IAEA-CN301-77

Toward Laser-Driven accelerators: exploring the potential of advanced Double-Layer Targets

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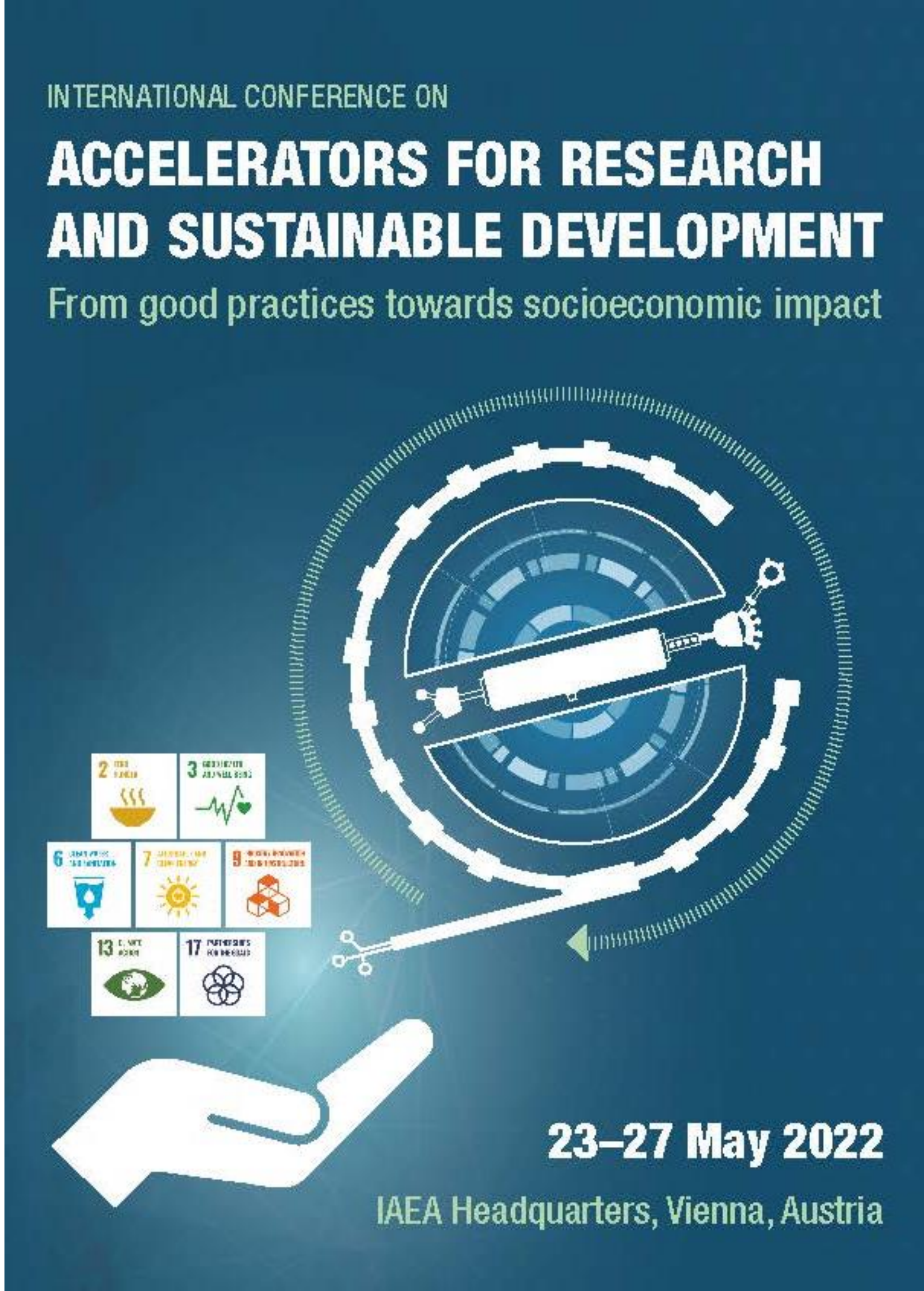

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- What is Laser-Driven Acceleration (and why) ?
- Case study 0: Laser-Driven Proton Induced X-ray Analysis
- Why Double-Layer Targets (DLTs)?
- Case study 1: Photon Activation Analysis with DLTs
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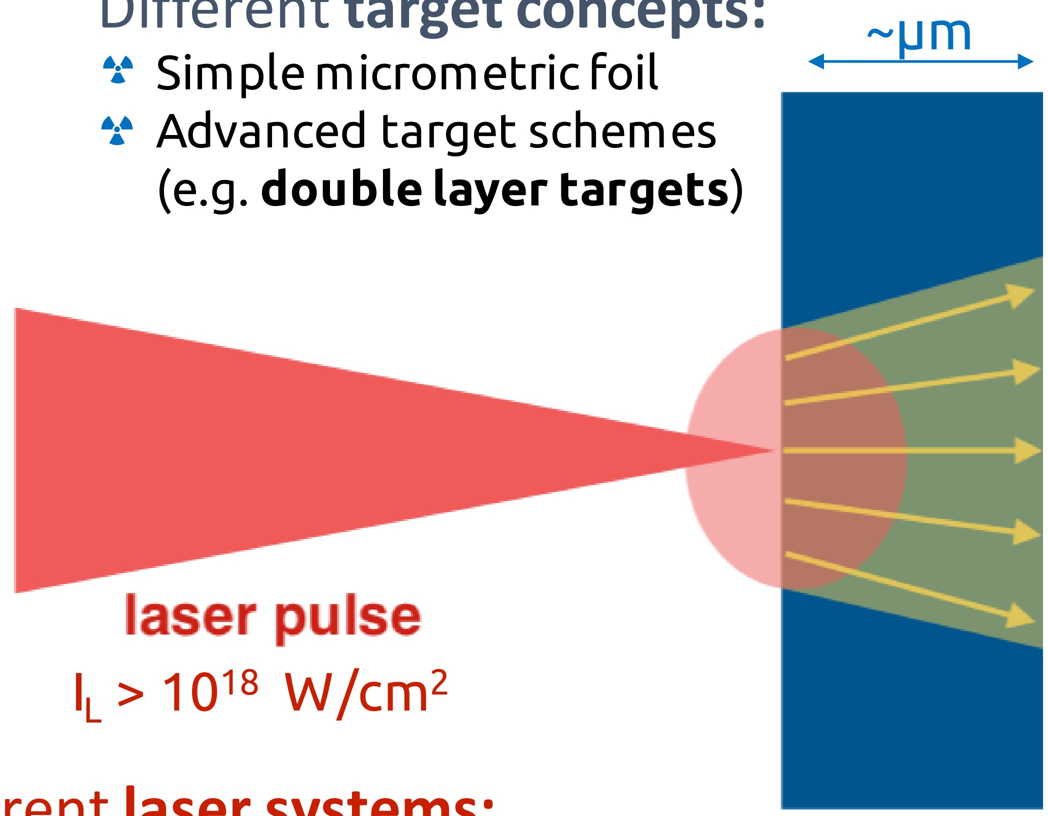
Laser-driven particle acceleration

Different **target concepts:**

- Simple micrometric foil
- Advanced target schemes (e.g. **double layer targets**)



Different **laser systems:**

- 0.1-1 J (30 fs), **10s TW**, 1-10 Hz, **Table-top**
- 1-20 J (30 fs), **0.1-1 PW**, < 1 Hz, **Room size**
- 50 J-1 kJ (~ ps), **0.1-1 PW**, 10s/day, **Building size**

M. Passoni et al., PPCF 61, 014022 (2020)

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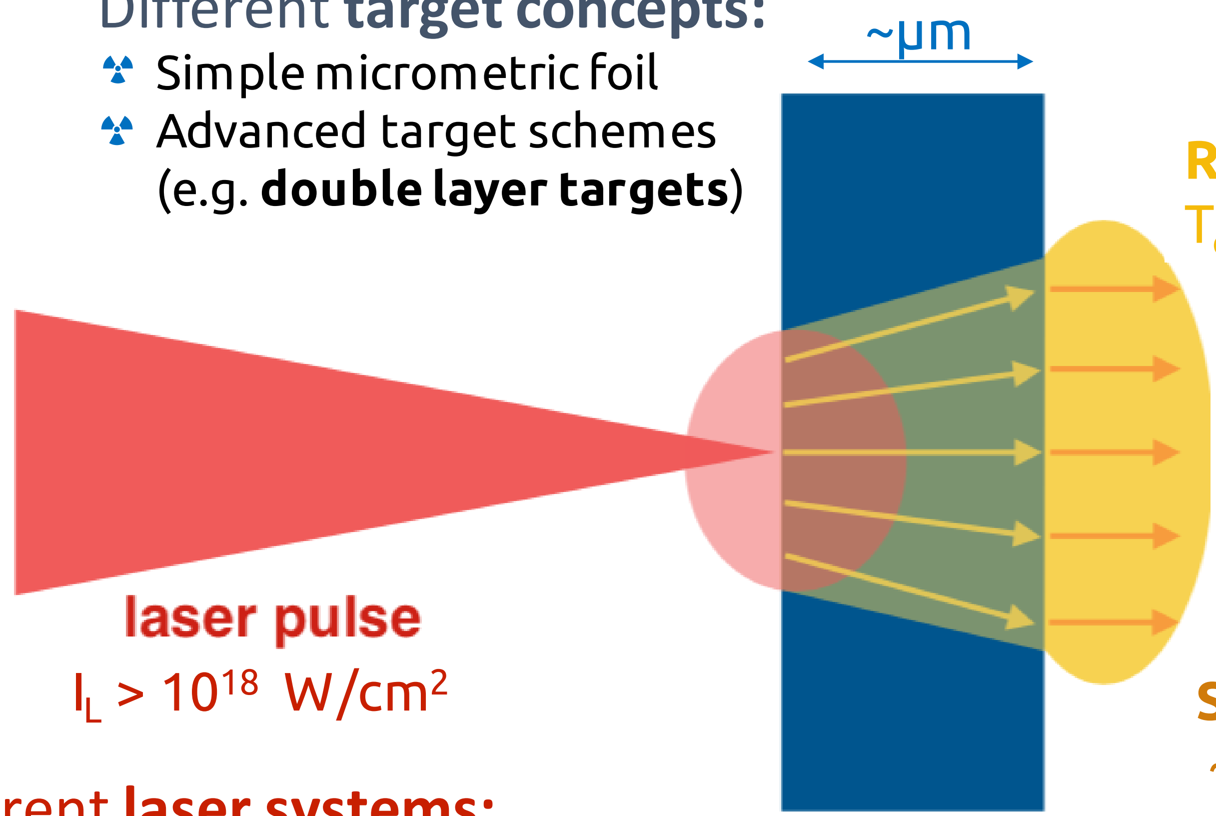

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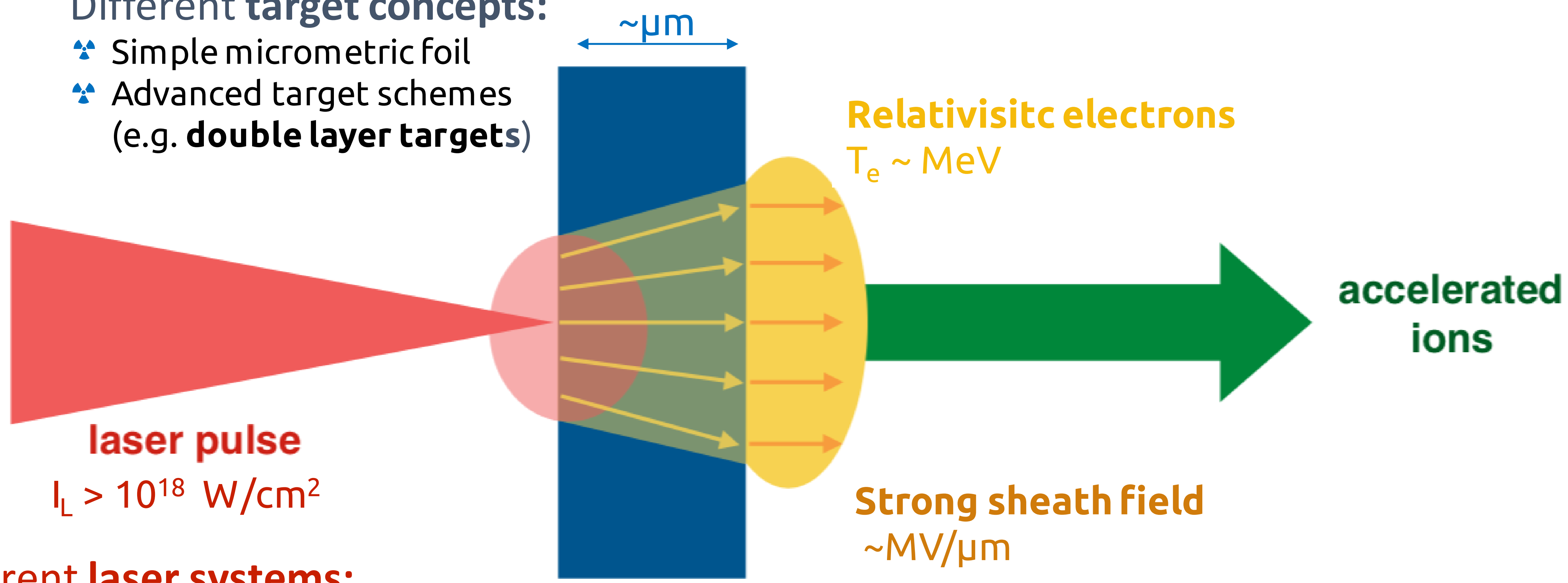

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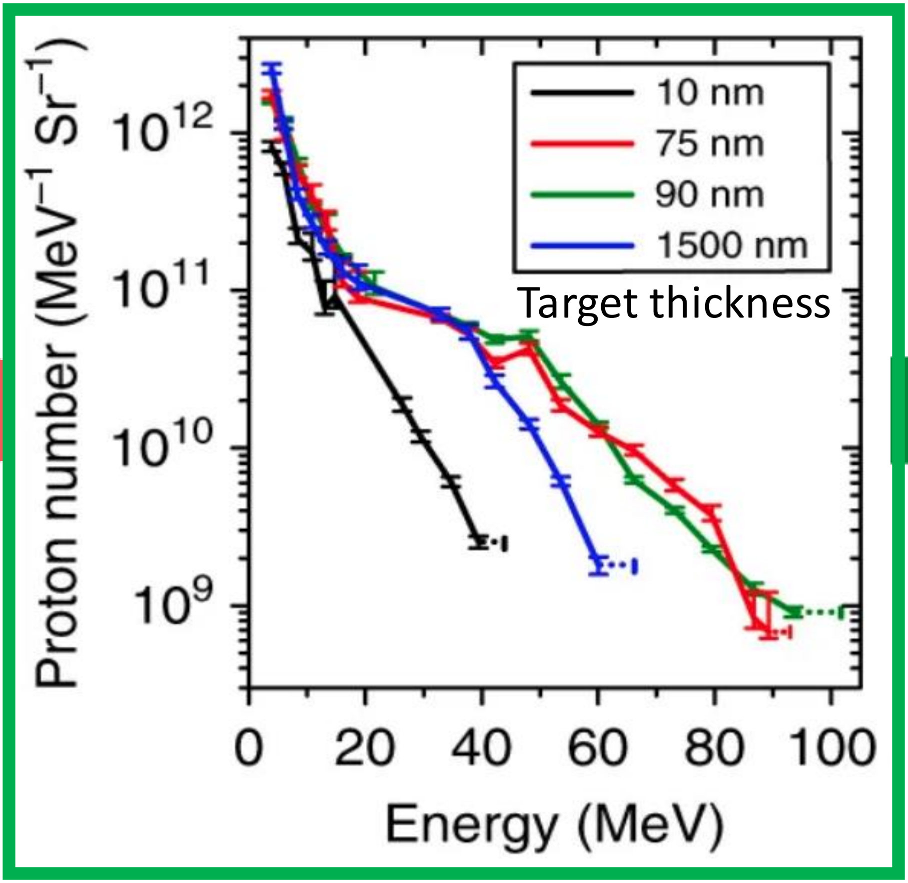


