POLITECNICO
MILANO 1863

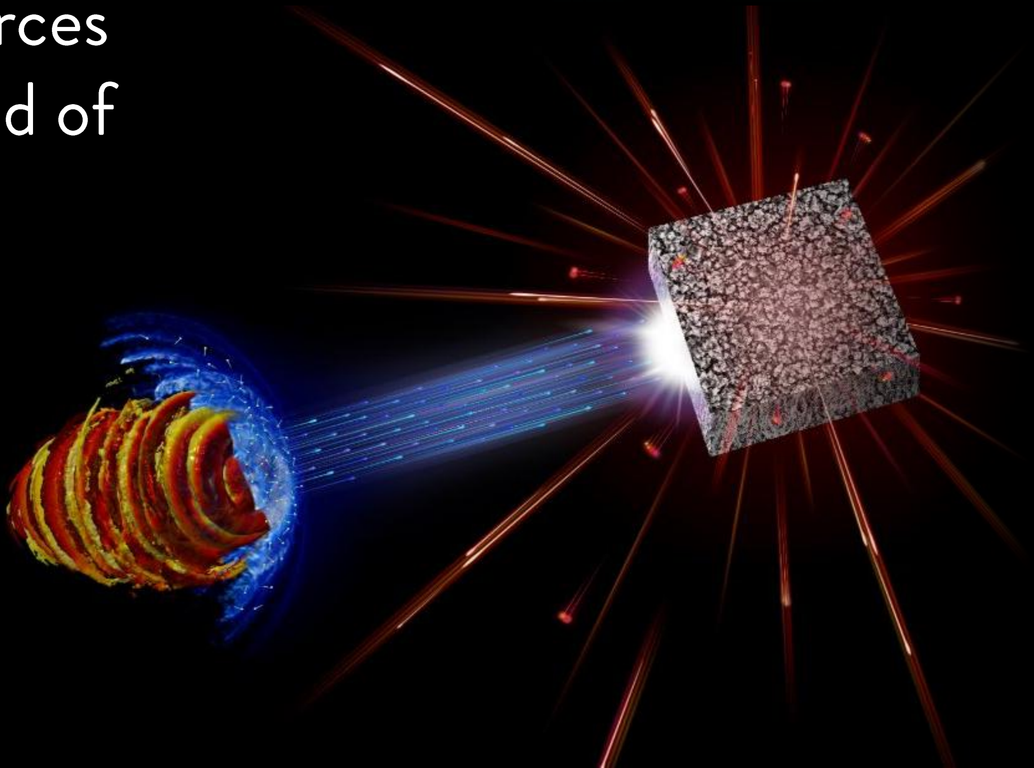
NanoLab
DIPARTIMENTO DI ENERGIA

ENEA

Advancing Laser–Plasma Radiation Sources for Materials Characterization in the field of Cultural Heritage Analysis

Francesco Mirani

4th February 2026



- 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

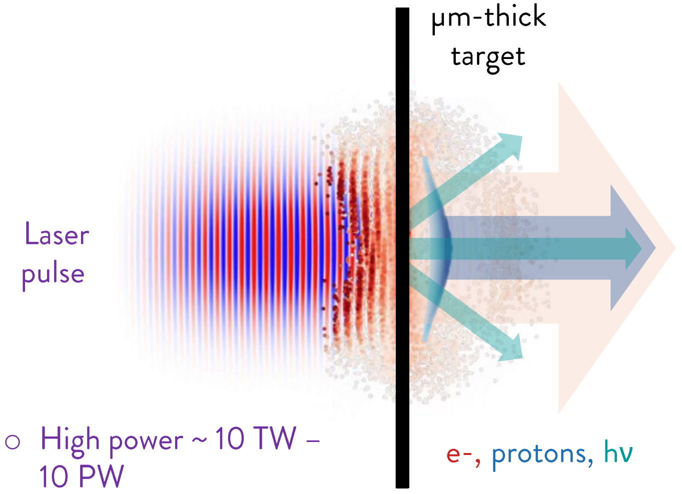

A. Pola


F. Casamichiela

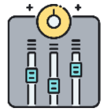
- The LULI with  L. Lancia (Laboratoire pour l'Utilisation des Lasers Intenses)
- The CLPU CENTRO DE LÁSERES PULSADOS with  L. Volpe
- The eli Beamlines with  D. Margarone  L. Giuffrida

  (Access to the facility through the 5th User call)
- The Consiglio Nazionale delle Ricerche | ISPC ISTITUTO DI SCIENZE DEL PATRIMONIO CULTURALE with  C. Conti
- The RAYLAB DETECTING INNOVATION company with  D. Rastelli

What types of laser–plasma radiation sources do we study?

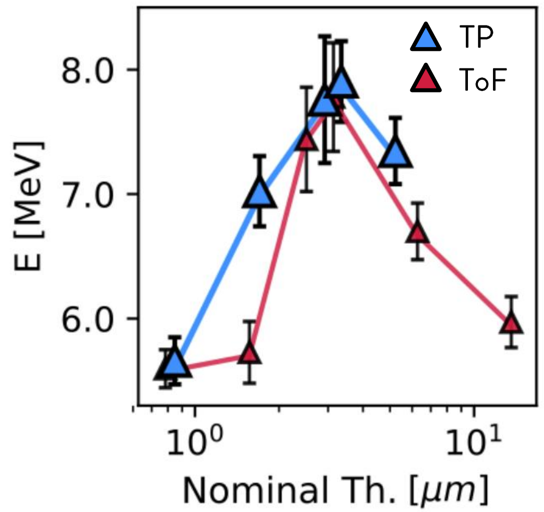


- High power ~ 10 TW – 10 PW
- Ultra-short ~ 10 fs
- Super-intense ~ 10^{18} – 10^{22} W/cm^2

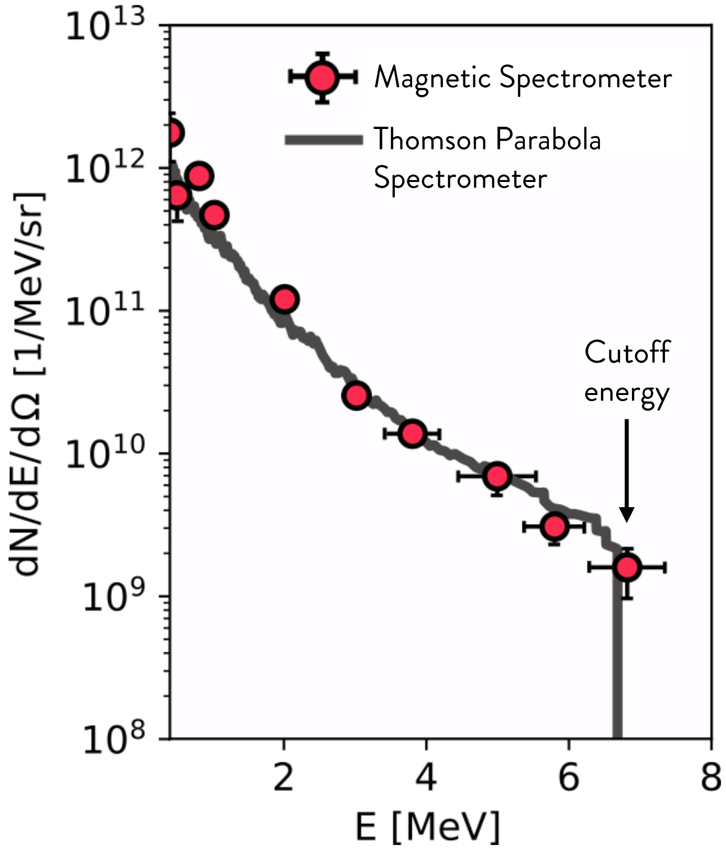


Tune particle energy controlling plasma parameters via laser intensity and target thickness!

- Interaction of a **super-intense laser** pulse with a **solid target**
  - MV/µm **acceleration gradients in the plasma**
  - Particles emitted in bunches
  - Broad energy spectra



Formation of a plasma: e- ejection from target and **ions accelerated** by the electric field via Target Normal Sheath Acceleration (TNSA)



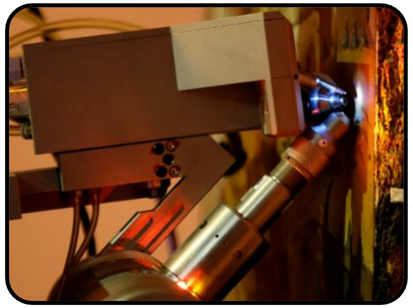
H. Daido, et al. *Reports on progress in physics* 75.5 (2012): 056401.
A. Macchi, et al. *Reviews of Modern Physics* 85.2 (2013): 751-793.
F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

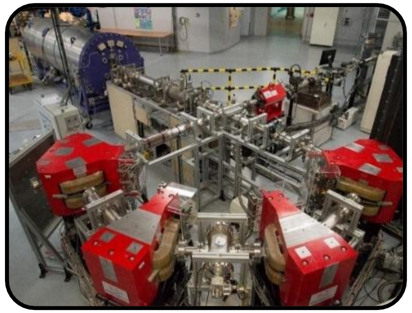
Why laser-plasma sources can be interesting for the analysis of artworks?

