Semiconductor-based proton spectrometer for laser-driven sources applications

Francesco Gatti

23/10/2024

ERC-2022-PoC No. 101069171
PANTANI

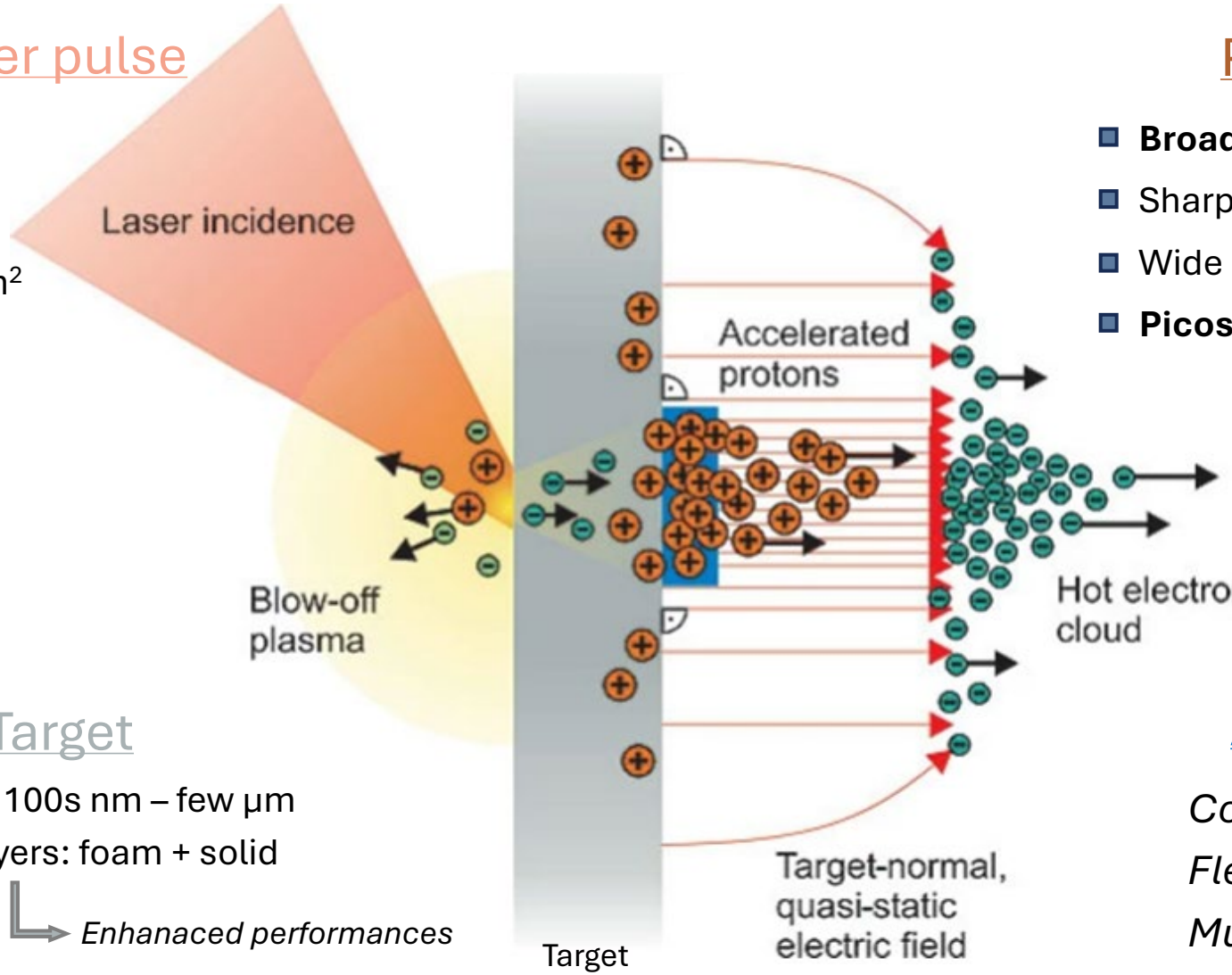
Istituto Nazionale di Fisica Nucleare

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Laser-driven ion acceleration - TNSA

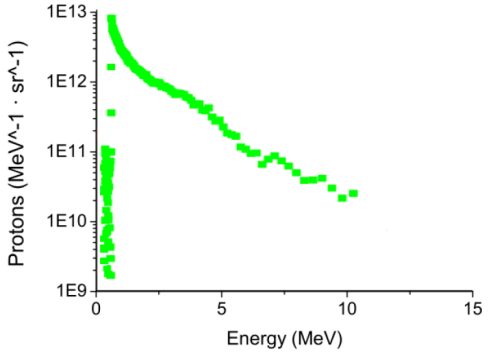
Superintense Laser pulse

τ	30 fs – 1 ps
E	0.1 – 10s J
P	10s TW – 1 PW
I	10^{18} – 10^{22} W/cm^2



Proton bunch

- **Broad exponential** spectrum
- Sharp cut-off **10s MeV**
- Wide divergence of **~10-20°**
- **Picoseconds** duration



