Enhanced laser-driven proton acceleration through Formvar film production

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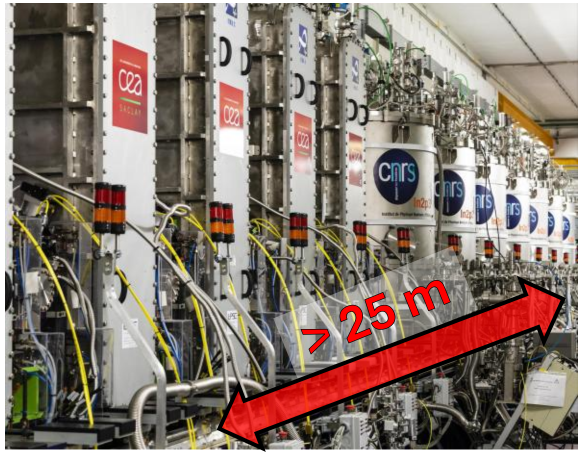
Introduction

Laser-driven ion acceleration is an emerging alternative to conventional acceleration for low-energy:

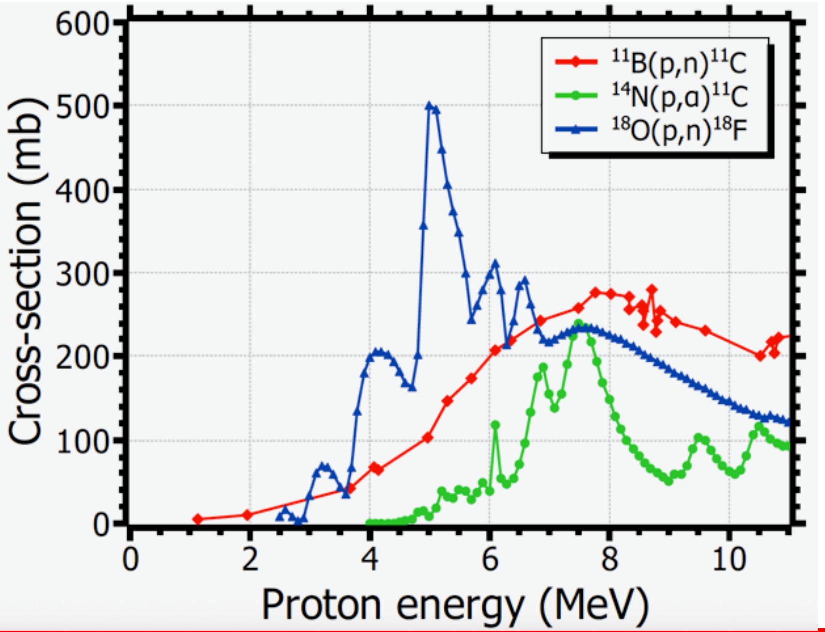
- Electric field gradients on the order of GV/cm to TV/m;
- Require less space;
- Exceptional accelerator-like spatial quality.



The linear accelerator SPIRAL2-LINAC from GANIL.

Picture of the laser-driven accelerator from L2A2-USC.

Key requirement: produce a stable beam, capable of operating for prolonged periods of time, with optimum flux and energies.



J. Peñas *et al*, *Scientific Report 14, 11448 (2024)*

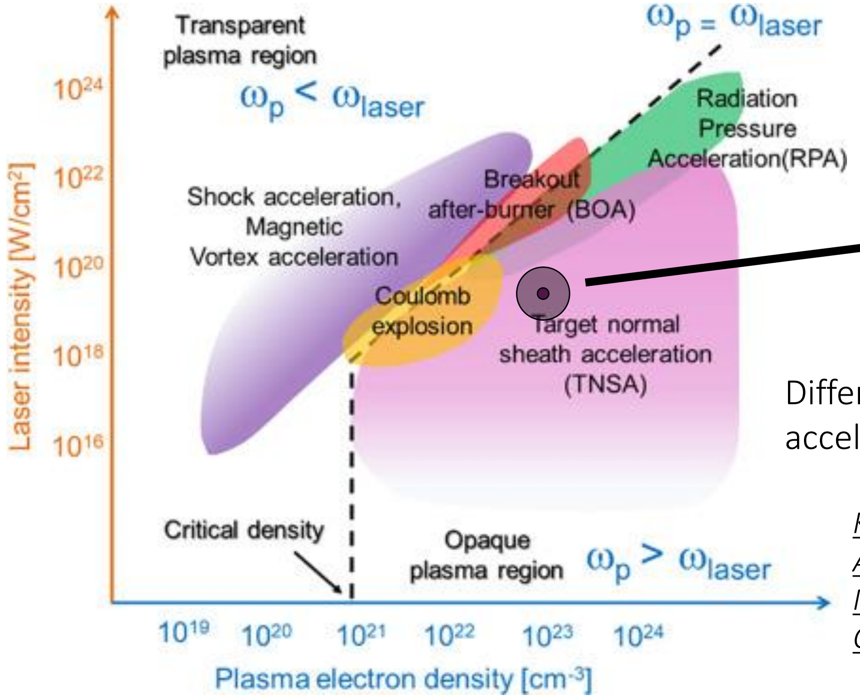
Cross-sections of some proton-induced production reactions of radioisotopes of interest in PET.

TNSA mechanism

1. Laser impinges on the target ⟹ a cloud of hot electrons is formed.

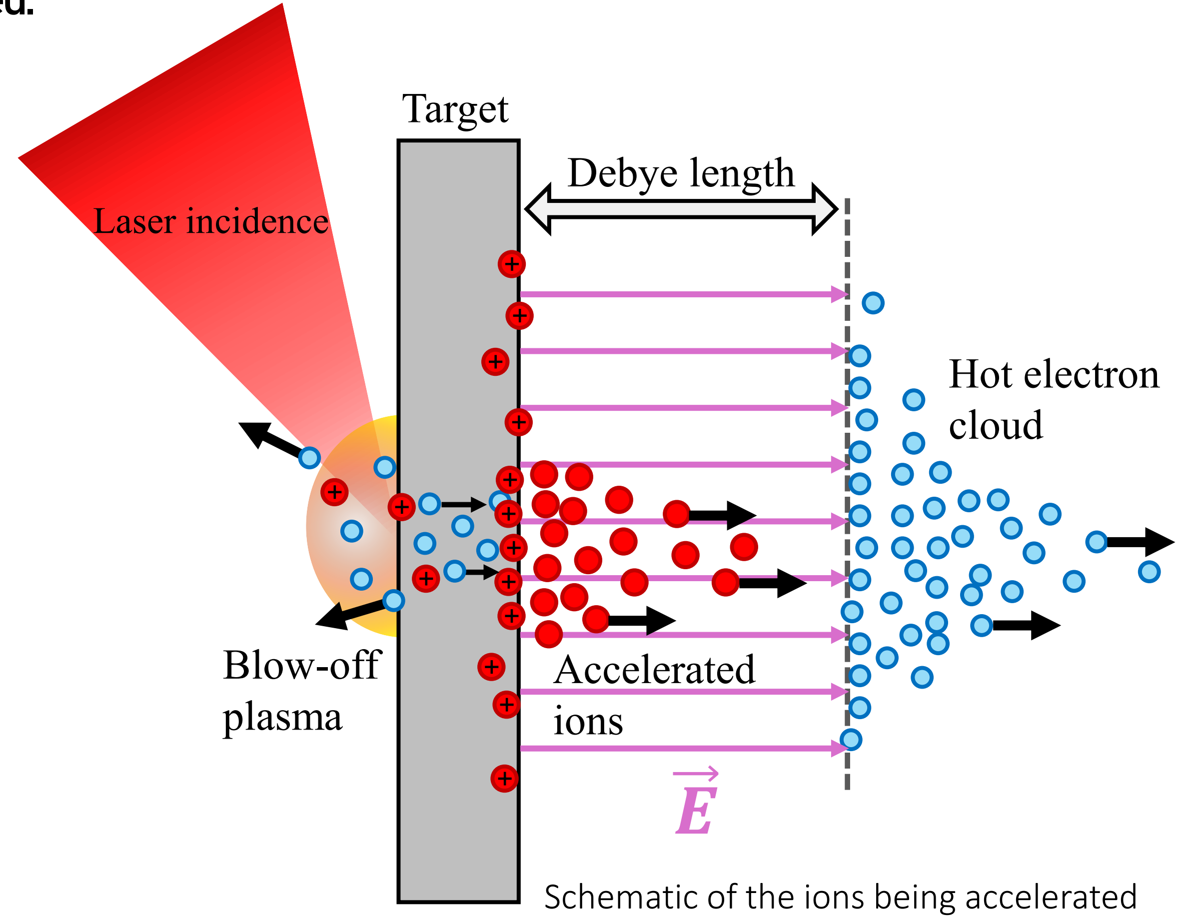
2. A Debye-sheath from the target's rear side is formed.

3. The ideal target ⟶ ultra-thin, low-Z, highly conducting target.



Different laser-driven acceleration mechanisms.

Kojima and Hata, Advances in Accelerators and Medical Physics (Book), Chapter 31 (2023)

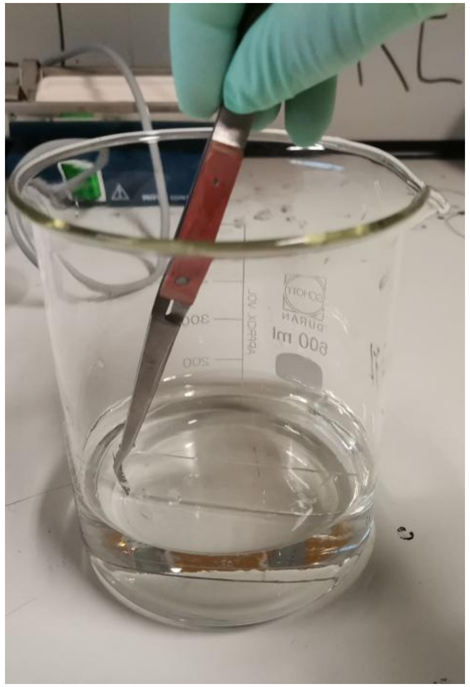


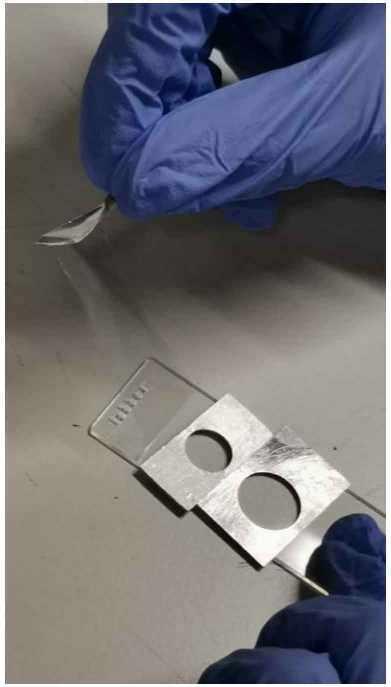
Schematic of the ions being accelerated by the electrons (not to scale).

