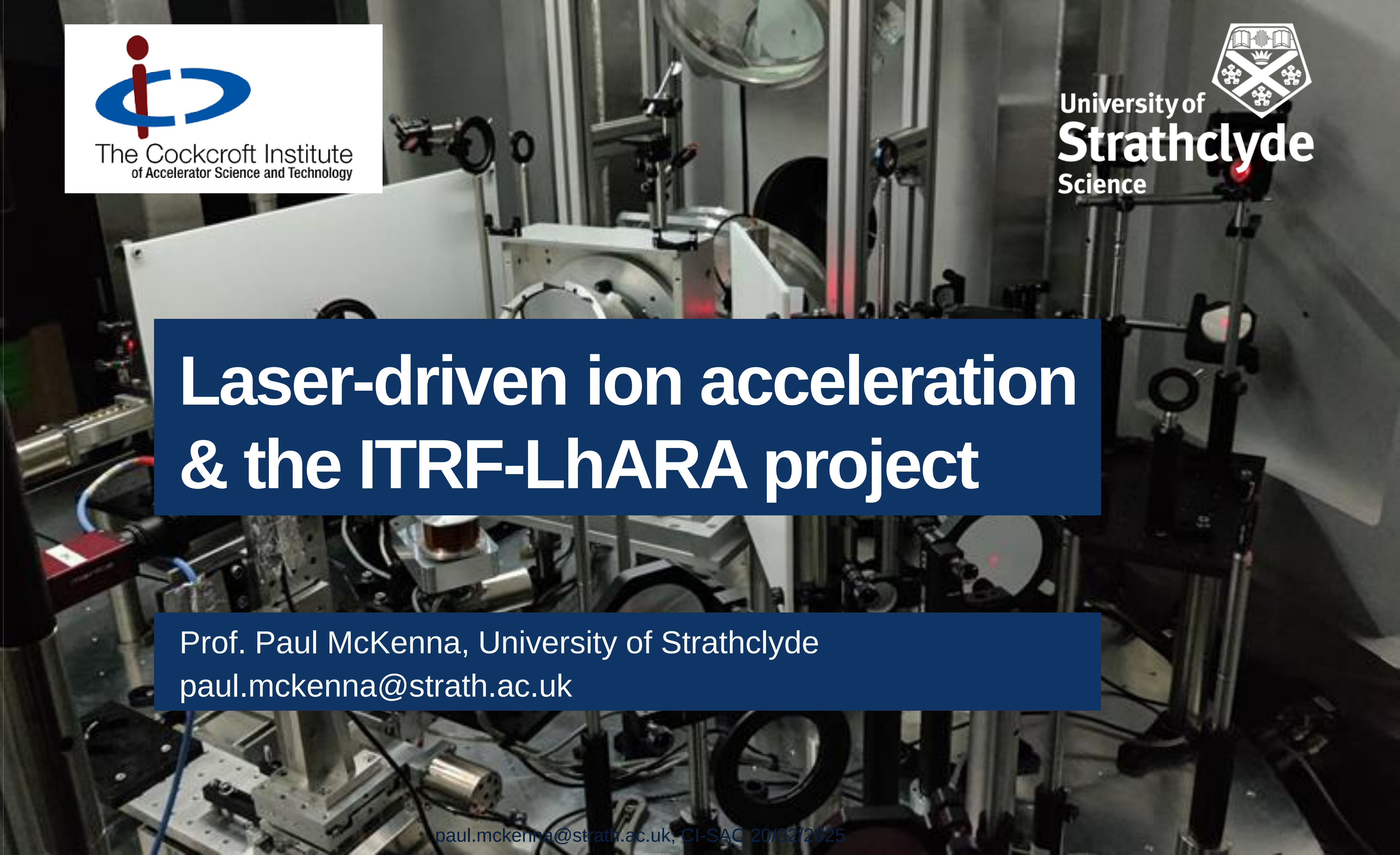


X THE PLACE OF USEFUL LEARNING

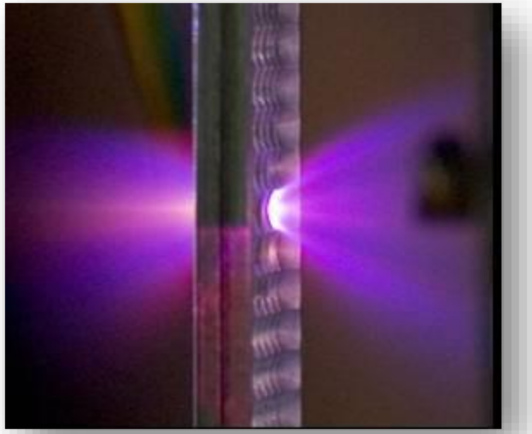
Laser-driven ion acceleration & the ITRF-LhARA project

Prof. Paul McKenna, University of Strathclyde
paul.mckenna@strath.ac.uk

Talk outline

The Cockcroft Institute of Accelerator Science and Technology

University of Strathclyde Glasgow



1. Scientific Advances

- Machine learning applied to laser-driven ion acceleration
- High-flux proton beams with plasma collimation
- Narrow-band acceleration of gold ions

2. Laser-ion acceleration platform at SCAPA

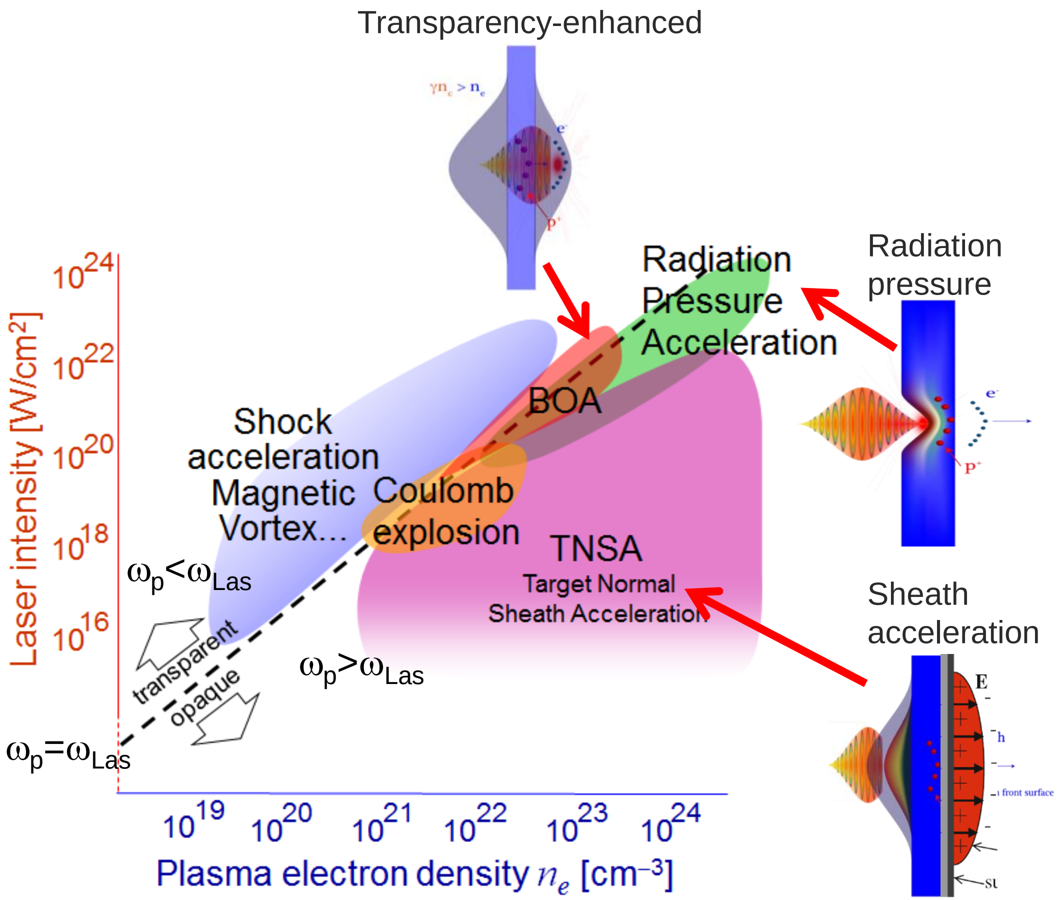
- Recent progress in source characterisation and technology development

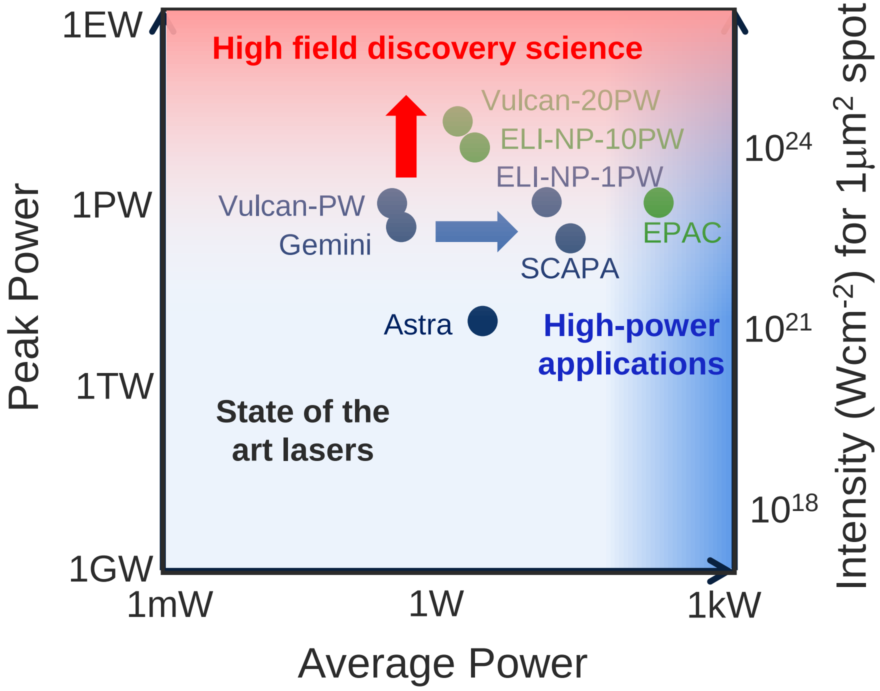
3. ITRF-LhARA project

- Project summary and progress
- Planned PoPLAR experiment

Laser-driven ion acceleration mechanisms

There are various mechanisms of laser-driven ion acceleration, with the dominant one depending on the laser and plasma parameters





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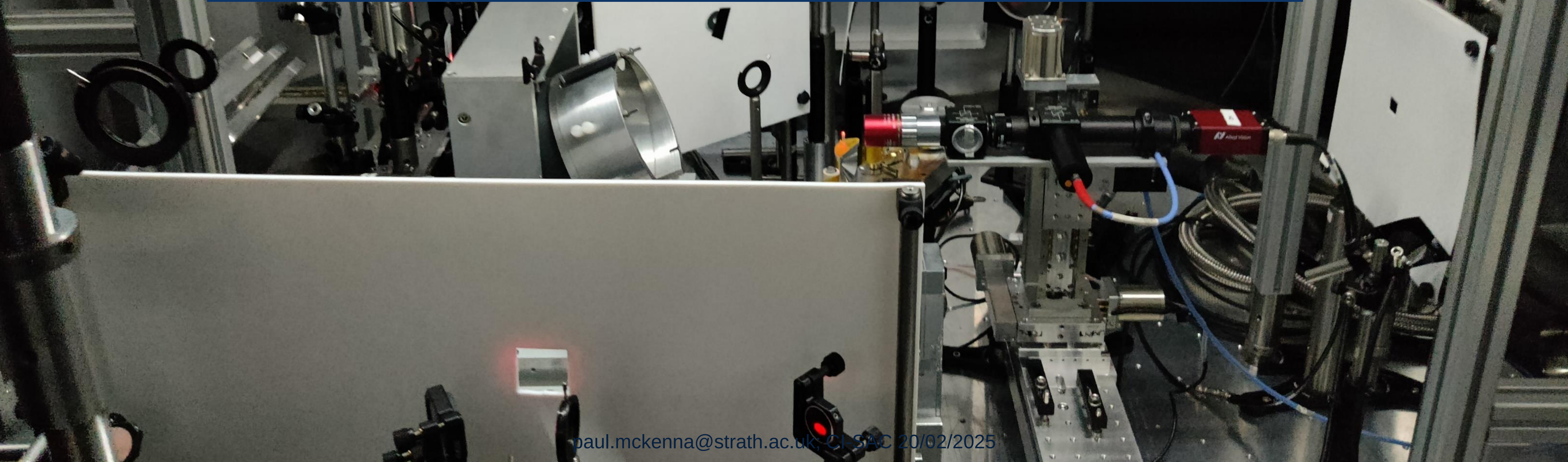
1. Scientific Advances

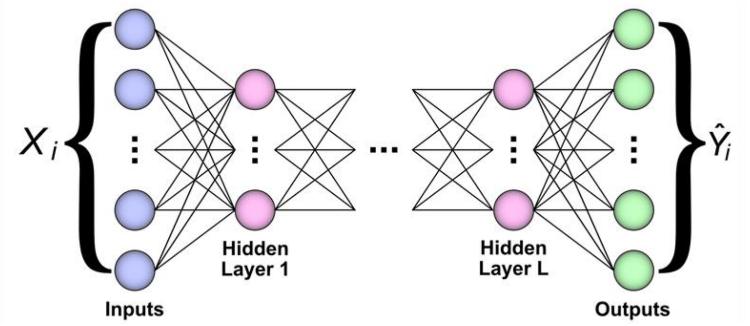
- Neutral network-based model and synthetic diagnostic of ion acceleration
- High-flux proton beams with plasma collimation
- Narrow-band acceleration of gold ions



Neutral network-based synthetic diagnostic of proton 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**, 66 (2025)



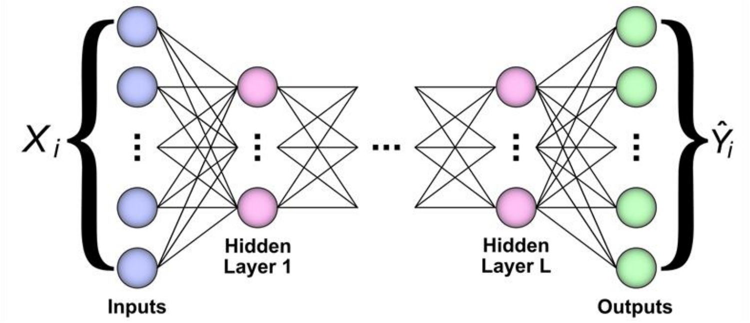
STFC/Cockcroft-funded PhD student Chris McQueen's project involves developing and applying a neural network-based model of laser-driven proton acceleration.

