WP2 Update: Underpinning Science, Challenges and Recent Developments

Ross Gray

Research Fellow

University of Strathclyde, Glasgow, UK

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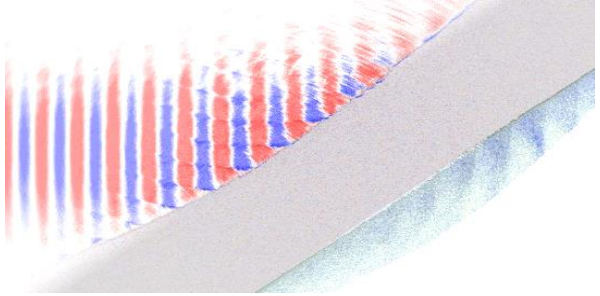
Planned objectives for WP2 activity

Years 1-2: preliminary activity

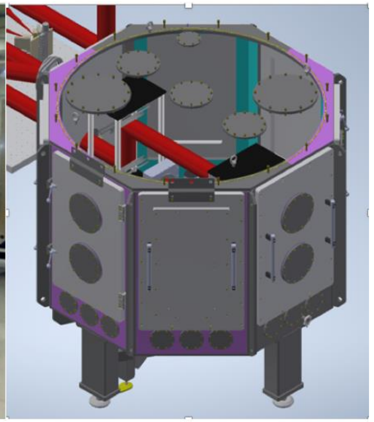
Baseline simulation campaign to optimise source

- Hydrodynamics simulations of low intensity "prepulse"
- Full-scale 3D particle-in-cell simulations of ion generation



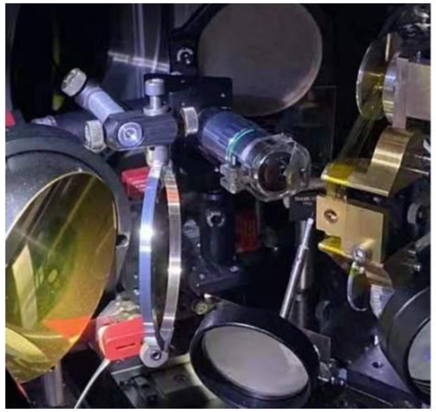
Single-shot LhARA spec. proton generation (SCAPA, Strath)

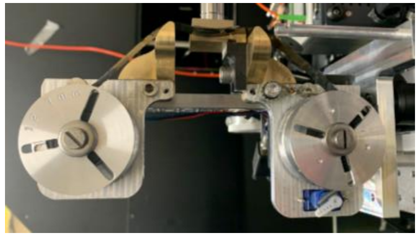
- Proton generation on SCAPA, matched to LhARA laser
- Parametric optimisation



Ion generation at 10 Hz (Zhi/Cerberus lasers, ICL)

- Targetry requirements at 10 Hz
- Source monitoring and stabilisation

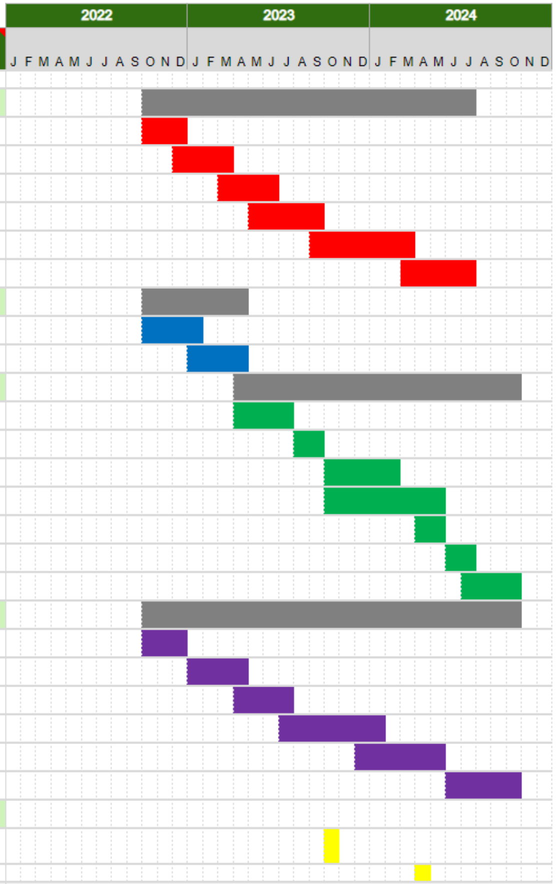




WP2 project plan…

LhARA WP2 Gantt Chart

TASK DESCRIPTION	START	END	TYPE
O1 - Baseline Simulations (Lancaster)	01/10/2022	01/07/2024	
Convergence Testing and Benchmarking	01/10/2022	01/12/2022	R
Hydrodynamic modelling of laser contrast	01/12/2022	01/03/2023	R
2D PIC modelling of TNSA for proton acceleration on SCAPA	01/03/2023	01/06/2023	R
3D 'full scale' simulations for proton acceleration on SCAPA	01/05/2023	01/09/2023	R
2D PIC modelling of TNSA for heavy ion acceleration on SCAPA	01/09/2023	01/03/2024	R
3D 'full scale' simulations for heavy ion acceleration on SCAPA	01/03/2024	01/07/2024	R
O2 - Diagnostic Package (Strath/IC)	01/10/2022	01/04/2023	
Concept design for diagnostic platform	01/10/2022	01/01/2023	B
Testing preliminary ion diagnostics	01/01/2023	01/04/2023	B
O3 - Baseline SCAPA experiments (Strath)	01/04/2023	01/10/2024	
Experiment Planning, Design and Preparation	01/04/2023	01/07/2023	G
SCAPA ion source commissioning experiment	01/08/2023	01/09/2023	G
Data Processing and Analysis	01/10/2023	01/02/2024	G
Simulation Benchmarking and Iteration	01/10/2023	01/05/2024	G
Experiment Planning, Design and Preparation	01/04/2024	01/05/2024	G
SCAPA experiment on parametric optimisation of source	01/06/2024	01/07/2024	G
Data Processing and Analysis	01/07/2024	01/10/2024	G
O4 - Advanced targetry, debris and stablisation studies (IC/Lanc)	01/10/2022	01/10/2024	
Experiment Planning, Design and Preparation	01/10/2022	01/12/2022	P
Initial Baseline Experiment at IC for source characterisation and stability	01/01/2023	01/04/2023	P
Data Processing and Analysis	01/04/2023	01/07/2023	P
Experiment Planning, Design and Preparation	01/07/2023	01/01/2024	P
Base line experiment for debris and contaminant removal studies	01/12/2023	01/05/2024	P
Data Processing and Analysis	01/06/2024	01/10/2024	P
WP2 milestones			
M2.1: Prediction of optimised proton source for 100+ TW laser systems based on hydrodynamic and kinetic simulations	01/10/2023	01/10/2023	Y
M2.2: First SCAPA ion source simulations and experiment completed	01/04/2024	01/04/2024	Y

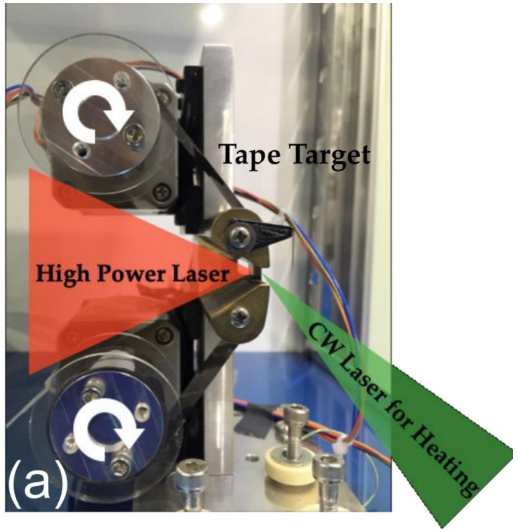


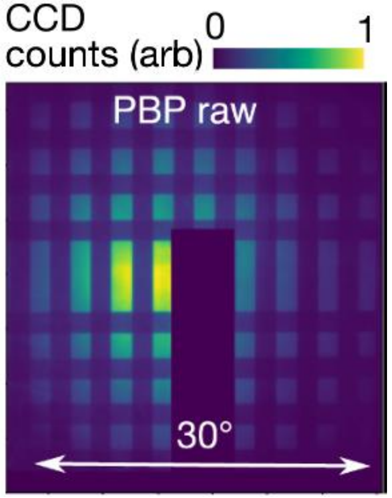
Elisabetta will cover this in the next talk

I will cover this (*mostly* experimental) work in this talk

- Deliverables for the first two years are focused on early experiments and source benchmarking in simulations, as well as initial technology development in diagnostics and targetry.

