HEDS

SEMINAR SERIES

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Low velocity proton stopping power measurements Dense Matter

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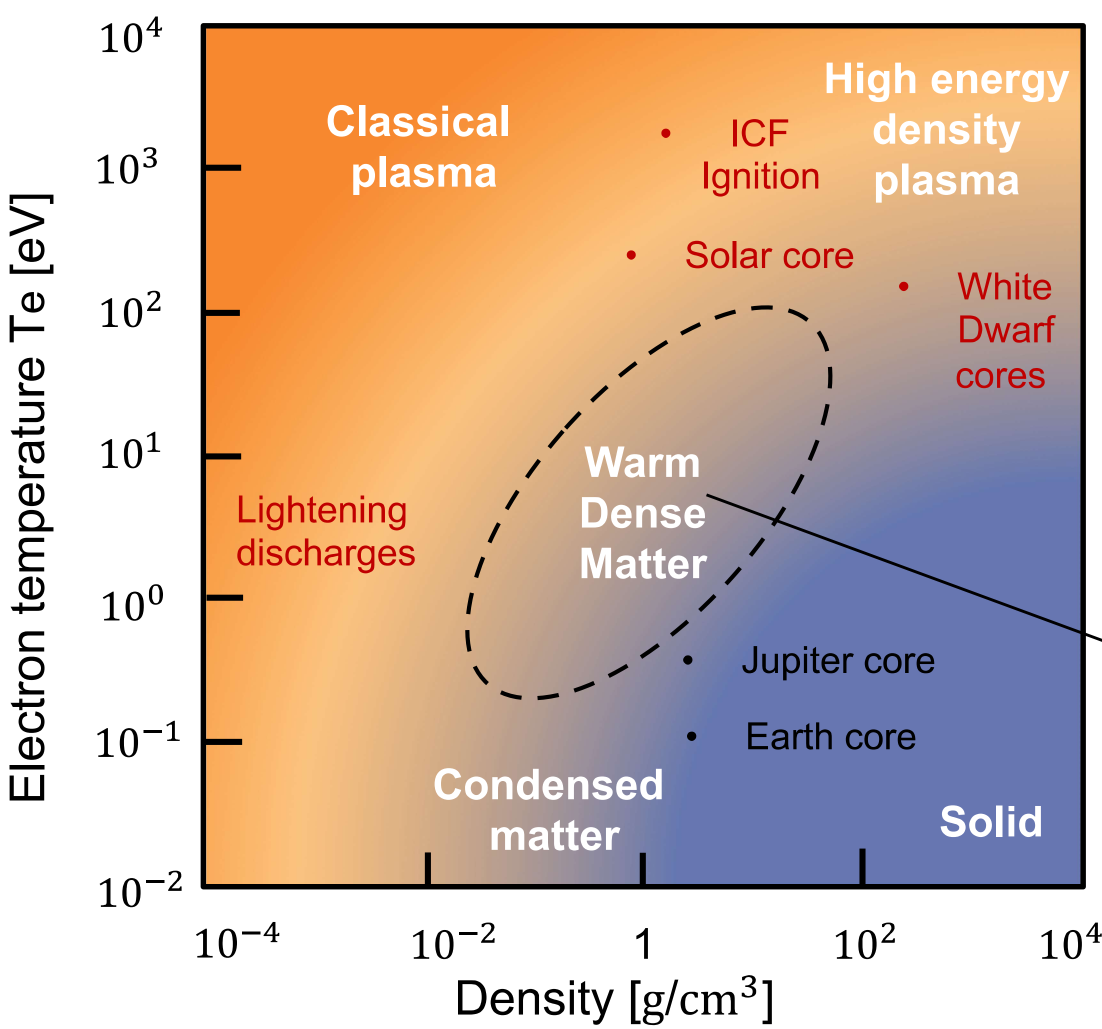
Warm Dense Matter



- Inertial Confinement Fusion implosions
- Laser driven plasma
- White Dwarf He envelope
- Shocks driven by Z pinches
- Highly compressed solids

- **Electron dege**

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

- **Coupling para**

$$\Gamma = \frac{< E_p >}{< E_k >} = $$

- **Partial ioniza**

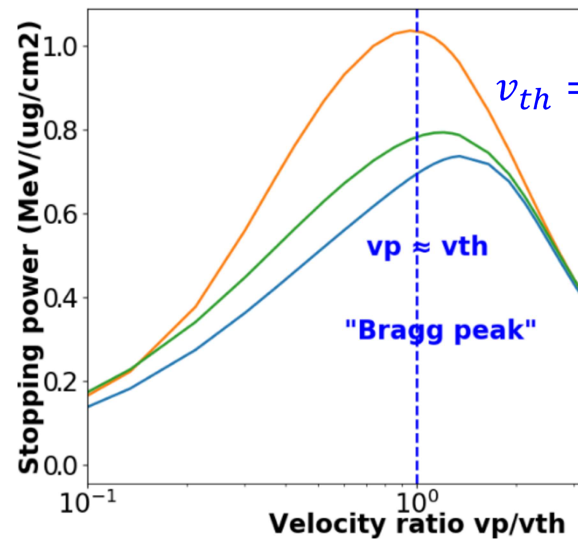
Ion stopping power in Warm Dense Matter: θ < 10 and Γ > 0.1

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]

Experiments are challenging!

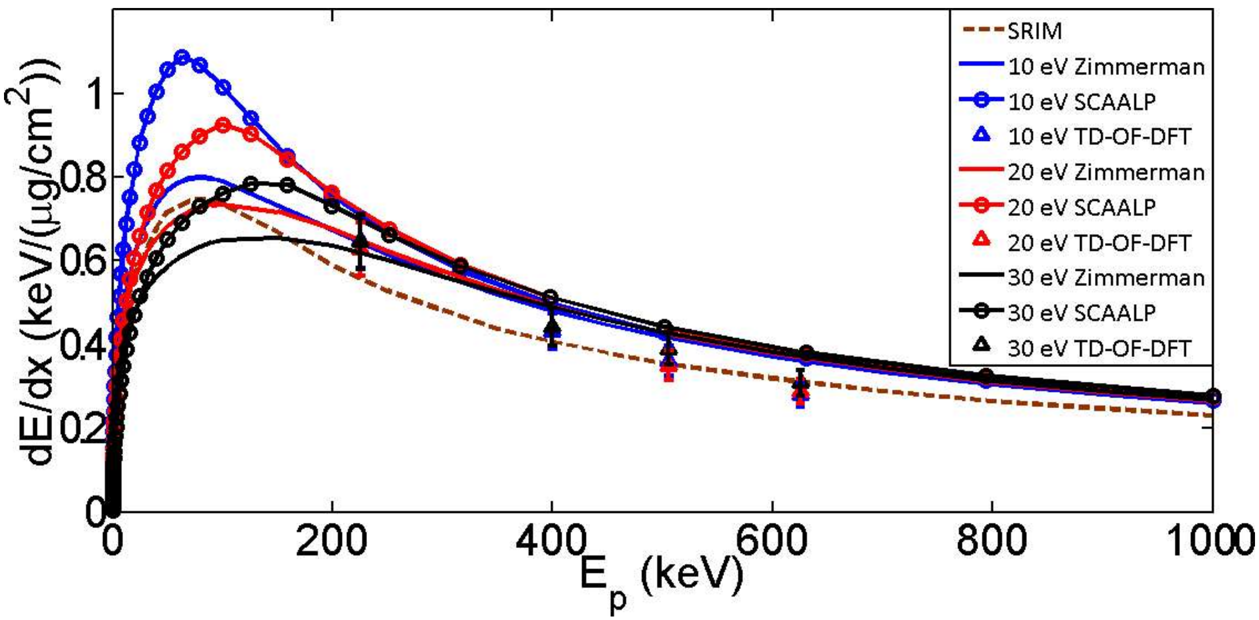
- v_p/v_{th} ≈ **13** monoenergetic protons in WDM [8]
- v_p/v_{th} ≈ **3** TNSA energy selected protons in WDM [9,10]



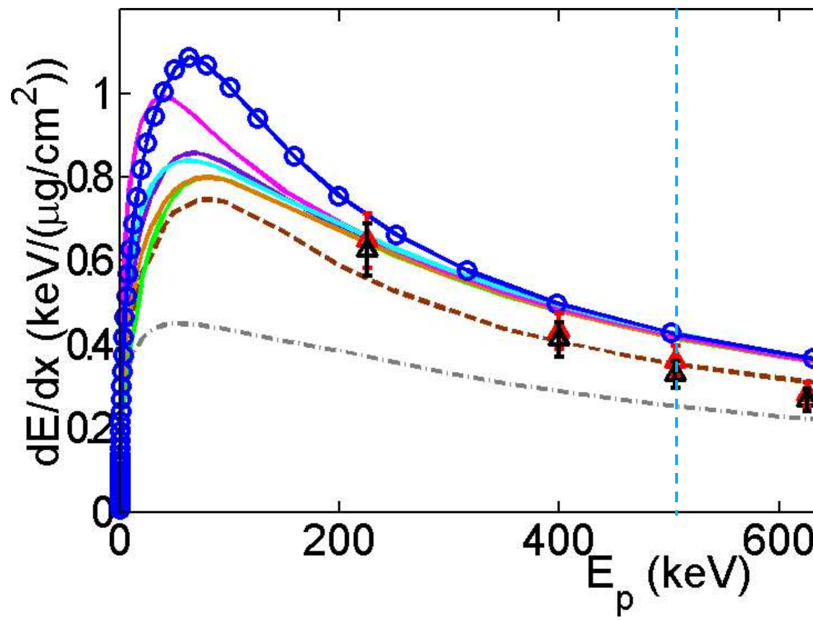
[1] *Zimmerman, G. Report no. ucrl-jc-105616. LLNL.(1990)*
[2] *Gericke, D. O. et al., Physical Review E,* ***65*** *(2003)*
[3] *Zylstra A. et al., Physics of Plasmas* ***26****, 122703 (2019)*
[4] *Casas D. et al., Phys. Review E* ***88****, (2013)*
[5] *Ding Y. et al., Phys. Rev. Lett.* ***121****, 145001 (2018)*
[6] *Faussurier G., et al., Physics of Plasmas* ***17****, 052707 (201*
[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 Communicatio*

There are large discrepancies between proton stopping power models in WDM regime

Carbon, T_e = 10 – 30 eV



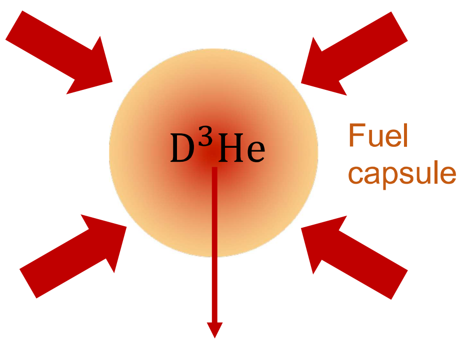
Carbon, $T_e = 10$ eV, ρ = 0.5 g/



Recent experimental approaches to measure ion stopping power at HED and classical plasma at $v_p/v_{th} \approx 1$

Exploding pusher

J. Frenje et al., Phys. Rev. Lett. ***122****, 015002 (2019)*



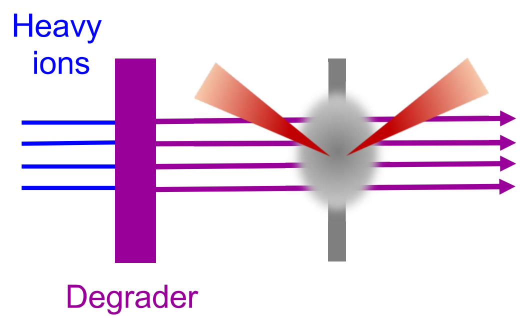
DD → T (1.01 MeV) + p (3.02 MeV)
D^3He → ^4He (3.71 MeV) + p (14.63 MeV)

