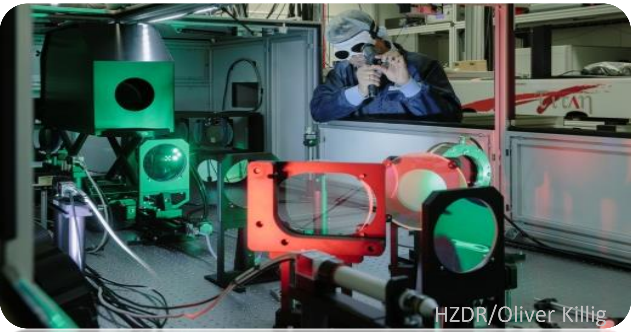
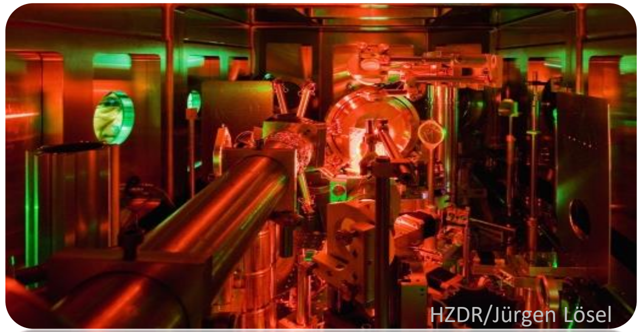
Laser Driven Proton Accelerators and Application

Towards High-Repetition Rate Petawatt Laser Experiments With Cryogenic Jets Using a Mechanical Chopper System





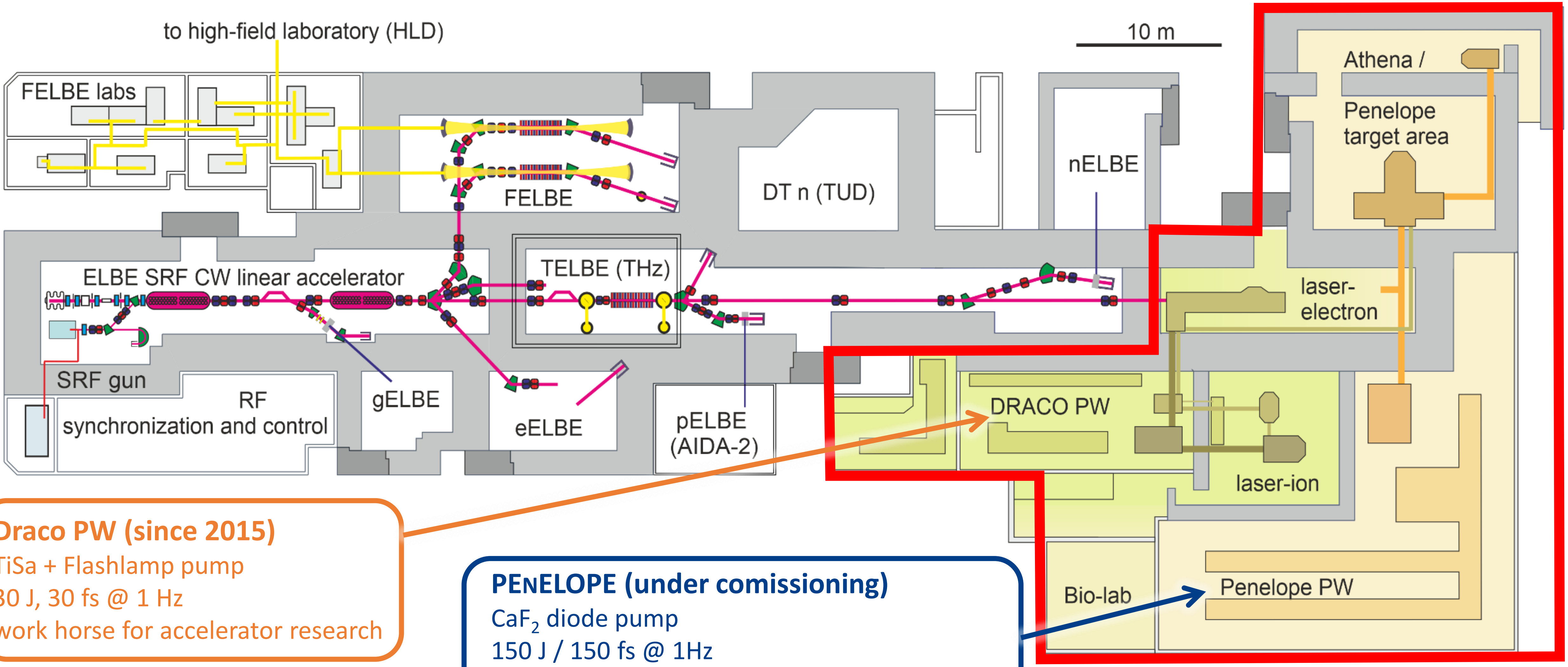
Karl Zeil
Helmholtz-Zentrum Dresden-Rossendorf