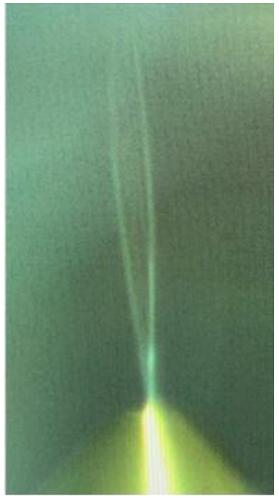
Planned objectives for WP2 activity

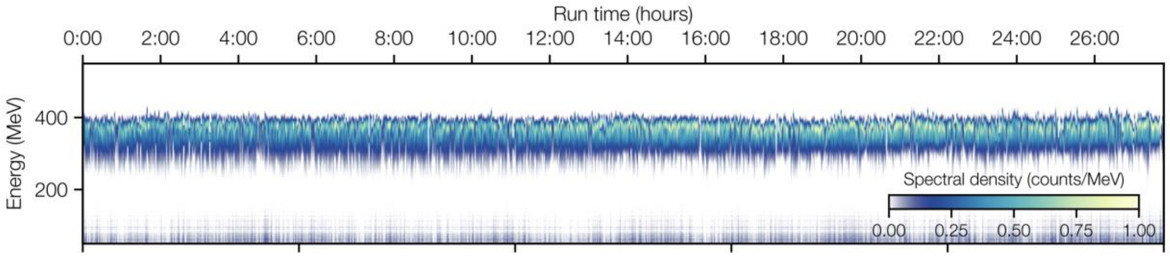


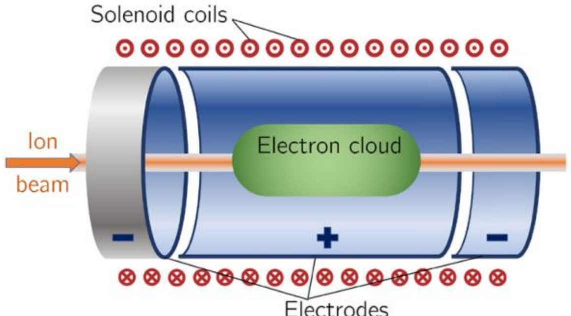


Years 3-5: preconstruction programme

- **Construction of bespoke diagnostic suite**
  - Laser spatial and temporal measurement
  - Ion spectral and spatial measurement
- **Optimisation of heavy ion acceleration**
  - Contaminant control at high repetition
- **Development of advanced 10 Hz target platform**
  - Water jet target
  - Active target stabilisation and debris control
- **Integration of developed laser ion source technologies**
  - Demonstrate integrated source and diagnostic system and compatibility with capture
- **LhARA specification beam generation at 5 Hz**
  - SCAPA experiments for near-full scale LhARA beam generation over ~1 hr duration







Aymar et al. Front Phys. (2020)

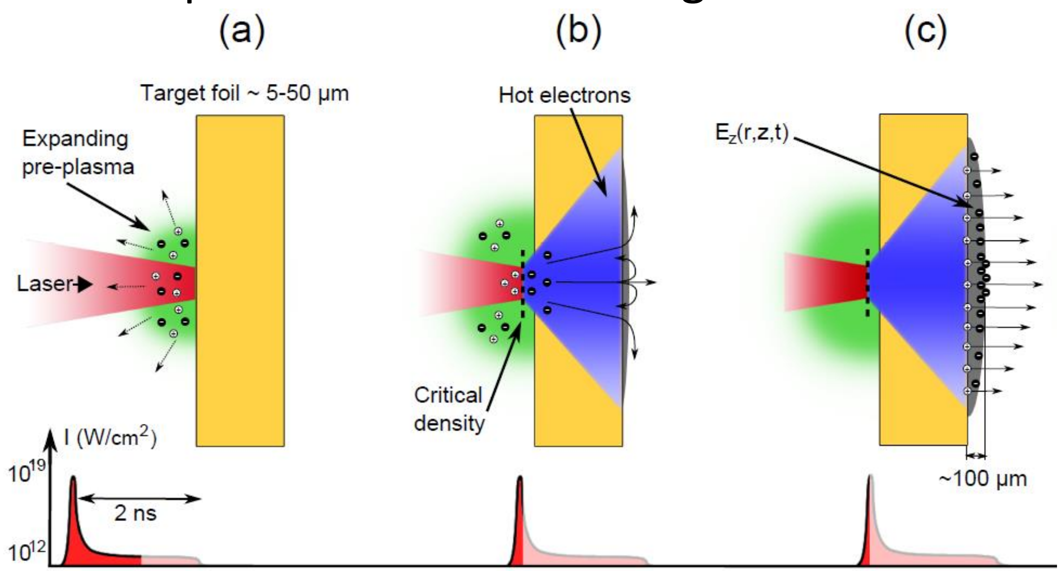
Why “laser-driven” ion acceleration…

- **High intensity laser driven ion sources have unique features:**
  - Naturally extremely high peak current (< ps generation time)
  - Triggerable and on-demand
  - High energy from source (up to ~100 MeV)

- **Attractive technology to deliver ions at high instantaneous dose rate**

- **Laser driven sources provide beams which are:**
  - Highly divergent (> 10º emission cone)
  - **Broad particle energy (quasi-thermal spectrum up to ≫10 MeV/u depending on laser)**

Considerations for a laser driven proton source from Target Normal Sheath Acceleration mechanism (TNSA)



$$k_B T_e = mc^2 \left(\sqrt{1 + a_L^2} - 1\right)$$

$$E_{max} = 2 k_B T_{hot} \ln^2 \left(\tau + \sqrt{1 + \tau^2}\right)$$

- **Fast electron temperature** and **fast electron density and total number** at the rear surface drive proton **spectral** characteristics
- Transport physics defined by **material, target properties** and **self generated fields** drive proton **spatial** characteristics
- These are sensitive to a wide range of input parameters:

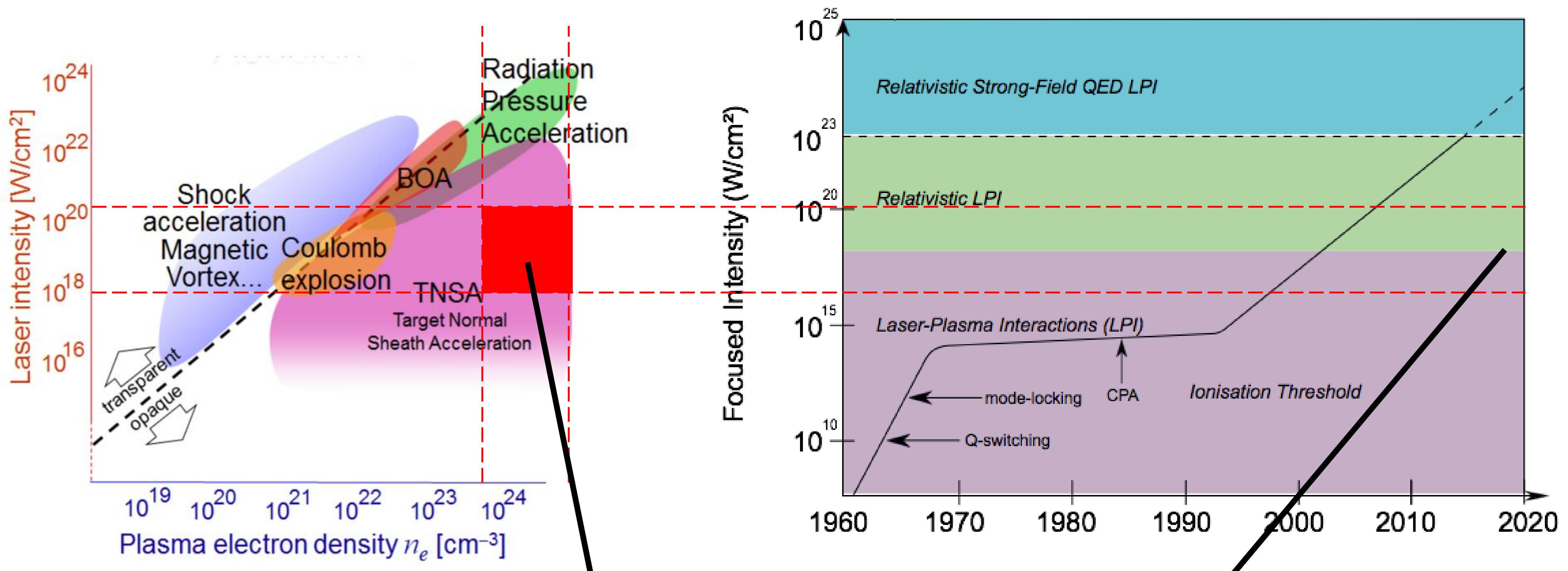
Laser:
- Intensity
- Energy
- Focal spot size
- Laser intensity contrast
- Polarisation
- …

Plasma:
- Energy conversion efficiency
- Fast electron divergence angle
- Z (scattering, resistivity)
- Preplasma scale length
- Incidence angle
- …

→

Experimental Implementation
- Focusing geometry
- Target Design
- Laser intensity contrast
- Polarisation
- Pulse duration
- …

