

POLITECNICO
MILANO 1863

 **NanoLab**
DIPARTIMENTO DI ENERGIA

Laser-Driven Radiation Sources for PIXE and XRF Applied to Cultural Heritage Analysis

Francesco Mirani

17th March 2026

ELIMED 2026

16 - 18 March 2026
ELI Beamlines Facility
Dolní Břežany, Czech Republic



- Our group from  **POLITECNICO** :
MILANO 1863



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Principal Investigator



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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

- Activities in collaboration with:

- The  **eli** Beamlines with

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



D. Margarone



L. Giuffrida



V. Kantarelou

...and the ELIMAIA team (F. Schillaci, etc.)

- The  |  **SPC** ISTITUTO DI SCIENZE DEL PATRIMONIO CULTURALE with



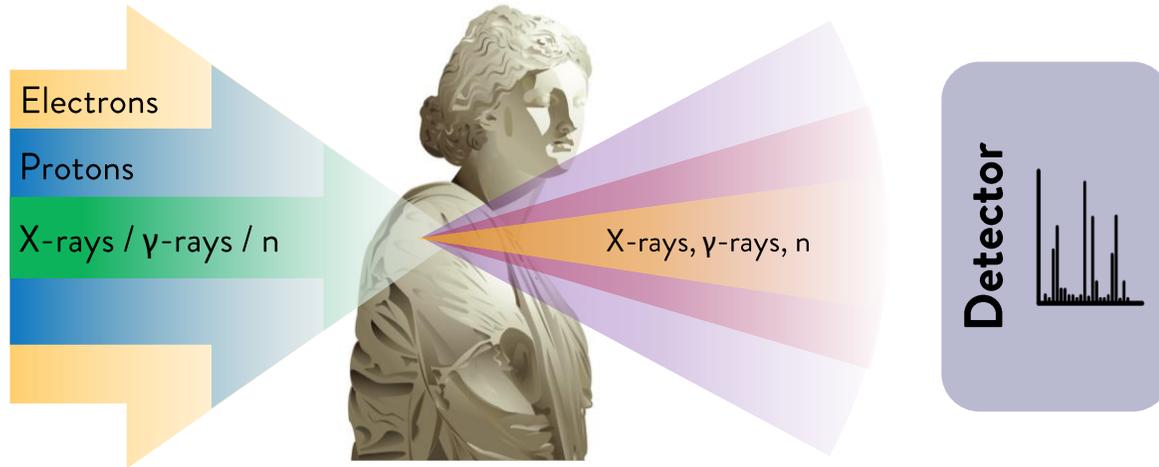
C. Conti

- The  **RAYLAB** company with



D. Rastelli

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



Particle Induced X-ray Emission (PIXE)

- MeV protons \rightarrow X-rays
- 0-10s μ m, homogeneous and stratigraphic
- low-Z elements



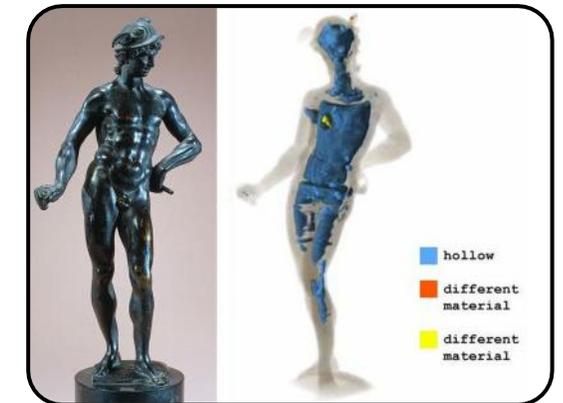
X-Ray Fluorescence (XRF) spectroscopy

- keV photons \rightarrow x-rays
- 10s μ m, homogeneous samples, elemental mapping
- high-Z elements



Activation Analysis (PAA, NAA) and Radiography

- Neutrons, MeV photons \rightarrow γ -rays
- Homogeneous, bulk

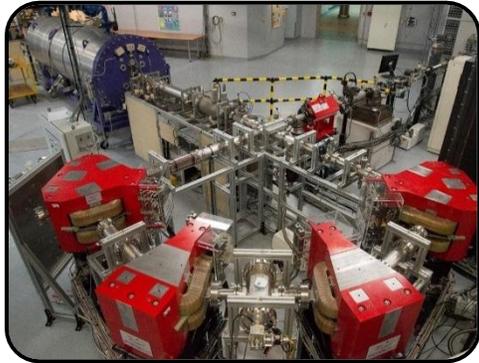


Verma, Hem Raj. Atomic and nuclear analytical methods. Springer, 2007.
E. H. Lehmann, J. Archaeol. Sci. Rep. 19 (2018): 397-404.

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?

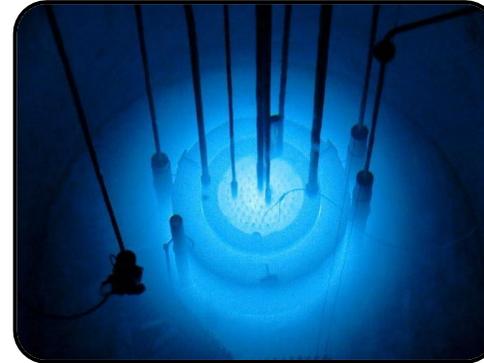
Particle accelerators



Portable X-ray tubes



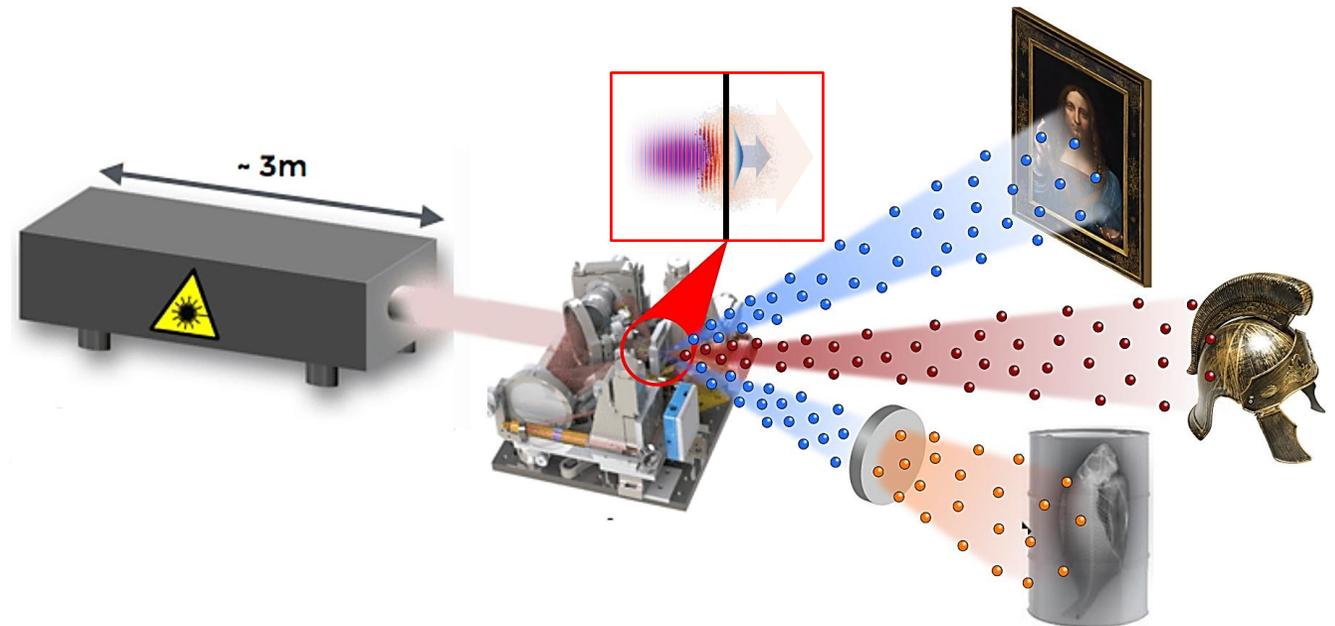
Neutron / γ -ray sources



- Different conventional sources for specific techniques



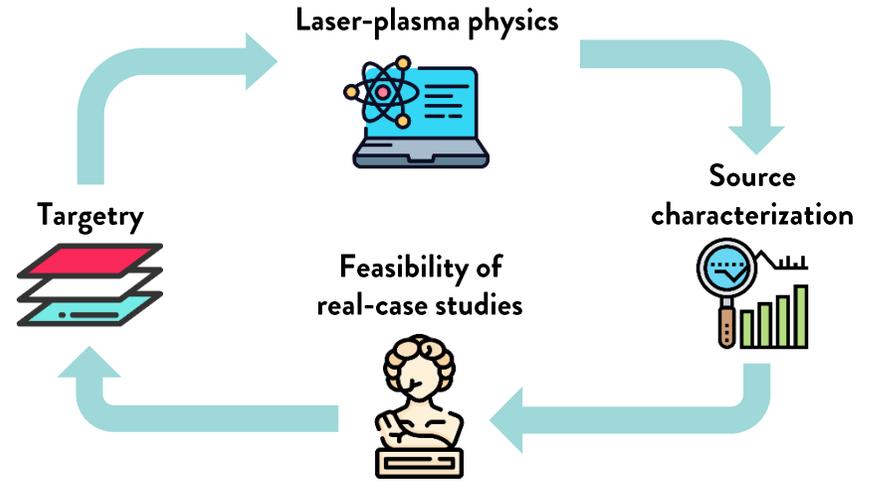
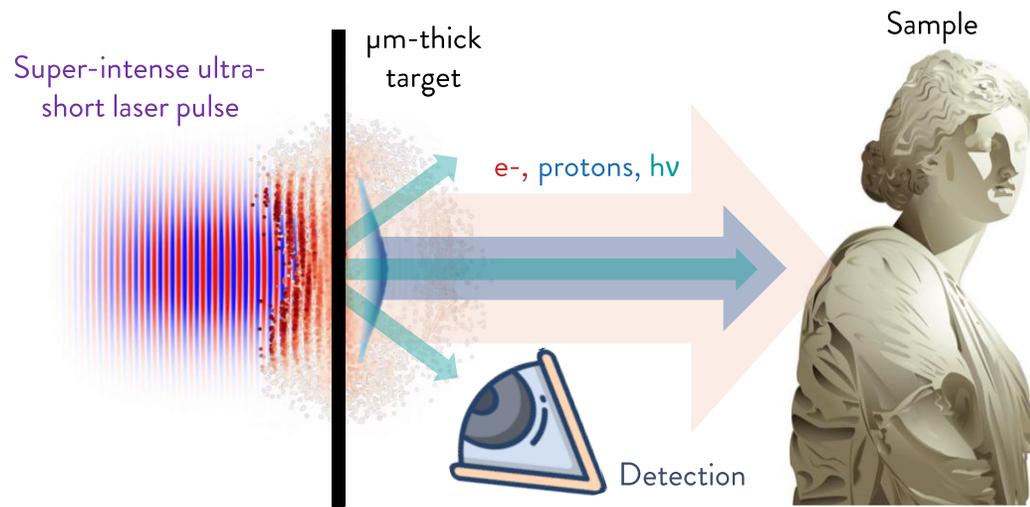
Laser-plasma accelerators are potentially compact and multi-purpose.