$T_e \approx 1.5 - 1.9$ keV
$n_e \approx 10^{23}$ cm^{-3}

Proton time spread 100 ps

Accelerator ions

W. Cayzac et al., Nat. Commun. ***8****, 15693 (2017)*



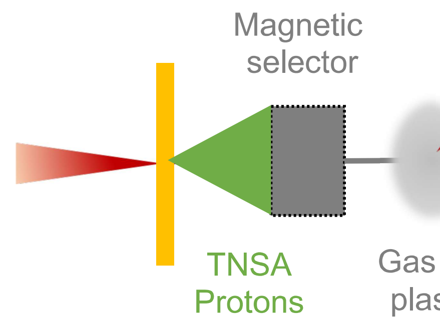
E_p = 0.586±0.016 MeV

$T_e \approx 150$ eV
$n_e \approx 10^{20}$ cm^{-3}

Ion time spread 5.5 ns

TNSA protons

S. Chen et al., Sci. Repor
14586 (2018)



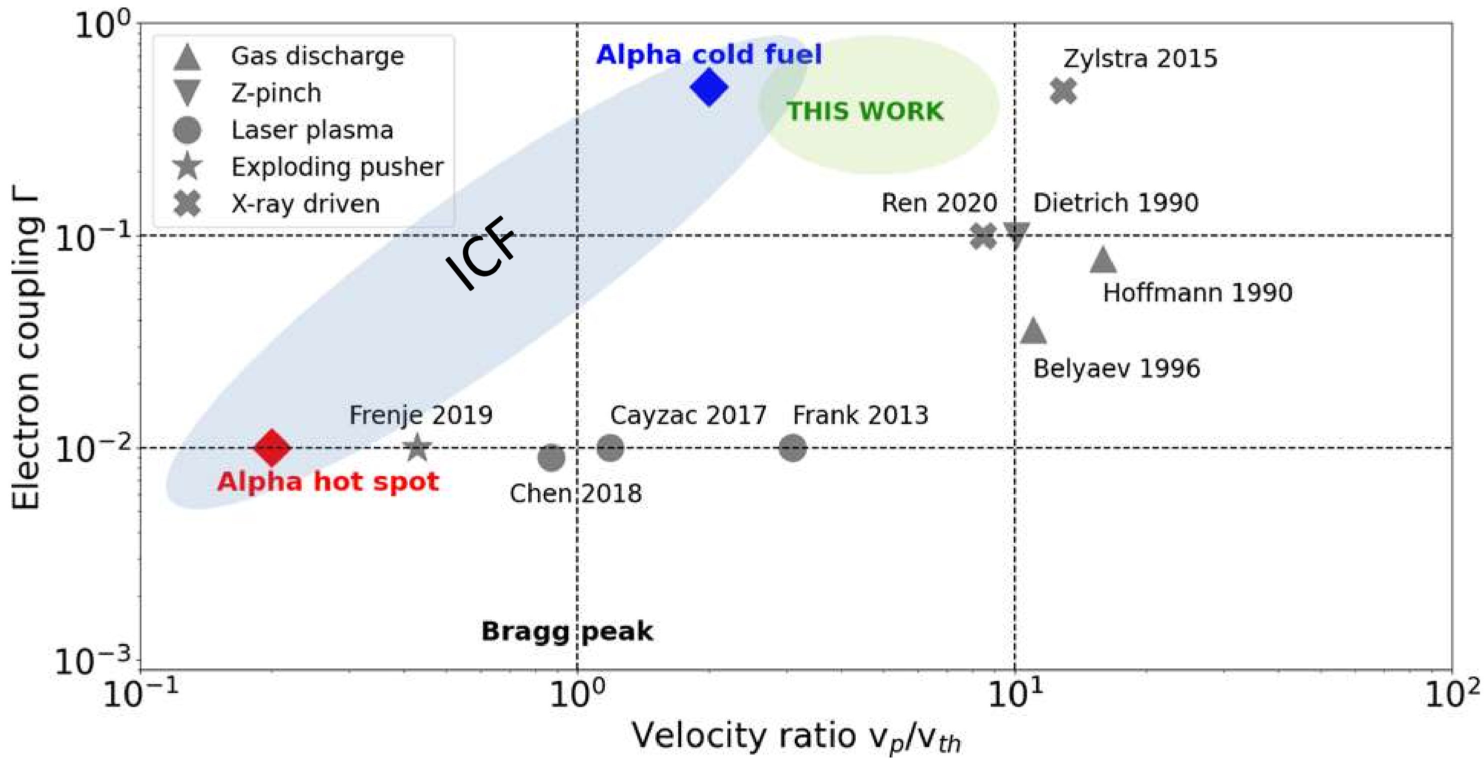
E_p = 0.5 – 0.7 MeV

$T_e \approx 100 - 200$ e
$n_e \approx 10^{20}$ cm^{-3}

Proton time spread 50

We probe a new parameter range, at $v_p/v_{th} \approx \mathbf{3}$ in WDM, close to the α-particle stopping in the cold fuel

Overview of published stopping power experiments



We developed and characterized a platform to achieve low v_p/v_{th} at CLPU VEGA II

THIS WORK: Malko S., Cayzac W., Ospina-Bohorquez V. et al. in submission to Nature Communications (2021)

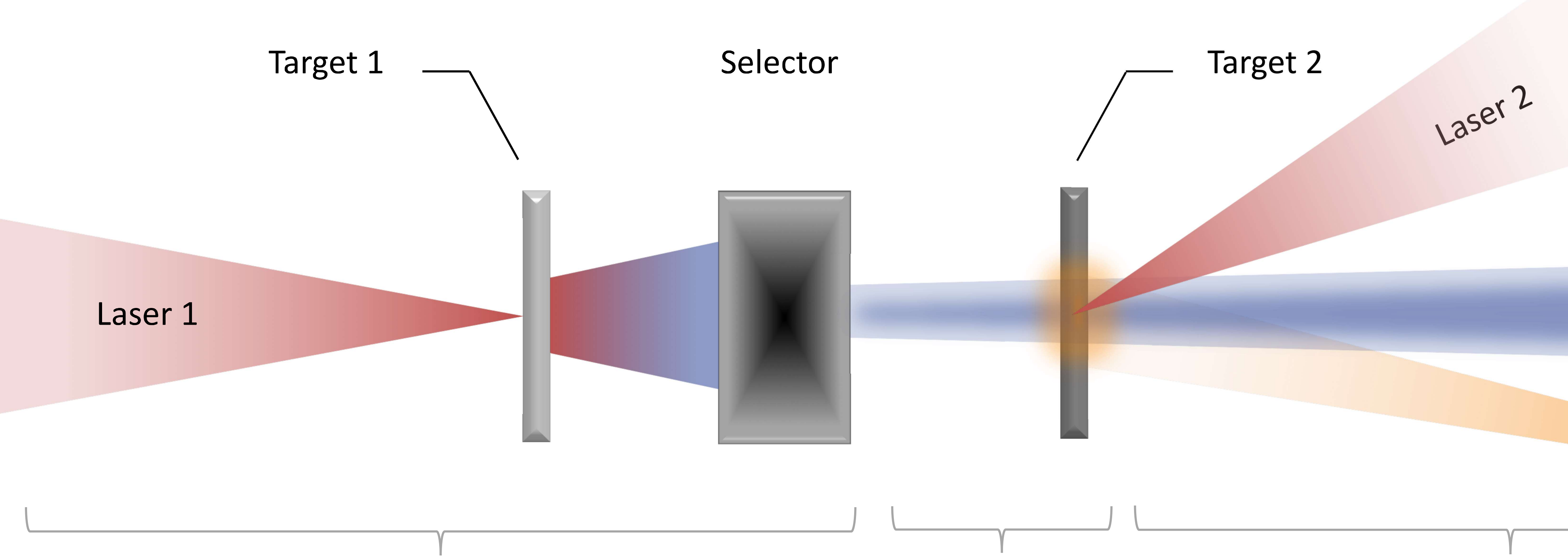
Summary of results

- **We developed a novel platform for stopping power measurements at hi**
  rate at CLPU laser facility

- **We performed a first measurement of proton stopping power at low vel**
  projectile ratio $v_p/v_{th} \approx 3$ - 10 **in WDM**

- **Simultaneously we characterized WDM by two independent target tem**
  diagnostics to verify the measurements conditions

We developed a new experimental concept to reach low $v_p/v_{th} \approx 3$ ir Warm Dense Matter at CLPU laser facility