Building on our previous work on the application of Bayesian algorithms to optimise laser-ion acceleration reported at the 2023 SAC meeting:

E J Dolier *et al.,* New J. Phys. 24, 073025 (2022)

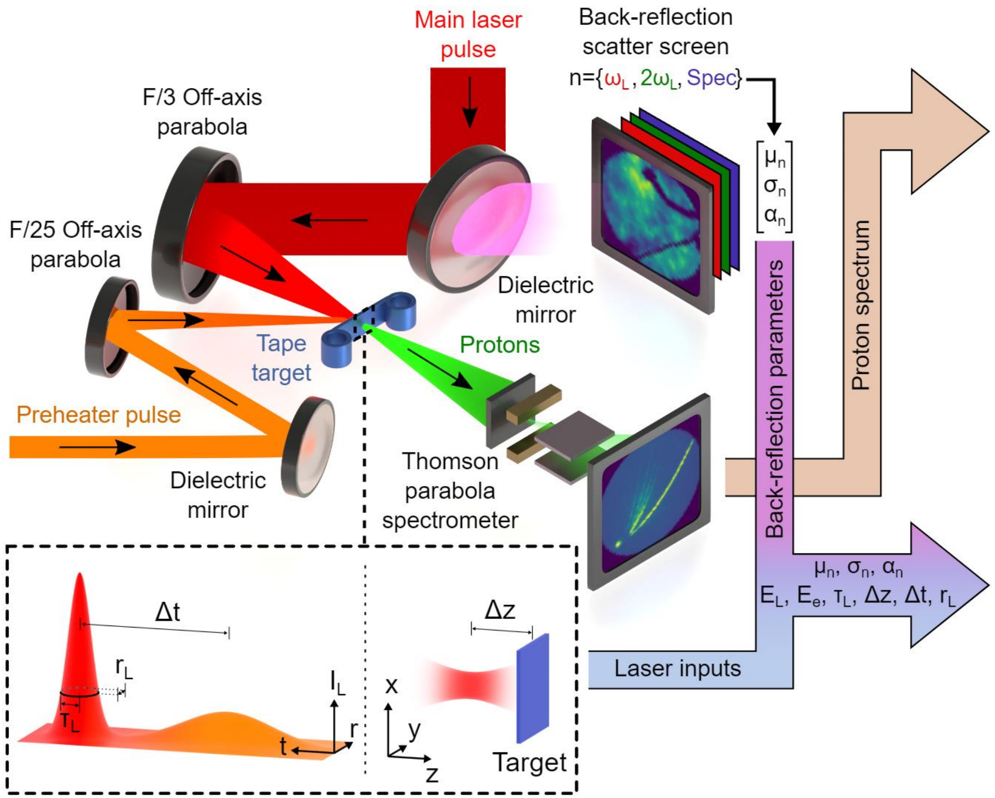
J. Goodman et al., High Power Laser Sci. Eng. Vol. 11, e34 (2023)

Neutral network-based synthetic diagnostic of proton spectra



Experiment conducted using the Gemini laser at the Central Laser Facility to produce a dataset to train a neutral network model.

Objective to develop a synthetic diagnostic of proton spectra using input laser parameters and measured back-reflected laser light from the interaction with the plasma



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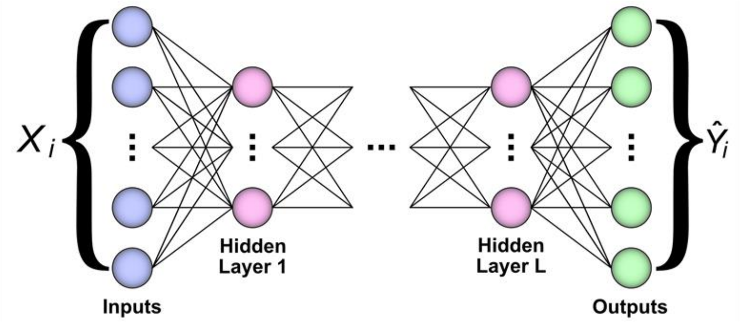
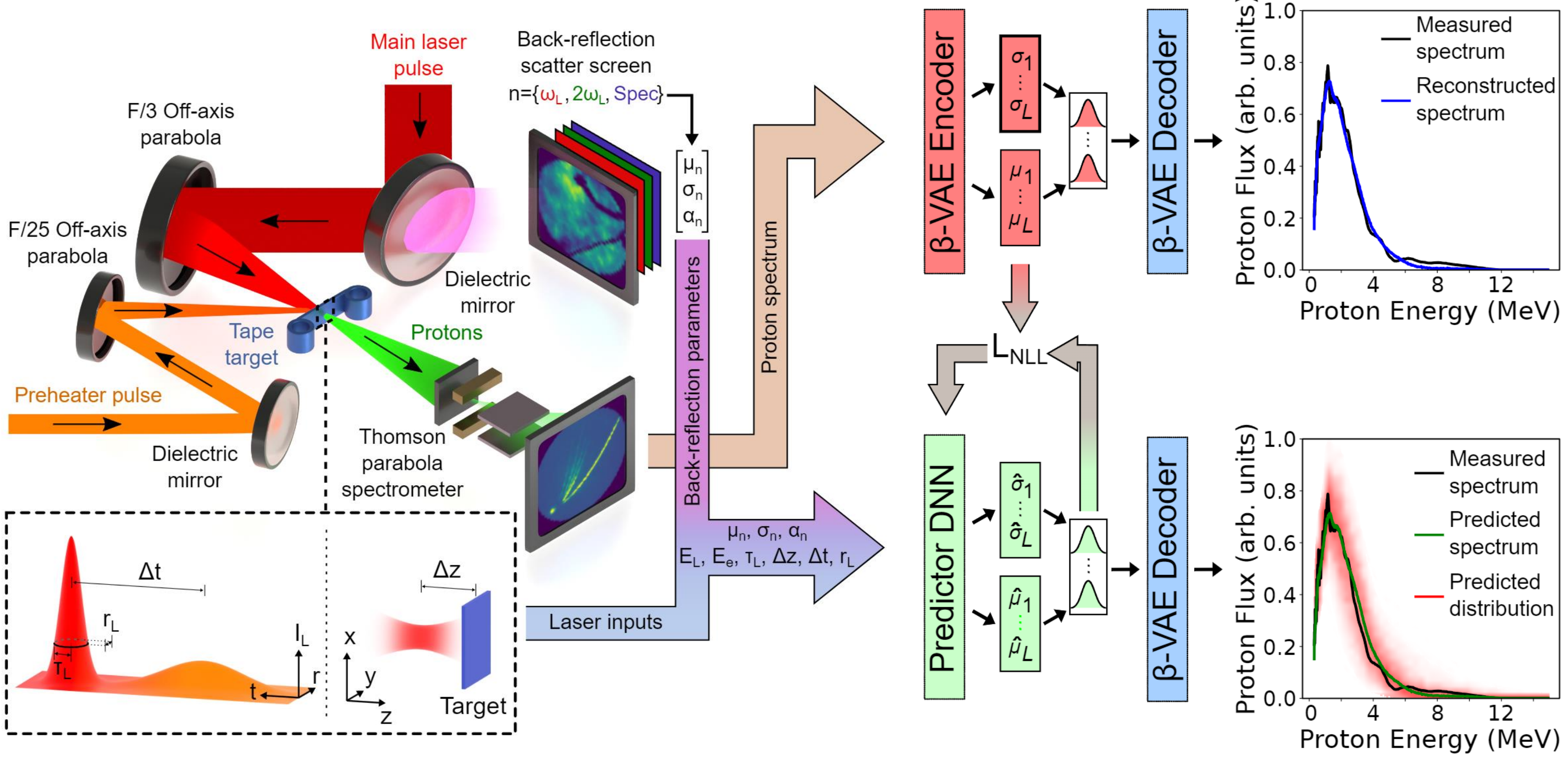
Neutral network-based synthetic diagnostic of proton spectra

The neutral network model was trained on 80% of the dataset, with 20% reserved for testing.

Trained on data from fewer than 700 laser-plasma interactions, the model achieves an error level of 13.5%, and improves with more data.





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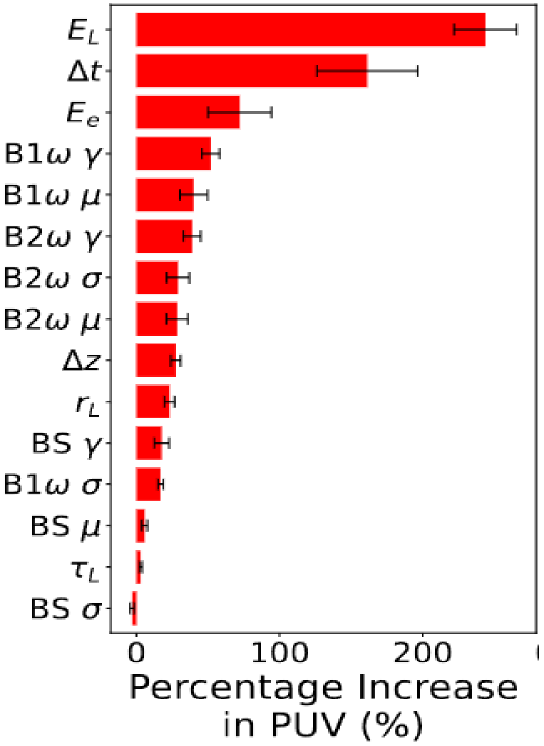
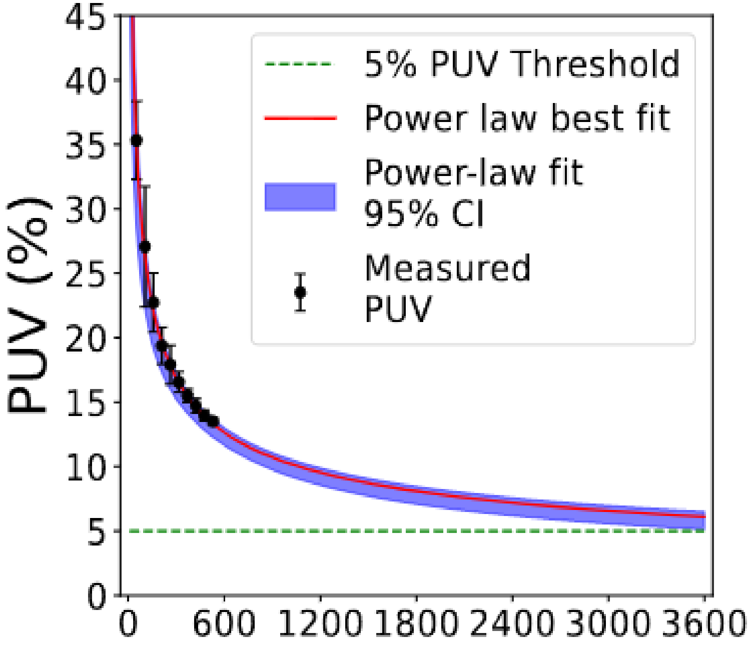
Neural network-based surrogate model of laser-ion acceleration

McQueen *et al*, Communications Physics **8**, 66 (2025)

% increase and RMS in the ensemble PUV during PFI for various laser parameters:



Ensemble predictive error as a function of training set size:



PUV = percentage of unexplained variance, a relative error metric proportional to the mean squared error

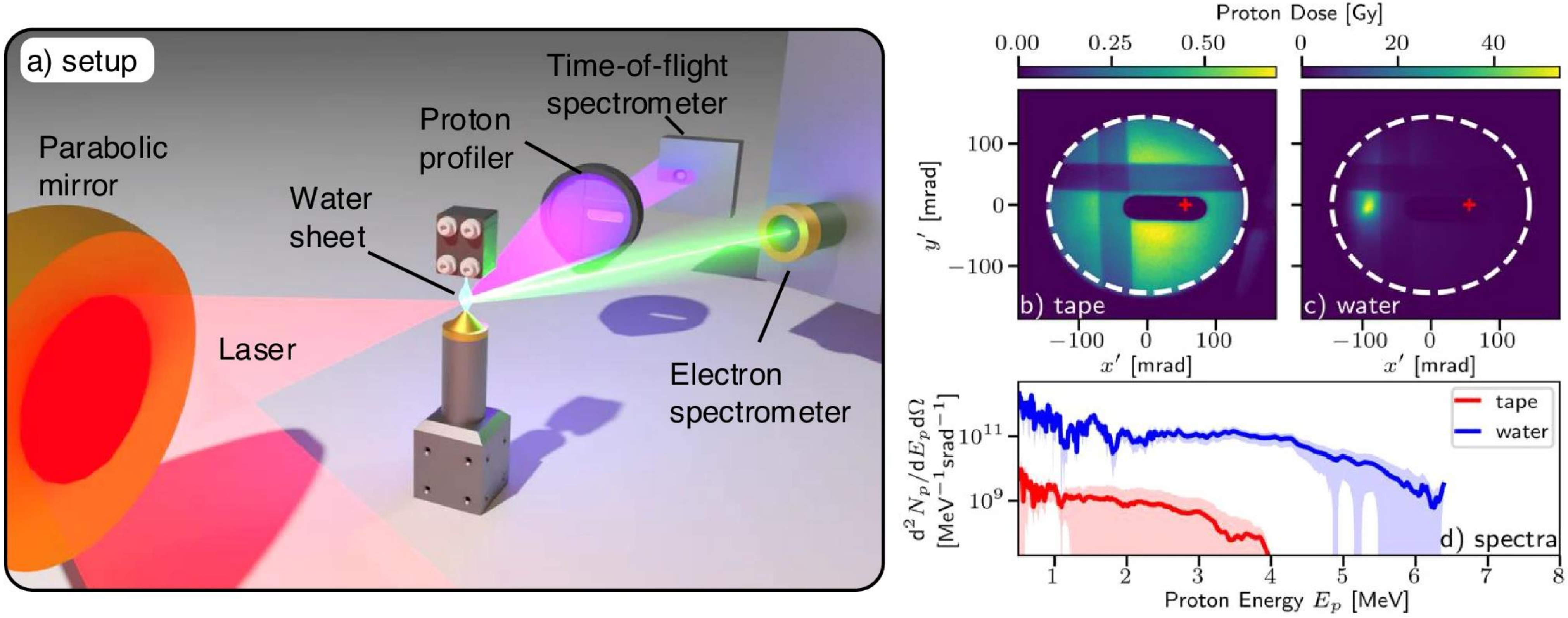
Stable laser-acceleration of high-flux proton beams with plasma collimation

M. J. V. Streeter, G. D. Glenn, S. Dilorio, F. Treffert, B. Loughran, H. Ahmed, S. Astbury, M. Borghesi, N. Bourgeois, C. B. Curry, S. J. D. Dann, N. P. Dover, T. Dzelzainis, O. C. Ettlinger, M. Gauthier, L. Giuffrida, S. H. Glenzer, R. J. Gray, J. S. Green, G. S. Hicks, C. Hyland, V. Istokskaia, M. King, D. Margarone, O. McCusker, P. McKenna, Z. Najmudin, C. Parisuaña, P. Parsons, C. Spindloe, D. R. Symes, A.G.R. Thomas, N. Xu, C. A. J. Palmer

Nature Communications **16**, 1004 (2025)

Generation of multi-MeV proton beams from a fast-replenishing ambient-temperature liquid sheet.