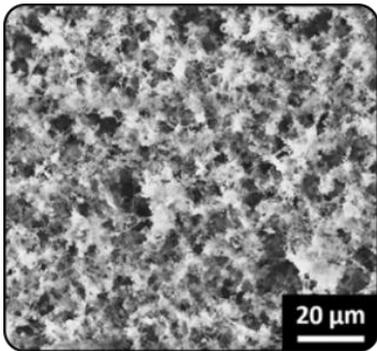
M. Passoni, et al. *PPCF*, 62(1), (2019): 014022.

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

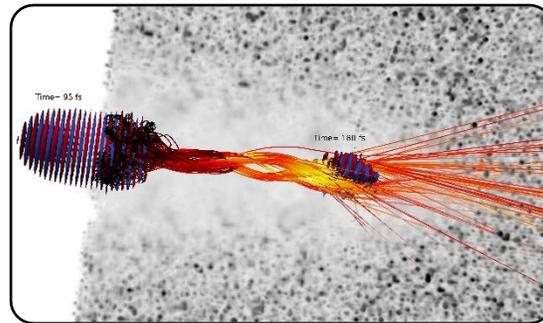
To this aim, several aspects must be investigated...



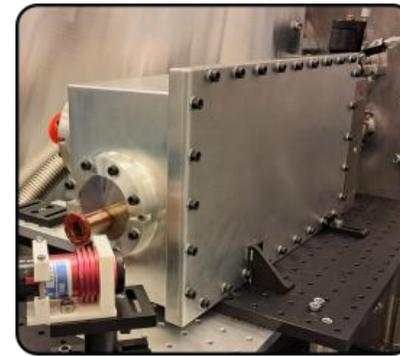
Production of **advanced targets** with deposition techniques



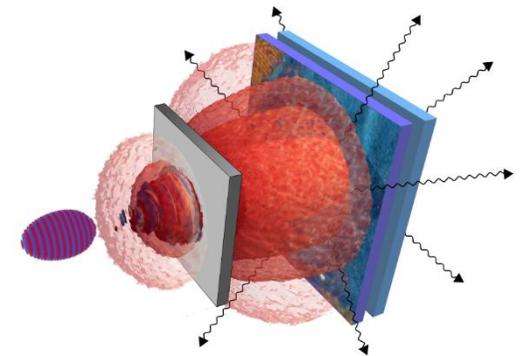
Theoretical and experimental investigation of **laser-plasma interaction**



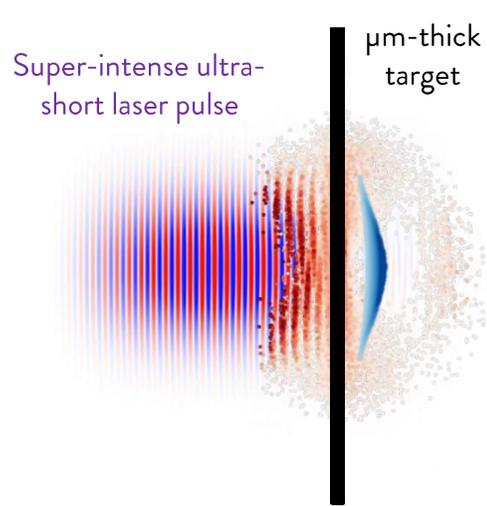
Development of **diagnostics** of laser-driven proton beams



Assessment of applications like **artworks characterization**



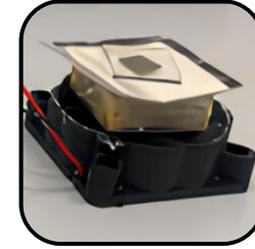
Advanced targets with deposition techniques: solid foils



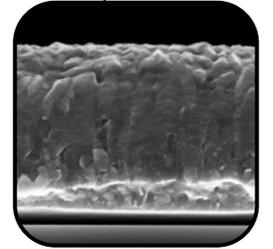
- **Control target** properties (thickness, composition, etc.)  **Tune the energy** of TNSA ions
- Shot-to-shot **stability crucial for applications**  **Not ensured** by commercial targets

-  Developed strategy for **metallic target deposition** via Magnetron Sputtering
 - 0.05 – 5 μm thicknesses, negligible uncertainty
 - Al, Ti, Cu, ...

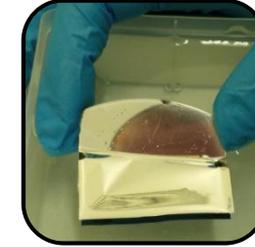
Spin coating of soap layer on glass



Metallic target deposition



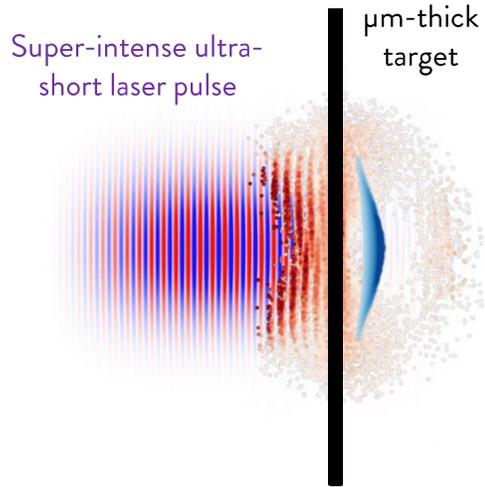
Soap removal in water



Target fishing on the holder



Advanced targets with deposition techniques: solid foils

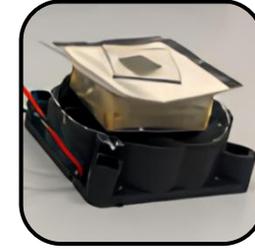


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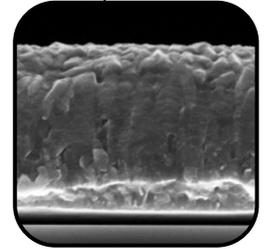
Developed strategy for **metallic target deposition** via Magnetron Sputtering

- 0.05 – 5 µm thicknesses, negligible uncertainty
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- Tested @ **CLPU** CENTRO DE LÁSERES PULSADOS and **eli** Beamlines

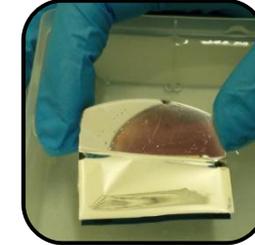
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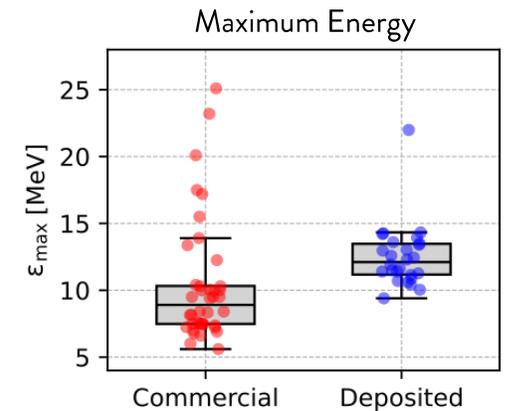
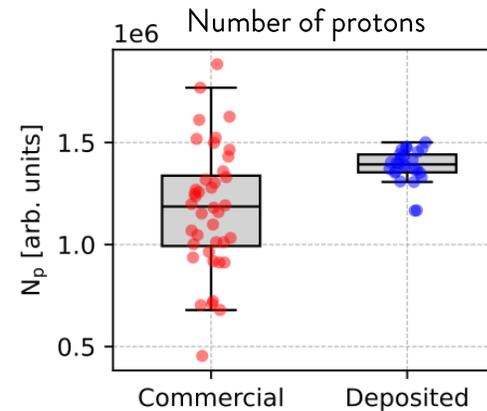
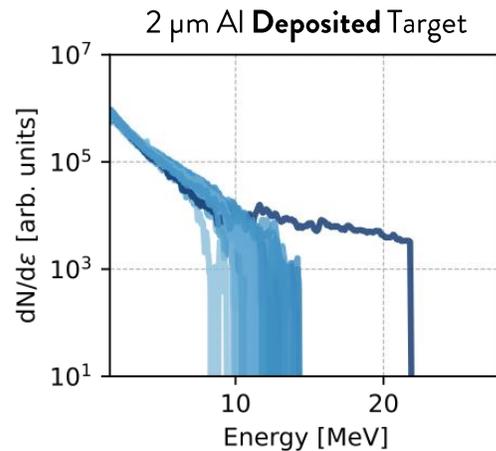
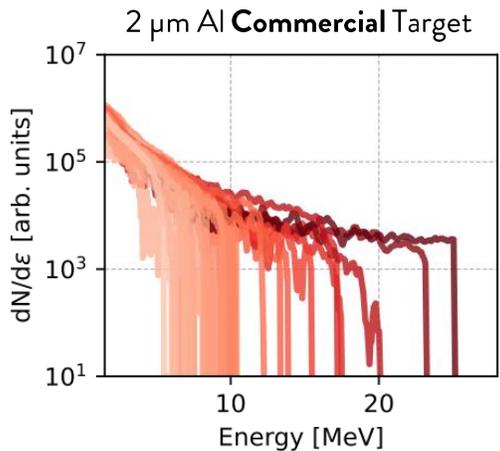
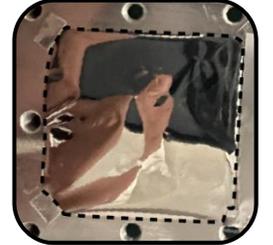
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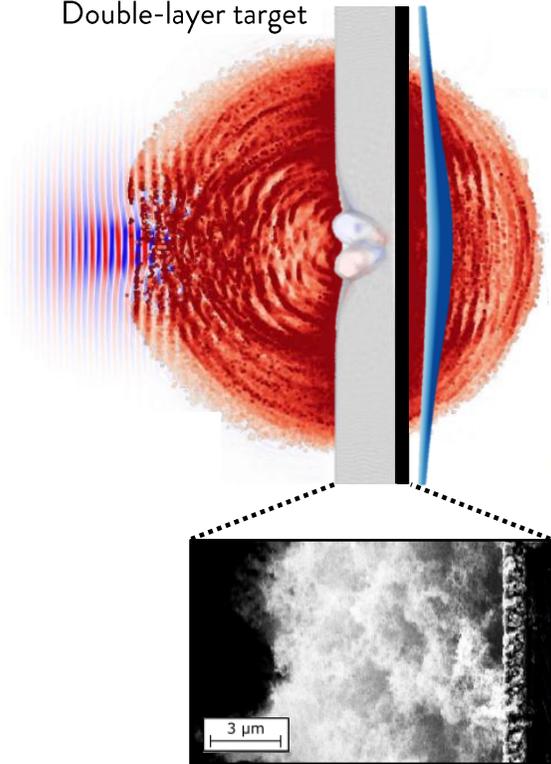


