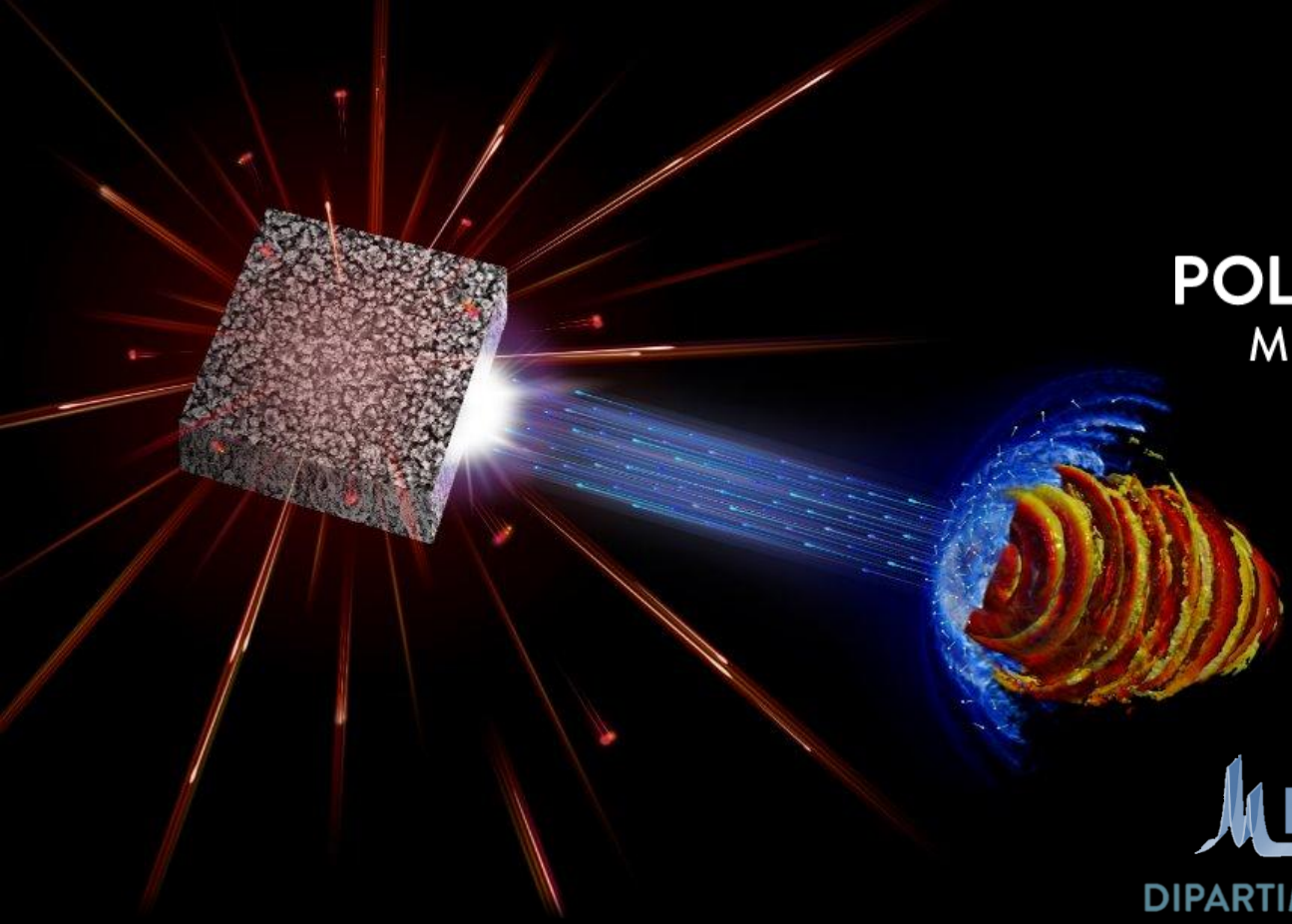


POLITECNICO
MILANO 1863

Francesco Mirani

NanoLab
DIPARTIMENTO DI ENERGIA

Laser-Driven Particle Acceleration Research at Politecnico di Milano and its Applications to Cultural Heritage Studies

18th November 2025

2nd INFN School and Workshop on **"High Power Lasers for Fundamental Science and Applications" (HPLA2025)**

- Our group from POLITECNICO MILANO 1863 and collaborations:


M. Passoni
Principal Investigator


A. Maffini


F. Mirani


M. Galbiati


D. Vavassori


K. Ambrogioni


S. De Magistris


D. Orecchia


D. Dellasega


V. Russo


M. Iaccarino


D. Mazzucconi


A. Pola


F. Casamichiela

- The ELI with


L. Lancia

(Laboratoire pour l'Utilisation des Lasers Intenses)

- The CLPU CENTRO DE LÁSERES PULSADOS with


L. Volpe

- The eli Beamlines with

(Access to the facility through the 5th User call)


D. Margarone


L. Giuffrida

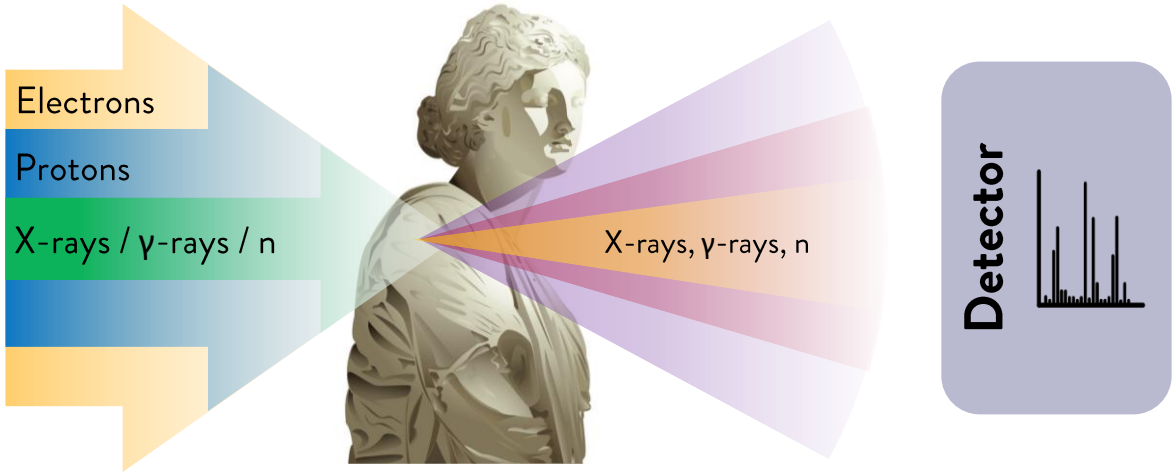
- The Consiglio Nazionale delle Ricerche | SPC ISTITUTO DI SCIENZE DEL PATRIMONIO CULTURALE with


C. Conti

- The RAYLAB DETECTING INNOVATION company with


D. Rastelli

What are the materials analysis techniques used in cultural heritage studies?



Particle Induced X-ray Emission (PIXE)

- MeV protons → X-rays
- 0-10s μm, homogeneous and stratigraphic
- low-Z elements

X-Ray Fluorescence (XRF) spectroscopy

- keV photons → x-rays
- 10s μm, homogeneous samples, elemental mapping
- high-Z elements

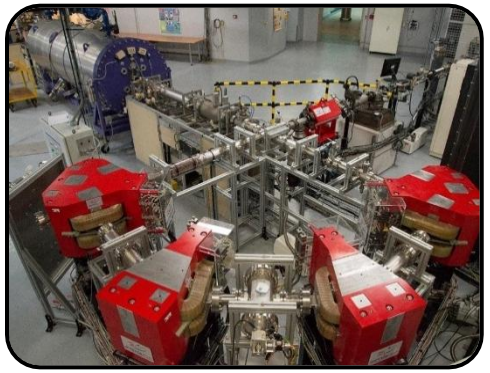
Activation Analysis (PAA, NAA) and **Radiography**

- Neutrons, MeV photons → γ-rays
- Homogeneous, bulk

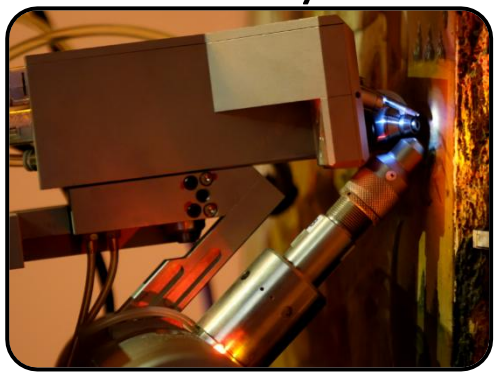
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.
E. H. Lehmann, *J. Archaeol. Sci. Rep.* 19 (2018): 397-404.
P. A. Mandò, et al. *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At.* 239.1-2 (2005): 71-76.
J. Salomon, et al. *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At.* 266.10 (2008): 2273-2278.

Why laser-plasma sources can be interesting for the analysis of artworks?

