High-repetition rate laser proton acceleration and plasma benchmark experiments using cryogenic hydrogen jets

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

TECHNISCHE UNIVERSITÄT DRESDEN

Martin Rehwald, Stefan Assenbaum, Constantin Bernert, Chandra B. Curry, Thomas E. Cowan, Maxence Gauthier, Sebastian Göde, Ilja Goethel, Siegfried H. Glenzer, Lingen Huang, Thomas Kluge, Daniel Loureiro, Josefine Metzkes-Ng,Thomas Miethlinger, Christopher Schoenwaelder, Ulrich Schramm, Milenko Vescovi, Long Yang, Tim Ziegler, and Karl Zeil

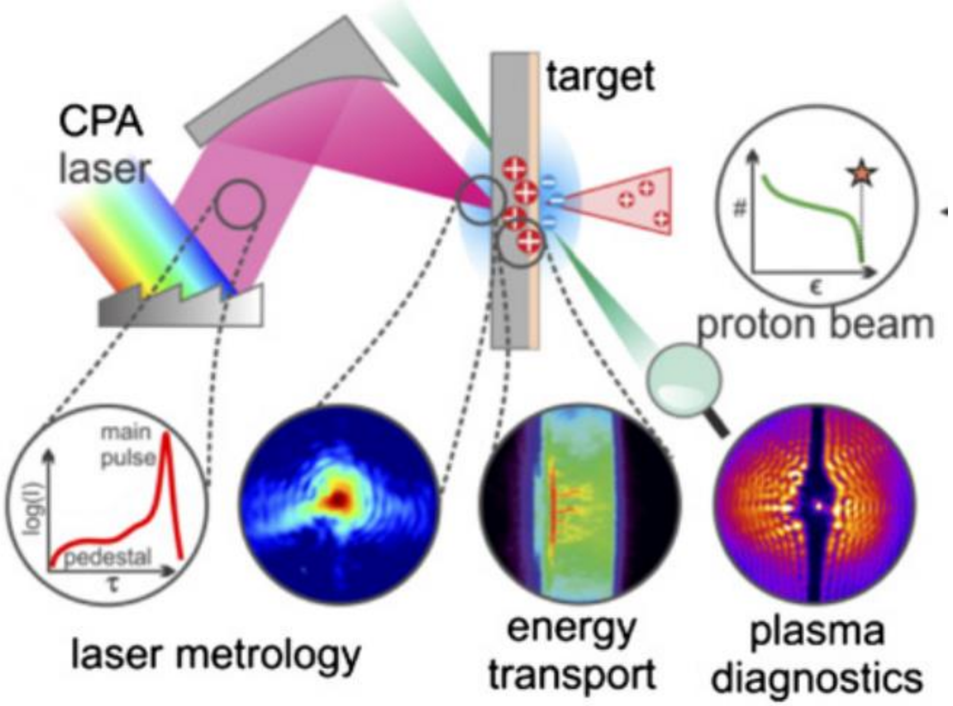
Partner von DRESDEN concept exzellenz-dresden.de

European XFEL

Advanced Accelerator Concepts 2024 – 07/22/2024

SLAC

Developing high energy, high repetition rate laser-driven proton accelerators



Energy scaling challenge

- Technological limits for larger laser systems
- More efficient acceleration than TNSA

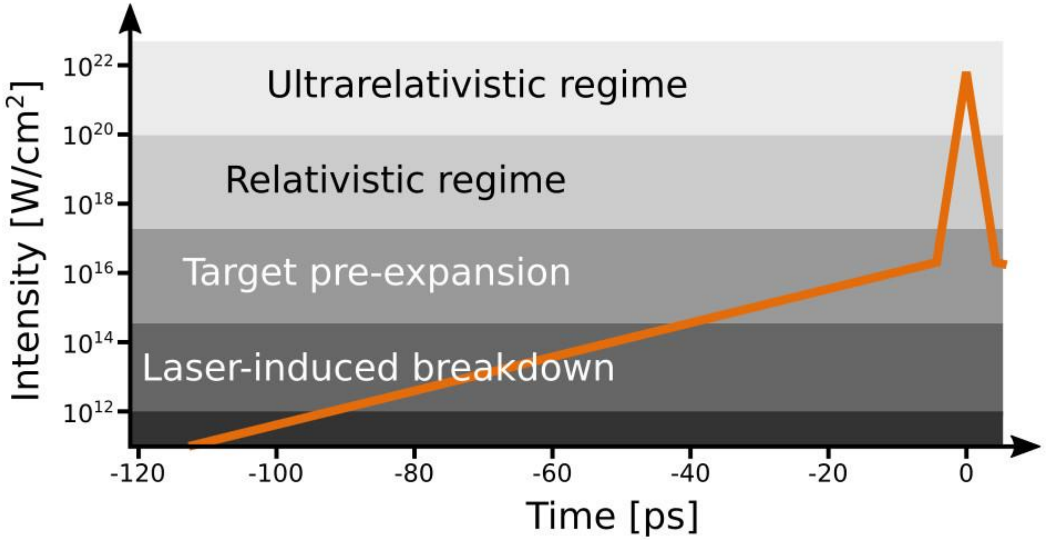
→ Predictive modeling capabilities are needed

2020 Roadmap on Plasma Accelerators, NJP (2021)

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

High-intensity laser-solid 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**)