F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

A. Maffini, et al. *PPCF* 68 (2025): 035007.

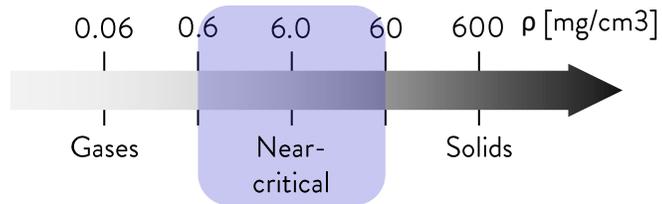
Advanced targets with deposition techniques: Double Layer Targets (DLT)

Double-layer target



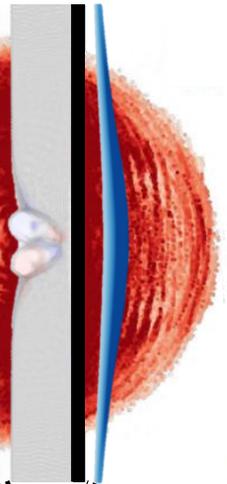
- **Control target** properties (thickness, composition, etc.) → **Tune the energy** of TNSA ions

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



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

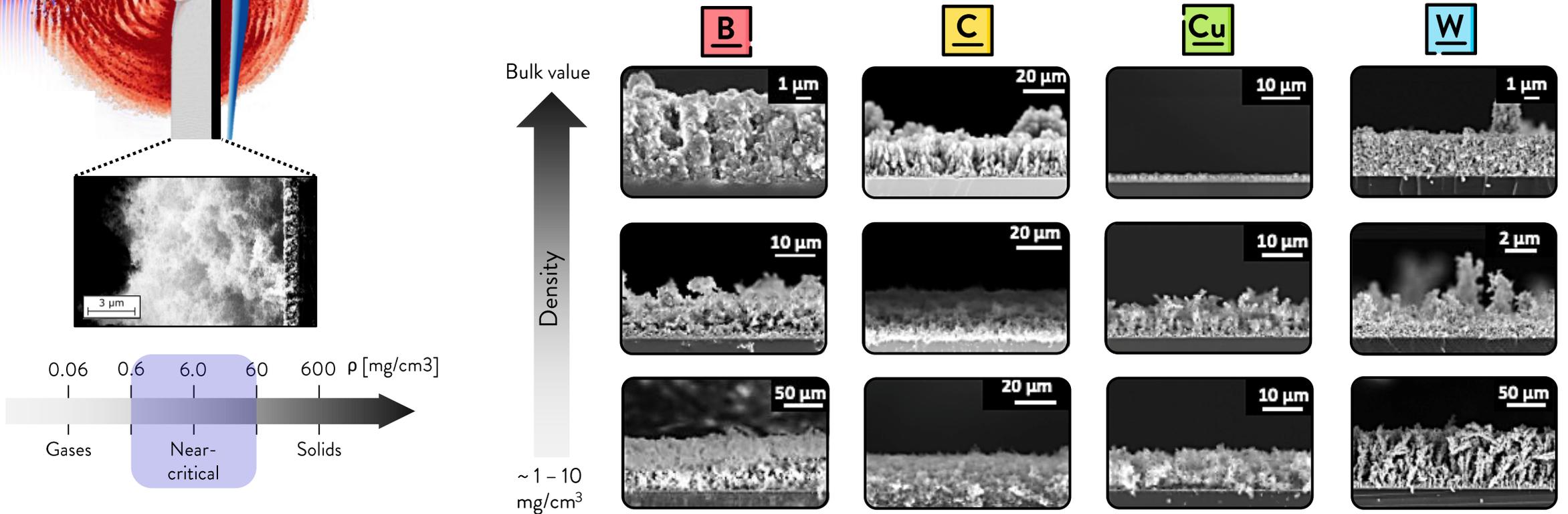
Double-layer target



- **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**.

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



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

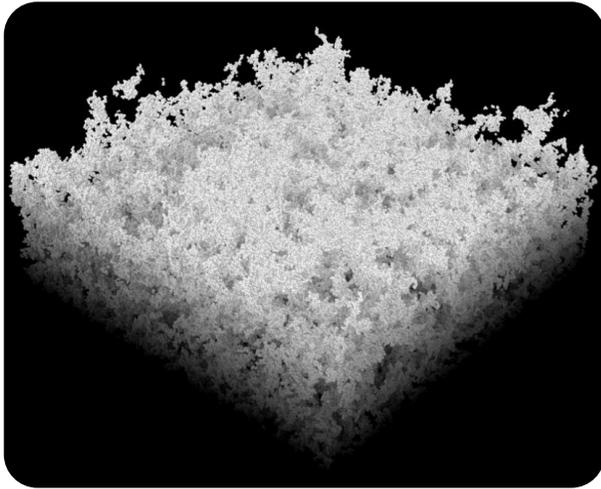
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Investigation of laser interaction with near-critical DLT

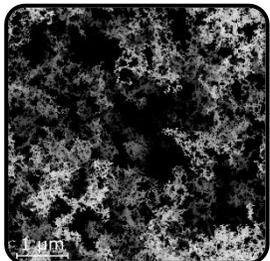
- Laser interaction with low-density nanostructured materials is complex → **Theoretical investigation should include the real structure.**



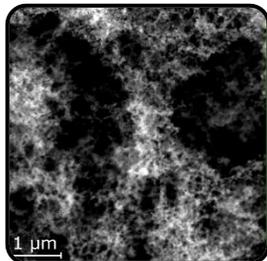
Development of a diffusion-limited cluster-cluster aggregation code to **growth synthetic nanostructures.**



Synthetic foam



Real foam



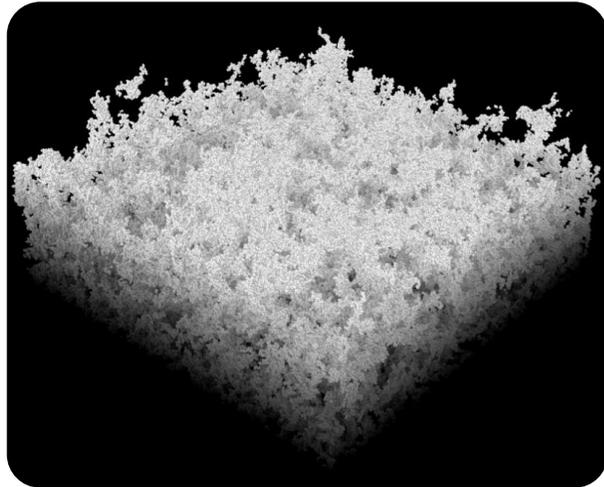
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Investigation of laser interaction with near-critical DLT

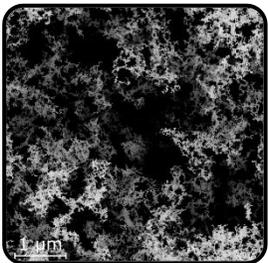
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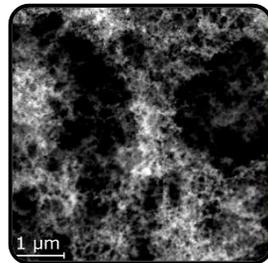
Development of a diffusion-limited cluster-cluster aggregation code to **grow synthetic nanostructures.**



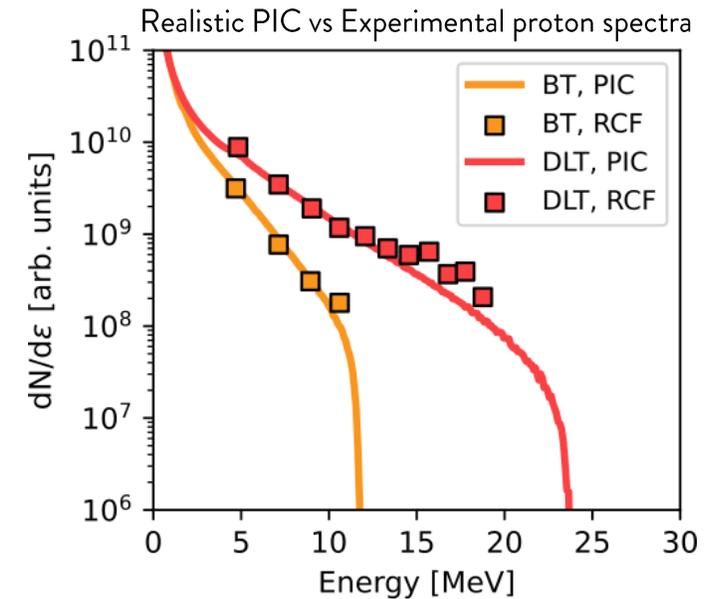
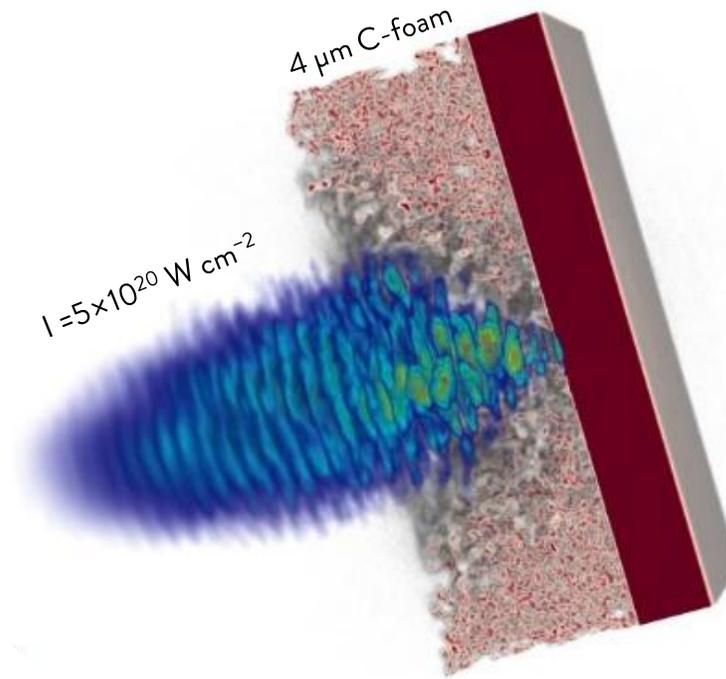
Synthetic foam



Real foam



- 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.