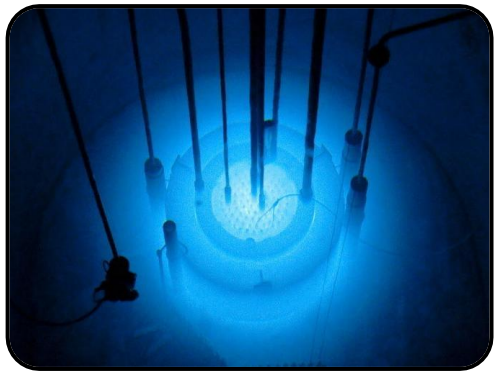
Particle **accelerators**



Portable **X-ray tubes**

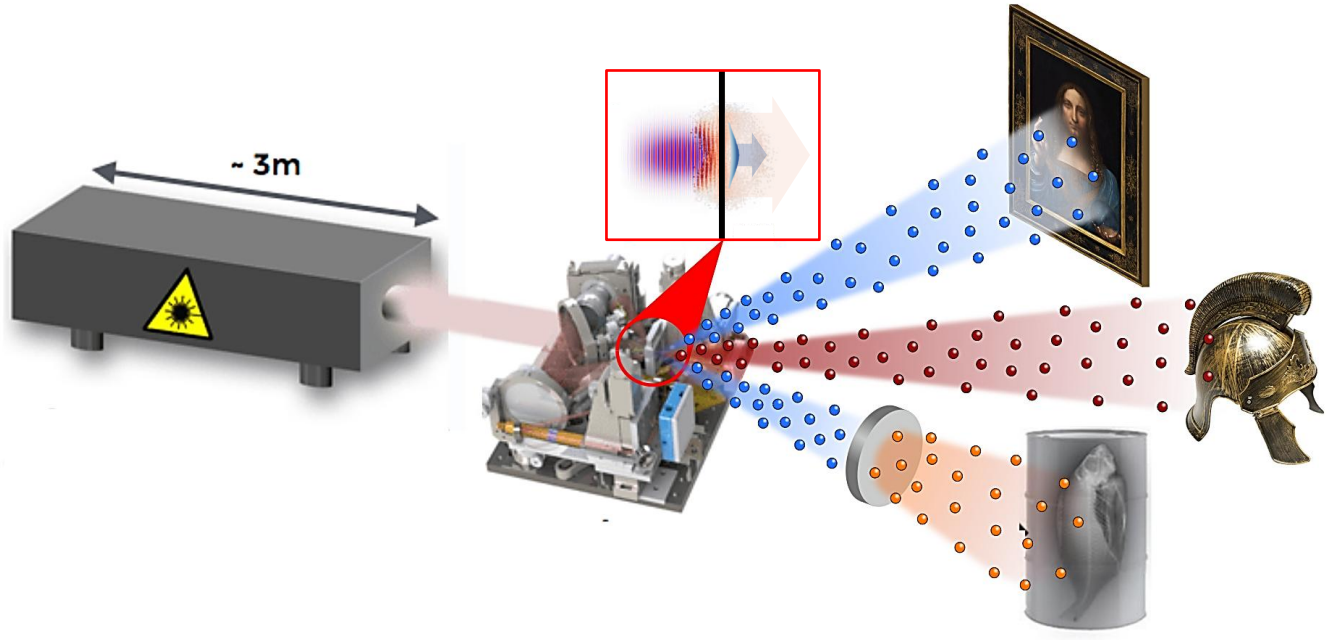


Neutron / γ-ray **sources**



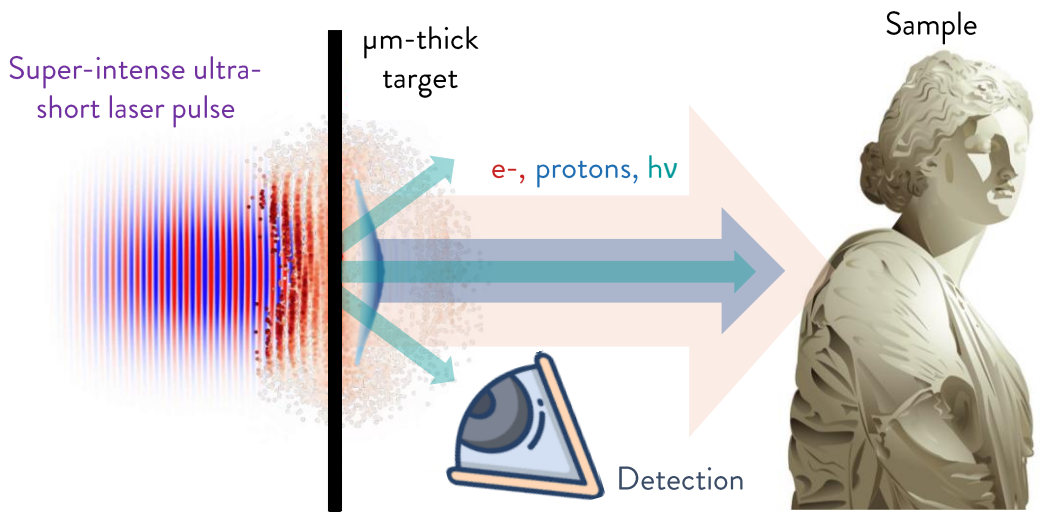
- **Different conventional sources** for specific techniques

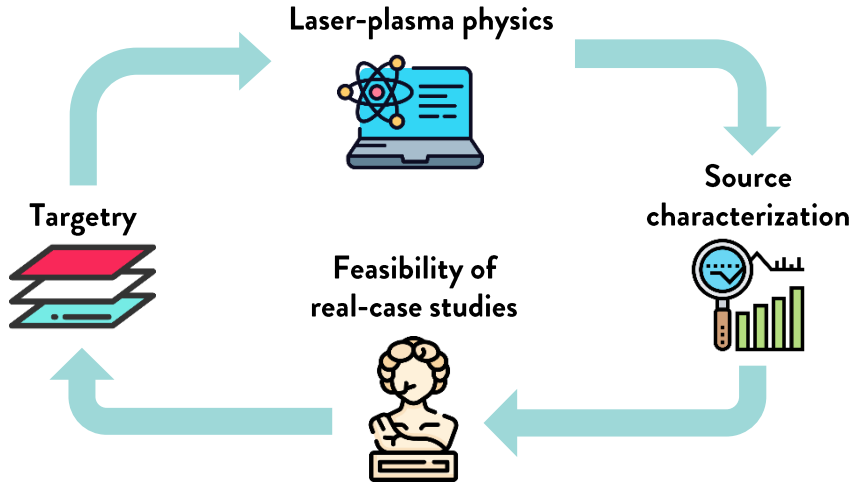
Laser-plasma accelerators are potentially **compact** and **multi-purpose.**



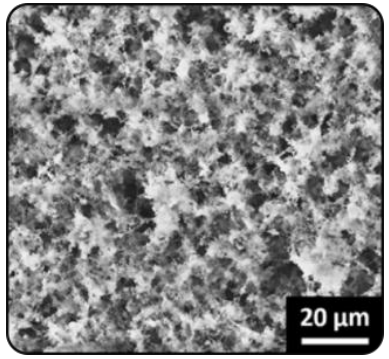
M. Passoni, et al. *PPCF*, 62(1), (2019): 014022.
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.

To this aim, several aspects must be investigated…

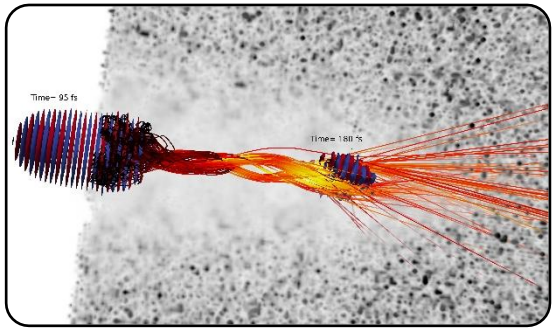




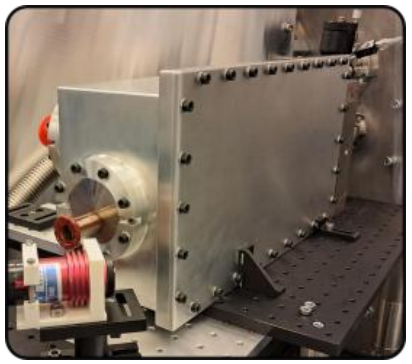
Production of **advanced targets** with deposition techniques



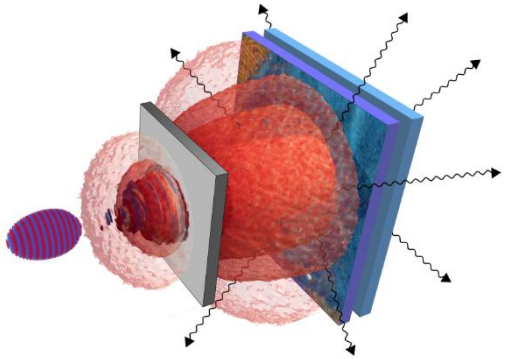
Theoretical and experimental investigation of **laser-plasma interaction**



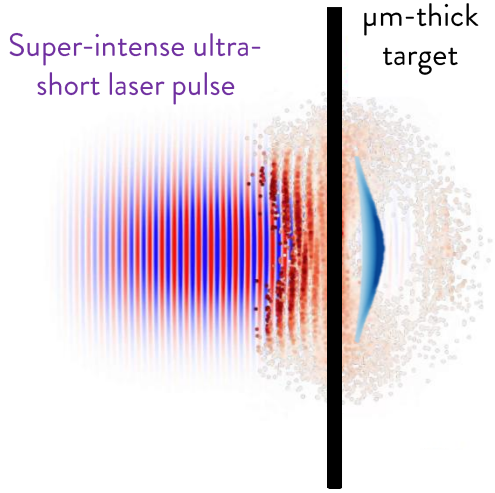
Development of **diagnostics** of laser-driven proton beams



