Developments in laser-driven ion acceleration relevant to nuclear physics with lasers

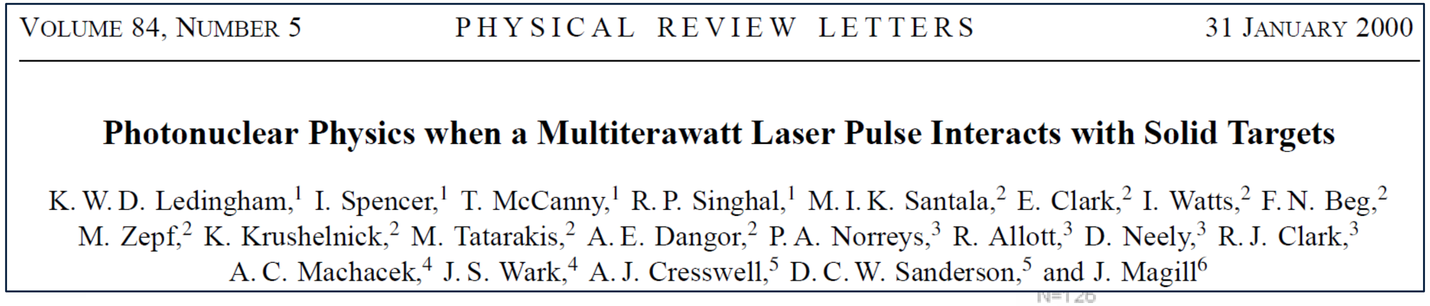
Paul McKenna

University of Strathclyde, Scotland, UK

Talk overview:

1. Early studies on nuclear activation using laser-accelerated ions and challenges emerging
2. Opportunities for enhancing ion acceleration in expanding ultrathin foils
3. Challenges at ultrahigh intensities: Importance of spatial- and temporal-intensity contrast, and high field phenomena
4. Opportunities for application of machine learning techniques: Bayesian Optimisation and neural network-based approaches
5. New high repetition rate experiment platform at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)

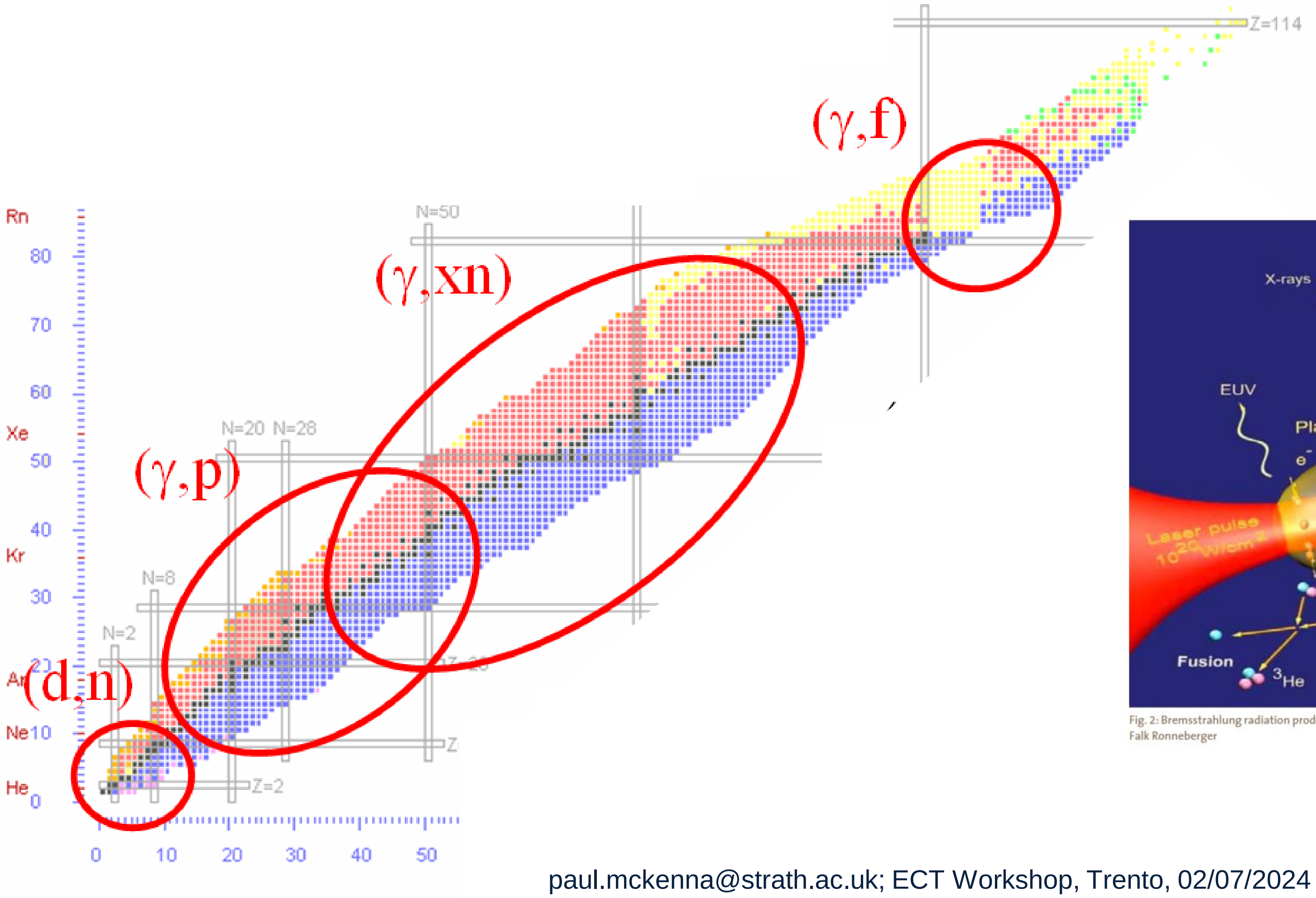
Early experiments on laser-driven nuclear physics



VOLUME 84, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 2000

Photonuclear Physics when a Multiterawatt Laser Pulse Interacts with Solid Targets

K. W. D. Ledingham,[1] I. Spencer,[1] T. McCanny,[1] R. P. Singhal,[1] M. I. K. Santala,[2] E. Clark,[2] I. Watts,[2] F. N. Beg,[2] M. Zepf,[2] K. Krushelnick,[2] M. Tatarakis,[2] A. E. Dangor,[2] P. A. Norreys,[3] R. Allott,[3] D. Neely,[3] R. J. Clark,[3] A. C. Machacek,[4] J. S. Wark,[4] A. J. Cresswell,[5] D. C. W. Sanderson,[5] and J. Magill[6]



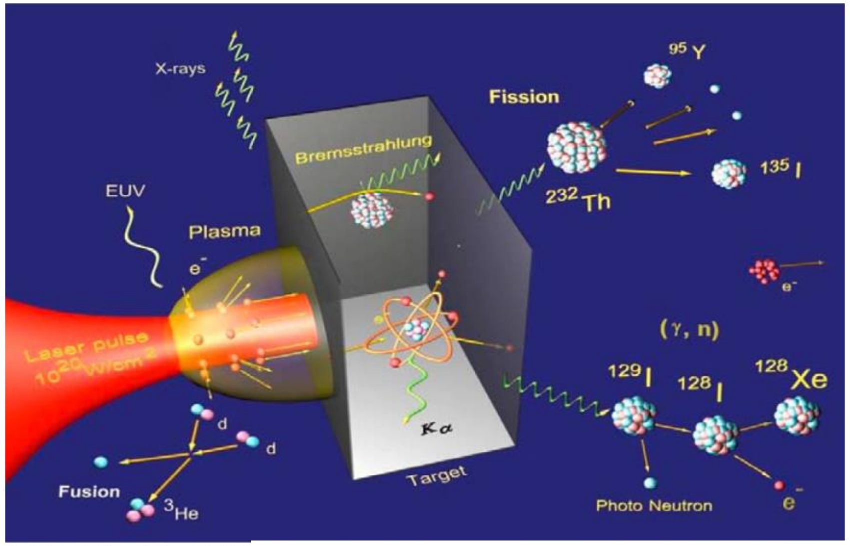
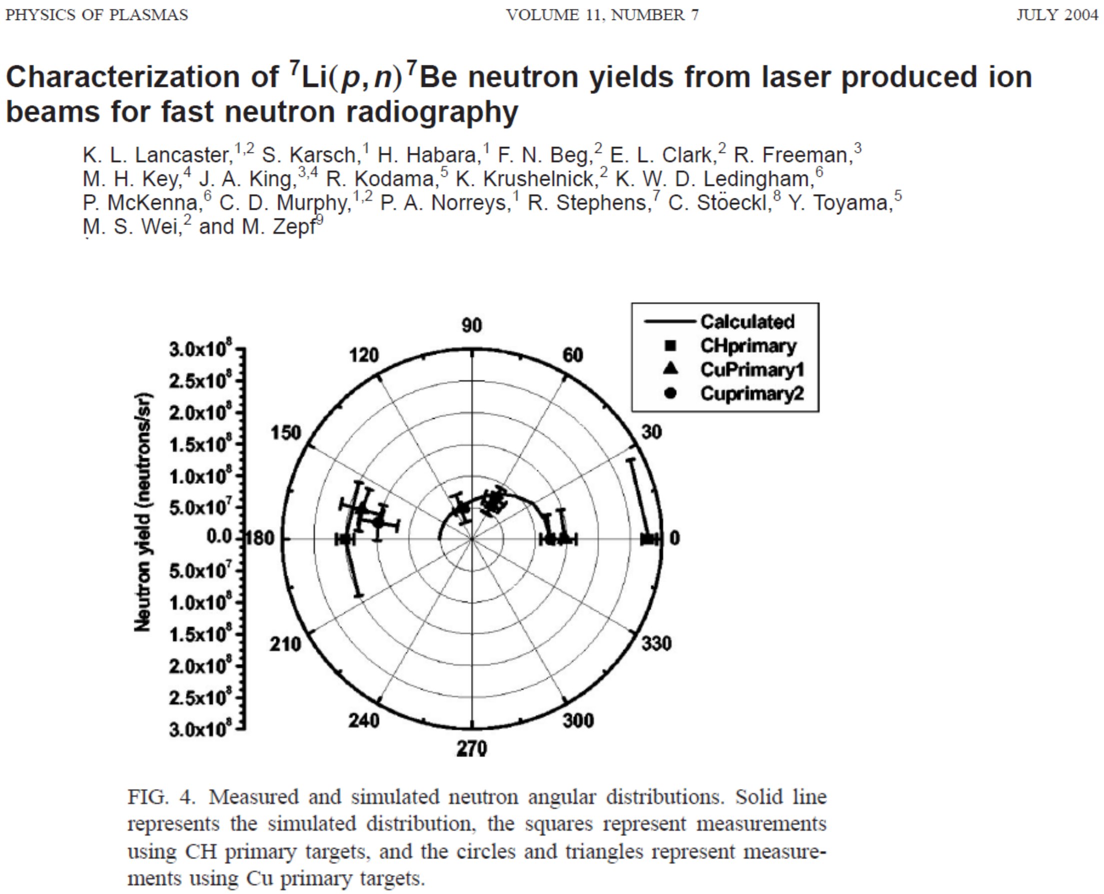


Fig. 2: Bremsstrahlung radiation production
Falk Ronneberger

Courtesy: IOQ Jena, Falk Ronneberger

Example 1: Laser-accelerated protons as a driver for fast neutron generation

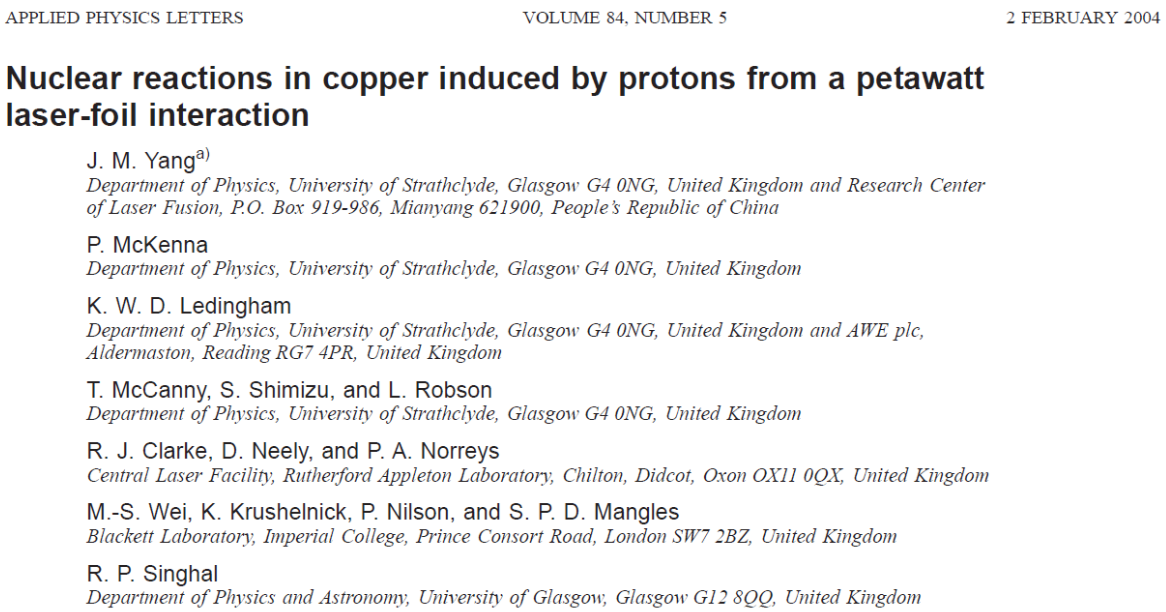


PHYSICS OF PLASMAS VOLUME 11, NUMBER 7 JULY 2004

Characterization of $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ neutron yields from laser produced ion beams for fast neutron radiography

K. L. Lancaster,[1,2] S. Karsch,[1] H. Habara,[1] F. N. Beg,[2] E. L. Clark,[2] R. Freeman,[3]
M. H. Key,[4] J. A. King,[3,4] R. Kodama,[5] K. Krushelnick,[2] K. W. D. Ledingham,[6]
P. McKenna,[6] C. D. Murphy,[1,2] P. A. Norreys,[1] R. Stephens,[7] C. Stöeckl,[8] Y. Toyama,[5]
M. S. Wei,[2] and M. Zepf[9]

FIG. 4. Measured and simulated neutron angular distributions. Solid line represents the simulated distribution, the squares represent measurements using CH primary targets, and the circles and triangles represent measurements using Cu primary targets.



APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 5 2 FEBRUARY 2004

Nuclear reactions in copper induced by protons from a petawatt laser-foil interaction

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R. J. Clarke, D. Neely, and P. A. Norreys
Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom

M.-S. Wei, K. Krushelnick, P. Nilson, and S. P. D. Mangles
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R. P. Singhal
Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom

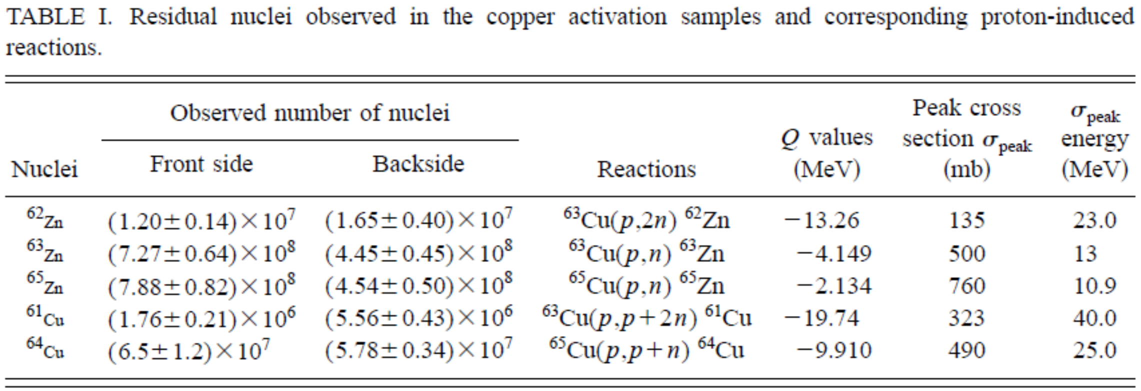
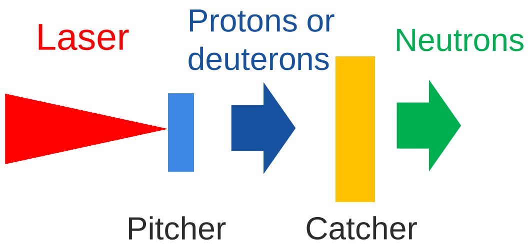


TABLE I. Residual nuclei observed in the copper activation samples and corresponding proton-induced reactions.

