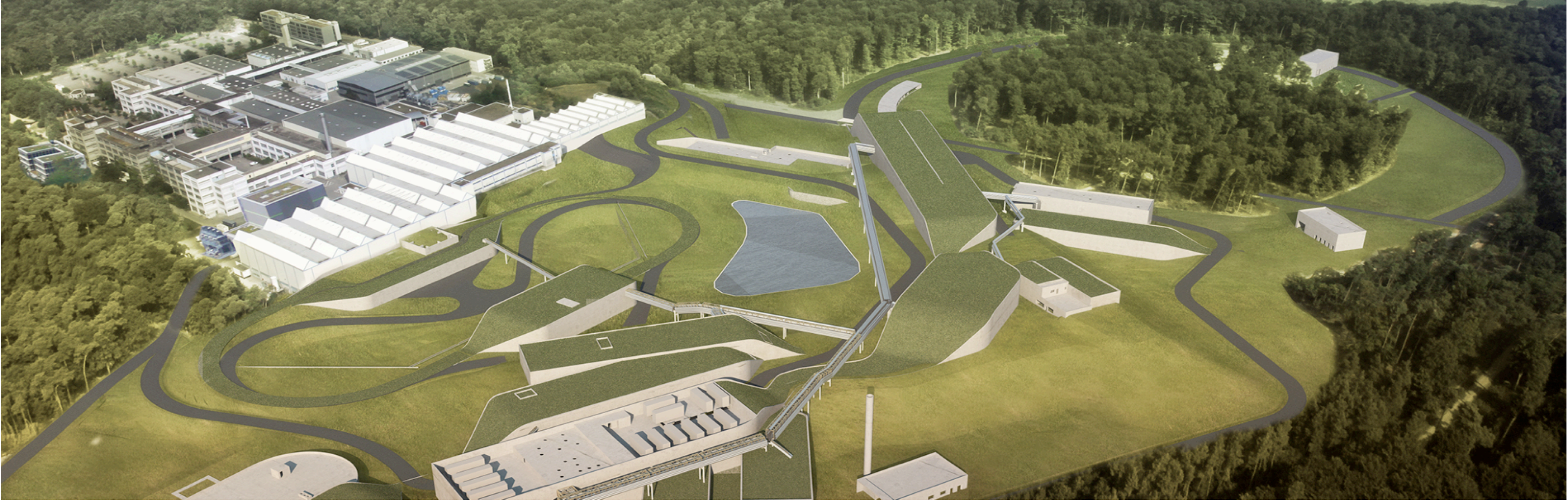


Luca Volpe

Polytechnic University of Madrid (UPM)

&

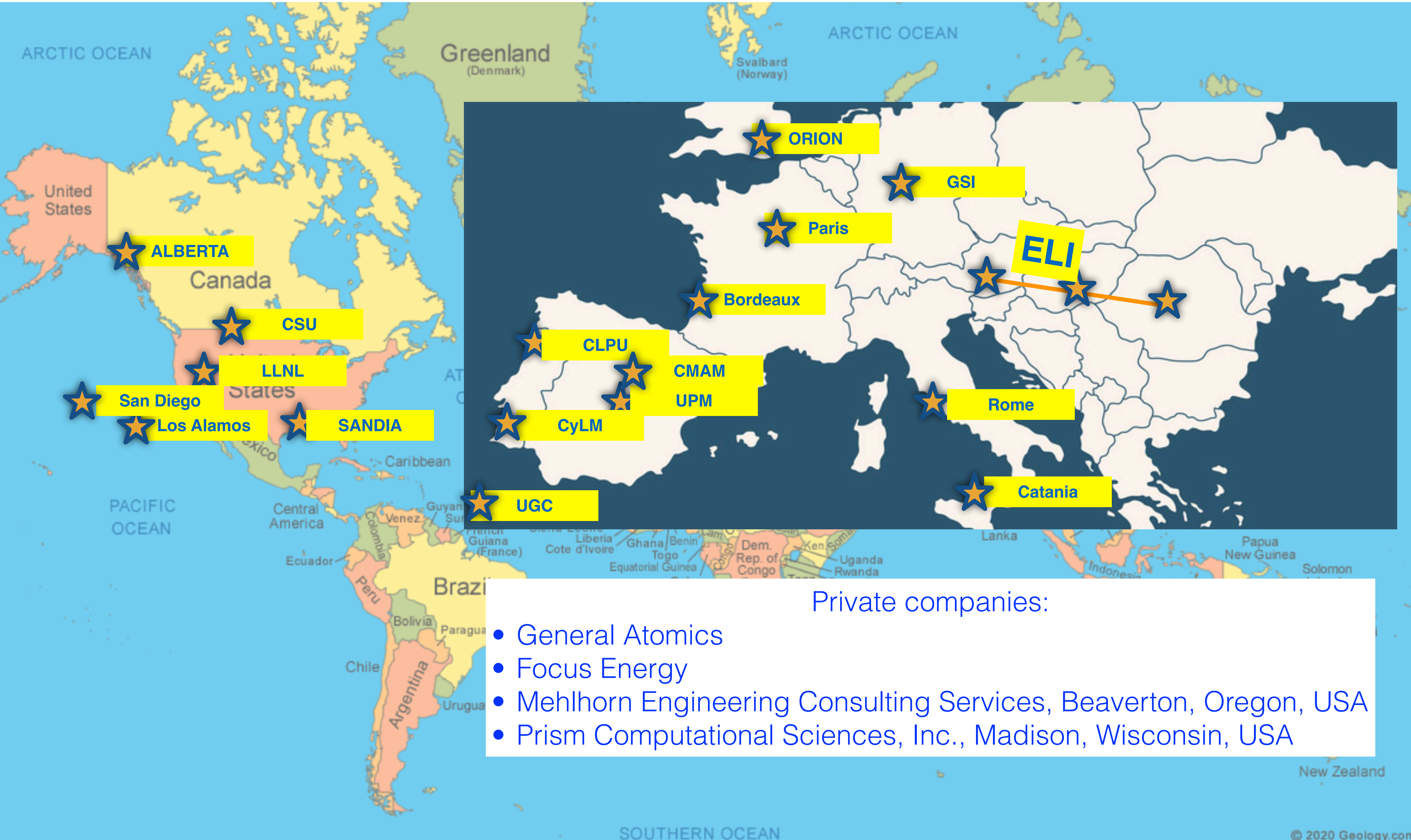
Spanish Center for Pulsed lasers (CLPU)

Workshop on High Energy Density Physics Opportunities at FAIR

"Ion Interaction with laser-driven extreme plasmas"

Friday - November 18, 2022

Spanish+International collaboration



Private companies:

- General Atomics
- Focus Energy
- Mehlhorn Engineering Consulting Services, Beaverton, Oregon, USA
- Prism Computational Sciences, Inc., Madison, Wisconsin, USA

LIST OF COLLABORATORS

- **T. A. Mehlhorn**
- *Mehlhorn Engineering Consulting Services, Beaverton, Oregon, USA*
- **M. F. Gu, I. E. Golovkin**
- *Prism Computational Sciences, Inc., Madison, Wisconsin, USA*
- **Sophia Malko, Will Fox, Frances Kraus**
- Princeton *Plasma Physics Laboratory, 100 Stellarator Road, Princeton, New Jersey 08536, United States*
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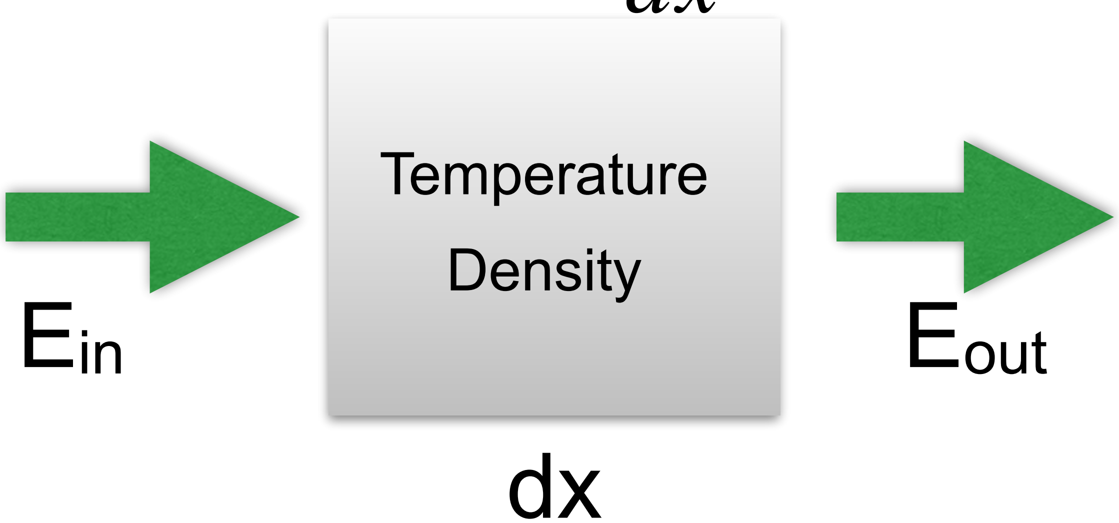
- *Laboratory for Laser Energetics, University of Rochester, 250 E. River Road, Rochester, New York 14623, United States*
- **Xavier Vaisseau**
- *Focused Energy, USA*
- **Robert Fedosejevs**
- *University of Alberta, Department of Electrical and Computing Engineering. Edmonton, Alberta, Canada*
- **Witold Cayzac, Valeria Ospina-Bohorques**
- *CEA, DAM, DIF, F-91297 Arpajon, France*
- **Paul Grabowski, Alfredo Correa**
- *Lawrence Livermore National Laboratory*
- **Alexander White, Lee Collins**
- *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, United States*
- **Stephanie Hansen, Andrew Baczewski, Tommy Hentschel, Alina Kononov**
- *Sandia National Laboratory, Albuquerque, New Mexico 87185, United States*
- **Mathieu Bailly- Grandvaux, Krish Bhutwala, Fahrat Beg**
- *Center for Energy Research, University of California San Diego, La Jolla, California 92093, United States*
- **Chris McGuffey**
- *General Atomics, San Diego, California 92121, United States*
- **Dimitri Batani, Joao Jorge Santos**
- *University of Bordeaux, CNRS, CEA, CELIA (Centre Lasers Intenses et Applications), UMR 5107, F-33405 Talence, France*

Why research in Ion Stopping Power?

- ✓ Inertial confinement fusion alpha particle heating
- ✓ Direct drive approach to ICF proton fast ignition
- ✓ Plasma Diagnostics (time-dependent proton radiography and deflectometry)
- ✓ Study of Equation of States and transport properties in materials
- ✓ kinetic simulations (Fokker-Planck collision operator) Multi-fluid plasma simulations
- ✓ Medical applications (Proton therapy),
- ✓ Material science (PIXE, Aerospace)

$$S(E) = \frac{dE}{dx}$$



Measurement requirement

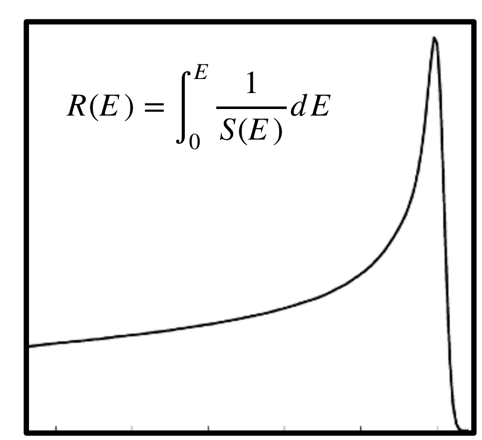
-Mono energetic beam -Defined State of matter

