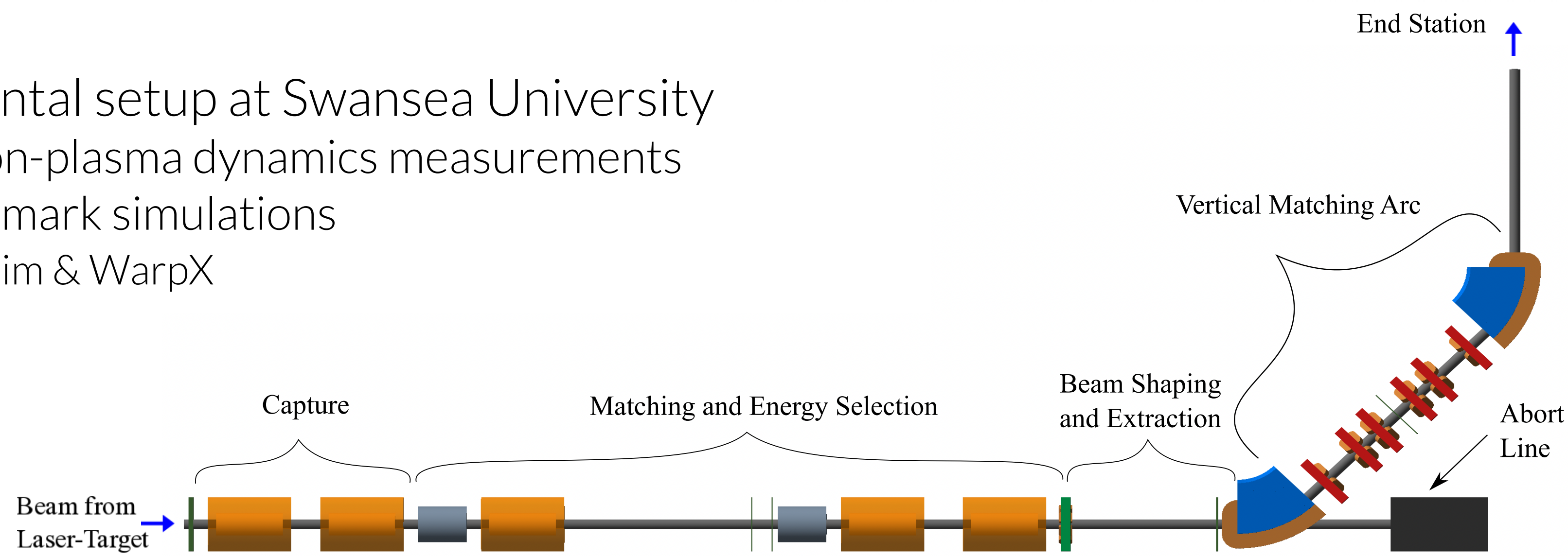
Beam Capture

- Novel Gabor electron-plasma-lens
  - Capture & focusing
  - Strong focusing without high power, high-field solenoid
  - Focus in both planes simultaneously
  - Energy-dependent focusing strength