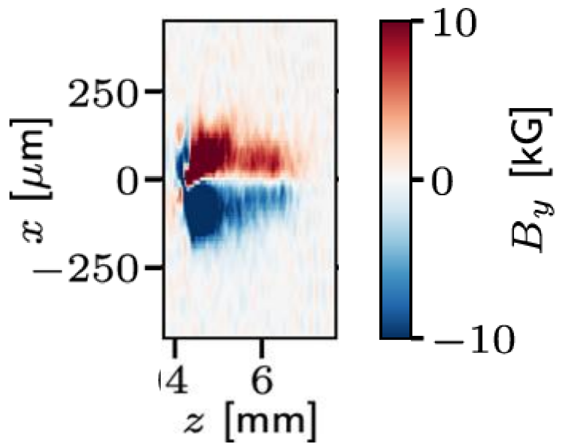
Experiment using the Astra laser at the Central Laser Facility

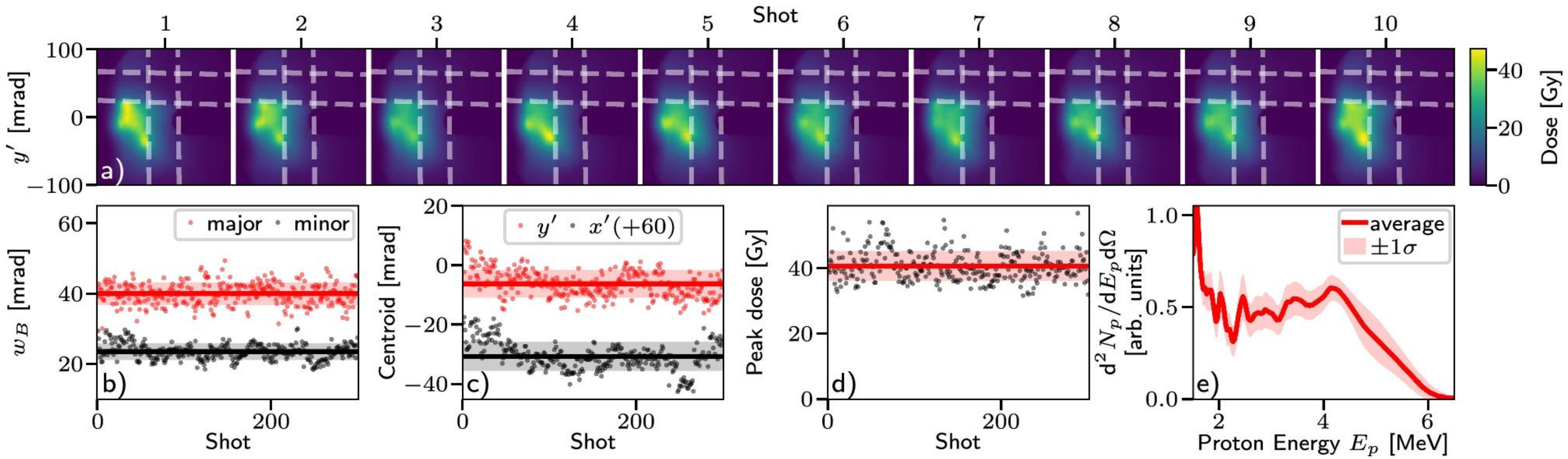


Stable laser-acceleration of high-flux proton beams with plasma collimation

Streeter *et al*., Nature Communications **16**, 1004 (2025)

- Unprecedentedly low divergence of 1° (≤20 mrad), resulting from magnetic self-guiding of the proton beam during propagation through a low density vapour.
- The proton beams, generated at a repetition rate of 5 Hz, exhibit a hundred-fold increase in flux compared to beams from a solid target.





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Narrow-band acceleration of gold ions to GeV energies from ultra-thin foils

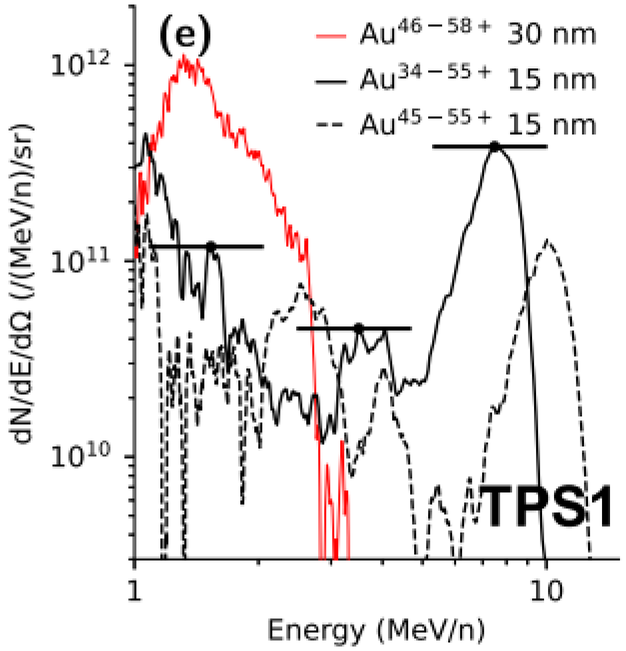
Martin, P., Ahmed, H., Doria, D., Cerchez, M., Hanton, F., Gwynne, D., Alejo, A., Fernández-Tobias, J., Green, J., Macchi, A., Maclellan, D., McKenna, P., Ruiz, J. Á., Swantusch, M., Willi, O., Zhai, S., Borghesi, M. & Kar, S

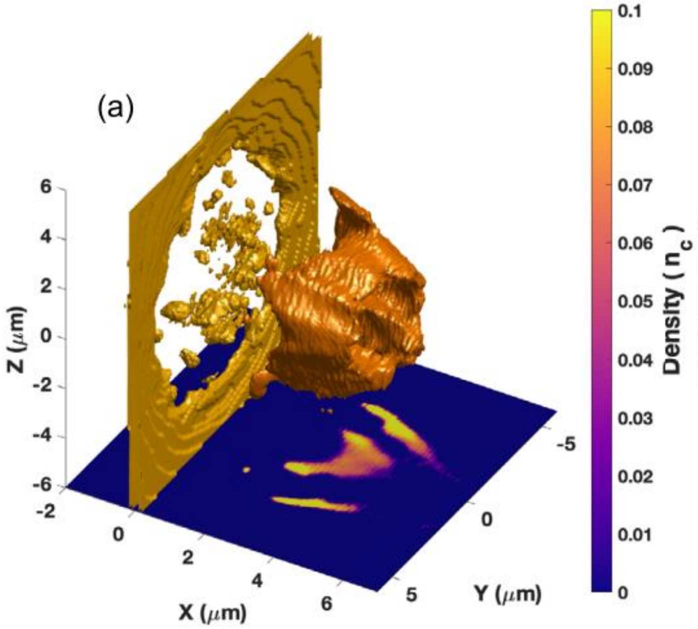
Communications Physics **7**, 3 (2024)

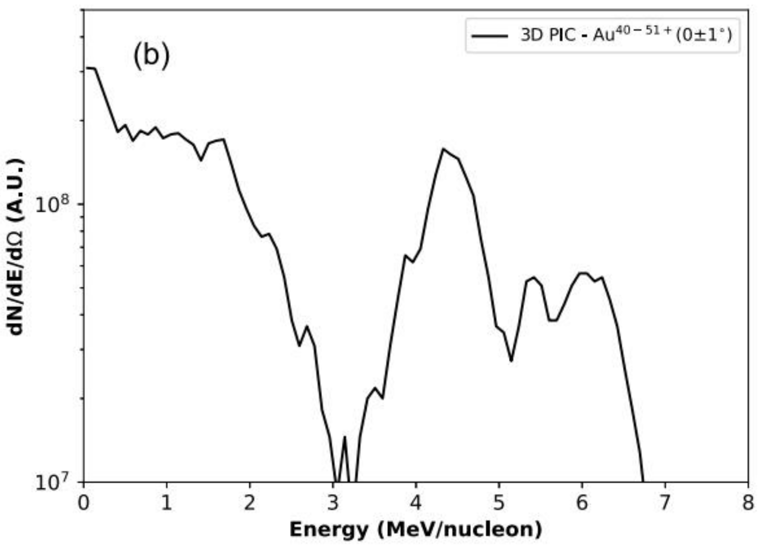
Measured narrow-band acceleration of heavy Au ions from ~15 nm Au foils with spectral peaks of 1.5 ± 0.5 GeV

Simulations show that spectrally peaked Au ion bunches stem from strong radiation pressure acceleration on a heavy-ion dominant plasma in the moments just before relativistic transparency.