Exponential-like
Proton Spectrum

laser pulse
$I_L > 10^{18}$ W/cm^2

accelerated ions

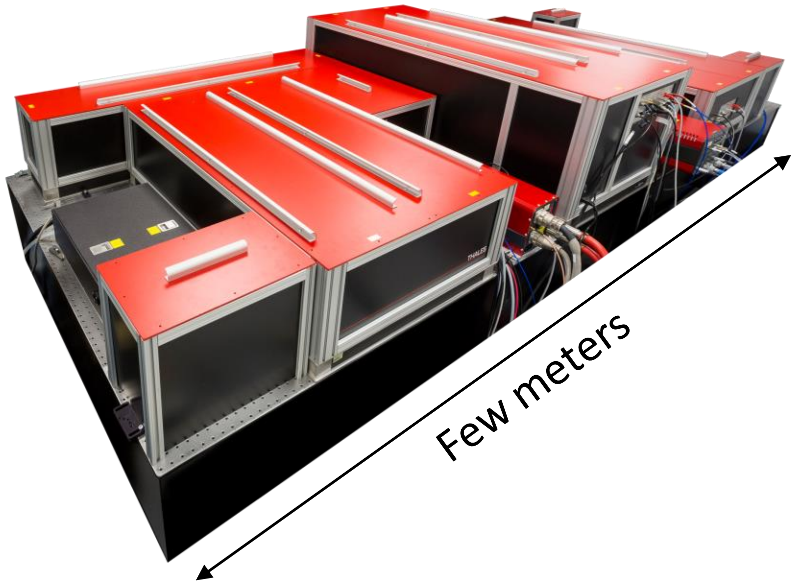
Time width ~ few ps
T_p ~ a few MeV
E_{max} ~ 10s of MeV

A. Higginson et al., Nature Comm. 9, 724 (2018)

Why should we try with lasers?

Potential advantages of laser-driven accelerators

- **Compactness**: portability & cost reduction
- **Flexibility**: changing the laser/target parameters, you change the neutrons/ions properties
- **Ultra-short**: access to ultra-fast (~10 ps - ns) dynamics
- **Pulsed**: pump and probe experiments
- **Multi-purpose**: with a single shot you can produce different types of radiation



Commercial example of a laser system:
QUARK 45 TW, Thales Group

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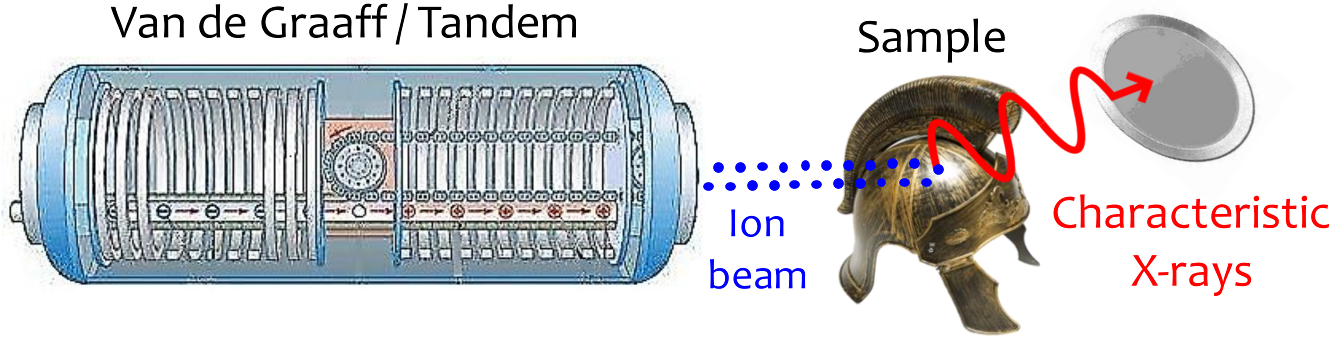
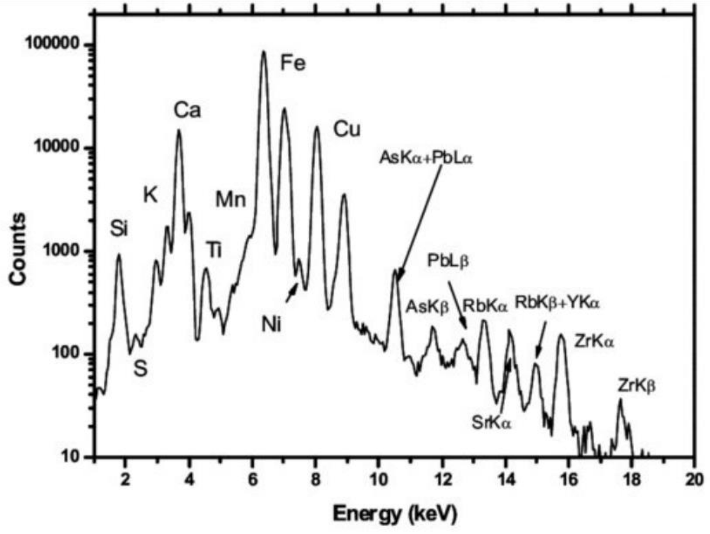
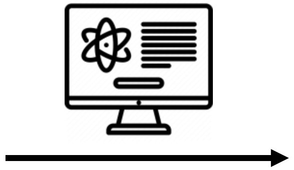
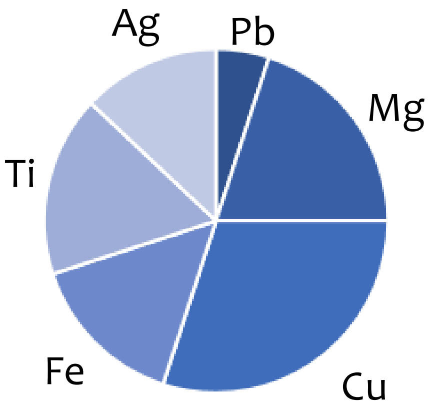
Conventional PIXE

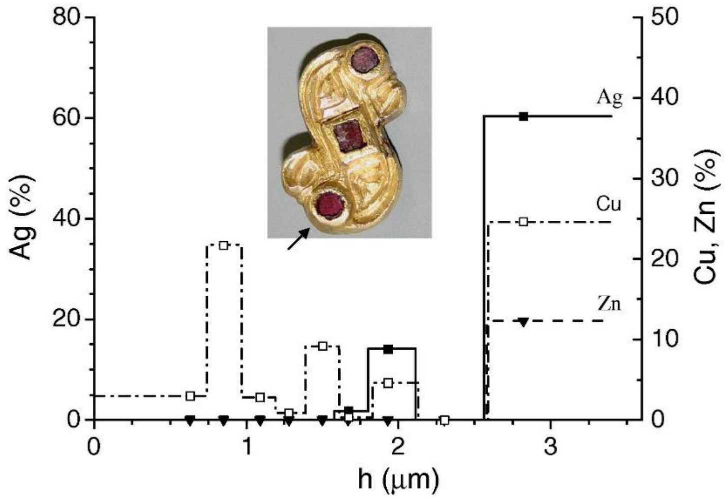


- **2-5 MeV/u** monoenergetic ions
- **Concentrations** & **Depth profiles**
- Cultural heritage, environment, biology, forensic analysis







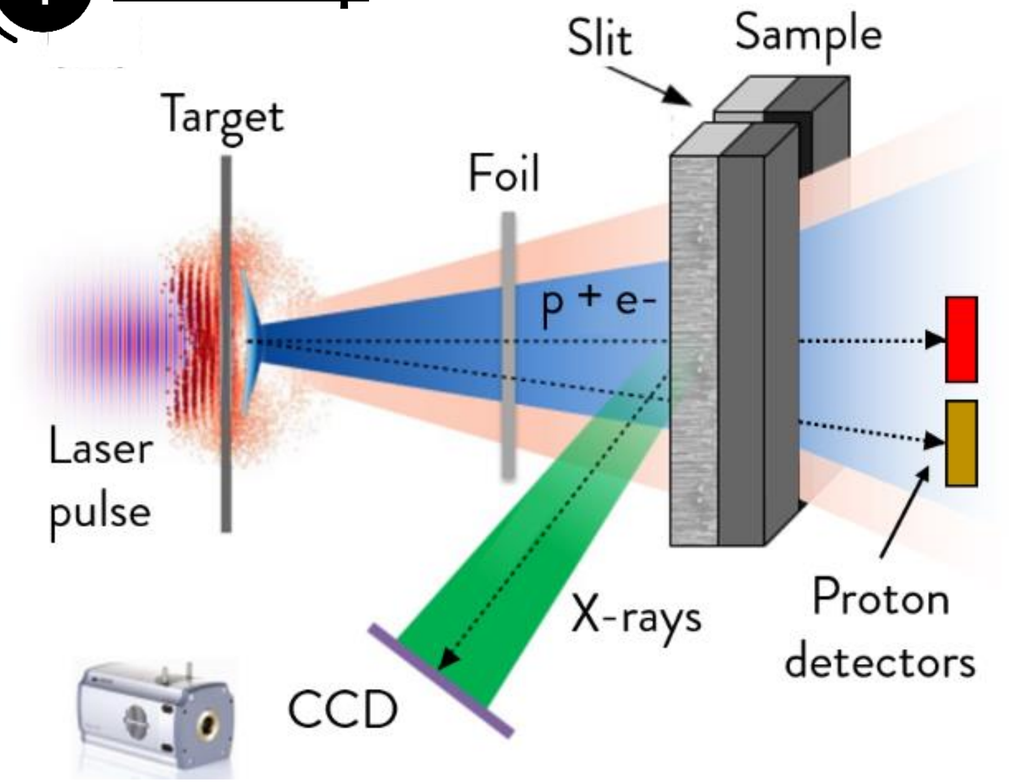


Verma, Hem Raj. Atomic and nuclear analytical methods. Springer-Verlag Berlin Heidelberg, 2007.

