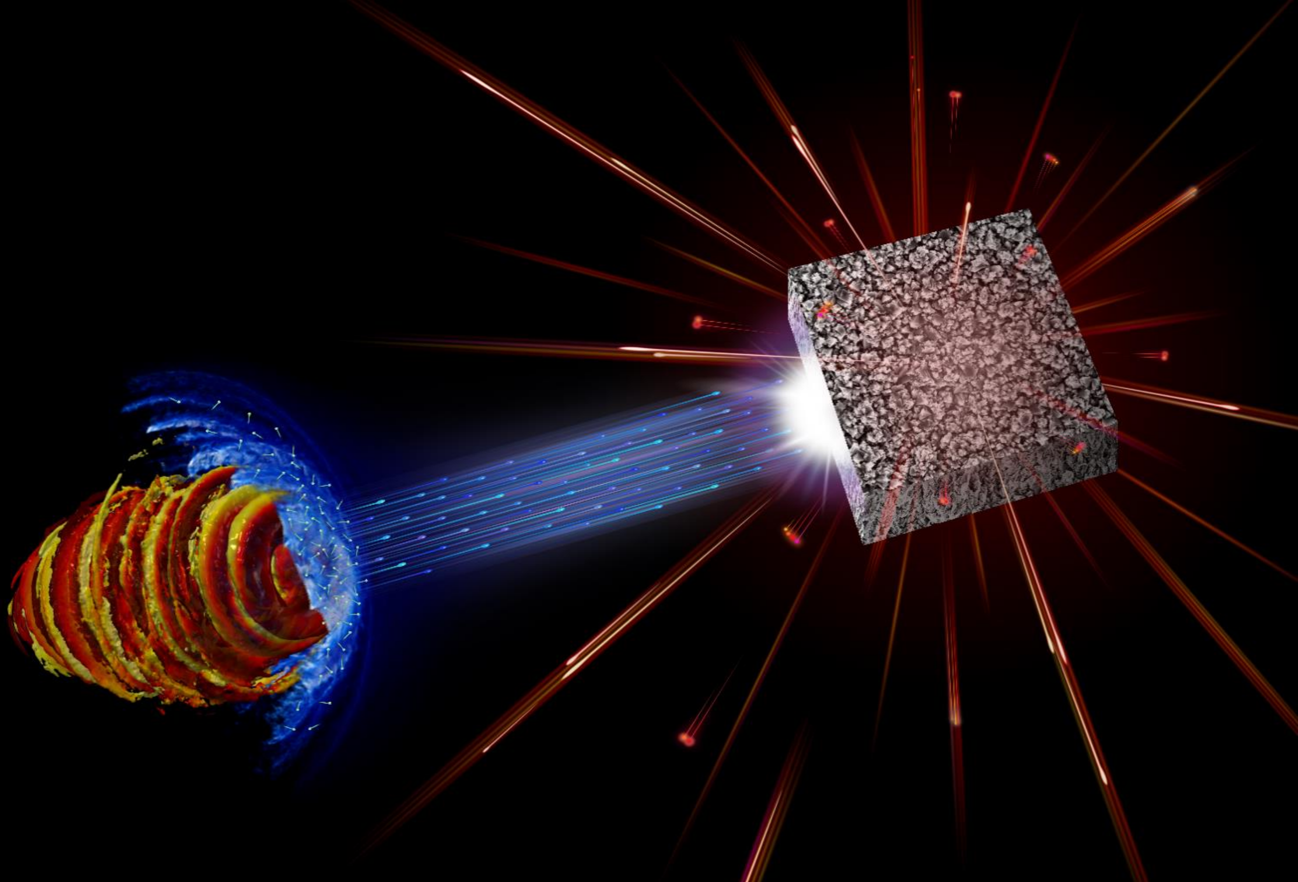
IOP Institute of Physics

IBA/PIXE & SIMS

11-15 October 2021

Laser-driven particle sources for the elemental analysis of materials



Francesco Mirani

ERC-2014-CoG No. 647554
ENSURE

POLITECNICO
MILANO 1863

NanoLab
Department of Energy

- 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 at **Politecnico di Milano:**


D. Dellasega


M. Zavelani


V. Russo

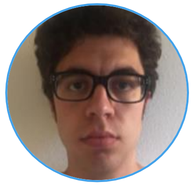

M. Passoni
Principal investigator


A. Pola


A. Maffini


A. Formenti


F. Mirani


D. Vavassori


M. Galbiati


D. Orecchia

www.ensure.polimi.it

Laser-driven particle acceleration

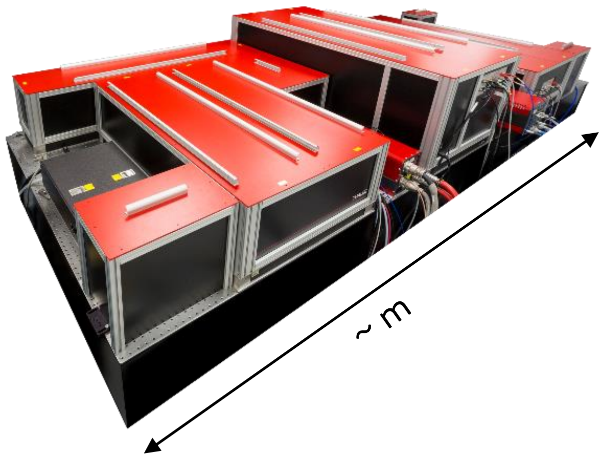
Super-intense laser pulse

Electron and **ion** bunch

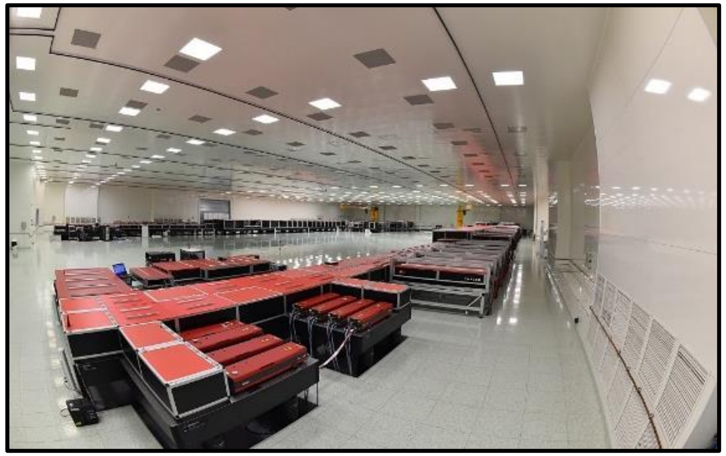
Laser parameters:

- ✓ High powers ~ **10 TW – 10 PW**
- ✓ Ultra-short durations ~ **10 fs**
- ✓ Repetition rate ~ **10^{-3} – 10s Hz**
- ✓ Small areas focal spot ~ **1 – 100 μm^2**
- ✓ Intensity ~ **10^{18} – 10^{23} W/cm^2**

QUARK 30 TW, Thales Group



ELI-NP laser, 10 PW (Romania)

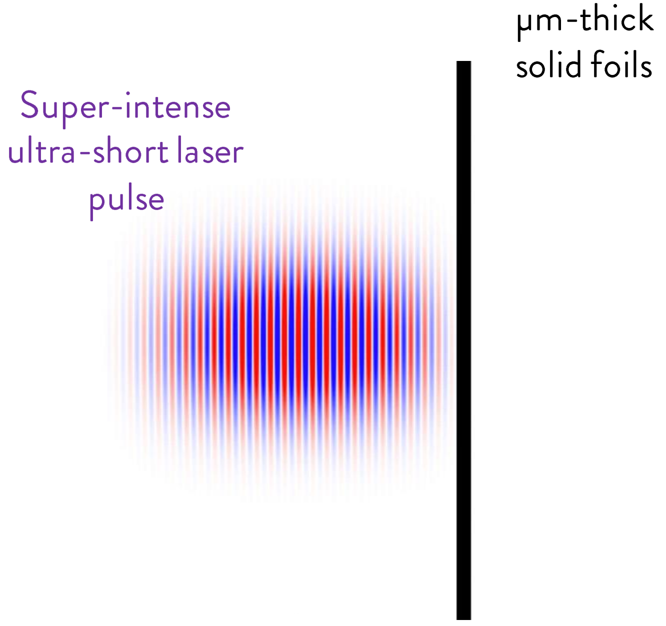


Daido, H., et al. (2012). *Reports on progress in physics*, 75(5), 056401.

Macchi, A., et al. (2013) *Reviews of Modern Physics*, 85(2), 751.

Laser-driven particle acceleration from solid targets

- **Target Normal Sheath Acceleration** (TNSA) ⟶ **Super-intense** ultra-short **laser pulse** + Micrometric thick **foil**



Macchi, A., et al. (2013) *Reviews of Modern Physics*, 85(2), 751.

(1) Rosmej, O. N., et al *PPCF* 62.11 (2020): 115024.

(2) Prencipe, I., et al. *PPCF*, 58(3), (2016): 034019.

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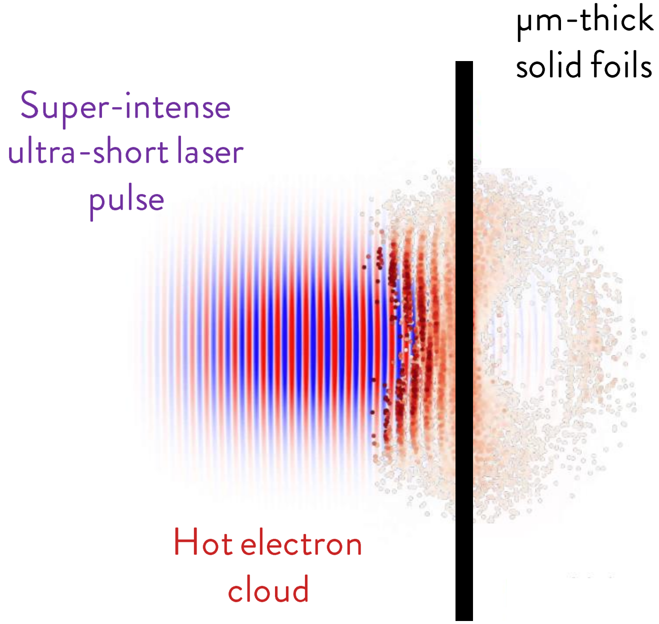

- Formation of **plasma** → **Particle acceleration** driven by **charge separation**.

Macchi, A., et al. (2013) *Reviews of Modern Physics*, 85(2), 751.
(1) Rosmej, O. N., et al *PPCF* 62.11 (2020): 115024.
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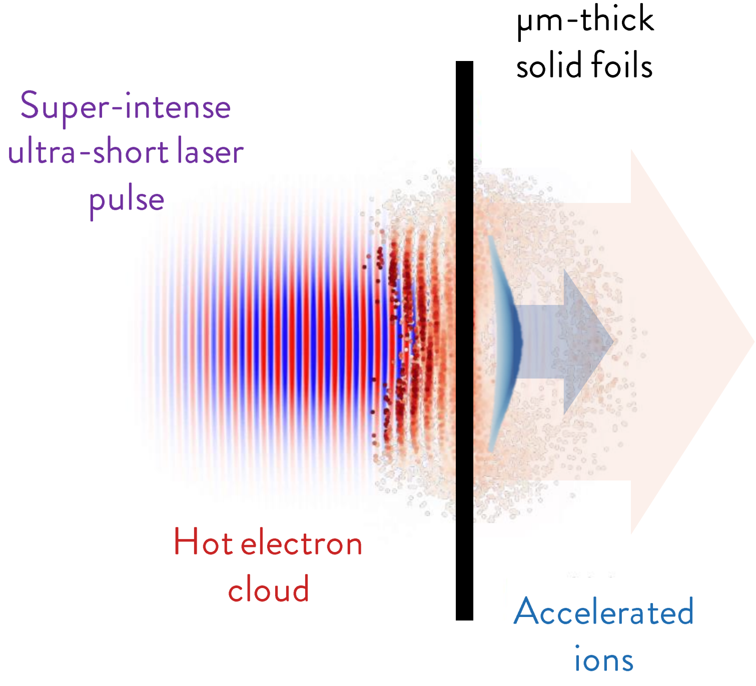
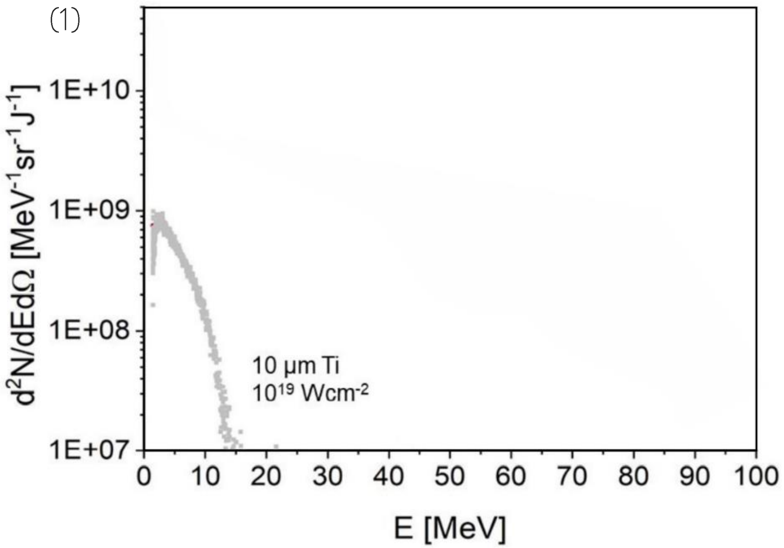