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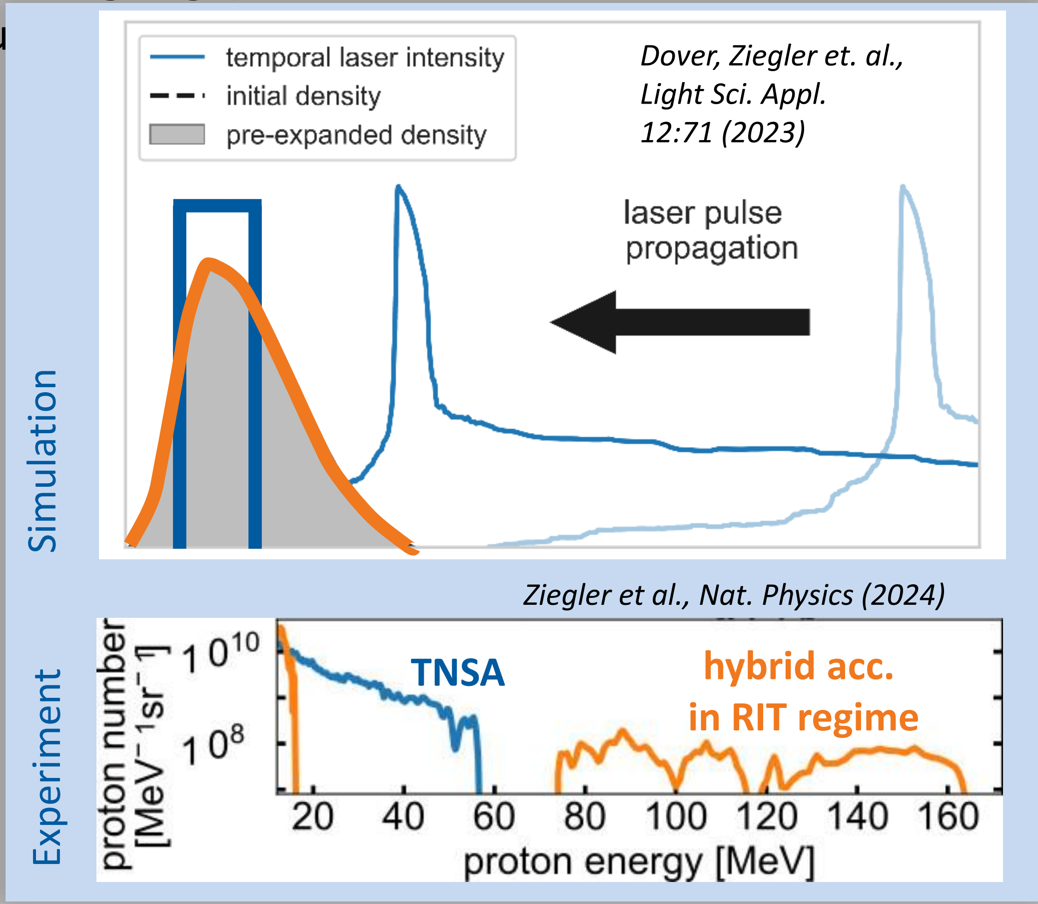
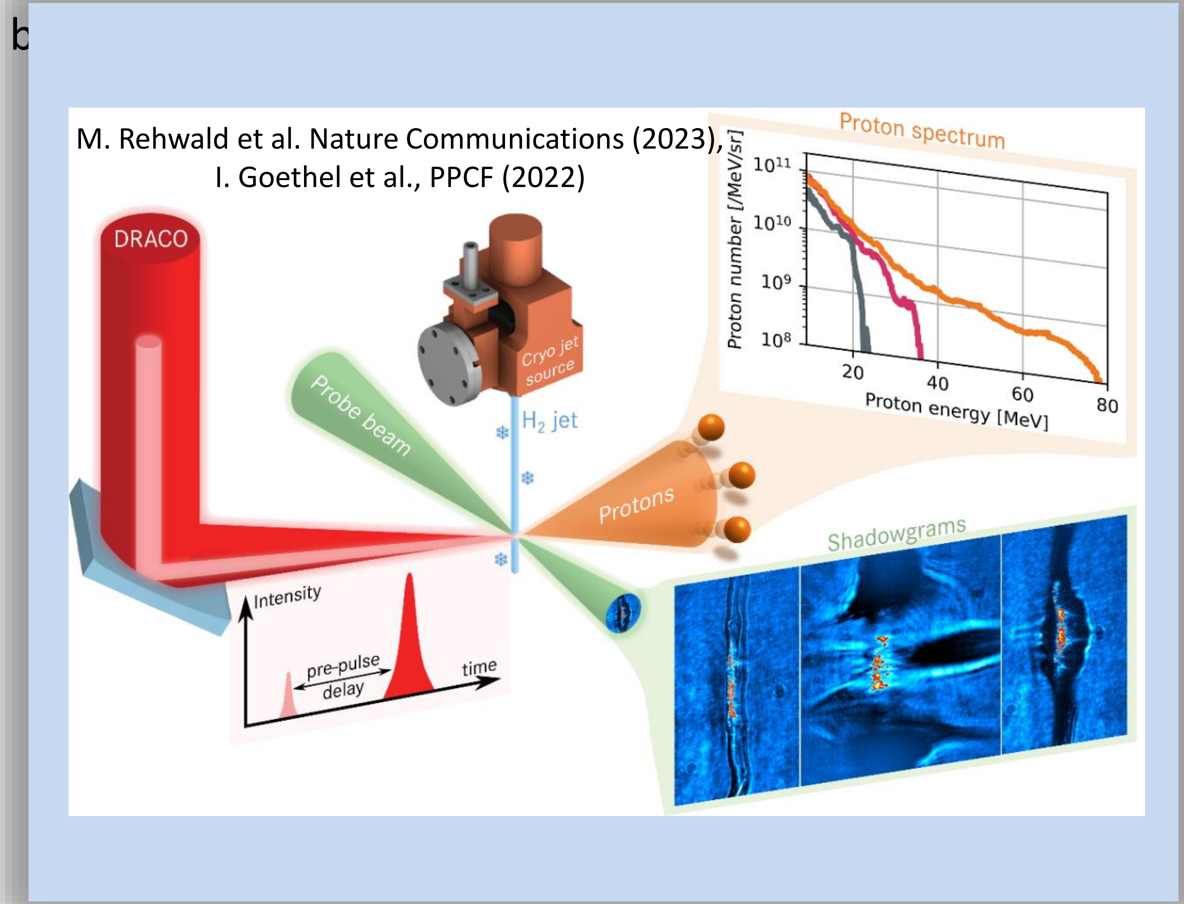
- Su… th… …rget b…





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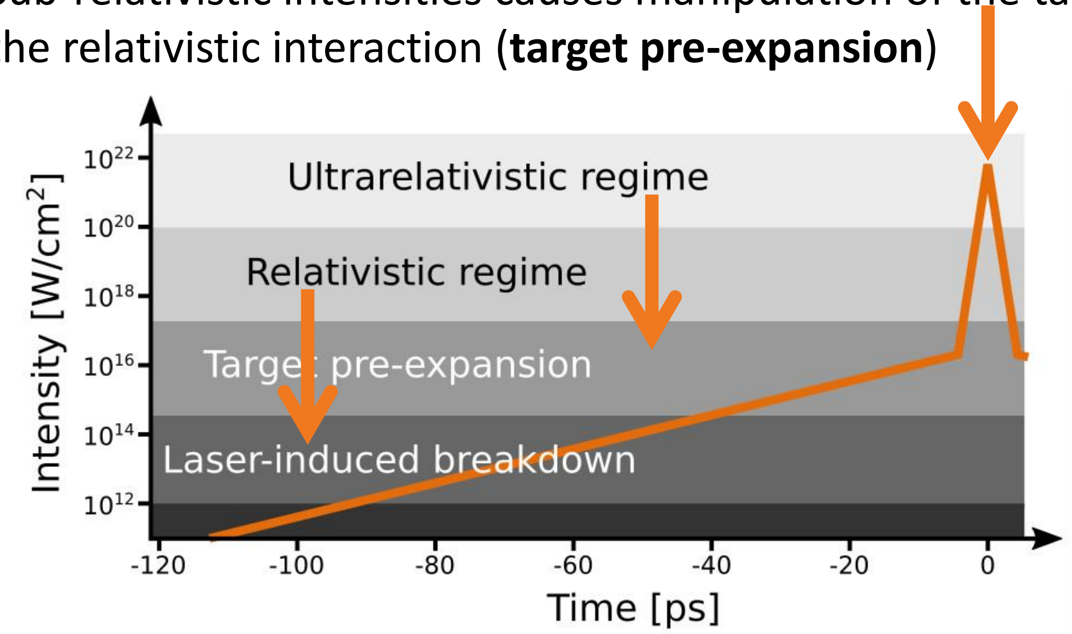

- **Numerical modeling** follows staged approach:
  - **0.** Determine the starting point of target pre-expansion
  - **1.** Hydrodynamic pre-expansion
  - **2.** Relativistic interaction of the peak

Content of this work:

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

High repetition rate (HRR) **expands our experimental toolkit.**

HRR will provide new methods to **understand, enhance and control** laser ion acceleration

- Outlook: Rep. rate ion acceleration:

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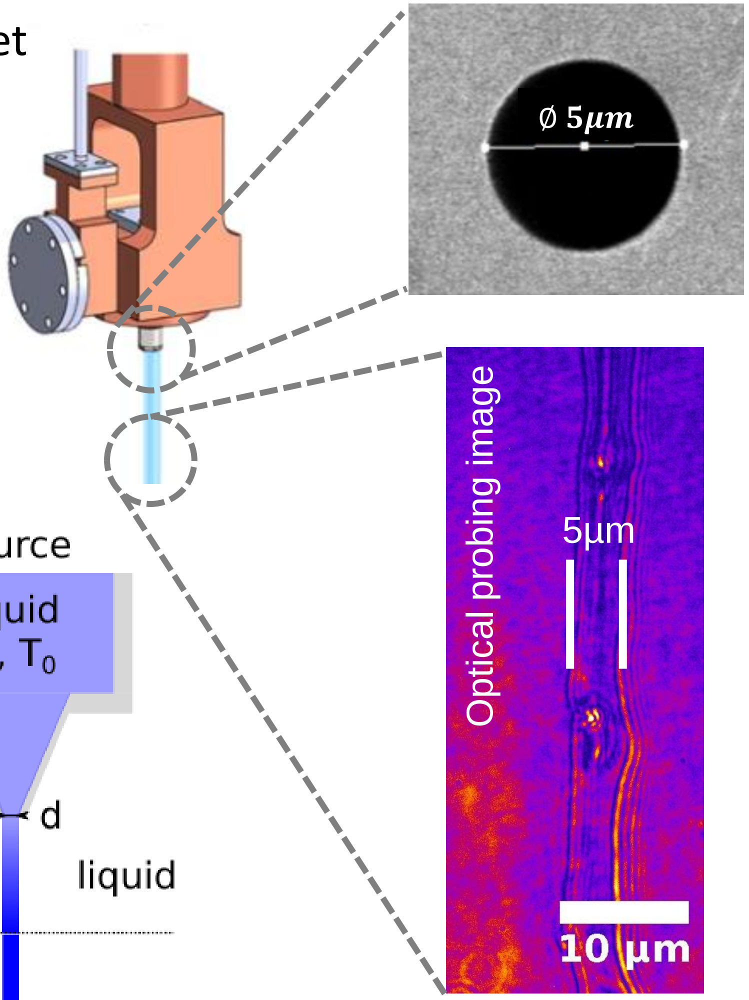
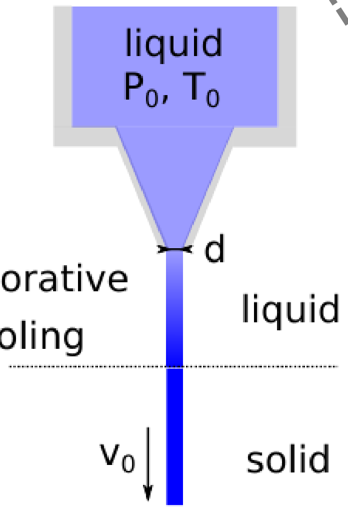
Hydrogen jets for laser ion acceleration and plasma benchmark experiments

European XFEL SLAC

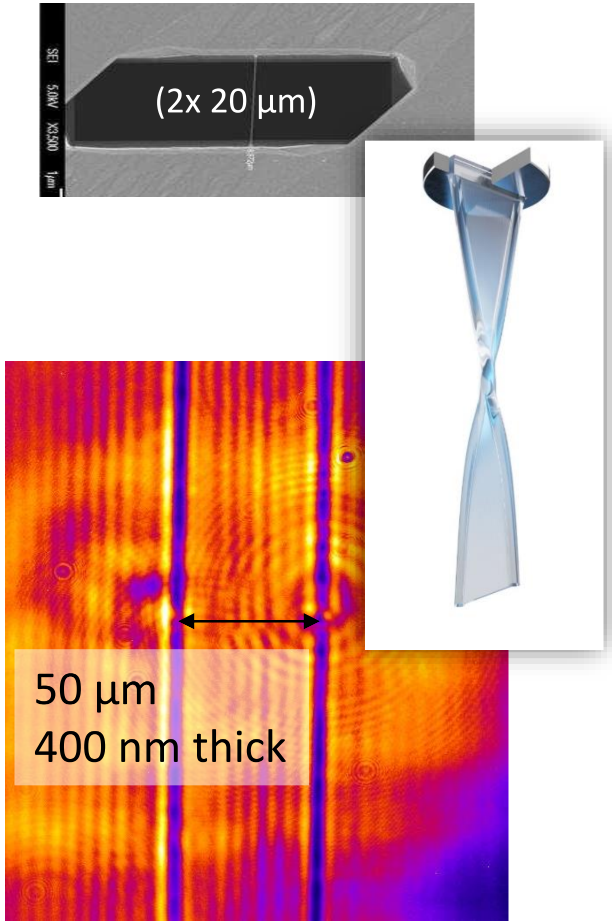
Cryogenic solid hydrogen jet

cylindrical jet





Sheet jets



- debris free, high rep rate target
- single species (pure hydrogen), simple ionization dynamics, low density → facilitates modelling
- small geometries enable probing
- Different species: D2, Ar, Ne, Ch4, He(?)
- Platform realized on many systems: Draco PW, Phelix GSI, SLAC-MEC, XFEL-HED, Texas PW

L. Obst Scientific Reports (2017), M. Gauthier Applied Physics Letters (2017), T. Ziegler PPCF (2018), L. Obst et al. Nat. Comm. (2018), S. Göde et al. Phys. Rev. Lett. (2017), Curry JoVE (2020), Bernert Scientific Reports (2022)

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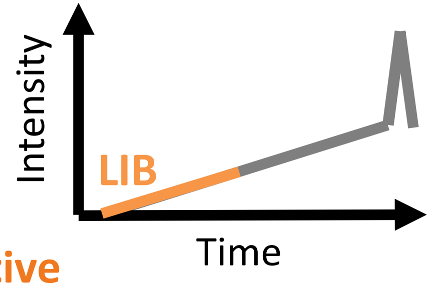
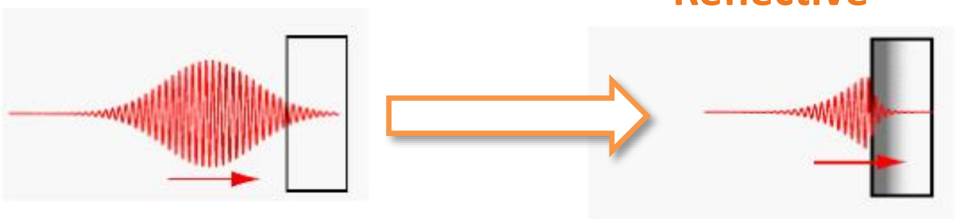
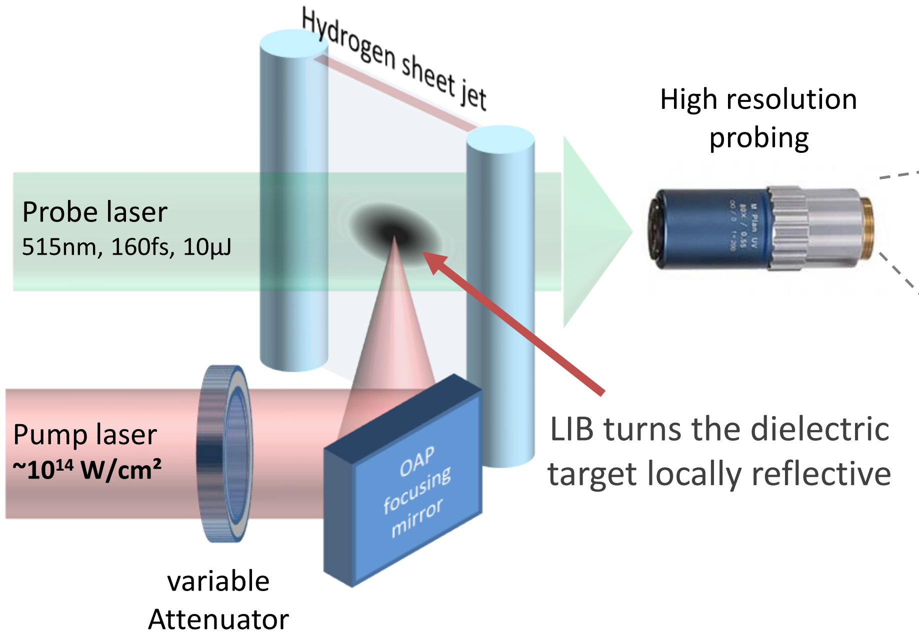
Determining the onset of target pre-expansion - Measuring the laser-induced breakdown (LIB) threshold of solid H2

