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Overview of Preparations at SCAPA

LhARA Collaboration Meeting #7

7th April 2025

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SCAPA: Scottish Centre for the Application of Plasma-based Accelerators

- Research is focused on the development and application of laser-driven particle acceleration.

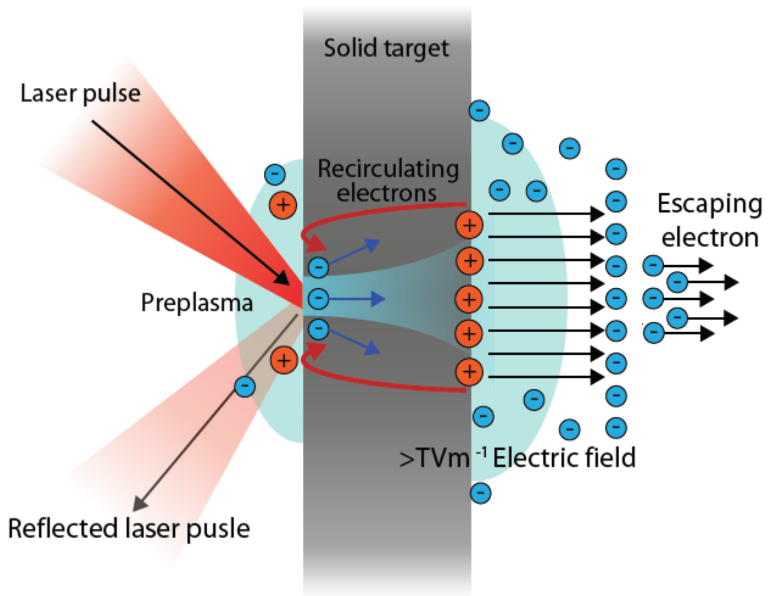
- Can deliver high proton numbers, within the MeV energy range, at Hz level reception rate.

Parameters	
Peak Power	*≥350 TW*
FWHM pulse duration	*~25 fs*
Energy per pulse (on target)	*up to 7 J*
Pulse repetition rate	*1 Hz*
Temporal intensity contrast	*10^{10}:1 @ 100 ps* *10^{8}:1 @ 30 ps* *10^{4}:1 @ 2 ps* *ASE contrast 10^{10}:1*
Central wavelength	*800 nm*
Beam quality Strehl ratio	*≥0.85*

Laser-solid interaction beamline B1 in Bunker B.

Mechanism for laser-driven ion acceleration

Target Normal Sheath Acceleration (TNSA)



Laser energy absorbed producing large population of hot electrons

↓

Hot electrons injected and propagate through the target

↓

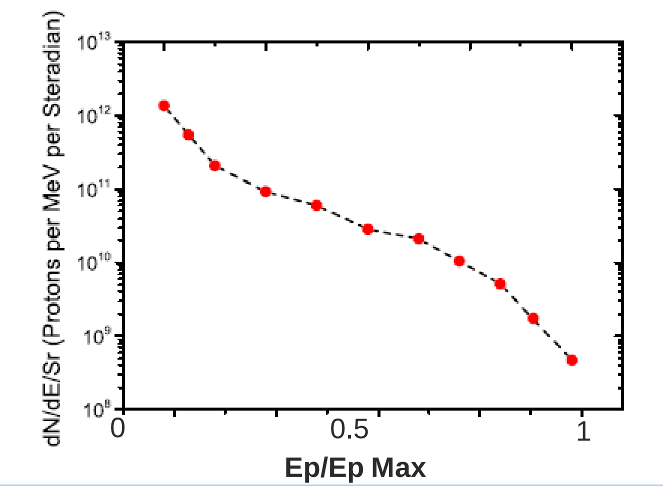
Generates strong (~TV/m) electrostatic sheath fields at target rear

↓

Drives acceleration of high energy protons

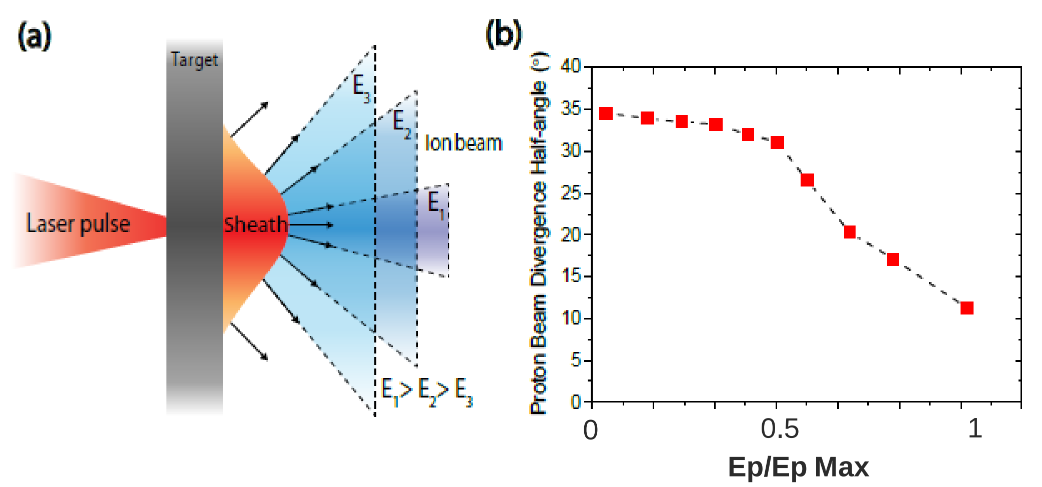
Proton beam characteristics

i)



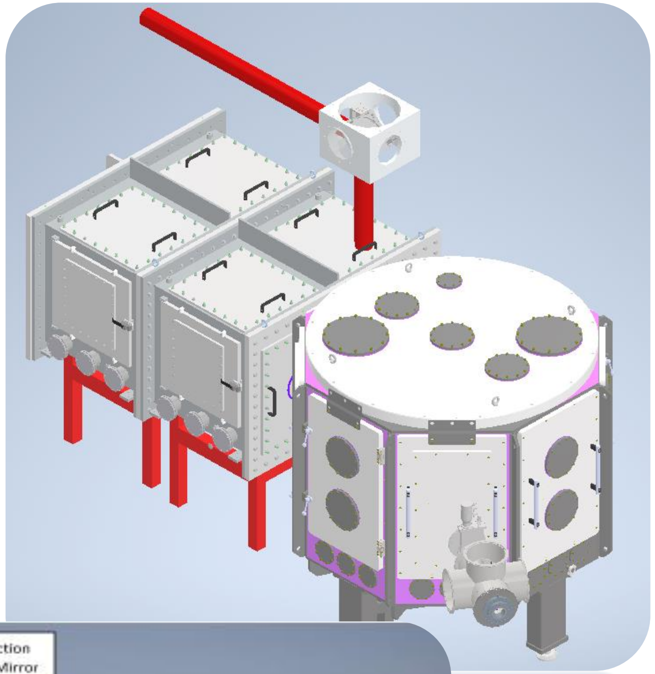
- Broad energy spectrum, up to a maximum cut off energy.

ii)

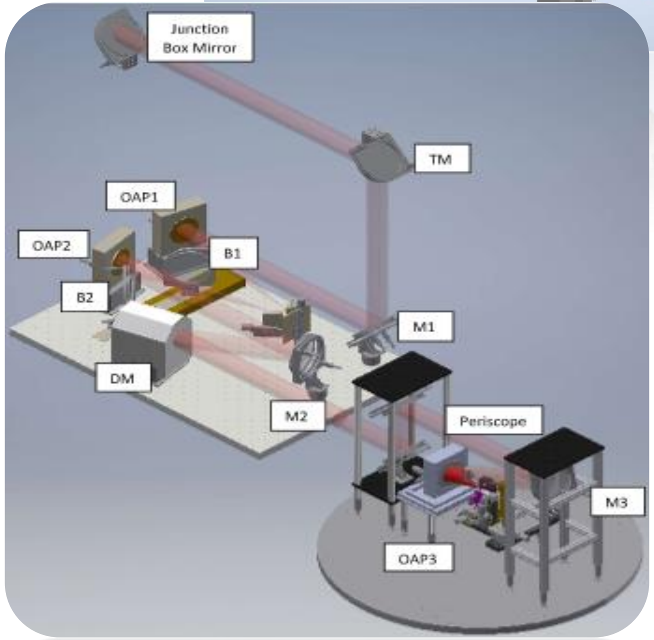


- Proton energy dependent beam divergence.