A. Maffini, et al. *PPCF* 68 (2025): 035007.

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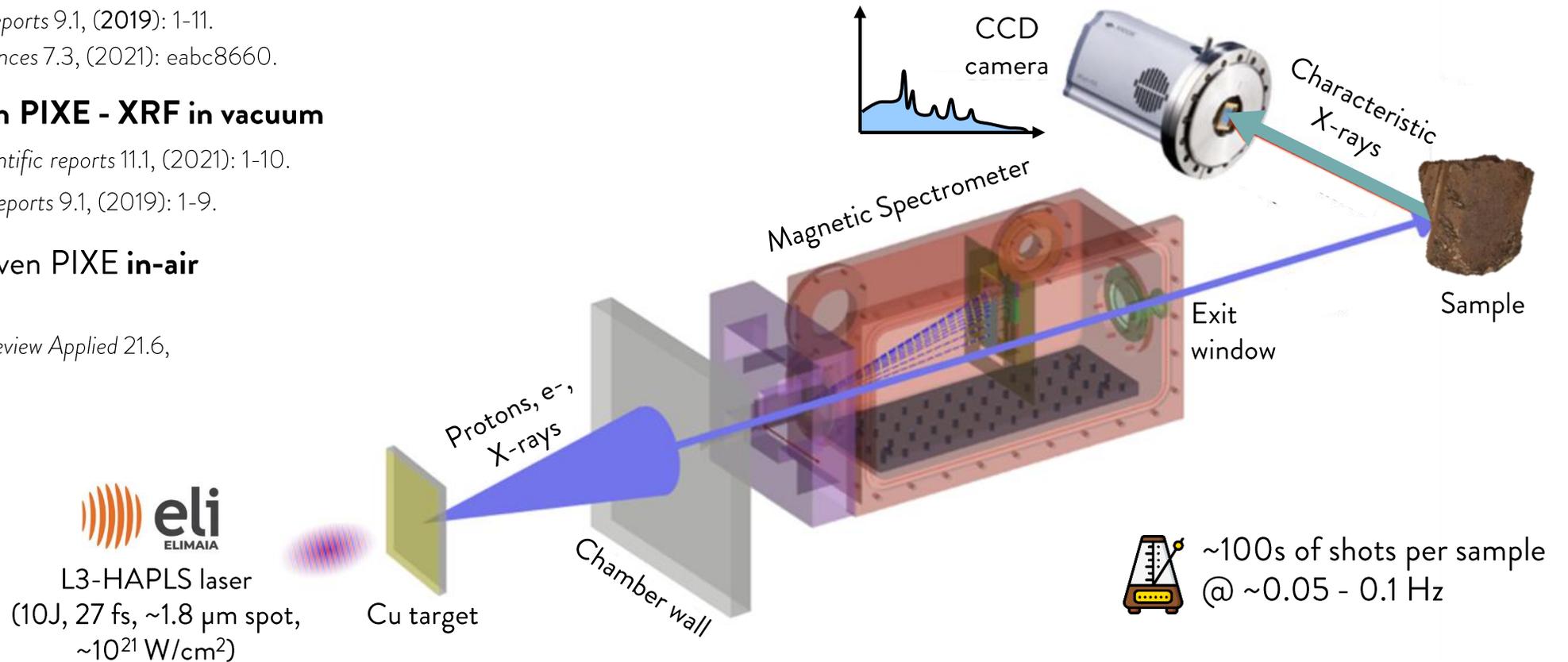
- **Quantitative** laser-driven PIXE **in-air** **with standards**

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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



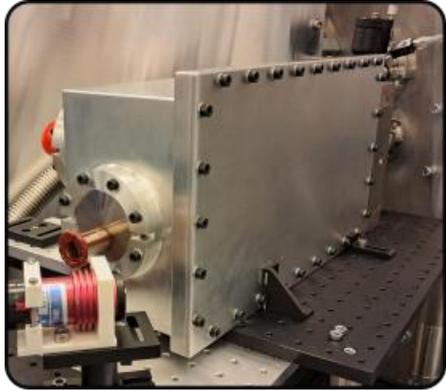
K. Ambrogioni, et al. *Under review* @ *Science Advances* (2026).

Exploit an application-oriented proton spectrometer developed with RAYLAB

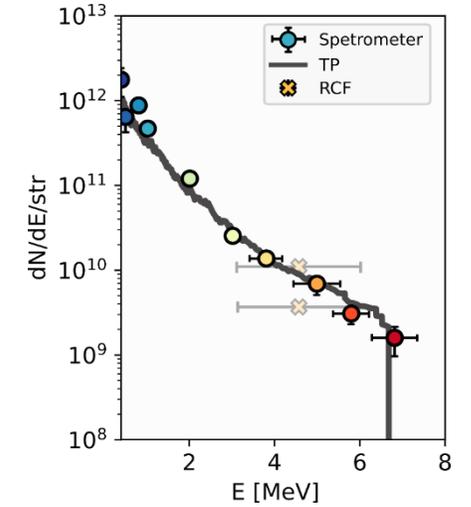
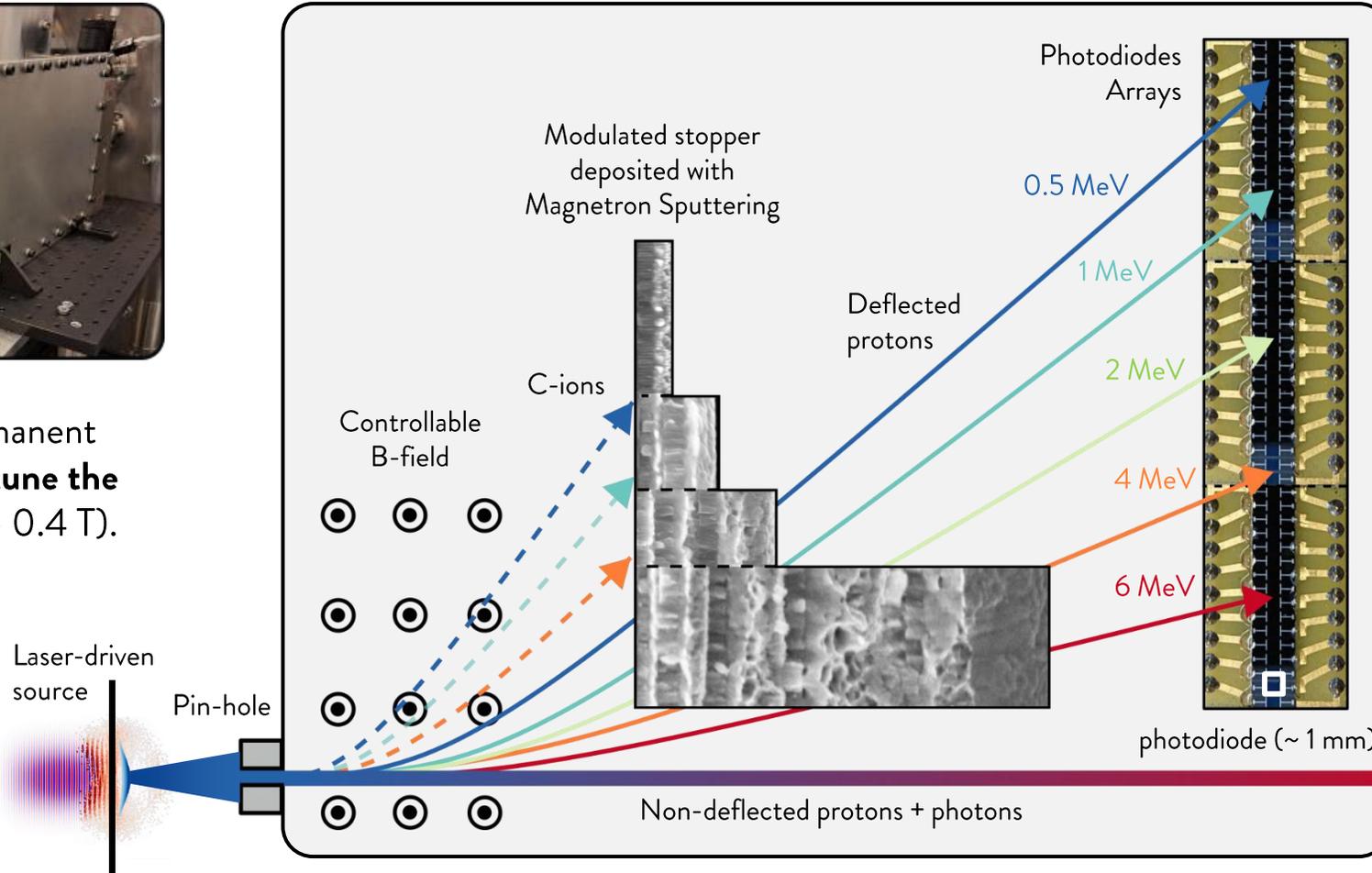
DETECTING INNOVATION



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).



