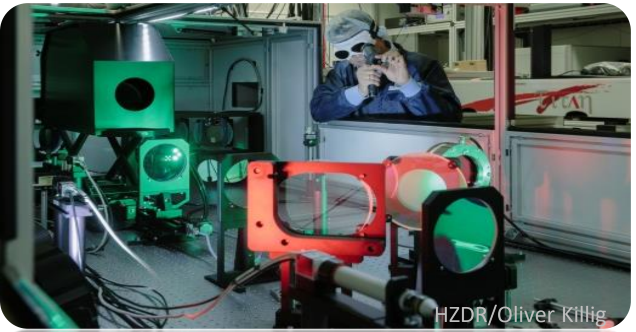
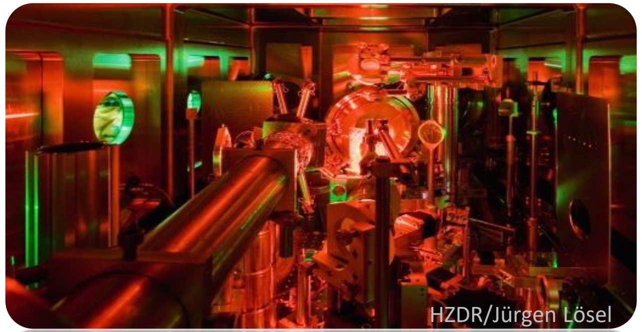
High energy proton acceleration at DRACO-PW and radiobiological applications

6th European Advanced Accelerator Concepts Workshop, La Biodola Bay, Isola d'Elba (Italy), 2023

21.09.2023





Josefine Metzkes-Ng

Young Investigator Group *Application-oriented laser-plasma accelerators*

Institute of Radiation Physics

Helmholtz-Zentrum Dresden – Rossendorf

Acknowledgements

K. Zeil & T. Kluge and teams for laser-driven ion acceleration experiment & theory

J. Metzkes-Ng and team for realization of application experiments

E. Beyreuther & J. Pawelke and team for radiobiological studies

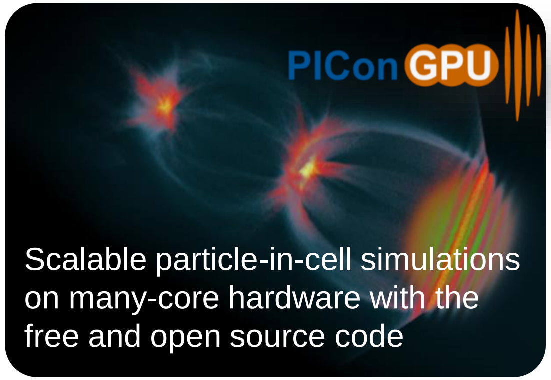
S. Assenbaum, C. Bernert, F.-E. Brack, C. Bernert, S. Bock, E. Bodenstein, K. Brüchner, M. Bussmann, A. Corvino, T. E. Cowan, M. Garten, L. Gaus, R. Gebhardt, I. Goethel, U. Helbig, L. Huang, A. Hübl, S. Kraft, M. Krause, F. Kroll, E. Lessmann, M. Löser, S. Meister, T. Miethlinger, L. Obst-Hübl, J. Pietzsch, I. Prencipe, T. Püschel, M. Reimold, M. Rehwald, C. Richter, H.-P. Schlenvoigt, M. Siebold, M. E. P. Umlandt, M. Vescovi, L. Yang, T. Ziegler, U. Schramm

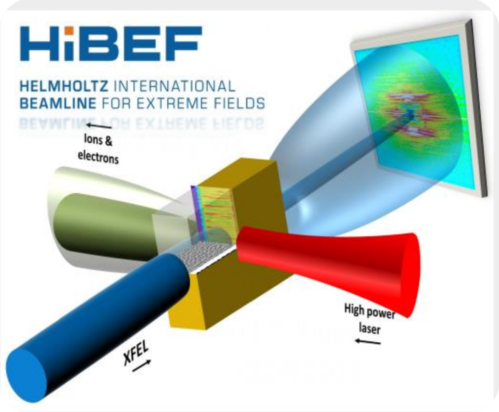
N. Dover, H. Kiriyama, A. Kon, M. Nishuichi

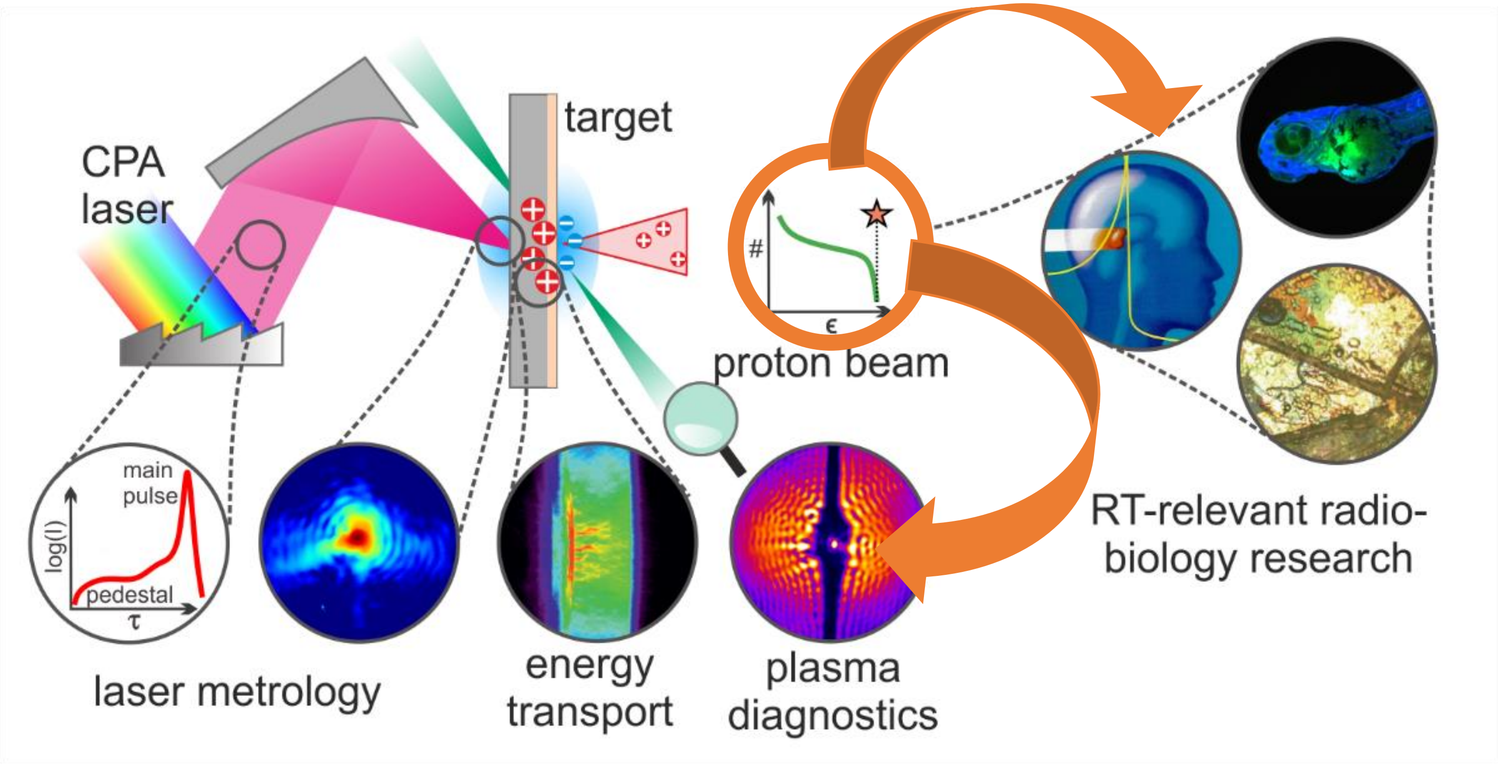
C. B. Curry, F. Fiuza, M. Gauthier, S. Göde, S. H. Glenzer, J. B. Kim, C. Schoenwaelder, F. Treffert

Motivation

High power laser solid matter interaction for plasma-based proton acceleration







1. **Achieving highest proton energies beyond TNSA**
2. **Stable laser-driven proton beams for ultra-high dose rate radiobiology**

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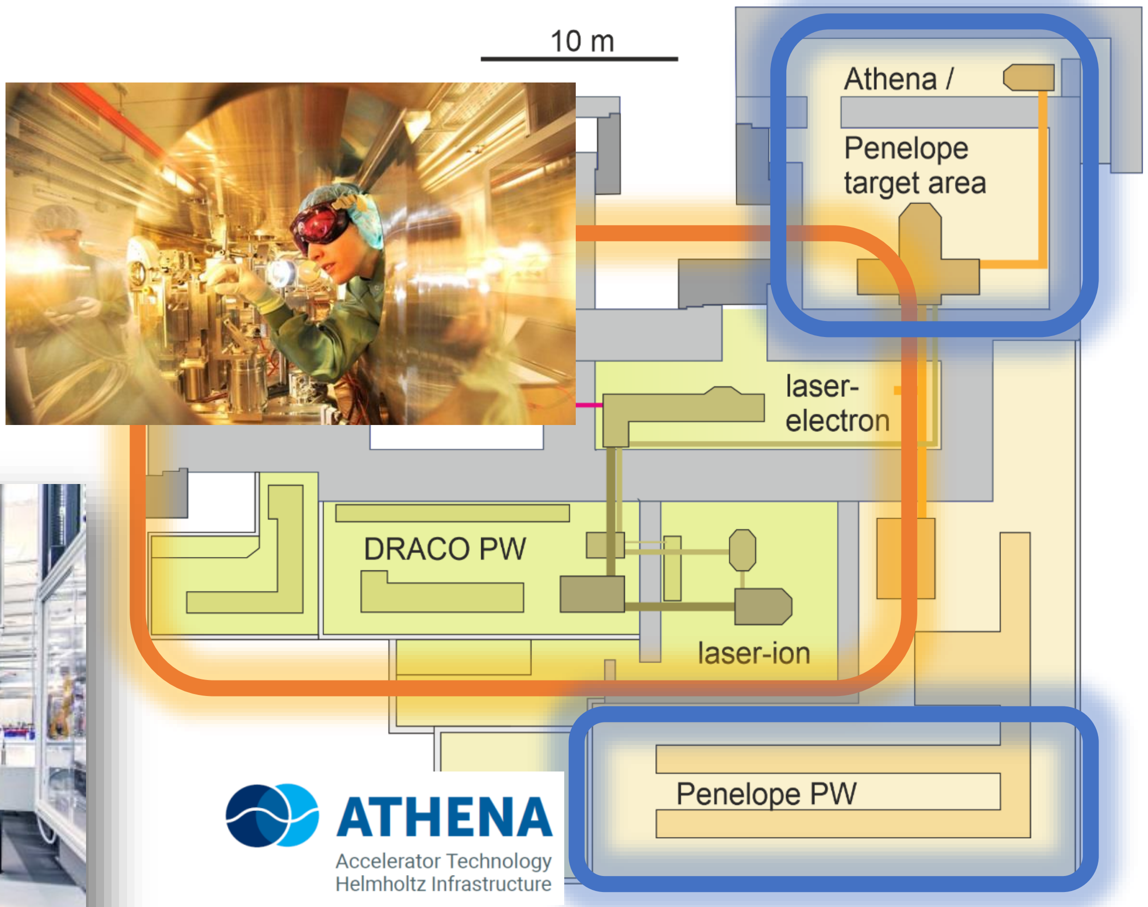
High power lasers at HZDR