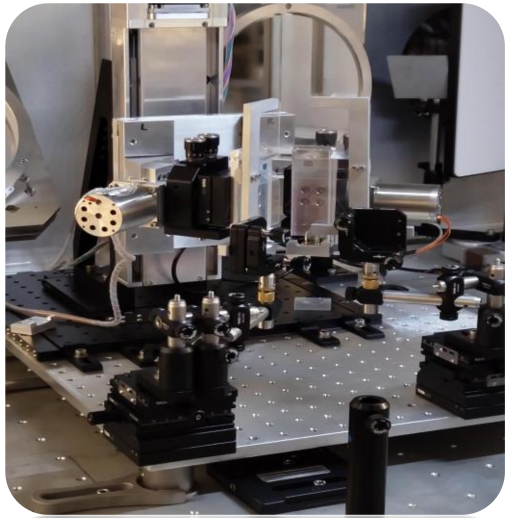
SCAPA Bunker B Target Station



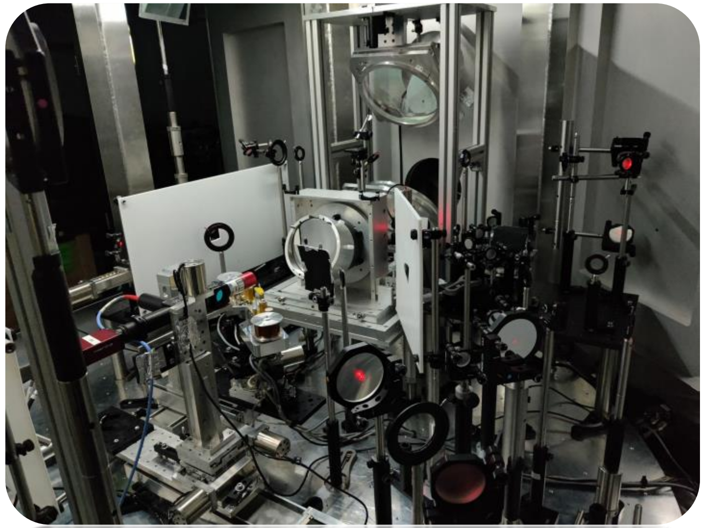
Beamline

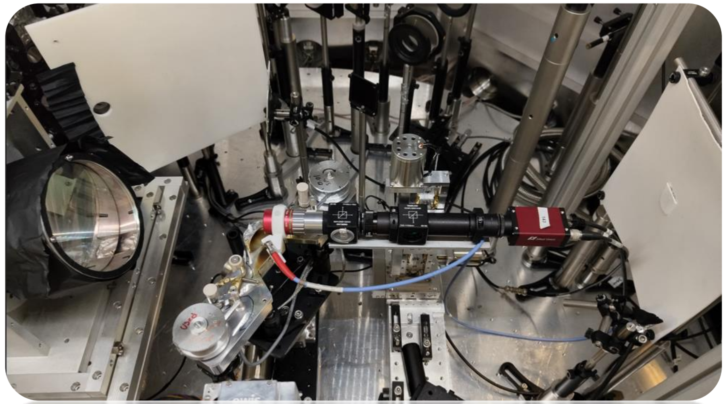


Plasma Mirror Chamber Internals



Main Chamber Internals





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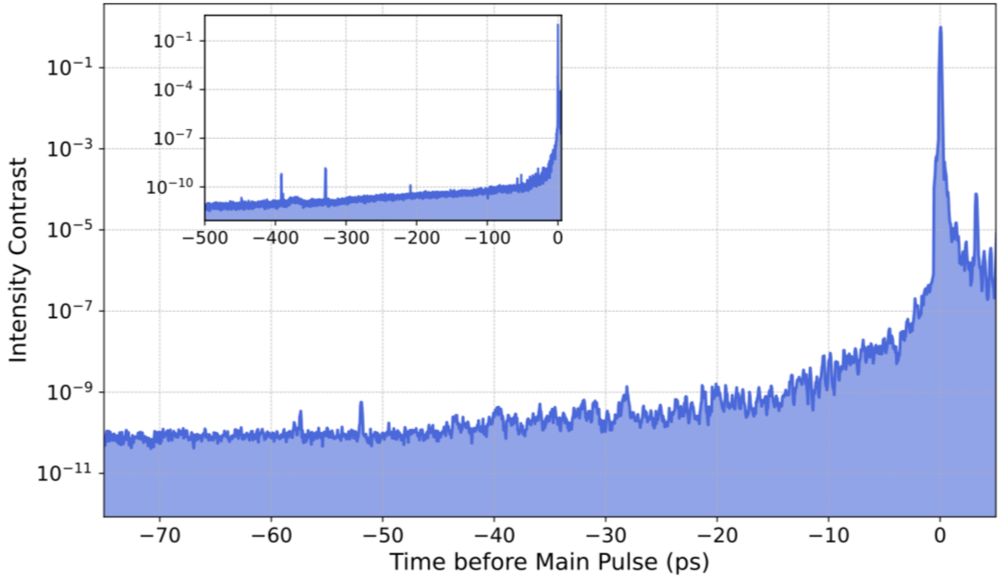
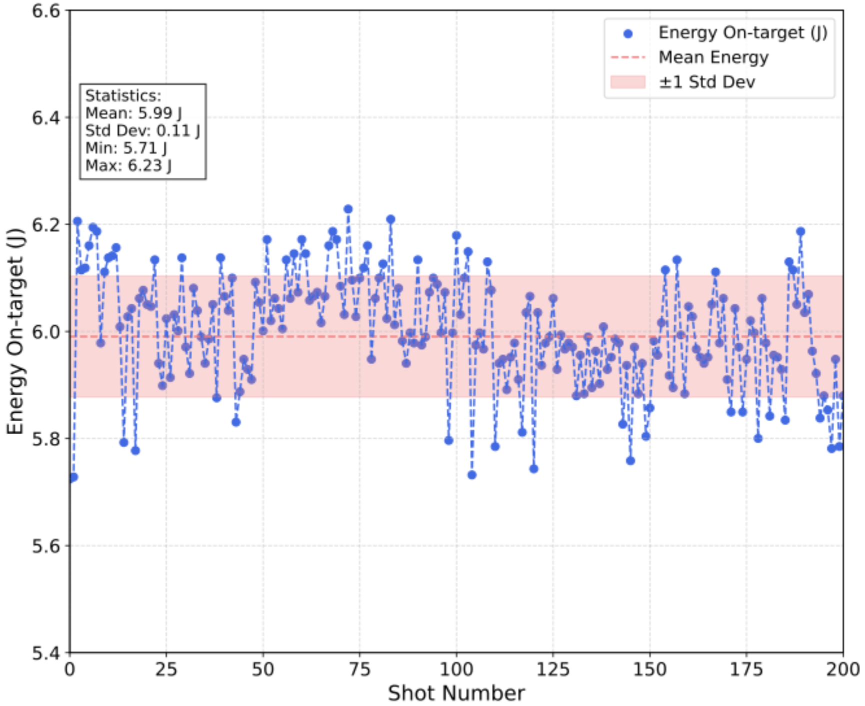
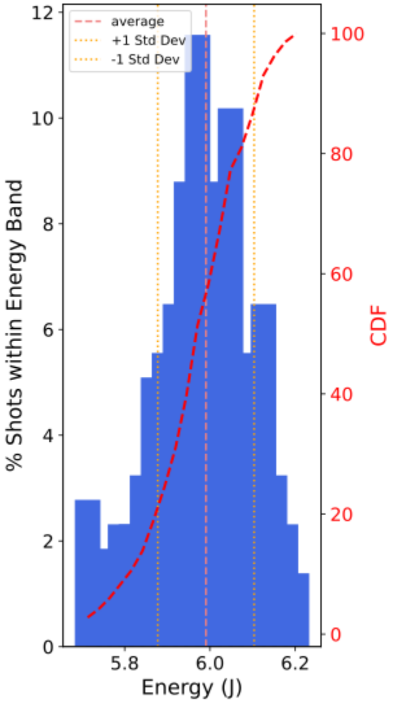
SCAPA Development Challenges

i) Pulse Temporal-Intensity Contrast

- High temporal contrast is essential for avoiding premature ionisation of the target.
- In early experiments there were significant prepulses measured in the system which were limiting our proton energy and flux.
- These have been removed, significantly improving contrast, laser energy stability, and focal spot jitter.







ii) Laser Energy Stability

- Performed stability run of N=200 equivalent shots.
- Laser energy demonstrated to be stable with a std. dev. of 1.8 %.