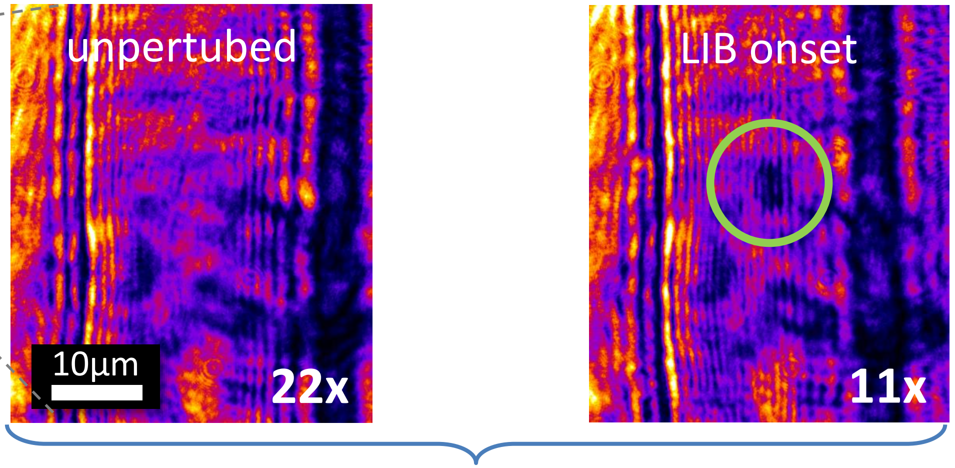


- **LIB** of the target ↔ $\mathbf{n_e}$ [conduction band] ≥ $\mathbf{n_c}$
  - Target: transmittive → reflective





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



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

C. Bernert et al., (2023) *Phys. Rev. Appl.*, *10*, 14070.

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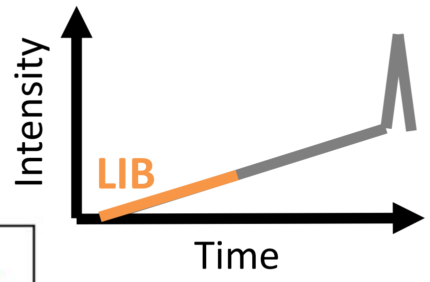
Determining the onset of target pre-expansion - Measuring the laser-induced breakdown (LIB) threshold of solid H2



- **LIB** of the target ↔ n_e [conduction band] ≥ n_c
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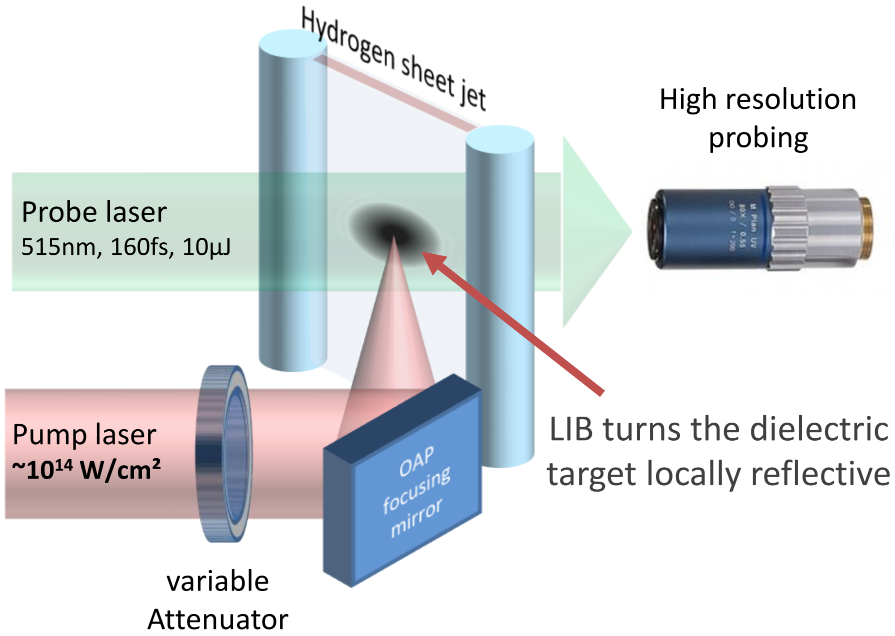

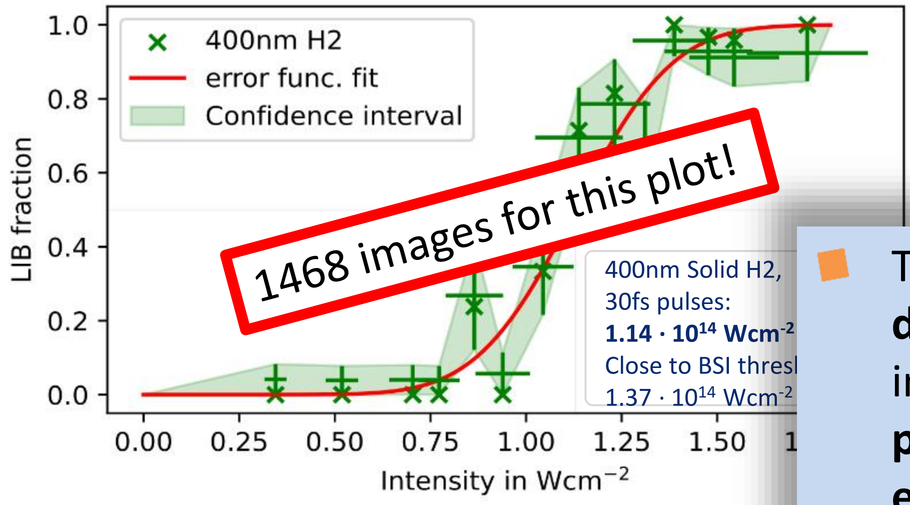

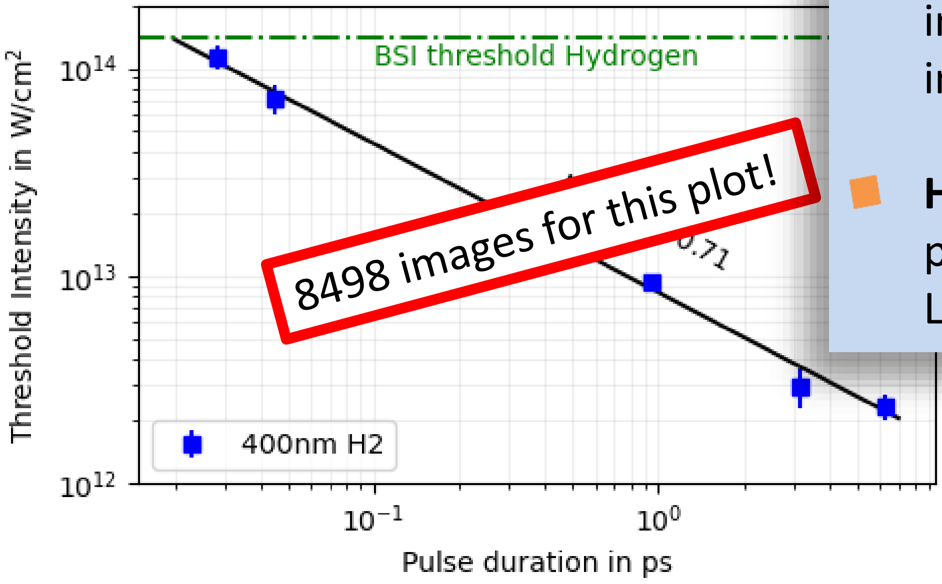

- The **pulse-duration dependence** of **LIB** impacts the **starting point of target pre-expansion** in high-intensity laser-solid interactions
- **HRR enables** to precisely determine LIB thresholds

