Efficient proton acceleration in the near critical density regime

Martin Rehwald

Helmholtz-Zentrum Dresden-Rossendorf

Laser and Plasma Accelerators Workshop 2025

April 14, 2025

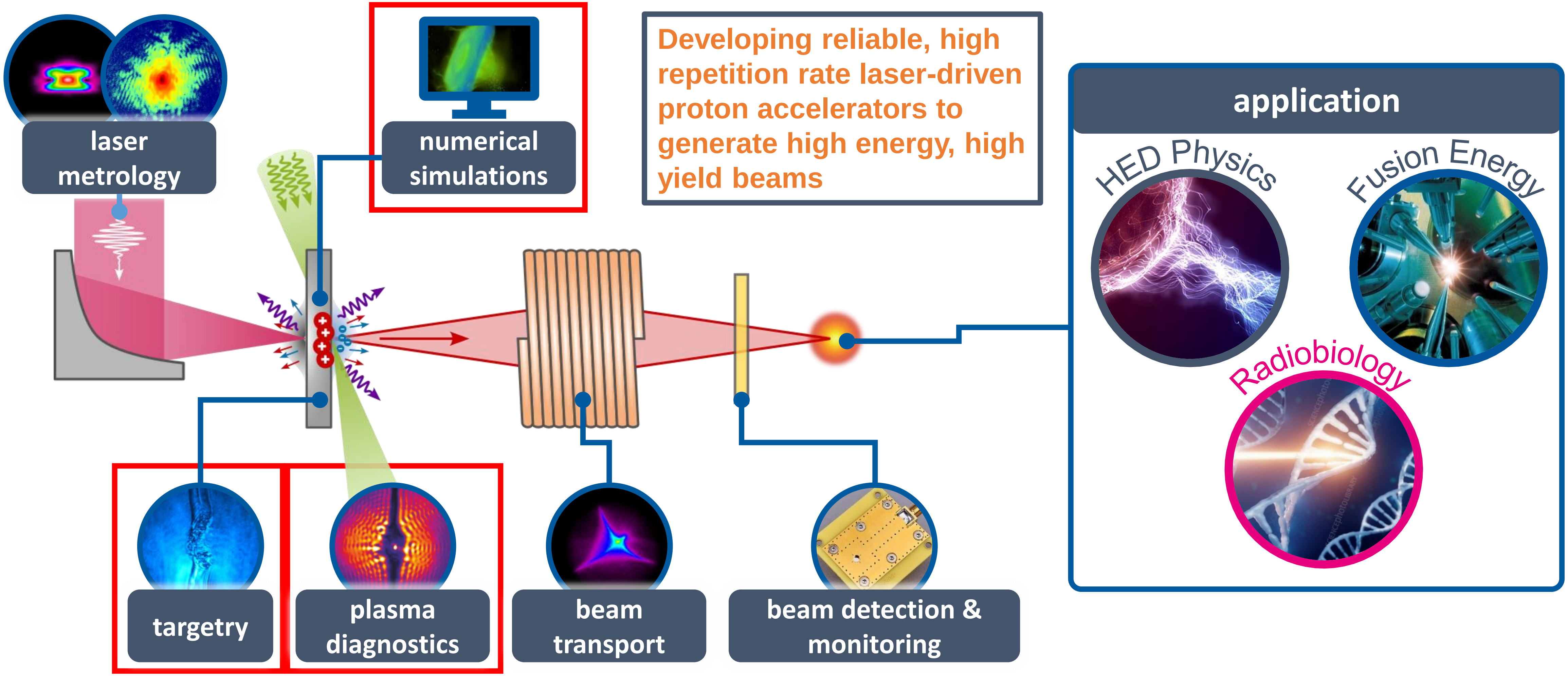
Efficient proton acceleration in the near critical density regime

Helmholtz-Zentrum Dresden-Rossendorf:
M. Rehwald, S. Assenbaum, C. Bernert, M. Müller, T. Streil, J. Garreis, J. Schilz, T. Ziegler, J. Metzkes-Ng, T. Kluge, M. Vescovi, M. Umlandt, I. Göthel, L. Yang, L. Huang, T. Miethlinger, P. Ordyna, J. Vorberger, P. Wang, T. E. Cowan, Ulrich Schramm and K. Zeil

EuXFEL HED/HiBEF experimental team:
S. Göde, D. Loureiro, J. P. Schwinkendorf, H. Höppner, A. Laso-Garcia, A. Pelka

HEDS group from SLAC:
M. Gauthier, C. Schönwälder, C. Curry, L. Fletcher, F. Treffert, G. Glenn, S. Glenzer

Motivation: Laser-driven proton acceleration



Helmholtz-Zentrum Dresden-Rossendorf – Research portfolio

Correlation of lase- and plasma diagn stics ... ard foil t...

Talk T. Ziegler

Talk K. Zeil

Hydrogen jets for advanced acceleration schemes a... physics b... rk

Talk S. Assenbaum

Poster S. Assenbaum

Application of laser-driven proton beams e.g. radi... y, nuclear p...

Talk J. Metzkes-Ng

Talk F. Kroll

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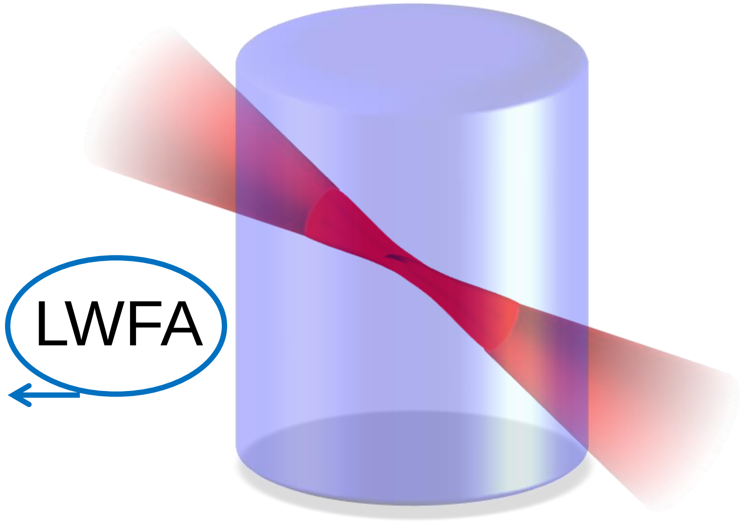
Improving efficiency in the near-critical density regime

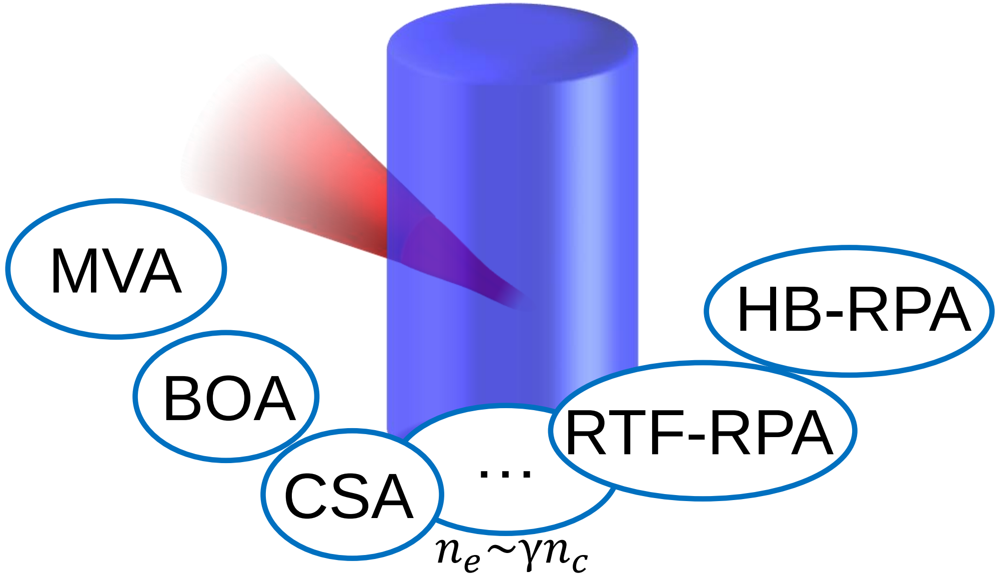
Underdense, transparent target



$n_e \ll \gamma n_c$

Laser pulse mostly transmitted

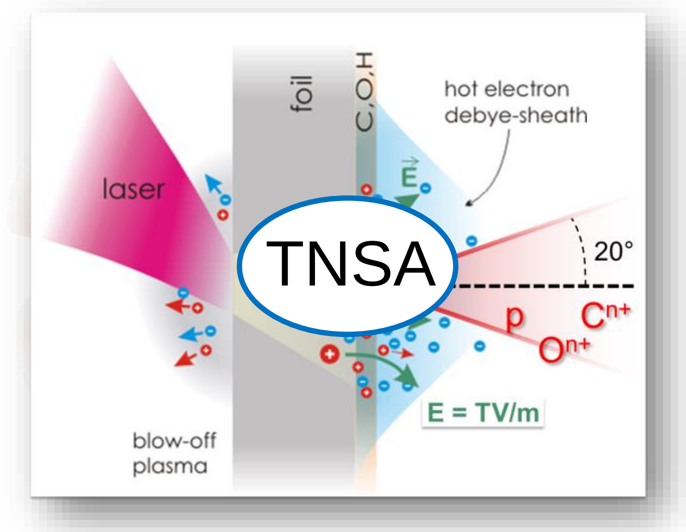
Near-critical density target



$n_e \sim \gamma n_c$

Laser pulse mostly absorbed
-> volumetric interaction

Dense, opaque target



$n_e \gg \gamma n_c$

Laser pulse mostly reflected
(mirror-like behavior)

Density

Under-critical density - Gases

Near-critical density

Over-critical density - Solids

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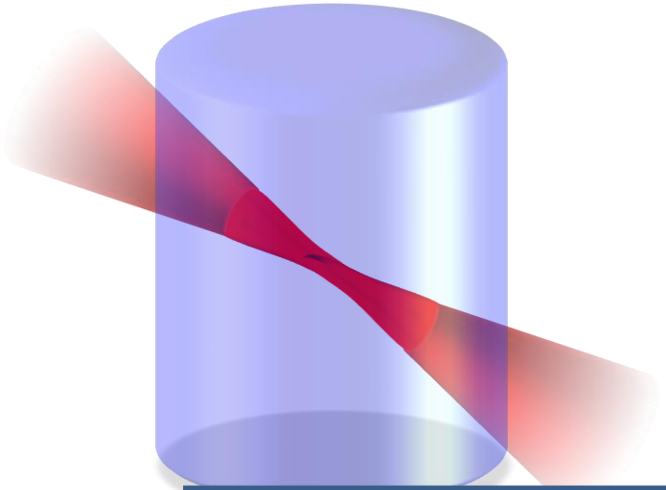
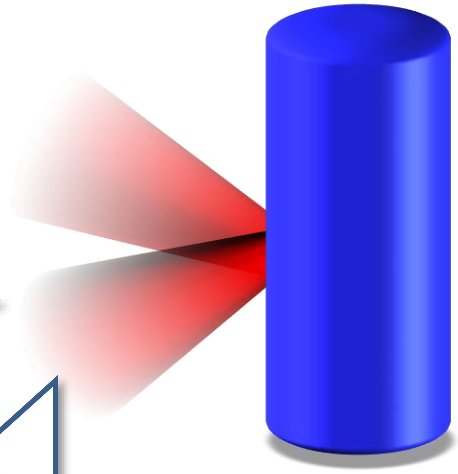
Improving efficiency in the near-critical density regime

Underdense, transparent target



Dense, opaque target



- **Near-critical density targets are required** to access advanced acceleration schemes

Nanostructured Materials

(Prencipe PPCF (2016), Bin PRL (2015), Willingale PRL (2009), Margarone (2012), ….)

