Design of proton diagnostics operating at high repetition rate to advance proton fast ignition

PPPL FOCUSED

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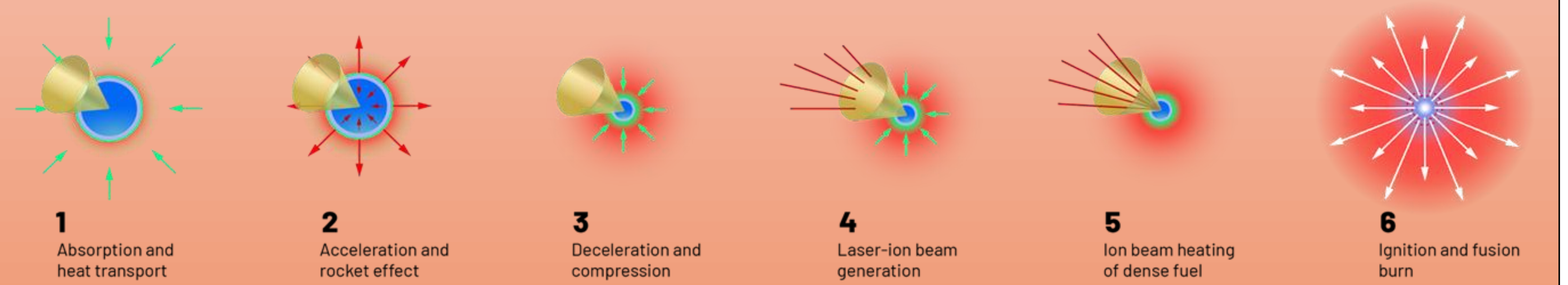
Problem Statement

Laser-driven proton fast ignition (PFI) is a promising path toward high-gain inertial fusion energy because it separates fuel compression and heating, enabling higher gain, relaxed symmetry requirements, and more robust implosions. Focused Energy Inc. considers PFI as one of the approaches for commercializing the fusion energy.

PFI ignition requires a ~ 20 kJ, 4–8 MeV proton beam focused to 15–20 µm within 10–20 ps in the fuel assembly



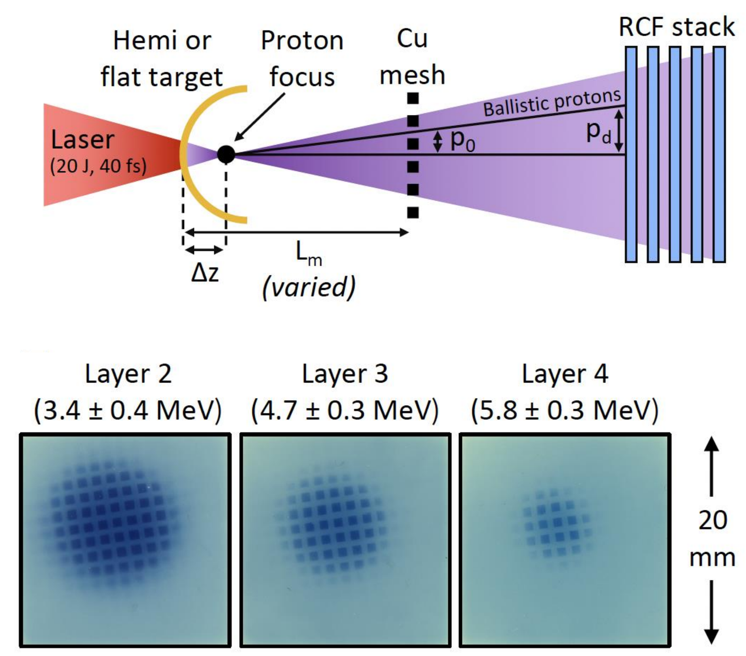
- **New-gen fusion facilities are coming online to demonstrate proton fast ignition and optimize performance at scale**

- To enable these studies, novel diagnostics are required that can:
  - Measure angularly-resolved proton spectra (3–50 MeV)
  - Resolve 2D proton profiles with <5 µm spatial precision across energy bins
  - Operate at shot-every-few-minutes repetition rates
  - Survive multi-kJ, picosecond-class laser EMP environments