I. Proton source generation and characterization

- Low energy protons < 1 MeV
- Small energy bandwidth
- Short time spread

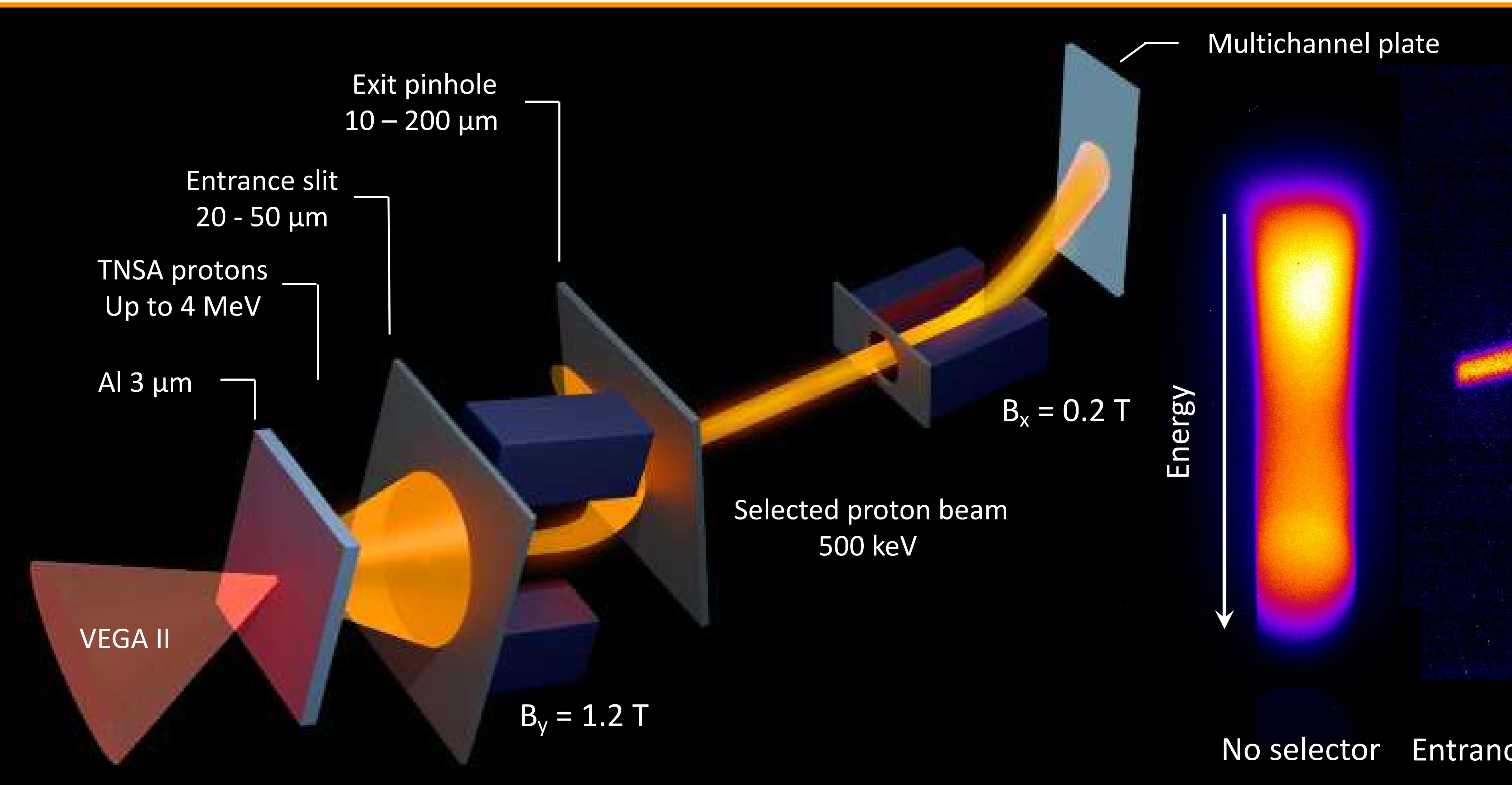
II. WDM generation and characterization

- Uniform heating
- T_e = 5-20 eV

III. Proton energy

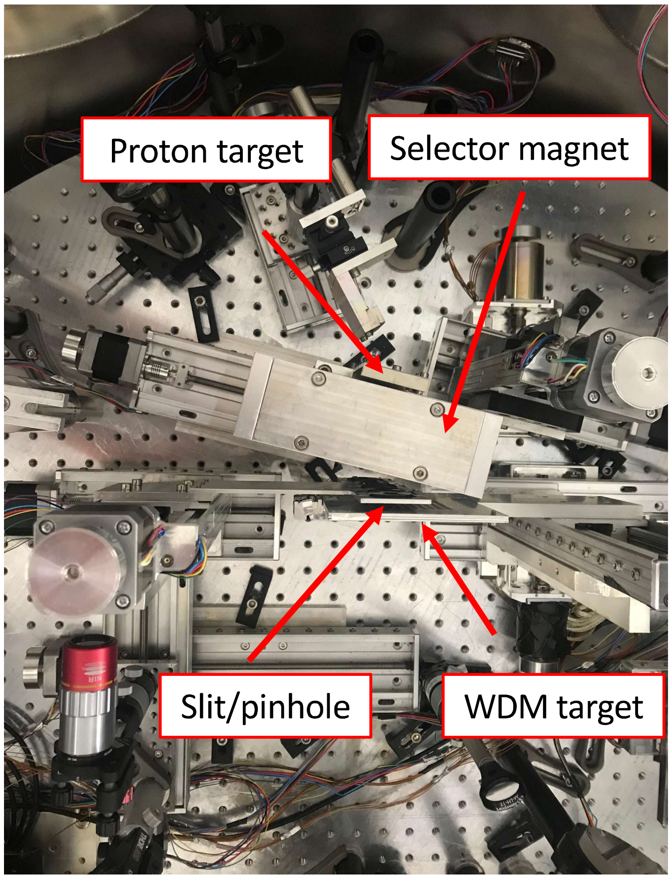
- Measuremen

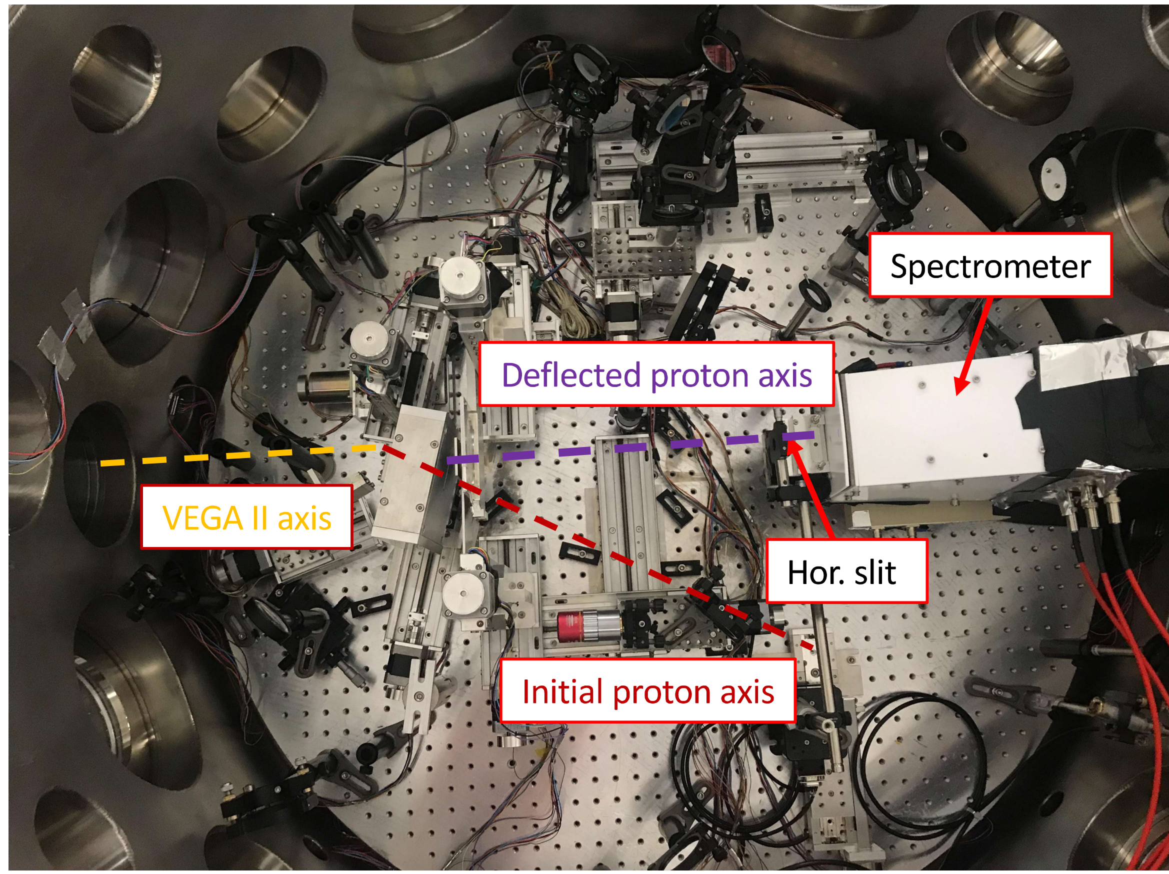
I. Energy selector for generation of quasi-monoenergetic pencil like proton beams in high repetition rate



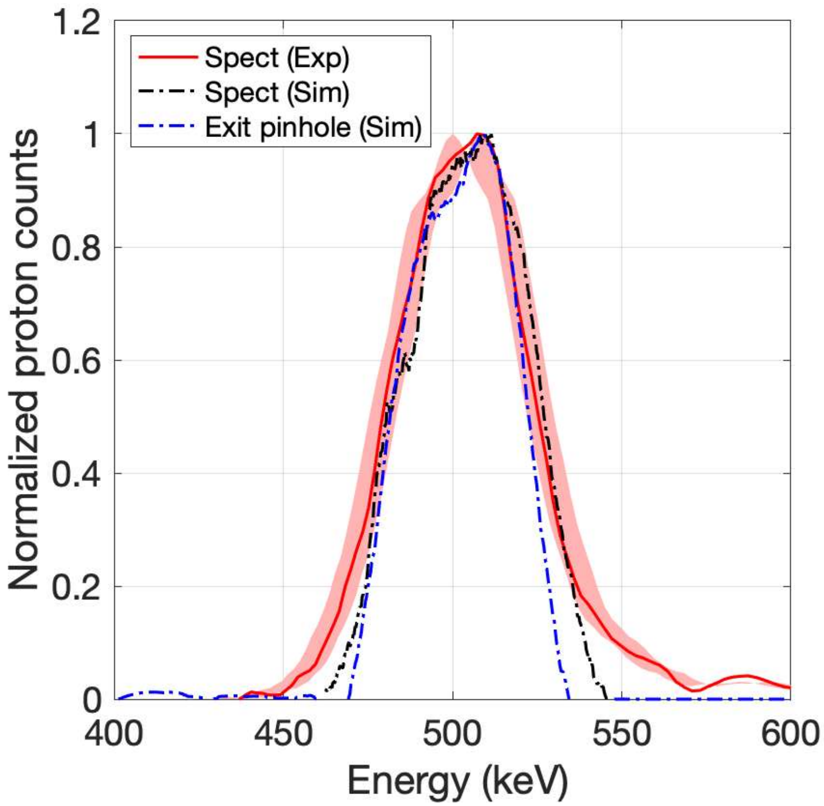
Apiñaniz J. I, Malko S., Fedosejevs R. et al., *Scientific Reports* **11**, 6881 (2021).

Experimental setup at CLPU VEGA II laser facility





We selected 500 keV proton beam with 44 keV energy bandwidth (FWHM) and time spread of < 400 ps



- Central energy: 498 ± 4 keV
- Energy bandwidth: 44 ± 4 keV (FWHM)
- Time spread: 360 ± 15 ps (FWHM)

Proton source has a size and divergence

- How proton divergence affect the energy bandwidth of selected beam?
- Is apparent bandwidth is identical to the real bandwidth at the exit of pinhole?
- Can we go below 44 keV of energy bandwidth?

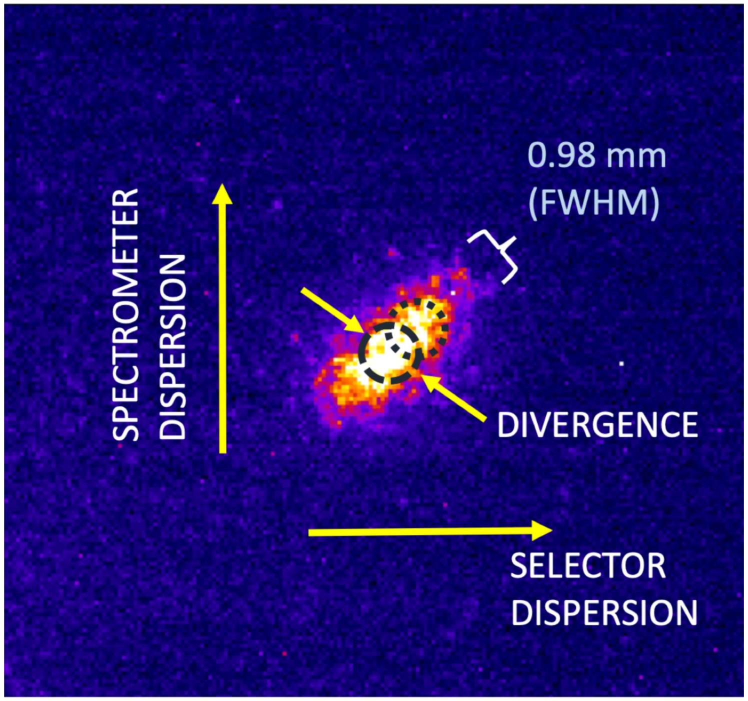
* The experimental curve is averag

** Simulations performed with Mo

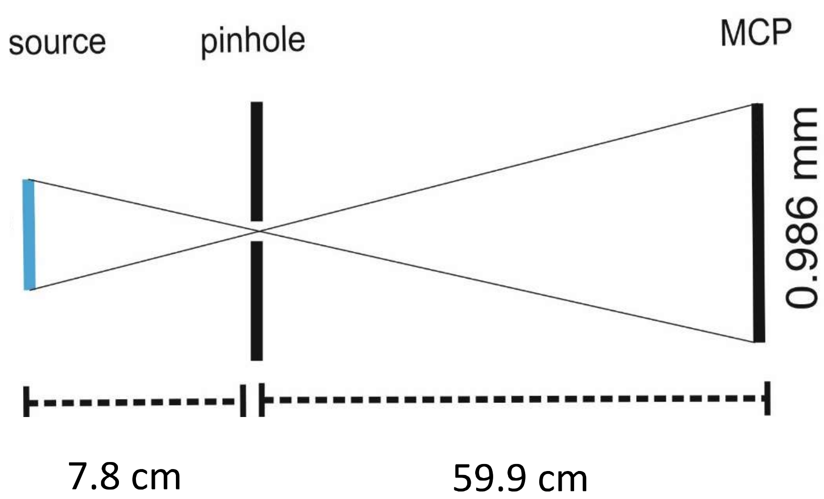
We performed analytical and numerical calculations to understand better the effect of divergence