Driving advanced accelerator research

Draco – accelerator research (e^-/p^+) & application

- commercial Ti:Sapphire dual-beam laser system
  - 150 TW (4 J in 30 fs routinely on target) @ 10 Hz
  - ~PW (> 20 J on target in 30 fs) @ 1 Hz



PENELOPE – prototype driver for radiobiology with protons

- diode-pumped, energy-efficient 150 J / 150 fs laser @ 1Hz
- lighthouse project for proton/ion acceleration within ATHENA

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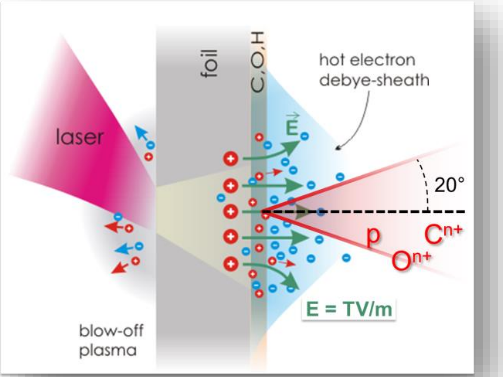
Accessing different proton acceleration schemes via target density tailoring

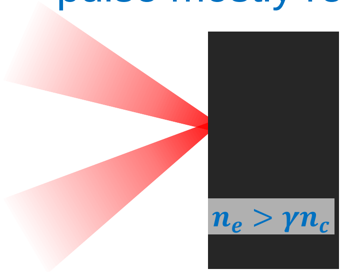
Acceleration regimes

TNSA

Snavely (2000), Clark (2000), Wilks (2001)

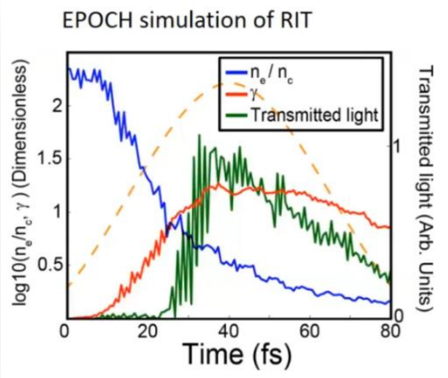


mirror-like behaviour
pulse mostly reflected

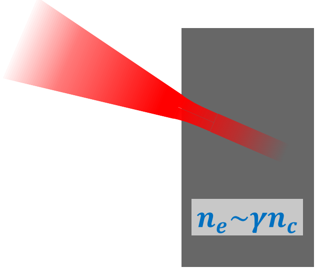


Relativistic transparency

Henig PRL (2009), Yin POP (2011), D'Humieres POP (2015), Higginson Nat. Comm. (2018), McKenna, Gonzales-Izquierdo et al. SPIE (2021) & ApplSci (2018)

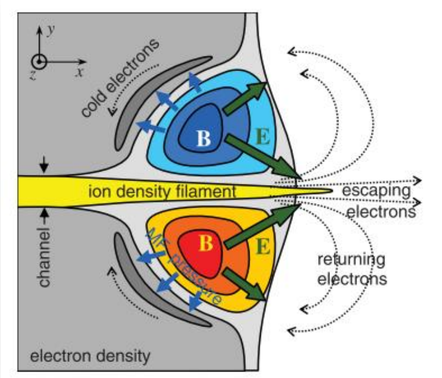


pulse mostly absorbed,
volumetric interaction

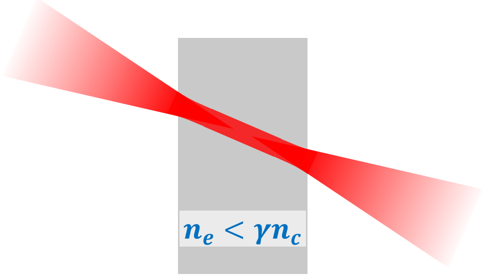


Magneto vortex acceleration

Bulanov & Esirkepov PRL (2007)



pulse mostly transmitted



typ. > 10^{23} cm^{-3}
dense, opaque target

1.7 x 10^{21} cm^{-3} = $n_{critical}$[800nm]
near-critical density

typ. < 10^{20} cm^{-3}
transparent target

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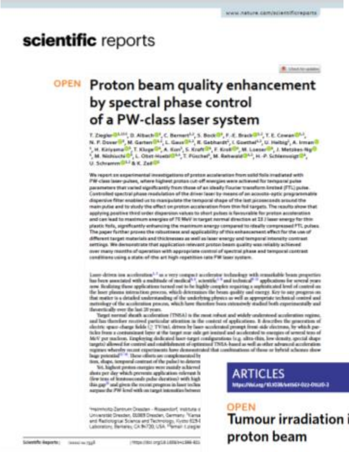
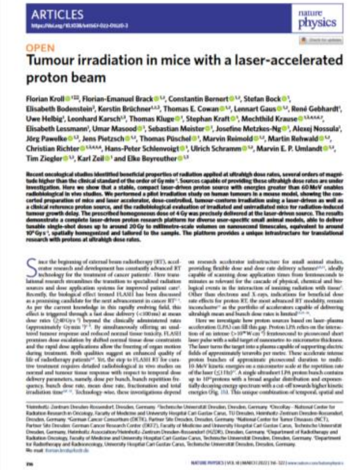
Accessing different proton acceleration schemes via target density tailoring

Experimental realization

TNSA | **Relativistic transparency** | **Magneto vortex acceleration**





Formvar foils

- stable acceleration performance up to 70 MeV
- application: *in vivo* irradiations of mice
- proton acceleration up to 150 MeV

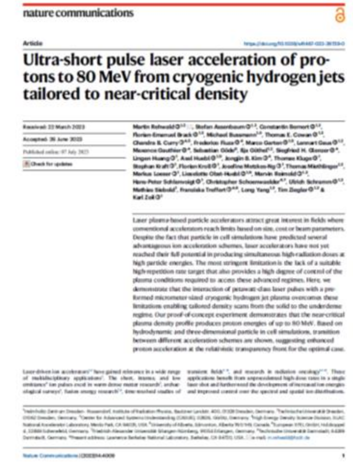
laser intensity contrast & dispersion management

T. Ziegler et al., Sci Rep 11, 7338 (2021)

F. Kroll et al., Nat Phys 18, 316 (2022)

T. Ziegler et al., under review

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



solid H_2

- proton acceleration up to 80 MeV

density tuning via single prepulses

typ. > 10^{23} cm^{-3}	1.7 x 10^{21} cm^{-3} = $n_{critical}$[800nm]	typ. < 10^{20} cm^{-3}
dense, opaque target	near-critical density	transparent target

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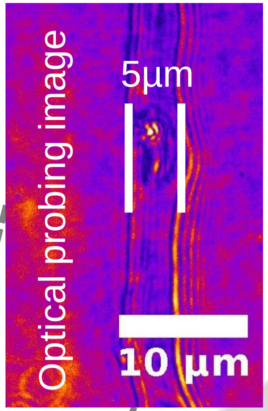
Efficient proton acceleration from a solid hydrogen target

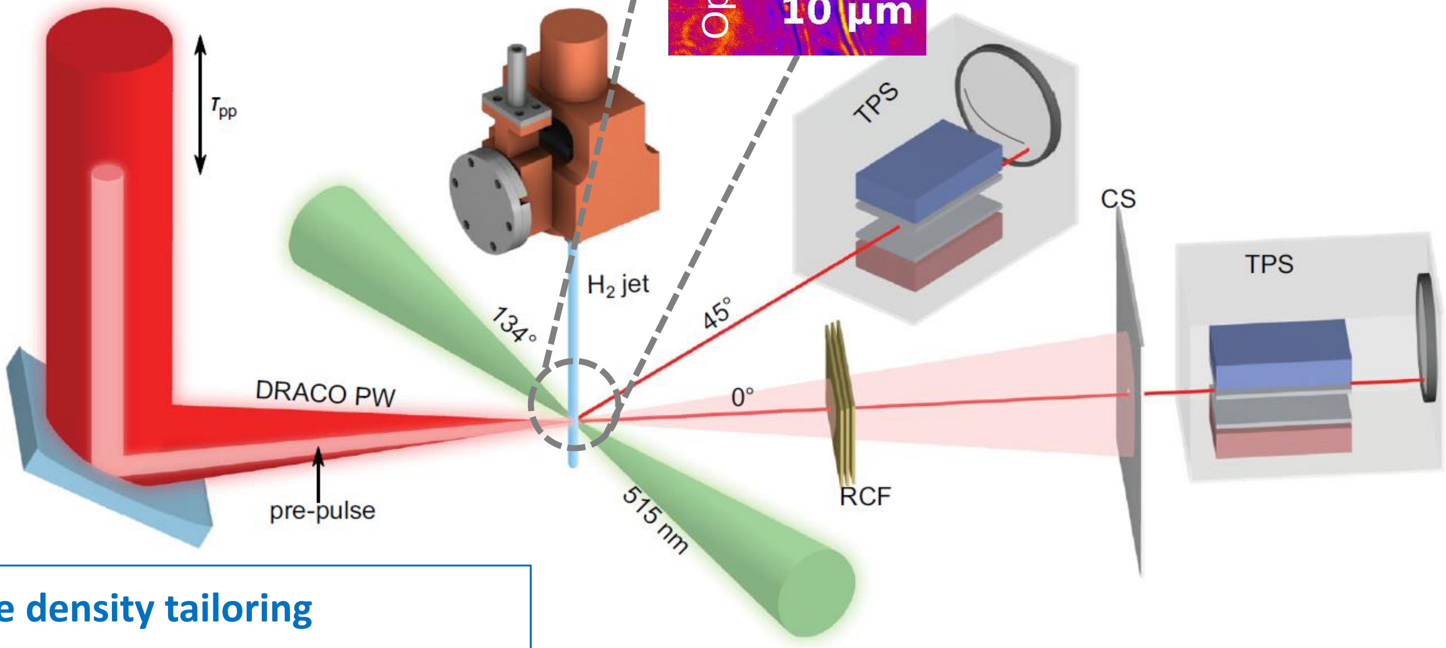
Experimental realization

DRACO PW

- 18 J, 30 fs, 800 nm, ~2.6 µm focus
  → I ~ 5.4 x 10^{21} W/cm^2
- enhanced laser contrast (PM cleaned)



- pure proton source → application & modeling
- 30 n_c @ 800 nm (5x10^{22} e-/cm³)
- high repetition rate capability w/o debris
- free-standing geometry → diagnostic access
- flexible geometry and gas mixture



M. Rehwald et al., Nat Com 14, 4009 (2023)
J. B. Kim et al., RSI 87, 11E292 (2016)
C. B. Curry et al., J Vis Exp 159, e61130 (2020)
T. Ziegler et al., PPCF 60 074003 (2018)
M. Löser et al., Opt Exp 29, 9119 (2021)
C. Bernert et al., Sci Rep 12, 7287 (2022)