- Particles emitted in short **bunches** (**≤ ns** time duration)
- Huge accelerating field gradients: **MV/μm**
- Broad energy **spectra** (~ **exponential**)
- Maximum energy ~ **1 - 10s MeV**

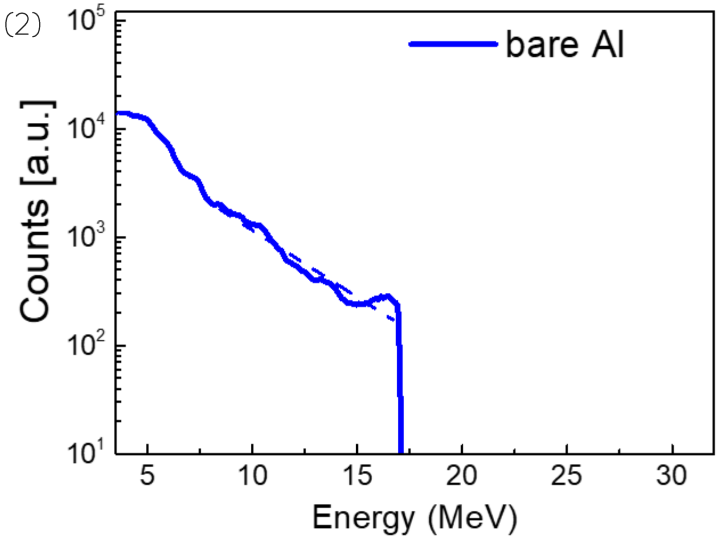
✓ **Electron** spectrum:

(1)



✓ **Proton** spectrum:

(2)



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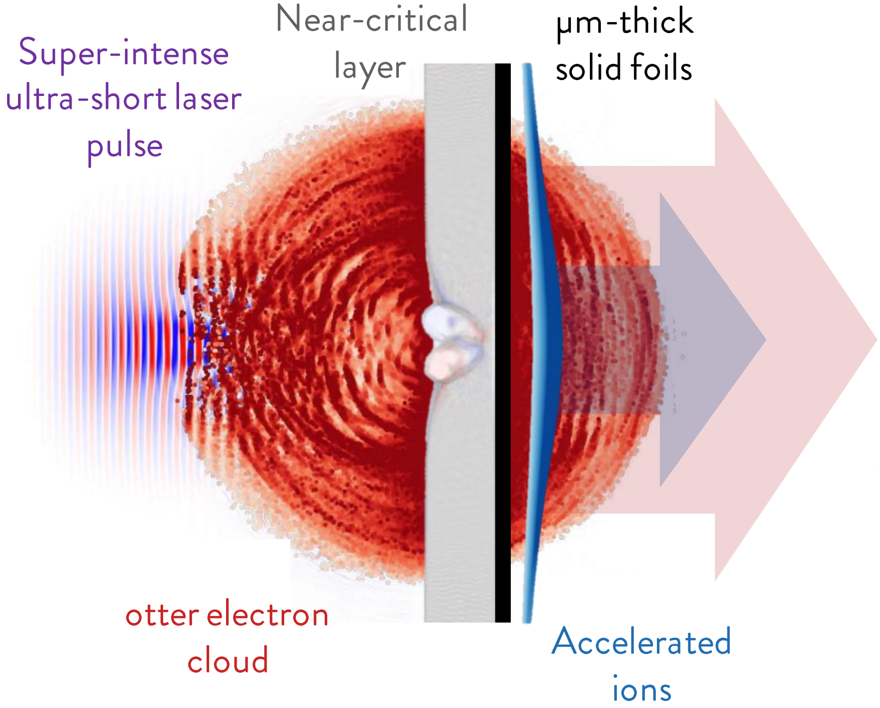
Laser-driven particle acceleration from solid targets

- **Enhanced Target Normal Sheath Acceleration** ⟶ Advanced **near-critical** double-layer **targets** (DLTs)

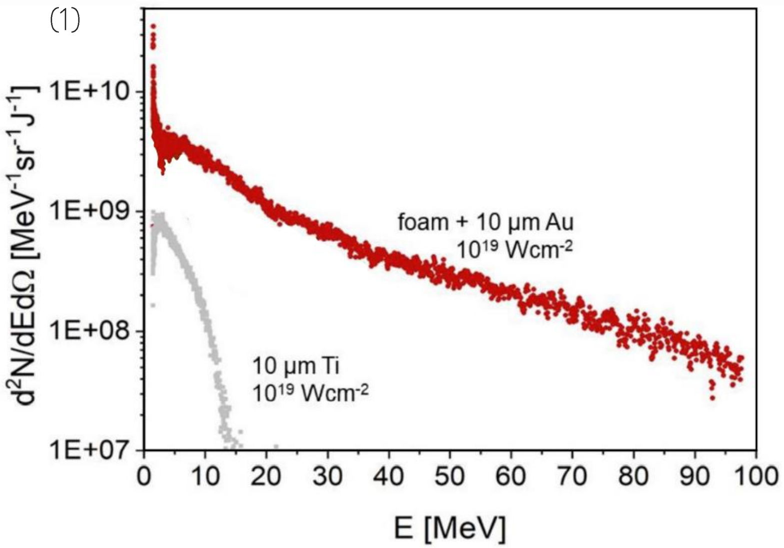


- **Low density** (~ mg/cm³), **near-critical material** to **enhance laser absorption**

👍 **Increase** the **energy** and **number** of the particles

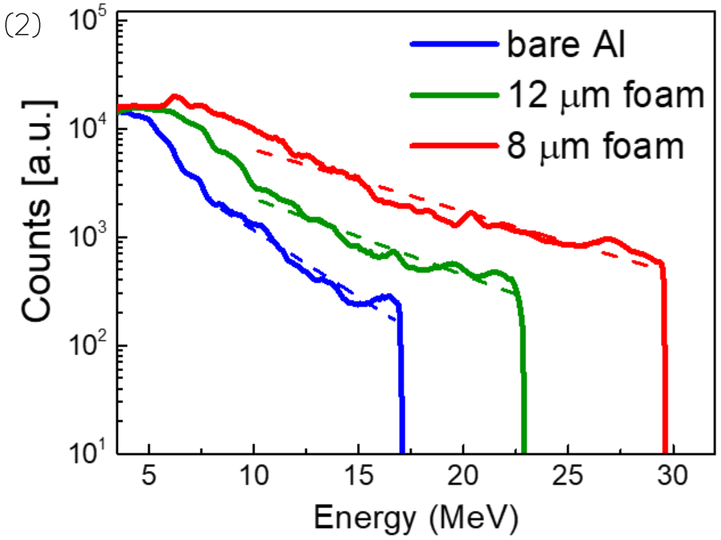
✓ **Electron** spectrum:

(1)



✓ **Proton** spectrum:

(2)



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Laser-driven particle acceleration from solid targets

- Laser accelerators have many **potential appealing features:** **Compactness** **Cheapness** **Moderate radiation protection**

  Energy tunability (**flexibility**) **Multiple** radiation **fields** **Ultrafast** temporal duration

Laser-driven particle acceleration from solid targets

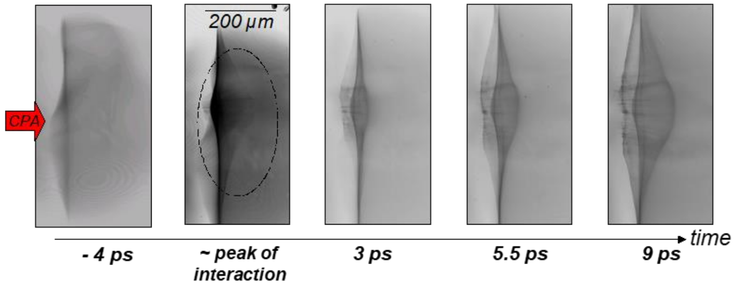
- Laser accelerators have many **potential appealing features:** **Compactness** **Cheapness** **Moderate radiation protection**

  Energy tunability (**flexibility**) **Multiple** radiation **fields** **Ultrafast** temporal duration

- **Several applications** under investigation:

✓ Proton **imaging**

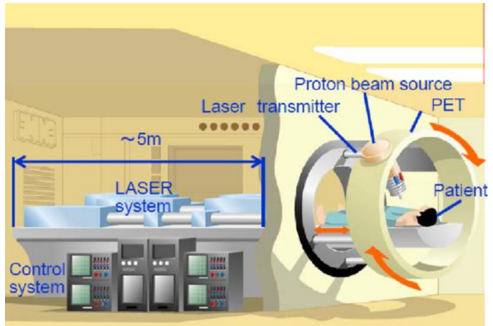
L. Romagnani, et al., *Phys. Rev. Lett.* 95, 195001 (2005)



✓ Production of **PET radioisotopes** & **hadron-therapy**

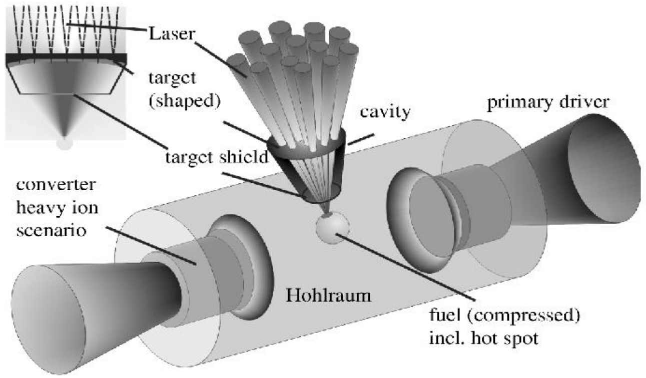
Sun, Z. *AIP Advances*, 11(4), 040701 (2021).

Bulanov, S. V et al. (2014) *Physics-Uspekhi*, 57(12), 1149 (2014).



✓ Nuclear Fusion (ICF) proton-ion based **Fast Ignitor**

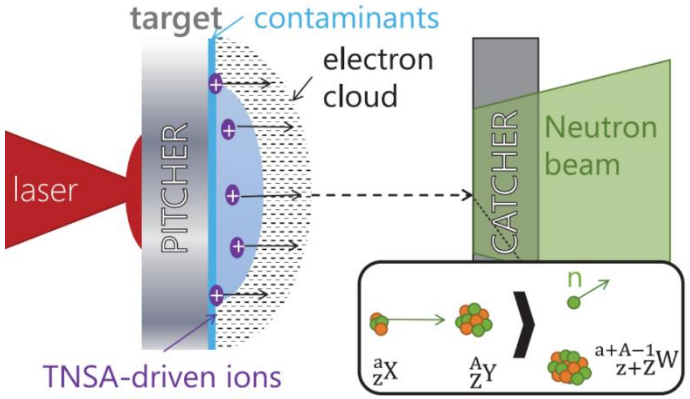
Fernández, J. C., et al. *Nuclear fusion*, 49(6), 065004 (2009).



✓ **Neutron** production & **inspection**

Brenner, C. M., et al. *PPCF*, 58(1), 014039 (2015).