- Estimation of initial proton source size

Raw MCP signal



Pinhole imaging system

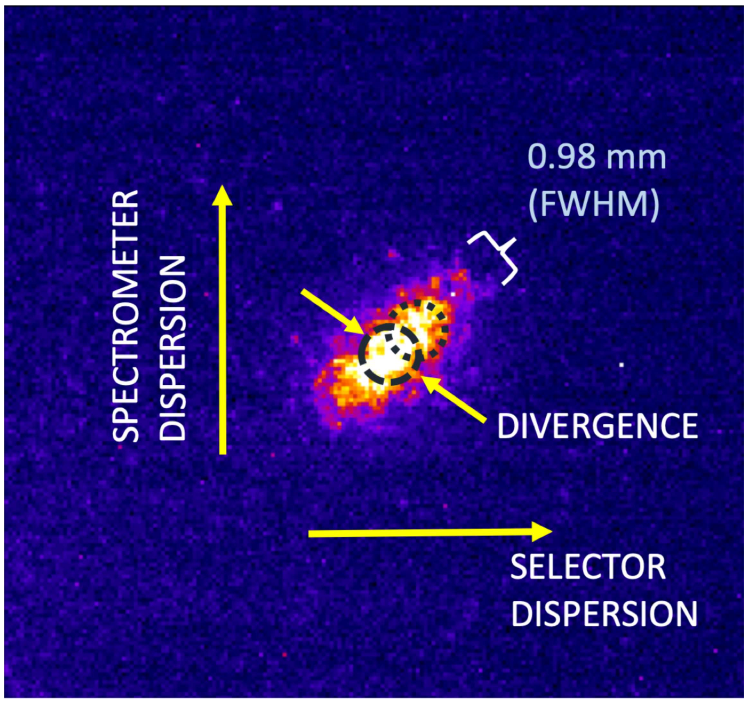


Using magnification factor ~ 7.7 we obtain proton source size ~ 150 μm

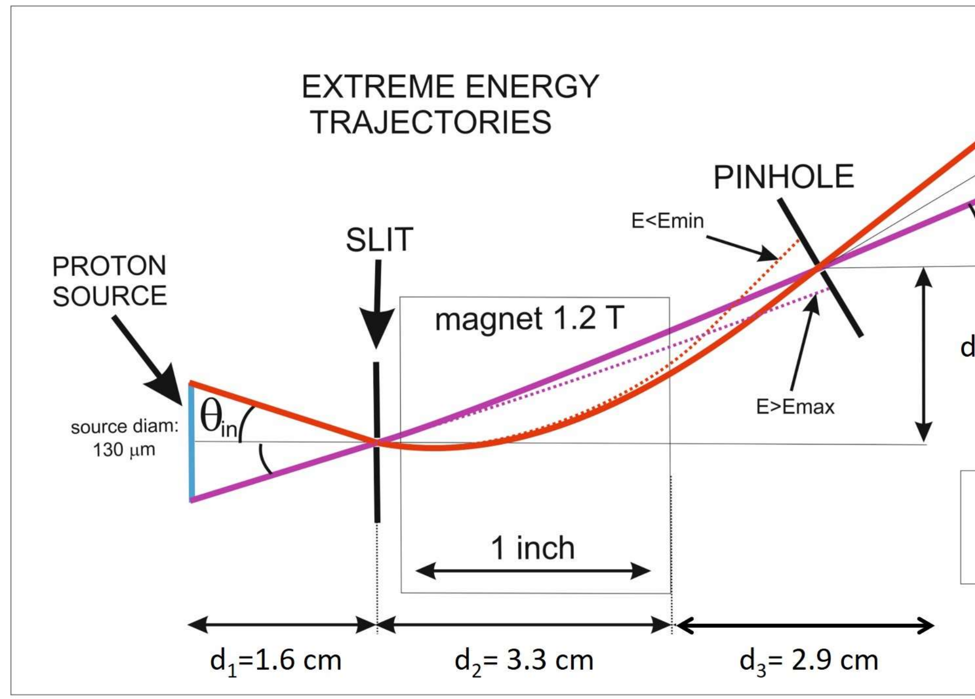
We performed analytical and numerical calculations to understand better the effect of divergence

- Estimation of the minimum achievable energy bandwidth

Raw MCP signal



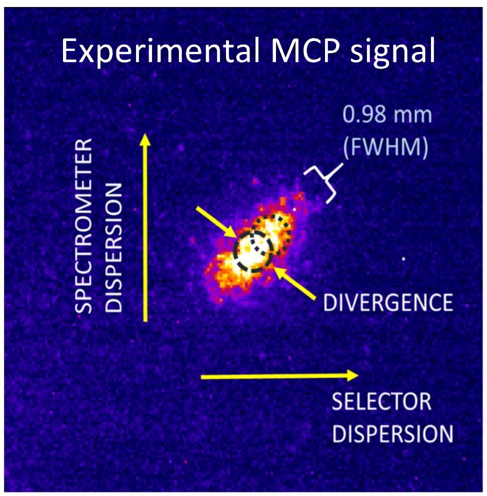
Analytical model

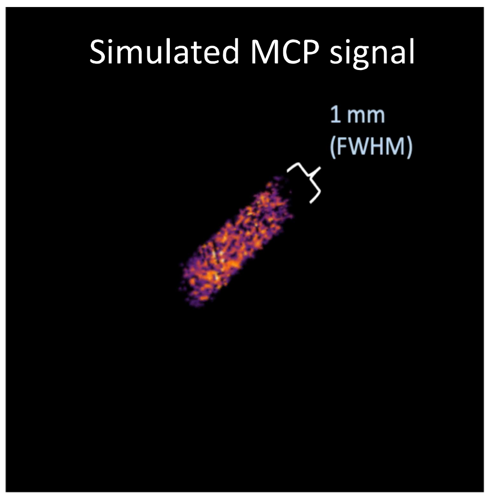


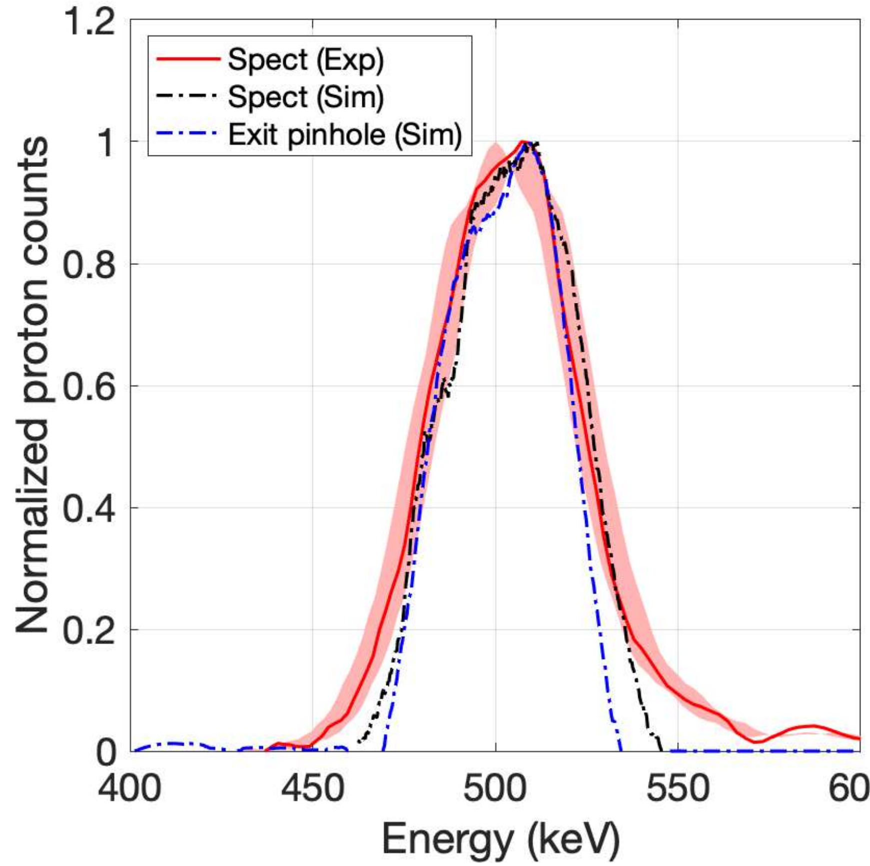
The ultimate energy bandwidth strictly depends on the initial proton source size!

Monte – Carlo simulations for data interpretation: varying source sizes to match an experimental bandwidth

Source size [μm]	Width [mm]	ΔE_P [keV]	ΔE_S [keV]
100	0.72	27.5	33.8
110	0.77	32.1	32.5
120	0.88	34.4	35
130	0.96	36.9	39
150	**1.00**	**41.9**	**43.6**
180	1.19	51.2	54