Assessment of applications like **artworks characterization**



Advanced targets with deposition techniques: solid foils

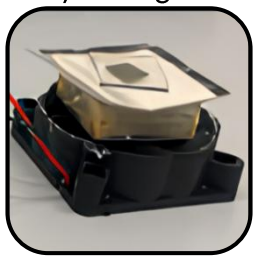


- **Control target** properties (thickness, composition, etc.) → **Tune the energy** of TNSA ions
- Shot-to-shot **stability crucial for applications** → **Not ensured** by commercial targets

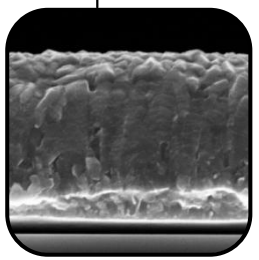
Developed strategy for **metallic target deposition** via Magnetron Sputtering

- 0.05 – 5 μm thicknesses, negligible uncertainty
- Al, Ti, Cu, …

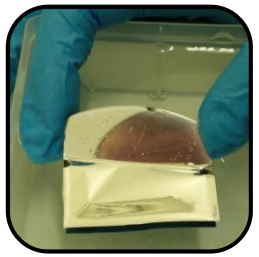
Spin coating of soap layer on glass



Metallic target deposition



Soap removal in water

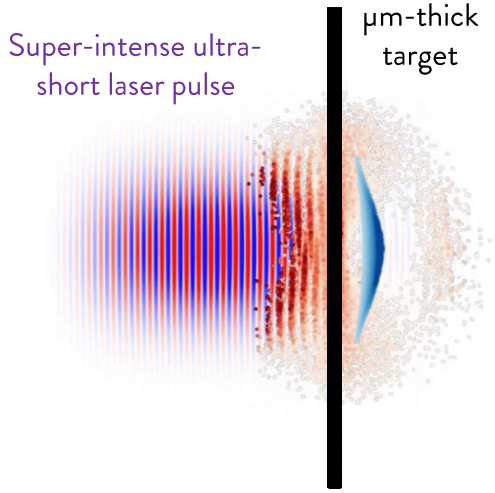


Target fishing on the holder

F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

A. Maffini, et al. *Submitted to PPCF* (2025).

Advanced targets with deposition techniques: solid foils



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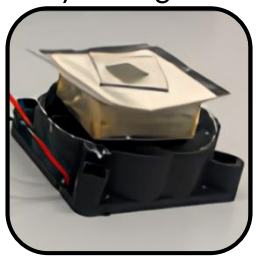

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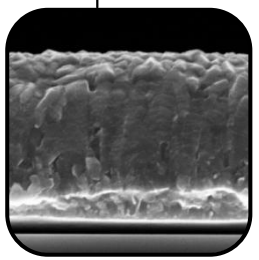
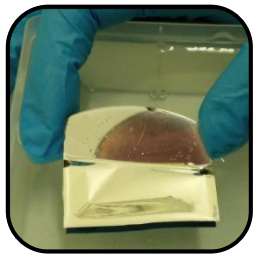
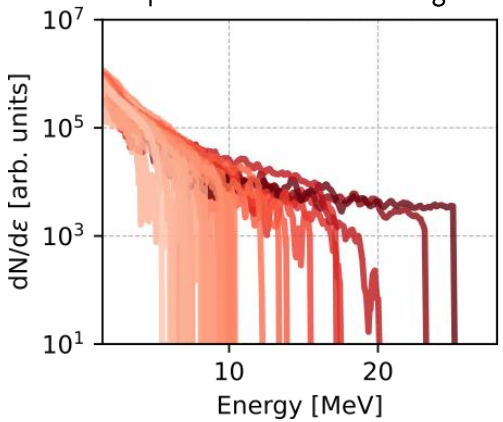


Soap removal in water

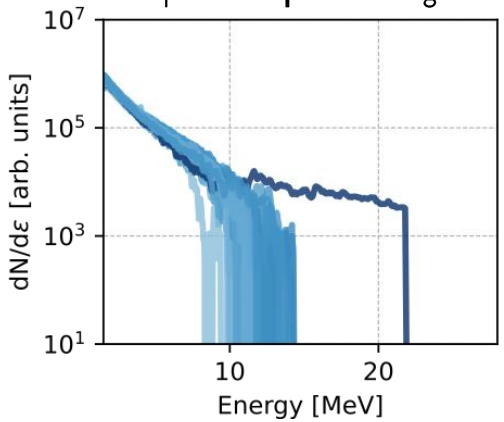


Target fishing on the holder

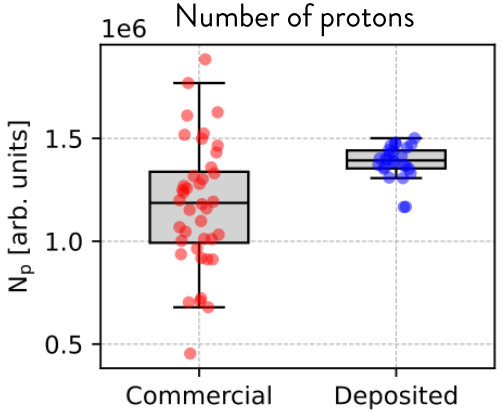
2 μm Al **Commercial** Target



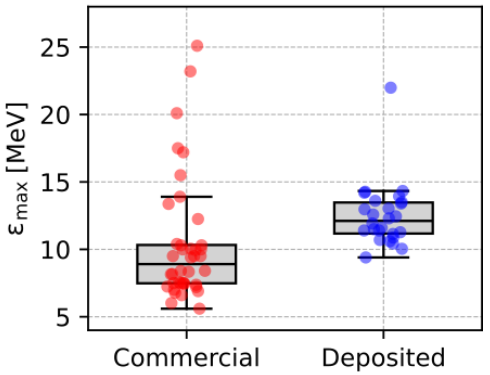
2 μm Al **Deposited** Target



Number of protons



Maximum Energy



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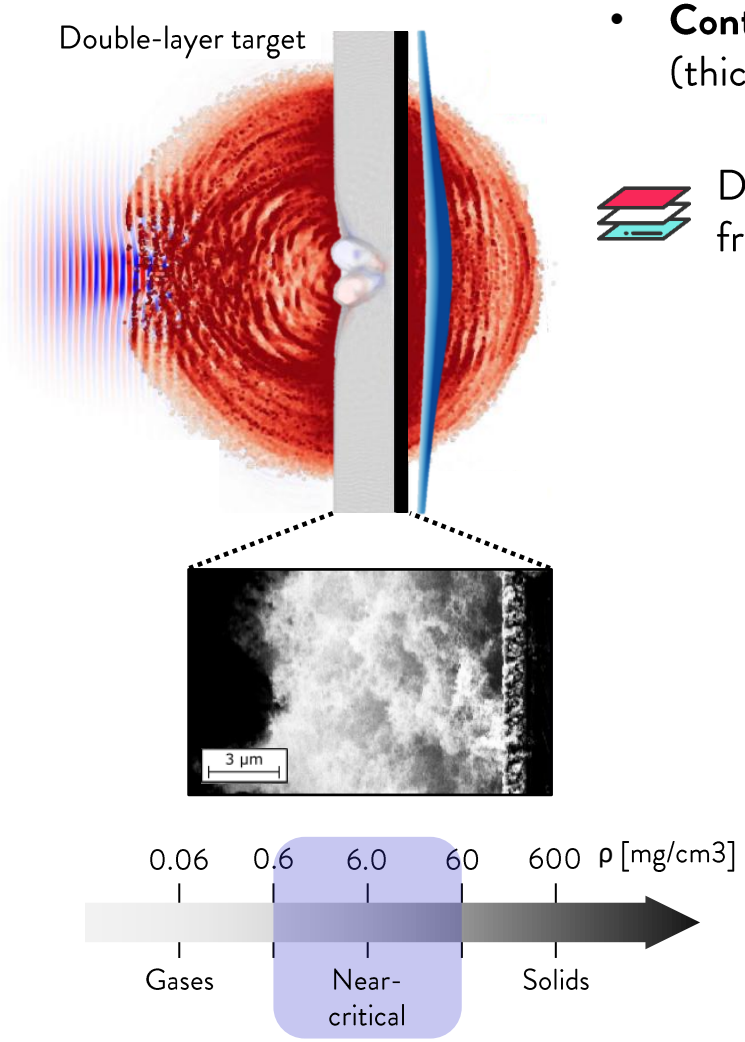
Advanced targets with deposition techniques: Double Layer Targets (DLT)



- **Control target** properties (thickness, composition, etc.) → **Tune the energy** of TNSA ions

Deposition of a **low-density nanostructured layer** in front of the solid foil to **increase laser absorption**.