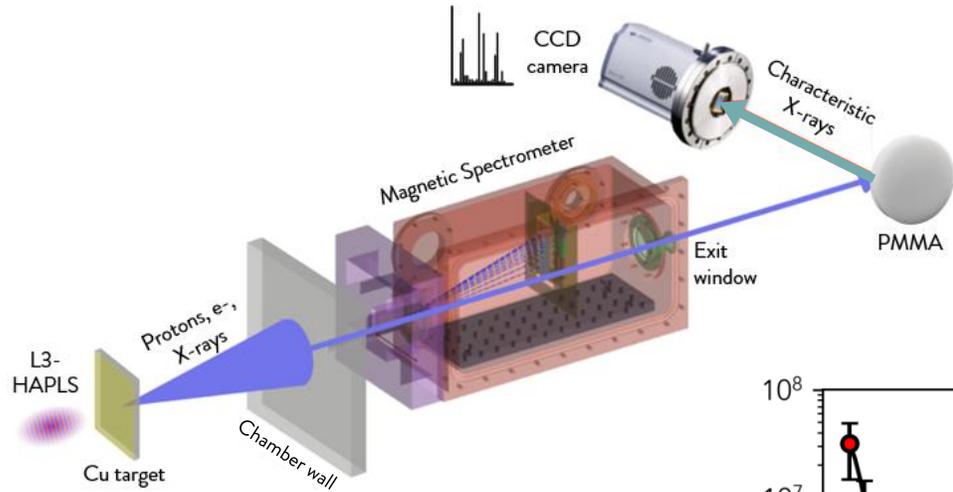
- **Agreement with the shape of proton spectrum from Thomson Parabola.**

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

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

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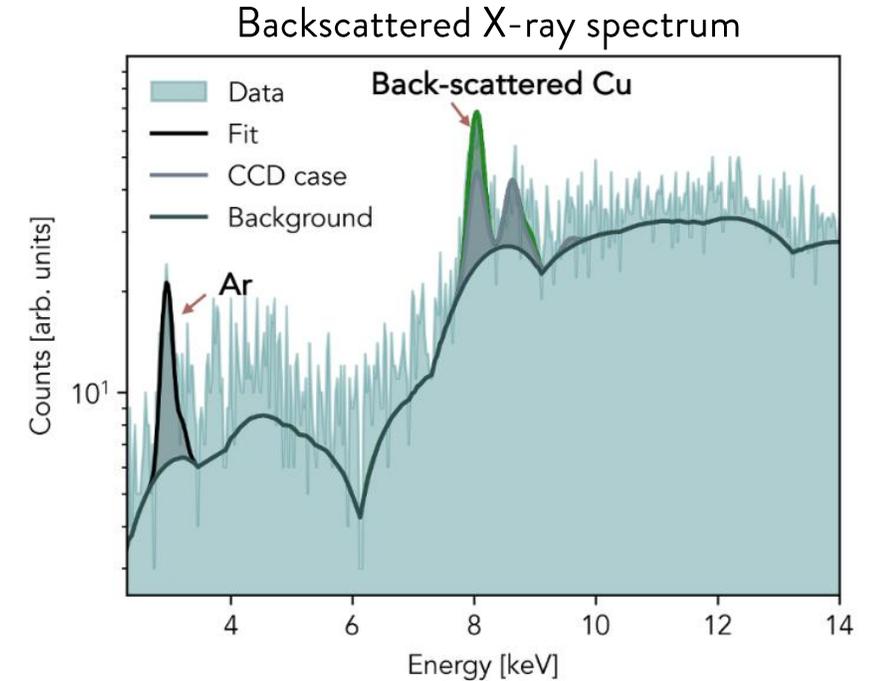
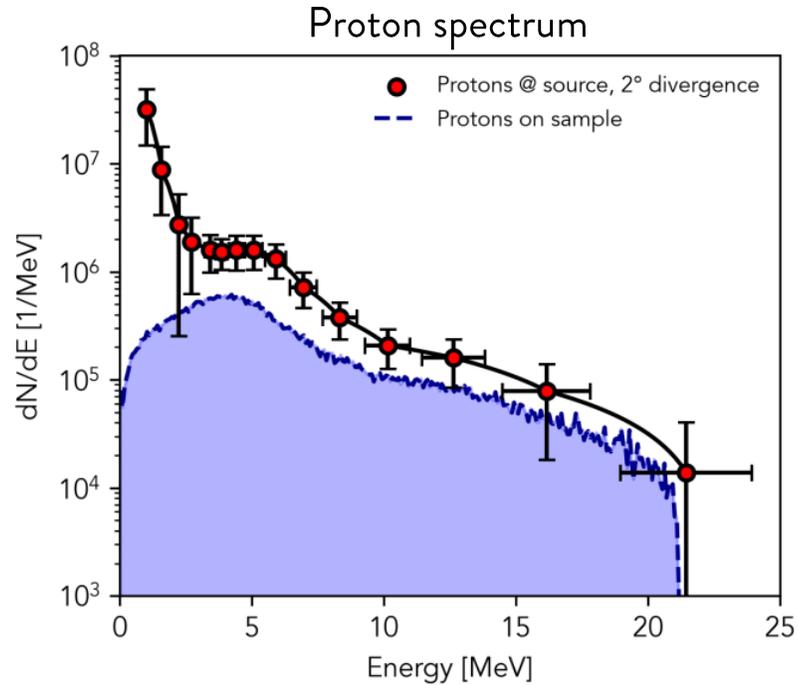
Characterization of protons and X-rays emitted by the laser-plasma source



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

GEANT4 simulation to estimate 1.3×10^5 **Cu-X-rays** per laser shot on sample.

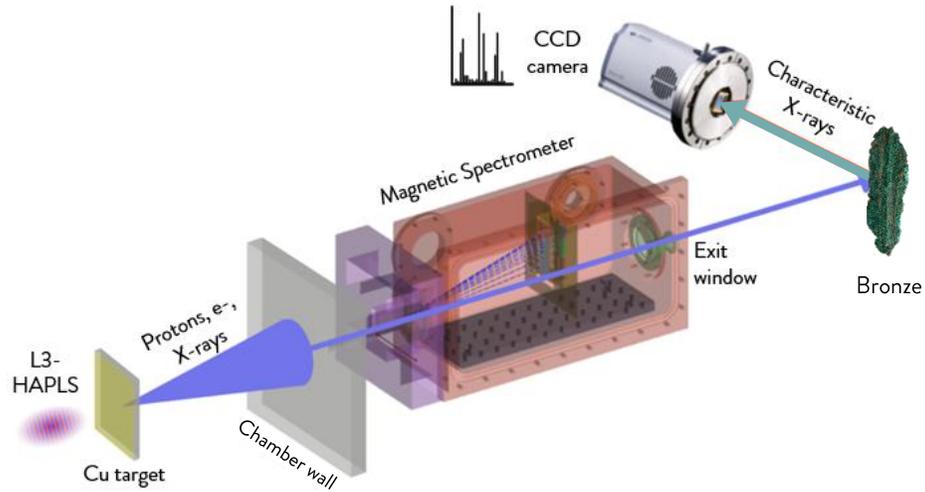
Proton spectrum measured @ source with spectrometer.



GEANT4 simulation to estimate 4×10^5 **protons** per shot on sample.

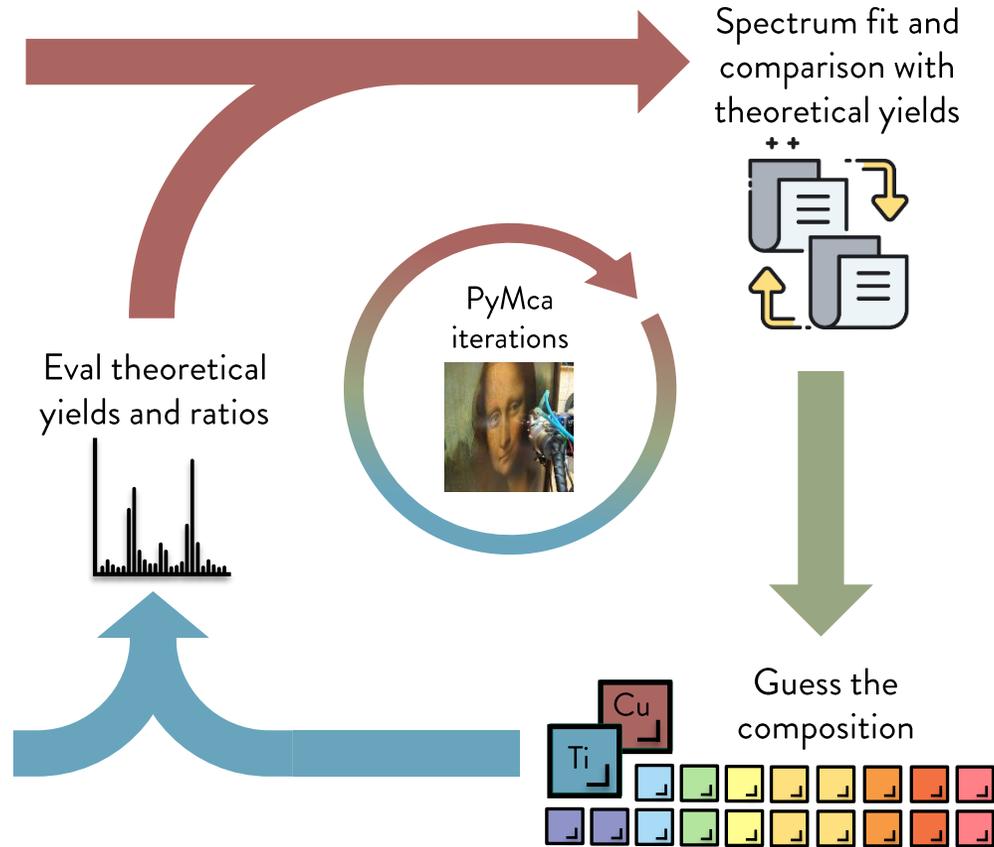
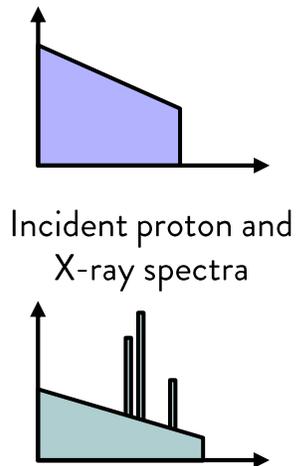
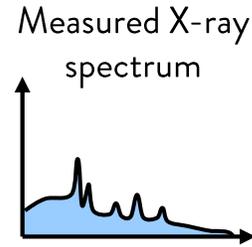
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Quantitative laser-driven PIXE-XRF analysis: procedure to get elemental concentrations