SCAPA Maximum Energy Performance

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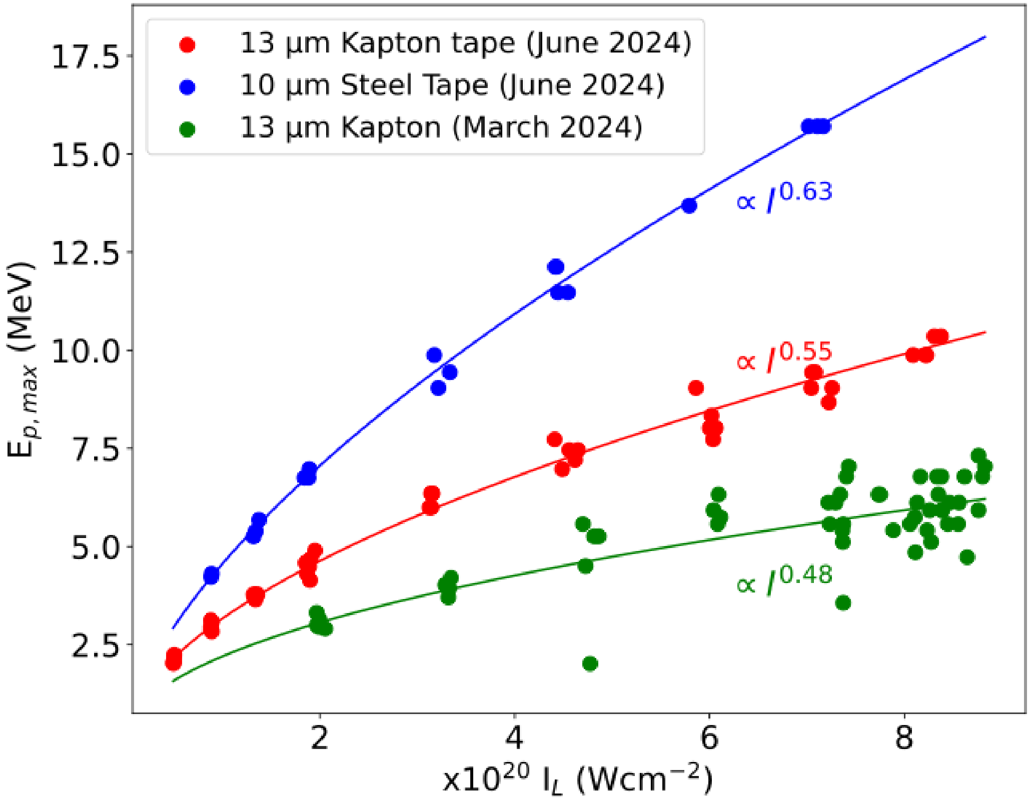
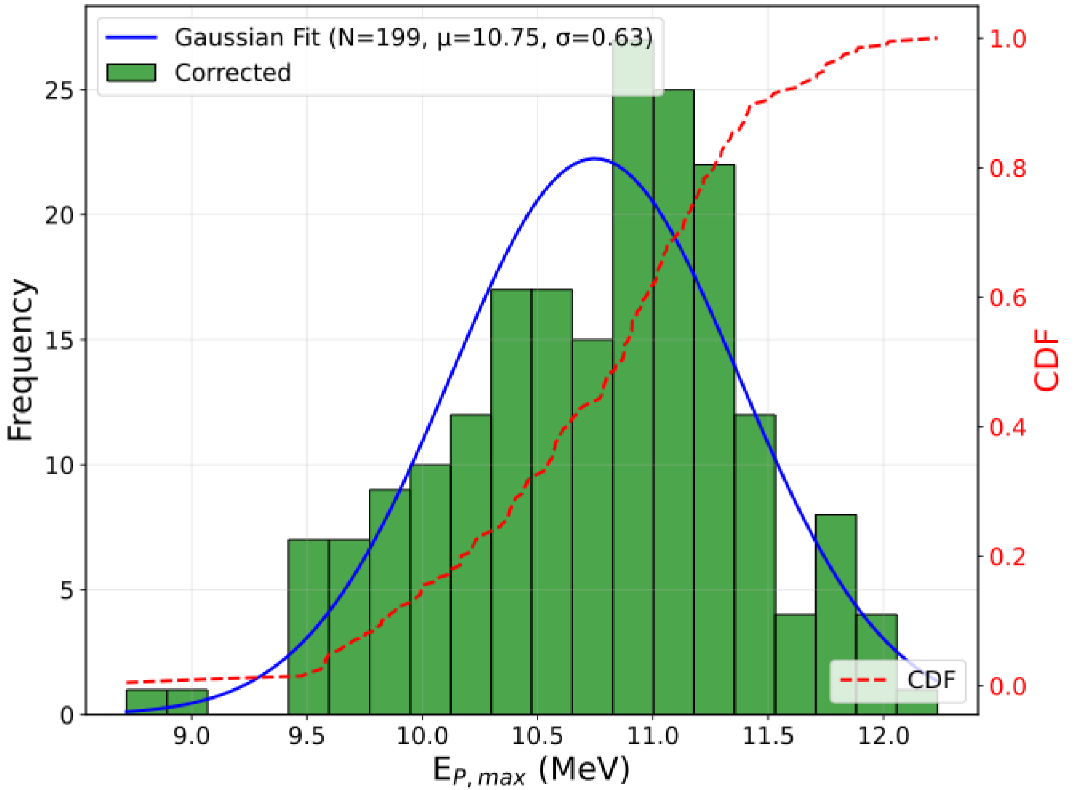
i) $E_{p,max}$ Intensity Scaling

- Below: Comparison of both $E_{p,max}$ due to contrast improvements (March-June 2024) and comparison between Kapton & steel tape (values from Thomson parabola spec.).

- Investigation underway to determine target material effects





ii) Proton Stability

- Above: The spread of the $E_{p,max}$ across 199 equivalent shots with correction for burning of the pellicle.

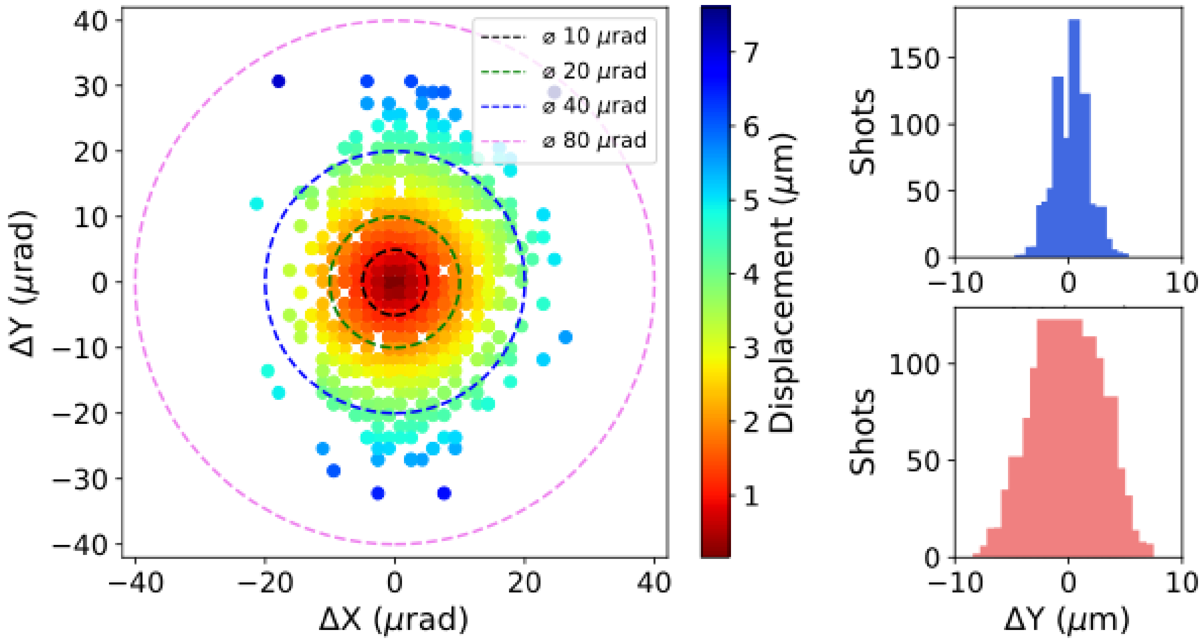
- <10 % fluctuation .

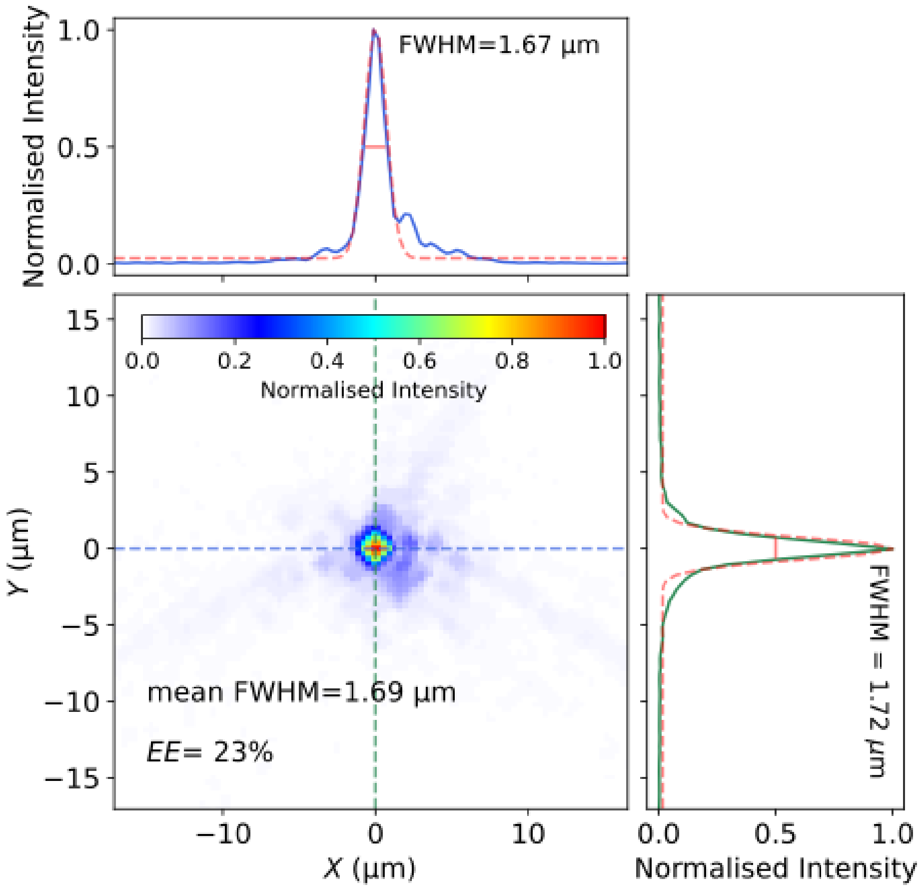
- In reality it is around 2% as TP biases for beam structure and jitter.