Possible conditions

Cold matter T=0, n=const

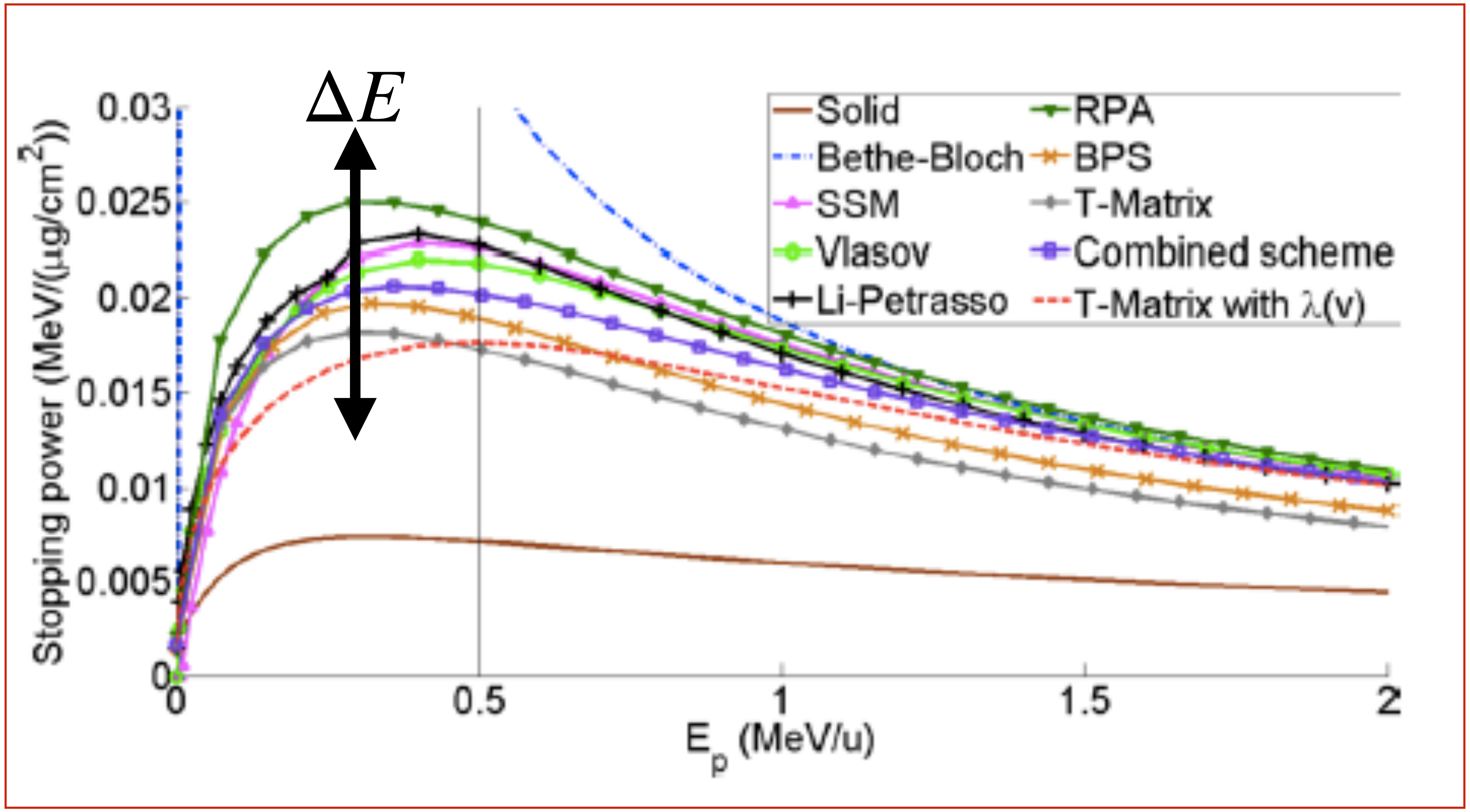
Plasma T(t) & n(t)

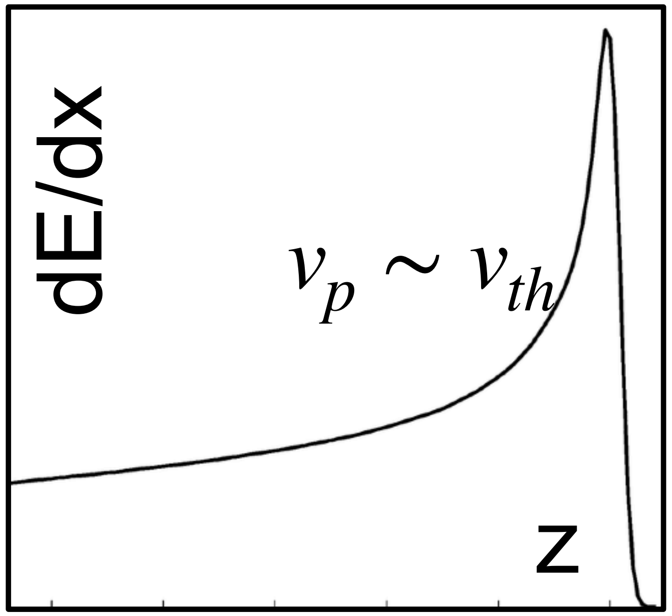
1. Constant Volume
2. $T_{Probe} < T_{plasma}$



Which conditions?

- Most of the discrepancies between different theoretical approaches are located around the Bragg peak $v_p \sim v_{th}$
- experimental results are necessary to discriminate theoretical predictions with errors below few tens of KeV

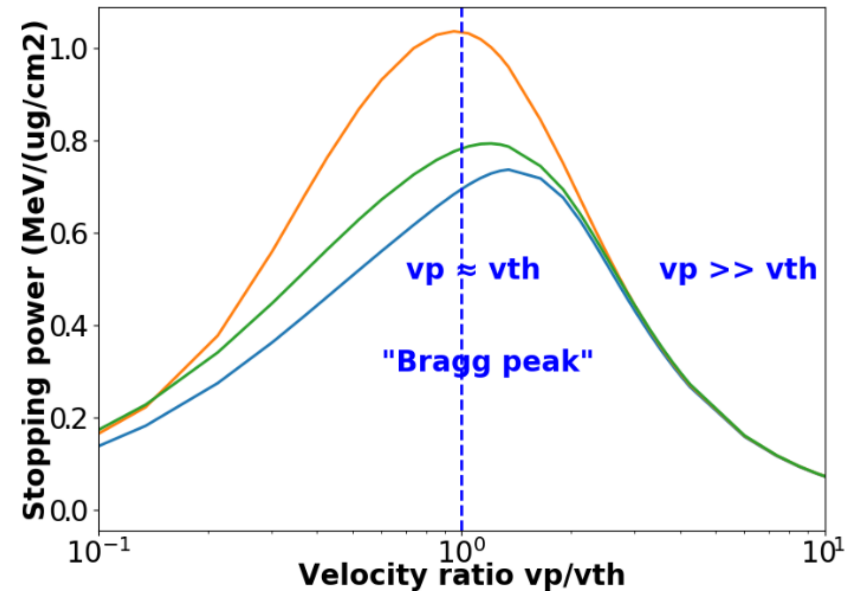




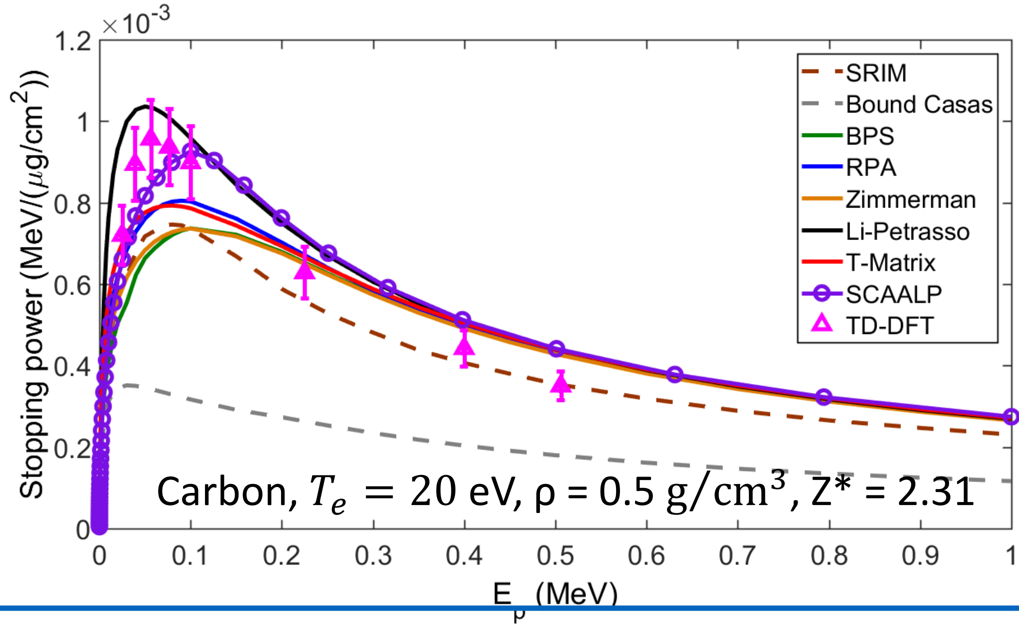
Ion Stopping Power theories

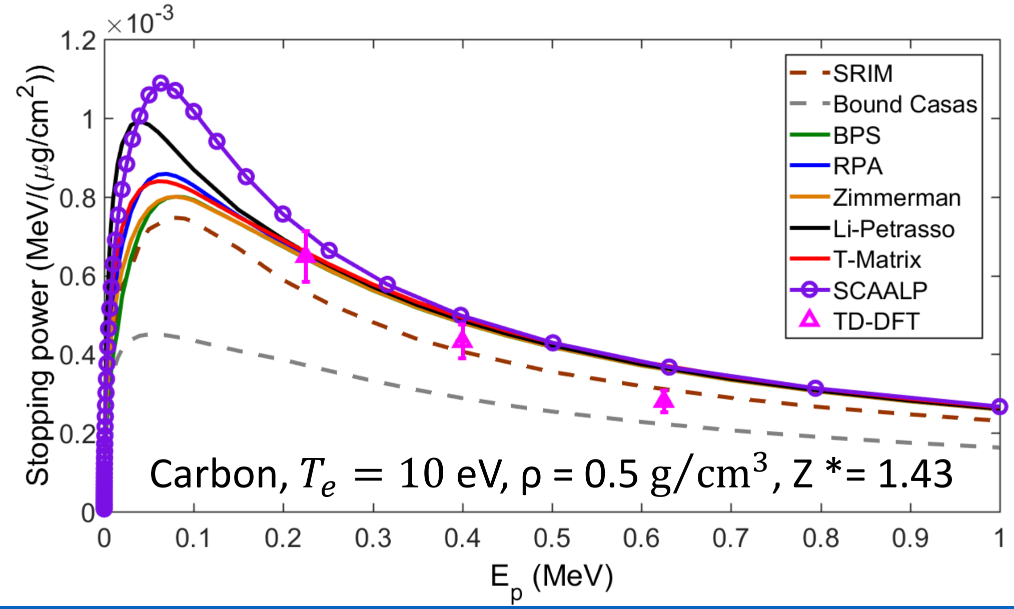
Theoretical modelling is challenging!

