Luca Volpe, "Laser-driven particles & extreme plasmas",

1st INFN Workshop on "High Power Lasers and their Applications" - HPLA2024

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Laser-driven particle and extreme plasmas

A required experimental platform

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- ELI ERIC Co-ordinator for laser-induced fusion research

Main Message of the talk

✓ Ion energy deposition in matter at **extreme conditions** is relevant for ICF, planetology and laboratory astrophysics

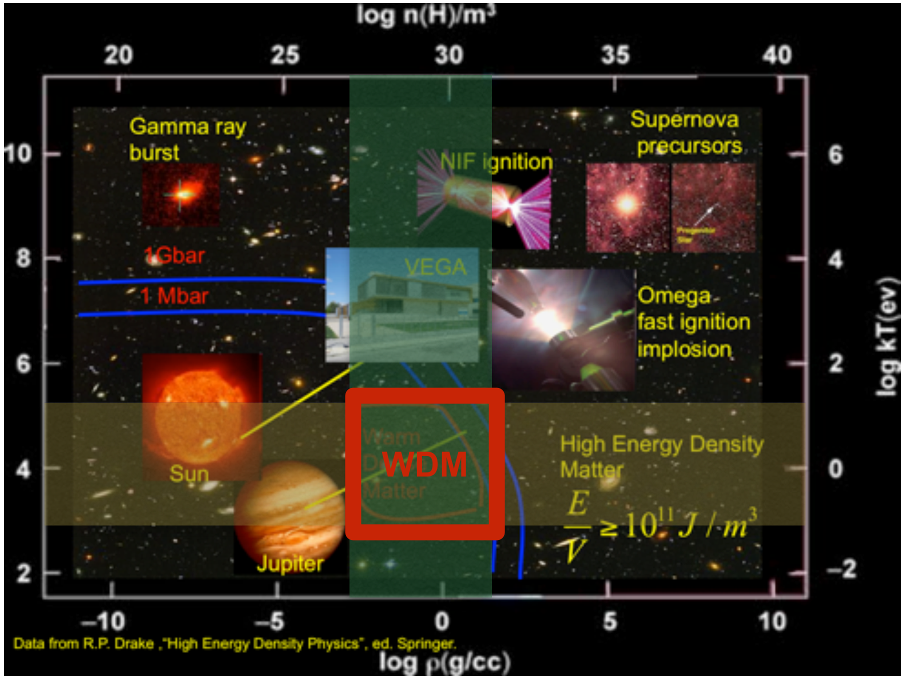
✓ It was demonstrated the **scalability** of the physical process from high energy long pulses to low energy short pulses laser systems.

✓ Ultra short high power lasers can provide **dedicated experimental platforms** for the study of ultra fast extreme plasmas

Extreme plasmas

EXTREME STATES are challenge

- ✓ Low Temperature & High density
- ✓ **(Theory)** Requires Quantum (T) many bodies (ρ) theories
- ✓ **(Experimentally)** require High frequency probes and XUV & X-ray technics



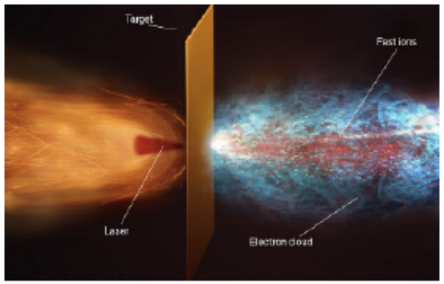
WDM parameters

$$\theta = \frac{k_B T_e}{E_F} < 10$$

$$\Gamma = \frac{e^2}{a(k_B T_e + E_F)} > 0.1$$

Laser-driven proton beams

TNSA sources



$\Delta t_p \sim \Delta t_L \sim$ ps ; $n_p \sim 10^{12}$ $j \sim 2x10^5$ A

$\varepsilon_\perp \sim 10^{-4}$ mm mrad;