SCAPA Development Challenges

i) Focal Spot Pointing Stability

- Centroid position of focal spot over N=1000 pulses relative to the nominal average position.





ii) Focal Spot Quality

- Focal spot calculated to have FWHM size of 1.69 μm
- Encircled energy (EE) = 23 %
- Looking to improve EE through changing objective lens & pellicle, as well as redesigning our HASO line

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SCAPA Development Challenges

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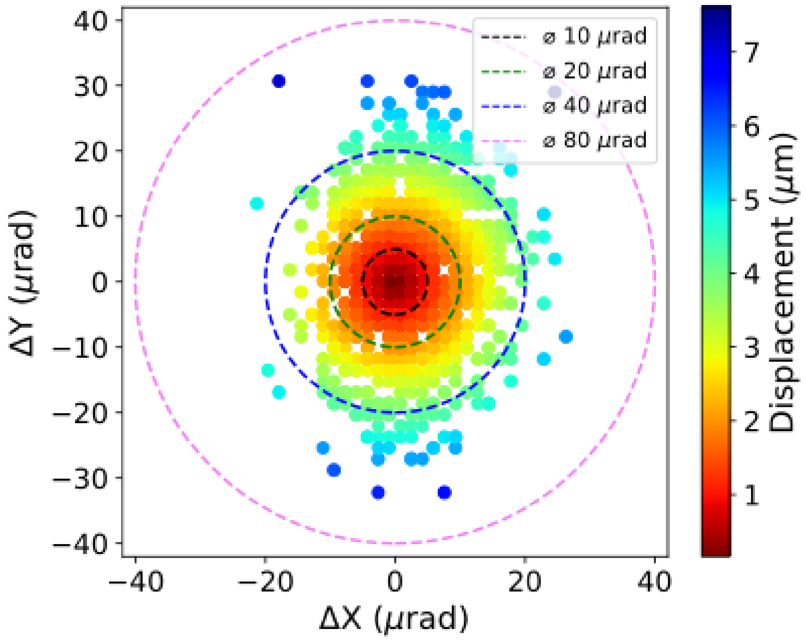

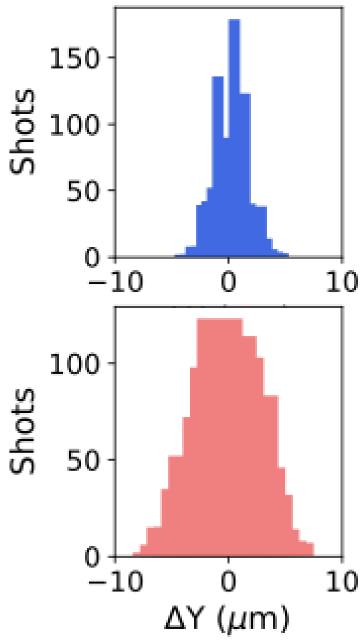

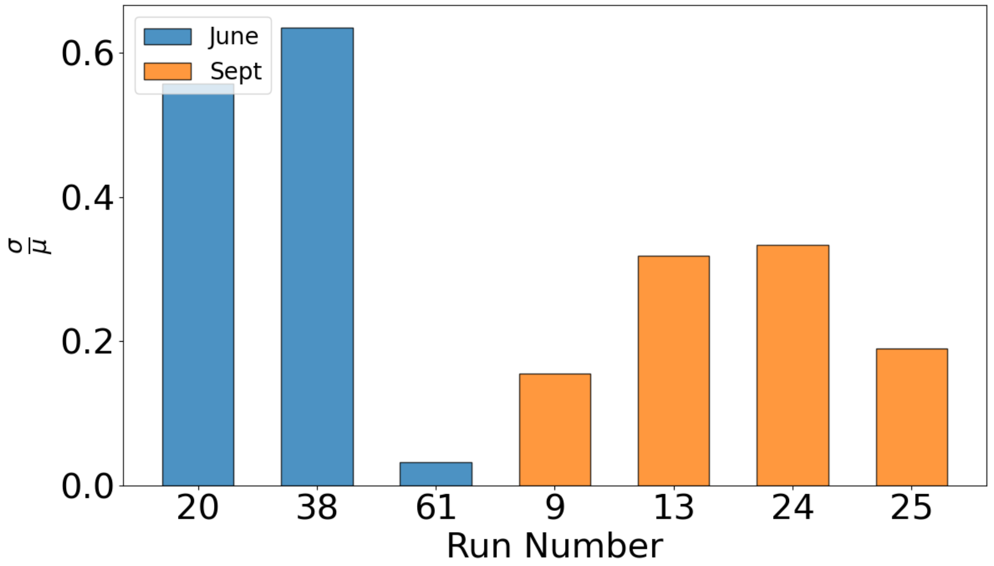

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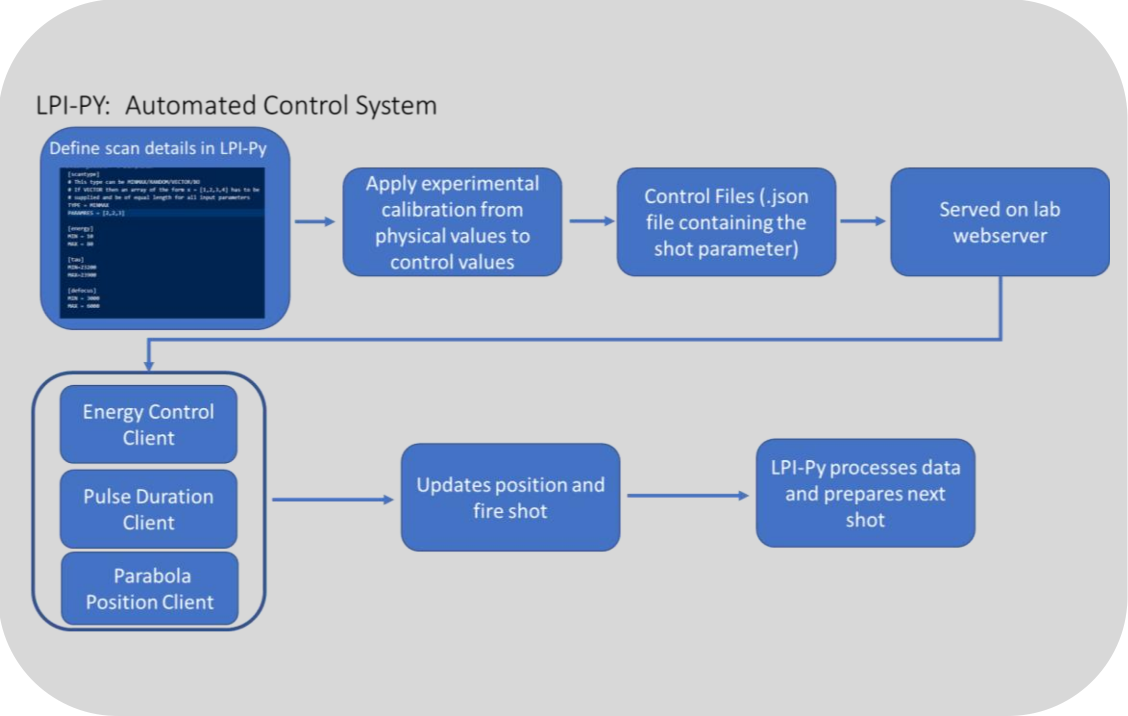
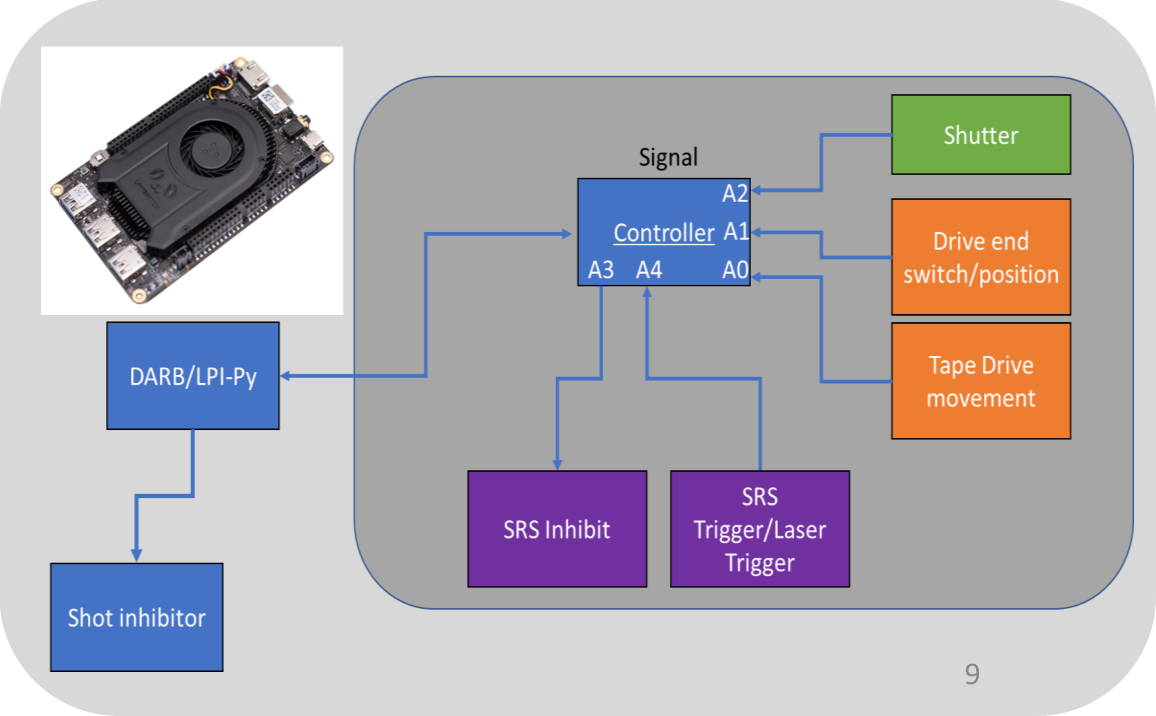
Data capture and high repetition rate operations

- DARB software successfully employed to capture and structure experimental data. Data capture rates at 1 Hz and is now running in a stable manner.
- Systems to i) automate parameter selection and ii) introduce a machine safety shutoff. These significantly improve shot rate, time taken to repeat a data given scan, and data quality.

