Innovative proton spectrometer for laser-driven accelerators

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Context and motivation

Ion acceleration

- **Short laser pulses** with **relativistic intensities**
  - Peak power: **10s TW - PW**
  - Duration: **10s fs**
  - Spot size: **few µm**
  - Intensity: **10^{18} - 10^{23} W/cm²**

$$a_0 = \frac{eE_0}{m_e \omega_0 c} > 1$$
$$\gamma = \sqrt{1 + a_0^2/2}$$

- Interaction with micrometric **solid foils** [1]: Target Norma Sheat Acceleration (**TNSA**)
- **Plasma generation**: overdense regime $n_e > n_c$

$$n_c = \frac{m_e \omega^2}{4\pi e^2}$$

- **Plasma heating:** Ponderomotive force

$$F_p = -m_e c^2 \nabla < \gamma > \qquad T_e \sim m_e c^2 (\gamma - 1)$$

- **Charge separation**: strong electric field (**MV/µm**)

$$\lambda_D = \sqrt{\frac{T_e}{4\pi n_e e^2}} \qquad eE_s \lambda_D \sim T_e$$

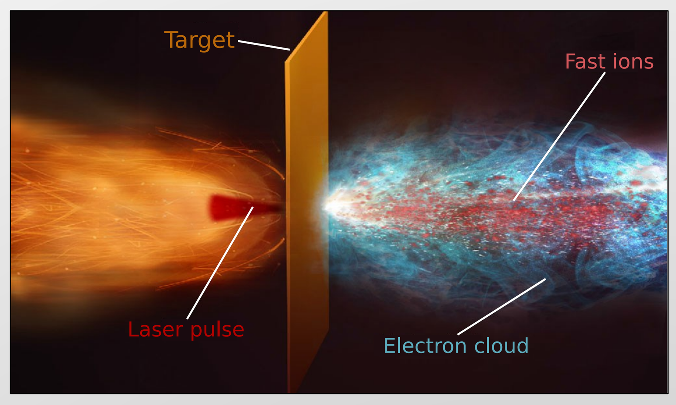
- **Acceleration** of high energy **e⁻** and **ions (H, C)**

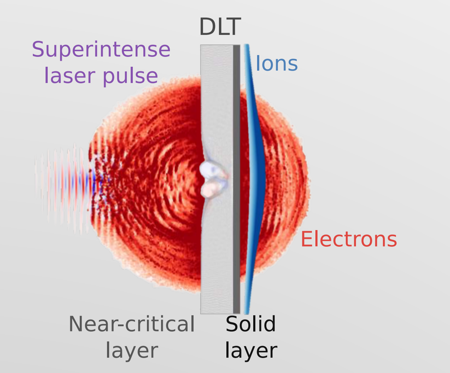
$$\epsilon_i \sim ZeE_s \lambda_D \sim ZT_e$$

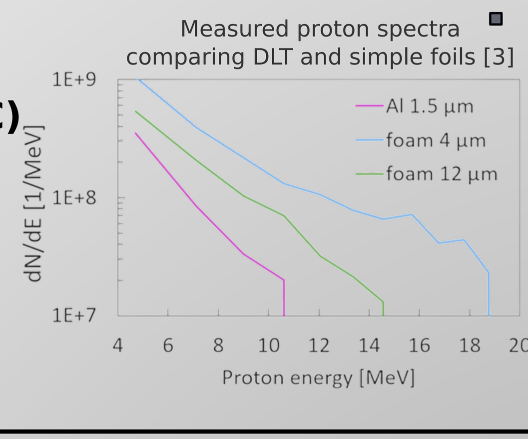
- Main characteristics of laser-driven **protons**:
  - **Short bunches** of particles (<ns)
  - **Broad energy spectra** (exponential)
  - Maximum **energy up to 10s MeV**

- **Enhanced TNSA** [2, 3]: double layer targets **(DLTs)** to **control** and improve **energy and number of particles**

⟶ **Near-critical plasma: Volumetric laser-plasma interaction + Relativistic self-focusing**





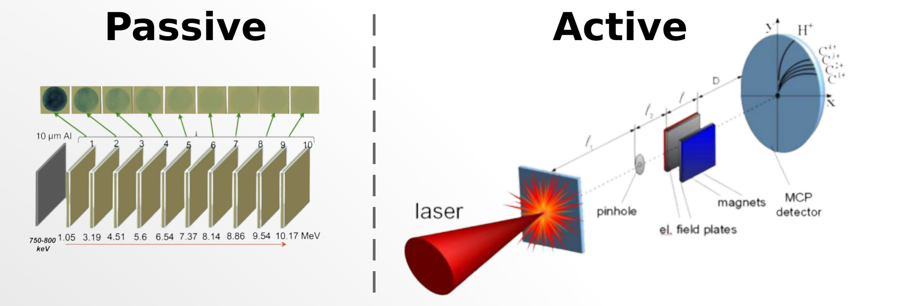


- **Compact and flexible sources** for:
  - **Materials science** (e.g., PIXE [4, 5])
  - **Radioisotopes** production
  - Physics experiments
  - ...