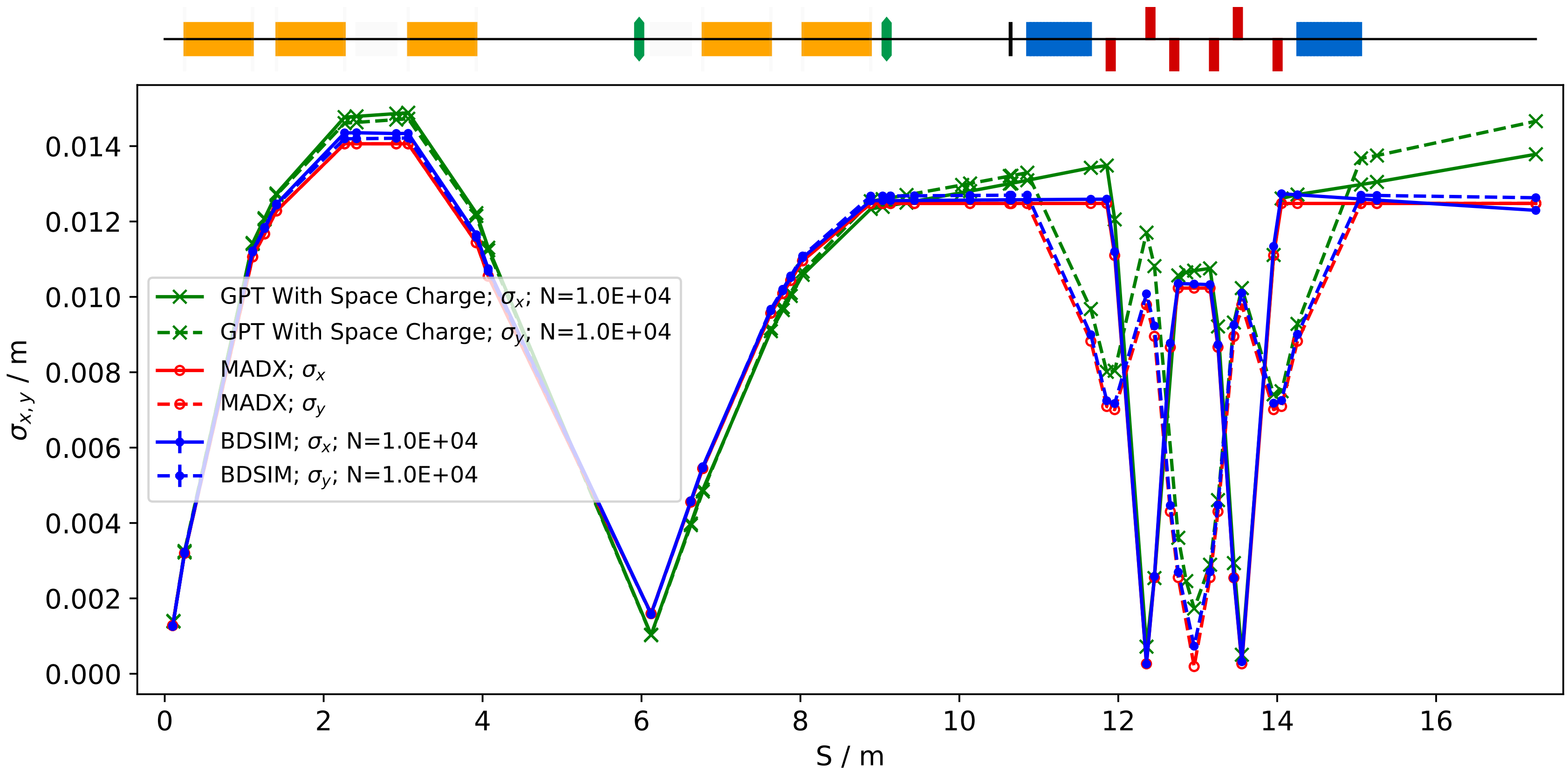


- Develop a detailed design of the next generation Gabor-lens prototype

- Experimental setup at Swansea University
  - Electron-plasma dynamics measurements
  - Bench-mark simulations
    - VSim & WarpX



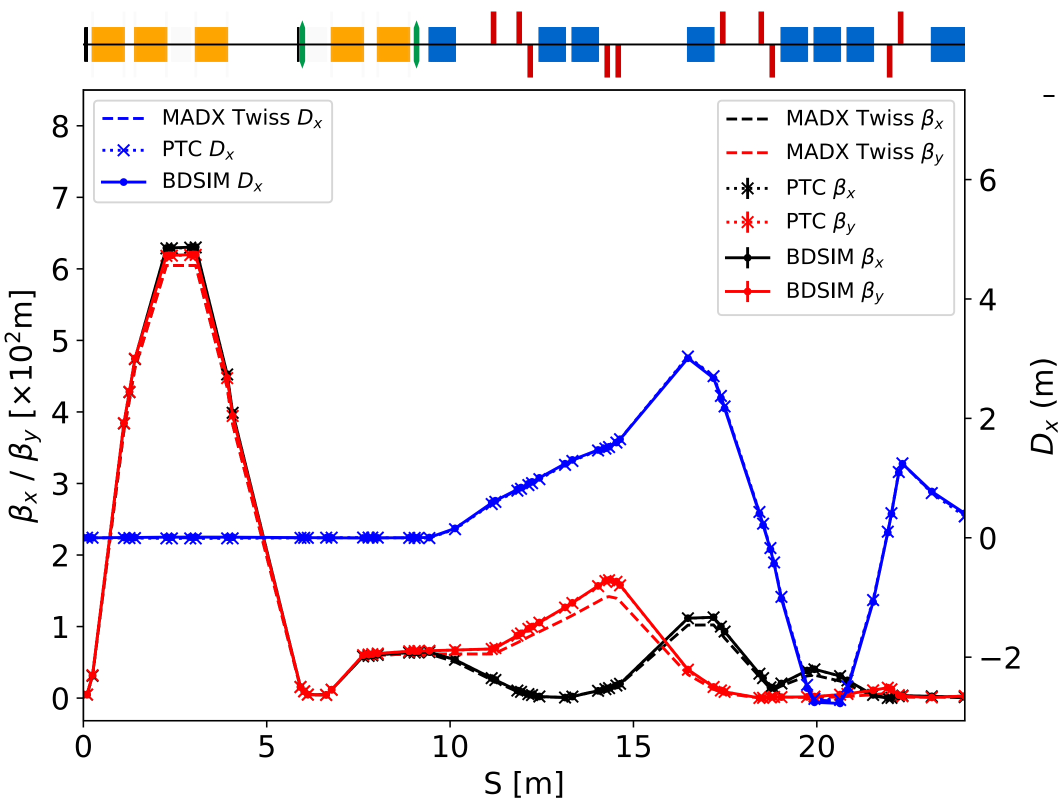
Baseline Transport Performance



- Requirements:
  - Parallel beam between GL2 & GL3
    - Flexibility: RF, shielding wall, ...
  - GL3 focal plane at the stage 1 energy collimator location
  - Parallel beam after GL5