Automated Control System

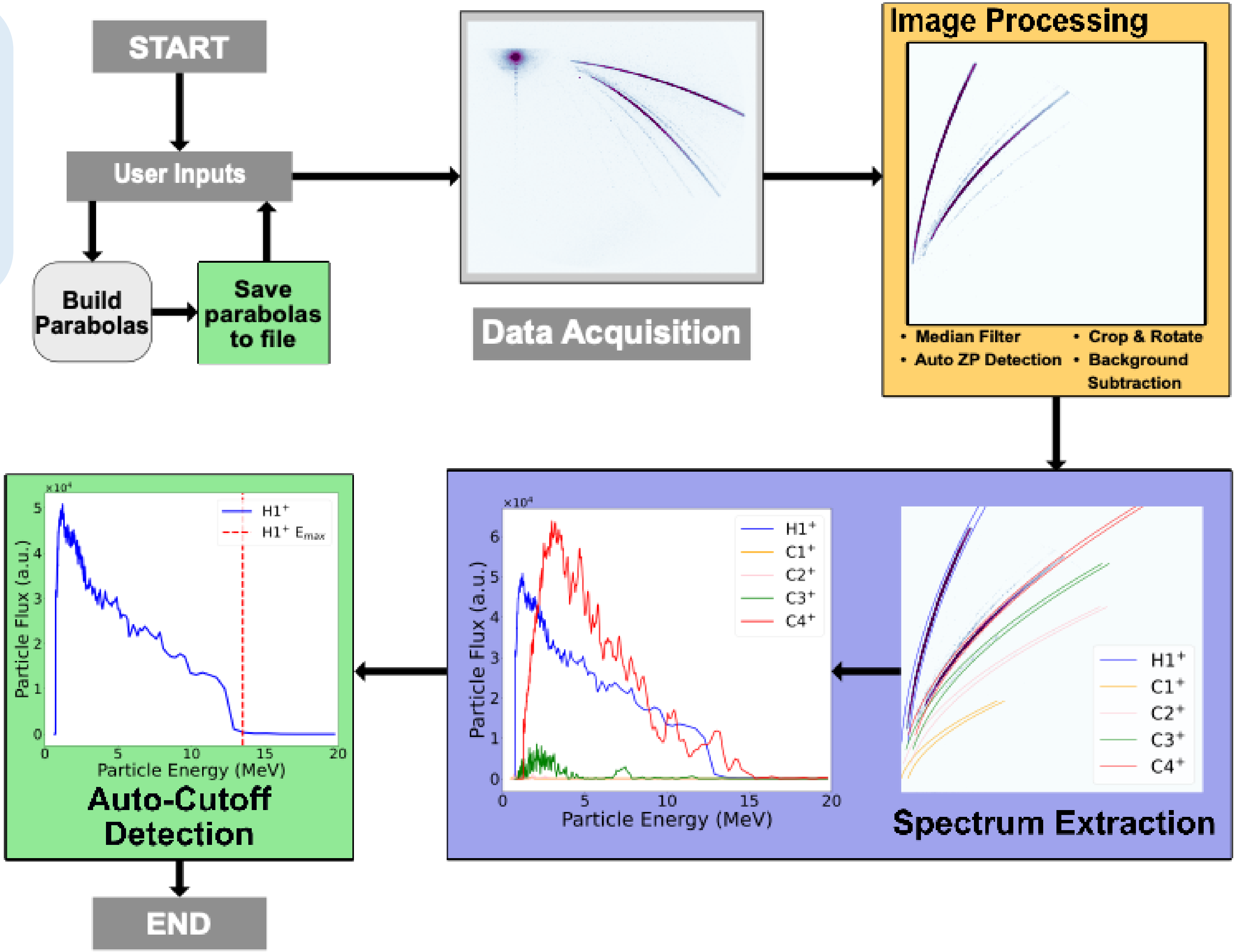


Shot control system

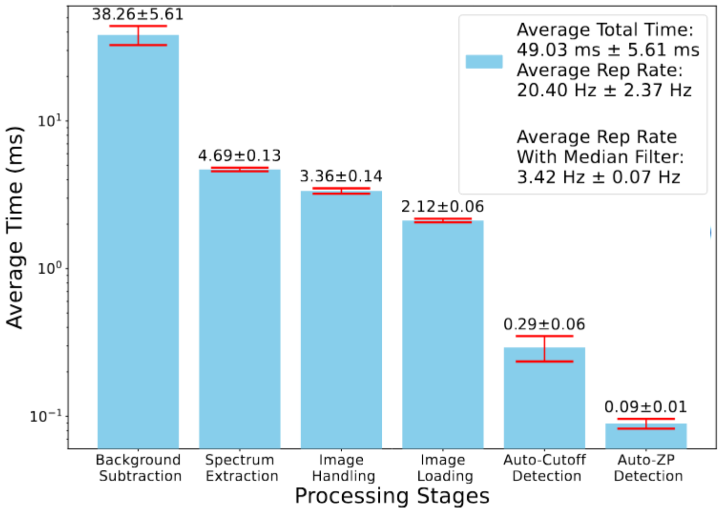


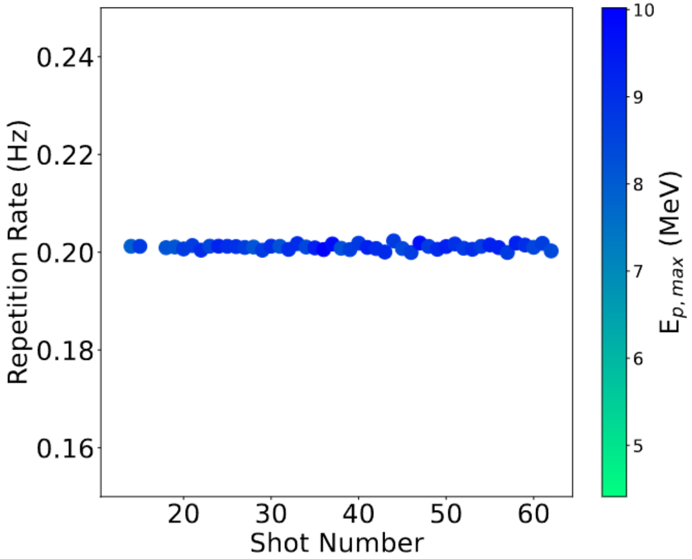
ARISE: An Algorithm for Rapid Ion Spectrum Extraction

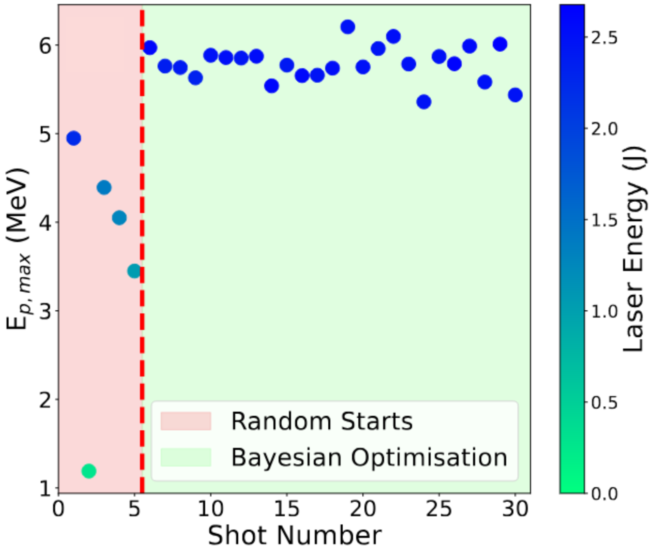
- We have developed a Thomson parabola spectrometer analysis code named ARISE.
- ARISE code workflow:



LPI-PY: High Repetition rate proton source optimisation



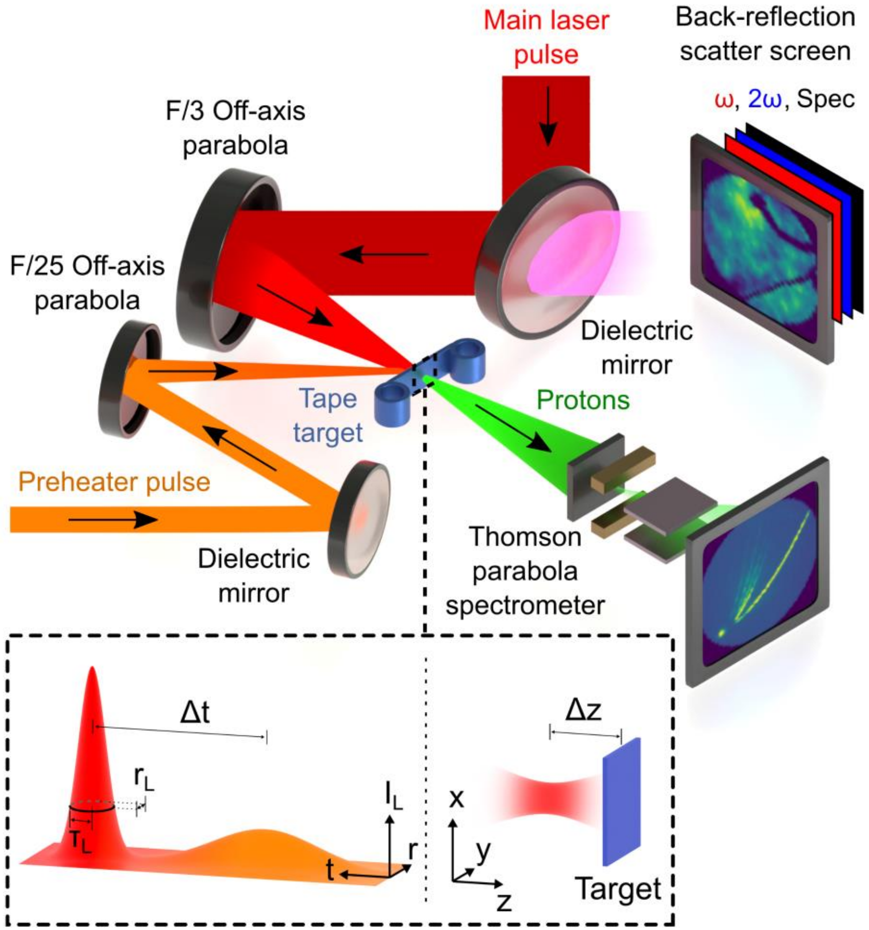


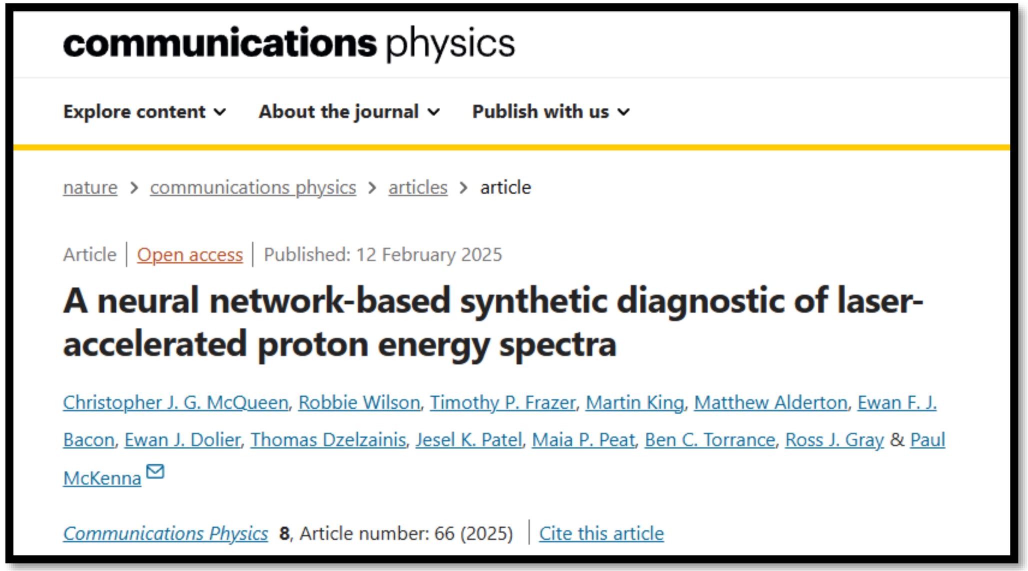


- We have demonstrated a (camera readout limited) repetition rate of 0.2 Hz and direct, fully automated Bayesian optimisation of the maximum proton energy. Updates to lab IT services have will enable higher repetition rates.
- LPI-Py interfaces directly with control system in SCAPA and thus outputs from ARISE can be fed into the BO model.
- High repetition rate leads to better statistics and the capability to generate large training data sets for neural networks [1].

[1] C. J. McQueen et al., Communications Physics 8, 66 (2025)

LPI-PY: High Repetition rate proton source optimisation

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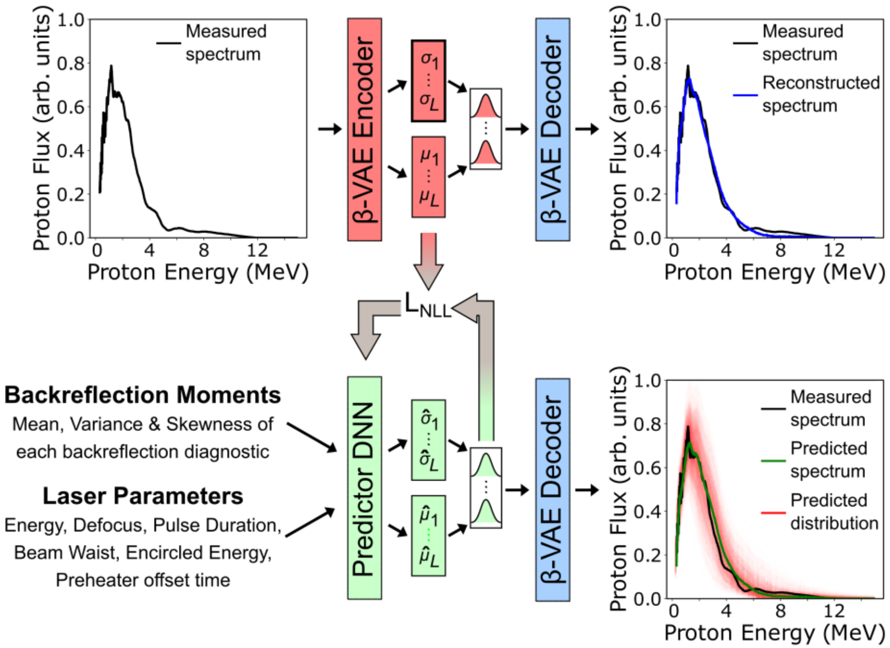
A neural network-based synthetic diagnostic of laser-accelerated proton energy spectra

Christopher J. G. McQueen, Robbie Wilson, Timothy P. Frazer, Martin King, Matthew Alderton, Ewan F. J. Bacon, Ewan J. Dolier, Thomas Dzelzainis, Jesel K. Patel, Maia P. Peat, Ben C. Torrance, Ross J. Gray & Paul McKenna

Communications Physics 8, Article number: 66 (2025) | Cite this article

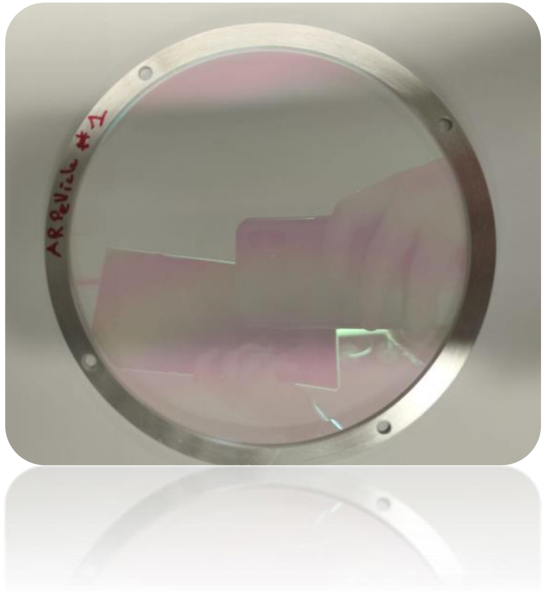


C. J. McQueen et al., Communications Physics 8, 66 (2025)

Beamline Lifetime Issues

i) Pellicle burning

- One common issue with HRR beamlines is pellicle burning.
- Leads to decrease of energy on target → decrease in ion energies.
- Still an ongoing problem in the field needing to be resolved.

