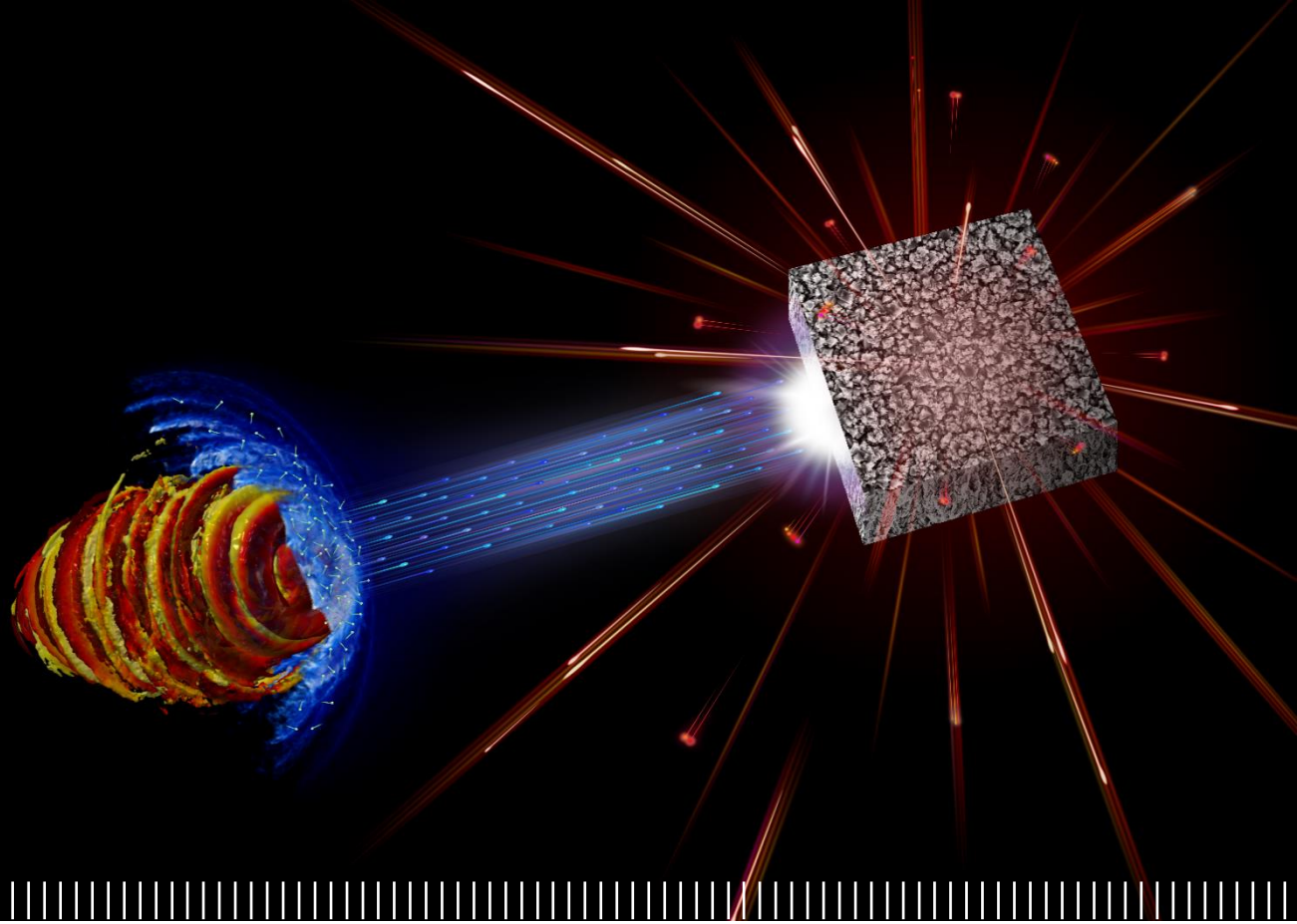
SPIE. OPTICS+ OPTOELECTRONICS

Applying Laser-driven Particle Acceleration III: Uses of Distinctive Energetic Particle and Photon Sources

Laser-driven particle acceleration for multi-purpose elemental analysis of materials



Francesco Mirani

ERC-2022-PoC No. 101069171
PANTANI

POLITECNICO MILANO 1863

NanoLab
DEPARTMENT OF ENERGY

- Activities performed within the framework of an **ERC-PoC grant** ERC-2022-PoC No. 101069171 **PANTANI** at POLITECNICO MILANO 1863
- Present **team** members:

M. Passoni

Principal Investigator

D. Dellasega

M. Zavelani

V. Russo

A. Pola

A. Maffini

F. Mirani

F. Gatti

D. Vavassori

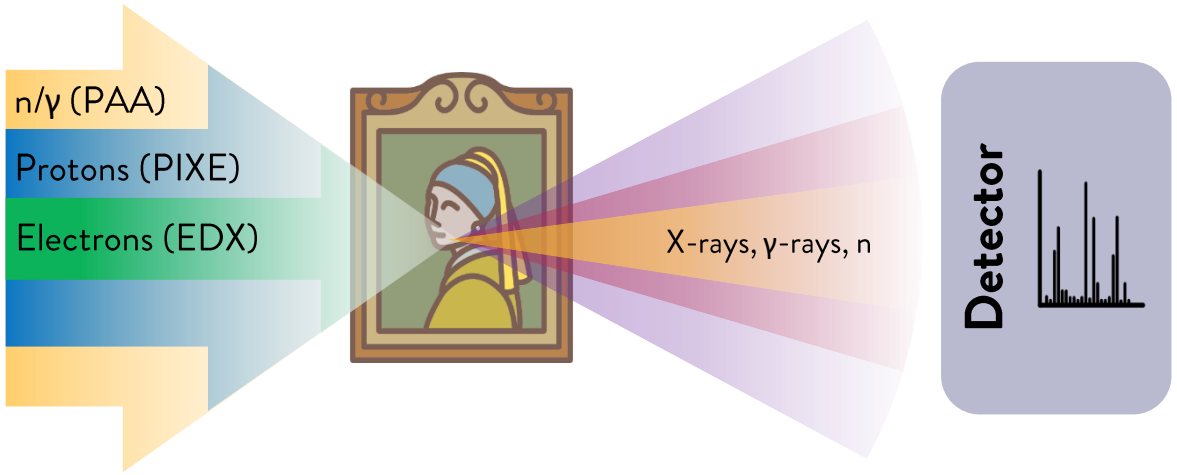
M. Galbiati

D. Orecchia

- **Collaboration** with industrial companies: RAYLAB DETECTING INNOVATION, spin off POLITECNICO DI MILANO, SourceLAB

www.ensure.polimi.it

Characterization of materials via radiation sources



- **Concentrations** & **Depth profiles** (differential PIXE) at surface.
- Bulk analysis of **large objects**.
- **Imaging** and **elemental radiography** of non-homogeneous samples.

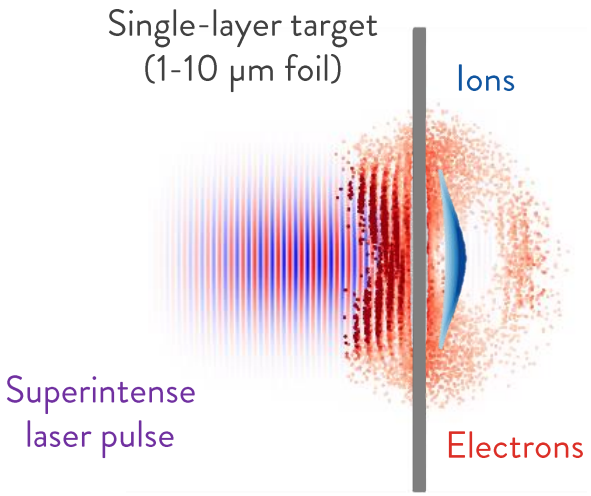
- Broad range of applications:

Different sources / accelerators, **lack of flexibility** (e.g. energy control).

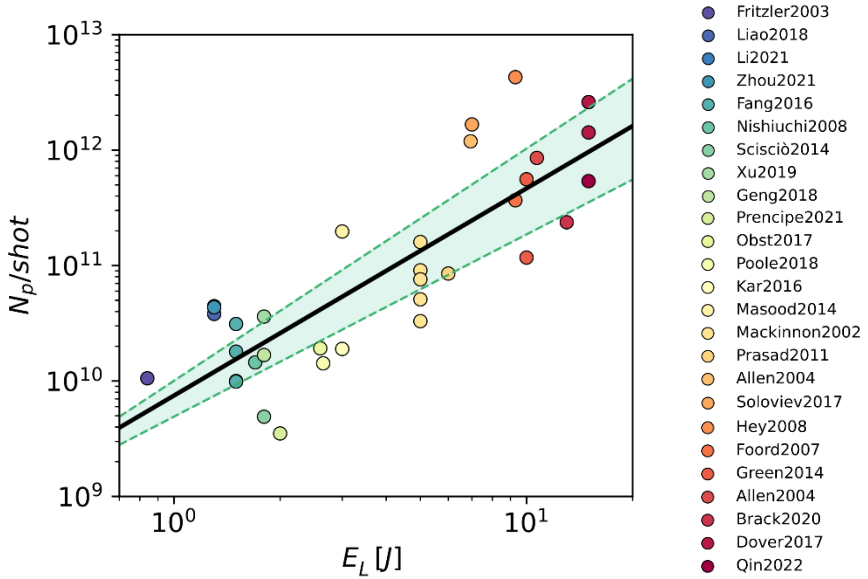
H. R. Verma, Atomic and nuclear analytical methods. *Springer*, 2007.
E. H. Lehmann, *J. Archaeol. Sci. Rep.* 19 (2018): 397-404.

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.

Laser-driven particle acceleration



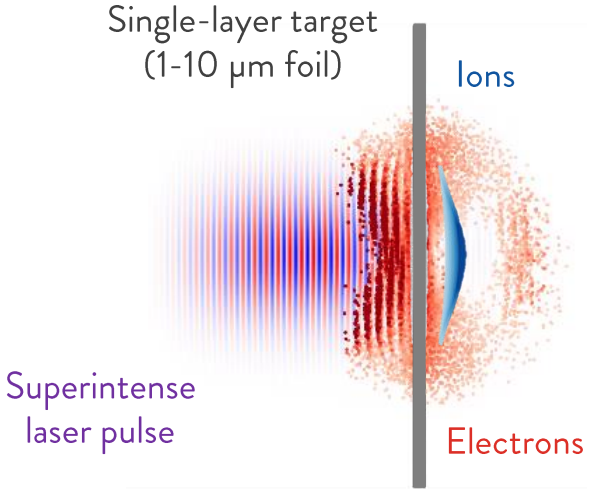
- Emission of **electrons** and **ions.**
- **10^9 - 10^{12} protons/shot** accelerated (depending on laser and target properties).
- **Broad** energy **spectra** (max ~ 1 - 10s MeV).
- **Control target properties (e.g. thickness)** → tune the energy.



F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.

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

Laser-driven particle acceleration



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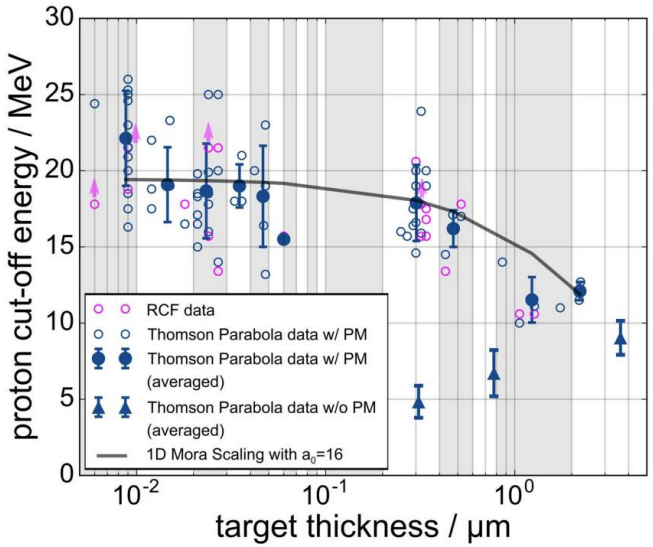
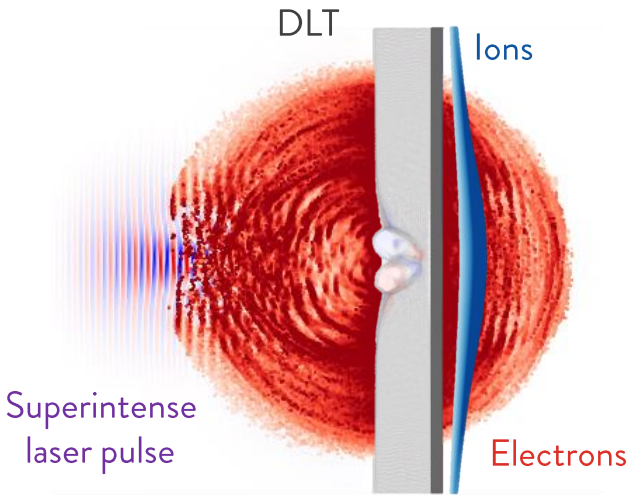


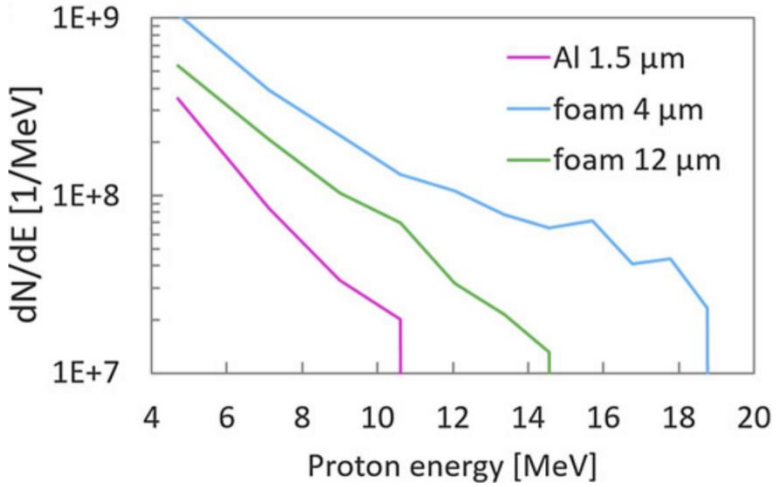
P. L. Poole, et al. *New J. Phys.* 20.1 (2018): 013019.