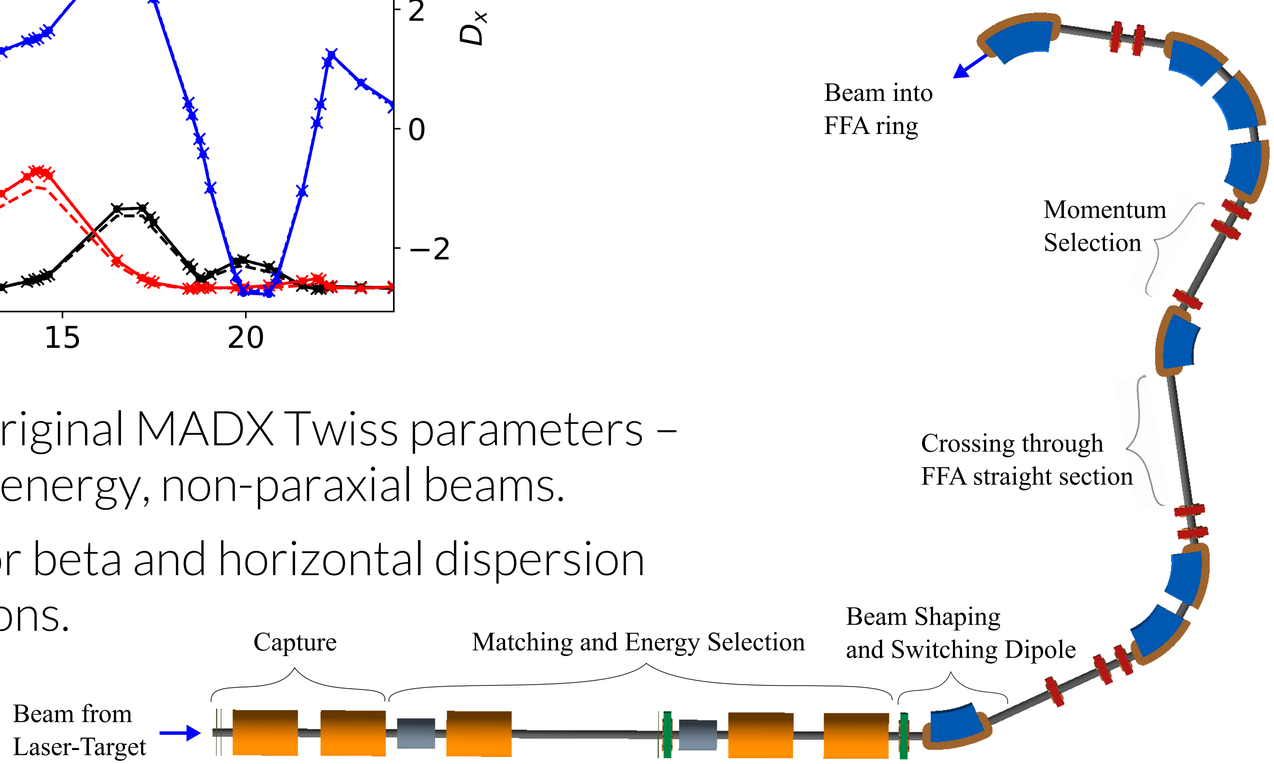
- Solutions found
  - 1.4 T solenoid field limit
  - Optimise collimation, octupoles, etc….

FFA Injection Line

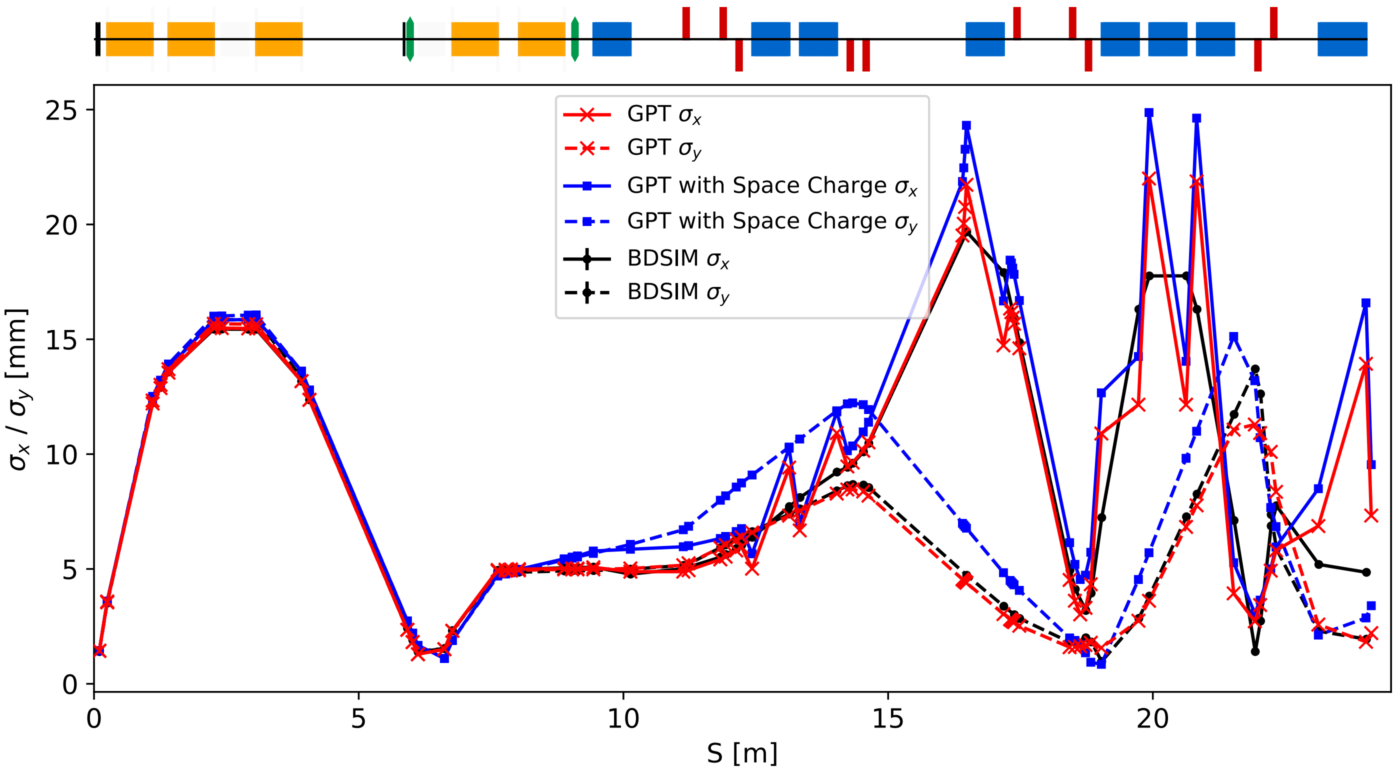


- BDSIM and PTC show excellent agreement for the beta function and dispersion.
  - 10000 particles tracked in BDSIM & PTC – idealised beam.

- 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.