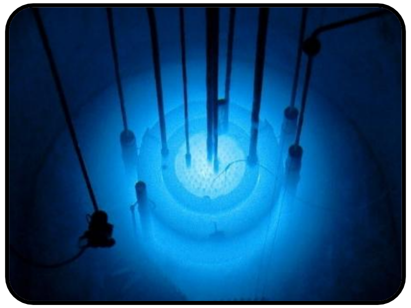
- Well **established analytical techniques** exploiting radiations → e.g. X-Ray Fluorescence spectroscopy (**XRF**), Particle Induced X-ray Emission (**PIXE**) uses photons and protons to **induce characteristic X-ray emission**



- **Different conventional sources** for specific techniques


Portable **X-ray tubes**


Particle **accelerators**


Neutron / γ-ray **sources**

Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.

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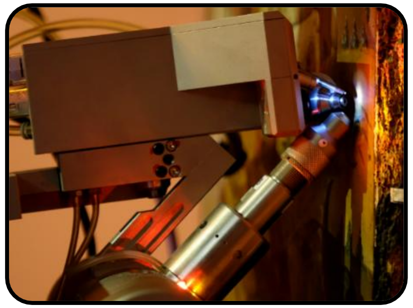
Laser-plasma accelerators are potentially **compact** and **multi-purpose**

- **Different conventional sources** for specific techniques



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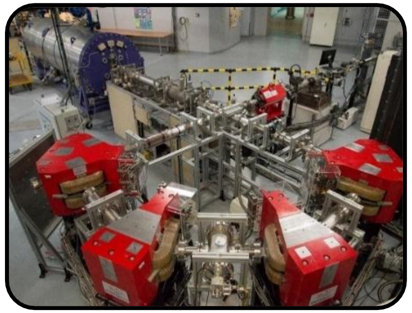

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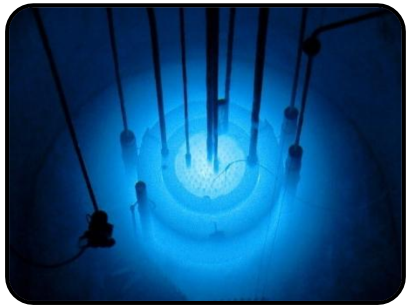

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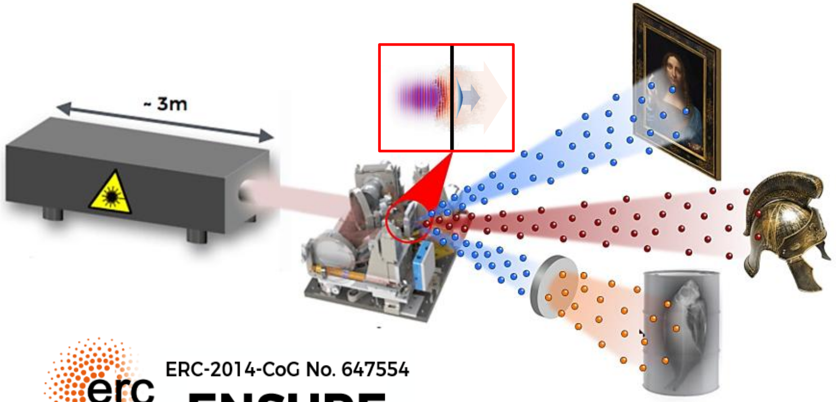


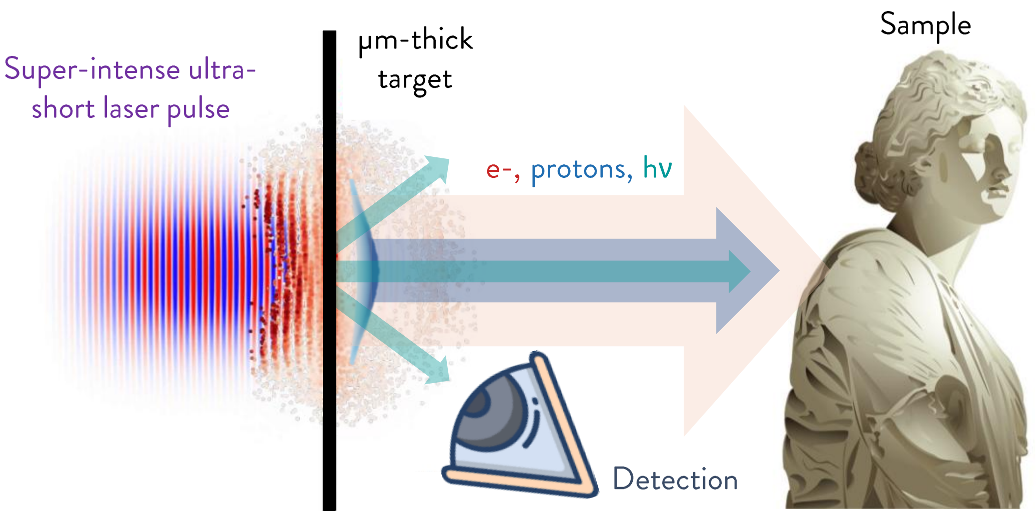
erc ERC-2014-CoG No. 647554 **ENSURE**

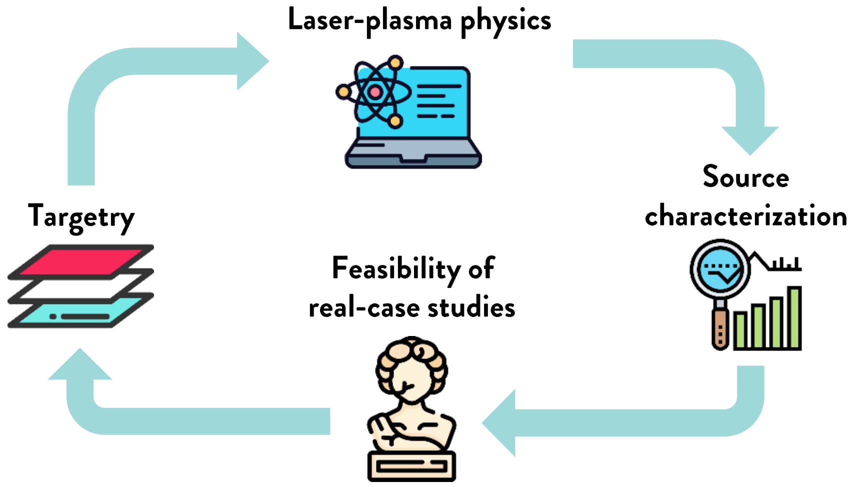
erc ERC-2022-PoC No. 101069171 **PANTANI**

M. Passoni, et al. *PPCF*, 62(1), (2019): 014022.

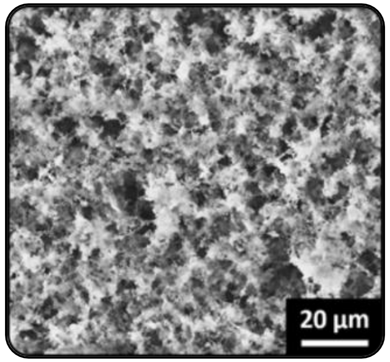
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.

To this aim, several aspects must be investigated…

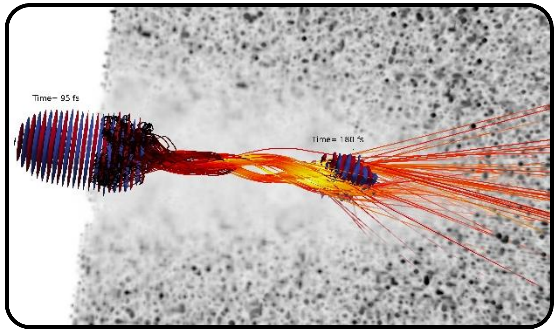




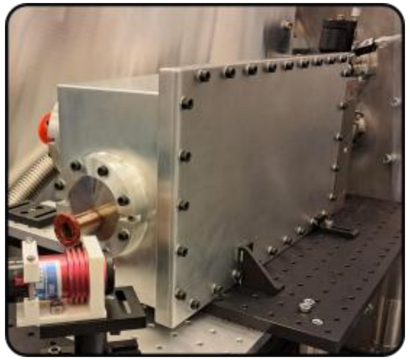
Production of **advanced targets** with deposition techniques



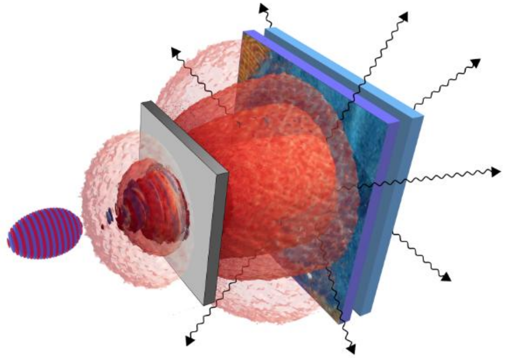
Models, **simulations** and **experimental** investigation of **laser-plasma interaction**