Laser driven ion acceleration…



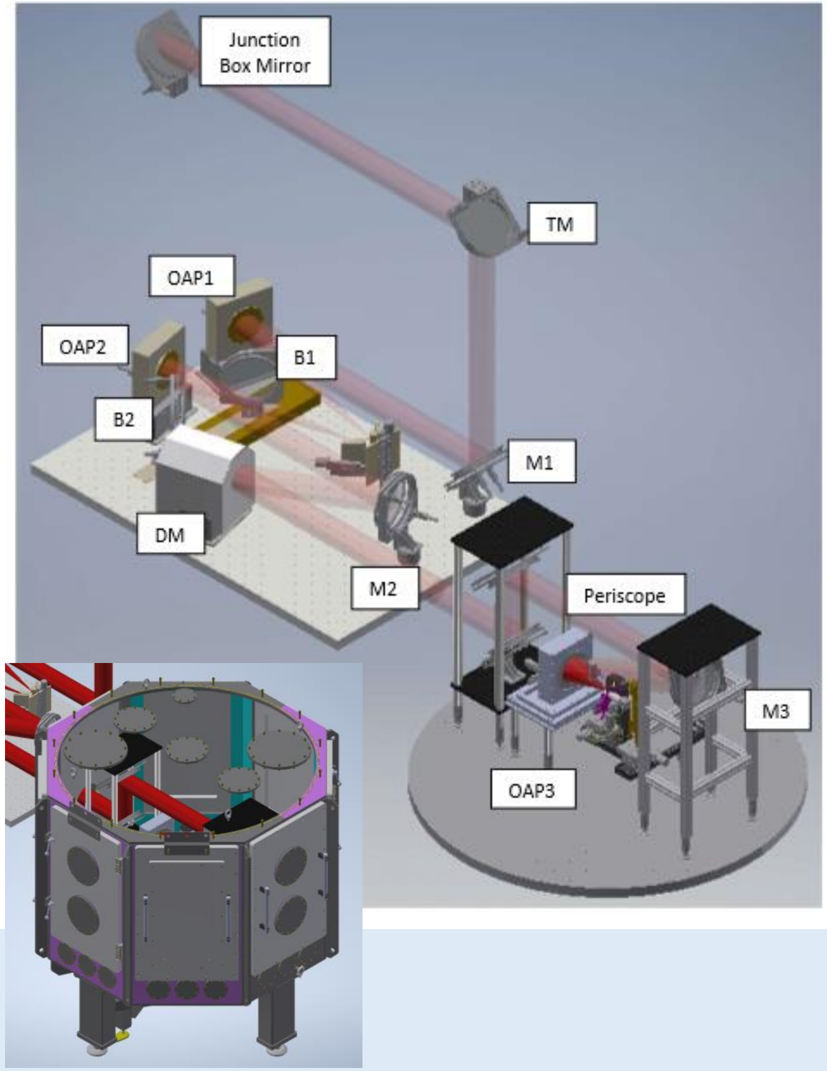
Well established, widely studied acceleration mechanism

University scale & commercially available laser systems

- There are various modes/mechanisms of ion acceleration we could aim for but TNSA is the most stable, most well developed and occurs in an intensity range which is now feasible at the university scale…

SCAPA: Scottish Centre for Application of Plasma based Accelerators

Laser-solid interaction beamline B1 in Bunker B.



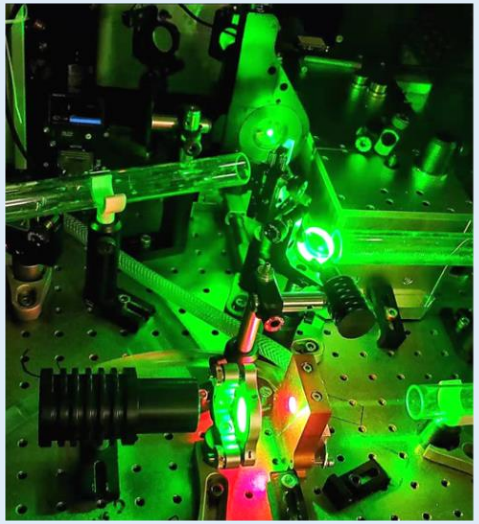
- 8 J, 25 fs at 5 Hz repetition rate up to ~10^{20} W/cm^2
- We would expect ~30 MeV proton beams
- Three experimental areas (A,B,C) with Bunker B dedicated to ion acceleration
- Two distinct vacuum chambers for beam conditioning and another variable experimental configurations.

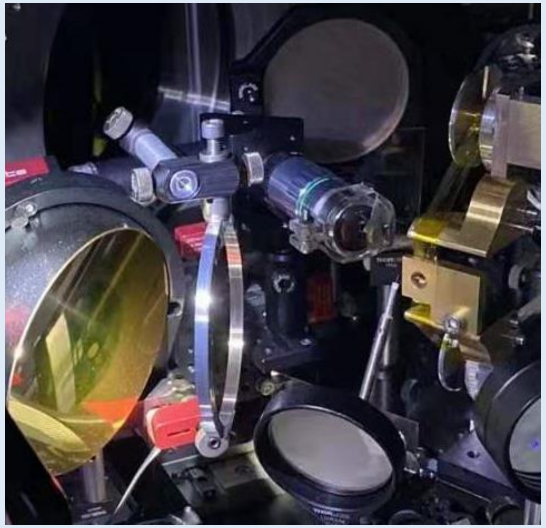
LhARA relevant lasers at Imperial College London

Cerberus laser (Prof. Roland Smith)

- Multibeam high energy, high power laser system
- Low energy high repetition (100 mJ at 10 Hz) or high energy low repetition (20 J at 0.001 Hz) , ~500 fs pulse length
- Regularly used as driver of laser proton source exceeding 5 MeV

Zhi laser (Prof. Zulfikar Najmudin)





- Newly commissioned high repetition rate system
- Up to 200 mJ at 100 Hz operation , ~40 fs pulse length
- Ready for application to ion generation with expected energies > 2 MeV

WP2 Technology Development Programme:

Underpinning technology development on WP2

Ion Source Parameters and Stability:

- **Particle**, Radiation and Laser Diagnostics
- Optimisation and Feedback

Continuous Operations:

- Debris Studies
- Activation Studies
- Advanced Targetry

- 10 Hz capable ion diagnostic system (spectral & spatial)
- Dedicated laser diagnostic platform with capability to feed back to shot control system

- Clear understanding of debris and activation problem for long term 10 Hz operation
- Mitigation via advanced targetry or shielding

Experiments & Technology Development in 2-year Programme: Characterising Source and Benchmarking Simulations

Established Diagnostics…

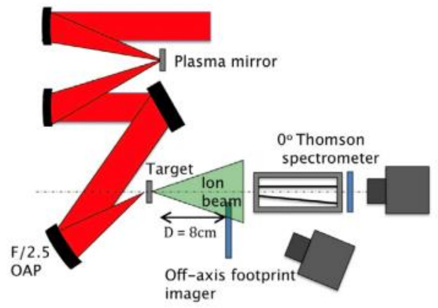
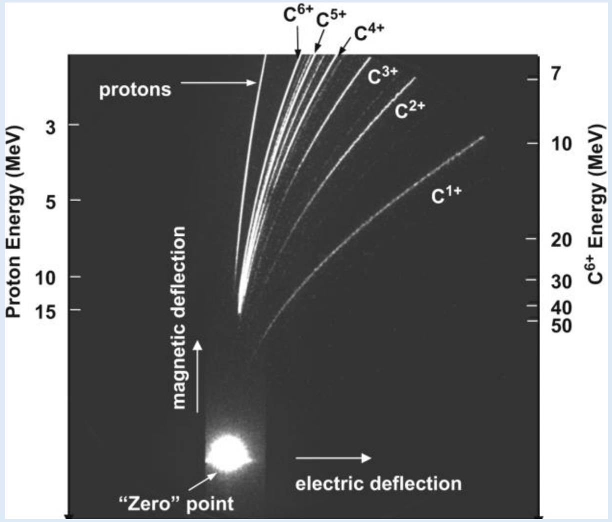


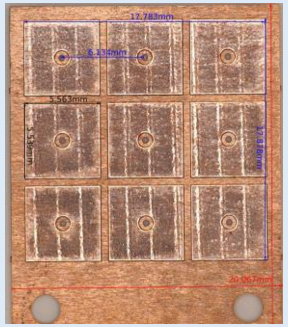
Figure 1. Experimental setup. A Thomson spectrometer deflects the ions onto a piece of plastic scintillator, which is imaged using an EMCCD camera. A second sheet of scintillator images the off-axis portion (>6° off-target normal) of the ion beam.

J.S Green *et al.,* NJP. 12 (2010) 085012

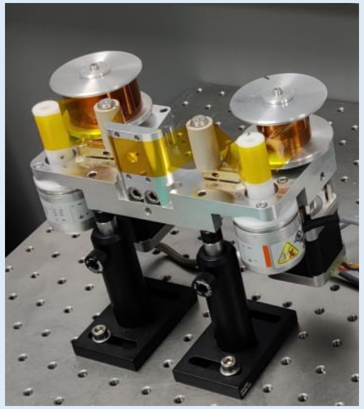


R. Prasad *et al.,* Nucl. Instrum. Methods. 623.2 (2010): 712-715.

Established Targetry…moving toward Hz-level targetry



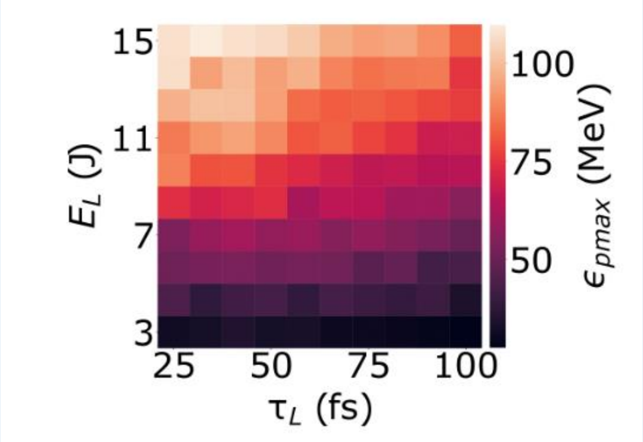
Typical 9-target array



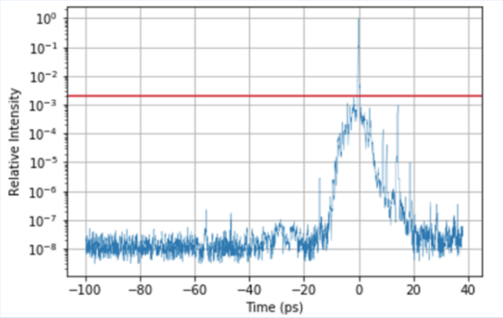
Tape targetry system (online in SCAPA 2022)