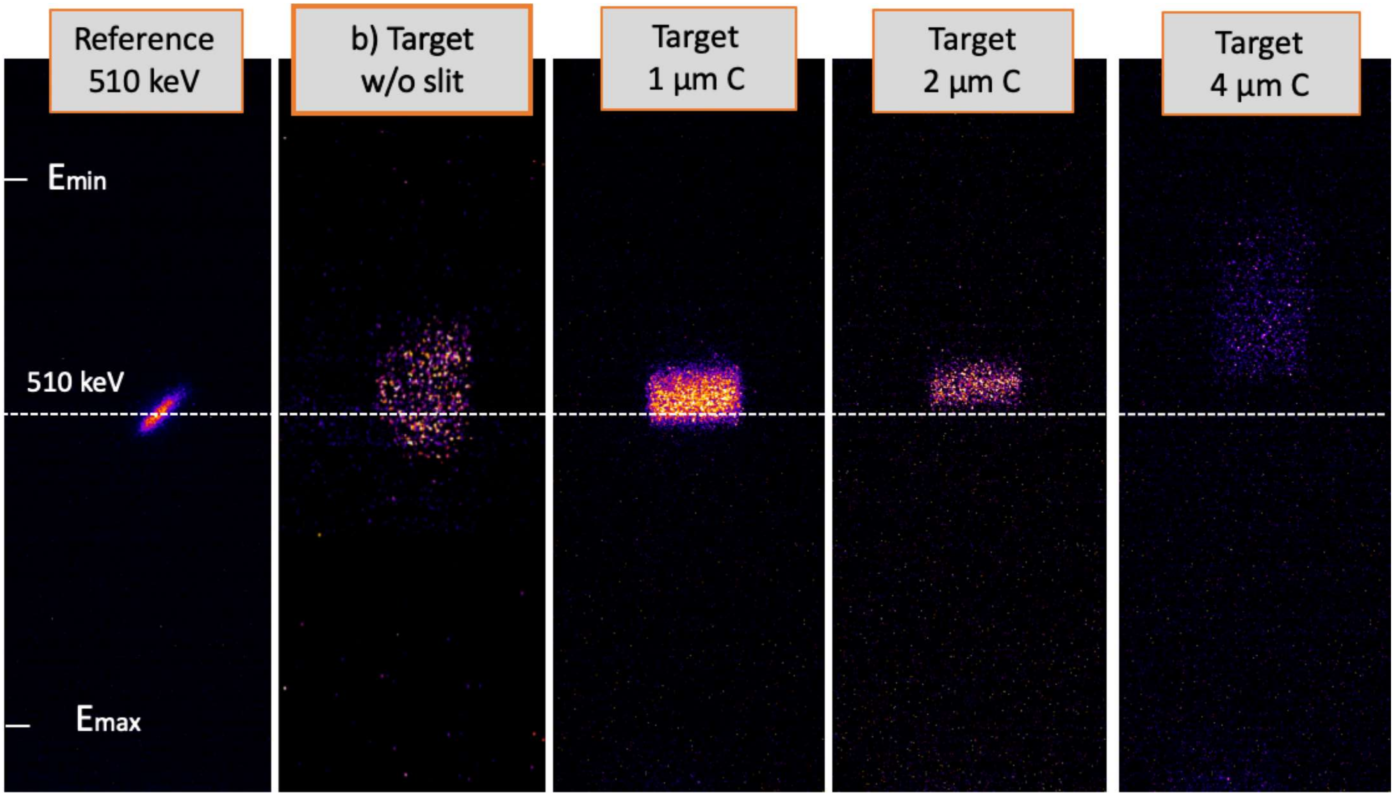


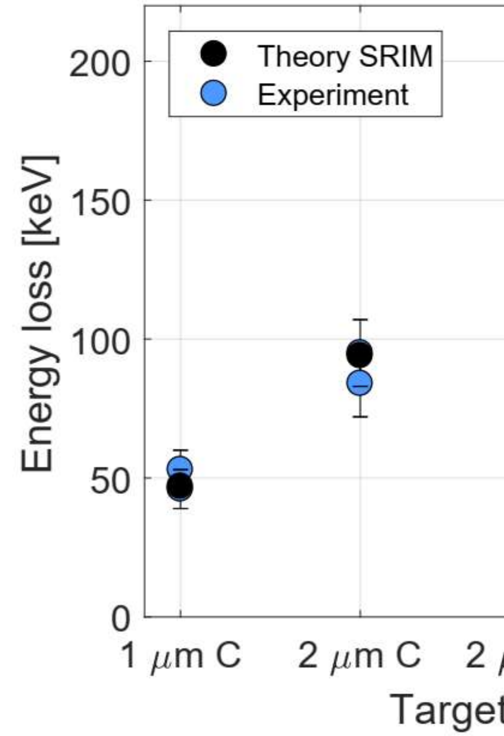


<u>Simulation shows:</u>

- The difference between observed bandwidth and bandwidth at exit pinhole < 2 keV
- MC simulations are in agreement with analytical model proving a source size of 150 μm

Demonstration of feasibility of the platform for stopping power measurements: proton beam energy loss measurement in solid targets

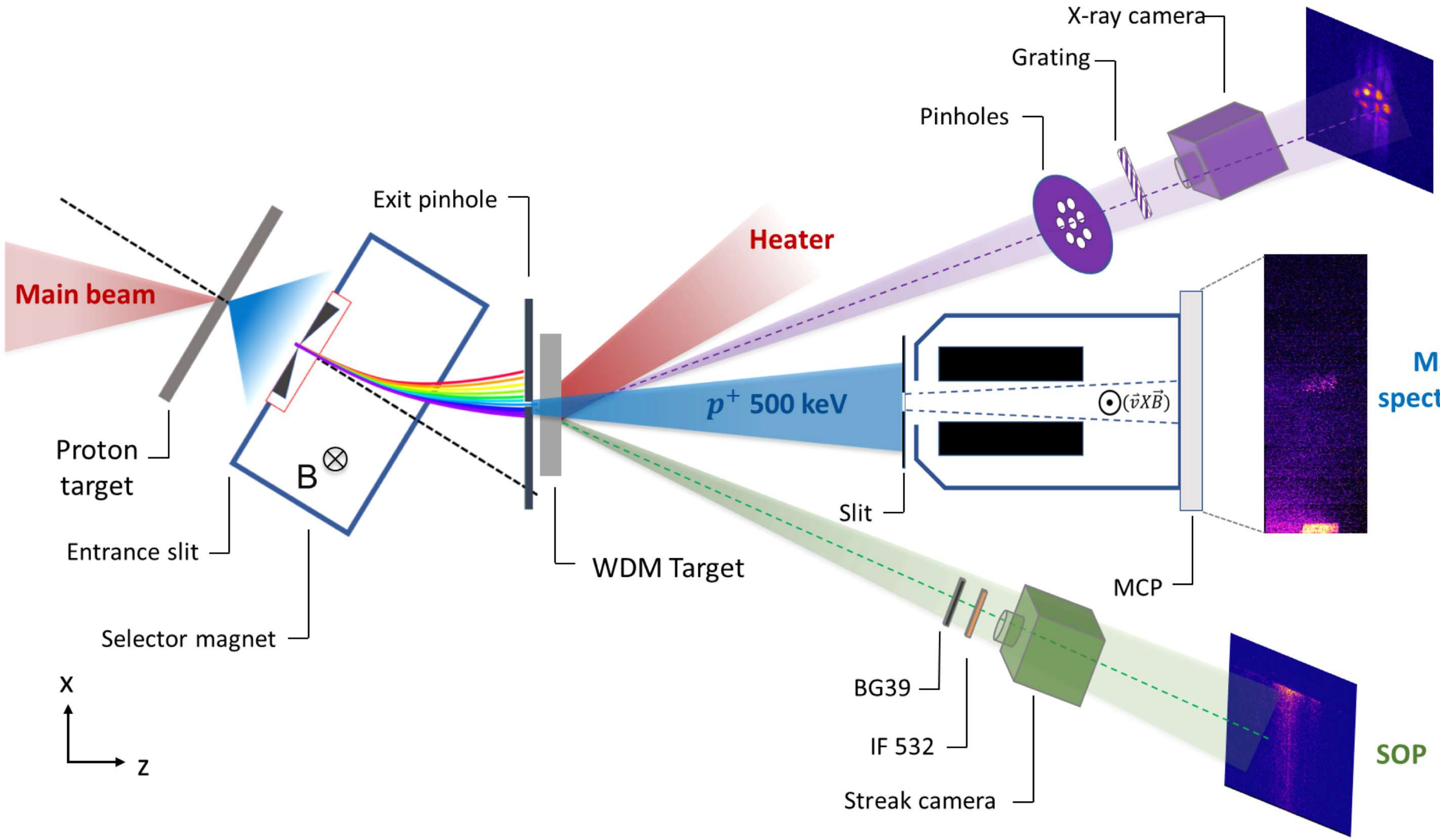




We observed:

- The proton beam after passing solid sample experience struggling
- Insertion of the slit in front of the spectrometer is introducing additional error of partial collection σ_{sys2}
- The accuracy of energy loss measurement is $\sigma_{tot} = \sqrt{{\sigma_{stat}}^2 + {\sigma_{sys1}}^2 + {\sigma_{sys2}}^2} = 5$ keV $(\sigma_{stat} = \sigma/\sqrt{N}$,

II. WDM generation and temperature characterization

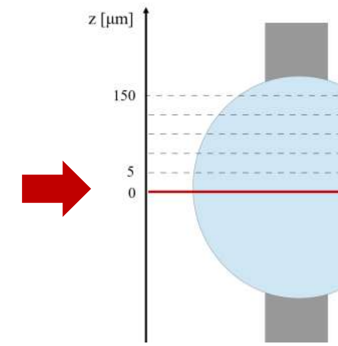


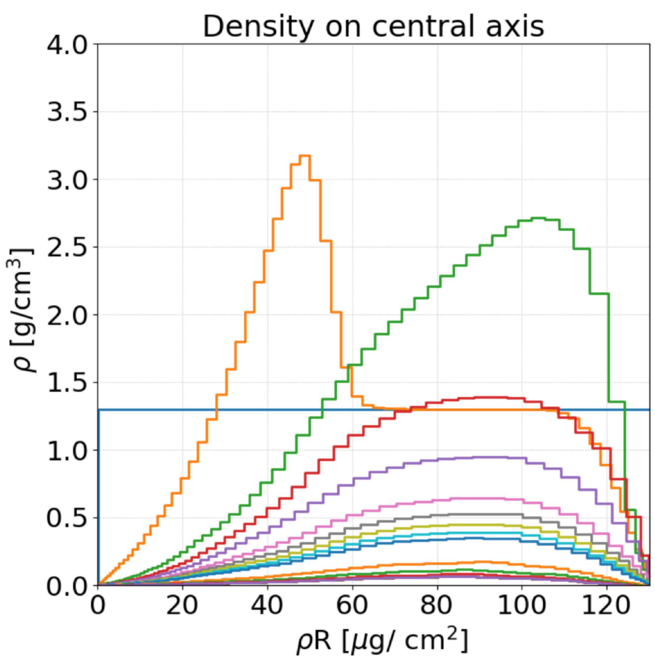
RALEF-2D Hydrodynamic simulations of WDM generation

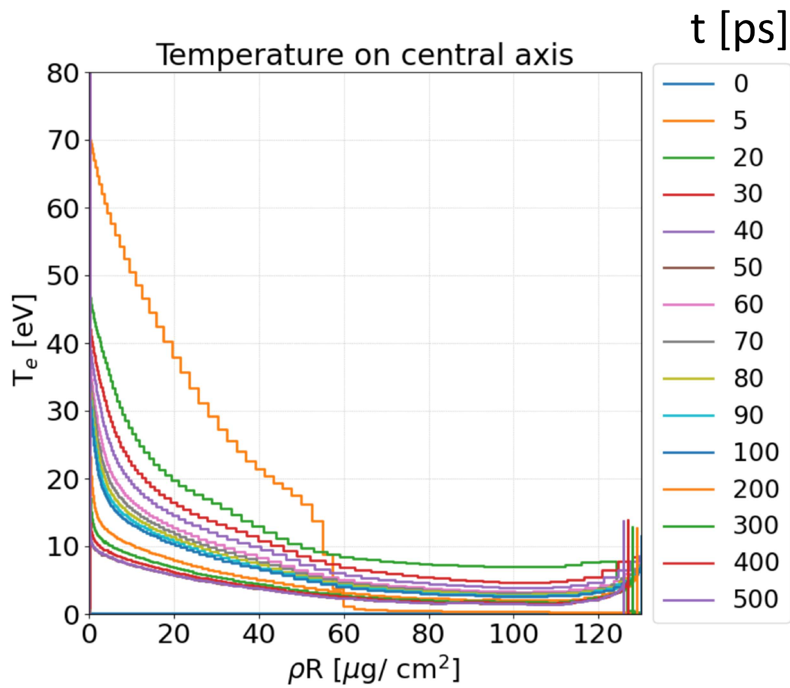
Simulation setup

Target:
- Carbon foil
- Thickness: 1 µm
- Initial :ρ ≈1.3 g/cc

Heater VEGA -II:
- Experimental laser profile
- I $\sim 10^{16}$ W. cm^{-2} , $\tau = 216$ fs
- $\phi = 300\ \mu$m , E = 0.5 J





