SPIE. OPTICS+ OPTOELECTRONICS

Applying Laser-driven Particle Acceleration Session

ERC-2014-CoG No. 647554
ENSURE

POLITECNICO MILANO 1863

NanoLab
Department of Energy

Non-destructive materials analysis using a laser-driven particle source

Matteo Passoni

Politecnico di Milano

April 2021

- Largest university of engineering, architecture and design in Italy.
- More than 40000 students, ~1400 academic staff, 900 doctoral students.
- 32 BSc, 34 MSc, 18 PhD programmes.

- Activities performed within the framework of an **ERC consolidator grant** (from 2015 to 2020).

ENSURE erc -2014-CoG No.647554

Exploring the **N**ew **S**cience and engineering unveiled by **U**ltraintense ultrashort **R**adiation interaction with matt**E**r

POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

- Present **team members**:

M. Passoni
Principal investigator

D. Dellasega

M. Zavelani

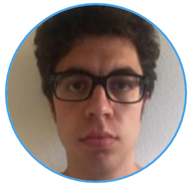
V. Russo

A. Pola

A. Maffini

A. Formenti

F. Mirani



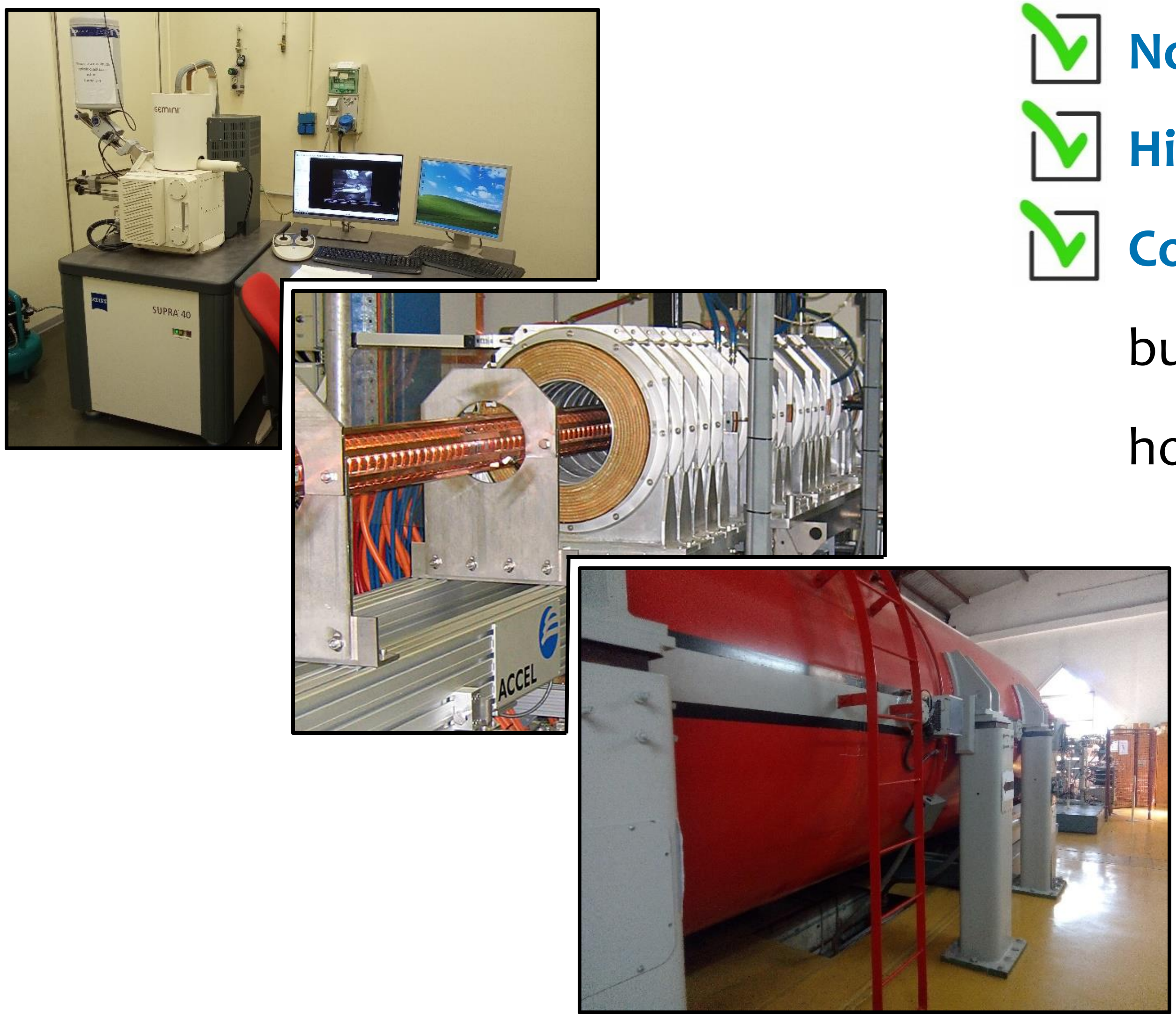
D. Vavassori

M. Galbiati

D. Orecchia

www.ensure.polimi.it

Atomic and nuclear analytical methods for materials characterization



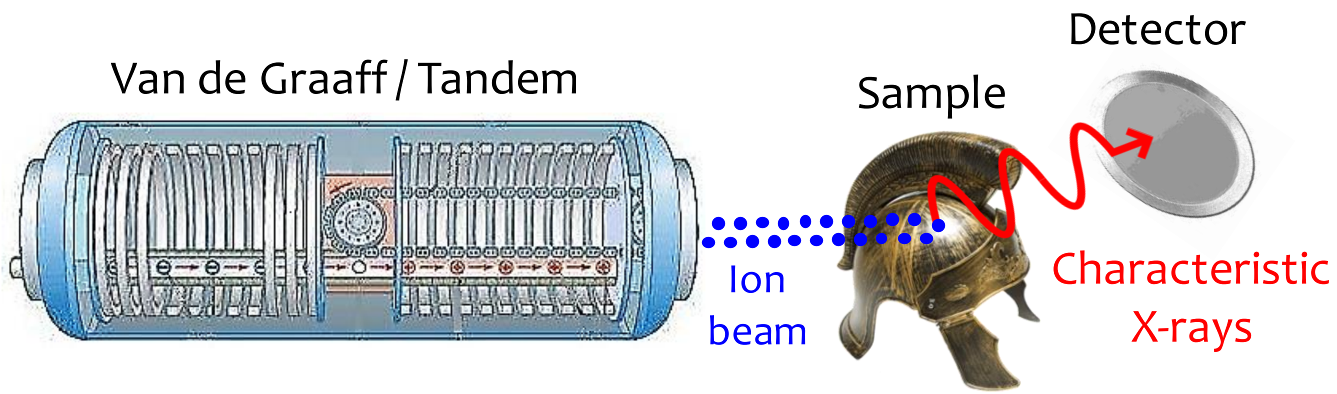
- ✔ **Non-destructive**
- ✔ **High** detection **capabilities**
- ✔ **Complementary** (element/isotope specific, bulk/surface analysis, homogeneous/stratigraphic)

…but often…

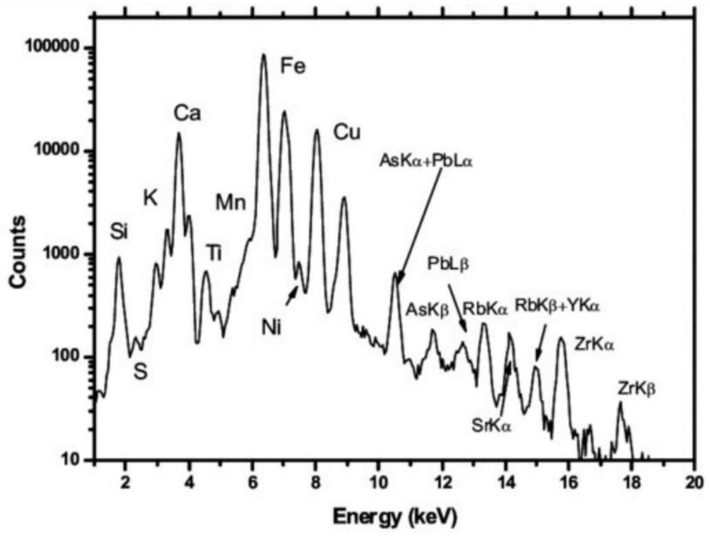
- ✘ **Large** and **expensive**
- ✘ **Non-tunable** particle energy
- ✘ Only **one kind of particle** is provided

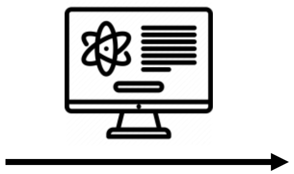
Can laser-driven sources be an option?

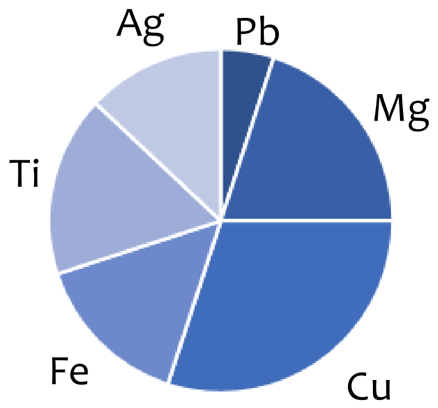
Materials characterization: Particle Induced X-ray Emission (PIXE)

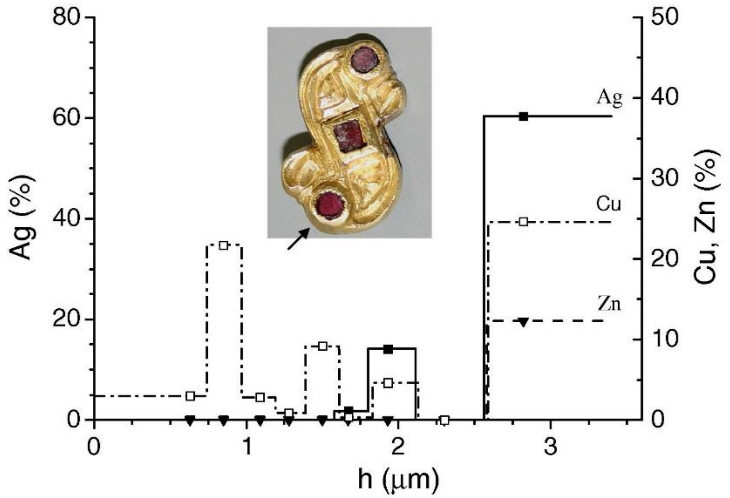


- **2-5 MeV/u** monoenergetic ions
- **Concentrations** & **Depth profiles**
- Cultural heritage, environment, biology, forensic analysis





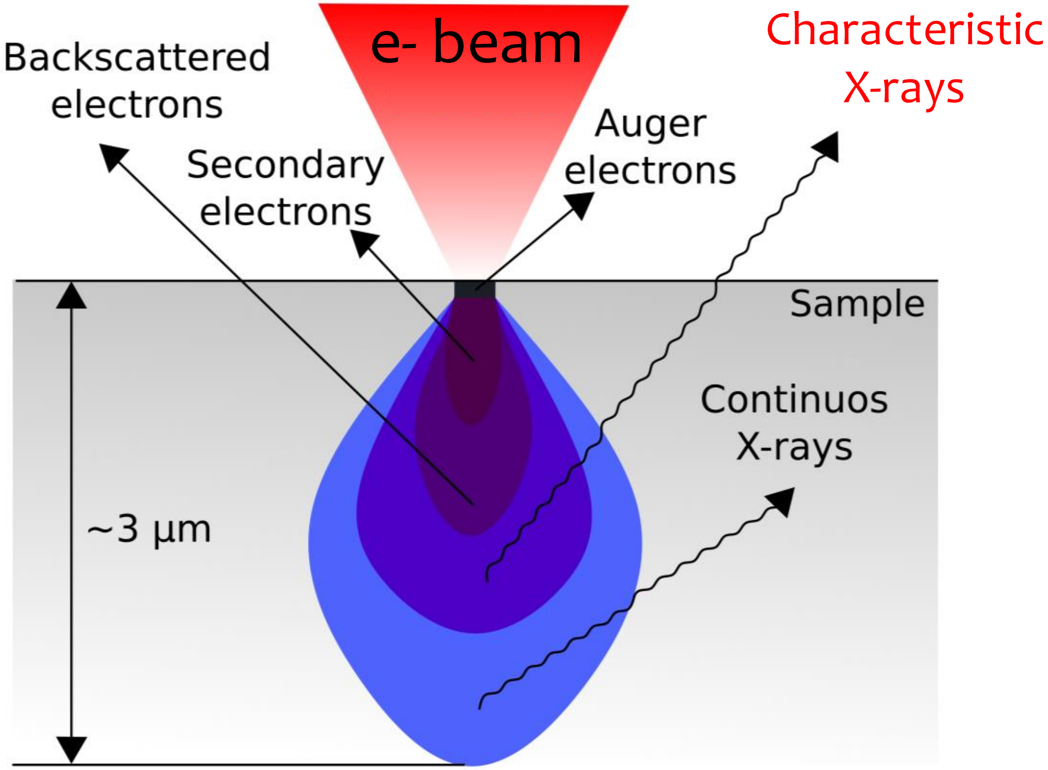




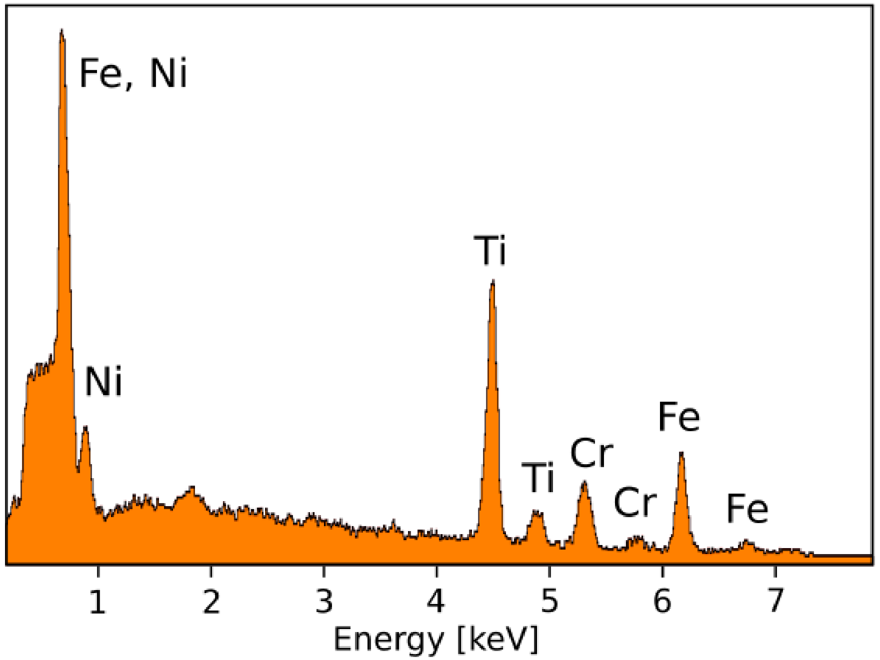
Verma, Hem Raj. Atomic and nuclear analytical methods. Springer-Verlag Berlin Heidelberg, 2007.