I. Prencipe, et al. *New Journal of Physics* 23.9 (2021): 093015.

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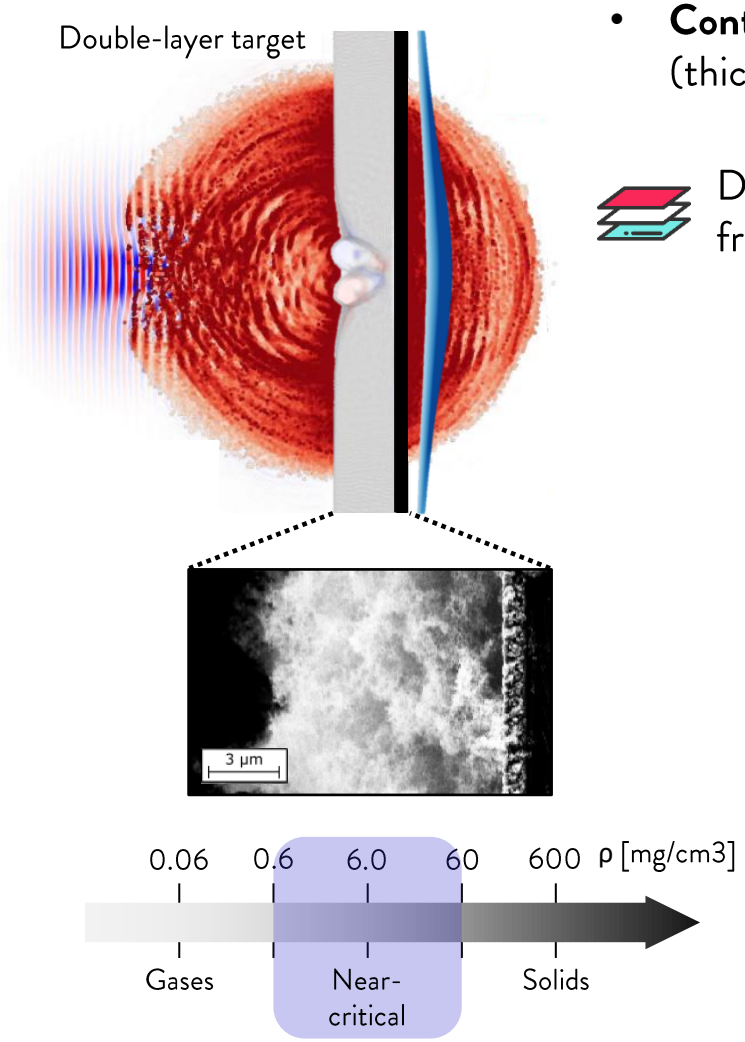

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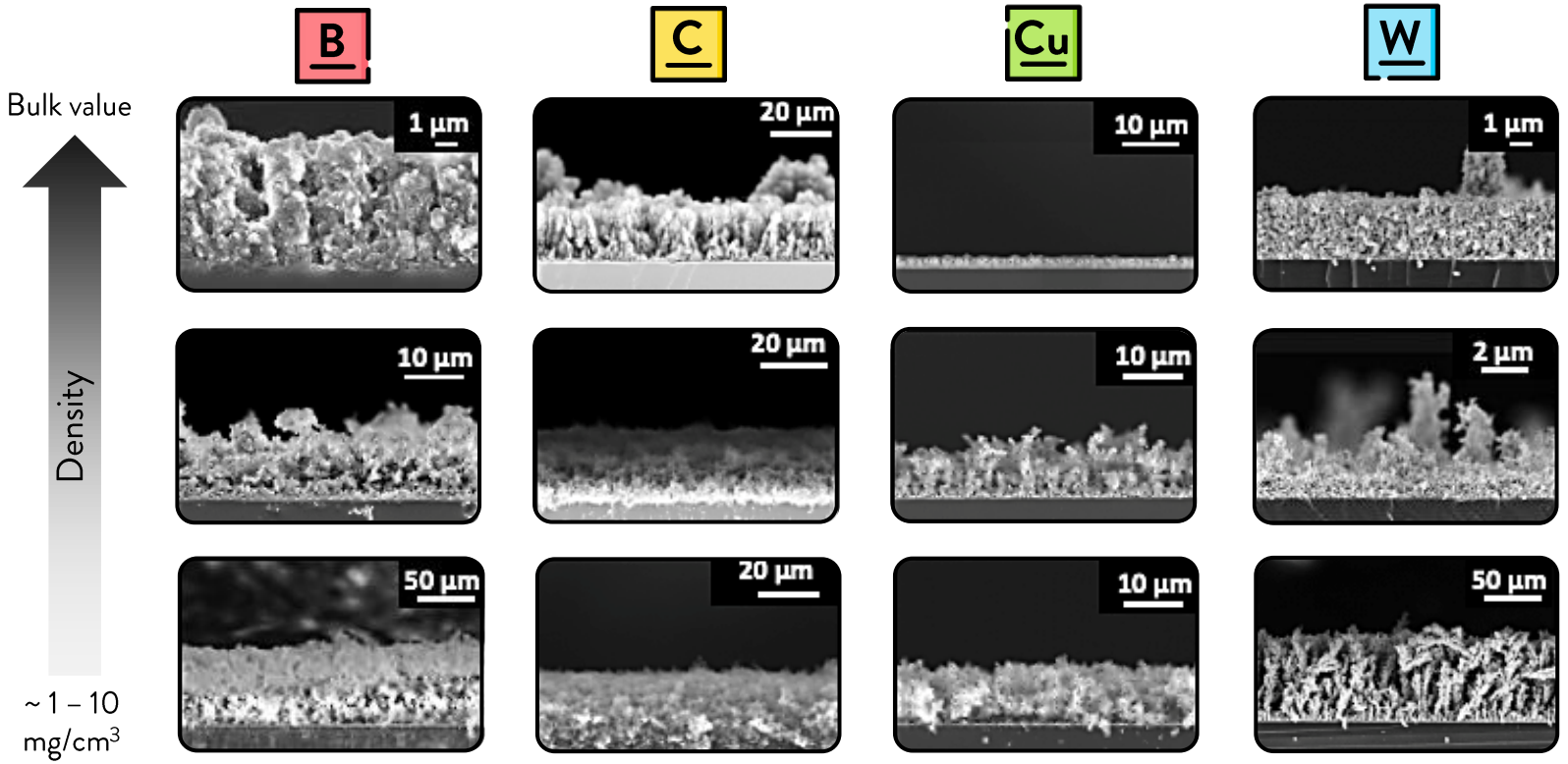
Deposition of a **low-density nanostructured layer** in front of the solid foil to **increase laser absorption**.

- **Pulsed-Laser Deposition** (PLD) allows to control the **morphology** (foams, tree-like,...), **density** and **composition** of the nanostructure.



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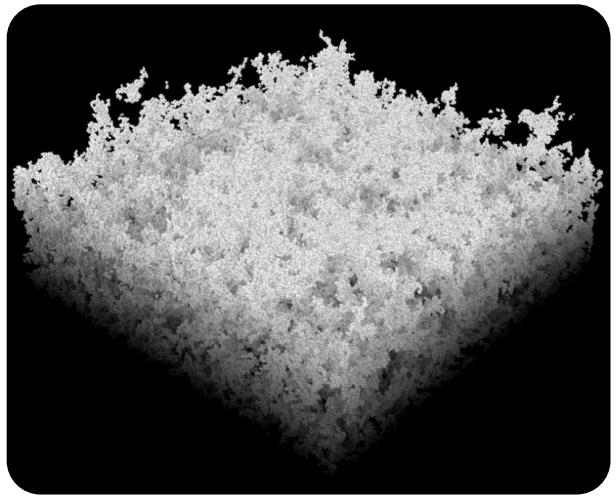
A. Maffini, et al. *Submitted to PPCF* (2025).

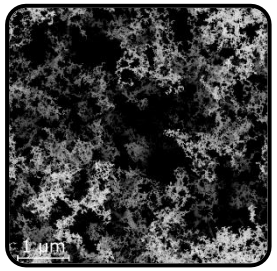
Investigation of laser interaction with near-critical DLT

- Laser interaction with low-density nanostructured materials is complex → **Theoretical investigation** should **include the real structure**.

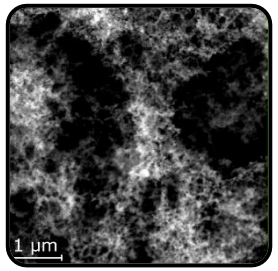
Development of a diffusion-limited cluster-cluster aggregation code to **growth synthetic nanostructures.**