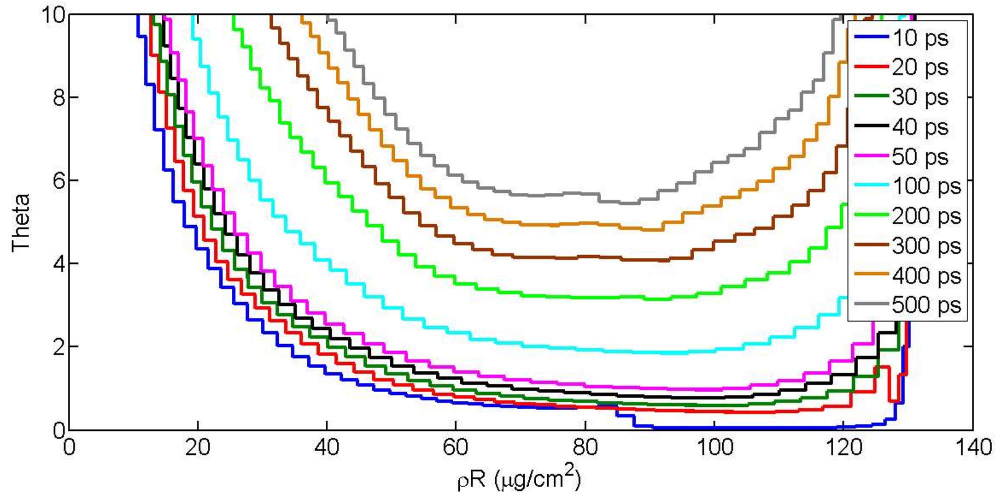


Simulations predict:

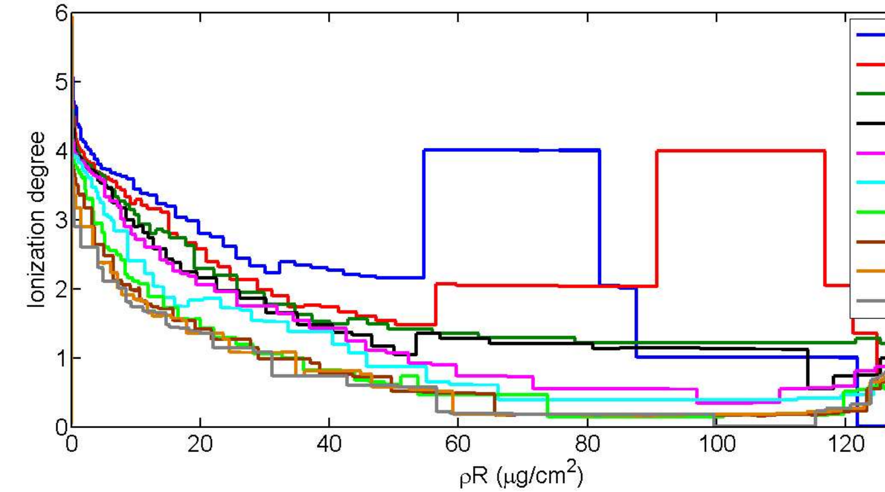
- Stable WDM conditi
within 50 µm centra
- T_e = 7.5 eV (mass w
weighted time integ

WDM Parameters

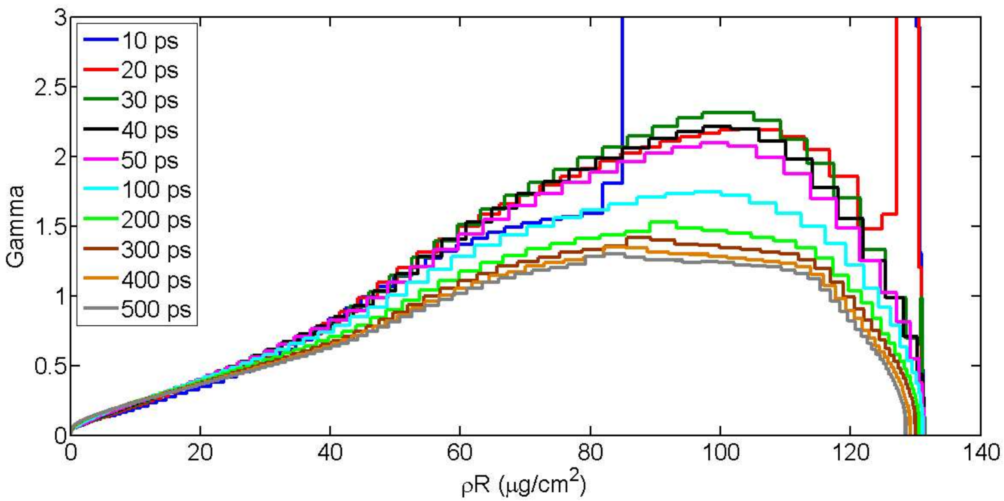
Electron degeneracy $\theta \leq 10$



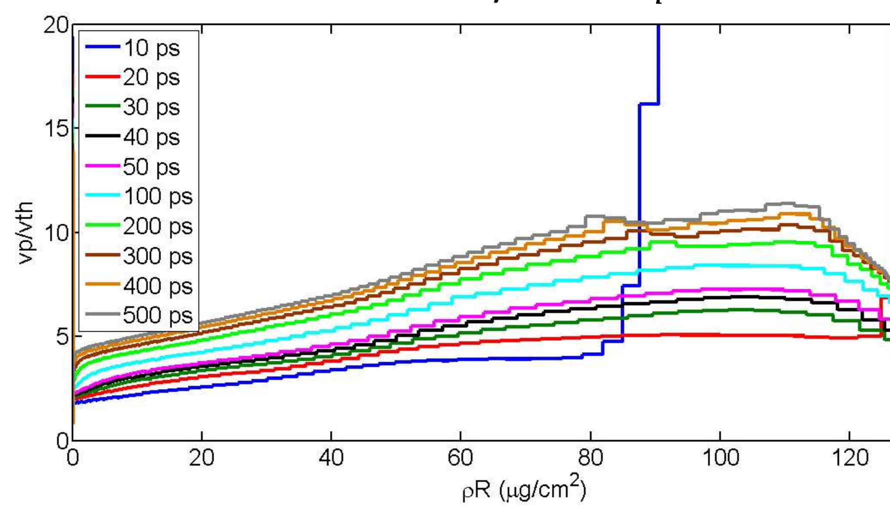
Mean ionization $Z^* \leq 4$



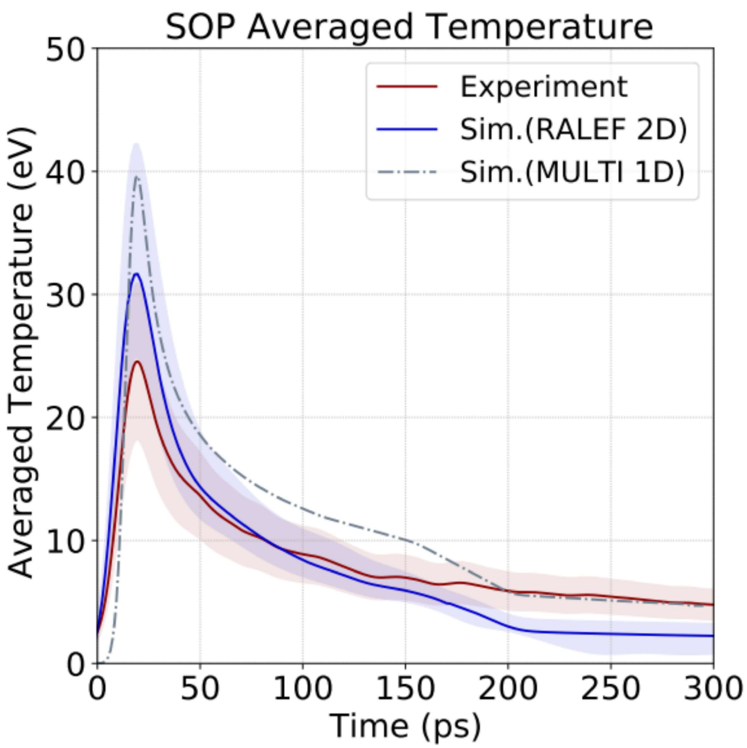
Electron coupling $\Gamma \approx 0.1$ -2



Velocity ratio v_p/v_{th} < 10



Warm dense matter characterization by two independent diagnostics: time resolved SOP and time integrated XPHG

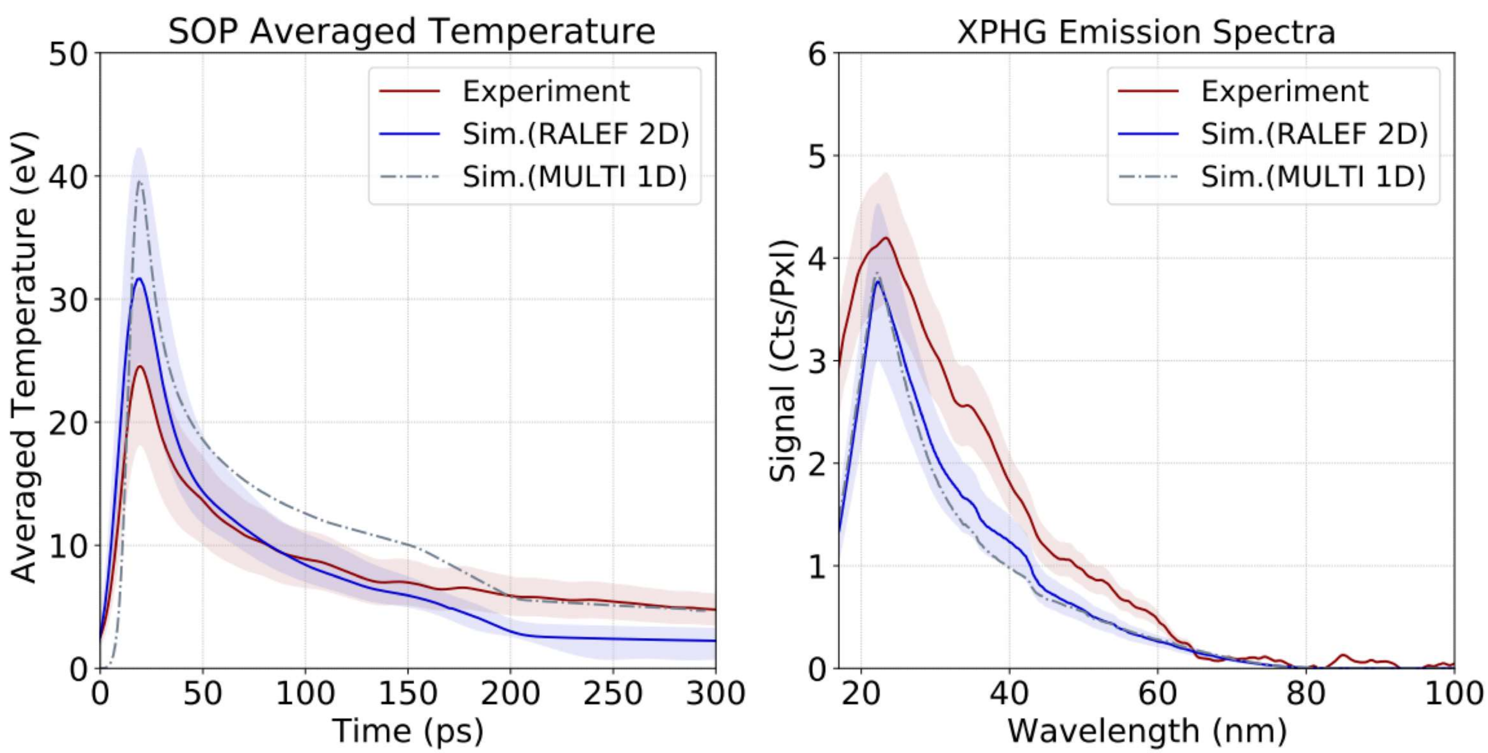


Streak optical pyrometr

- SOP provides temper
critical density at 532
- The SOP measures sl
temperature predicte
agrees with simulatio