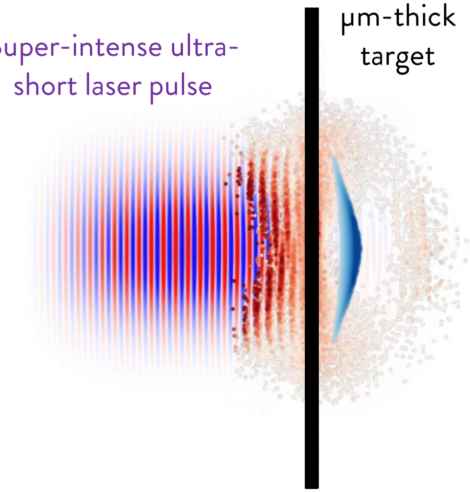
Development of **diagnostics** of **laser-plasma proton** beams



Assessment of applications like **artworks characterization**



Advanced targets with deposition techniques: solid foils

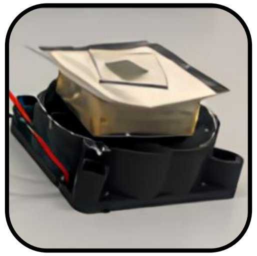


Developed strategy for **metallic target deposition** via Magnetron Sputtering

- 0.05 – 5 µm thicknesses, negligible uncertainty
- Al, Ti, Cu, ...
- Tested @ CLPU and eli Beamlines

- Shot-to-shot **stability crucial for applications** → **Not ensured** by commercial targets

Spin coating of soap layer on glass



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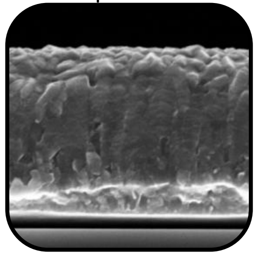
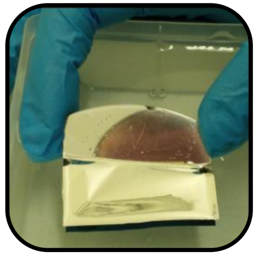


Soap removal in water



Target fishing on the holder

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

A. Maffini, et al. *Accepted by PPCF* (2026).

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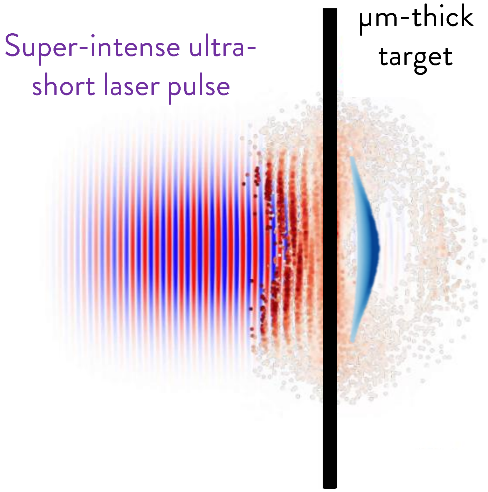

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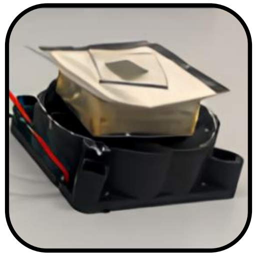

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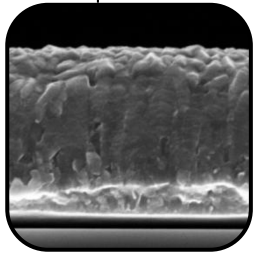
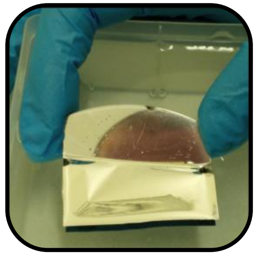


Soap removal in water



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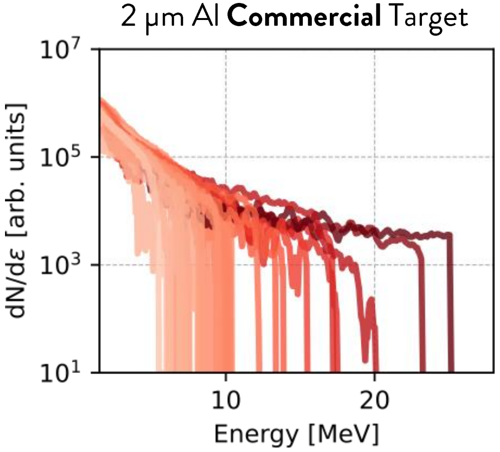

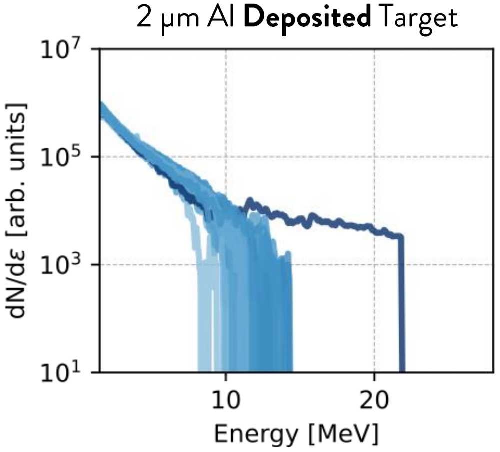

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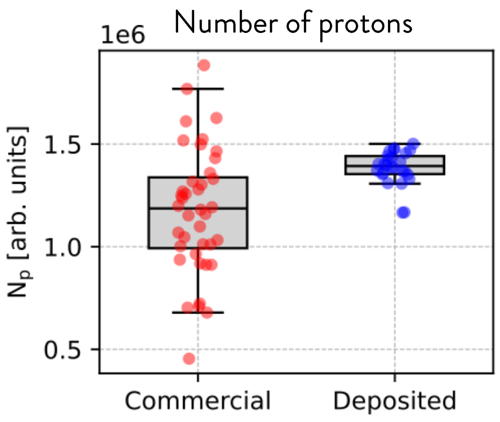
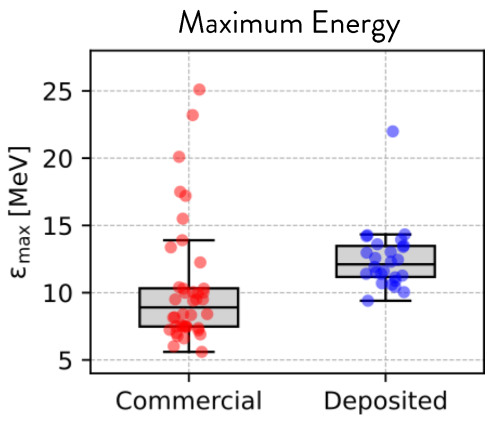
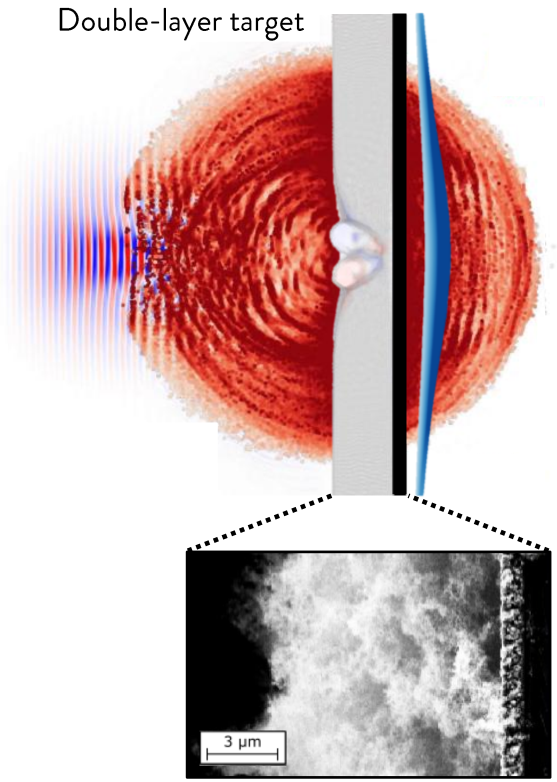




A. Maffini, et al. *Accepted by PPCF* (2026).

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

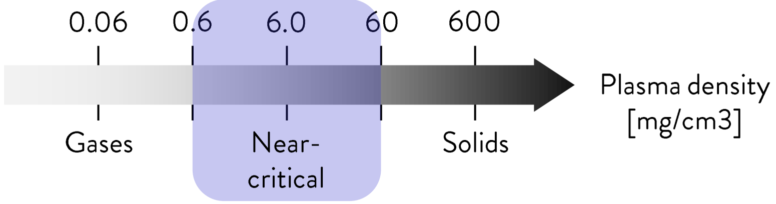


Deposition of a **low-density nanostructured layer**. → Average density close to the plasma **critical density** → **Increase laser energy absorption** and enhance TNSA

- **Control nanostructured plasma** properties (thickness, composition, morphology, etc.)