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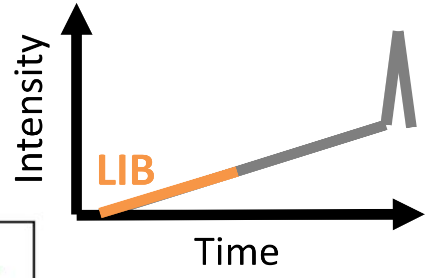
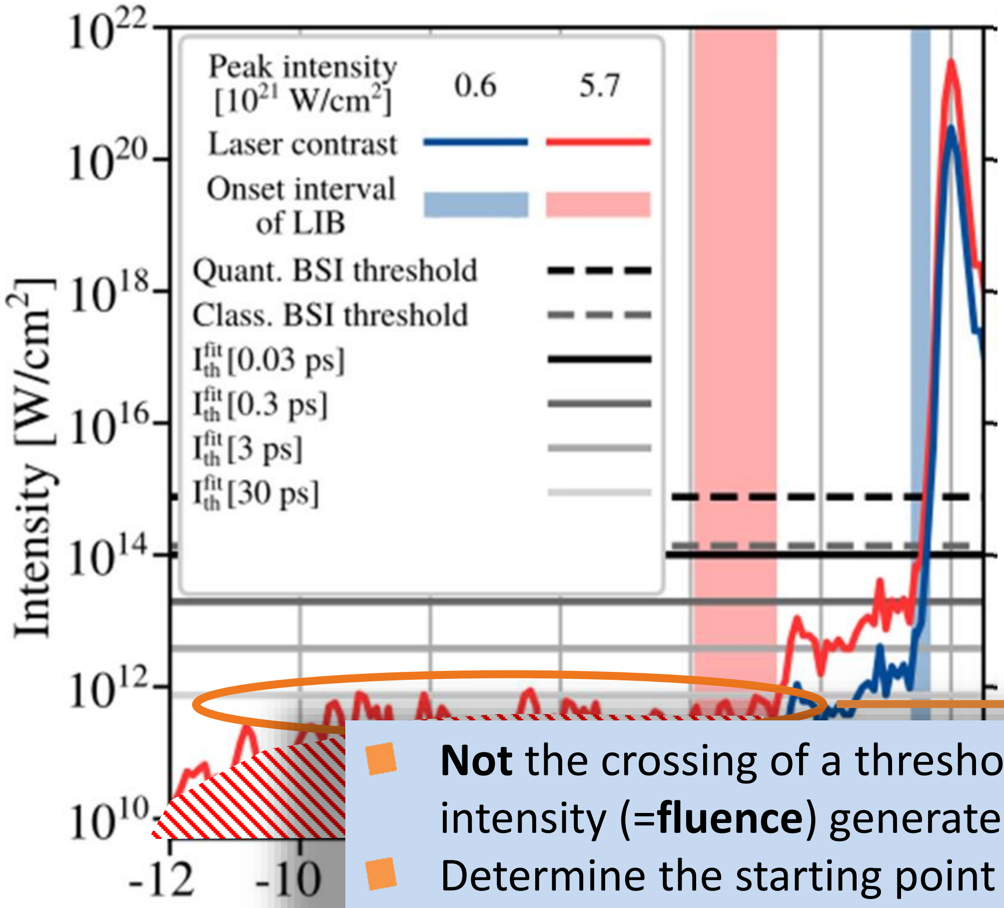
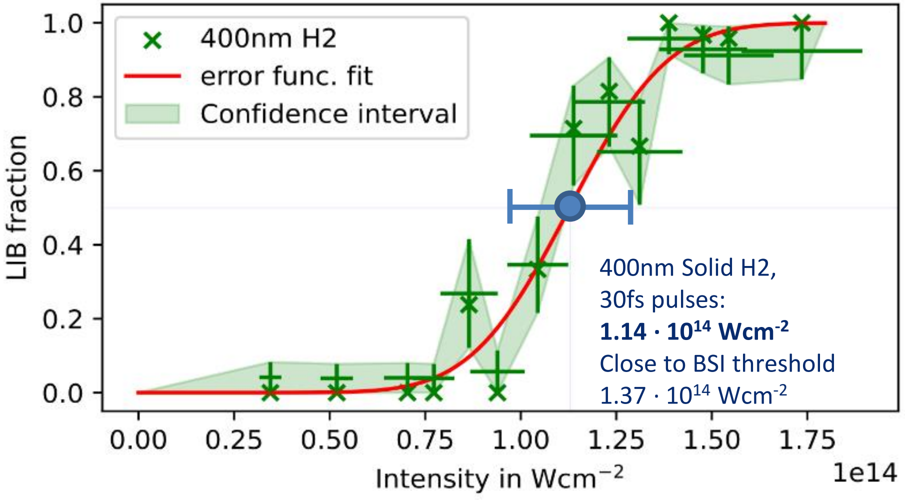
Determining the onset of target pre-expansion - Measuring the laser-induced breakdown (LIB) threshold of solid H2

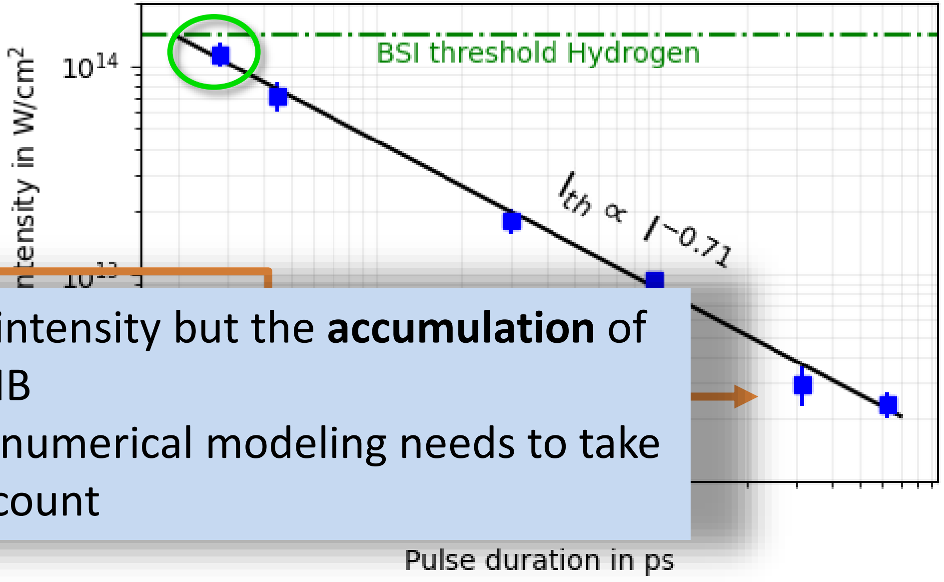


Correlate to the full energy temporal laser contrast

(here PM contrast with different intenstities of DRACO PW)





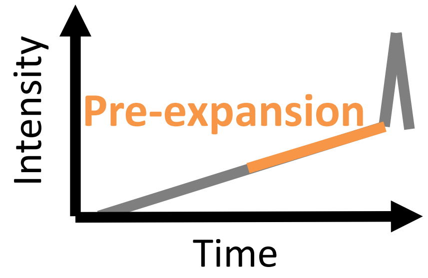


- **Not** the crossing of a threshold intensity but the **accumulation** of intensity (=**fluence**) generates LIB
- Determine the starting point of numerical modeling needs to take the entire laser contrast into account

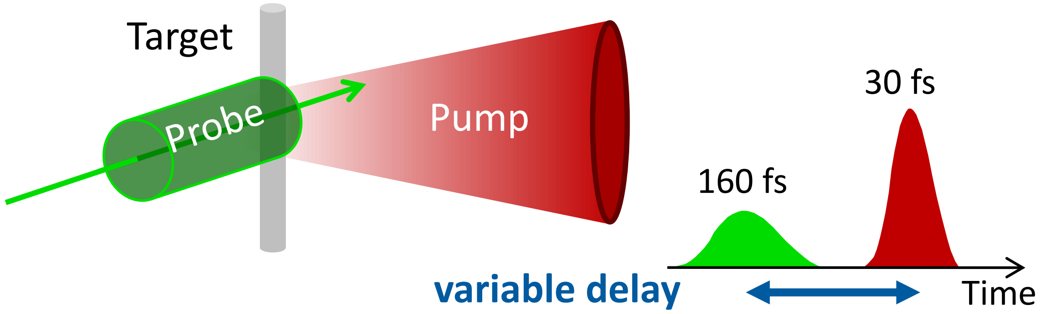
C. Bernert et al., (2023) *Phys. Rev. Appl.*, *10*, 14070.