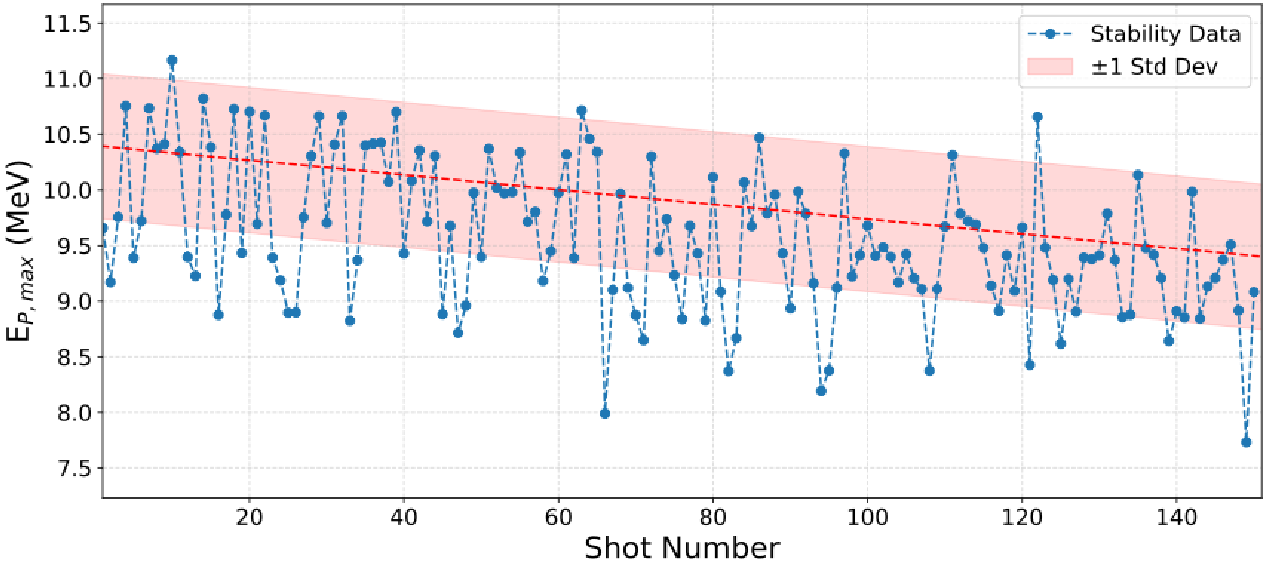


ii) Debris build-up

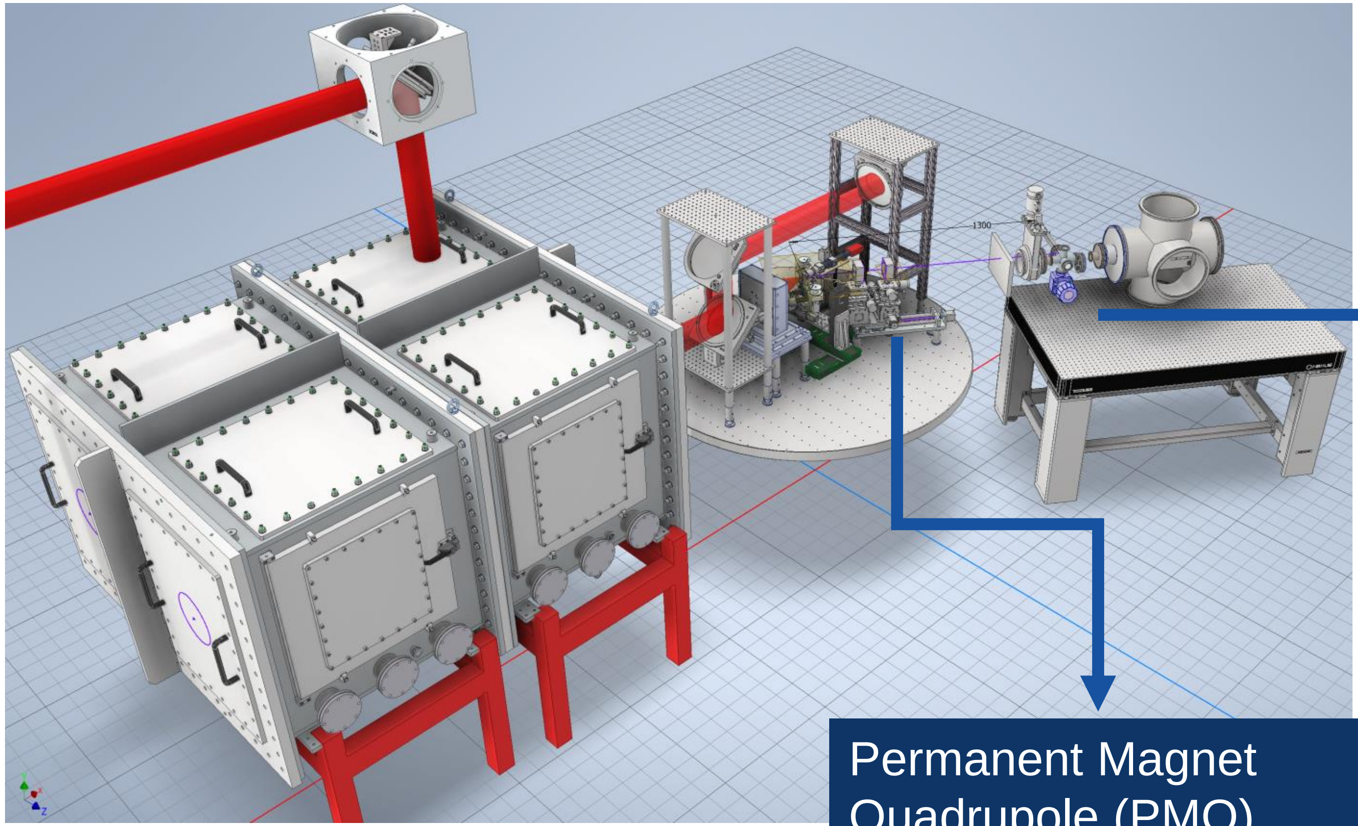
- Another, more within laser-solid interactions is debris build-up.
- Can coat optics, mirrors etc leading to a reduction in the quality of the beam reaching the target → decrease in ion energies.

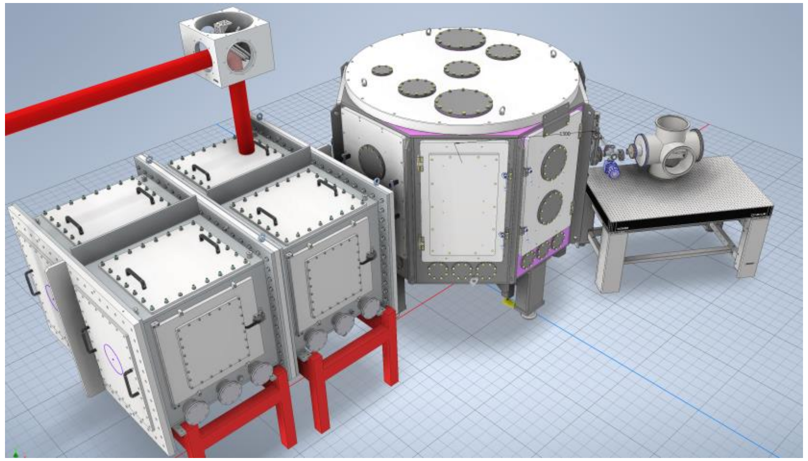
iii) Bunker B Experiment

- Bottom right figure shows a run of equivalent shots for a stability scan.
- Can clearly see reduction of the $E_{p,max}$ due to the afformentioned issues.