Experiment using the Vulcan laser at the Central Laser Facility

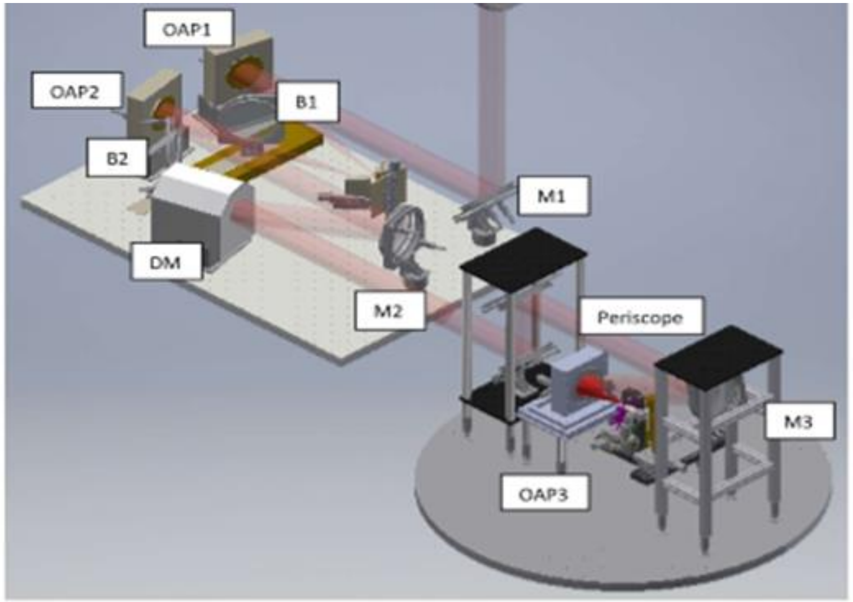


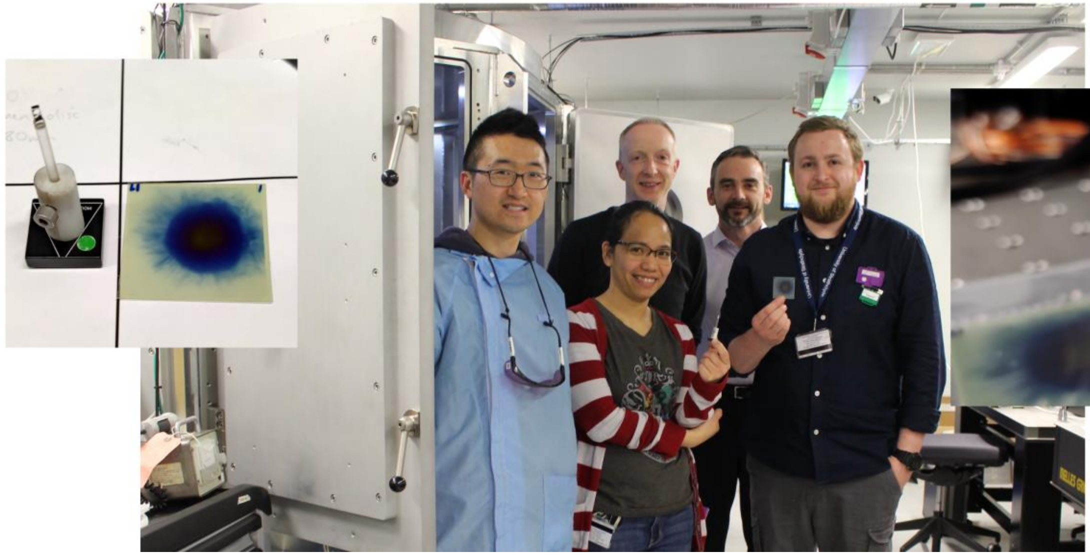


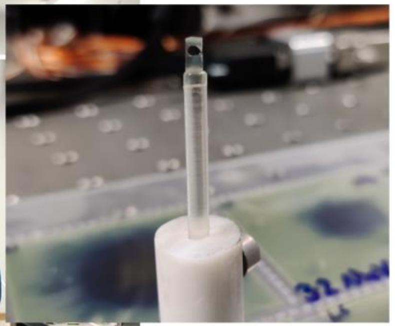


2. Laser-ion acceleration platform at SCAPA

First proton acceleration at SCAPA – winter 2022



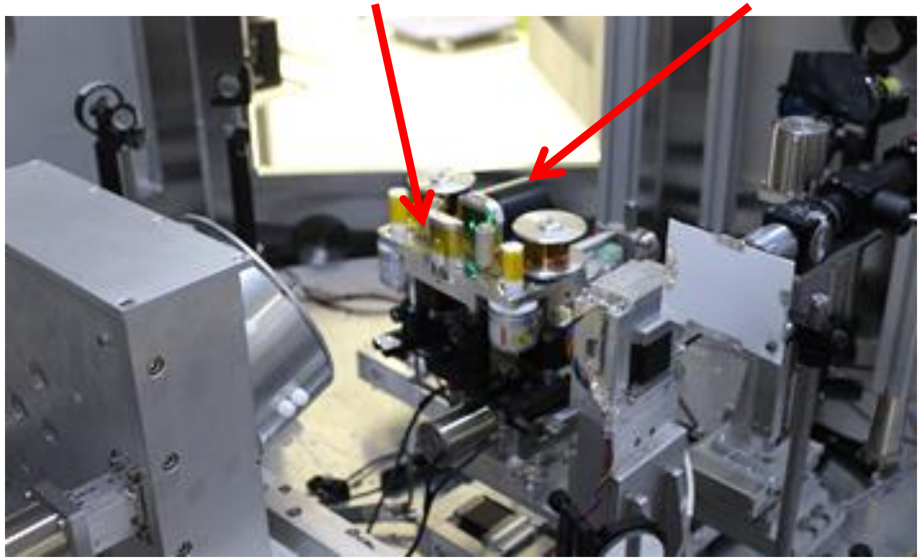




~5MeV protons on first shot

Tape drive target

Active proton detector



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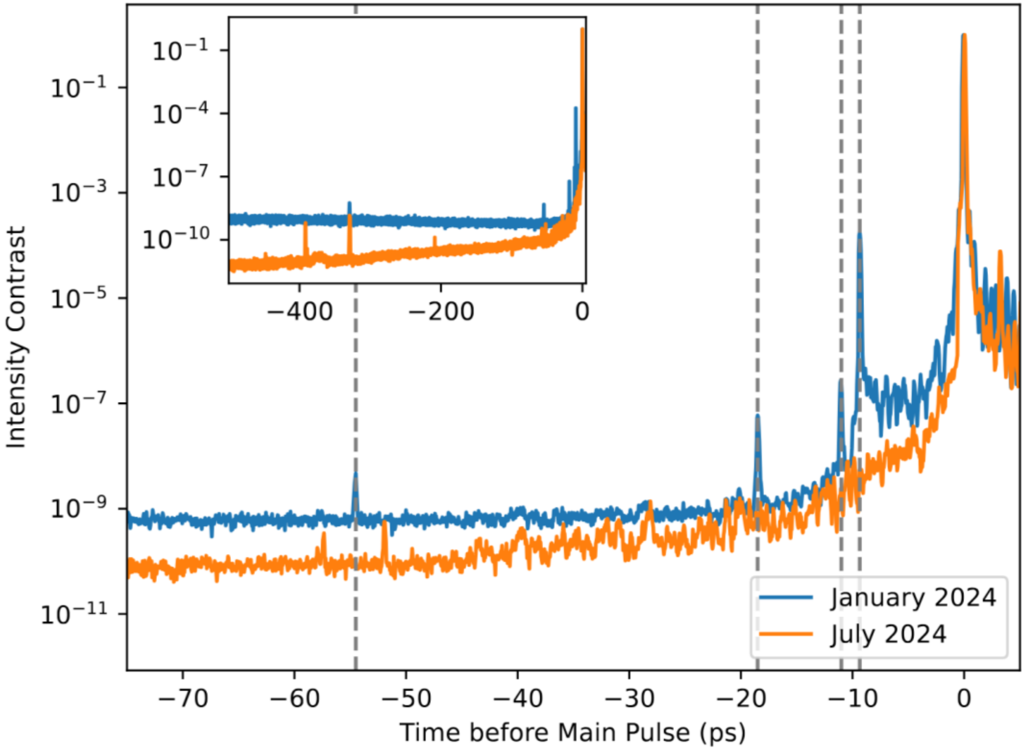
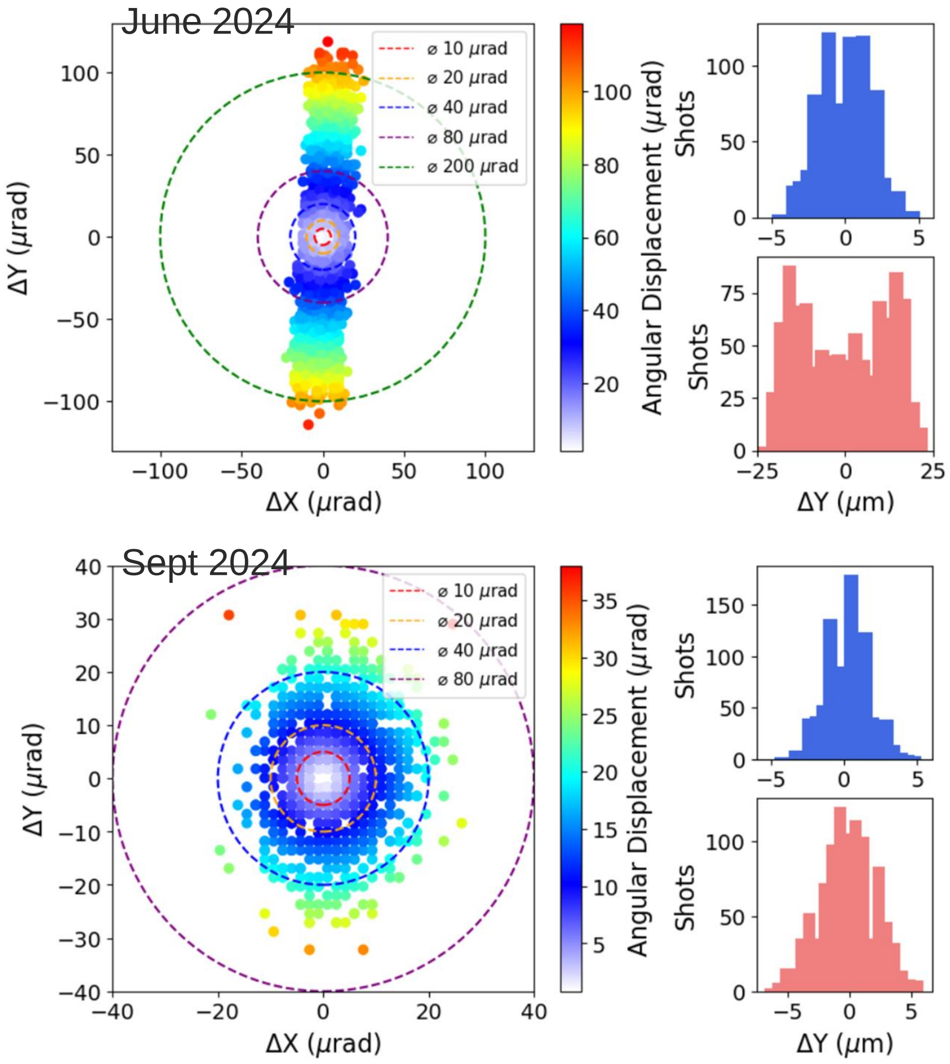
Enhancing laser beam properties for ion acceleration

- There were significant prepulses which were limiting proton energy and flux.
- The main prepulses have now been removed and the contrast is significantly enhanced.
- Proton energy increased from 5 MeV to 15 MeV.



- Characterisation and improvement of laser focus pointing stability.



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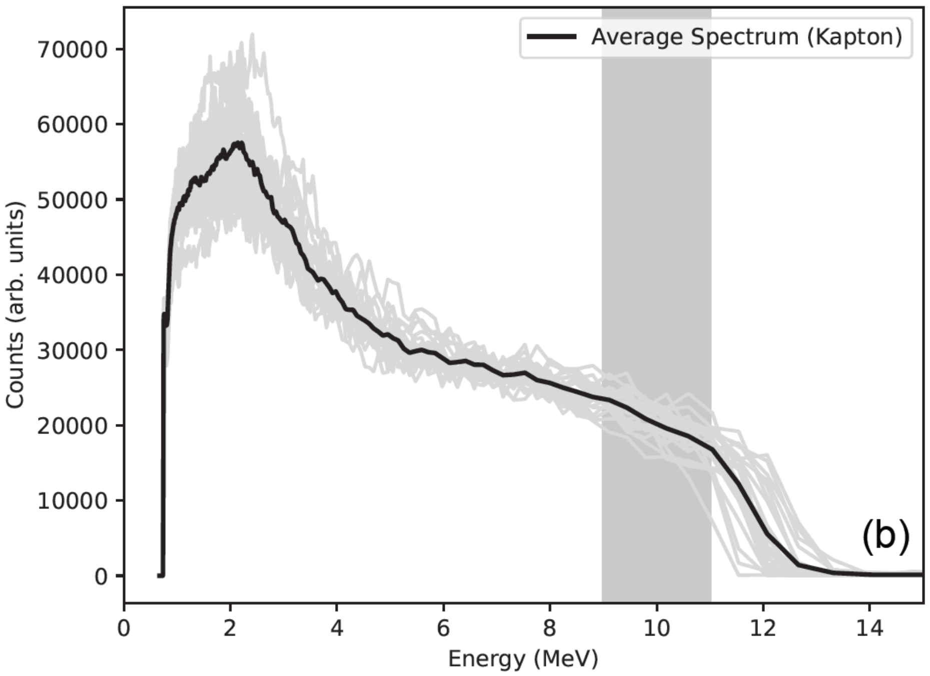
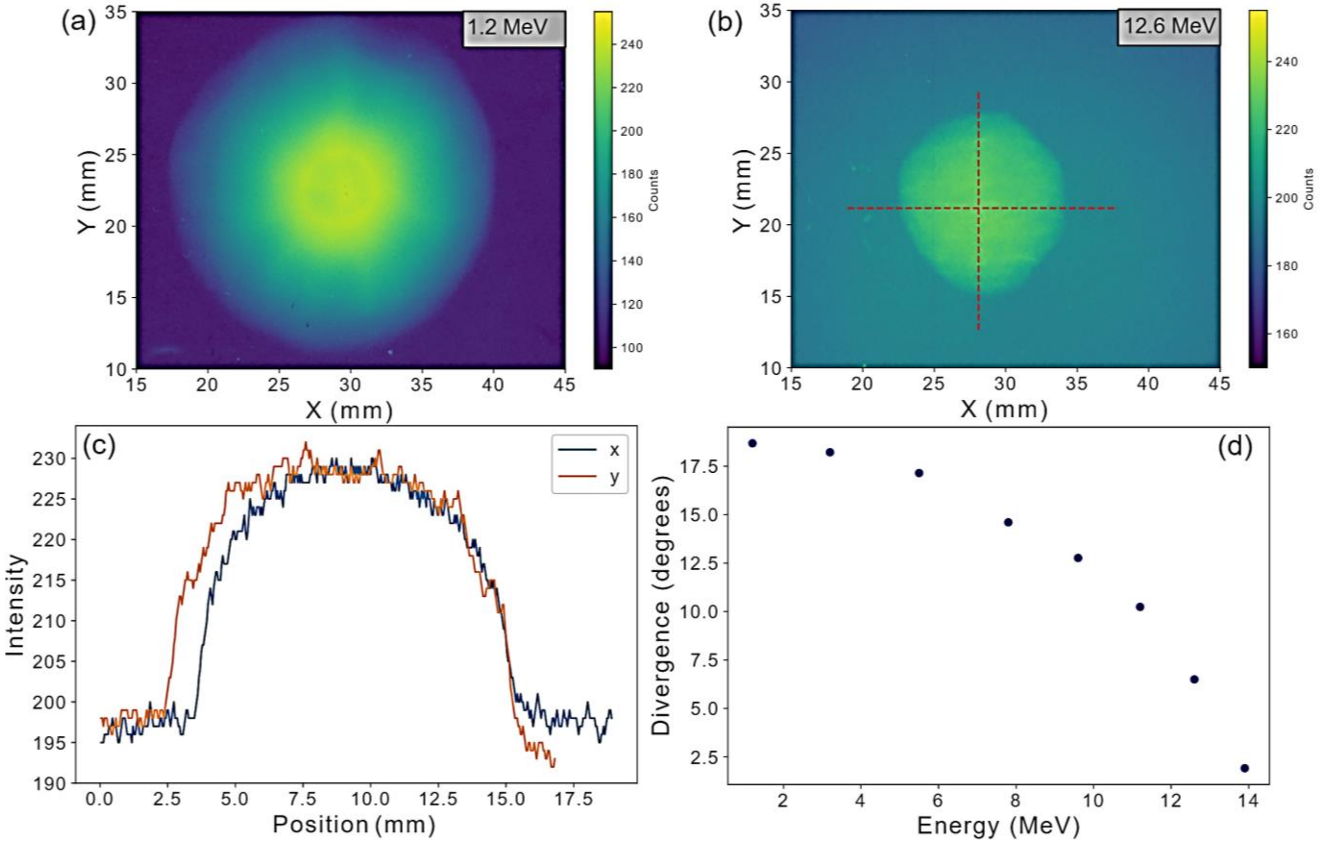
Proton source characterisation

- Have now measured protons >15 MeV on SCAPA at up to 1 Hz repetition rate.
- Experiment focusing on measuring shot-to-shot stability of the proton spectrum (<5% variation).
- Uniformity is good at the relevant energies and divergence follows expected trend with energy.

Proton spectrum from Kapton tape target

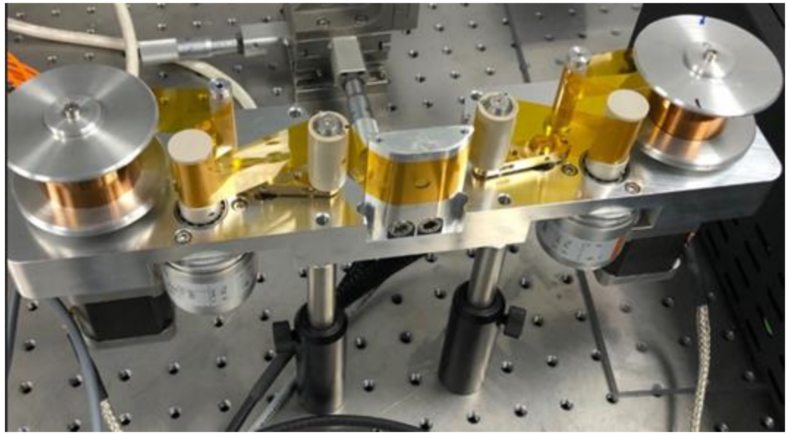


Proton spatial distribution and divergence

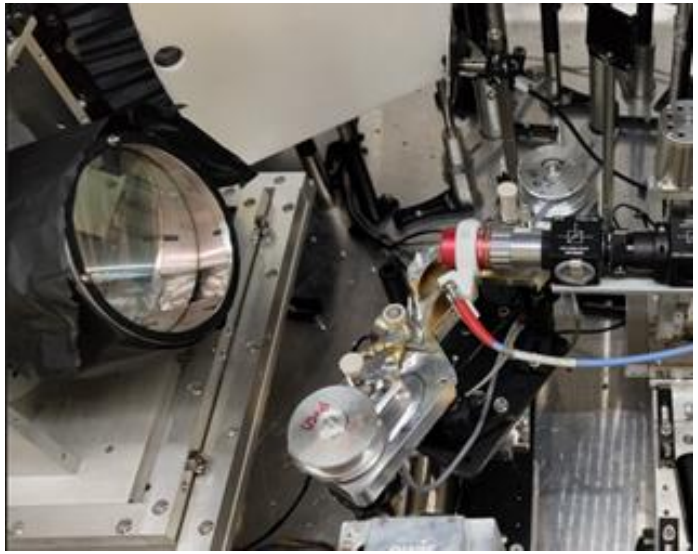


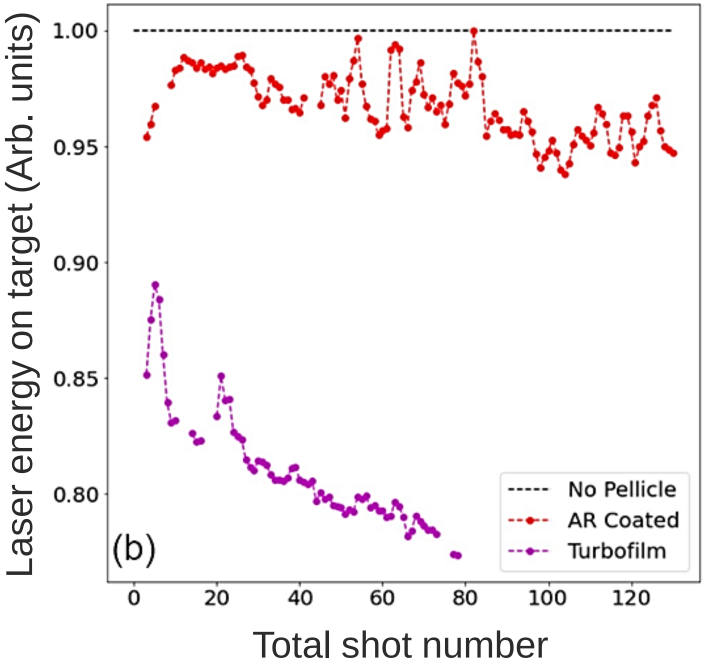
Technology developments

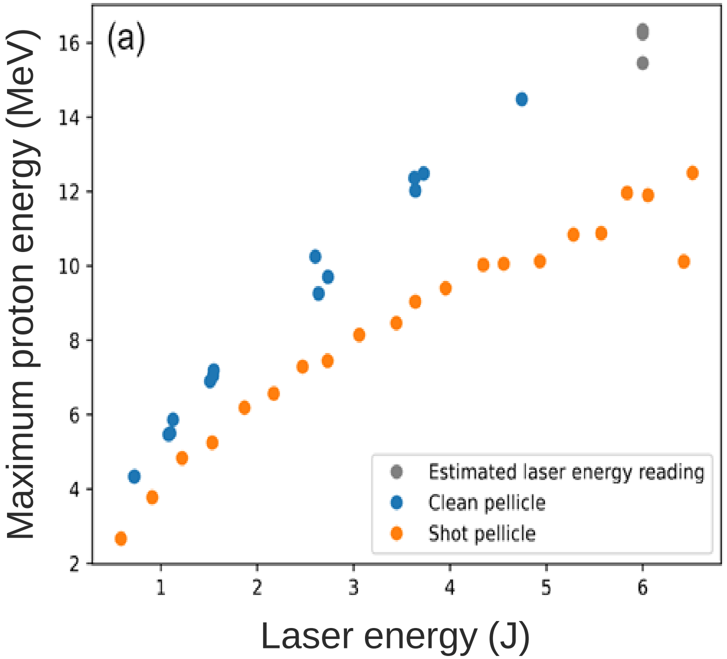
Development and testing of tape targetry in collaboration with the Central Laser Facility, for use at the high repetition rate Extreme Photonics Applications Centre (EPAC) facility at the Rutherford Appleton Laboratory.