Žiga Šmit, et al. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 266(10):2329–2333, 2008.

Materials characterization: Energy Dispersive X-ray (EDX) spectroscopy



- **KeV** energy **electrons**
- **Small** and solid **samples**
- Fast **identification** of the elements and **concentrations** reconstruction from

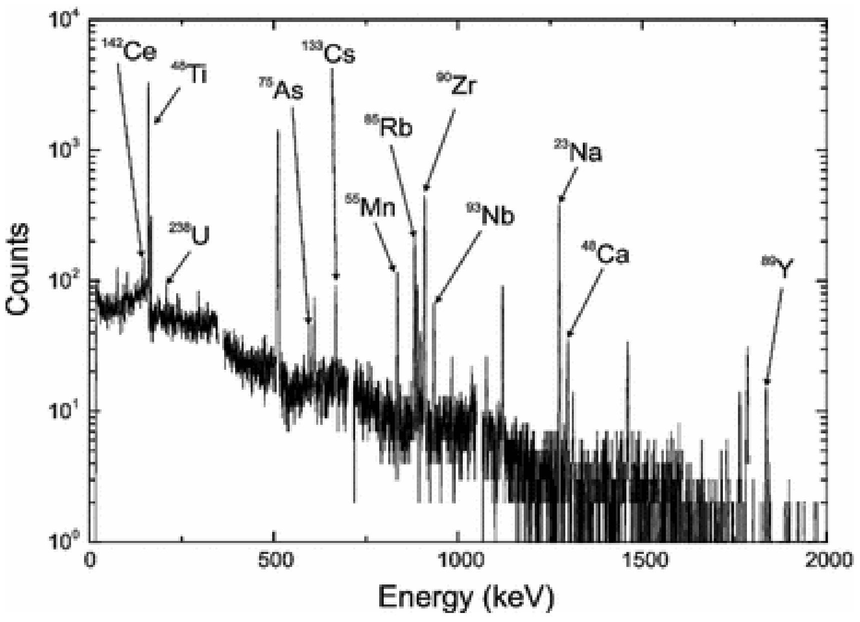


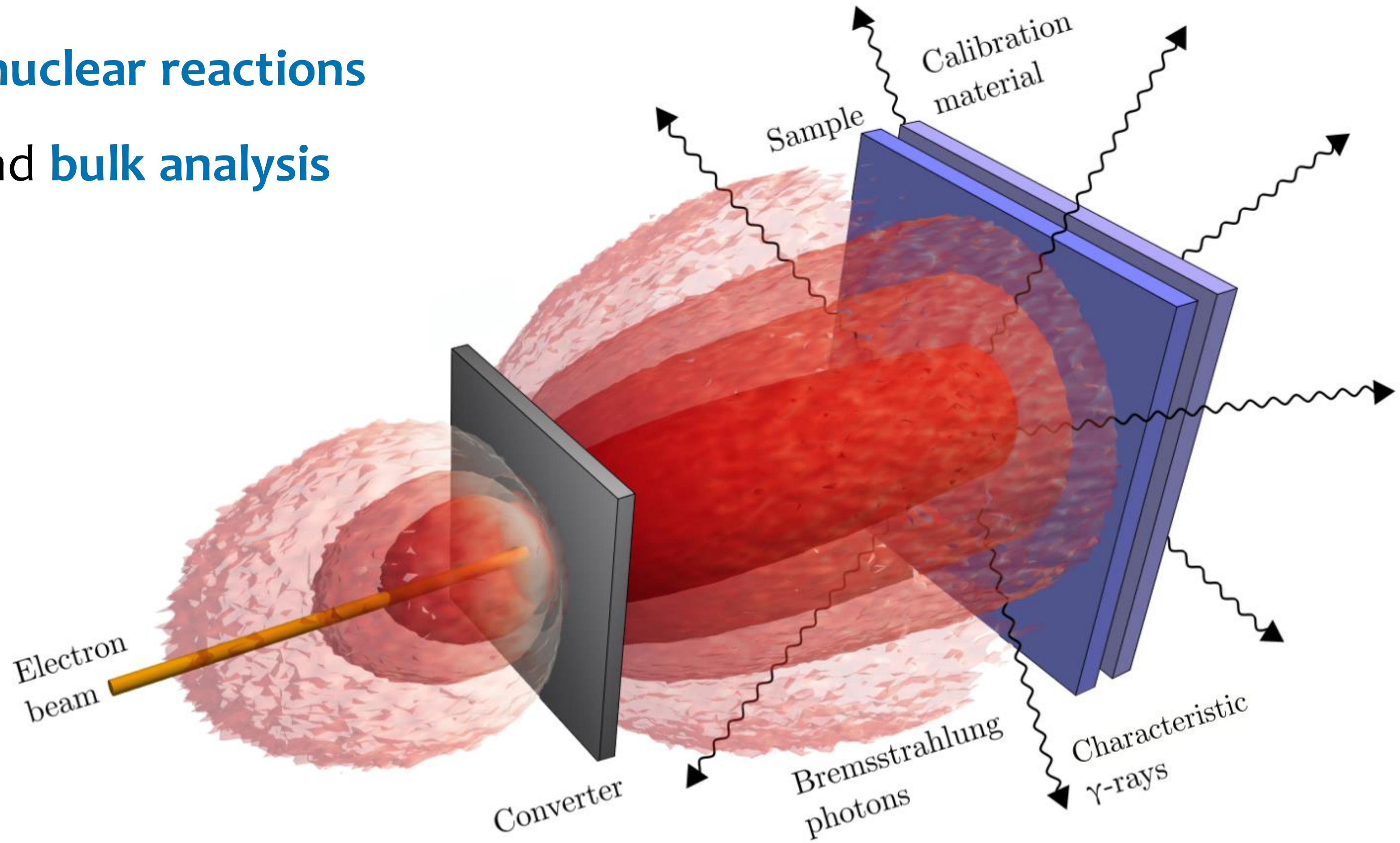
DC Bell and AJ Garratt-Reed. Energy dispersive X-ray analysis in the electron microscope, volume 49. Garland Science, 2003.

A Pazzaglia, et al. Materials Characterization, 153:92–102, 2019.

Materials characterization: Photon Activation Analysis (PAA)

- **10s MeV e- → bremsstrahlung**
- **Sample activation** due to **photonuclear reactions**
- **Identification** of the elements and **bulk analysis**

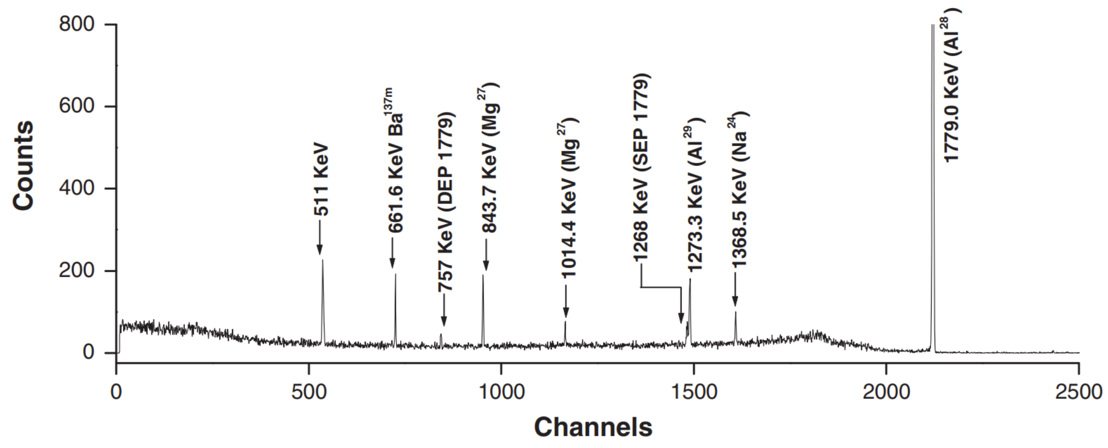


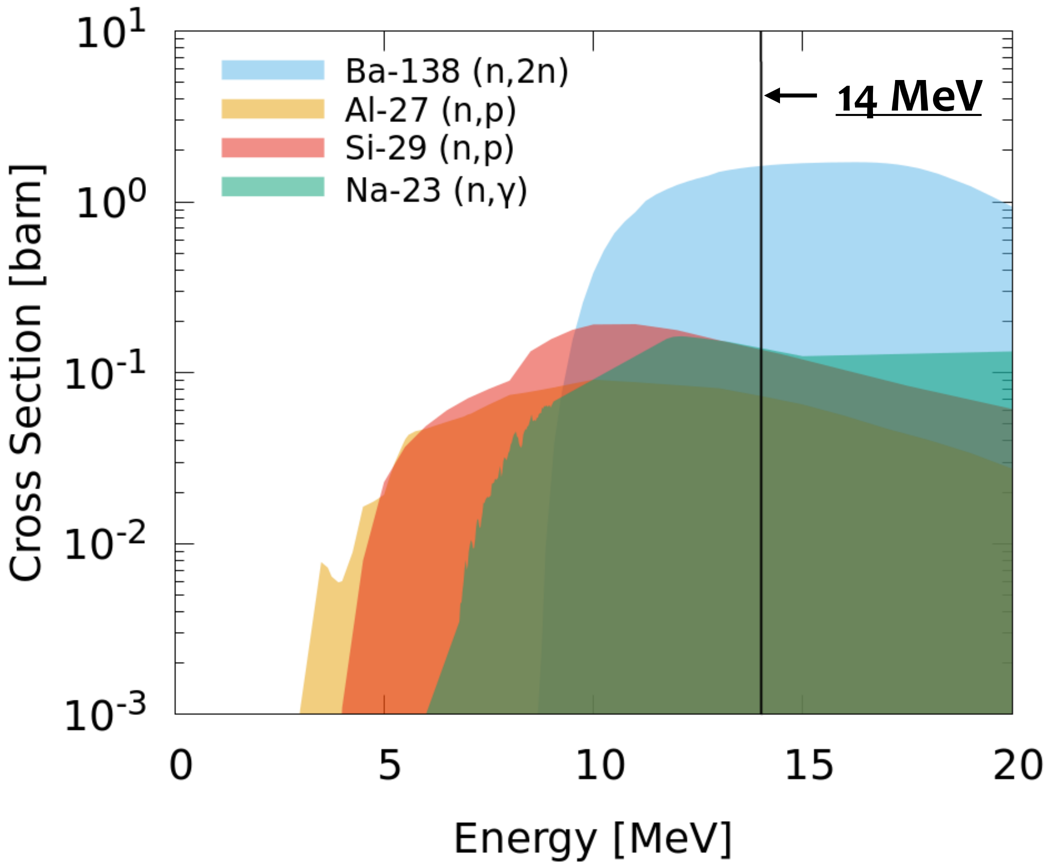


Segebade, Christian, et al. "Principles, methodologies, and applications of photon activation analysis: a review." Journal of Radioanalytical and Nuclear Chemistry 312.3 (2017): 443-459.