Target

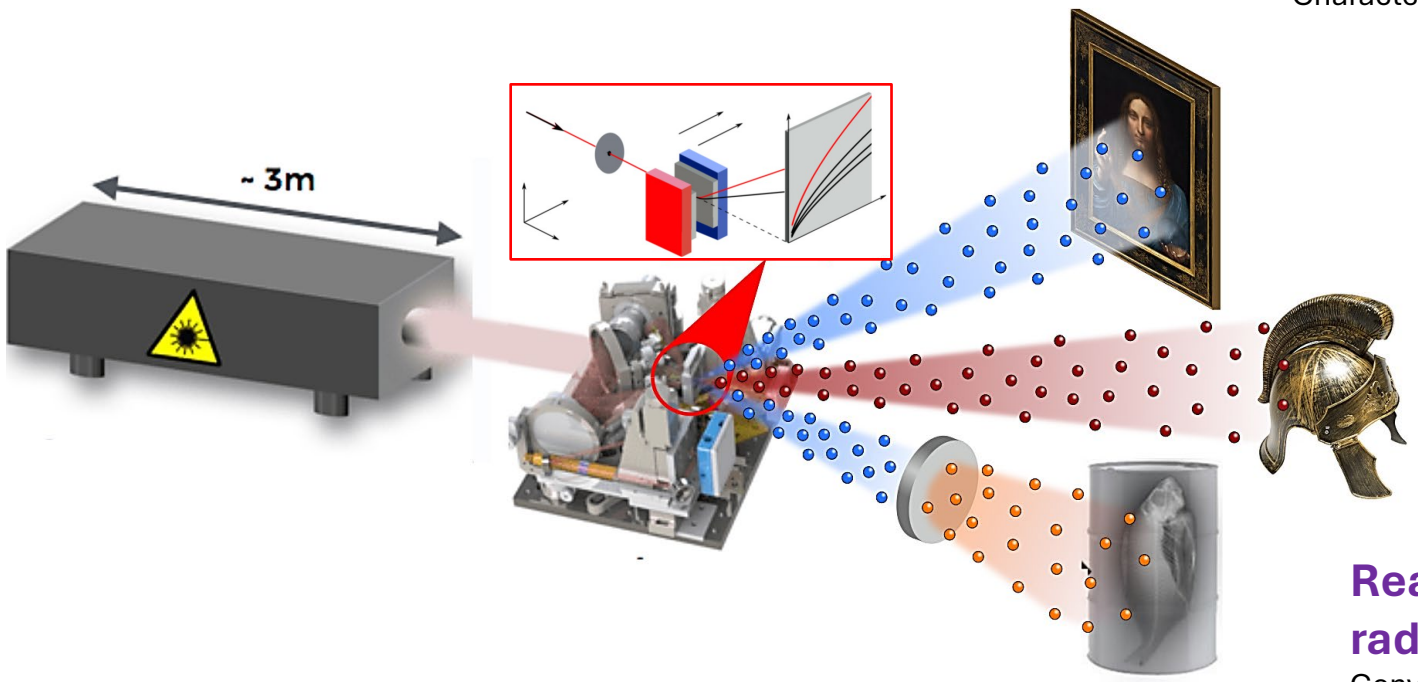
- Solid foils 100s nm – few µm
- Double layers: foam + solid
  - *Enhanaced performances*

Advantages

Compact, Cheaper, Flexible, Ultra-short, Multi-purpose

A. Macchi, et al., Rev. Mod. Phys. 85.2 (2013): 751.

Laser-driven ion acceleration - Applications



Particle Induced X-ray Emission (PIXE)

Characteristic X-rays emission induced by protons

Proton radiography

Proton Activation Analysis (pAA)

Characteristic γ-rays emission induced by protons

Reaction analysis and radiography (FNAA, FNRR)

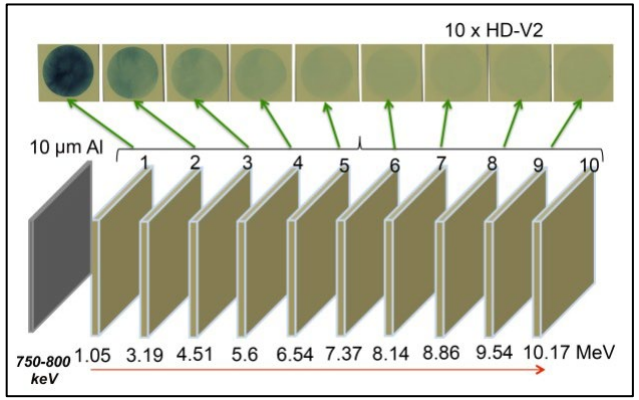
Conversion in neutrons
Characteristic γ-rays emission
Light element mapping

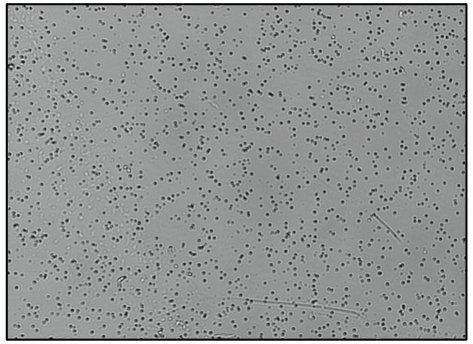
Ion diagnostics in laser-driven acceleration

Passive

Imaging by stacked layers

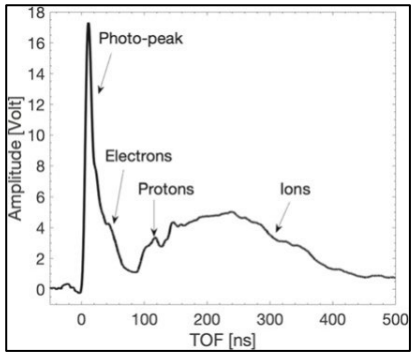
- **Radiochromic films**
- **Track detectors** (CR-39)
- Imaging plates
- Activation analysis





Spectral + agular distribution
Simple and cheap

Time consuming analysis
Calibration and saturation



Active

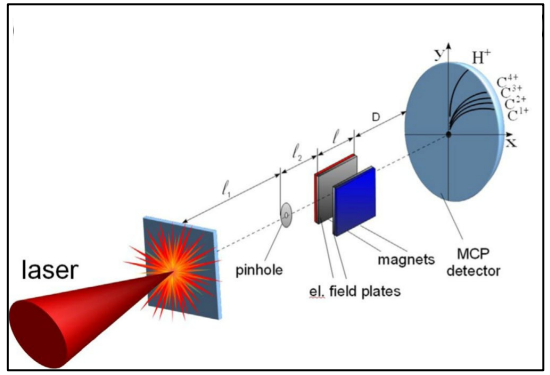
Time-of-Fligth (temporal dispersion)

Thomson Parabola (spatial dispersion)

- Microchannel plates (MCPs) + CCD
- Semiconductor detectors
- Scintillators + CCD