FFA Injection Line Performance

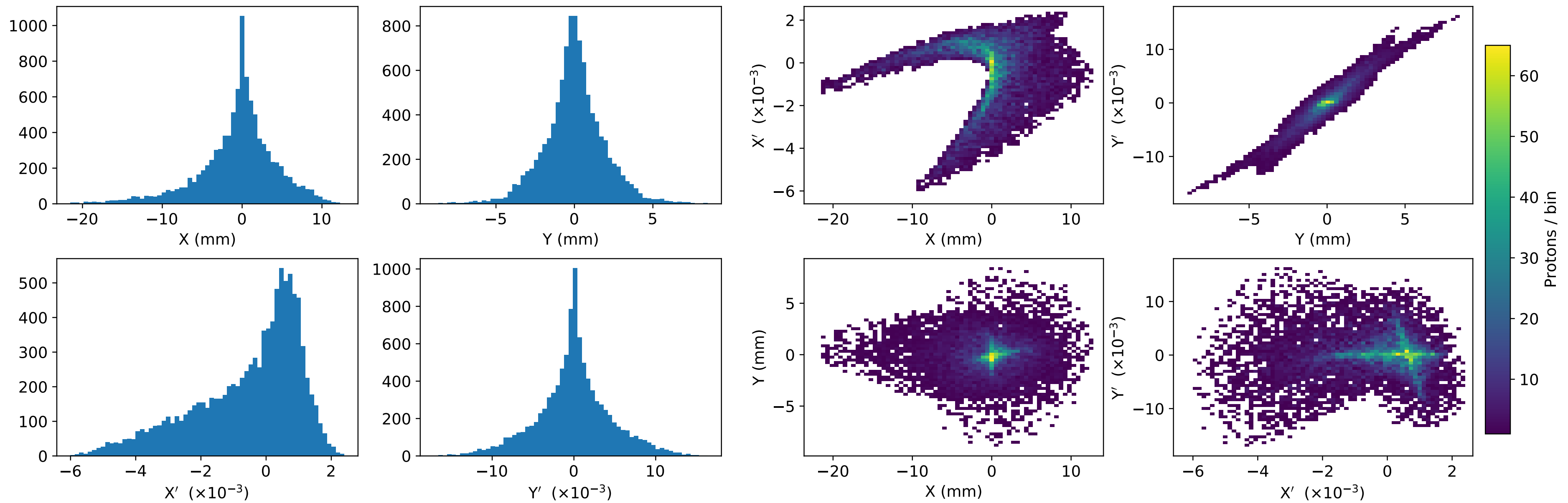


- 10000 particles representing a total bunch charge of 10^9 protons.
- Good agreement between BDSIM and GPT without space charge.
- Beam size jumping is a GPT simulation artefact

- Emittance growth impacts performance
  - Final dimensions do not match FFA cell requirements - optimisation is required

- Remodelling with FFA redesign required
  - Dependant on stage 1 optics solutions

FFA Injection Line Performance



- Aberration originates in the solenoids / Gabor lenses
  - Challenging to mitigate
  - Anticipate little impact on tracking performance & FFA acceptance

- Further momentum selection / cleaning studies are required.