Materials characterization: Fast Neutron Activation Analysis (FNAA)

- **E > 5 MeV** is required → **14 MeV** exploited (**$^{3}H(d, n)^{4}He$** generators)
- **Sample activation** due to **neutron induced reactions** → delayed emission of γ-rays
- **Identification** of the elements & **bulk analysis**

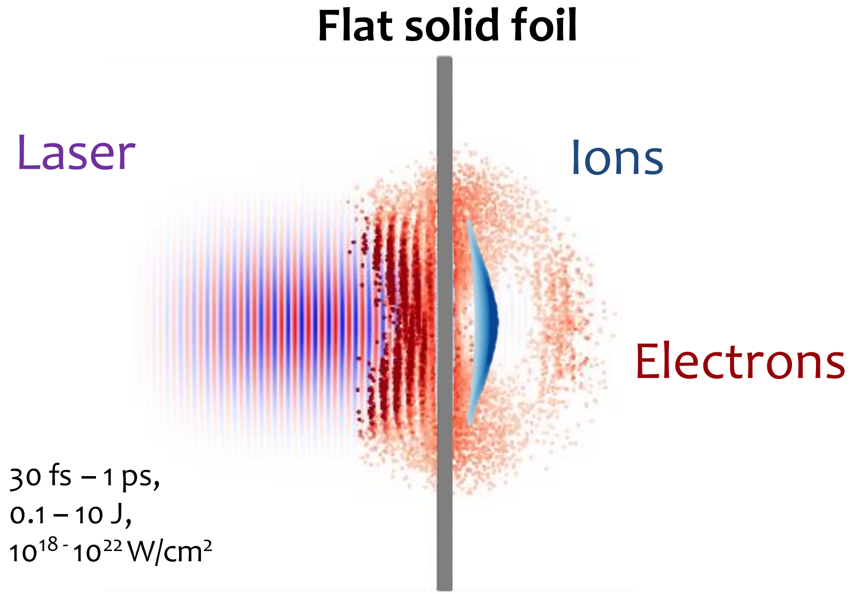


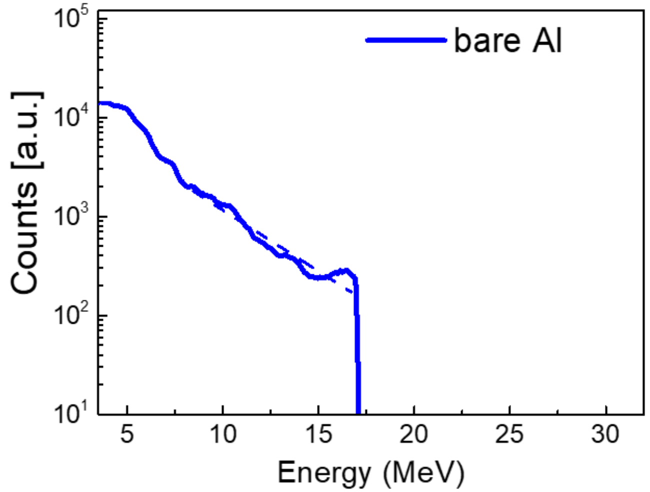


Chadwick, M. B., et al. "ENDF/B-VII. 0: next generation evaluated nuclear data library for nuclear science and technology." Nuclear data sheets 107.12 (2006): 2931-3060.

Medhat, M. E. "Fast neutron activation analysis by means of low voltage neutron generator." Results in physics 6 (2016): 860-862.

Laser-driven radiation sources for materials characterization, our approach



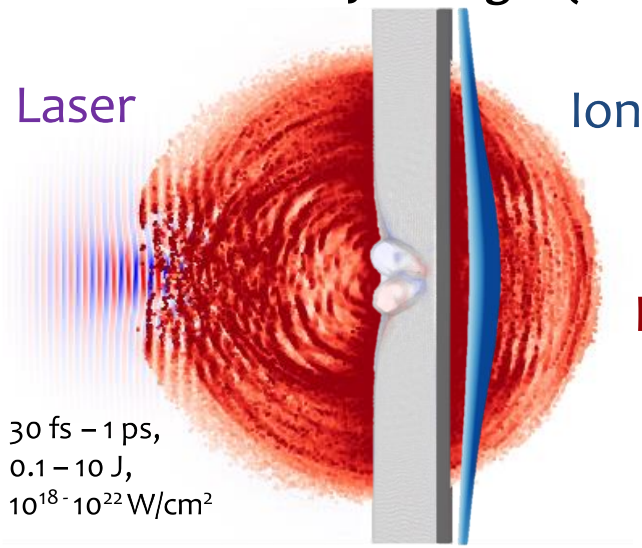


TNSA → Reliable mechanism, both electrons and ions → **Multi-purpose**

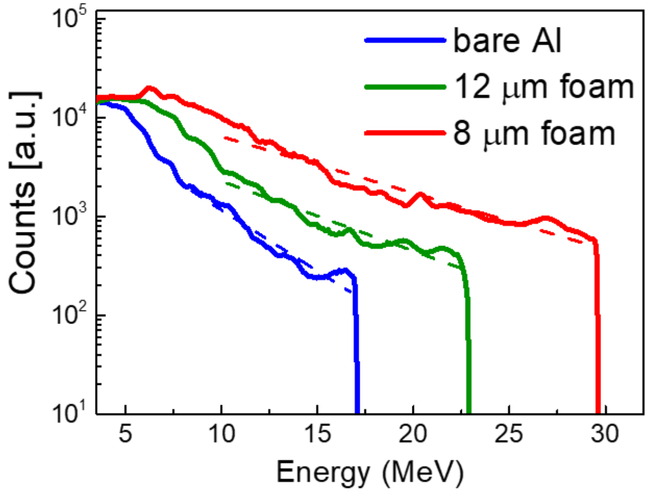
Passoni, M., et al. "Advanced laser-driven ion sources and their applications in materials and nuclear science." Plasma Physics and Controlled Fusion 62 014022 (2020)

Laser-driven radiation sources for materials characterization, our approach

Double Layer Target (DLT)



30 fs – 1 ps,
0.1 – 10 J,
10^{18} - 10^{22} W/cm^2



TNSA ⟶ Reliable mechanism, both electrons and ions ⟶ **Multi-purpose**

DLT ⟶ Reduce laser requirements ⟶ **Compactness**

⚠ **Unconventional** features of the laser-driven **particles**

Investigation through **theoretical** & **experimental** methods

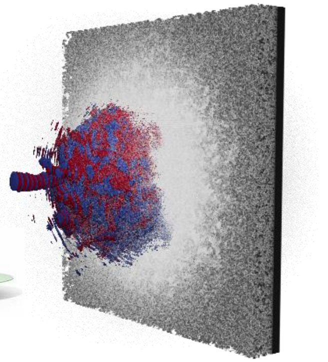
Analytical models, PIC and Monte Carlo simulations

piccante

Smilei

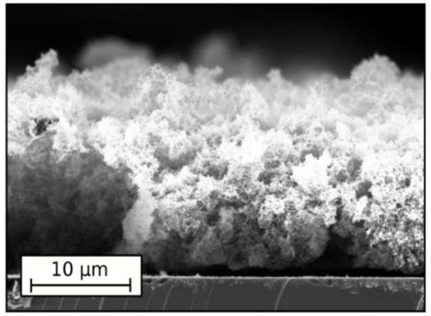
GEANT4

FLUKA



DLTs production with controlled properties

Deposition techniques:
- PLD
- HiPIMS

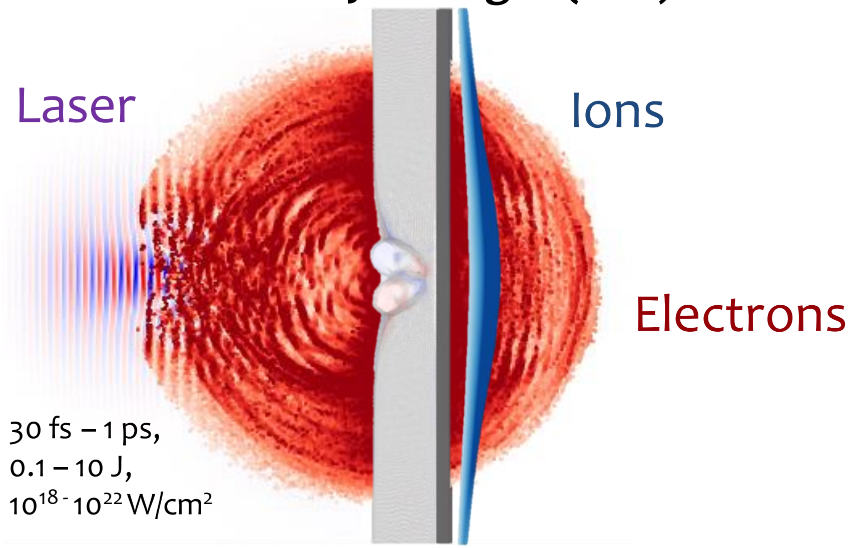


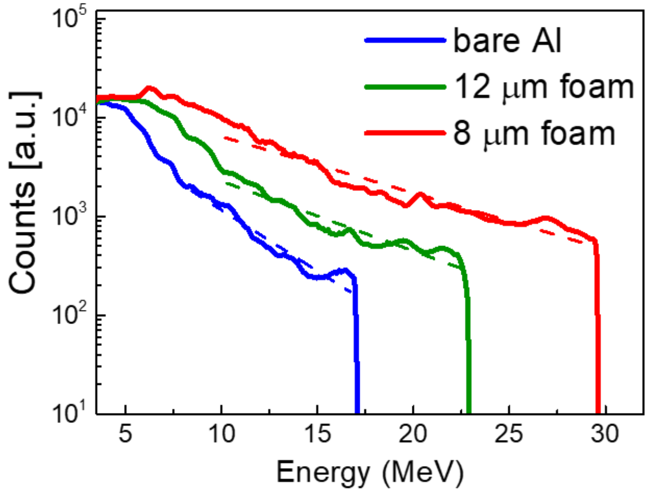
Passoni, M., et al. "Advanced laser-driven ion sources and their applications in materials and nuclear science." Plasma Physics and Controlled Fusion 62 014022 (2020)

POLITECNICO MILANO 1863

Laser-driven radiation sources for materials characterization, our approach

Double Layer Target (DLT)





👍 **TNSA** ⟶ Reliable mechanism, both electrons and ions ⟶ **Multi-purpose**

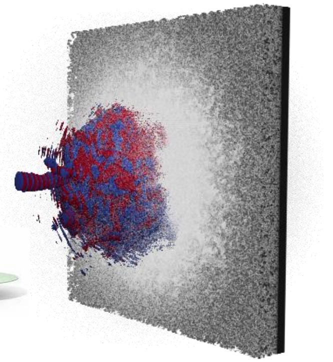
👍 **DLT** ⟶ Reduce laser requirements ⟶ **Compactness**

⚠ **Unconventional** features of the laser-driven **particles**

Investigation through **theoretical** & **experimental** methods

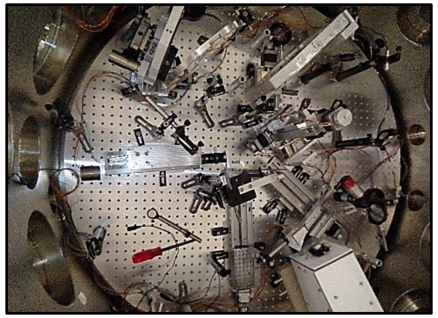
Analytical models, PIC and Monte Carlo simulations