- Free + Bound electron stopping [1,2,3,4]
- Density Functional Theory (DFT) TD OF DFT [5]
- Average atom approach [6,7]



- $v_p/v_{th} \approx$ **13** monoenergetic protons in WDM [8]
- $v_p/v_{th} \approx$ **3** TNSA energy selected protons in WDM [9,10]





[1] *Zimmerman, G. Report no. ucrl-jc-105616. LLNL.(1990)*
[2] *Gericke, D. O. et al., Physical Review E, **65** (2003)*
[3] *Zylstra A. et al., Physics of Plasmas **26**, 122703 (2019)*
[4] *Casas D. et al., Phys. Review E **88**, (2013)*
[5] *Ding Y. et al., Phys. Rev. Lett. **121**, 145001 (2018)*
[6] *Faussurier G., et al., Physics of Plasmas **17**, 052707 (2010)*
[7] *Wang P. et al., Phys. Plasmas **5**, 2977 (1998)*
[8] *Zylstra A. et al., Phys. Rev. Lett. **114**, 2015002 (2015)*
[9] *Malko S., PhD Thesis (2020)*
[10] *Malko S. et al., in submission to Nature Communications (2021)*

Interest in Ion stopping power

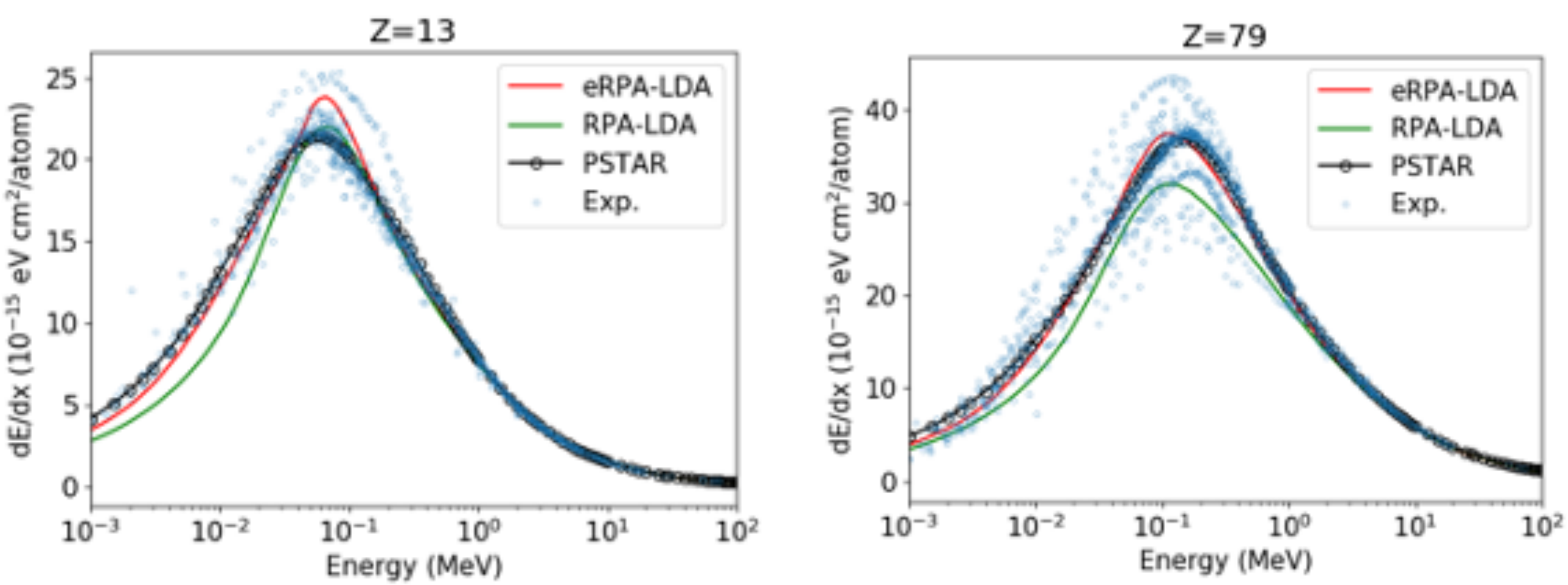
—*High Energy Density material*; —**High Z materials**; —**Warm Dense Matter**

Recent advances in theory and experiments related to SP in Plasmas

- ✓ Improvements of RPA-LDA and TD-DFT theories have been recently presented by some of the authors
- ✓ RPA-LDT: close agreements with experiments for a wide range of cold materials
- ✓ There is gap and a need of experimental data to benchmark the theoretical prediction
- ✓ Comparison with theory still needs:
    - ✓ Data from Ion SP in Plasma
    - ✓ HRR acquisition to reduce the Uncertainty (to apply also to cold matter)
- ✓ Improvements in experimental techniques have been obtained by some of the authors
- ✓ new small-scale HRR laser facilities can host dedicated (pump and probe) experiments
- ✓ ELIMAIA can provides unique proton (ion) beams selected in energy, collimated and relatively short (~ hundreds of ps)+ 1 ns long 2 kJ laser.

Improvements in theoretical description of Ion SP in Plasma

- ✓ More accurate RPA-LDA model than Wang[1] through local field corrections & binding energy corrections - average atom model for electron density from Flexible Atomic Code (FAC)[2].
- ✓ *eRPA-LDA*[3] proton stopping powers are in close agreement with experimental data in the NIST PSTAR database across the periodic table.
- ✓ SP in Plasma still require validation[4,5]



Comparison with PSTAR https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

New open access database available on GitHub (https://github.com/dedx-erpa/dedx)

1.P. Wang, T. M. Mehlhorn, and J. J. MacFarlane, "A unified self-consistent model for calculating ion stopping power in ICF plasma," Physics of Plasmas, vol. 5, no. 8, pp. 2977-87, 1998

2.M. F. Gu, Canadian Journal of Physics 86, 675 (2008).

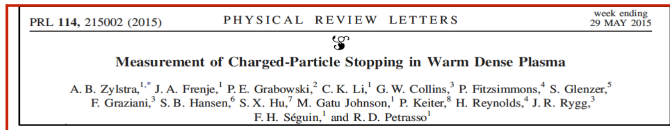
3.“Development of Ion Stopping Models for HED Plasmas Using Unified Self-Consistent Field Models and Self-Consistent Electron Distributions: Prism Computational Sciences Report for US DOE, PCS-R-180, October 2022

4.P. E. Grabowski et al., "Review of the first charged-particle transport coefficient comparison workshop,", HEDP, Review vol. 37, p. 29, Nov 2020

5.A. J. White, L. A. Collins, K. Nichols, and S. X. Hu, arXiv e-prints arXiv:2112.01638 (2021), 2112.01638.

Improvements in experimental activities in Ion SP measurement in Plasma

From High energy Large scale single shot to low energy small scale HRR


PRL 114, 215002 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Measurement of Charged-Particle Stopping in Warm Dense Plasma

A. B. Zylstra,[1,*] J. A. Frenje,[1] P. E. Grabowski,[2] C. K. Li,[1] G. W. Collins,[3] P. Fitzsimmons,[4] S. Glenzer,[5] F. Graziani,[3] S. B. Hansen,[6] S. X. Hu,[7] M. Gatu Johnson,[1] P. Keiter,[8] H. Reynolds,[4] J. R. Rygg,[3] F. H. Séguin,[1] and R. D. Petrasso[1]

Proton Stopping power (Warm Dense Matter)

PROTON PROBE

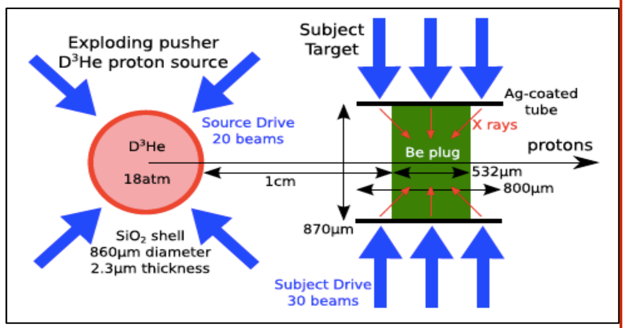
- Omega Laser facility has been used to to create a pulsed monoenergetic sources of Proton to probe a subject plasma isochorically heated at WDM condition
- Shock-driven imploding-pusher implosion to produce protons via D_2+^{3}He reaction.
- 20 beam at 3w 10 kJ 1ns
- 100 ps long proton burst

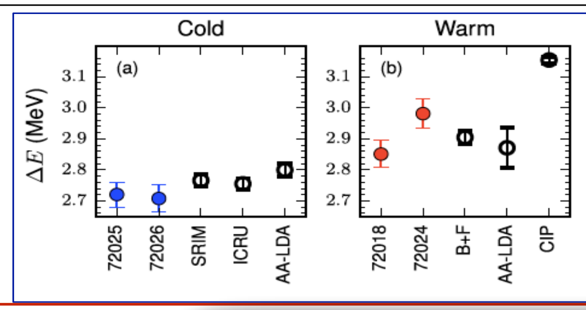
TARGET

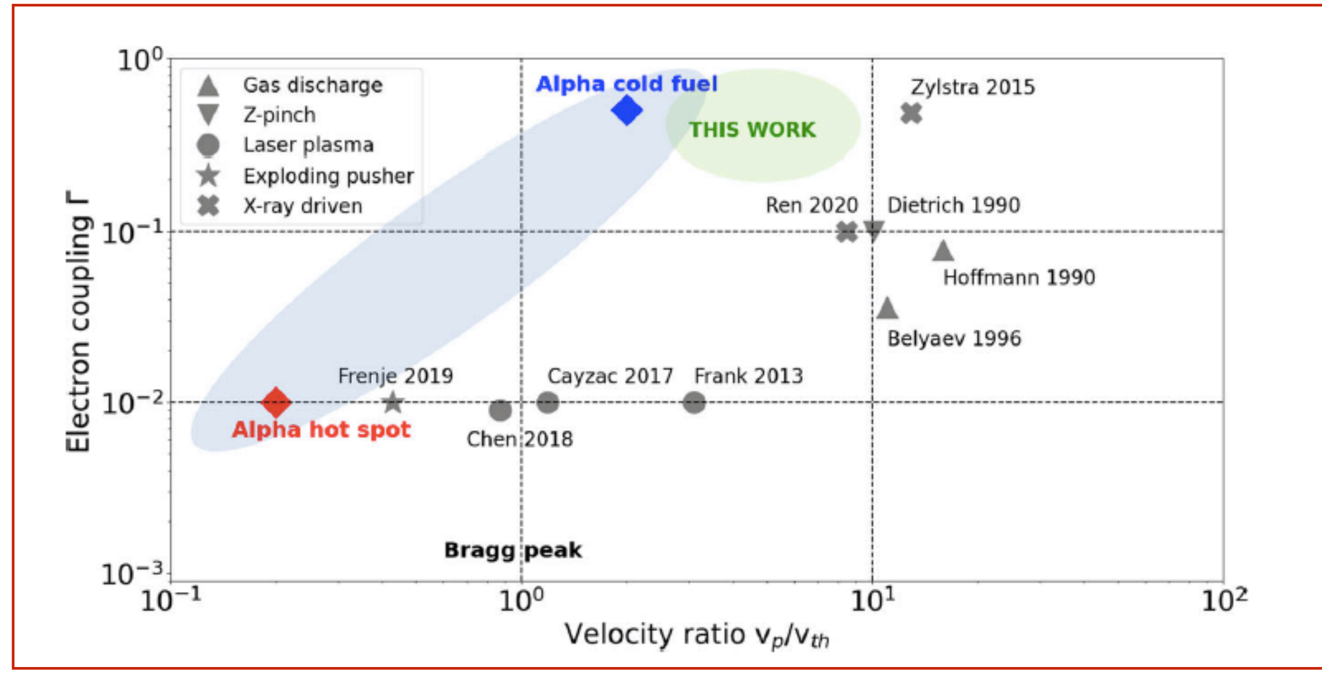
- A 800 mm long plastic tube coated with 2 mm Ag and internal diameter of 870 mm. Wall thickness of 24 mm
- The tube is filled with Be with a total areal density of ~ 95 g/cm^2

LASER-TARGET HEATING

- 30 beams 30 kJ 100 mm spot each onto the cylinder external Ag coated surface
- 3-4 keV X-rays heat the inner of the cylinder to T~ 32 eV, Z*~2.5 and n_e~ 3 g/cc

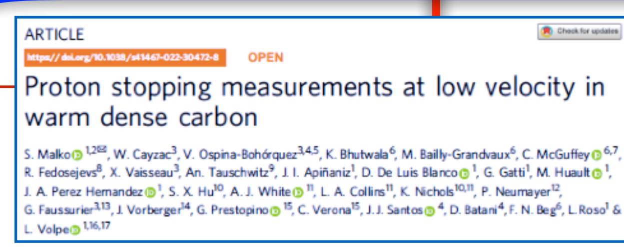






measurement @ OMEGA

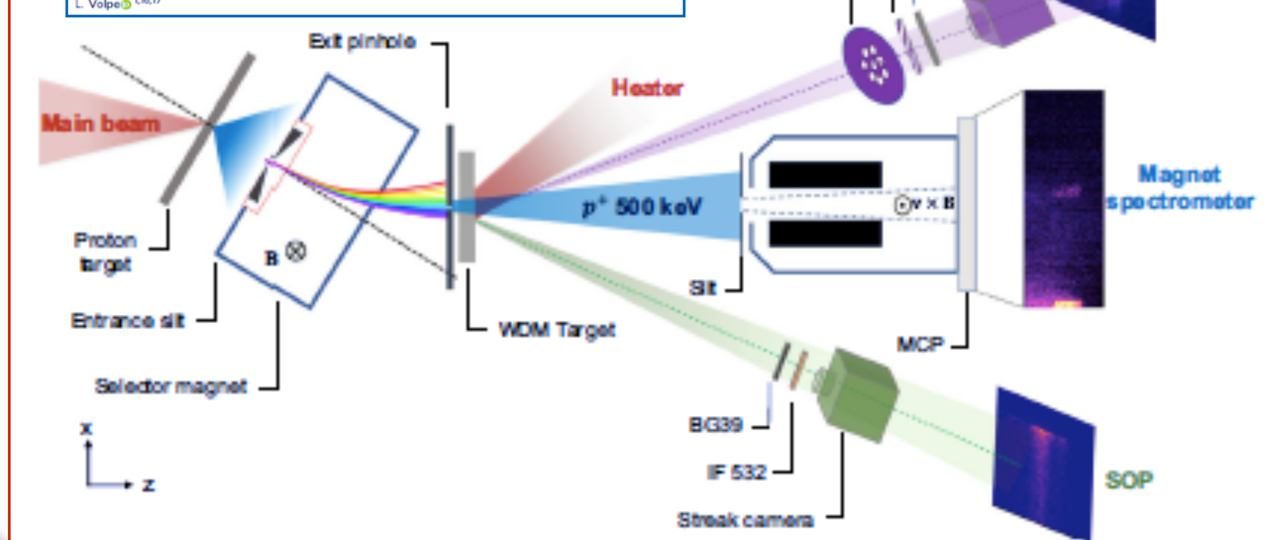
- ✓ Single shot
- ✓ Big volume
- ✓ High energy beams
- ✓ ns duration
- ✓ v_p/v_{th}~ 10