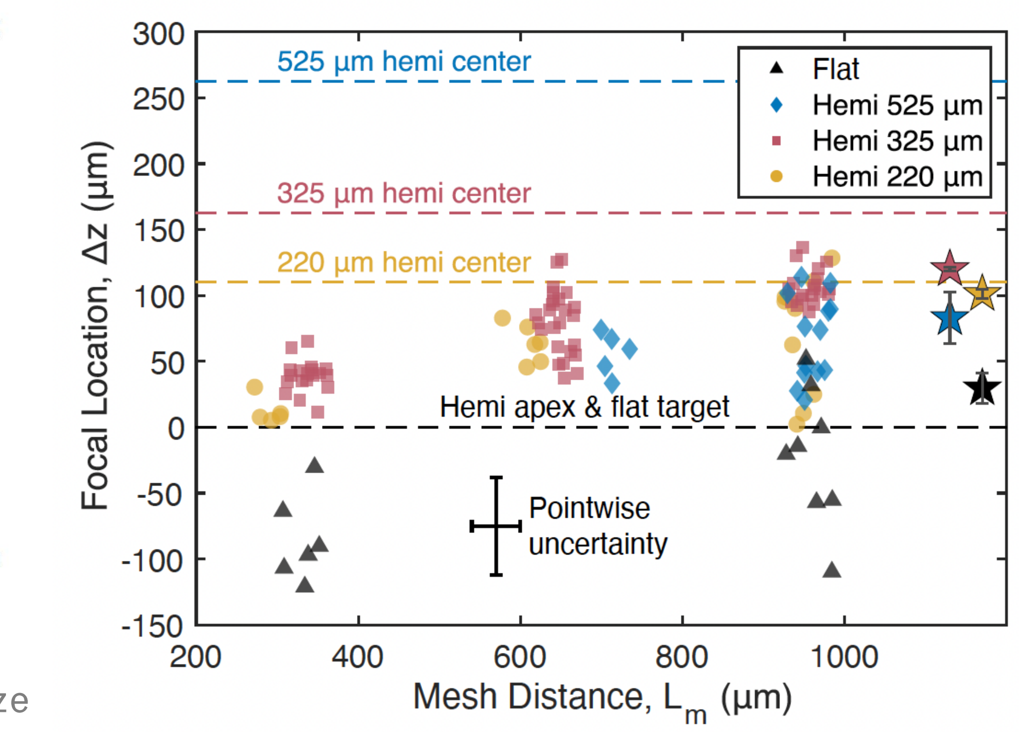
Our team is developing diagnostic systems that meet these requirements through an integrated approach combining high-rep experimental validation and numerical modeling.

2D proton imaging for studying proton focusing dynamics

- We performed the first high-shot-rate parametric study of laser-driven proton focusing from hemispherical targets at LaserNetUS CSU ALEPH laser facility [1]
- **Goals:**
  - Understand how target geometry ($\Psi = D_{hemi}/D_{laser}$) influences focusing quality
  - Assess requirements for high repetition rate 2D proton imaging detector



Mesh radiography setup used to characterize proton focusing.



Virtual focal location Δz as the mesh distance L_m is varied. RCF layers 2, 3, and 4 are shown. The stars on the right side are the inferred physical focus from fitting hyperbolic trajectories to the data with error bars indicating the fit uncertainty

Findings:

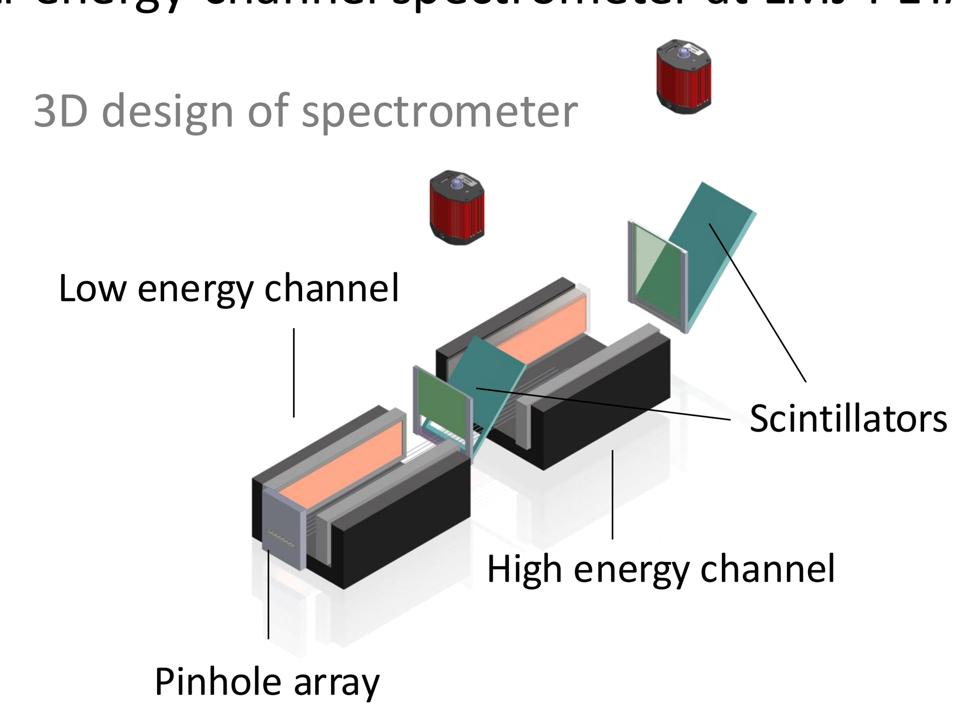
- Smaller hemispheres (Ψ ≈ 6) focus protons near the geometric center
- Larger hemispheres (Ψ > 10) show degraded focusing, similar to flat targets
- Physical focal location shifts inside the hemisphere as diameter increases
- → best focusing at Ψ ≈ 6
- Beam pointing more sensitive for small hemispheres due to laser pointing jitter
- Large dataset enabled reliable statistical trends, unlike prior <5-shot studies