↓

Tune the energy of TNSA ions



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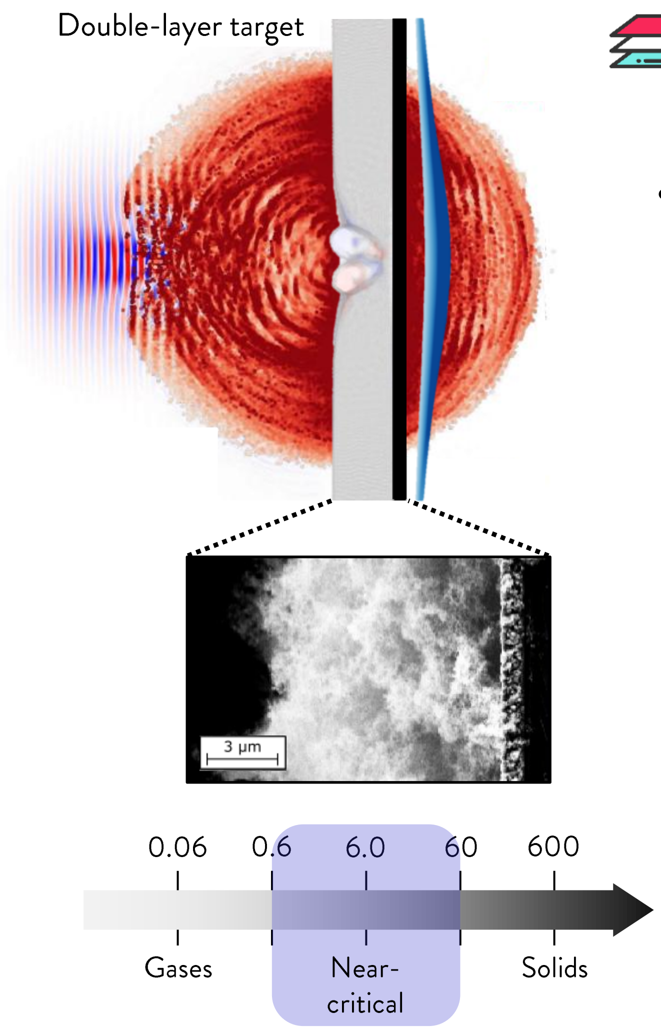

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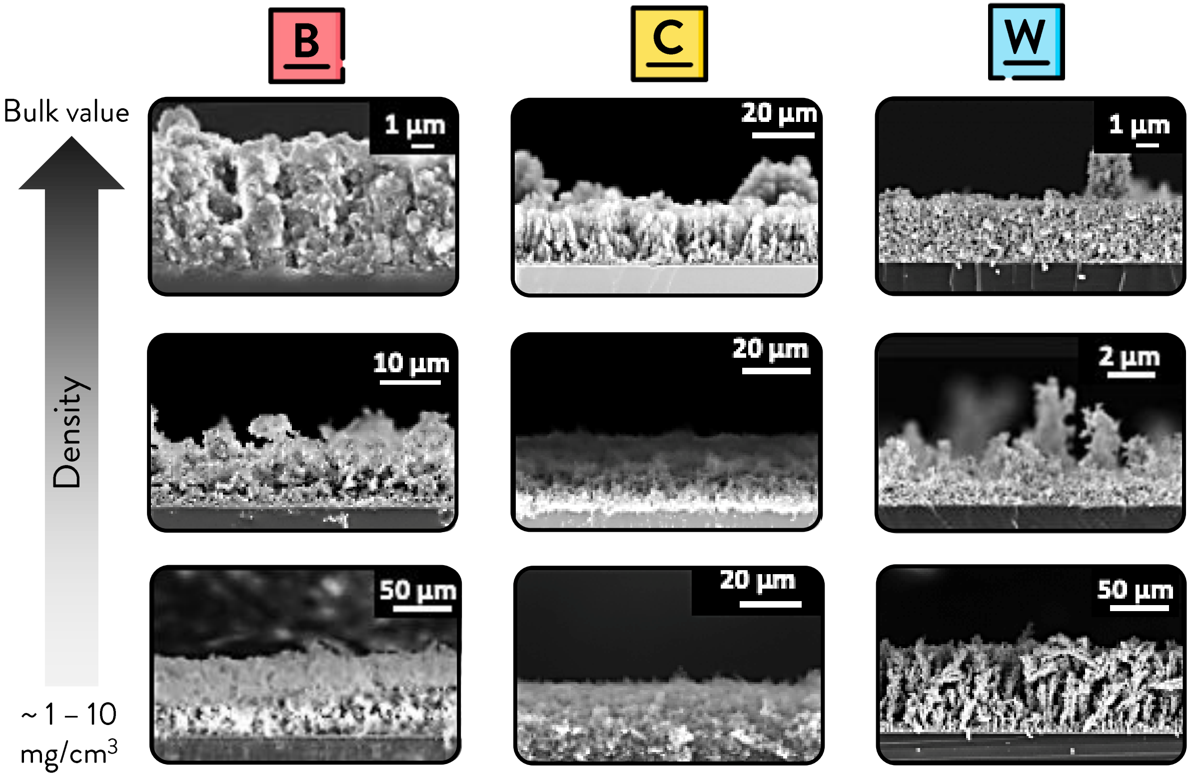
Tune the energy of TNSA ions

- Produced via **Pulsed-Laser Deposition** (PLD)



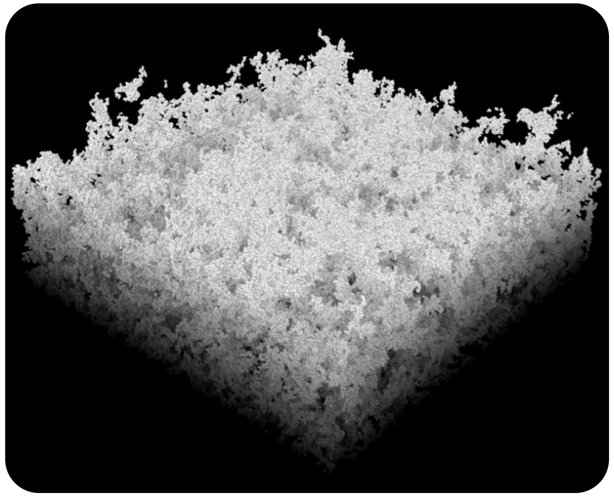
M. Passoni, et al. *PPCF* 62.1 (2019): 014022.

A. Maffini, et al. *Accepted by PPCF* (2026).

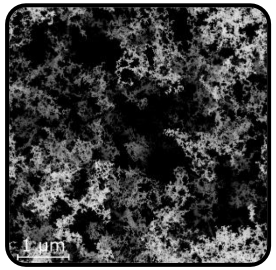
Investigation of laser interaction with near-critical DLT

- Laser interaction with **nanostructured plasma** is complex ➡ **Theoretical investigation** including **real structure**

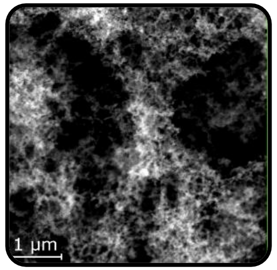
Development of a diffusion-limited cluster-cluster aggregation code to **growth synthetic nanostructures**



Synthetic foam

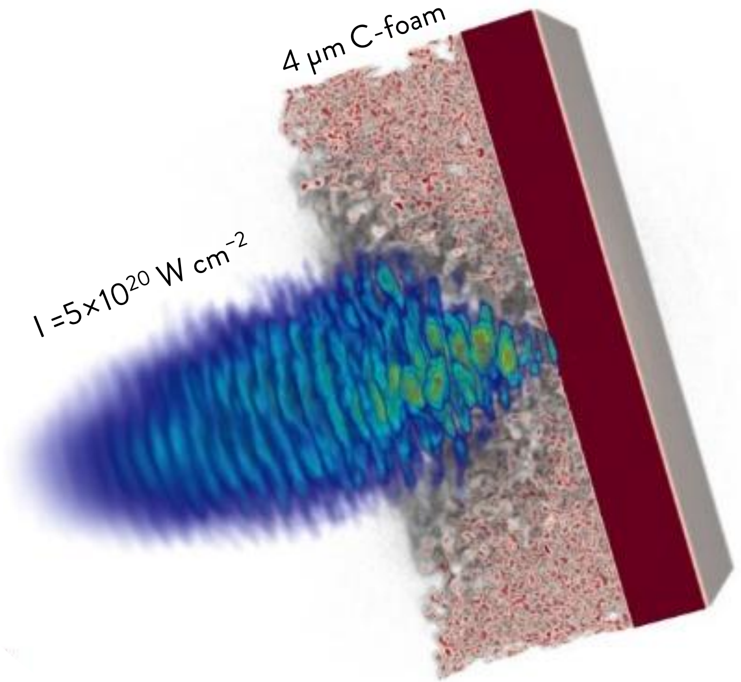


Real foam



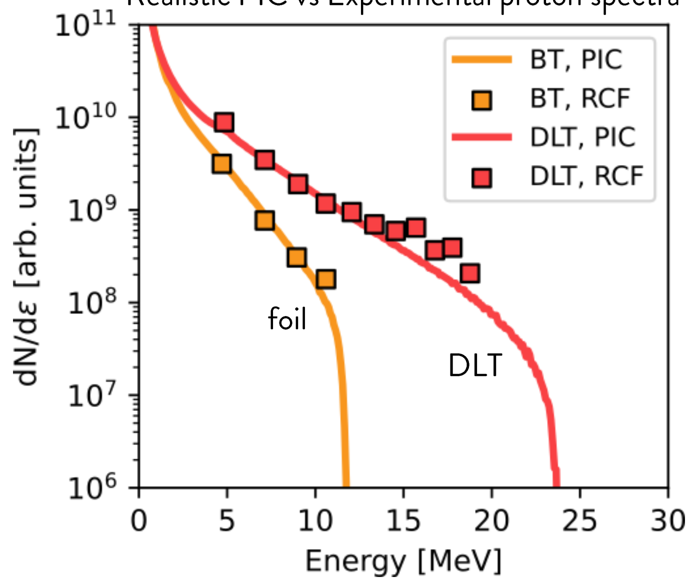
A. Maffini, et al. *Accepted by PPCF* (2026).