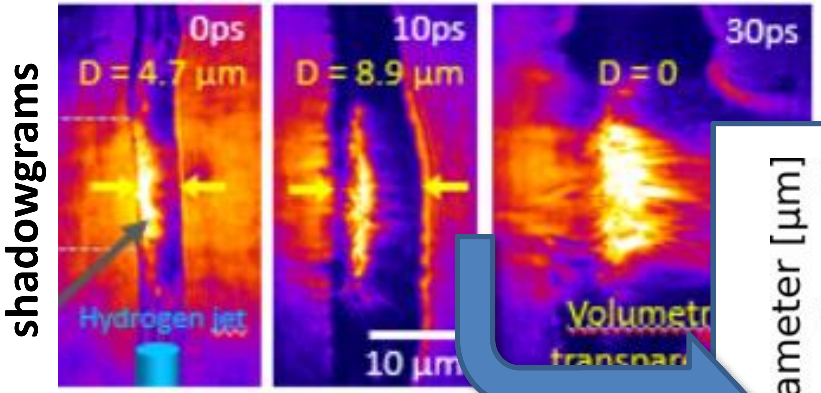
Martin Rehwald • m.rehwald@hzdr.de • www.hzdr.de • HZDR

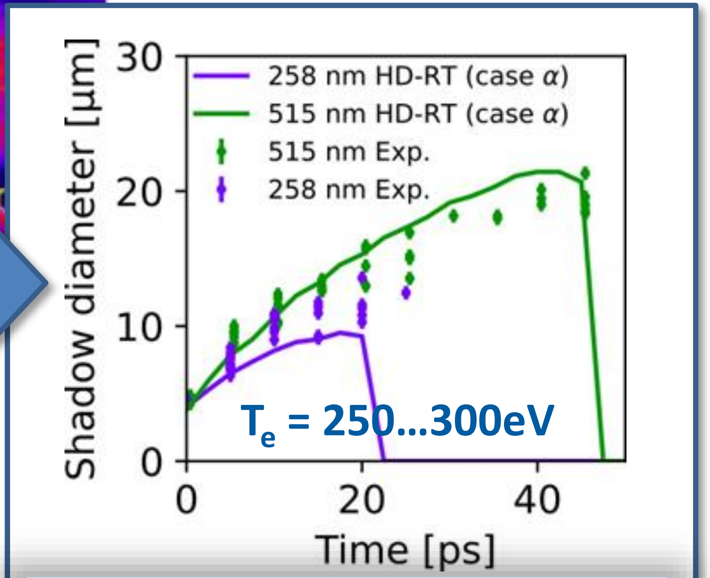
Testbed to benchmark simulations
Determining the plasma temperature by expansion measurements



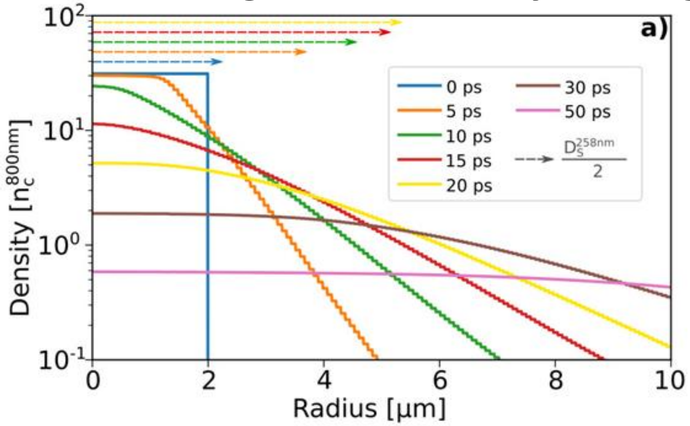
- **Isochoric heating** by short-pulse lasers with $\mathbf{a_0 = 0.1\ldots1}$ as a showcase study
- **Time-resolved shadowgraphy** of expanding plasma after irradiation with $I = 1.6 \cdot 10^{18}$ W/cm² pulses

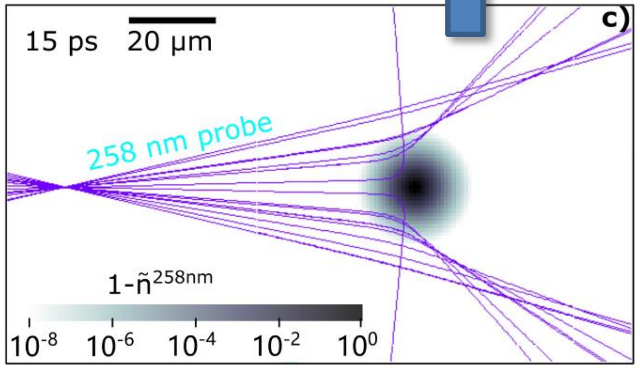






- Simulate expansion using **Hydrodynamics simulation** (HD), create synthetic shadowgrams with **Ray Tracing** (RT) -> HD-RT method





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

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

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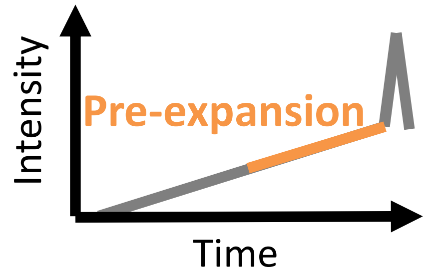
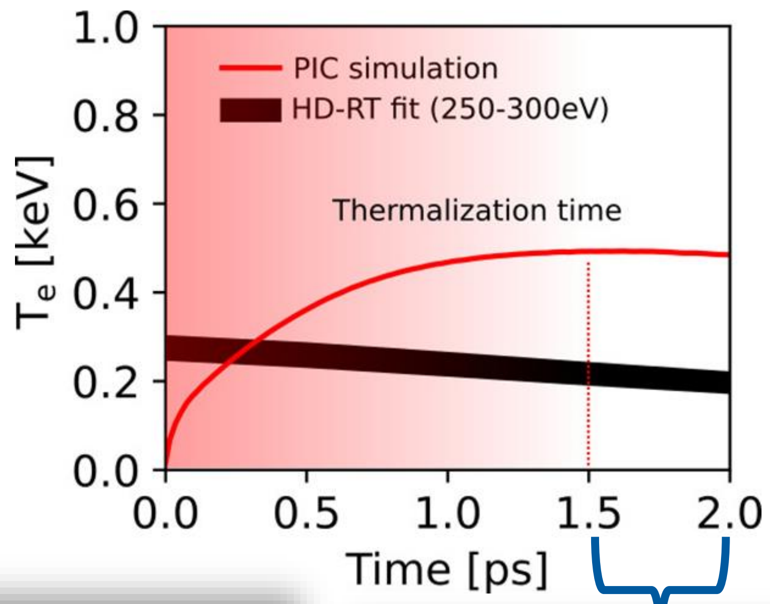
Testbed to benchmark simulations
Determining the plasma temperature by expansion measurements

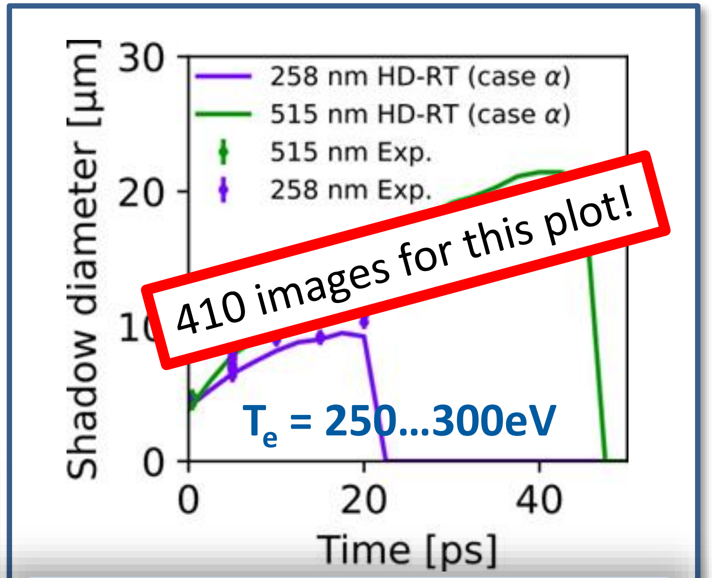


- **Isochoric heating** by short-pulse lasers with **a_0 = 0.1…1** as a showcase study