	Observed number of nuclei					
Nuclei	Front side	Backside	Reactions	Q values (MeV)	Peak cross section σ_{peak} (mb)	σ_{peak} energy (MeV)
^{62}Zn	$(1.20\pm0.14)\times10^{7}$	$(1.65\pm0.40)\times10^{7}$	$^{63}\mathrm{Cu}(p,2n)\,^{62}\mathrm{Zn}$	−13.26	135	23.0
^{63}Zn	$(7.27\pm0.64)\times10^{8}$	$(4.45\pm0.45)\times10^{8}$	$^{63}\mathrm{Cu}(p,n)\,^{63}\mathrm{Zn}$	−4.149	500	13
^{65}Zn	$(7.88\pm0.82)\times10^{8}$	$(4.54\pm0.50)\times10^{8}$	$^{65}\mathrm{Cu}(p,n)\,^{65}\mathrm{Zn}$	−2.134	760	10.9
^{61}Cu	$(1.76\pm0.21)\times10^{6}$	$(5.56\pm0.43)\times10^{6}$	$^{63}\mathrm{Cu}(p,p+2n)\,^{61}\mathrm{Cu}$	−19.74	323	40.0
^{64}Cu	$(6.5\pm1.2)\times10^{7}$	$(5.78\pm0.34)\times10^{7}$	$^{65}\mathrm{Cu}(p,p+n)\,^{64}\mathrm{Cu}$	−9.910	490	25.0



Laser

Protons or deuterons

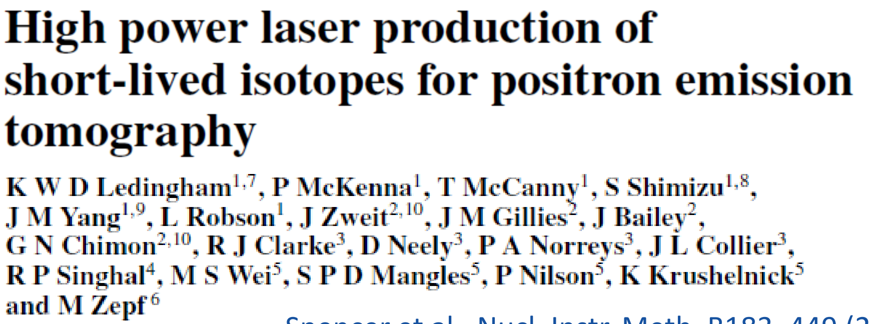
Neutrons

Pitcher

Catcher

Need higher repetition rate to produce a usable source of neutrons

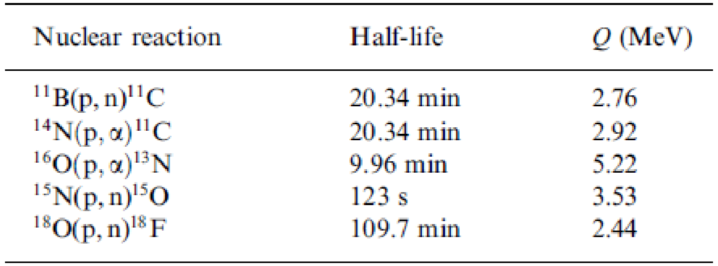
Example 2: PET isotope generation with laser-accelerated protons



High power laser production of short-lived isotopes for positron emission tomography

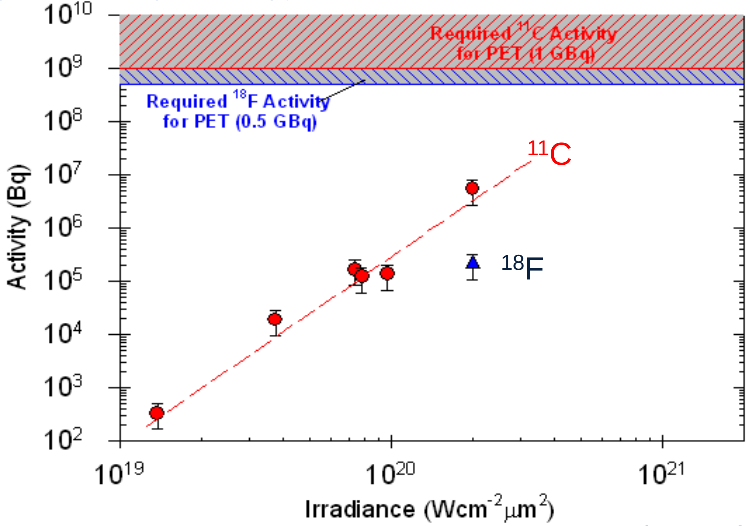
K W D Ledingham[1,7], P McKenna[1], T McCanny[1], S Shimizu[1,8], J M Yang[1,9], L Robson[1], J Zweit[2,10], J M Gillies[2], J Bailey[2], G N Chimon[2,10], R J Clarke[3], D Neely[3], P A Norreys[3], J L Collier[3], R P Singhal[4], M S Wei[5], S P D Mangles[5], P Nilson[5], K Krushelnick[5] and M Zepf[6]

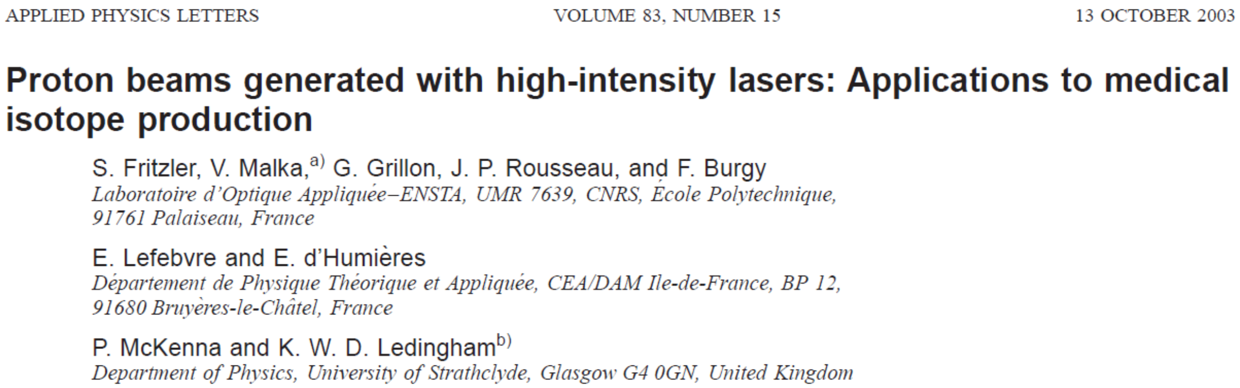
Spencer et al., Nucl. Instr. Meth. B183, 449 (2001)
Ledingham et al., J. Phys. D., 37, 2341 (2004)



Nuclear reaction	Half-life	Q (MeV)
^{11}B(p, n)^{11}C	20.34 min	2.76
^{14}N(p, α)^{11}C	20.34 min	2.92
^{16}O(p, α)^{13}N	9.96 min	5.22
^{15}N(p, n)^{15}O	123 s	3.53
^{18}O(p, n)^{18}F	109.7 min	2.44

Single shot high energy laser (Vulcan):





APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 15 13 OCTOBER 2003

Proton beams generated with high-intensity lasers: Applications to medical isotope production

S. Fritzler, V. Malka,[a)] G. Grillon, J. P. Rousseau, and F. Burgy
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E. Lefebvre and E. d'Humières
Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, BP 12, 91680 Bruyères-le-Châtel, France

P. McKenna and K. W. D. Ledingham[b)]
Department of Physics, University of Strathclyde, Glasgow G4 0GN, United Kingdom

Projections for high repetition rate (Ti:Sapphire) lasers:

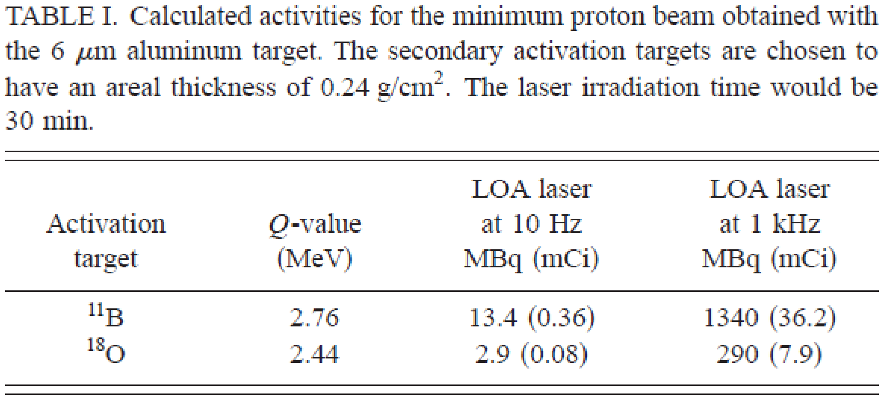
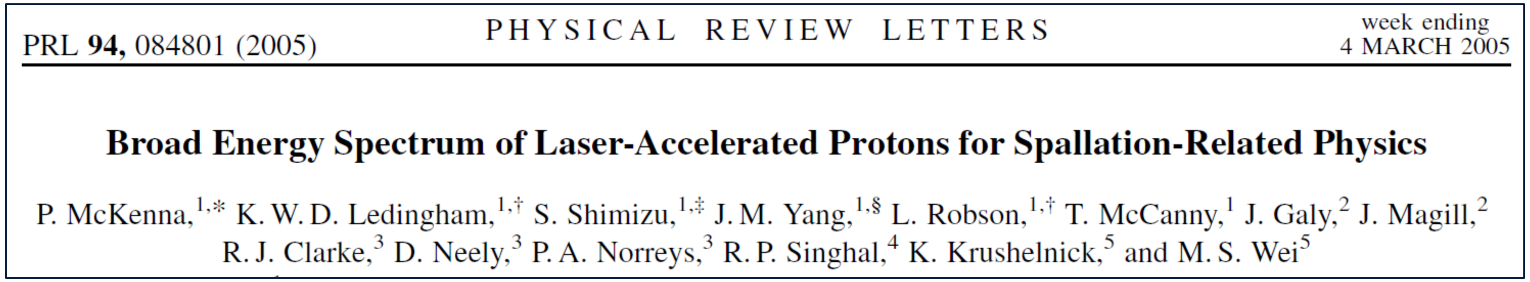


TABLE I. Calculated activities for the minimum proton beam obtained with the 6 μm aluminum target. The secondary activation targets are chosen to have an areal thickness of 0.24 g/cm^2. The laser irradiation time would be 30 min.

Activation target	Q-value (MeV)	LOA laser at 10 Hz MBq (mCi)	LOA laser at 1 kHz MBq (mCi)
^{11}B	2.76	13.4 (0.36)	1340 (36.2)
^{18}O	2.44	2.9 (0.08)	290 (7.9)

The need for high repetition rate was evident!

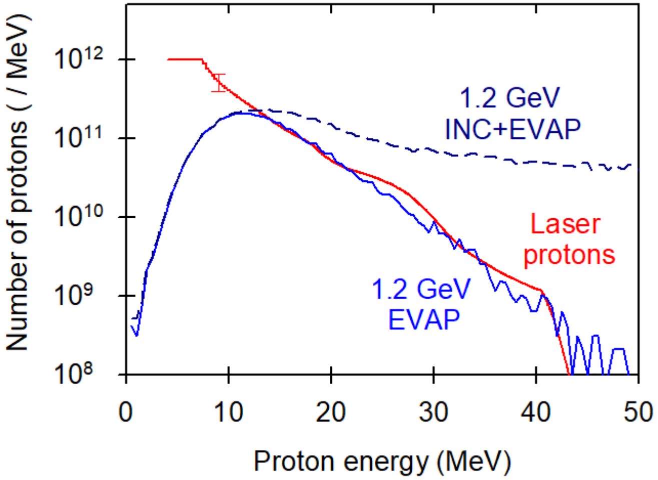
Example 4: Using unique features of laser-accelerated ions

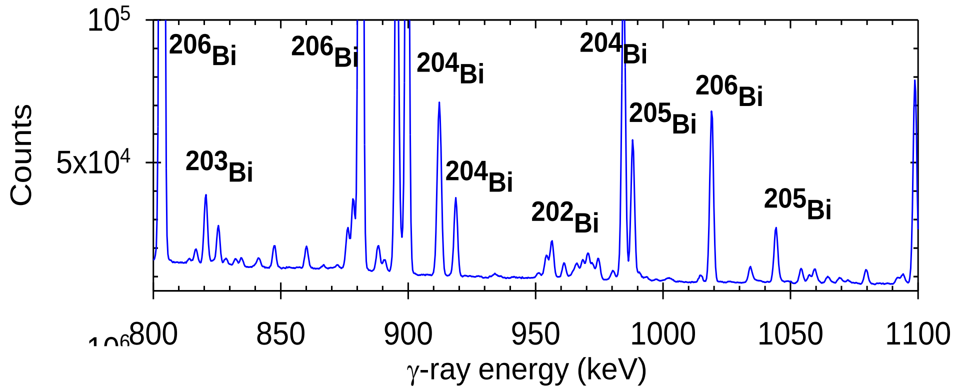


PRL **94,** 084801 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Broad Energy Spectrum of Laser-Accelerated Protons for Spallation-Related Physics

P. McKenna,[1,*] K. W. D. Ledingham,[1,†] S. Shimizu,[1,‡] J. M. Yang,[1,§] L. Robson,[1,†] T. McCanny,[1] J. Galy,[2] J. Magill,[2] R. J. Clarke,[3] D. Neely,[3] P. A. Norreys,[3] R. P. Singhal,[4] K. Krushelnick,[5] and M. S. Wei[5]





Testing the output of nuclear codes?