Target production – Formvar foils

- Polyvinyl formal is a hydrophilic and oleophilic polymer → a resin.
- The resin used was:
  - Vinylec E Polyvinyl Formal Resin;
  - Chemical monomer: $[C_5H_8O_2]_n$;
  - Density: $\rho = 1.23\ \mathrm{g/cm^3}$.
- The resin was dissolved in chloroform.

Polyvinyl formal resin.


Dipping glass slide in Formvar solution.


Getting a Formvar foil into target frames.

Target production – Metal coatings

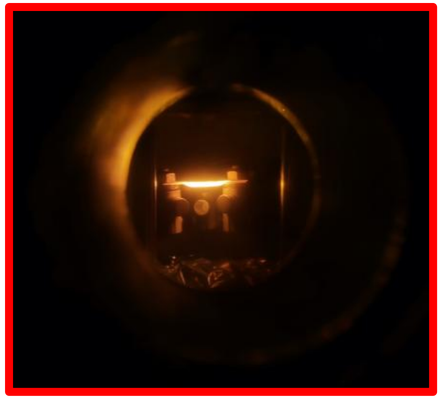
Thermal vacuum evaporation is targeted for "materials with a melting point lower than 1850 K".

A. Stolarz, J Radioanal Nucl Chem 299, (2014)

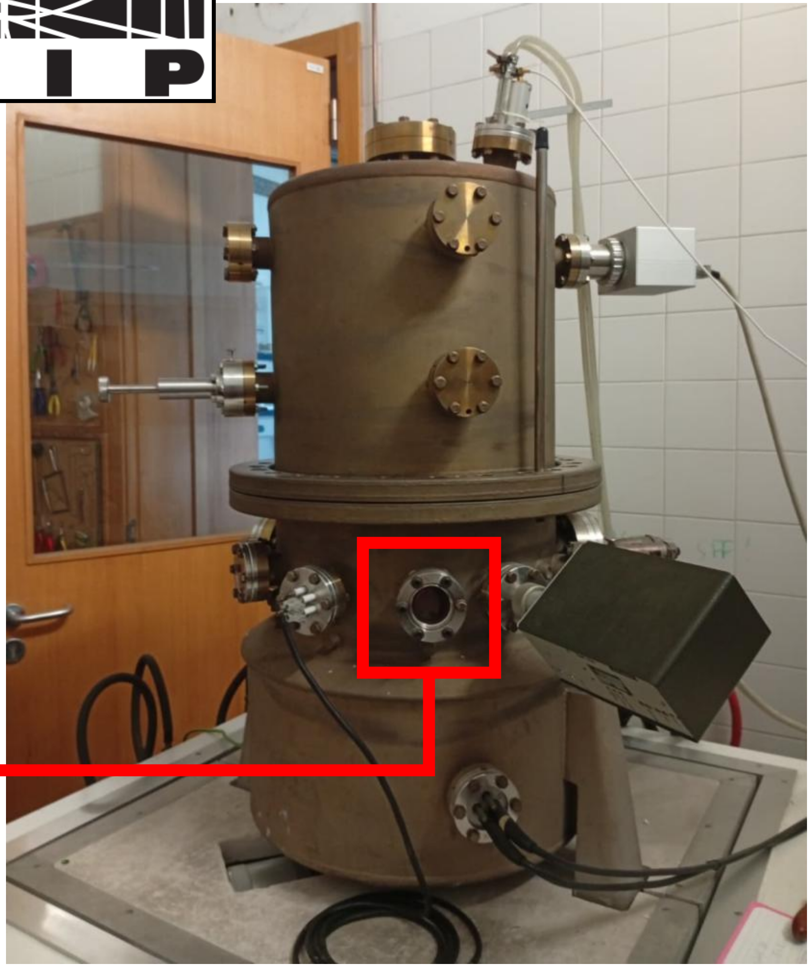
Evaporations were performed under similar conditions:

1. To characterise the coatings;
2. To test the performance in laser-driven proton acceleration.

Top-view of the support for the glass slides.



Boat heating-up during evaporation.

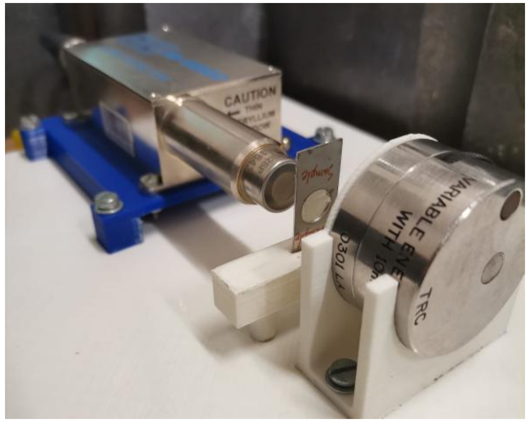


Evaporation facility at the **Target Design Laboratory.**

Target characterisation

Alpha Energy Loss technique

Rutherford Backscattering Spectrometry technique



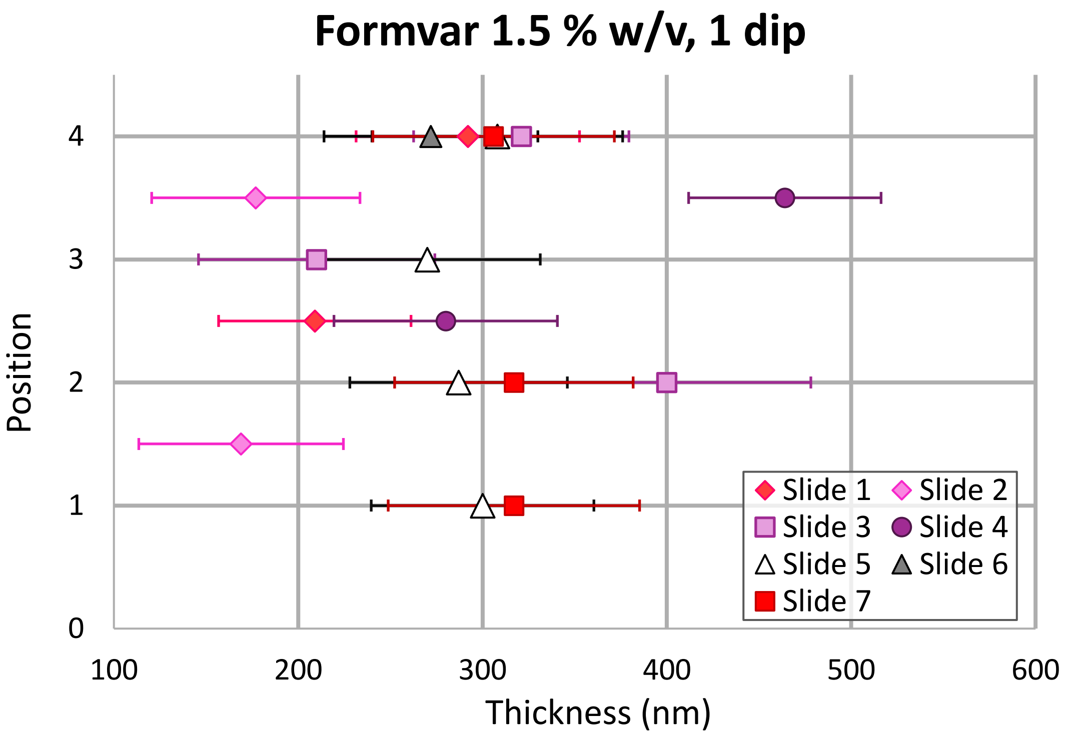
X-Ray Attenuation technique

Formvar foils

Metal-coatings

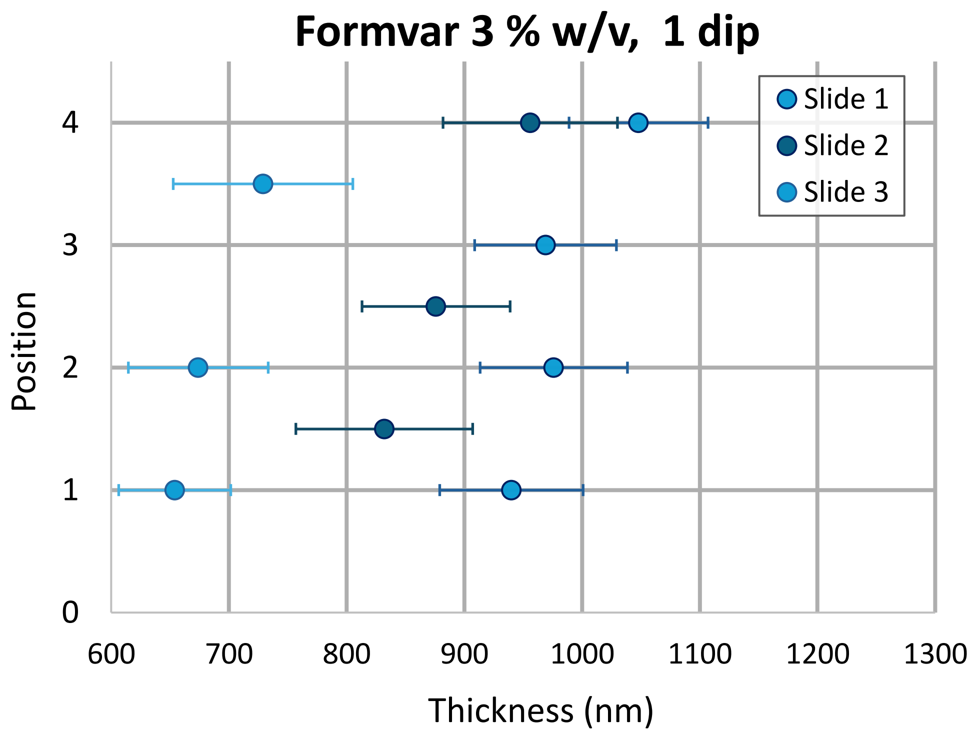
Formvar foil characterisation

For the AEL technique, the foil thickness is calculated through CSDA: $d = \sum_{E_j=E_i}^{E_f} -\frac{\delta E}{S_{\text{avg}}(E_j)}$



Thickness of Formvar 1.5 % w/v foils.

$$\langle d \rangle = (290 \pm 70)\ \text{nm}$$



Thickness of Formvar 3 % w/v foils.

$$\langle d \rangle = (870 \pm 140)\ \text{nm}$$

Metal-coating characterisation

The closest facility where we could perform RBS measurements:

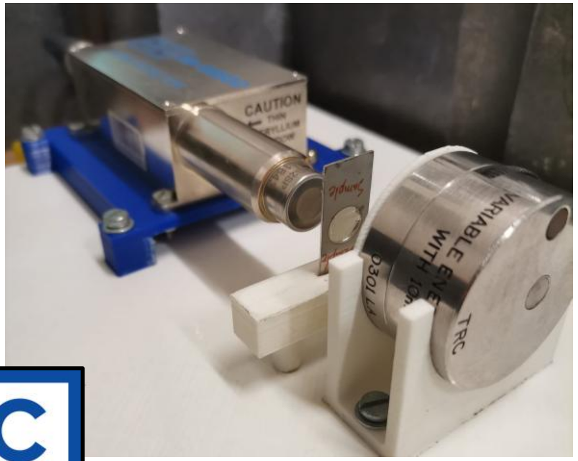
- LATR facility of the CTN-IST.