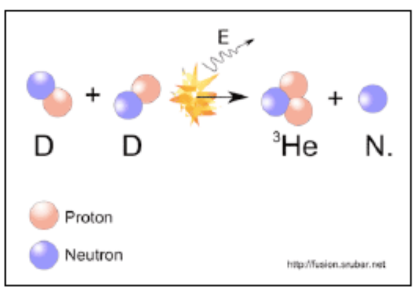
$\varepsilon_{//} \sim 10^{-4}$ eV

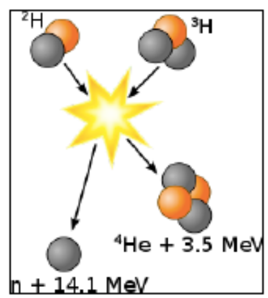
- few joules
- fs pulses
- um scale

Nuclear sources

$$D + D \rightarrow T\ (1.01\ MeV) + p\ (3.02\ MeV)$$

$$D + 3He \rightarrow 4He\ (3.71\ MeV) + p\ (14.63\ MeV)$$

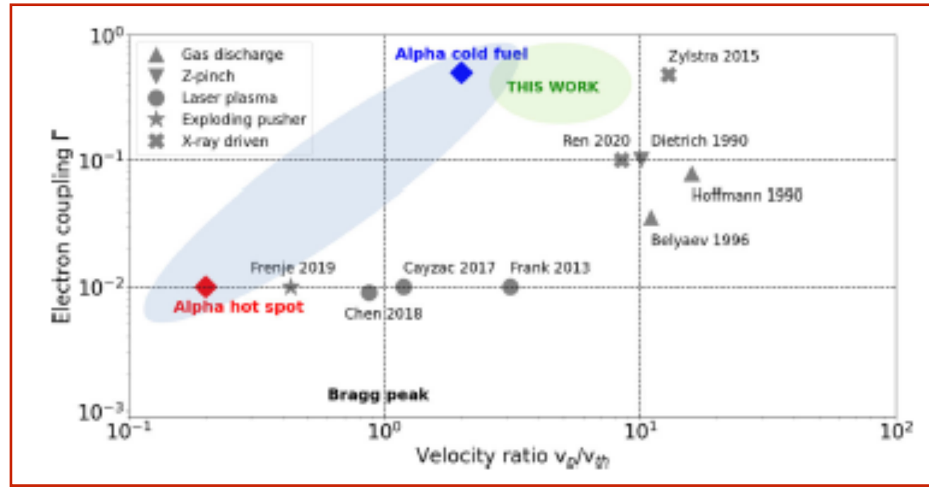


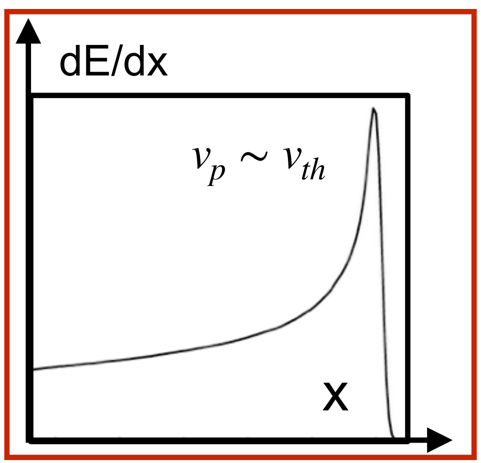


- k-M Joules
- ns pulses
- cm scale

Ion stopping power measurements in plasmas

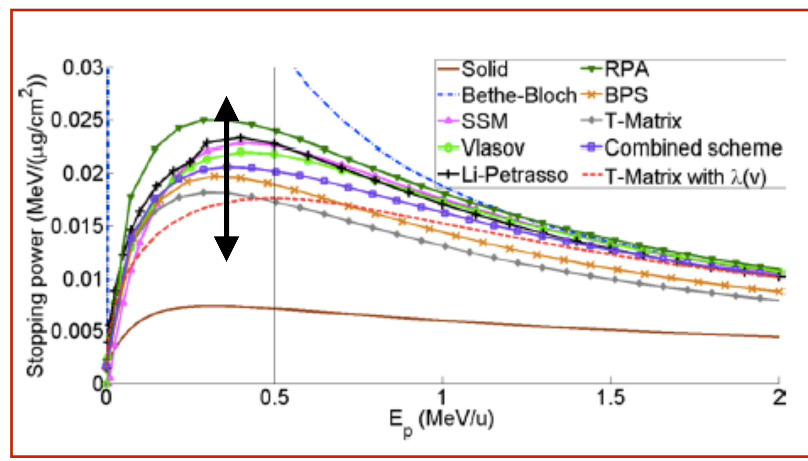
- dE/dx in cold matter well known
- Linear with density (bound electrons)
- dE/dx in plasma (T(t),rho(t)) (free electrons)
  - Bragg peak $v_p \sim v_{th}$
  - WDM $T \sim T_F \; \rho \sim \rho_{Solid}$
- experimental results with resolution below tens of KeV





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

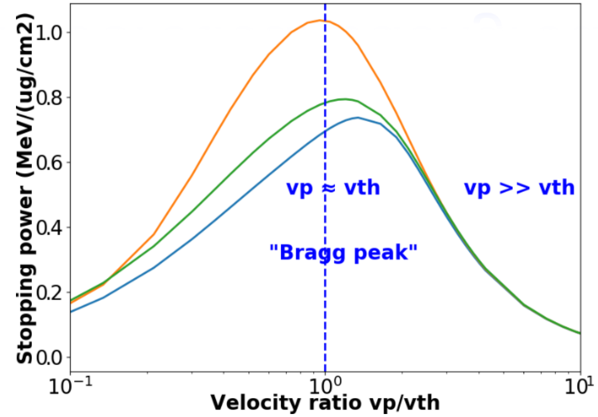
$$R(E) = \int_0^E \frac{1}{S(E)} dE$$



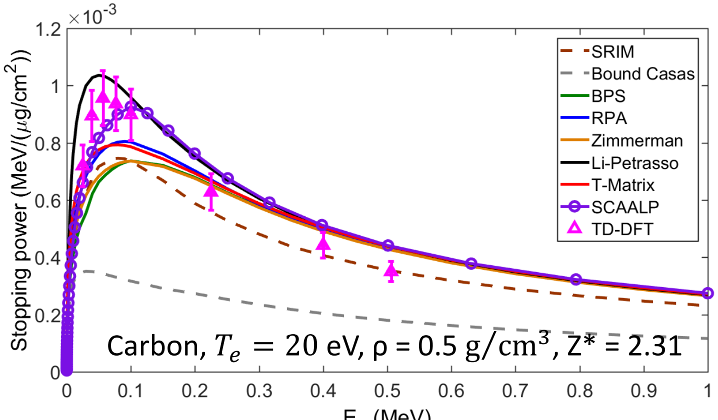
Theoretical background

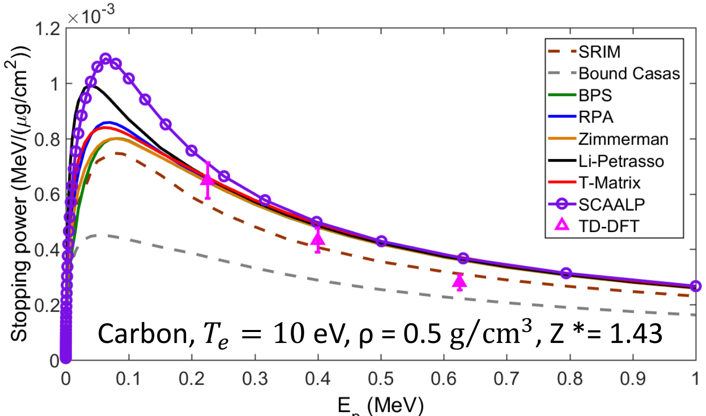
Theoretical modelling is challenging!

- 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)*

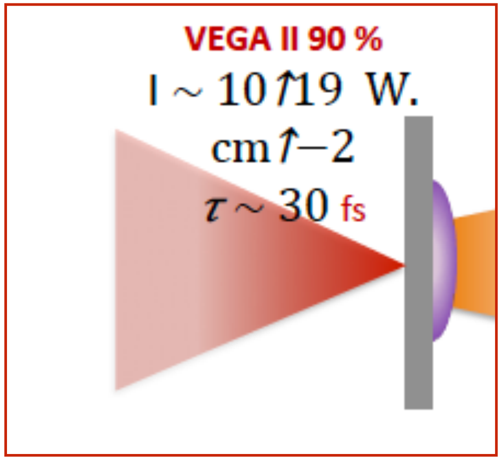
[8] *Zylstra A. et al., Phys. Rev. Lett. **114**, 2015002 (2015)*

[9] *Malko S., PhD Thesis (2020)*

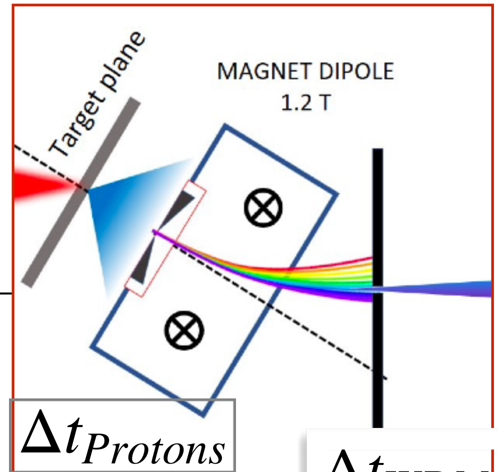
[10] *Malko S. et al., in submission to Nature Communications (2021)*