See the poster F. Mirani, "Target production for particle acceleration from laser interaction with near-critical nanostructured plasmas"

Ion detection

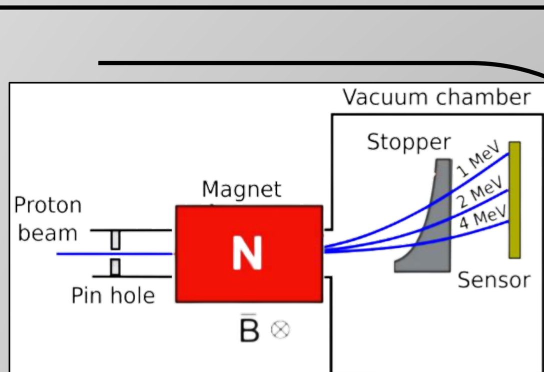
- The **characteristics of laser-driven sources** requires specific solutions for ion characterization
- Commonly adopted solutions are both active (**TPS, TOF**) and passive (**RCF, CR39**) ones

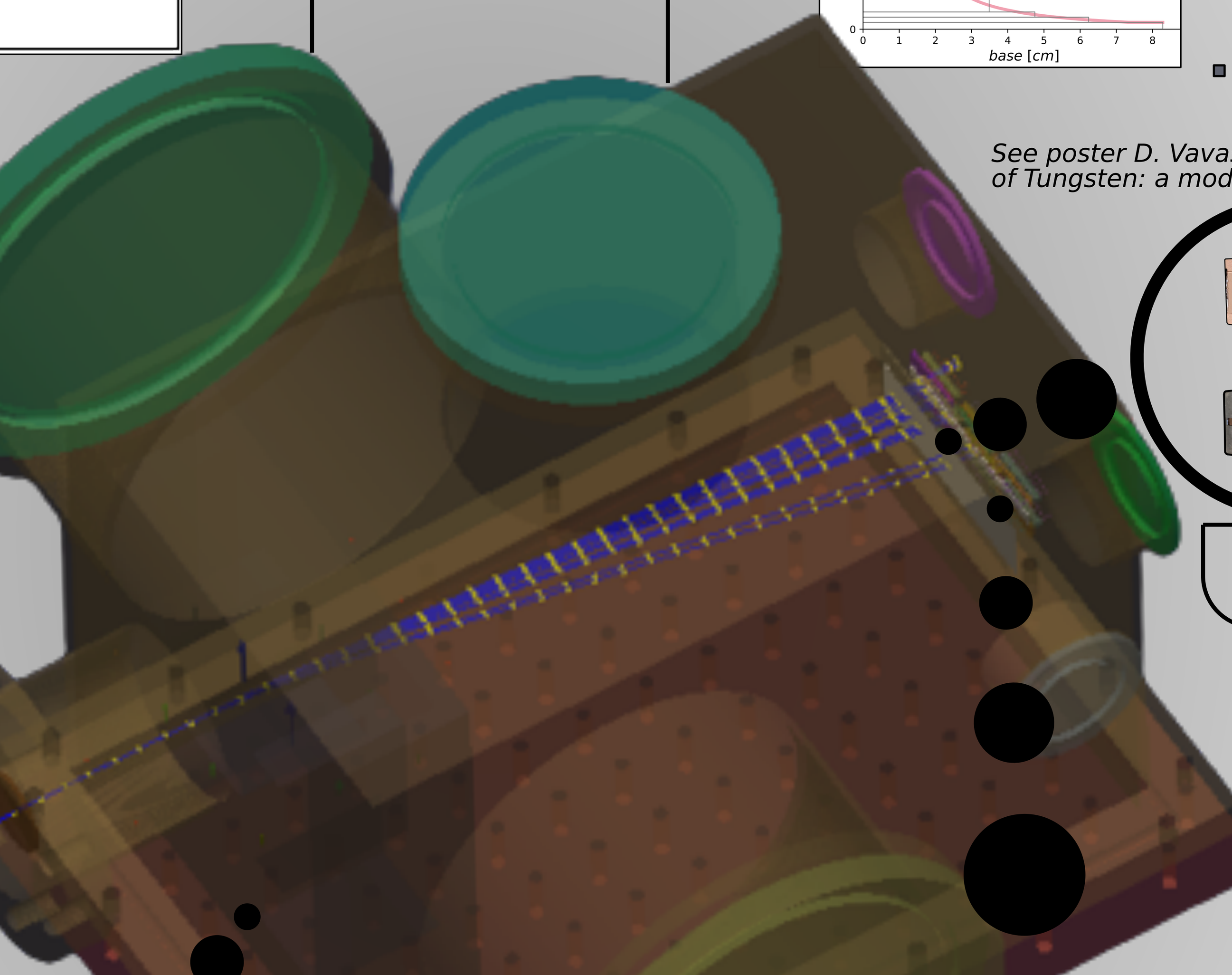


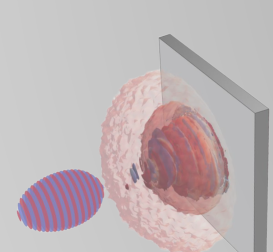
- The **standard diagnostic** is the **Thomson Parabola Spectrometer** coupled to a MCP +CCD:
  - Parallel **electric and magnetic fields**
  - Parabolic trajectories according to **q/m**
  - Position along the parabolas depend on **energy**
- General detection **chacteristics** and limits:
  - **Offline/online** data analysis
  - Energy **resolution** and range
  - Info on **angular** distribution
  - **Absolute calibration**
  - **Discriminating** different particles
- Precise characterization of the accelerated ions can give **insights on laser and plasma properties**

Concept & design

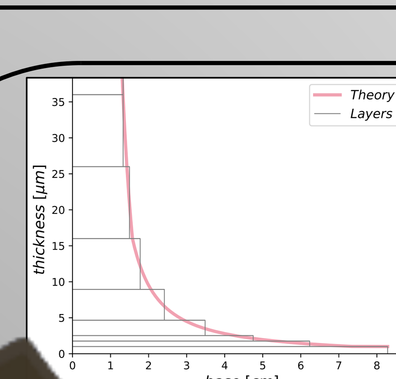