Roth, M., at al. *PRL*, 110(4), 044802 (2013)



Strategy and methods of the erc-ENSURE project

Investigate the possibility to **apply laser-accelerators** to **elemental characterization:**

- ✓ **Particle Induced X-ray Emission** (PIXE)
- ✓ **Energy Dispersive X-ray Spectroscopy** (EDX)
- ✓ **Photon Activation Analysis** (PAA)

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

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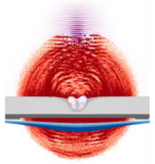

Advanced DTLs to efficiently accelerate particles with **reduced laser requirements**

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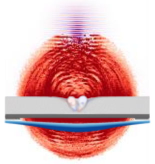
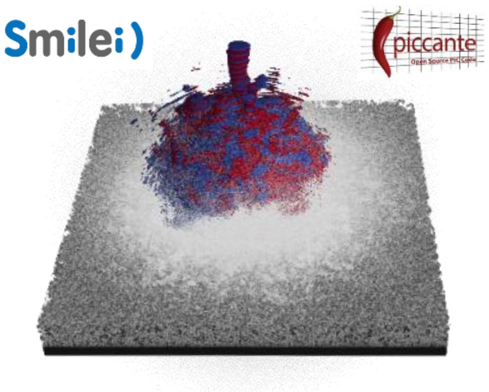
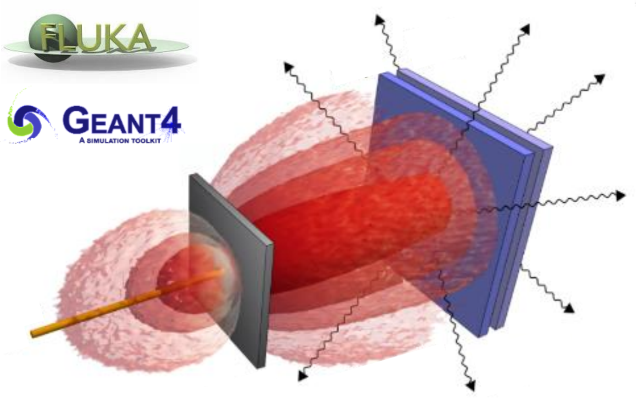


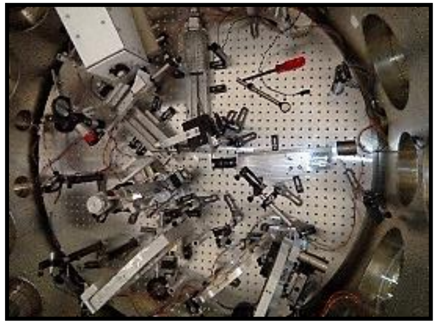
Advanced DTLs to efficiently accelerate particles with **reduced laser requirements**

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

- ✓ Laser-driven source: **models, Particle-In-Cell**
- ✓ Particle propagation in matter: **Monte Carlo**
- ✓ **Campaigns** in laser facilities







CoReLS
CLPU
HZDR

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

Numerical study of laser-driven PIXE feasibility

? **Unconventional features** of proton beam (ns duration, broad spectrum, mixed radiation).

Simulations of real-case scenarios of **laser-driven PIXE** experiment coupling **PIC** and **Monte Carlo** simulations

M. Passoni, L. Fedeli, F. Mirani. *Scientific Reports*, 9.1 (2019): 9202.

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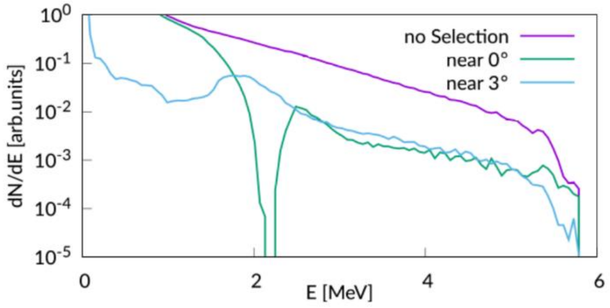
Simulations of real-case scenarios of **laser-driven PIXE** experiment coupling **PIC** and **Monte Carlo** simulations

- 3D Particle-In-Cell

20 TW laser;

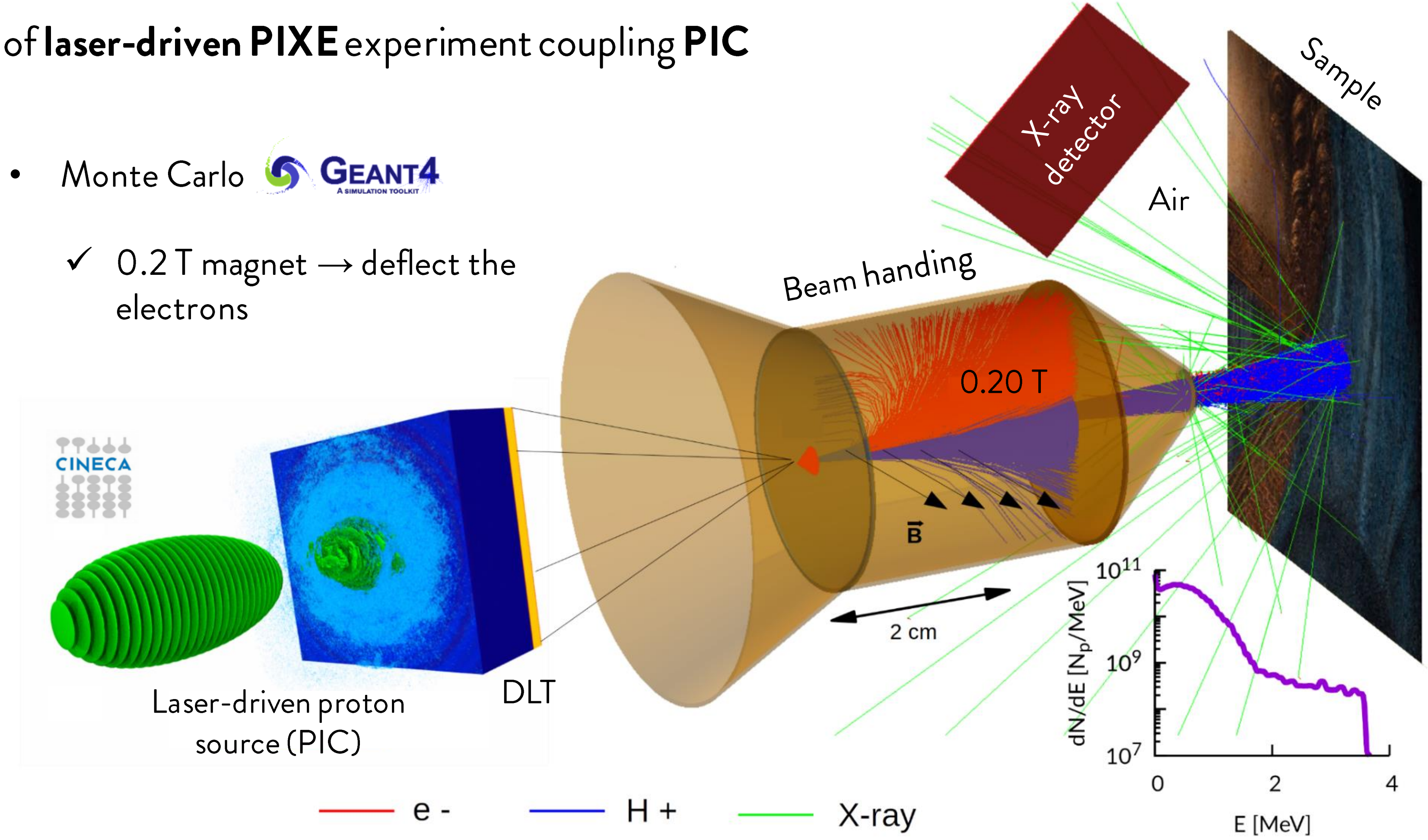
DLT target;



- Particle momentum distribution provided to the Monte Carlo

- Monte Carlo

✓ 0.2 T magnet → deflect the electrons



M. Passoni, L. Fedeli, F. Mirani. *Scientific Reports*, 9.1 (2019): 9202.

Laser-driven PIXE code

Unconventional features of proton beam (ns duration, broad spectrum, mixed radiation).

Dedicated software to process X-ray spectra and retrieve the **sample composition**.

Equation for the X-ray yields (e.g. homogeneous sample case) accounts for the broad energy spectrum:

$$Y_i = \frac{\Delta\Omega}{4\pi} \varepsilon_i \frac{N_{Av}}{M_i} W_i \int_{E_{p,max}}^{E_{p,min}} f_p(E_p) \int_{E_p}^{0} \sigma_i(E)\ \omega_i\ e^{-\mu_i \int_{E_0}^{E'} \frac{dE'}{S(E')} \frac{\cos\theta}{\cos\varphi}} \frac{dE}{S(E)}\ dE_p$$

X-ray yields — Elemental concentrations — Proton spectrum — X-ray production cross section, attenuation, etc.

M. Passoni, L. Fedeli, F. Mirani. *Scientific Reports*, 9.1 (2019): 9202.

Powell, M. J. (2009). *Cambridge NA Report* NA2009/06, University of Cambridge, 26-46.

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X-ray yields | Elemental concentrations | Proton spectrum | X-ray production cross section, attenuation, etc.

X-square minimization: $X^2 = \sum_i \left(\frac{Y_i^{calc} - Y_i^{exp}}{\sqrt{Y_i^{exp}}} \right)^2$

lib C++ Library Bobyqa

Method for function optimization applied to the X^2 and **perform iteration**

M. Passoni, L. Fedeli, F. Mirani. *Scientific Reports*, 9.1 (2019): 9202.

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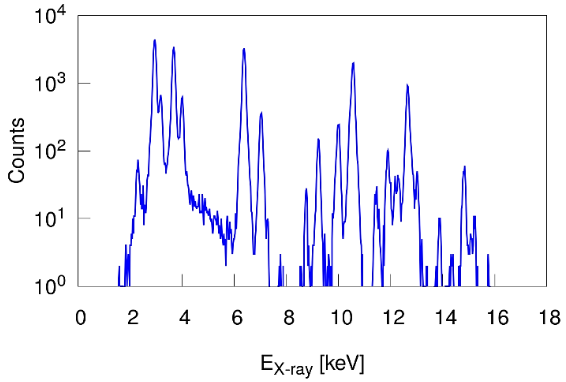
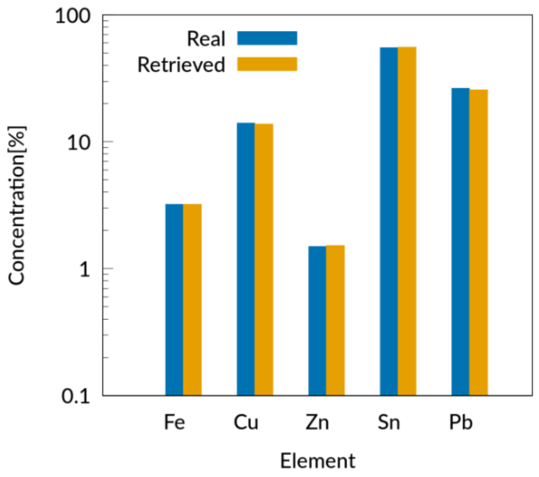
Tested on the **“synthetic” X-ray spectra** from the Monte Carlo



- **Homogeneous** sample:



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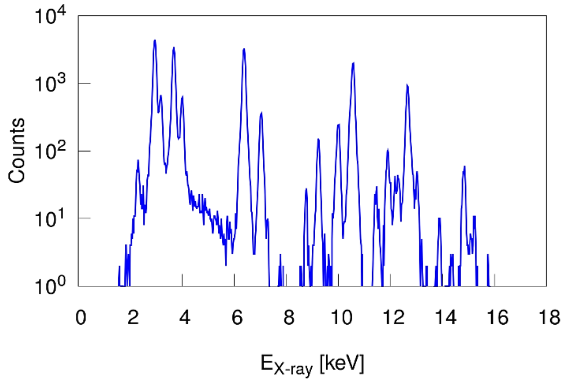