ARTICLE

https://doi.org/10.1038/s41467-022-30472-8 OPEN

Proton stopping measurements at low velocity in warm dense carbon

S. Malko[1,2], W. Cayzac[3], V. Ospina-Bohórquez[3,4,5], K. Bhutwala[6], M. Bailly-Grandvaux[6], C. McGuffey[6,7], R. Fedosejevs[8], X. Vaisseau[3], An. Tauschwitz[9], J. I. Apiñaniz[1], D. De Luis Blanco[1], G. Gatti[1], M. Huault[1], J. A. Perez Hernandez[1], S. X. Hu[10], A. J. White[11], L. A. Collins[11], K. Nichols[10,11], P. Neumayer[12], G. Faussurier[3,13], J. Vorberger[14], G. Prestopino[15], C. Verona[15], J. J. Santos[4], D. Batani[4], F. N. Beg[6], L. Roso[1] & L. Volpe[1,16,17]



measurement @ CLPU

- ✓ HRR
- ✓ Small volume
- ✓ Small energy beams
- ✓ Ps duration
- ✓ v_p/v_{th}~ 3

Proton stopping power measurement @ OMEGA

PRL 114, 215002 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

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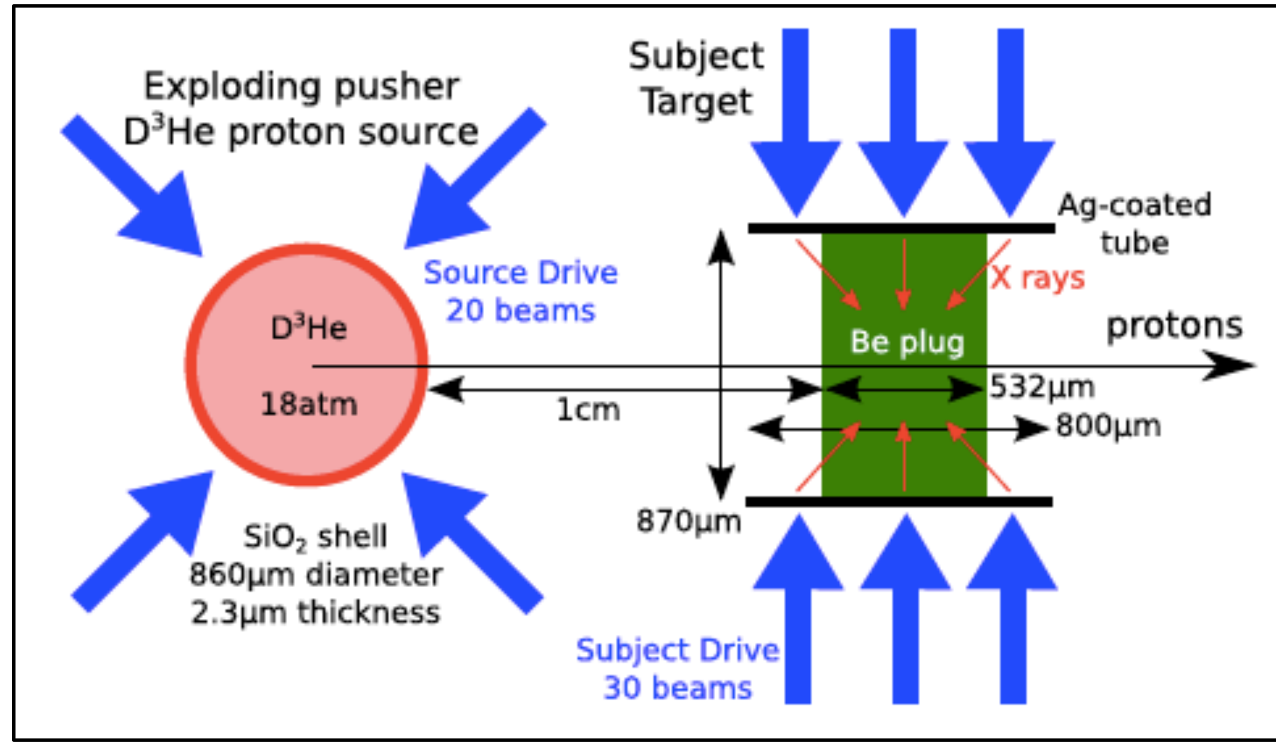
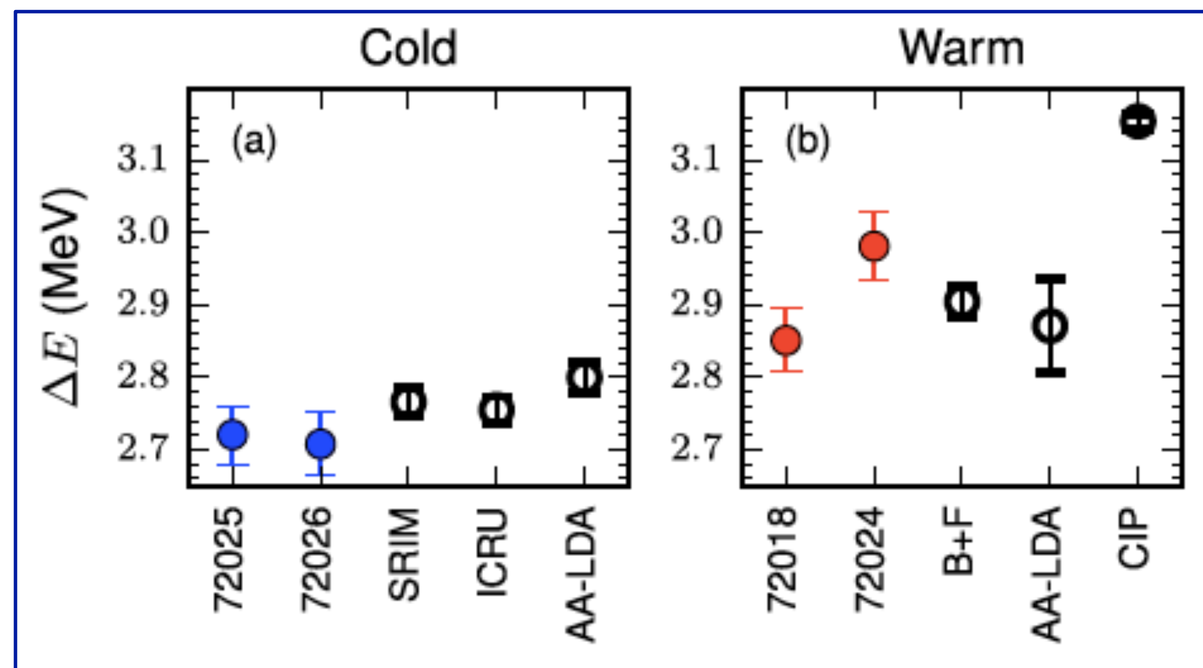
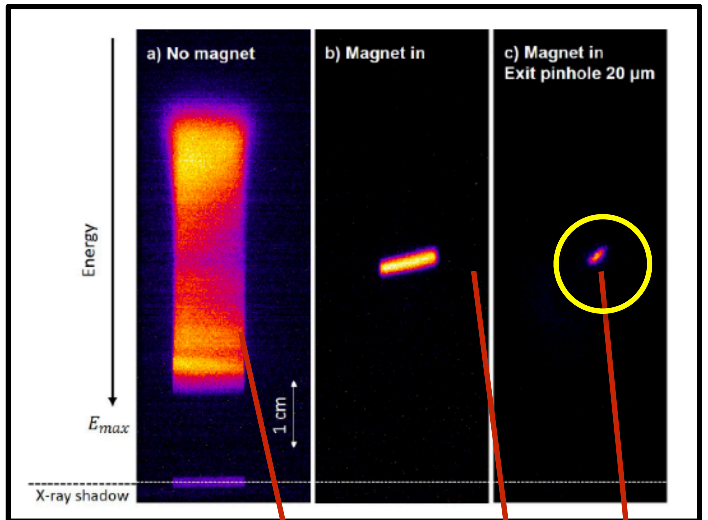
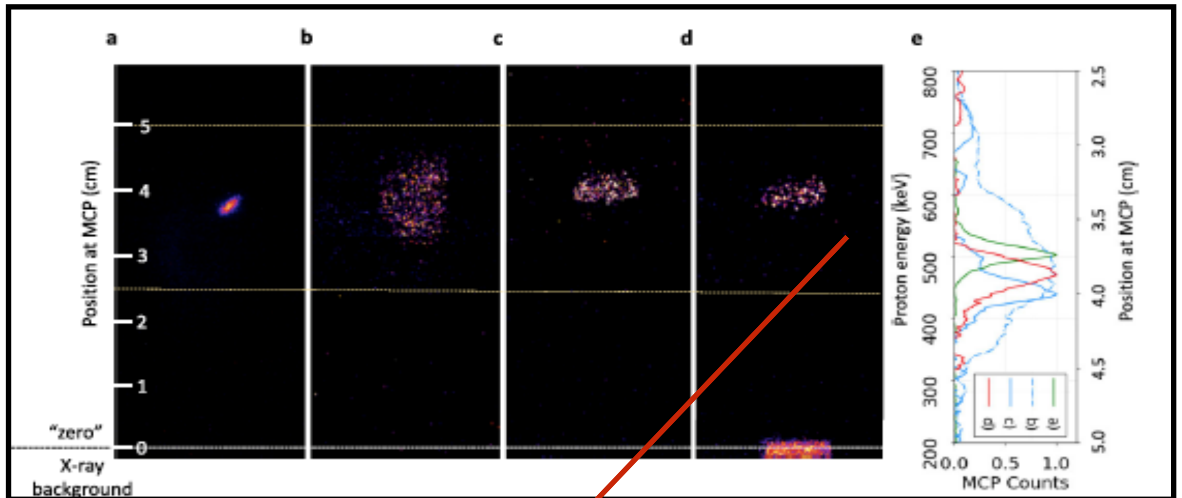
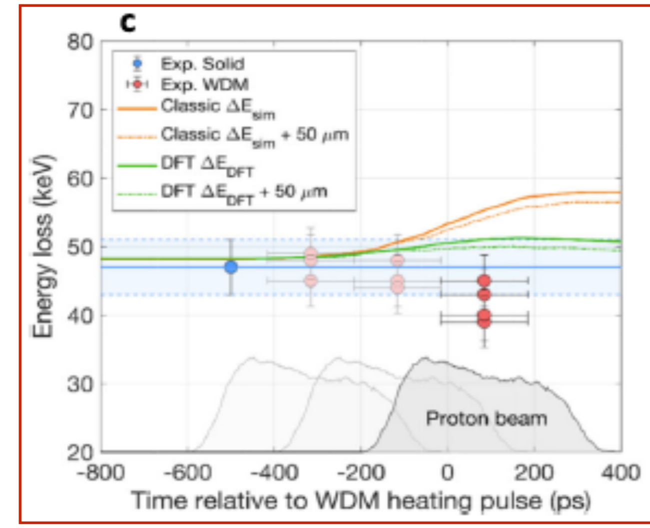