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

Laser-driven particle acceleration with Double-Layer Targets



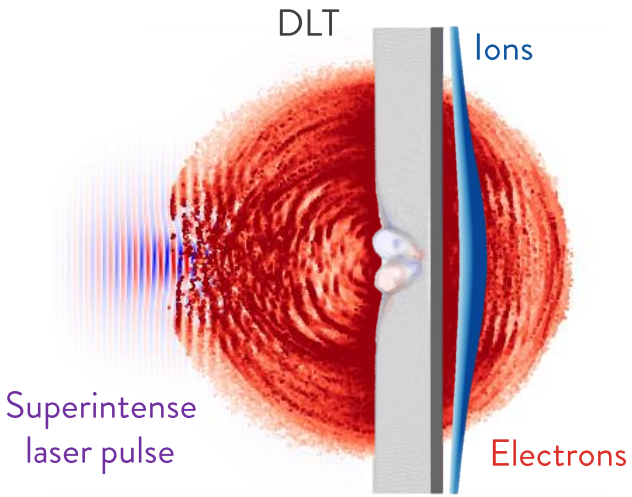
- Emission of **electrons** and **ions.**
- **10^9 - 10^{12} protons/shot** accelerated (depending on laser and target properties).
- Double-Layer Target (**DLT**) → **Increase** the **energy** and **number** of the particles → Mitigate laser requirements.



I. Prencipe, et al. *New J. Phys.* 23.9 (2021): 093015.

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

Laser-driven particle acceleration



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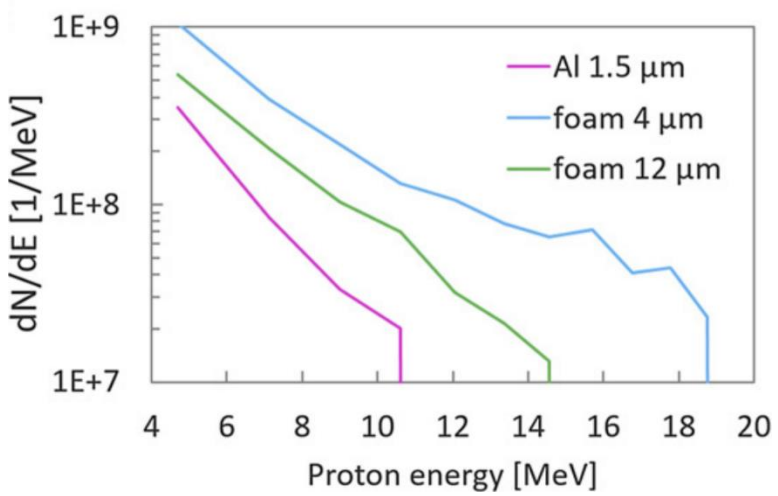


Investigate **applications of laser-driven particle acceleration to materials characterization.**

...many **potential appealing features**:

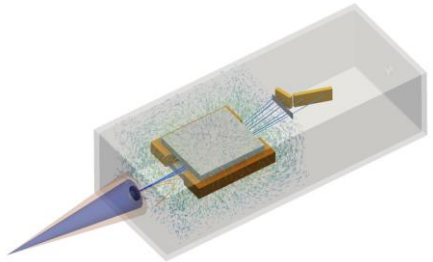
Compactness | **Cheapness** | Energy tunability (**flexibility**) | **Multiple** radiation **fields**

I. Prencipe, et al. *New J. Phys.* 23.9 (2021): 093015.

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

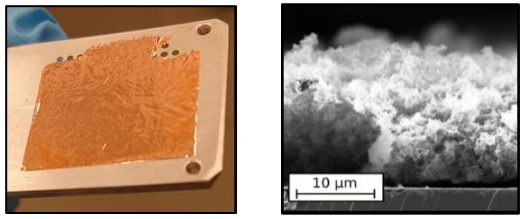
Activities @ Politecnico di Milano

Detectors development;



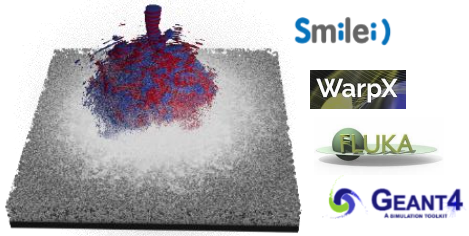
@ BLIN

Production of DLTs;



@ TARG

Theoretical studies;



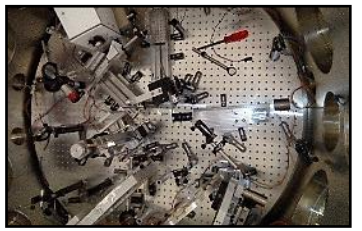
Smilei

WarpX

FLUKA

GEANT4

Experimental campaigns.



@ ALPA

Activities @ Politecnico di Milano

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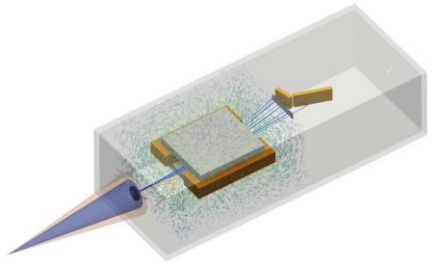

@ BLIN

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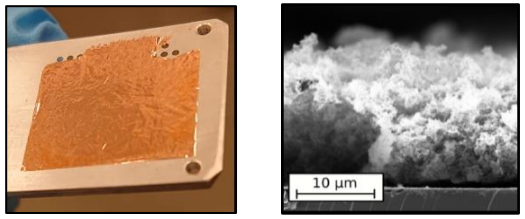

@ TARG

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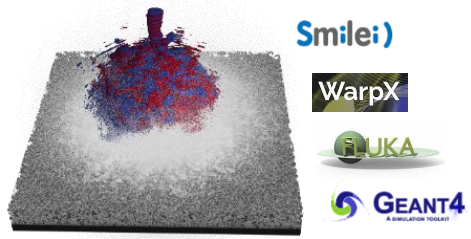

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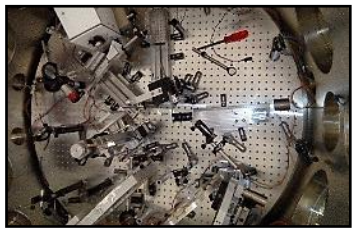
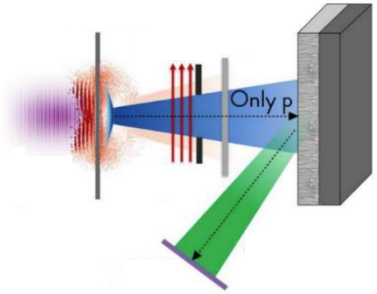
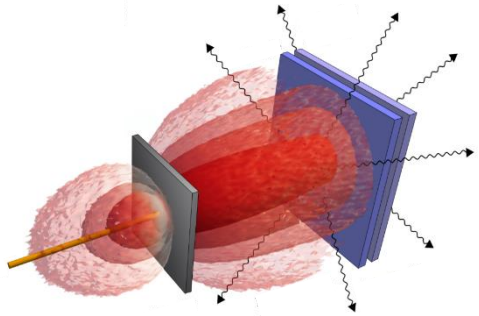


@ ALPA

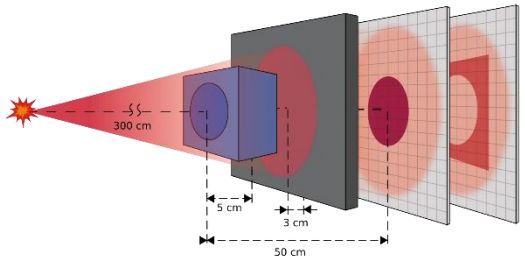
Particle Induced X-ray Emission



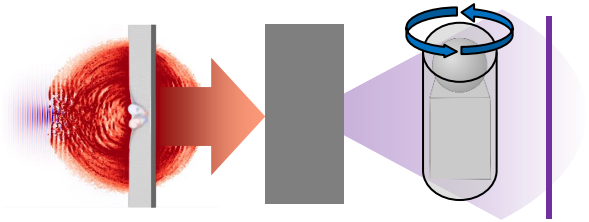
Photon Activation Analysis



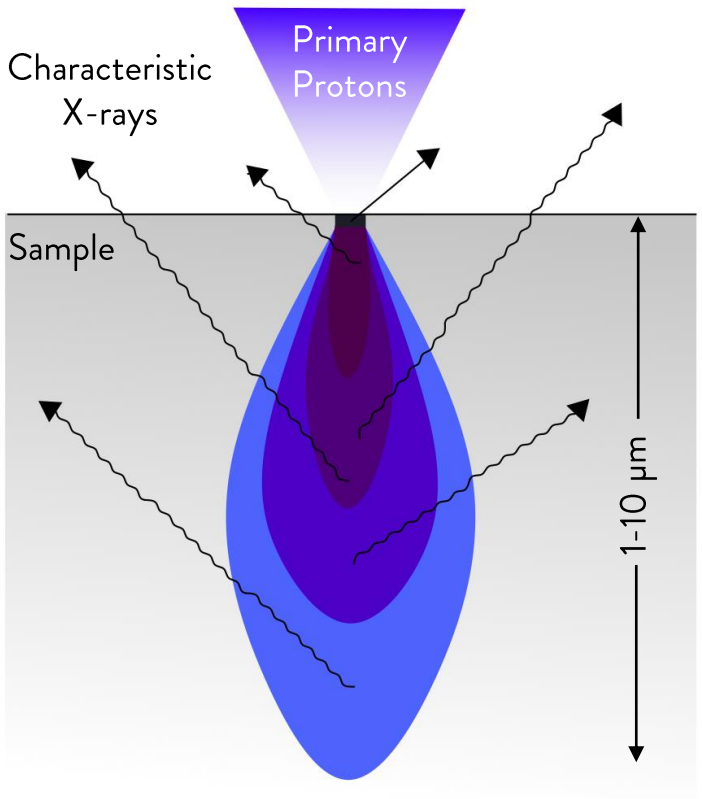
Fast Neutron Resonance Radiography



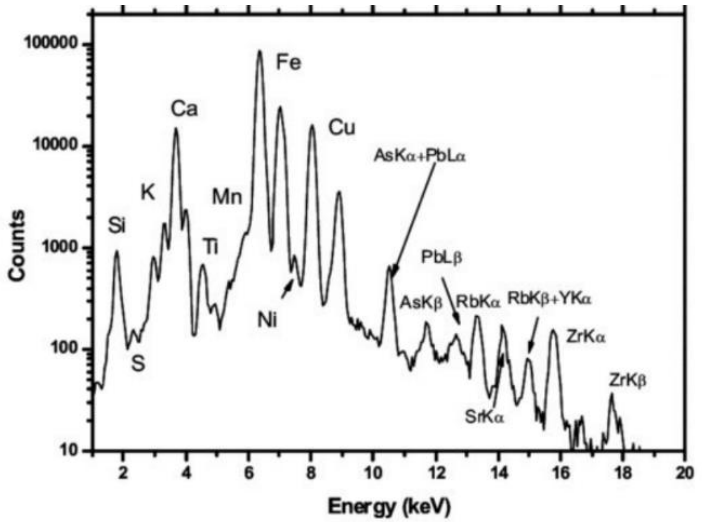
Computed Tomography

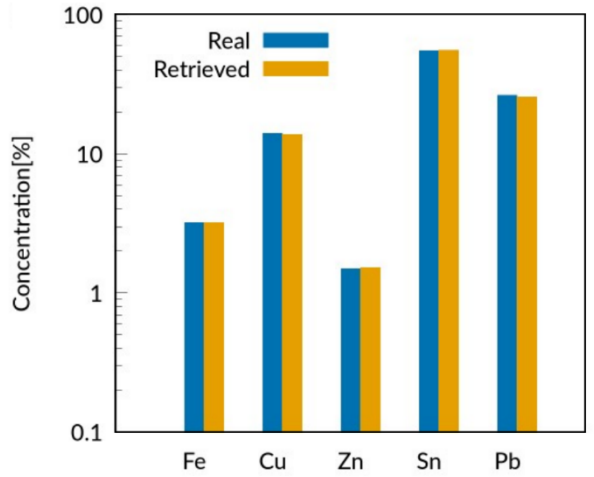


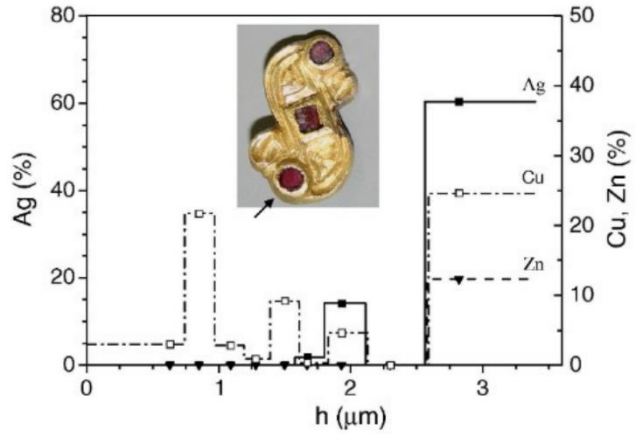
Particle Induced X-ray Emission (PIXE)



- **2-5 MeV** monoenergetic ions (**protons**).
- Detection of the emitted **X-rays.**
- **Concentrations** & **Depth profiles** (*differential PIXE*)
- Probed thickness **~ 1 – 10 µm** in solids.