….to build a systematic parameter space map of the source performance

- Energy, Flux, Divergence across multiple ion species

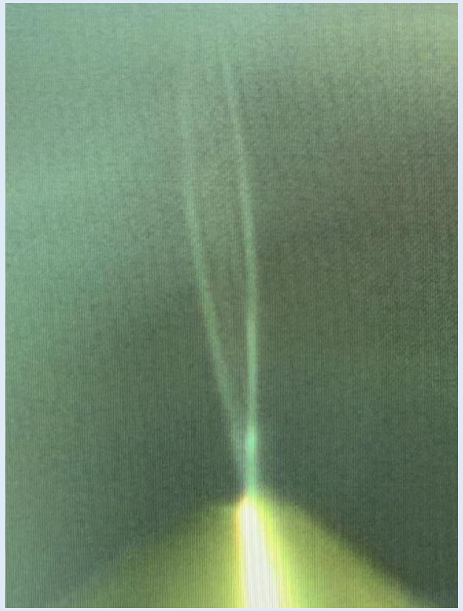


..but also need to consider some other experimental contributions like temporal contrast



Experiments & Technology Development in 3-year Programme: Producing a stable, high-rep source

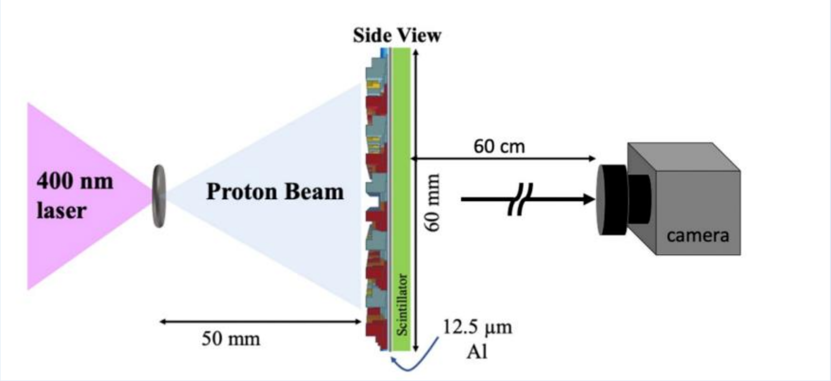
Novel Liquid Targetry



Courtesy of C. Palmer

- Reduces production of debris
- Increases operational time and possible rep rate

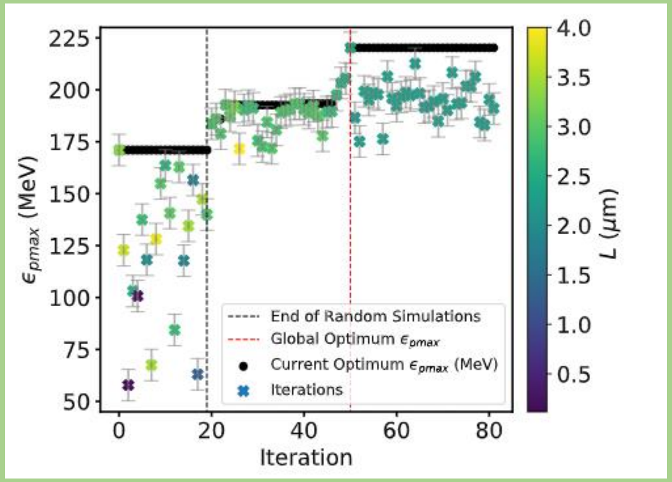
Advanced Particle & Laser Diagnostics



D. Marsical *et al.* , Plasma Phys. Control. Fusion 63 (2021) 114003

- Implementation of advanced (existing) particle diagnostics, taking account of long term operation.
- Implementation of full laser diagnostic suite to support automation, stabilisation.

ML/AI Control & Optimisation



- Application of ML techniques (e.g Bayesian Optimisation) for parameter space
- Application of AI techniques (DNNs, CNNs) for system control and virtual diagnostics

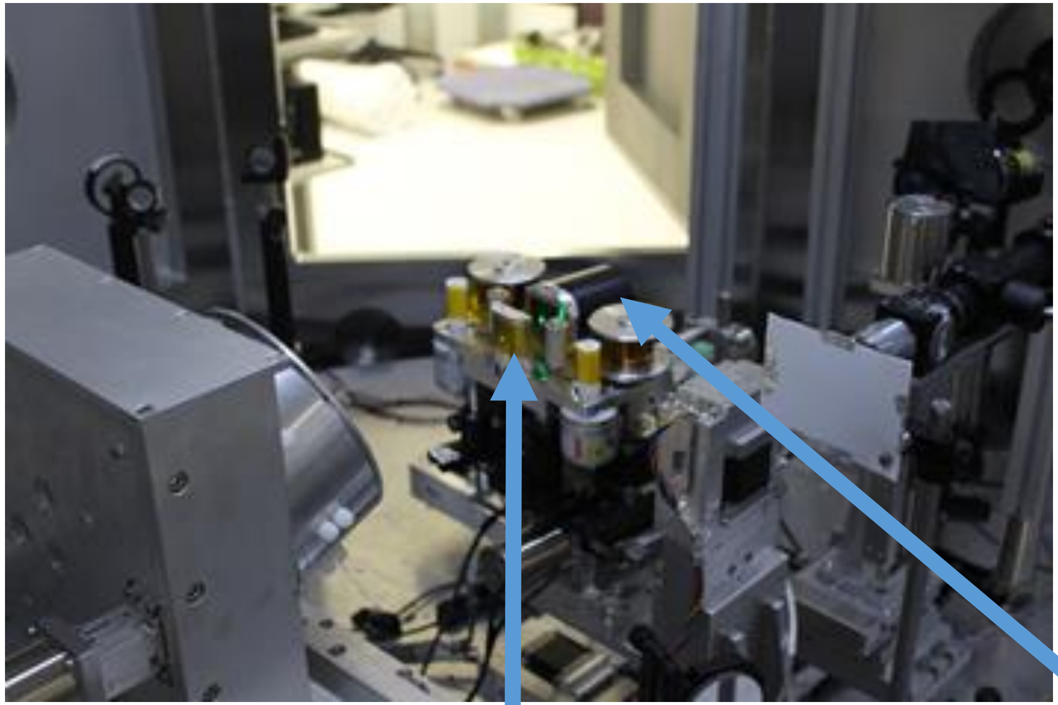
Recent results mean we can be optimistic about making progress in these areas!

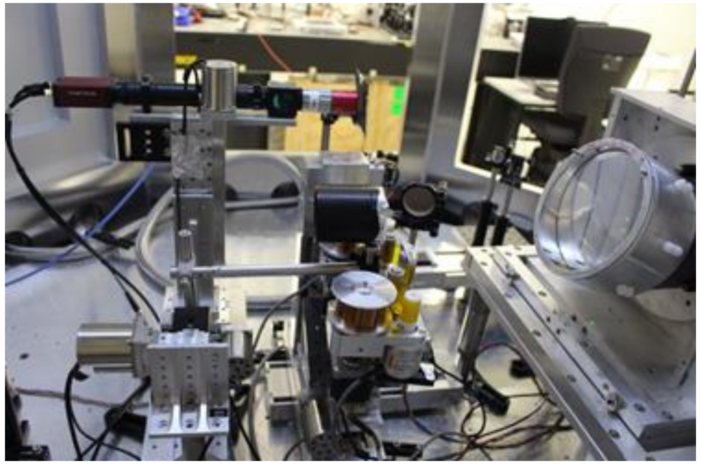
Update on SCAPA Bunker B

- First Bunker B commissioning experiment completed in September 2022
- Over 1000 laser shots taken in 3 weeks (in terms of shots taken that is equivalent to ~4x typical Gemini experiment)
- Tape drive target, online proton beam profiler, Thomson parabola spectrometer and laser absorption diagnostics all brought online
- Continuous repetition rate of ~0.1 Hz demonstrated but this is only limited by data transfer speeds and some manual data capture
- No evidence of debris issues so far!
- 1Hz operation within reach on the next beamtime

Update on SCAPA Bunker B

Laser-solid interaction beamline B1 in Bunker B.

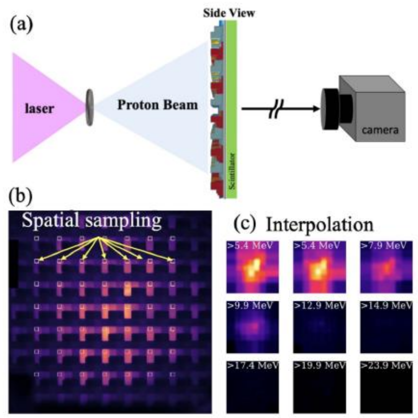




Tape drive target

Active proton detector

Update on SCAPA Bunker B – New detectors (Probies)