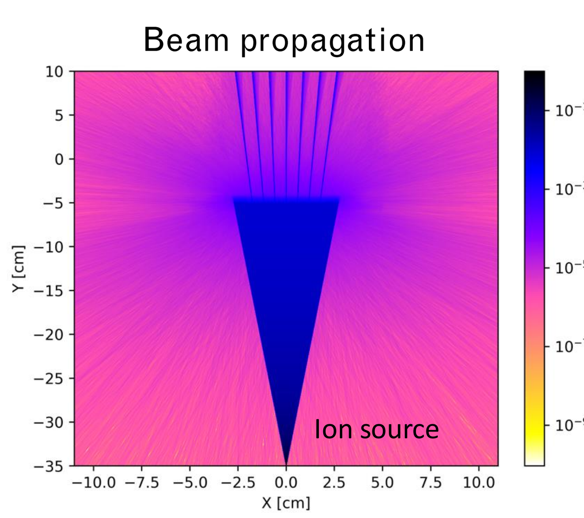
[1] J. Griff-McMahon, X. Vaisseau, W. Fox, K. Lezhnin, K. Bhutwala, R. Nedbailo, V. Ospina-Bohorquez, T. Karpowski, P. K. Patel, and S. Malko , "Geometric scaling of laser-driven proton focusing from hemispherical foils" submitted to PRR (Oct. 2025)

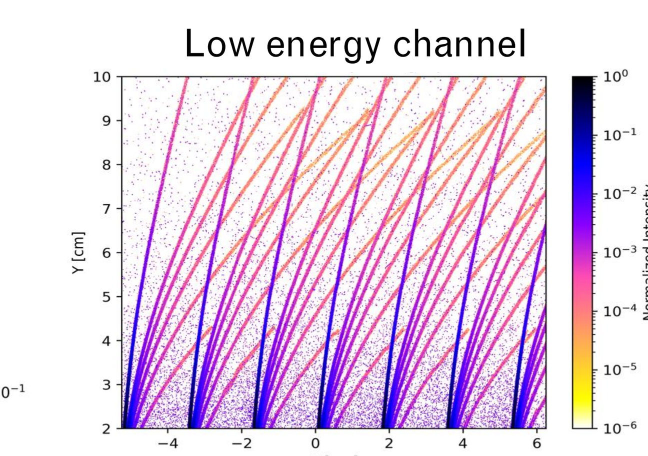
Angularly-Resolved Multi-Channel Ion Spectrometer Concept

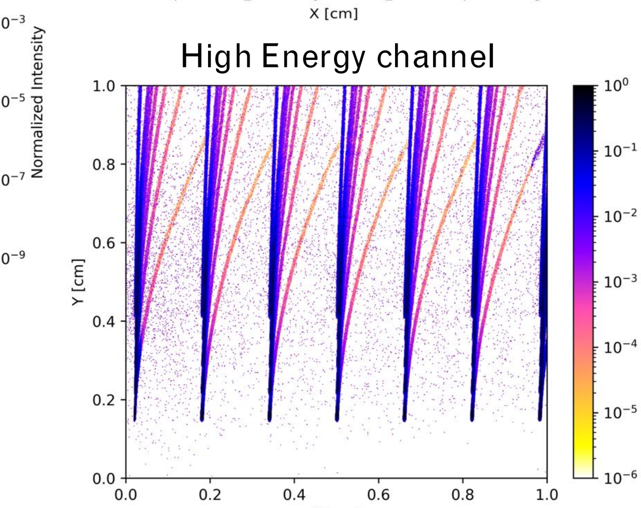
An extensive design study was performed using FLUKA Monte-Carlo simulations to develop an ion spectrometer architecture. The design draws inspiration from two approaches: multi-pinhole Thomson parabola systems [1] and the SEPAGE multi-energy-channel spectrometer at LMJ-PETAL [2].

- Our concept combines angular and spectral resolution, enabling: **±5° angular acceptance and 3 – 80 MeV proton energy range.**
- To support high-repetition-rate operation, the design incorporates scintillator-based detection for fast signal readout and radiation tolerance









[1] Salgado-López et al, "Angular-Resolved Thomson Parabola Spectrometer for Laser-Driven Ion Accelerators", Sensors, 22(9), 3239 (2022) ,

[2] Lantuéjoul I. et al "SEPAGE: a proton-ion-electron spectrometer for LMJ-PETAL", Proc. SPIE 10763, Radiation Detectors in Medicine, Industry, and National Security XIX, 107630X (2018)

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