Real time
Discrimination of particles
High resolution and range

No angular distribution
Difficult calibration
Allignment-sensitive

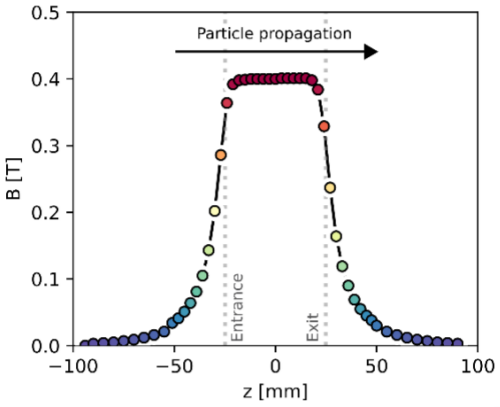


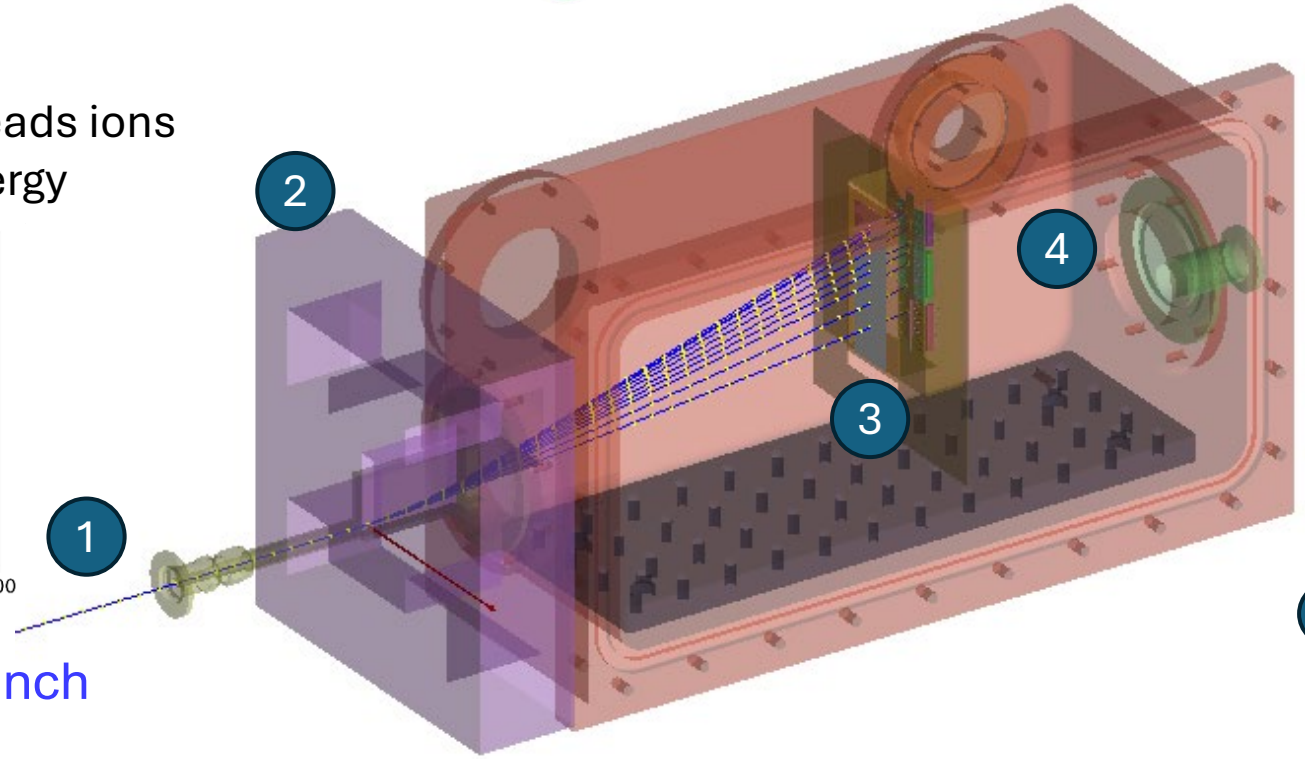
P.R. Bolton et al., Phys. Med. 30.3 (2014): 255-270.
G. Milluzzo et al., Eur. Phys. J. Plus 136.11 (2021): 1170.

Spectrometer design

1 A pinhole reduces the angular spread by selecing a small solid angle

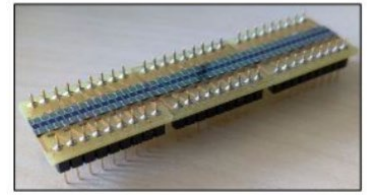
2 A dipole magnet spreads ions according to their energy





- 1 mm pinhole
- 0.4 T magnetic field
- 28.5 cm deflection distance
- 0.4 – 30 MeV energy range
- 48 pixels, ~2 mm^2

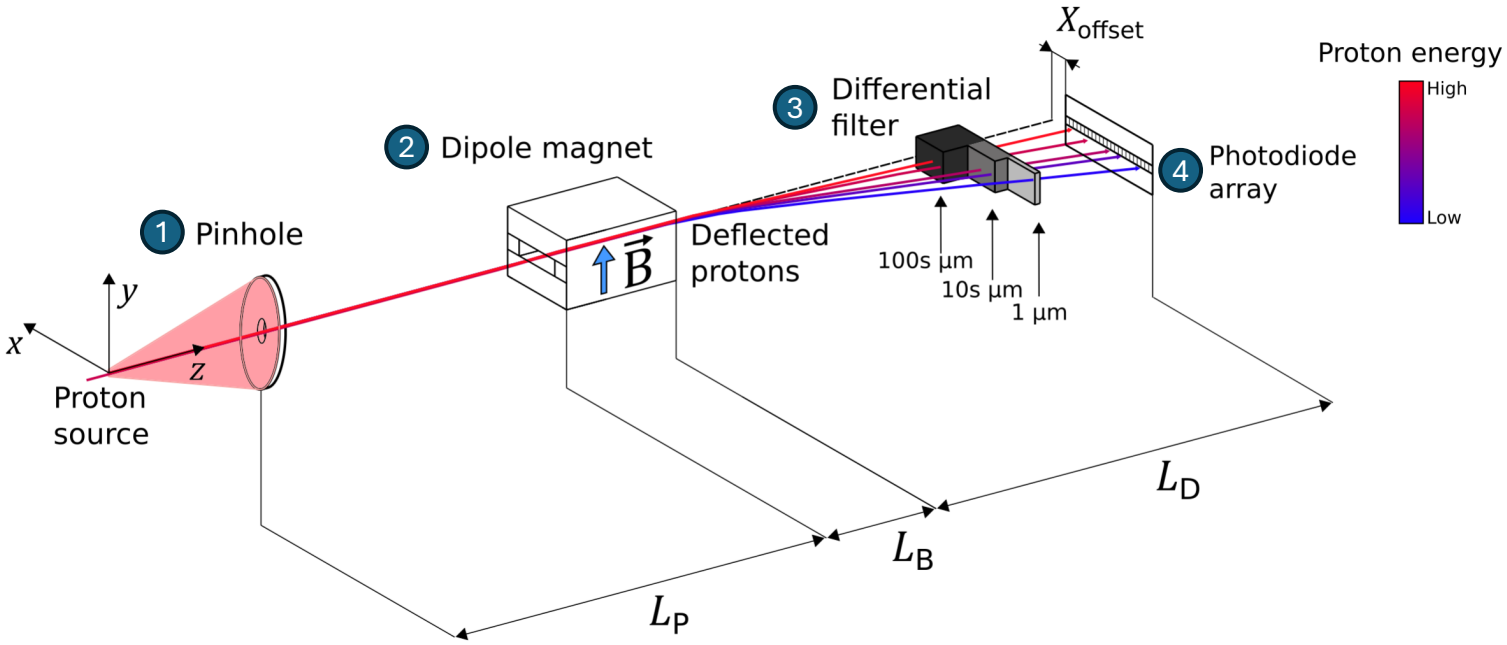
4 Photodiode arrays are used for direct proton detection