Include PIXE theoretical description in the XRF PyMca workflow

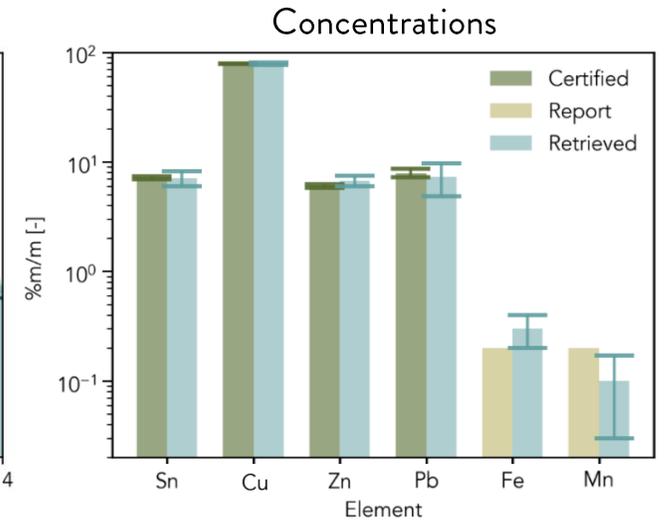
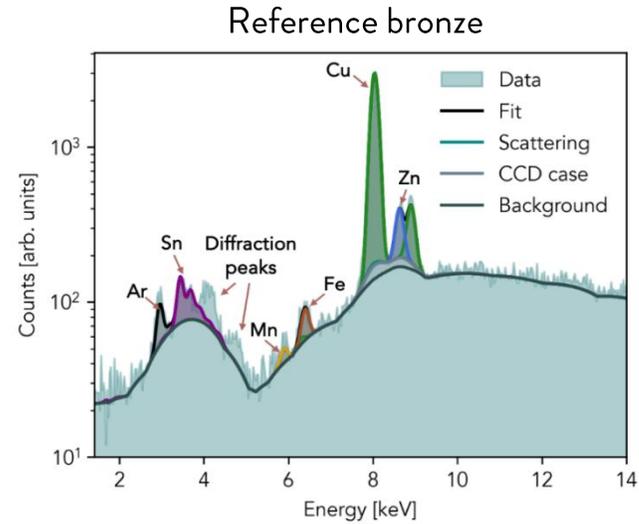
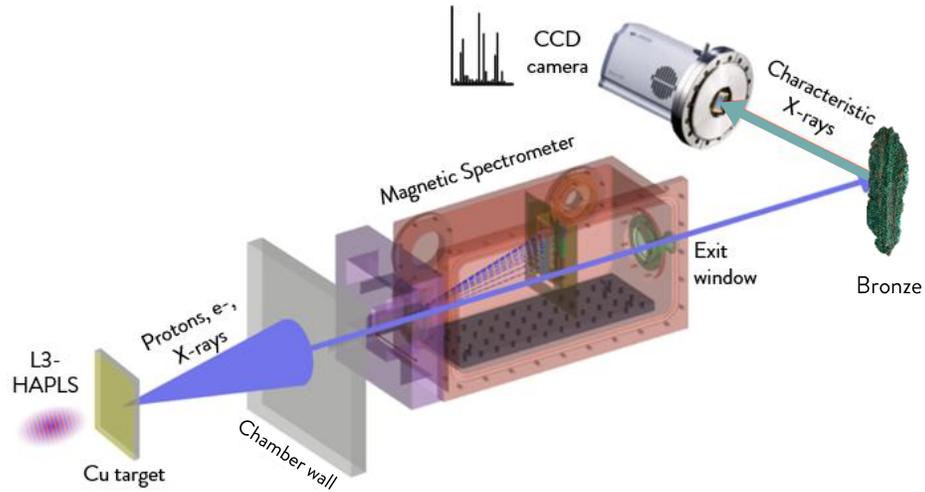
- High accuracy in considering atomic physics and matrix effects.
- Standard in conventional quantitative XRF.



V.A. Solé, et al. *Spectrochimica Acta Part B: Atomic Spectroscopy* 62.1 (2007): 63-68.

K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

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

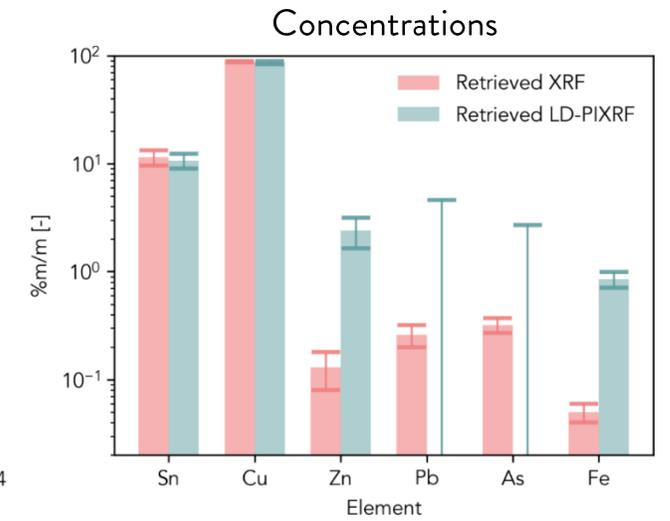
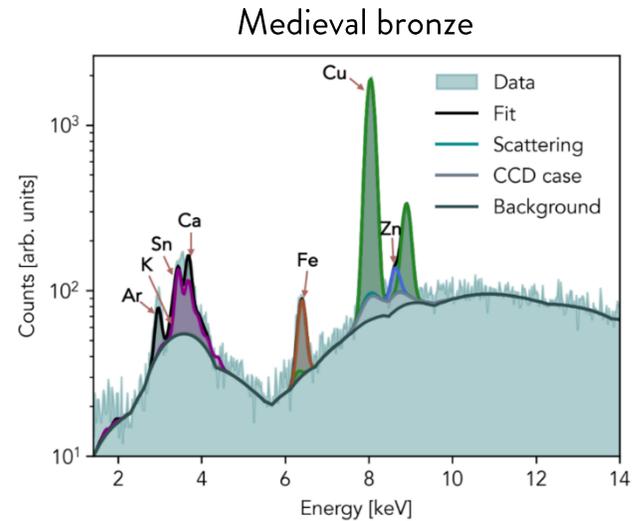


Analyze spectra and **get elemental concentrations**



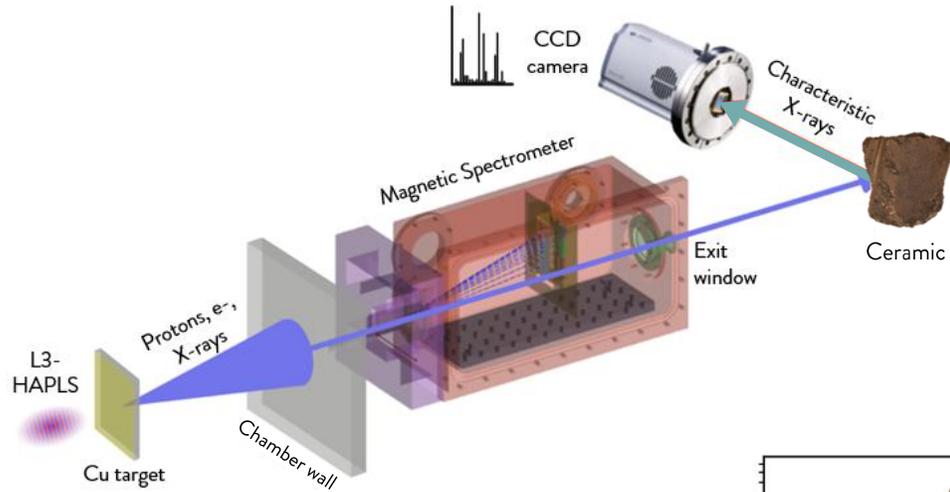
Include PIXE theoretical description in the **XRF PyMca** workflow

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



K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

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

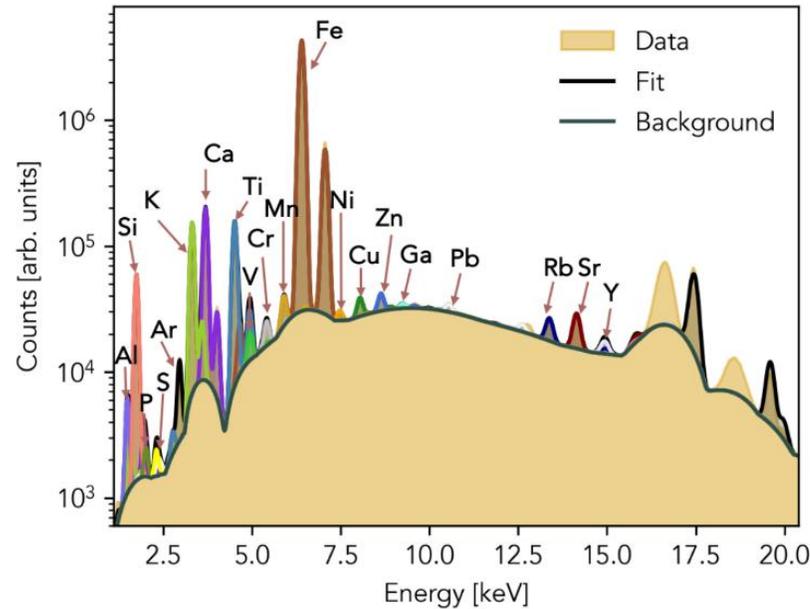
- Main elements (down to ~0.1%) identified with laser-driven PIXE-XRF
- Trace low-Z and high-Z elements not recognized...**improvements are needed**