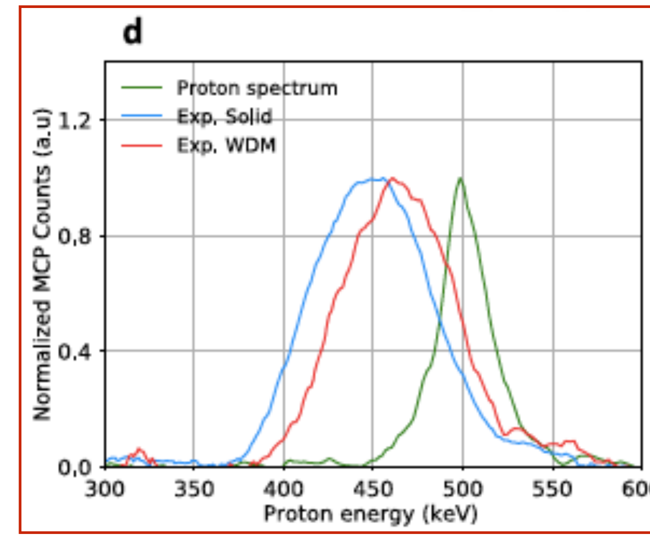


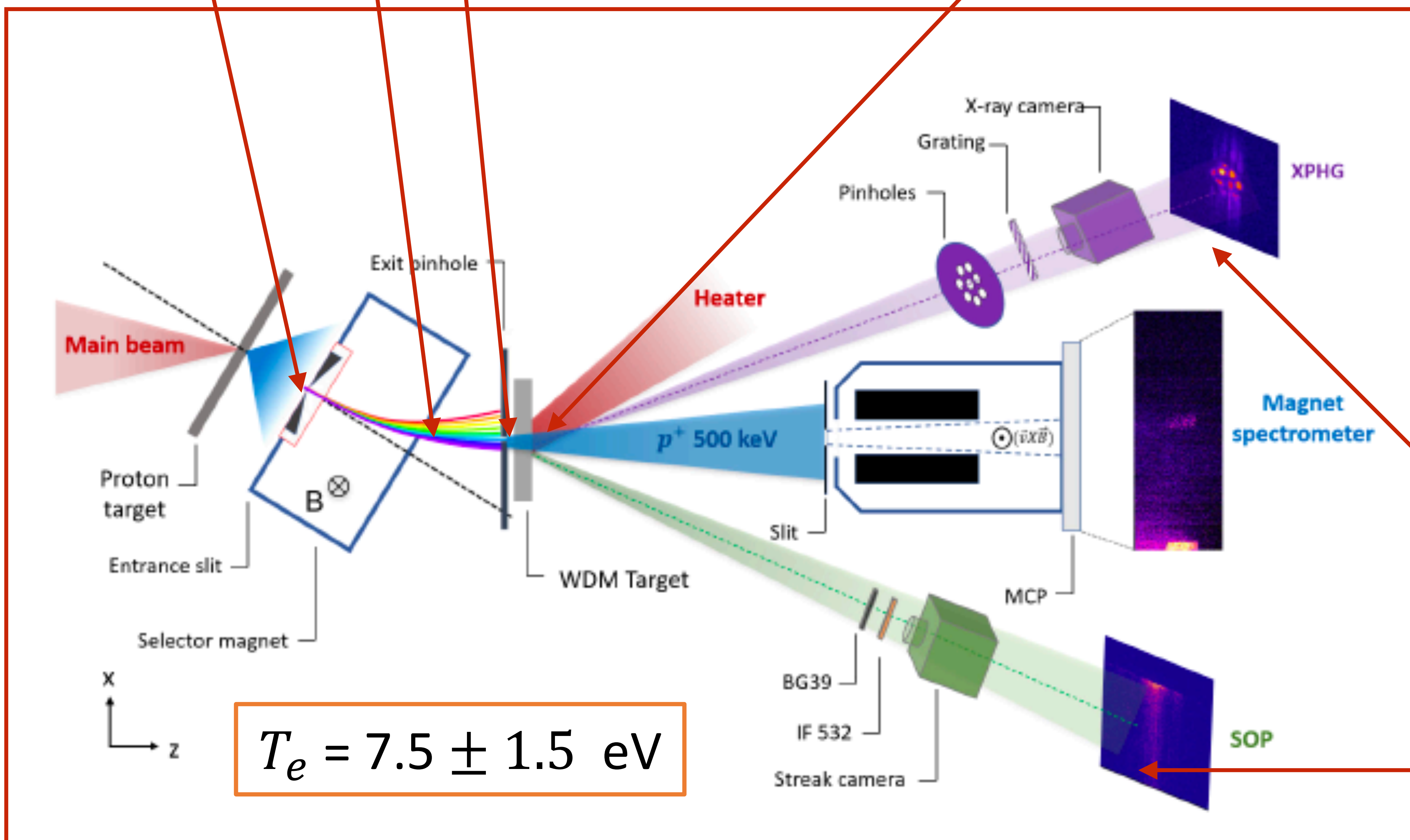
Ion Stopping Power in WDM driven by laser @CLPU











X-ray Pinhole Grating Camera

- XPHG measures time integrated area weighted x-ray emission in XUV range
- XPGH X-ray spectra is within 15 % agreement with the convoluted X-ray emission from RALEF-2D simulations

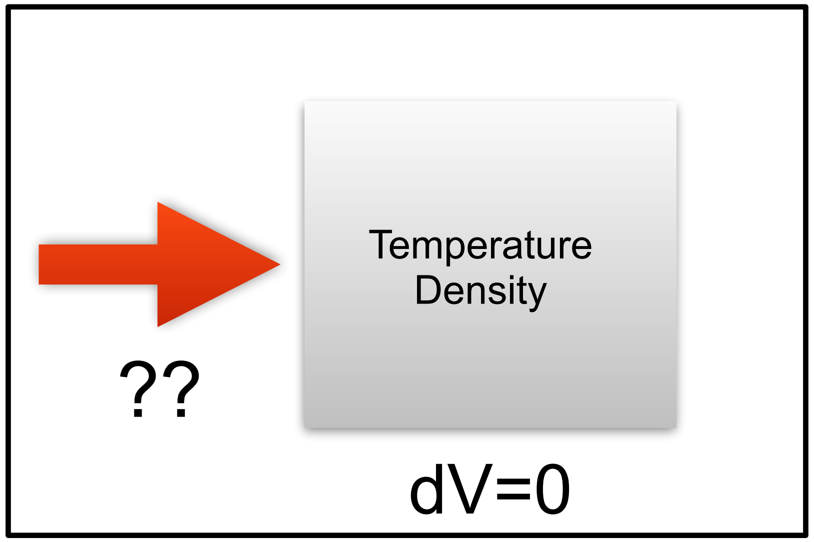
Streak optical pyrometry

- SOP provides temperature evolution at critical density at 532 nm
- The SOP measures slightly lower temperature predicted by RALEF-2D and agrees with simulations within 20 %

PLASMA CONDITIONS

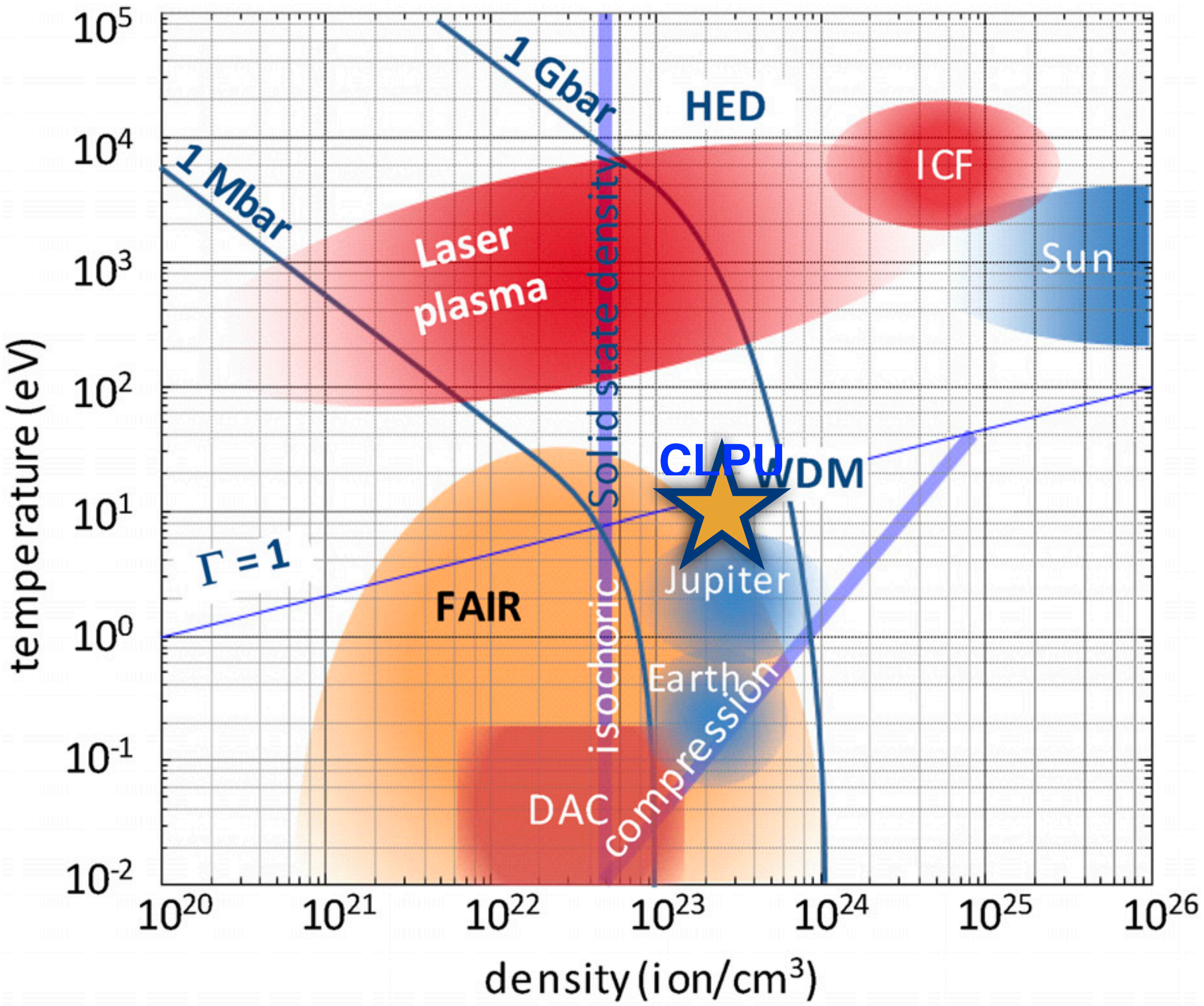
Heating mechanisms

- Charged particle
- Laseres
- X rays (incoherent)
- X-rays laseres X-FEL



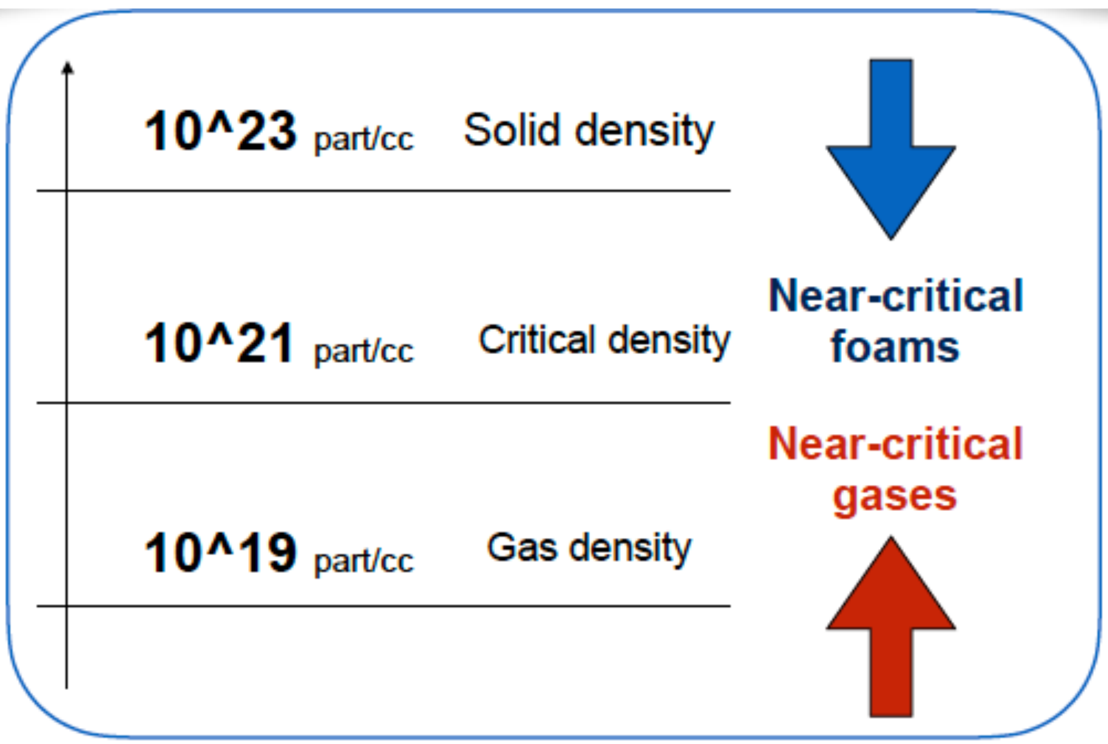
Ideal Experimental conditions

- ✓ Heat matter at a given temperature T
- ✓ Before hydrodynamic expansion
- ✓ Maintain constant volume
- ✓ Maintain constant temperature
- ✓ Maintain constant density