Synthetic foam



Real foam



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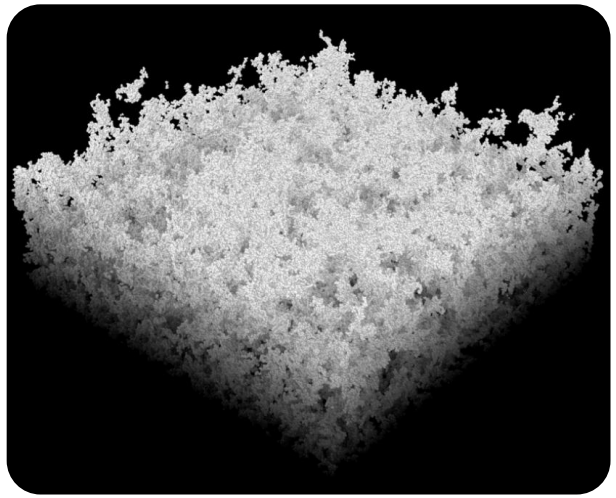
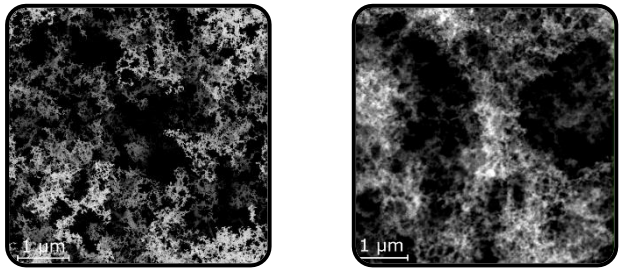
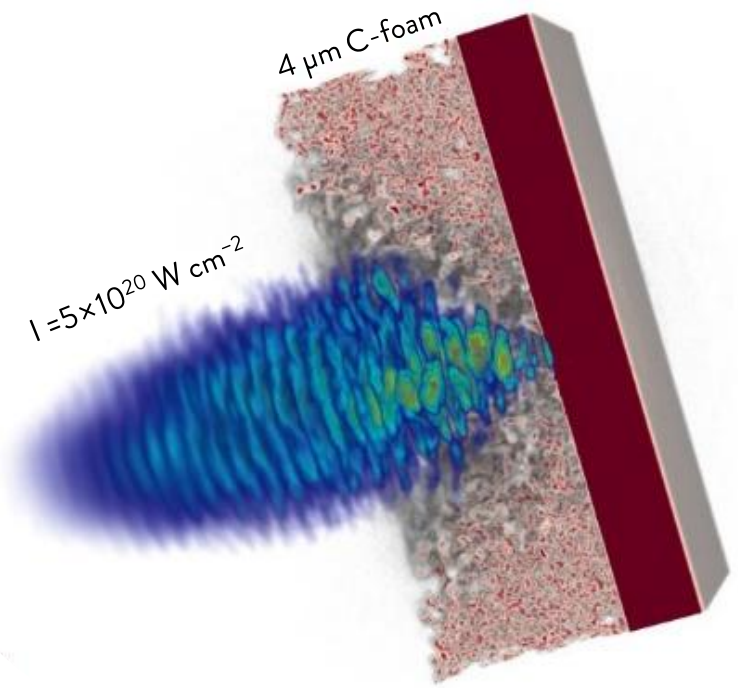
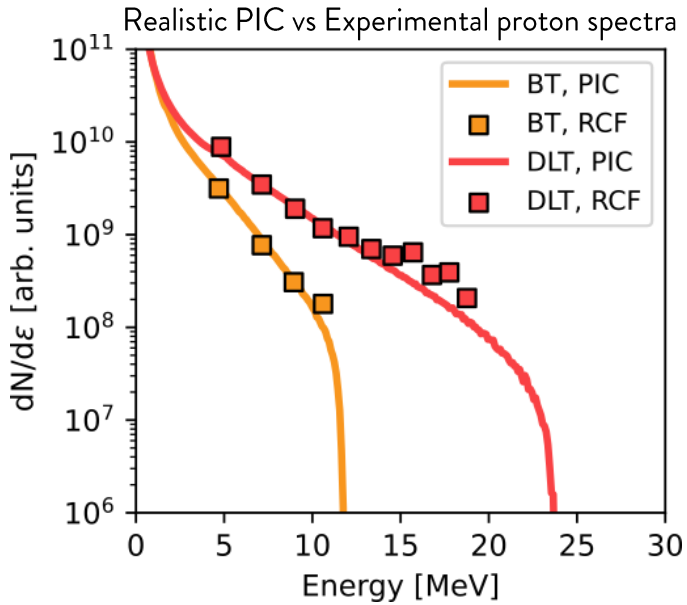




A. Maffini, et al. *Submitted to PPCF* (2025).

- **3D PIC simulations** (Smilei) and WarpX) to interpret and reproduce **enhanced-TNSA experimental data.**



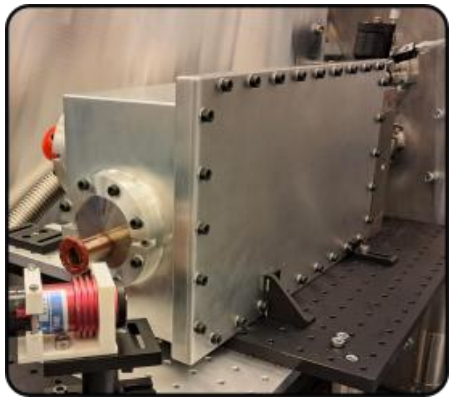


- **DLTs increase** the **energy** and **number** of protons → **Mitigate laser requirements** in view of **practical applications**!

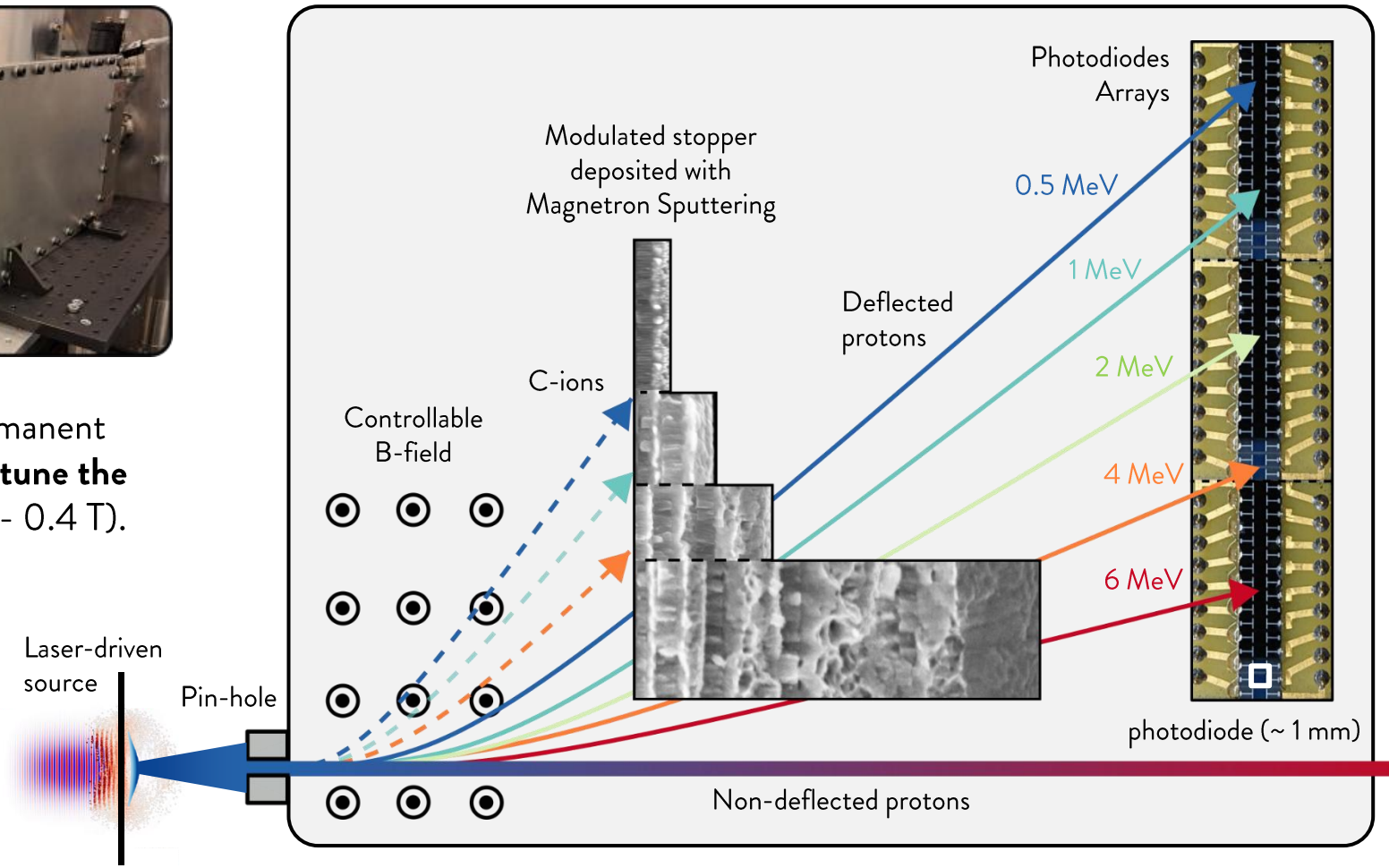
A. Maffini, et al. *Frontiers in Physics* 11 (2023): 1223023.
I. Prencipe, et al. *New Journal of Physics* 23.9 (2021): 093015.

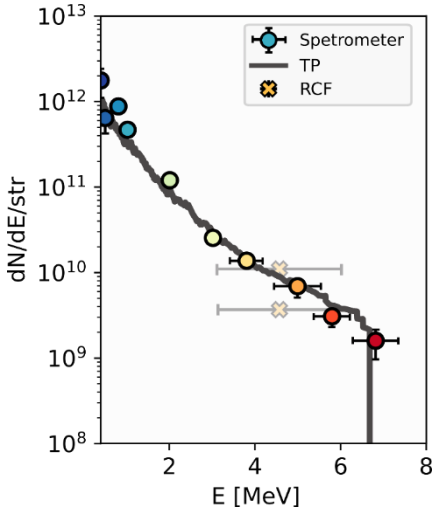
Development of an application-oriented proton spectrometer with RAYLAB

Materials analysis requires **precise knowledge** of the source. → Magnetic system for **proton beam** characterization and irradiation.



- Elettropermanent magnet **to tune the B-field** (0 - 0.4 T).