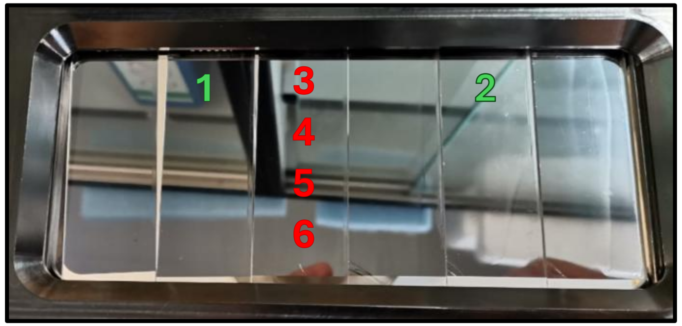
Soft X-ray attenuation of Formvar foils is very low!

- Allows to characterize the metal-coatings' thickness with accuracy *in situ*.

2.5 MV Van de Graaff accelerator at LATR.

Setup to characterize targets with X-rays.



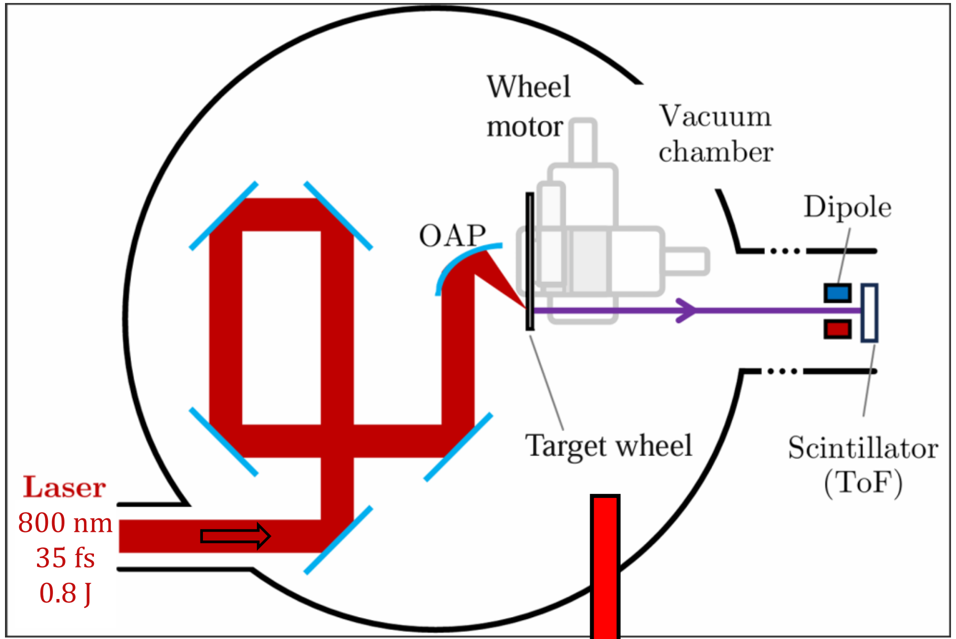


Position of characterised targets from glass slides (viewed from above).

Characterisation of the Ag-coatings.

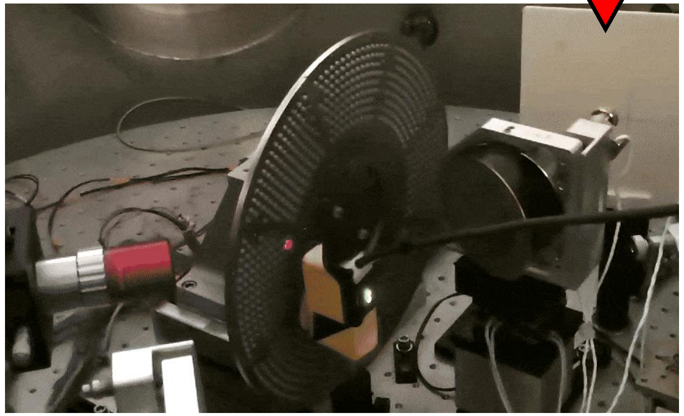
Film ID	XRA ($\mu g/cm^2$)	RBS ($\mu g/cm^2$)
1	70 ± 10	71 ± 4
2	77 ± 7	---
3	110 ± 30	---
4	90 ± 10	78 ± 4
5	90 ± 10	79 ± 9
6	100 ± 10	81 ± 9

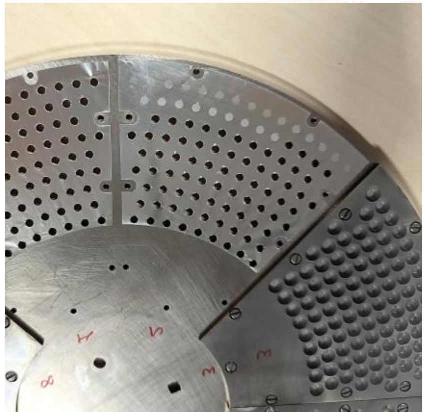
L2A2 setup

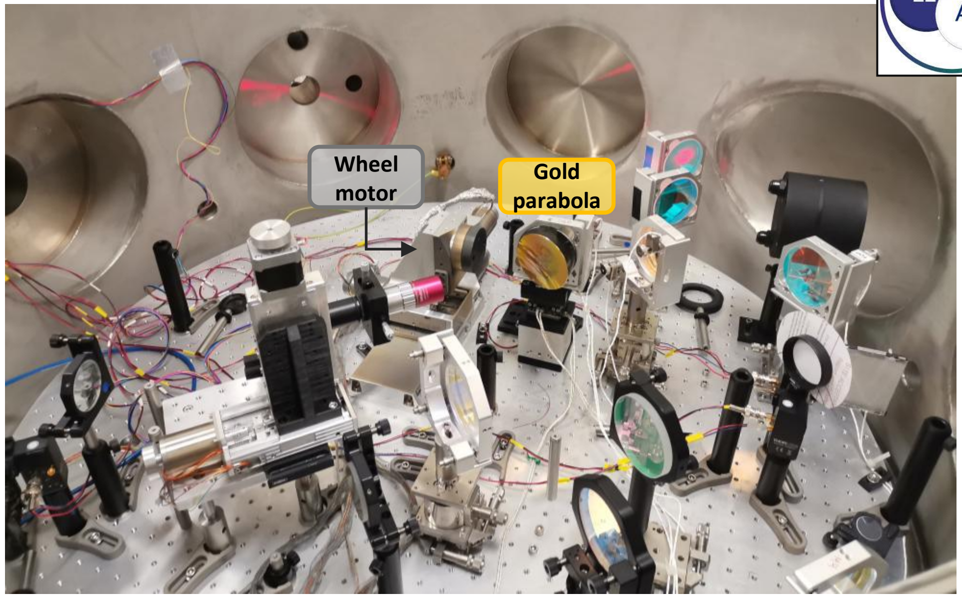


J. Penãs et al, High Power Laser Science and Engineering, Vol. 12 (2024)

- STELA laser system:
  - Ti:Sapphire, 45 TW laser;
  - p-polarized, 800 nm-wavelength pulses;
  - Intensity: $I \sim 7 \times 10^{19}$ $\mathrm{W\ cm^{-2}}$.
- Multi-shot target wheel assembly:
  - Hosts more than 5000 targets;
  - Operates at rates up to 10 Hz.

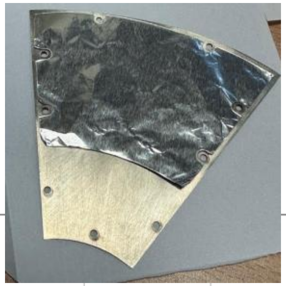






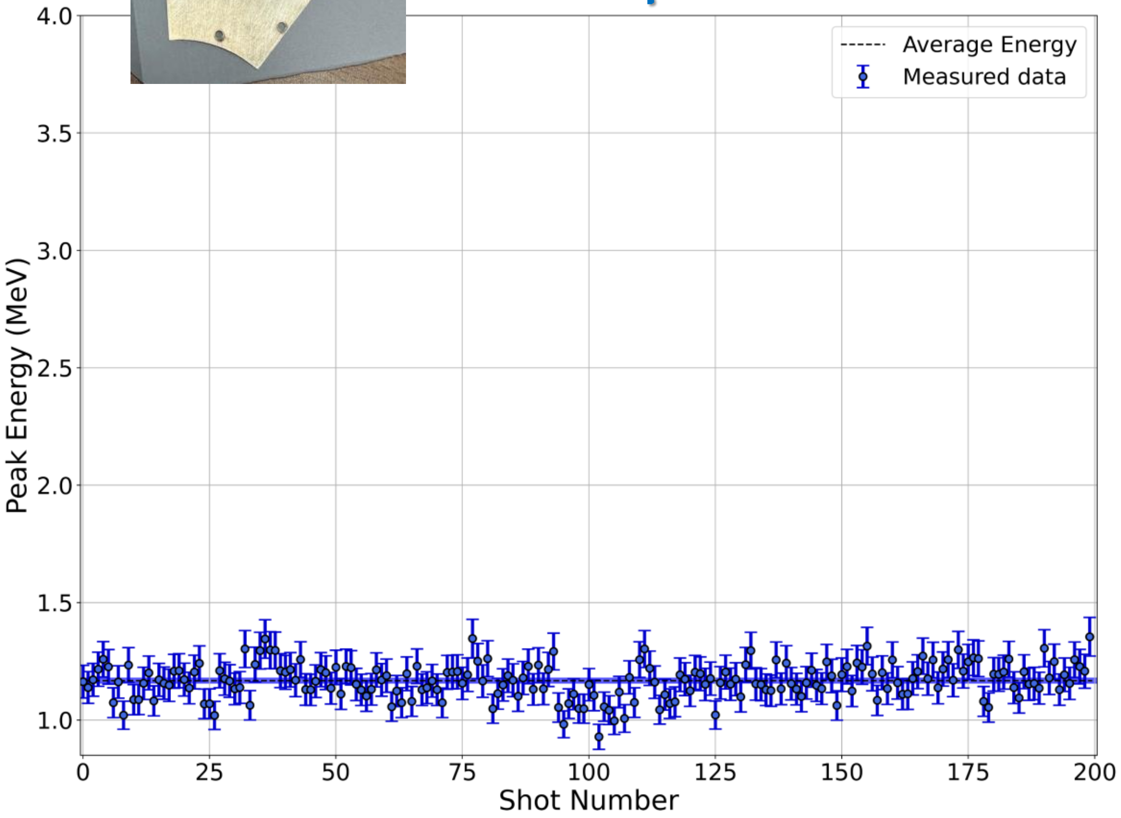
Picture of the vacuum chamber's interior from the experimental setup used at L2A2-USC.