Proof of Principle LhARA Radiobiology (PoPLaR) Experiment





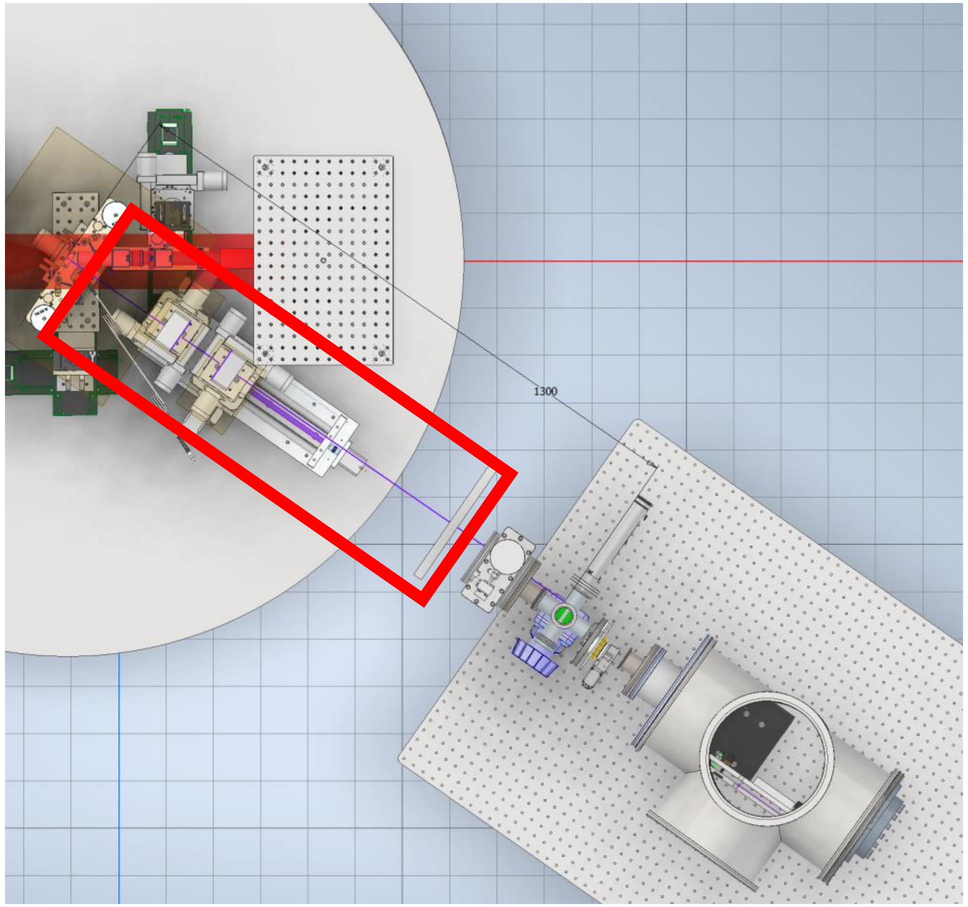
Cell Irradiation End Station

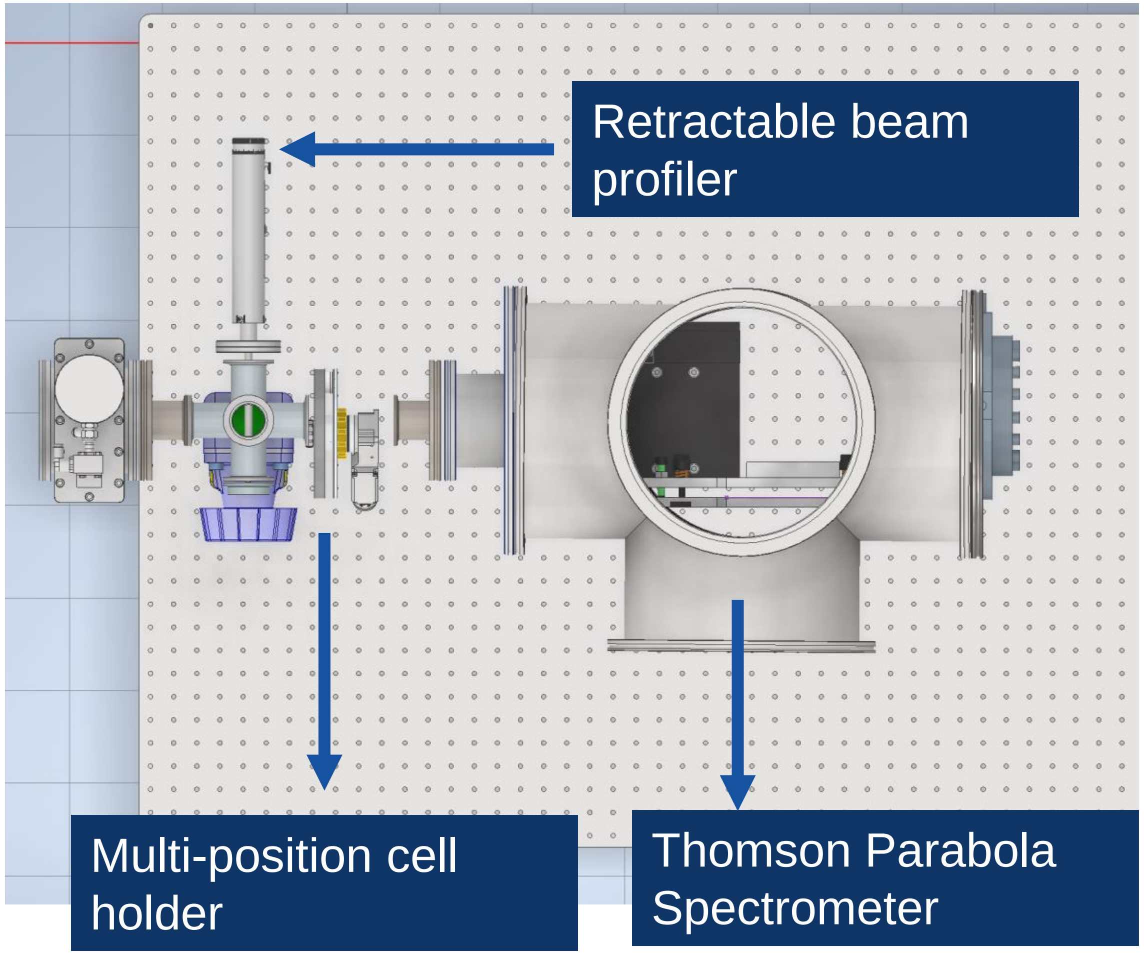
Permanent Magnet Quadrupole (PMQ) System

- We are in the process of designing and adding a capture beamline to SCAPA bunker B to guide and focus the laser-driven proton source to a cell irradiation end station.

- Major challenges are in purchasing, mechanical design and PMQ alignment

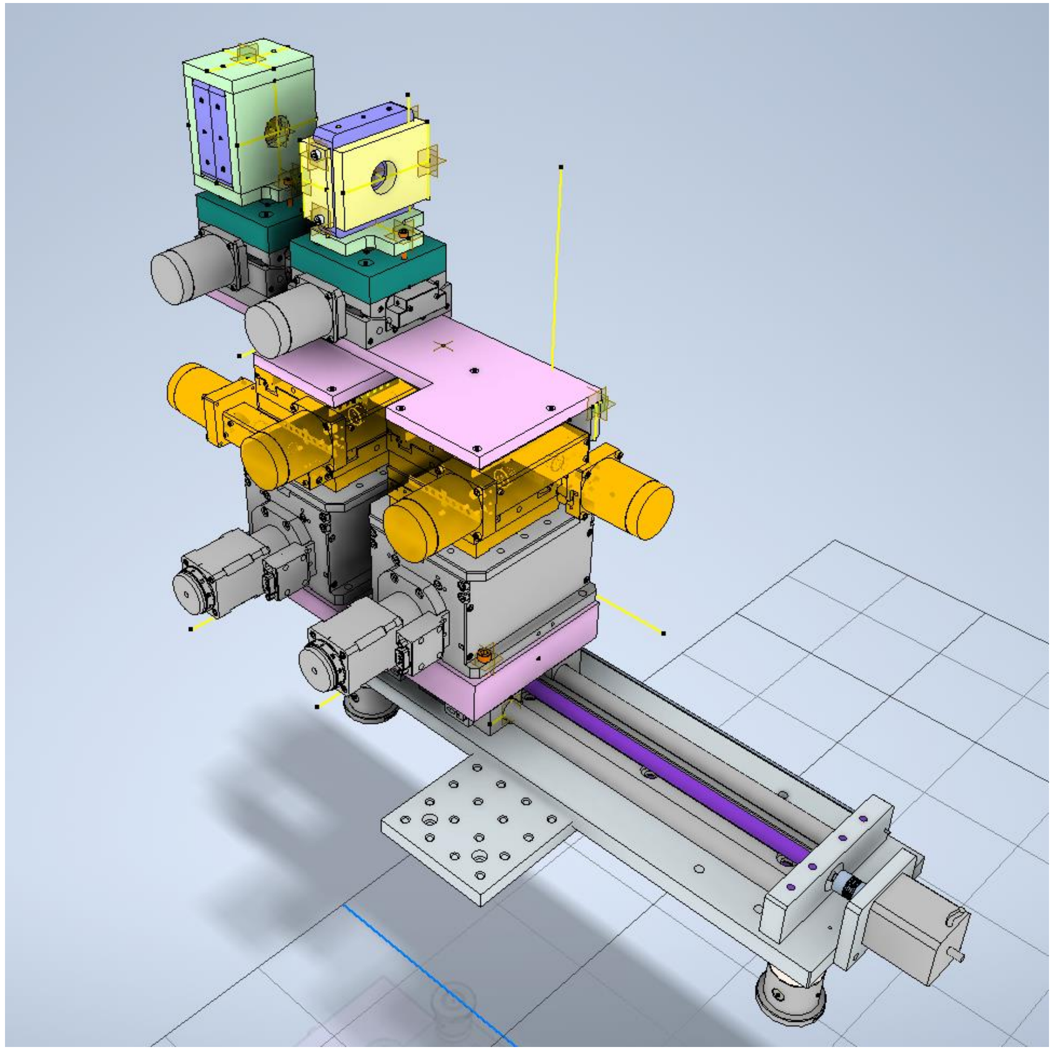
Proof of Principle LhARA Radiobiology (PoPLaR) Experiment





- We are in the process of designing and adding a capture beamline to SCAPA bunker B to guide and focus the laser-driven proton source to a cell irradiation end station.
- Major challenges are in equipment costs, mechanical design and PMQ alignment sensitivity

Update on beamline design



- We are progressing with a simplified PMQ design
- 2 PMQs will be used with one being fixed in place and the other having XYZ and rotation about the central axis as degrees of freedom
- PMQ setup is designed so the magnets are detachable and moveable on a large stage
- This enables normal beam characterisation activity before PMQ optimisation and cell irradiation

Proposed Experiment Stages & Gateways

I. Design & Procurement

- Start of BP1 funding
- Order of PMQ XYZ stage (5-7 week delivery)
- Order of cell station vacuum parts (4 weeks delivery)
- Manufacture of thin window
- Manufacture of Oxford cell station

II. Assembly & Alignment

- Construction of the cell station and updated TP beamline
- Definition of an offline alignment line
- Construction and offline alignment of PMQ setup
- Install of PMQ system in vacuum chamber
- Change of parabola

III. Source Characterisation: 16th – 28th June

- 1/2 weeks of SCAPA beamtime
- Laser Beamline alignment (0.5 days)
- Source optimisation w/o PMQ (0.5 days)
- PMQ transmission, activation and debris test (0.5 days)
- Lanex/beam profiler measurement at end of beamline (1 day)
- PMQ position optimisation (0.5 days)
- RCF measurements through beamline (0.5 days)
- Full cell assembly RCF measurement (0.5 days)

IV. Radiobiology: 21st July – 1st August

- 2 weeks of SCAPA beamtime (with a gap between the alignment week)
- Laser Beamline alignment (0.5 days)
- Source optimisation with PMQs (1 day)
- Dosimetry and source stability measurements (2 days)
- Cell irradiation (6.5 days) + regular dosimetry

Summary

- We are in a generally good position for the beam time. The proton source has been developed and optimised during experiments in July, September and December 2024…PoPLar will run in June and July 2025

- The experiment will ramp up from beam and diagnostic optimisation, to dose calibration and then finally the irradiation.

- The source is in a good position. We are aiming for $E_{p,max}$ > 10 MeV for the run.

- Potential issues are purchase of the PMQ parts, alignment of the beamline and the long term performance of the system due to pellicle damage

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Collaborators

University of Strathclyde

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