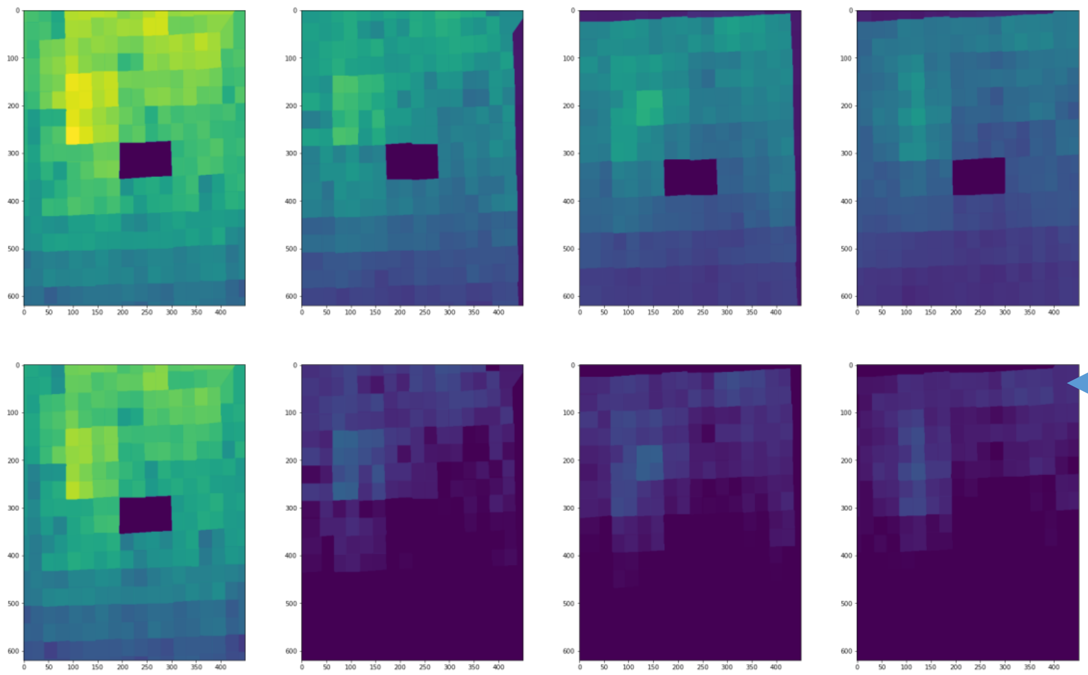


D.A. Mariscal *et al.* PPCF 2021

Probies is a high repetition rate pixelated spatial-spectral proton detector

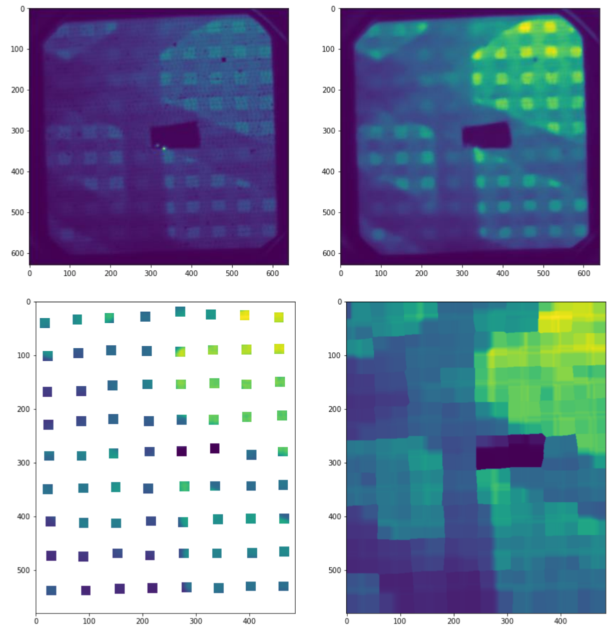
Progress to date:

- 3D printed prototyping, using 4 energy bins and 81 spatial points
- Only expecting to observe protons up to 4 MeV, illuminating only the lowest bin (0.9 MeV)
- Reconstruction of a spatial profile

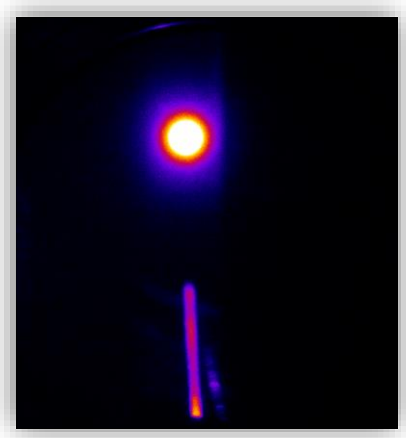


Test deconvolution with (bottom) and without (top) mean background subtraction. Bins of 0.9, 6.9, 8.9, 10.9 MeV

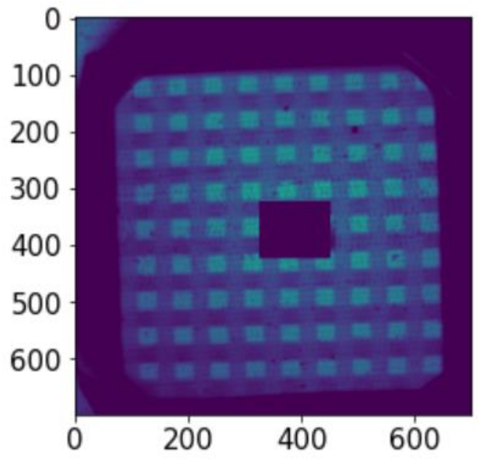
Spatial reconstruction test



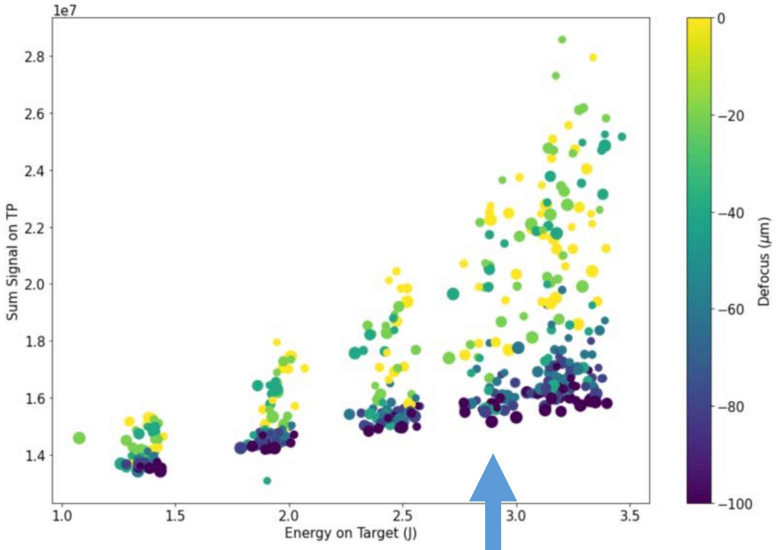
Update on SCAPA Bunker B – Early Results