Talk overview:

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2. Opportunities for enhancing ion acceleration in expanding ultrathin foils
3. Challenges at ultrahigh intensities: Importance of spatial- and temporal-intensity contrast, and high field phenomena
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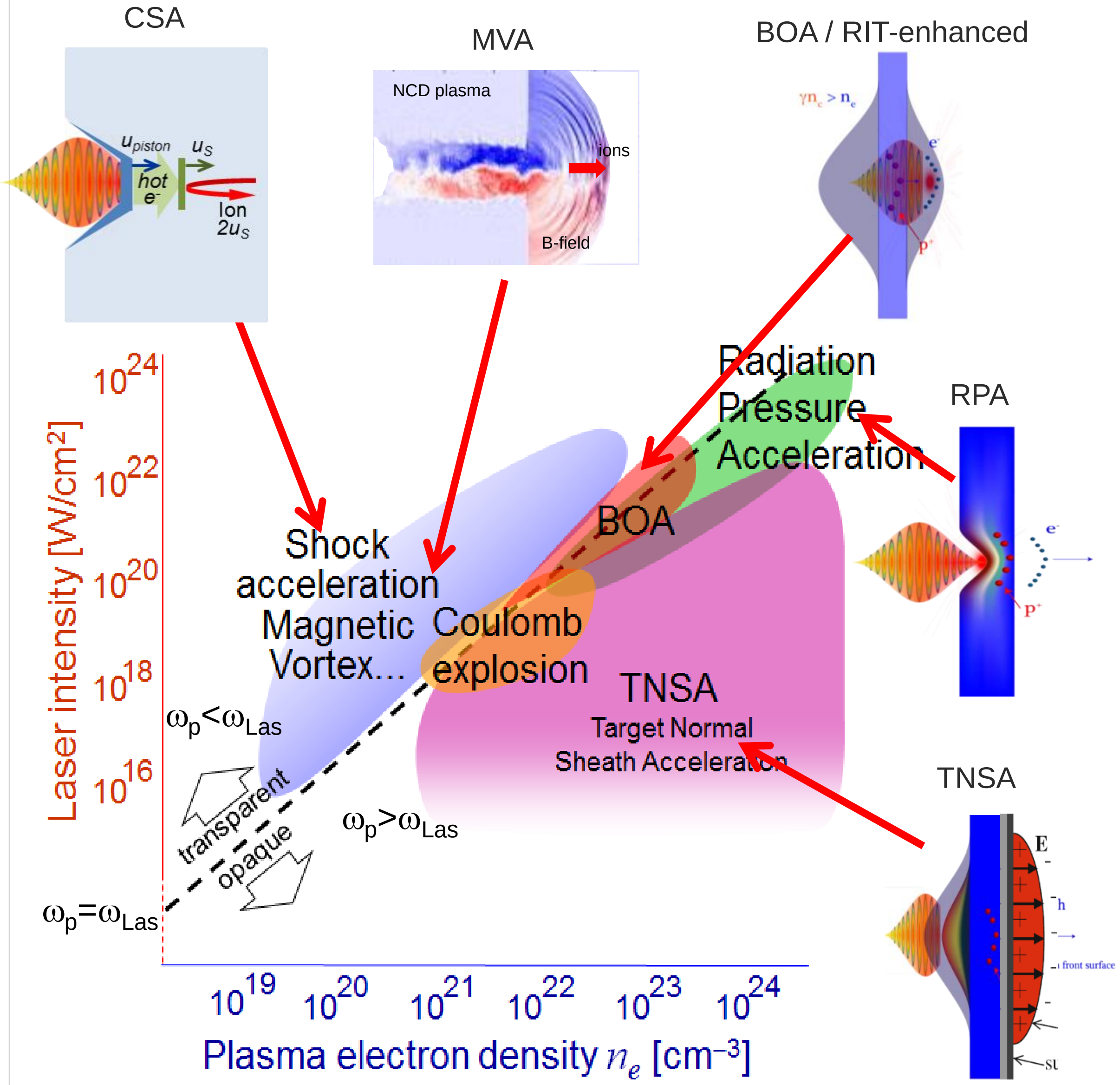
5. New high repetition rate experiment platform at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)

Conclusions, opportunities and challenges:

- Proof-of-concept experiments on nuclear activation, but higher repetition rates needed.

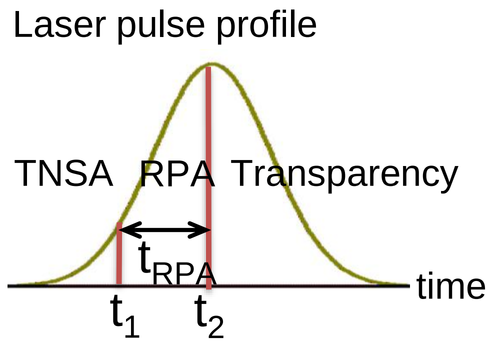
Laser-driven ion acceleration schemes

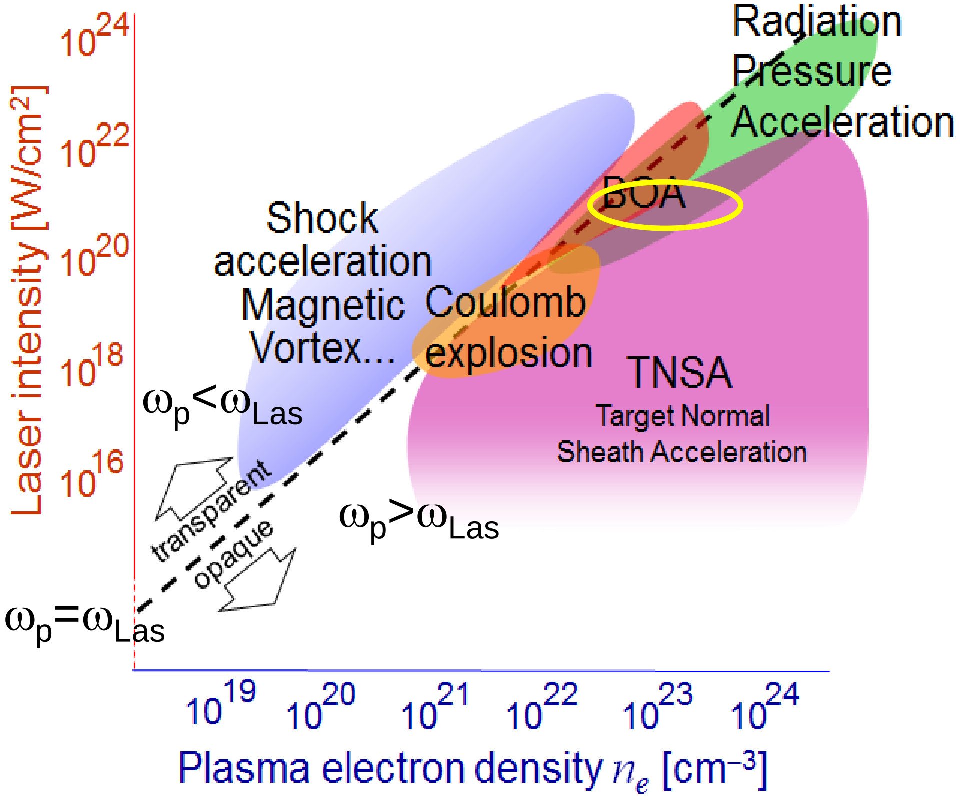


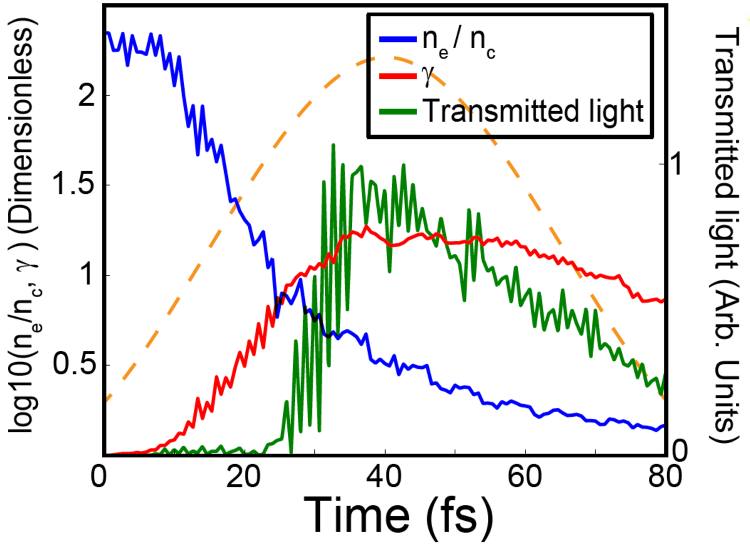
paul.mckenna@strath.ac.uk; ECT Workshop, Trento, 02/07/2024

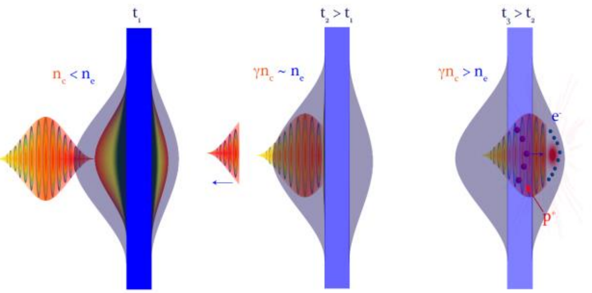
Transparency-enhanced hybrid RPA-TNSA

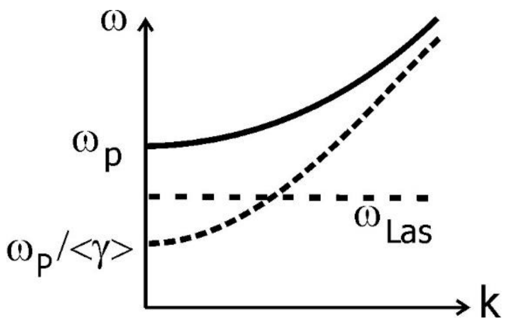
- Ultrathin foils (≪1 μm)
- Target expands and electrons are relativistically heated, when $n_e < \gamma_e n_c$ laser begins to propagate through target
- Laser couples energy to electrons within target volume





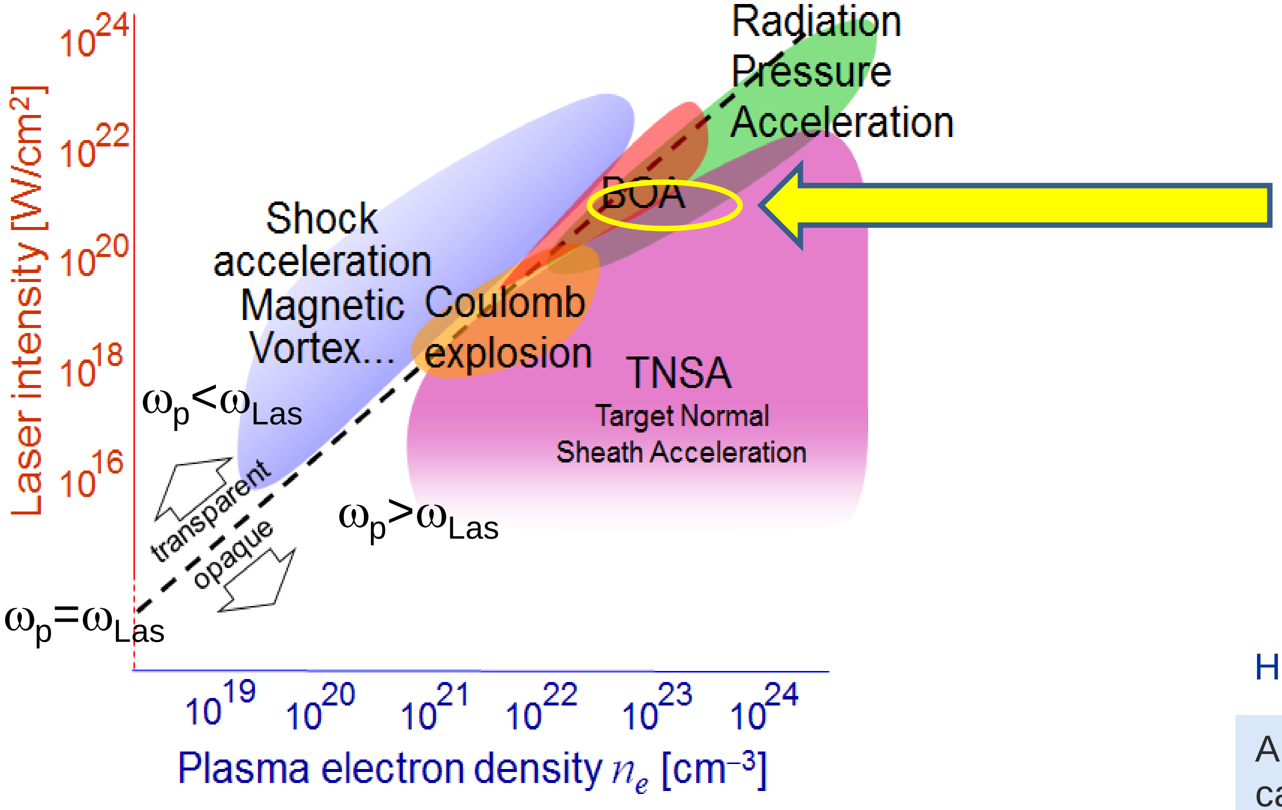


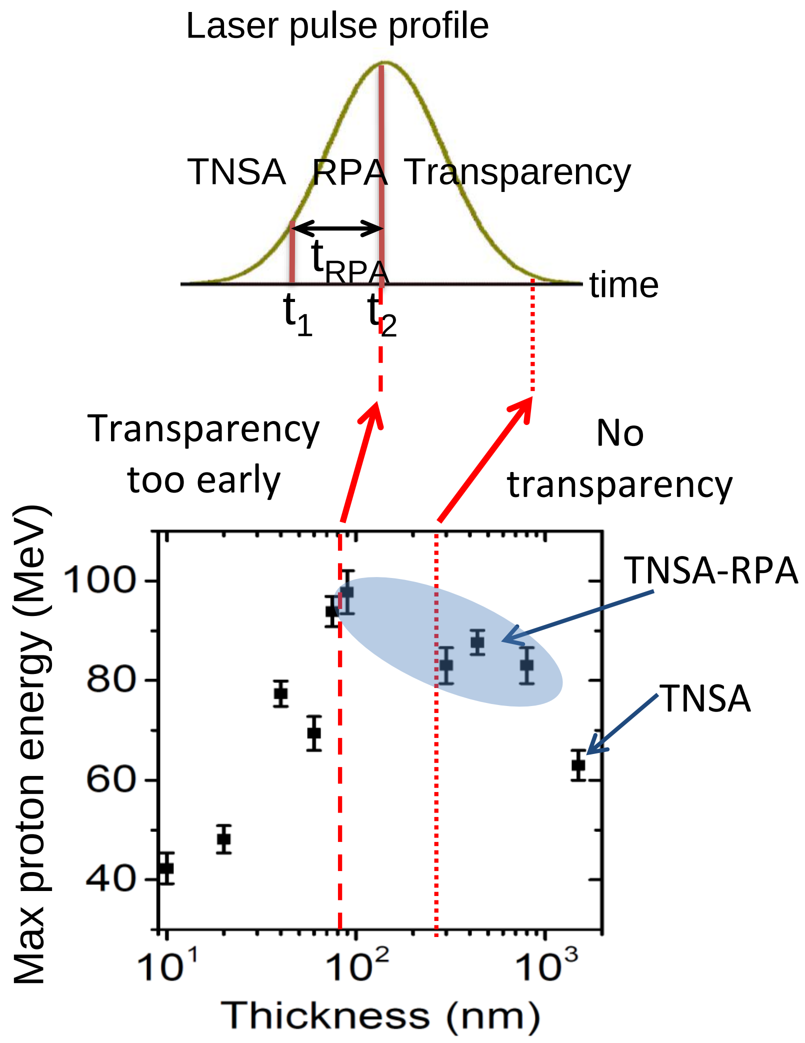




Transparency-enhanced hybrid RPA-TNSA

High energy protons achieved with ultrathin foils expanding to NCD and becoming relativistically transparent during the interaction



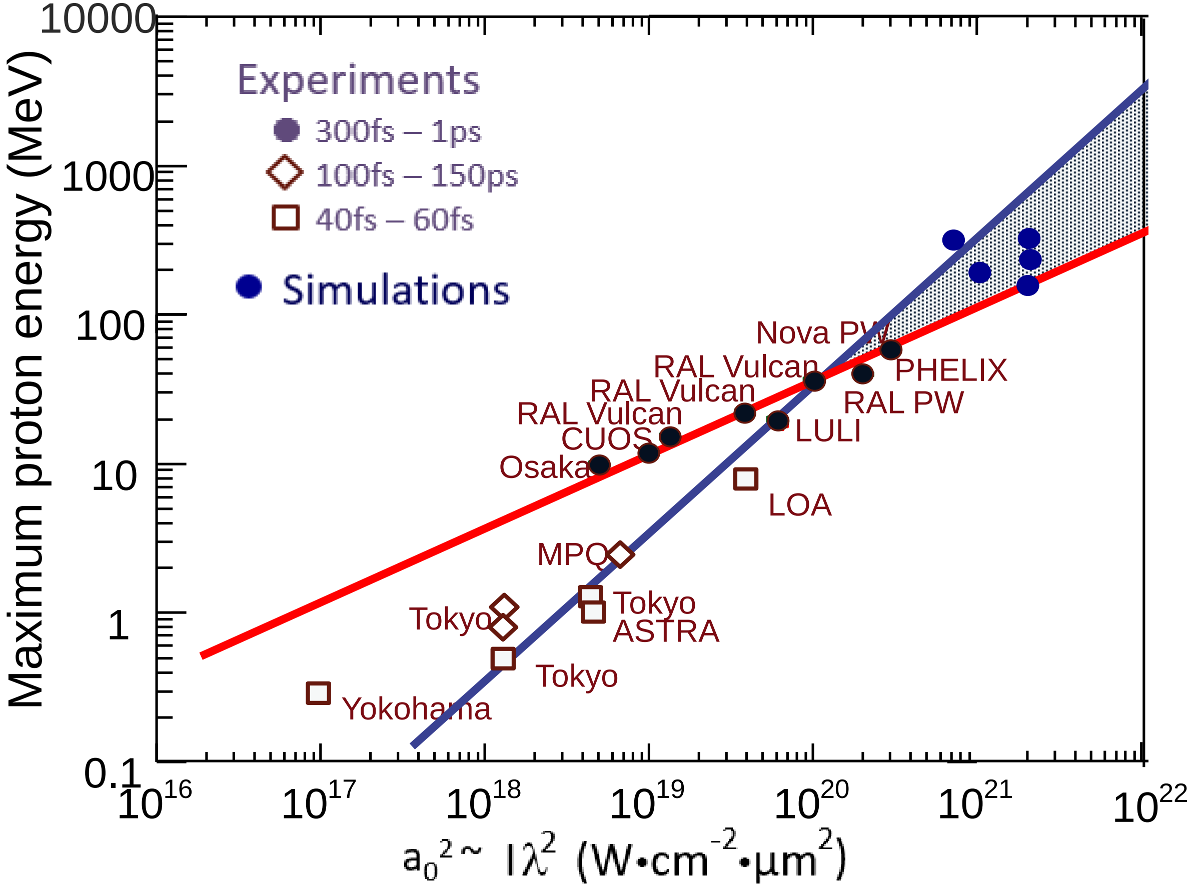


Higginson *et al*, Nature Communications, 9, 724 (2018)