piccante
Smilei
GEANT4
FLUKA



Experimental campaign

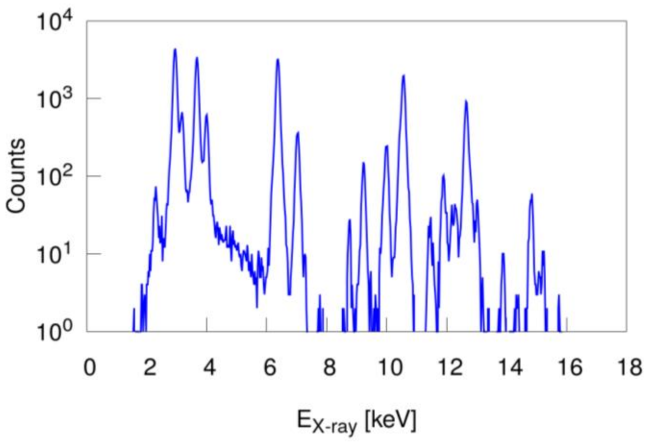
- Test DLTS
- Mat. science

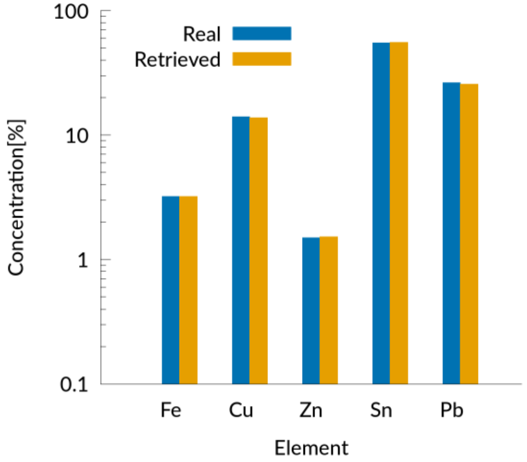


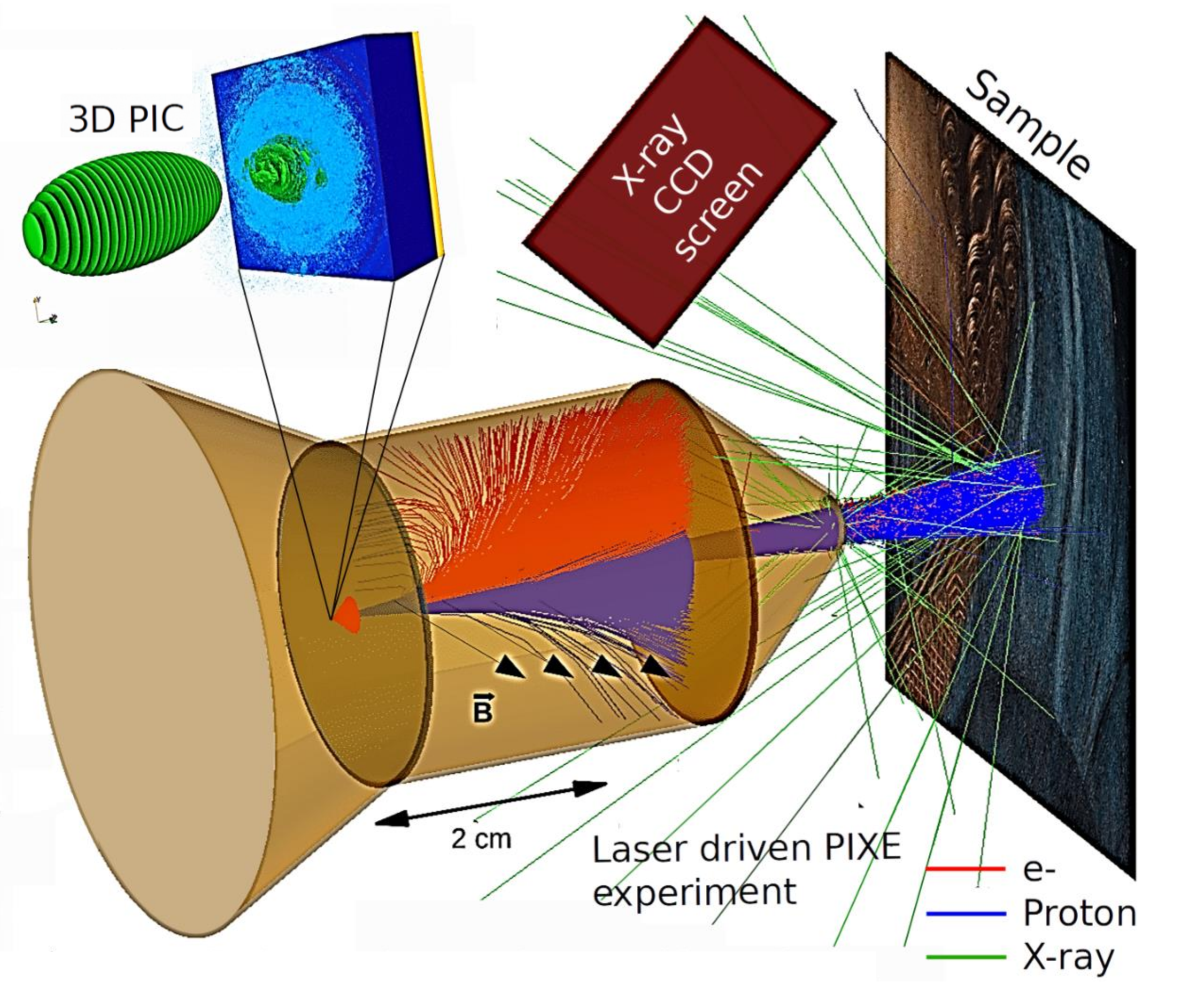
Passoni, M., et al. "Advanced laser-driven ion sources and their applications in materials and nuclear science." Plasma Physics and Controlled Fusion 62 014022 (2020)

Laser-driven PIXE, a numerical investigation

- Pixe theory with non-monoenergetic proton
- **Simulation** of laser-driven PIXE **realistic scenarios** (piccante , GEANT4)
- **Software** development for the **analysis** of the **X-ray spectra** → Sample composition reconstruction



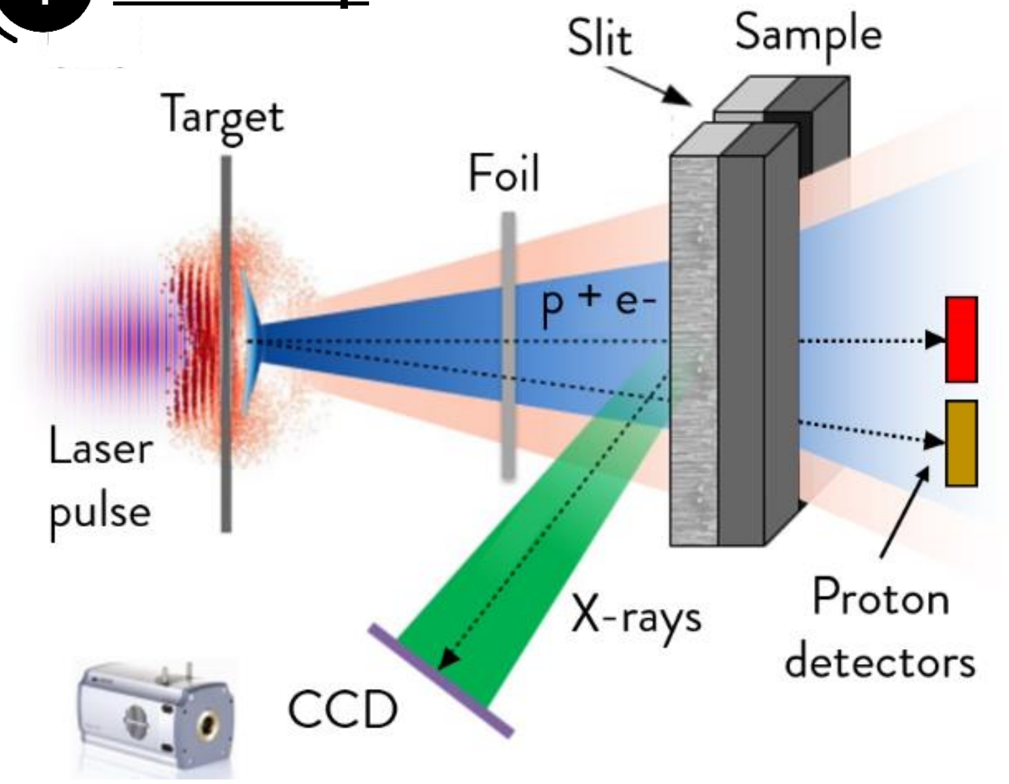




Passoni, Matteo, Luca Fedeli, and Francesco Mirani. "Superintense laser-driven ion beam analysis." Scientific reports 9.1 (2019): 1-11.

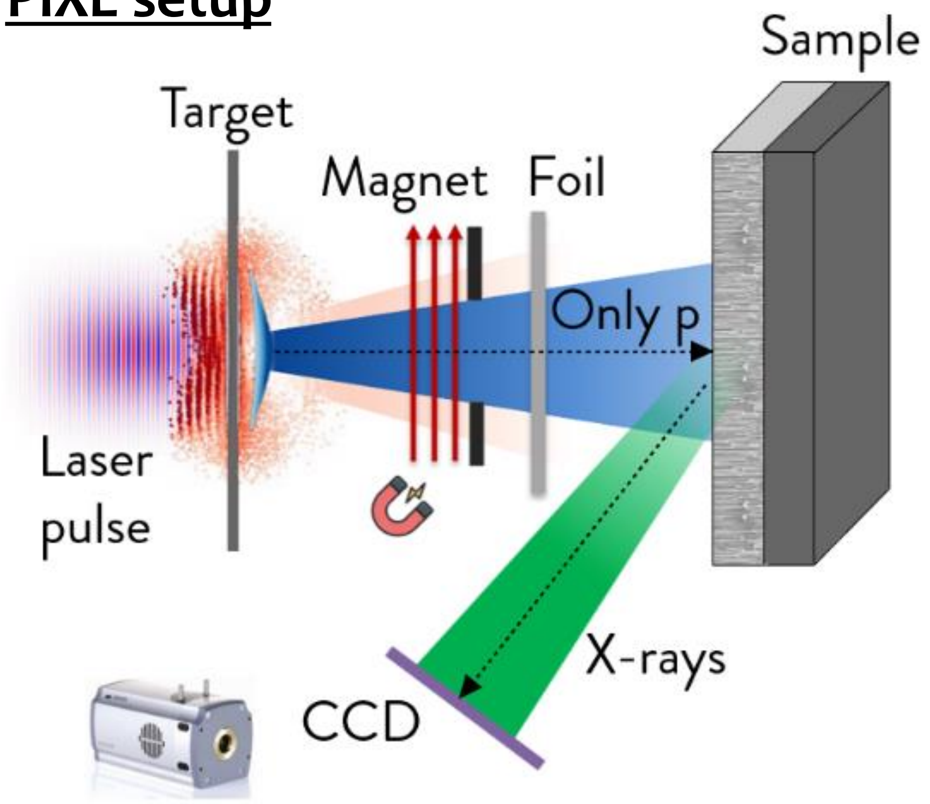
Laser-driven PIXE and EDX experiment @ CLPU Salamanca

1 EDX setup



❖ Sample **irradiation** with **both electrons** and **protons**

2 PIXE setup



❖ Magnet to **remove** the **electrons**

Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

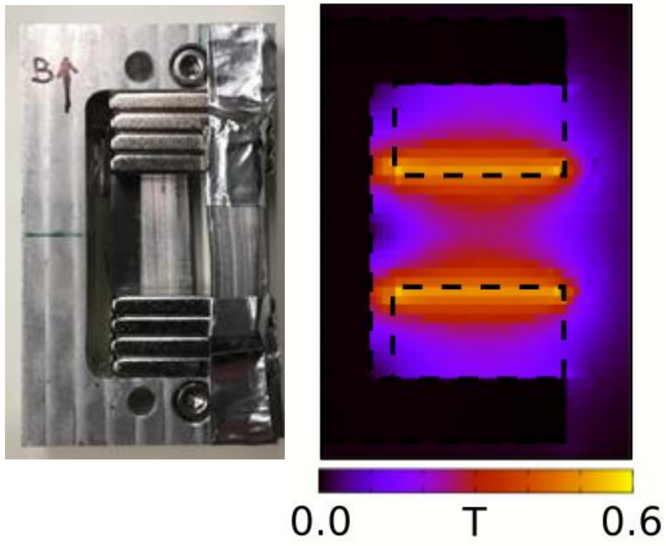
Laser-driven PIXE and EDX experiment @ CLPU