Experiment: how to

step0: TNSA protons



Step1: select protons



step2 Generate WDM

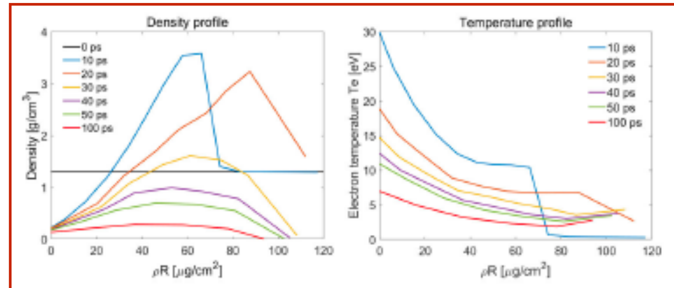
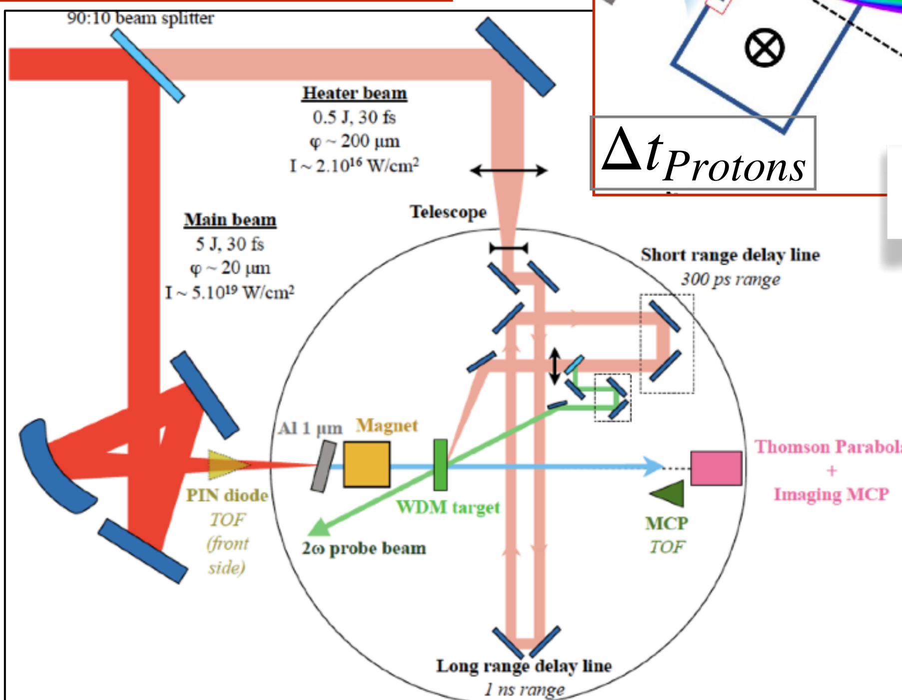
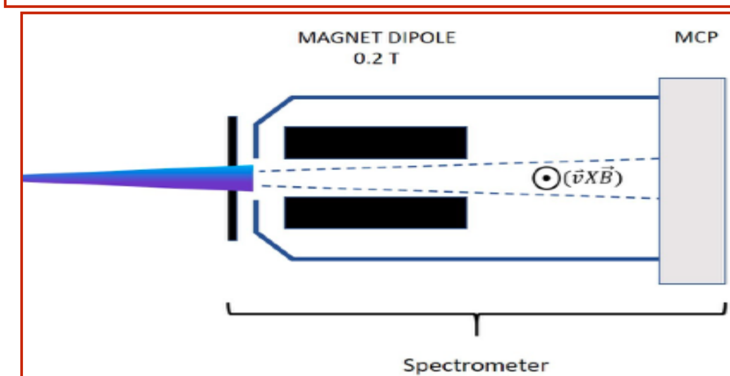


Fig. 4.10 Density profiles as function of areal density simulated with 2D hydrodynamic code RALEF2D for different expansion times from 10 - 50 ps (left). Corresponding temperature profiles for the expansion times from 10 - 50 ps (right).

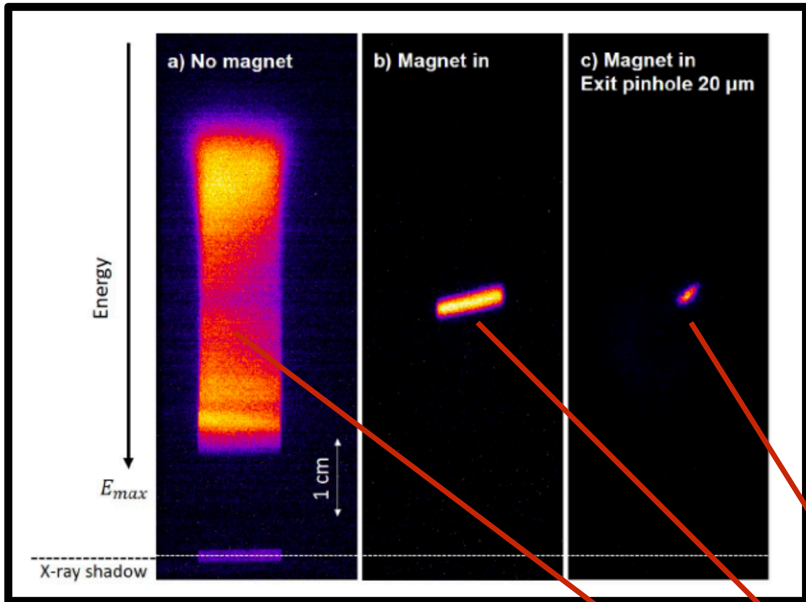
$$\Delta t_{WDM} \sim \Delta t_{protons}$$