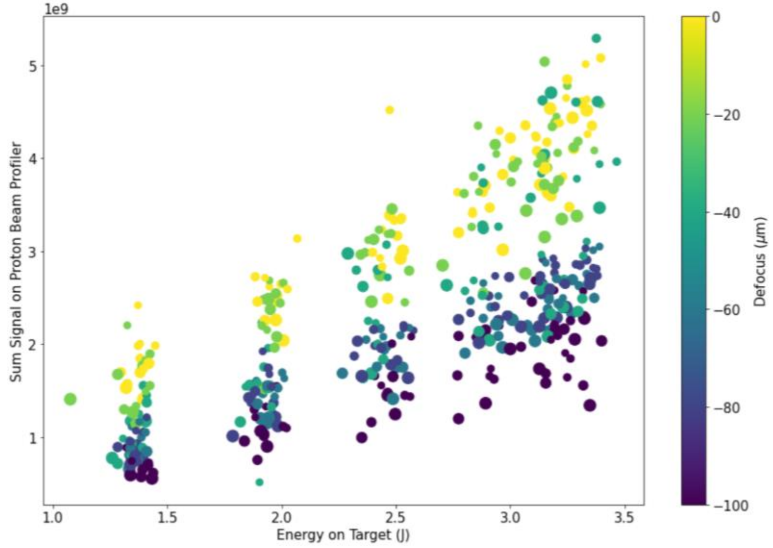


Active TP Spectrometer

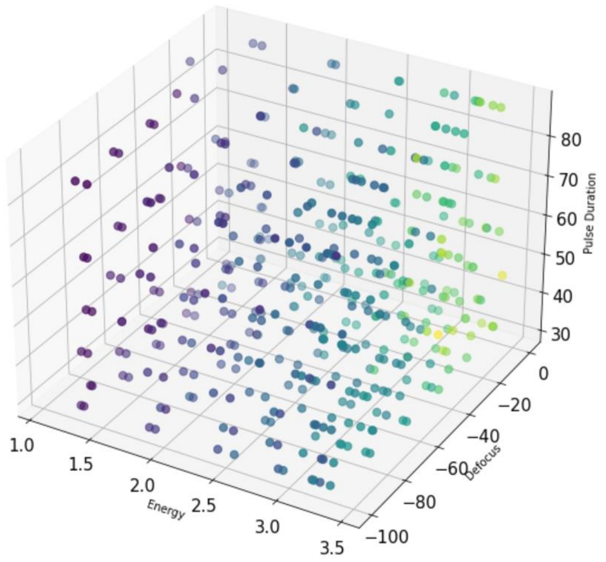


Active Proton Beam Profiler



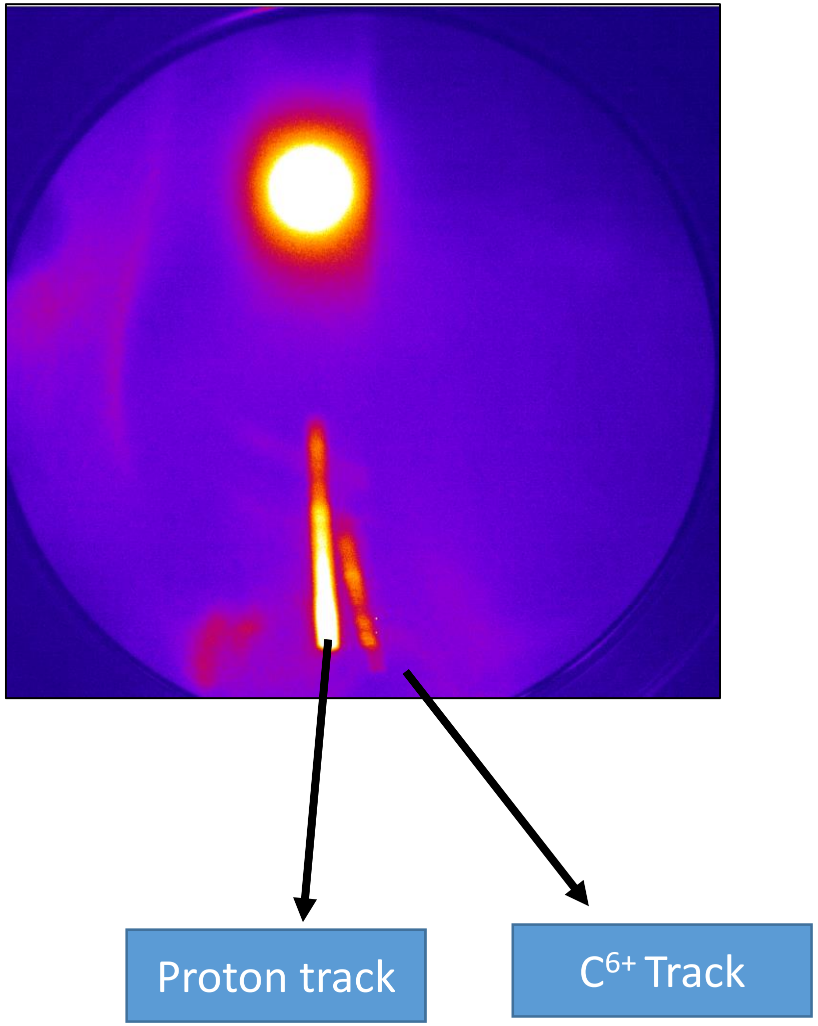


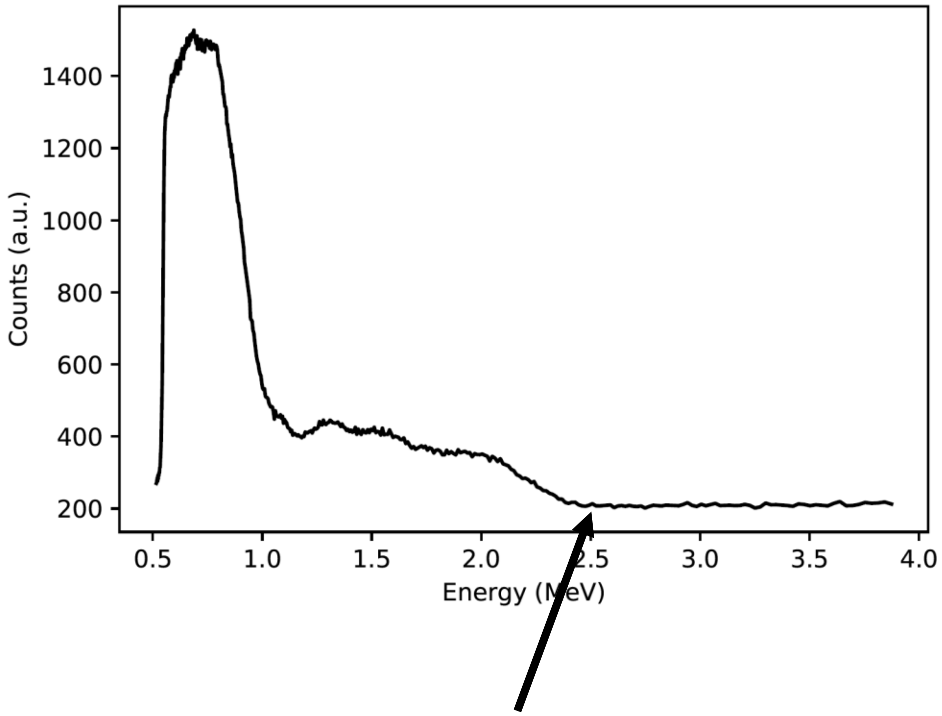
- 3D parameter space scan of pulse duration, laser energy and defocus measuring total proton energy
- ~450 shots taken over 4 hour period



Update on SCAPA Bunker B – Early Results

Thomson Parabola Spectrometer





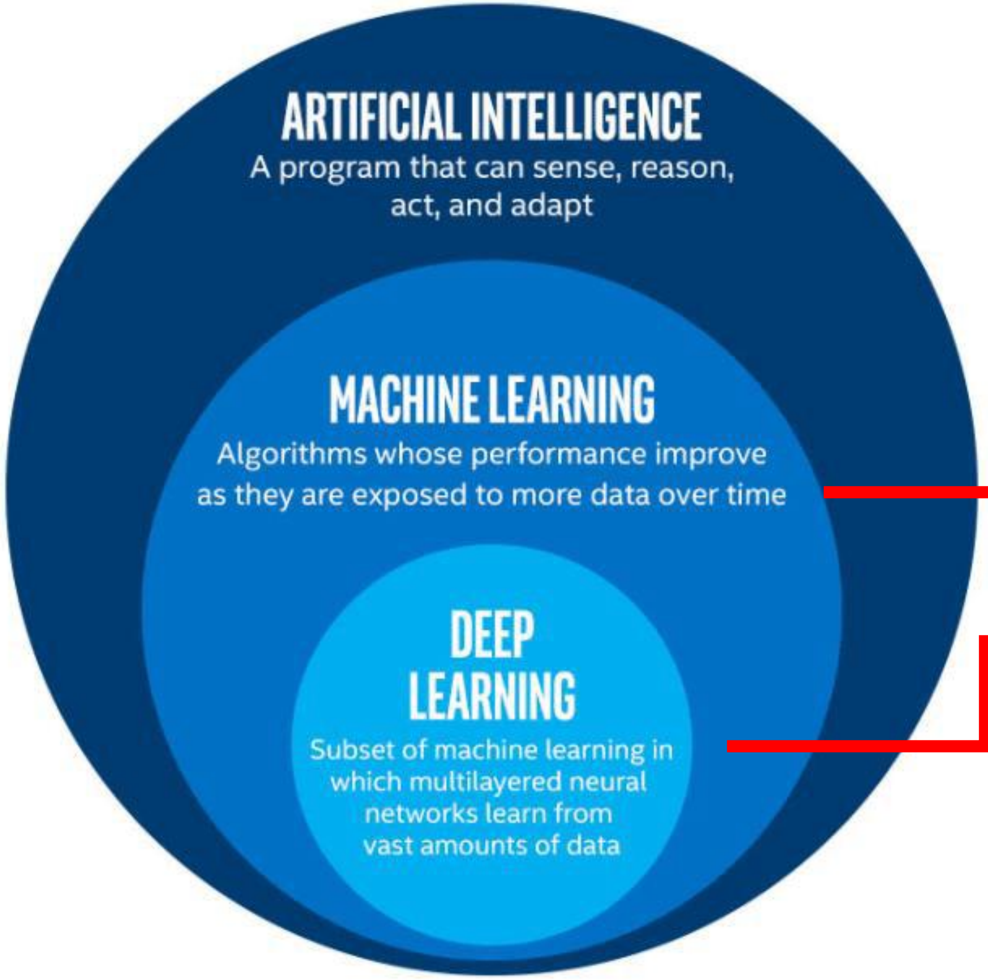
Proton energy cutoff is only ~2.5 MeV but next experiment will significantly increase laser energy and we will be able to use thinner targets

Update on SCAPA Bunker B – Next Steps

- Increase in on target laser energy by addition of second amplifier – up to 8.5 J on target (2.6x higher)
- Tests with thinner tape targets
- Absolute calibration of ion diagnostics
- Increase of repetition rate by improving laser data capture and data transfer rate
- Addition of optical probe diagnostic (plasma scale length measurements on shot)
- Introduction of direct feedback and ML/AI optimisation and control…

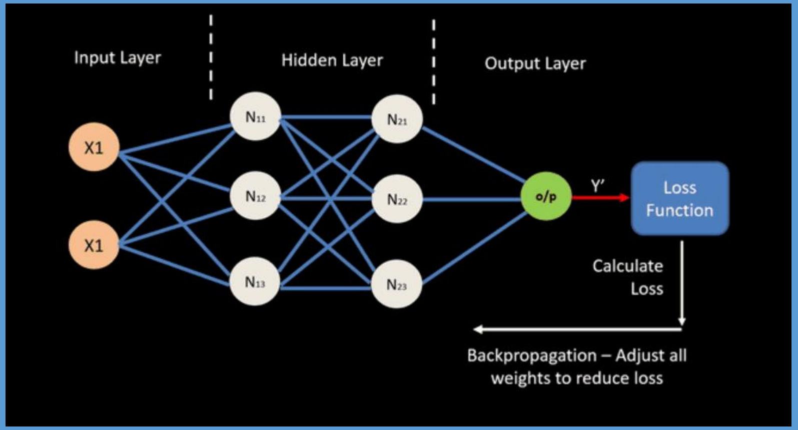
Machine Learning & Deep Learning for Laser-Plasma Science:

What is Machine Learning?