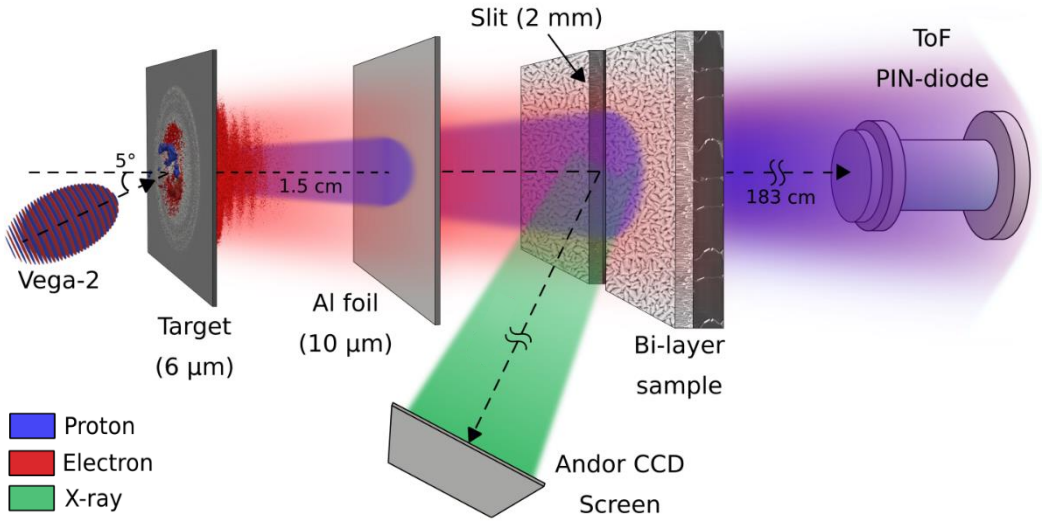
No standard materials are required → Spectra analysed with **software** in literature (theoretical description of PIXE).

H. R. Verma, Atomic and nuclear analytical methods. *Springer*, 2007.

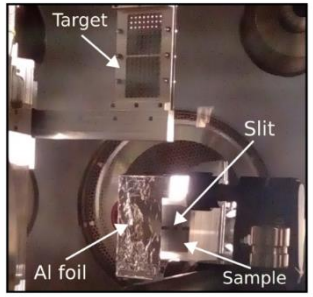
Ž. Šmit, et al. *Nucl Instrum Methods Phys Res B* 266.10 (2008): 2329-2333.

Laser-driven particle induced X-ray emission with bare targets

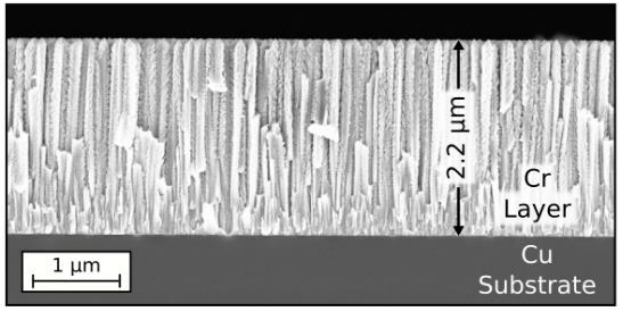
- Experiment performed @ CLPU with **200 TW**.



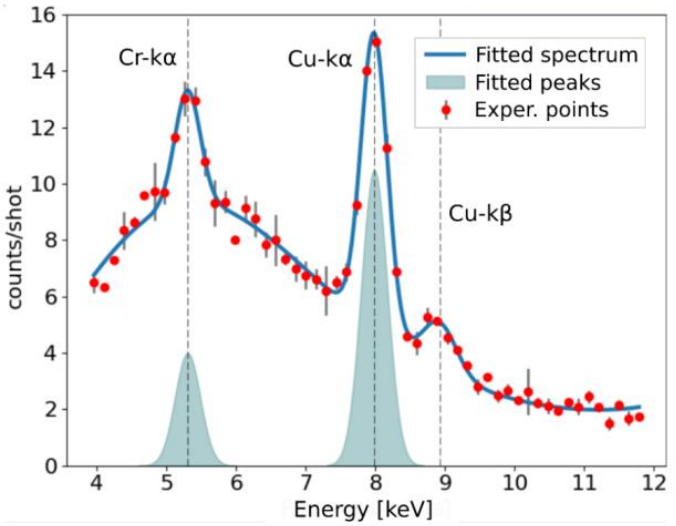
- Vega-2 laser intensity ≈ **2×10^{20} W/cm^2.**
- 30 fs time duration, 3 J on target.
- **6 µm thick** Al target.
- Proton **energies** up to **6 MeV**.

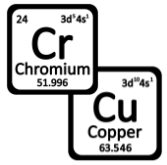


- Sample irradiation with **both e- and protons up to 6 MeV**.



Bi-layer sample (Cr layer + Cu substrate)





Fast **elemental analysis**

F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

Laser-driven particle induced X-ray emission with bare targets

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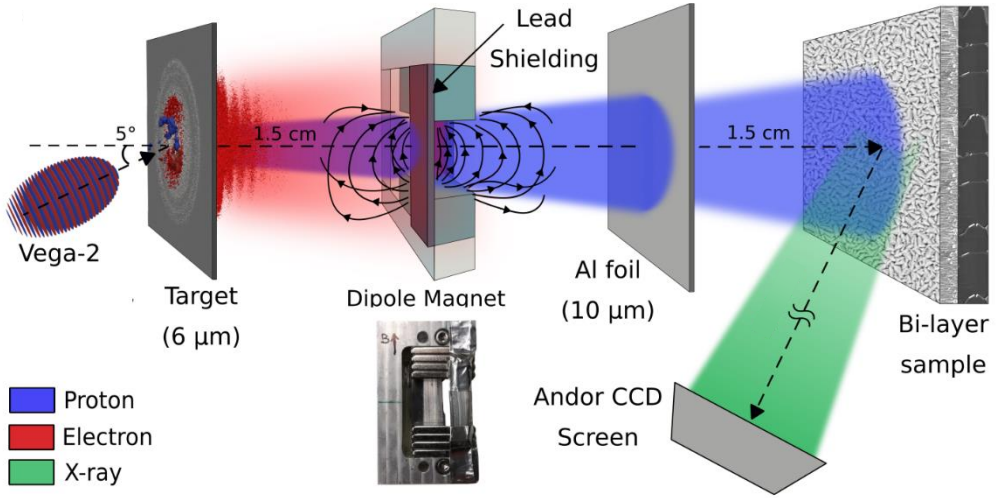
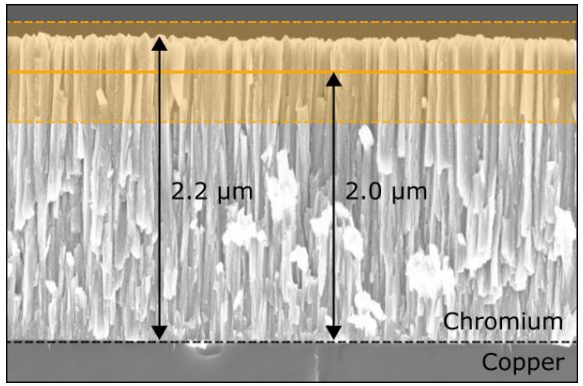


- Irradiation performed **only with protons**.
- Retrieve the **thickness of a micrometric** thick **layer**.



F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

P. Pilar, et al. *Sci. Rep.* 11.1 (2021): 1-10.

F. Boivin, et al. *New J. Phys.* 24.5 (2022): 053018.

Laser-driven particle induced X-ray emission with bare targets

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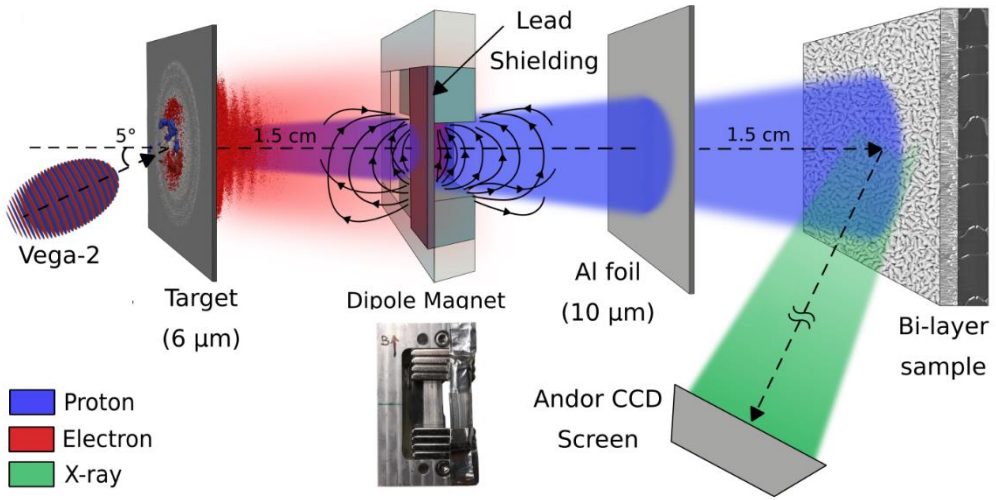

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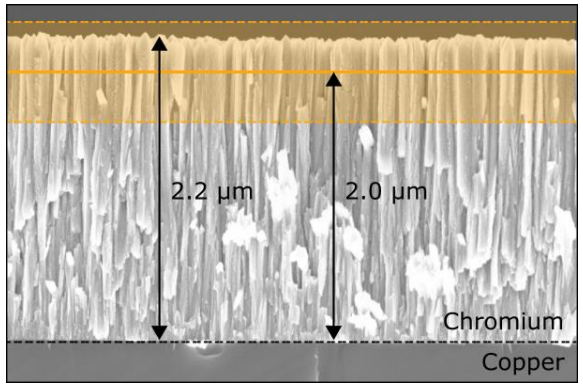
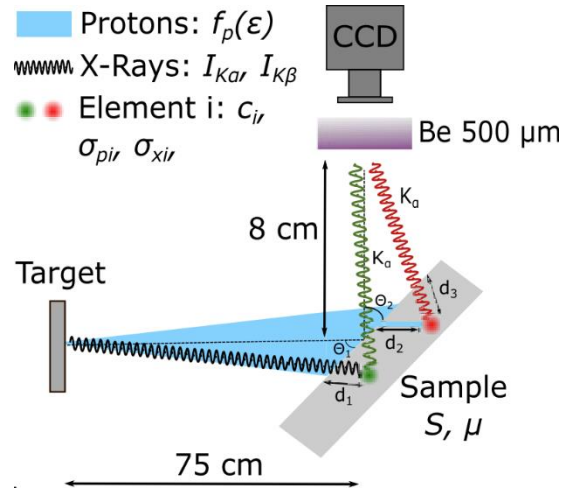
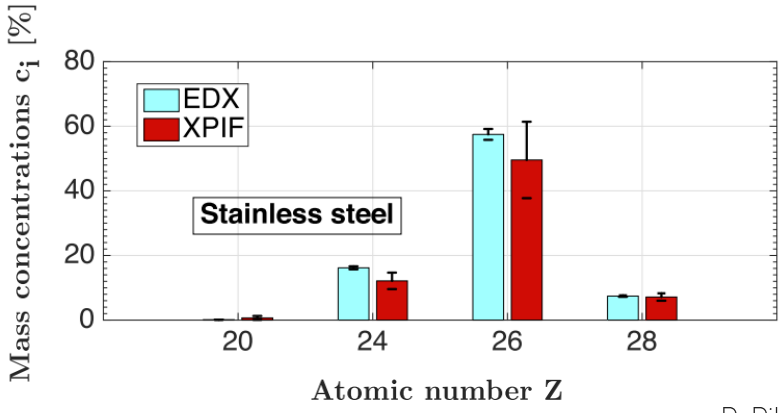


F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

- Sample irradiation with **both photons and protons.**
- **100 TW** laser.
- Retrieve **concentrations** in homogeneous samples.
- **Faster analysis of thicker samples** with PIXE + XRF.





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F. Boivin, et al. *New J. Phys.* 24.5 (2022): 053018.

Laser-driven particle induced X-ray emission with DLTs

How do we make the **PIXE suitable for** the analysis of **artworks** (compact and flexible)?

Exploit **Double Layer Targets** to reduce the laser requirements!

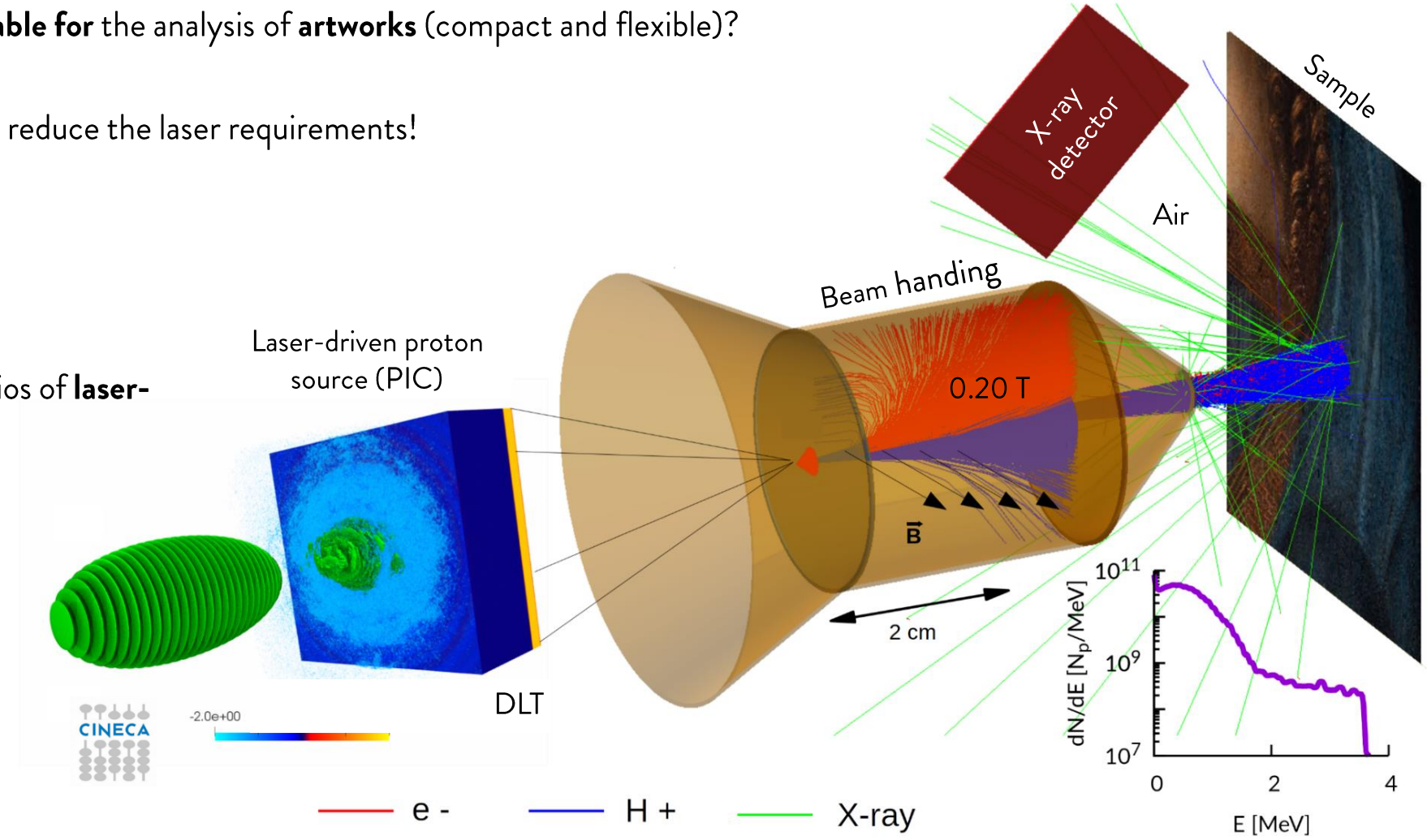
20 TW laser;

DLT target;

Simulations of real-case scenarios of **laser-driven PIXE** experiments.