Also 150 MeV - Laser-driven high-energy proton beams from cascaded acceleration, Ziegler et al., Nature Physics (2024)

Towards higher laser intensity, using focusing plasma mirrors

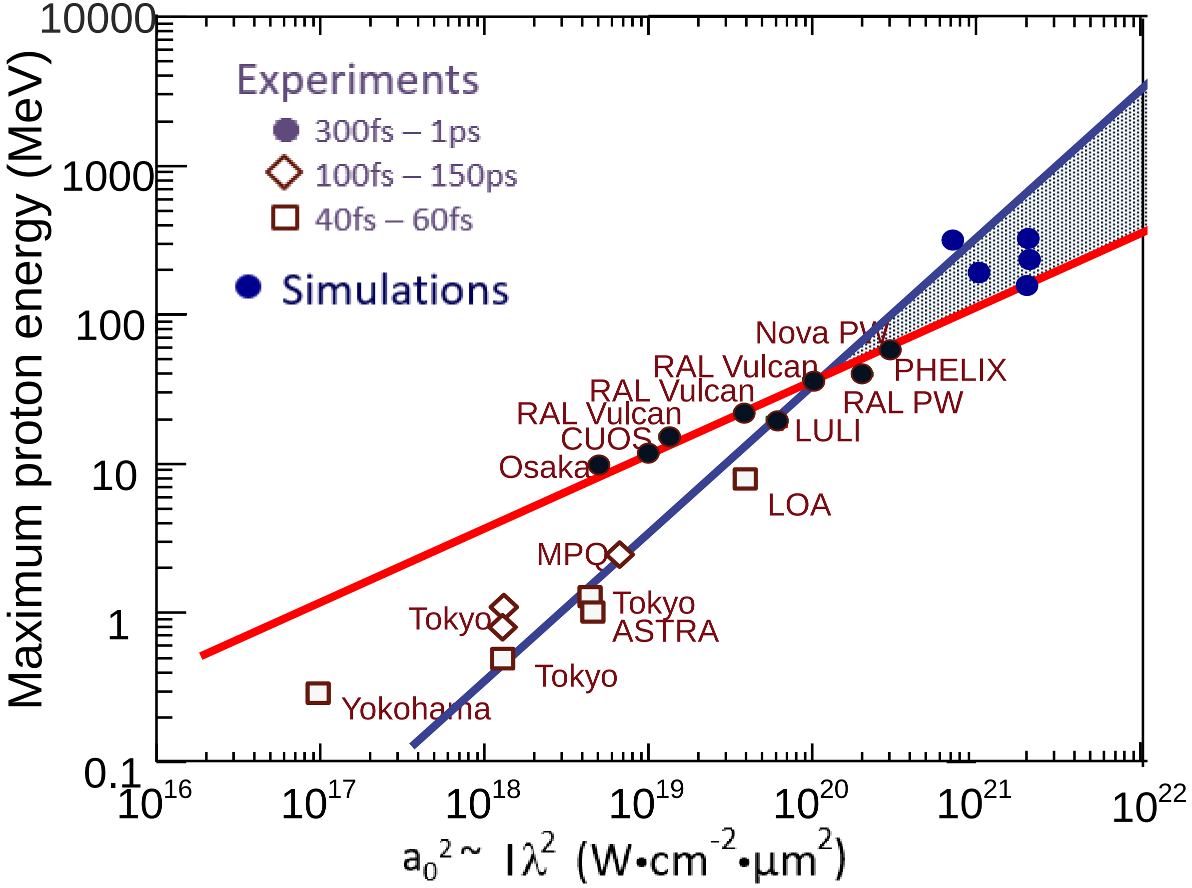
Expected TNSA scaling:



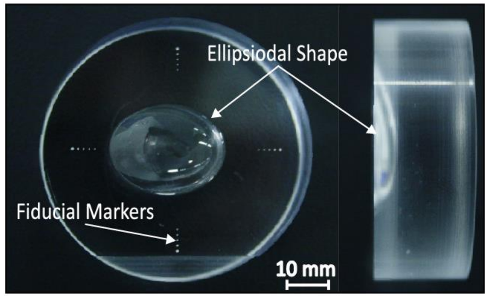
A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)

Towards higher laser intensity, using focusing plasma mirrors

Expected TNSA scaling:

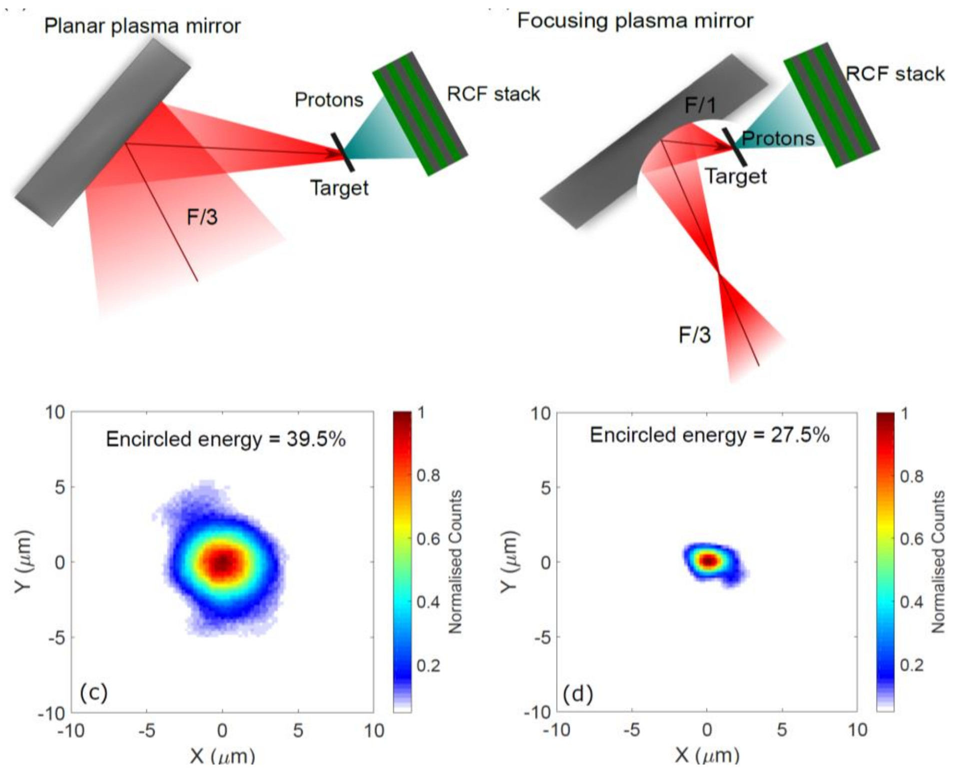


A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)



F/3 – planar PM

F/1 – Focusing PM



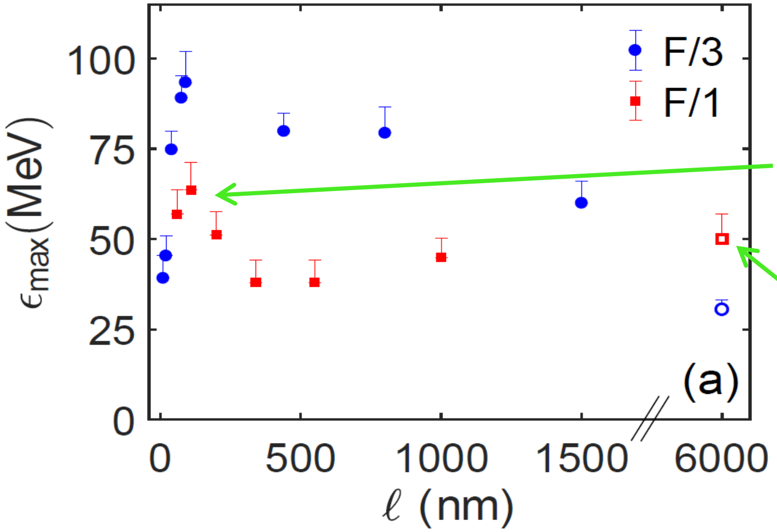
Increases intensity by almost an order of magnitude from 3×10^{20} Wcm^{-2} to 2×10^{21} Wcm^{-2}

Scaling of transparency-enhanced hybrid RPA-TNSA

Frazer *et al*, Phys. Rev. Research 2, 042015(R) (2020)

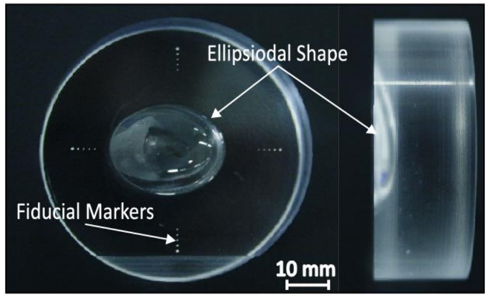
F/3 nominal intensity = 3×10^{20} Wcm^{-2}

F/1 nominal intensity = 2×10^{21}Wcm^{-2}



Proton energy is lower with F/1 focusing for ultrathin foils!

Proton energy is higher for thick foils!



F/3 – planar PM

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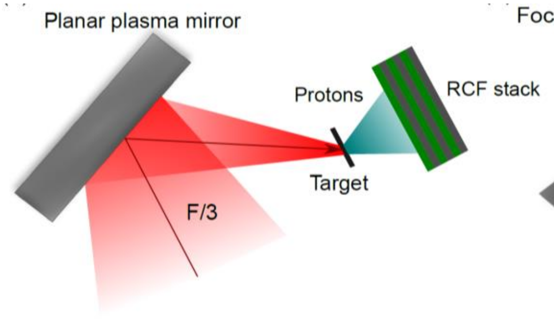
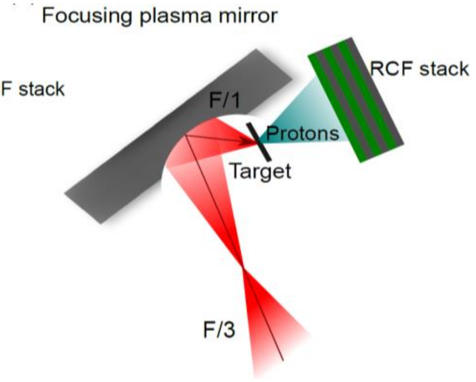
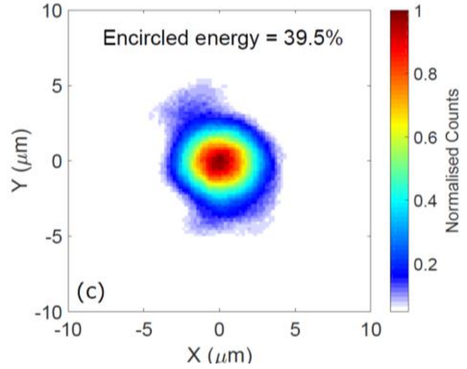
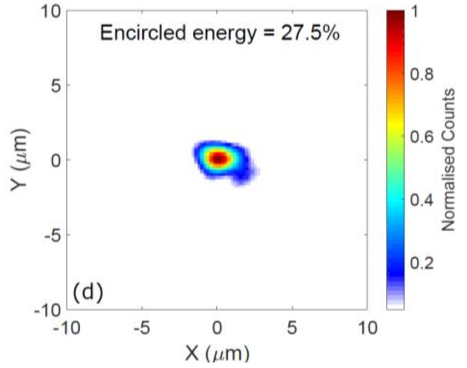
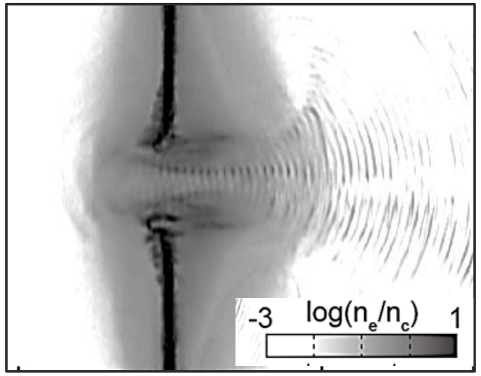








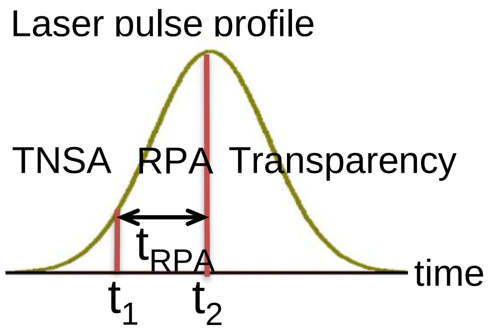
Laser light self-focuses in the expanding thin foil plasma, enhancing laser intensity

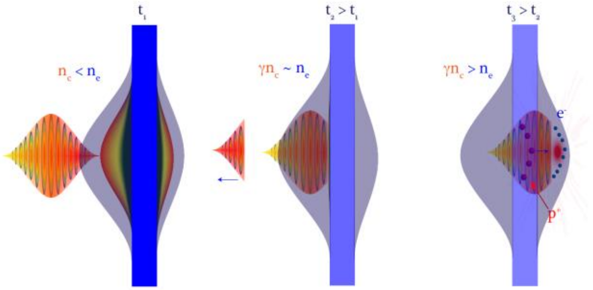


Increases intensity by almost an order of magnitude from 3x10^{20} Wcm^{-2} to 2x10^{21} Wcm^{-2}

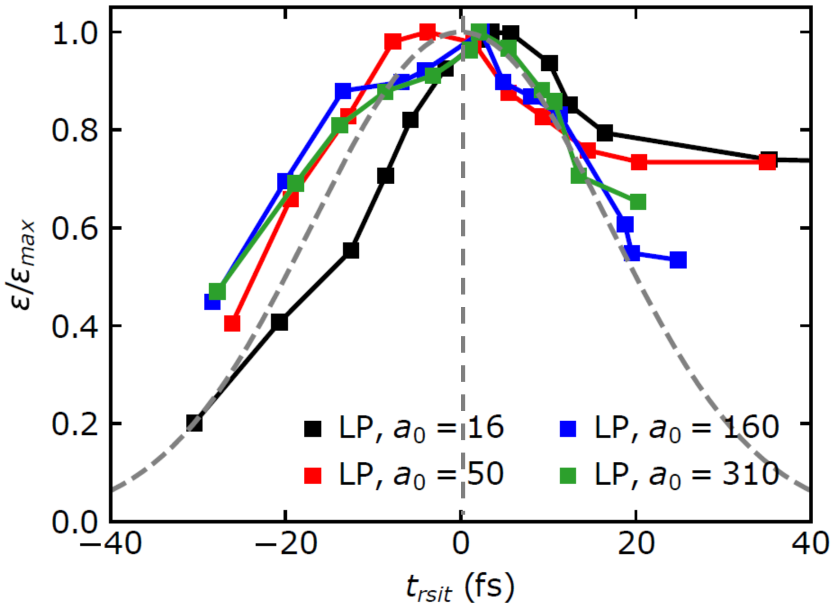
Proton beam properties as a function of relativistic transparency onset time: scaling to multi-PW lasers