Prepulse density tailoring

- 55 fs, 800 nm, ~30 x 19 µm² focus
  → I ~ 6 x 10^{17} W/cm^2
- variable delay

- off-harmonic (515/1030 nm) optical probing w 160 fs probe pulse

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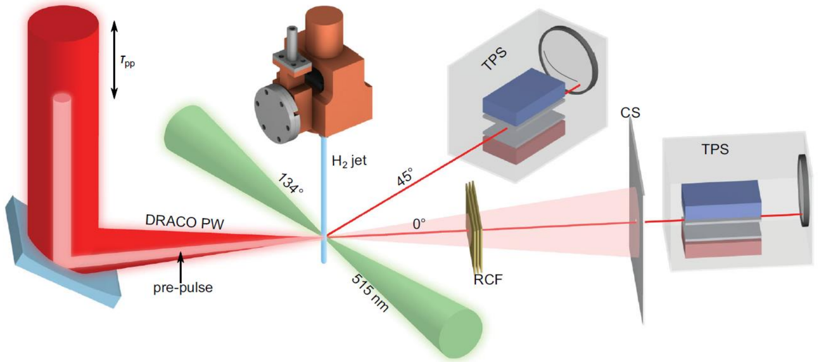
Efficient proton acceleration from a solid hydrogen target

Results – optimum acceleration regime



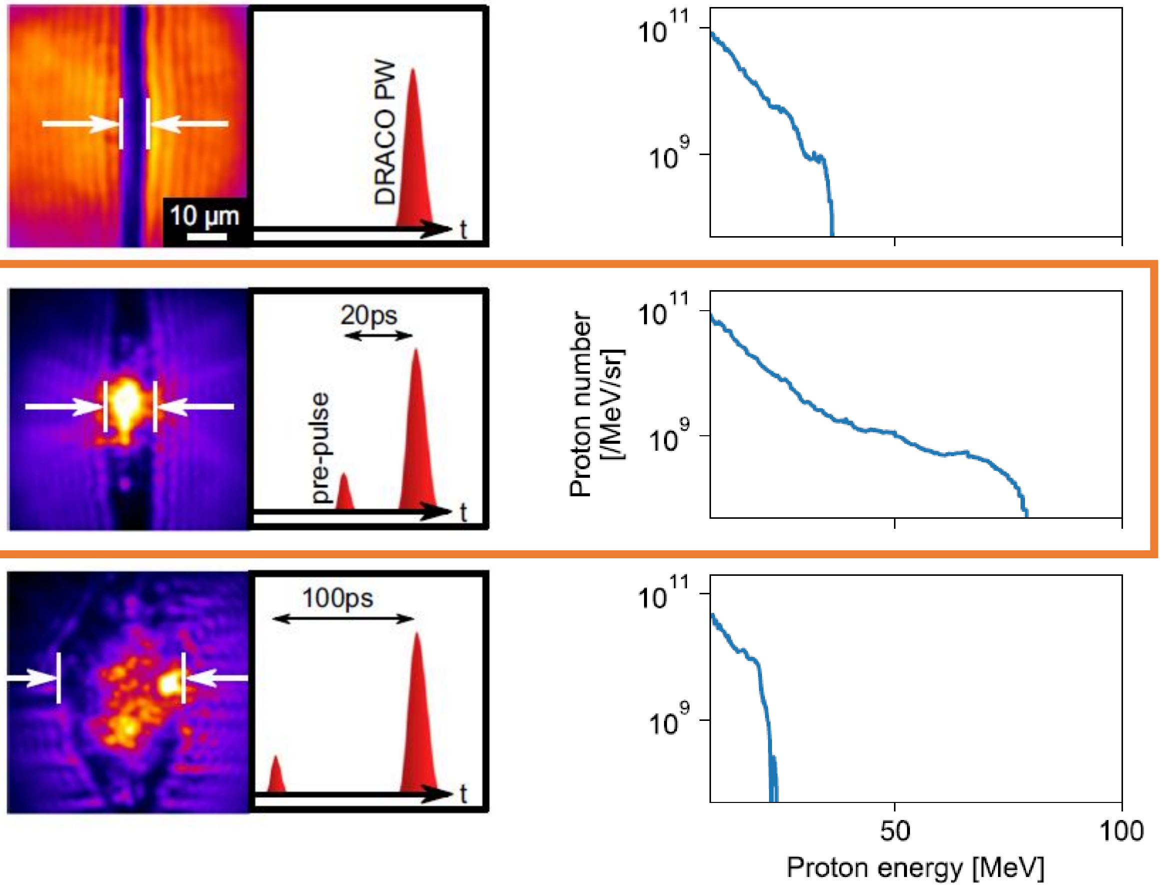
prepulse-only geometry characterization | prepulse + DRACO PW

Shadow diameter | Shadowgraphy images | Proton spectra

5 µm

11 µm

28 µm



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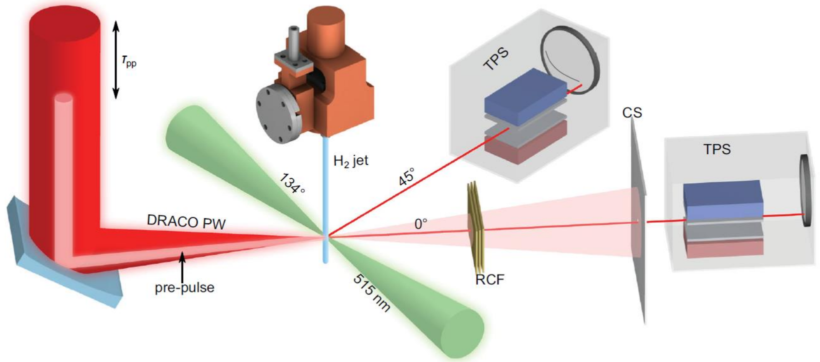
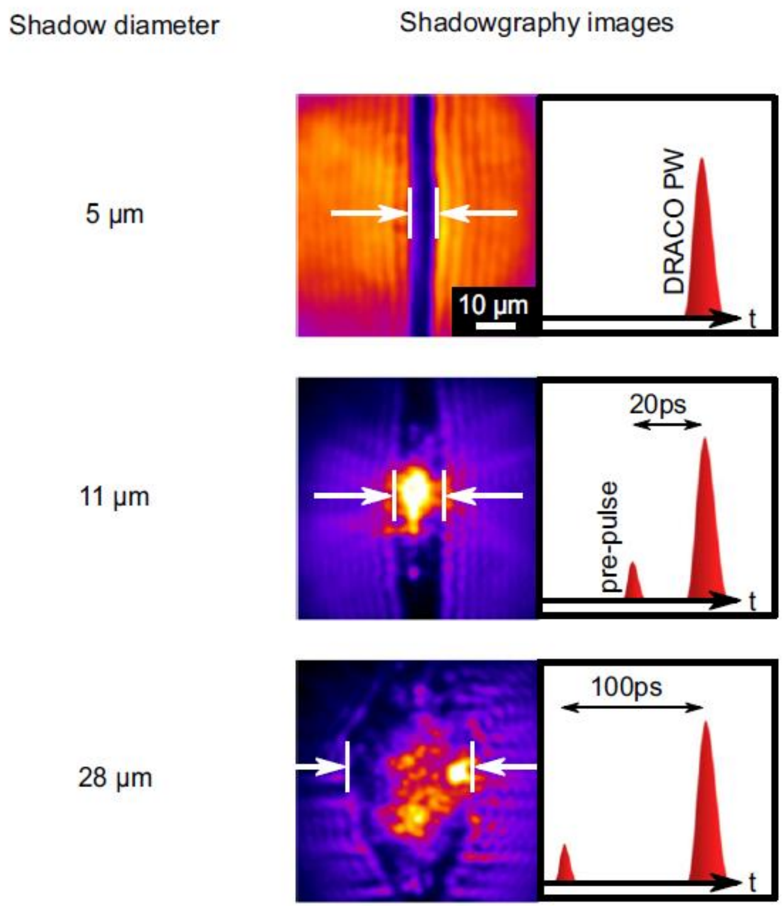
Efficient proton acceleration from a solid hydrogen target

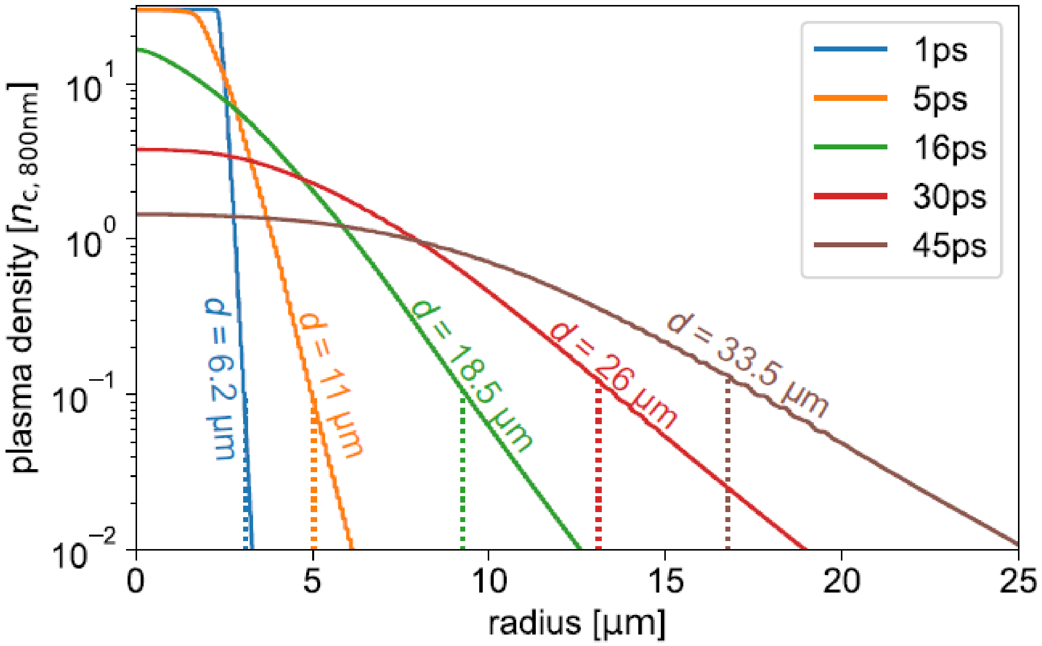
Results – target density & shape characterization



prepulse-only geometry characterization



optical raytracing
hydrodynamic expansion modeling



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

C. Bernert et al., Sci Rep 12, 7287 (2022)

L. Yang et al., under review

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Efficient proton acceleration from a solid hydrogen target