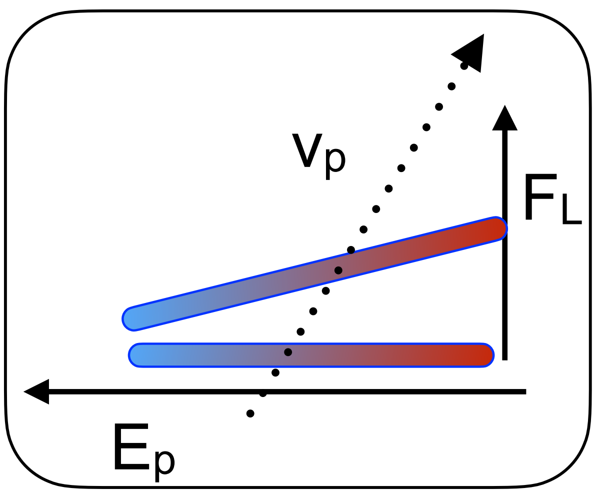
Step3: Measure proton energy

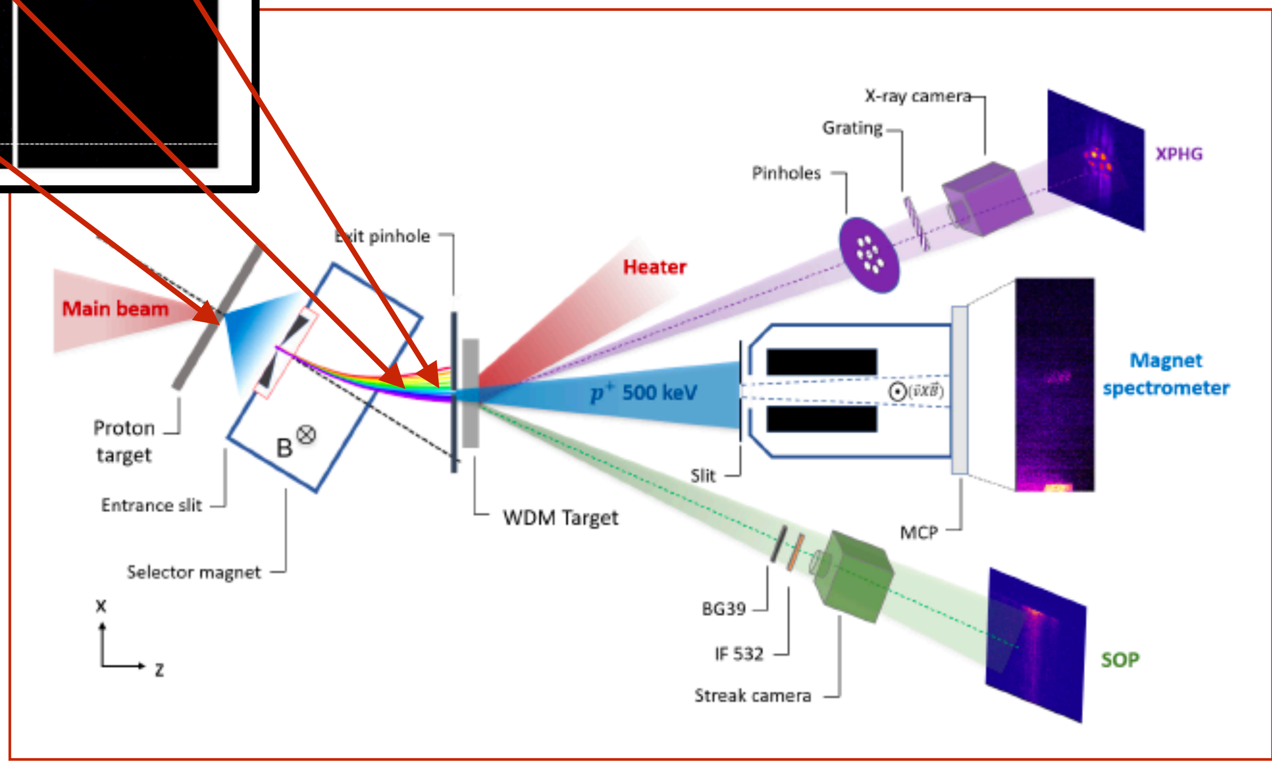


Proton energy

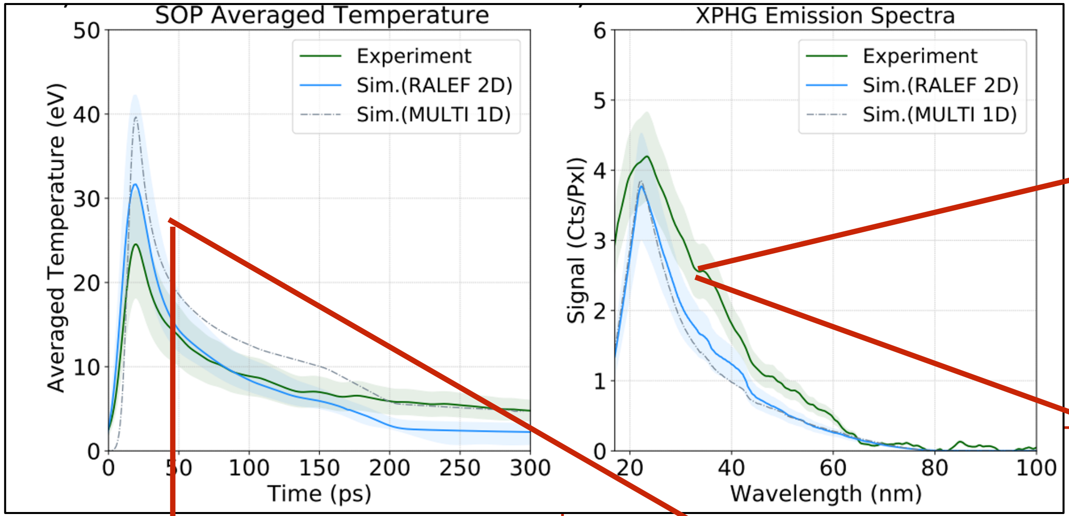


Entrance slit	Exit pinhole/slit	Bandwidth [keV]
50 μm slit	200 μm slit	79
50 μm slit	20 μm pinhole	54
20 μm slit	20 μm pinhole	44
20 μm slit	10μm pinhole	33