- **Agreement with** the shape of proton spectrum from **Thomson Parabola.**

F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

F. Gatti, et al. *IEEE Transactions on Instrumentation and Measurement* (2024).

K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

Focusing on laser-driven PIXE and XRF…what has already been done and what are our goal?

Few theoretical **studies** and proof-of-principle experiments **with simple materials**

- Reference-free **quantitative** and **stratigraphic** analysis **in vacuum**

  M. Passoni, et al. *Scientific reports* 9.1, (**2019**): 1-11.
  F. Mirani, et al. *Science advances* 7.3, (2021): eabc8660.

- Combined **laser-driven PIXE - XRF in vacuum**

  P. Puyuelo-Valdes, et al. *Scientific reports* 11.1, (2021): 1-10.
  M. Barberio, et al. *Scientific reports* 9.1, (2019): 1-9.

- **Quantitative** laser-driven PIXE **in-air with standards**

  M. Salvadori, et al. *Physical Review Applied* 21.6, (2024): 064020.

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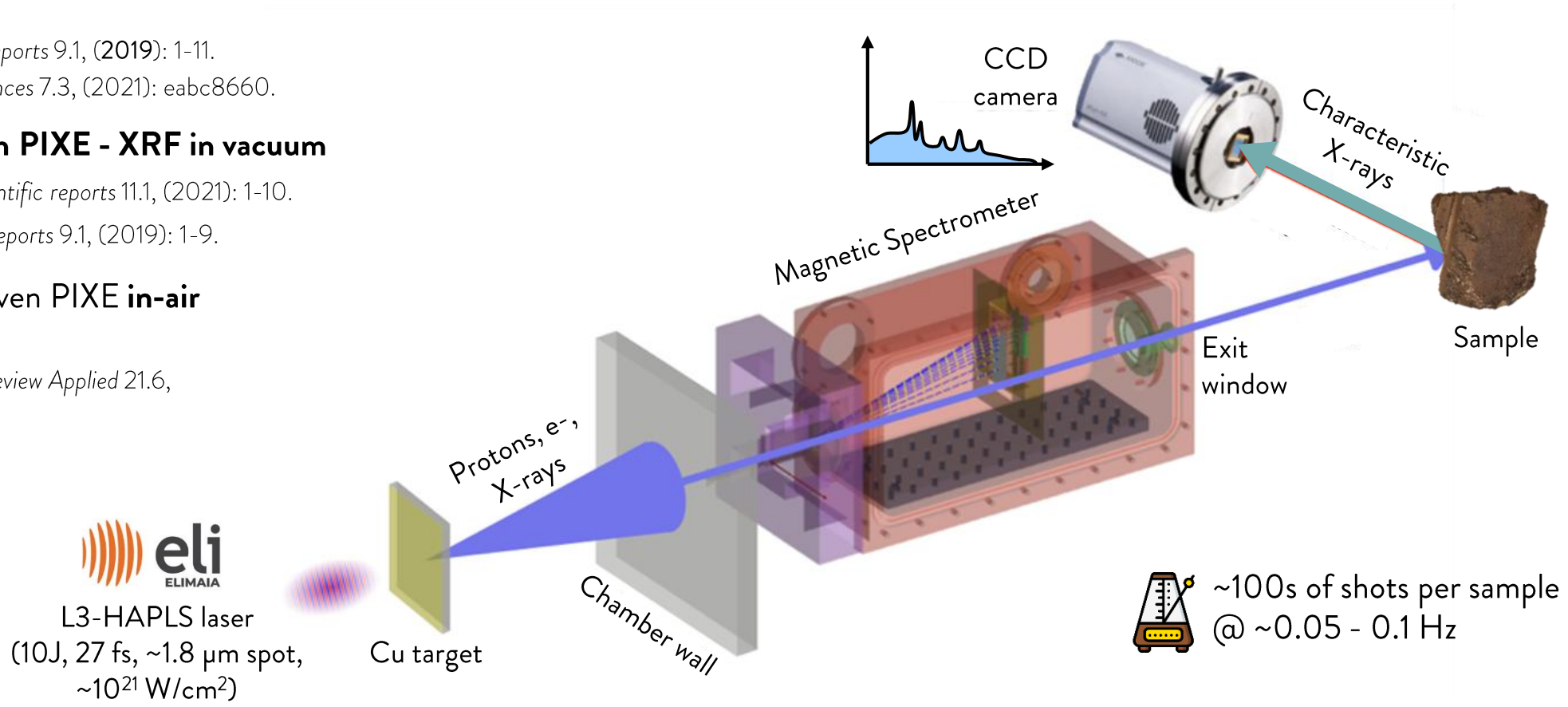
- **Quantitative** laser-driven PIXE **in-air with standards**

  M. Salvadori, et al. *Physical Review Applied* 21.6, (2024): 064020.

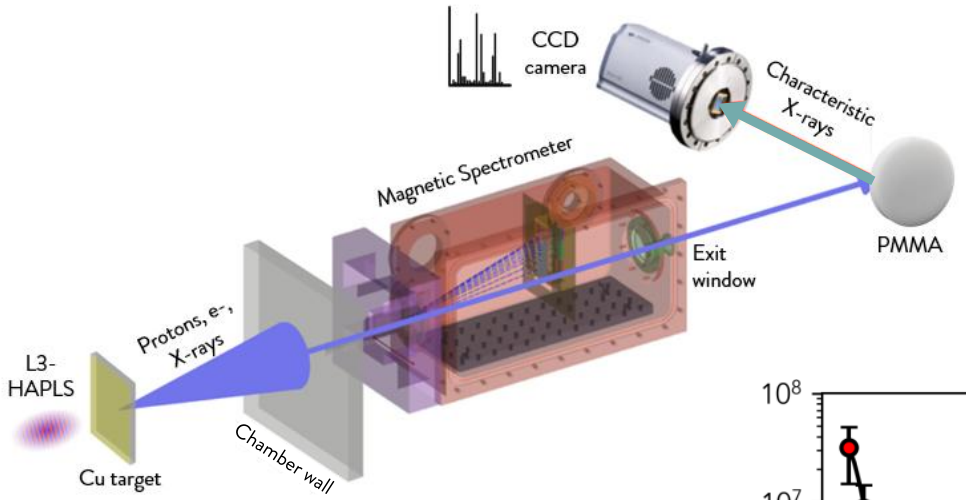
Investigate **quantitative** PIXE-XRF **in-air** on **cultural heritage** materials with a laser-plasma source

- Access to eli MAIA beamline through 5th User call



K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

Characterization of protons and X-rays emitted by the laser-plasma source



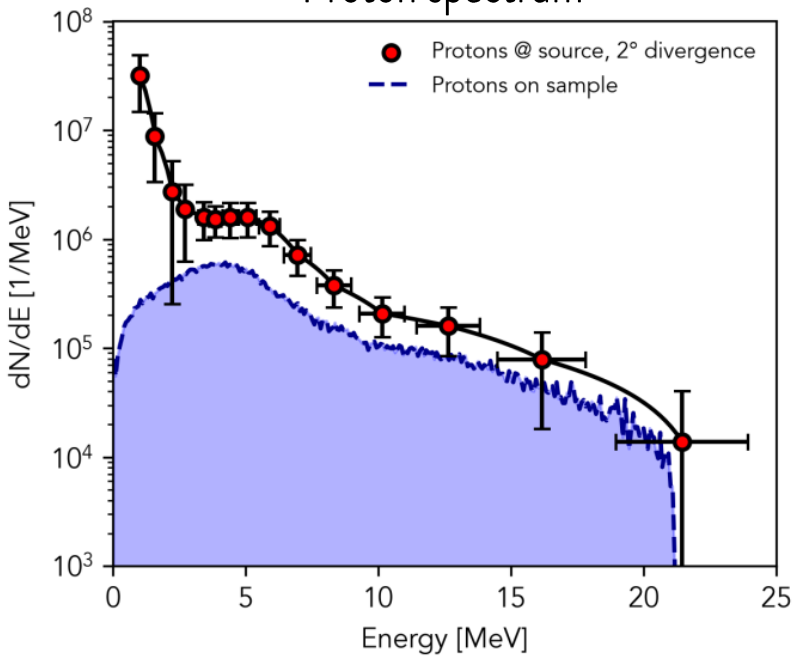
Irradiation of a **PMMA sample** and detection of **backscattered photons.**

GEANT4 simulation to estimate **1.3×10⁵** Cu-**X-rays** per laser shot on sample.

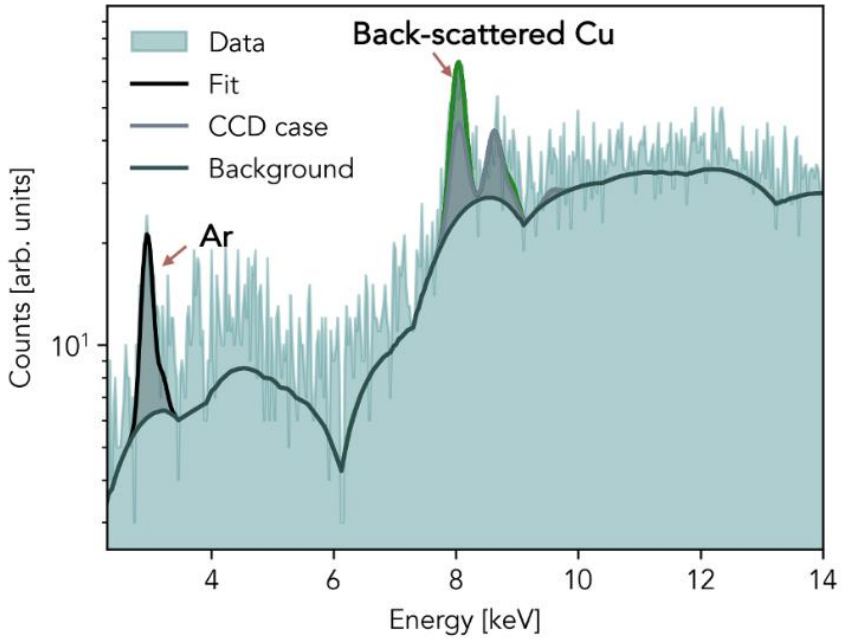
Proton spectrum measured @ source with spectrometer.