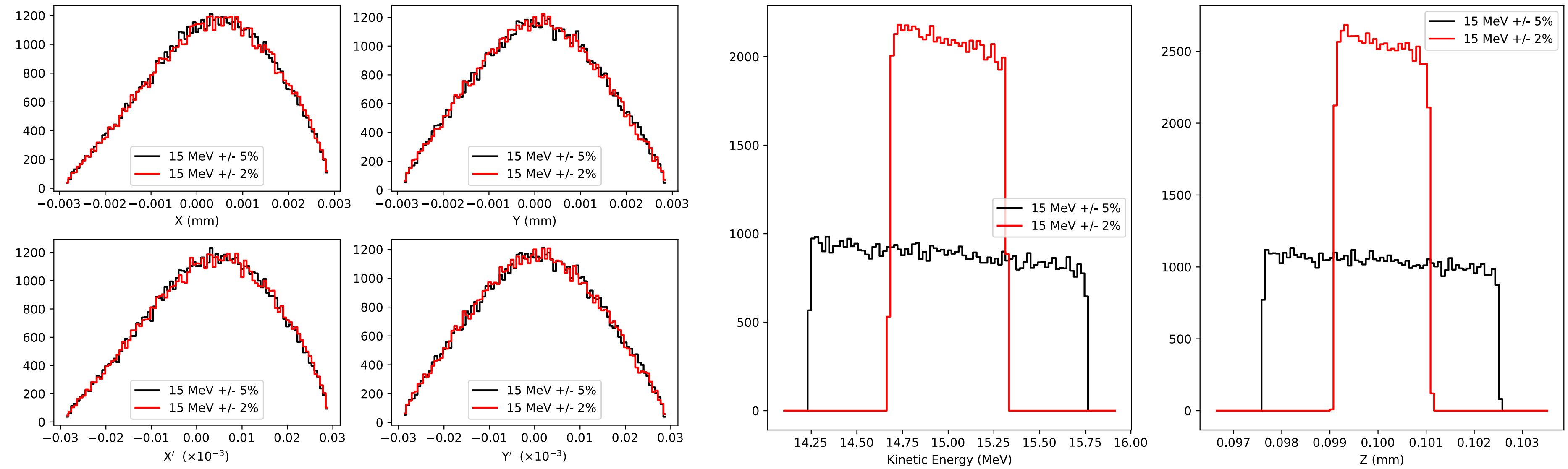
Nozzle Beam Parameters

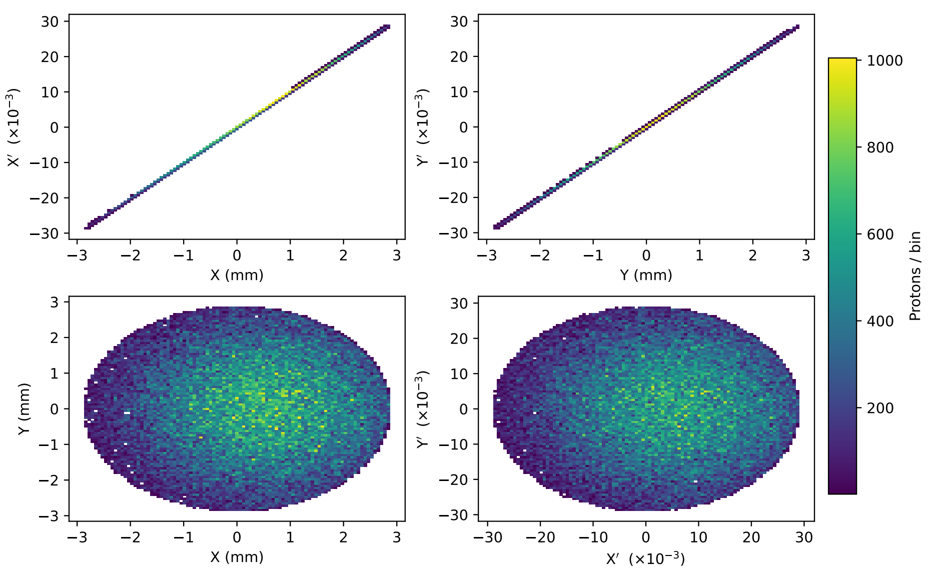
	Smilei Sampled Beam	SCAPA Beam	Pre-CDR Beam
Mean RMS emittance [m]	1.43×10^{-8}	7.98×10^{-8}	3.26×10^{-7}
Mean beta [m]	141.34	21.62	4.89
Mean alpha	-1418.43	-222.23	-50.22

- Large discrepancy between SMILEI sampled beam and assumed pre-CDR emittance
  - Not fully understood. 2D simulations known to suffer from several issues.
  - <u>SMILEI beam not considered reliable</u>

- 3D SCAPA simulation shows improved agreement
  - Down-sample to 15 MeV ± 2%
    - 15 MeV ± 5% for collimation studies

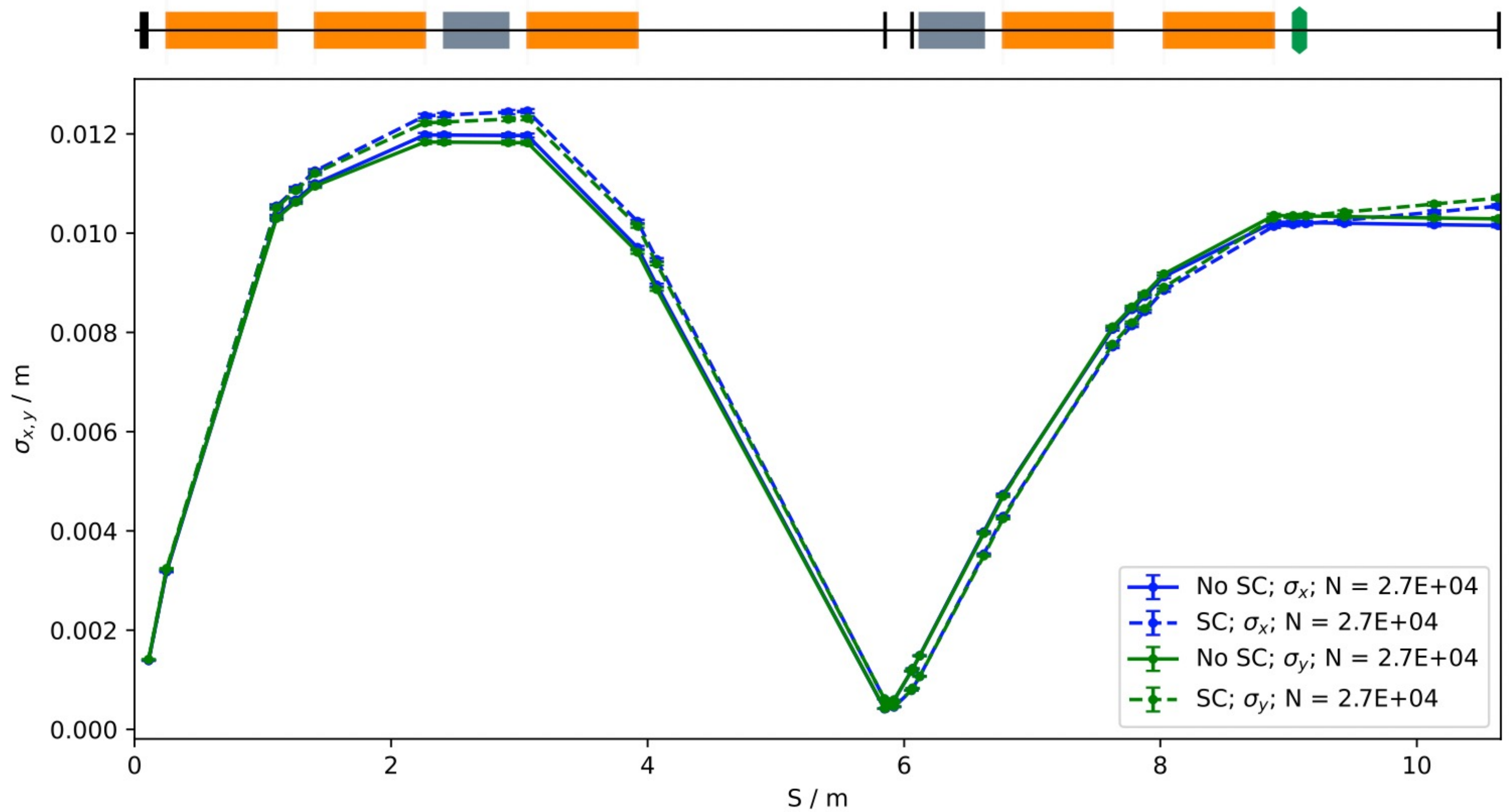
Stage 1 SCAPA Beam





- Vacuum nozzle transmission ~ 77%
- Minimal spectral impact
  - Greater emphasis on downstream collimators performance
- Horizontal offset does not impact tracking performance