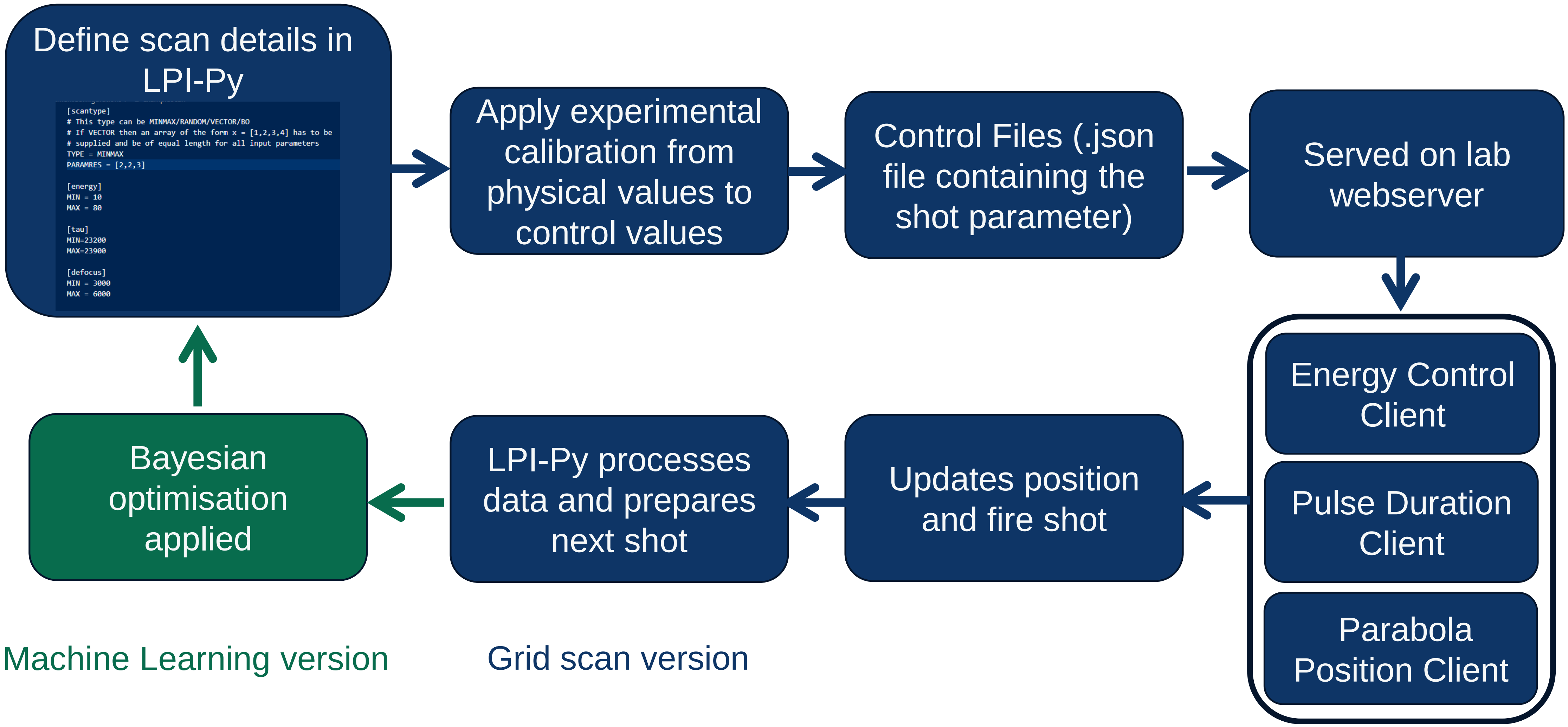
Characterising the effect of accumulated damage on pellicle protecting the main focusing optic





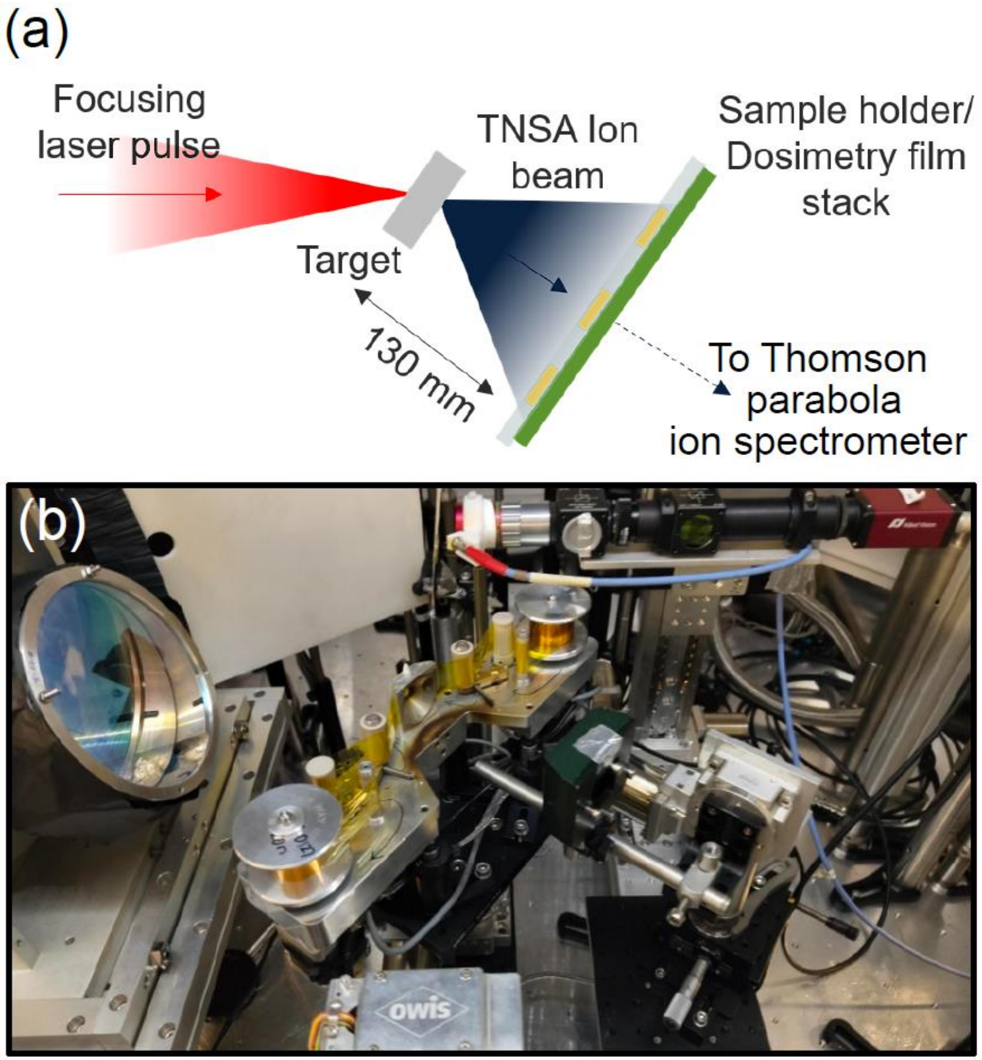


LPI-PY: An automated high-repetition rate control system

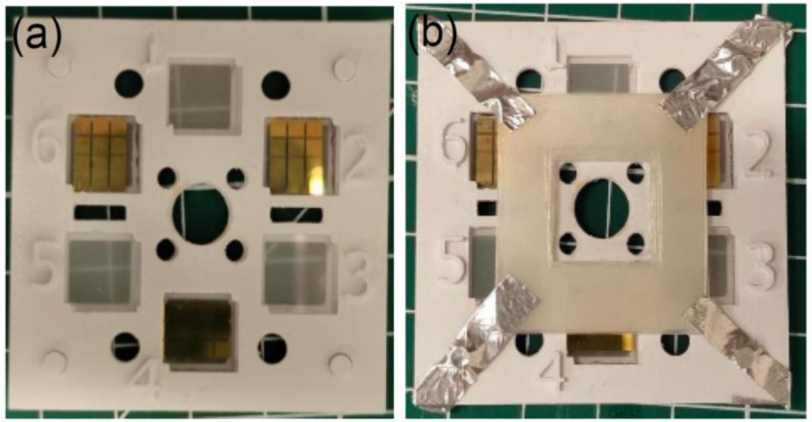


Applications: UK Space Agency-funded project on radiation damage

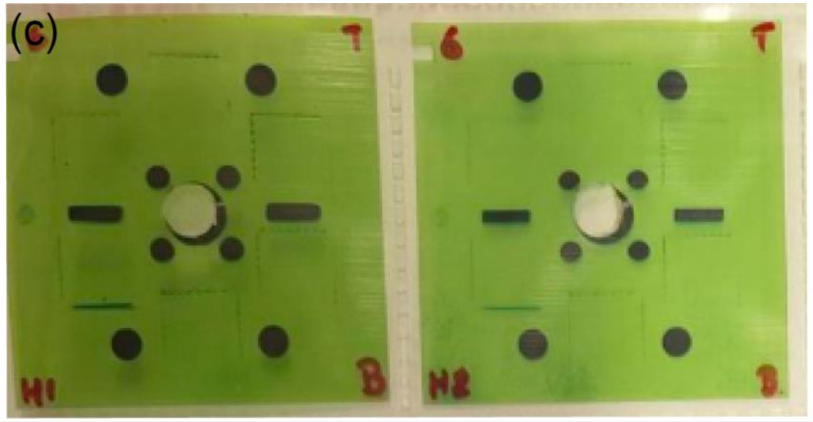
Production and testing of radiation-resilient photodetectors led by F. Massabuau (Strathclyde)

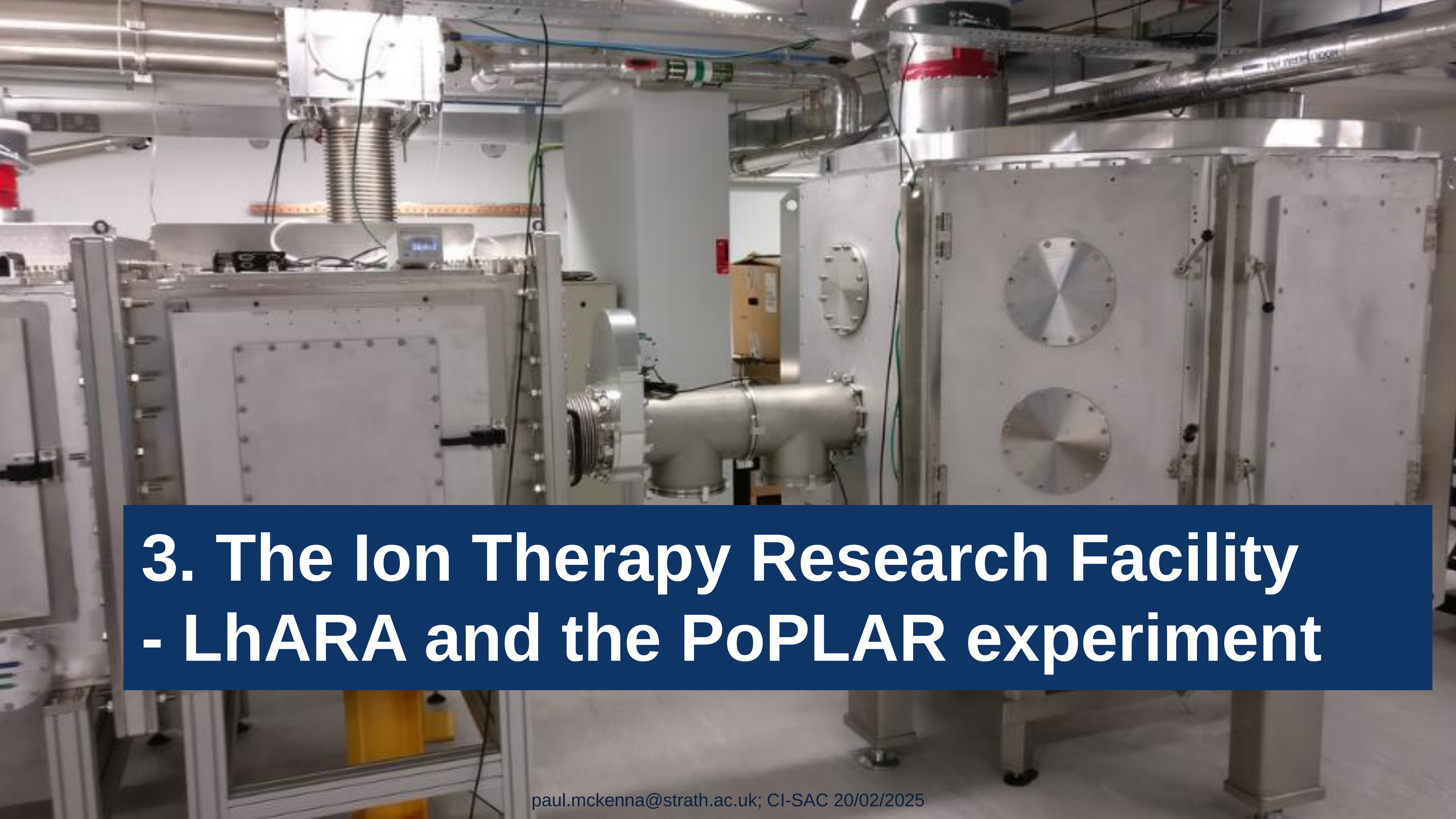


Photodetector samples



Proton dose measurements





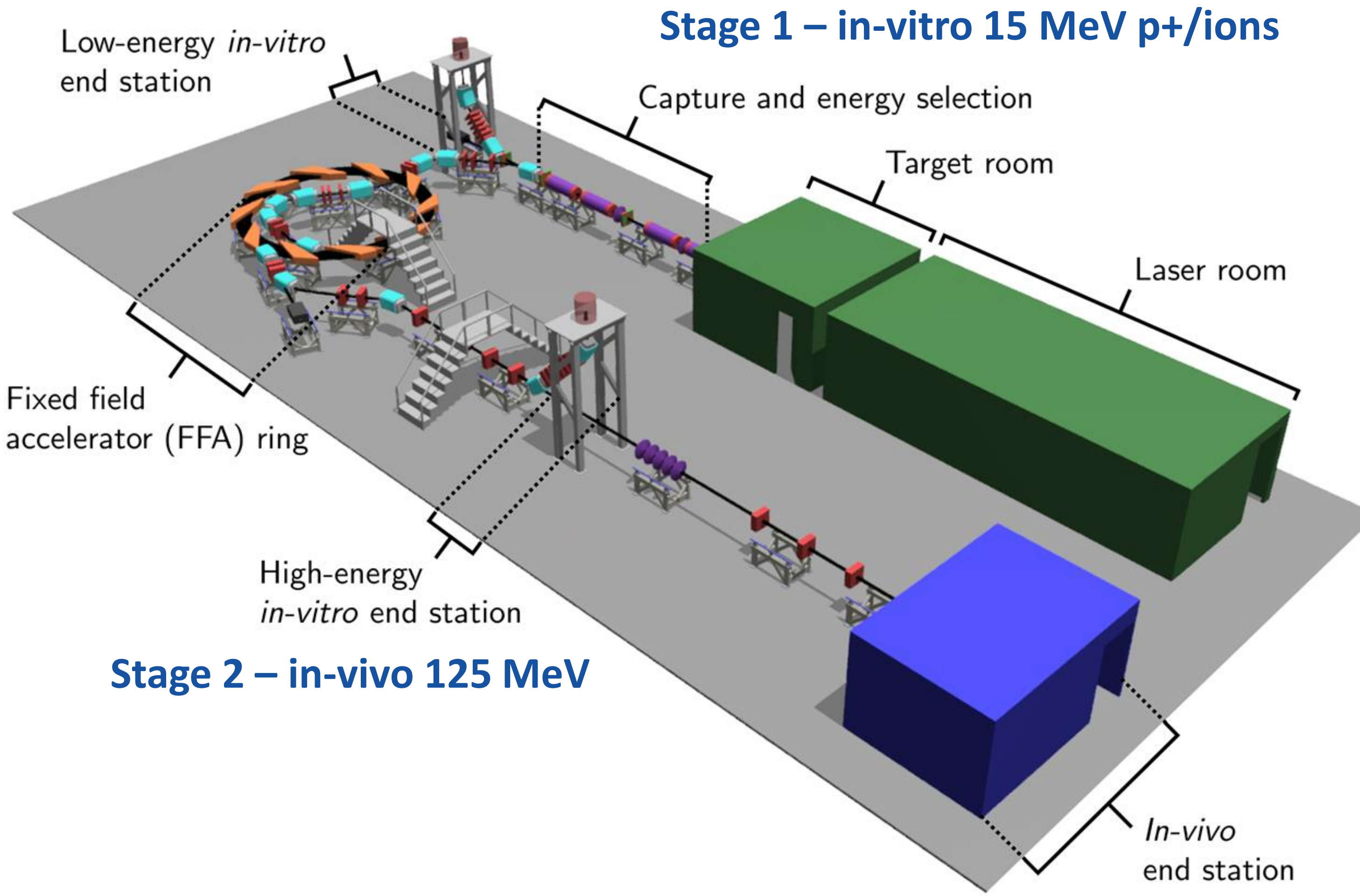
3. The Ion Therapy Research Facility - LhARA and the PoPLAR experiment

What is the Ion Therapy Research Facility (ITRF)?