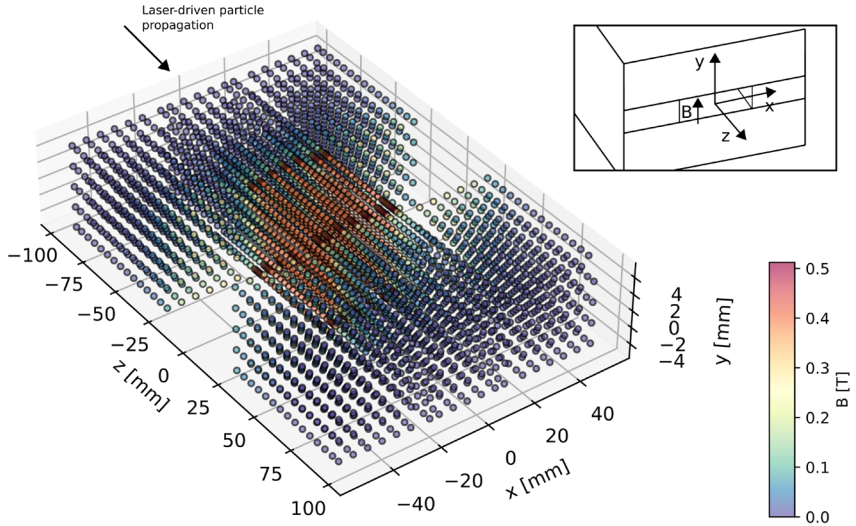
3 A differential filter is used to remove heavy ions (C-ions mainly)

F. Gatti, et al., IEEE Trans. Instrum. Meas., Early access

Characterization and modelling

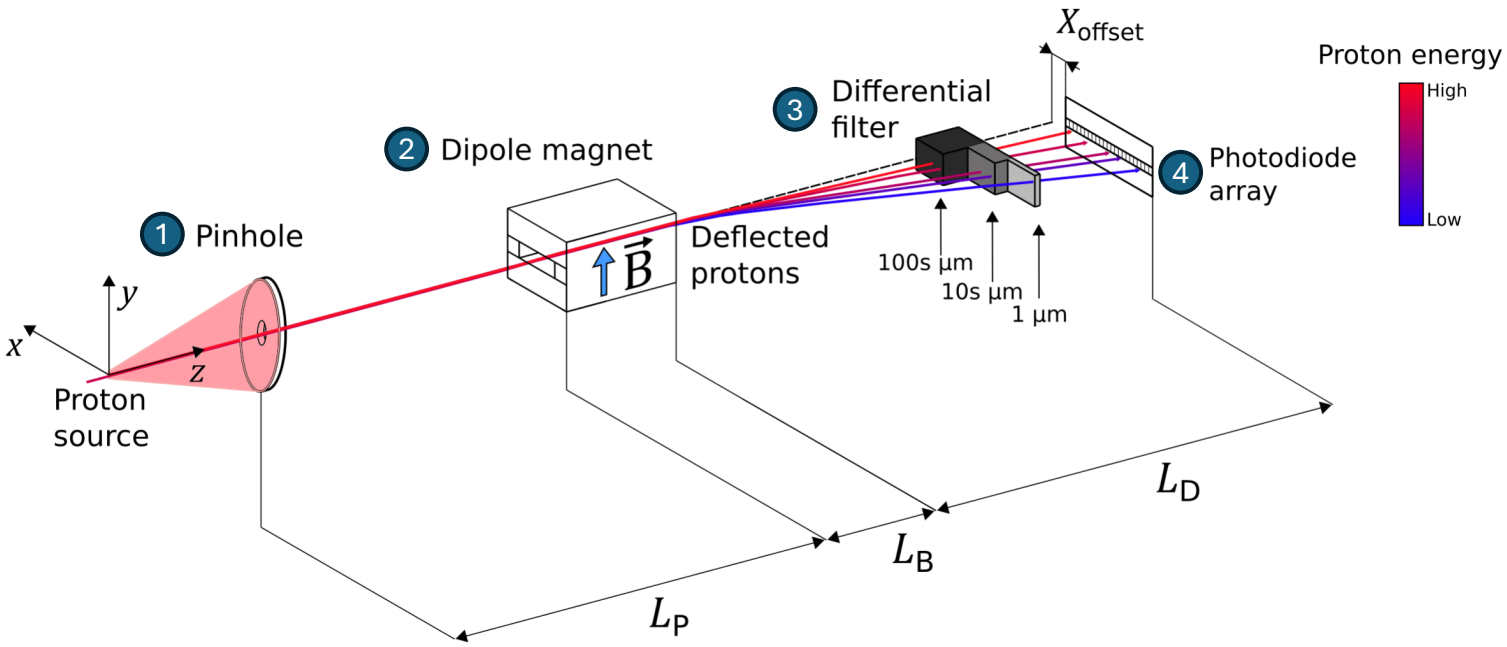


2 Electropermanent dipole magnet



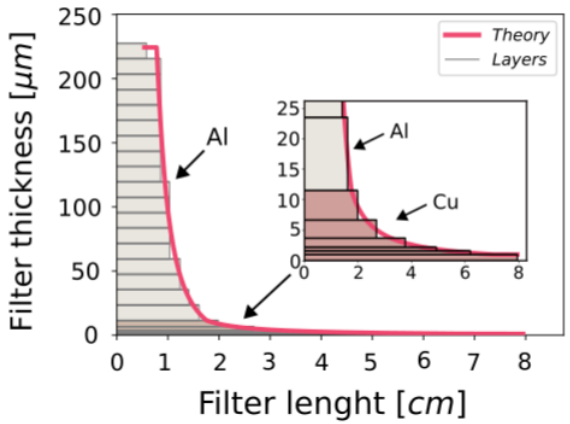
- Deflects particles according to their charge, mass and energy
- Removes electrons from the beam
- Measure of the magnetic field map
- Can be tuned and turned off; not require power supply to work; high stability