High-pressure gas jets

(e.g. Sylla et al. RSI (2012); Willingale et al., PRL (2006); Salehi et al. RSI (2019), Chen et al, Sci. Rep. (2017) …)

Solid hydrogen jet target

Foils

(Higginson Nat. Comm. (2018), A. Henig PRL (2009), N. Dover, Nat. Light (2023), Yogo RPL (2008), T. Ziegler Nat. Phys. (2024),…)

Density

typ. < 10^{19} cm^{-3} — 1.7×10^{21} cm^{-3} = $n_{c,800nm}$ — 5.1×10^{22} cm^{-3} — typ. > 10^{23} cm^{-3}

Under-critical density - Gases

Near-critical density

Over-critical density - Solids

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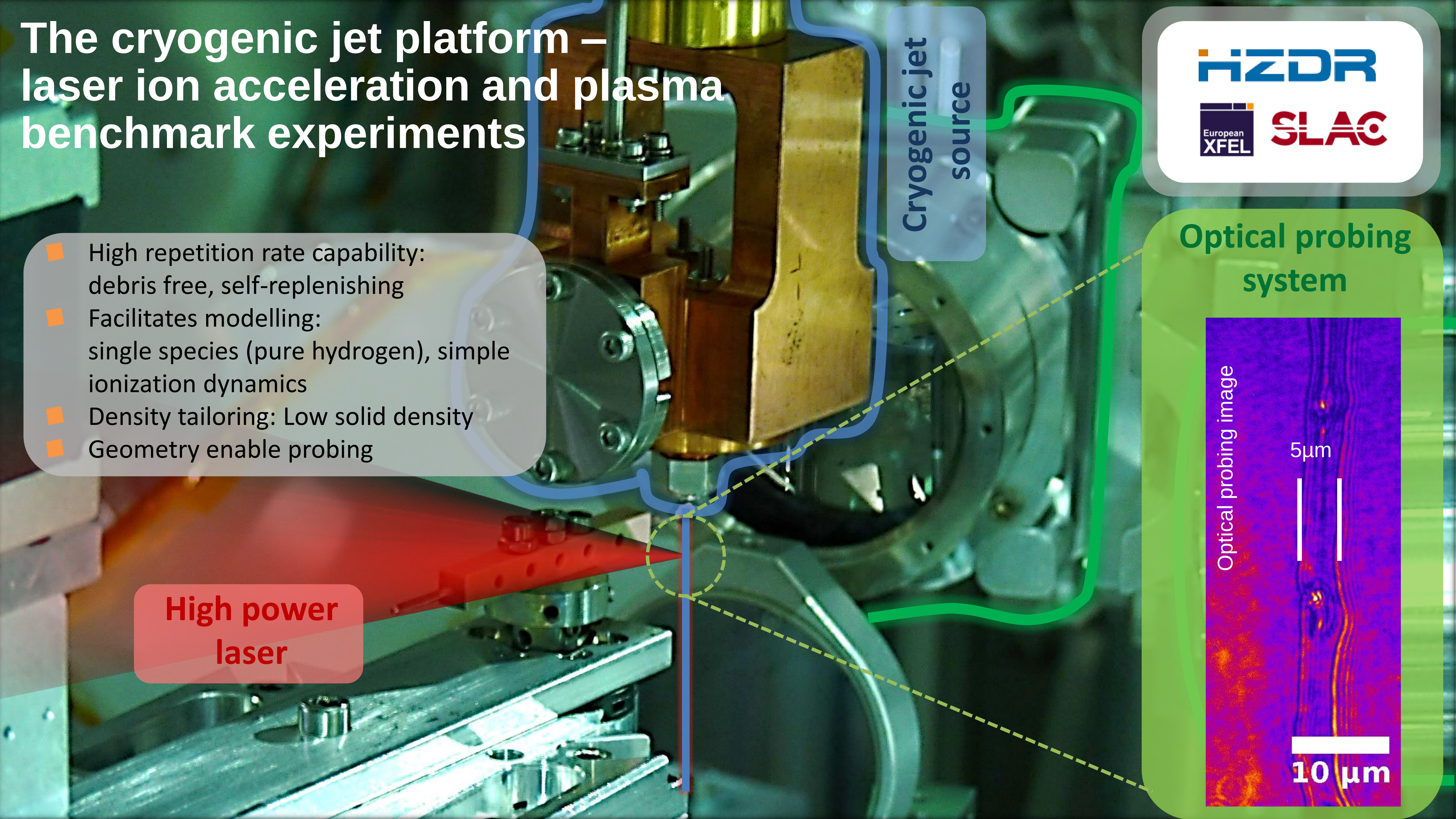
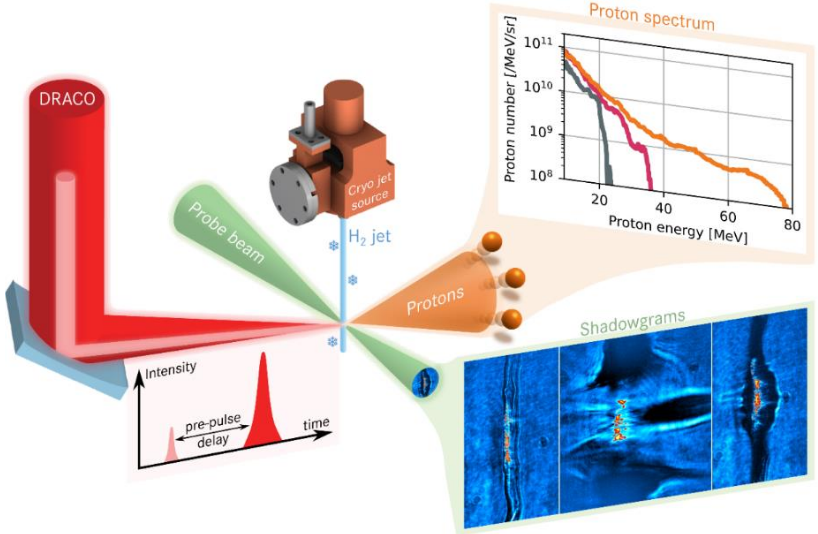
The cryogenic jet platform – laser ion acceleration and plasma benchmark experiments

- High repetition rate capability: debris free, self-replenishing
- Facilitates modelling: single species (pure hydrogen), simple ionization dynamics
- Density tailoring: Low solid density
- Geometry enable probing

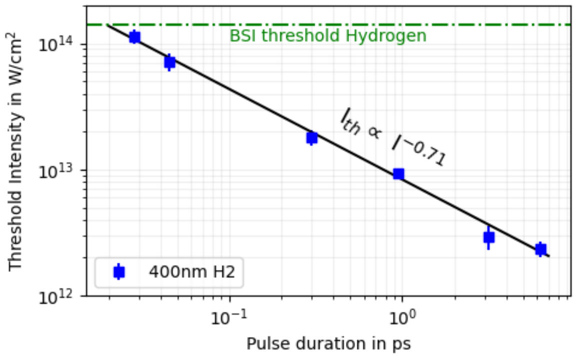


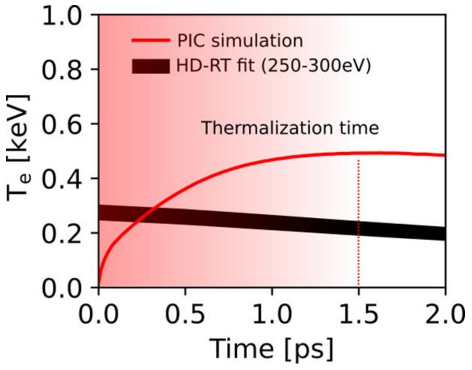
Outline

Proton energy increase in the near-critical regime using cryogenic hydrogen jets



Developing the simulation tools and experimental benchmark scenarios for optimized density profiles





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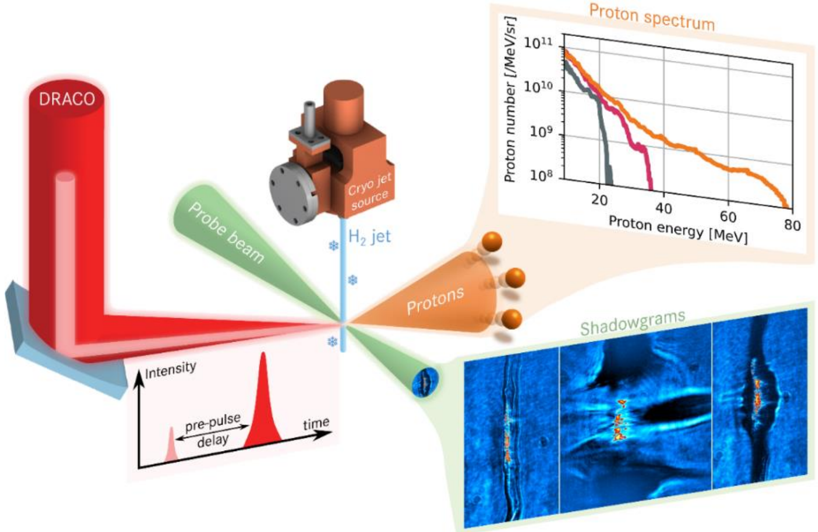