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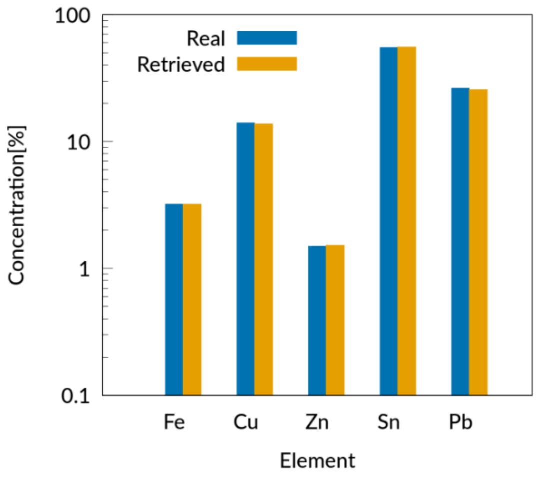
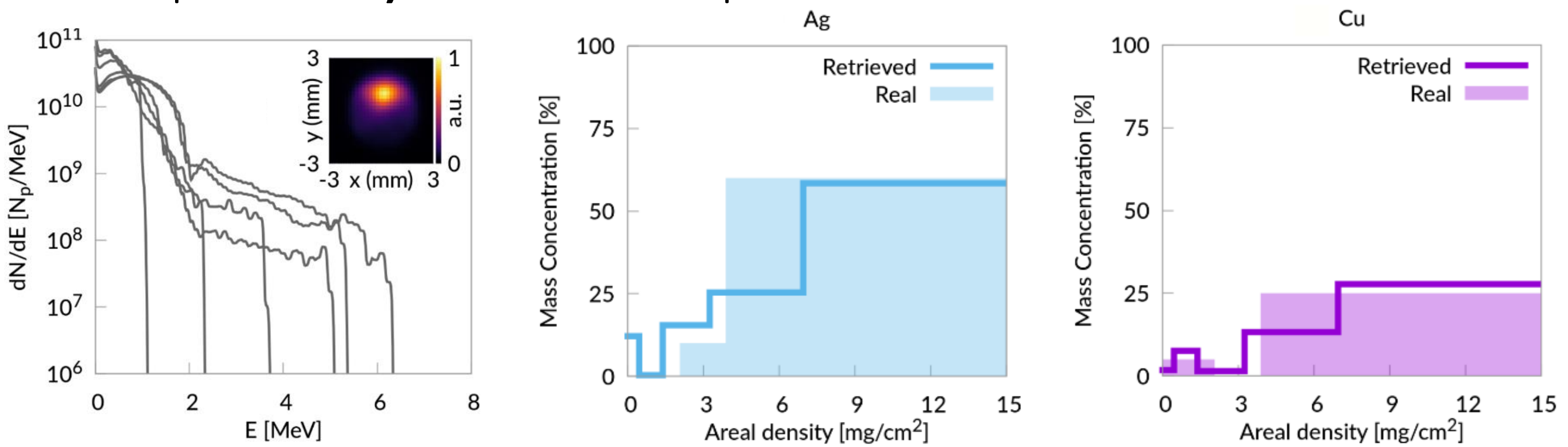


- Complex **multilayer** structured samples:

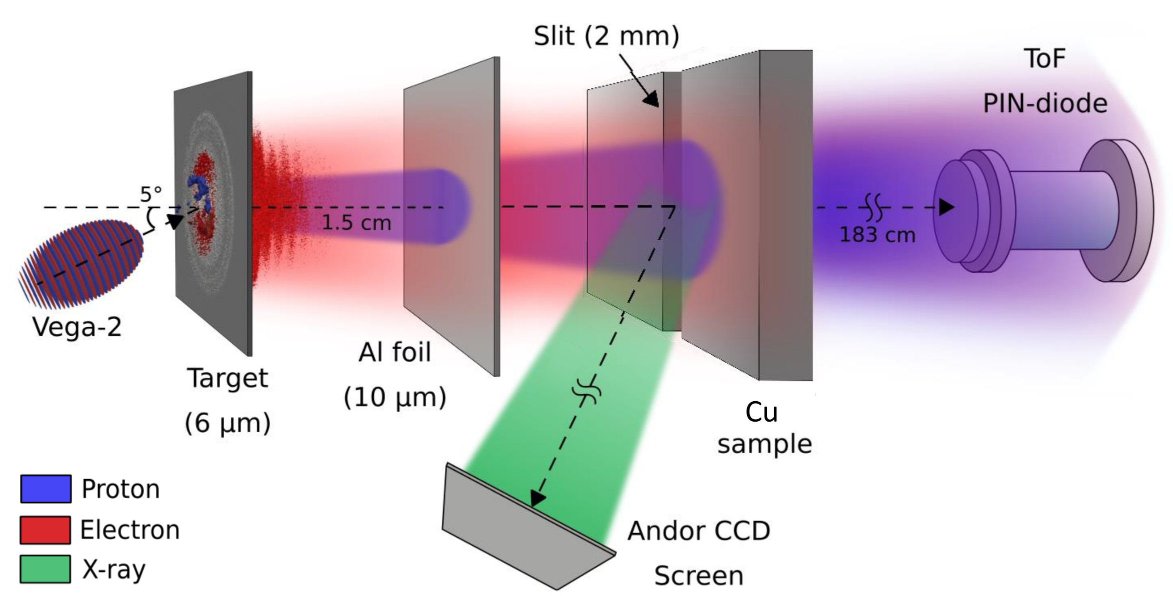


✓ Irradiation with **different proton spectra** varying the laser intensity.

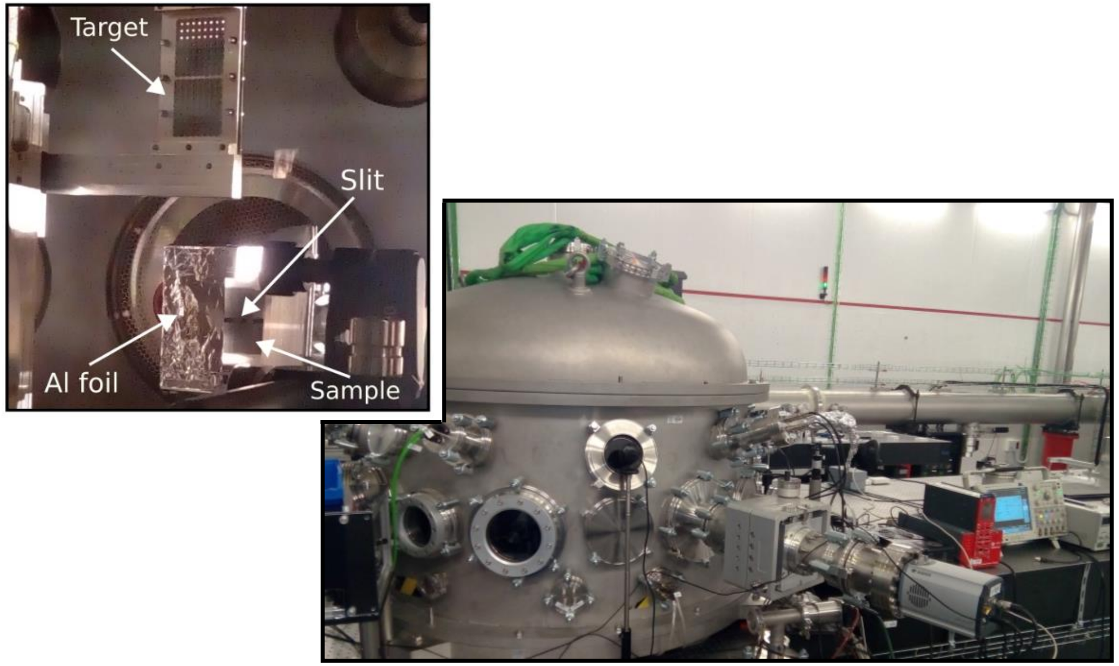
M. Passoni, L. Fedeli, F. Mirani. *Scientific Reports*, 9.1 (2019): 9202.

Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU

EDX setup → Sample irradiation with both **e-** & **protons**



- Vega-2 laser intensity ≈ **2×10^{20} W/cm^2**
- **30 fs** time duration, **3 J on target**
- Laser spot size (FWHM) ≈ 7 μm



- Al **foil** to **stop** the **debris** and C ions
- **Aperture slit** in the middle of the sample
- **Time-of-Flight** spectrometer for proton characterization
- **CCD** for **X-ray** detection

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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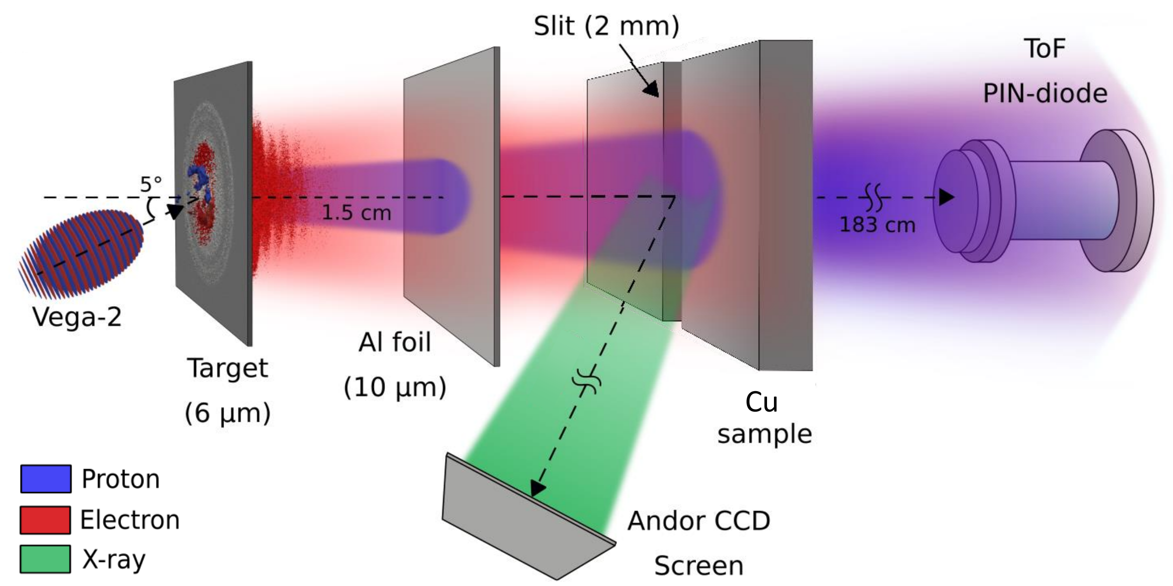

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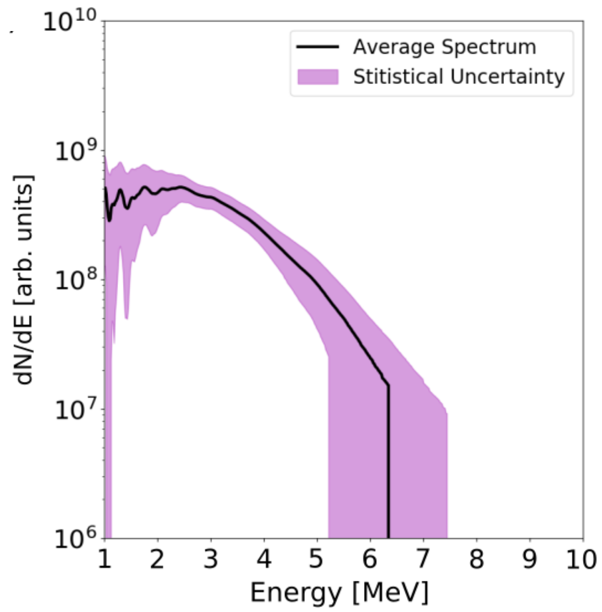
- **Proton spectrum** characterization (from 6 μm thick aluminum target)