Proton energy



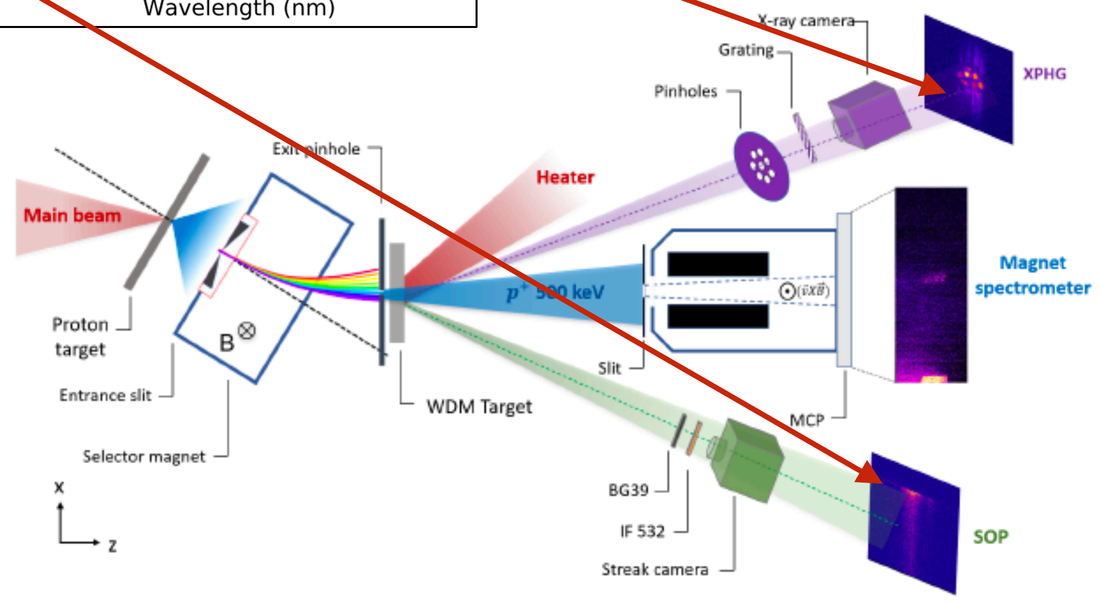
X-ray Pinhole Grating Camera

- 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

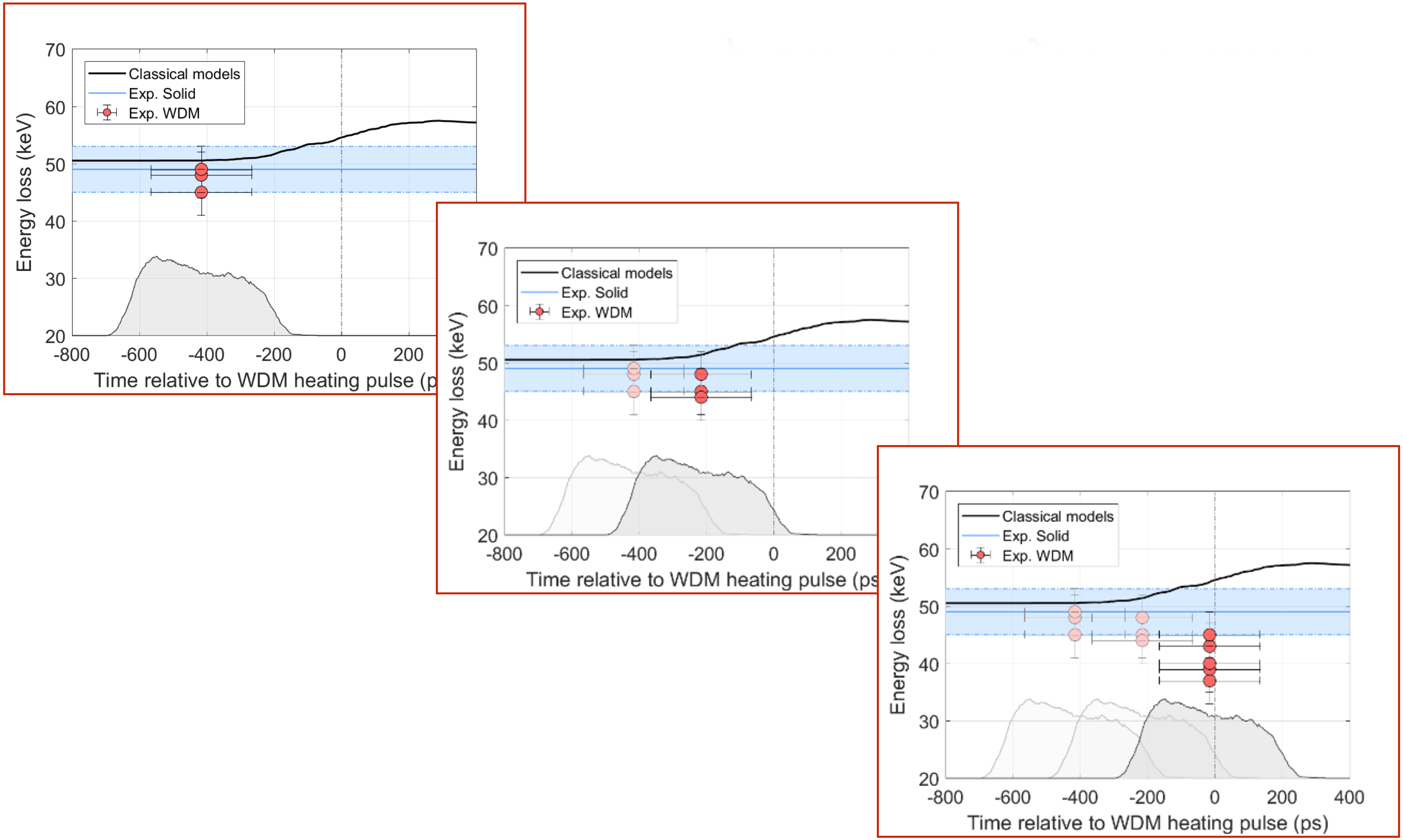
Streak optical pyrometry

- 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 %

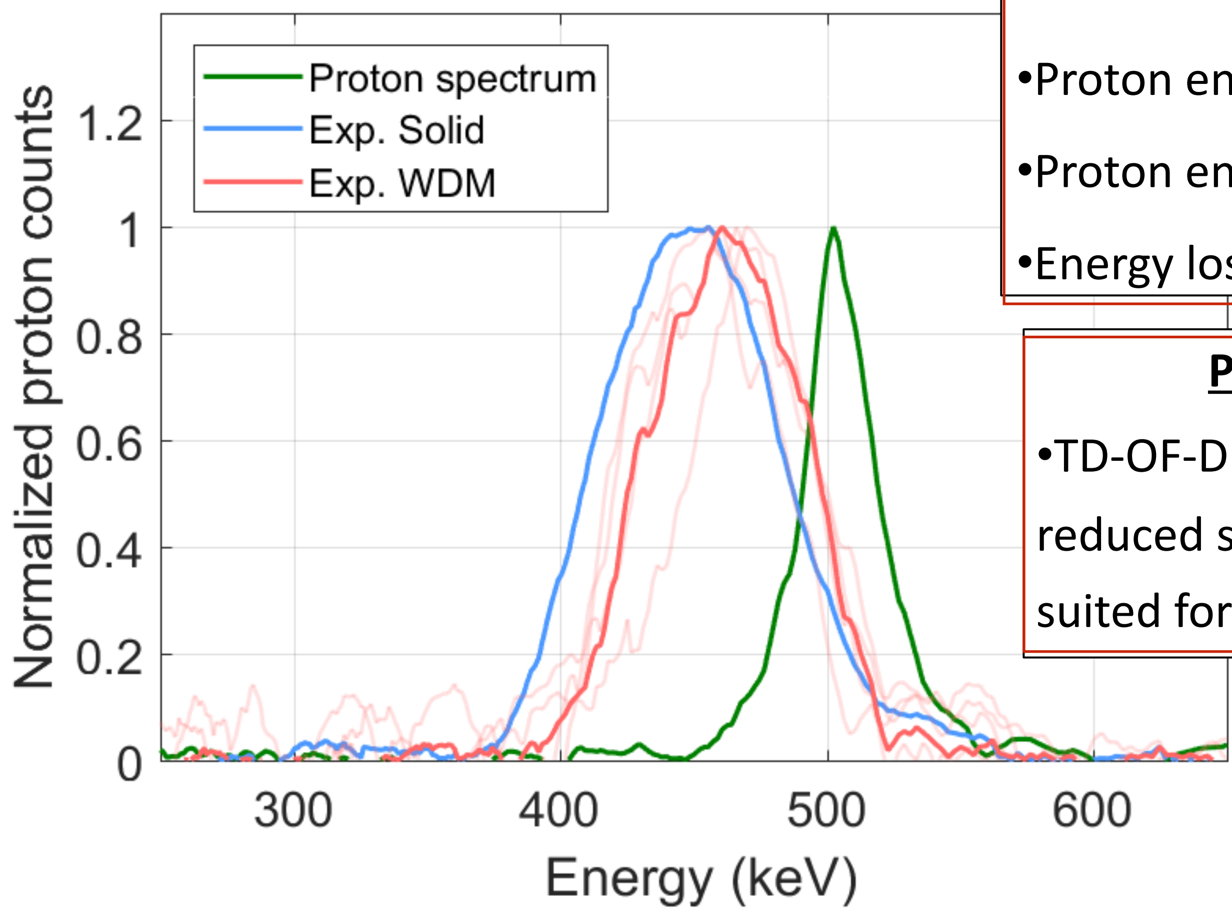
$$T_e = 7.5 \pm 1.5 \text{ eV}$$



proton wdm synchronisation



Proton energy



Observation:

- Proton energy loss in solid is 47 ± 4 keV
- Proton energy loss in WDM is 39 ± 5 keV
- Energy loss in WDM is 18% ± 8 % < solid

Possible interpretation:

- TD-OF-DFT model, which predicts reduced stopping power in WDM is best suited for this interaction regime

final outcome @ CLPU

ARTICLE

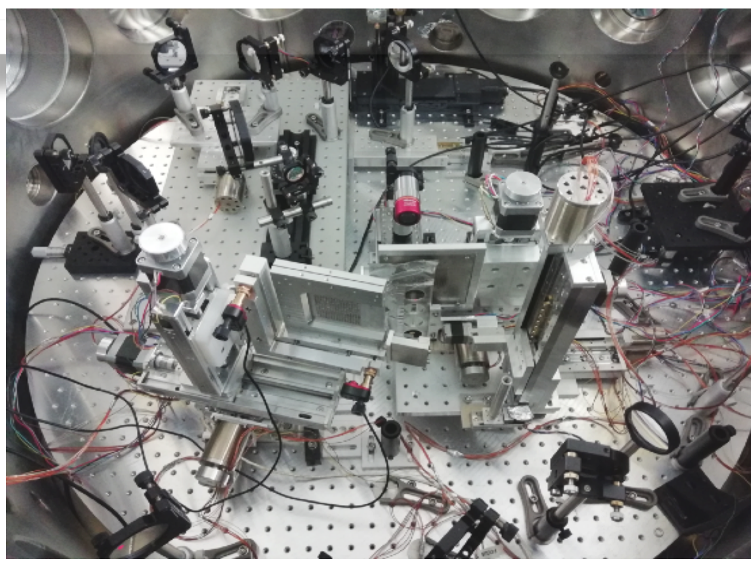
nature COMMUNICATIONS

Check for updates