Vision: To transform the clinical practice of proton- and ion-beam therapy by creating a fully automated, highly flexible system to harness the unique properties of laser-driven ion beams.

Stage 1: proton beams with energies in the range 12 MeV to 15 MeV to the Low-energy *in-vitro* End Station;

Stage 2: proton beams of 127 MeV and ion beams of 33.4 MeV/nucleon to the High-energy *in-vitro* and *In-vivo* End Stations.



Research Need:

- Ion biology not yet well understood
- Likely benefits from heavier ions
- Clinical choice will require understanding of effects in tumour and normal tissue
- Ultimately might require individual patient research

Imperial College London

ICR The Institute of Cancer Research

Medical Research Council
UKRI
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

LhARA Laser-hybrid Accelerator for Radiobiological Applications

Manchester 1824 The University of Manchester

University of Birmingham

University of Liverpool

NHS University Hospitals Birmingham NHS Foundation Trust

NHS The Clatterbridge Cancer Centre NHS Foundation Trust

NHS The Christie NHS Foundation Trust

institut Curie

Queen's University Belfast

Swansea University Prifysgol Abertawe

UCL Medical Physics & Biomedical Engineering

University — Clinical — Laboratory — Industry — Accelerator

Partners

Netherlands Cancer Institute Antoni van Leeuwenhoek

Hampton University Proton Therapy Institute Fighting Cancer, Saving Lives

University of Strathclyde Glasgow Department of Physics

Royal Holloway University of London

Lancaster University

Queen Mary University of London

UKRI Science and Technology Facilities Council

CLF central laser facility

ASTeC
Daresbury Laboratory
Particle Physics Department
ISIS Neutron and Muon Source

University of Birmingham | Cyclotron Facility | Positron Imaging Centre

Corerain 鲲云科技

INFN Catania

The Cockcroft Institute of Accelerator Science and Technology

CERN

LEO Cancer Care

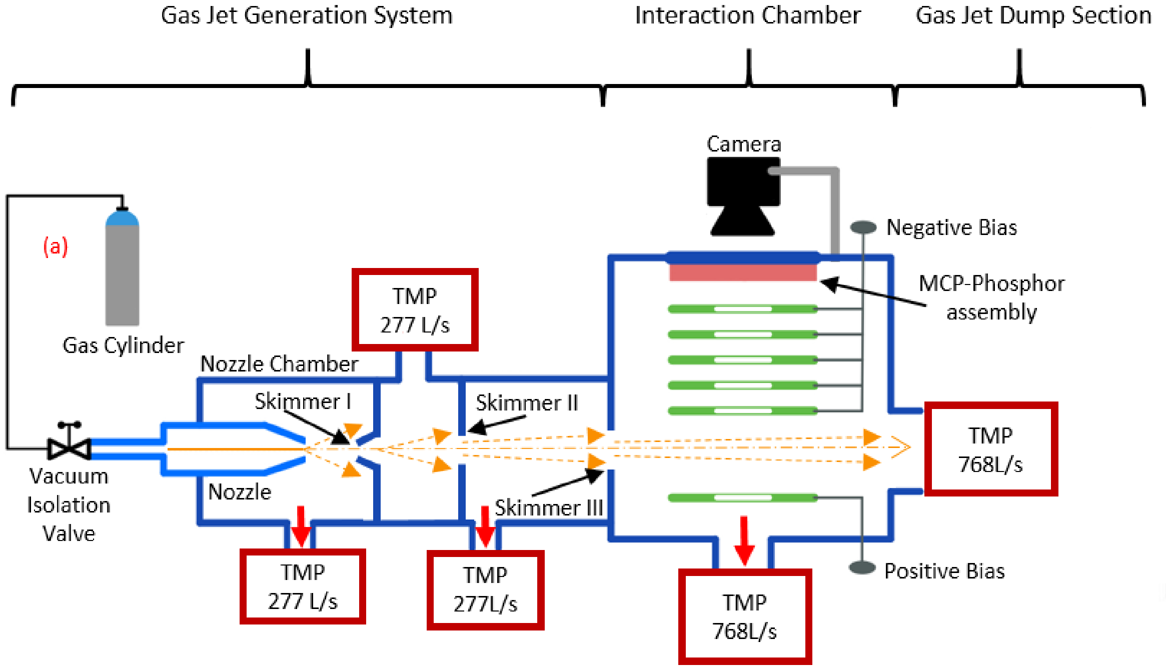
Maxeler Technologies Maximum Performance Computing

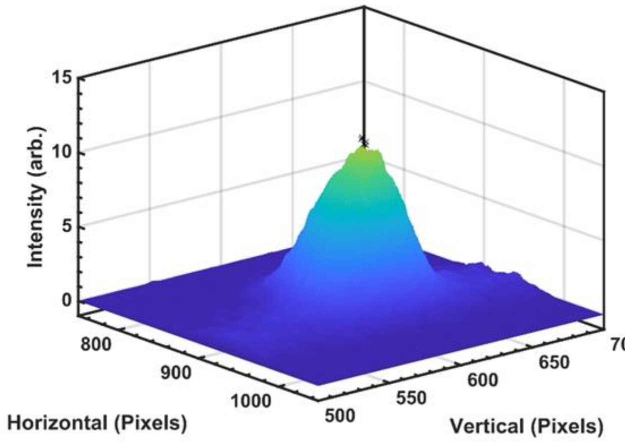
The Rosalind Franklin Institute

NPL National Physical Laboratory

Supersonic Gas Curtain based real-time Ionization Profile Monitor

- Development of gas jet ionization profile monitor of the ion beam.
- Proof of concept measurements relating to LhARA ion beam parameters.
- Courtesy of Narender Kumar, Liverpool





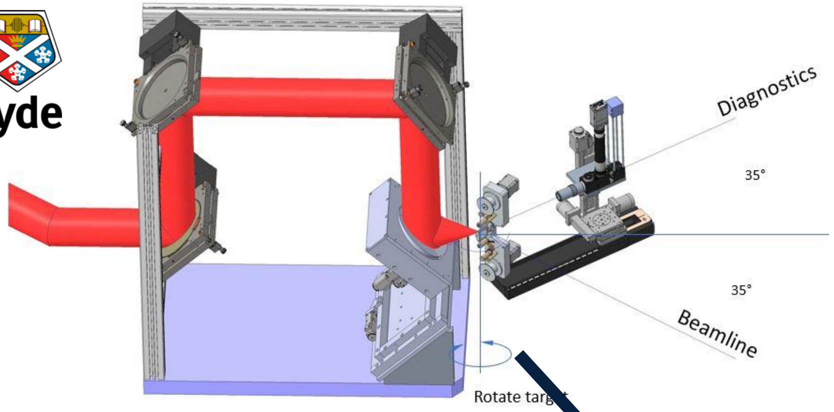
Beam (LhARA)	C^{6+} (33.4MeV/u)
Instantaneous dose rate	9.70E+08
Pulse length (ns)	75
Repetition rate	10 Hz
Charge per laser shot (pC)	100
Ions per bunch (no.)	1.04E+08
instantaneous beam current (mA)	1.333
Square 3.5×3.5 cm (ions/sq.mm/bunch)	8.49E+04
Round 3 cm (ions/sq.mm/bunch)	1.47E+05
Pencil 1 mm (ions/sq.mm/bunch)	1.32E+08

	for C^{6+}, 2.33MeV/u	
	Argon	Nitrogen
D_{limit}(ions/sq. mm/count)	9.45E+06 ± 3.79E+06	1.85E+07±7.42E+06
Minimum additional gain required for	To generate on an average 5 counts/mm^2	
Square 3.5×3.5 cm	780	1527
Round 3 cm	450	882
Pencil 1 mm	0.50	0.98

UNIVERSITY OF LIVERPOOL

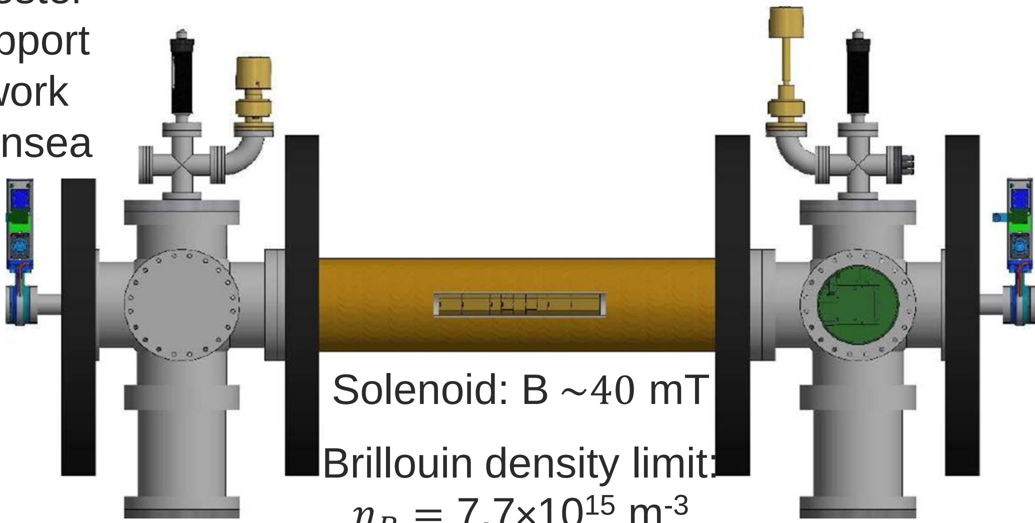
Stage 1: 15 MeV TNSA to Gabor capture line

Laser-driven ion source



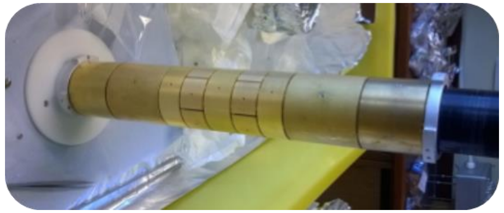
Will Bertsche, Manchester is providing theory support for the experimental work on Gabor lens at Swansea

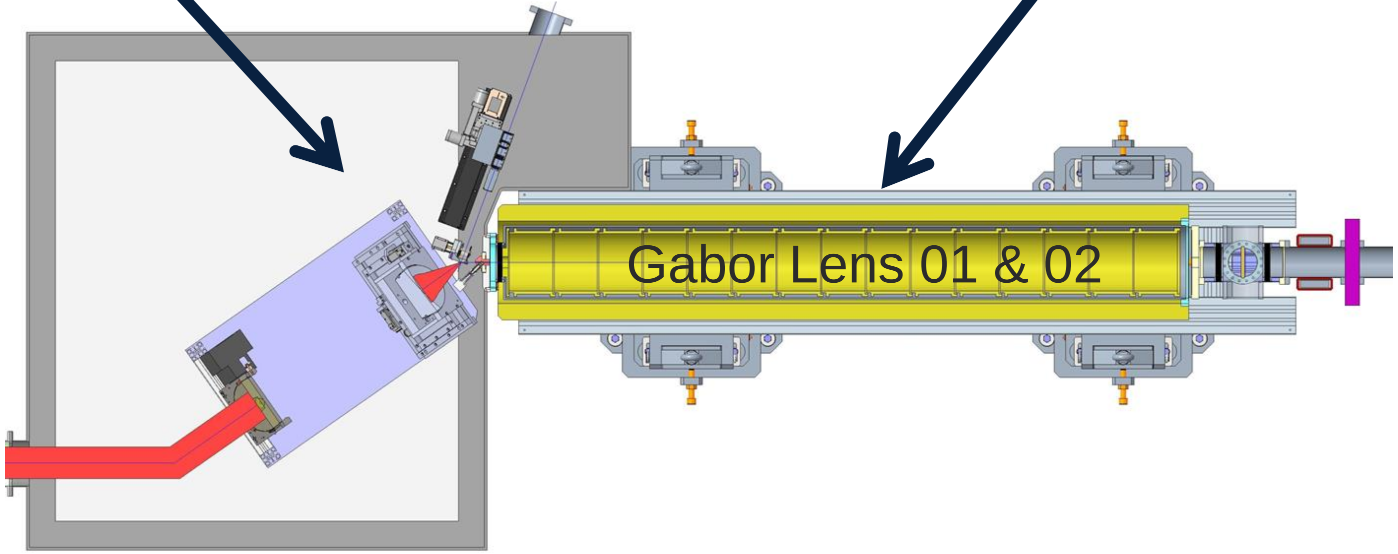
Gabor capture setup



Solenoid: B ~40 mT

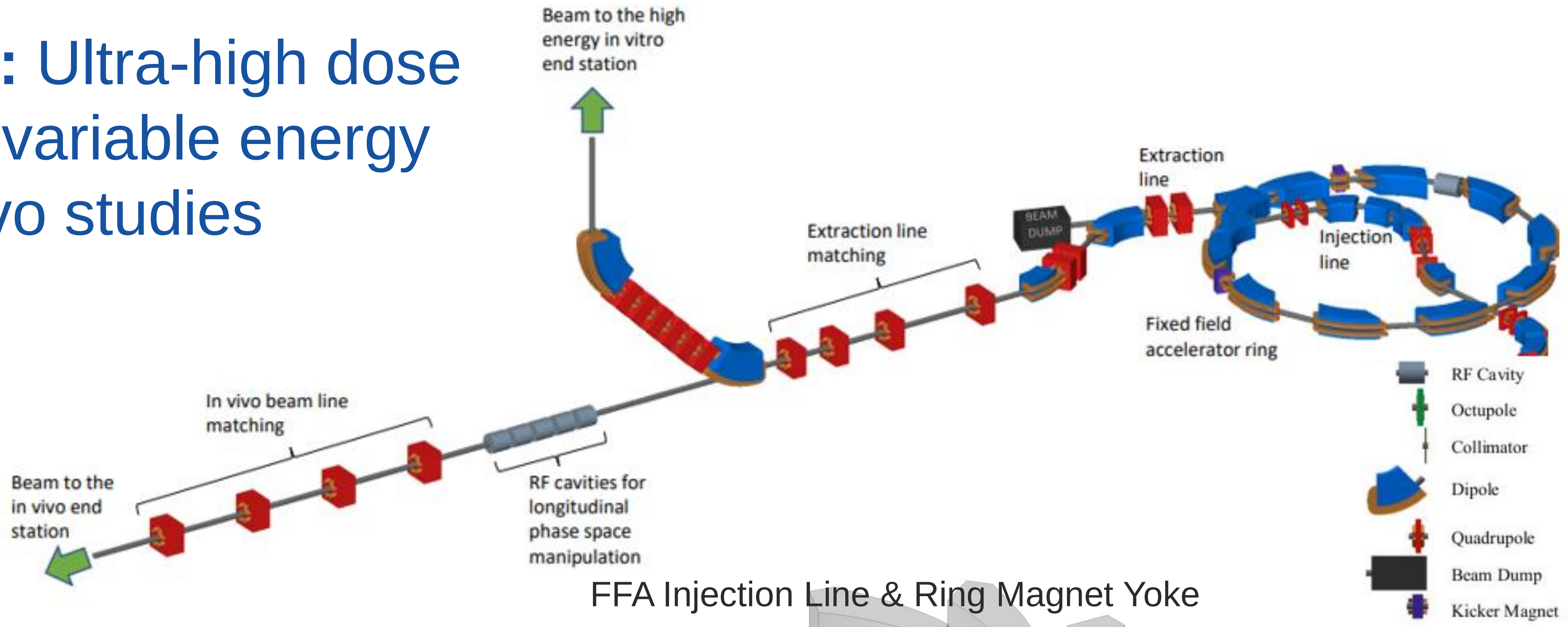
Brillouin density limit:
n_B = 7.7×10^{15} m^{-3}