3D Particle-In-Cell

Monte Carlo



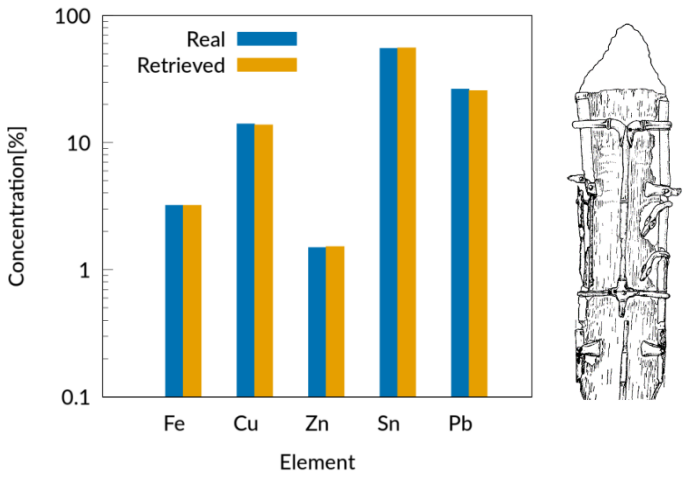
M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.

Laser-driven particle induced X-ray emission with DLTs

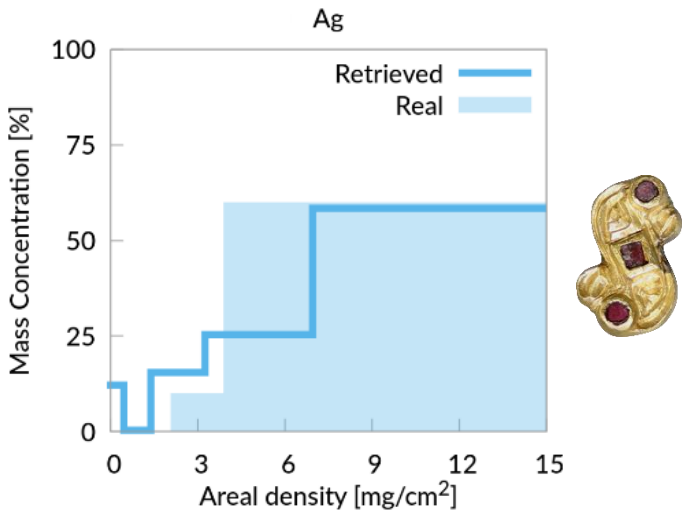
Application to **artworks** analysis.

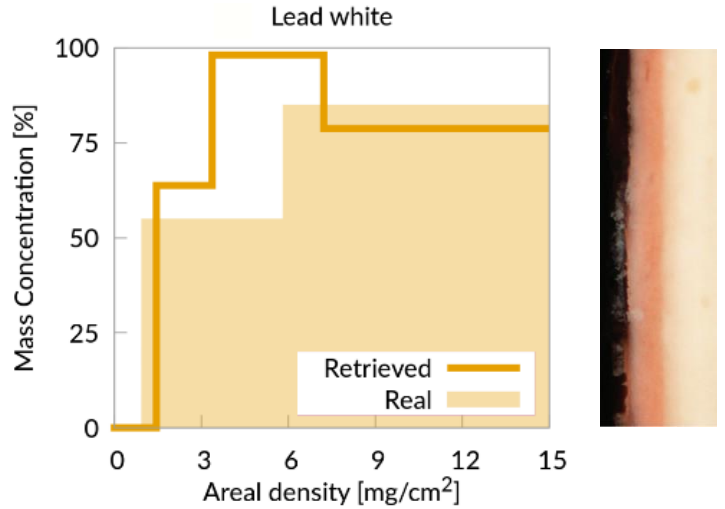
Process **"synthetic"** X-ray spectra and retrieve the **sample composition**.

- **Homogeneous** sample (Roman sword-scabbard):



- **Complex structured** samples (Medieval brooch and Renaissance painting) :





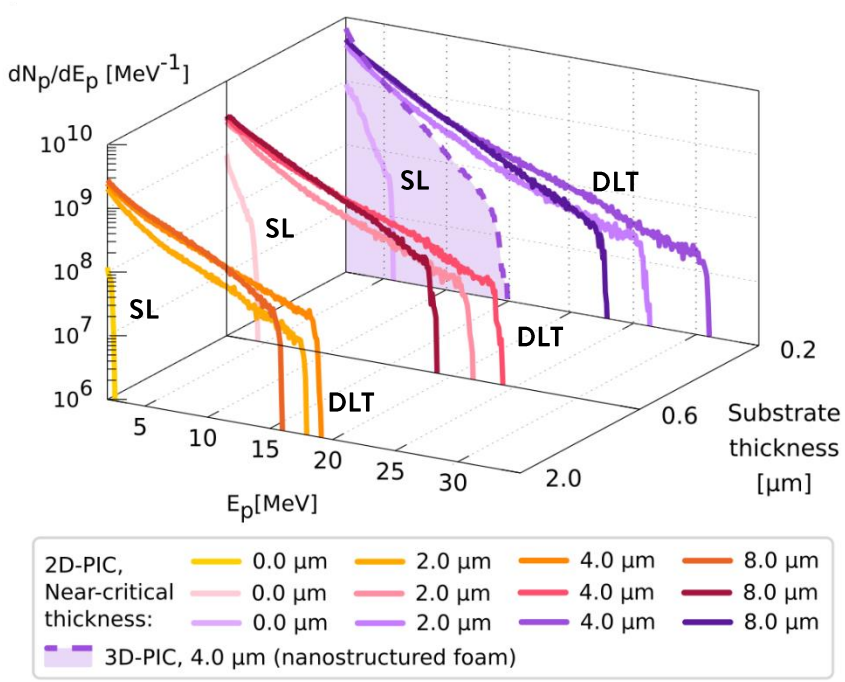
Ž. Šmit, et al. Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At. 239.1-2, (2005): 27-34.
Ž. Šmit, et al. Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At. 266.10, (2008): 2329-2333.

L. De Viguerie, et al. Analytical chemistry 81.19, (2009): 7960-7966.
M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.

Laser-driven particle induced X-ray emission with DLTs

Application to **environmental** analysis.

- PIC simulations: **20 TW laser – DLT interaction**.
- Broad **scan** of nc layer and substrate **thicknesses**.



A. Maffini, et al., *submitted at EPJ Techniques and Instrumentation* (2023)

Laser-driven particle induced X-ray emission with DLTs

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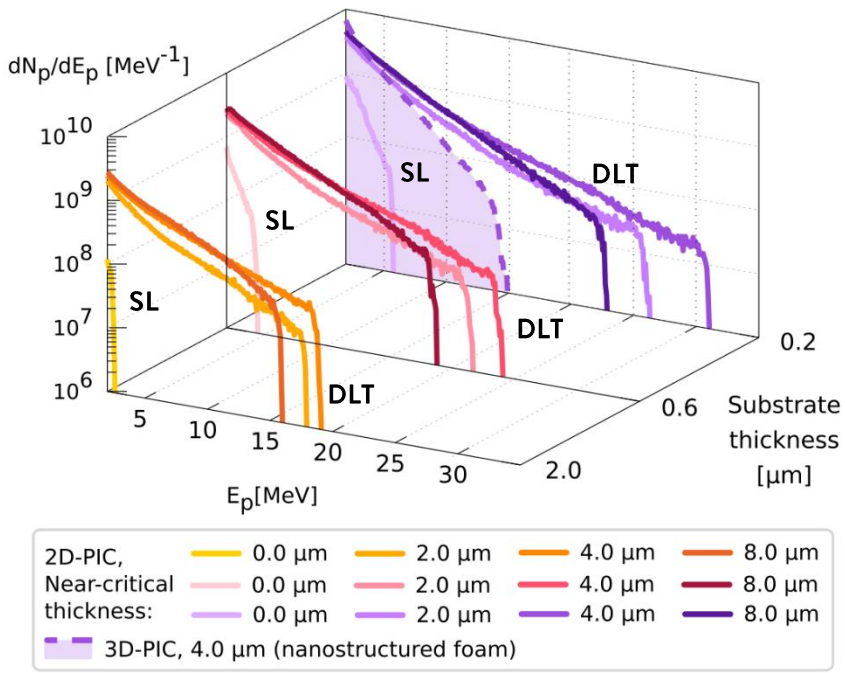
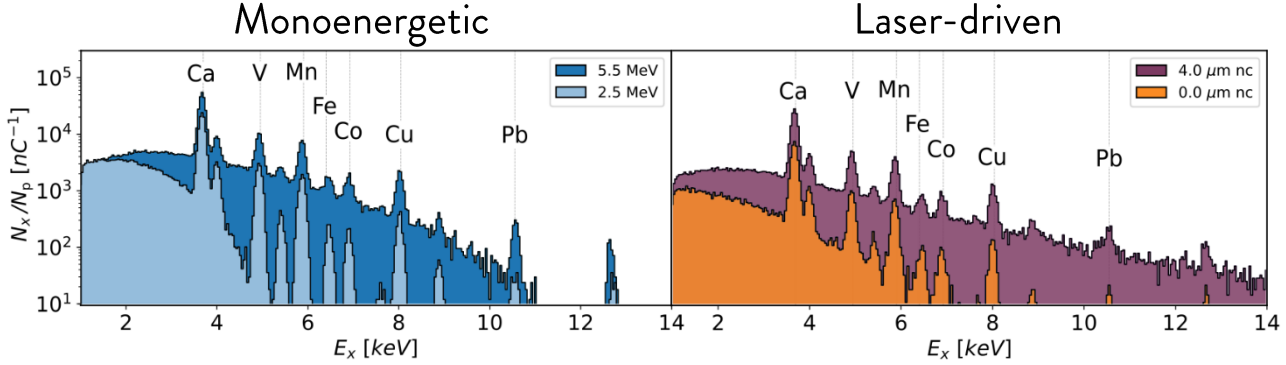
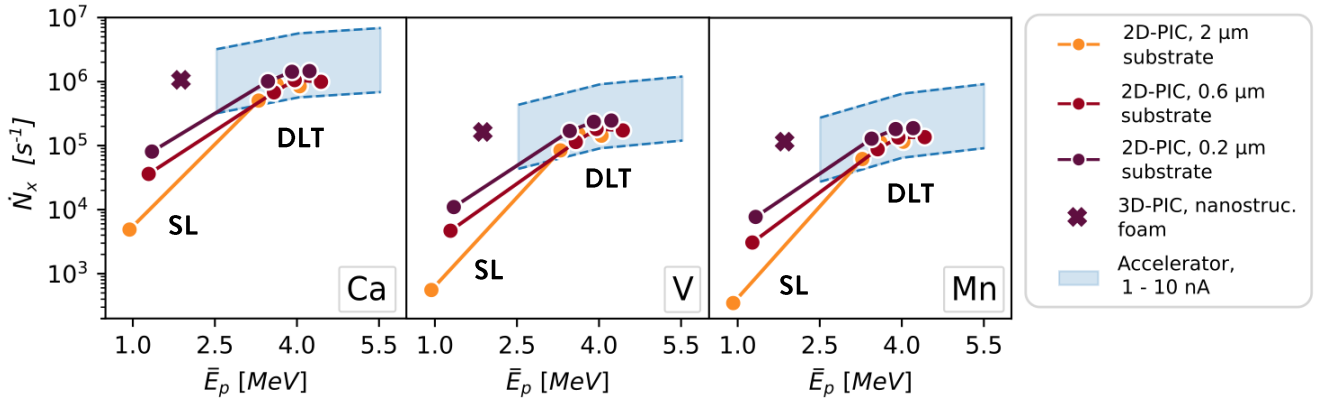


- GEANT4 simulations of **aerosol sample irradiation** with **monoenergetic** and **laser-driven protons**.



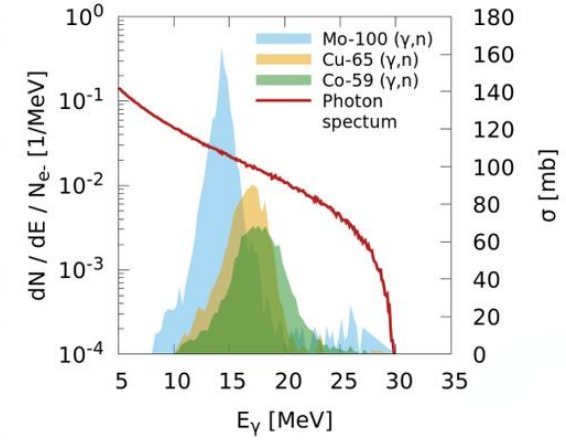
- **Number of emitted X-rays comparable** with that achieved **with accelerators**

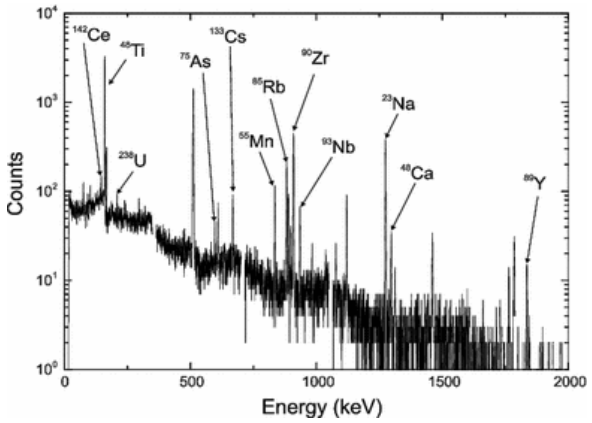


A. Maffini, et al., *submitted at EPJ Techniques and Instrumentation* (2023)

Photon Activation Analysis

- **10s MeV e-** on converter → **high-energy** bremsstrahlung **photons.**
- Sample activation due to **photonuclear reactions** → Characteristic γ-rays.
- **Identification** of the **elements** and **bulk** analysis.