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

Laser-driven EDX and PIXE

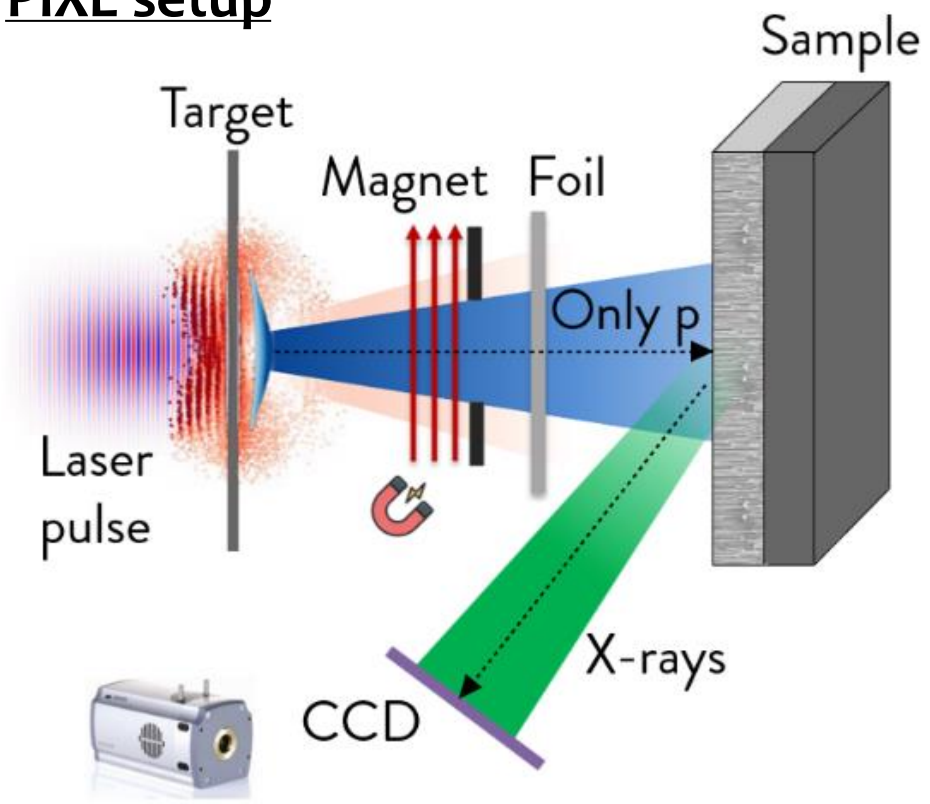
1 EDX setup



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

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

2 PIXE setup

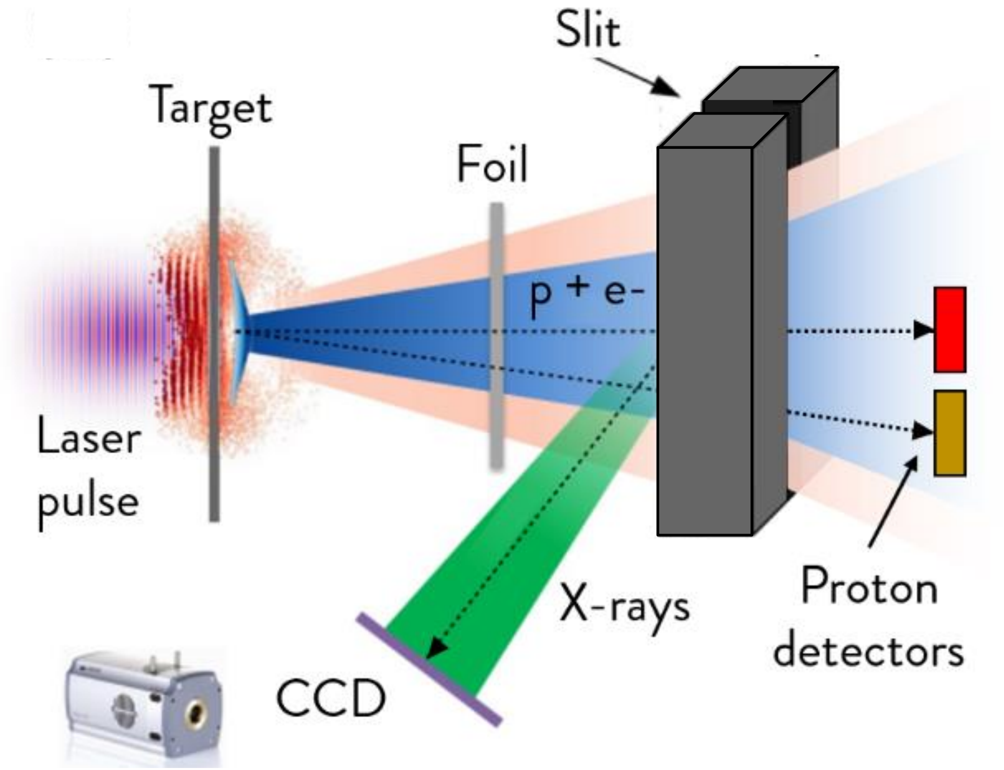


- Magnet to **remove** the **electrons**
- **Experiment @ Vega-II (200 TW)**

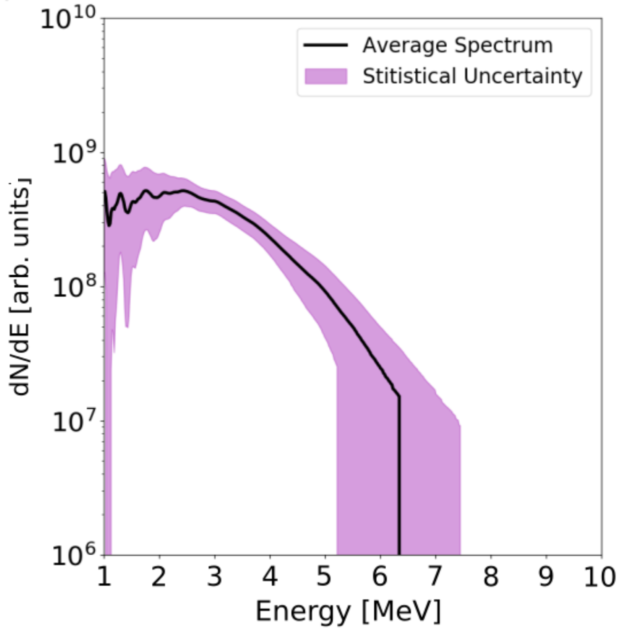
CLPU

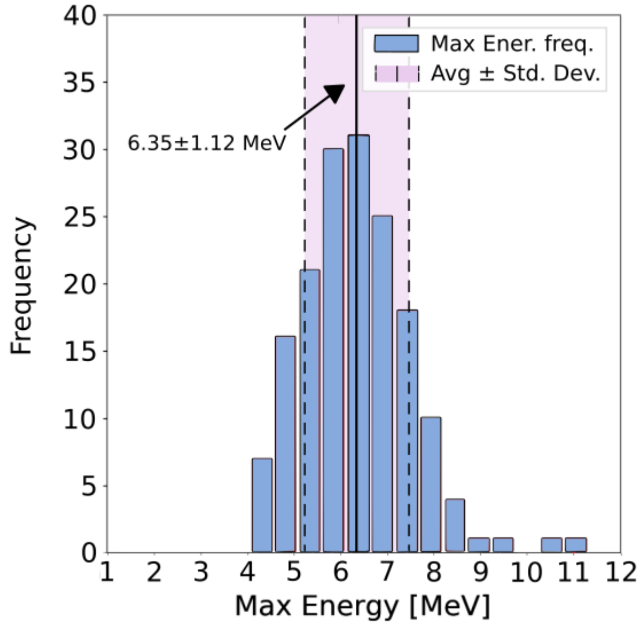
Laser-driven EDX and PIXE

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



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





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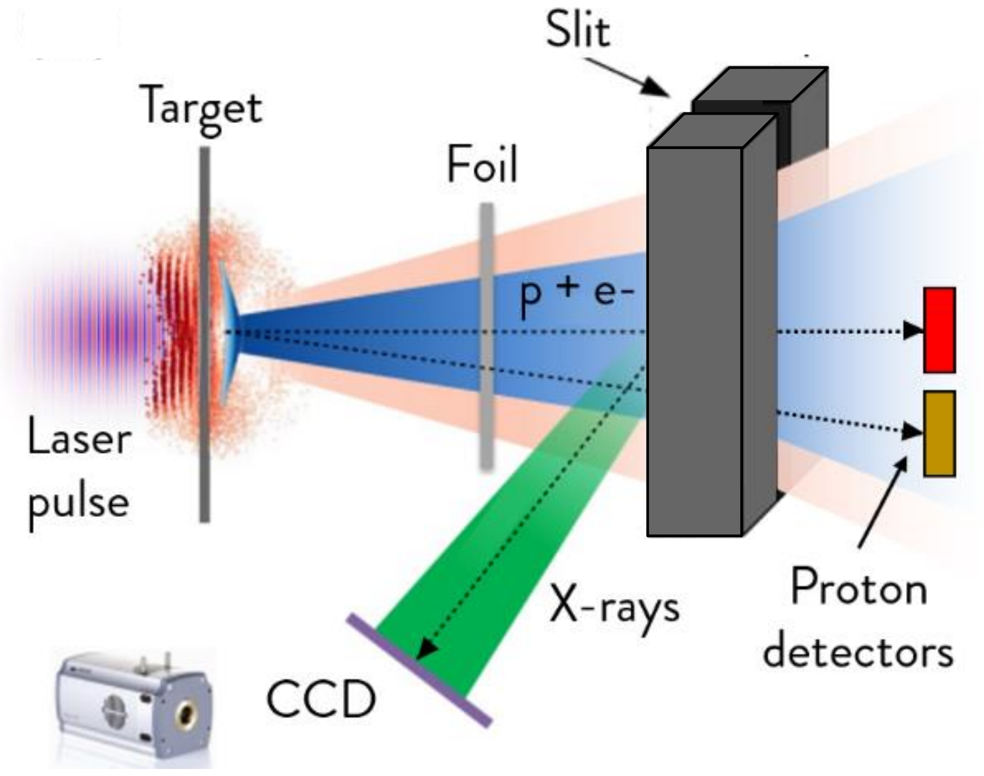
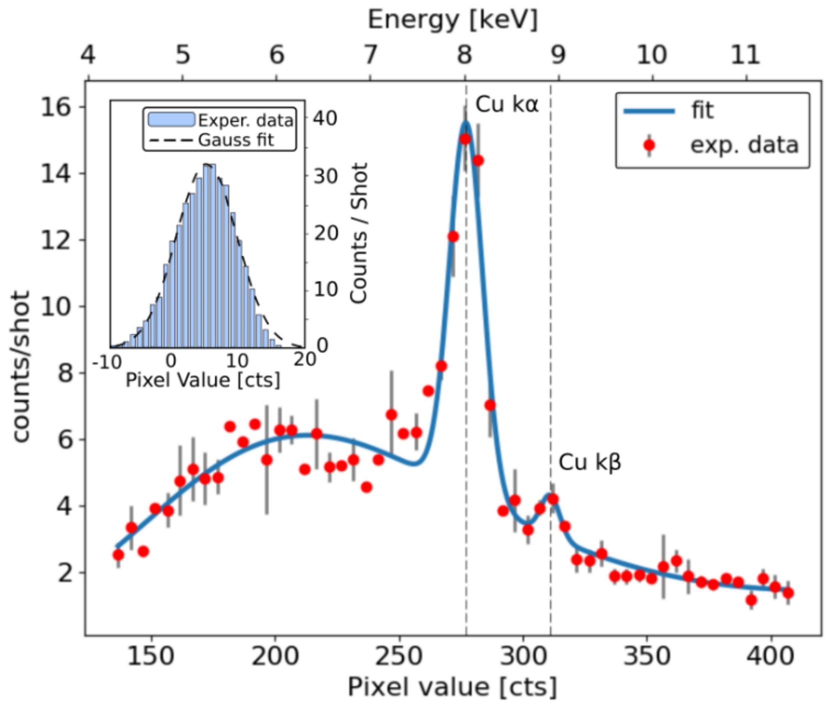


Mirani, F., et al., Science Advances 7.3 (2021): eabc8660.

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



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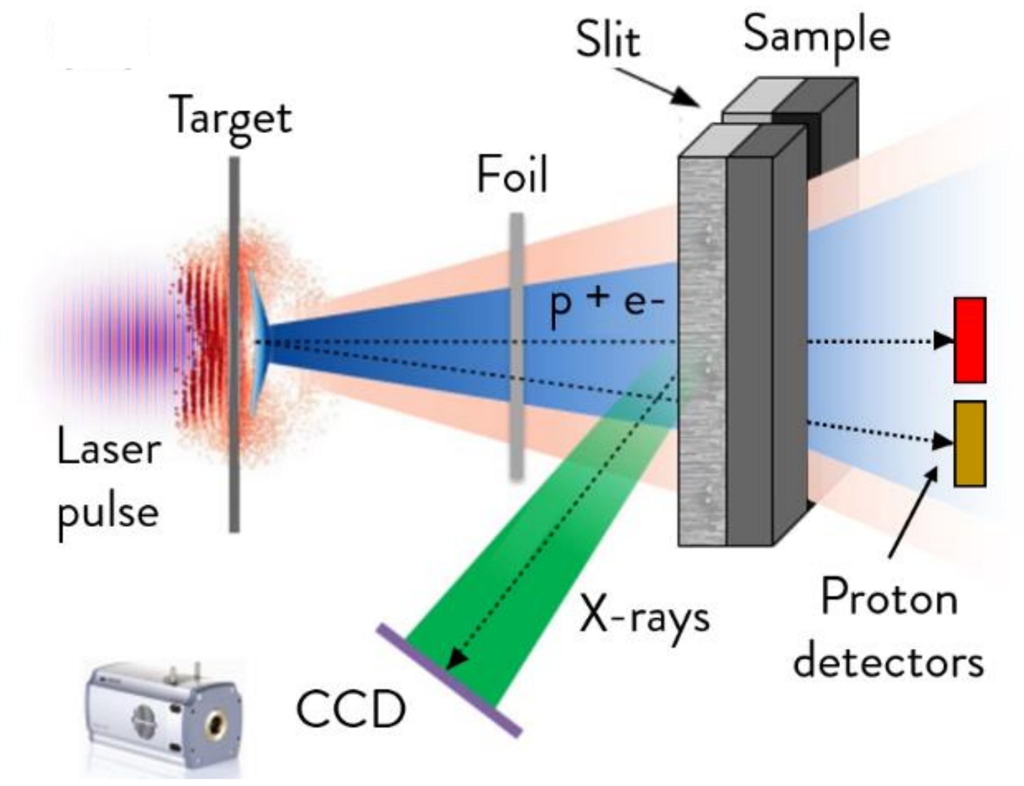
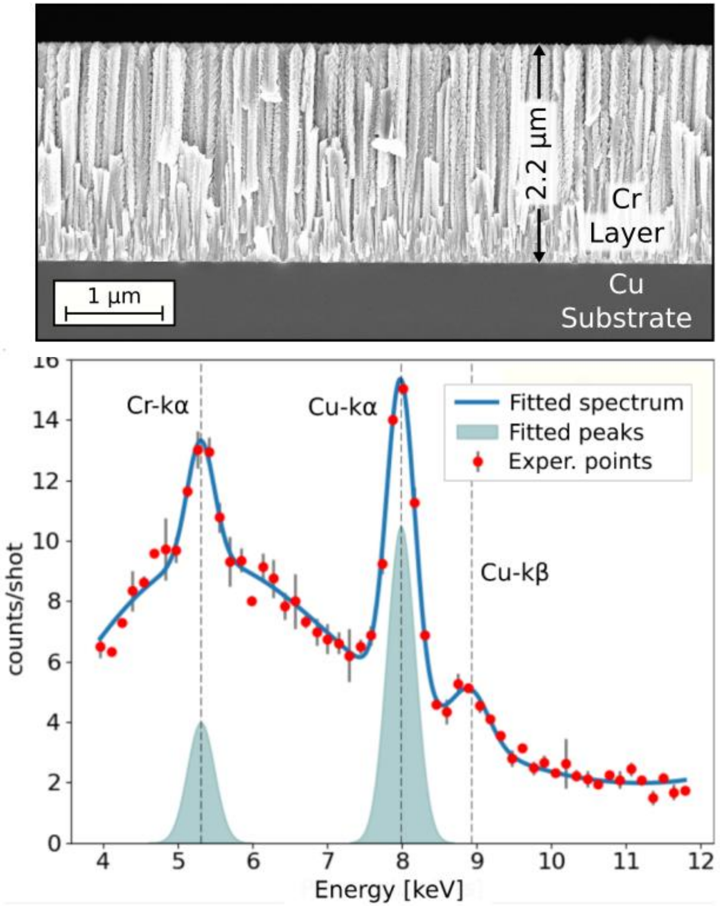
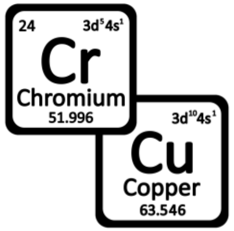




Bi-layer sample (Cr layer + Cu substrate)

→



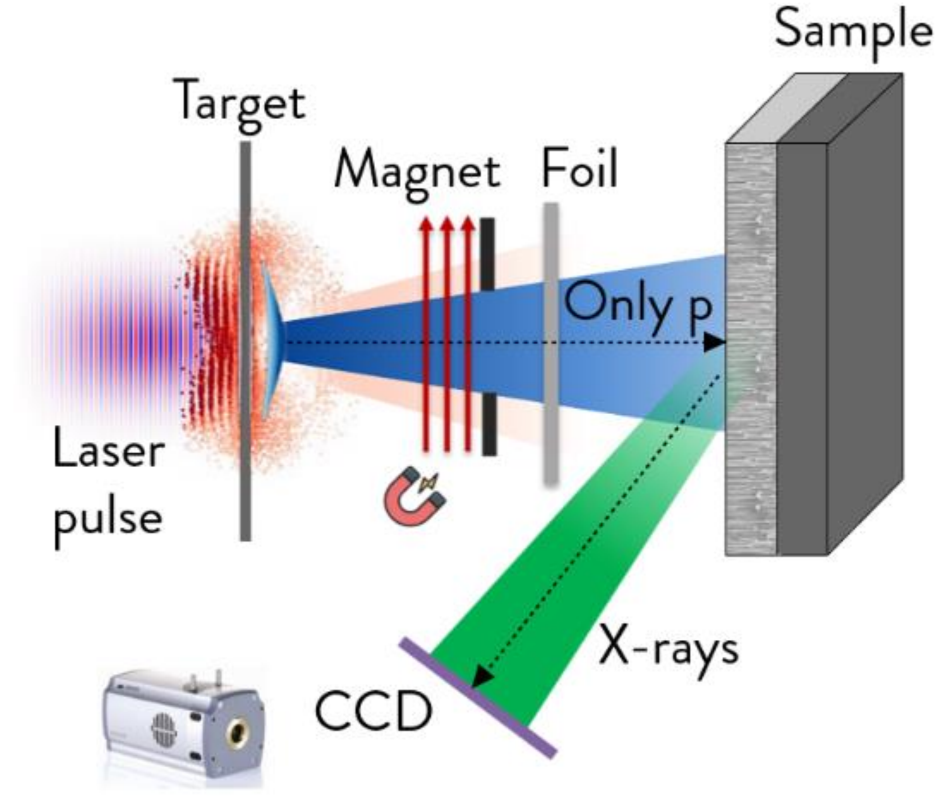
Elements are correctly **recognized**

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

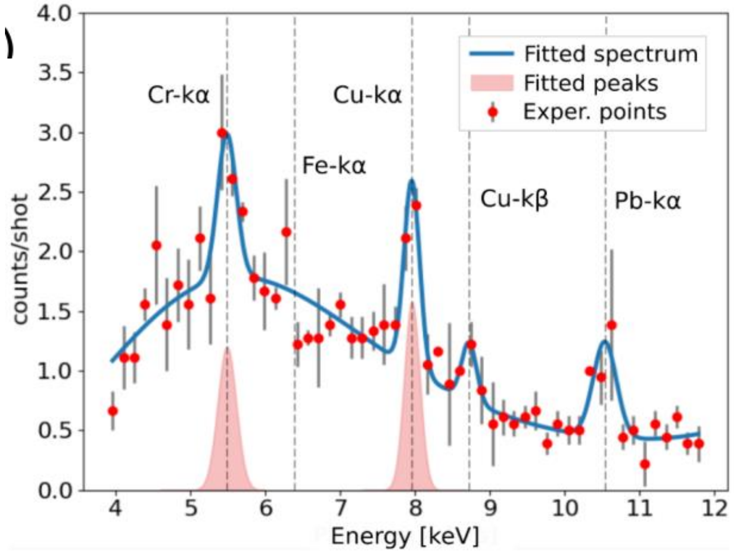
❖ **Experiment @ Vega-II (200 TW)** CLPU

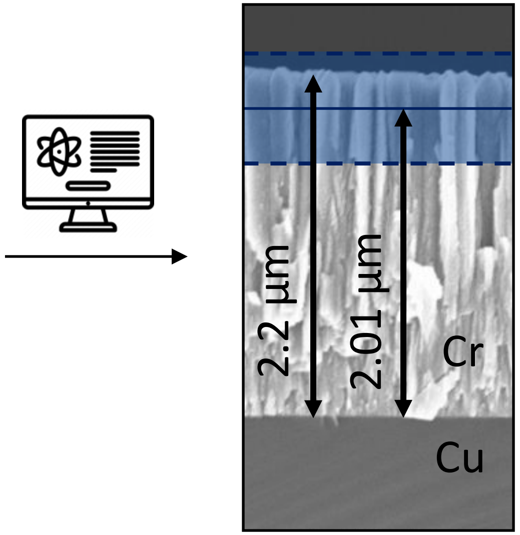
Laser-driven EDX and PIXE

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





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- **Experiment @ Vega-II (200 TW)** CLPU

Should we try with lasers?