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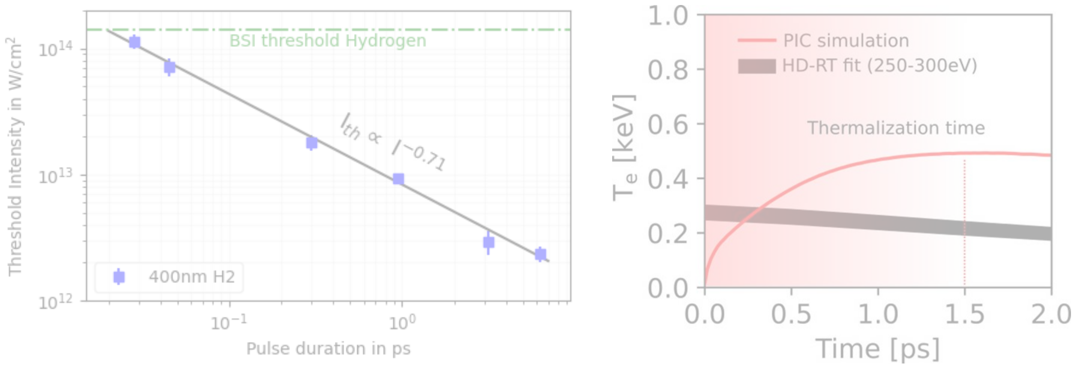
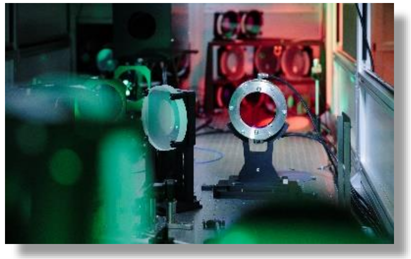
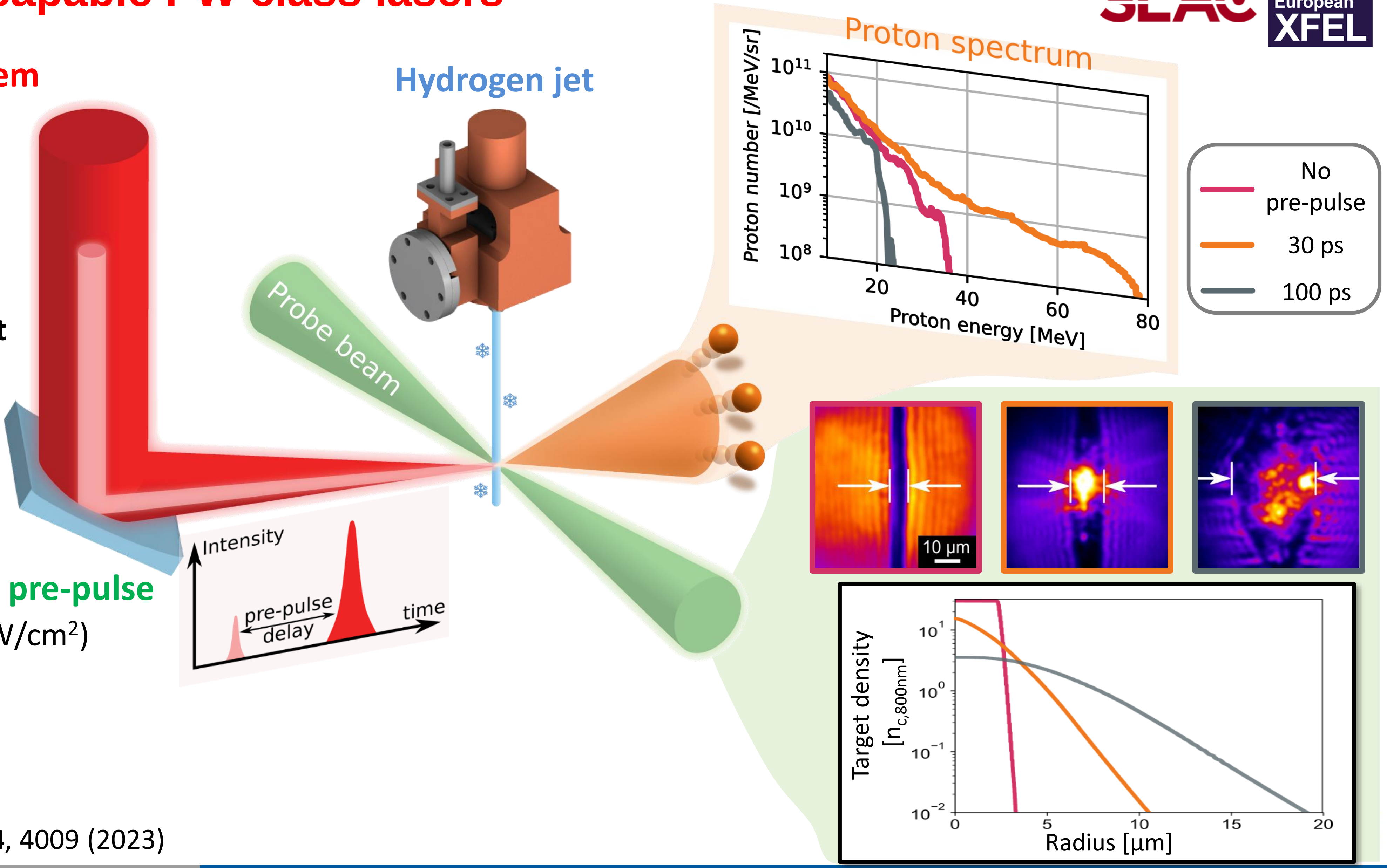


Density tailored self-replenishing cryogenic hydrogen jet target and repetition rate capable PW class lasers

DRACO PW laser system



enhanced laser contrast
18J, 30fs, 800nm,
5.4 x 10^{21}W/cm^2



Density tailoring with a pre-pulse

(30fs, 800nm, 5 x 10^{17} W/cm^2)

M. Rehwald et al., Nat. Com. **14**, 4009 (2023)

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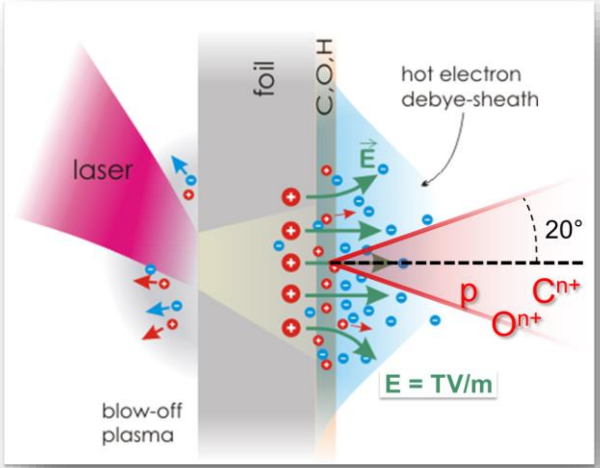
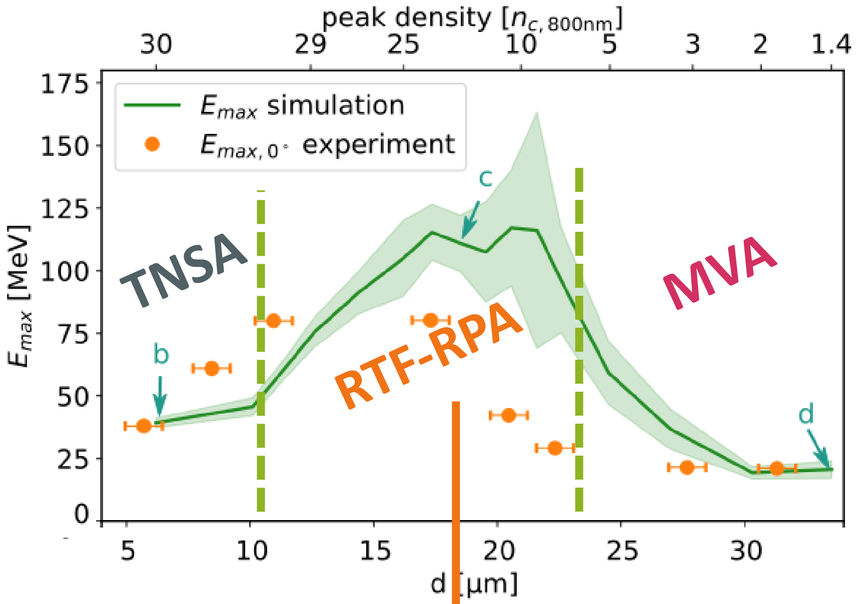
Simulation results suggest enhanced proton acceleration at the relativistic transparency front

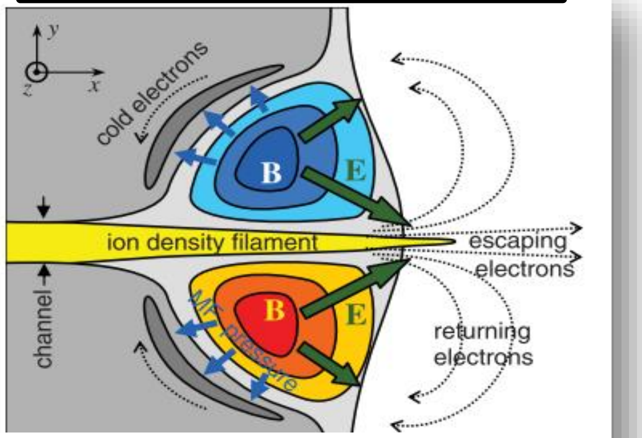
PIConGPU (3D, a_0 = 33, τ =30 fs)

Target Normal Sheath Acceleration





Magnetic Vortex Acceleration



[Bulanov et al. reply to PRL 98, 049503 (2007)]

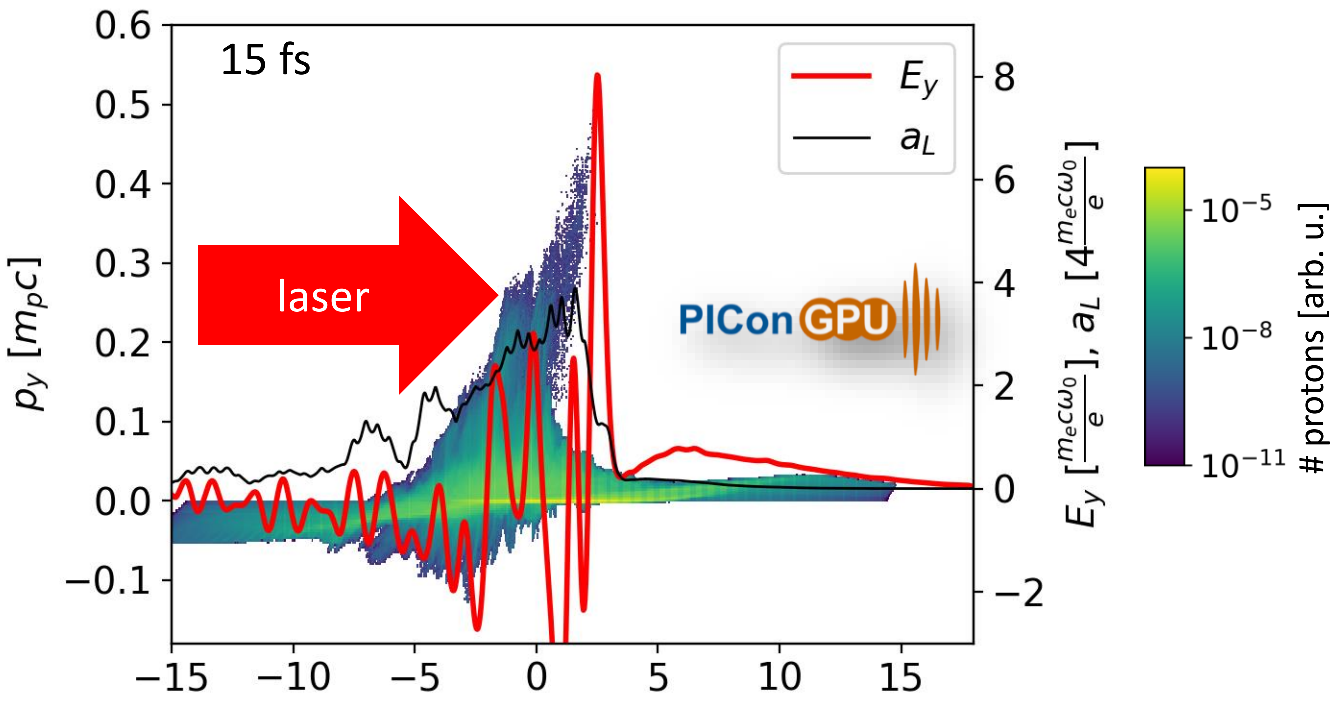
- Simulation and experiment match quantitatively well for the unexpanded and strongly expanded jets
- Optimal expansion with increased energies in sim. and exp.