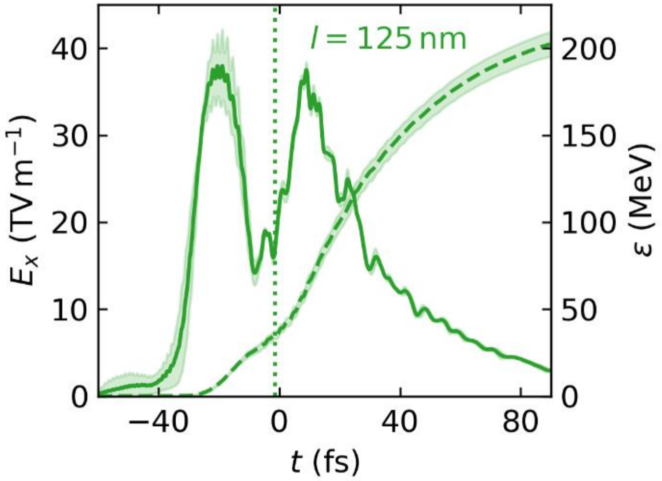
J Goodman *et al* New J. Phys. **24** 053016 (2022)





Maximum proton energy

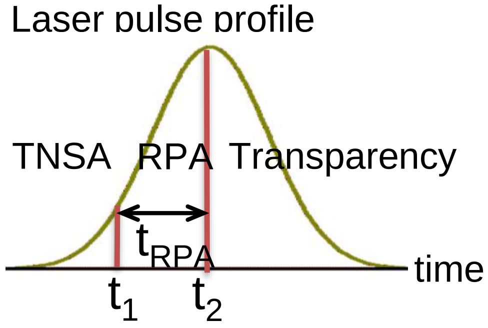




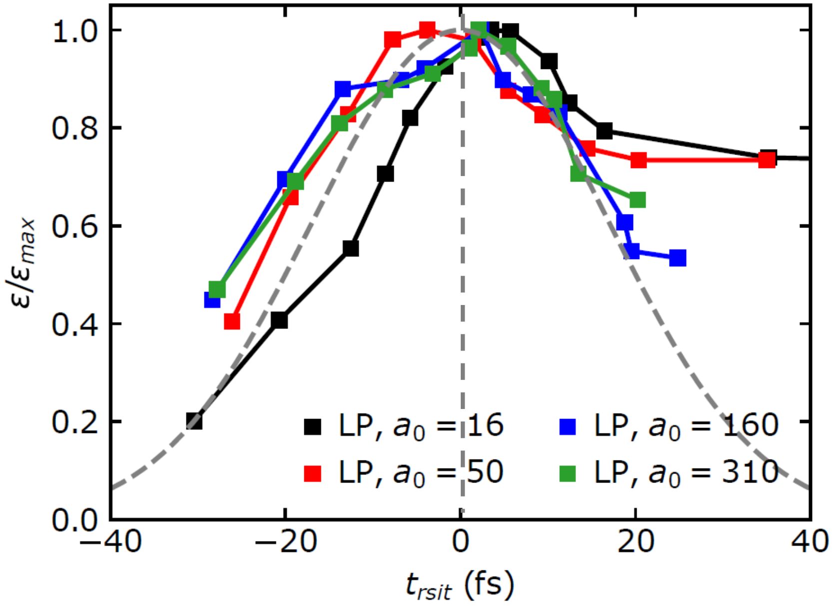
- Proton energy is maximised when transparency occurs at the peak of the laser pulse interaction

Proton beam properties as a function of relativistic transparency onset time: scaling to multi-PW lasers

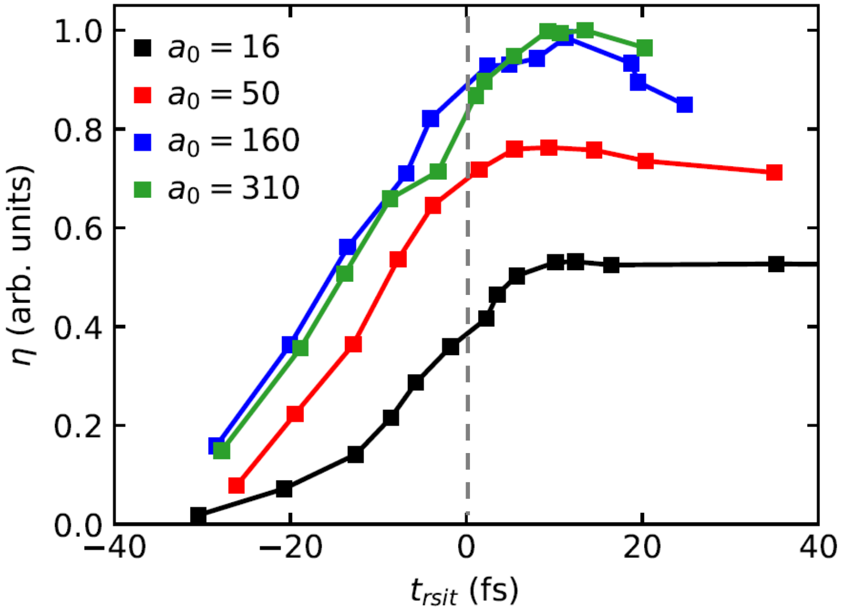
J Goodman *et al* New J. Phys. **24** 053016 (2022)



Maximum proton energy



Energy conversion efficiency



- Proton energy is maximised when transparency occurs at the peak of the laser pulse interaction
- Energy conversion efficiency saturates if transparency occurs later in time (~10 fs after peak)

Talk overview:

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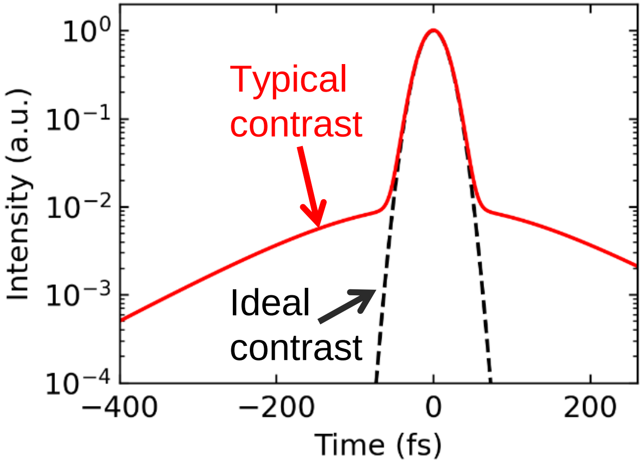
Conclusions, opportunities and challenges:

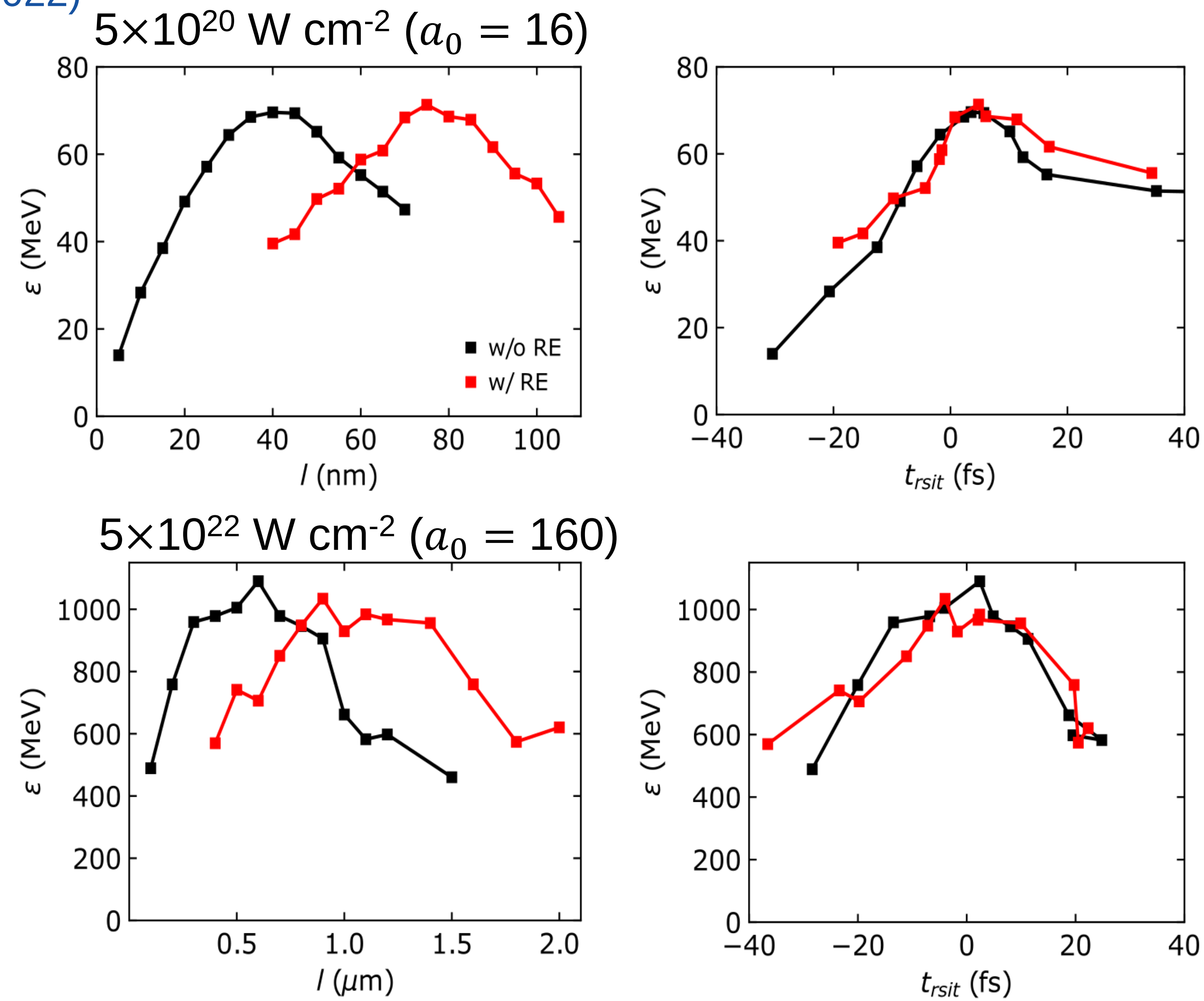
- Proof-of-concept experiments on nuclear activation, but higher repetition rates needed.
- Highest energies obtained when transparency occurs at pulse peak, but higher flux after peak.
- Focal spot size matters (affects self-focusing).

Effects of temporal-intensity contrast on ion acceleration

J Goodman *et al,* New J. Phys. **24** 053016 (2022)

Simulated laser rising edge profile



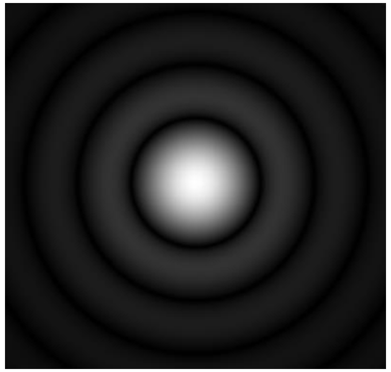


Increase in the optimum foil thickness, but energy still maximised when transparency occurs at the peak

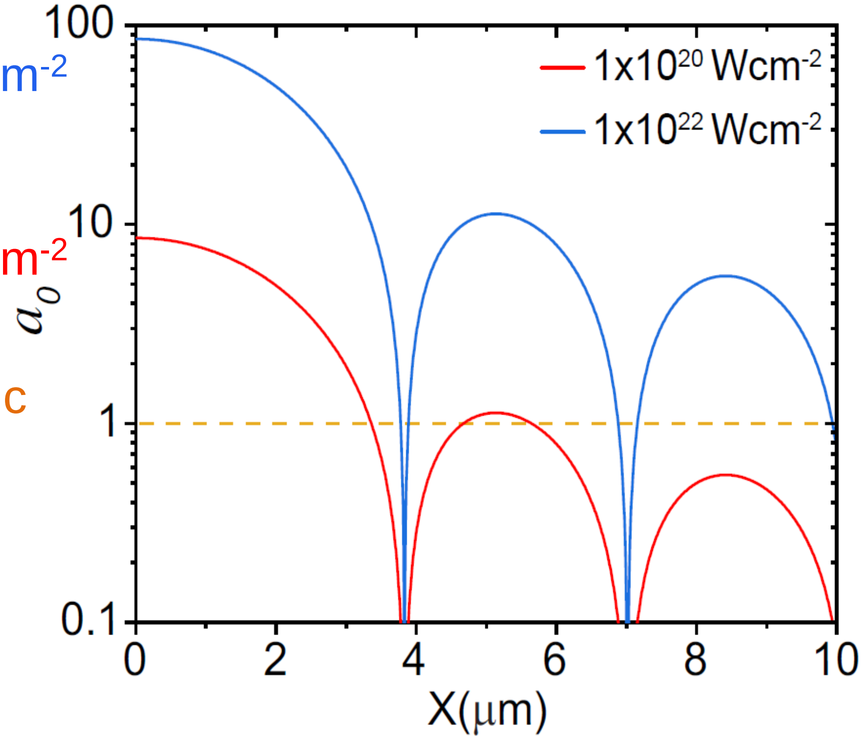
Importance of laser pulse spatial-intensity contrast

R. Wilson et al., Sci. Rep. 12, 1910 (2022)

Spatial-intensity contrast ratio: ratio of the intensity in the peak of the laser focal spot to the halo surrounding it (analogous to temporal-intensity contrast)



Conditions for which the intensity in the wings is relativistic

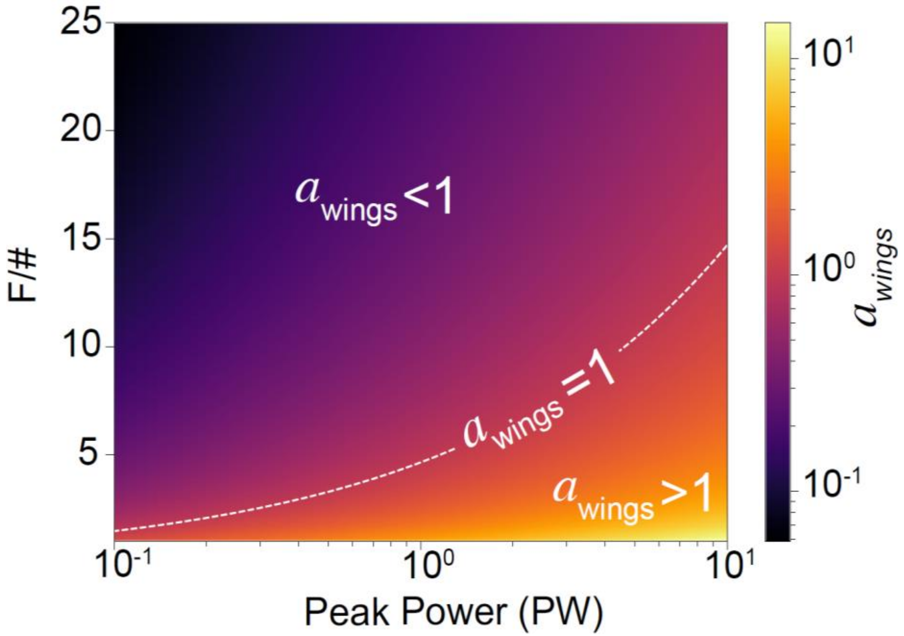


Airy disk, I_0=10^{22}Wcm^{-2}

Airy disk, I_0=10^{20}Wcm^{-2}

Relativistic threshold

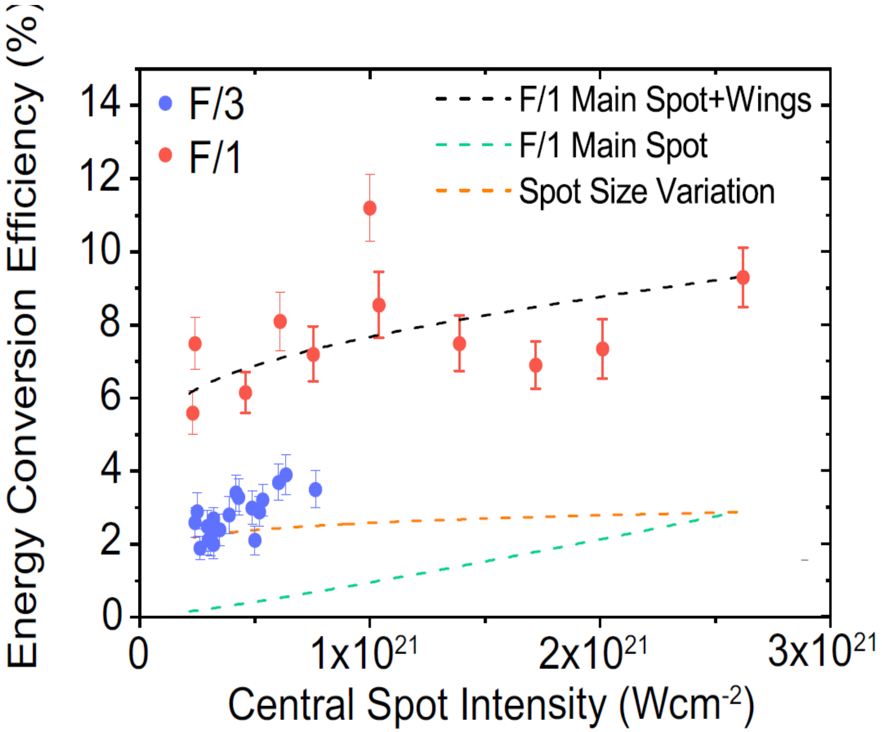
Normalised vector potential of the laser light in the wings, a_{wings}, as a function of laser pulse power and focusing geometry.