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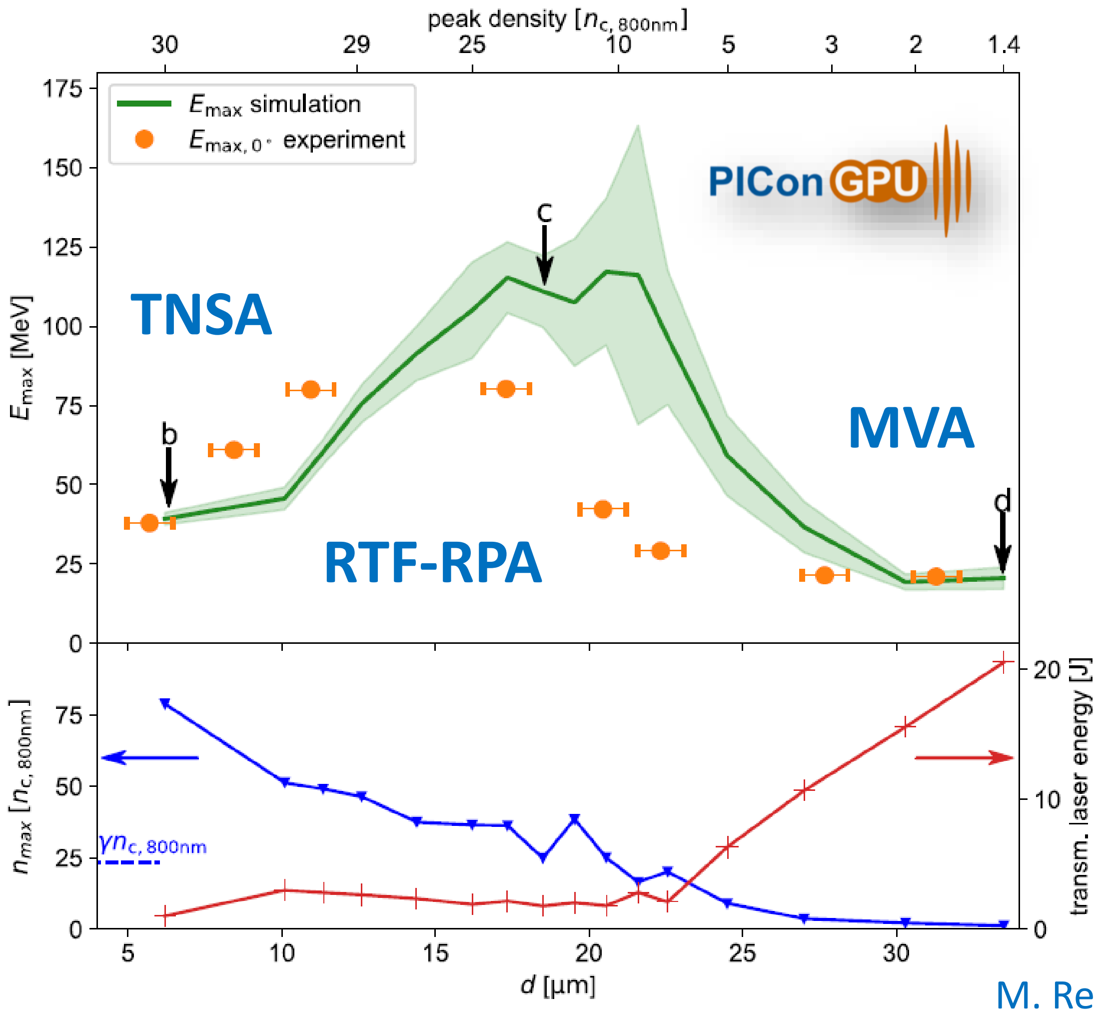

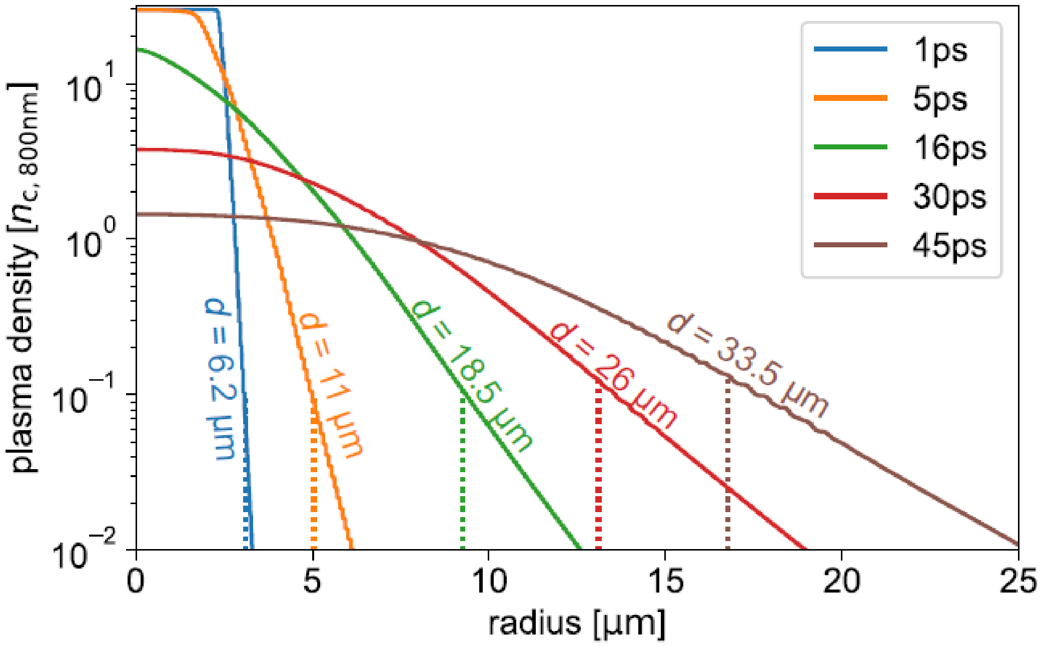

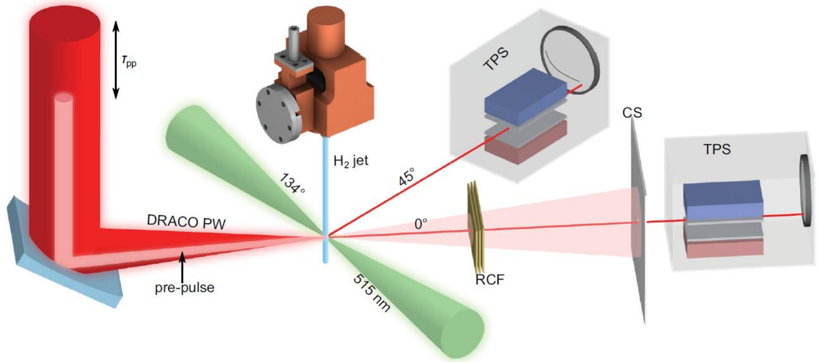

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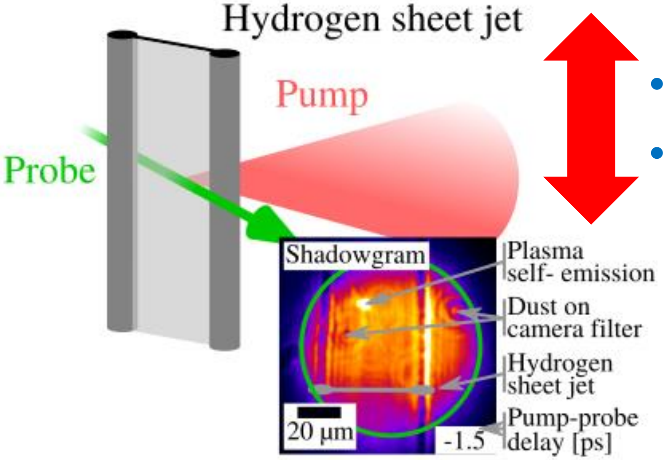
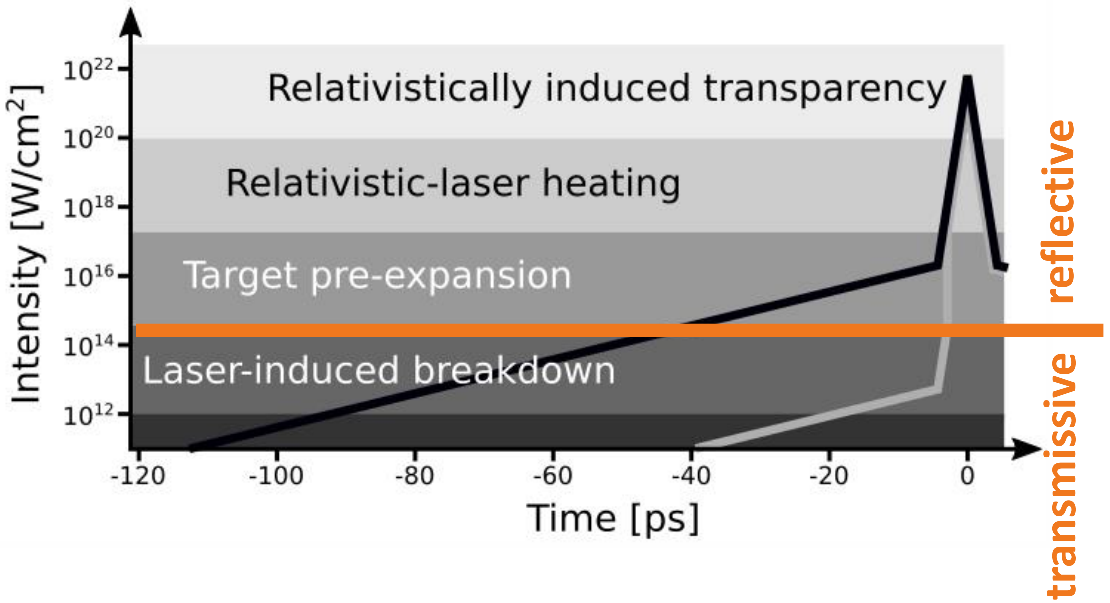
Investigating ionization dynamics with a solid hydrogen target

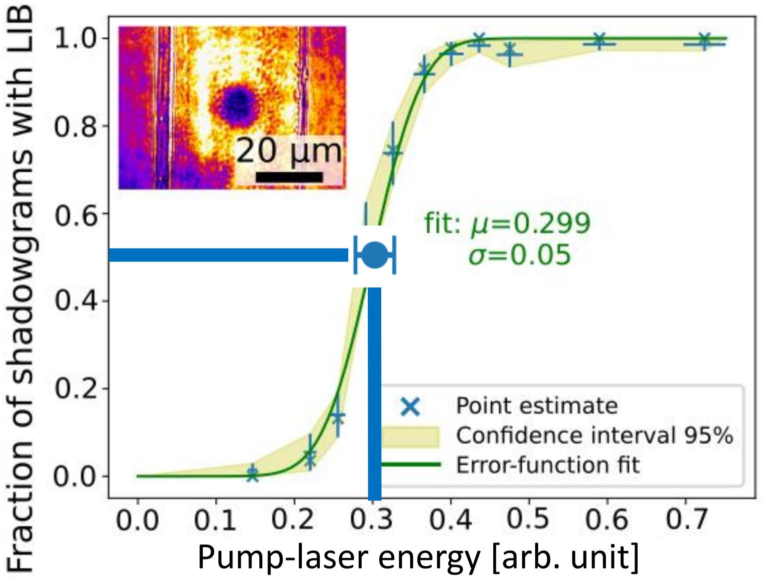
Laser-induced breakdown of cryogenic hydrogen

- **modeling requires input on onset of plasma evolution**
- temporal evolution of laser intensity on targets
  - determines target pre-expansion (density profile)
  - **governs acceleration regime & performance**



- pump laser energy
- pulse duration





C. Bernert et al., Phys Rev Appl 19, 014070 (2023)

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Investigation ionizating dynamics with a solid hydrogen target