- Broad energy spectrum
- Maximum energy up to **6.3 MeV**

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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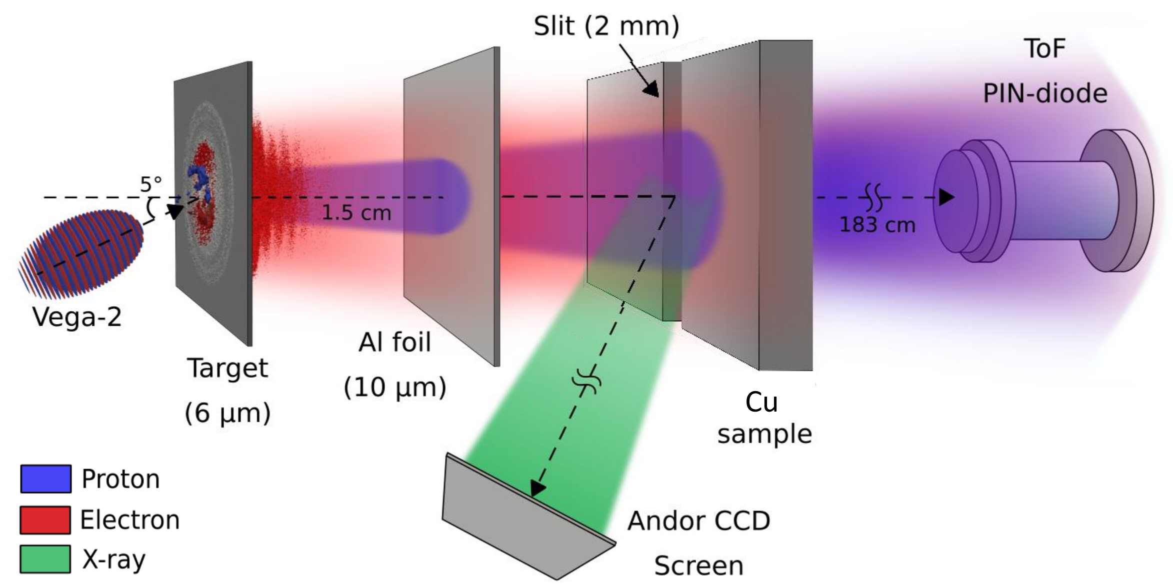

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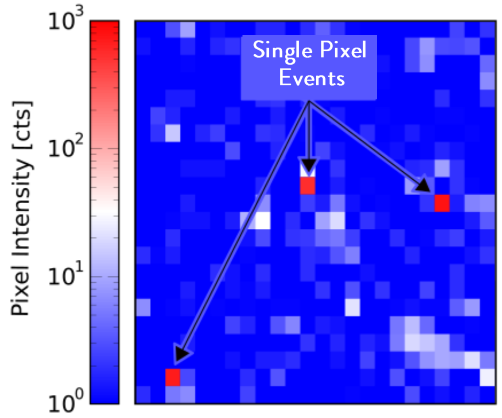
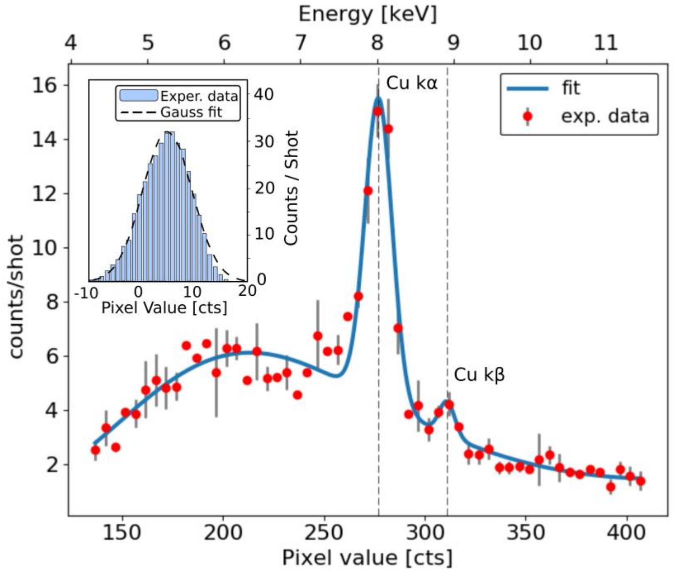
- **CCD** for **X-ray** detection

- **Single photon counting** spectra reconstruction.





- X-ray **CCD** energy **calibration** with a Cu sample.

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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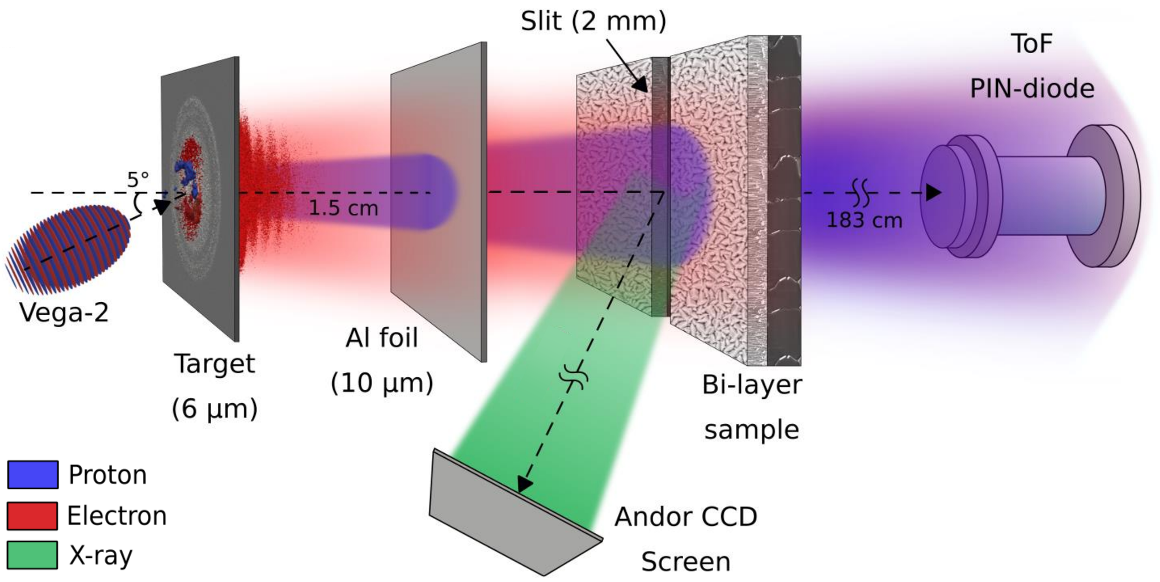
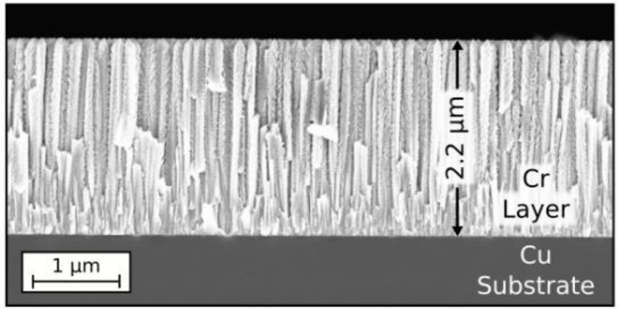
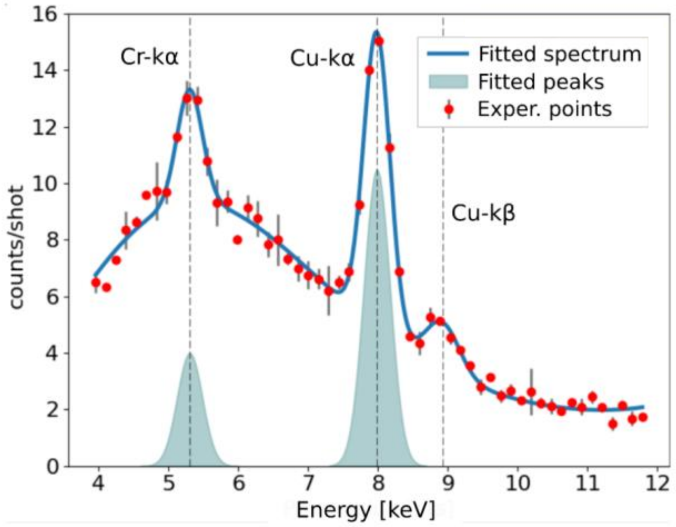


- Al **foil** to **stop** the **debris** and C ions
- **Aperture slit** in the middle of the sample
- **Time-of-Flight** spectrometer for proton characterization
- **CCD** for **X-ray** detection

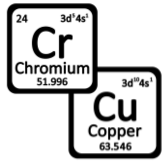
- **Bi-layer sample** (Cr layer + Cu substrate)



Produced with **DCMS** (controlled thickness and composition)



Form the peak energies:



Elements are correctly **recognized**

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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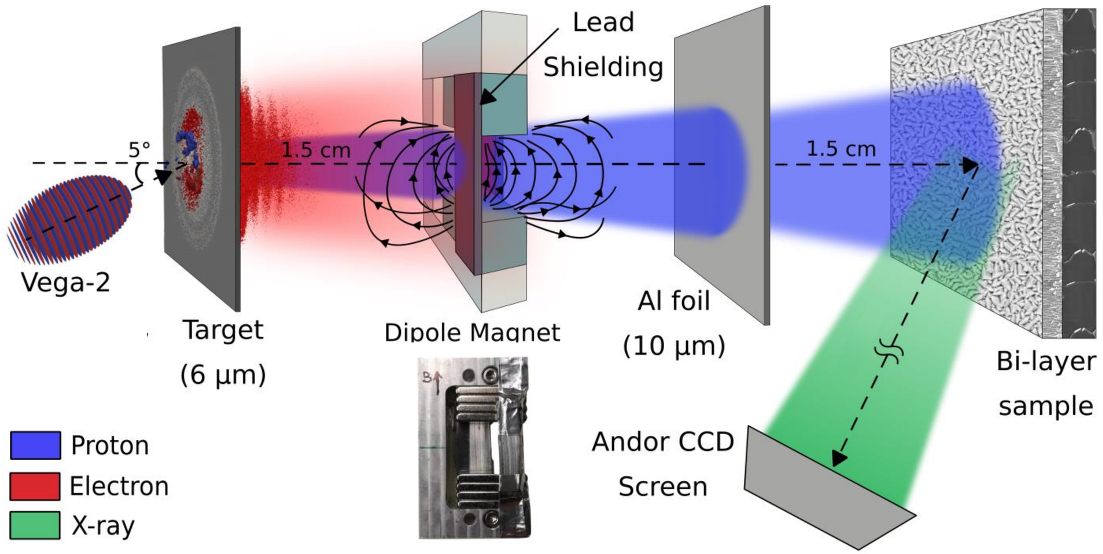
PIXE setup → Sample irradiation only with **protons**

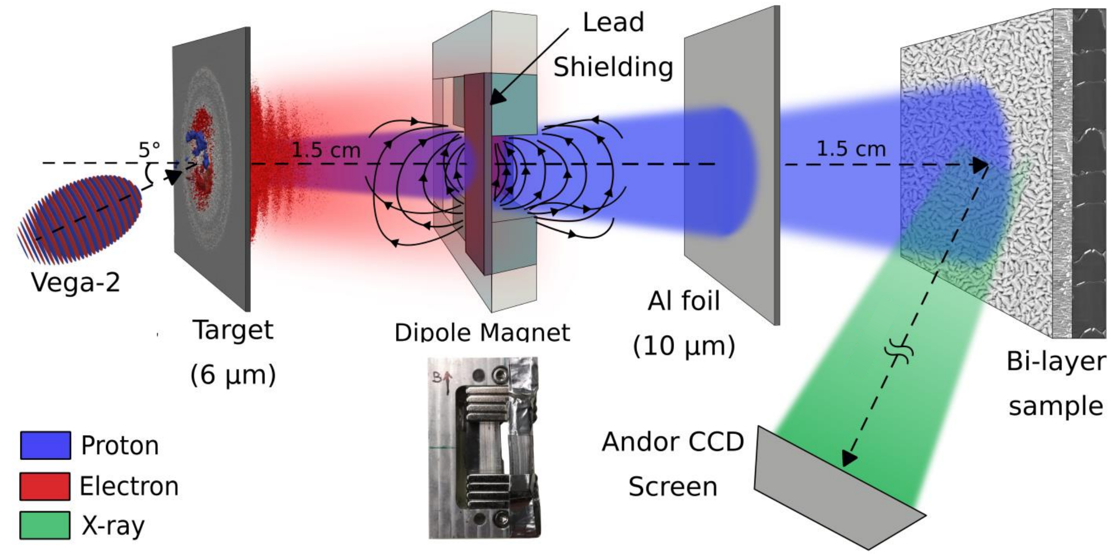


- Al **foil** to **stop** the **debris** and C ions
- **CCD** for **X-ray** detection
- Removal of the electrons with **dipole magnet** (0.26 T) and **lead shielding**