- In collaboration with **XRAYLab** at

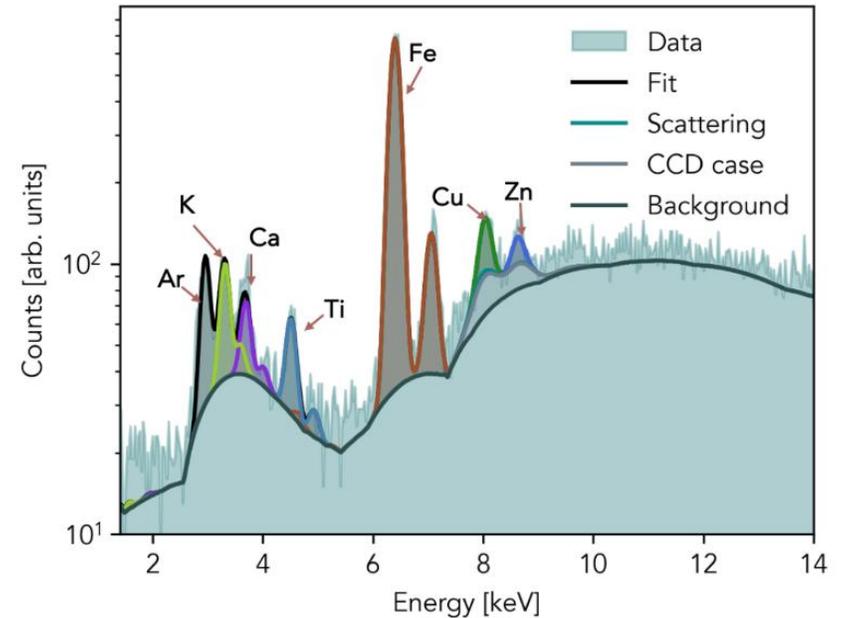


in Catania (Francesco Paolo Romano)

Conventional XRF



Laser-driven PIXE-XRF



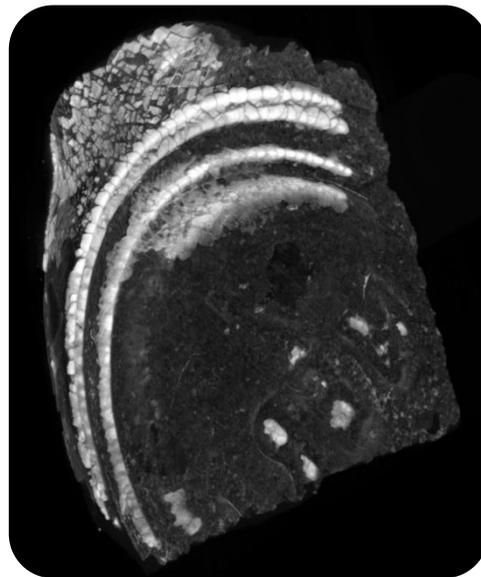
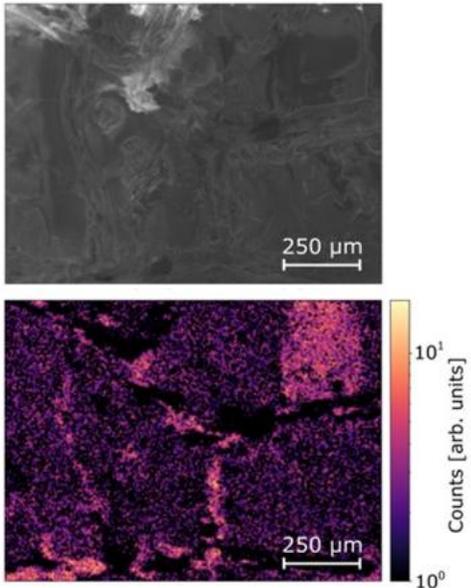
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Qualitative analysis of Celtic ceramic with laser-driven PIXE-XRF and conventional XRF

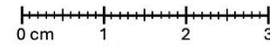
This ceramic case-study is part of a **broader analysis** on a large set samples with **different techniques**.

- Raman spectroscopy
- Conventional and Differential PIXE
- Rutherford Backscattering spectroscopy
- Energy Dispersive X-ray Spectroscopy
- X-ray computed Thomography Scan

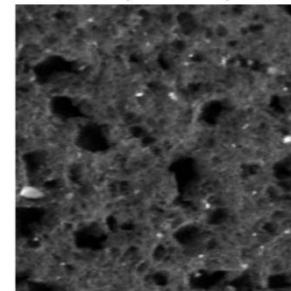
• In collaboration with



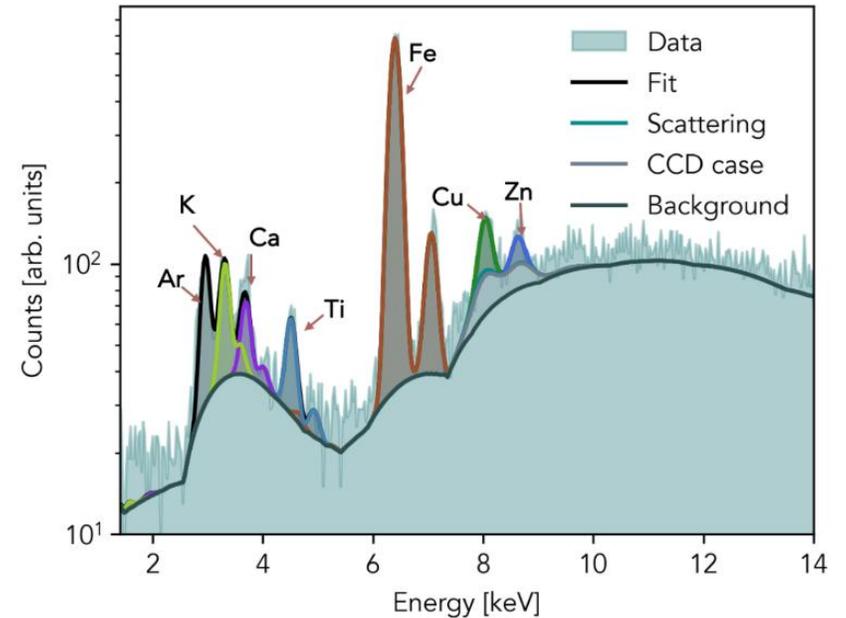
• μ -XRF



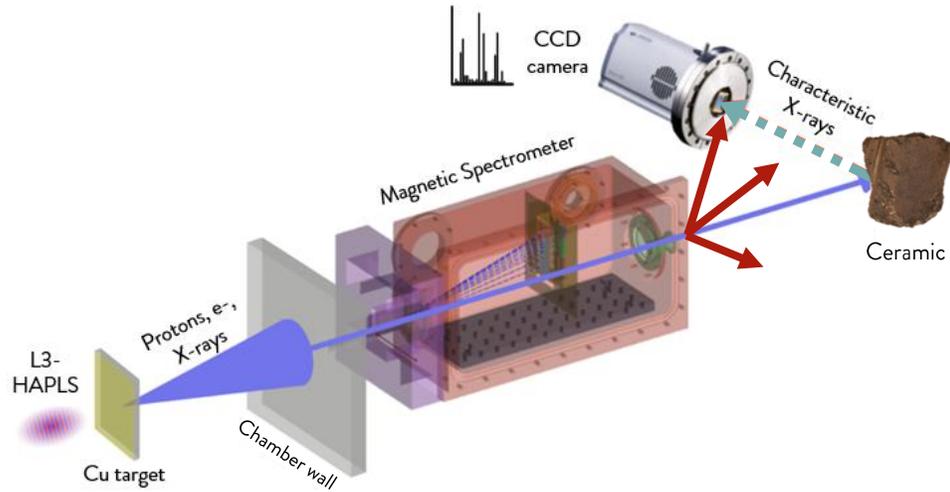
Iron μ -XRF map



• Laser-driven PIXE-XRF

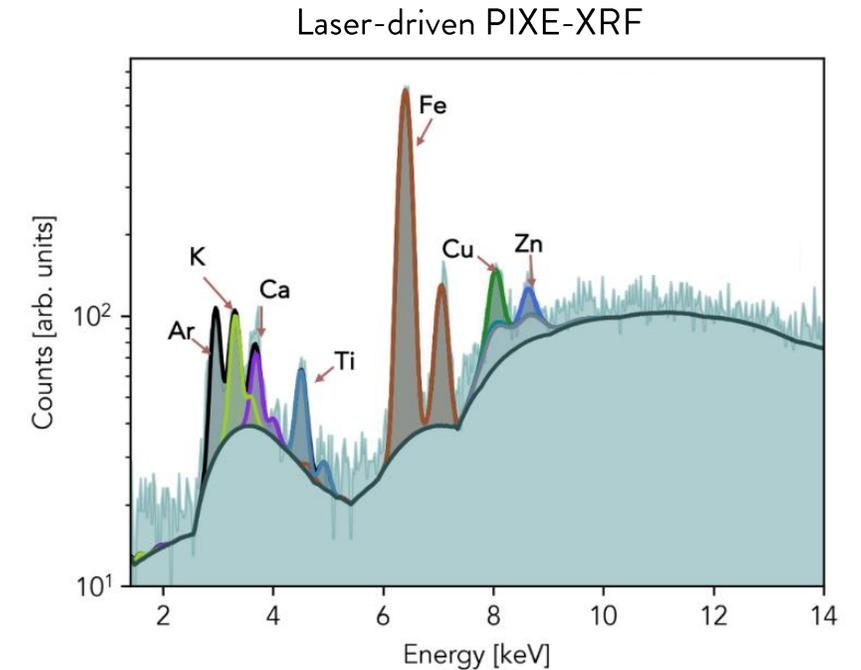
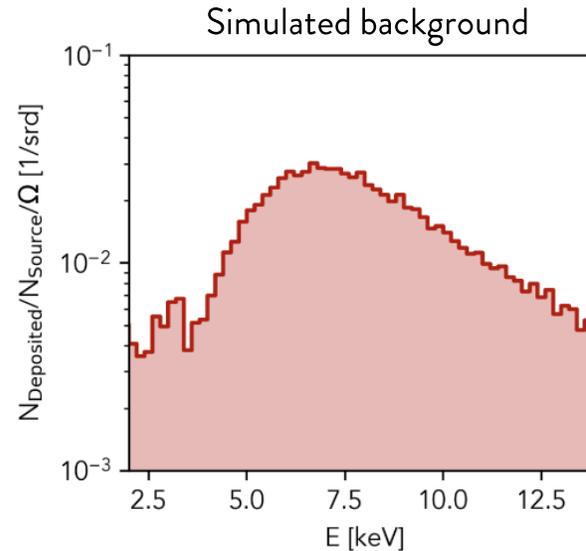


What's next?... Optimization of laser-driven PIXE-XRF setup for cultural heritage analysis