GEANT4 simulation to estimate **4×10⁵ protons** per shot on sample.

Proton spectrum

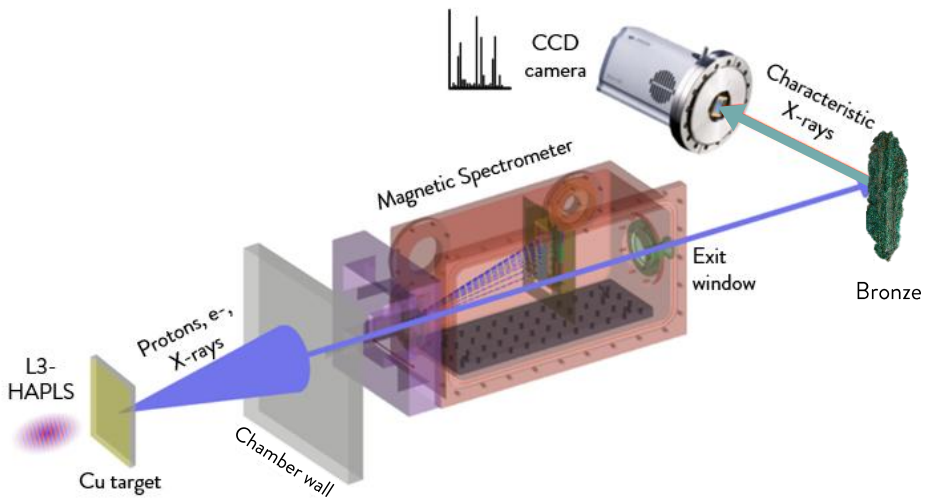


Backscattered X-ray spectrum



K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

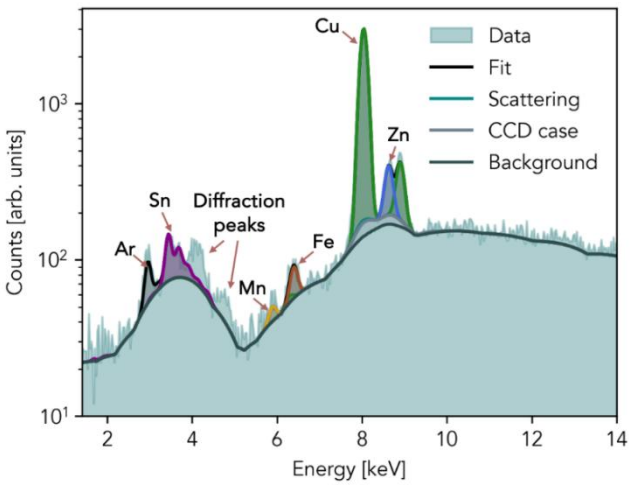
Quantitative laser-driven PIXE-XRF analysis of reference and medieval bronze

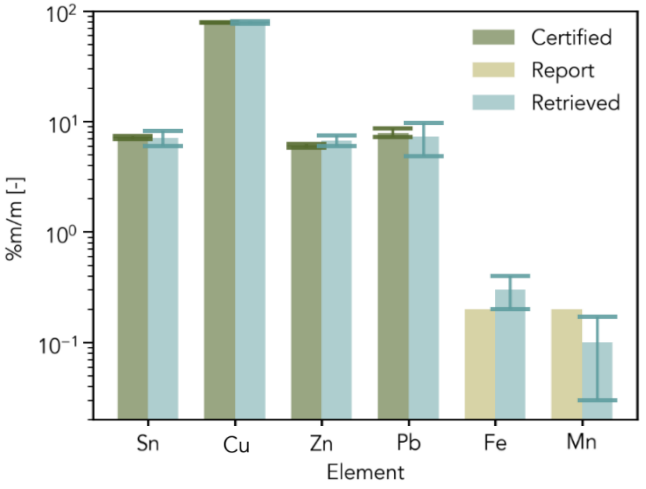


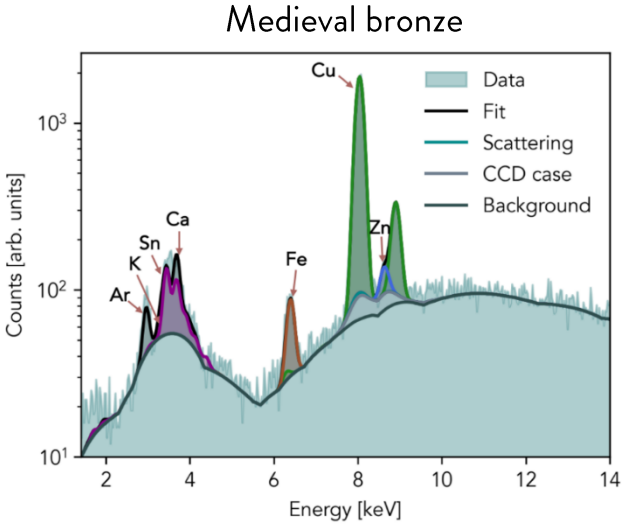
Analize spectra and **get elemental concentrations**

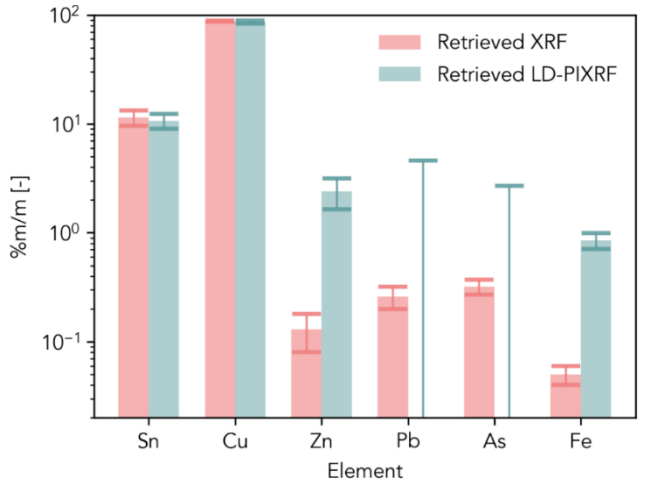
Include PIXE theoretical description
in the XRF PyMca workflow

- Test with **reference** material
- Analysis of a **medieval** bronze



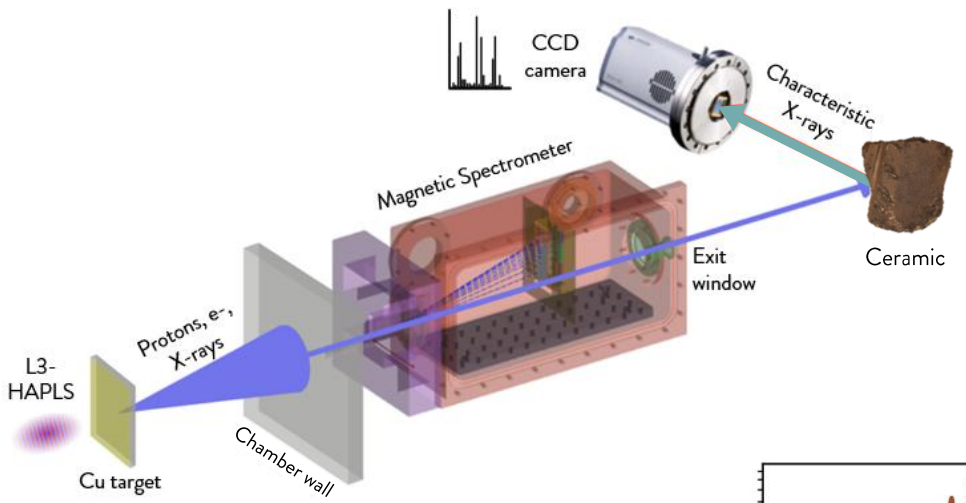






K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

Qualitative analysis of Celtic ceramic with laser-driven PIXE-XRF and conventional XRF