Characterization and modelling



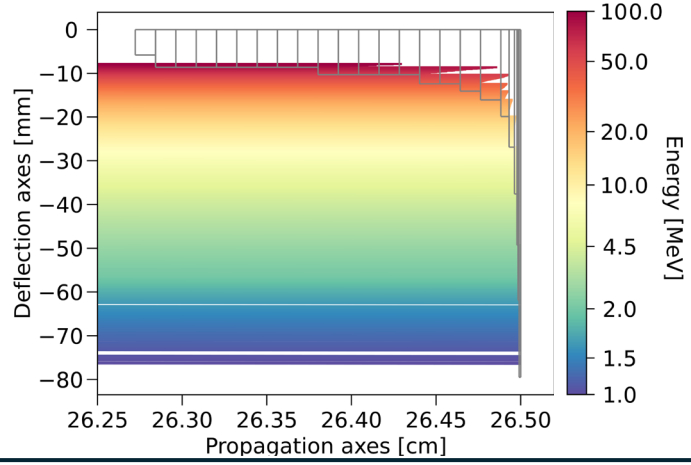
3 Differential filter

Optimized layered structure

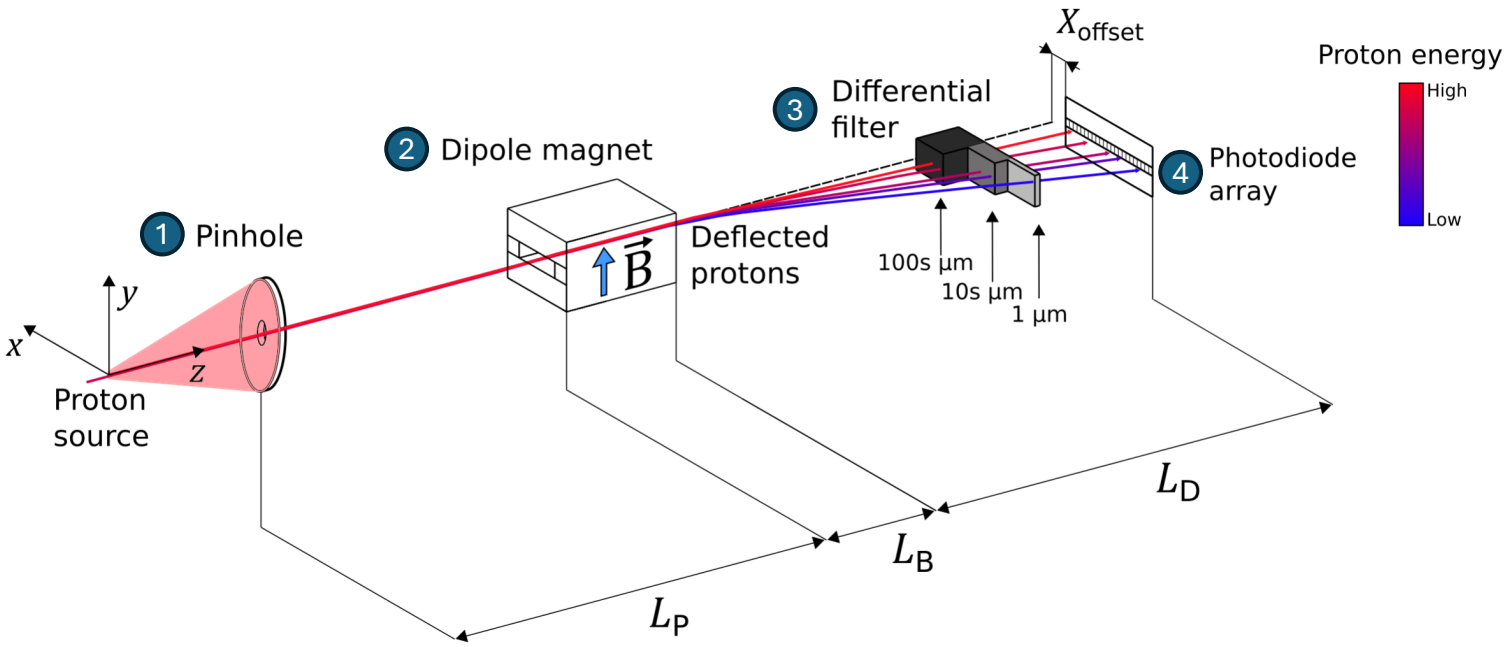


- Profile follows C-ions range in matter + magnet deflection
- Optimization of layered structure
- Produced with Magnetron Sputtering

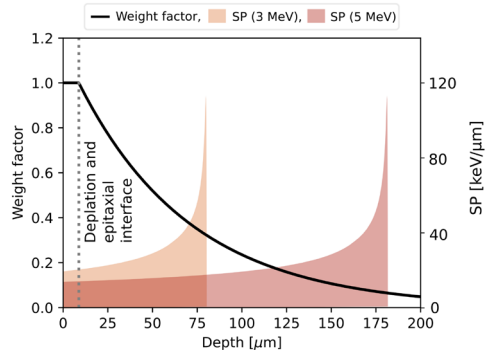
C^{6+} ions stopping efficacy GEANT4 simulations