Laser-induced breakdown of cryogenic hydrogen

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- temporal evolution of laser intensity on targets
  - determines target pre-expansion (density profile)
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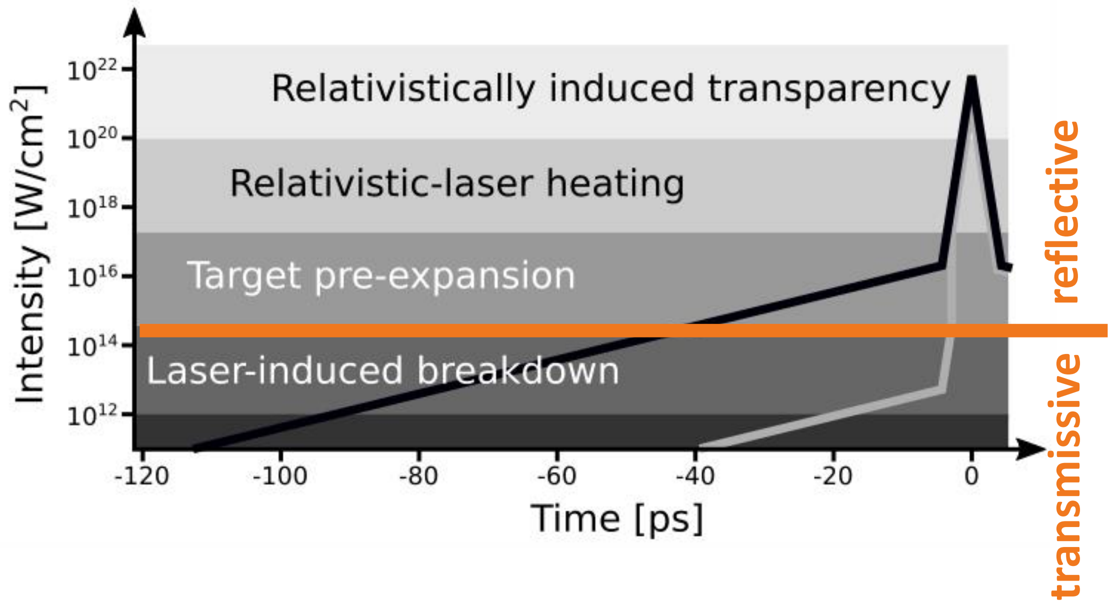

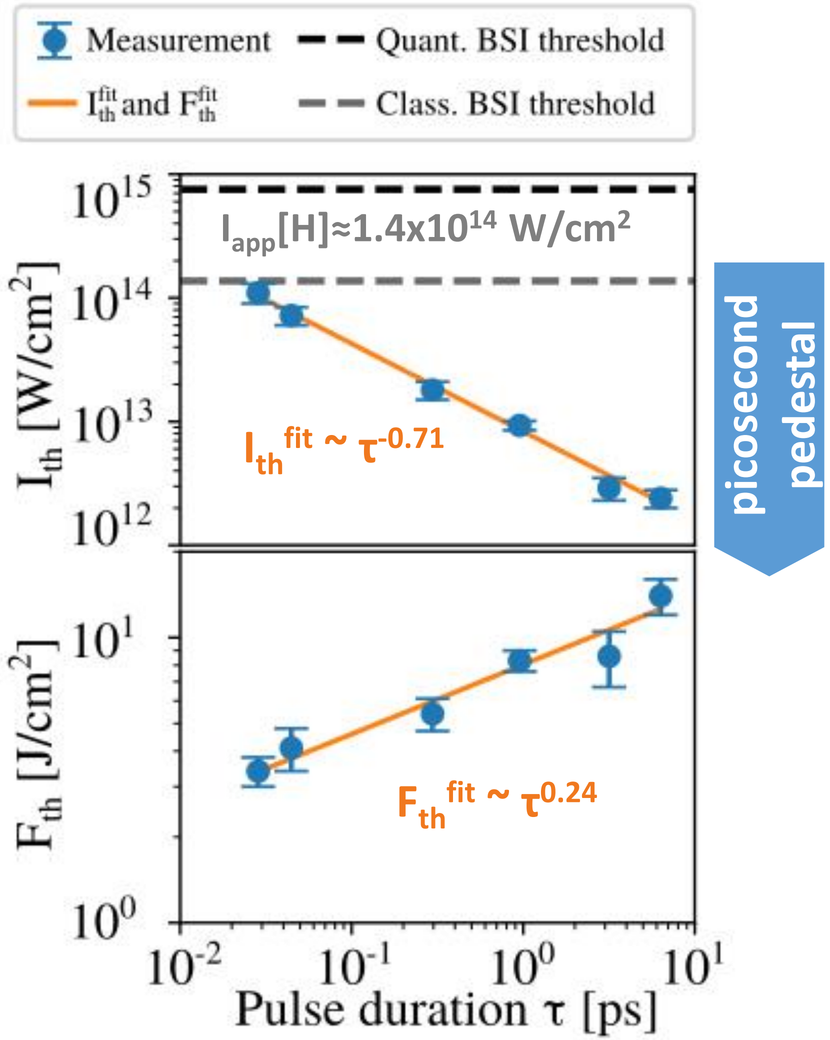

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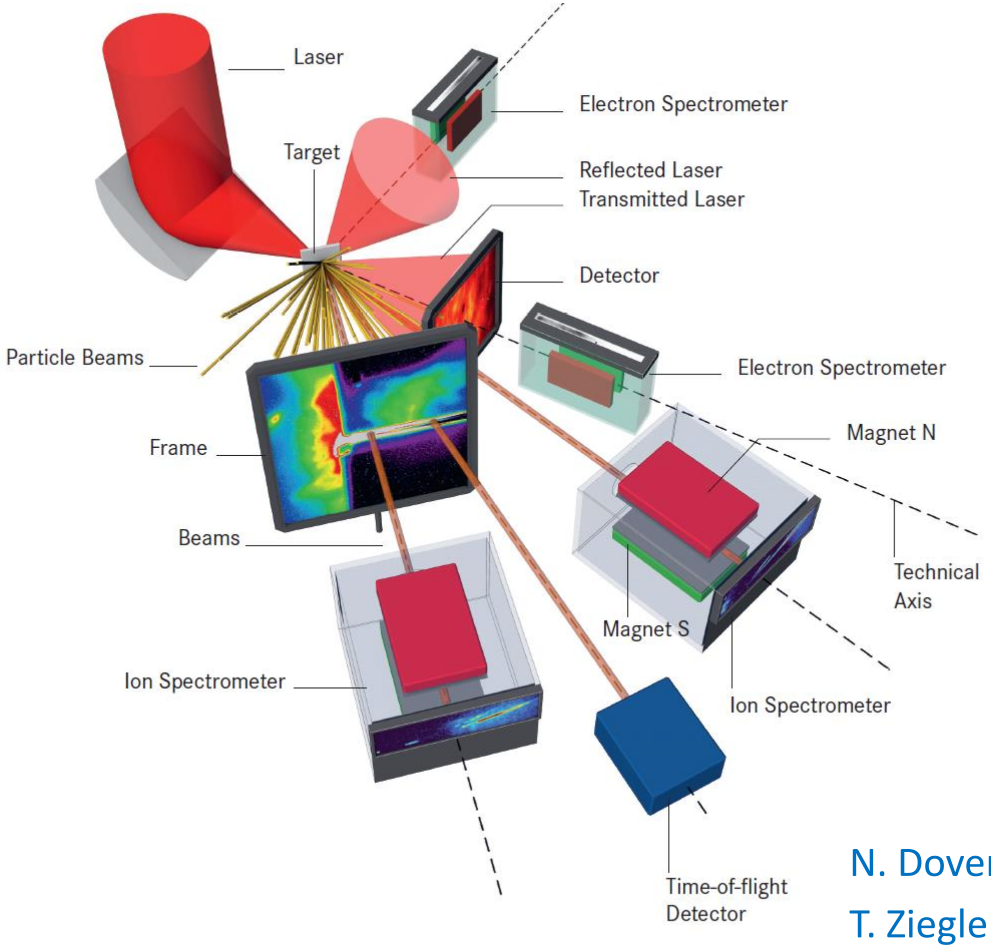
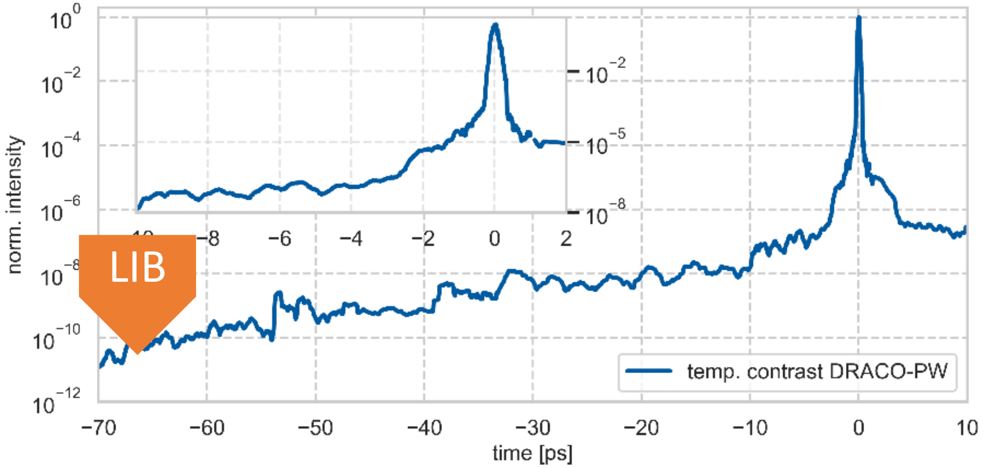
Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental realization

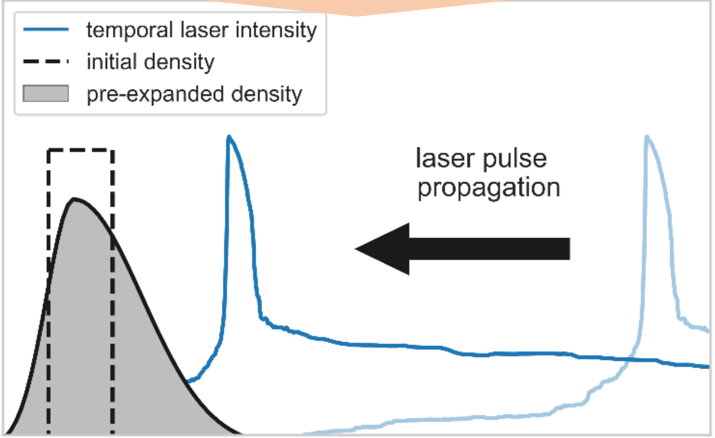
DRACO PW

- 22.4 J, 30 fs, ~2.3 µm focus
  → I ~ 6.5 x 10^{21} W/cm^2





hydrodynamic expansion modeling
FLASH



N. Dover et al., Light Sci Appl 12, 71 (2023)
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Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental results