* The experimental curve is averaged over 80 – 100 consecutive shots

Warm dense matter characterization by two independent diagnostics: time resolved SOP and time integrated XPHG



T_e = 7.5 $\pm$ 1.5 eV

* The experimental curve is averaged over 80 – 100 consecutive shots

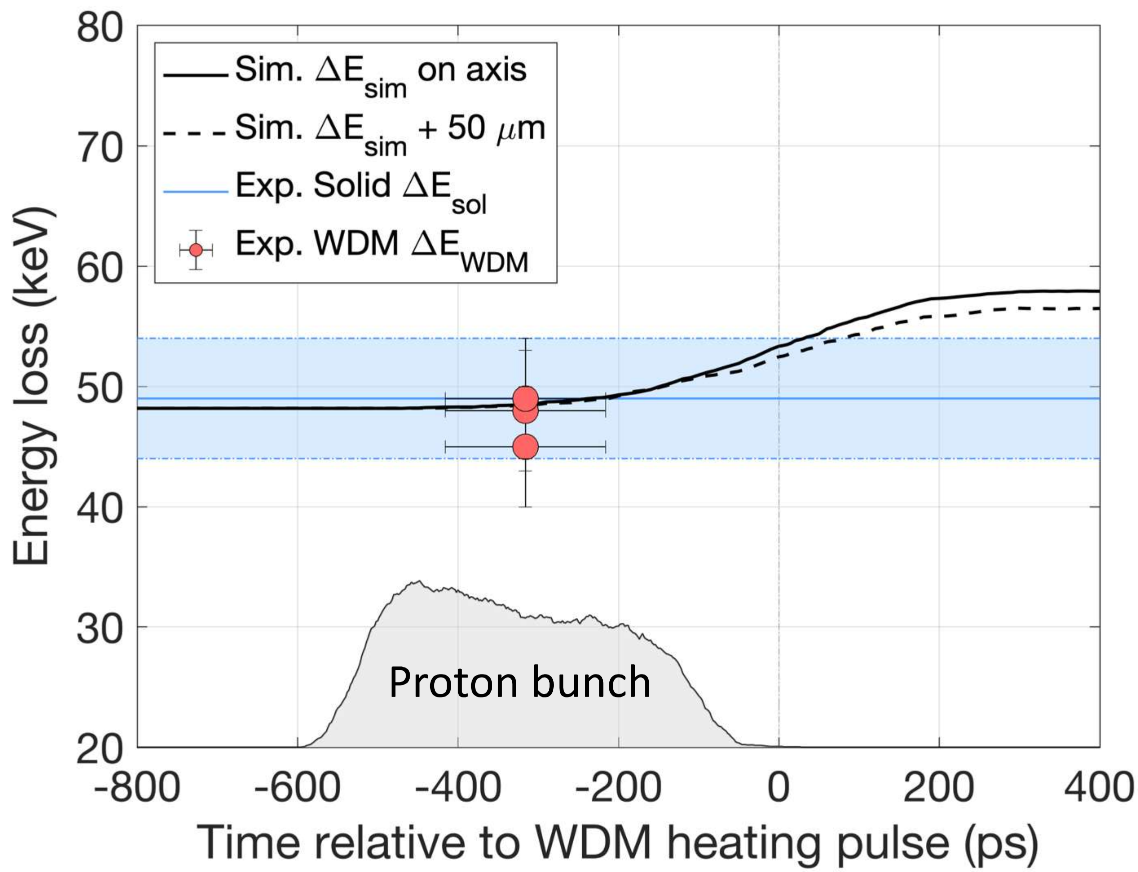
Streak optical pyrometr

- SOP provides temper critical density at 532
- The SOP measures sl temperature predicte agrees with simulatio

X-ray Pinhole Grating Ca

- XPHG measures time weighted x-ray emiss
- XPGH X-ray spectra i agreement with the emission from RALEF

500 keV proton beam energy loss measurement in Warm Dense Matter



Classical models:

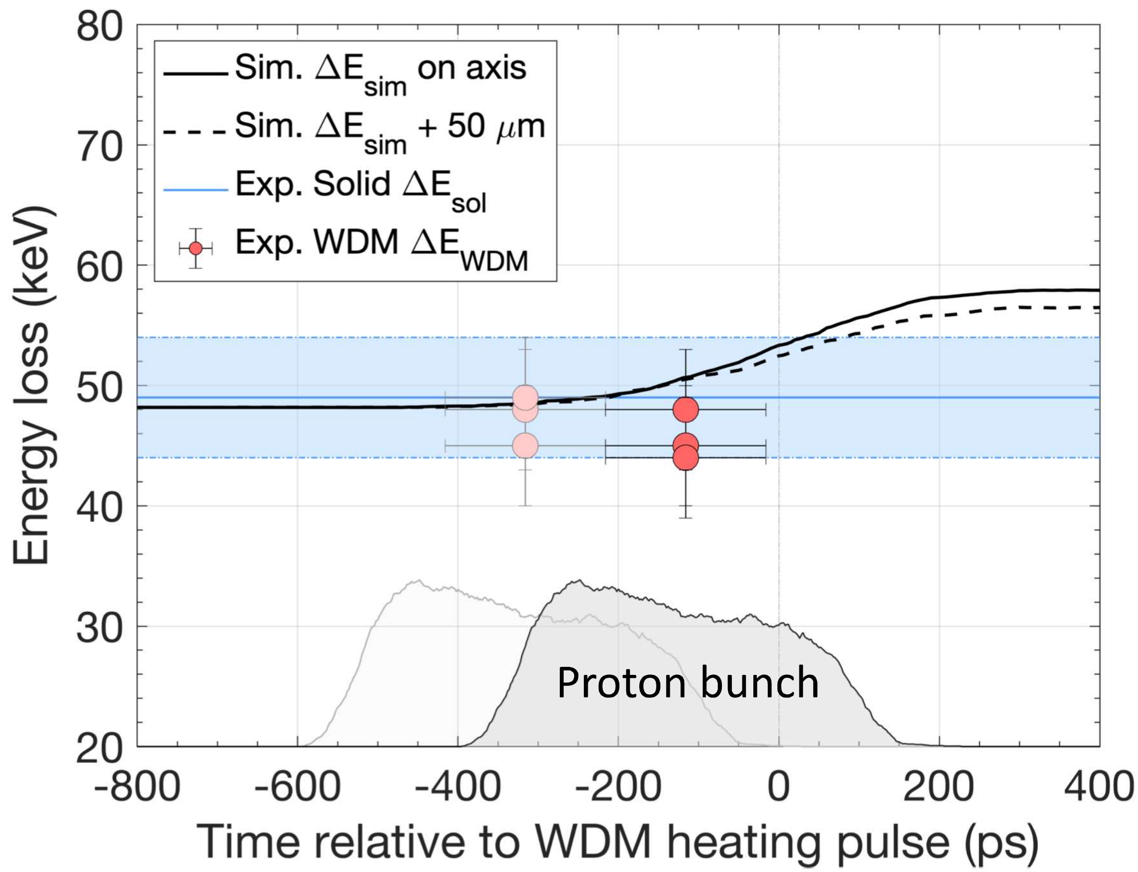
[1] *Zimmerman, G. Report no. ucrl-jc-105616. LLNL.(1990)*

[2] *Gericke, D. O. et al., Physical Review E, **65** (2003)*

[3] *Zylstra, A . et al., Physics of Plasmas **26**, 122703 (2019)*

* Experimental energy loss in solid is

500 keV proton beam energy loss measurement in Warm Dense Matter



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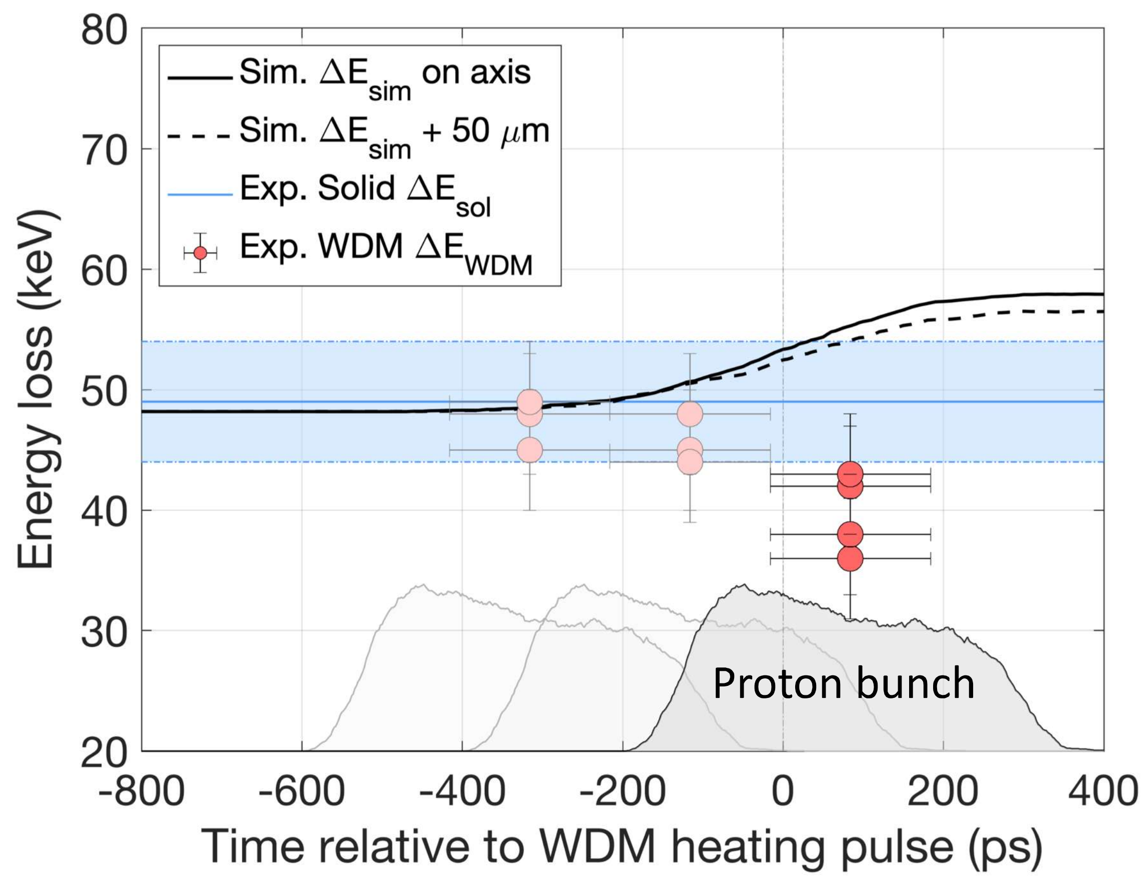