Standard materials usually required to retrieve concentrations.

C. Segebade, et al., Photon activation analysis. *de Gruyter*, 1987.

C. Segebade, et al. *J. Radioanal. Nucl. Chem.* 312 (2017): 443-459.

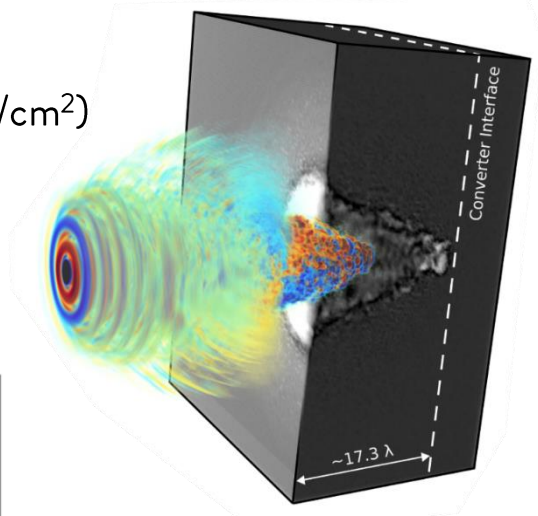
Numerical study of laser-driven PAA feasibility

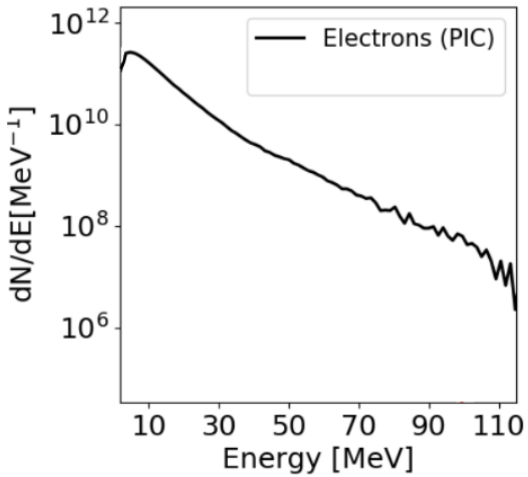
Development of a **scheme** to perform laser-driven Photon Activation Analysis.

1. Super-intense **laser** interacting with **near-critical** layer (model from literature and **3D PIC**).

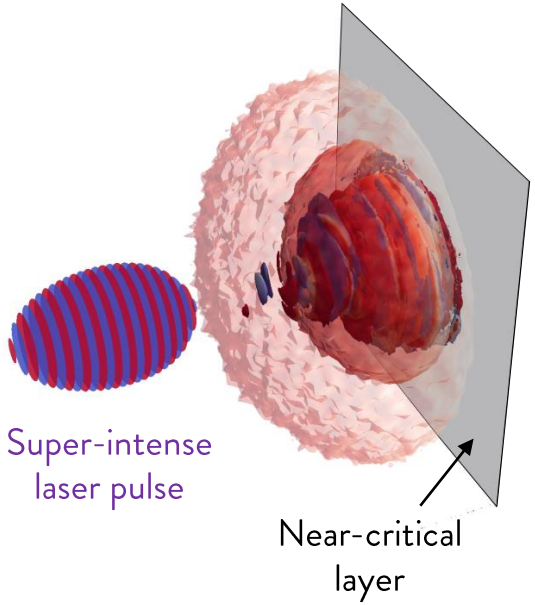
200 TW laser (8×10^{20} W/cm^2)

Near-critical layer





- **Hot e-** generation with $E_{max} \approx 110$ MeV.



A. Pazzaglia, et al. *Commun Phys* 3.1 (2020): 133.

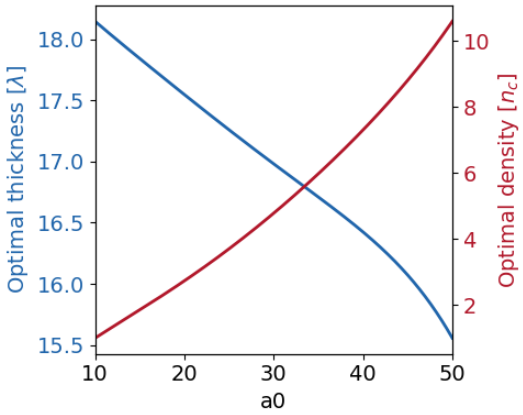
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

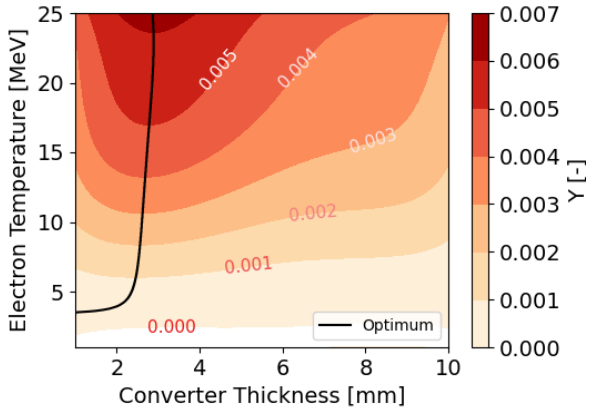
Numerical study of laser-driven PAA feasibility

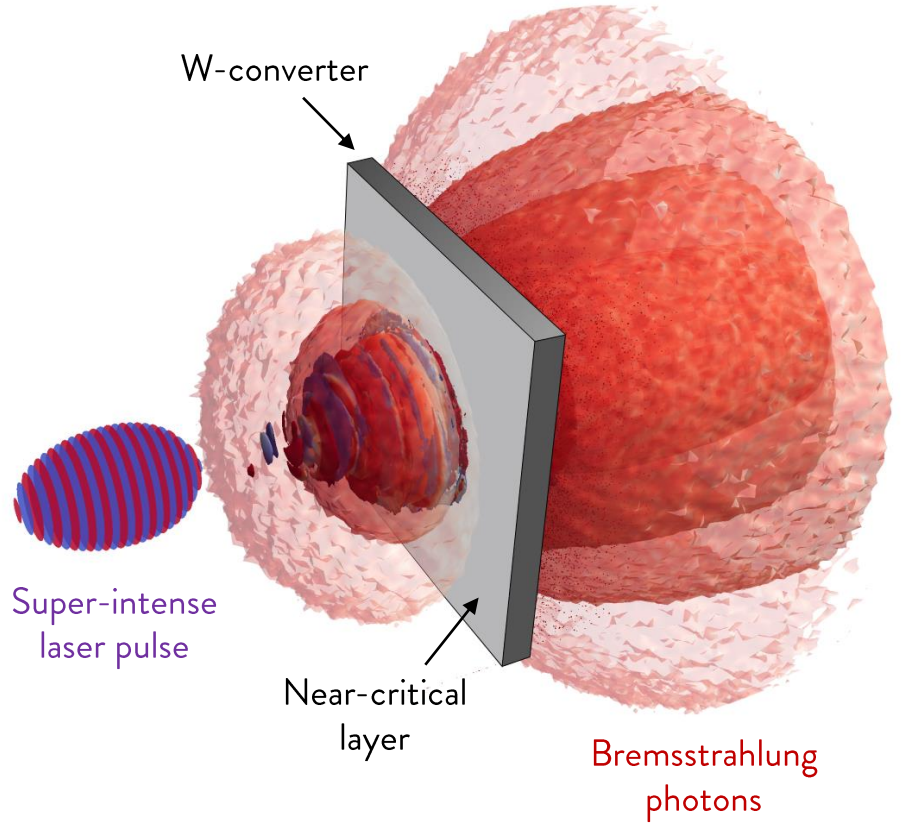
Development of a **scheme** to perform laser-driven Photon Activation Analysis.

2. **Hot e-** interaction with mm-thick **W converter** → **Bremsstrahlung photons** generation (**Monte Carlo** FLUKA).

- Broad scan to retrieve the **optimal target and converter parameters** (maximum Bremsstrahlung photon emission) exploiting the model from literature.







A. Pazzaglia, et al. *Commun Phys* 3.1 (2020): 133.

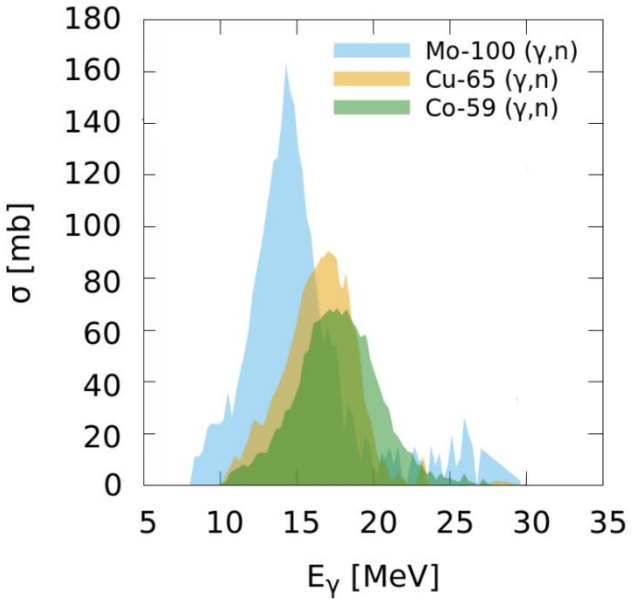
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

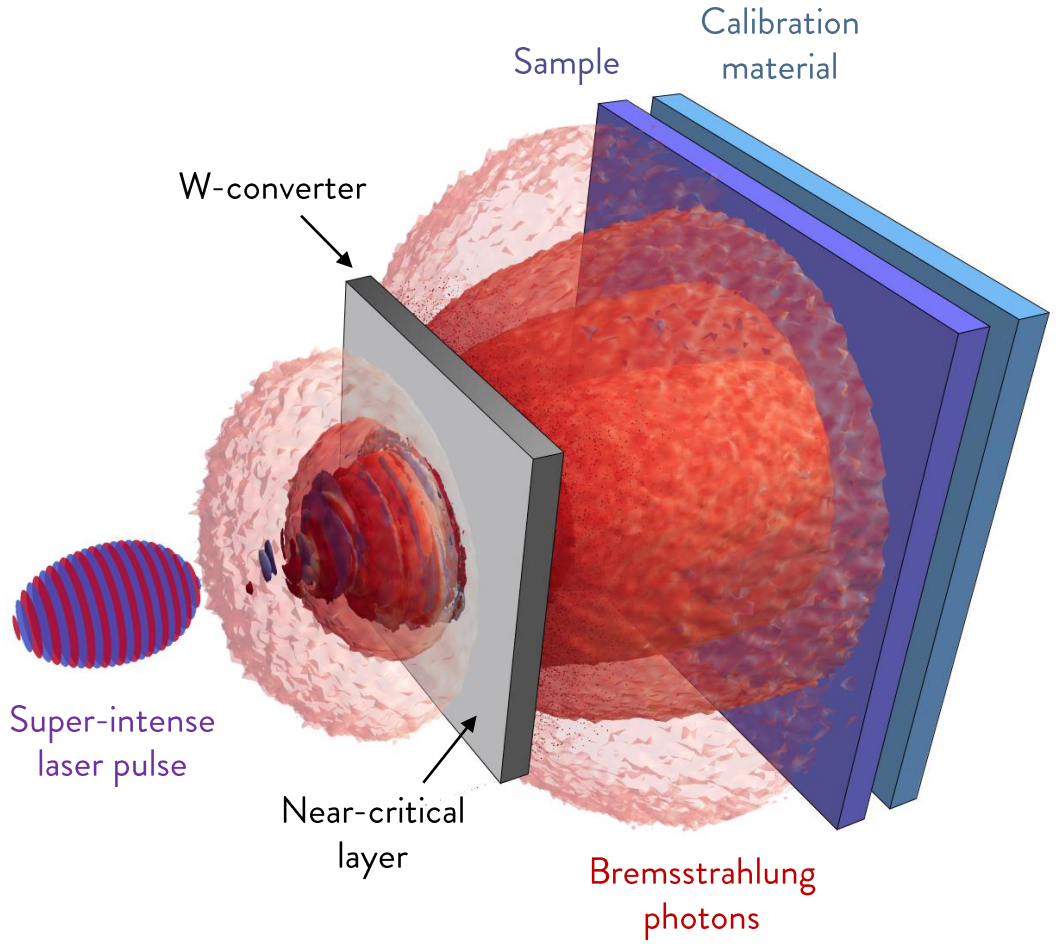
Numerical study of laser-driven PAA feasibility

Development of a **scheme** to perform laser-driven Photon Activation Analysis.