Baseline Transport Performance



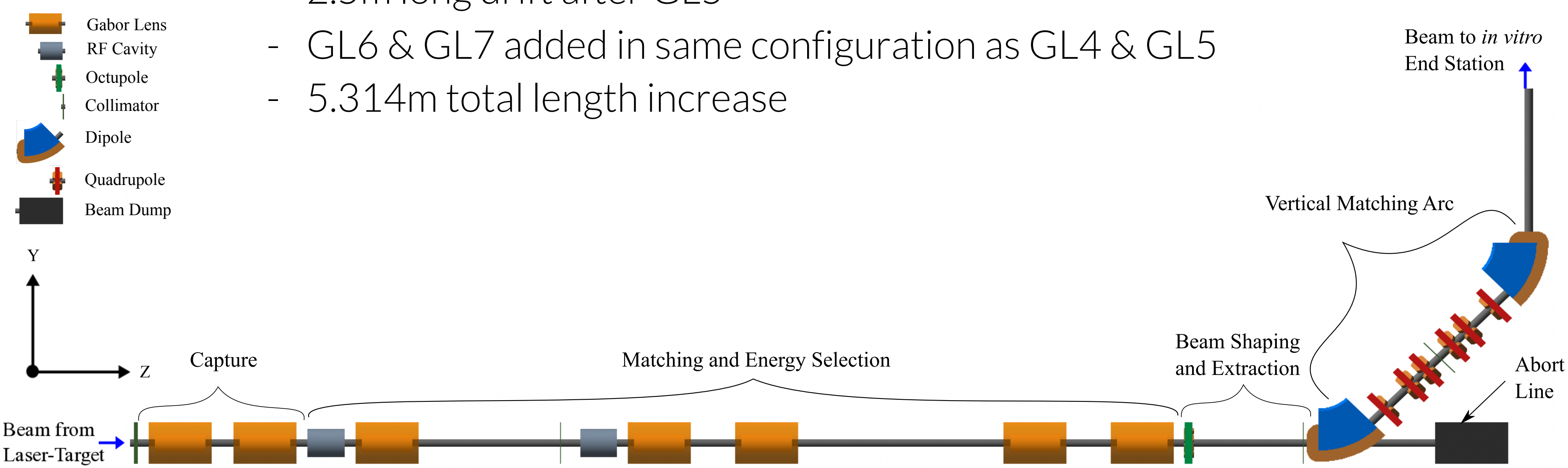
- Nominal stage 1 Gabor lens settings optimised
- Additional solutions for smaller spot sizes
- Difficulties in achieving beam parameters for FFA injection requirements (β = 50m).
    - Challenging without space-charge considerations

7 Gabor Lens Configuration

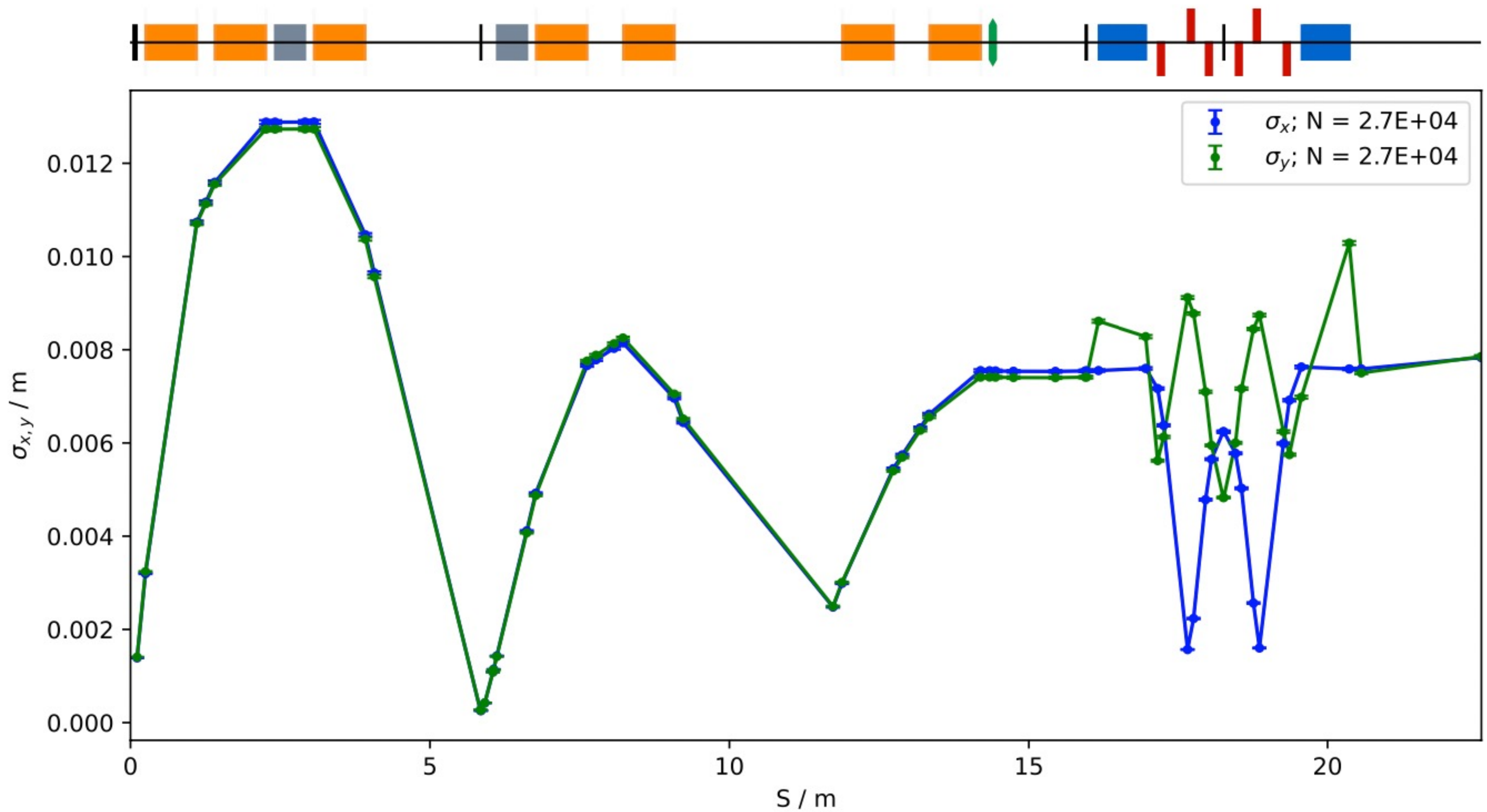
- Investigation of 7 Gabor lens / solenoids configuration