- **Electron** and **proton contribution** to the **X-ray production?** GEANT4

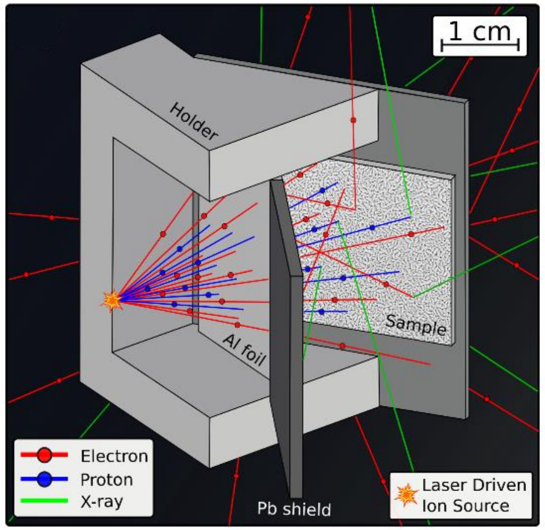
Finite Element Analysis

↓

3D **Magnetic field** distribution



1 EDX setup

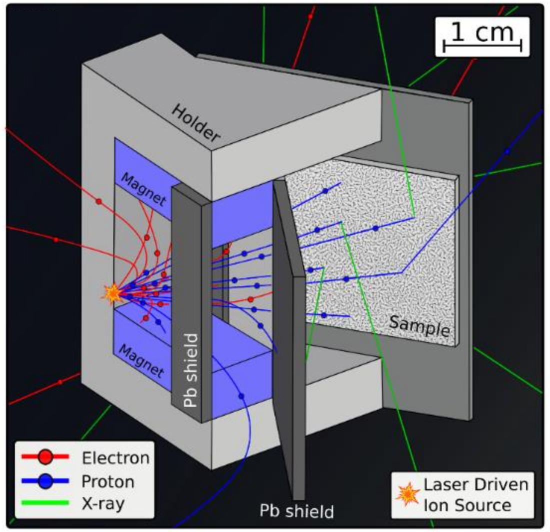


- **Electron** contribution is **dominant**

↓

Fast elemental analysis

2 PIXE setup



- ~98% of **electrons** are **removed**

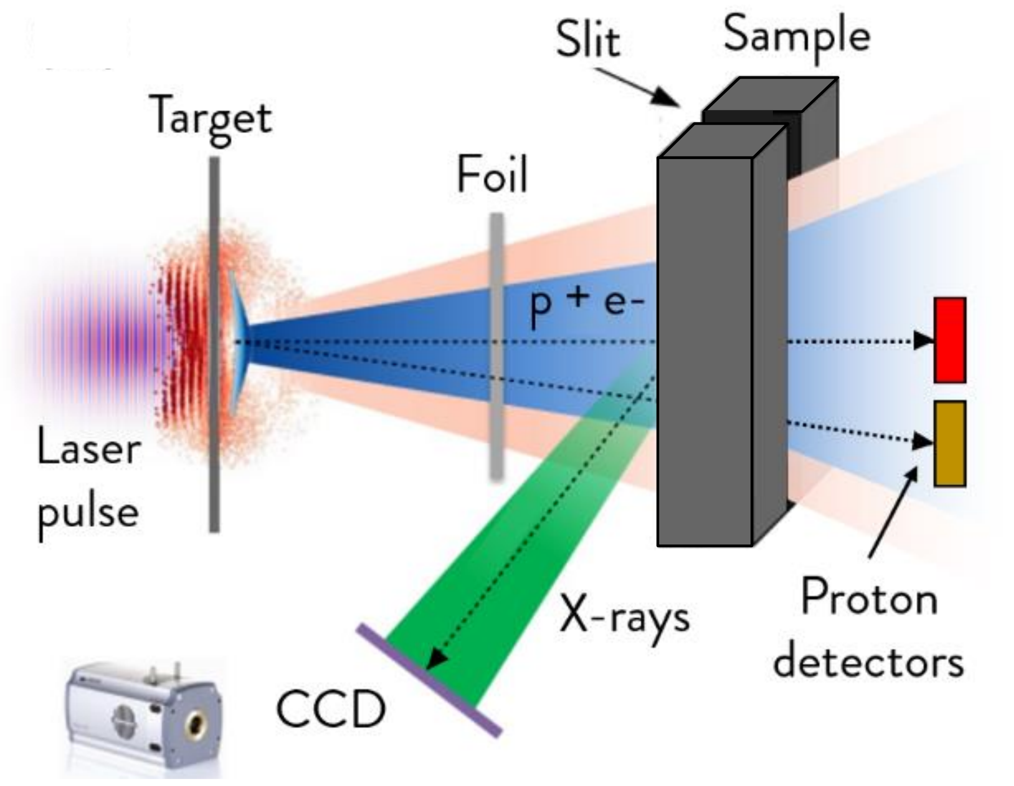
↓

Quantitative analysis

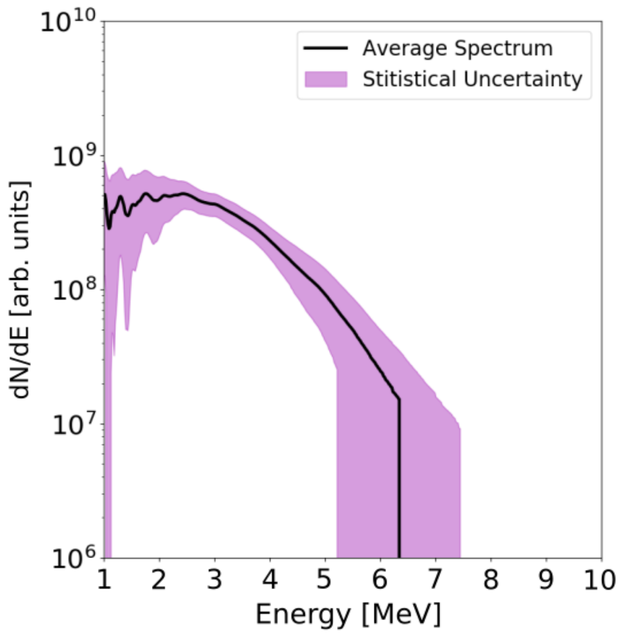
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

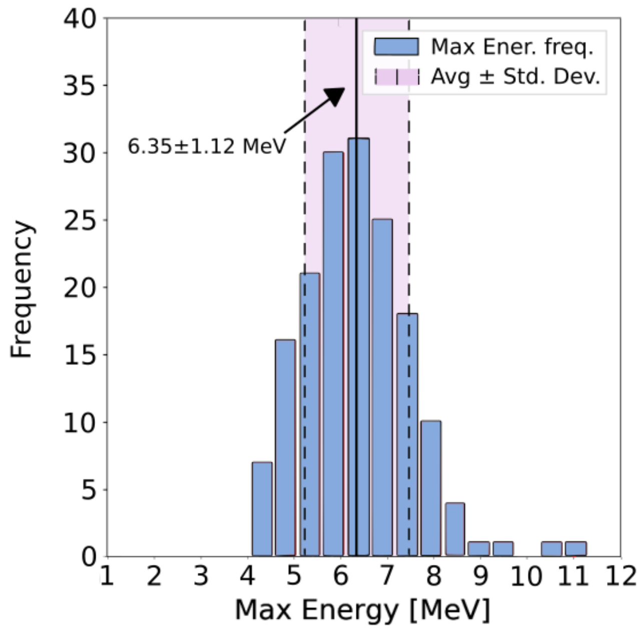
Laser-driven PIXE and EDX experiment @ CLPU

1 <u>**EDX setup**</u> → Sample **irradiation** with **both electrons** and **protons**



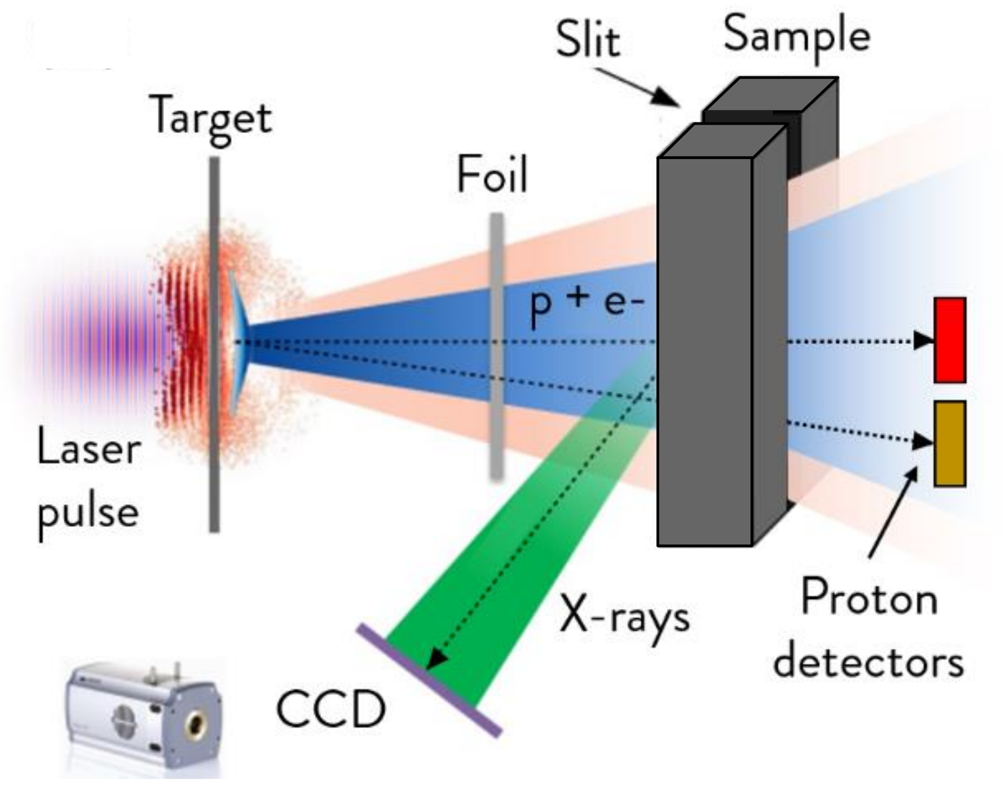
- **Aperture slit** in the middle of the sample
- **Proton** spectrum **characterization** (ToF)



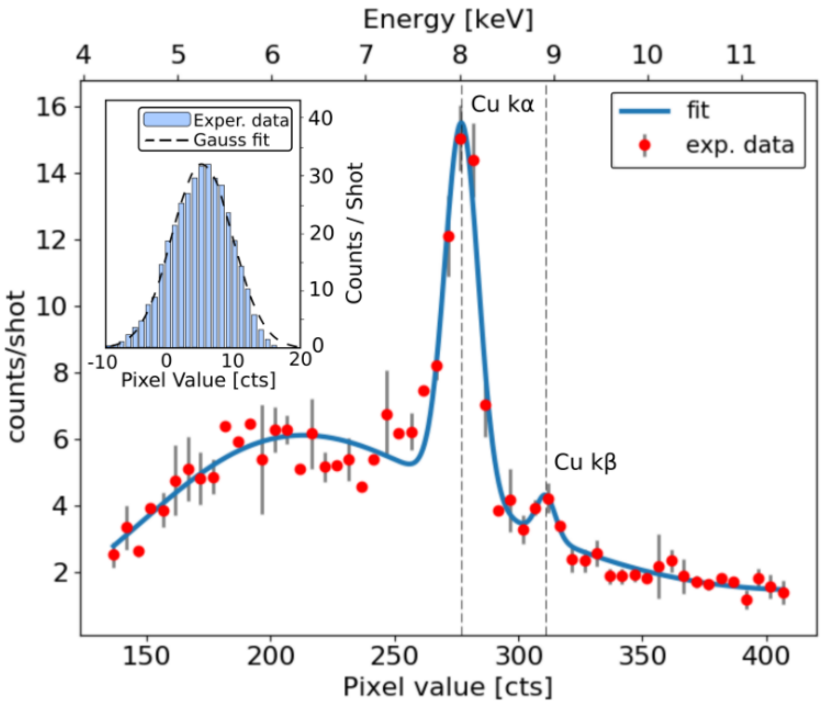


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

1 **EDX setup** → Sample **irradiation** with **both electrons** and **protons**

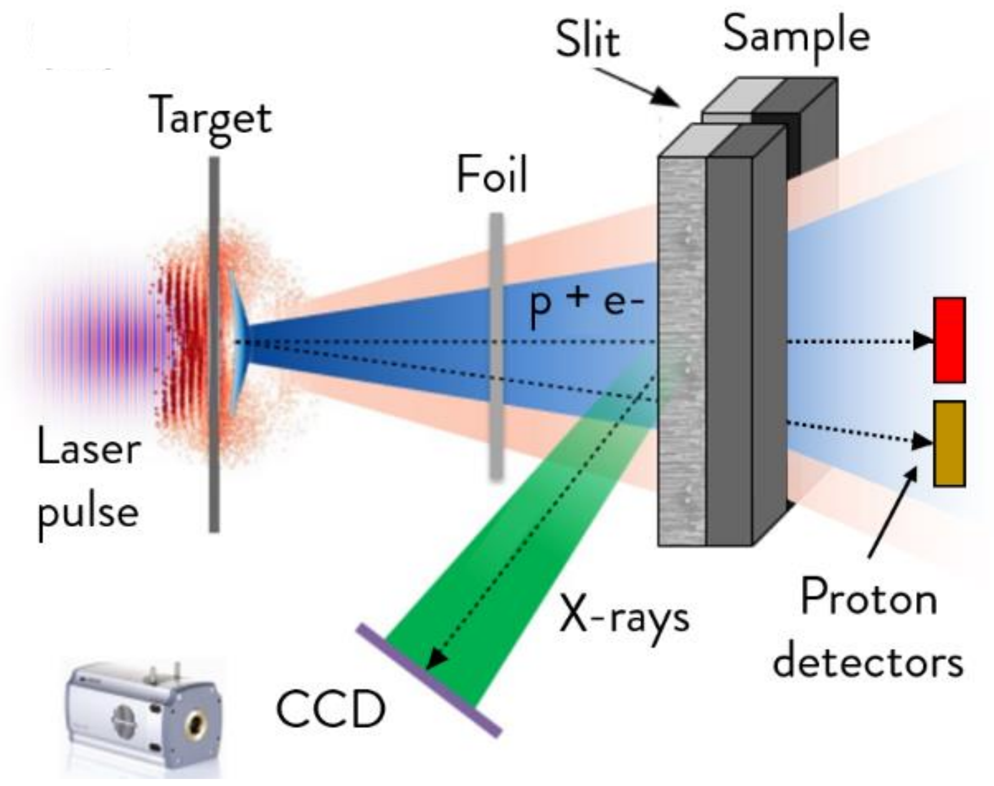


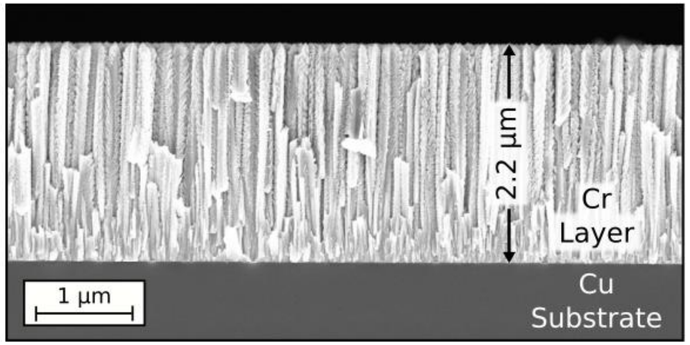
❖ X-ray **CCD** energy **calibration** (pure Cu sample)