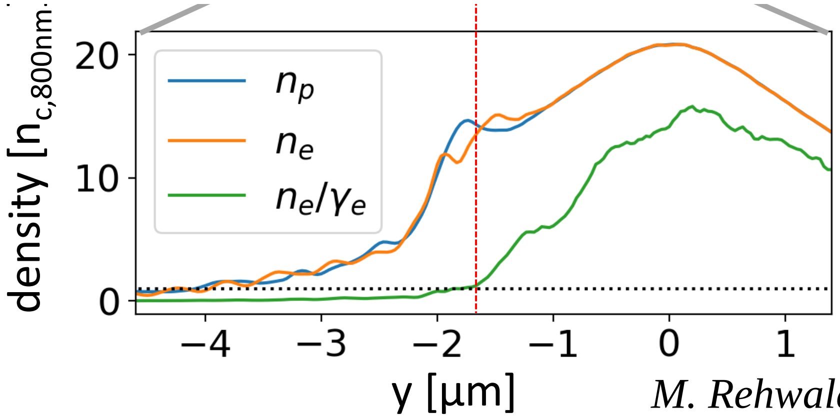
Efficient laser ion acceleration in the near-critical regime

M. Rehwald et al., Nat. Com. **14**, 4009 (2023)

Laser ion acceleration at the relativistic transparency front

Phase space evolution





- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk

M. Rehwald et al., Nat. Com. **14**, 4009 (2023)*; I. Göthel et. al., PPCF* ***64*** *044010 (2022)*

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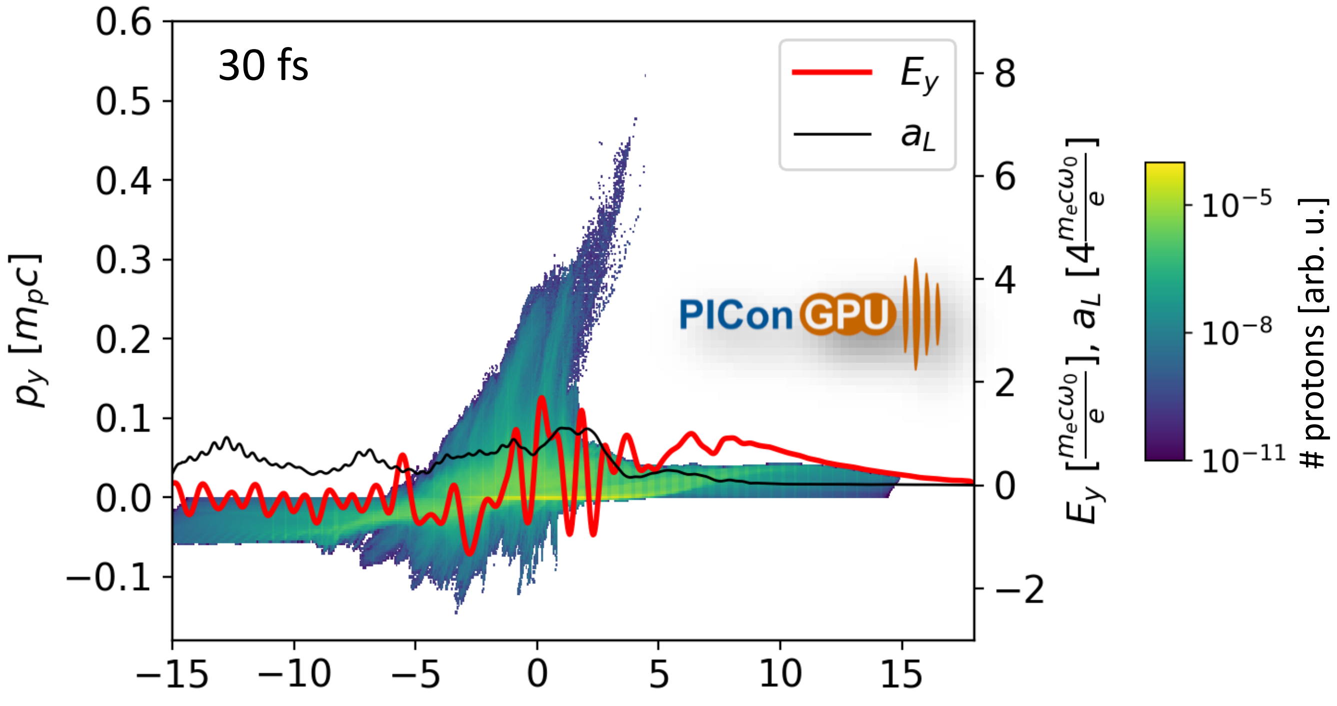
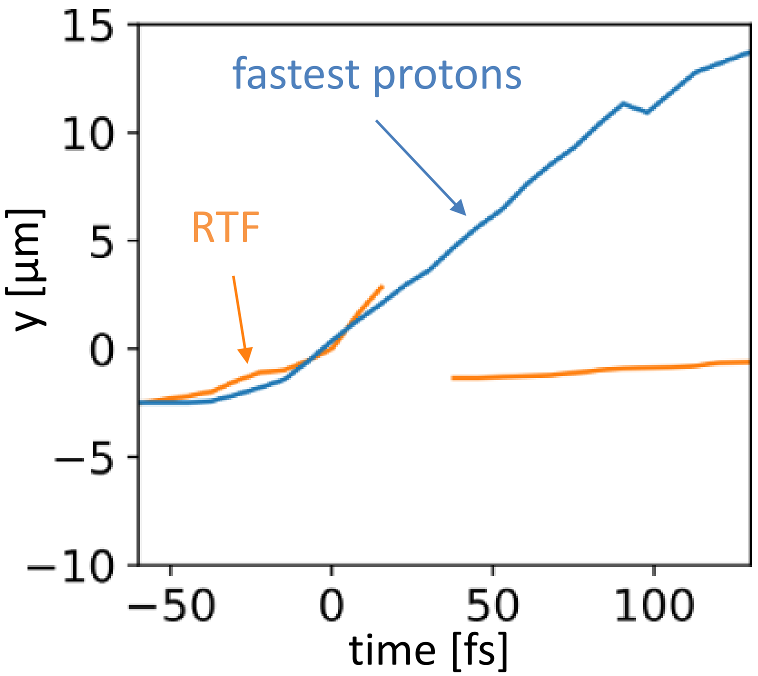
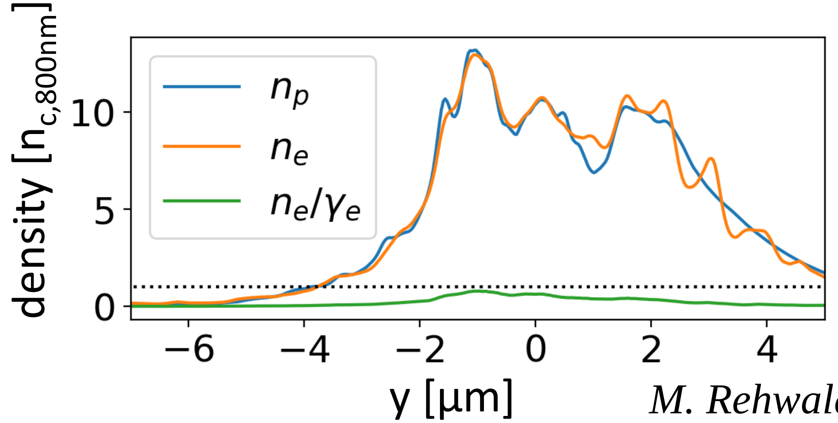
Laser ion acceleration at the relativistic transparency front

Phase space evolution







- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk

  → **quasi co-moving accelerating field structure**

M. Rehwald et al., Nat. Com. **14**, 4009 (2023)*; I. Göthel et. al., PPCF* ***64*** *044010 (2022)*

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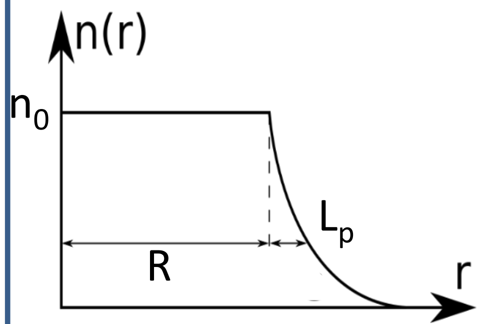
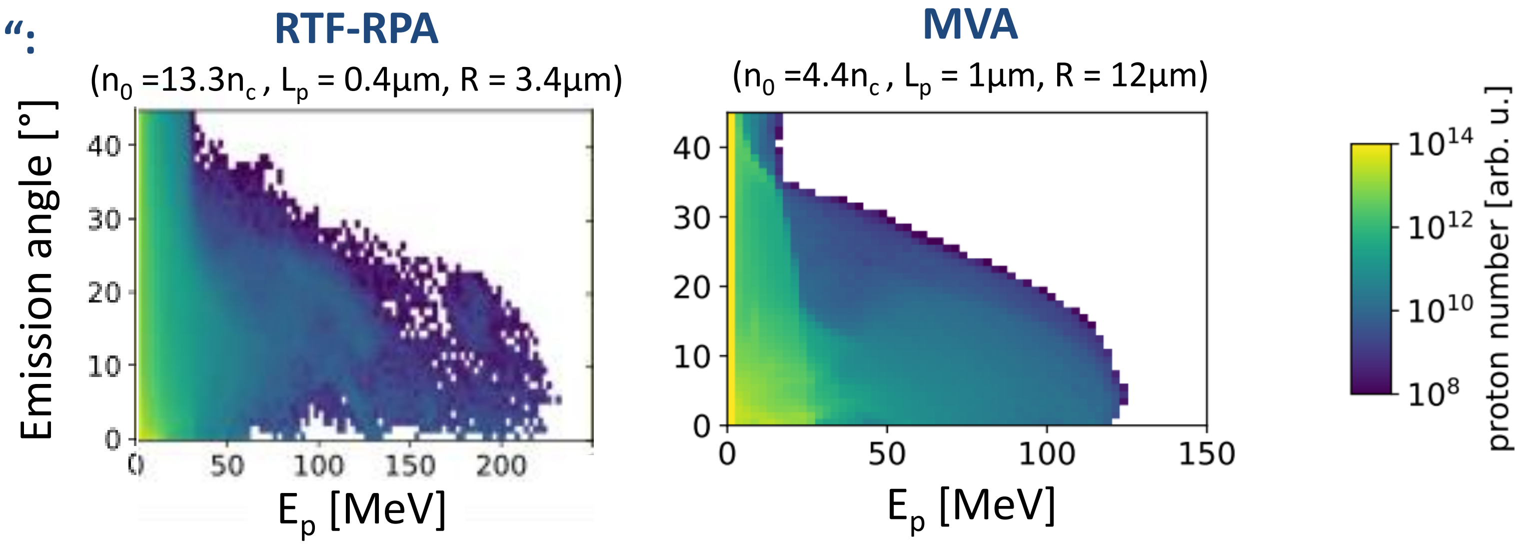
Intermediate summary

- Proof-of-concept showcasing density tailored cryogenic jet targets lead to efficient proton acceleration in the near-critical density regime
- Can we increase proton energies even further?

Simulations of„Toy model“: flat top profile with scale length





- Simulations indicate a boost of protons energies for an optimized target profile

- How can we generate more optimal target density profiles?