Proton cut-off energy – plain Al and Formvar foils



Plain Al foils

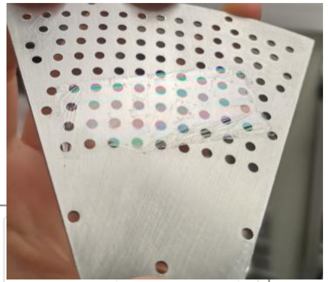
$d = 8\ \mu m$

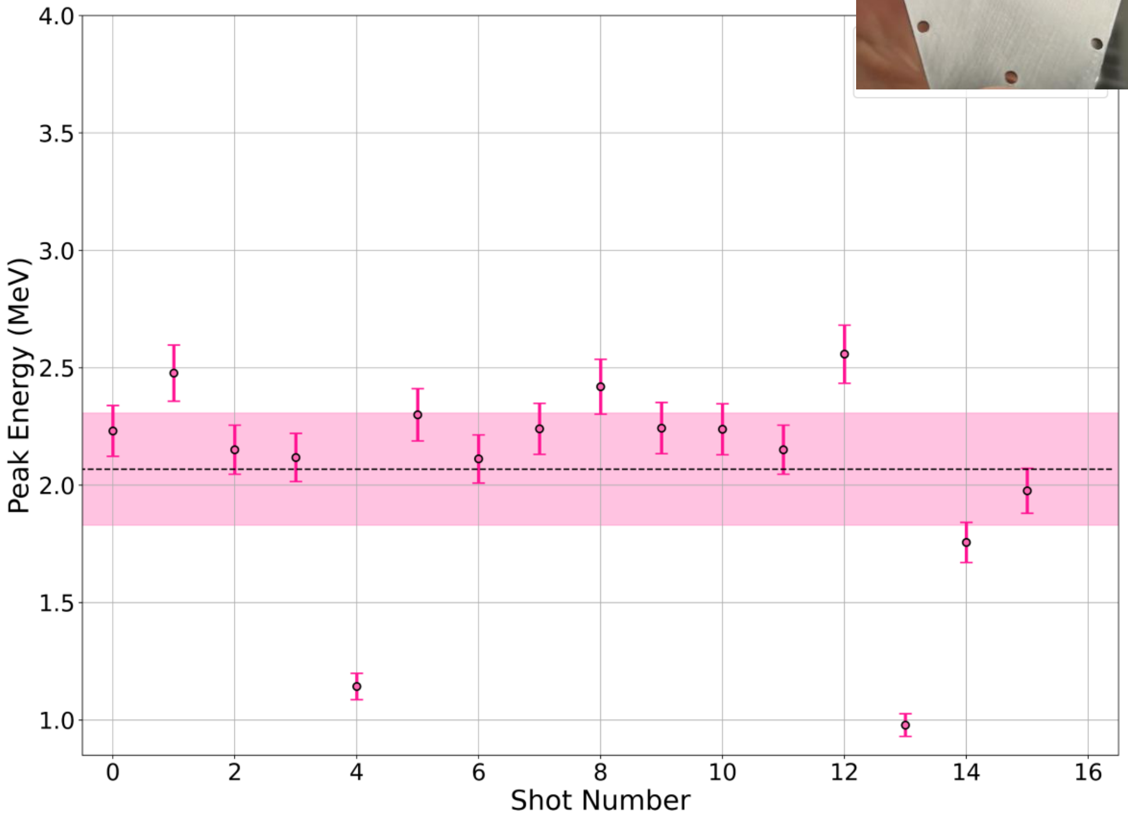


$\langle E_{peak} \rangle = (1.17 \pm 0.01)$ MeV

Plain Formvar 3% w/v foils

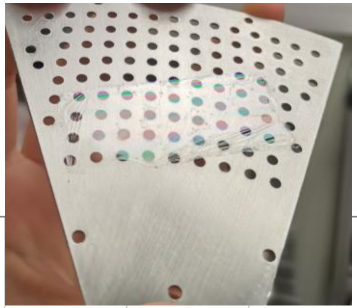
$\langle d \rangle = 870$ nm





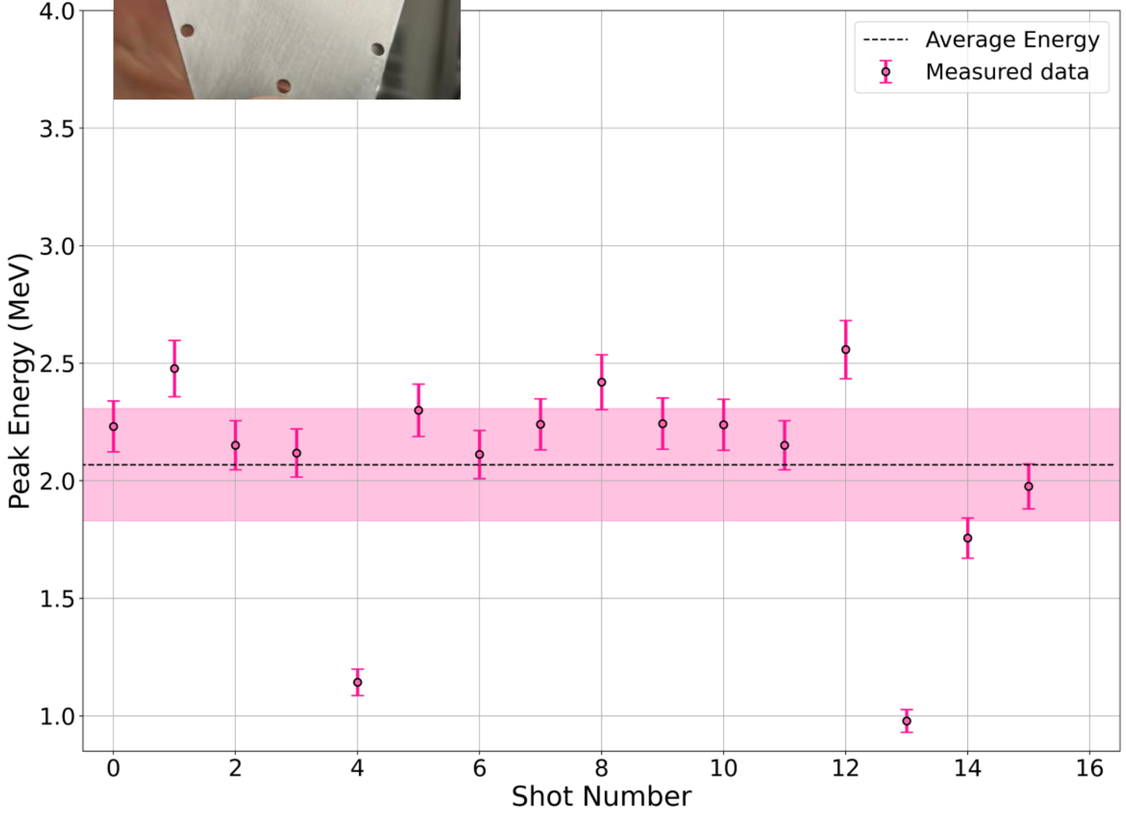
$\langle E_{peak} \rangle = (2.1 \pm 0.2)$ MeV