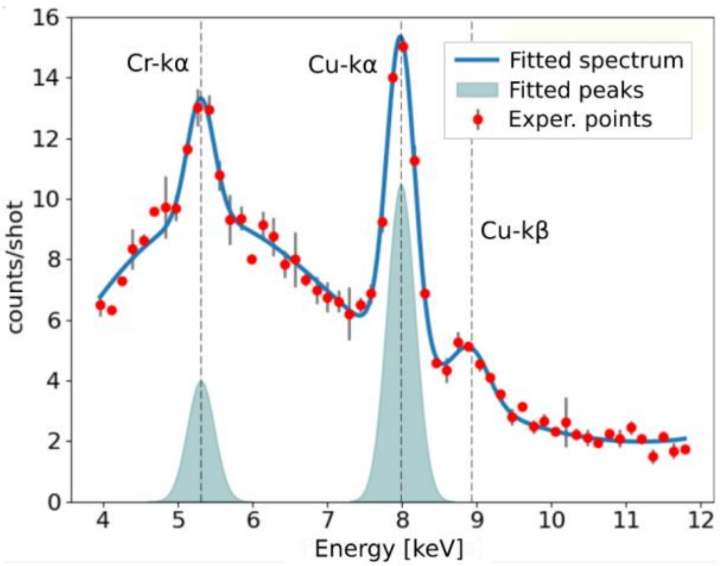


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

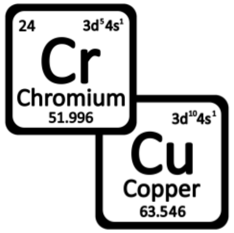
1 **EDX setup** → Sample **irradiation** with **both electrons** and **protons**







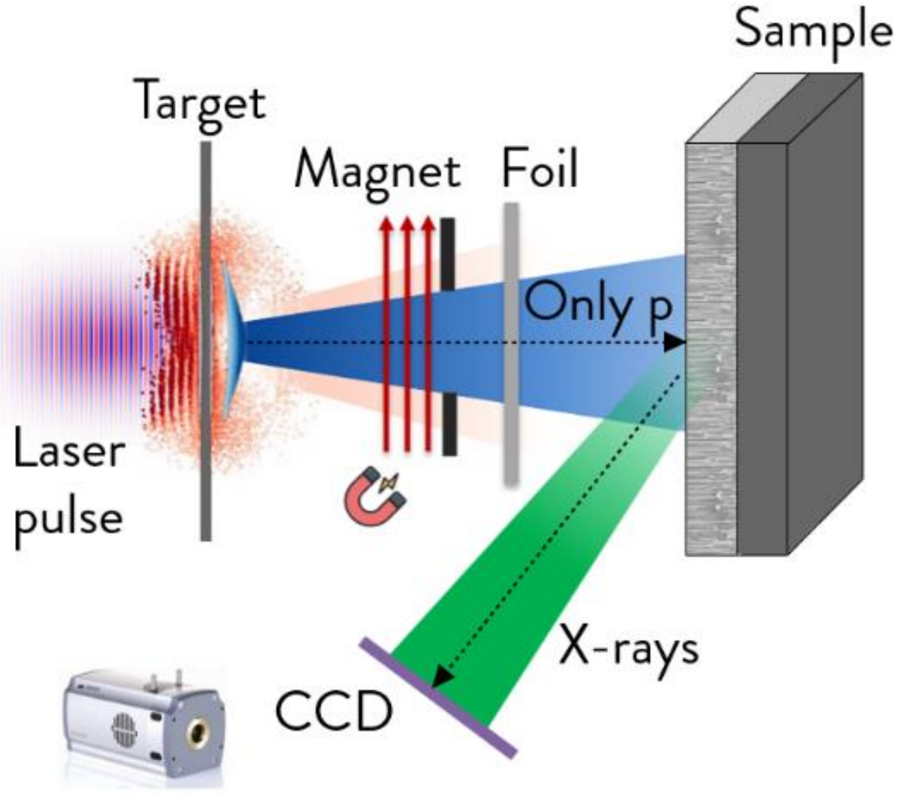
Bi-layer sample (Cr layer + Cu substrate)



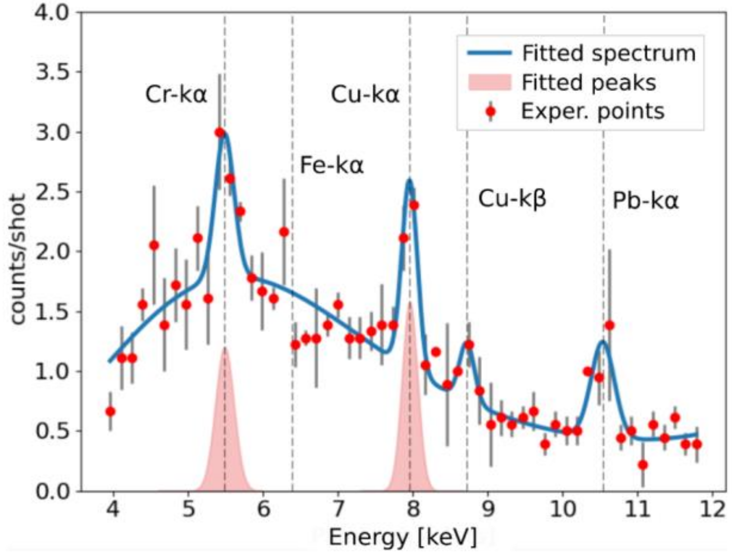
Elements are correctly **recognized**

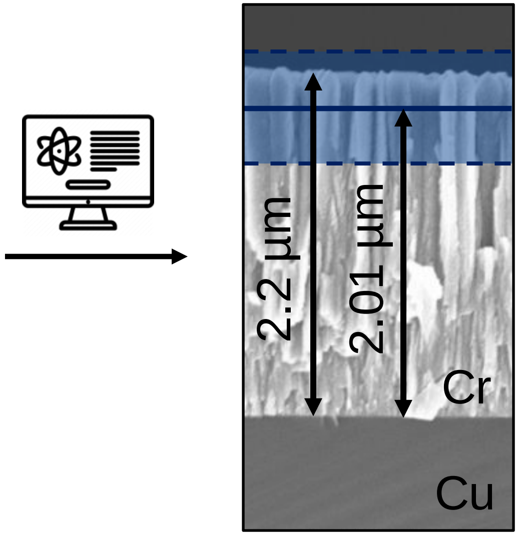
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

2 PIXE setup → **Removal** of the **electrons** with dipole magnet (0.26 T) and lead shielding



- **Sample thickness reconstruction** exploiting the model developed for the laser-driven PIXE analysis



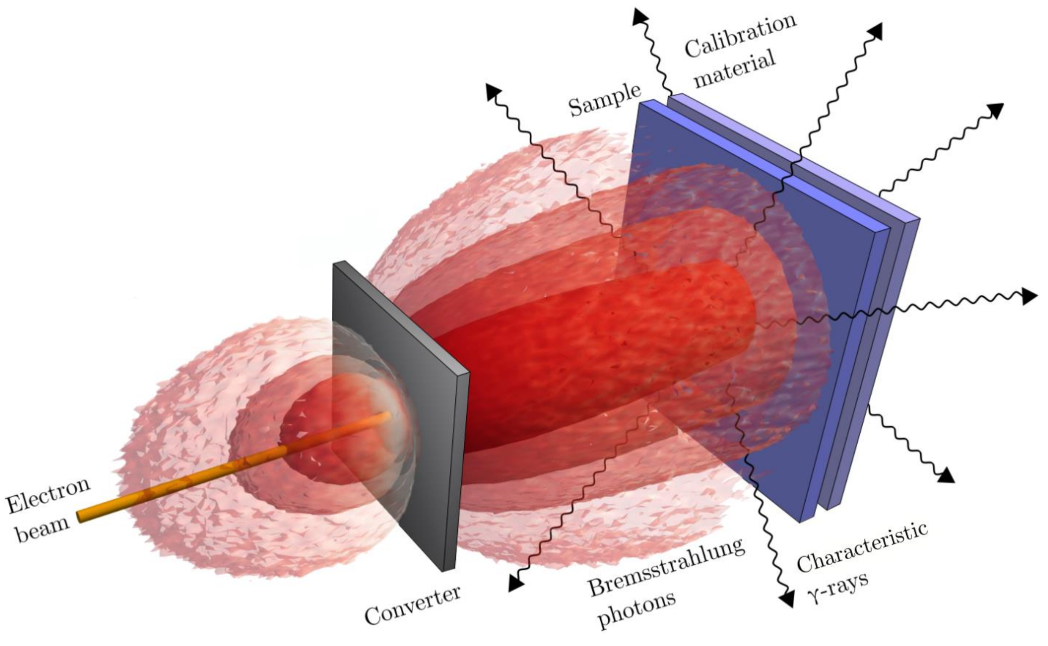


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

Laser-driven PAA, a numerical investigation

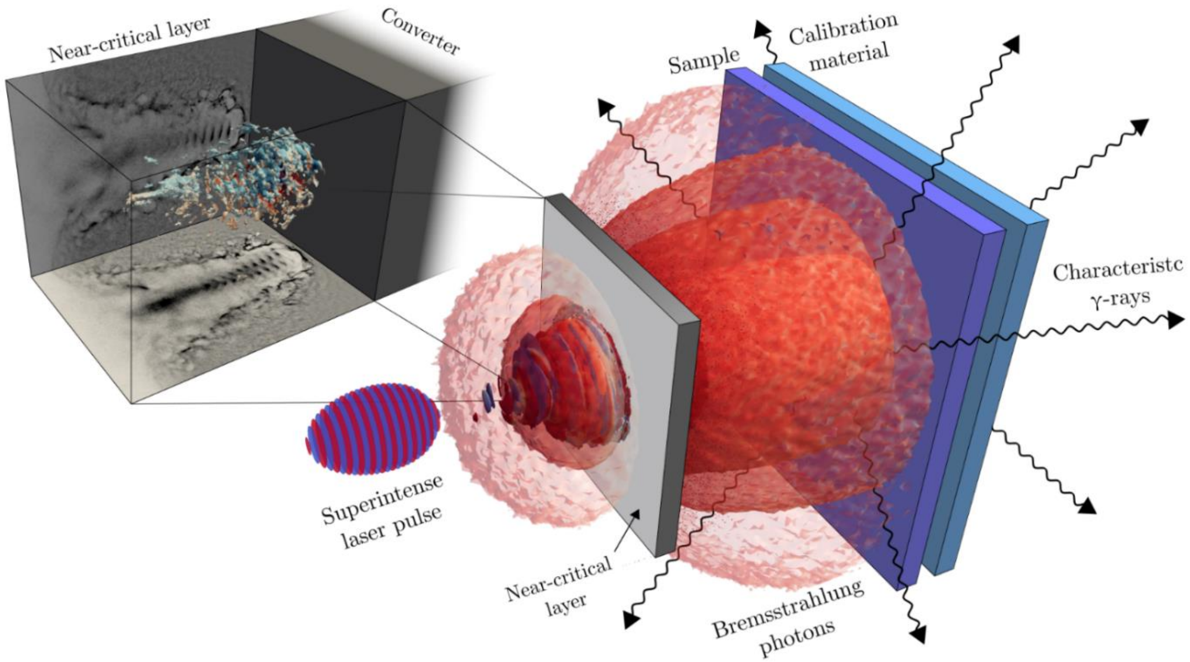
Theoretical description of:

❖ Conventional PAA



- **Input** parameters: Electron **energy** & **current**
- **Output**: activation rate

❖ Laser-driven PAA



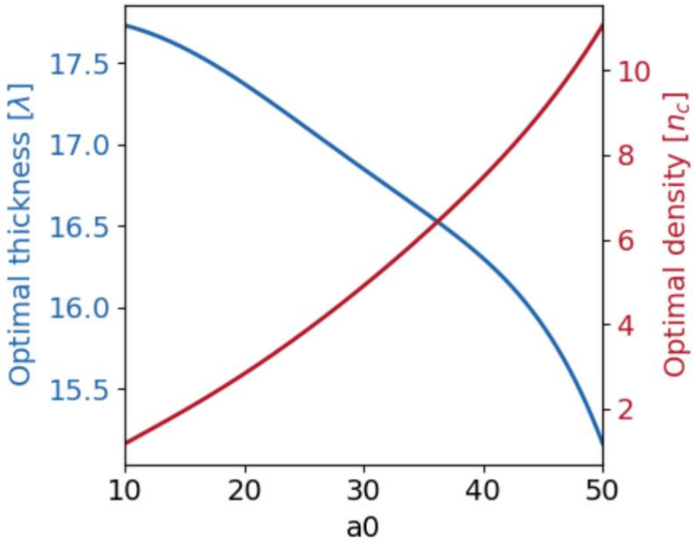
- **Input** parameters: Laser **Intensity** & **Repetition rate**
- **Output**: activation rate

Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

Laser-driven PAA, a numerical investigation

❖ From the <u>laser-driven PAA model</u>:

- **Optimal near-critical layer** density and thickness

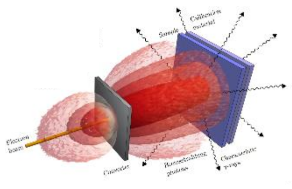


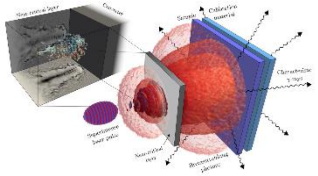
- **Optimal converter** thickness (~2.6 mm)