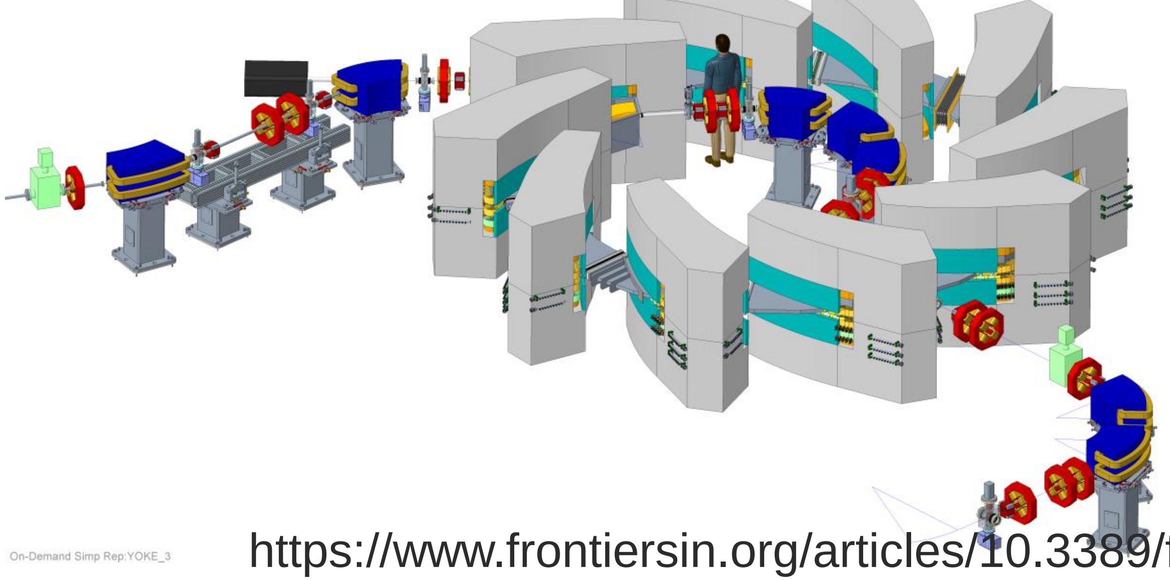


Stage 2: Ultra-high dose rates at variable energy for in-vivo studies

Science and Technology Facilities Council



FFA Injection Line & Ring Magnet Yoke



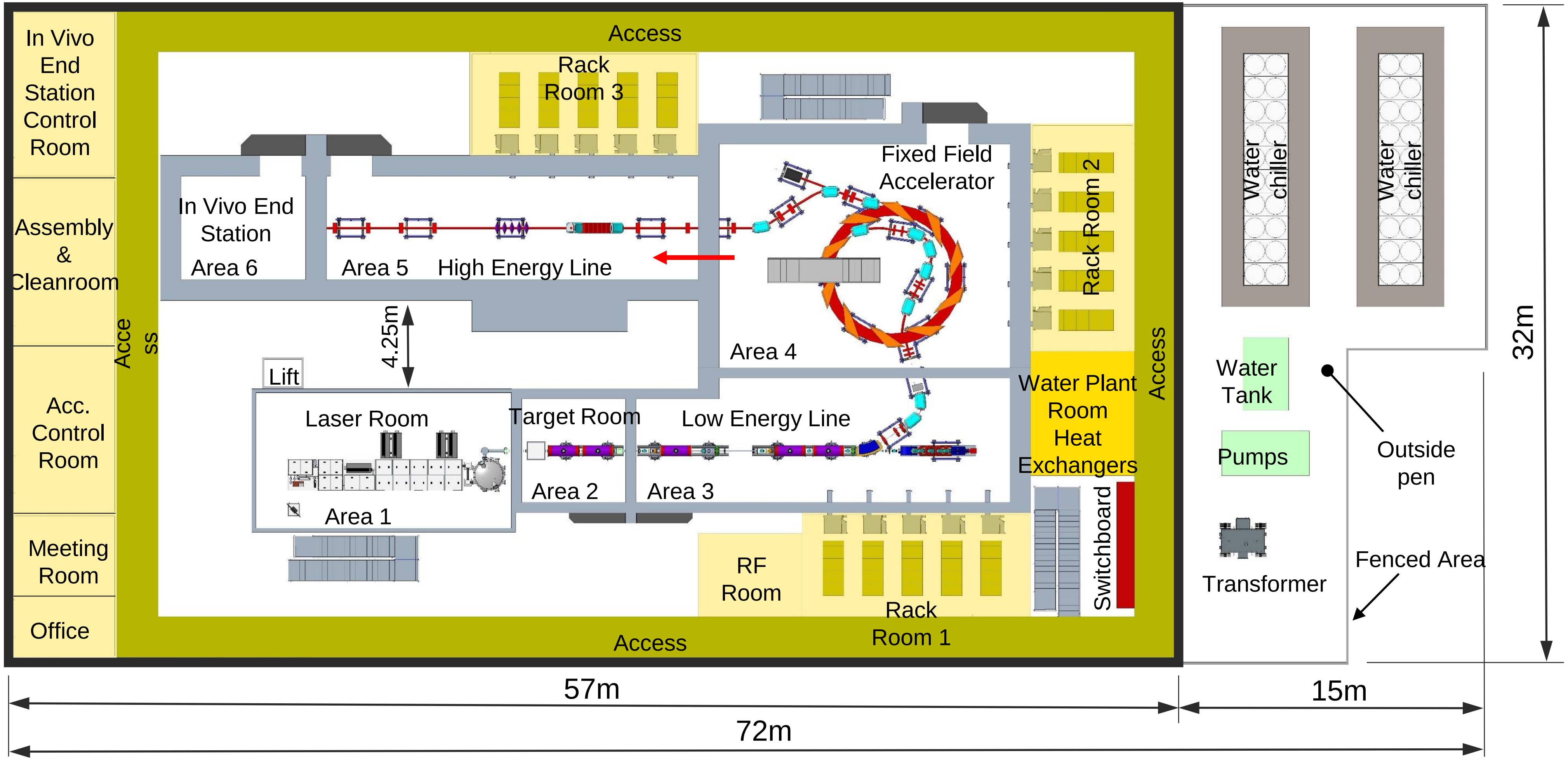
Pasternak, Kurup, Shields et al.

Evolution of RACCAM design

Benefits from extensive UK and international experience in FFA developments for particle physics and neutron sources

https://www.frontiersin.org/articles/10.3389/fphy.2020.567738/full

ITRF Baseline Layout



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

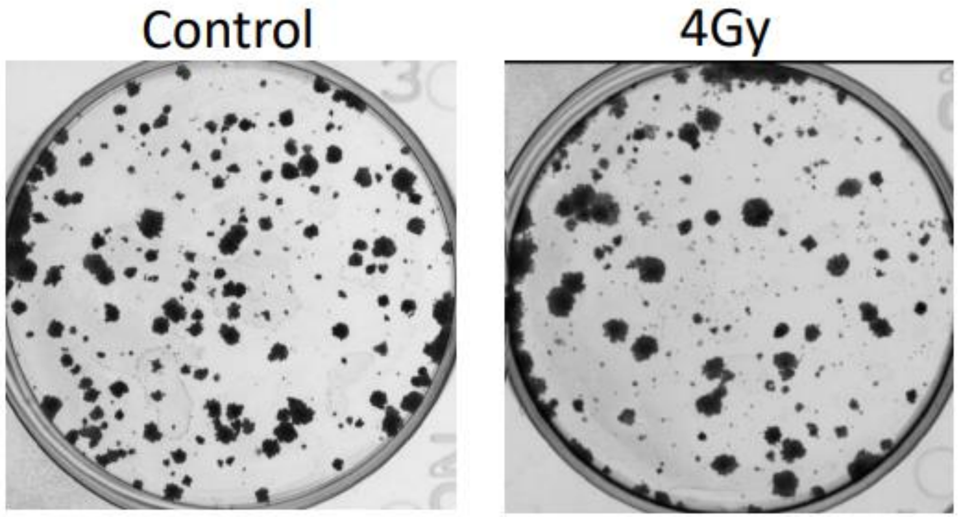
ITRF Project and LhARA Status

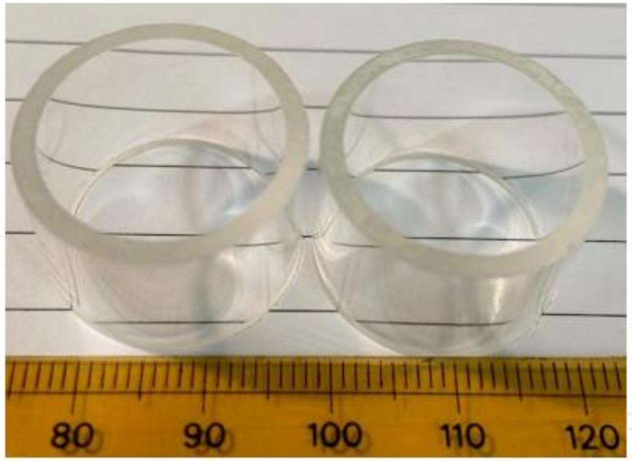
- Oct 22 to Oct 24: Infrastructure Fund Preliminary Activity to deliver ITRF facility Conceptual Design.
- Oct 24 to May 25: Abbreviated bridging funding allows us to deliver much of planned PoPLAR proof-of-principle experiment (supports ITRF Stage 1 and science case).
- Have not yet achieved approval of further funding to take ITRF facility forward.
- LhARA Collaboration will continue and is seeking alternative funding to pursue experimental and technology development.

Proof-of-principle LhARA radiobiology (PoPLAR) experiment

- As a proof of principle experiment for LhARA we aim to capture the laser-driven proton beam from SCAPA Bunker B to irradiate cells at conventional and ultra-high dose rates.
- The key aim is to show high throughput irradiation at controllable dose and dose rates from a laser driven source:

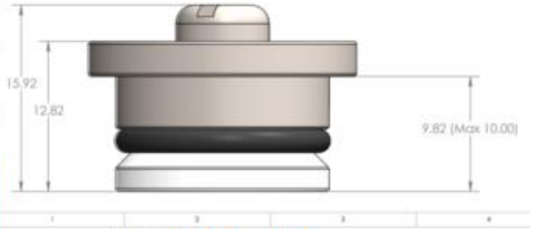
~10 MeV – grow cells on 2.5 μm mylar in glass rings





Internal diameter – 18.5 mm

Outer diameter – 22.5 mm



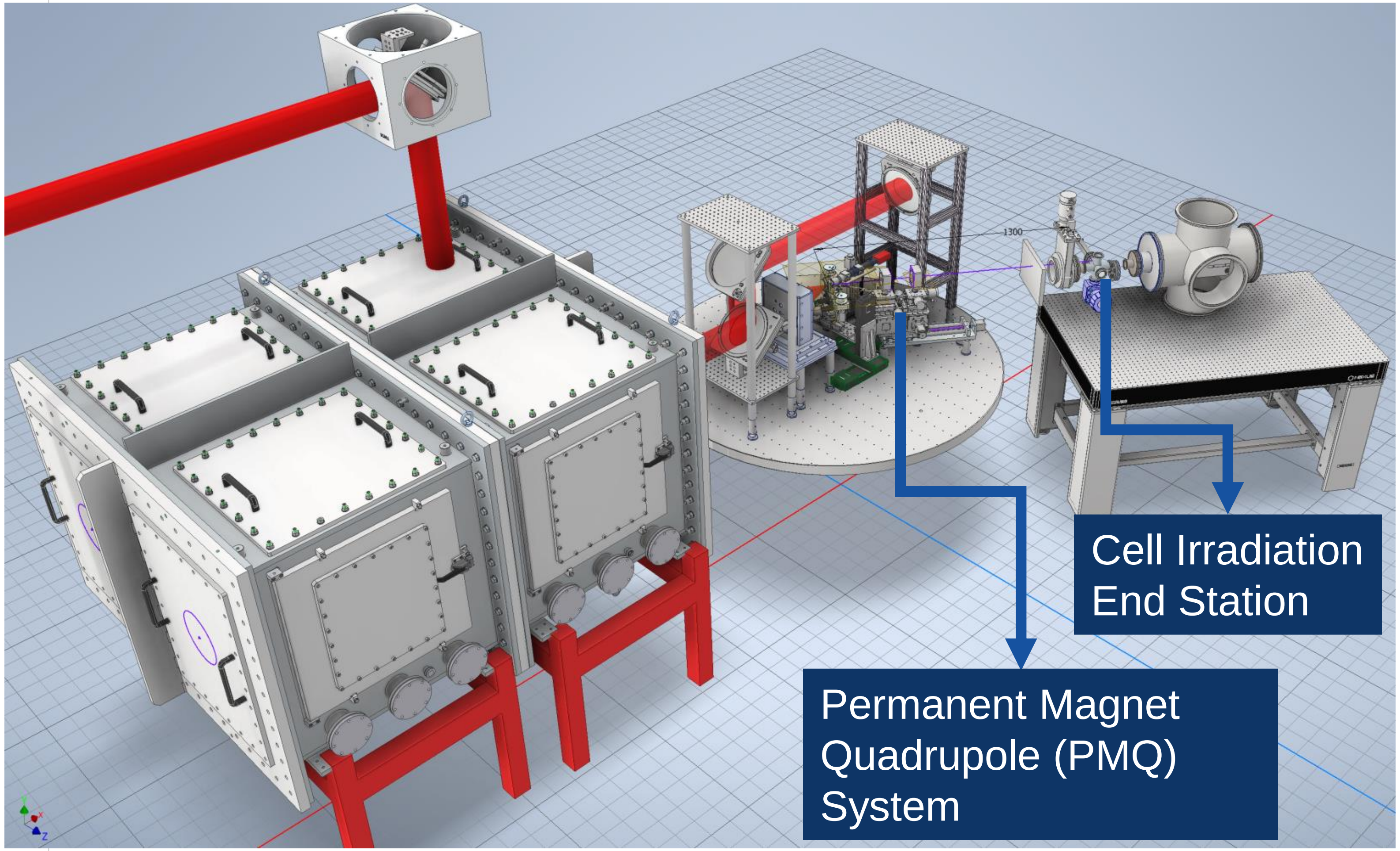
Sealable lids

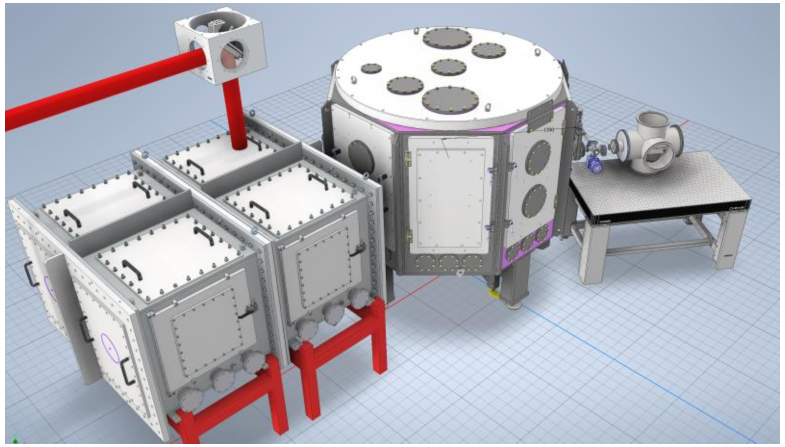
CONVENTIONAL - 0.1Gy per pulse separated by 1 sec = **6Gy/min**