Proton cut-off energy – plain Formvar foils



Plain Formvar 3% w/v foils

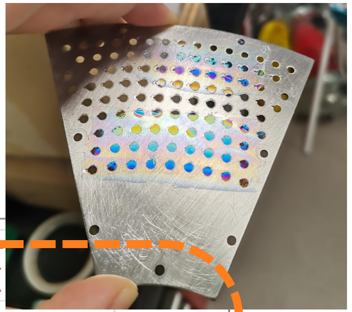
$\langle d \rangle = 870$ nm

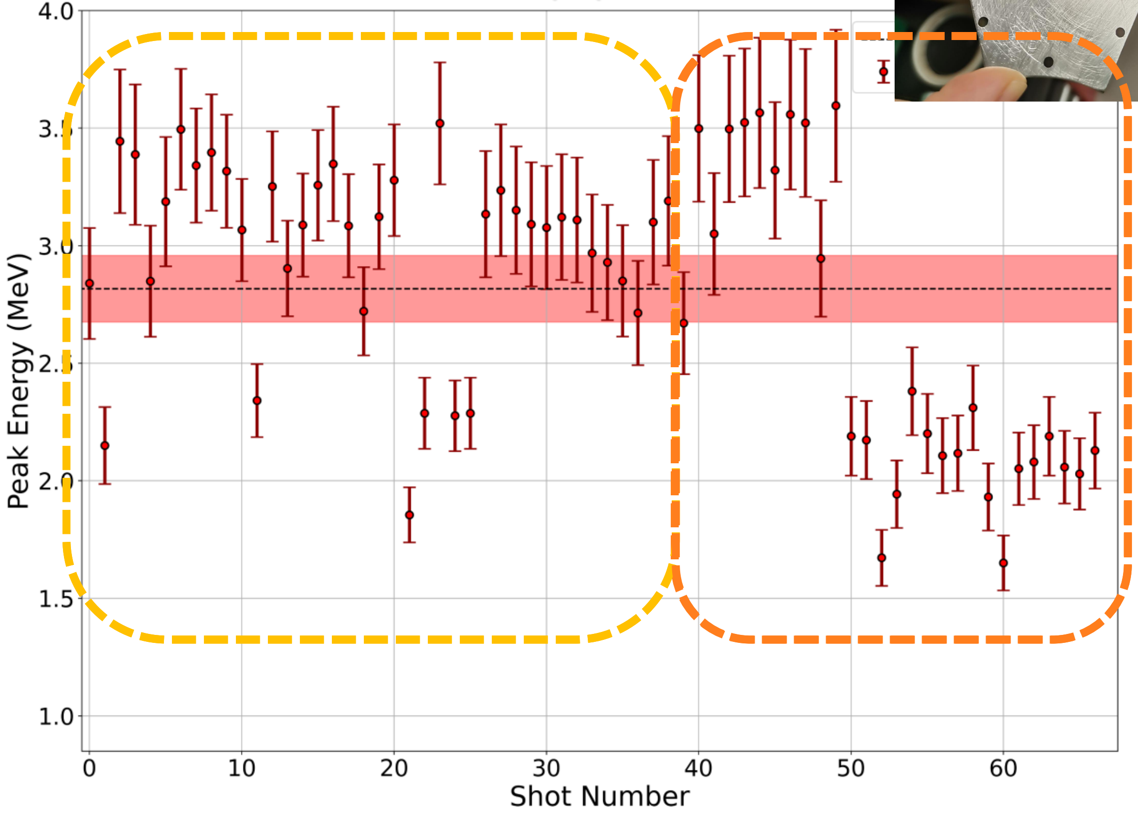


$\langle E_{peak} \rangle = (2.1 \pm 0.2)$ MeV

Plain Formvar 1.5% w/v foils

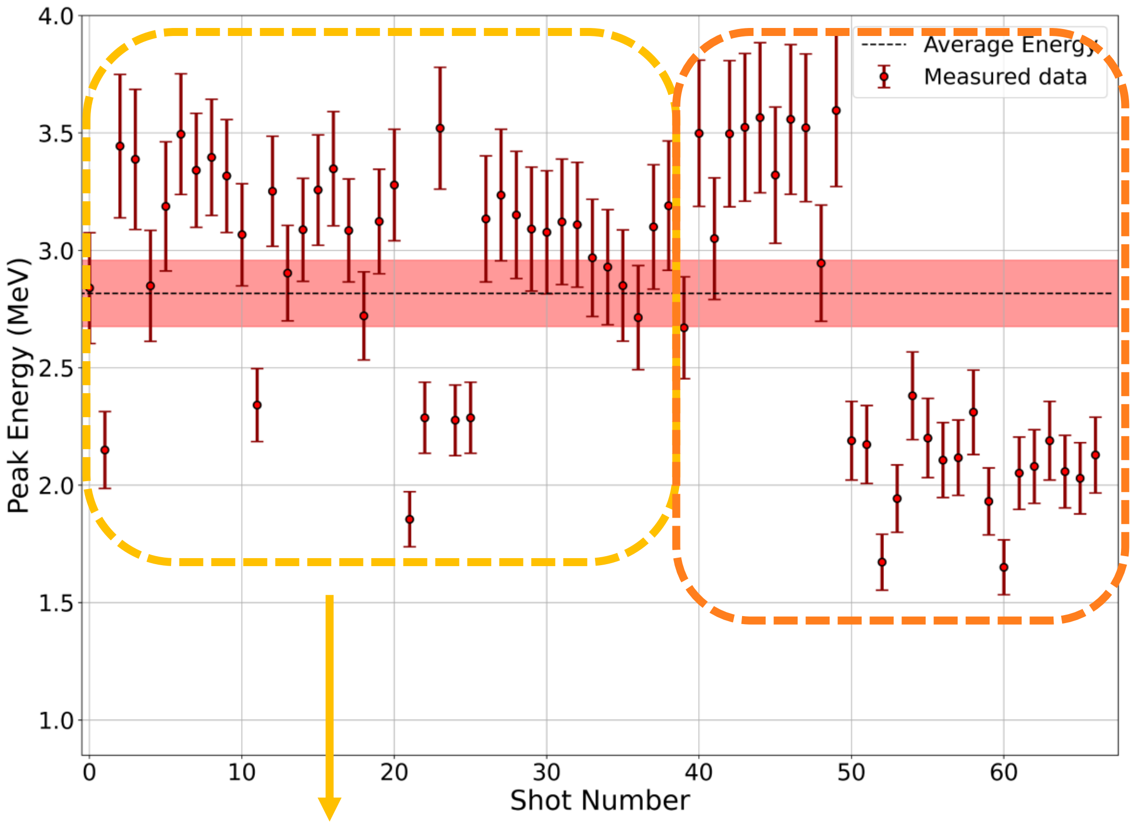
$\langle d \rangle = 290$ nm



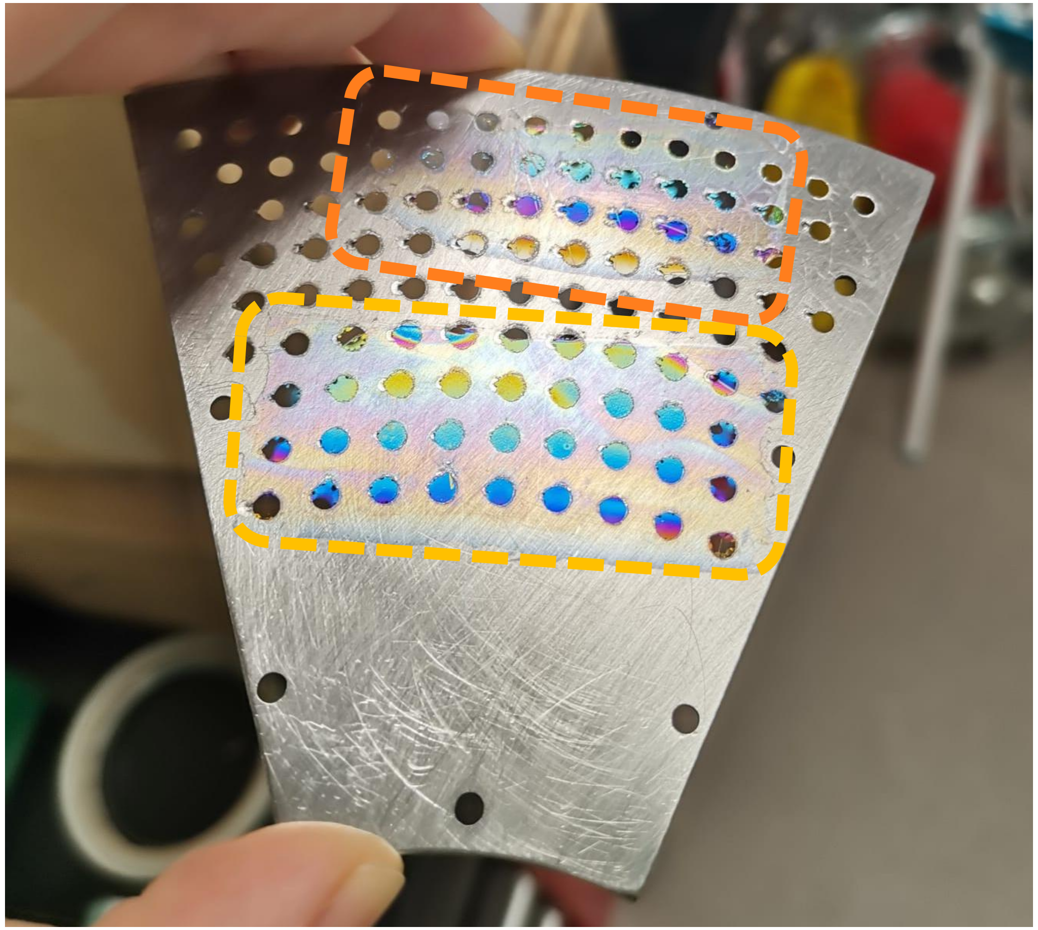


$\langle E_{peak} \rangle = (2.8 \pm 0.1)$ MeV

Proton cut-off energy – plain Formvar foils

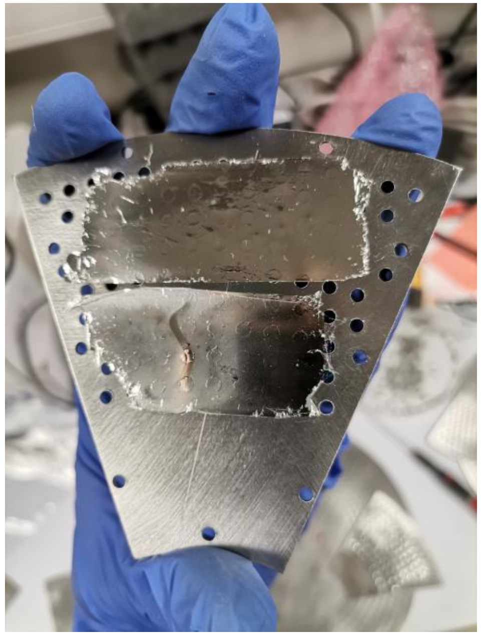


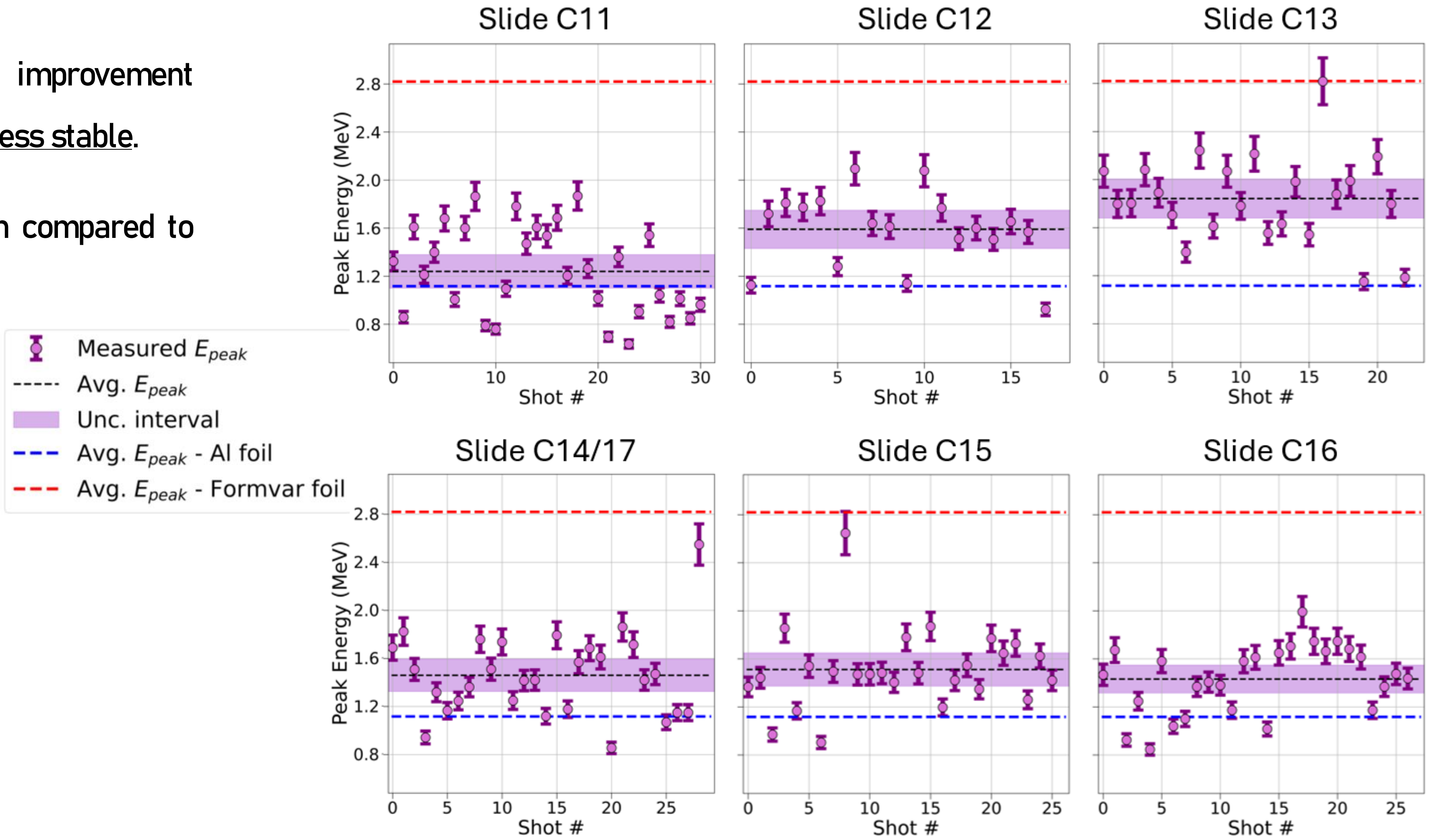
$\langle E_{peak} \rangle = (3.0 \pm 0.1)$ MeV