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]

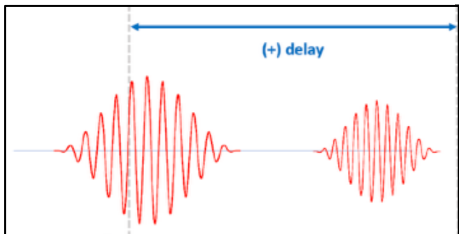


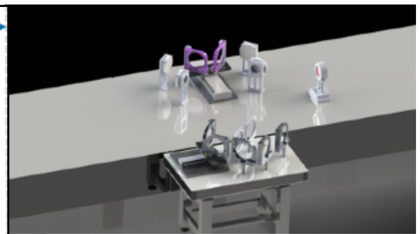
First demonstration of:
ion stopping power in WDM
for ultra-short conditions

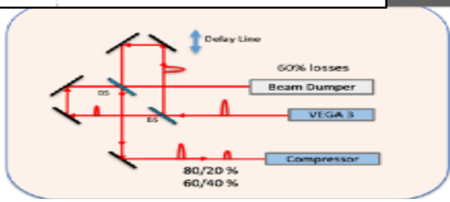
Possible improvements

- ✓ **Proton divergence needs to be reduced**
- ✓ **Proton pulse duration spread along the transport to go toward V_p/V_{th}**
- ✓ We need to measure the proton pulse duration (ToF)
- ✓ Number of protons at the detector are very few need to increase efficiency (quadrupole)
- ✓ **Warm Dense Matter generation must be optimise (Long focal pump)**
- ✓ **How to measure WDM temperature at the kinetic level?**

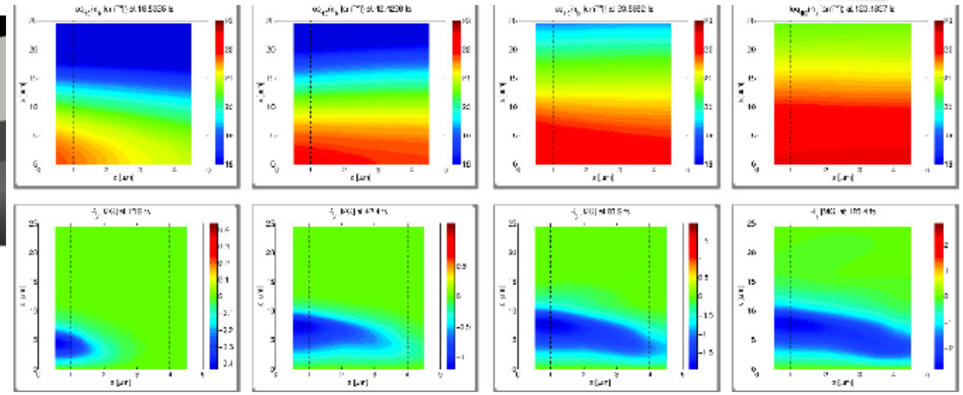
✓ **Proton divergence needs to be reduced (generation methods)**