3. Sample and comparative **material irradiation** (**Monte Carlo** FLUKA)

   - Photonuclear reaction cross sections:



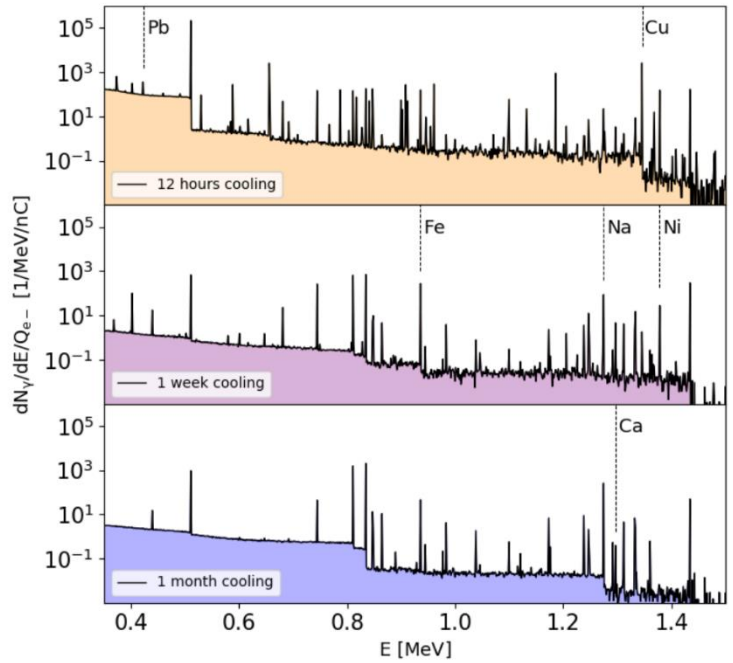


F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

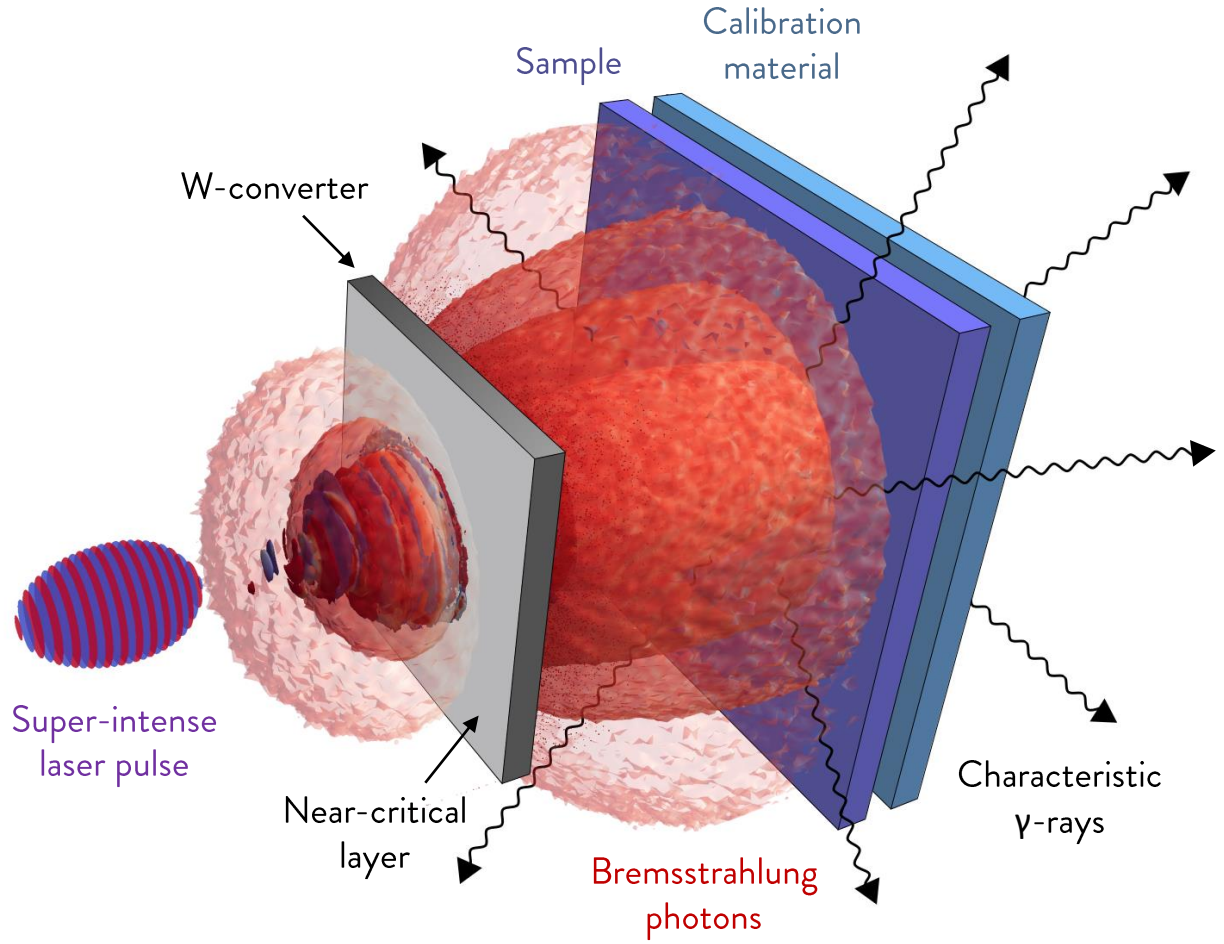
Numerical study of laser-driven PAA feasibility

Development of a **scheme** to perform laser-driven Photon Activation Analysis.

3. Sample and comparative **material irradiation** → **Delayed** emission of characteristic **γ-rays** (**Monte Carlo** FLUKA).



→ **Peak intensities**



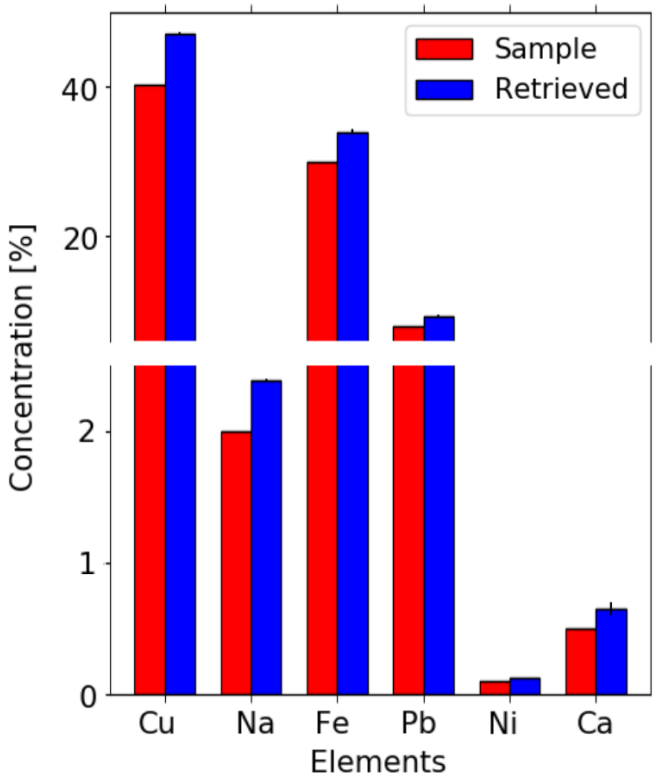
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

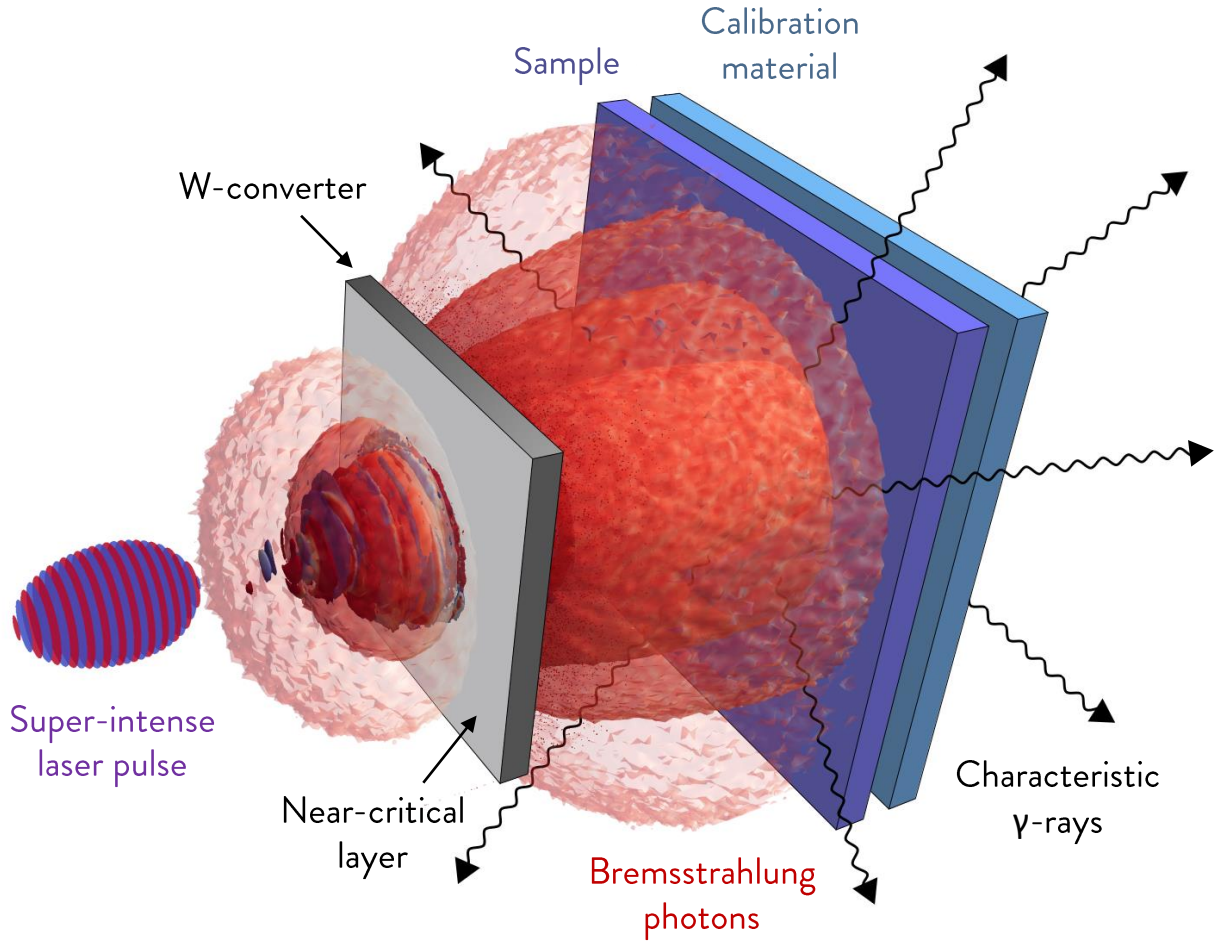
Numerical study of laser-driven PAA feasibility

Development of a **scheme** to perform laser-driven Photon Activation Analysis.

3. Retrieve the **elemental composition** of a cm-thick homogeneous sample (South-Levantine bronze sculpture).

Comparison with the calibration



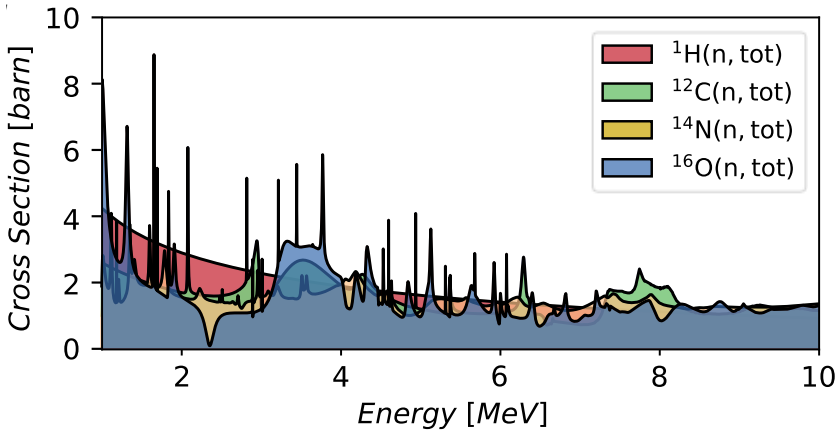


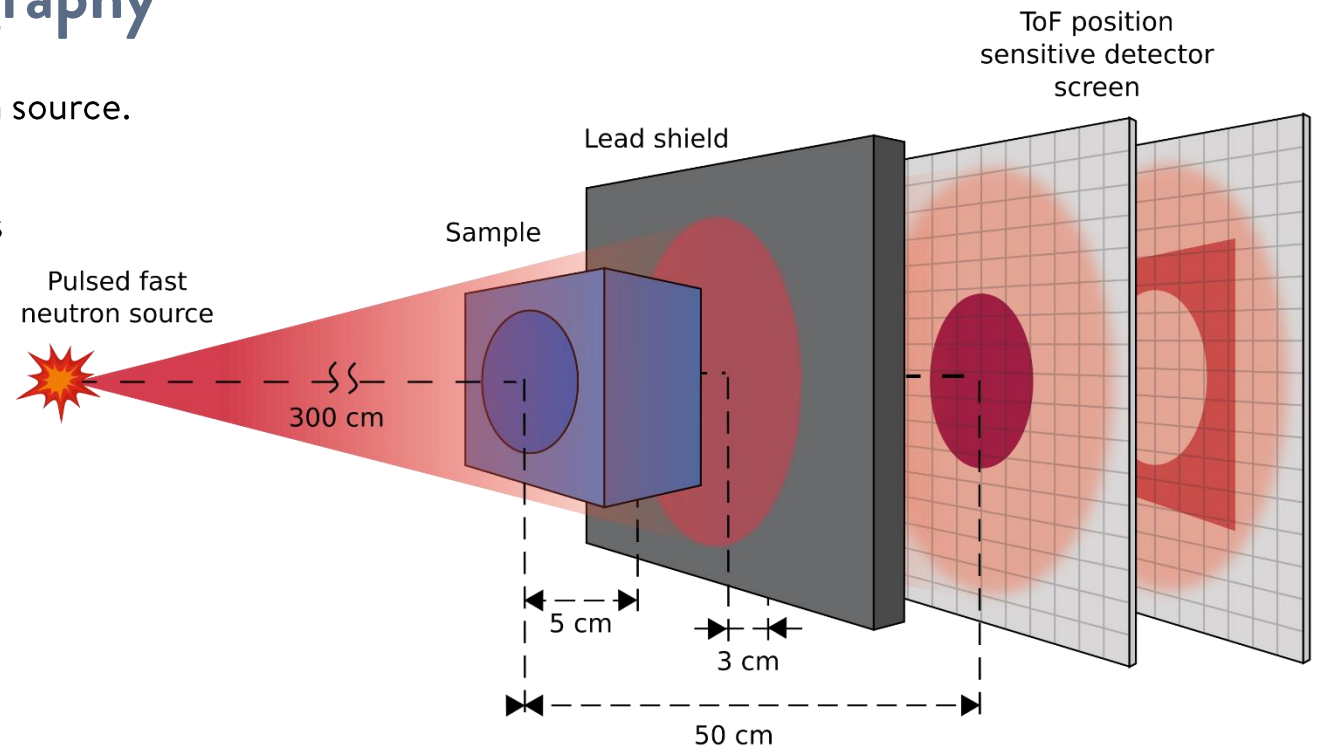
B. Maróti, et al. J. Radioanal. Nucl. Chem. 312.2 (2017): 367-375.