ULTRA-HIGH - 1-3Gy/pulse (2ns) = 0.5-1.5 GGy/sec (~**10^9 Gy/s**)

paul.mckenna@strath.ac.uk; CI-SAC 20/02/2025

Proof-of-principle LhARA radiobiology (PoPLAR) experiment

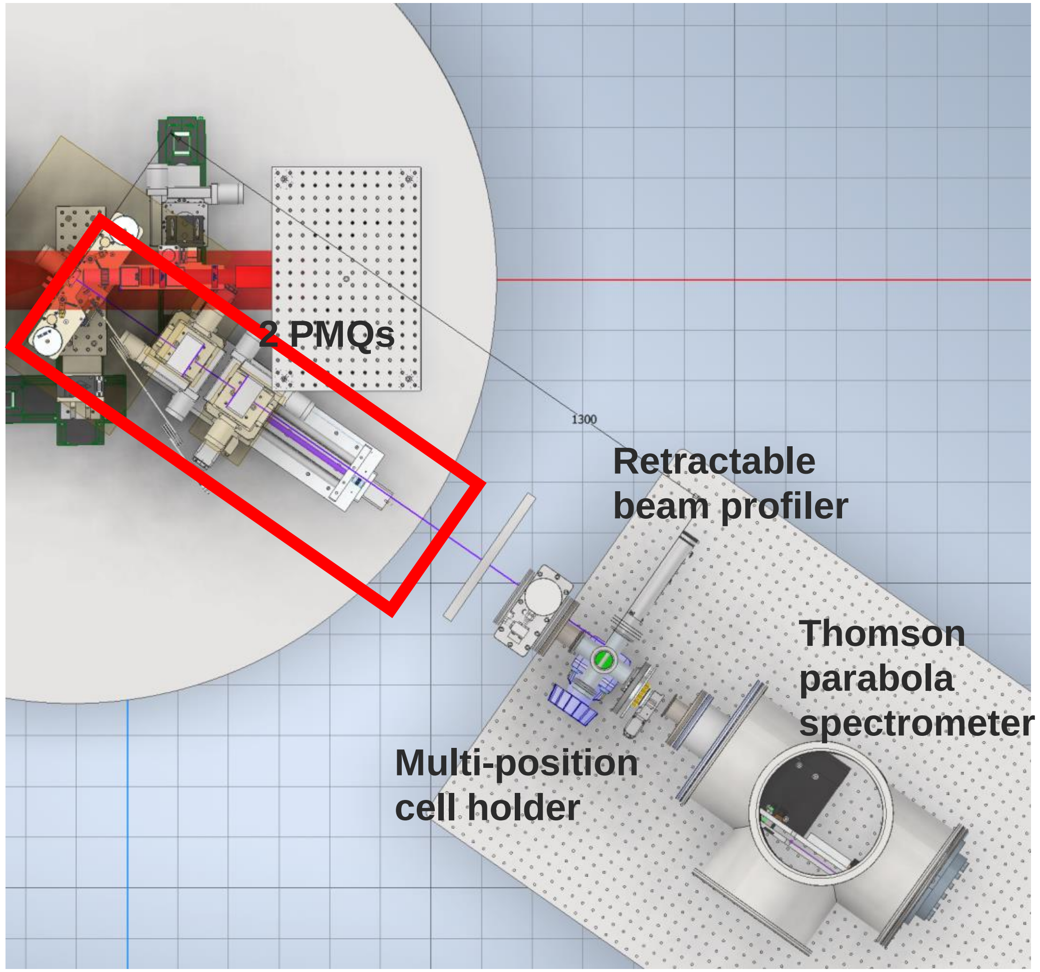


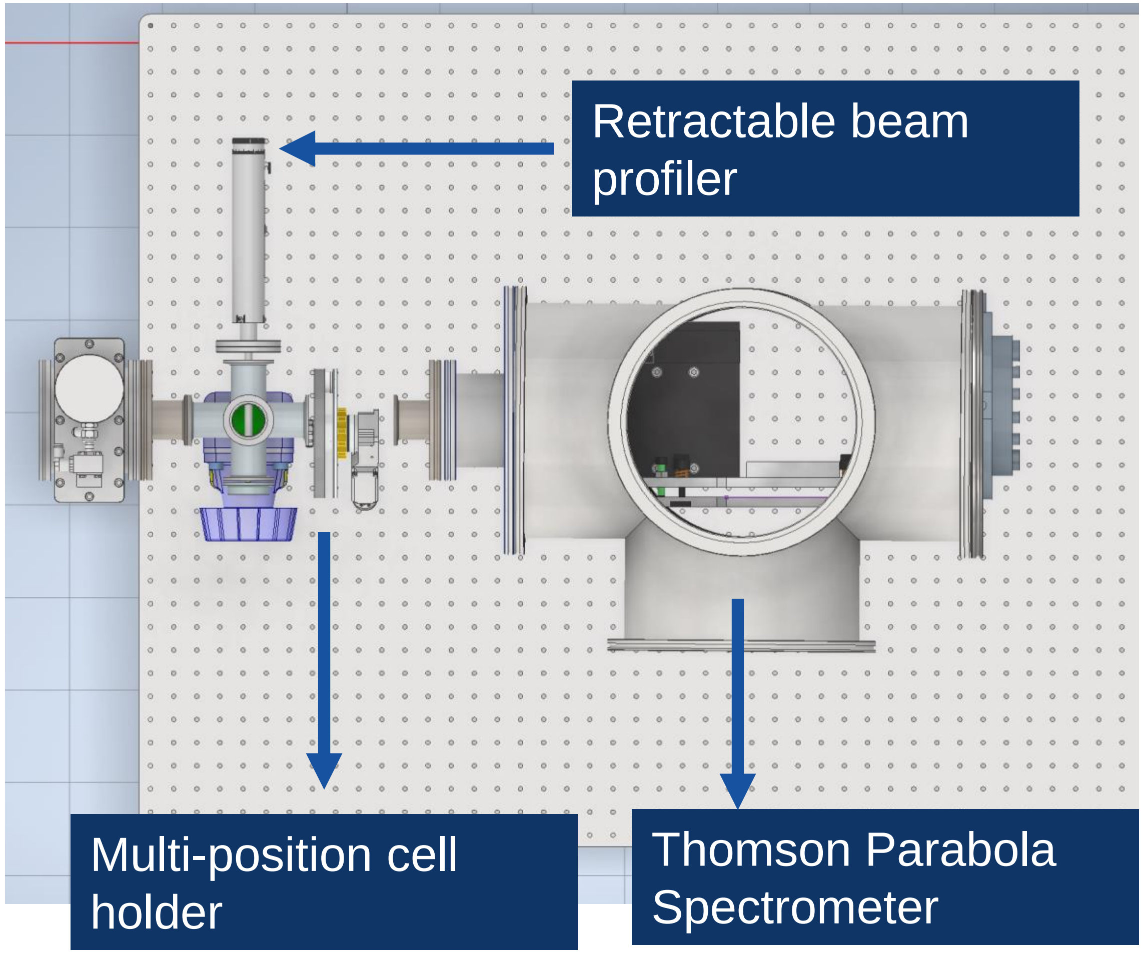


- We are in the process of designing and adding a capture beamline to SCAPA bunker B to guide and focus the laser-driven proton source to a cell irradiation end station.
- Major challenges are in purchasing, mechanical design and PMQ alignment

PoPLAR beamline engineering

- 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.
- Challenges are in equipment costs, mechanical design and PMQ alignment sensitivity

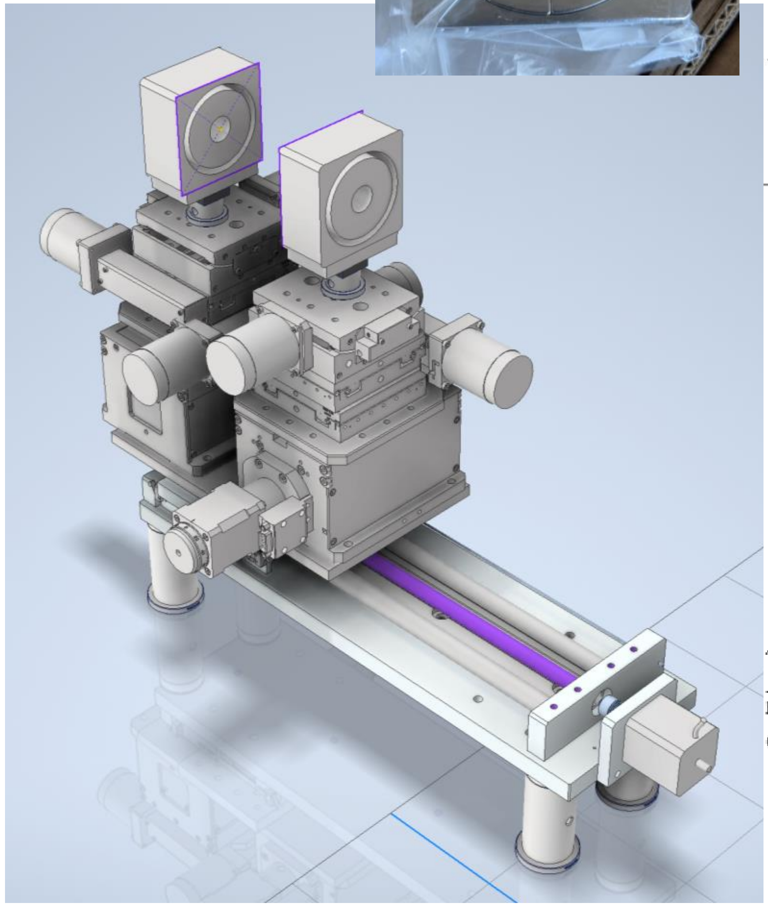


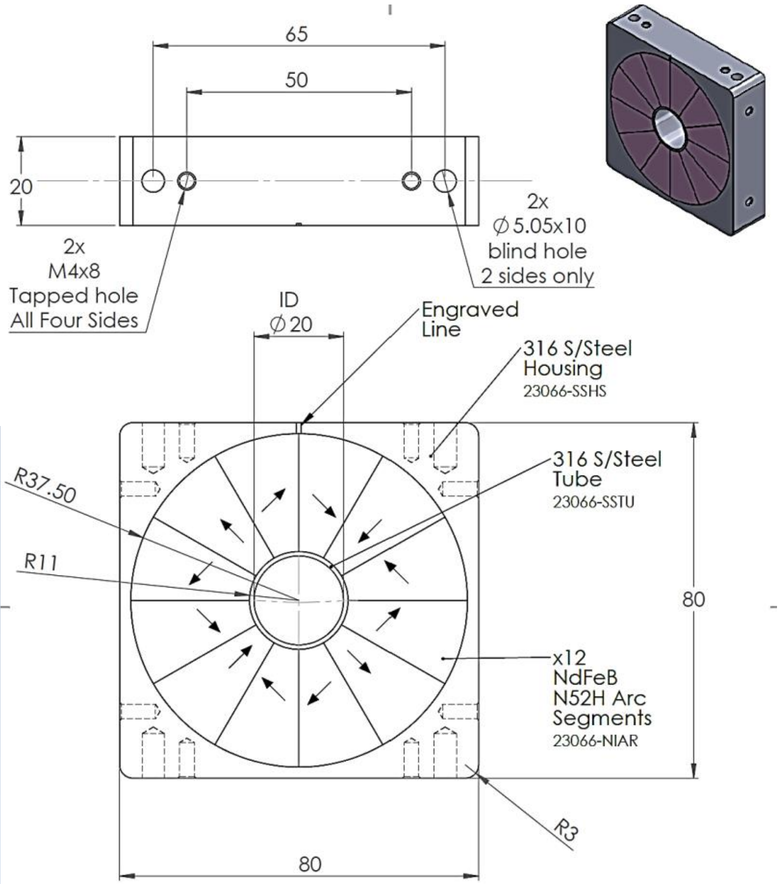


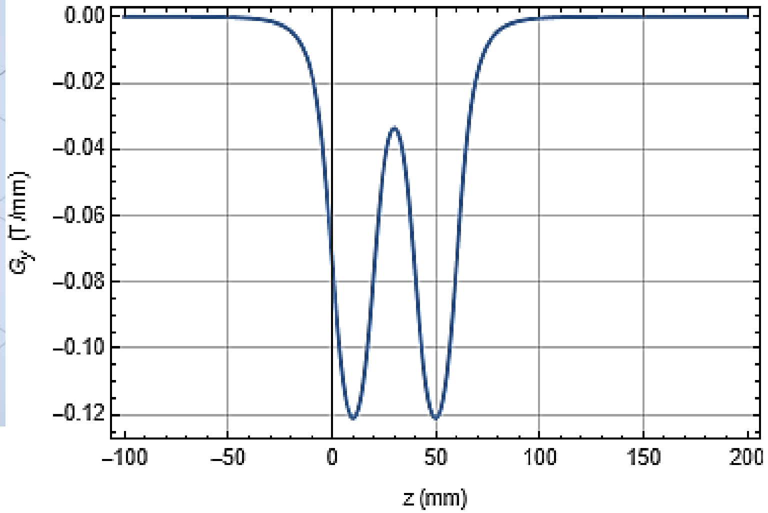
PoPLAR beamline engineering

- 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

Science and Technology Facilities Council







Proof-of-principle LhARA radiobiology (PoPLAR) experiment

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