13th International Particle Accelerator Conference (IPAC'22)
June 15, 2022

Advanced accelerator research embedded in independent national programs (Helmholtz Association)

Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

ELBE Center for high power radiation sources - a user facility and advanced accelerator R&D



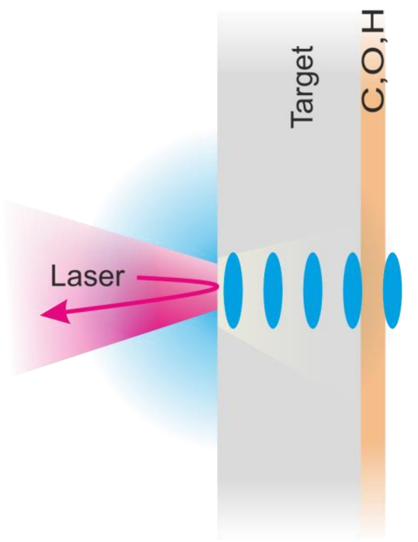
Draco PW (since 2015)
TiSa + Flashlamp pump
30 J, 30 fs @ 1 Hz
work horse for accelerator research

PENELOPE (under comissioning)
CaF_2 diode pump
150 J / 150 fs @ 1Hz
prototype driver for radiobiology with protons

Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Laser-driven ion acceleration recap – Target normal sheath acceleration (TNSA)

Plasma generation & electron acceleration

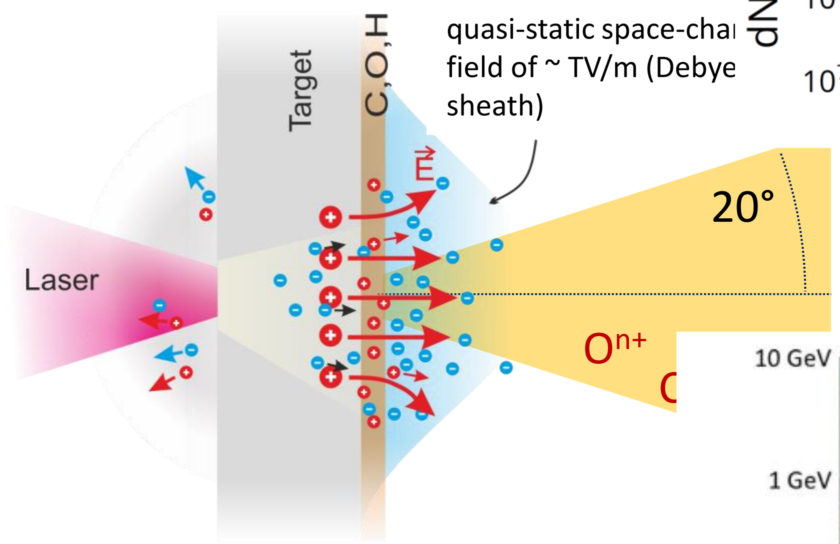


- hot electrons

$$T_h\,(I_L) \sim \mathbf{MeV}$$

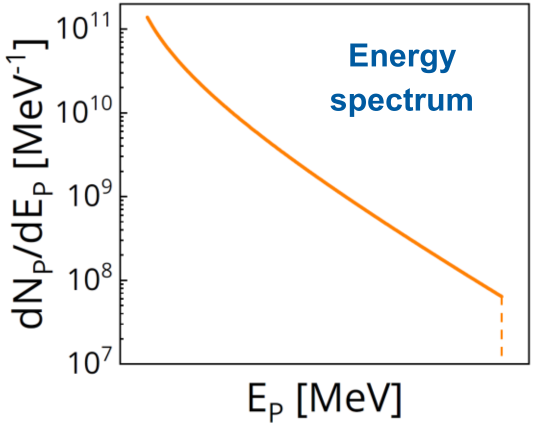
$$n_h \sim 10^{22}\,cm^{-3}$$

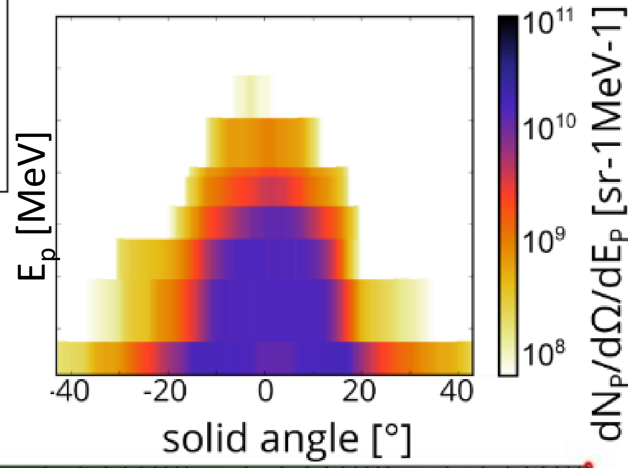
Electron transport & field generation for ion acceleration