Proton cut-off energy – Ag-coated Formvar films

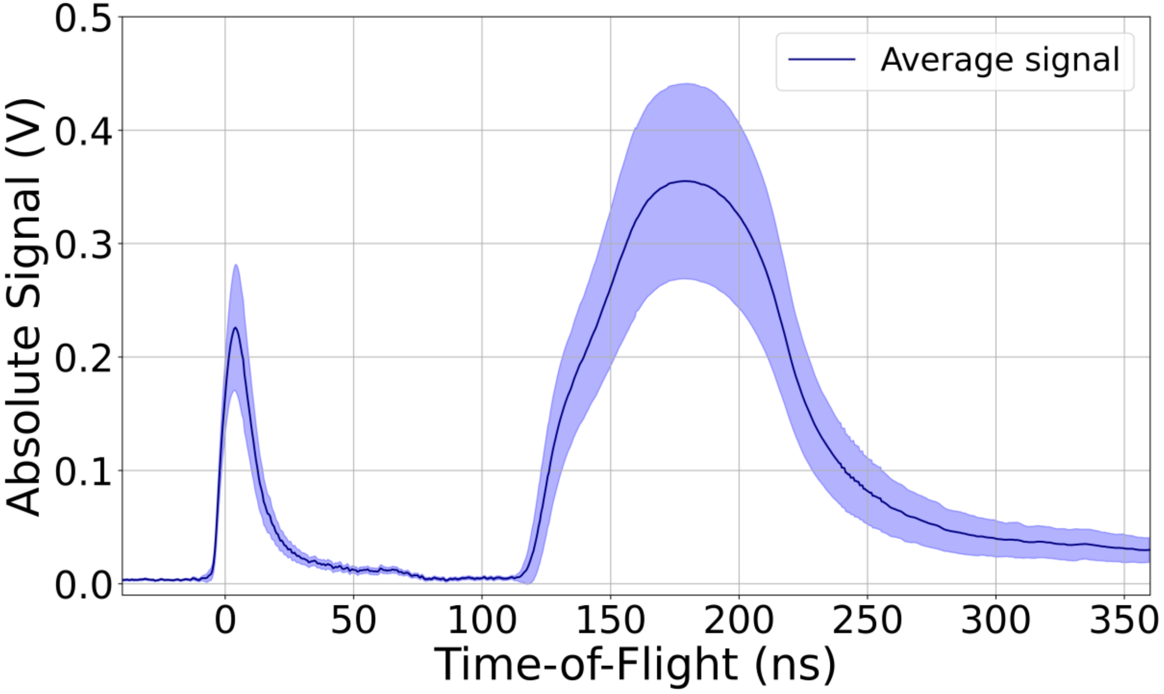
- Ag-coated Formvar films show an improvement over plain Al foils, but they are also <u>less stable</u>.
- Peak energy values are <u>lower</u> when compared to plain Formvar foils.



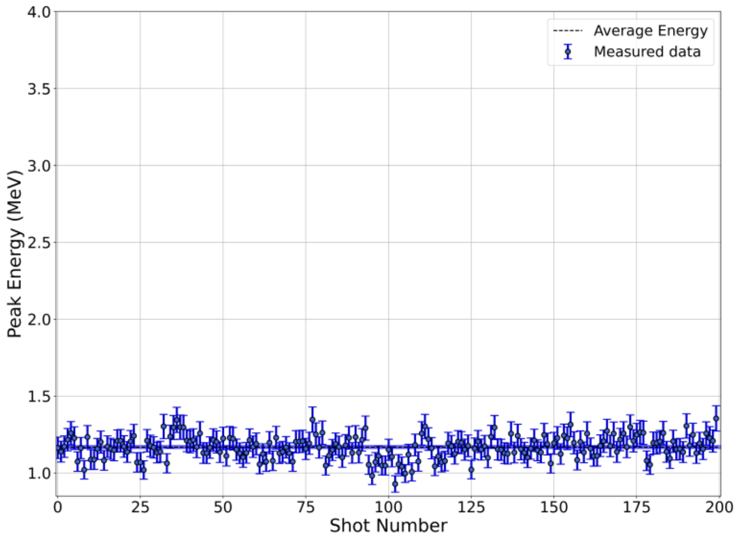


Peak energy evolution from **Ag-coated** Formvar film burst measurements.

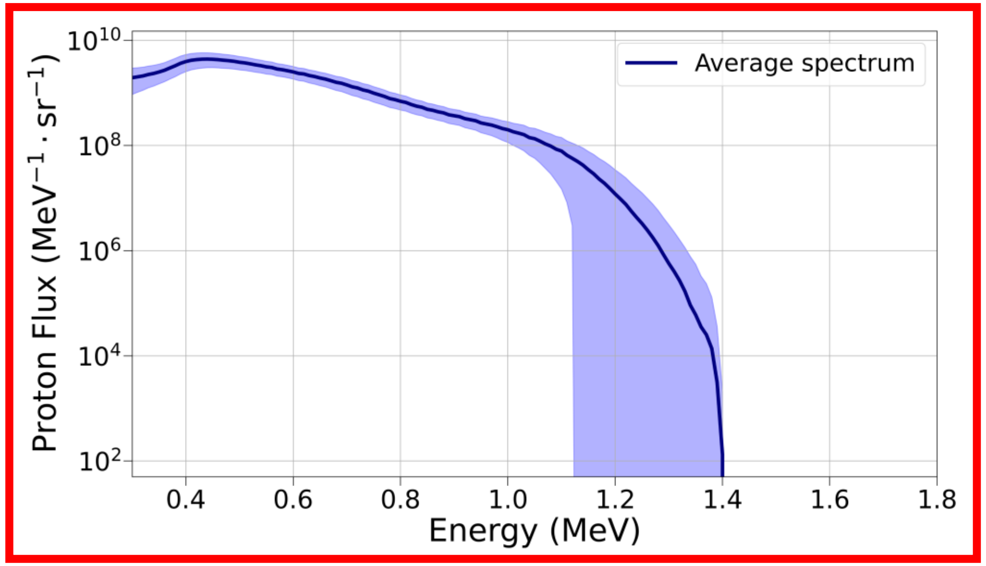
Proton flux – plain Al foils



Average ToF-signal curve from the plain Al foils.

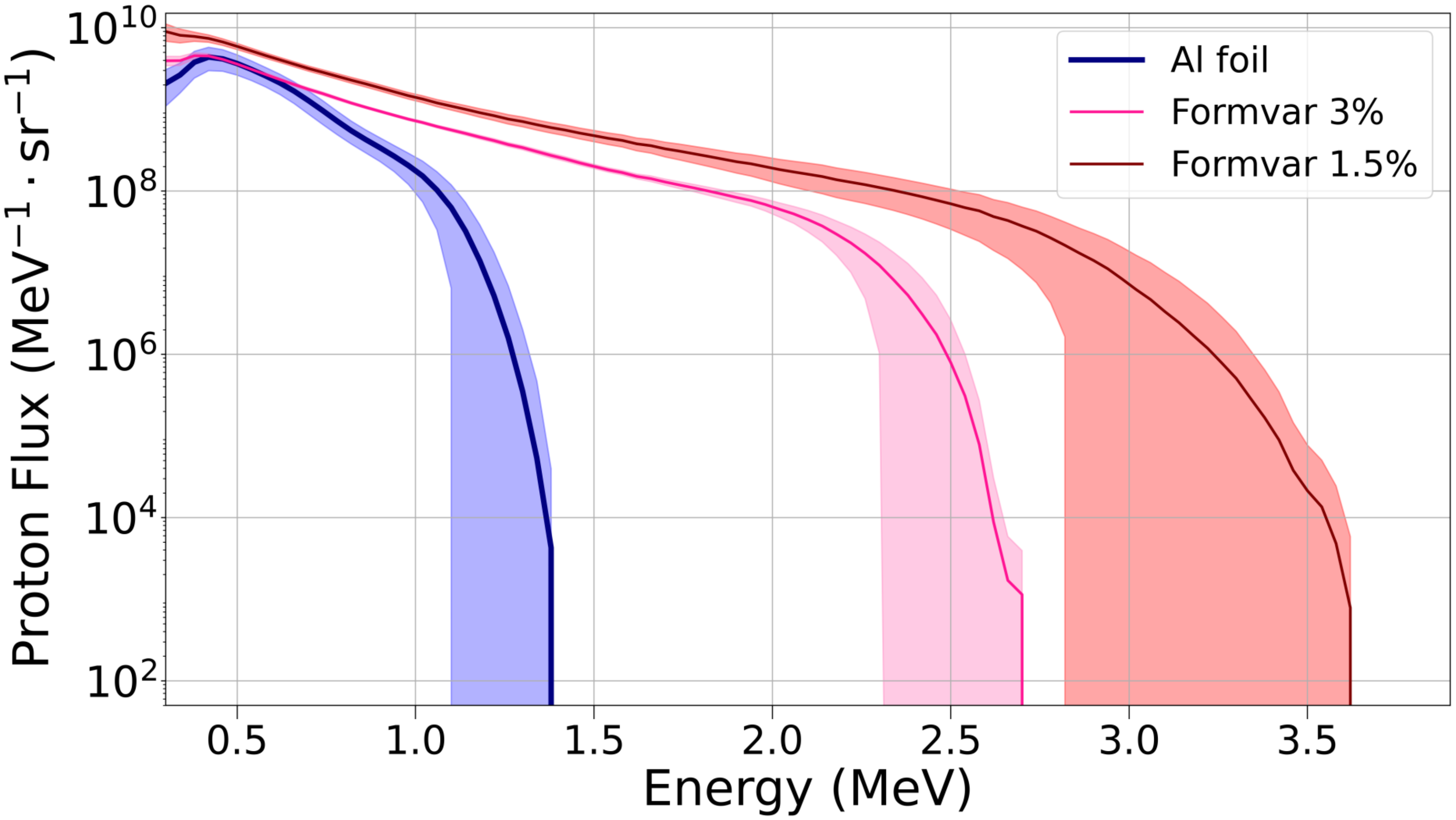


Peak energy from the plain Al foils.



Average flux spectrum from the plain Al foils.

Proton flux – improvements from plain Formvar foils

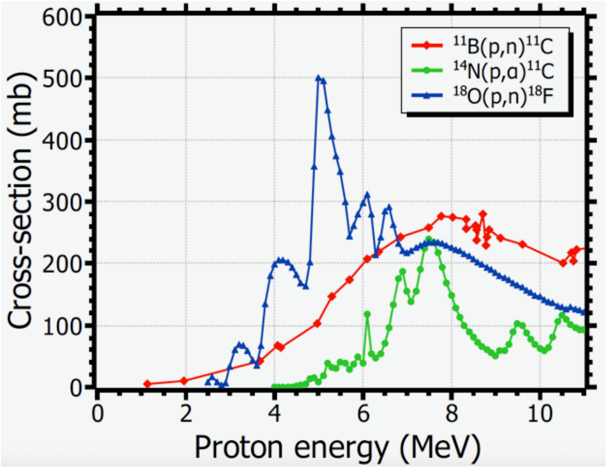


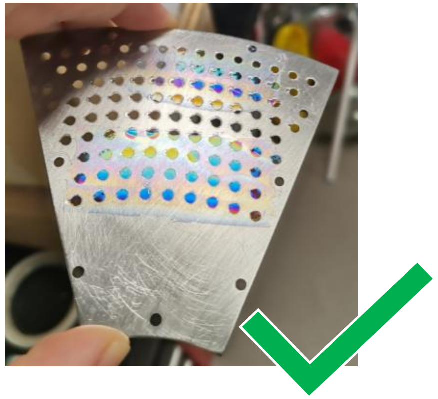
Comparison of average proton flux curves for the Al, Formvar 1.5 % w/v and 3 % w/v foils.