Potential advantages
of laser-driven accelerators

- **Compactness**: portability & cost reduction
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- **Low current** (Np*Rep.Rate): 0.1 - 10 nA
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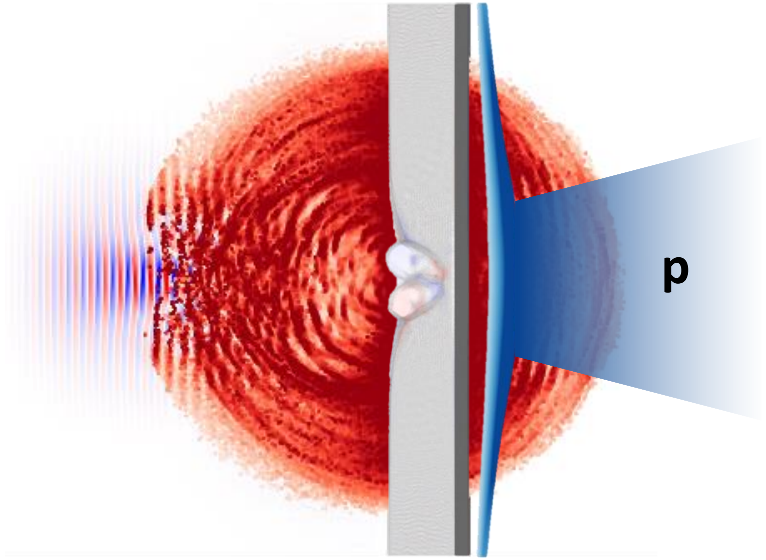
Possible solution: Double-Layer Targets



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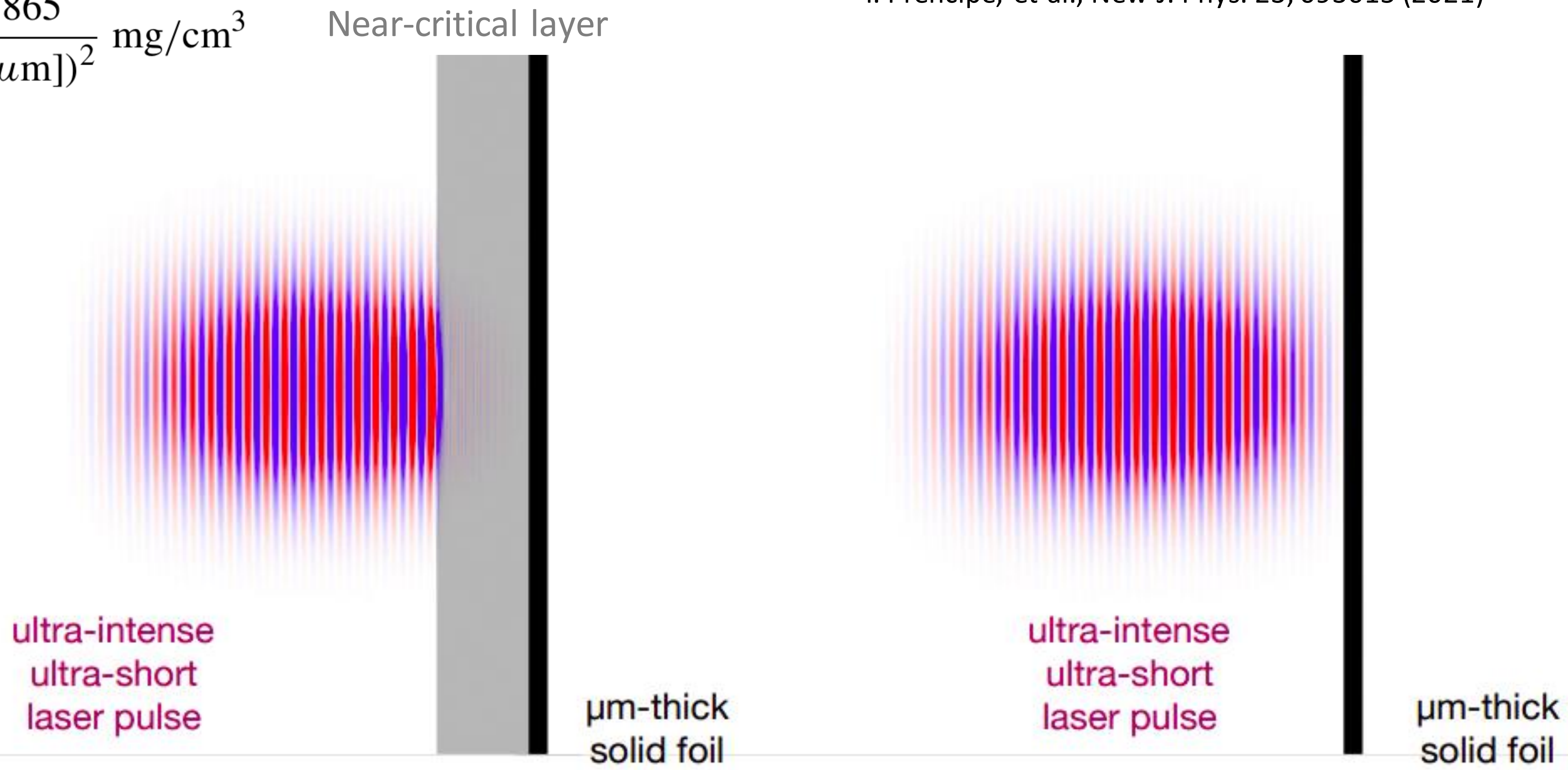
Why Double-Layer Targets?

Near-critical layer density:

$$\rho_c \approx \frac{A}{Z} \frac{1.865}{(\lambda\,[\mu\mathrm{m}])^2}\ \mathrm{mg/cm^3}$$

A. Pazzaglia, et al., Communications Physics 3, 133 (2020)
I. Prencipe, et al., New J. Phys. 23, 093015 (2021)



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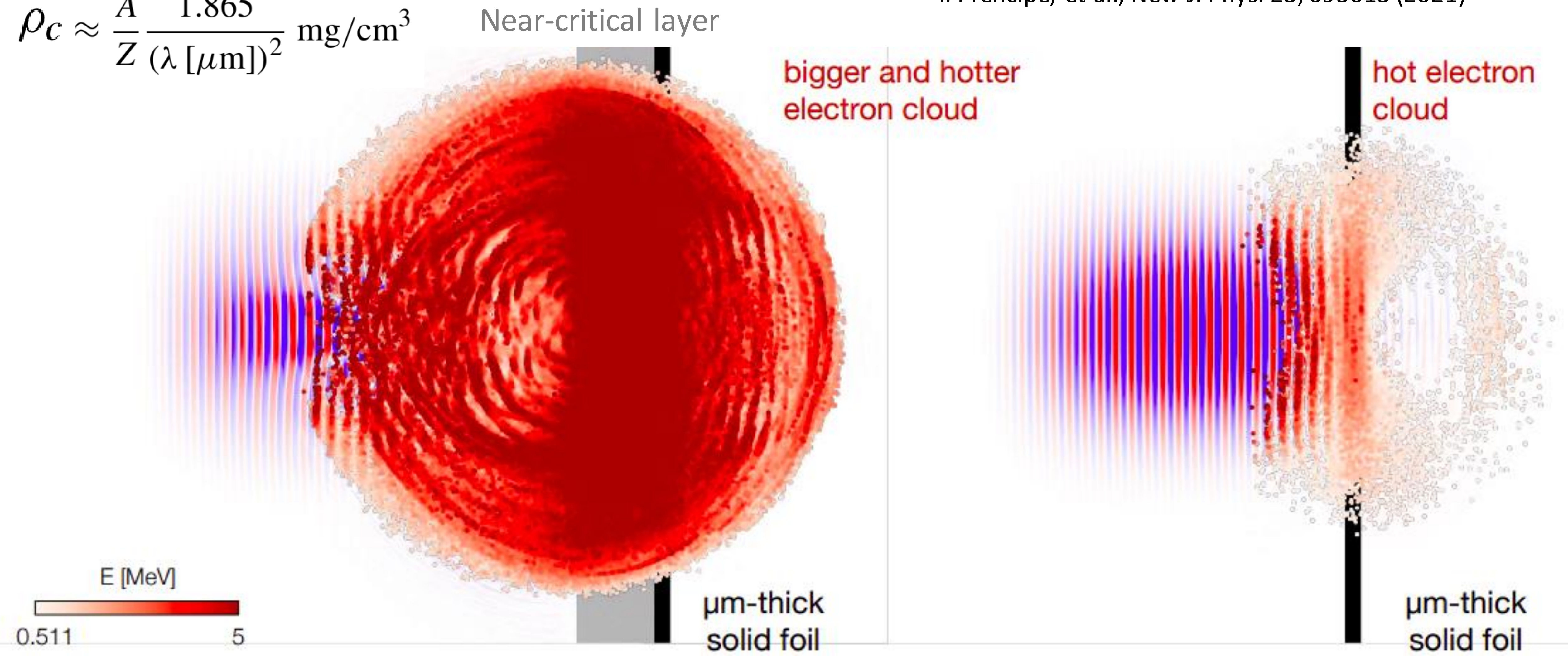

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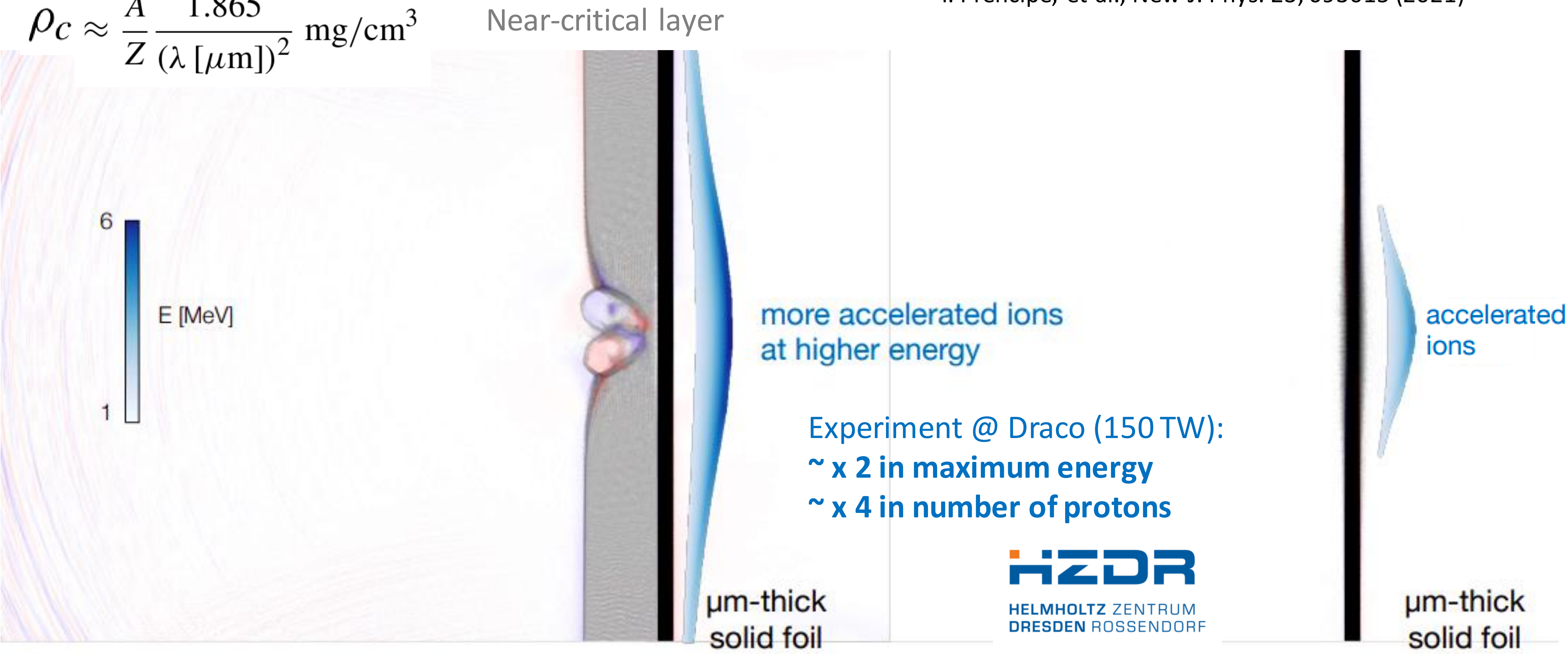


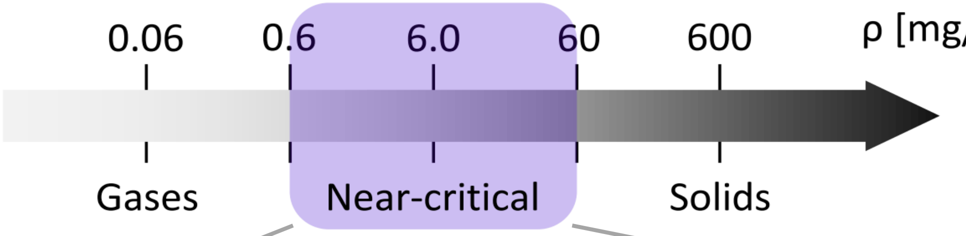
Experiment @ Draco (150 TW):

~ x 2 in maximum energy

~ x 4 in number of protons

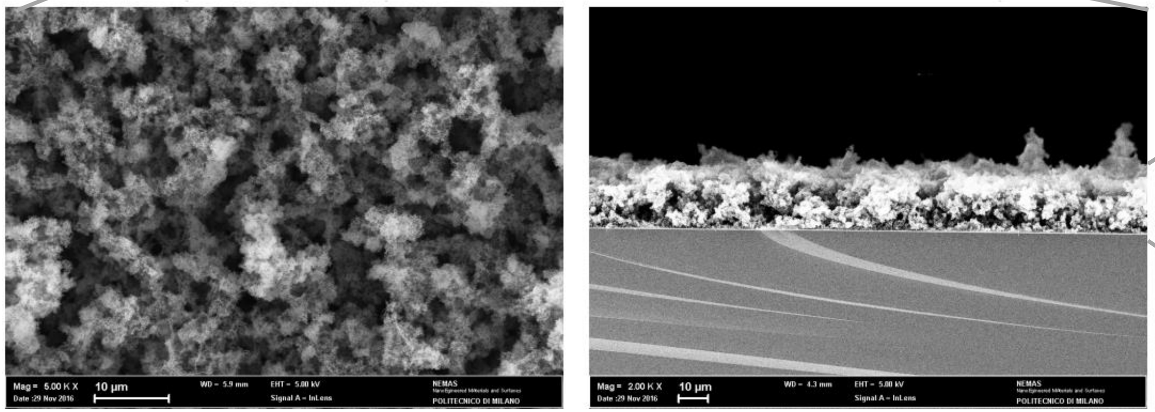
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

How to make double layer-targets?