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU

PIXE setup → Sample irradiation only with **protons**

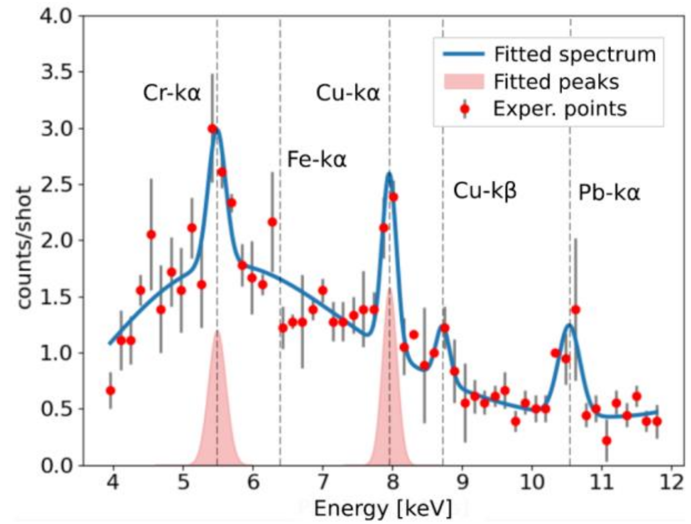


- Al **foil** to **stop** the **debris** and C ions
- **CCD** for **X-ray** detection
- Removal of the electrons with **dipole magnet** (0.26 T) and **lead shielding**

Layer thickness reconstruction exploiting the **software** developed for the laser-driven PIXE quantitative analysis

- Total **number** of **protons**
- **Monoenergetic** spectrum

→ not required



F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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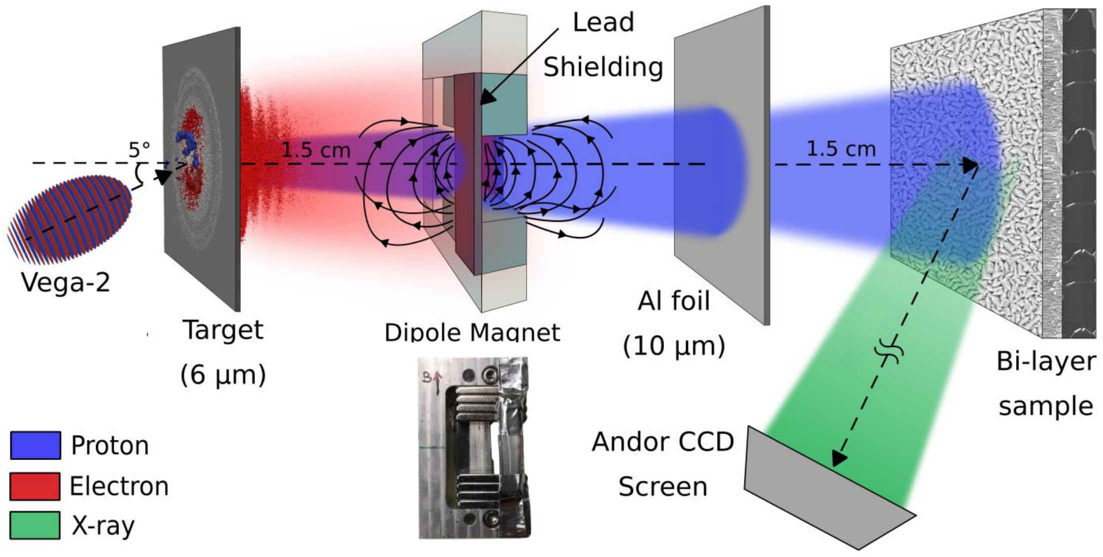

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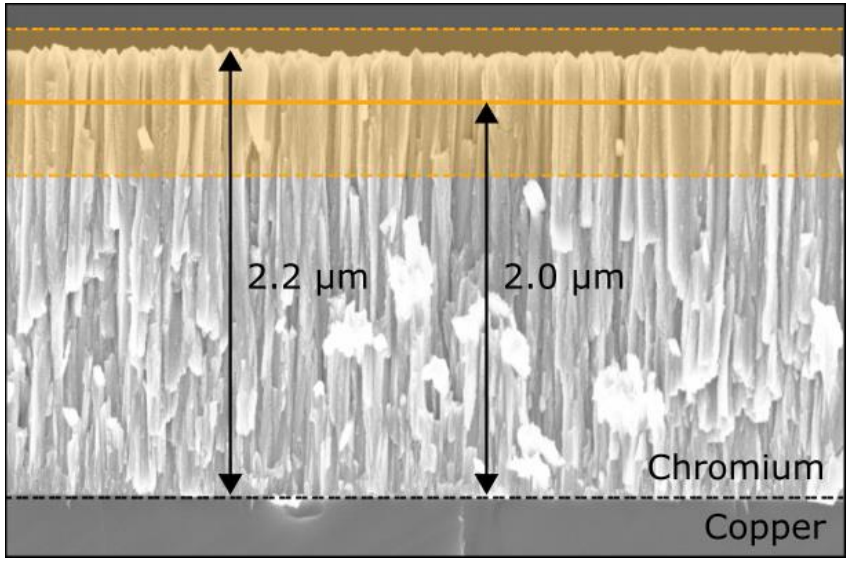

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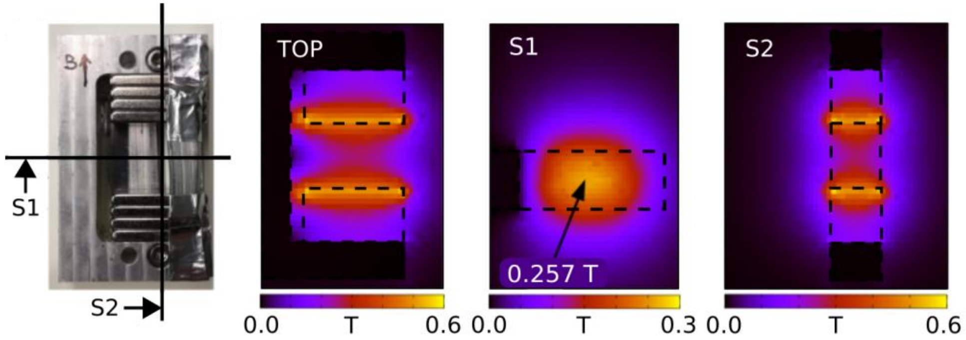
Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU

Study the **electron** and **proton contribution** to the **X-ray production** via GEANT4 Monte Carlo simulations.

- 3D **magnetic field** distribution from Finite Element Analysis (**FEA**)



- **Experimental** spectrum → **Proton energies**
- **Scaling law** (Cialfi et al.) → **electron temperature**

L. Cialfi, et al. *Physical Review E*, 94(5):053201, 2016.

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

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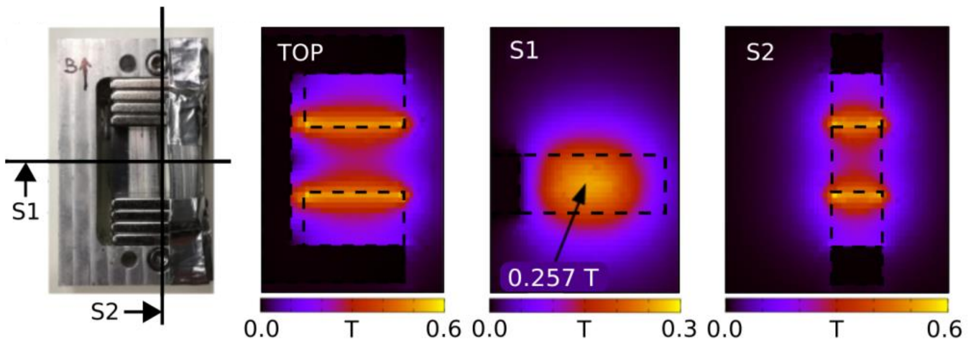

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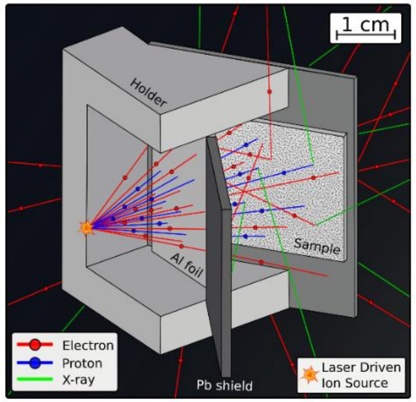
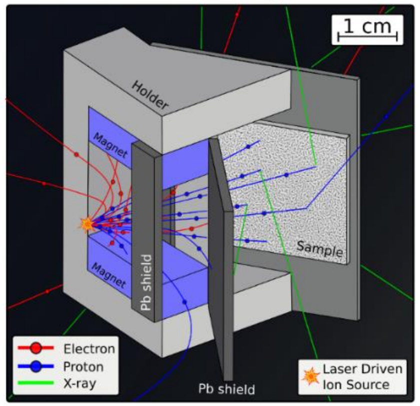


EDX setup

e- contribution is dominant (~ 90 % of the X-rays)

↓

Fast elemental analysis



PIXE setup

proton contribution is dominant (~ 98 % of e- removed)

↓

Quantitative analysis

L. Cialfi, et al. *Physical Review E*, 94(5):053201, 2016.

F. Mirani, et al., *Science Advances*, eabc8660 (2021).

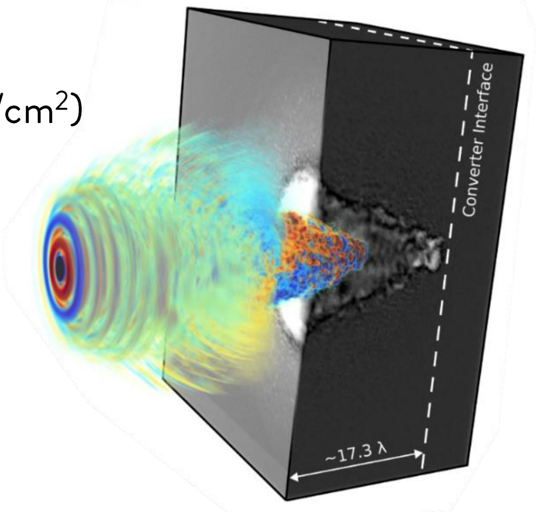
Numerical study of laser-driven PAA feasibility

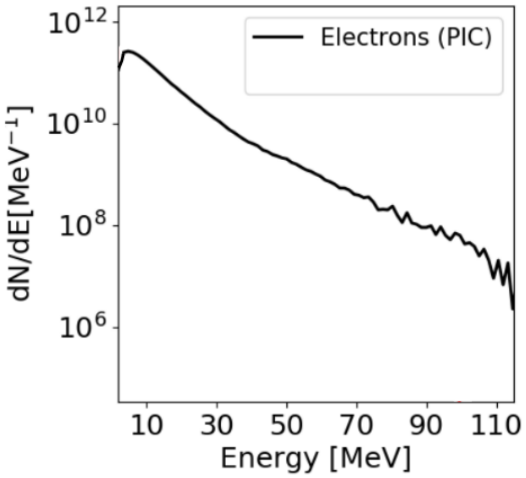
Development of a **scheme** to perform laser-driven Photon Activation Analysis

1. Super-intense **laser** interacting with **near-critical** material (**3D PIC**)

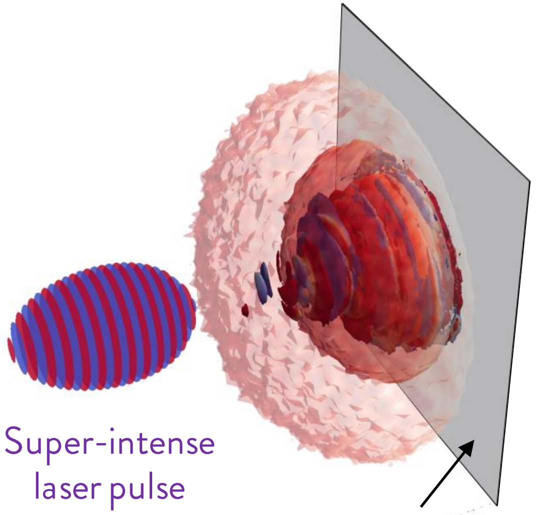
200 TW laser (8×10^{20} W/cm^2)

Near-critical layer





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



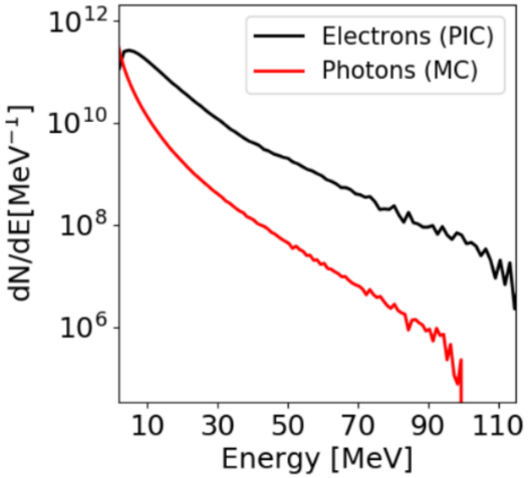
Mirani, F., et al. Superintense laser-driven photon activation analysis. *Commun Phys* 4, 185 (2021).