- **3D PIC simulations** (Smilei) and WarpX) of **enhanced-TNSA**.



M. Galbiati, et al. *Under review Scientific Reports* (2025).

Realistic PIC vs Experimental proton spectra

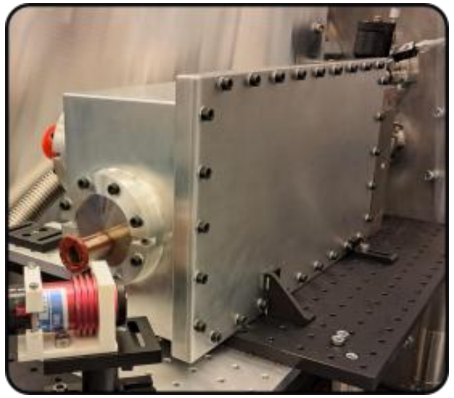


- **DLTs increase** the **energy** and **number** of protons → **Mitigate laser requirements** in view of **practical applications**!

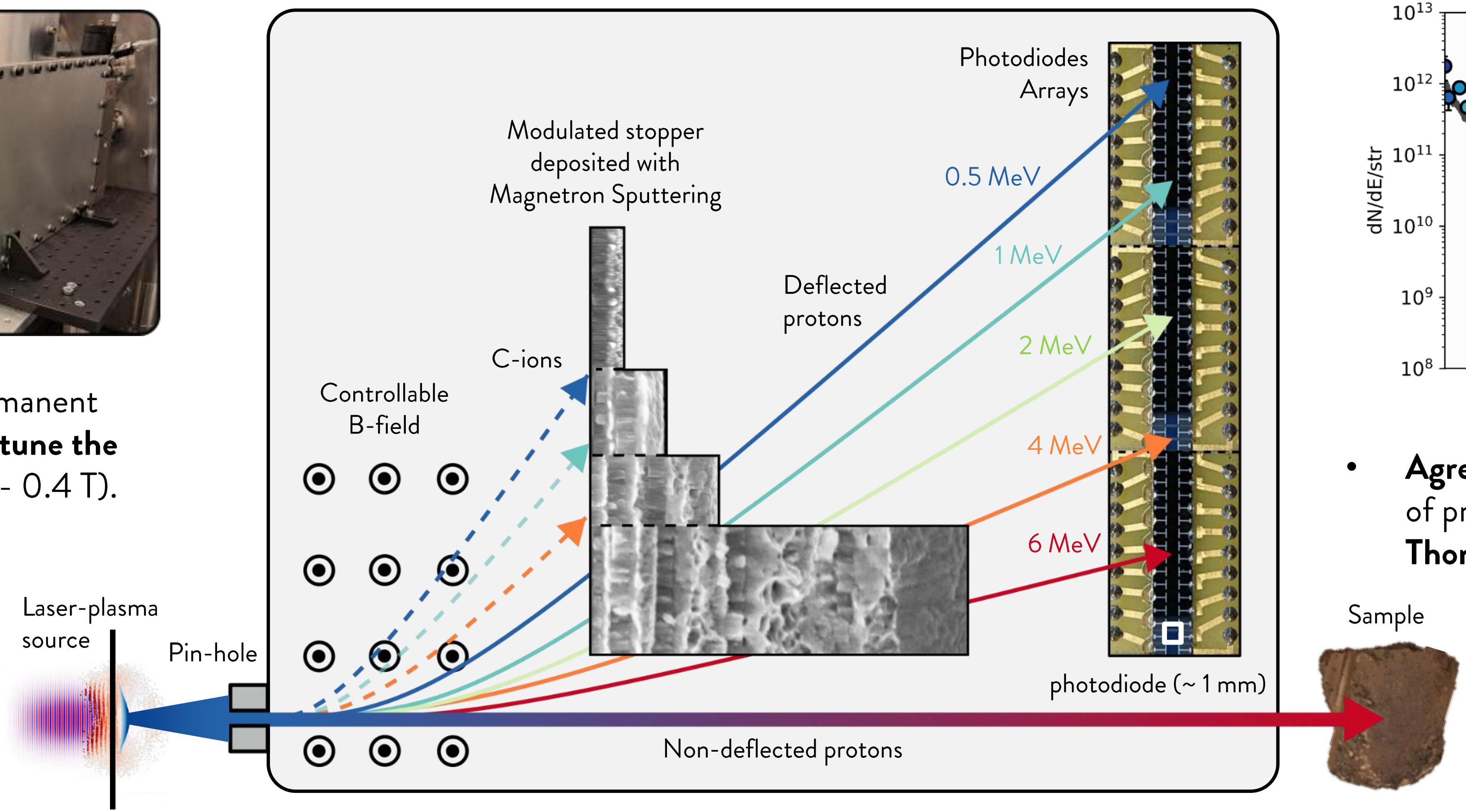
A. Maffini, et al. *Frontiers in Physics* 11 (2023): 1223023.
I. Prencipe, et al. *New Journal of Physics* 23.9 (2021): 093015.

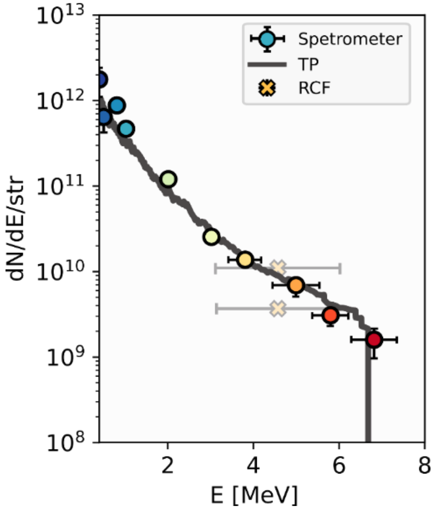
Development of an application-oriented proton spectrometer with RAYLAB

Materials analysis requires **knowledge** of the plasma 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. *Under review at Science Advances* (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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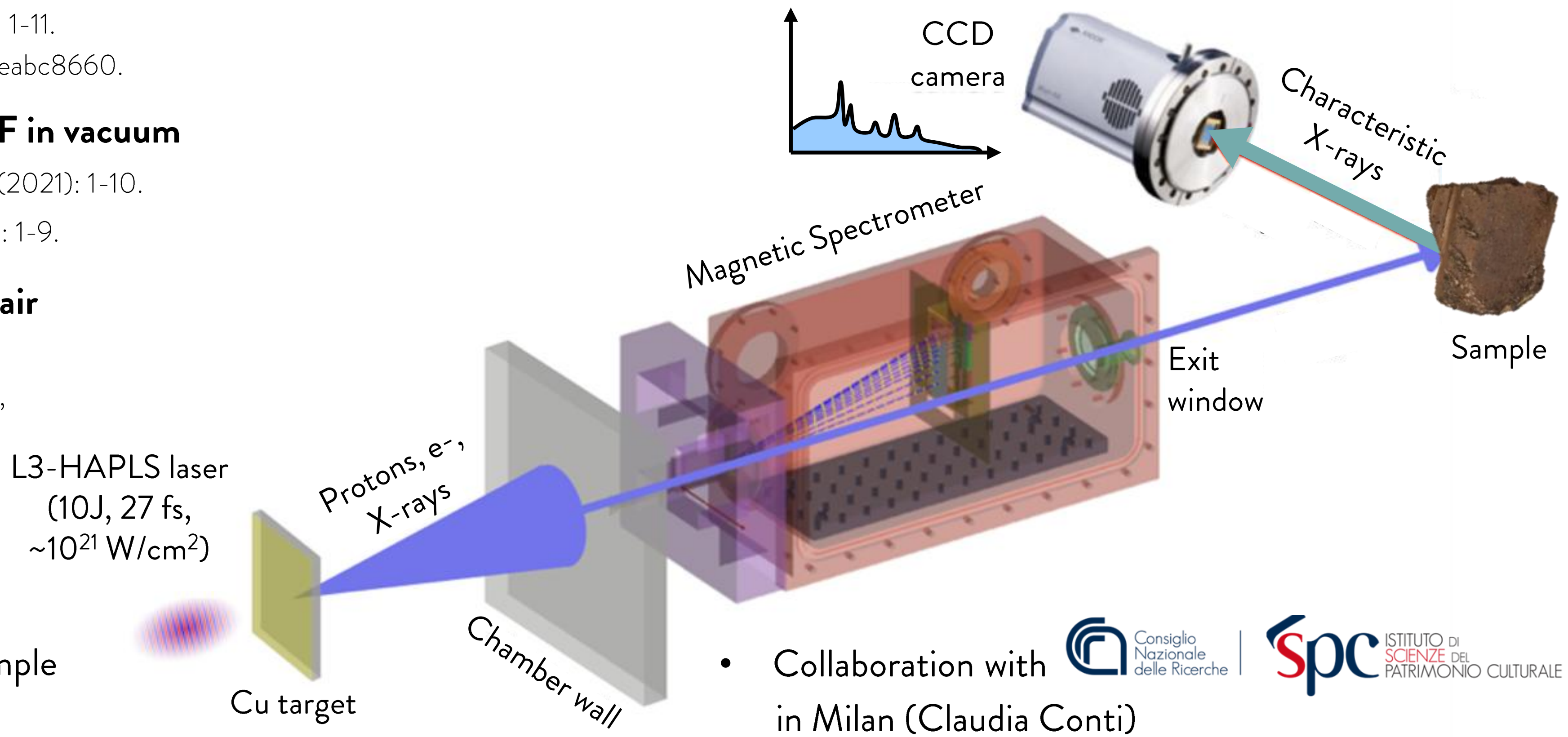
Investigate **quantitative** PIXE-XRF **in-air** on **cultural heritage** materials with a **laser-plasma source**