- **Challenge:** Develop simulation tools for **quantitative prediction making** of the evolution of the density prior to the main pulse

M. Rehwald et al., Nat. Com. **14**, 4009 (2023); *I. Göthel et. al., PPCF* **64** *044010 (2022)*

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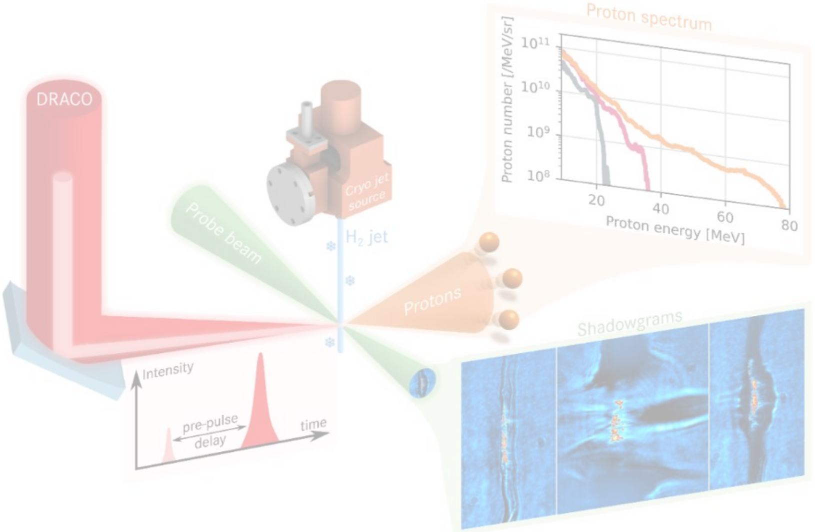
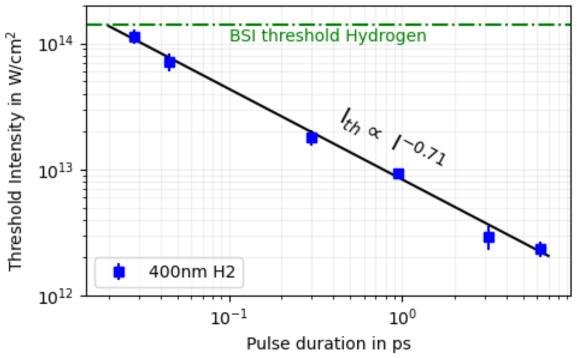
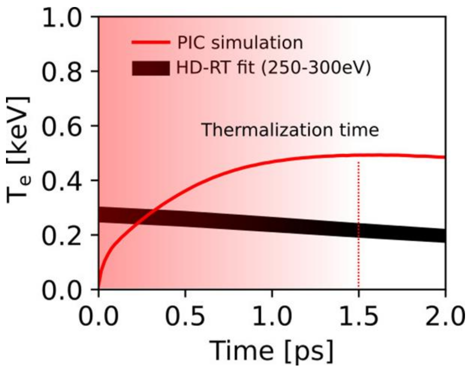
Outline

Proton energy increase in the near-critical regime using cryogenic hydrogen jets



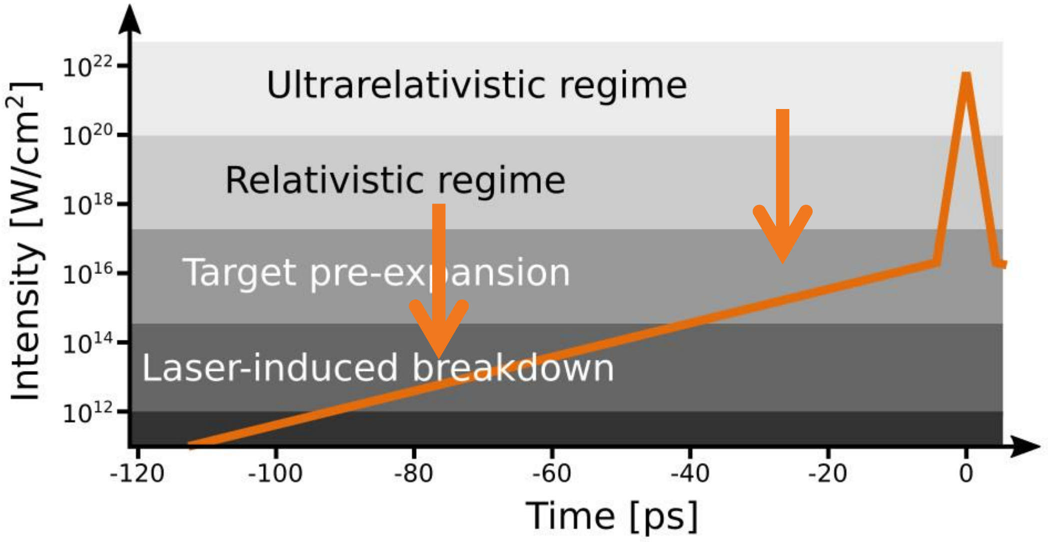
Developing the simulation tools and experimental benchmark scenarios for optimized density profiles





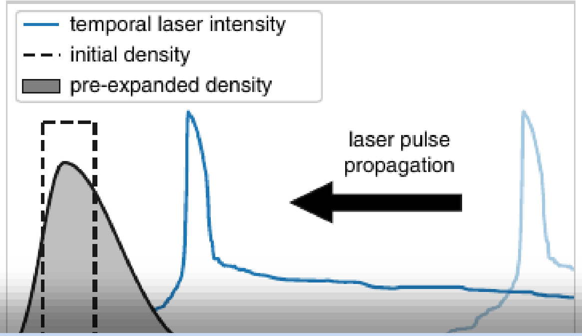
Analogous scenario: High-intensity laser-foil interactions and the leading edge

- High-intensity laser pulses are preceded by light of varying intensity (**leading edge**)
- Sub-relativistic intensities causes manipulation of the target before the relativistic interaction (**target pre-expansion**)



- **Numerical modeling** follows staged approach:
  - **1.** Determine the starting point of target pre-expansion
  - **2.** Pre-expansion
  - 3. High-intensity interaction

- **Laser-driven proton acceleration** is highly sensitive to target pre-expansion



Experiments at sub-relativistic intensities:

- 1. Pinpoint the **onset** of **Laser-Induced Breakdown (LIB)**
- 2. **Testbed to benchmark simulations** in the pre-expansion phase

  e.g. energy transfer mechanisms, modeling the plasma (fluid vs. kinetic particle motion), model atomic physics (collisions, ionizations)

Cryogenic hydrogen jet provides an ideal testbed
- rep. rate operation; pure “simple” hydrogen and optimal geometry for probing

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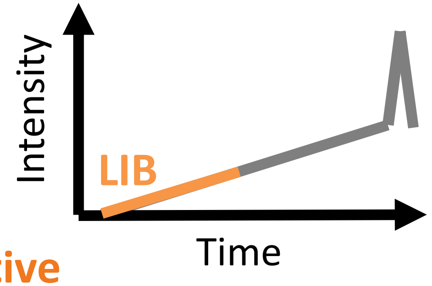
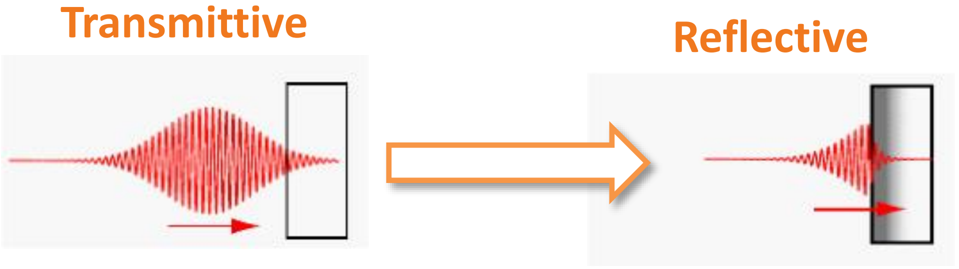
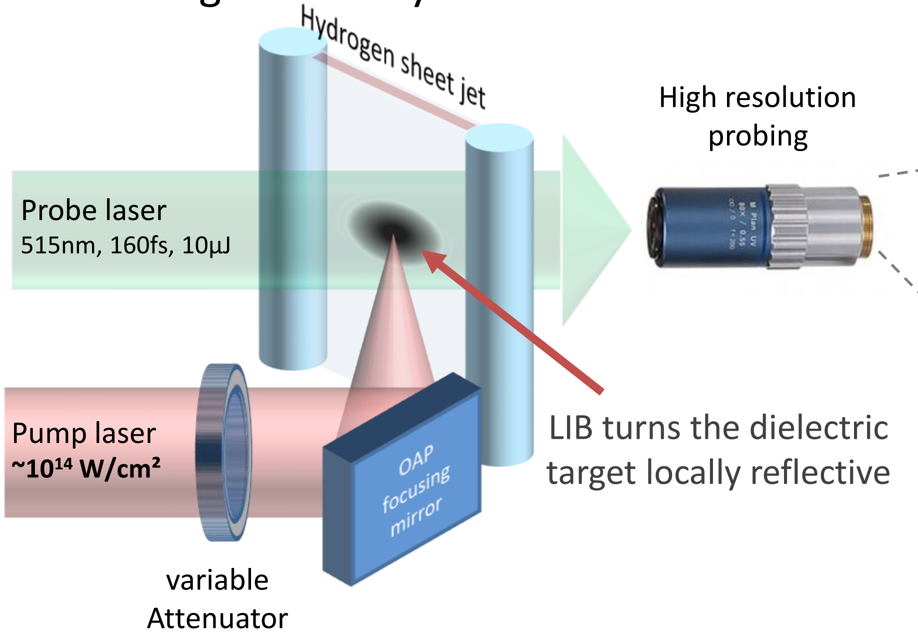
1. Determining the onset of target pre-expansion
Measuring the laser-induced breakdown (LIB) threshold of solid H2



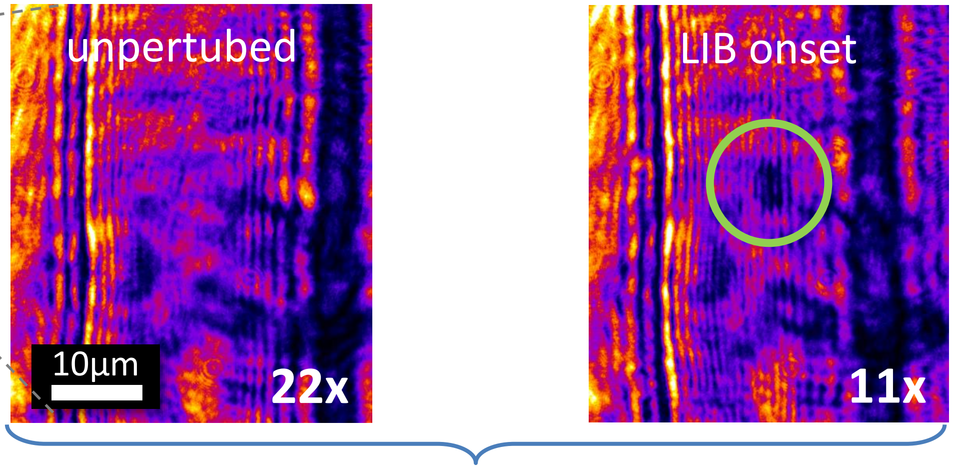
- **LIB** of the target ↔ $\mathbf{n_e}$ [conduction band] ≥ $\mathbf{n_c}$
  - Target: transmittive → reflective