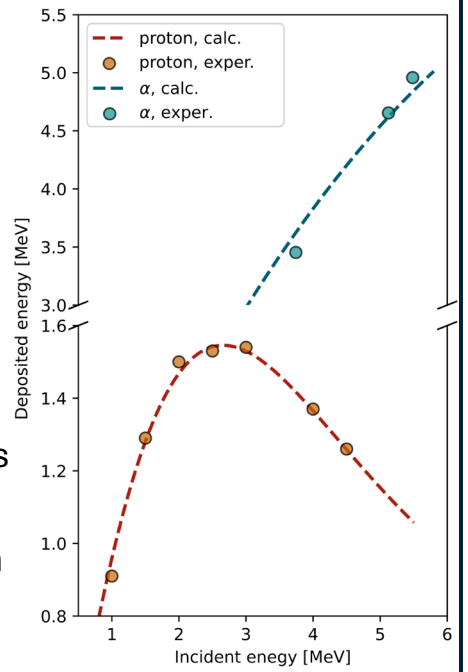


Characterization and modelling

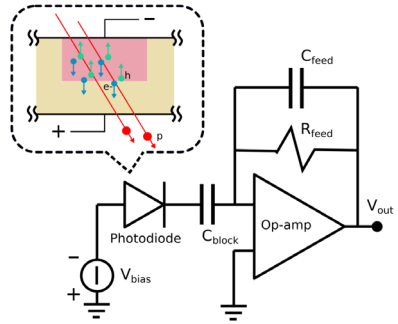


4 Photodiode arrays

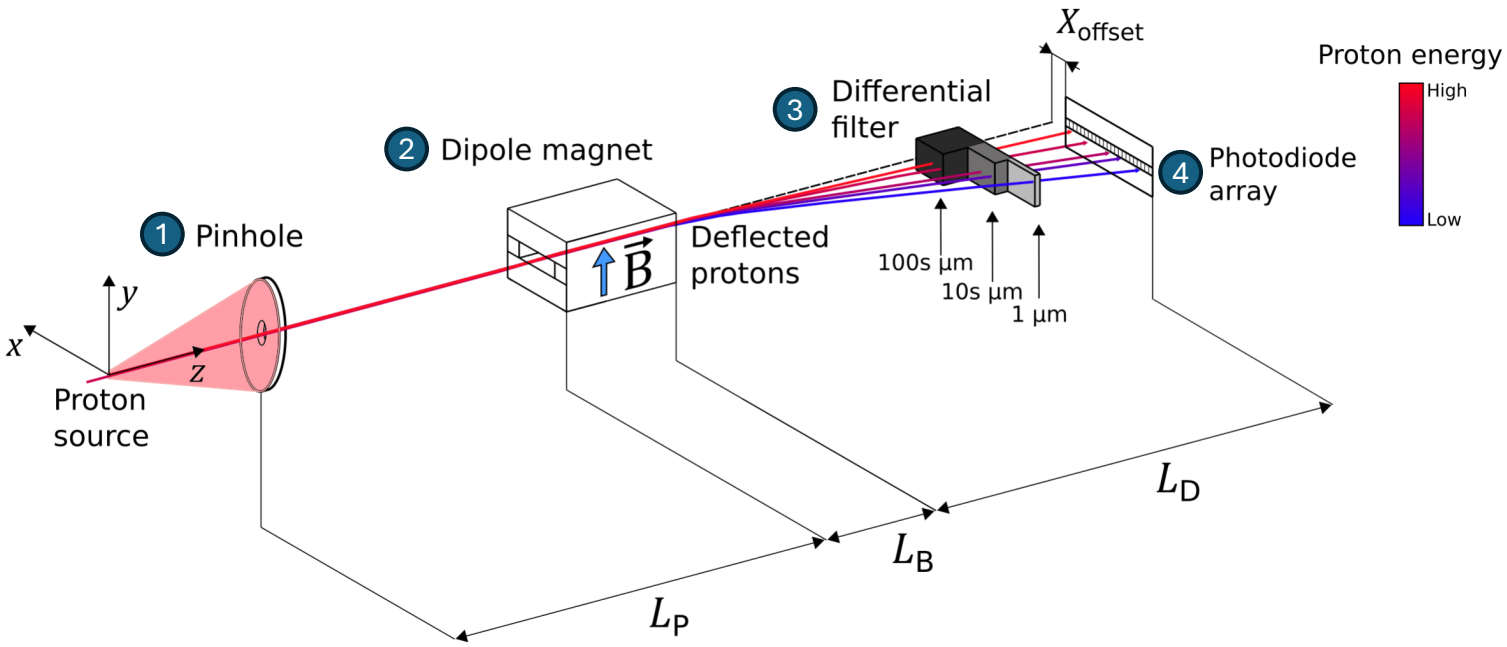




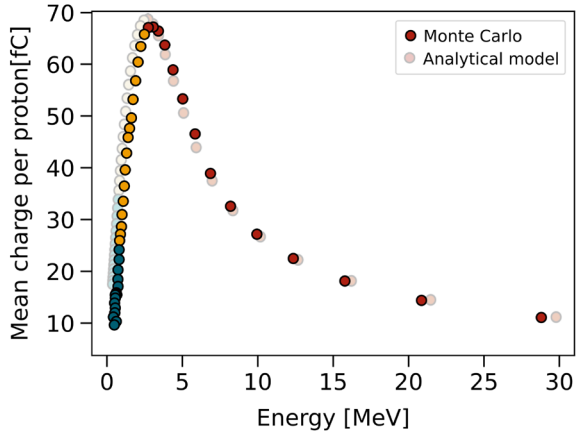
- Irradiation with alpha particles and protons
- Modelling of charge collection efficiency as constant (drift) + exponential (diffusion)
- Charge sensitive preamplifier front-end electronics single channels
- Feedback RC sized according to stopping power at different energies and exponential spectrum



Characterization and modelling



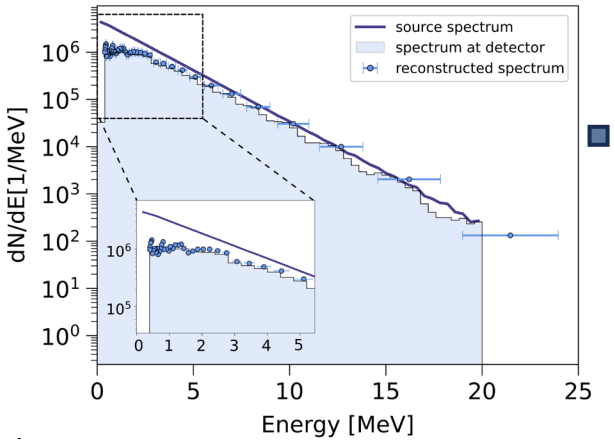
Spectrometer modelling and response matrix