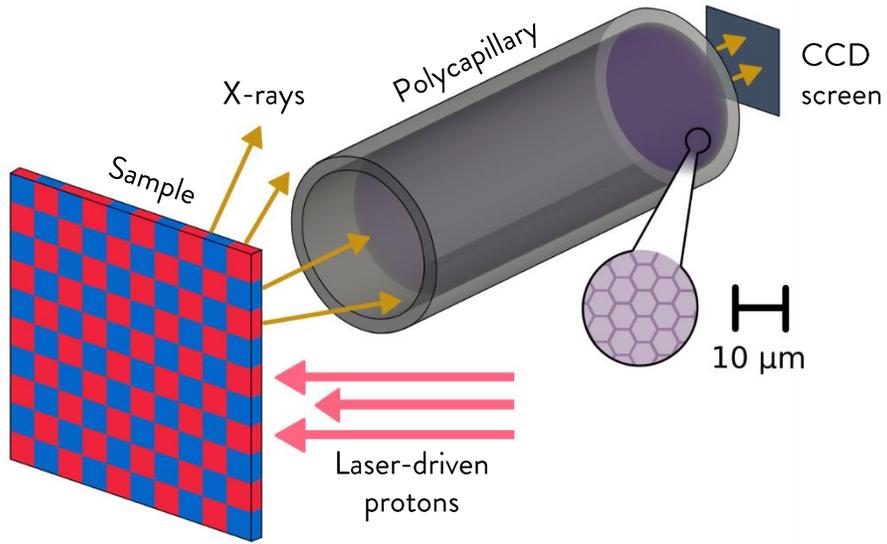
- **Mitigate** low-energy X-ray **attenuation in air** → He flux between sample and CCD camera
- Test alternative CCD cameras with **higher detection efficiency** in the energy region of interest

- A fraction of **high energy electrons** from the laser-plasma source deposit energy **in the CCD** → Shielding improvement
- Verified with  Monte Carlo simulations



K. Ambrogioni, et al. *Under review* (@ *Science Advances* (2026)).

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



Map the distribution of the elements on the surface of archeological samples from Prague museum.

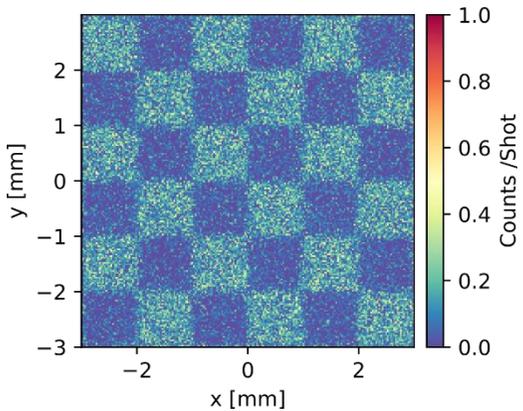


- Polycapillary between sample and CCD to **filter X-rays not orthogonal to the surface.**

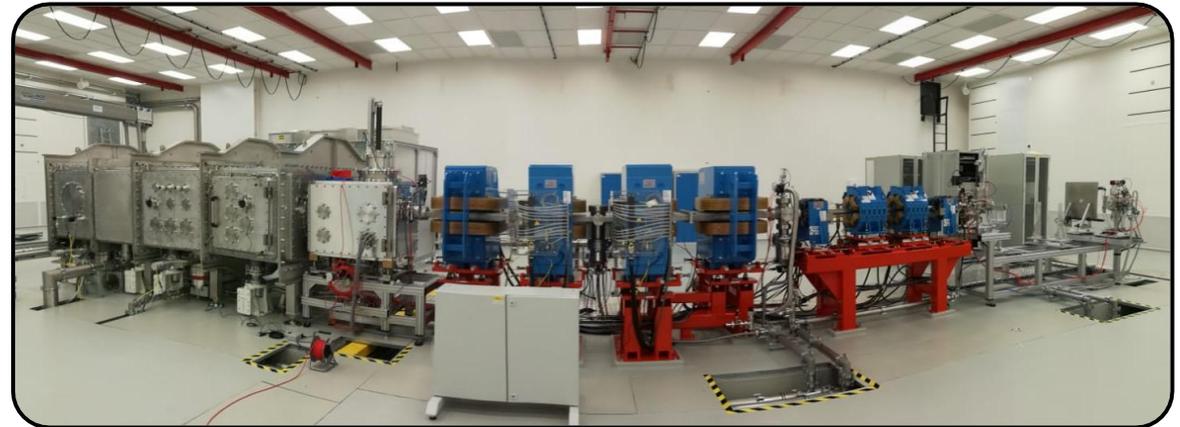


Experimental campaign @ ELI Beamlines in collaboration with the  team with the ELIMED beam line scheduled in May 2026 within the framework of the 6^o user call.

Fe elemental distribution



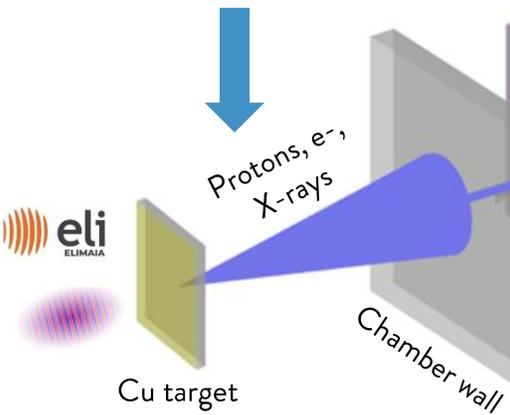
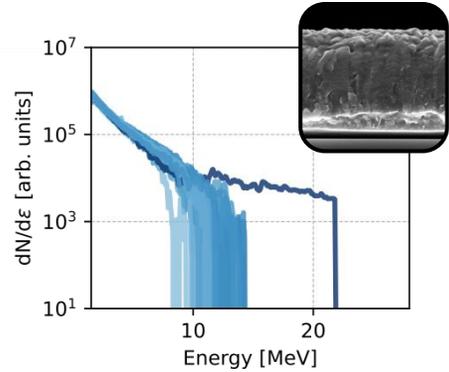
- Preliminary study performed with Monte Carlo simulations
- Very simple composition.



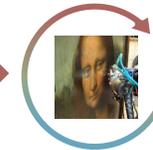
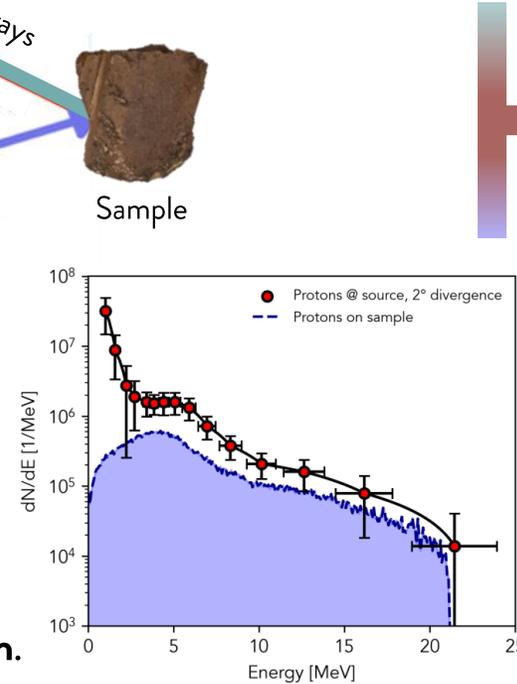
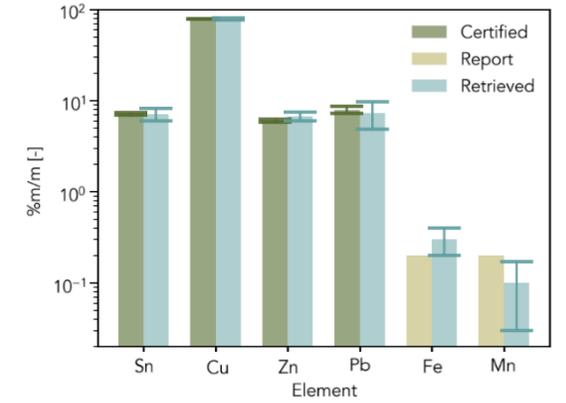
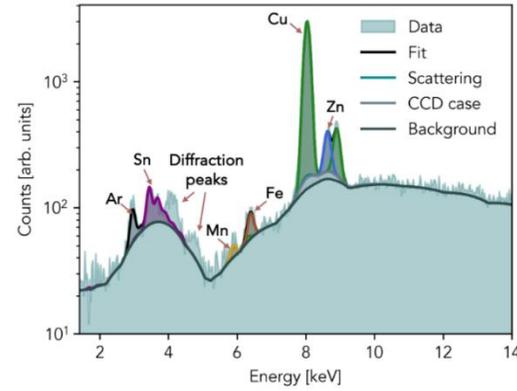
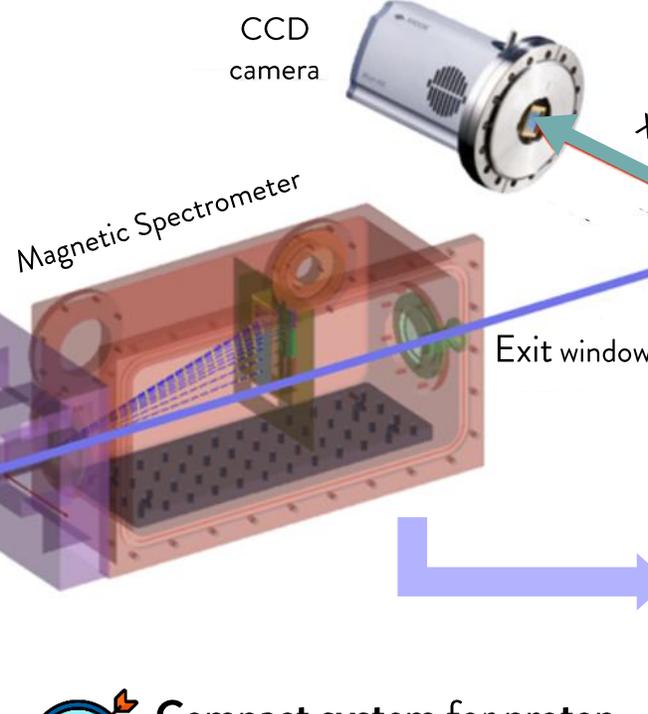
Final remarks and conclusions



Deposited foils and Double Layer Targets reduces shot-to-shot uncertainty.



Compact system for proton detection and sample irradiation.



Successful inclusion of PIXE physics in PyMca.

...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. *PPCF* (2025).

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

K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

Thank you for the attention!

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