- Plasma emission prevents direct observation of LIB in a high-intensity shot



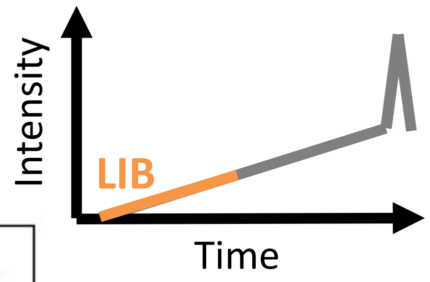
Example images at 1.04·10^{14} W/cm², 30fs:



Measurements: acquire **>100 images** at 1Hz
33% LIB fraction

C. Bernert et al., Phys. Rev. Appl., 10, 14070 (2023); S. Assenbaum et al. PPCF ***67*** *015032 (2025)*

1. Determining the onset of target pre-expansion -
Measuring the laser-induced breakdown (LIB) threshold of solid H2



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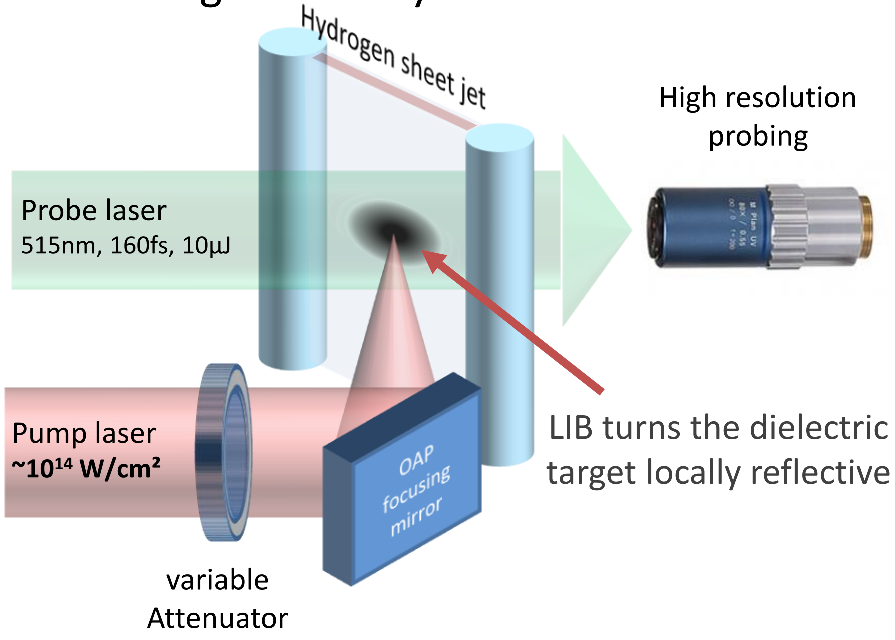

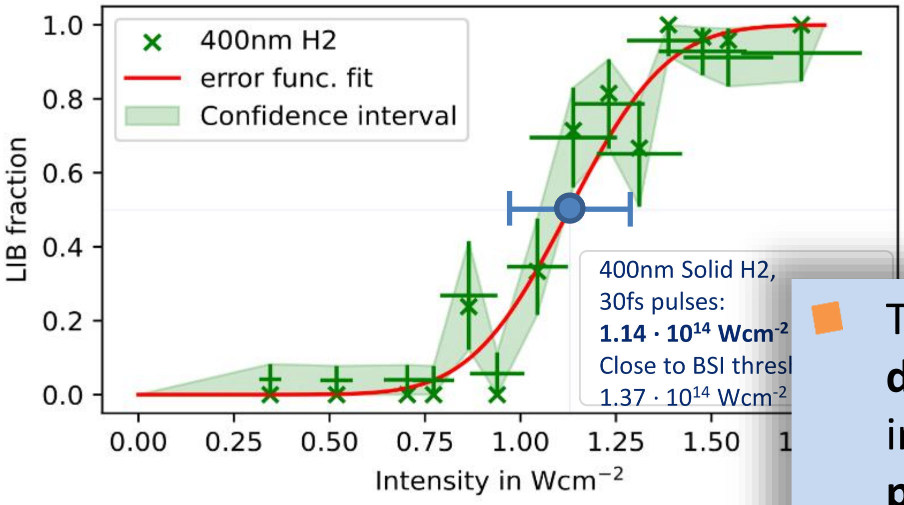

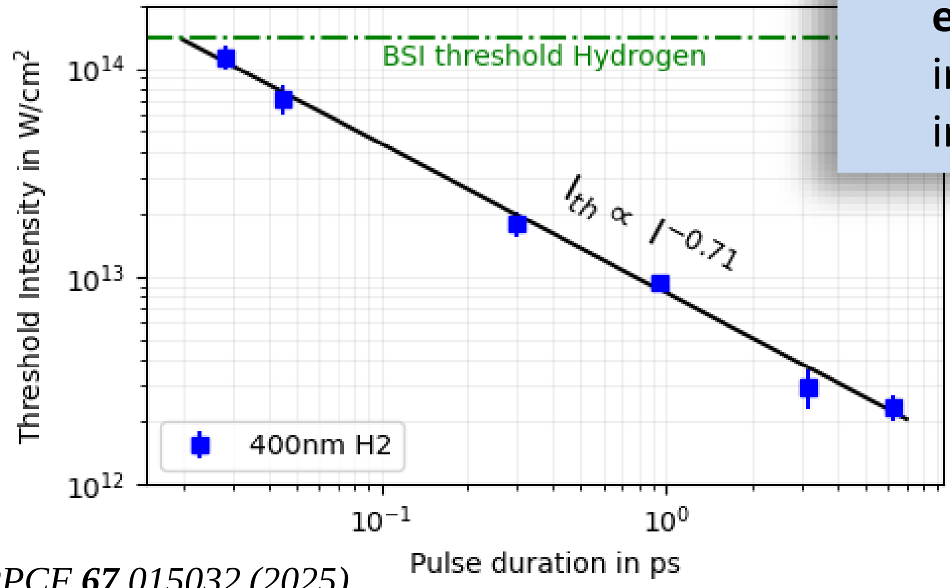

- The **pulse-duration dependence** of **LIB** impacts the **starting point of target pre-expansion** in high-intensity laser-solid interactions

C. Bernert et al., Phys. Rev. Appl., 10, 14070 (2023); S. Assenbaum et al. PPCF ***67*** *015032 (2025)*

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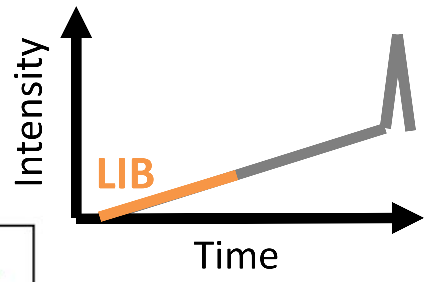
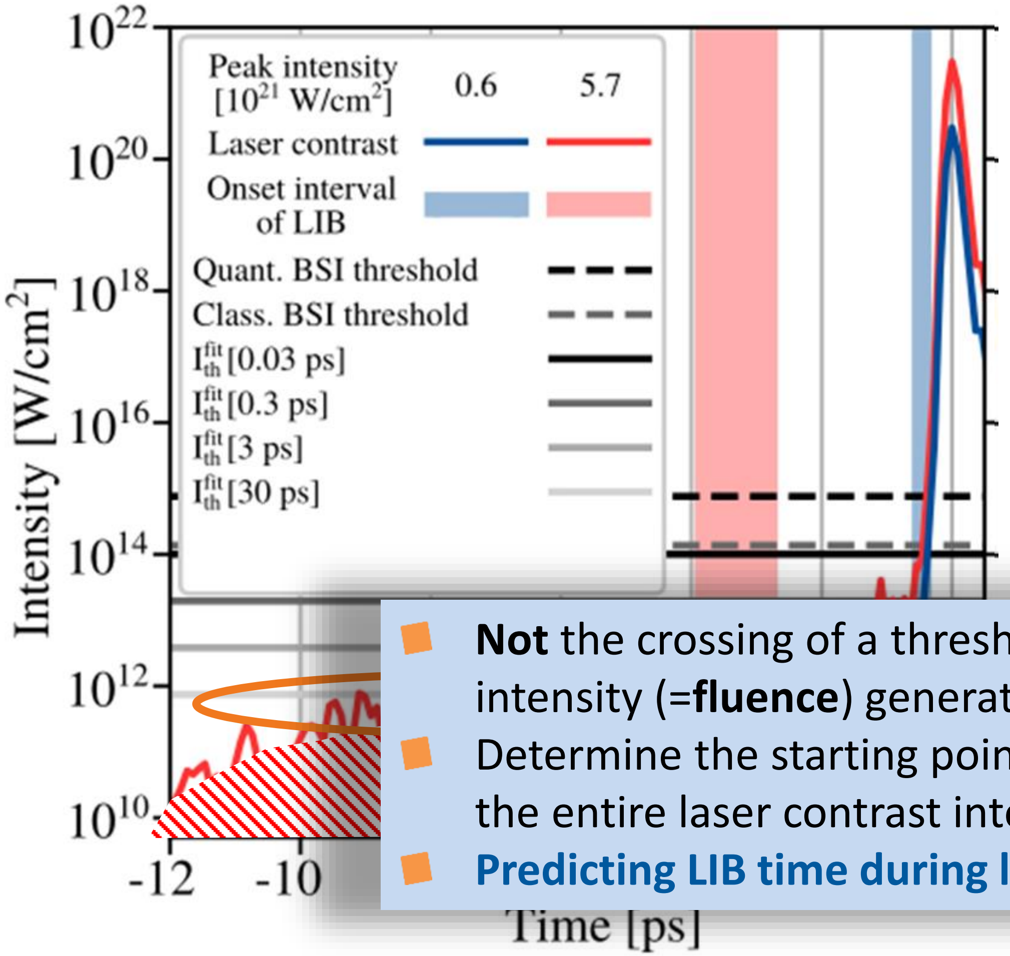
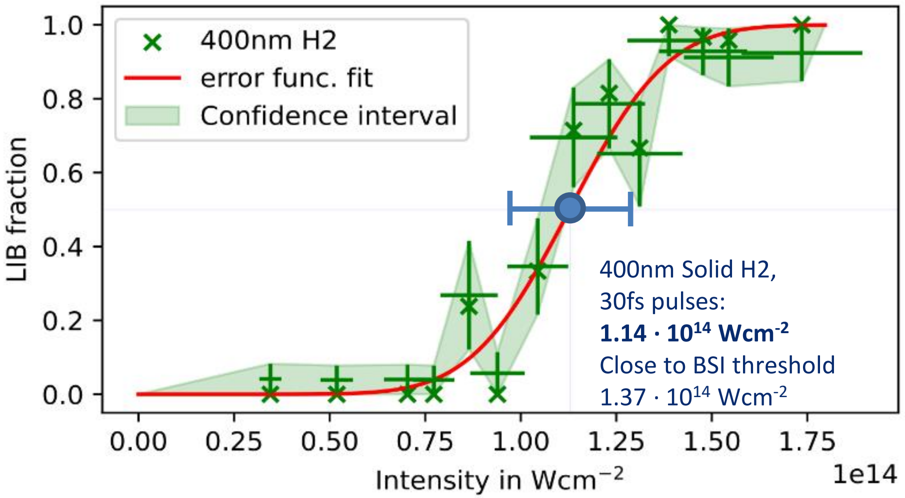
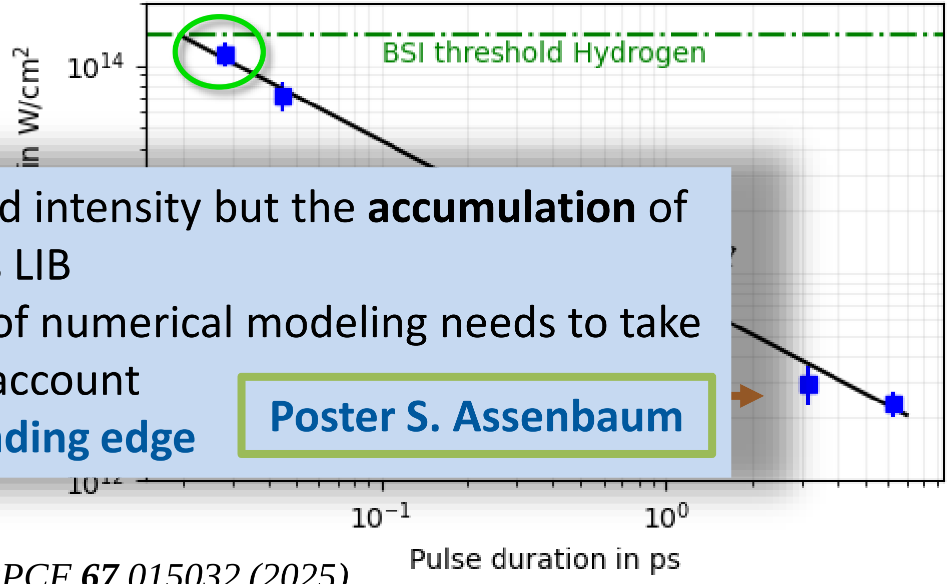