- <u>Improved spot-size flexibility & FFA injection performance</u>

- Geometry modifications:
  - Single energy collimator
  - Extra 0.2m between GL4 & GL5
  - 2.5m long drift after GL5
  - GL6 & GL7 added in same configuration as GL4 & GL5
  - 5.314m total length increase

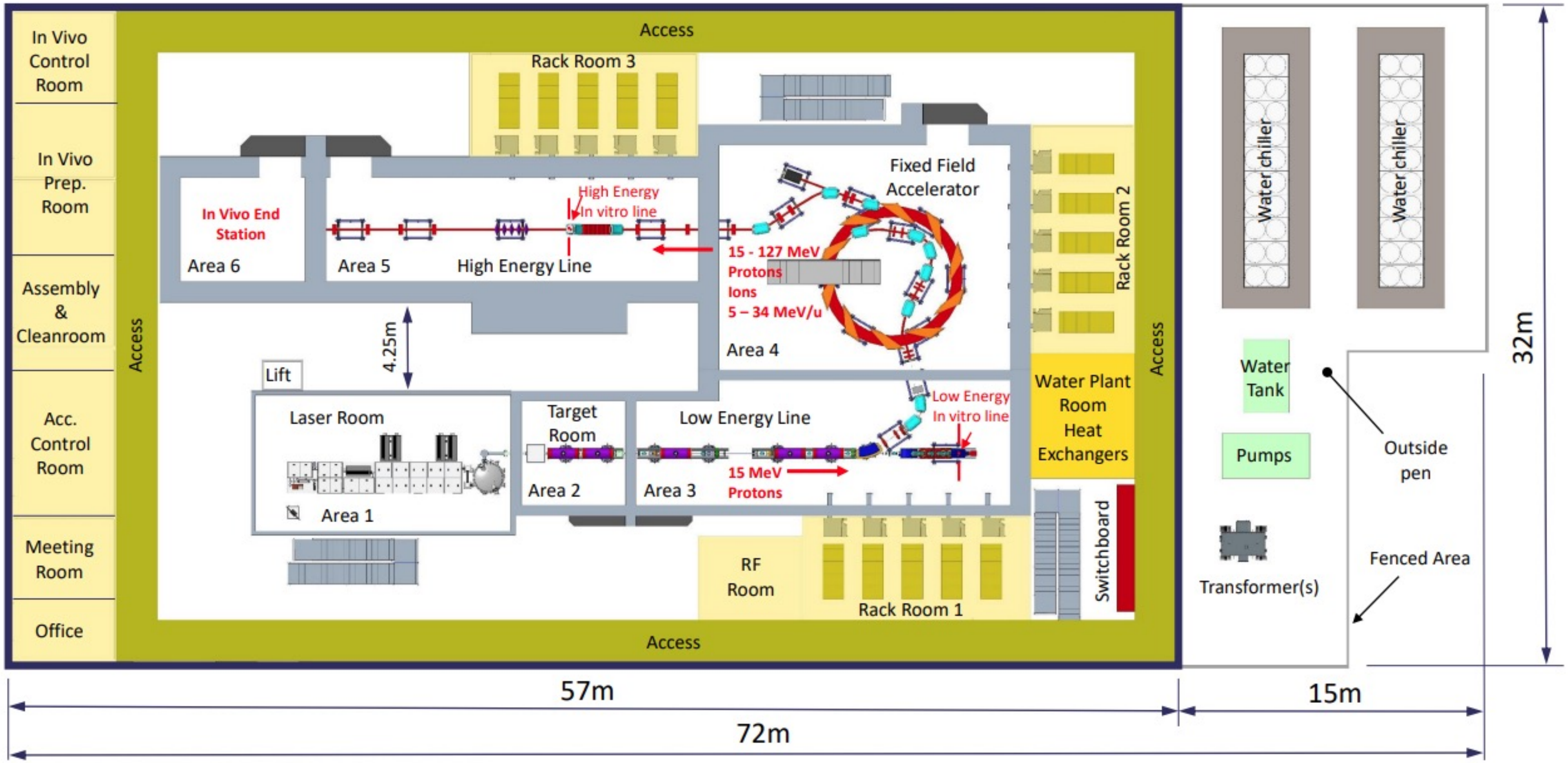


Performance



- Space charge impacting performance
  - Same requirements as 5 lens configuration
  - Optimised solutions for 3, 2.5, & 2 cm diameter spot sizes with space charge
  - Smaller beams remains focus of ongoing work.