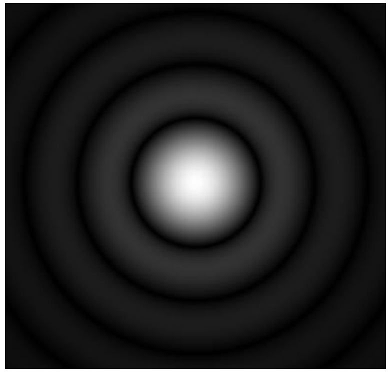


Importance of laser pulse spatial-intensity contrast

R. Wilson et al., Sci. Rep. 12, 1910 (2022)

In all cases, 6 µm-thick Al foil targets were irradiated (p-polarization) under F1 or F3 focusing





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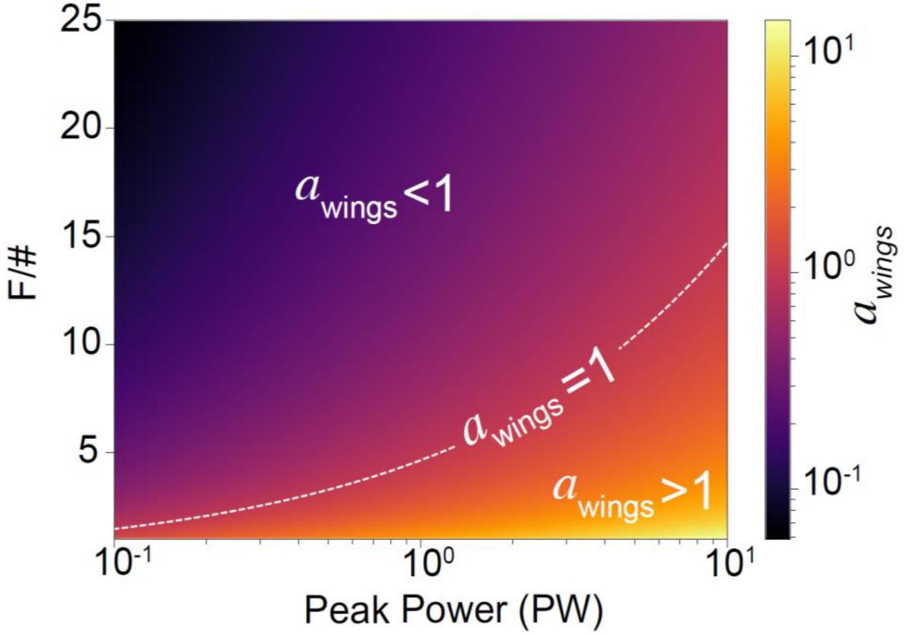

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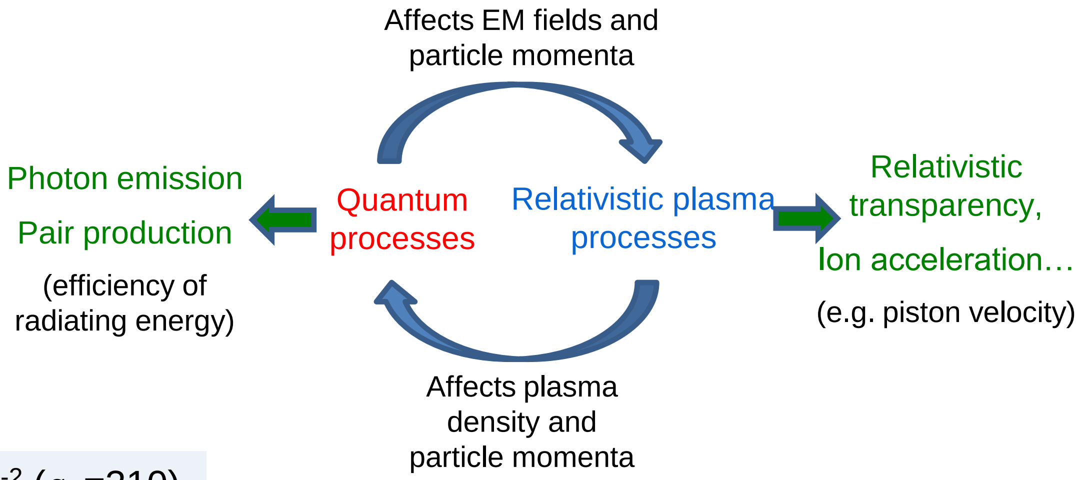
Ion acceleration at ultrahigh intensities is affected by high field processes

J Goodman *et al.*, New J. Phys. 24, 053016 (2022)

Strong field effects such as radiation reaction continuously change the basic plasma parameters (e.g., plasma density, plasma temperature, and plasma frequency) during the interaction of light and matter.

As a result, the collective behaviour of QED plasmas would be very different from those of the classical plasmas.



Affects EM fields and particle momenta

Photon emission

Pair production

(efficiency of radiating energy)

Quantum processes

Relativistic plasma processes

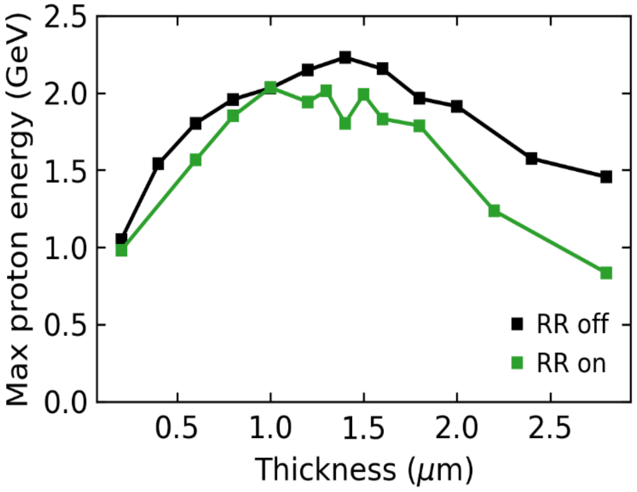
Relativistic transparency,

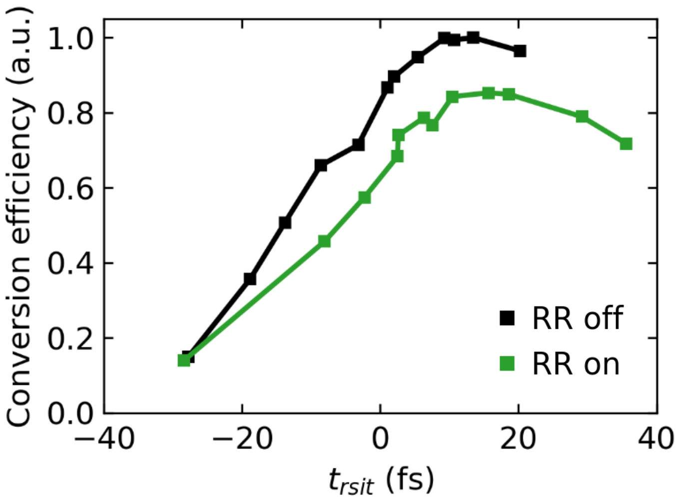
Ion acceleration…

(e.g. piston velocity)

Affects plasma density and particle momenta

Radiation reaction turned off and on in the PIC code for 2×10^{23} W cm^{-2} (a_0=310)





Talk overview:

1. Early studies on nuclear activation using laser-accelerated ions and challenges emerging
2. Opportunities for enhancing ion acceleration in expanding ultrathin foils
3. Challenges at ultrahigh intensities: Importance of spatial- and temporal-intensity contrast, and high field phenomena
4. Opportunities for application of machine learning techniques: Bayesian Optimisation and neural network-based approaches
5. New high repetition rate experiment platform at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)

Conclusions, opportunities and challenges:

- Proof-of-concept experiments on nuclear activation, but higher repetition rates needed.
- Highest energies obtained when transparency occurs at pulse peak, but higher flux after peak.
- Focal spot size matters (affects self-focusing).
- Temporal-intensity contrast determines the optimum target thickness.
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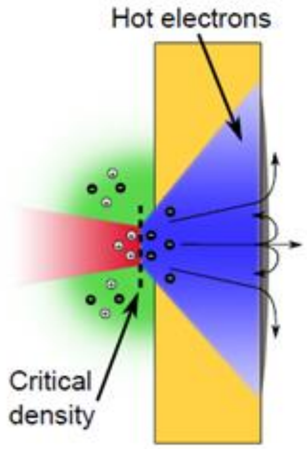
Machine learning applied to optimise laser-driven ion acceleration

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

Laser-driven ion acceleration is influenced by:

- **Fast electron temperature** and **density** at the rear surface drive proton **spectral** characteristics
- Transport physics defined by **material, target properties** and **self generated fields** drive **spatial** characteristics
- Target expansion and onset of relativistic transparency
- These are sensitive to a wide range of input parameters, creating a high dimensional optimisation problem!



Laser:

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

Plasma:

- Target thickness
- Energy coupling to electrons
- Fast electron divergence angle
- Z (scattering, resistivity)
- Preplasma scale length
- …

→ Very quickly this becomes a very high dimensional optimisation problem!

We can use machine learning to help

Machine learning can be a useful tool for optimisation

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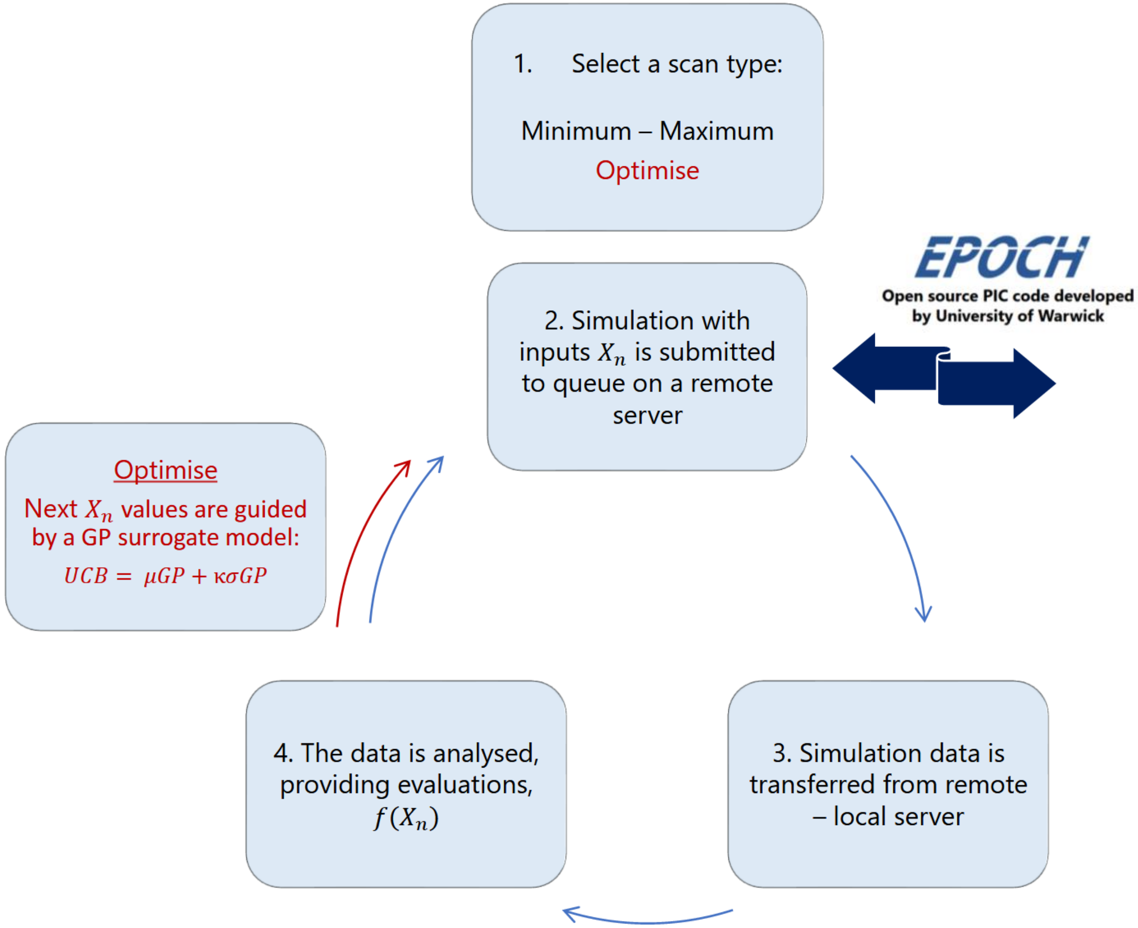
Machine learning can be a useful tool for optimisation