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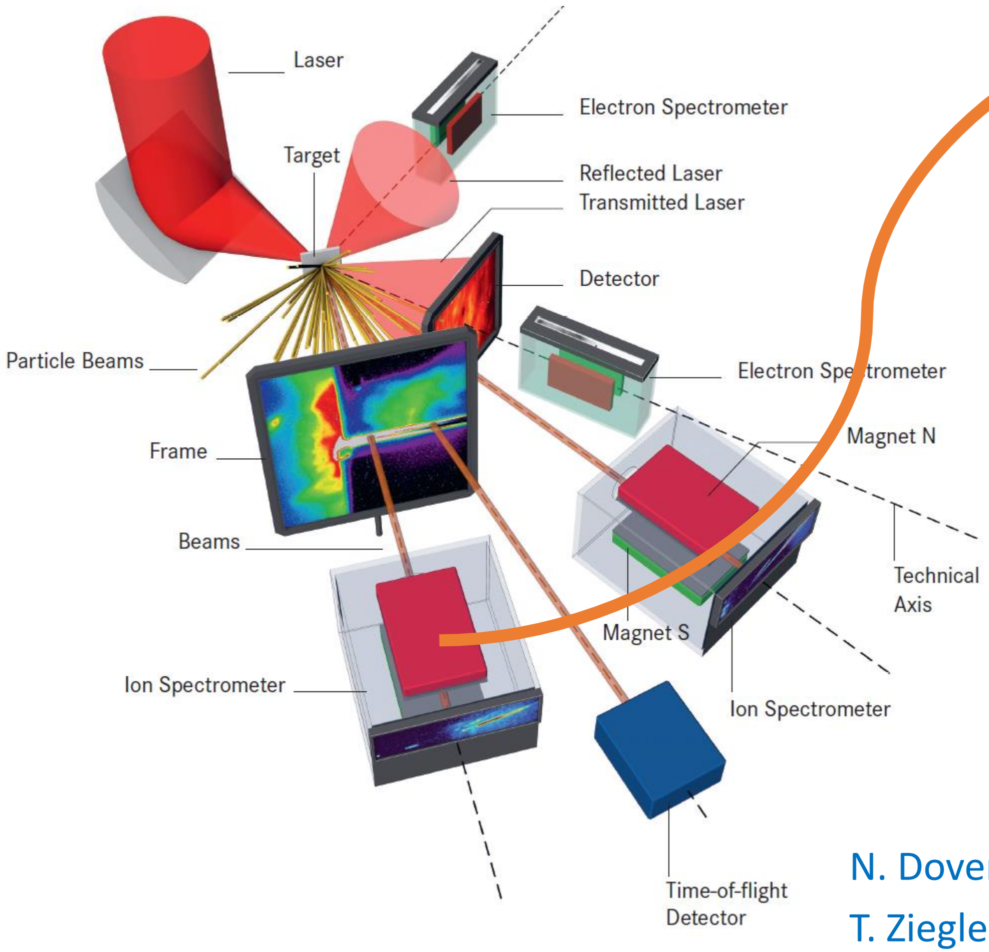

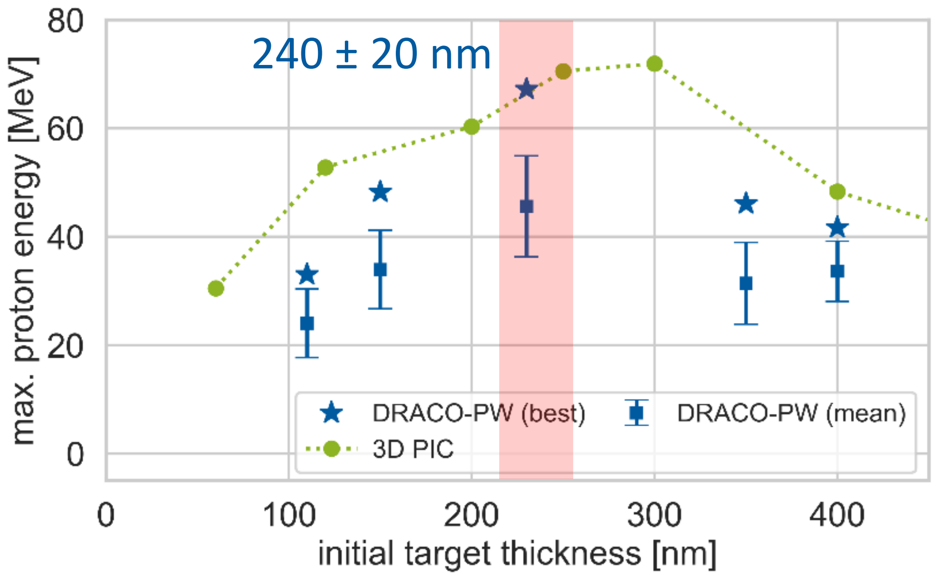

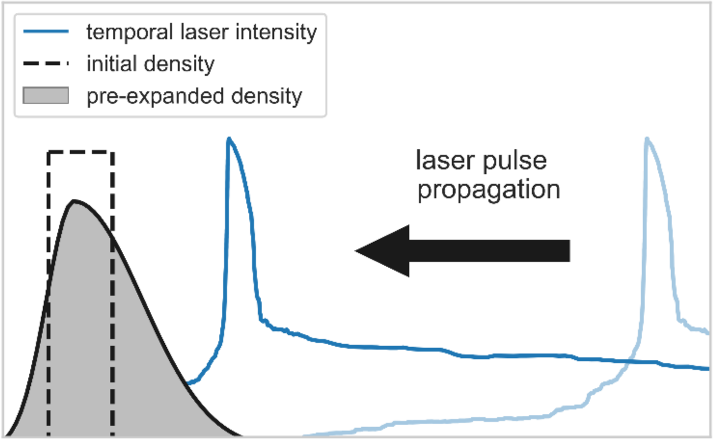

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Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental results

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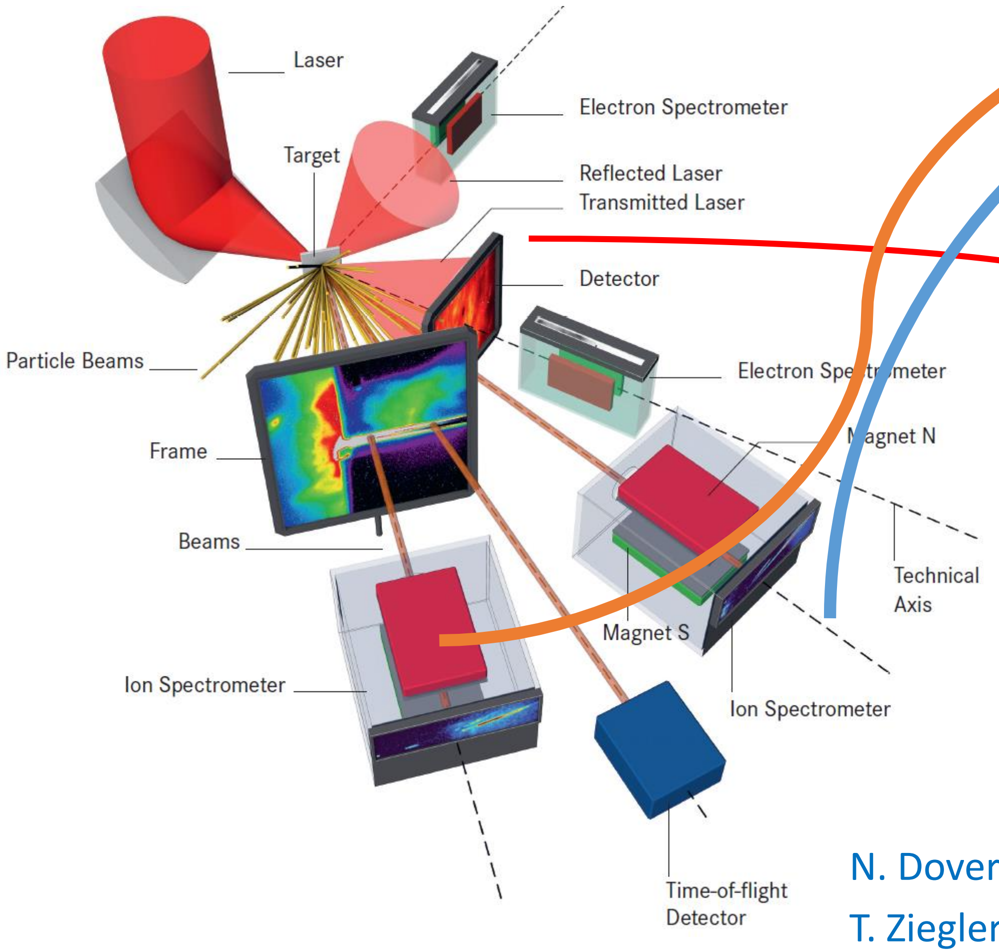