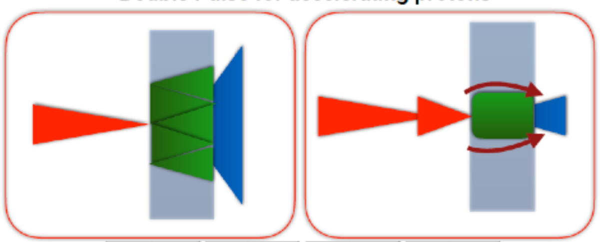


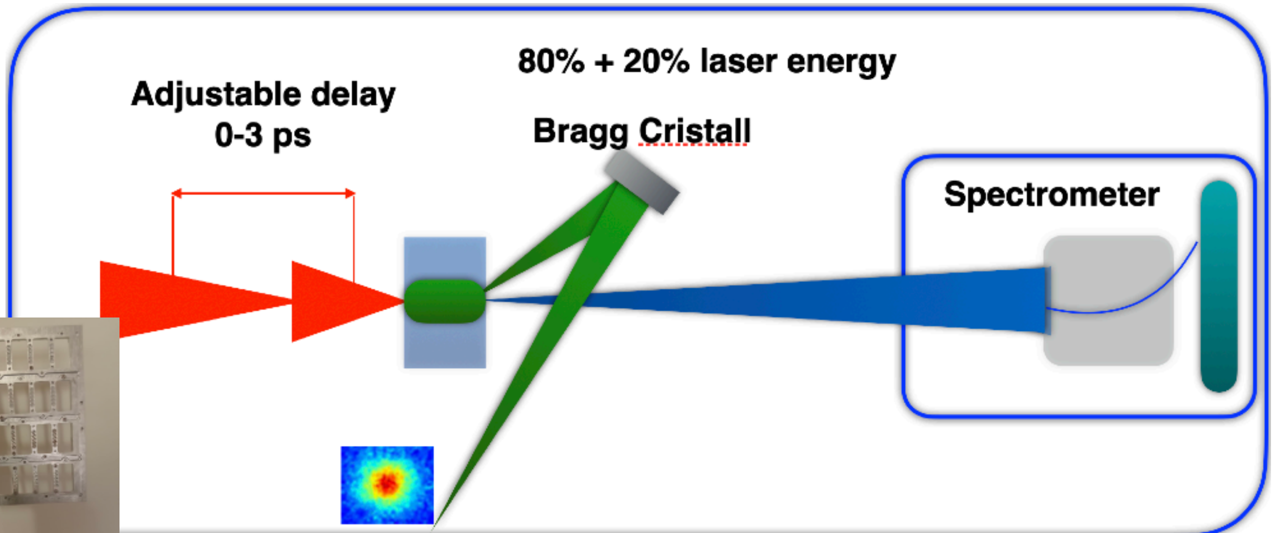


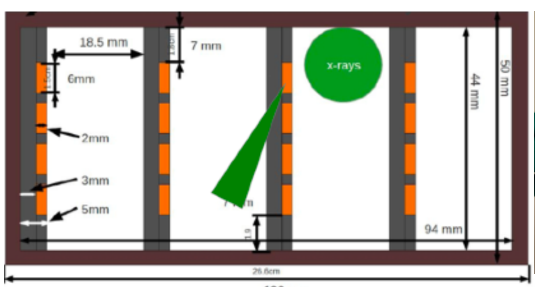


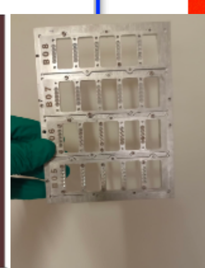
Double Pulse for accelerating protons





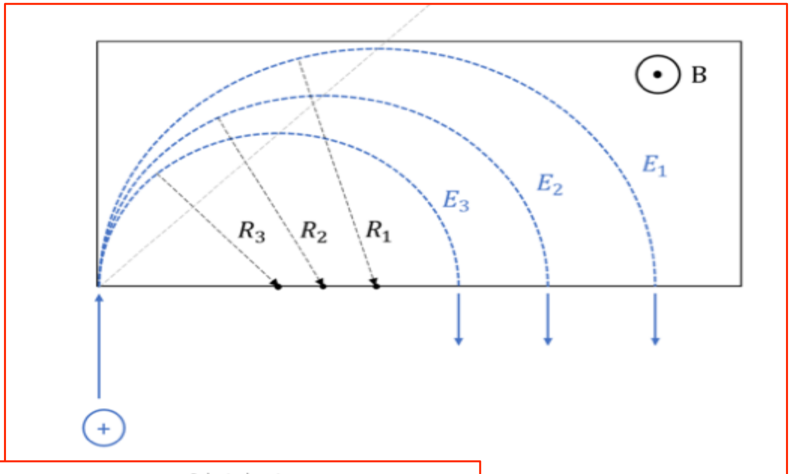


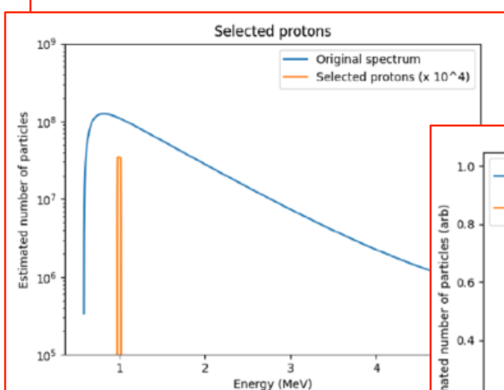


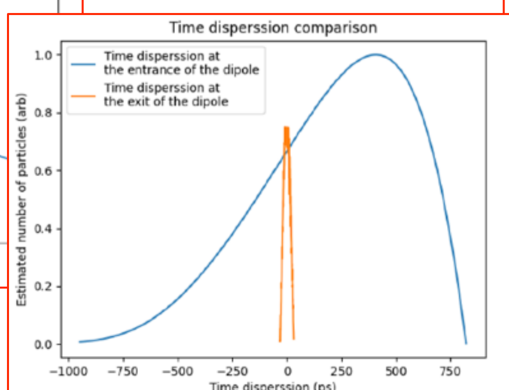


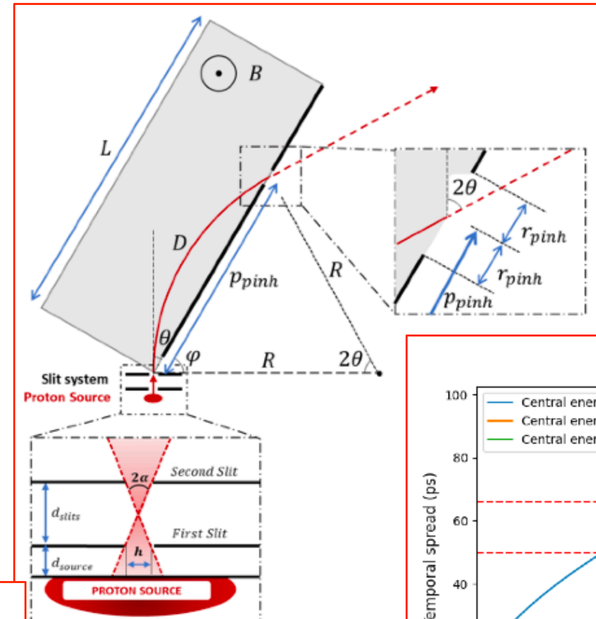
Possible improvements

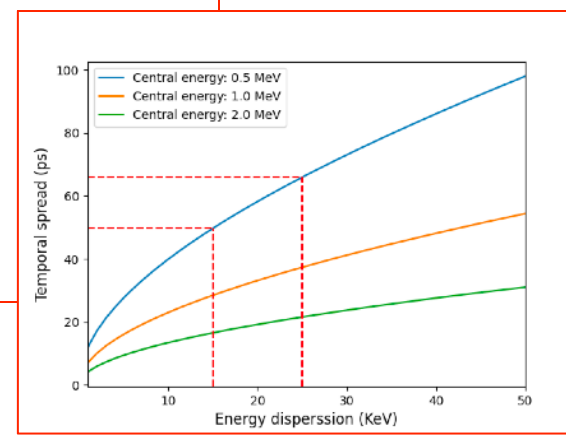
✓ **Proton pulse duration spread along the transport to go toward V_p/V_{th}**