- Analytical model from Maxwell eqs. do not account for the filter

- Monte Carlo simulations include the scattering

Simulation for proton spectrum recontruction

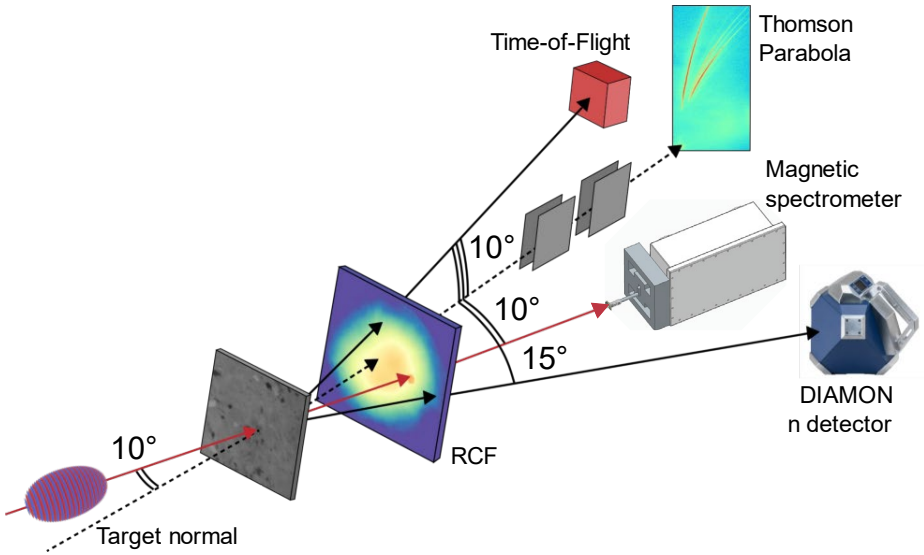


- Scattering from filter introduces a correction factor

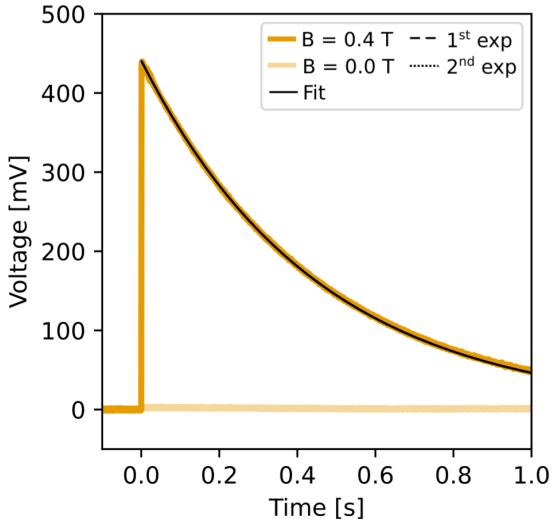
First measurements in laser experiment

Experimental campaign @ CLPU CENTRO DE LÁSERES PULSADOS with VEGA-3 laser:

- 1 PW (30 fs, 30 J)
- 12 μm FWHM focal spot
- ~1.25x10^{20} W/cm^2 on target



Recorded signals with and without magnetic field



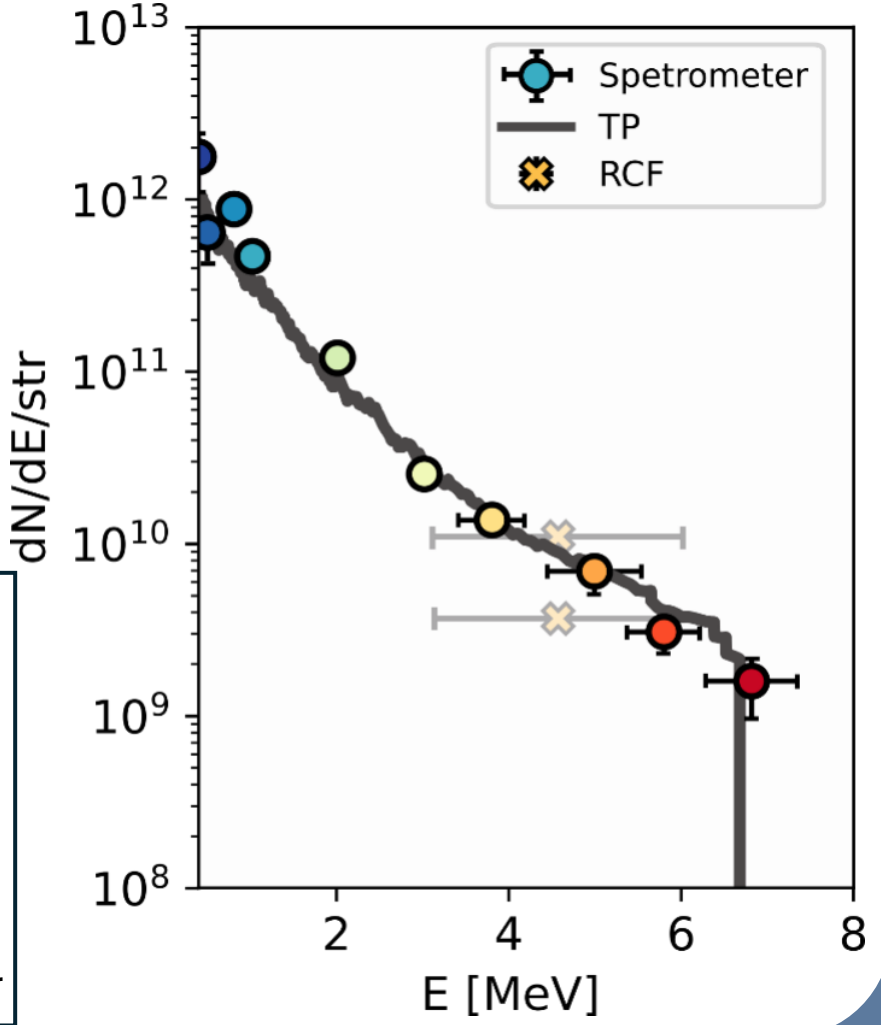
- TP: good agreement on spectrum shape
- RCF: good agreement for flux in energy range 3.5-6 MeV