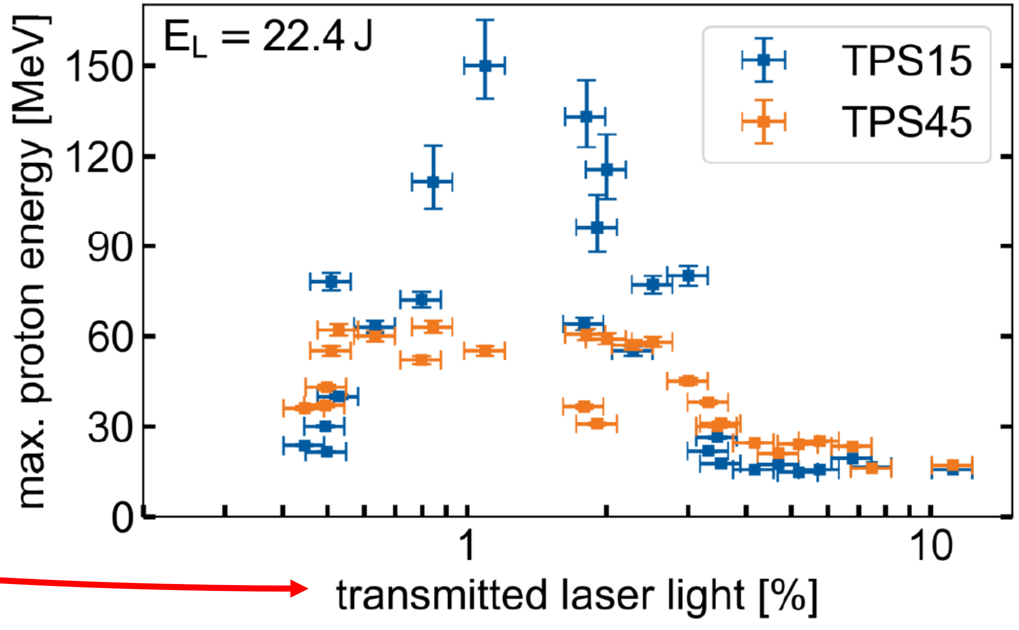

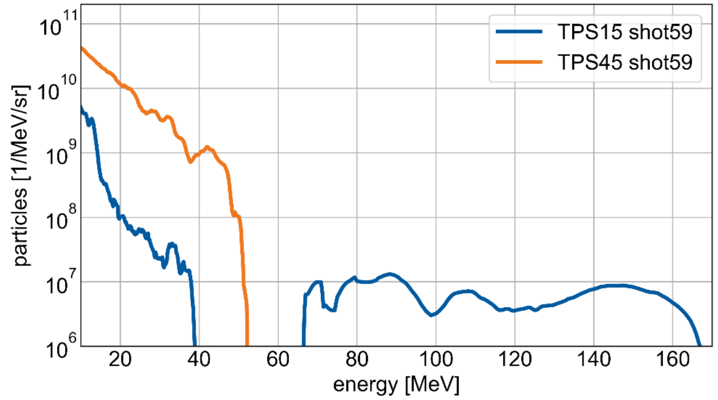

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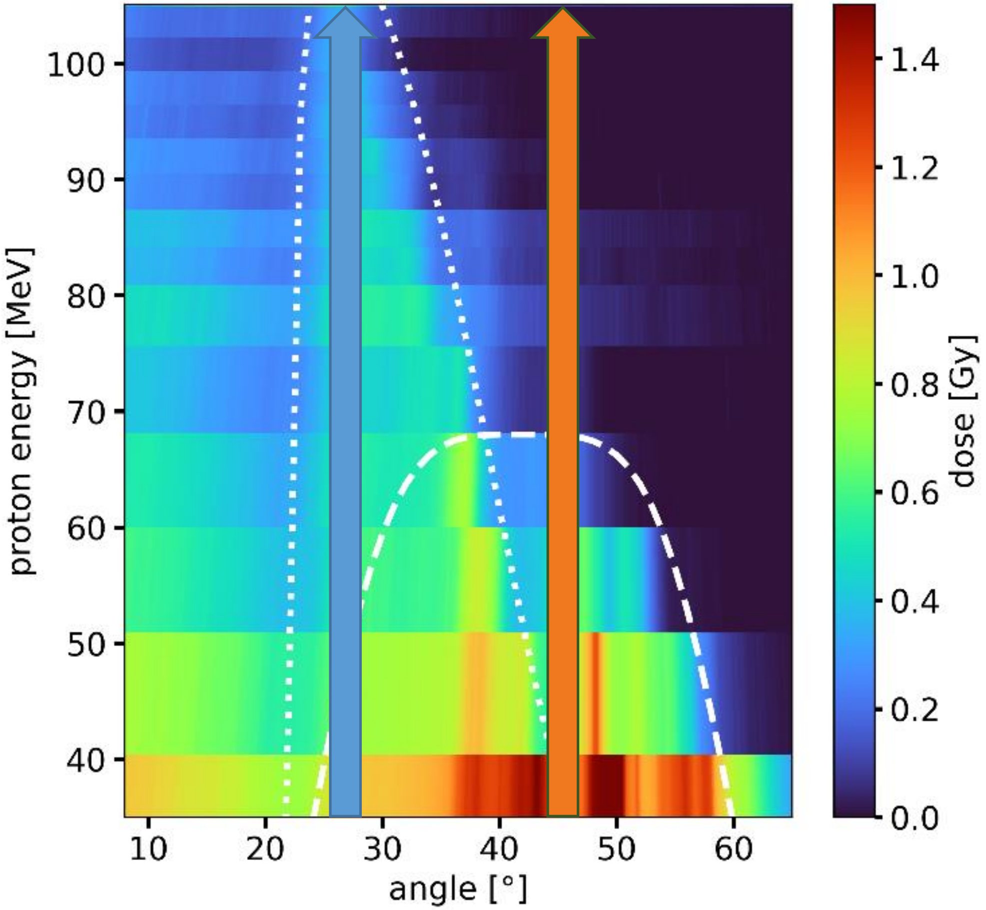
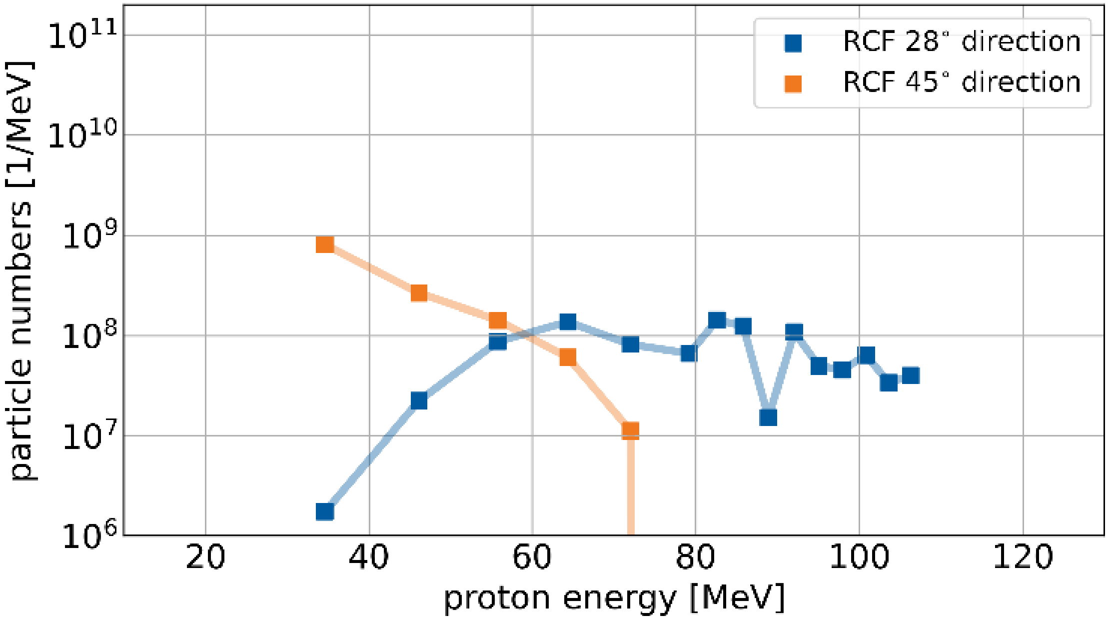
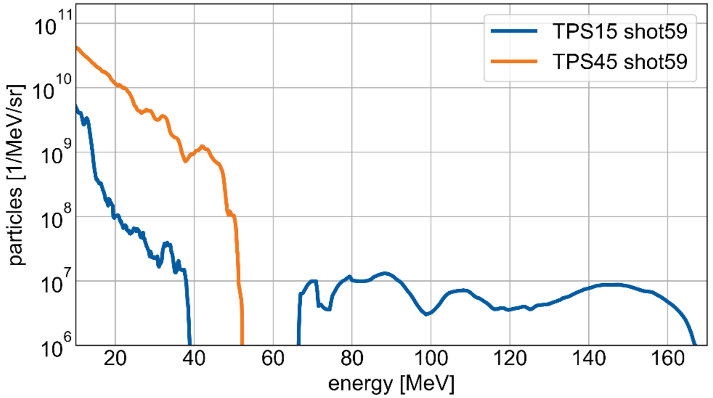
Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental results







- **bi-modal feature (low + high energy component)**
- **high-energy feature with reduced divergence**

T. Ziegler et al., under review

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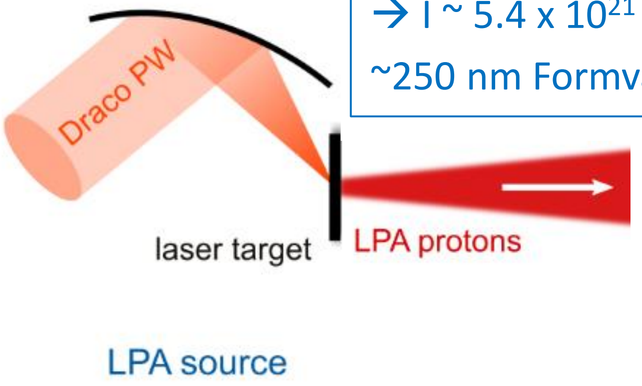
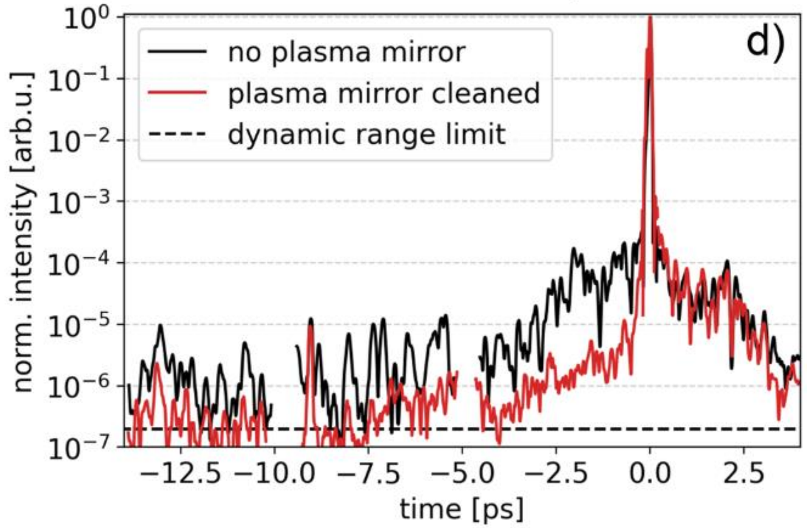
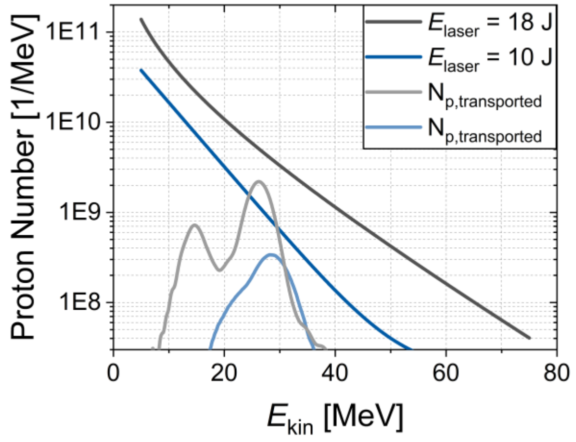
Stable proton beam generation with ultra-high intensity contrast

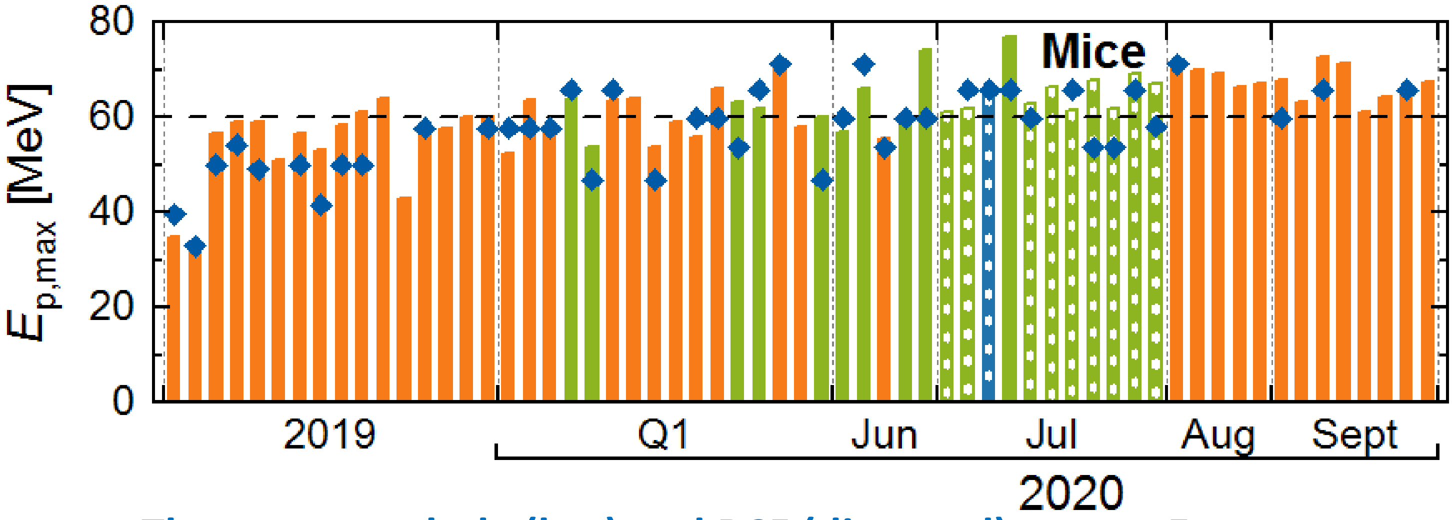
Experimental realization

18 J, 30 fs, ~2.3 µm focus
→ I ~ 5.4 x 10^{21} W/cm^2
~250 nm Formvar foils









F. Kroll et al., Nat Phys 18, 316 (2022)
T. Ziegler et al., Sci Rep 11, 7338 (2021)

- **Thomson parabola (bar) and RCF (diamond) proton E_{max}**
- **longterm stable operation > 60 MeV**