Conclusion

In summary:

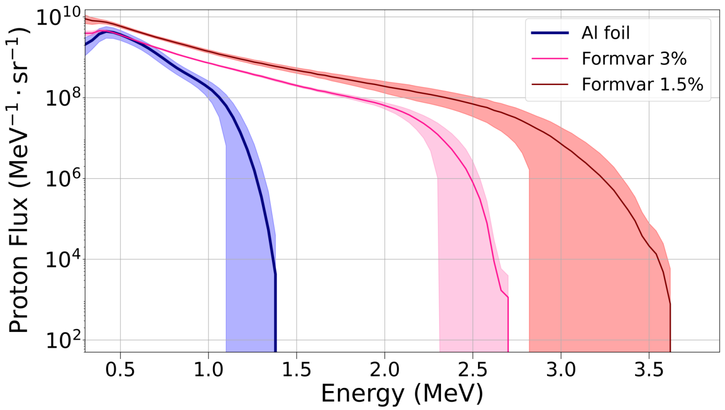
1. Plain Formvar foils achieved much higher energies and proton fluxes;
   - ➢ Surface quality is crucial for film performance;
2. Metal-coated Formvar films showed less improvements ⟹ <u>unexpected</u>





Outlooks:

- More in-depth study with particle-in-cell simulations;
- Further testing with <u>thinner</u> Formvar foils;
- Standardise film's shape for wheel sectors.



Acknowledgements

NUC-RIA and LIP:

Daniel Galaviz; Pamela Teubig; Ricardo Pires; Margarida Paulino; Raquel Nunes.

IGFAE-USC:

Aarón Alejo; Adrián Bembibre.

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Questions?

Time of flight techniques

Time to energy conversion

$$v_p = \frac{L}{\Delta t} = \frac{L}{t_p + L/c} \Longrightarrow E_{\text{proton}} = \frac{m_p}{2} v_p^2 = \frac{m_p}{2}\left(\frac{L}{t_p + L/c}\right)^2$$

Signal to ion flux conversion

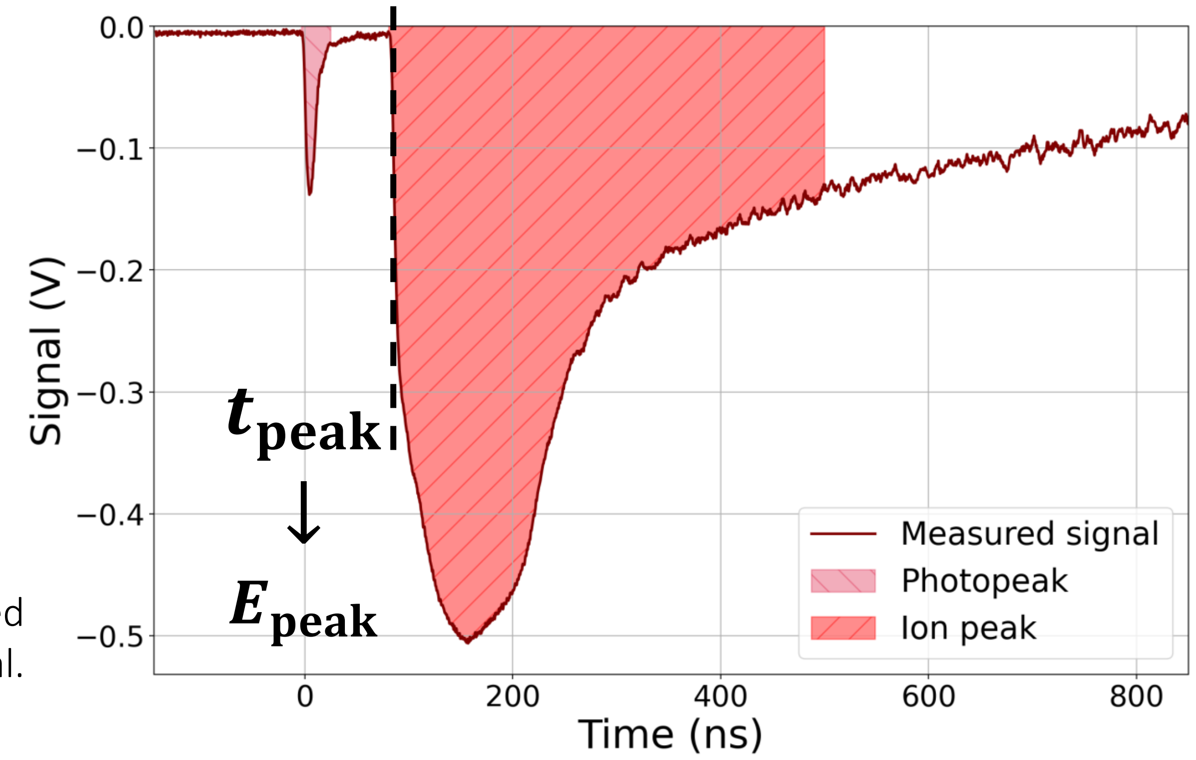
$$N_i = \frac{V_i}{m - \alpha V_i} \cdot \frac{1}{E_i \Omega_{\text{det}}} \cdot \frac{\delta t}{100\ \text{ns}}$$

M. Seimetz et all, IEEE Transactions on Nuclear Science

Calibration and Performance Tests of Detectors for Laser-Accelerated Protons

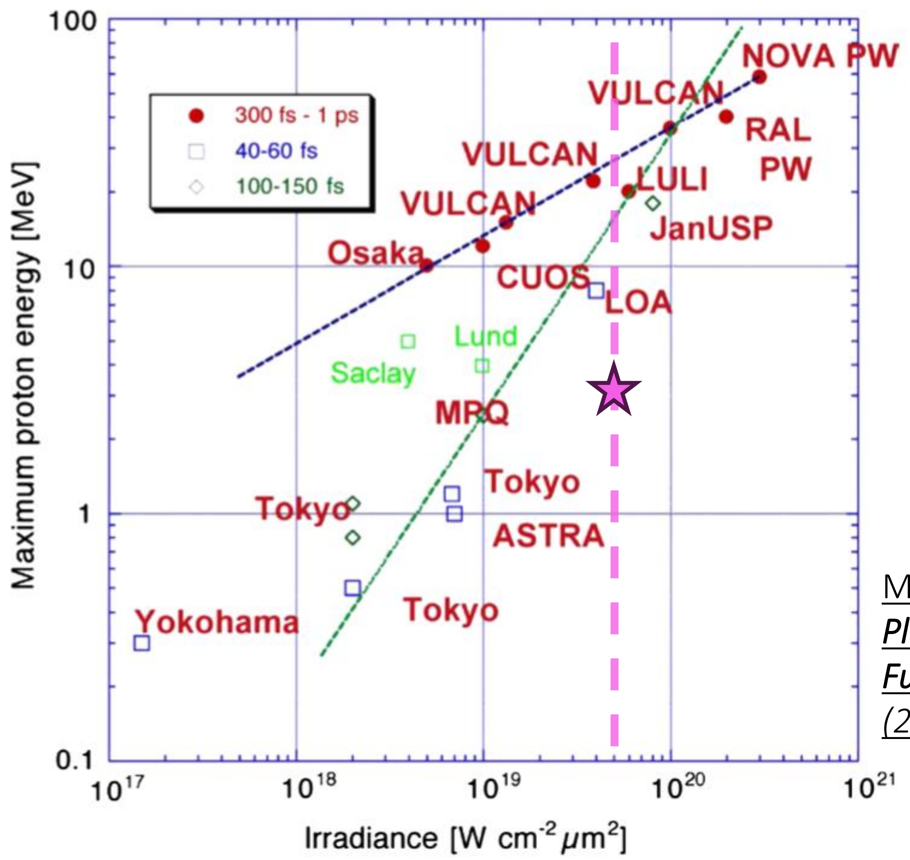
M. Seimetz, P. Bellido, A. Soriano, J. García López, M. C. Jiménez-Ramos, B. Fernández, P. Conde, E. Crespo, A. J. González, L. Hernández, A. Iborra, L. Moliner, J. P. Rigla, M. J. Rodríguez-Álvarez, F. Sánchez, S. Sánchez, L. F. Vidal, and J. M. Benlloch

Example of a measured time-of-flight signal.



Compared to other studies…

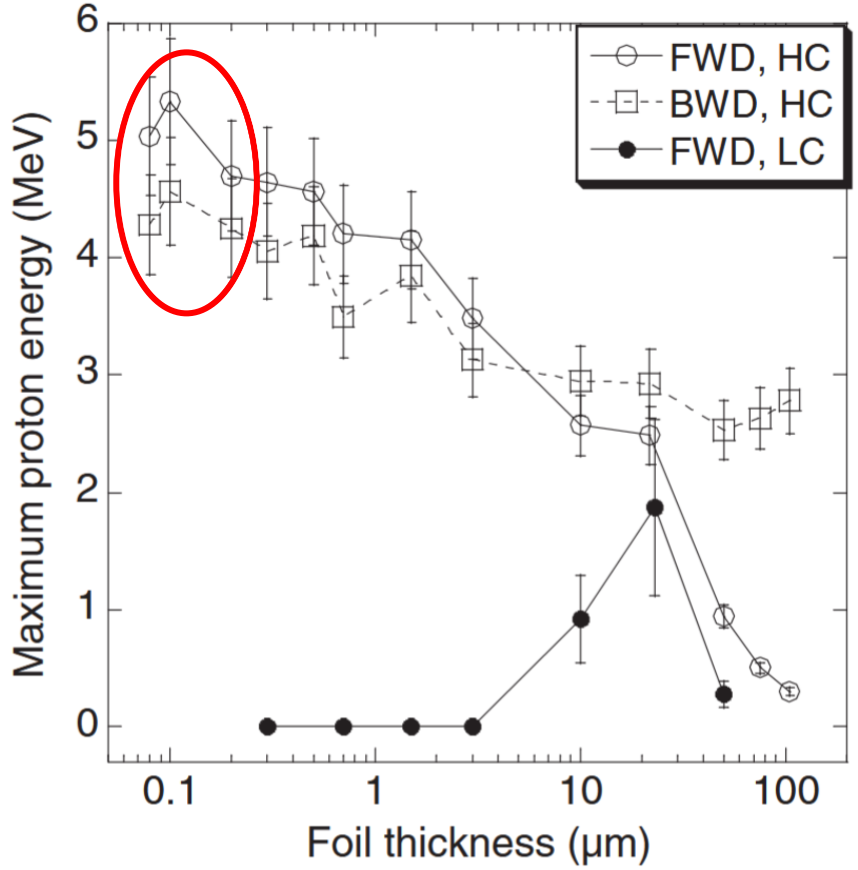
$$I\lambda^2 \sim 7 \times 10^{19} \times (800\text{ nm})^2 \sim 5 \times 10^{19}\text{ W cm}^{-2}\mu\text{m}^2$$