F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

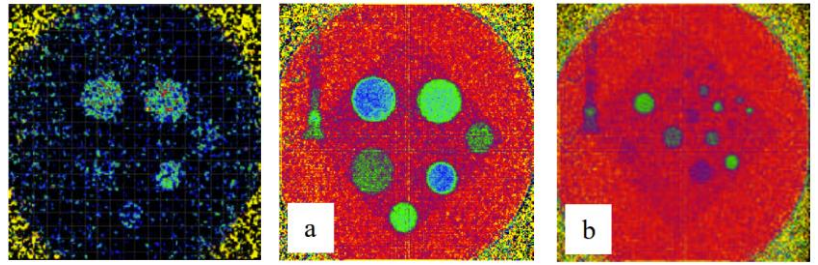
Pulsed Fast Neutron Resonance Radiography

- **Pulsed 1-10 MeV neutrons** from accelerators or laser-driven source.
- Exploit features in **total absorption cross section** of neutrons in low-Z elements (**H**,**N**,**O** and **C**).





- Detection of energy and position of transmitted neutrons → **elemental imaging** of **drugs** and **explosives**.



No standard materials are required.

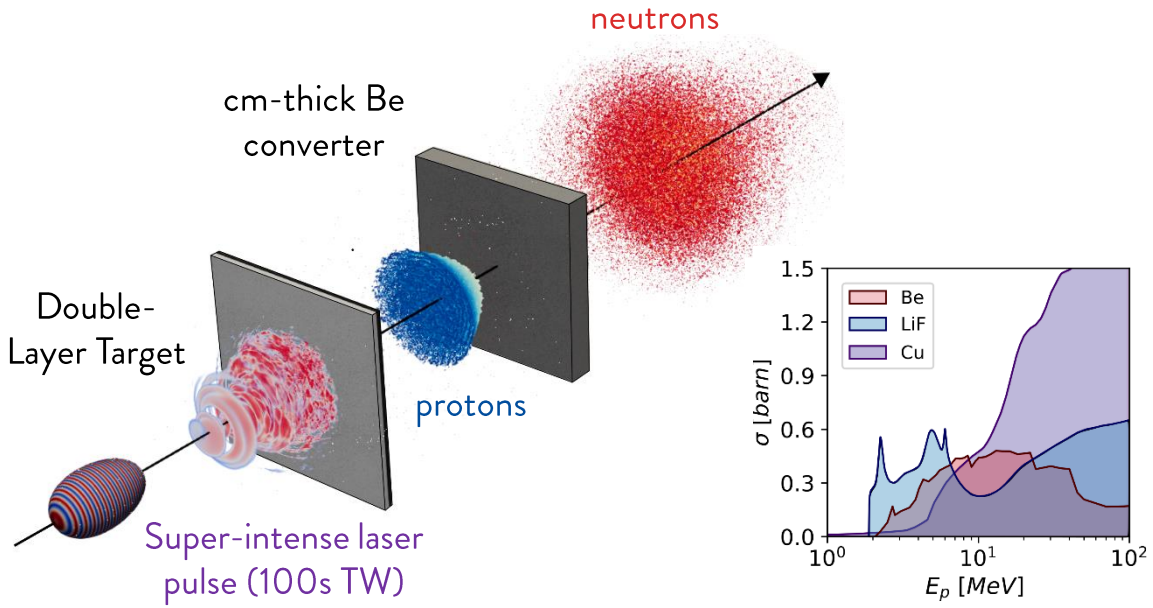
D. Perticone, et al. *Nucl. Instrum. Methods. Phys. Res. B NUCL INSTRUM METH A* 922 (2019): 71-75.
I. Kishon, et al. *Nucl. Instrum. Methods. Phys. Res. B NUCL INSTRUM METH A* 932 (2019): 27-30.

Numerical study of laser-driven FNRR feasibility

Exploit **laser-driven neutron source** to perform radiography of large samples.

1. Super-intense **laser** interacting with **Double-Layer Target** (model from literature).

2. Accelerated **protons** interaction with cm-thick **converter** → (p, n) reactions → **fast neutron** generation.



F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.
A. Pazzaglia, et al. *Commun Phys* 3.1, (2020): 1-13.

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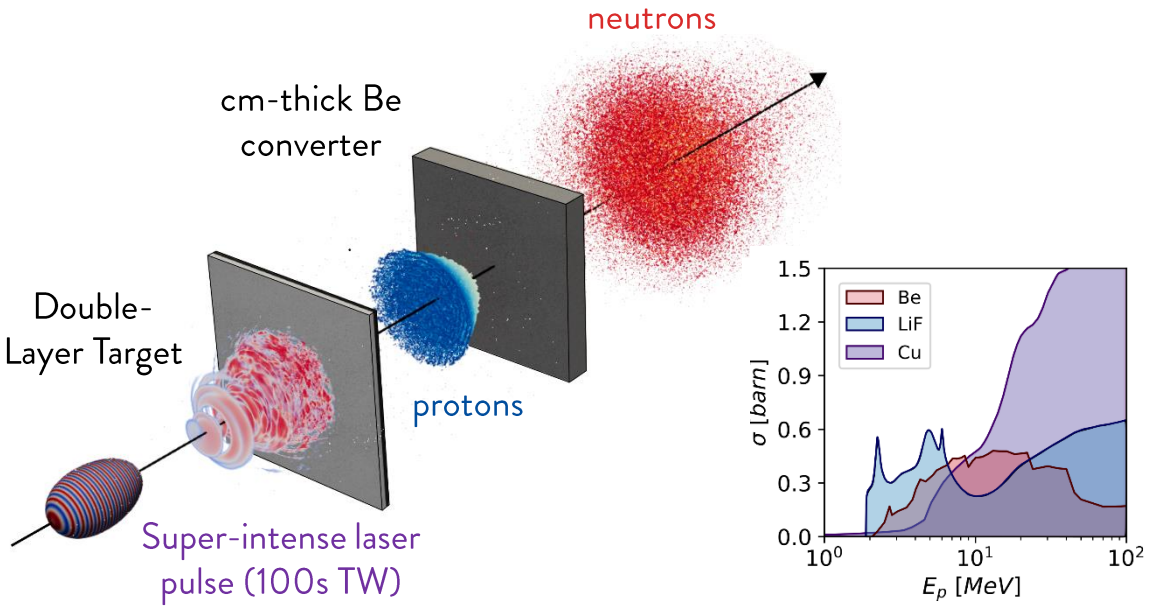
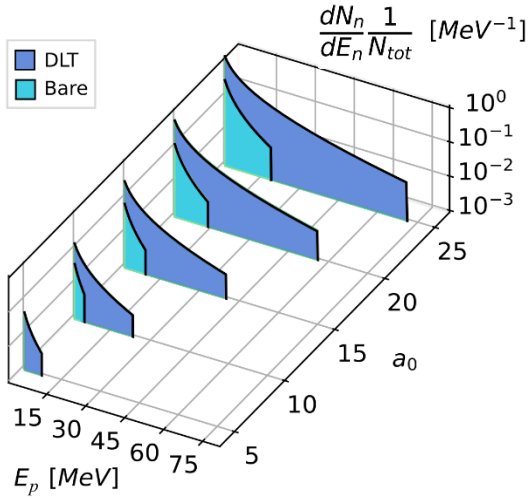
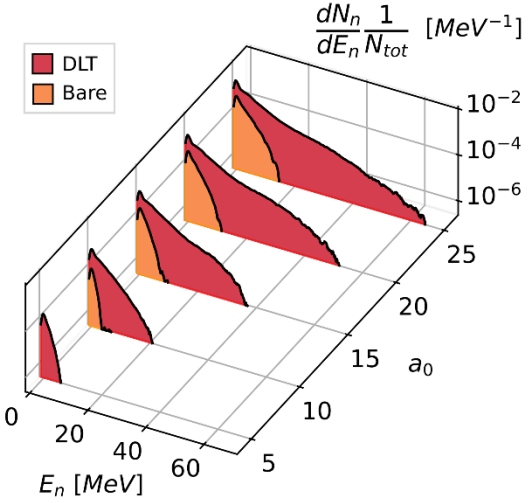


- Monte Carlo GEANT4 results:

Proton spectra:



Neutron spectra:



- Broad spectrum up to **10s MeV**.
- ≥ **10^4 n/cm²/s** at ≥ 3 m distance for $a_0 > 15$ (≈ 250 TW).

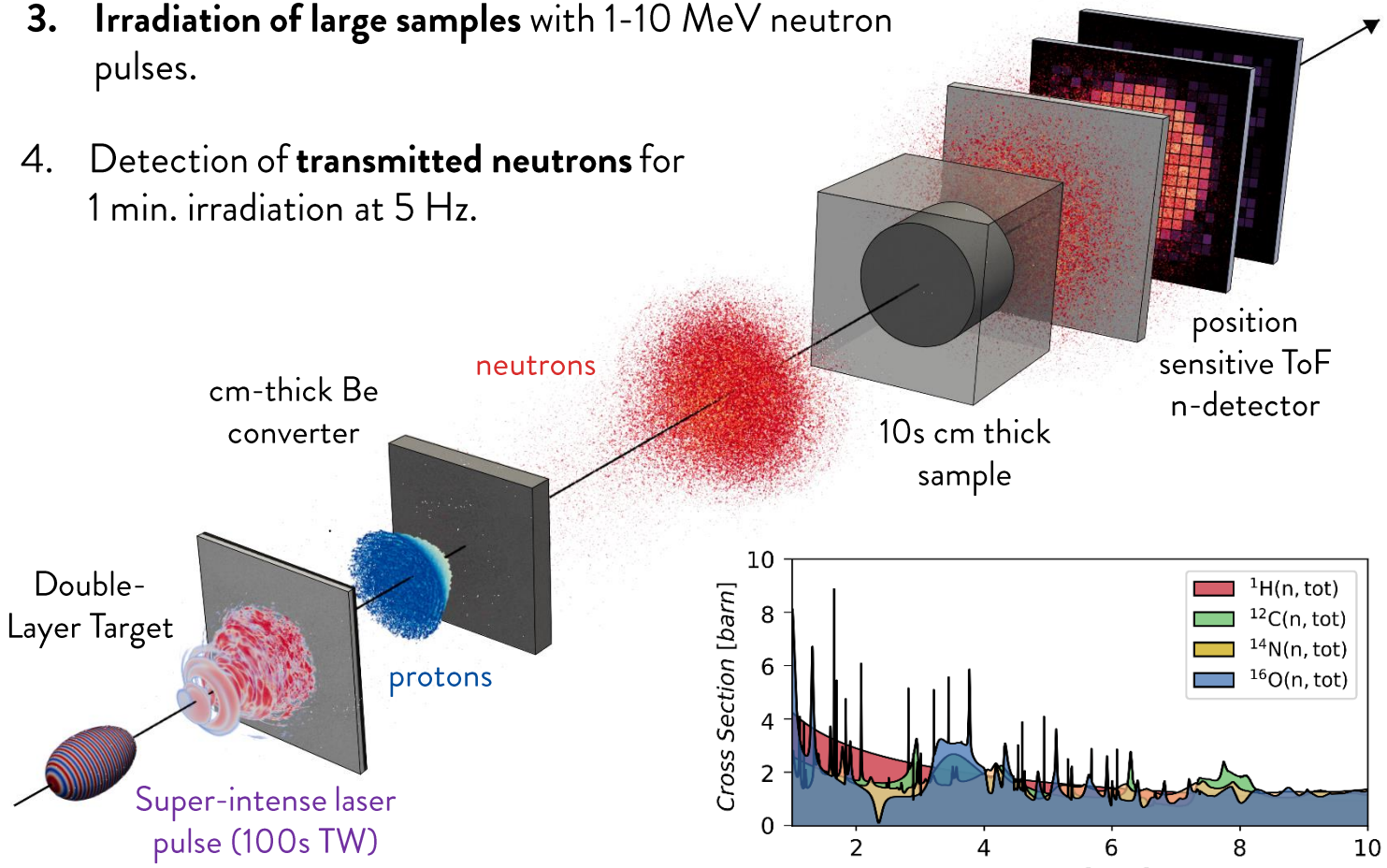
F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.
A. Pazzaglia, et al. *Commun Phys* 3.1, (2020): 1-13.

Numerical study of laser-driven FNRR feasibility

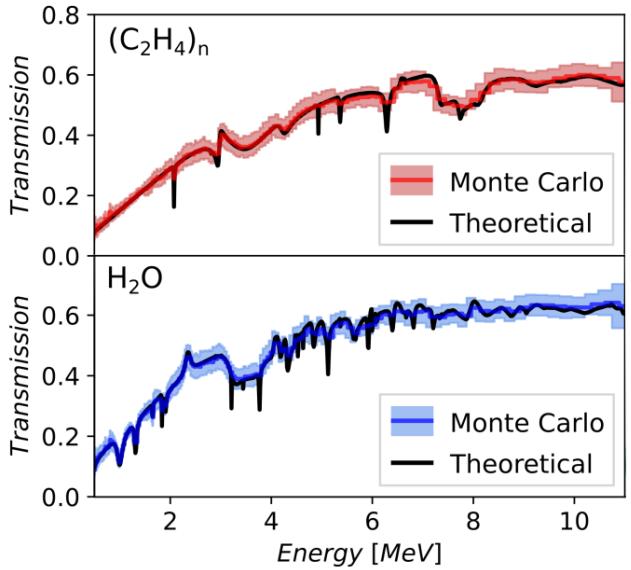
Exploit **laser-driven neutron source** to perform radiography of large samples.

3. **Irradiation of large samples** with 1-10 MeV neutron pulses.

4. Detection of **transmitted neutrons** for 1 min. irradiation at 5 Hz.



- **Transmitted neutron** spectra



$$\frac{I(E_n)}{I_0(E_n)} \sim e^{-c\sum_i \sigma_i r_i}$$

Transmission

Cross section

Sum over elements

Projected mass thickness

F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.
A. Pazzaglia, et al. *Commun Phys* 3.1, (2020): 1-13.