Conditions for WDM parameters measurement

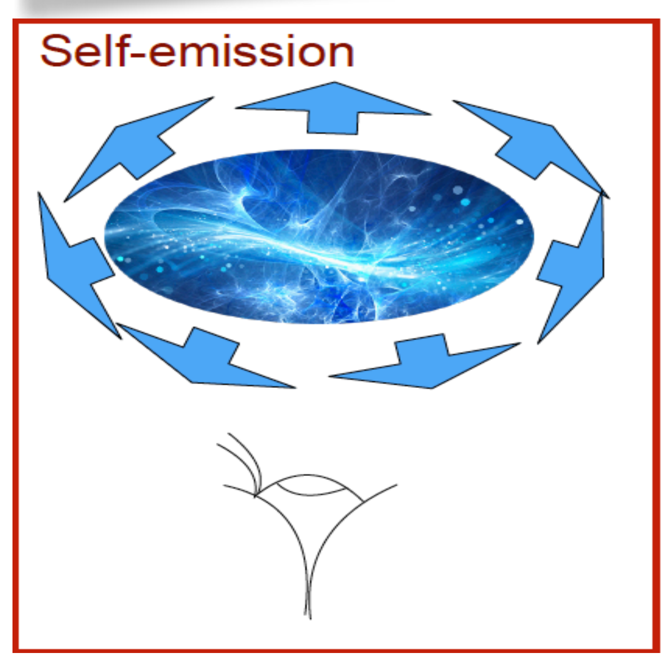
$$n_c = \frac{\omega^2 m_e \varepsilon_o}{e^2} = 1.113 \times 10^{21} \left(\frac{1 \mu m}{\lambda} \right)^2 cm^{-3}$$

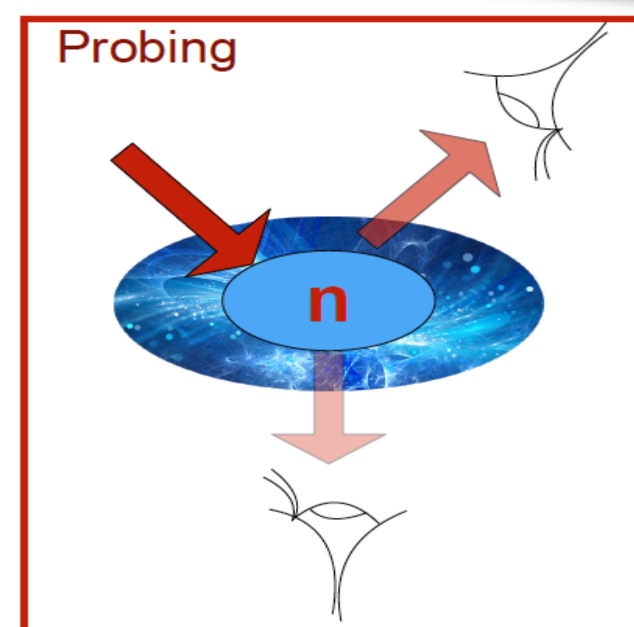


1. Constant Volume
2. $T_{Probe} < T_{plasma}$

Diagnostic methods

1. Full characterisation of the Plasma state
   1. UV, XUV and X-ray spectroscopy (T)
   2. shadowgraphs Under-Dense
   3. Proton and X-ray Radiography Over-Dense
2. Ion Spectrometer HRR
3. Ion Thomson parabola HRR, ToF
4. (X-ray) Streak techniques





- *The CLPU local expertise*

CLPU is a user facility opened to the domestic and international community through competitive access

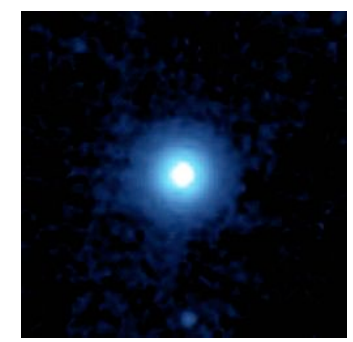
Funded by:

50 % Ministry of science and Innovation

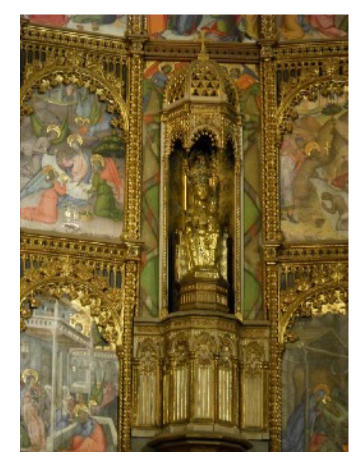
45 % region of Castilla y Leon

5 % University of Salamanca

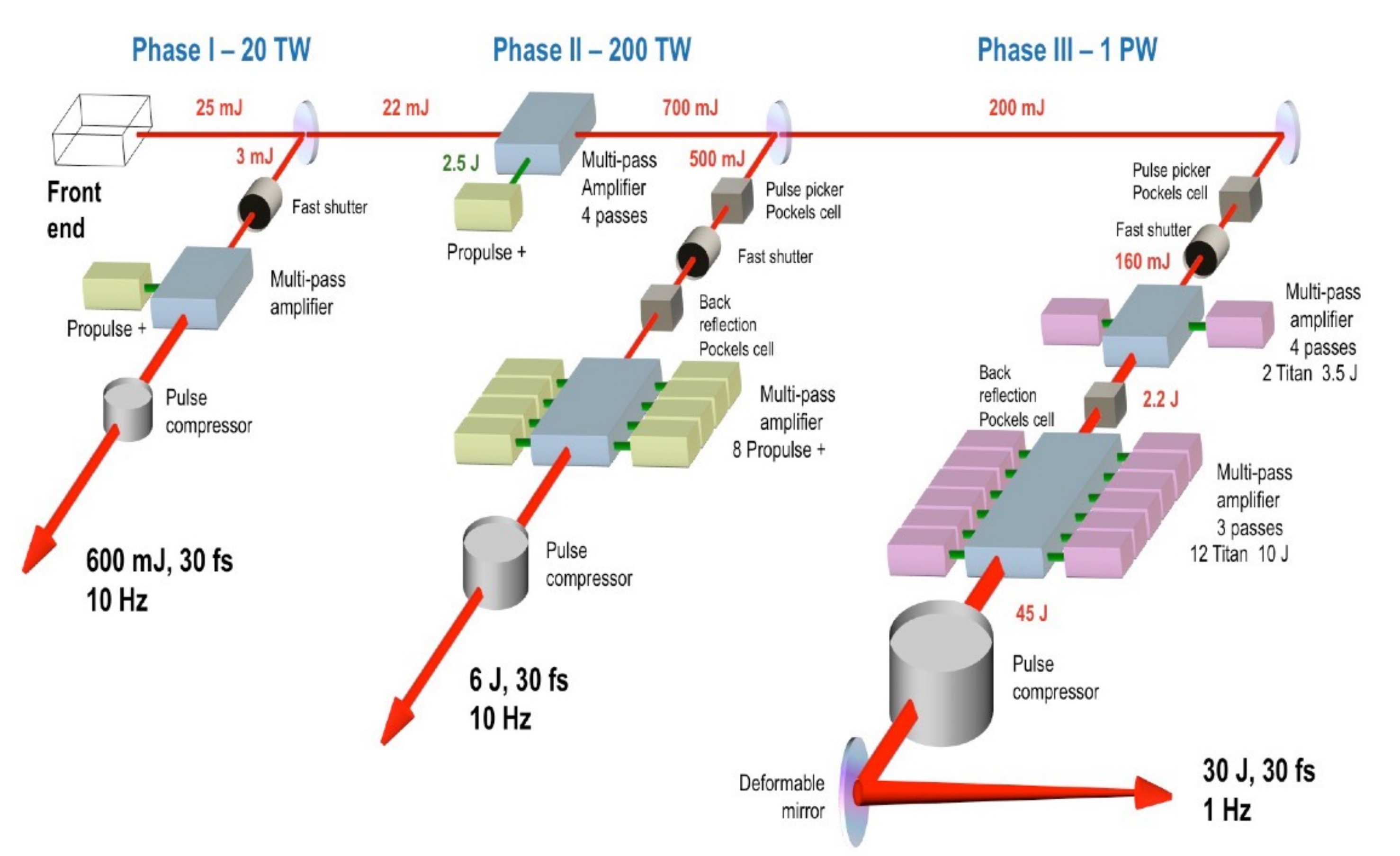
The cutting edge



Vega is the brightest star in the constellation of Lyra

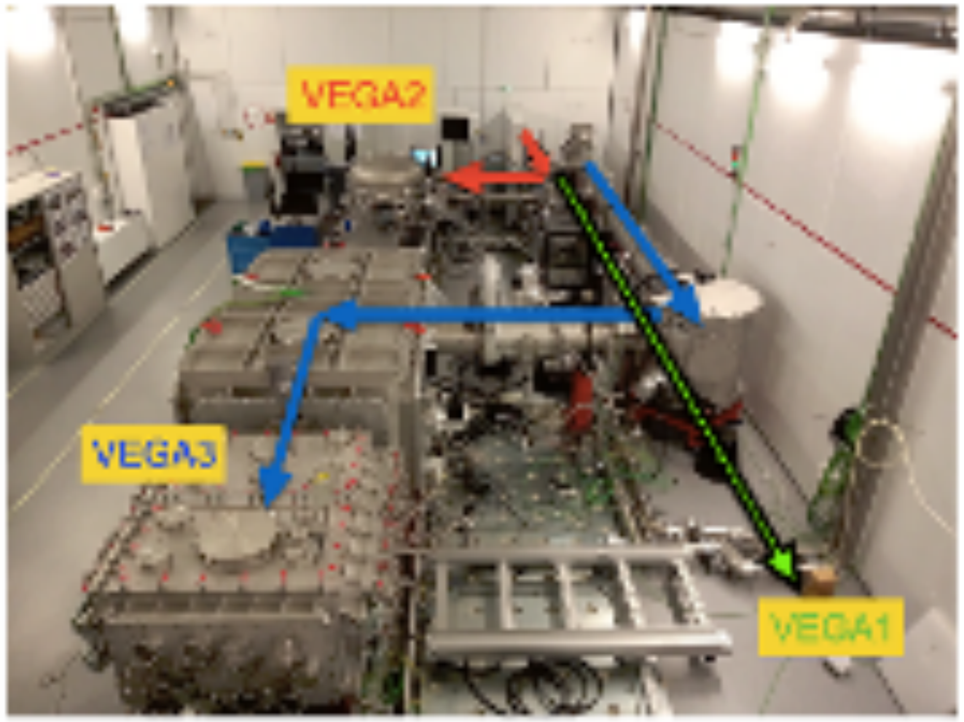


La vírgen de la Vega is patron of the city of Salamanca



The VEGA system

- *VEGA 2 parameters*
  - *E= 6 J*
  - *F/3 F/4 F/13*
  - *FWHM~ 5 6 20 um*
  - *I(W/cm²)~3x10^{20} 2x10^{20} 1x10^{19}*
- *VEGA 3 parameters*
  - *E=30 J*
  - *F/10*
  - *FWHM~ 14 um*
  - *I(W/cm²)~6 10^{20}*



VEGA System	VEGA-1	VEGA-2	VEGA-3
Energy /shot	600 mJ	6 J	30 J
Pulse duration	30 fs	30 fs	30 fs
Peak power	20 TW	200 TW	1 PW
Rep. Rate	30 J	30 fs	1 Hz