M.Borghesi *et all*, ***Plasma Phys. Controlled Fusion 50, 124040*** *(2008)*

Maximum proton energy from laser-irradiated solid targets as a function of the laser irradiance and for three ranges of pulse durations

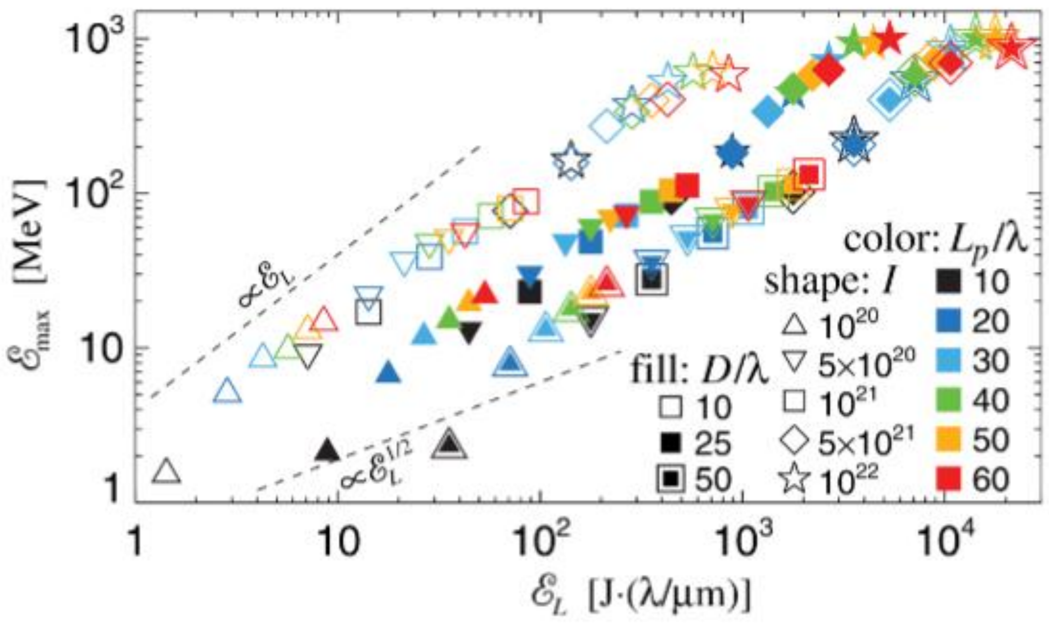
T. Ceccotti *et all, Proton Acceleration with High-Intensity Ultrahigh-Contrast Laser Puses,* ***PRL 99, 185002*** *(2007)*



Variation of maximum detectable proton energy as a function of target thickness for $10^{19}\ \text{W/cm}^2$. HC is 10^{10} and LC is 10^6.

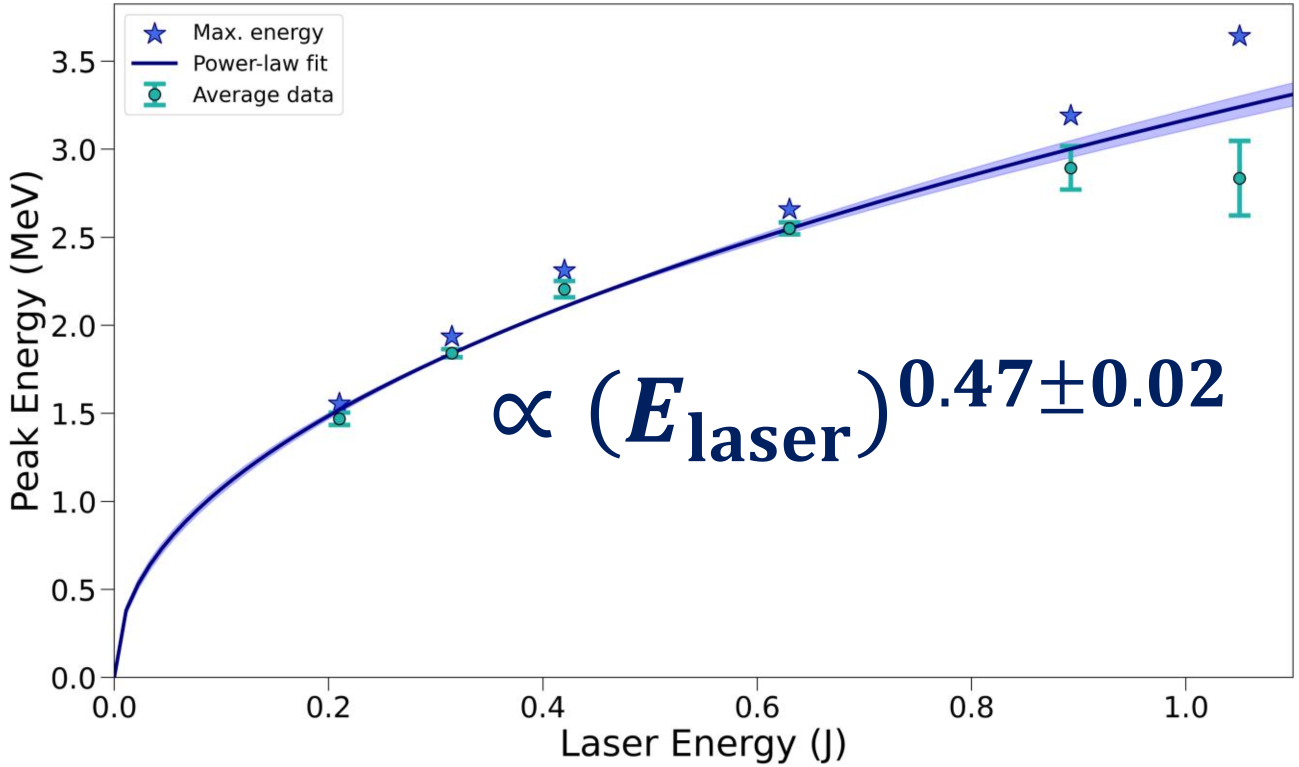
Normalisation to laser energy

Used as reference for



Results from multiparametric 2D simulations for a double layer target fit.

A. Macchi *et all, Ion acceleration by superintense laser-plasma interaction, RMP (2013)*

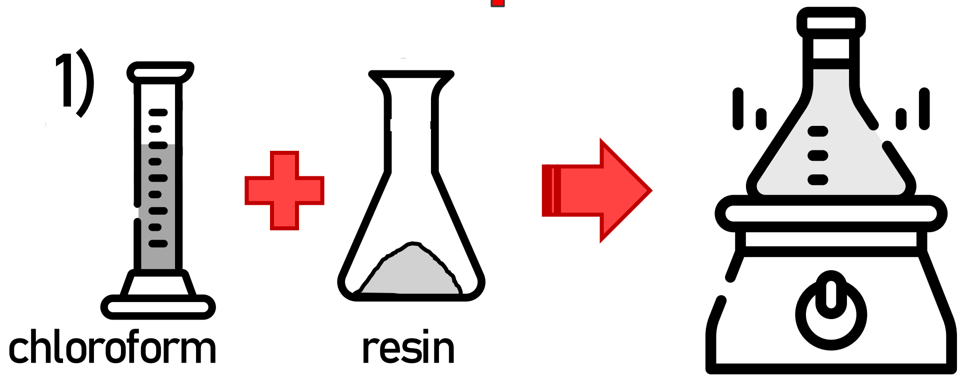


Measured peak energy — laser-energy relation, with power-law fit.

Formvar production – Protocol

General Steps:

1)



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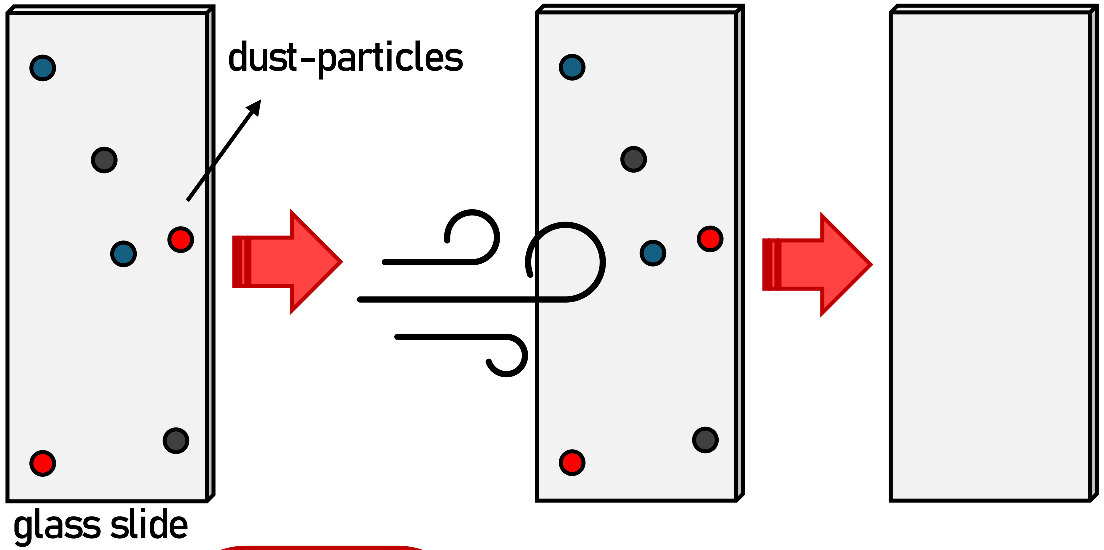

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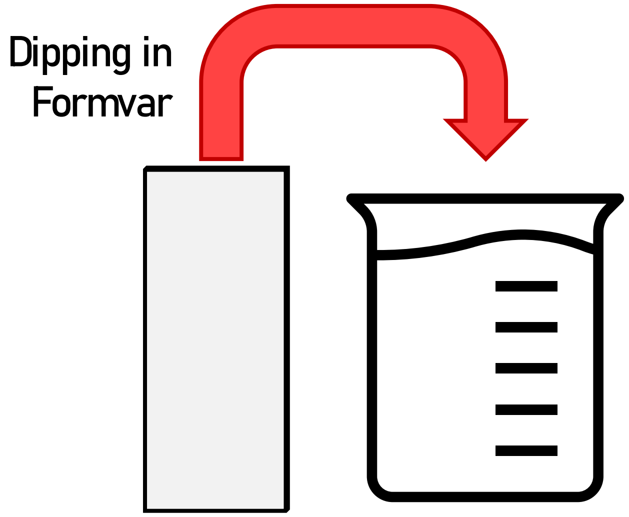

4)