- The concept of a **proton spectrometer** for laser-driven sources is presented
- A **pinhole** selects a small solid angle
  A **magnet** deflects the charged particles
  A **filter** is used to select the protons
  Pixelated detectors detect radiation
- **Real-time** spectral analysis with **broad energy range** and **absolute calibration**
- The **narrow entrance** + the **filter** will help against unwanted **radiation, EMPs** and **debris** from **laser-plasma interaction**
- GEANT4 **Monte Carlo simulations** allow to compure the **response matrix** to relate measured signals to the **number of incident protons**





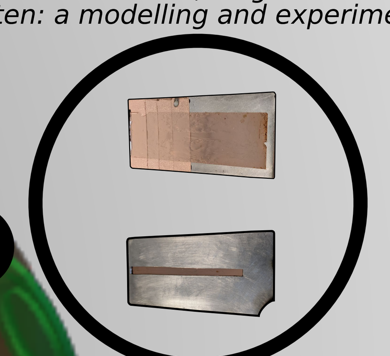


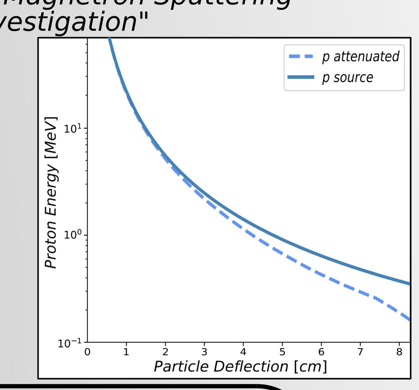
Differential filter



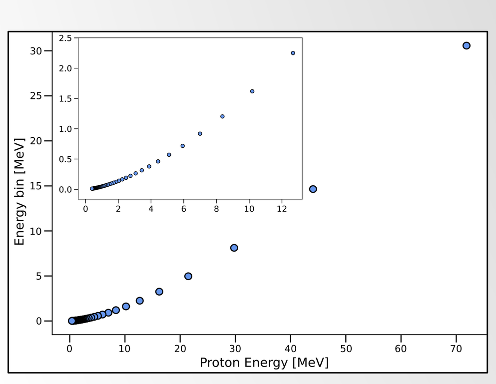
- Filter **shaped** according to **C-ion range** in matter **to stop** them and letting proton pass through with little energy loss
- Produced using **magnetron sputtering** (DCMS, HiPIMS), a **plasma-based** film deposition technique
- **Shields the detector** from other radiation (photons, EM, electrons) from laser-plasma int.