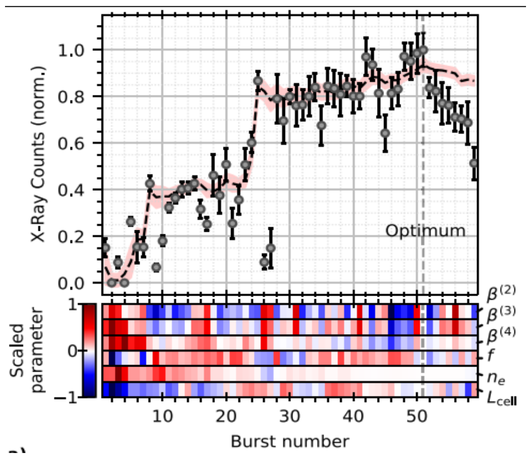
Many different data driven ML algorithms but three main branches

- **Unsupervised leaning:** Clustering, k-means, principal component analysis, SVD etc.
- **Supervised Learning:** Classification, Random Forest, Naïve Bayes, Logistic Regression, Linear/non-linear regression etc.
- **Reinforcement Learning:** a machine learning training method based on rewarding desired behaviours and/or punishing undesired ones. Can involve aspects of supervised and unsupervised learning



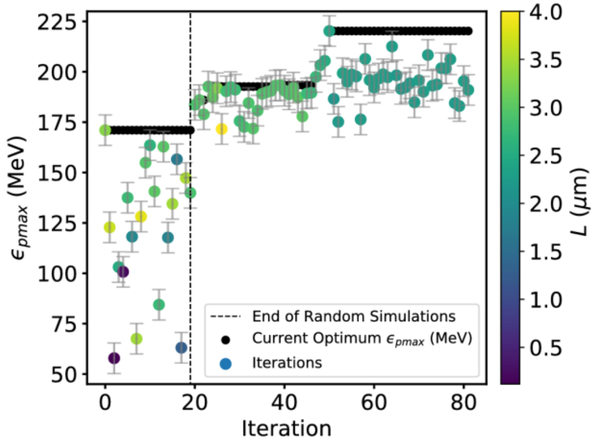
Machine Learning & Deep Learning for Laser-Plasma Science:

There have been a number of recent results in ML laser-plasma science



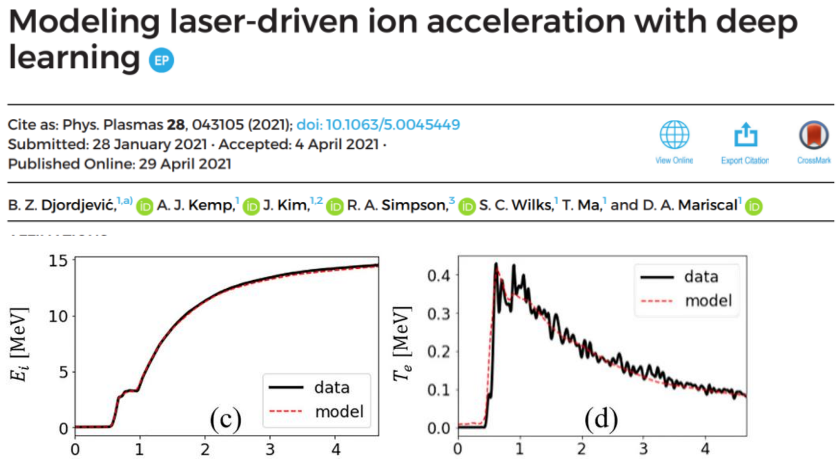
R.J Shaloo et al. Nature Communications **11**, 6355 (2020)

Bayesian Optimisation using Gaussian processes in experiments

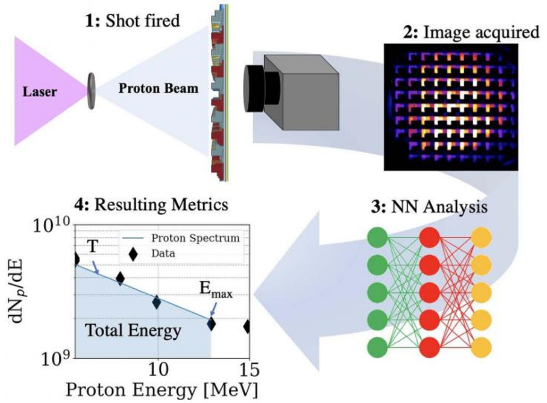


E.J Dolier et al., New J. Phys. 24 073025 (2022)

….and simulations



B. Djordjevic et al., Physics of Plasmas 28, 043105 (2021)



D.A Mariscal *et al.,* Plasma Phys. Control. Fusion 63 114003 (2021)

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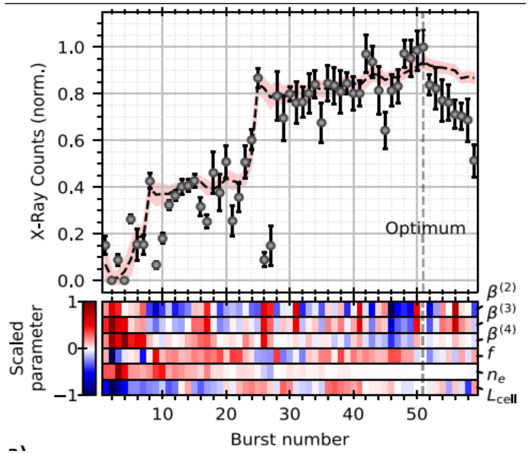

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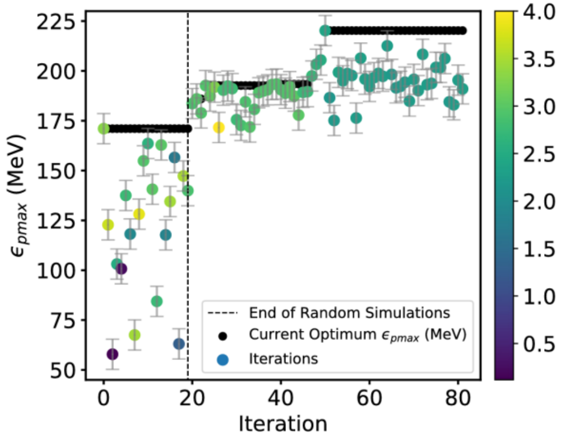
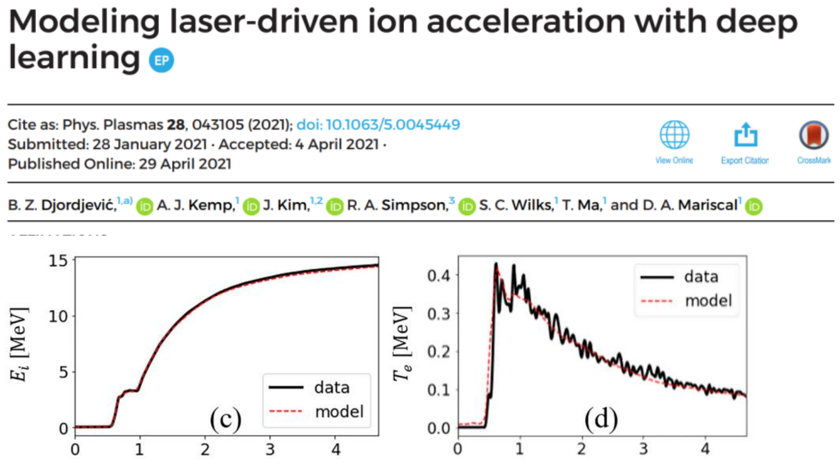


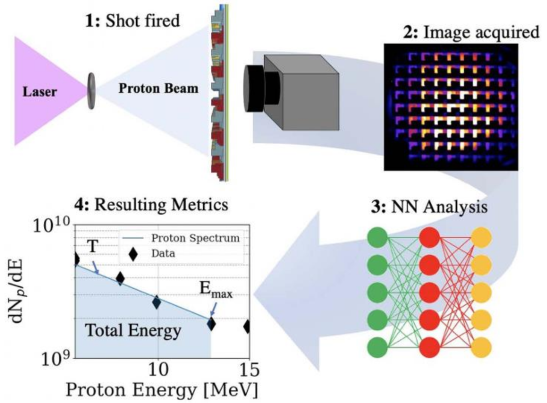
E.J Dolier et al., New J. Phys. 24 073025 (2022)

Deep neural networks trained on simulation data



B. Djordjevic et al., Physics of Plasmas 28, 043105 (2021)

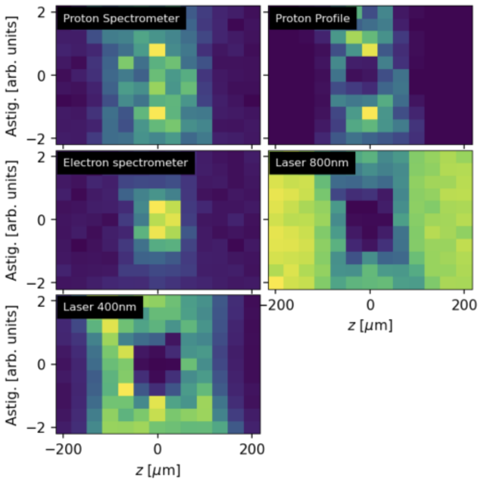
Deep neural networks for diagnostic analysis