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)





- HD-RT method to benchmark laser heating and thermalization in PIC simulations
- Testbed for physics models at sub-relativistic intensites

- HRR is necessary for the HD-RT fit in particular to enable benchmark studies with various parameters (intensity, pulse duration)

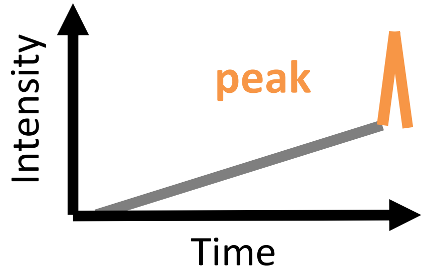
- Fit synthetic expansion data to the measured data → indirect temperature diagnostic

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

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

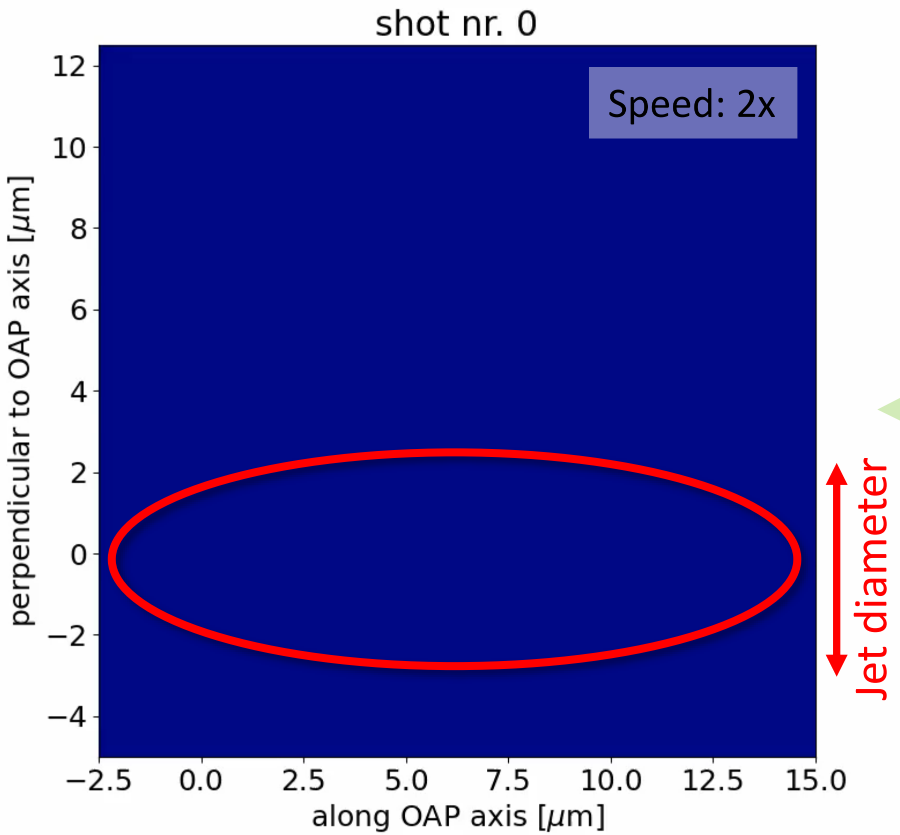
Outlook: Rep. rate data acquisition for ion acceleration studies

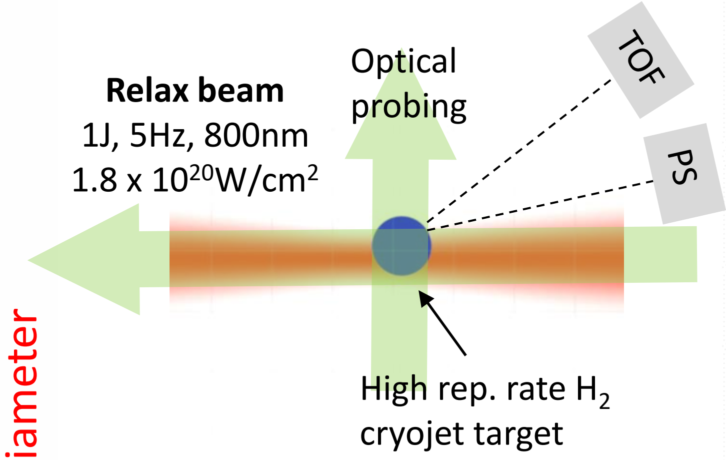
Proof-of-concept run with >1800 shots at 1J on target and 5Hz using the RELAX laser



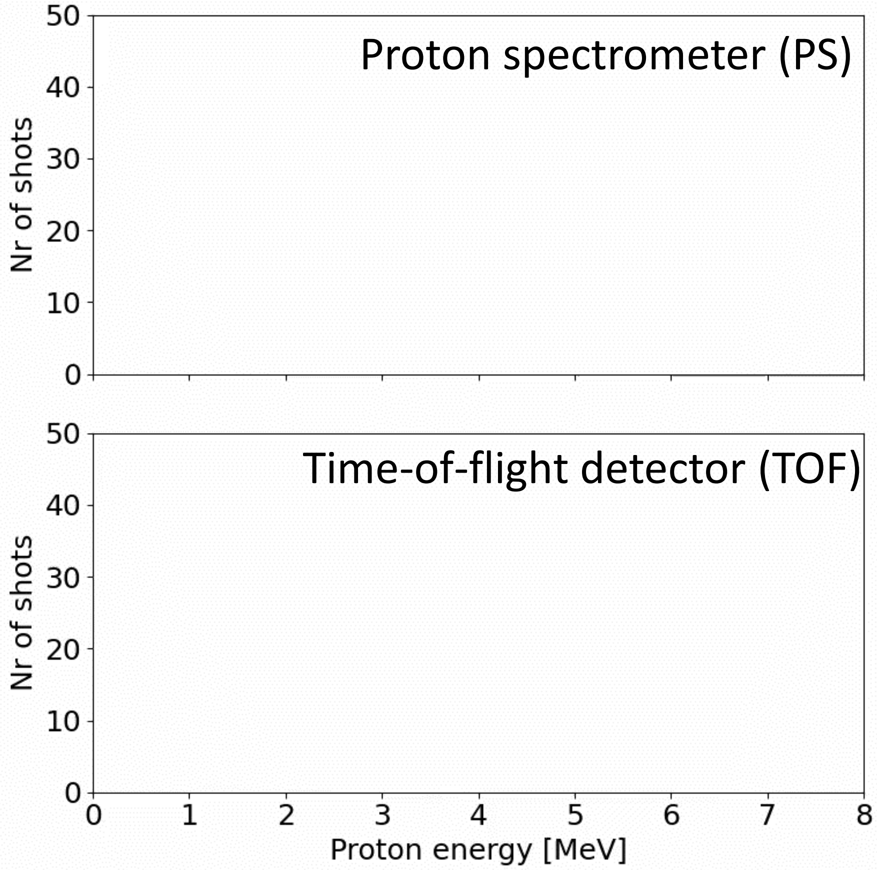
1) Online analysis and data filtering to actively compensate drifts or find best overlap during the run

Online target position monitor (first ~300 shots):





Maximum proton energy distribution:



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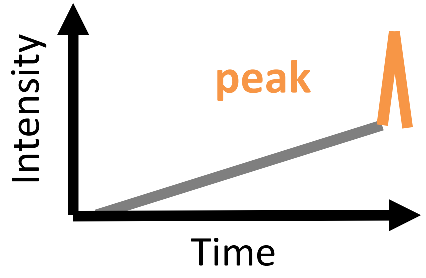
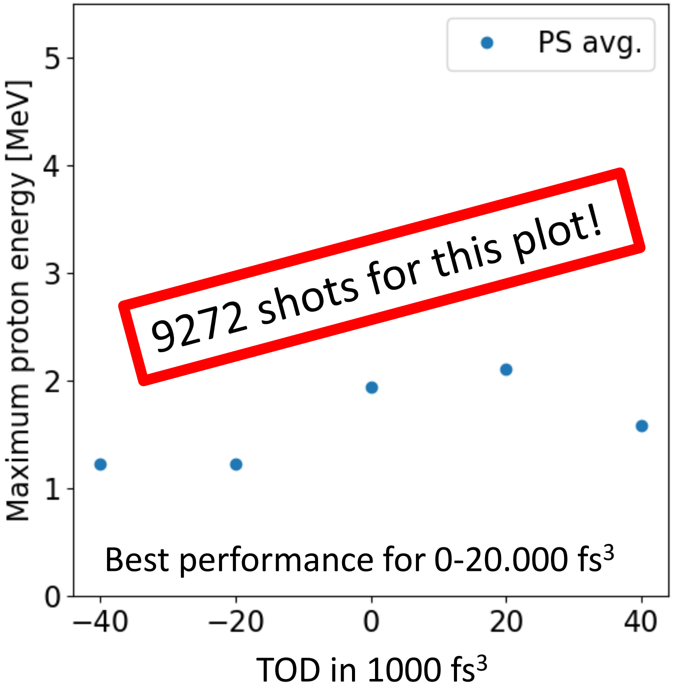
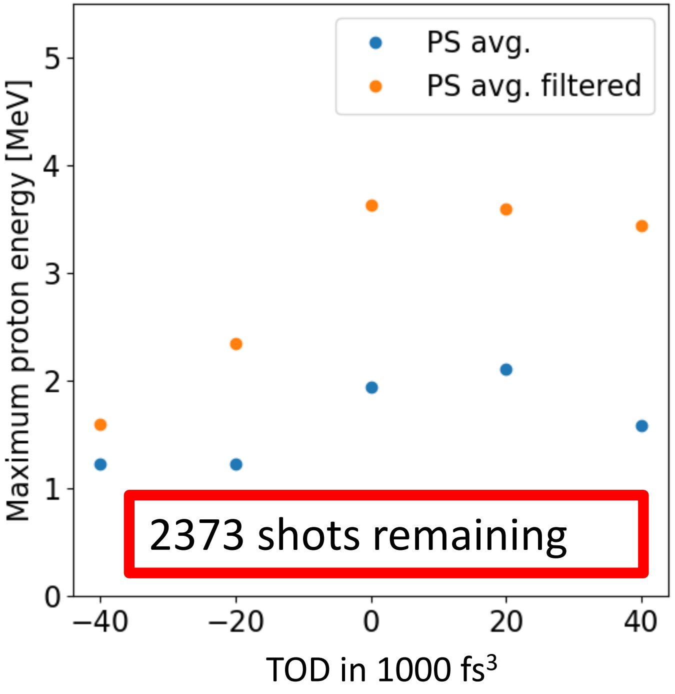


HRR allows to filter out fluctuation in den experimental conditions
2) Test case: Spectral phase influence on the p+ acceleration



Transmitted light filter (jet position + focus position)



Outlook: Additional filters (spectral phase) or ML methods

...

- Scans with high statistics not only reduce uncertainties but allow study effects with smaller amplitudes

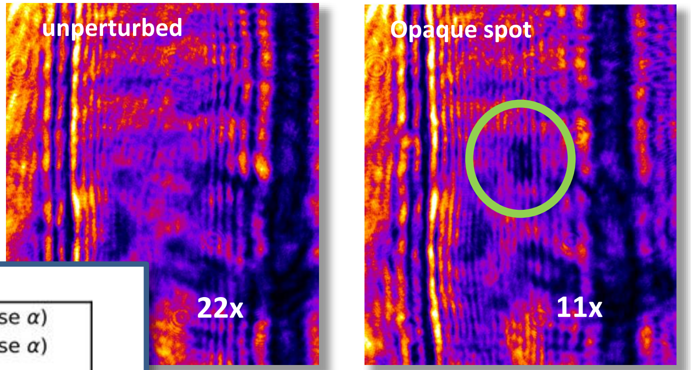
Martin Rehwald • m.rehwald@hzdr.de • www.hzdr.de • HZDR

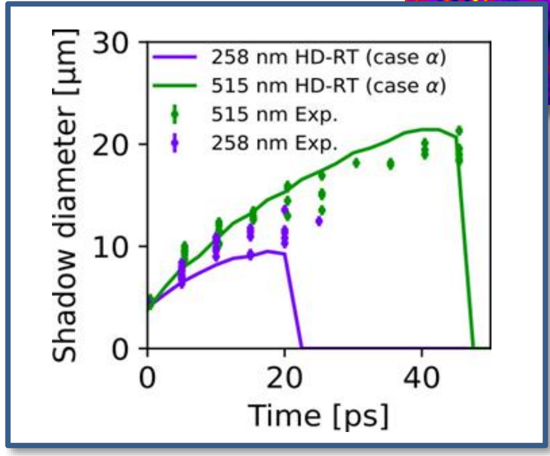
Conclusion

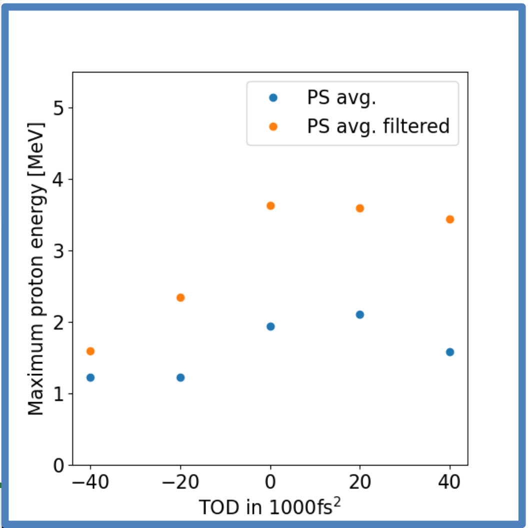
- Pinpoint the starting point of numerical studies **using Laser-Induced Breakdown (LIB)**
- **Testbed to benchmark simulations** in the pre-expansion phase -> extent to different conditions to benchmark various models
- **HRR experiments with relativistic laser intensity** Outlook: data set established the requirements for ion acceleration studies with ML methods
- HRR capabilities already fully used in low intensity experiments

HRR will expand our experimental toolkit under full energy

-> Preparation of a campaign at Draco TW & PW currently ongoing







1. Larger data sets:

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

2. Online optimization

- Laser/Target position → stable operation
- Tune target parameters → expansion
- Feedback to laser parameter (ML, Bayesian optimization)

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

Thank you for your attention

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Helmholtz-Zentrum Dresden-Rossendorf:

- Martin Rehwald, Stefan Assenbaum, Karl Zeil, Constantin Bernert, Ulrich Schramm, Milenko Vescovi, Maximilian Müller, Tim Ziegler, Marvin Umlandt, Josefine Metzkes-Ng, Ilja Göthel, Long Yang, Lingen Huang, Thomas Miethlinger, Thomas Kluge, Paweł Ordyna, Thomas Cowan,

TECHNISCHE UNIVERSITÄT DRESDEN

Partner von DRESDEN concept exzellenz-dresden.de

EuXFEL HED/HiBEF experimental team:

- Sebastian Göde, Daniel Loureiro, J. P. Schwinkendorf, H. Höppner, A. Laso-Garcia, V. Bouffetier, A. Pelka

European XFEL

HEDS group from SLAC:

- Maxence Gauthier, Christopher Schönwälder, Chandra Curry, Franziska Treffert, Griffin Glenn, Siegfried Glenzer

SLAC