See poster D. Vavassori, "High Power Impulse Magnetron Sputtering of Tungsten: a modelling and experimental investigation"

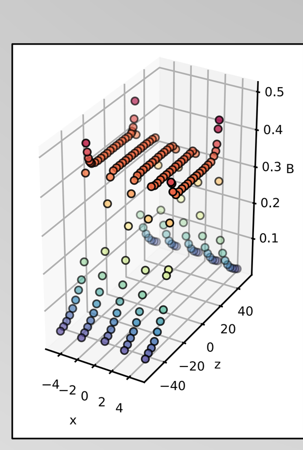




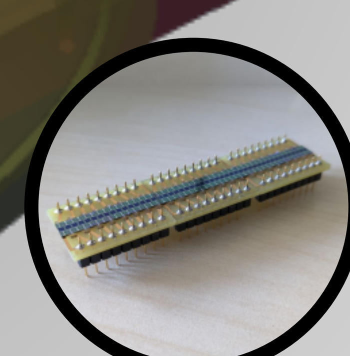
Dipole magnet



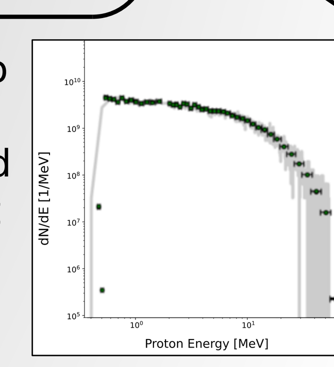
- The dipole magnet **deflects** particles according to ther **charge**, **mass** and **energy**
- **Electrons** are removed from the beam
- **Intensity and length** of the magnet are related to the **energy resolution** of the spectrometer
- Precise knowledge of the **magnetic field map** is needed for the design of the device:
  - Gaussmeter measurements
  - Test with charged particles (accelerator)

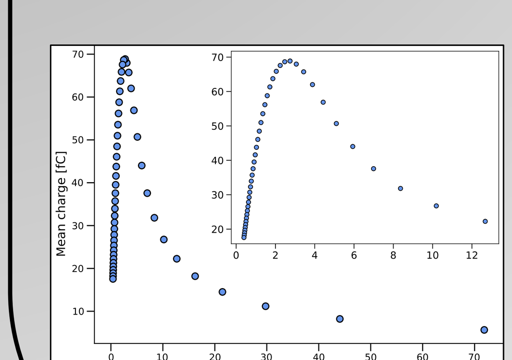


Pixelated detector



- Each pixel is associated to an **energy bin** related to its physical dimension and distance from the magnet
- Integrated data analysis with **ad-hoc electronics**





- The correspondance between proton energy and charges generated in the pixels allow to retrieve the **total number of interacting particles**
- Detectors are operated in **current mode**: the total signals are integrated and then divided by the **calibration curve**
- Total signals are the **convolution** of the calibration curve and the exponential shape of the proton energy spectrum

Conclusions and perspectives

- The proposed **spectrometer** is a promising device to **characterize** laser-driven **protons** in **real time** with **absolute calibration**
- **Magnetron sputtering** proved to be a good plasma technique to produce the layered ion **filter**
- **Theoretical modelling** and **first experimental characterization** of magnet, differential filter and sesors paved the way for **use in laser-driven experiments**

⇒

- Extensive **Monte Carlo** simulations to be performed to build the response matrix
- The ad-hoc **front-end electronics** have to be tested
- The device will be tested at an **electrostatic accelerator** (Oct-Dec 23 @ LNL)
- The spectrometer will be used in **PW-laser** experiments @ CLPU

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Bibliography:

[1] A. Macchi, et al., Rev. Mod. Phys. 85.2 (2013): 751.
[2] A. Maffini, et al., Appl. Surf. Sci. 599 (2022): 153859.
[3] I. Prencipe, et al., New J. Phys. 23.9 (2021): 093015.
[4] M. Passoni, et al., Sci. Rep. 9.1 (2019): 9202.
[5] F. Mirani, et al., Sci. Adv. 7.3 (2021): eabc8660.
[6] P.R. Bolton et al., Phys. Med. 30.3 (2014): 255-270.
[7] G. Milluzzo et al., Eur. Phys. J. Plus 136.11 (2021): 1170.