Correlate to the full energy temporal laser contrast
(here PM contrast with different intenstities of DRACO PW)







- **Not** the crossing of a threshold intensity but the **accumulation** of intensity (=**fluence**) generates LIB
- Determine the starting point of numerical modeling needs to take the entire laser contrast into account
- **Predicting LIB time during leading edge**

Poster S. Assenbaum

*C. Bernert et al., Phys. Rev. Appl., 10, 14070 (2023); S. Assenbaum et al. PPCF **67** 015032 (2025)*

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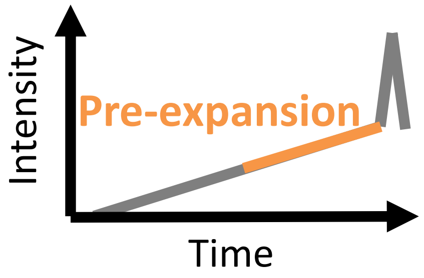
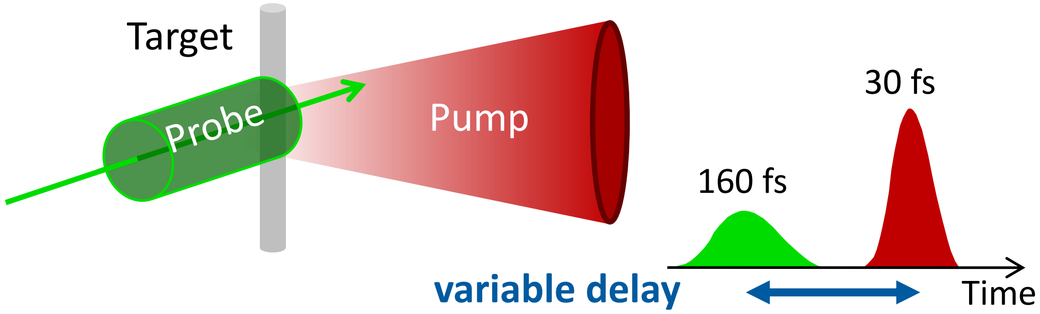
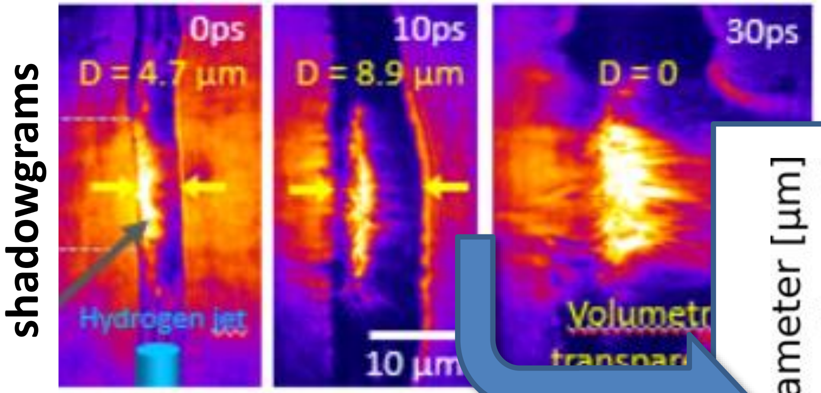
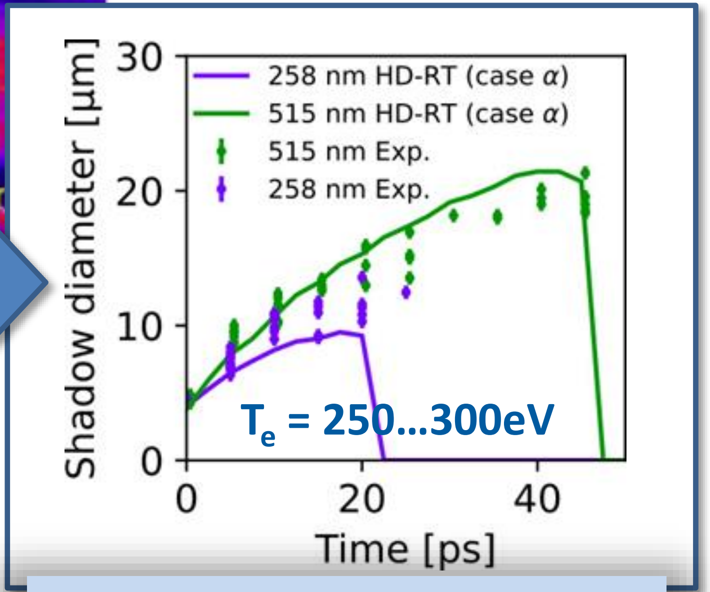
2. Testbed to benchmark simulations
Determining the plasma temperature by expansion measurements



- **Isochoric heating** by short-pulse lasers with $\mathbf{a_0 = 1}$ as a showcase study
- **Time-resolved shadowgraphy** of expanding plasma after irradiation with $I = 1.6 \cdot 10^{18}$ W/cm² pulses







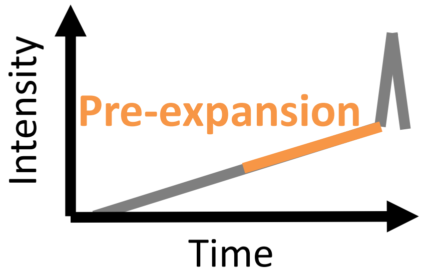
- Simulate expansion using **Hydrodynamics simulation** (HD), create synthetic shadowgrams with **Ray Tracing** (RT) -> HD-RT method

- Fit synthetic expansion data to the measured data → indirect temperature diagnostic

Yang et al., Commun. Phys. 6, 368 (2023)

2. Testbed to benchmark simulations

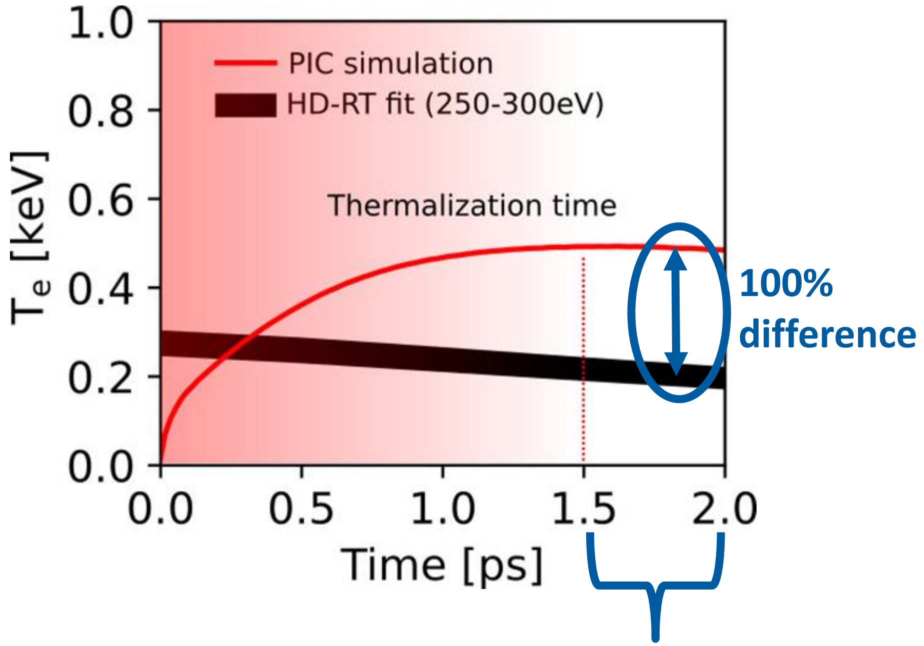
Determining the plasma temperature by expansion measurements

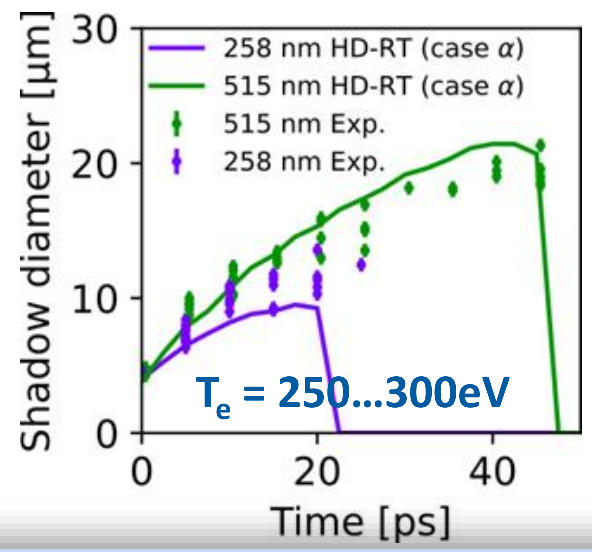


- **Isochoric heating** by short-pulse lasers with $\mathbf{a_0 = 1}$ as a showcase study

Simulation parameters:

- 2D3V sims using PIConGPU
- Fully ionized spherical hydrogen column (4.4µm diameter, 30n_c flat top with exponential surface gradient of 0.25µm)





T_e from PIC strongly depends on the initial **surface gradient**

- **Quantitative prediction making by PIC sims. requires precisely characterized target densities**
- **Indirect temperature measurement limited to late times and low density plasma**

- Fit synthetic expansion data to the measured data → indirect temperature diagnostic