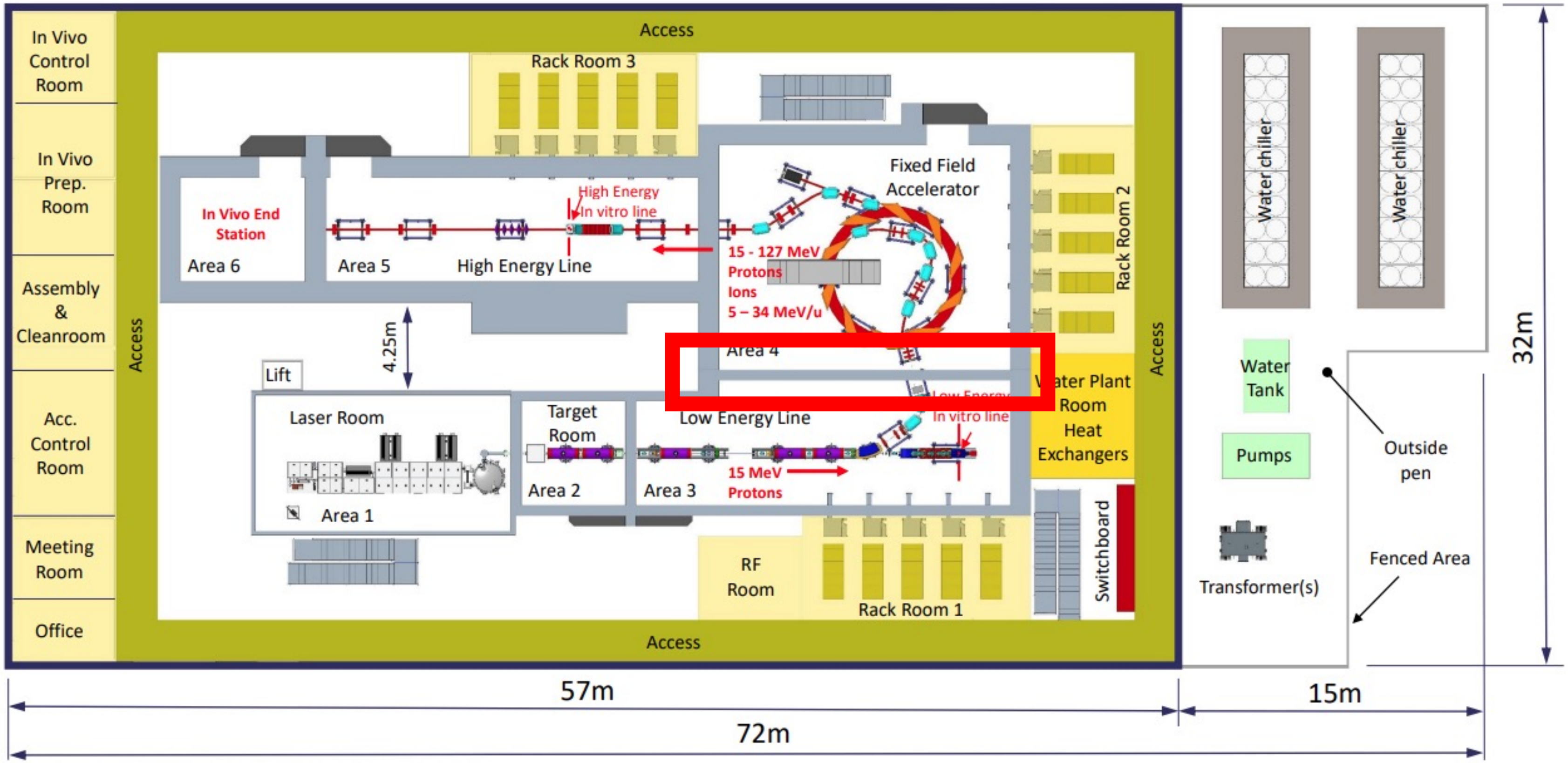
Facility Integration



- Engineering design underway
  - Iterate as accelerator design develops

Magnets, RF, Diagnostics, End stations, Shielding, Electrical power, Cooling, Vacuum, Controls, …

Injection Line Redesign



- Shielding wall for concurrent development/operation of stage 1 & stage 2.
- Injection line redesign needed.
  - Optics dependant on FFA injection requirements

Future Plans

- Continued evaluation of 7 Gabor lens configuration
  - Comparison to baseline design performance

- Stage 2 redesign efforts
  - FFA – today's raison d'être.
  - Injection line

- FFA Modelling
  - Optical performance, space-charge evaluation, injection & extraction, RF, ….

- Stage 2 post-FFA evaluation
  - Extracted beam parameters

Summary

- Established stage 1 performance of the baseline design
- Encouraging stage 1 experimental configuration in development
  - Impact studies on injection line performance planned
- Ongoing work program for FFA & injection line redesign

Thank you

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Baseline Parameter Summary

Stage 1 energy (protons / C^{6}+) [MeV/u]	15.0 / 4.0
Design energy spread [%]	± 2
Number of protons/ions per bunch	10^{9}
Mean RMS emittance at nozzle exit [m]	1.43×10^{-8}
Machine length [m]	17.255
End station spot size diameter [cm]	1 - 3
FFA injection* bunch length [ns]	8.1
FFA injection* beta [m]	50
FFA injection* dispersion [m]	0
SCAPA mean RMS emittance at nozzle exit [m]	7.98×10^{-8}

* Beam parameters at the exit of the septum magnet