Numerical study of laser-driven PAA feasibility

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

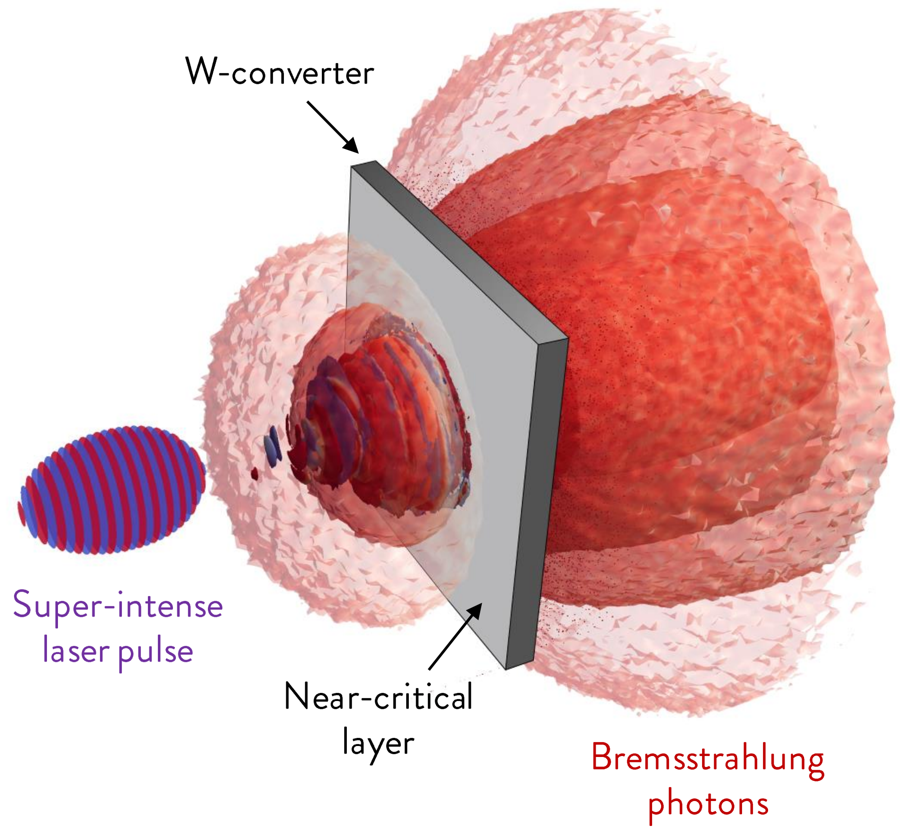
2. **Hot e-** interaction with mm-thick **W converter** → **Bremsstrahlung photons** generation (**Monte Carlo** FLUKA)

- W-converter thickness = **2.6 mm**



✓ Broad angular distribution

✓ Energy up to 100 MeV



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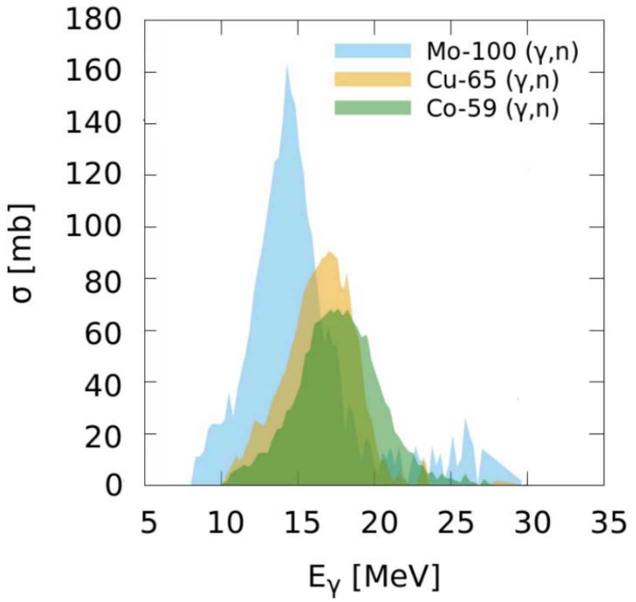
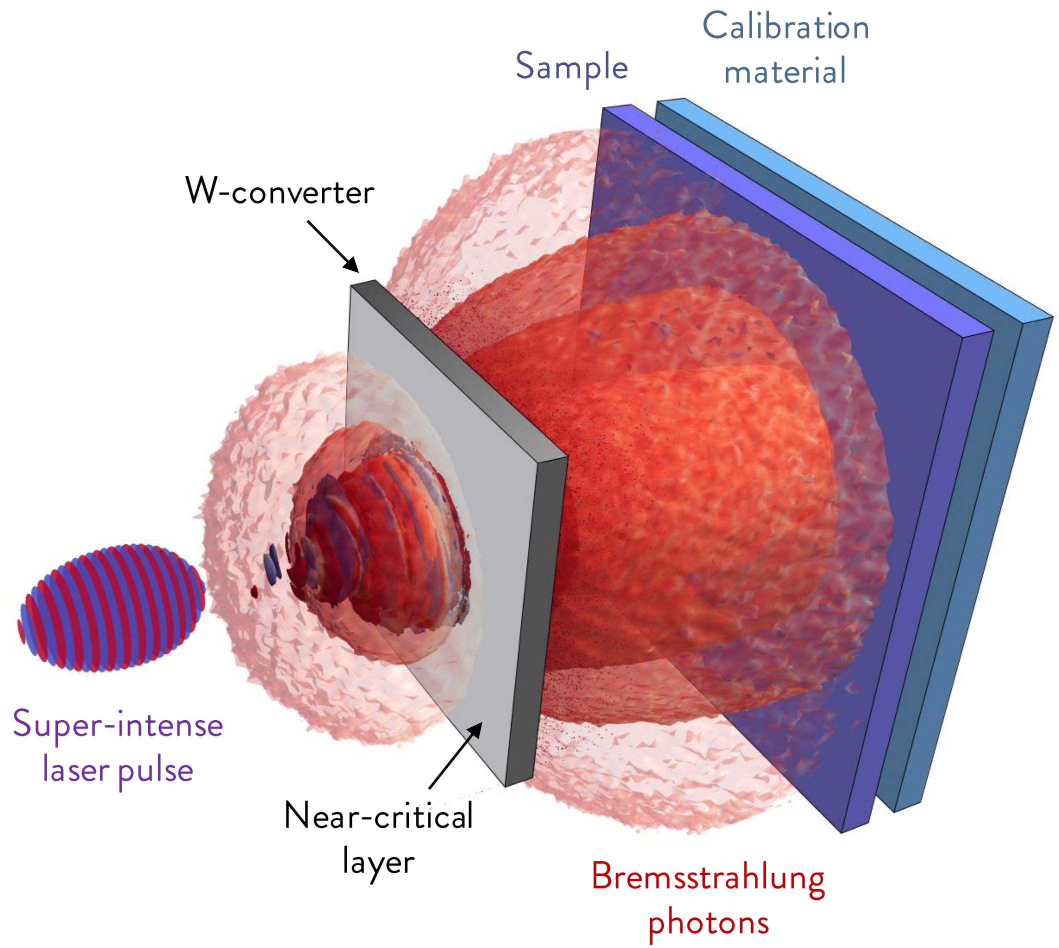
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

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

- Photonuclear reaction cross sections:





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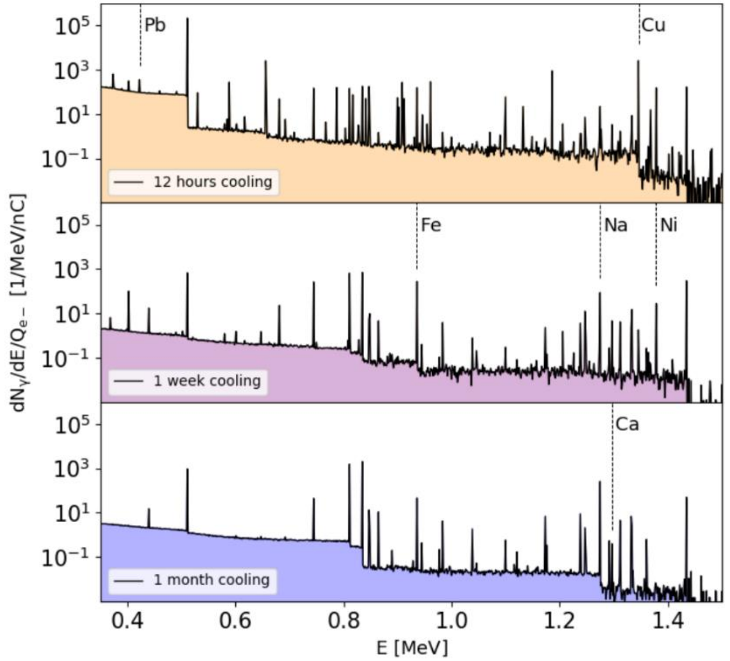
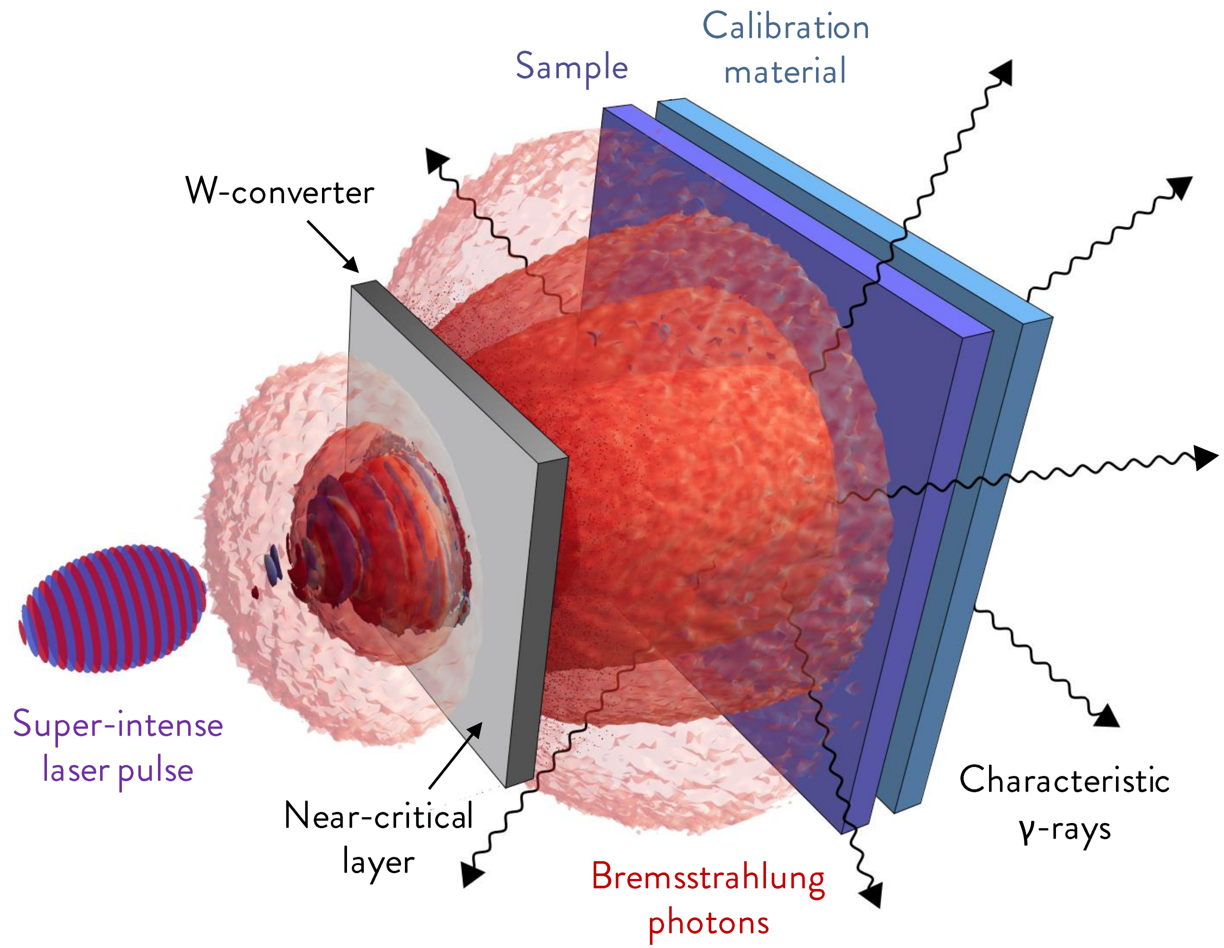
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