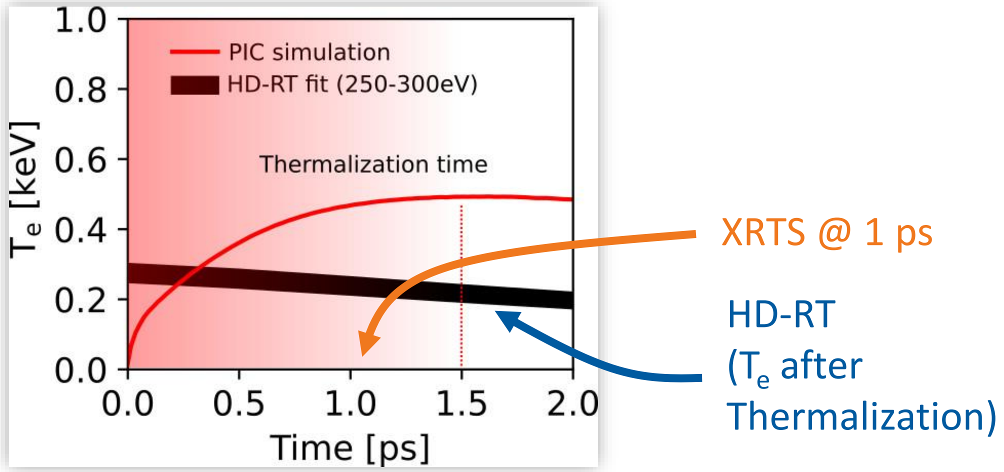
Yang et al., Commun. Phys. 6, 368 (2023)

2. Testbed to benchmark simulations

Extension towards direct temperature measurements

Recent experiment p4446 at EuXFEL, PI: Sebastian Göde

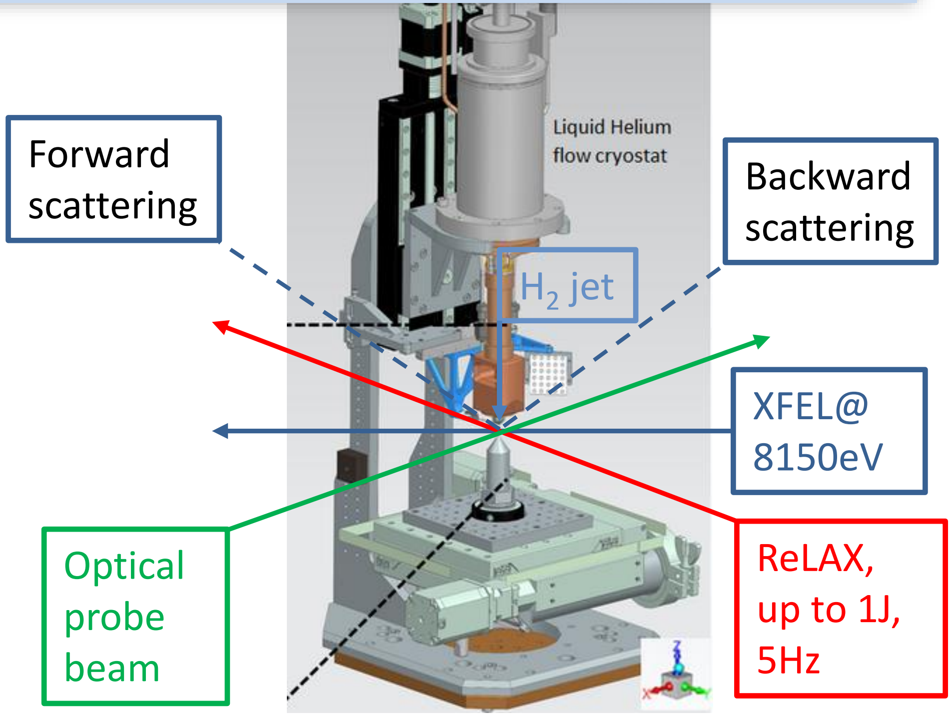
- Benchmark PIC sims. via isochoric laser heating at **a_0=0.1…1**
- **XRTS (**x-ray Thomson scattering) supplements measurements of T_e:



- **Preliminary Results:**

a_0	0.12	0.3	0.7
I [Wcm^{-2}]	3E16	2E17	1E18
HD-RT [eV]	25	200	350
XRTS [eV]	~30	*Analysis pending*	

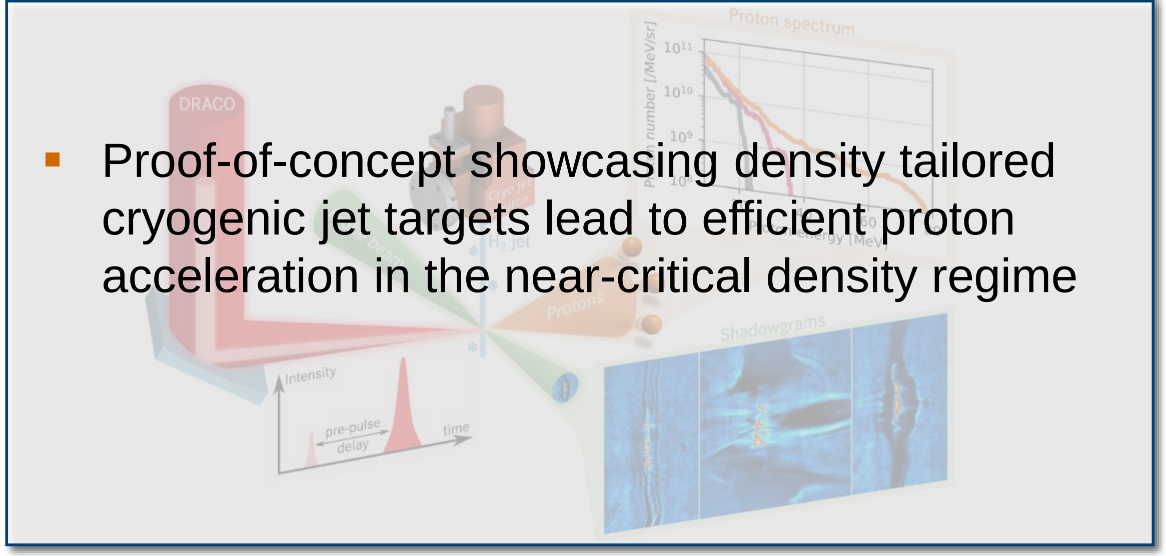
- **Cryogenic jet platform** now commissioned **at HED of EuXFEL**
  - Offers rep. rate operation (here 5Hz) with XFEL beam, Joule-class high intensity laser and optical probing



Martin Rehwald • m.rehwald@hzdr.de • www.hzdr.de • HZDR

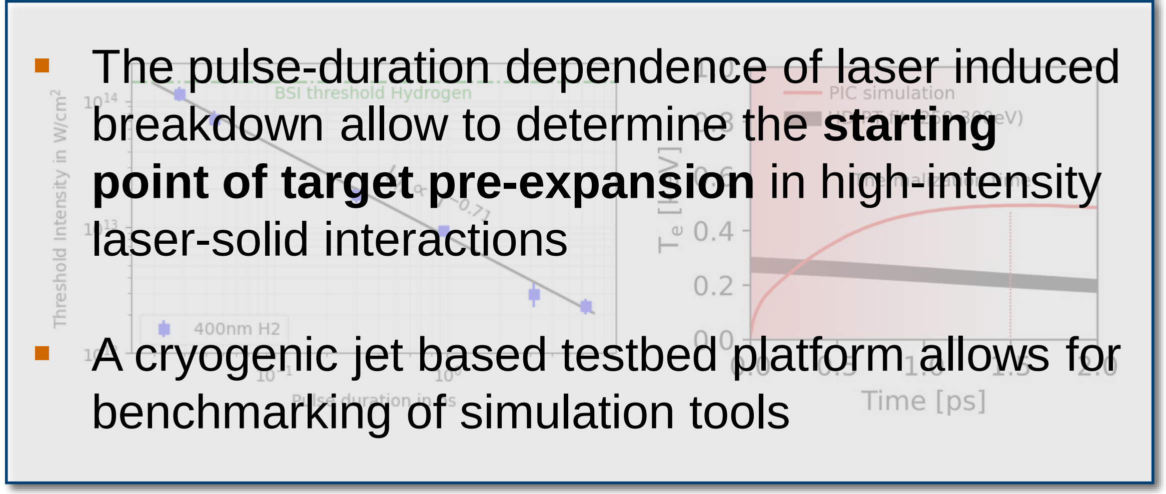
Summary

Proton energy increase in the near-critical regime using cryogenic hydrogen jets



- Proof-of-concept showcasing density tailored cryogenic jet targets lead to efficient proton acceleration in the near-critical density regime

Developing the simulation tools and experimental benchmark scenarios for optimized density profiles



- The pulse-duration dependence of laser induced breakdown allow to determine the **starting point of target pre-expansion** in high-intensity laser-solid interactions
- A cryogenic jet based testbed platform allows for benchmarking of simulation tools

Outlook: Transforming the single-shot performance of the proof-of-concept scenario towards a stable and high-repetition rate operation

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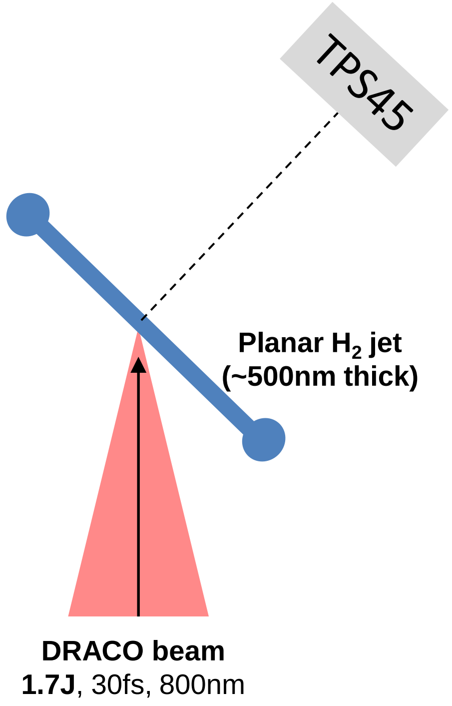
Outlook: Transforming the single-shot performance into a stable and high-repetition rate operation

- Laser-driven proton acceleration in the near critical regime is sensitive to on-shot conditions

➢ Scan large parameter spaces
➢ Measure small amplitude effects
➢ Good statistics & small errors

Larger data sets/
High rep. rate needed



Preliminary results: 1Hz operation
1000 consecutive shots

Talk S. Assenbaum

Martin Rehwald • m.rehwald@hzdr.de • www.hzdr.de • HZDR

Thank you for your attention

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Acknowledgements

Helmholtz-Zentrum Dresden-Rossendorf:
S. Assenbaum, C. Bernert, M. Müller, T. Streil, J. Garreis, J. Schilz, T. Ziegler, J. Metzkes-Ng, T. Kluge, M. Vescovi, M. Umlandt, I. Göthel, L. Yang, L. Huang, T. Miethlinger, P. Ordyna, J. Vorberger, P. Wang, T. E. Cowan, Ulrich Schramm and K. Zeil

EuXFEL HED/HiBEF experimental team:
S. Göde, D. Loureiro, J. P. Schwinkendorf, H. Höppner, A. Laso-Garcia, A. Pelka

HEDS group from SLAC:
M. Gauthier, C. Schönwälder, C. Curry, L. Fletcher, F. Treffert, G. Glenn, S. Glenzer

Partner von DRESDEN concept exzellenz-dresden.de

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