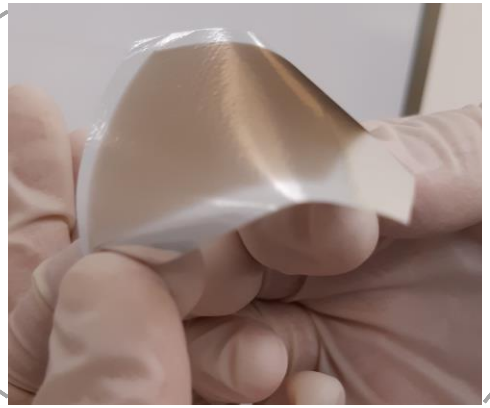


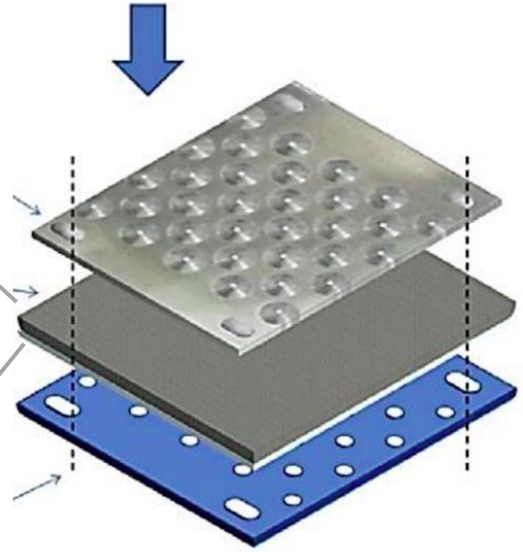
NanoLab

Carbon Nanofoams



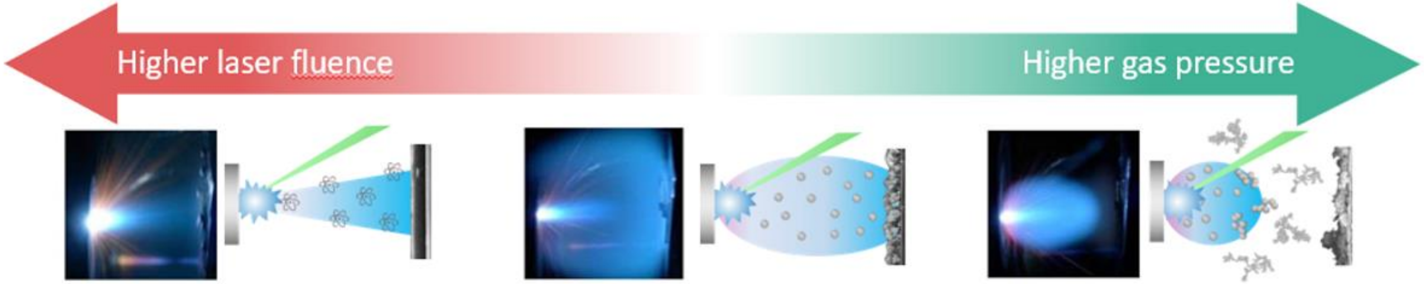
~10 µm carbon nanofoam on a micrometric Ti foil





Overall target assembly

Produced by **Pulsed Laser Deposition**



I. Prencipe, et al., Plasma Phys. Control. Fus. 58 (2016) 034019
A. Maffini, et al., Phys. Rev. Materials 3 (2019) 083404
A. Maffini, et al., App. Surf. Science (2022), in press

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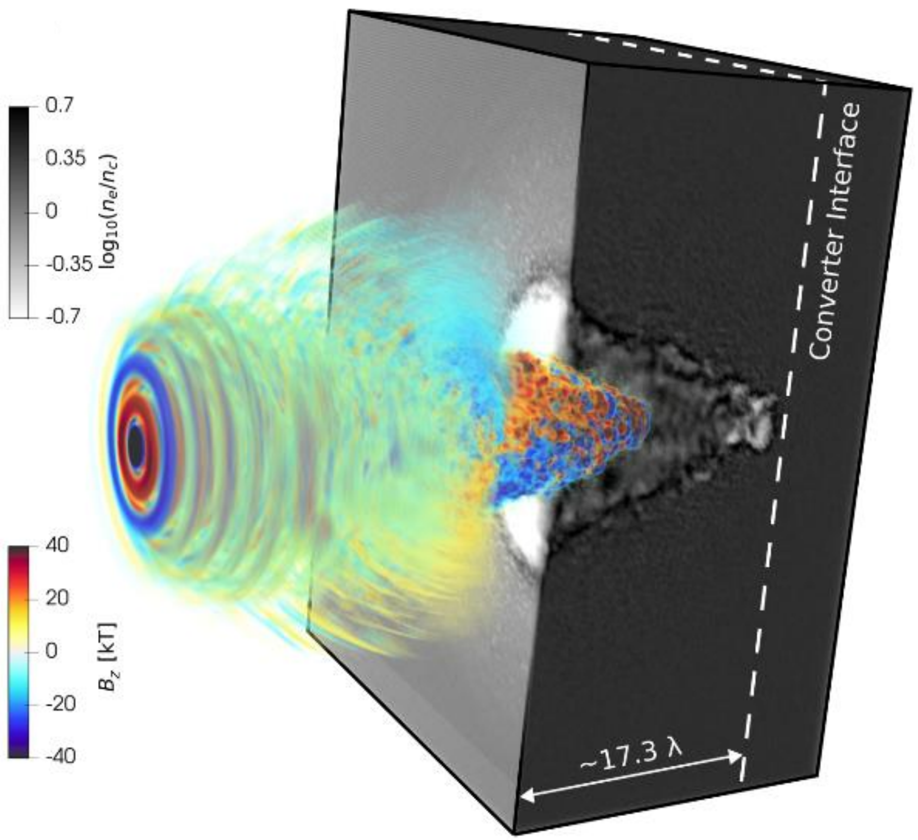
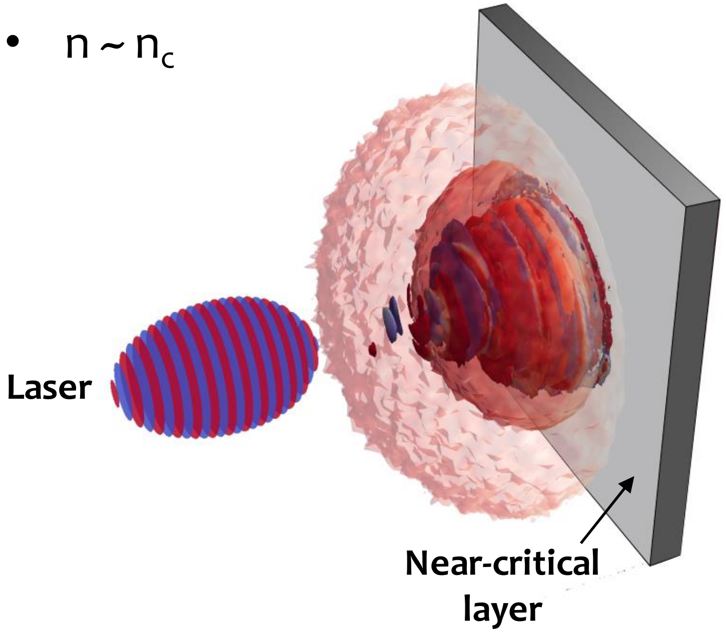
Laser-driven Photon Activation Analysis

1) **Laser** interaction with **near-critical** material → **Hot e- generation**



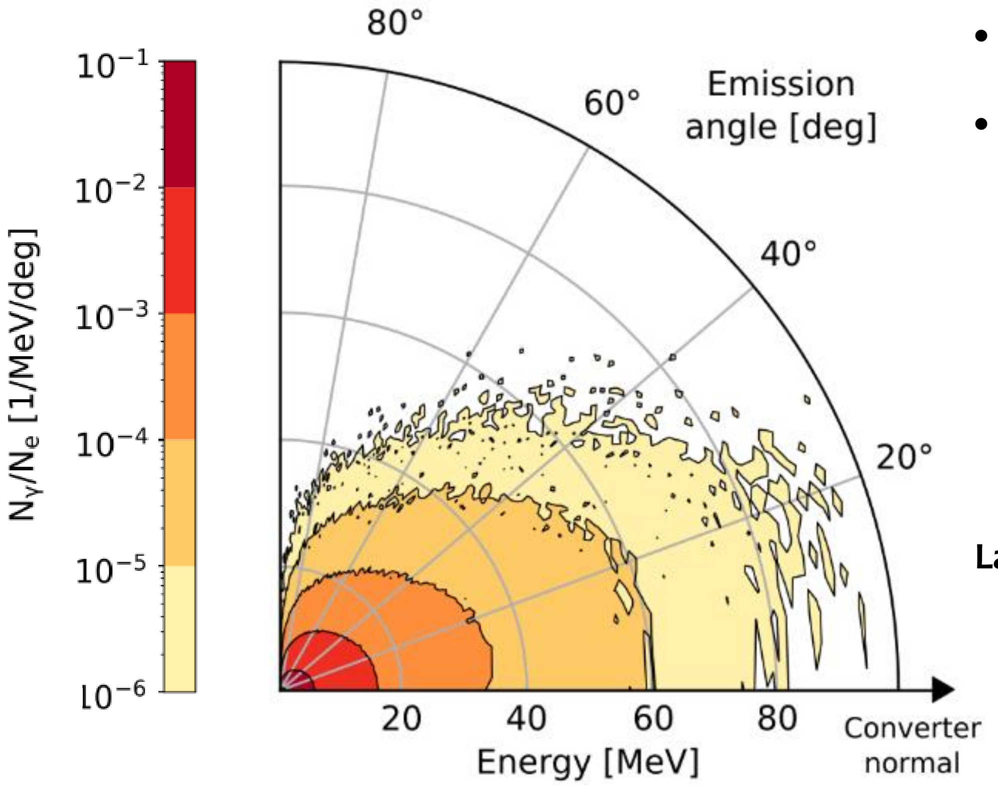
- $a_0 = 20$
- 10 μm foam
- $n \sim n_c$



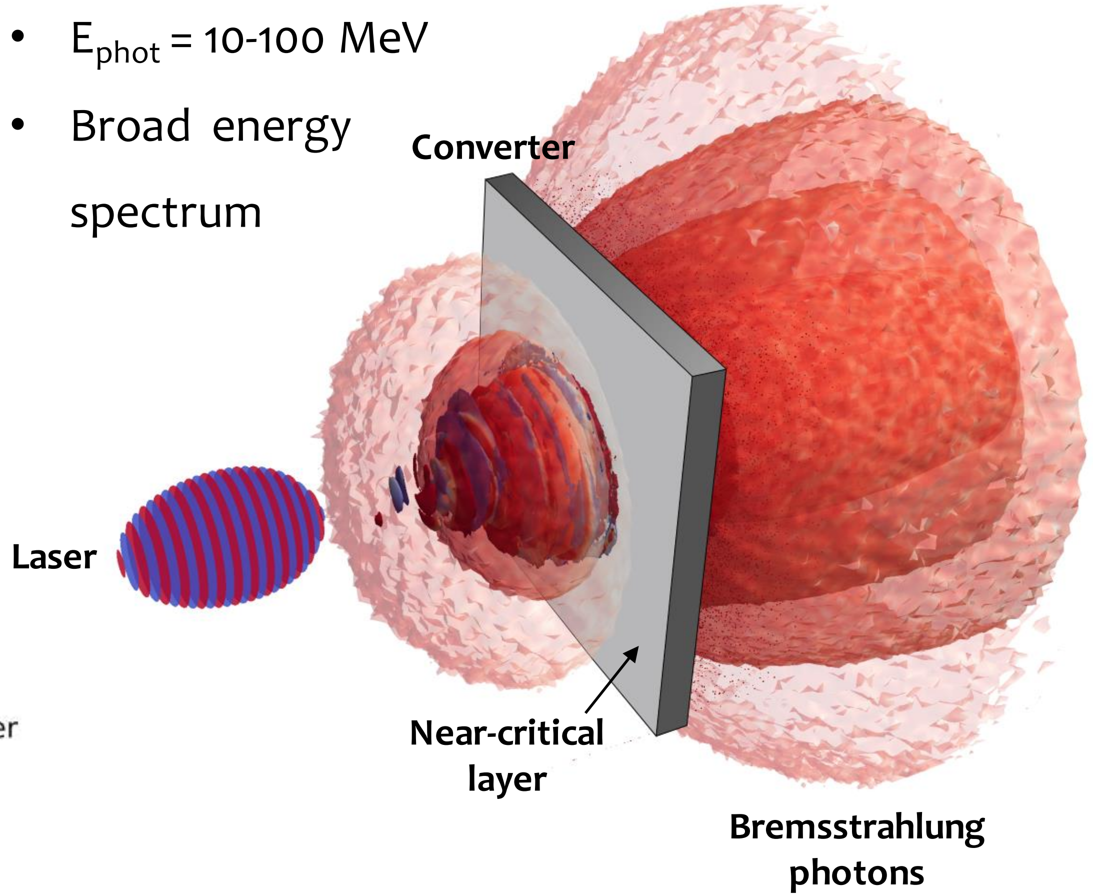
Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Communications Physics 4, 185 (2021)

Laser-driven Photon Activation Analysis

2) **Hot e-** interaction with **mm-thick substrate** → Bremsstrahlung **photons** generation