- Access to eli MAIA beamline through 5th User call

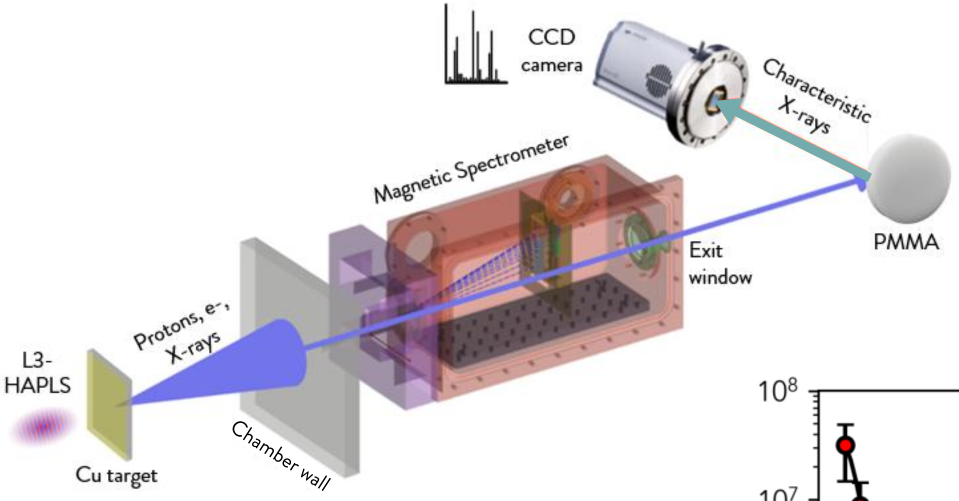


~100s of shots per sample @ ~0.05 - 0.1 Hz

- Collaboration with Consiglio Nazionale delle Ricerche | ISPC Istituto di Scienze del Patrimonio Culturale in Milan (Claudia Conti)

K. Ambrogioni, et al. *Under review at Science Advances* (2025).

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



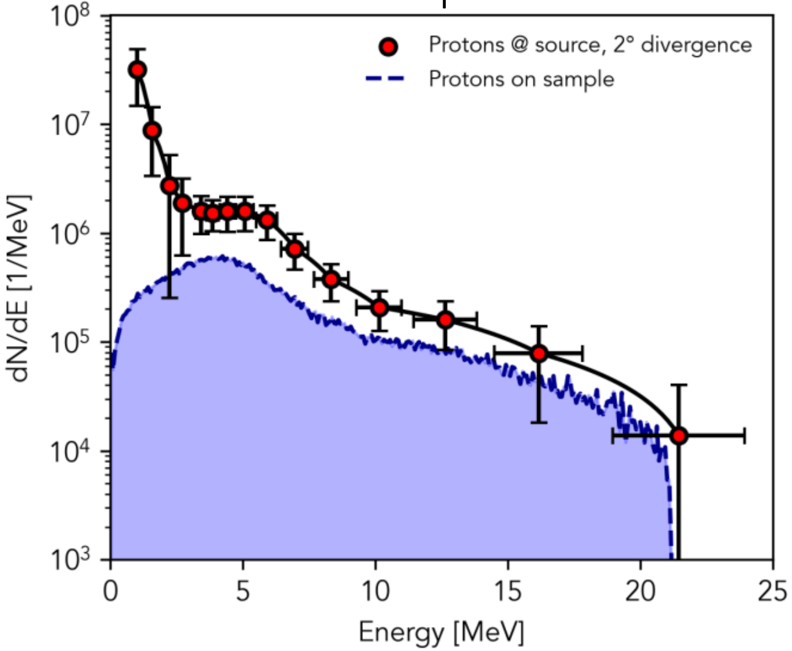
Irradiation of a **PMMA sample** and detection of **backscattered photons.**

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

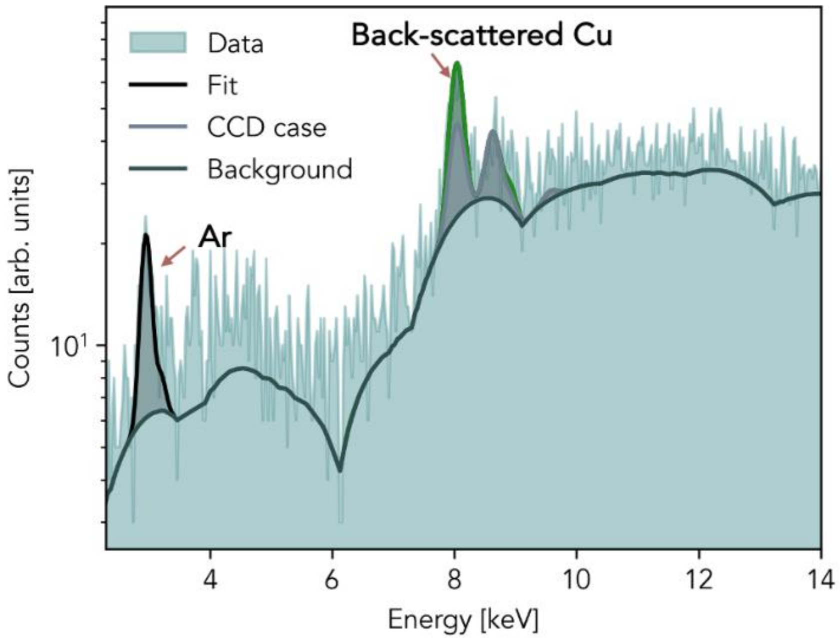
Proton spectrum measured @ source with spectrometer.

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

Proton spectrum



Backscattered X-ray spectrum



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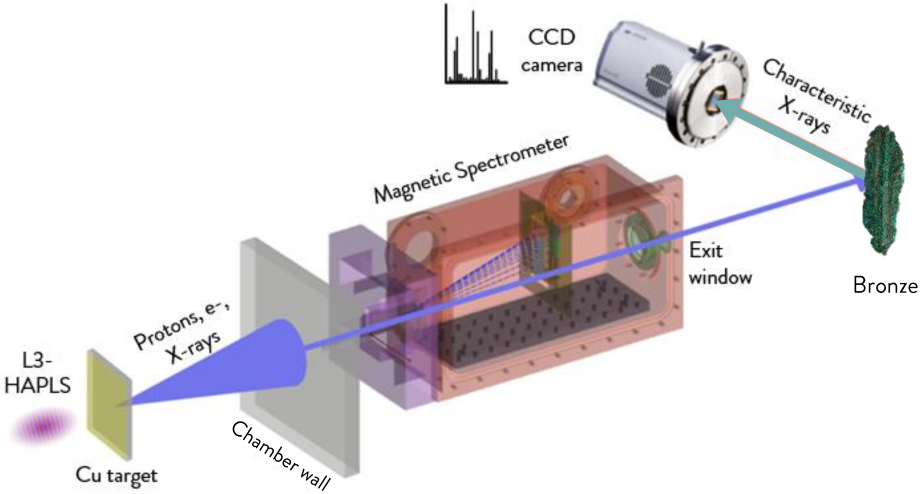
Quantitative laser-driven PIXE-XRF analysis of reference and medieval bronze