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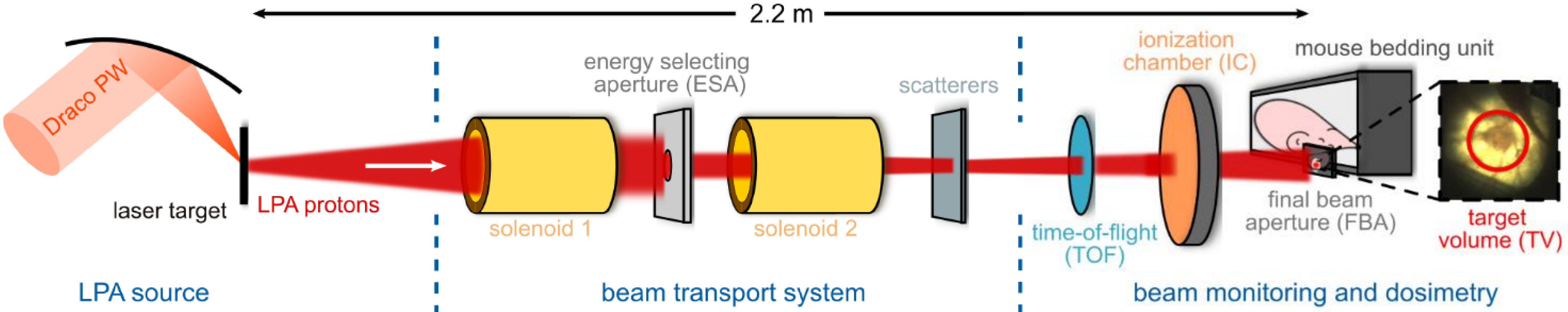
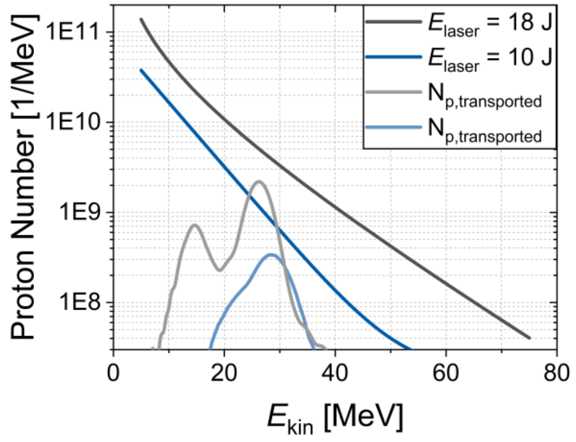
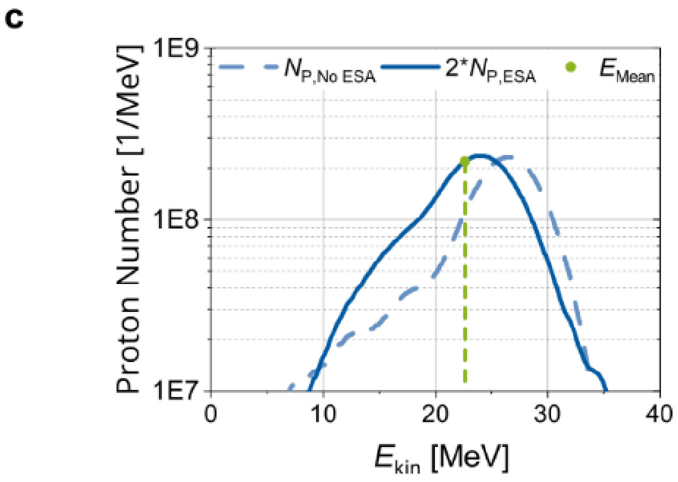
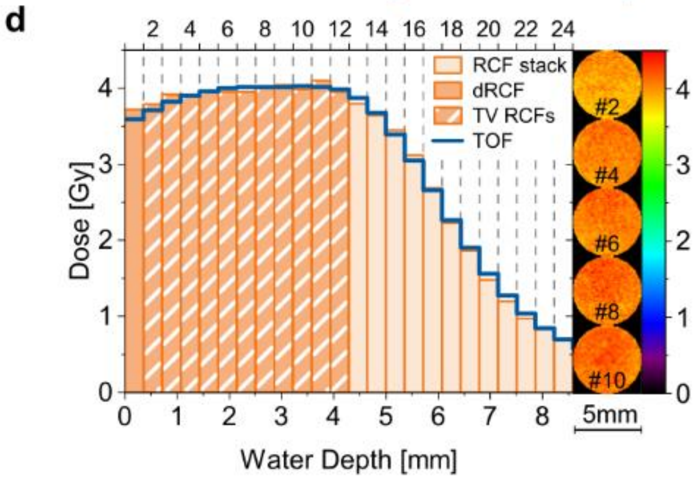
Ultra-high dose rate radiobiology at DRACO PW

ALBUS-2S beamline









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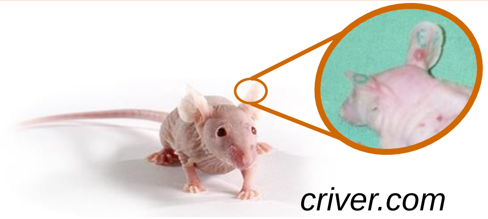
Worldwide-first pilot *in vivo* studies with LPA protons



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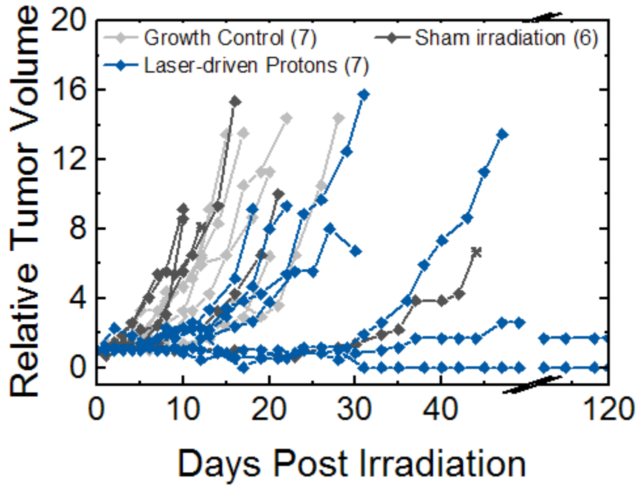
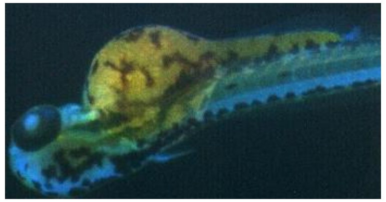
- **mouse model** (3D *in-vivo* tumour tissue)
- **pulse accumulation for precise dose delivery**
- endpoint: tumour-growth delay
- 4 Gy dose, < 10% precise total dose delivery

K. Brüchner et al., Radiat. Onc., Vol. 9 (2014)
M. Oppelt et al., Radiat Environ Biophys (2015)
Animal study approval DD24-5131/338/35

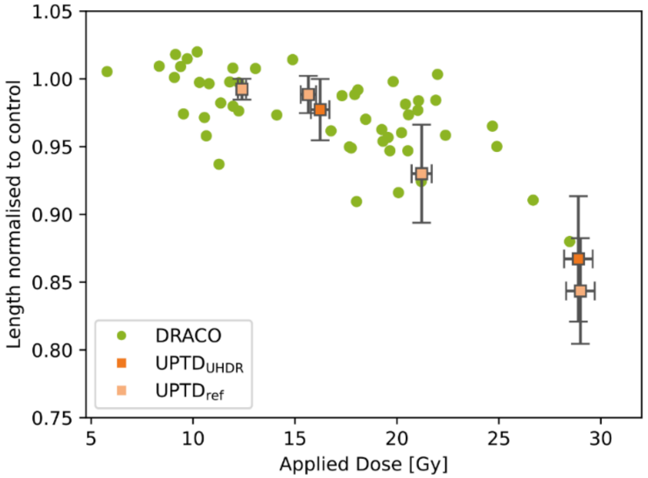


F. Kroll et al., Nat Phys 18, 316 (2022)



- **zebrafish embryo** (normal tissue, FLASH)
- **single-shot ultra-high dose rate delivery**
- endpoint: morphological changes, etc.
- dose escalation > 10 Gy

J. Pawelke et al., Radiotherapy and Oncology 158 (2021), 7-12
E. Beyreuther et al., Radiotherapy and Oncology 139 (2019), 46-50
E. R. Szabo et al., PLOS ONE 13 (2018)11, e0206879



J. Metzkes-Ng et al., under review

Accelerator readiness:

LPA capabilities for radiobiological applications confirmed

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Summary

Proton acceleration from cryogenic solid hydrogen

80 MeV proton acceleration
M. Rehwald et al., Nat Com 14, 4009 (2023)
I. Göthel et. al., PPCF 64, 044010 (2022)

Off-harmonic optical probing
T. Ziegler et al., PPCF 60 074003 (2018)
M. Löser et al., Opt Exp 29, 9119 (2021)
C. Bernert et al., Sci Rep 12, 7287 (2022)

Laser-induced breakdown
C. Bernert et al., Phys Rev Appl 19, 014070 (2023)

Proton acceleration from thin plastic foils

Proton acceleration in the transparency regime
N. Dover et al., Light Sci Appl 12, 71 (2023)

Highest proton acceleration in a cascaded acceleration regime
T. Ziegler et al., under review

Stable efficient proton acceleration for applications
T. Ziegler et al., Sci Rep 11, 7338 (2021)

Radiobiological studies with LPA protons

Radiobiological in vivo studies with LPA protons
F. Kroll et al., Nat Phys 18, 316 (2022)
J. Metzkes-Ng et al., under review

Source-to-sample proton bunch characterization for applications
M. Reimold et al., Sci Rep 12, 21488 (2022)
M. Reimold et al., Phys Med Biol 68 185009, (2023)
M. Reimold et al., HPLSE (accepted) (OCTOPOD)
A. Corvino et al., under review (miniSCIDOM)

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