Numerical study of laser-driven FNRR feasibility

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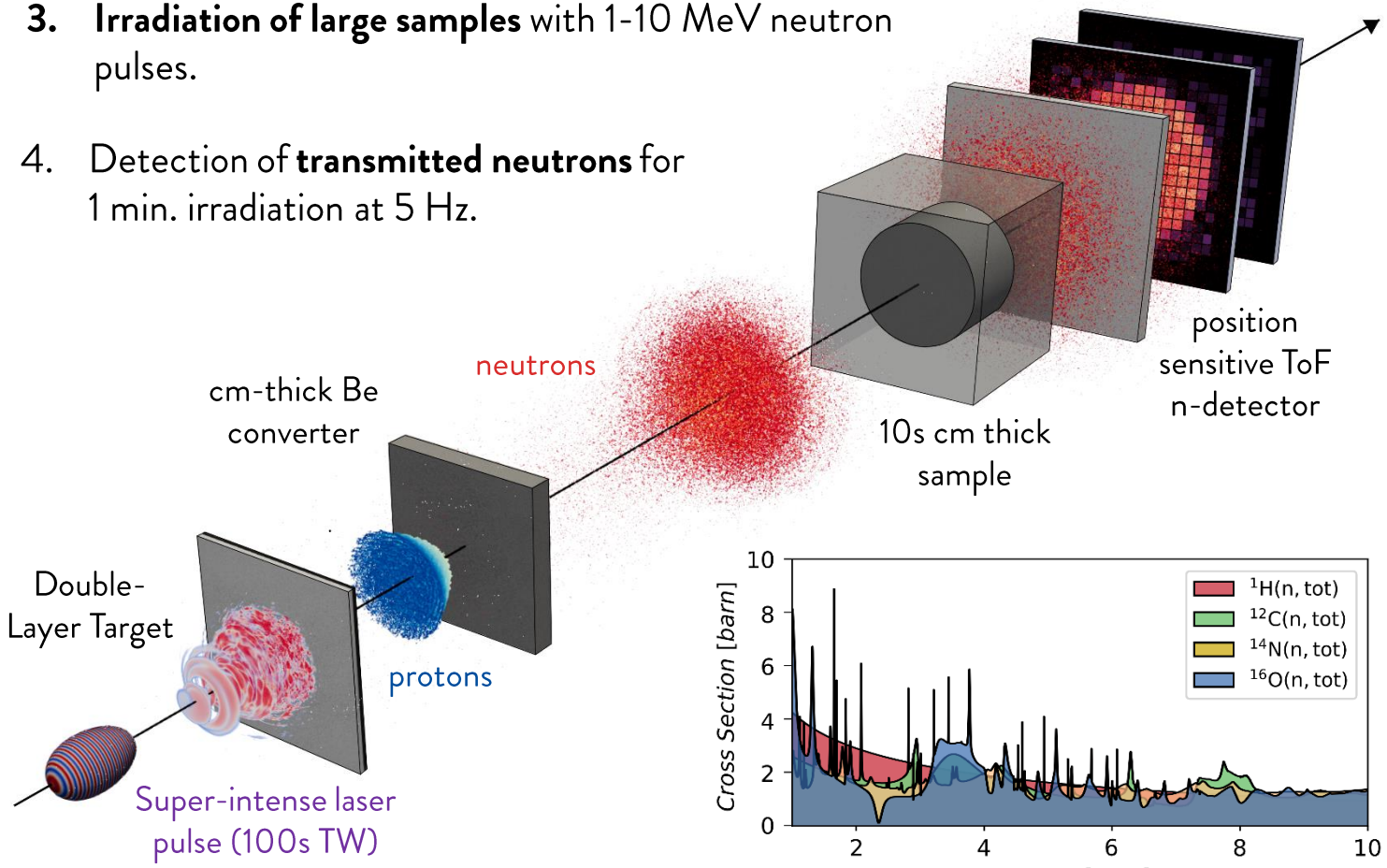
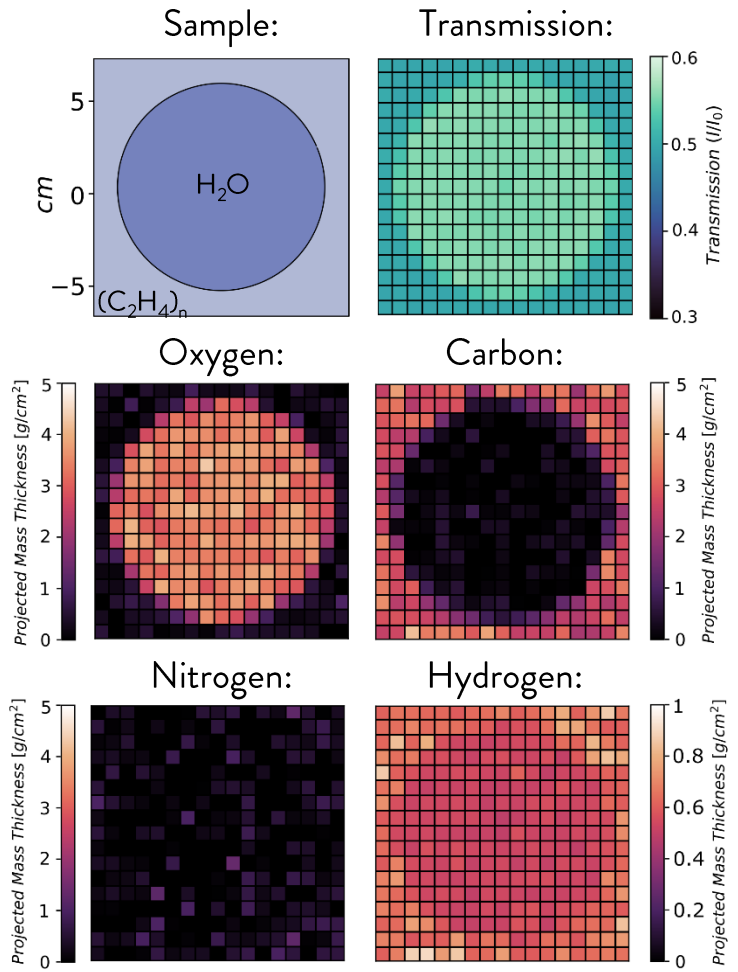
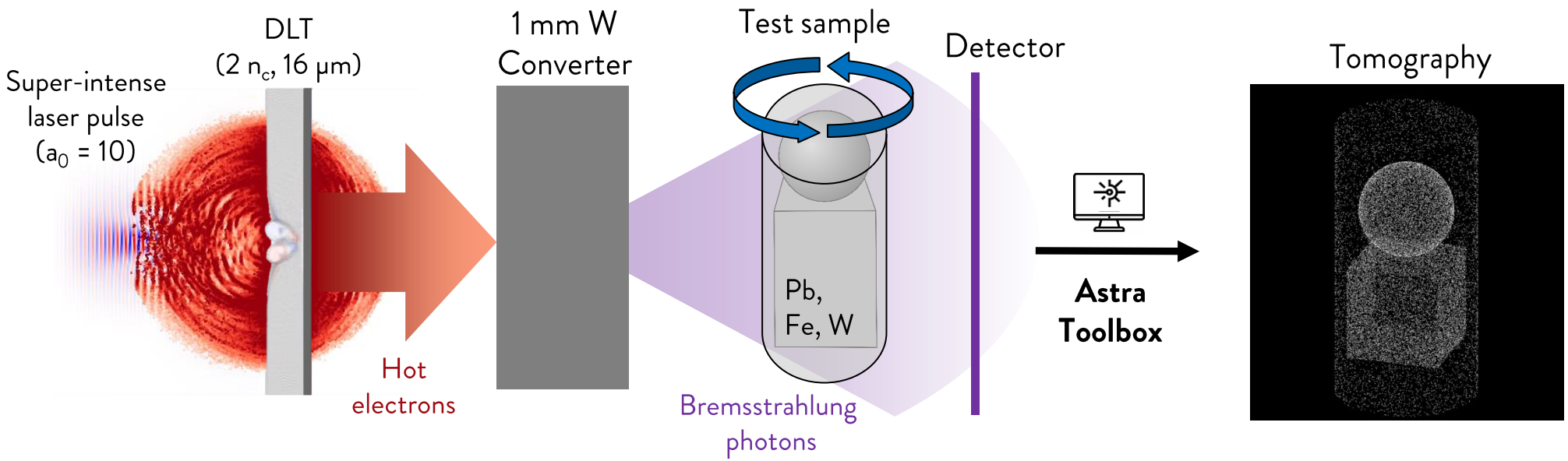


- **Elemental imaging** of O, C, N and H.

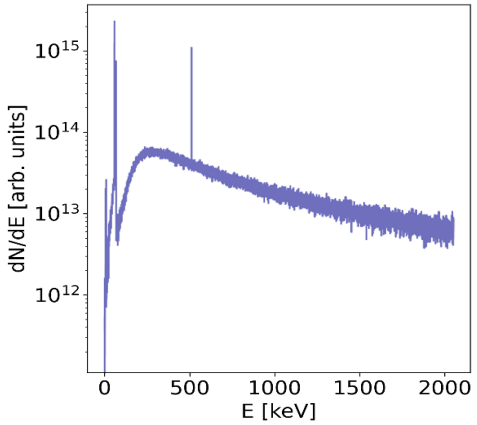


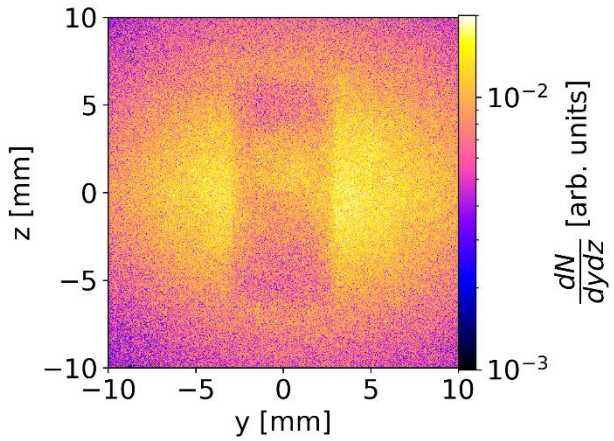
F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.

Numerical study of laser-driven computed tomography



- **Optimize** the source acting on **target parameters**.
- Simulation of the **whole setup** from laser to test sample reconstruction with





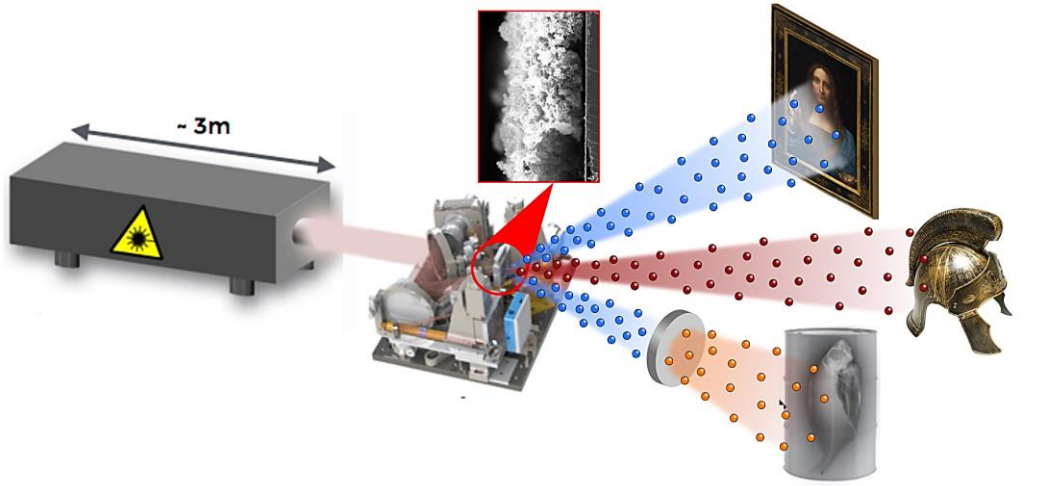
- **3D imaging by sections** using laser-driven x-rays from a compact laser source.

New activity started

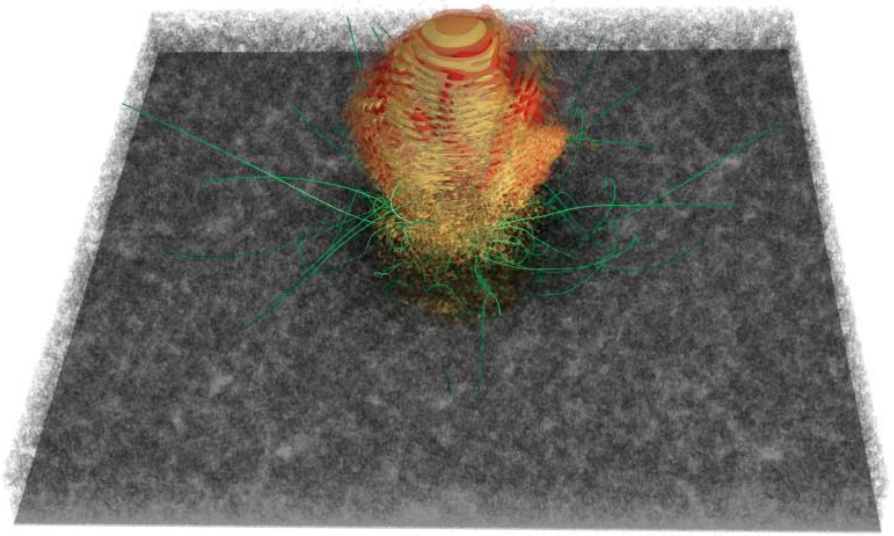
W. Van Aarle, et al. *Ultramicroscopy*, 157, (2015)ç 35-47.

Conclusions

- **Laser-driven radiation sources** are **promising** for **materials characterization** and in particular for artworks.
  - ➢ **Multiple radiations** → **multi-purpose** (surface, bulk, stratigraphic analysis and imaging).



- **DLTs** allow **enhancing** and **controlling the energy** of the accelerated particles.
  - ➢ **Mitigation** of laser **requirements.**



Thank you for the attention!

POLITECNICO MILANO 1863

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