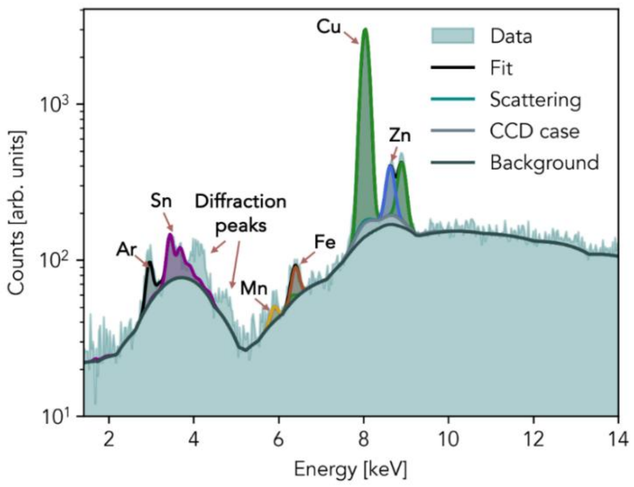


Analize spectra and **get elemental concentrations**

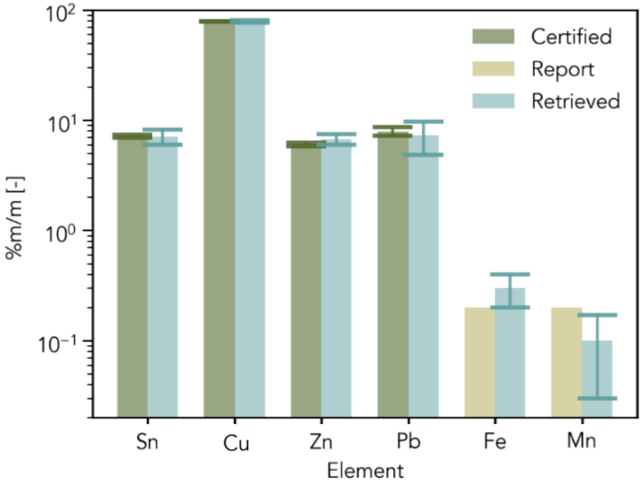
Include PIXE theoretical description
in the XRF PyMca workflow

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

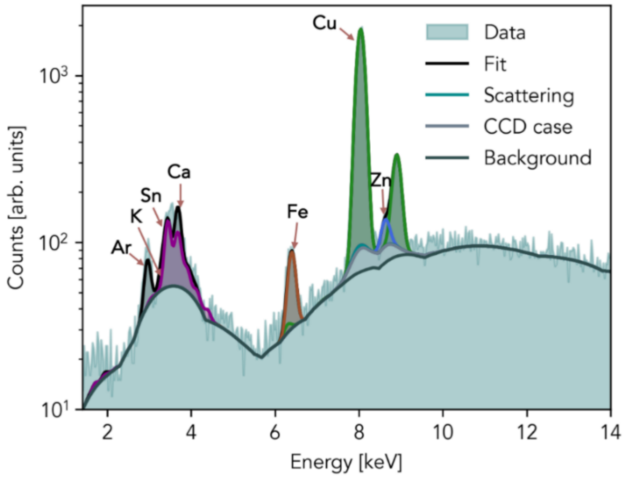
Reference bronze



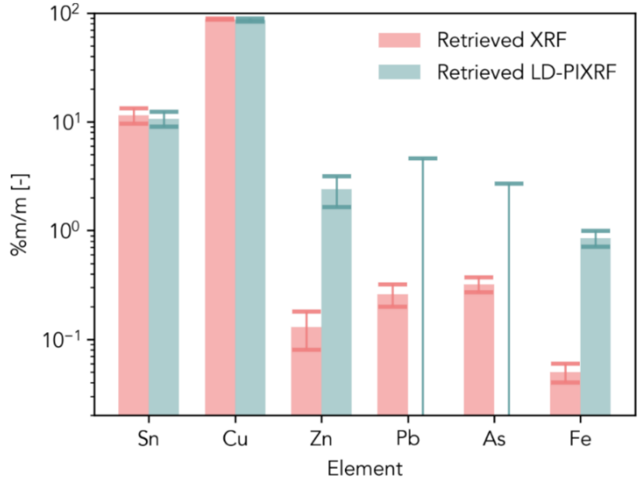
Concentrations



Medieval bronze

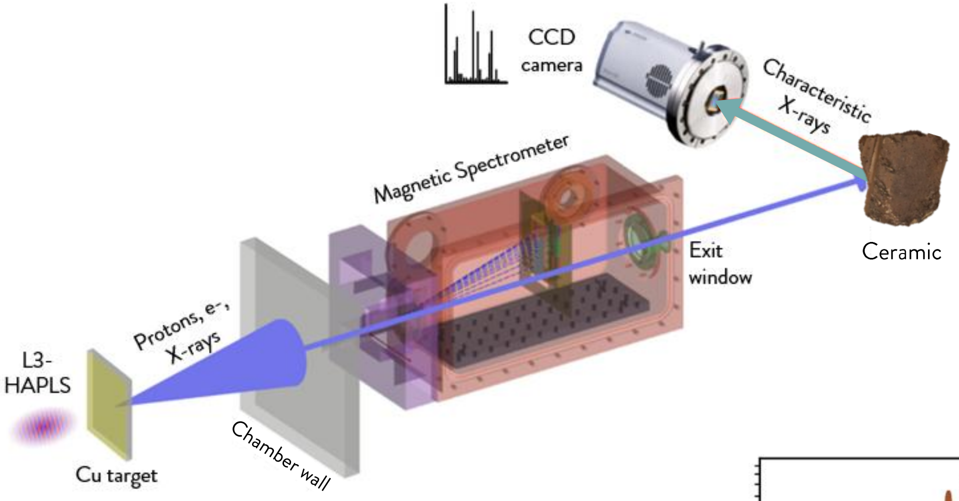


Concentrations



K. Ambrogioni, et al. *Under review at Science Advances* (2025).

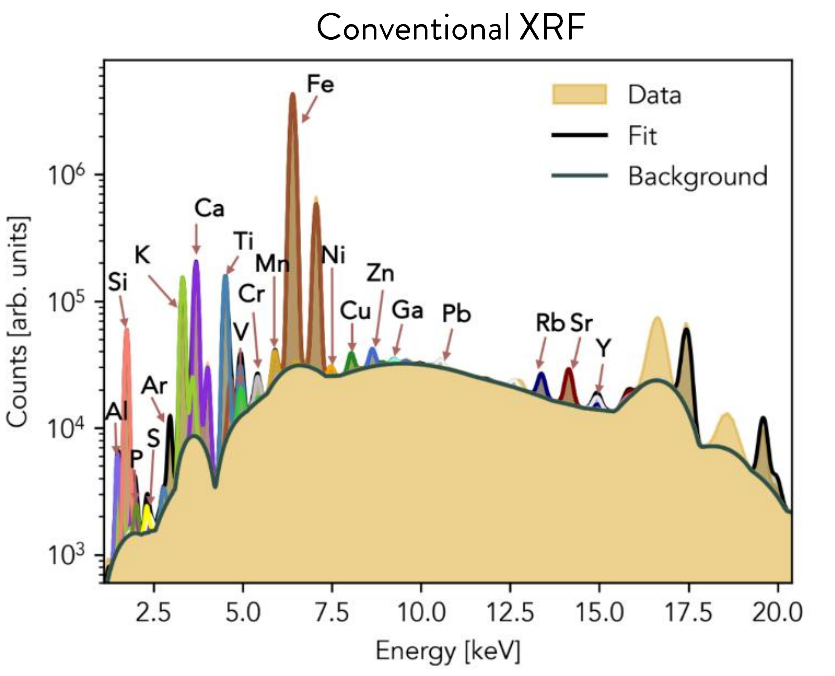
Qualitative analysis of Celtic ceramic with laser-driven PIXE-XRF and conventional XRF

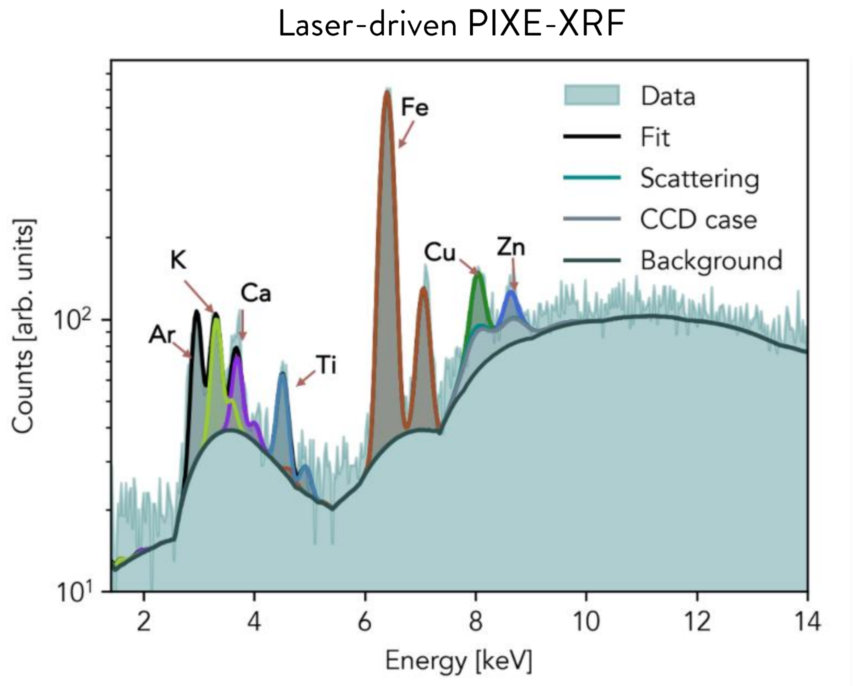


Investigate the **current limits** of the technique through **comparison** with **conventional XRF** on a challenging case study