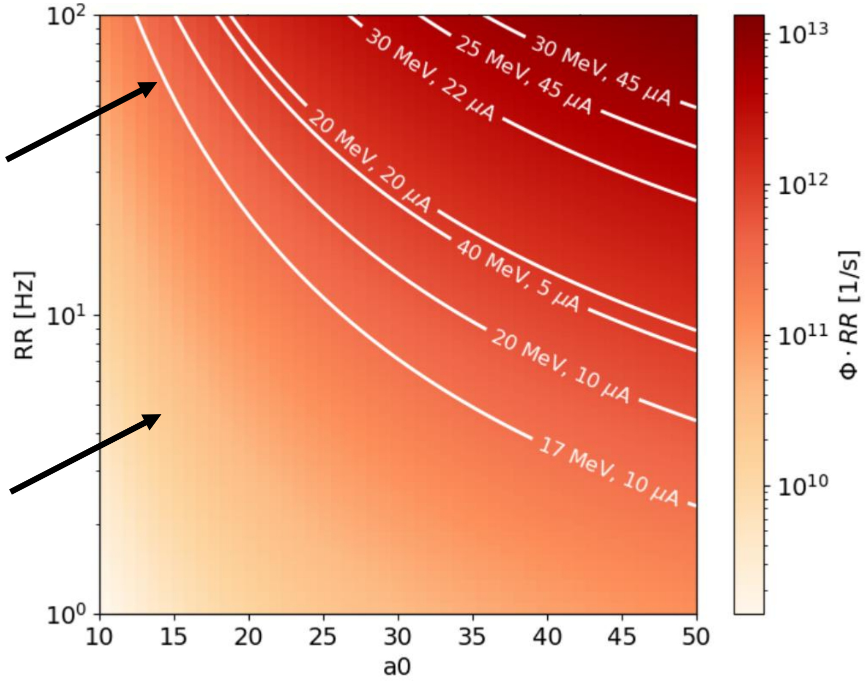
Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

❖ From the <u>both models</u>:

- **Comparison** between conventional and laser-driven **sources**







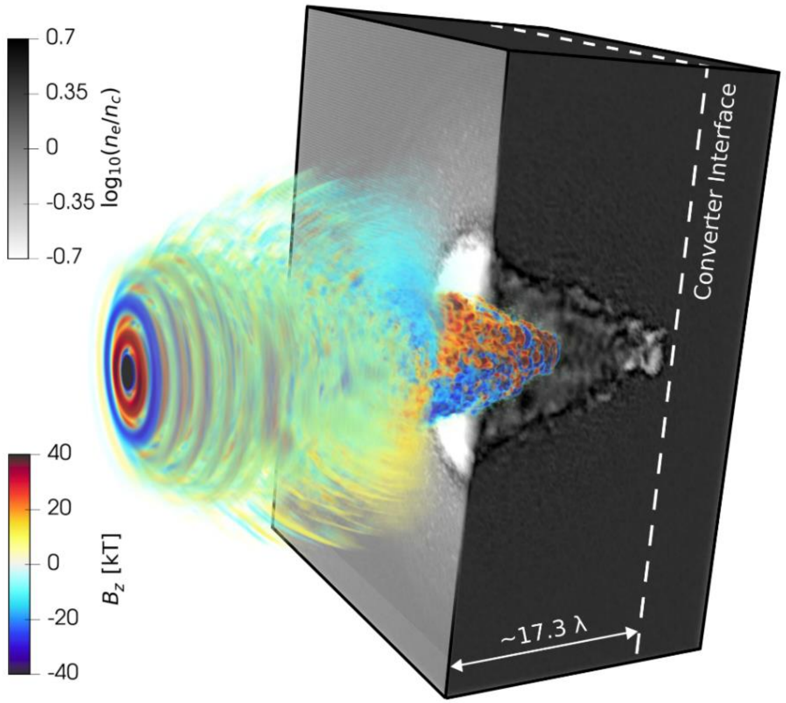
Activation Rate

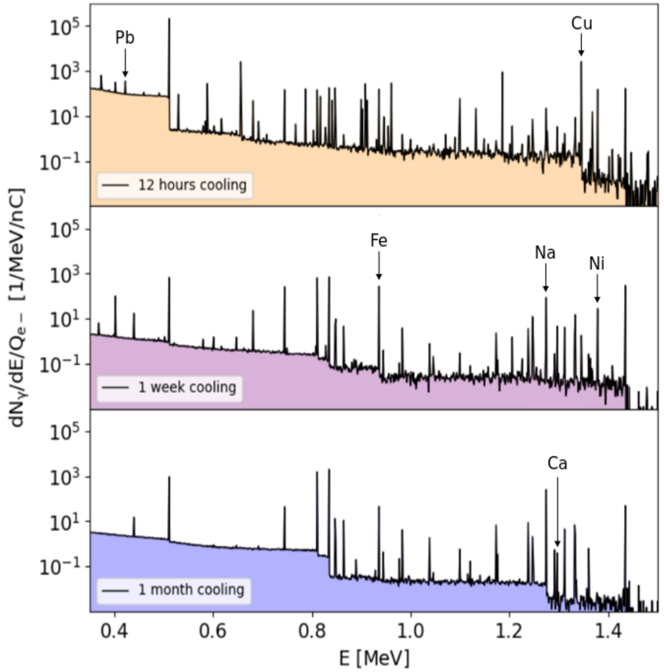
Pazzaglia, A. et al. (2020). A theoretical model of laser-driven ion acceleration from near-critical double-layer targets. Communications Physics, 3(1), 1-13.

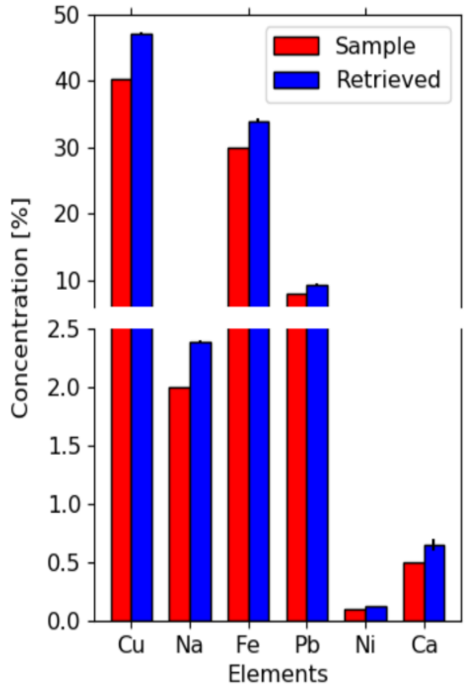
Laser-driven PAA, a numerical investigation

❖ **Simulations** of the **laser-driven PAA** experiments:

Electron source 3D PIC (WarpX) ⟶ **Bremss., activation** & **decay** (Fluka) ⟶ **Sample composition**





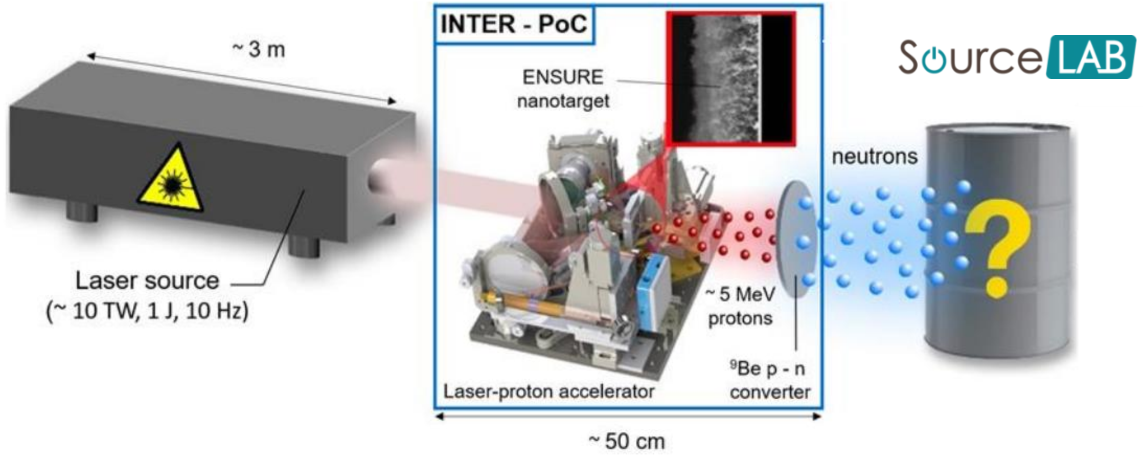


❖ Laser-driven **PAA achievable** with **existing laser** technology

❖ **Near-critical** targets + **100s TW** class lasers are **required**

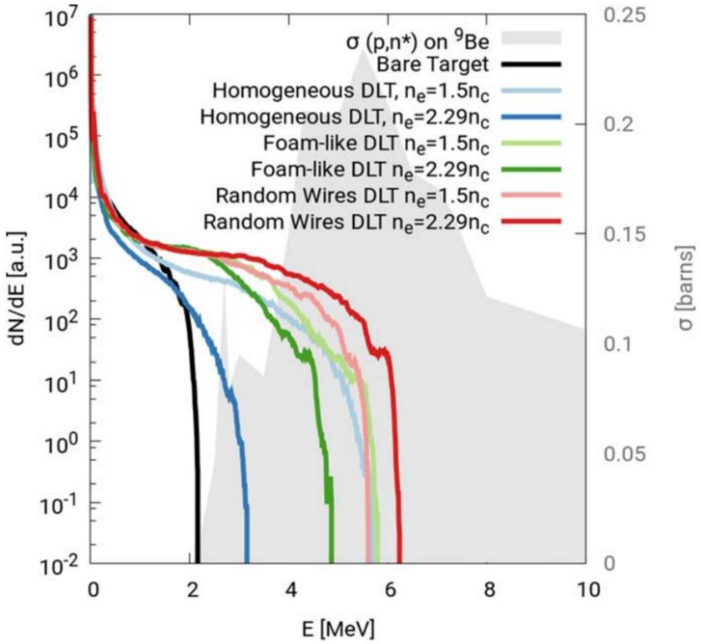
Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

Laser-driven neutron sources, a numerical investigation

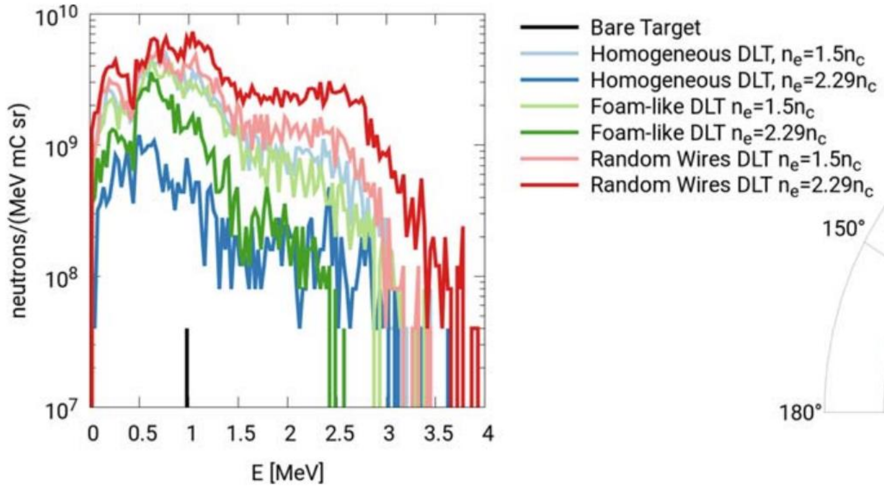


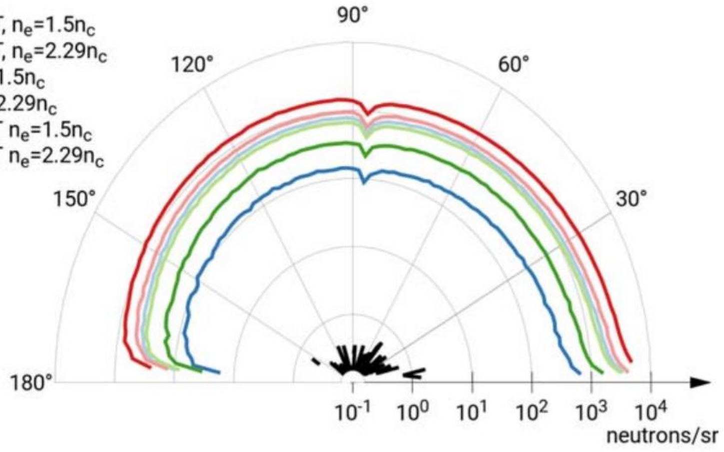
ERC-2016-PoC INTER → Compact **neutron source** based on **DLTs** and **Be converters**

- PIC (piccante) and Monte Carlo (GEANT4) **simulations** assuming a **compact laser** ($a_0 = 4$)
- Proton spectra:



- Neutron spectra and angular distributions:

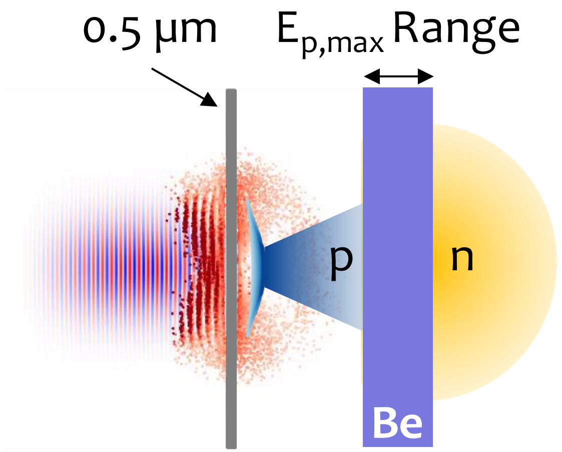




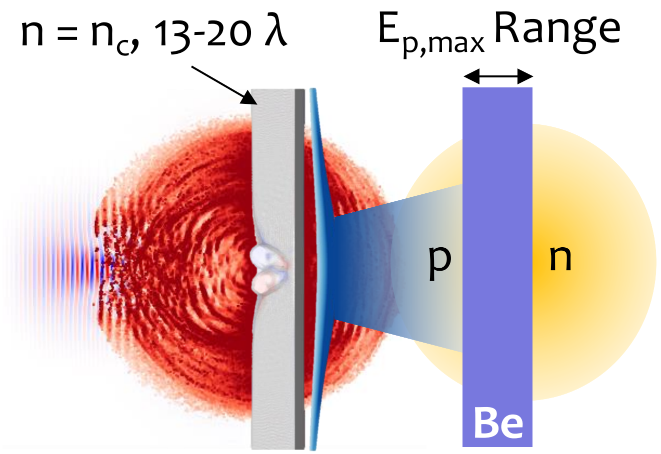
L Fedeli et al 2020 New J. Phys. 22 033045

Laser-driven FNAA, a numerical investigation

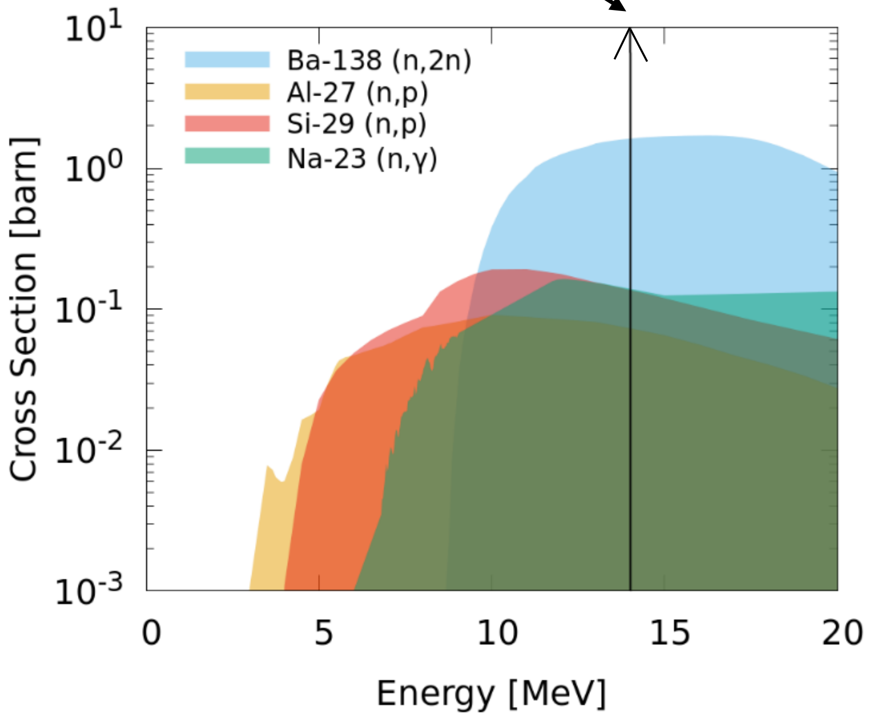
- **Monte Carlo simulations** of laser-driven neutrons
- **Proton** spectra from **Pazzaglia et al.**
- Scan for $a_0 = 5 \rightarrow 20$
- **Bare targets** vs **DLTs**



vs



Adopted **neutron energy** for **FNAA**

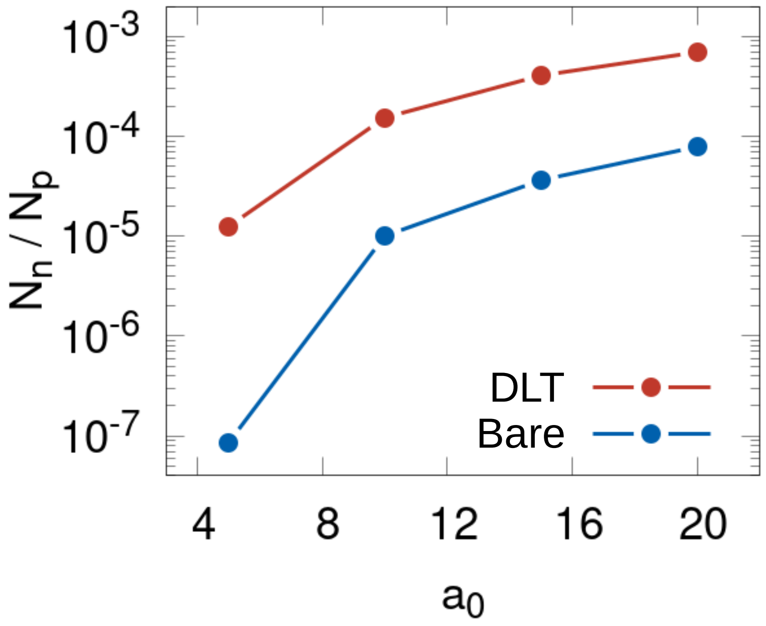


Pazzaglia, A. et al. (2020). A theoretical model of laser-driven ion acceleration from near-critical double-layer targets. Communications Physics, 3(1), 1-13.

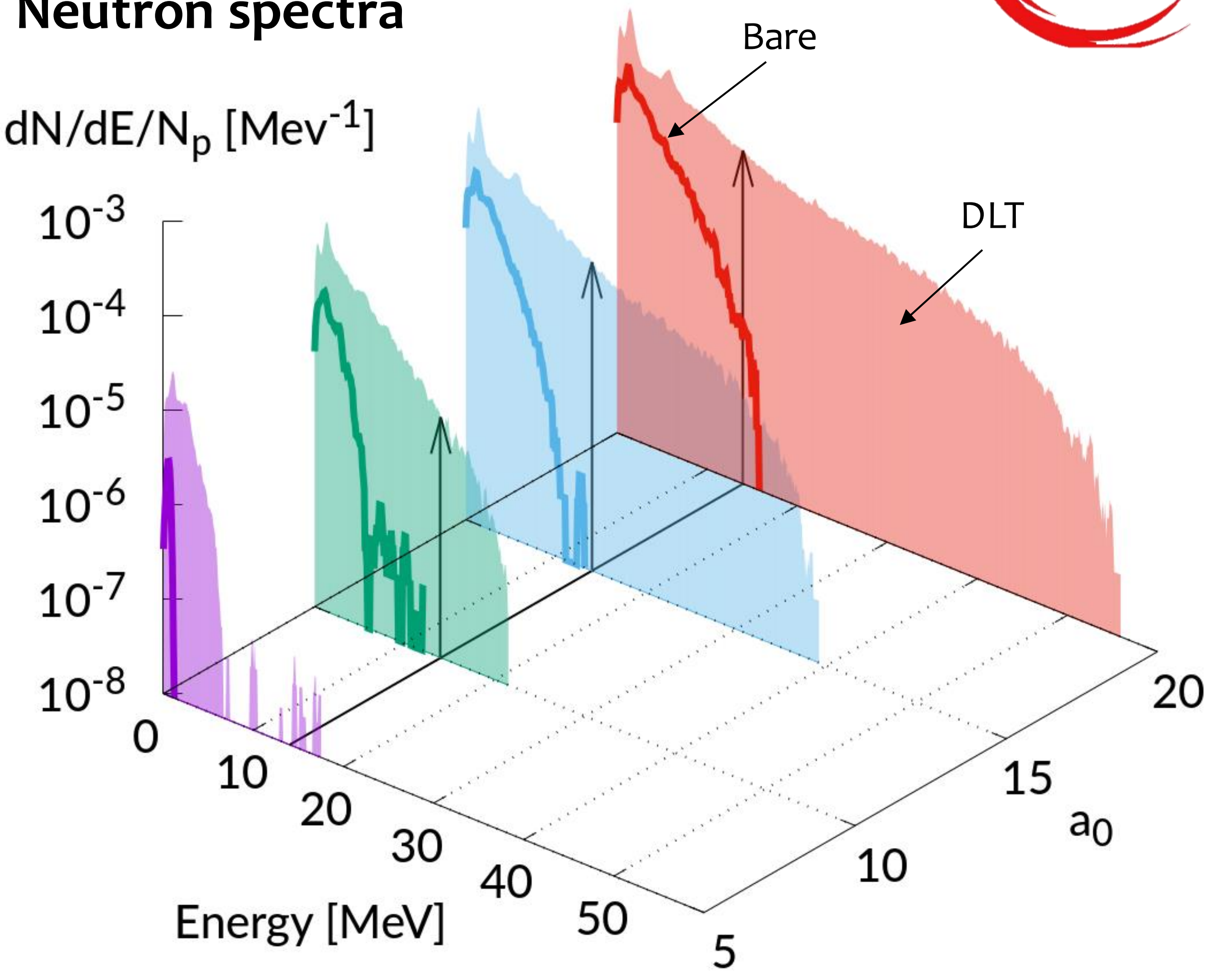
❖ **Bare targets** vs **DLTs**

Hp. Forward neutron between ±25°

Neutron yield



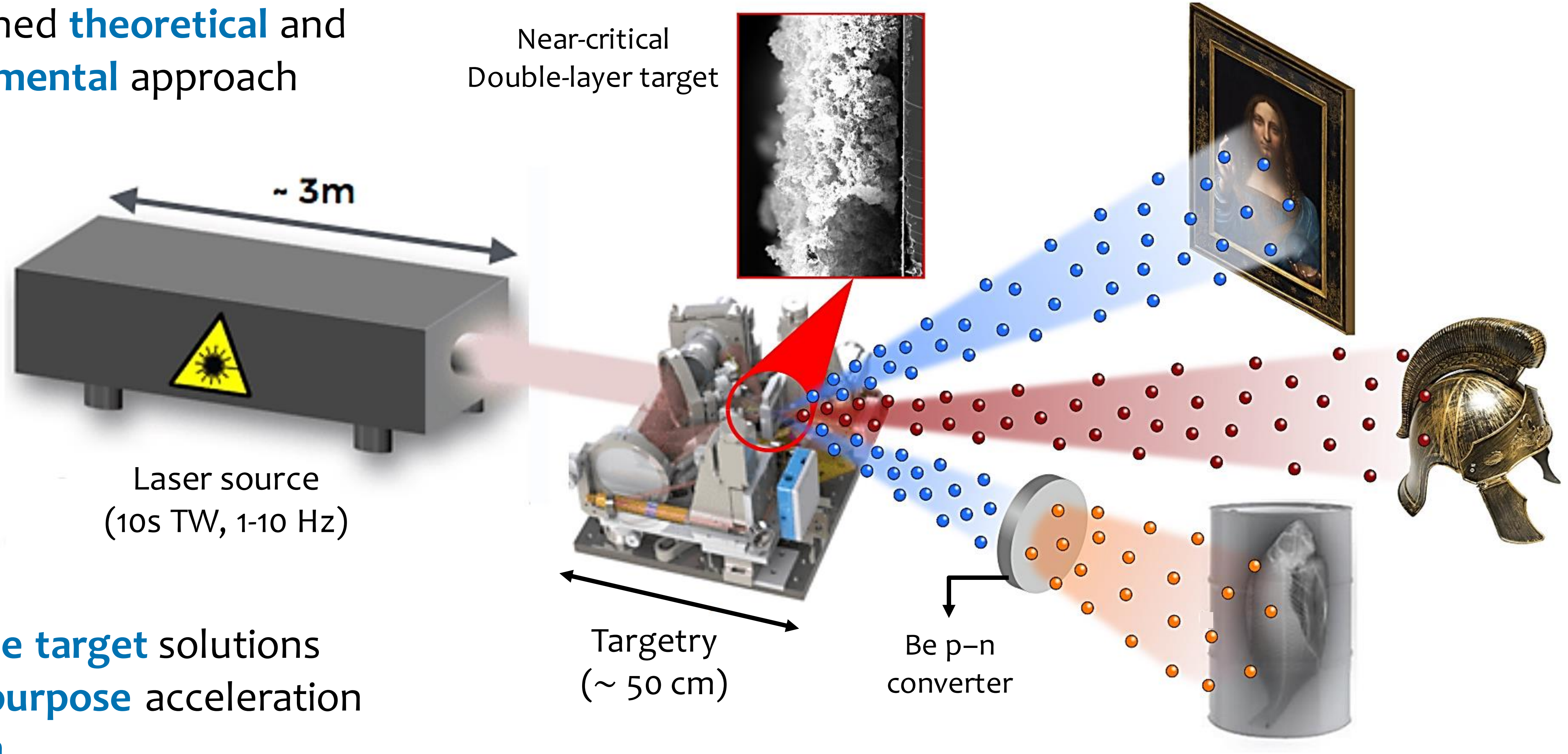
Neutron spectra



❖ Neutron energies for **FNAA** achievable **with a_0 ≥ 10** and **DLTs**

Conclusions

- Combined **theoretical** and **experimental** approach



- **Suitable target** solutions
- **Multi-purpose** acceleration **system**

Thank you for the attention!

NanoLab

ERC-2014-CoG No. 647554
ENSURE

POLITECNICO
MILANO 1863