- E_{phot} = 10-100 MeV
- Broad energy spectrum



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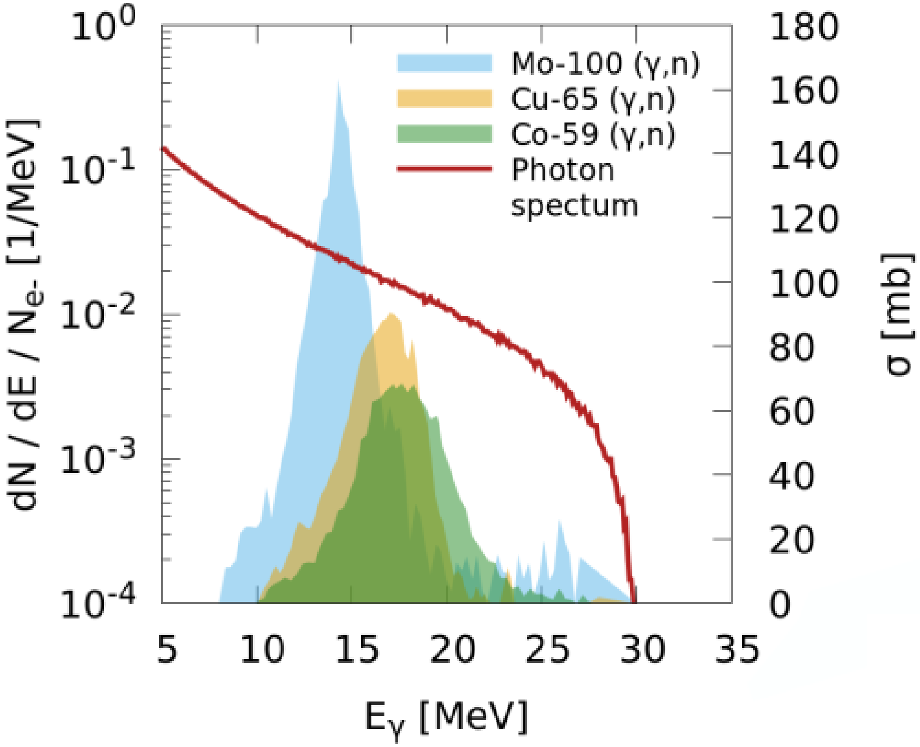
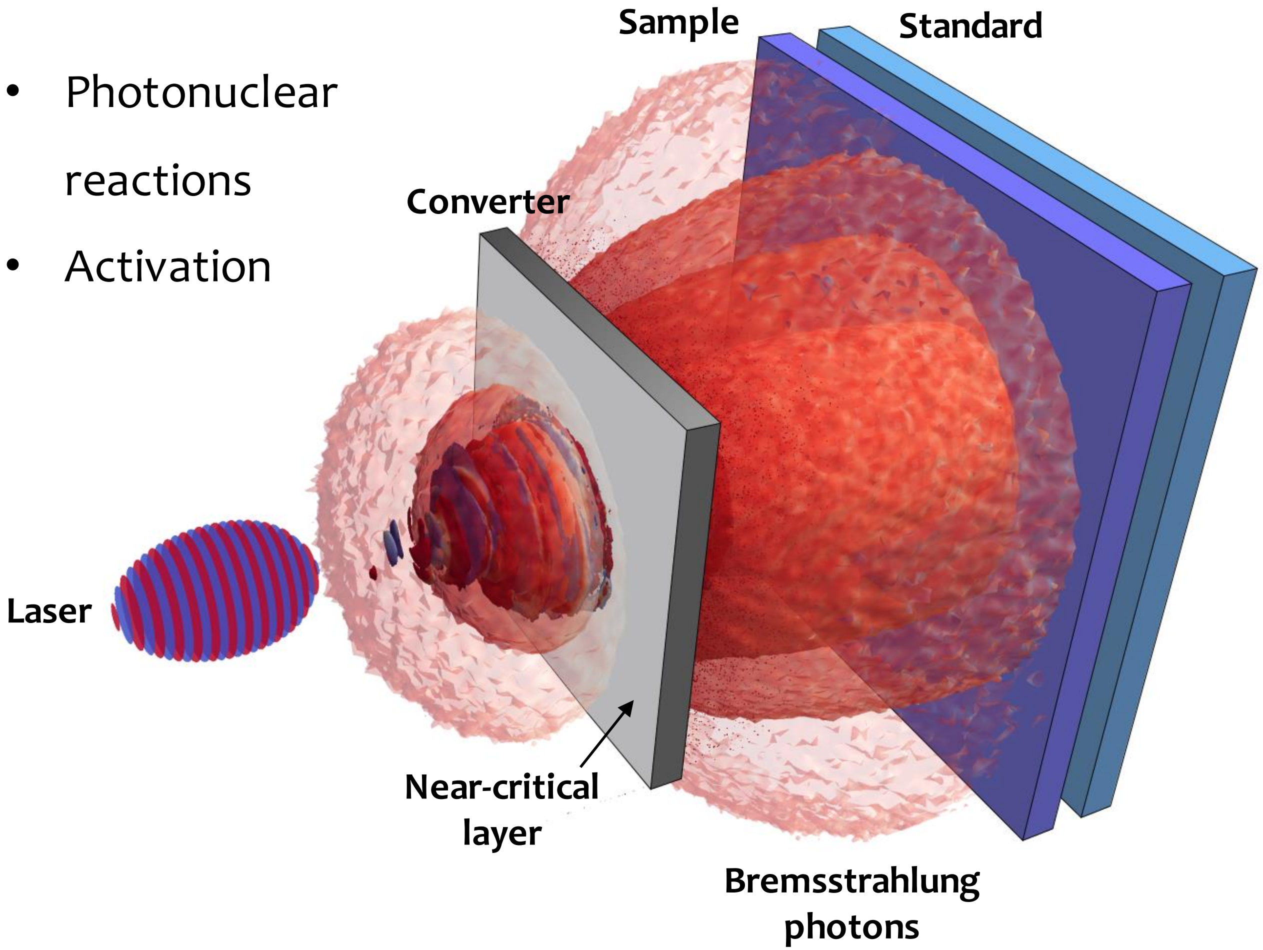
Laser-driven Photon Activation Analysis

3) Irradiation of sample and reference material



- Photonuclear reactions
- Activation



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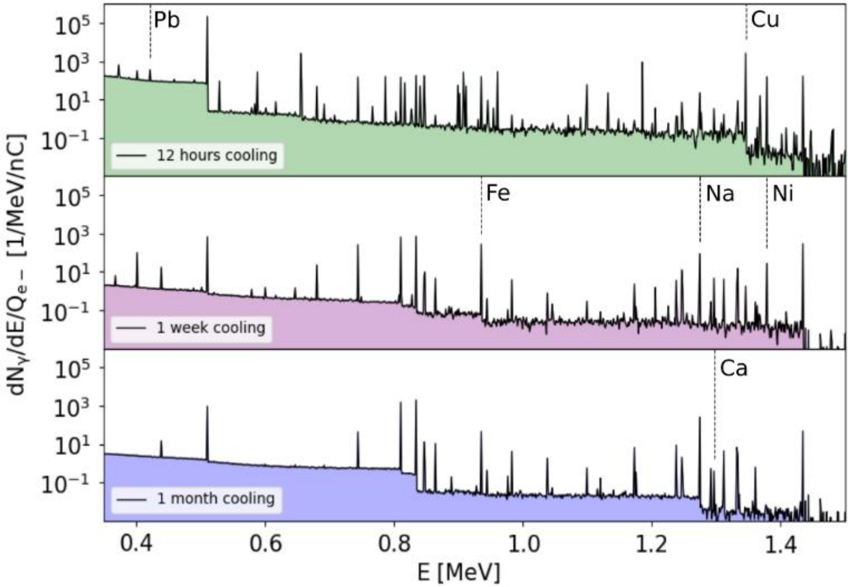
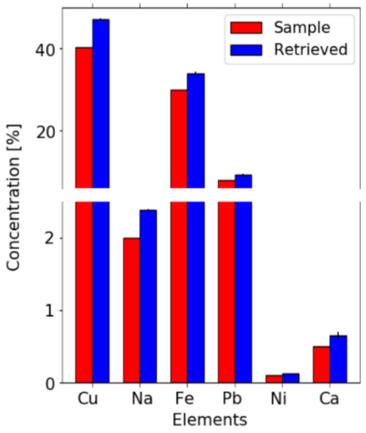
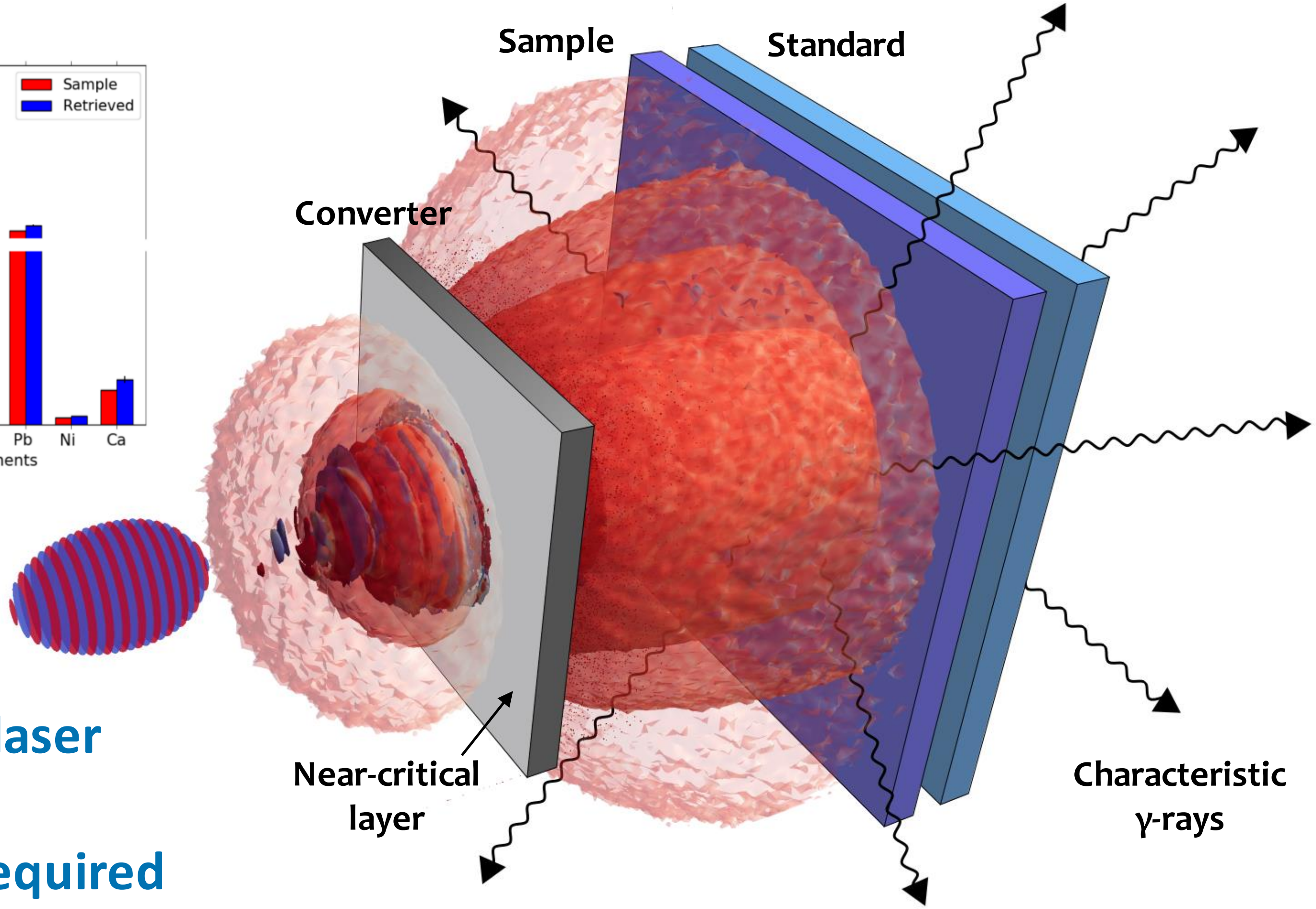
Laser-driven Photon Activation Analysis

4) Delayed emission of **characteristic γ-rays** → **Composition** reconstruction







- Laser-driven **PAA achievable** with **existing laser** technology
- Near-critical targets + **100s TW** lasers are **required**

Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Communications Physics 4, 185 (2021)

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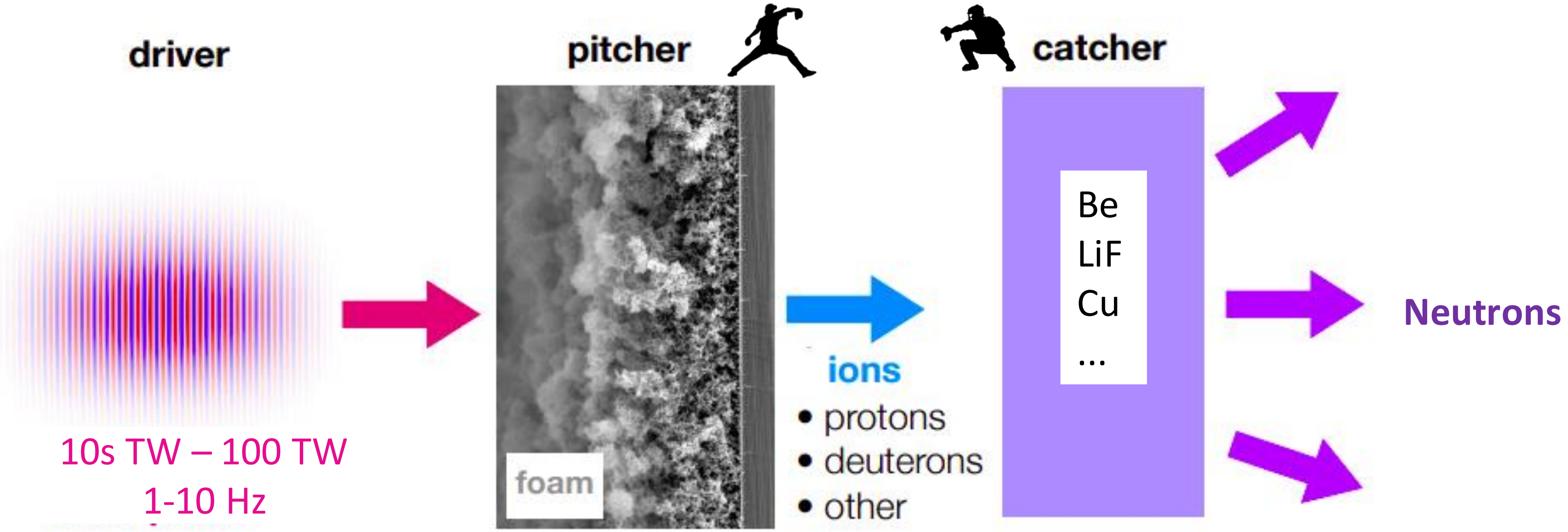
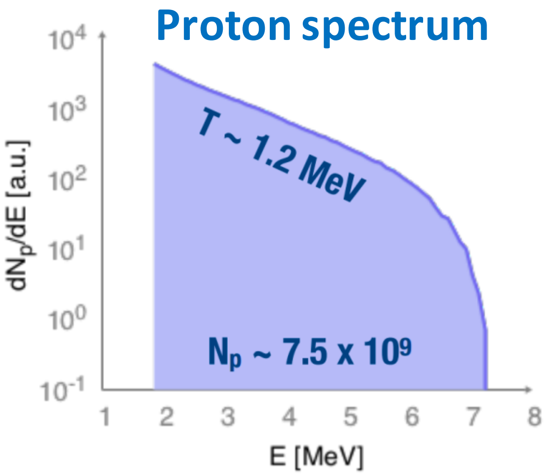
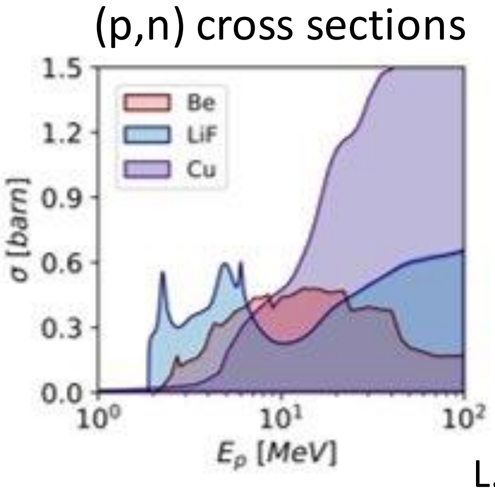
Compact laser-driven neutron generation with DLT