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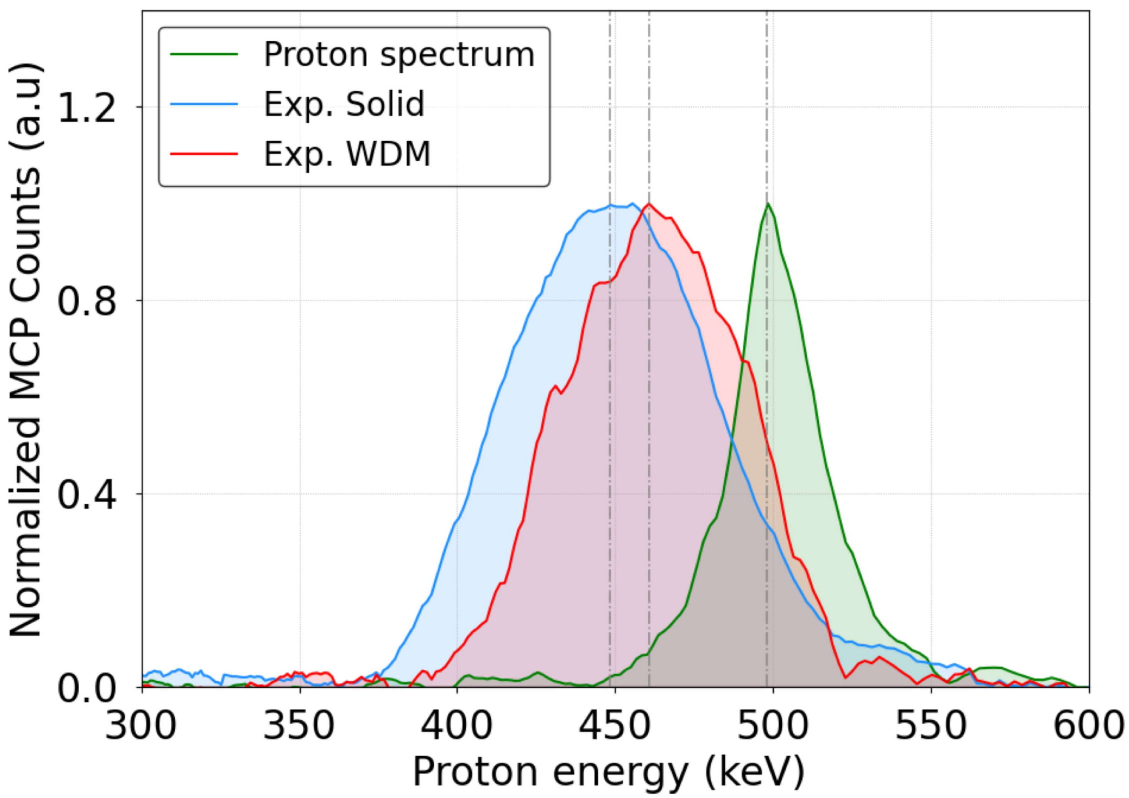


We observe:

- Proton energy loss in solid is 49
- Proton energy loss in WDM is 3
- Energy loss in WDM is 20 % ± 9 measured energy loss in solid
- Classic models overestimate ene

Our results suggest:

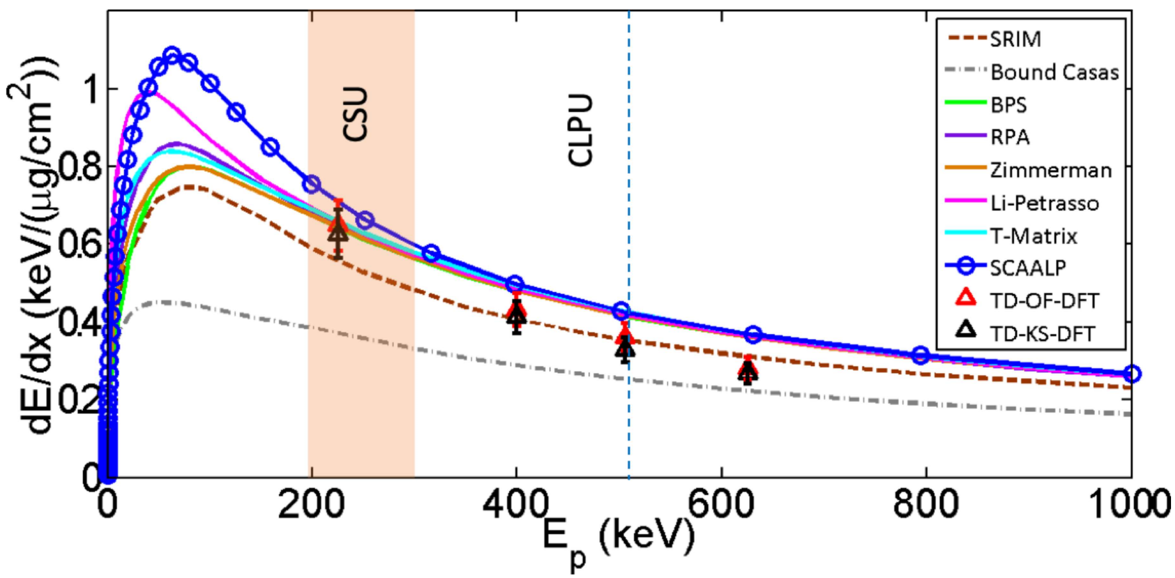
- TD-KS-DFT model, which predict stopping power in WDM is best interaction regime

S. Malko, W. Cayzac, V. Ospina-Bohorquez et al. in submission to Nature Communications (2021)

Next goal is to refine measurements and achieve $v_p/v_{th} \approx 2$ in upcoming experiment at CSU ALEPH laser facility

The experiment will be performed April 2022 in 3rd cycle of LaserNet US Call:

- Selection of the low energy proton beam of 200, 300 keV
- Optimization of the energy selector to decrease energy bandwidth and time spread
- WDM Generation WDM with T_e = 15 – 20 eV
- First measurement of proton stopping power in WDM approaching Bragg peak

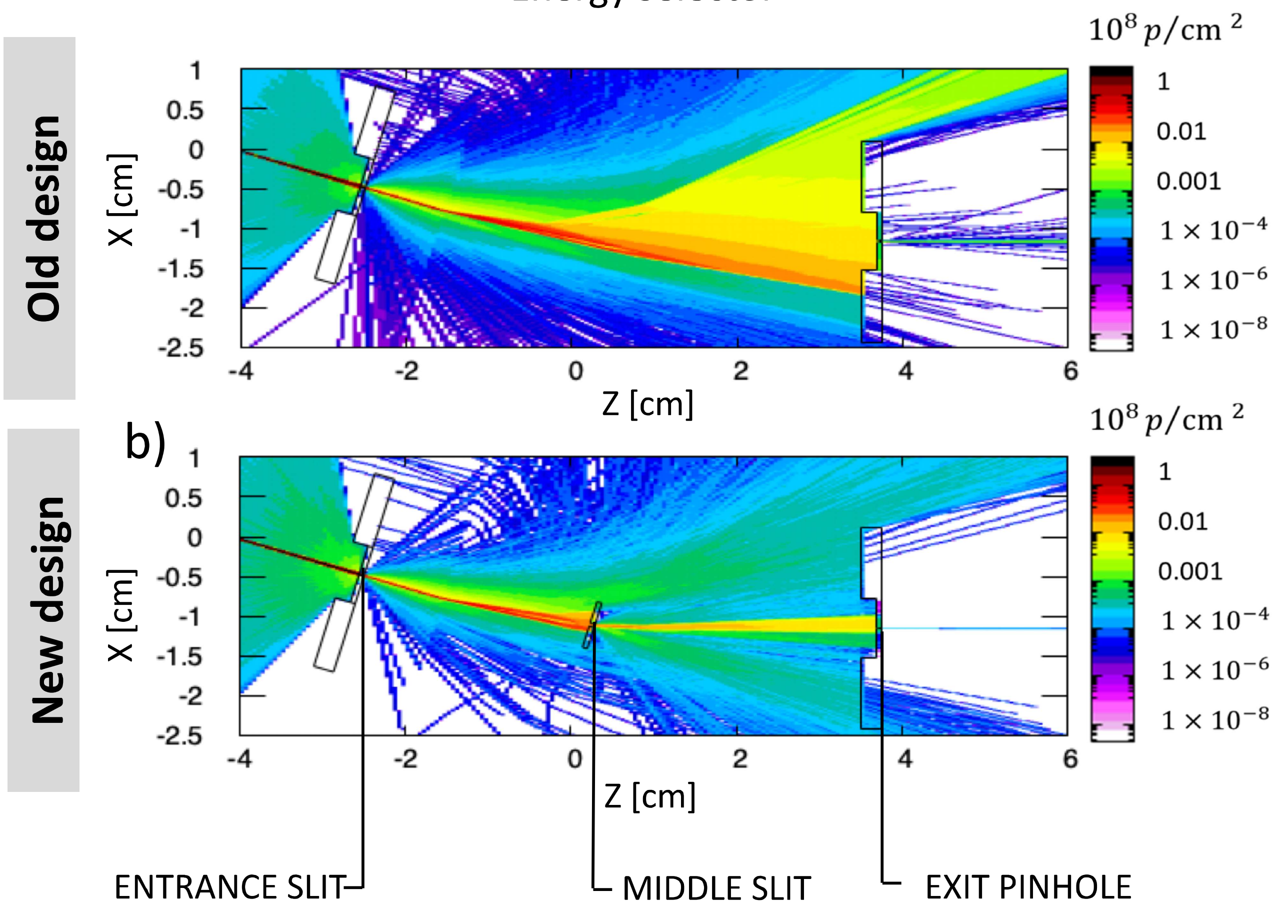


Parameter	CLPU
E_p	500 keV
δE_p	44 keV
Resolution	< 5 keV
WDM T_e	7.5 eV
v_p/v_{th}	3 - 7

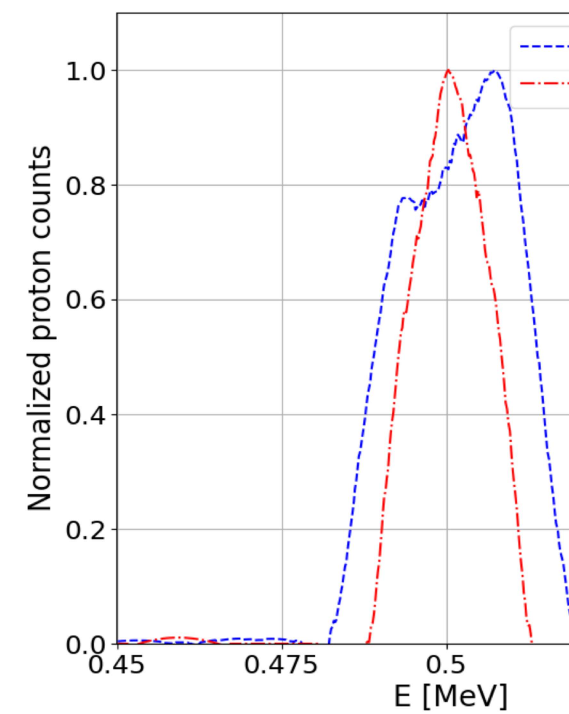
New design of energy selector will allow us to reduce selected proton beam energy bandwidth down to 20 keV

FLUKA Monte-Carlo simulations demonstrate a reduction of the bandwidth by factor of 2

Energy selector



Proton energy spectrum at t



Conclusions

- **We performed first measurement of proton stopping power $v_p/v_{th} \approx 3$ in WDM**
- **The results suggest that classical models overestimate the energy loss measurement a in WDM**
- **We find TD-OF-DFT model the best suited for our experimental results**
- **Simultaneous measurement of WDM temperature of 7.5 eV by two diagnostics**
- **Our next step is to refine measurements and approach region close to Bragg Peak at C Laser facility (USA)**

Thank you for attention