◉ Laser-Plasma HRR diagnostics development I

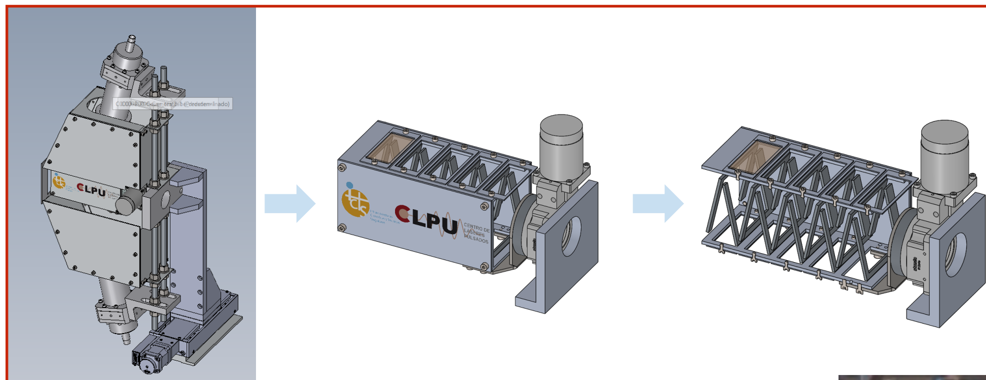
High Power Laser

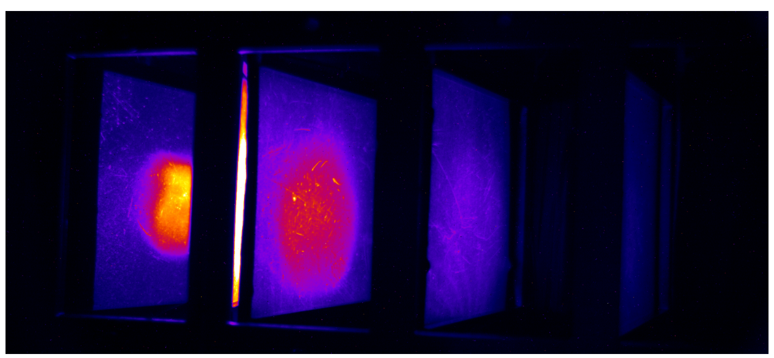
A 2D scintillator-based proton detector for high repetition rate experiments

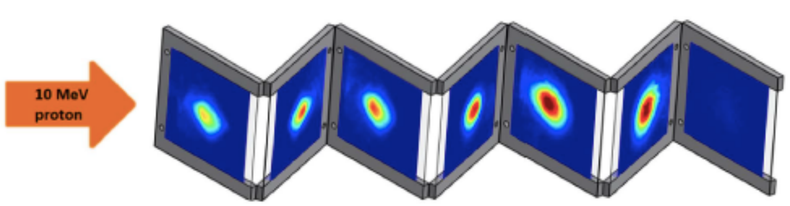
Part of: Editors' Pick

Published online by Cambridge University Press: **02 December 2019**

M. Huault, D. De Luis, J. I. Apiñaniz, M. De Marco, C. Salgado, N. Gordillo, C. Gutiérrez Neira, J. A. Pérez-Hernández, R. Fedosejevs, G. Gatti, L. Roso and L. Volpe





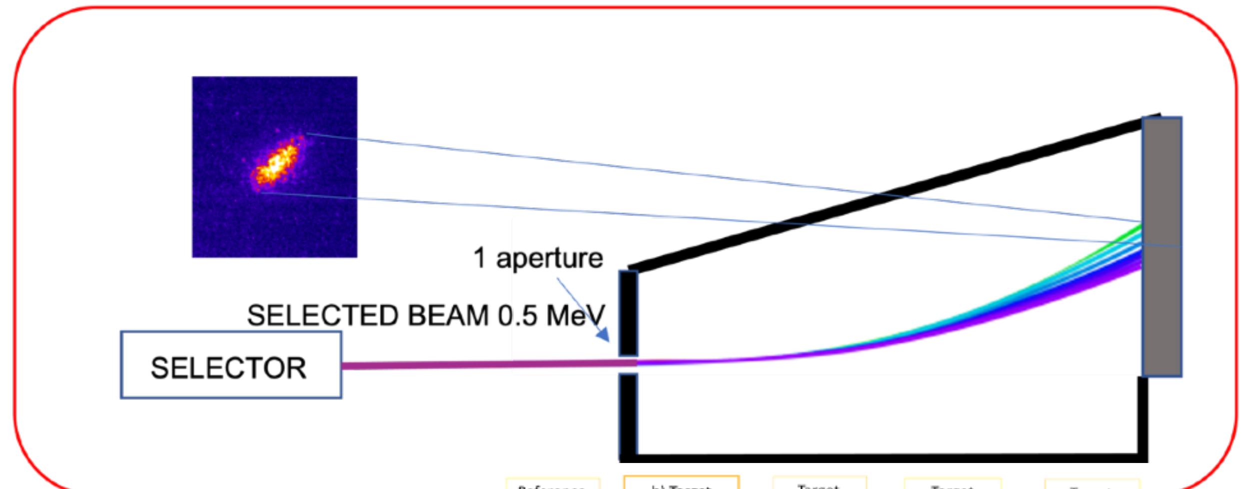


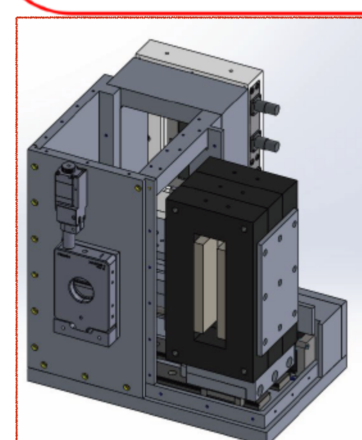
Article | Open Access | Published: 25 March 2021

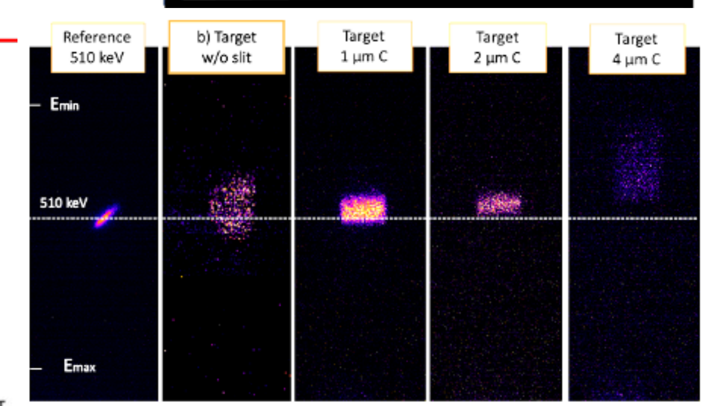
A quasi-monoenergetic short time duration compact proton source for probing high energy density states of matter

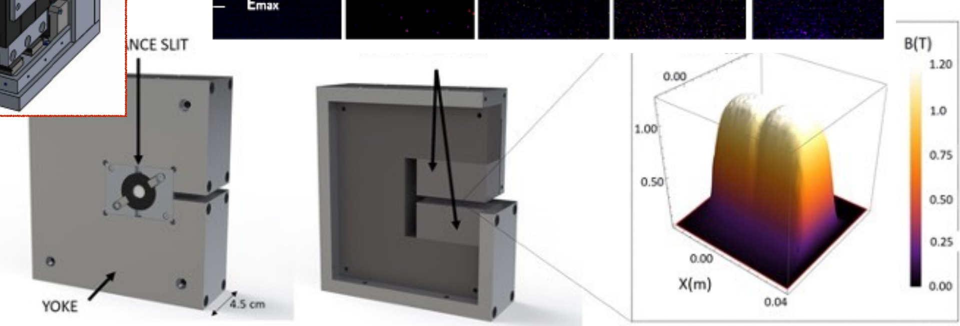
J. I. Apiñaniz, S. Malko, R. Fedosejevs, W. Cayzac, X. Vaisseau, D. de Luis, G. Gatti, C. McGuffey, M. Bailly-Grandvaux, K. Bhutwala, V. Ospina-Bohorquez, J. Balboa, J. J. Santos, D. Batani, F. Beg, L. Roso, J. A. Perez-Hernandez & L. Volpe

Scientific Reports **11**, Article number: 6881 (2021) | Cite this article









◉ *Laser-Plasma HRR diagnostics development II*

Implementation of a thin, flat water target capable of high-repetition-rate MeV-range proton acceleration in a high-power laser at the CLPU

P Puyuelo-Valdes[2,1], D de Luis[1], J Hernandez[1], J I Apiñaniz[1], A Curcio[1], J L Henares[1], M Huault[1], J A Pérez-Hernández[1], L Roso[1], G Gatti[1] and L Volpe[1]