BISHOP code to facilitate Bayesian Optimisation



1. Select a scan type:

Minimum – Maximum
Optimise

2. Simulation with inputs X_n is submitted to queue on a remote server

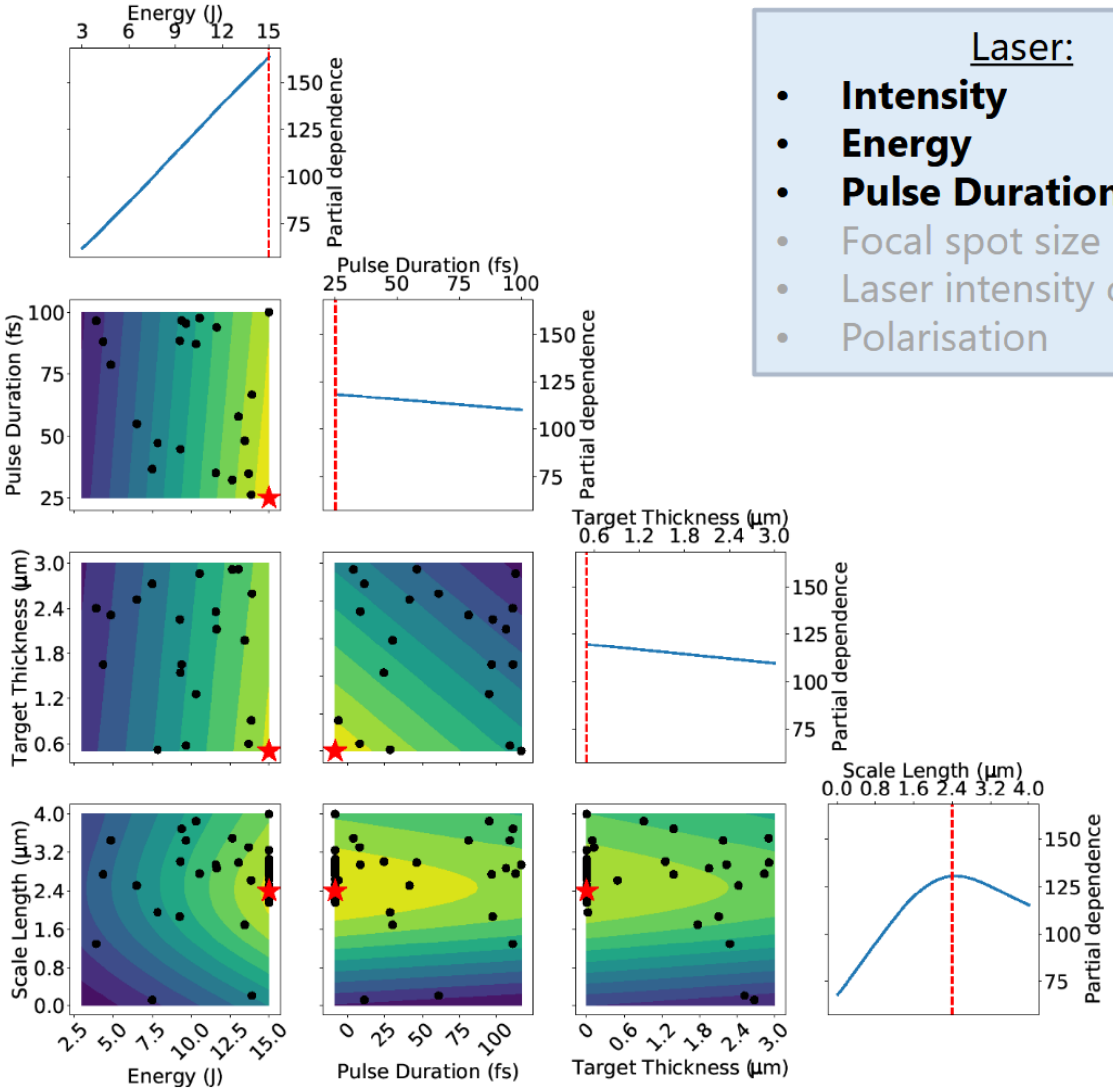
3. Simulation data is transferred from remote – local server

4. The data is analysed, providing evaluations, $f(X_n)$

Optimise
Next X_n values are guided by a GP surrogate model:
$UCB = \mu GP + \kappa\sigma GP$

Multi-parameter Bayesian optimisation of laser-driven ion acceleration in particle-in-cell simulations

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



Laser:

- **Intensity**
- **Energy**
- **Pulse Duration**
- Focal spot size
- Laser intensity contrast
- Polarisation

Plasma:

- Energy conversion efficiency
- Fast electron divergence angle
- Z (scattering, resistivity)
- **Preplasma scale length**
- **Target Thickness**
- Incidence angle

Optimised TNSA maximum proton energy (E_{max}) in **50 simulations** as a function of **4 laser-target parameters**

≈ **1000 x faster than by grid search**

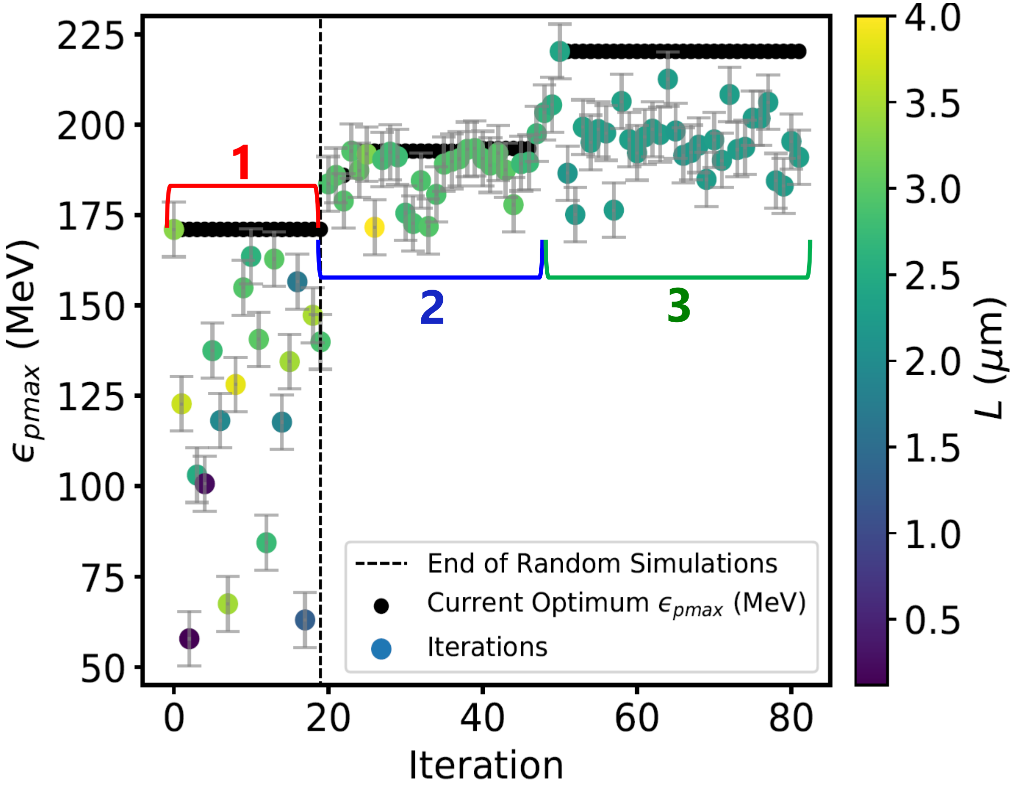
E_{max} = 220 MeV, for E_{L} = 15 J, τ_{L} = 25 fs, t = 500 nm, L = 2400 nm

≈ **2x increase in E_{max}** compared to varying 2 parameters

Multi-parameter Bayesian optimisation of laser-driven ion acceleration in particle-in-cell simulations

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

Plasma density scale length optimised to maximise the proton energy in the TNSA regime

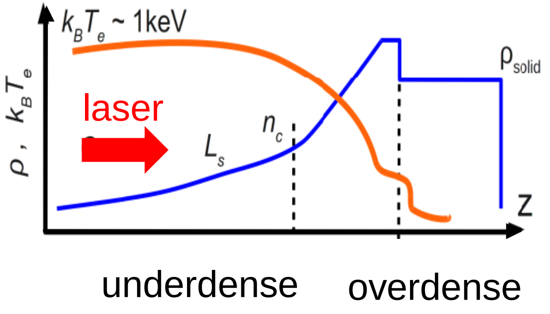


1. Inputs for each parameter are randomly varied to initialise the model

2. Model is created and is confident that optimal conditions for laser energy, pulse duration and target thickness have been found

Model focuses on varying scale length from ~ L = 2.7 µm - L = 4.0 µm

3. Model focuses on varying scale length from ~ L = 2.1 µm - L = 2.4 µm



L_s is the plasma density scale length at the target front side

$$n_e(z) = n_0 \exp\left(-\frac{z}{L_s}\right)$$

Also multi-objective optimisation: J. Goodman et al., High Power Laser Sci. Eng. Vol. 11, e34 (2023)

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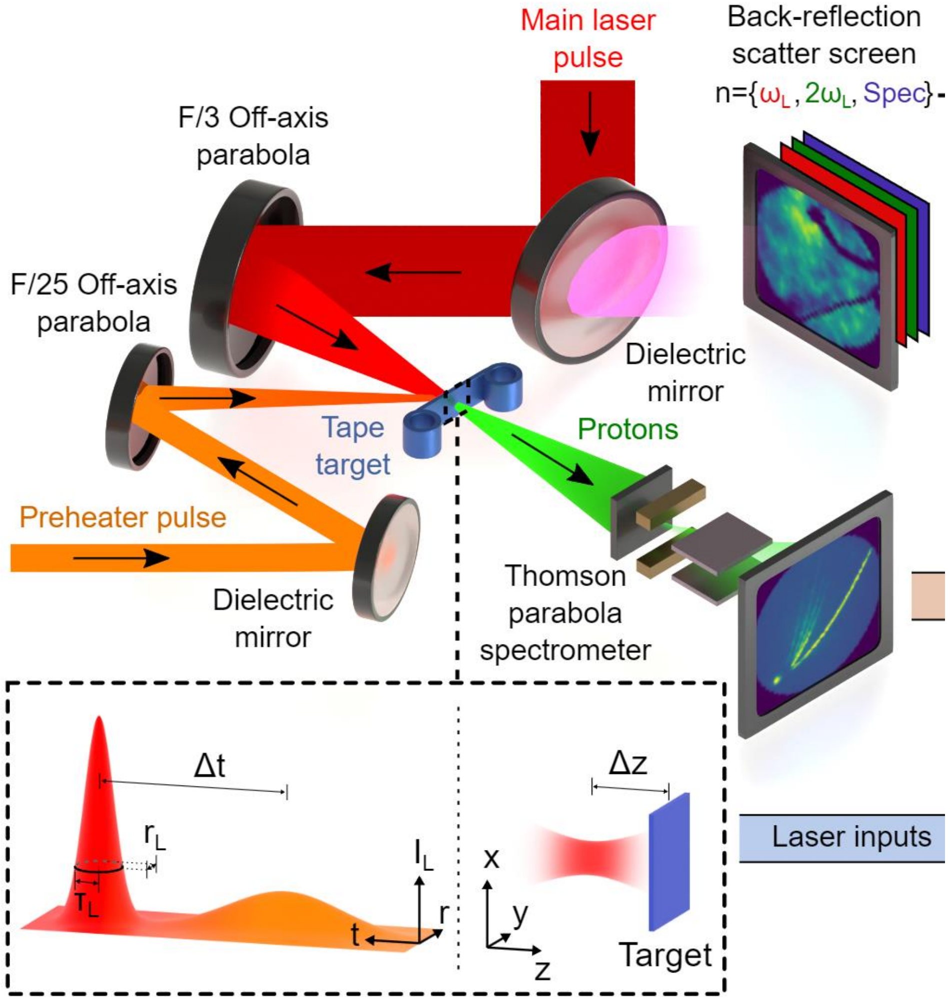
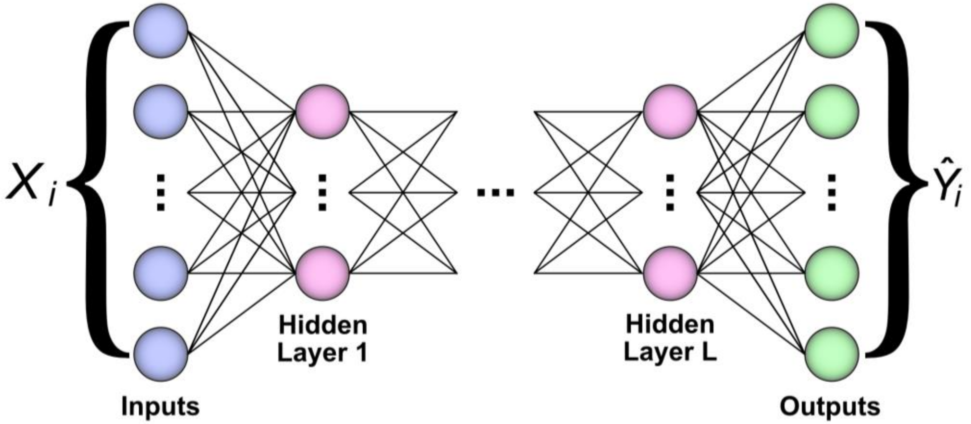
Neutral network-based synthetic diagnostic of proton spectra

Experimental arrangement:

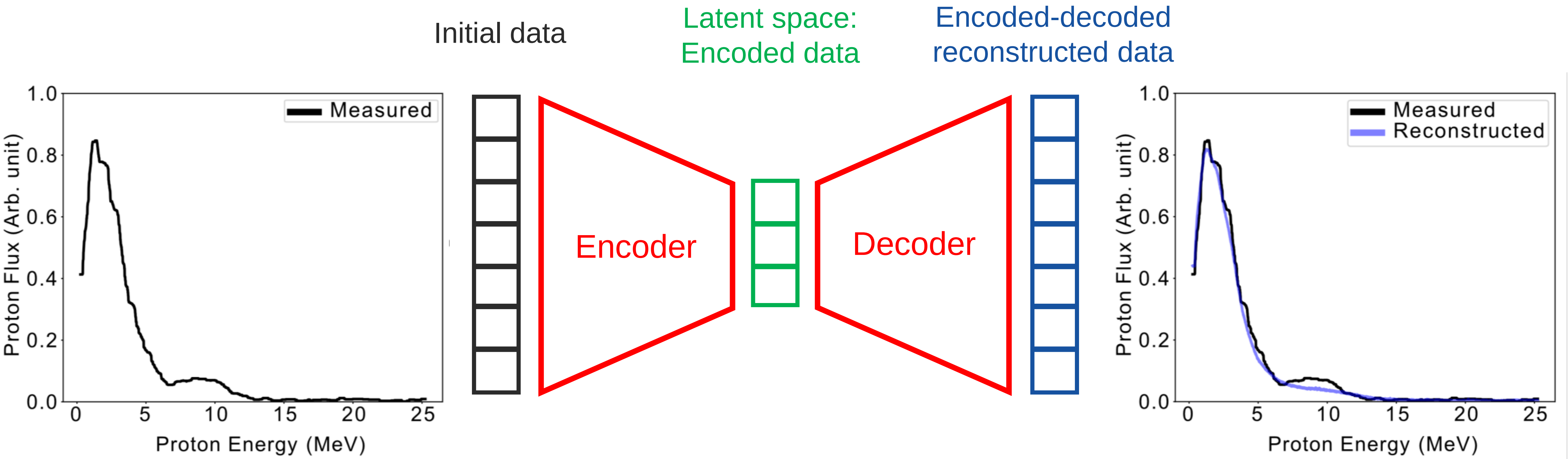


What is a neutral network?