TP not calibrated

↓

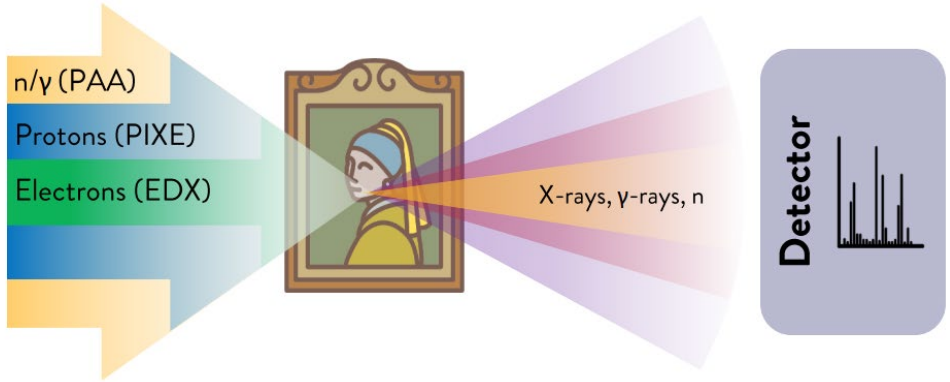
Cross calibration with our detector

Calibrate spectrum compared with the other diagnotics

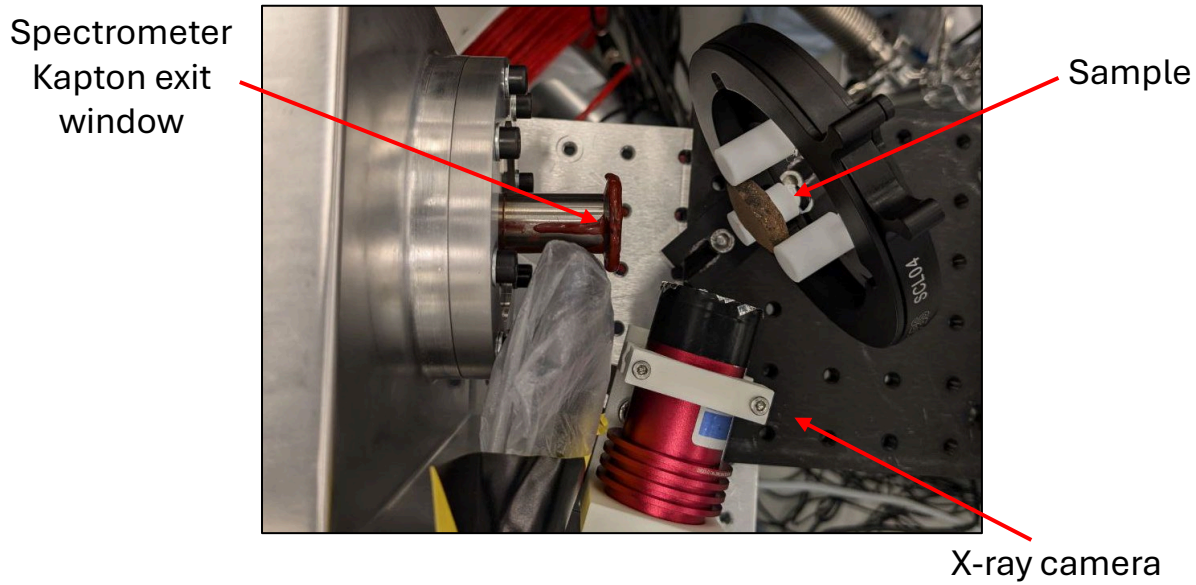


Laser-driven protons for Cultural Heritage

Experimental campaign @ eli on laser-driven PIXE for cultural heritage ongoing at this moment:



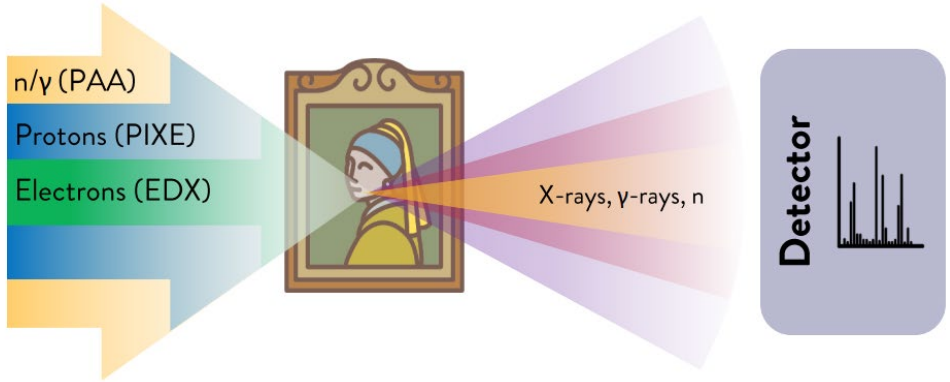
- Emission of characteristic X-rays
- Concentrations of elements and depth profiles (differential PIXE) at surface
- Probed thickness up to 1-10s μm in solids
  Non-destructive technique



- In-air measurement
- Reference metallic samples
- Archeological samples:
  - Ceramics
  - Basalt satues fragments
  - Bonze manufacts

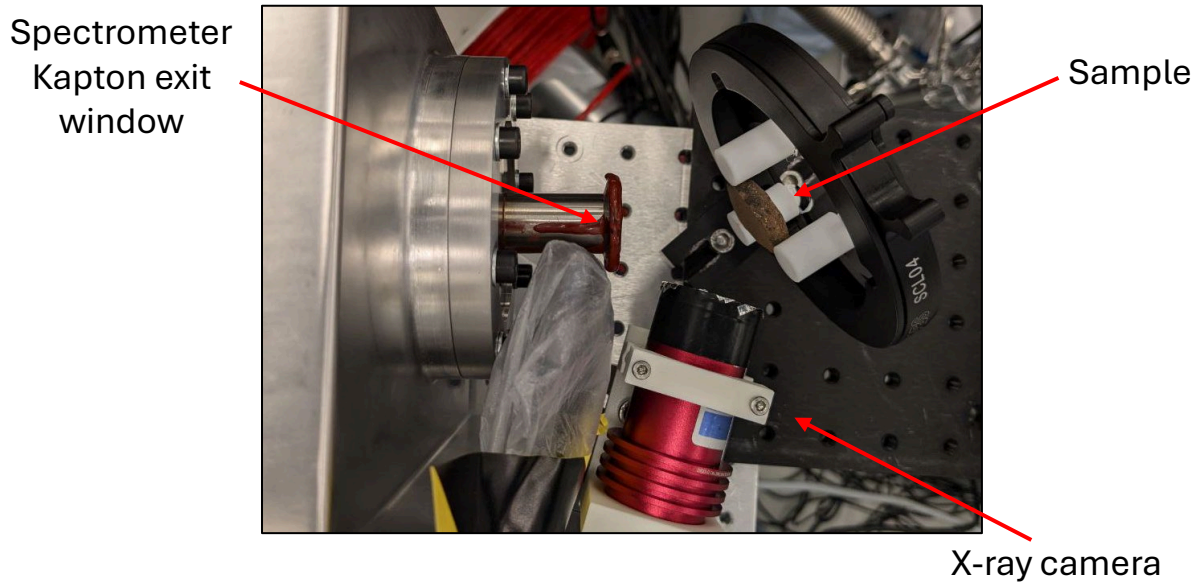
Laser-driven protons for Cultural Heritage

Experimental campaign @ eli on laser-driven PIXE for cultural heritage ongoing at this moment:



- Emission of characteristic X-rays
- Concentrations of elements and depth profiles (differential PIXE) at surface
- Probed thickness up to 1-10s μm in solids

Non-destructive technique



Tunable magnetic field of spectrometer allows different techniques exploiting the multi-radiation nature of laser-driven source:

- B → EDX + PIXE + XRF
- B → PIXE + XRF
- B → XRF

XRF depends on the target characteristic X-rays (Cu vs Al)

Conclusions and perspectives

- Magnetic spectrometers based on photodiodes can be online monitor for protons in the mixed TNSA field
- They can provide reliable quantitative spectral information
- The use of electropermanent magnet makes the instrument versatile for applications

M. Passoni
Principal investigator

A. Pola

D. Rastelli

F. Gatti

F. Mirani

D. Mazzucconi

- Complete the experiment @ eli
- Analyze the collected data on archeological samples
- Implement embedded read-out for the spectrometer
- Develop software for real-time spectrometry

www.ensure.polimi.it

ERC-2022-PoC No. 101069171
PANTANI

Thank you for the attention

POLITECNICO MILANO 1863

RAYLAB
DETECTING INNOVATION

spin off® POLITECNICO DI MILANO

ERC-2022-PoC No. 101069171

PANTANI

www.ensure.polimi.it