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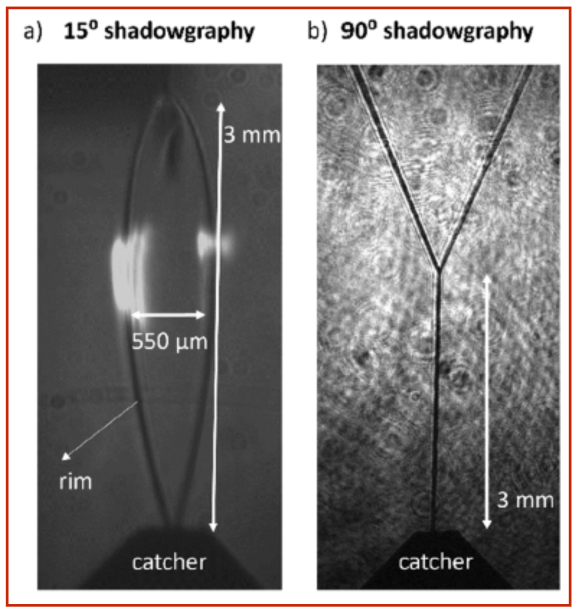
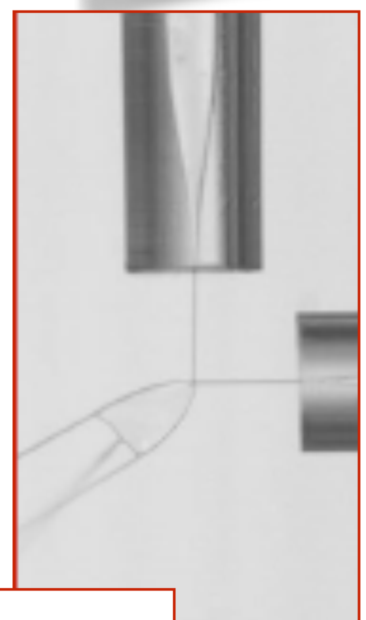
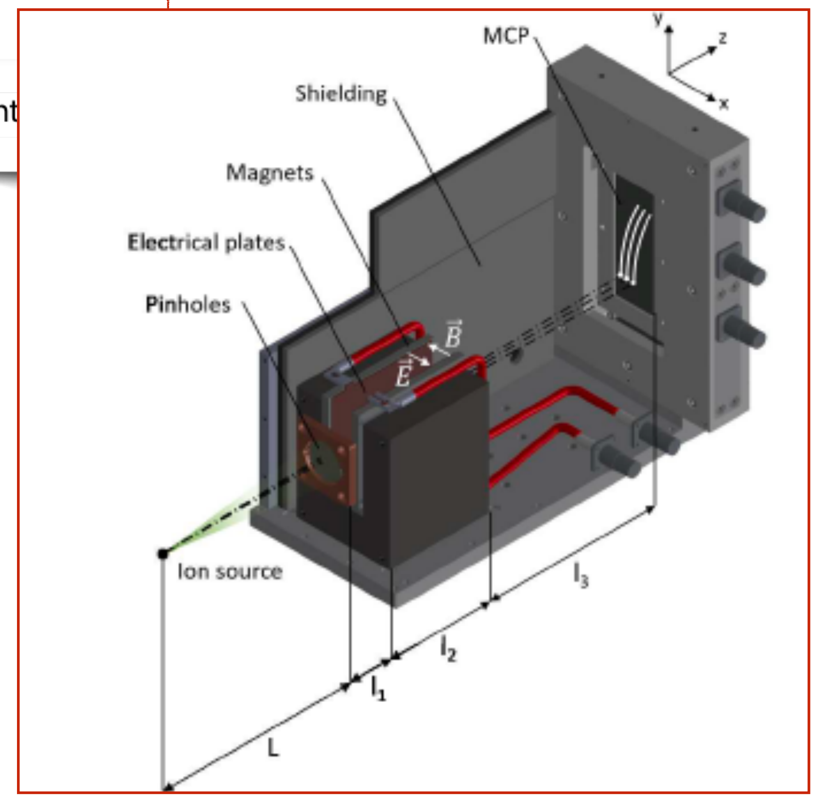
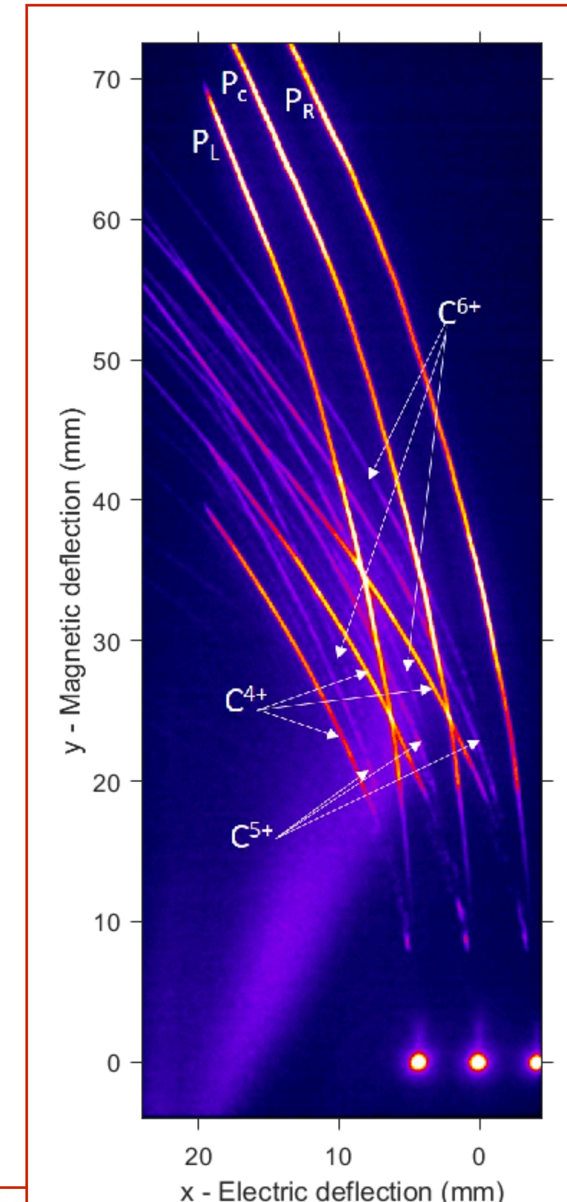
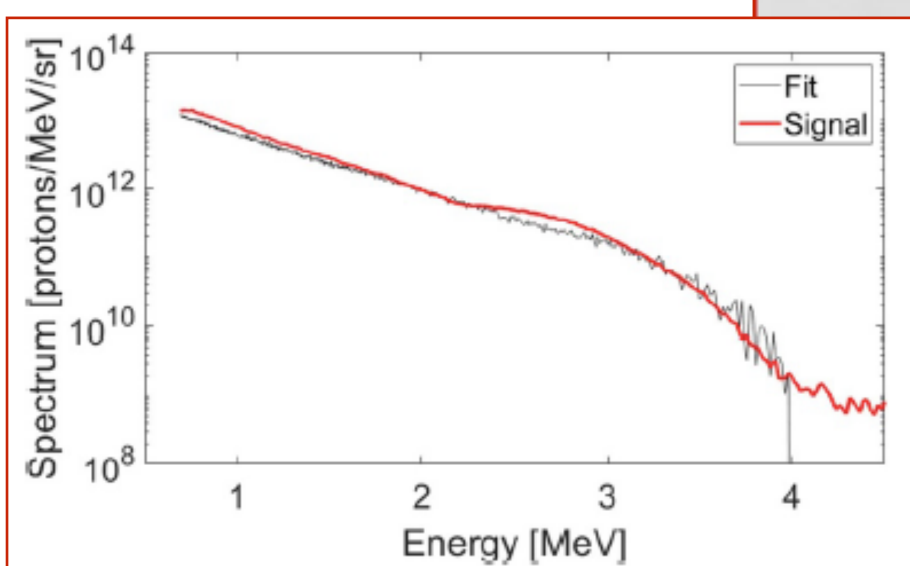
Plasma Physics and Cont











sensors
MDPI

Article

Angular-Resolved Thomson Parabola Spectrometer for Laser-Driven Ion Accelerators

Carlos Salgado-López *, Jon Imanol Apiñaniz, José Luis Henares, José Antonio Pérez-Hernández, Diego de Luis, Luca Volpe and Giancarlo Gatti

Centro de Láseres Pulsados (CLPU), Edificio M5, Parque Científico USAL, C/Adaja, 8, 37185 Villamayor, Salamanca, Spain; japinaniz@clpu.es (J.I.A.); jlhenares@clpu.es (J.L.H.); japerez@clpu.es (J.A.P.-H.); ddeluis@clpu.es (D.d.L.); lvolpe@clpu.es (L.V.); ggatti@clpu.es (G.G.)
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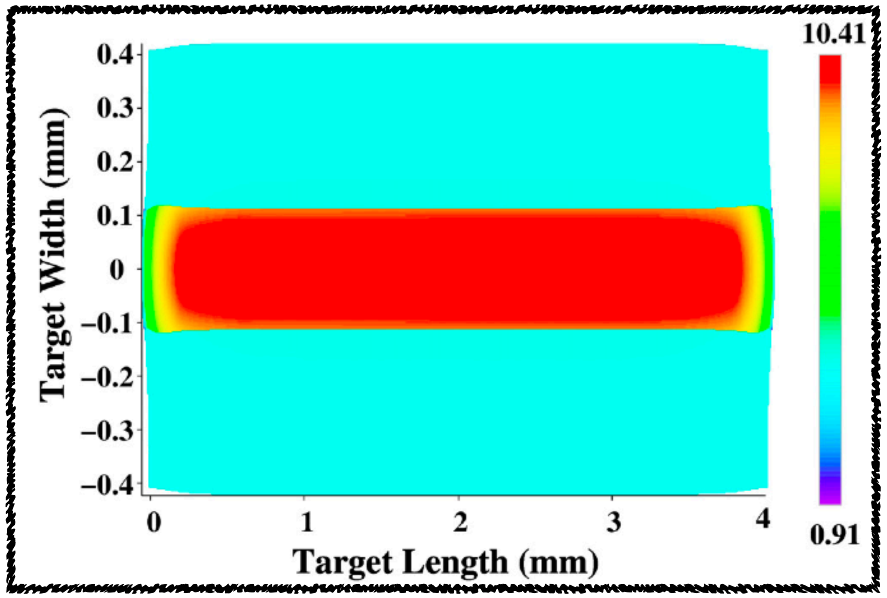
Conclusion and prospectives

- ✓ There is a **strong gap** between theoretical predictions and experimental validation in Ion stopping power.
- ✓ This **gap could be filled** with the advent of new Big Infrastructures
  - ✓ High Power Lasers
  - ✓ X-FEL
  - ✓ Ion accelerators
- ✓ FAIR is a "Unique" ion acceleration facility and extreme and uniform Plasma condition can be easily created
- ✓ Spanish Community can contribute with the experience on:
  - ✓ Ion stopping power theory (UPM, CyLM)
  - ✓ Plasma Diagnostics (CIEMAT, CLPU)
  - ✓ Laser-Plasma diagnostics (CLPU, SdC)

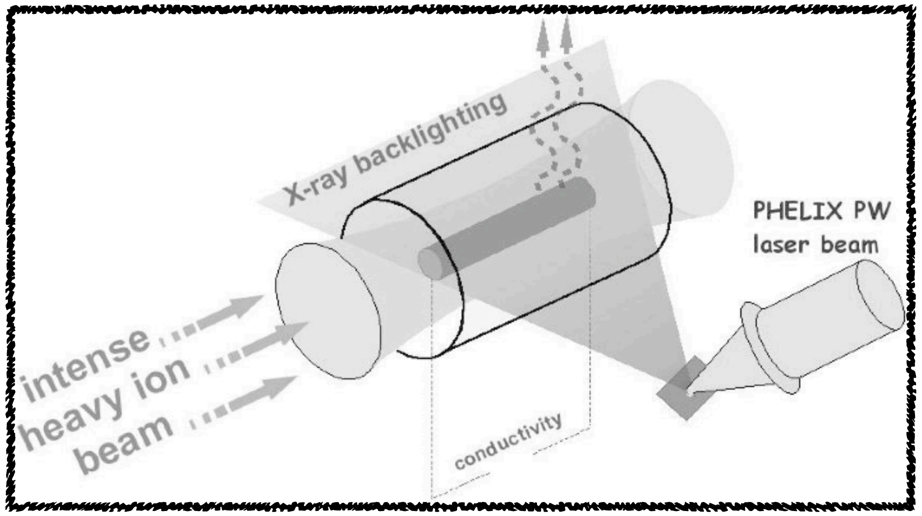
Thanks for the attention

◉ *Topics of possible common activities*

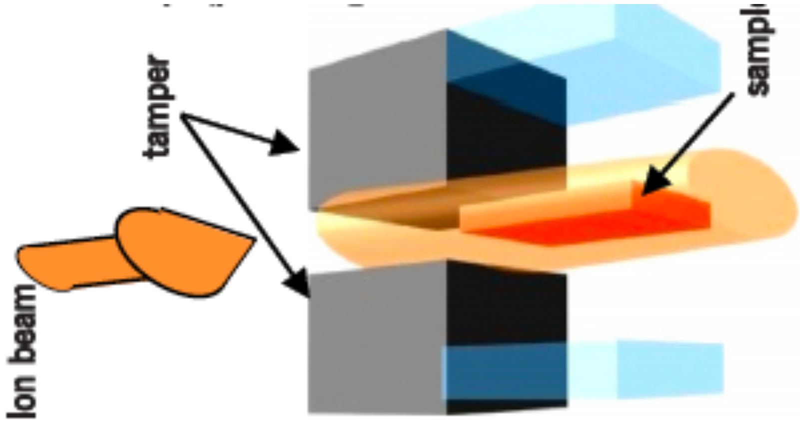
✓Proton isochoring heating how to maintain constant Volume high density WDM

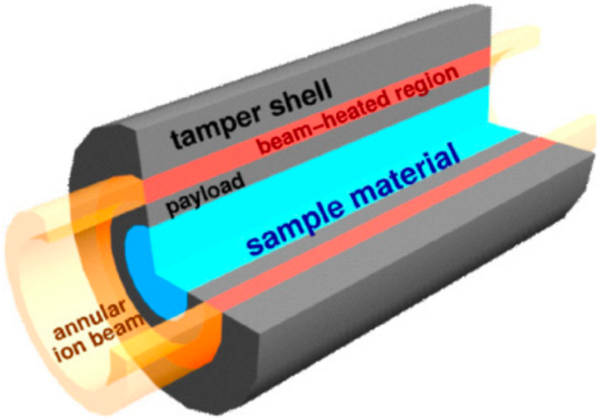


✓ Establish a series of diagnostics for High density plasmas



✓Tamper methods





✓Synchronisation

◉ *Topics of possible common activities*

- ✓ Measurements are interesting close to the Bragg peak $E_p \sim E_{th}$
- ✓ WDM require relatively law temperatures $T \sim 1 - 50eV$
- ✓ So the proton energy must be of the order of $E_p \sim$ hundreds of keV
- ✓The areal density of the WDM sample must be no more than few um
- ✓The stagnation time is then of the order of tens of ps or even less
- ✓ The time of the proton probe must be less than the stagnation time
- ✓ Or the diagnostic must be time dependent

CENTRO DE LÁSERES PULSADOS

TROC workshop: Technology & Research Opportunities @ CLPU

Salamanca – 17-19 April 2023

Network on Extreme Intensity Laser – NEILS @ LASERLAB

Salamanca – 20-21 April 2023

Laser Plasma Summer School - LaPlaSS

Salamanca –11-15 September 2023

50th European Physical Society Conference on Plasma Physics (EPS Conference) CLPU+UPM

Salamanca- June/July 2024

CONTACT US