X_i

Variational Autoencoder (VAE)



- Encoder learns to **encode** the input, allowing for (lossy) **compression** of data to a **smaller dimension** – the **Latent Space**
- Decoder learns to **decode** this compressed format into a **reconstruction** of the input

Talk overview:

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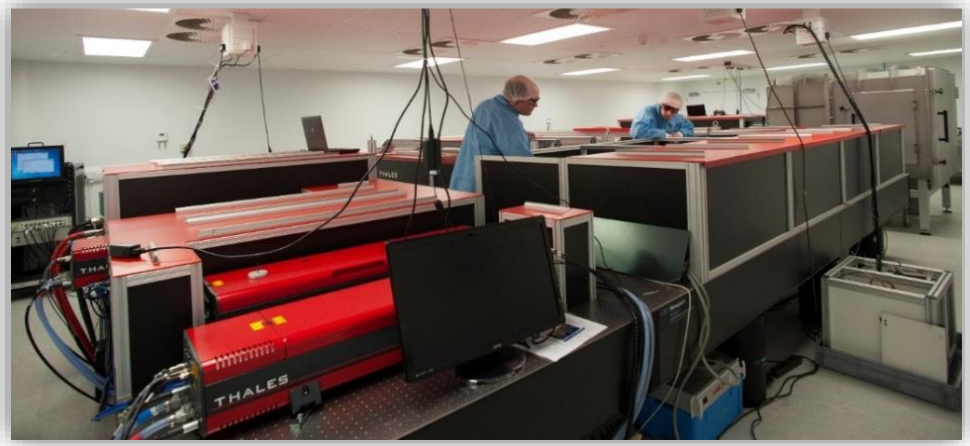
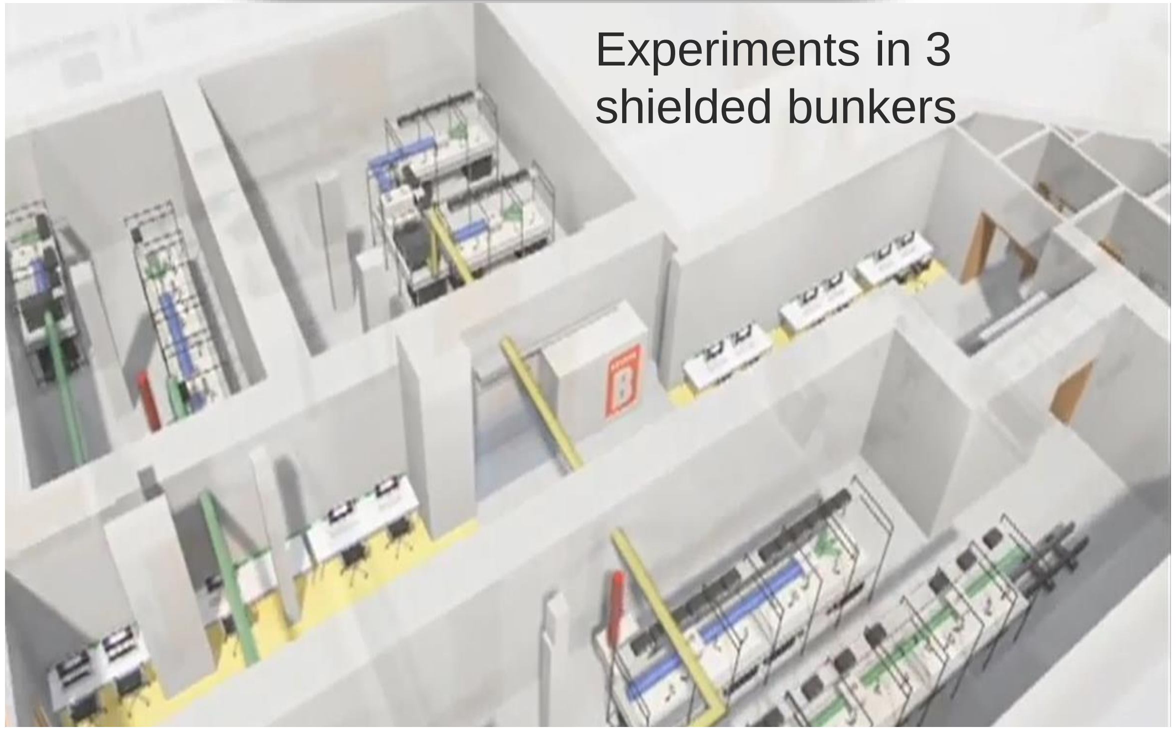
- Temporal-intensity contrast determines the optimum target thickness.
- Spatial-intensity contrast strongly affects ion flux.
- Radiation reaction lowers maximum energy and flux (conversion efficiency).
- Bayesian algorithms can be used for multi-parameter and multi-objective optimisation
- Neutral network-based model can be used to create synthetic diagnostics of ion acceleration.

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





Experiments in 3 shielded bunkers

350 TW laser parameters	
Peak Power	≥350 TW
FWHM pulse duration	≤25 fs
Energy (on target)	≥ 7 J
Pulse repetition rate	1 Hz (up to 5 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

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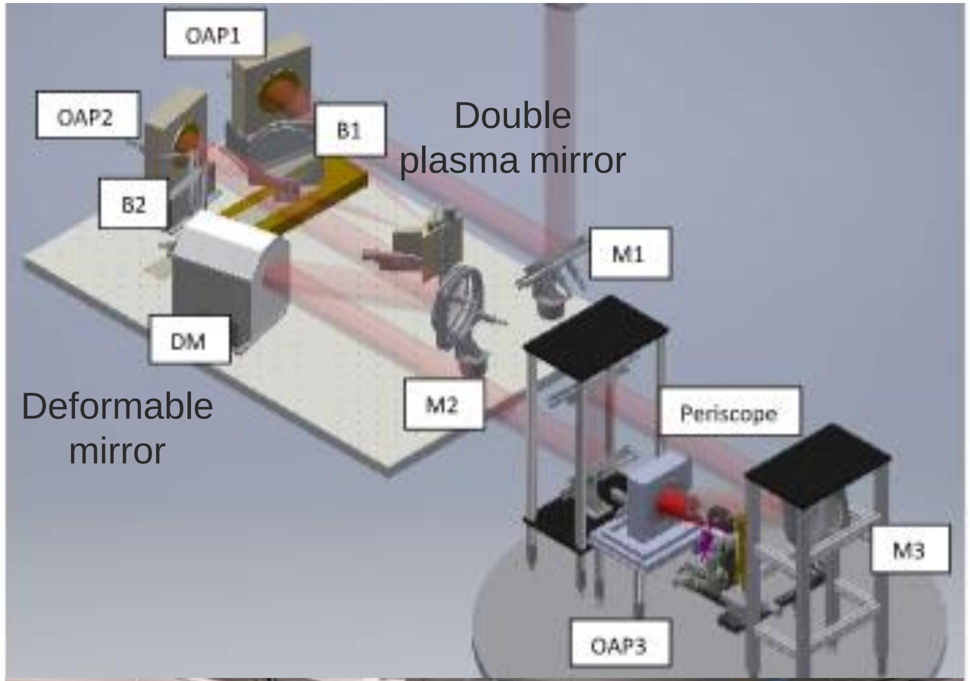
SCAPA Laser-ion acceleration target station (Bunker B)



Double plasma mirror

Deformable mirror

Temporal-intensity contrast (before plasma mirrors)

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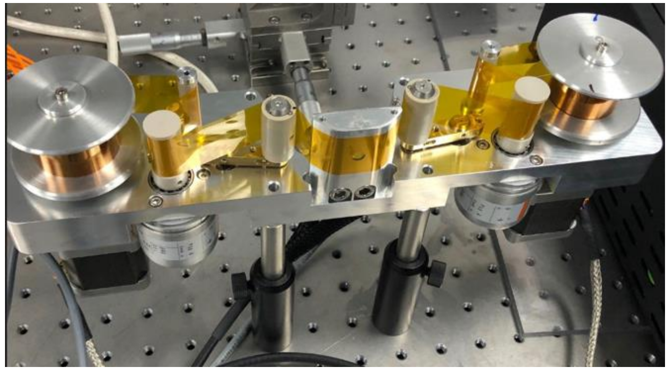
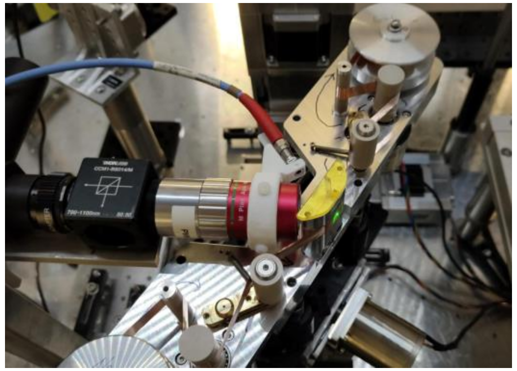
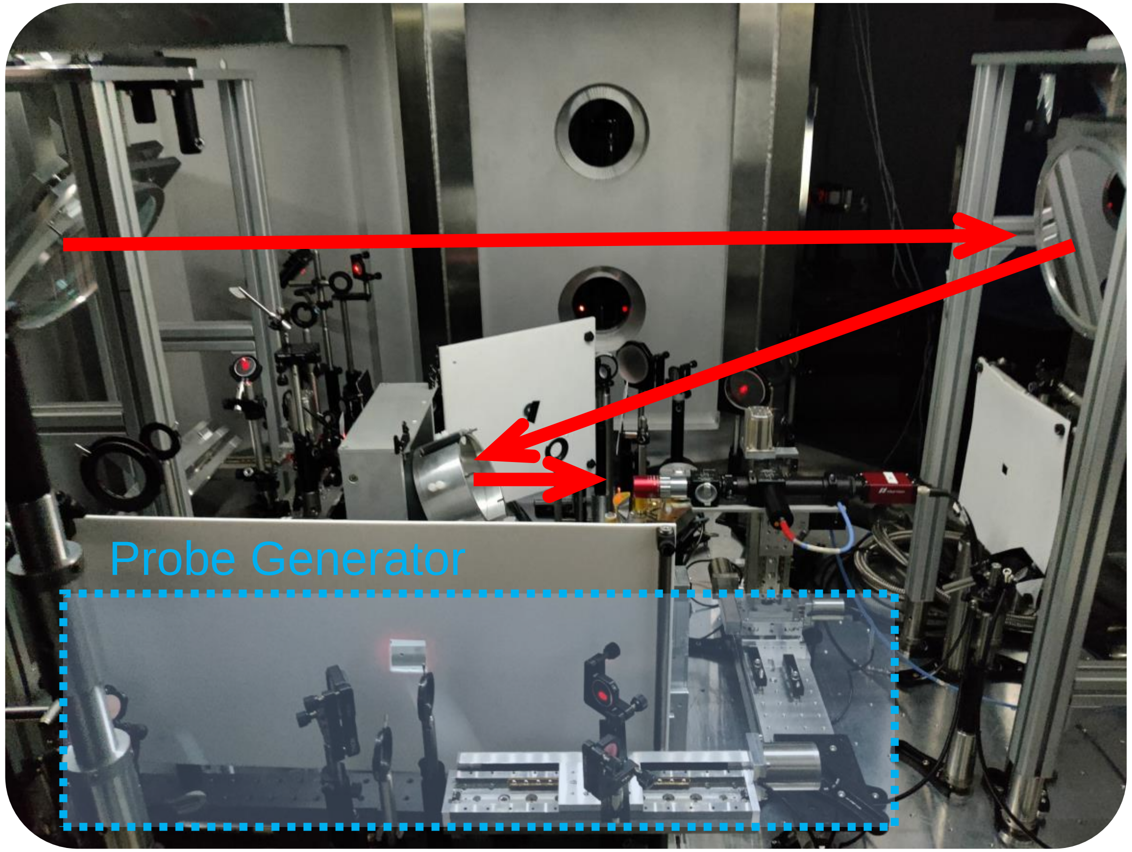
Inside the interaction chamber

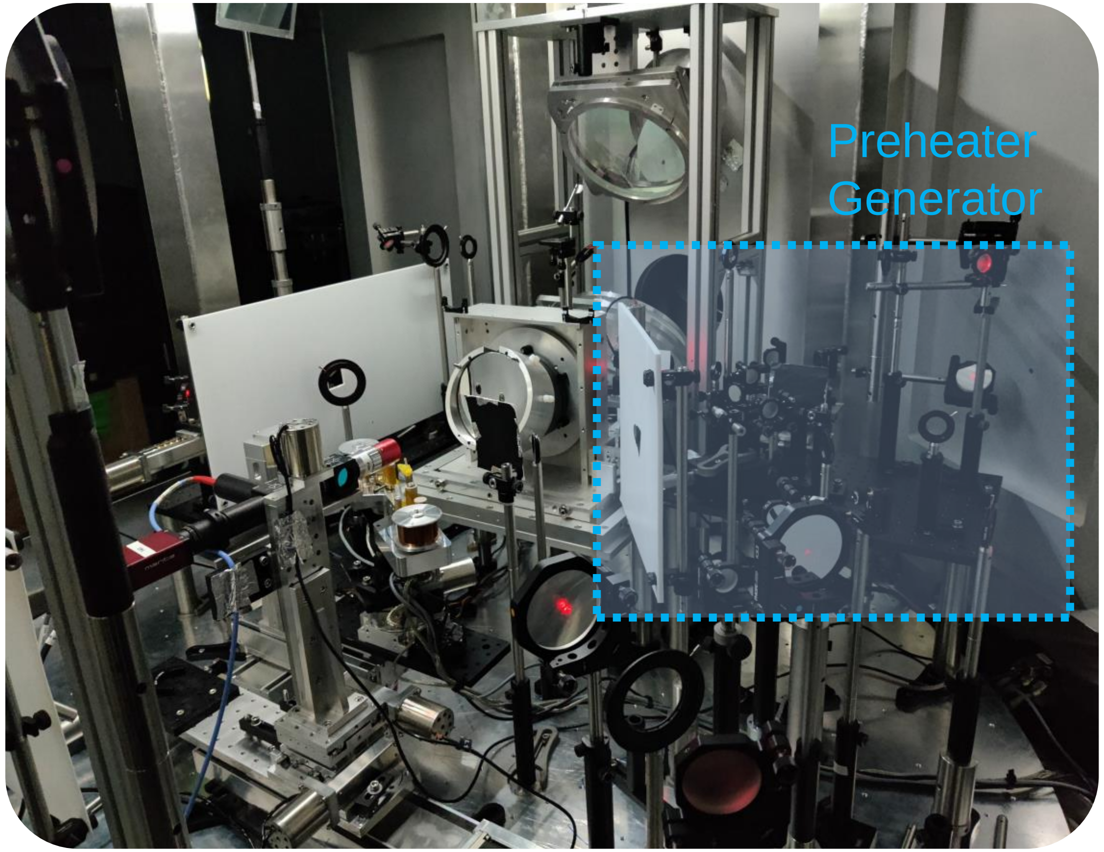
High rep-rate operation (1Hz):

- Tape-driven targets
- Active PROBIES spatial-energy monitor
- Thomson parabola with MCP
- Pre-heater beam
- Optical probe



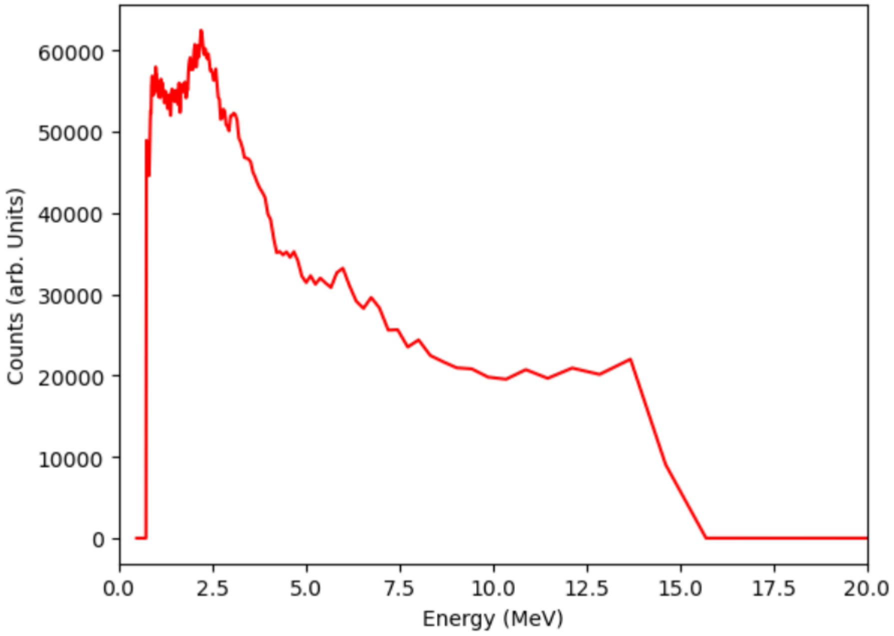






Preliminary proton acceleration results

- Very recent preliminary results include proton energies up to 15 MeV both on the Thomson parabola and RCF diagnostics.
- Now in an energy regime to undertake proton induced nuclear activation at 1 Hz – in a university laboratory!



Summary of challenges and opportunities for laser-ion-driven nuclear physics

Challenges:

- Optimisation and stabilisation of laser-ion acceleration:
  - Highest energies when transparency occurs at pulse peak, but higher flux after peak.
  - Focal spot size matters (affects self-focusing).
  - Temporal-intensity contrast determines the optimum target thickness.
  - Spatial-intensity contrast strongly affects ion flux.
  - Radiation reaction lowers maximum energy and flux (conversion efficiency).

Opportunities:

- Application of machine learning:
  - Bayesian algorithms can be used for multi-parameter and multi-objective optimisation.
  - Neutral network-based surrogate models and synthetic diagnostics of ion acceleration.
- Higher repetition rate operation:
  - Hz-rate lasers, targets and diagnostics for ion acceleration now available – enables high repetition rate nuclear activation.