Possible improvements

✓ **Warm Dense Matter generation must be optimise (Long focal pump)**

- ✓ Higher energy pump > 1 J
- ✓ Doubled in Frequency
- ✓ Long focal line focal spot of around 50-100 um
- ✓ Other schemes
    - ✓ Xray isochoring heating
    - ✓ Proton isochoring heating
- ✓ Improvement of synchronisation

WDM temperature @ X-FEL

✓ How to measure WDM temperature at the kinetic level?

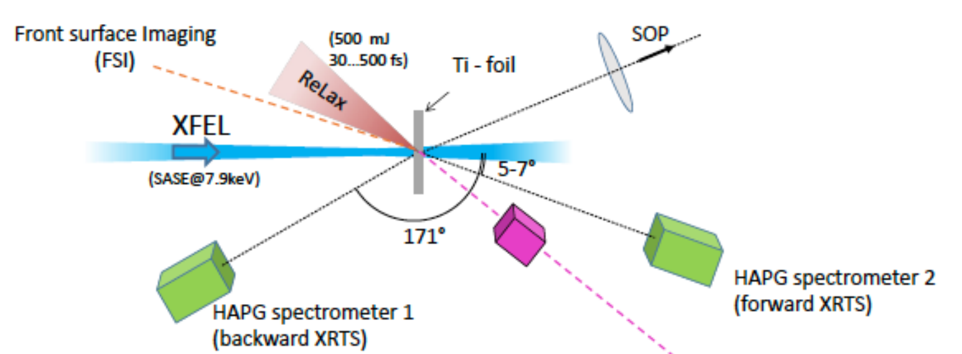
- To study heating mechanisms of Warm Dense Matter by irradiating Ti foil with fs- laser at intensities of $10^{16} - 10^{17}$ W/cm^2 : laser pulse duration will be varied from 30 fs to 200 fs
- To measure WDM conditions (T_e, T_i) using a comprehensive suit of diagnostics:

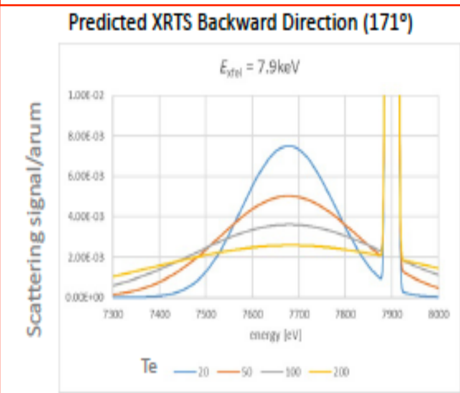
  - Spectrally resolved X-Ray Thomson Scattering (XRTS) in the noncollective regime (backward direction) to provide a direct measurement of the electron temperature;
  - XRTS in forward direction for measuring the elastic scattering to infer ion temperature
  - Streaked optical pyrometry (SOP) at 624 nm to infer the electron temperature at critical density.
- The experimental results will be used to benchmark hydrodynamics models RALEF-2D, MULTI-fs and density functional theory (DFT) models

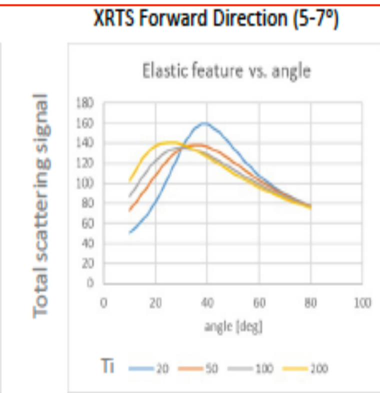
Goals of the Experiment

- **Setup A:** I = 5x10^{17} W/cm^2, τ = 30 fs, E = 0.5 J
- **Setup B:** I = 1x10^{16} W/cm^2, τ = 500 fs, E = 0.2 J

Requested spot size FWHM 30 – 50 μm







- X-ray probe: XFEL at 7.9 keV, 1 mJ pulse energy

  | Expected 2 - 4 ×10^7 scattered photons for 1 and 2 μm Ti.
- XRTS backward scattering (non-collective), inelastic feature with has sensitivity to electron temperature

  | Spectral range 7.3 – 8.16 keV | cumulative measurements (30-50 shots, 300 scattered photos on spectrometer per shot)
- XRTS forward scattering , (elastic scattering), scattering strength is determined by ion-ion structure factor which is strongly dependent on ion temperature (on small angles)

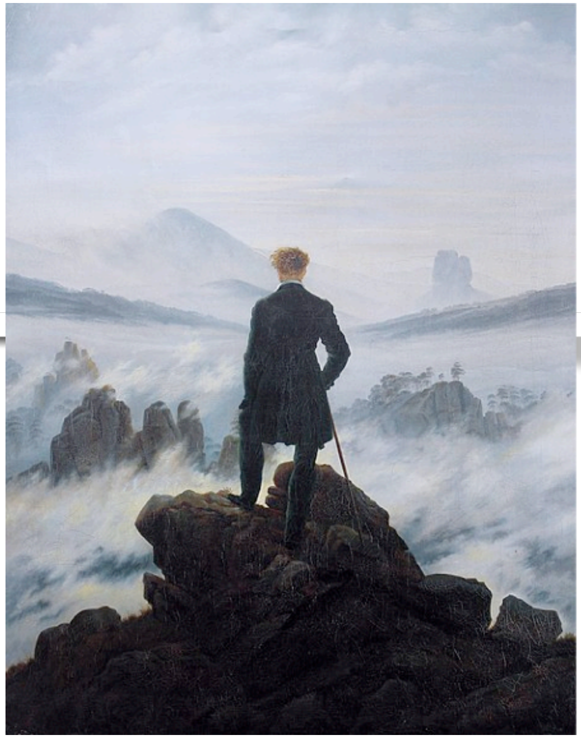
  | Spectral range 7.13 – 8.0 keV | single shot measurement

Thanks for the attention

It is by seeking the impossible that man has always achieved the possible.

Those who have wisely limited themselves to what appeared to them as possible have never advanced a single step.

(Michael Bakunin 1814-1876)



1818 Caspar David Friedrich - Wanderer above the sea of fog