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

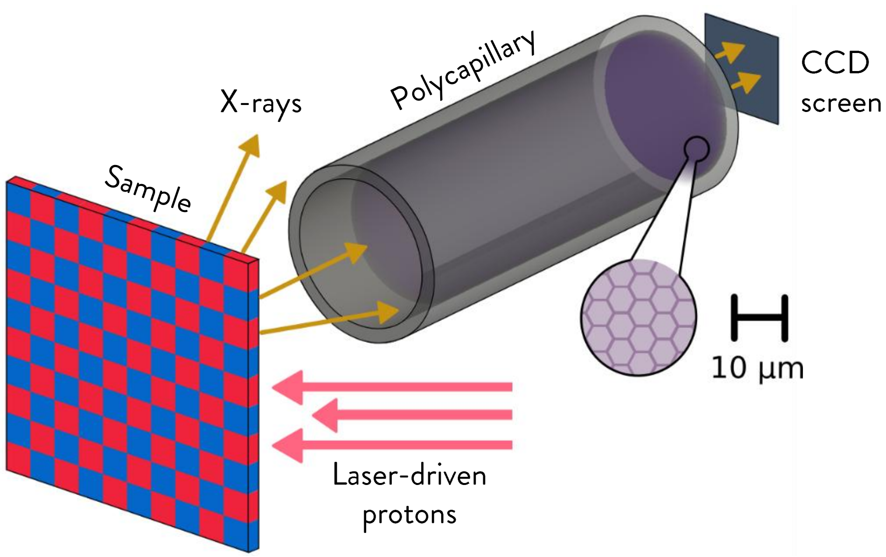
- In collaboration with **XRAYLab** at Consiglio Nazionale delle Ricerche | ISPC Istituto di Scienze del Patrimonio Culturale in Catania (Francesco Paolo Romano)





K. Ambrogioni, et al. *Under review at Science Advances* (2025).

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

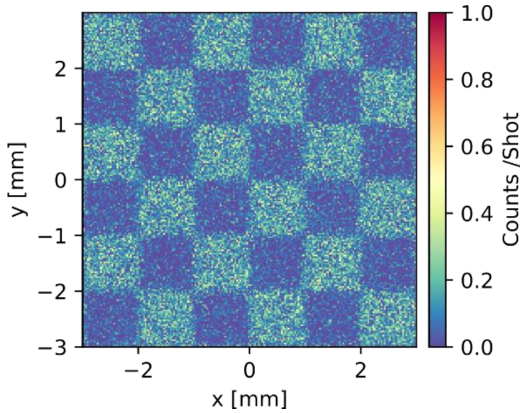


Map the distribution of the elements on the surface a non-homogeneous archeological sample.

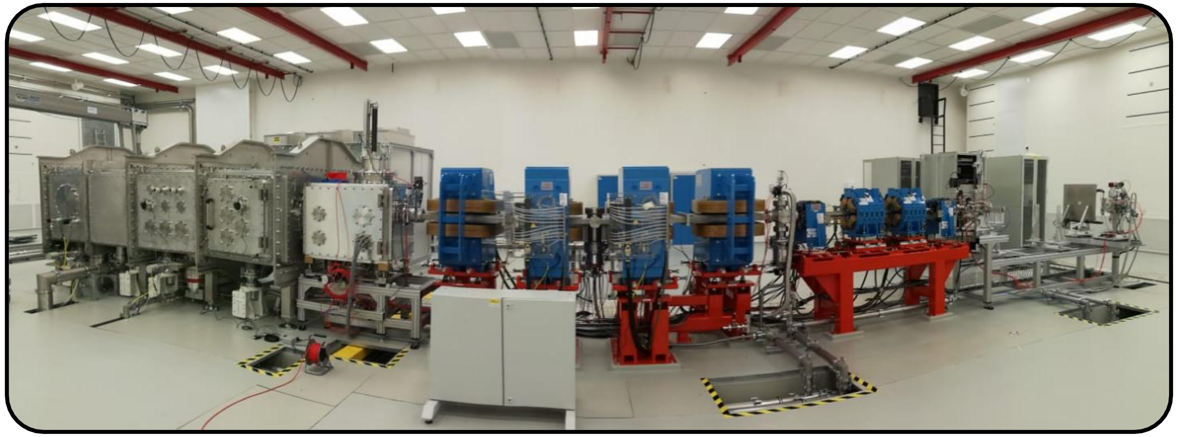
- Polycapillary X-ray optical component between sample and CCD to **filter X-rays not orthogonal to the surface**.

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

Fe elemental distribution

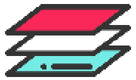


- Preliminary study performed with Monte Carlo simulations
- Very simple composition.



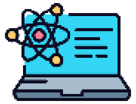
A. Maffini, et al. *Accepted by PPCF* (2026).

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-plasma** interaction **physics.**

→ **Proper models, include the effect of the pre-pulse** on the nanostructured plasma coupling Hydrodynamic and PIC simulation.

Combining photodiodes and electropermanent magnets in a single device allows **robust characterization of protons** and **manipulation** of the laser-plasma source.

→ Address the applicability of a similar detection scheme to **other laser-plasma emitted radiations**.

Many applications of laser-plasma 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-plasma 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).

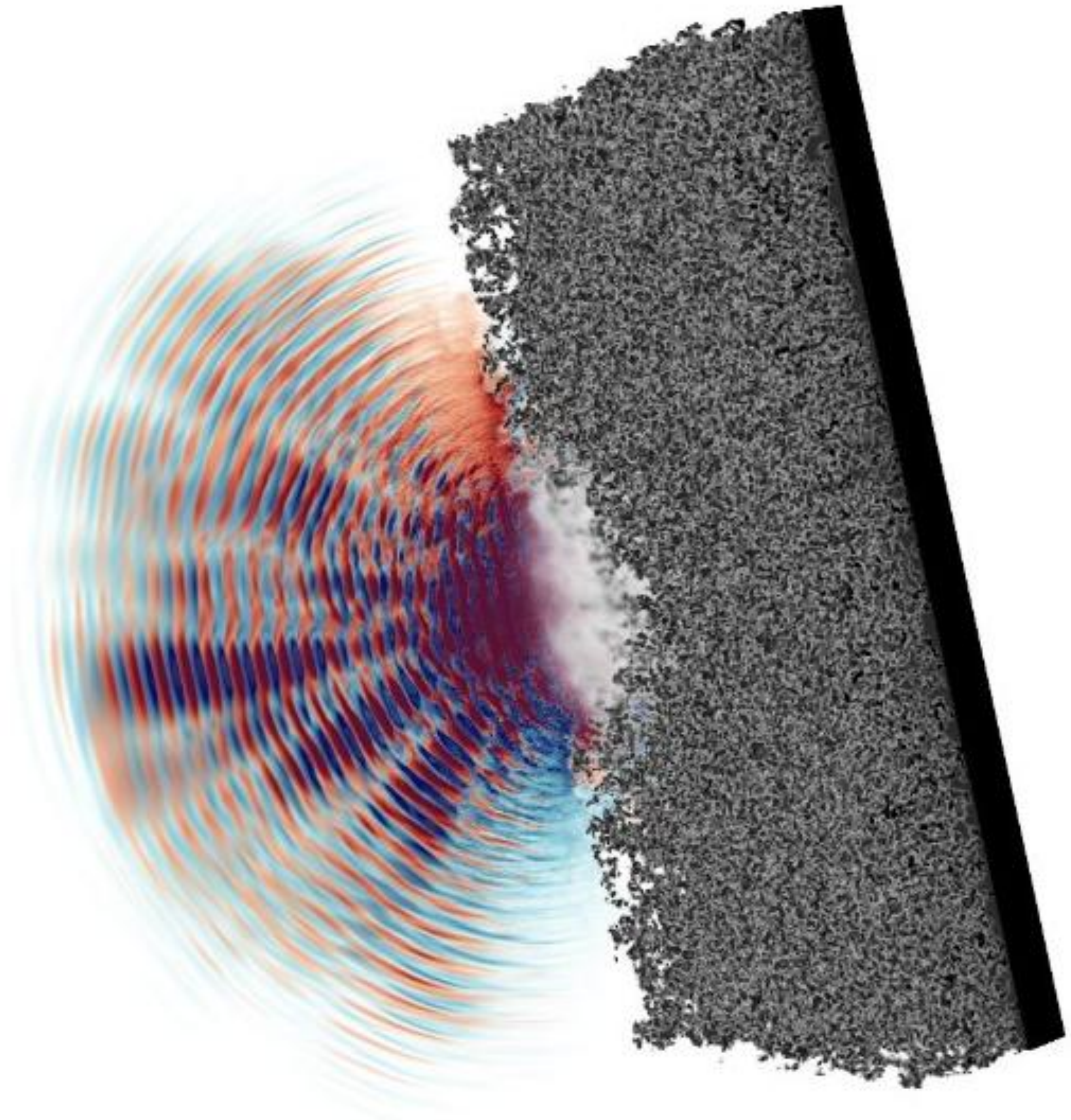
D. Orecchia, et al. *Small Structures* 5.6 (2024): 2300560.

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

A. Maffini, et al. *Accepted by PPCF* (2025).

M. Galbiati, et al. *Under review at Scientific Reports* (2025).

K. Ambrogioni, et al. *Under review at Science Advances* (2025).



Thank you for the attention!

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