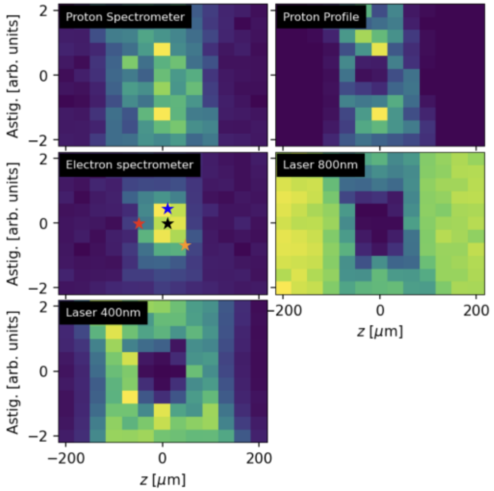


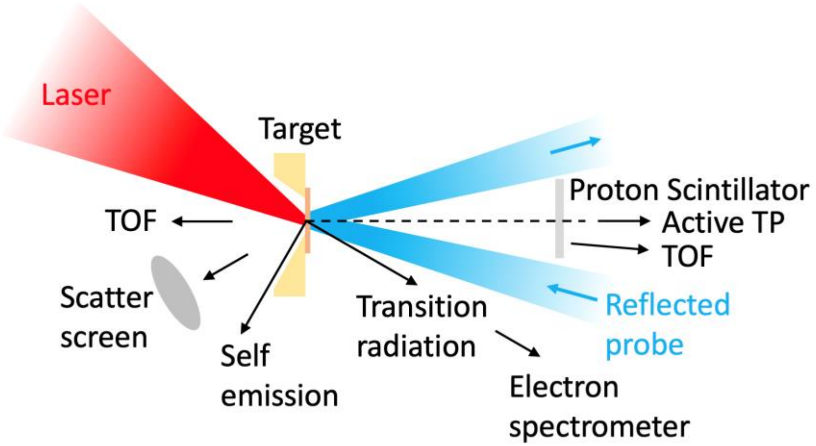
D.A Mariscal *et al.,* Plasma Phys. Control. Fusion 63 114003 (2021)

2D parameter maps with 15 shots per pixel with or without the stars to link to the optimisations.

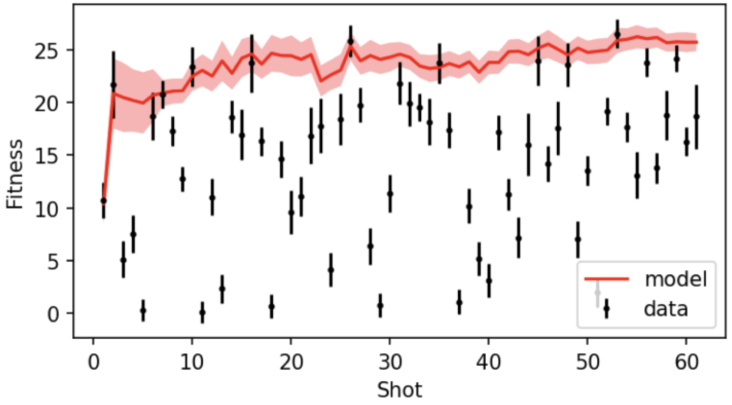
Courtesy of C. Palmer, QUB

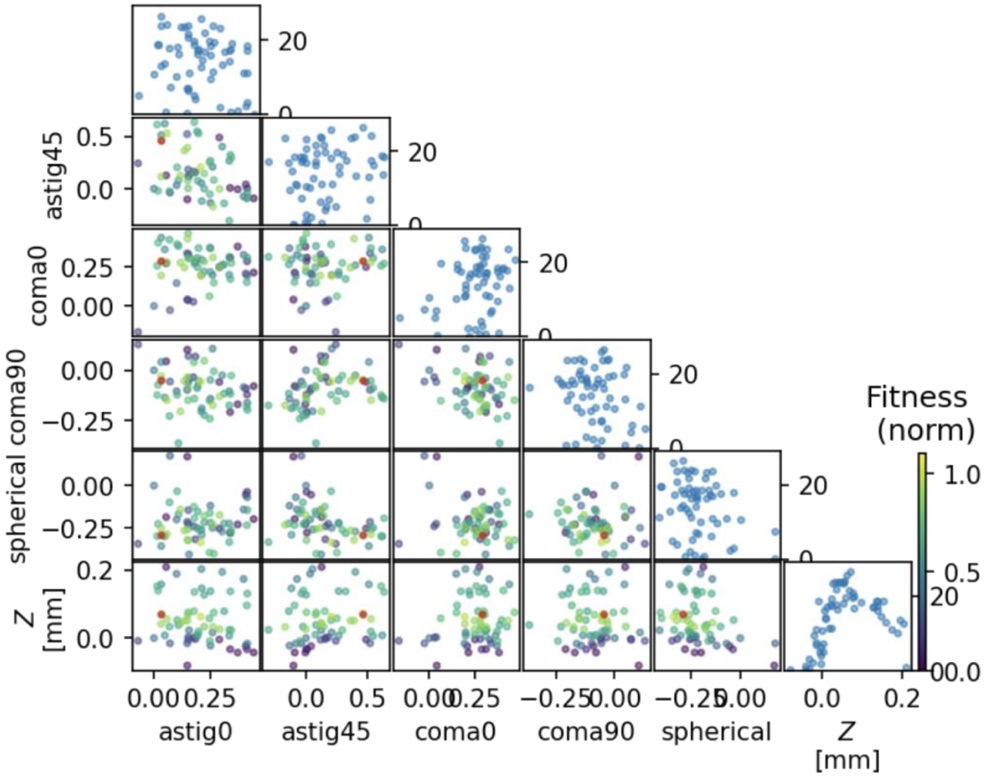




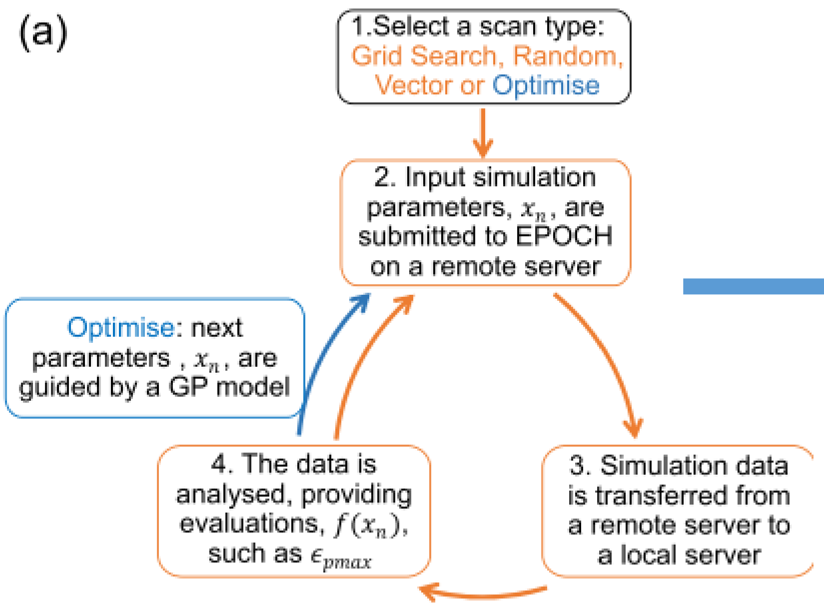


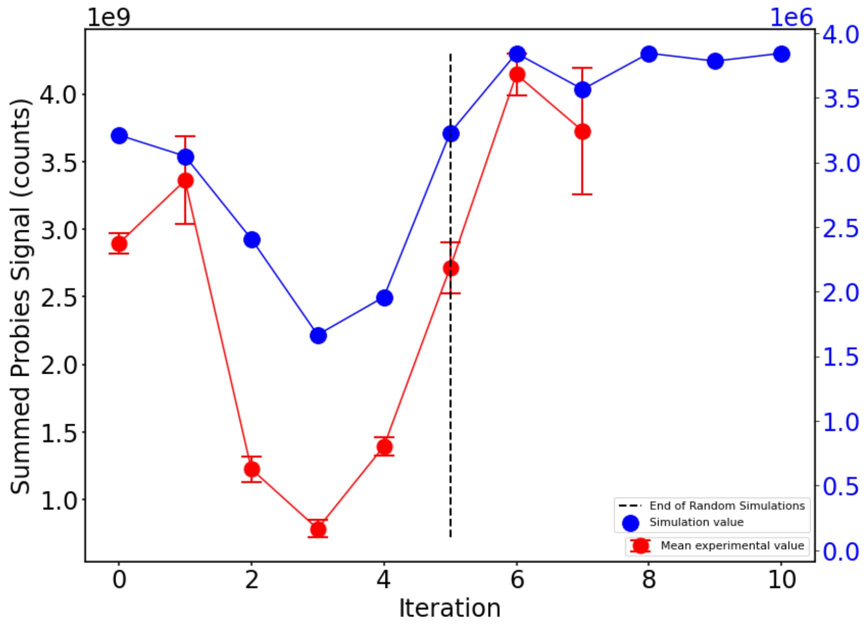
Optimisation of proton maximum energy using ToF readout and adjusting AO





Update on SCAPA Bunker B – Experimental control via Bayesian optimisation of PIC simulations





Gives us the ability to simulate the entire ‘possible’ parameter space and focus our experimental efforts in the optimal places for LhARA…

Summary

- Laser-Ion acceleration driven by the TNSA mechanism is now well established and key underpinning physics is well understood

- Our 2-year programme will use lasers at Imperial College and Stathclyde to demonstrate and benchmark an ion source within LhARA constraints, as well as simulations to support understanding and optimisation

- A 3-year programme will aim to implement an actively stabilised ion source within constraints that can operate at Hz-level for hour long periods by making use of advanced targetry, ML/AI and diagnostics.

- First beamtime on SCAPA has demonstrated a number of key concepts on diagnostics, targets and control but there is a way to go in order to meet the source requirements for LhARA

- Looking towards March 2023 for our first LhARA beamtime on SCAPA

University of Strathclyde Glasgow