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



→ **Peak intensities**



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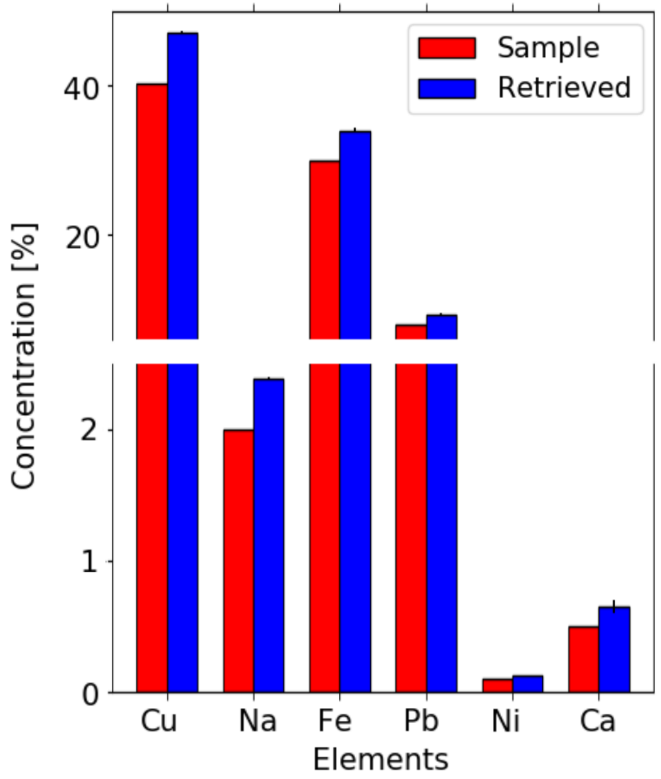
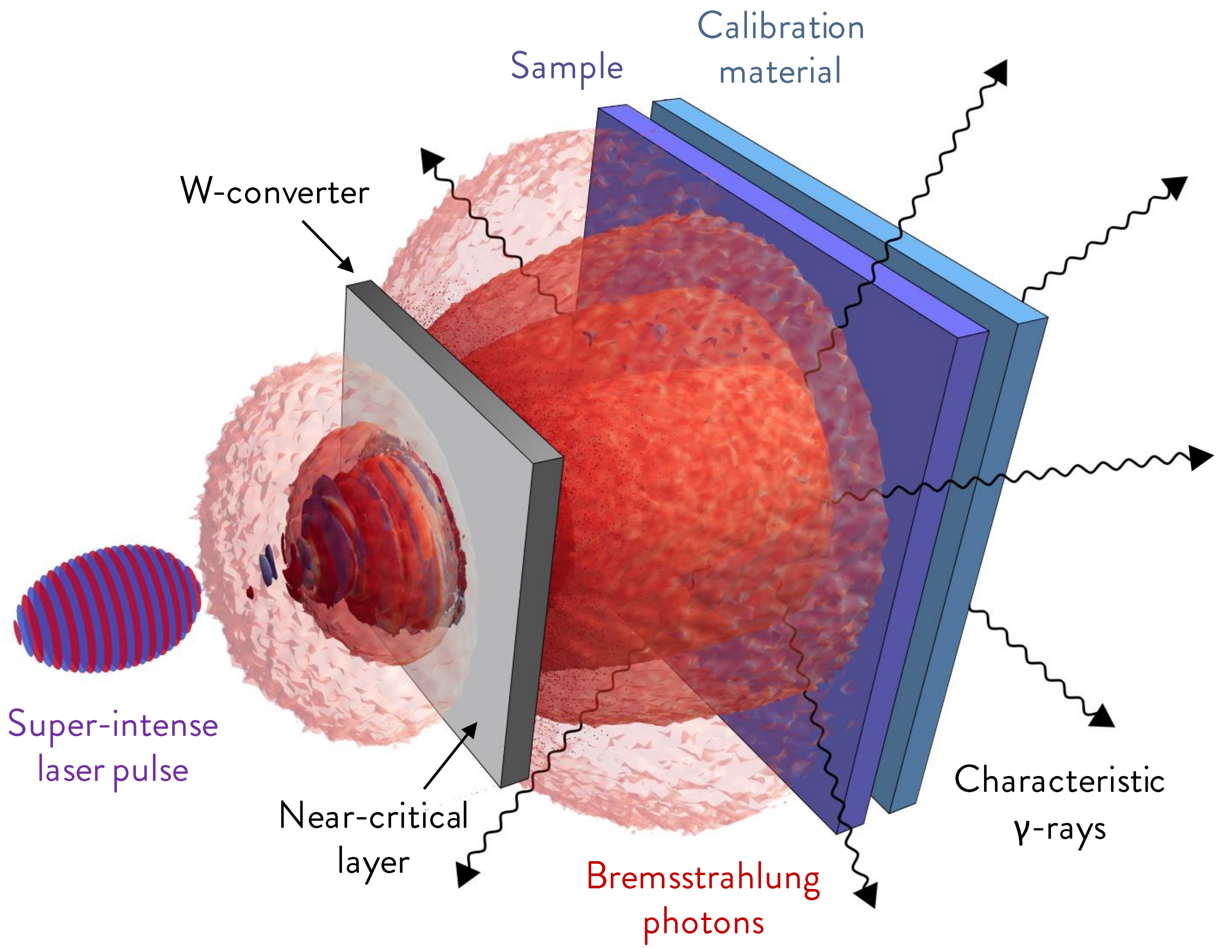
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

3. Retrieve the **elemental composition** of a cm-thick homogeneous sample

Comparison with the calibration →

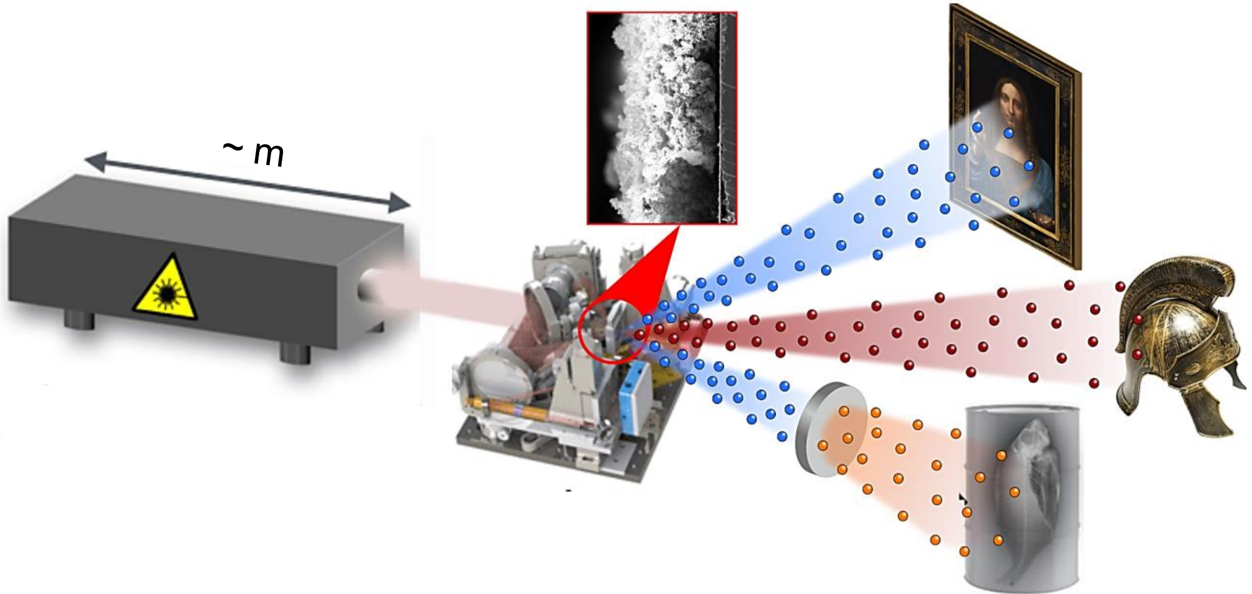




Mirani, F., et al. Superintense laser-driven photon activation analysis. *Commun Phys* 4, 185 (2021).

Conclusions and perspectives

- Combined **theoretical** and **experimental approach.**
- **Suitable target** solutions and compact lasers.
- Investigate and perform **laser-driven PIXE, EDX** and **PAA.**
- **Multi-purpose acceleration system.**



What next?

- **New experiments** of **laser-driven particle acceleration, PIXE, EDX** and **PAA** also with compact lasers and DLTs.

RAYLAB, SourceLAB, CLPU, GSI

- **Optimization** of the proof-of-principle **setups.**
- Investigate **laser-driven neutron** generation and n-based **materials characterization.**

Barberio M., et al *Scientific reports* 7.1 (**2017**): 1-8.

Passoni M., et al. *Scientific reports* 9.1 (**2019**): 1-11.

Barberio M., et al. *Science advances* 5.6 (**2019**): eaar6228.

Passoni M., et al. *Plasma Physics and Controlled Fusion* 62.1 (**2019**): 014022.

Barberio M., and P. Antici. *Scientific reports* 9.1 (**2019**): 1-9.

Morabito A., et al. *Laser and Particle Beams* 37.4 (**2019**): 354-363.

Zimmer, M., et al. *In EPJ Web of Conferences* (Vol. 231, p. 01006). (**2020**). EDP Sciences.

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

Puyuelo-Valdes P., et al. *Scientific reports* 11.1 (**2021**): 1-10.

Mirani, F., et al. *Communications Physics* 4, 185 (**2021**).

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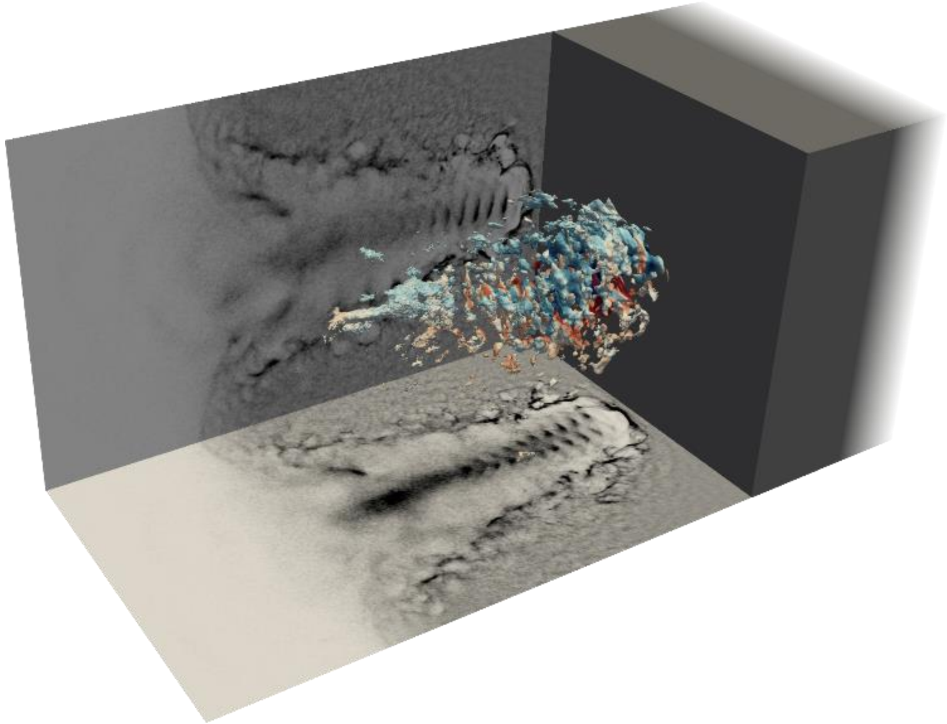

Thank you for the attention!

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