L. Fedeli, et al., New Journal of Physics 22, 033045 (2020)

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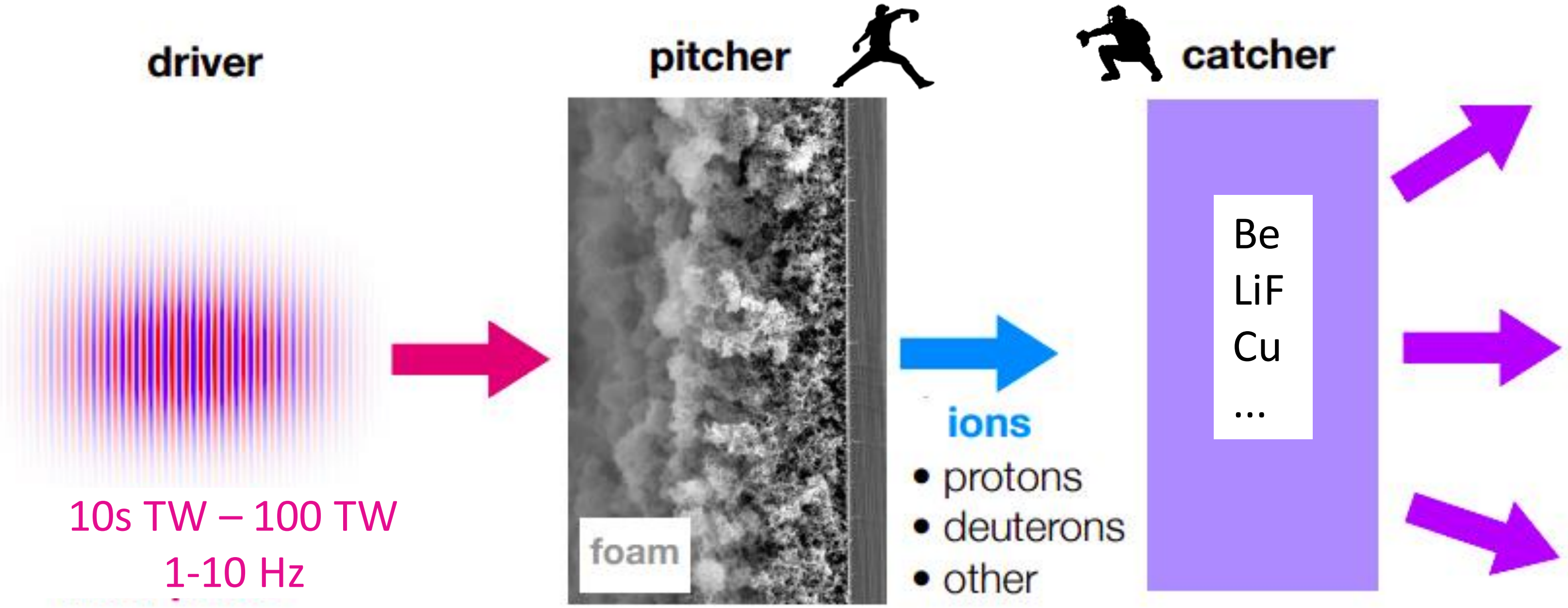
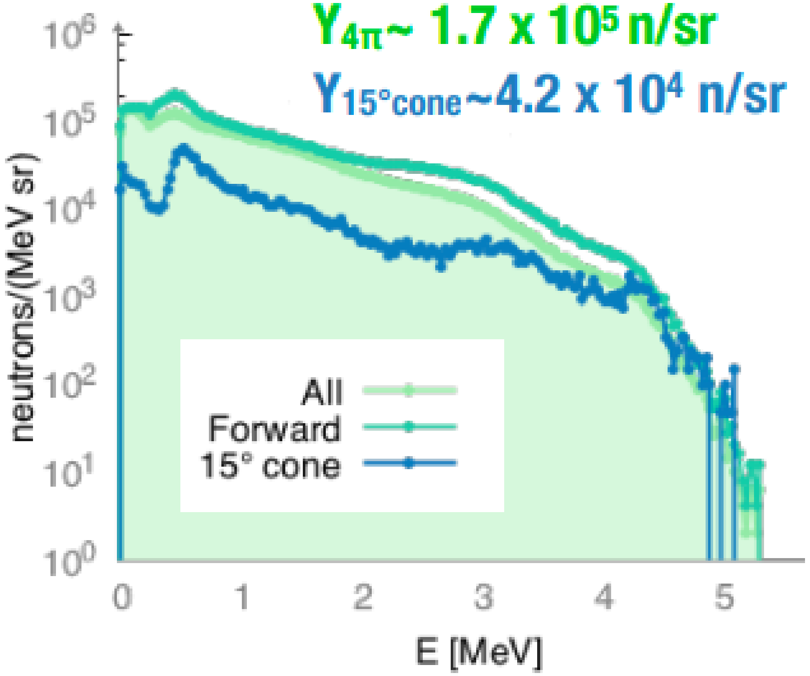
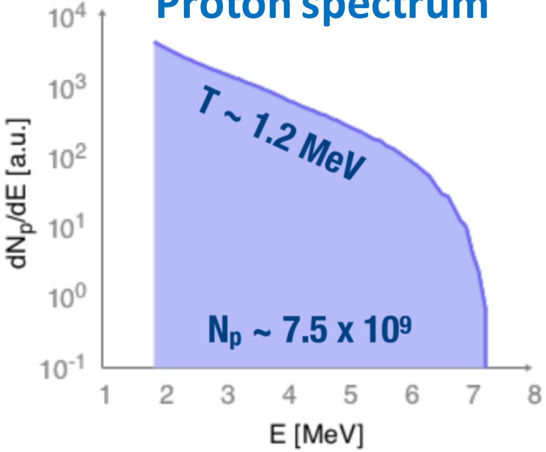


Neutron energy spectrum

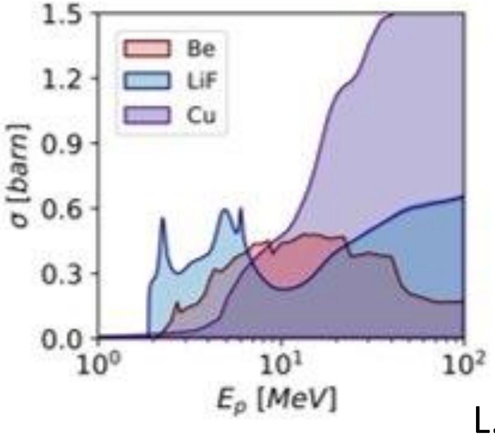


Conditions:
PIC + MonteCarlo Simulation
20 TW pulse (a0=3)
DLT: 4 µm foam ~1 n_c
LiF catcher, 1 mm

Proton spectrum



(p,n) cross sections

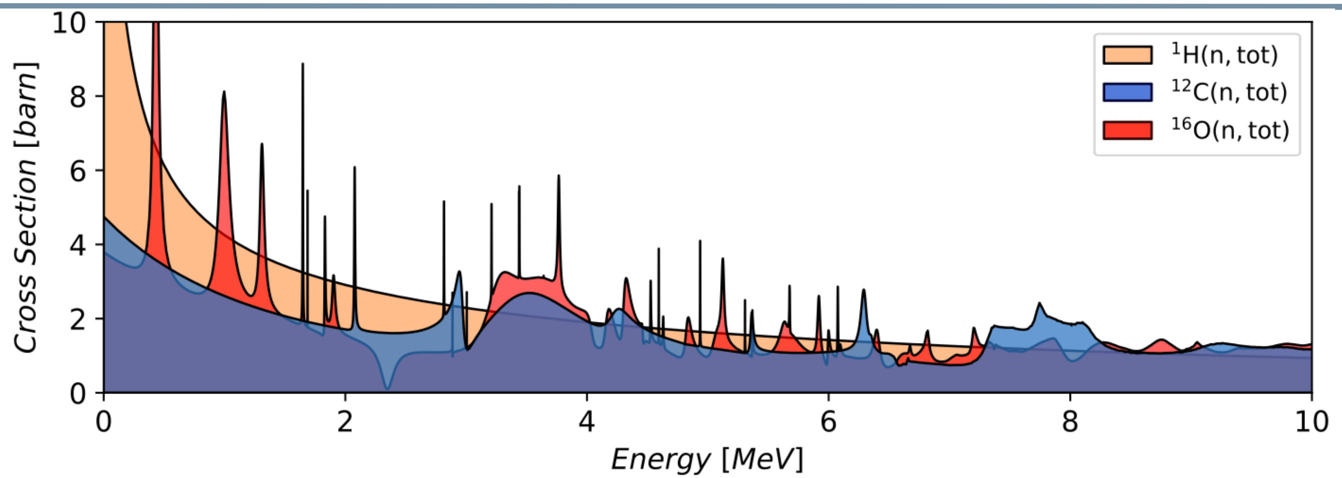


L. Fedeli, et al., New Journal of Physics 22, 033045 (2020)

Laser-driven Fast Neutron Reaction Radiography

Fast Neutron Resonance Radiography (FNRR)

- Detection and imaging of H, O, N and C (Relevant for drug & explosives)
- $\geq 10^4$ n/cm^2/s at $\geq$ 3 m distance
- Broad spectrum, 1-10 MeV



Laser-driven Fast Neutron Reaction Radiography

Fast Neutron Resonance Radiography (FNRR)

- Detection and imaging of H, O, N and C (Relevant for drug & explosives)
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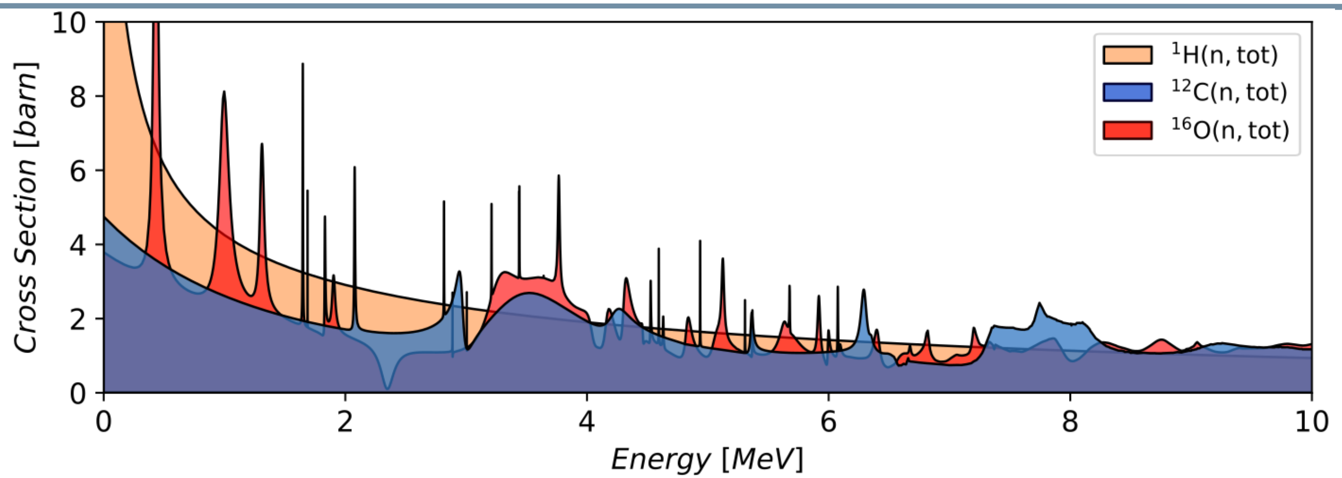
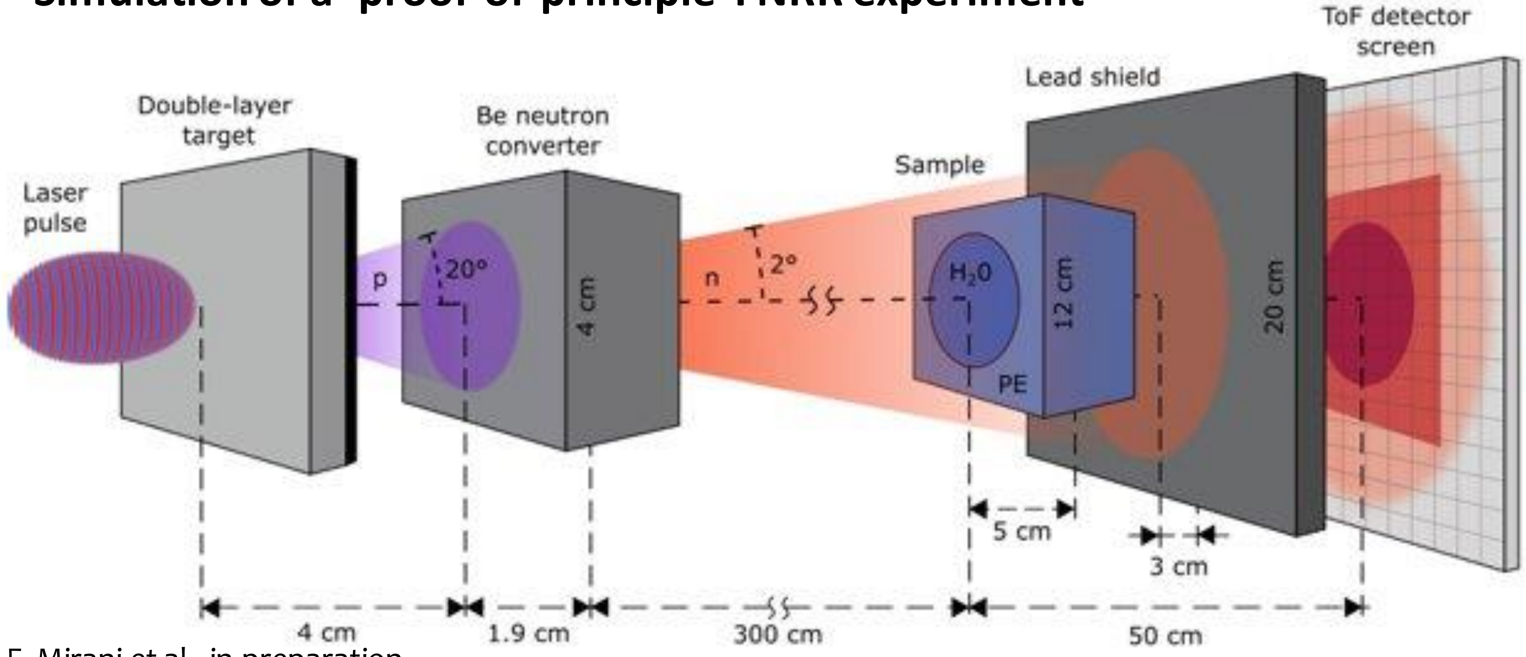


Simulation of a 'proof-of-principle' FNRR experiment



F. Mirani et al., in preparation

- PW class laser (a_0 = **10 – 20, 1-10 Hz)**
- **DLT:** 8 µm foam, ~3 nc
- Catcher: 19 mm **Be**
- Samples: $\mathbf{H_2O}$ + polythene & $\mathbf{C_{10}H_{15}N}$ + steel
- **Lead shield** ~30 mm to shield x-rays
- **Pixelated ToF detector**