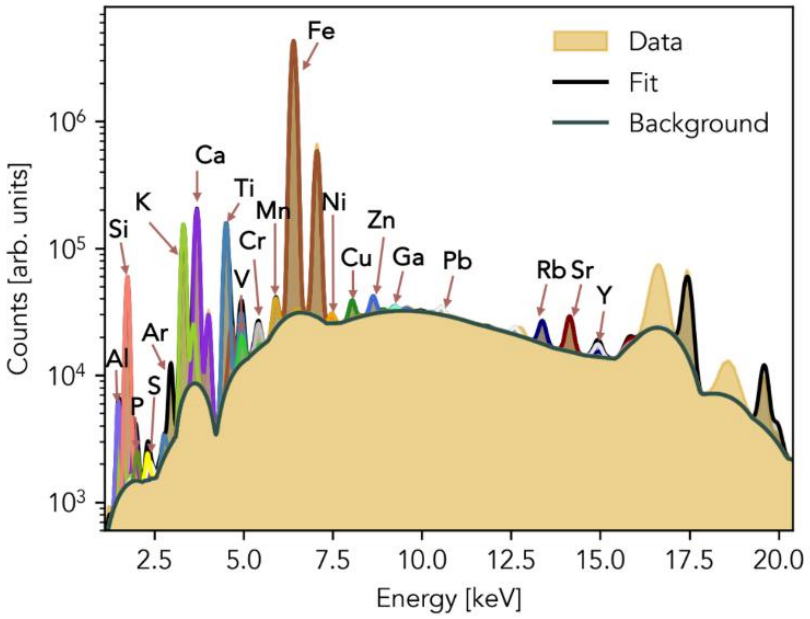


Investigate the **current limits** of the technique through **comparison** with **conventional XRF** on a challenging case study

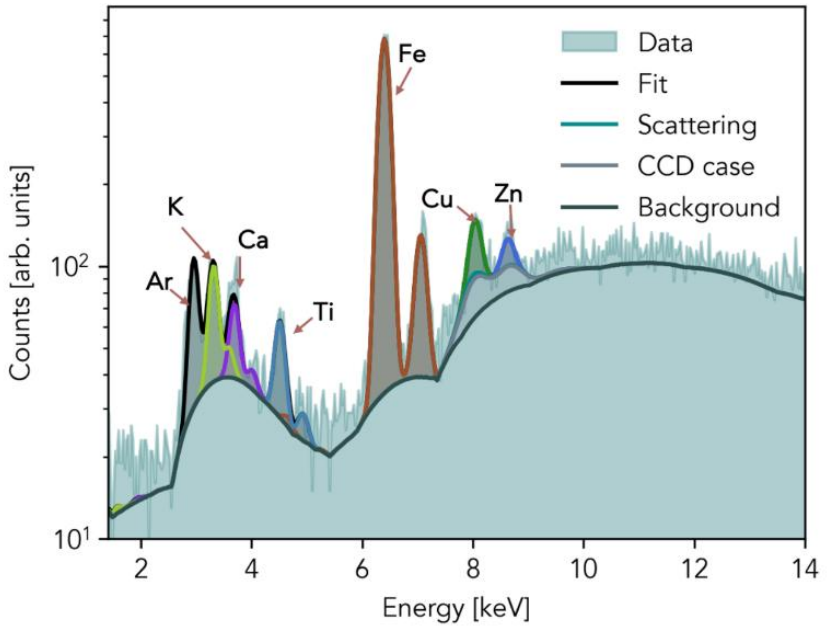
- Main elements (down to ~0.1%) identified with laser-driven PIXE-XRF
- Trace low-Z and high-Z elements not recognized…**improvements** are **needed**

- In collaboration with **XRAYLab** at Consiglio Nazionale delle Ricerche | SPC Istituto di Scienze del Patrimonio Culturale in Catania (Francesco Paolo Romano)

Conventional XRF

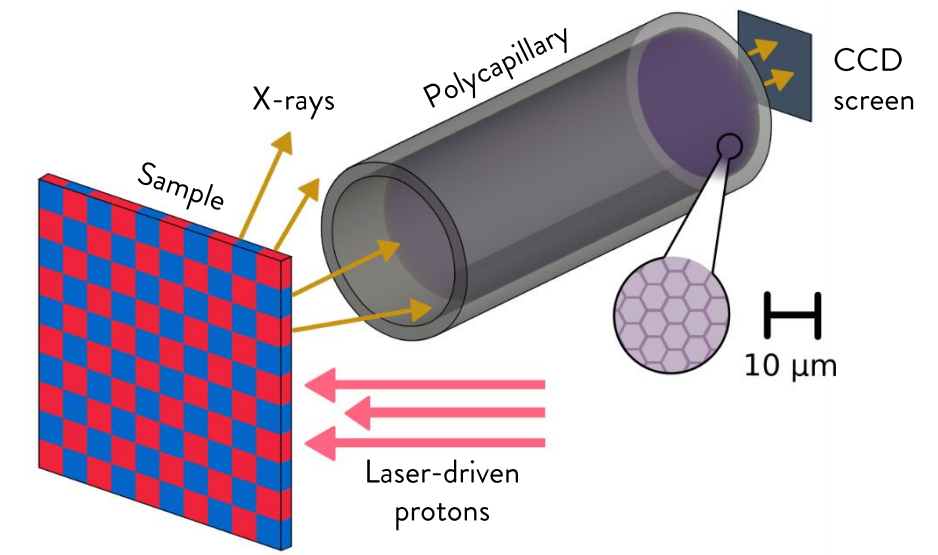


Laser-driven PIXE-XRF



K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

What's next?...Test complementary laser-driven PIXE configurations like full-field

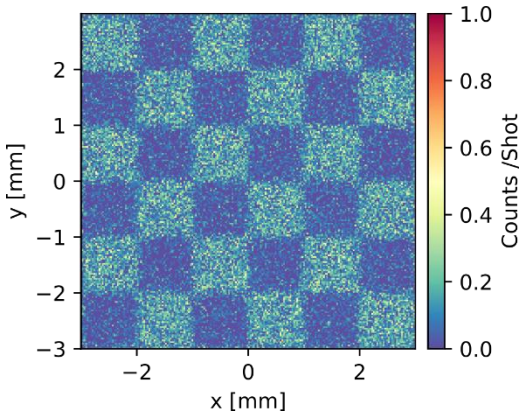


Map the distribution of the elements on the surface a non-homogeneous archeological sample.

- Polycapillary X-ray optical component between sample and CCD to **filter X-rays not orthogonal to the surface.**

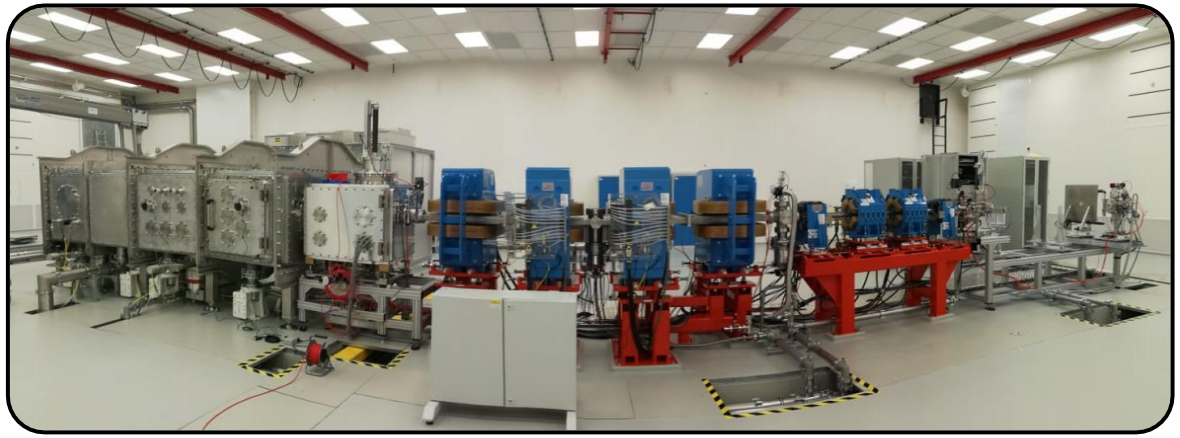
Experimental campaign @ ELI Beamlines in collaboration with the team with the ELIMED beam line scheduled in April 2026 within the framework of the 6° user call.

Fe elemental distribution



- Preliminary study performed with Monte Carlo simulations

- Very simple composition.



A. Maffini, et al. *Submitted to PPCF* (2025).

Final remarks and perspectives

Deposited foils and Double Layer **Targets reduces shot-to-shot uncertainty** and **enhances particle energy** and number.

→ **Scale-up of the production strategy** for high-repetition rate operation (crucial for many applications).

Nanostructure inclusion **in** Particle-In-Cell **simulation** allows deep **understanding** of the laser-DLT interaction **physics.**

→ **Include the effect of the pre-pulse** on the nanostructure coupling Hydrodynamic and PIC simulation.

Combining photodiodes and electropermanent magnets in a single device allows **robust characterization of protons** and **manipulation** of the beam.

→ Address the applicability of a similar detection scheme to **other laser-driven particles** useful for applications.

Many applications of laser-driven sources in materials science have been investigated with **proof-of-principle studies.**

→ Assess whether they can **truly compete with conventional sources**, considering the specific requirements of the techniques and the multifunctional nature of laser-driven sources.

...details can be found in the following articles:

F. Mirani, et al. *Communications Physics* 4.1 (2021): 185.

F. Mirani, et al. *Science advances* 7.3 (2021): eabc8660.

A. Maffini, et al. *Frontiers in Physics* 11 (2023): 1223023.

F. Gatti, et al. *IEEE Transactions on Instrumentation and Measurement* (2024).

D. Orecchia, et al. *Small Structures* 5.6 (2024): 2300560.

F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

A. Maffini, et al. *Submitted to PPCF* (2025).

M. Galbiati, et al. *Submitted to Scientific Reports* (2025).

K. Ambrogioni, et al. *Submitted to Nature Communications* (2025).

Thank you for the attention!

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