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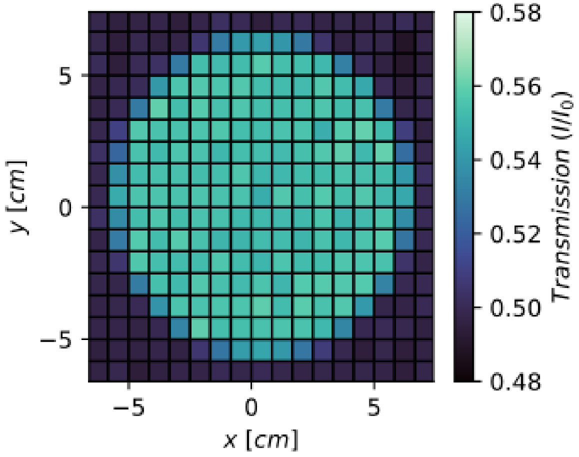
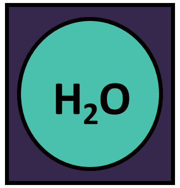
Laser-driven Fast Neutron Reaction Radiography

Transmission

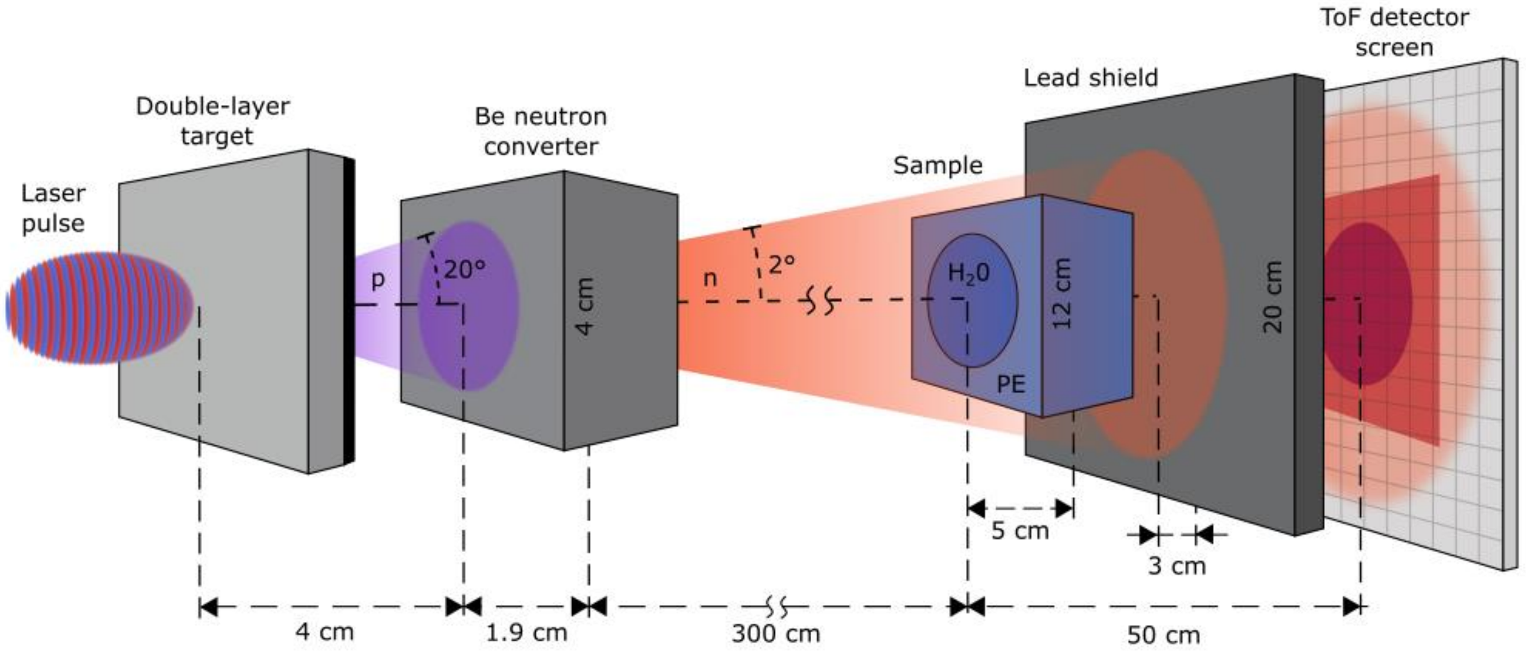


$(C_2H_4)_n$



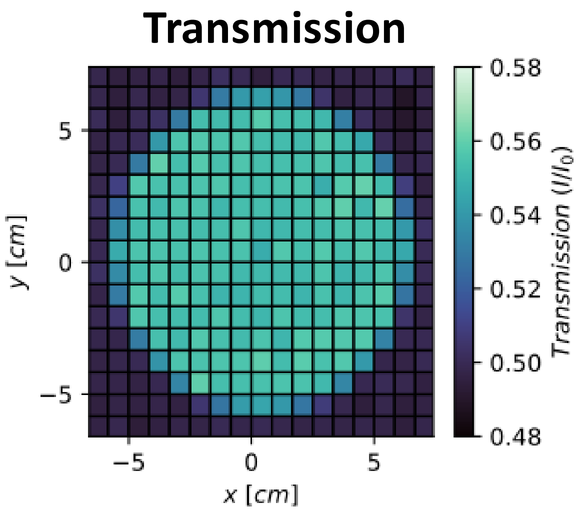
Imaging

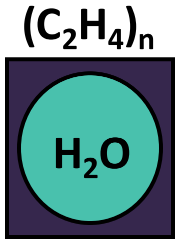
Does not discriminate elements



F. Mirani et al., in preparation

Laser-driven Fast Neutron Reaction Radiography





Imaging

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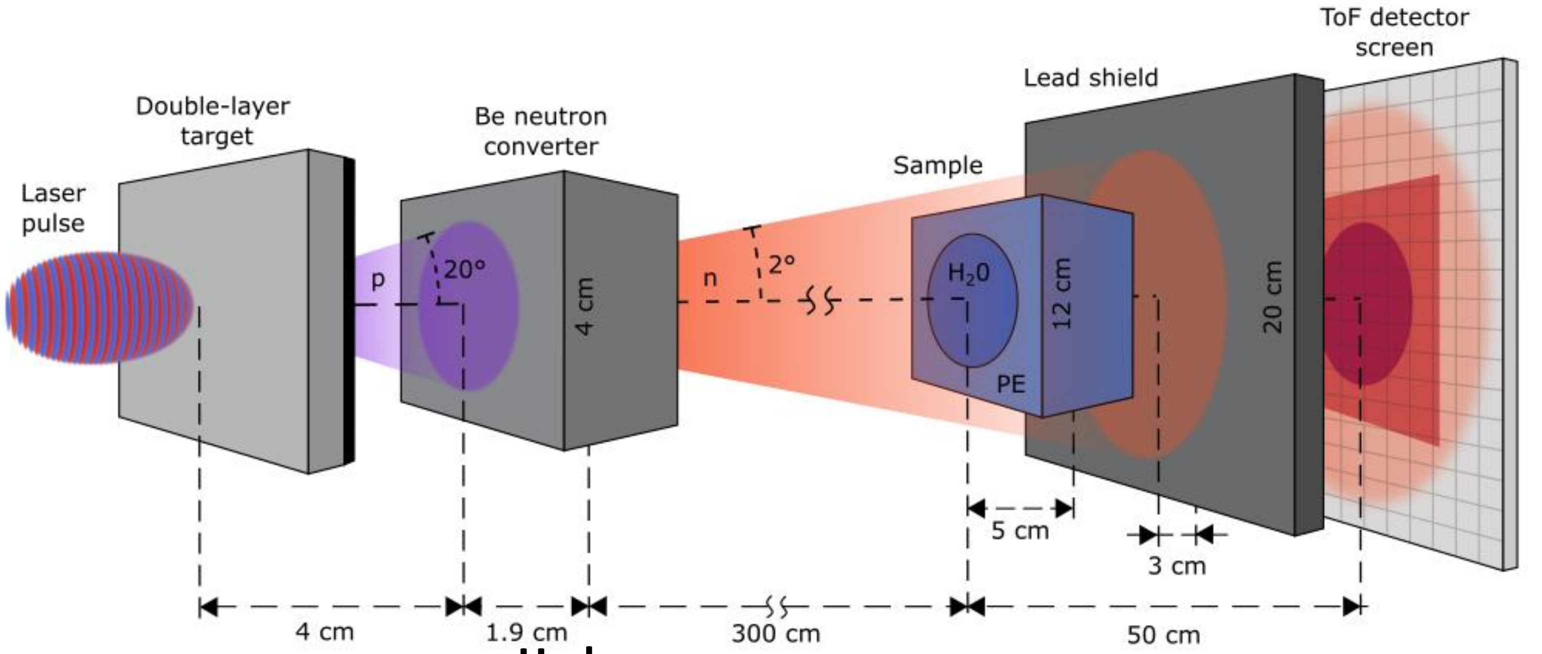
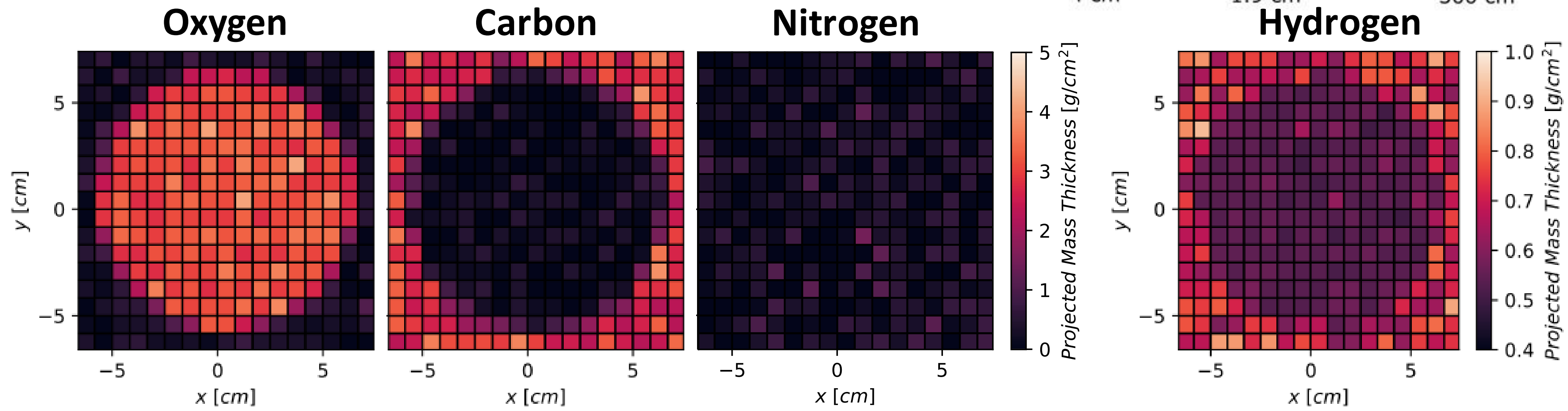




- 5 min irradiation at 1 Hz
- ~10^{11} n/sr total

Elemental Imaging Achieved

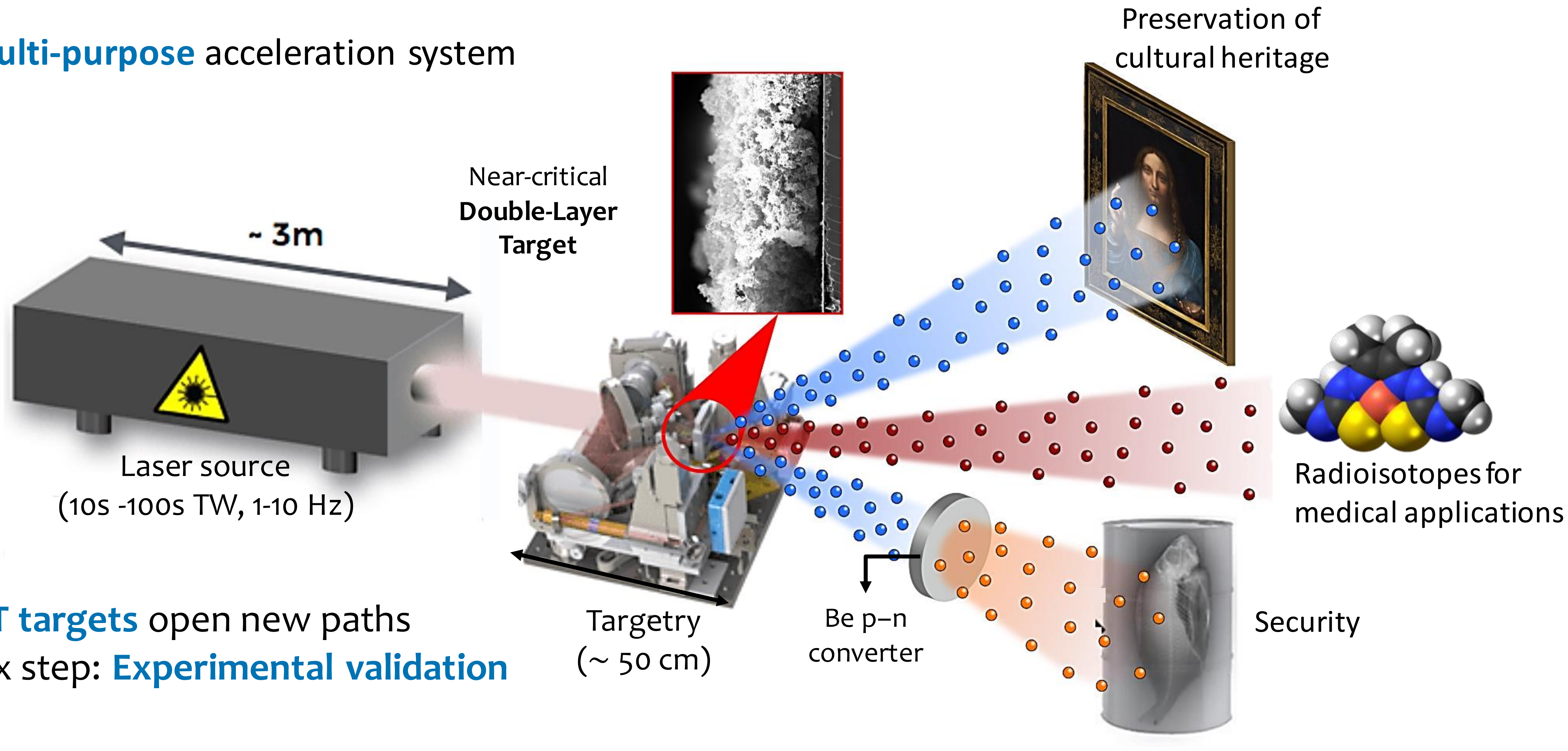
F. Mirani et al., in preparation

Outline:

- What is Laser-Driven Acceleration (and why) ?
- Case study 0: Laser-Driven Proton Induced X-ray Analysis
- Why Double-Layer Targets (DLTs)?
- Case study 1: Photon Activation Analysis with DLTs
- Case study 2: Fast Neutron Resonance Radiography with DLTs
- **Conclusion**

Conclusions and perspectives

❖ **Multi-purpose** acceleration system



❖ **DLT targets** open new paths
❖ Nex step: **Experimental validation**

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Thank you

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