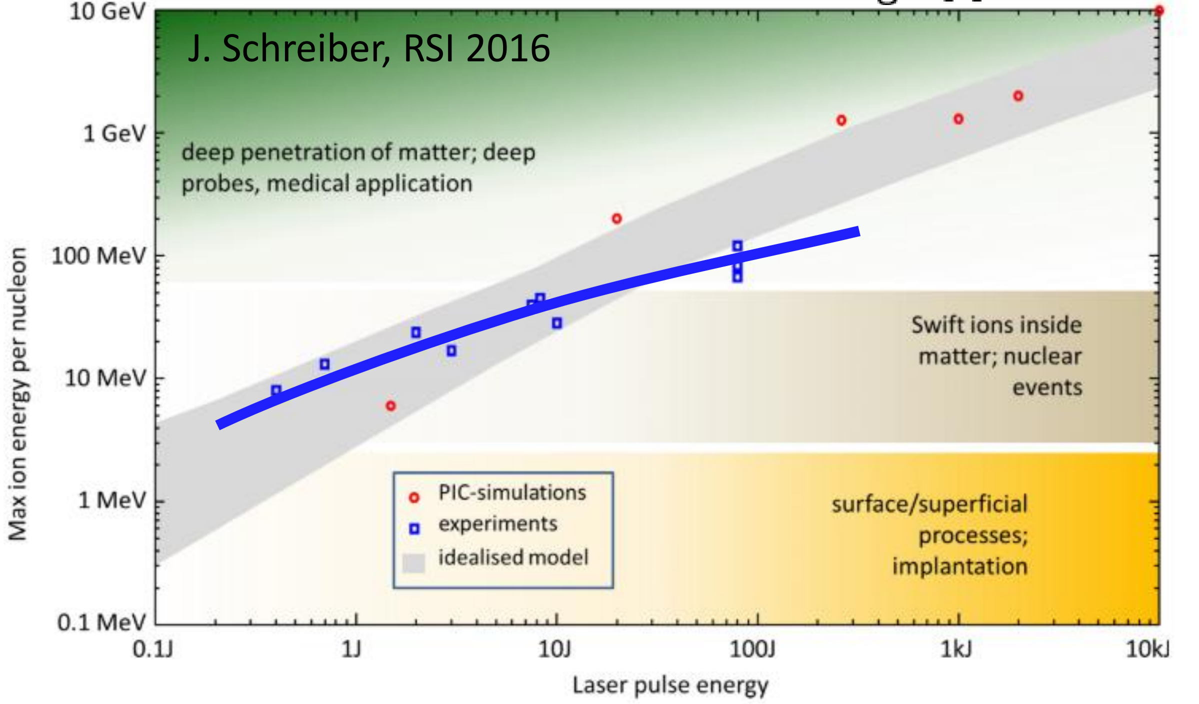


- Electric fields

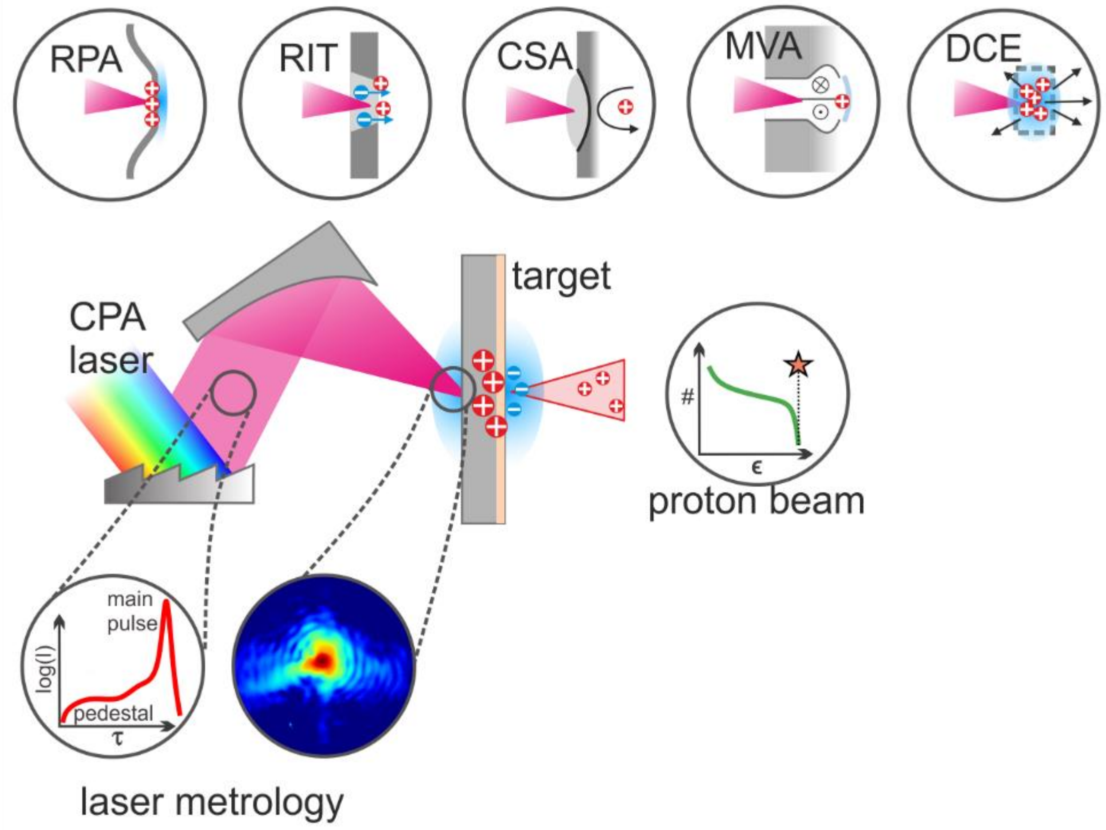
$$E \propto \frac{T_h}{\lambda_D} \propto \frac{T_h}{\sqrt{\frac{\varepsilon_0 \cdot T_h}{e^2 \cdot n_h}}} \sim \frac{TV}{m}$$





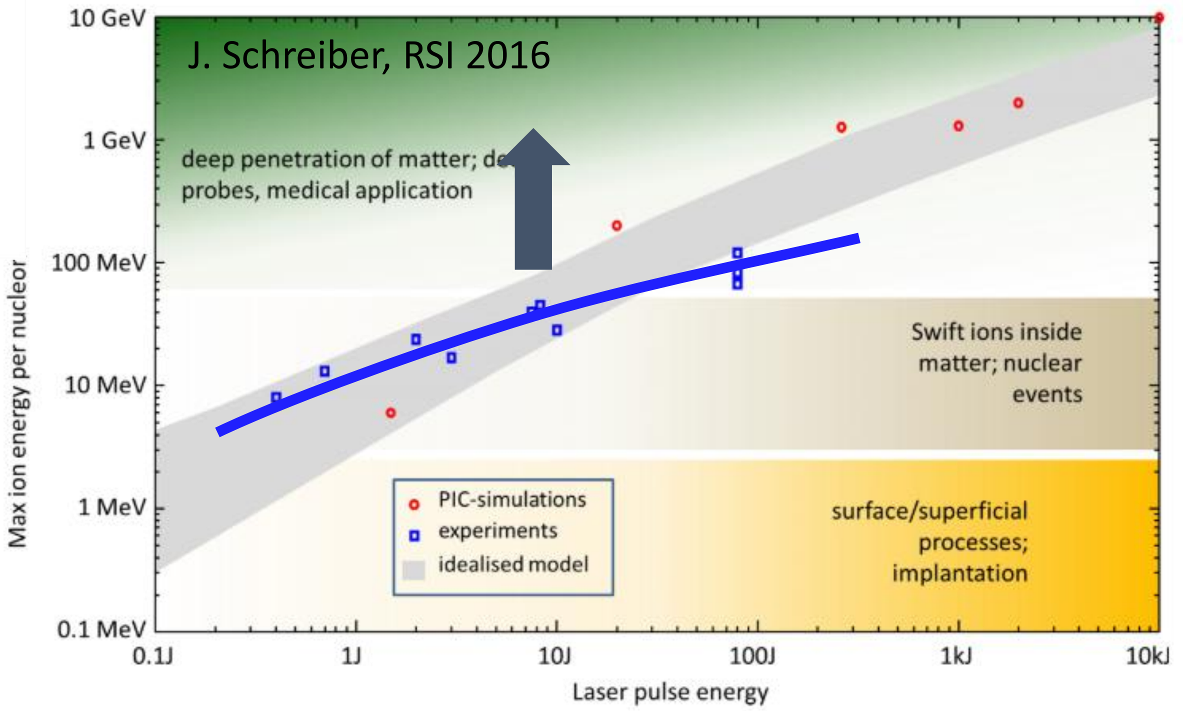


Laser-driven proton acceleration – Overview

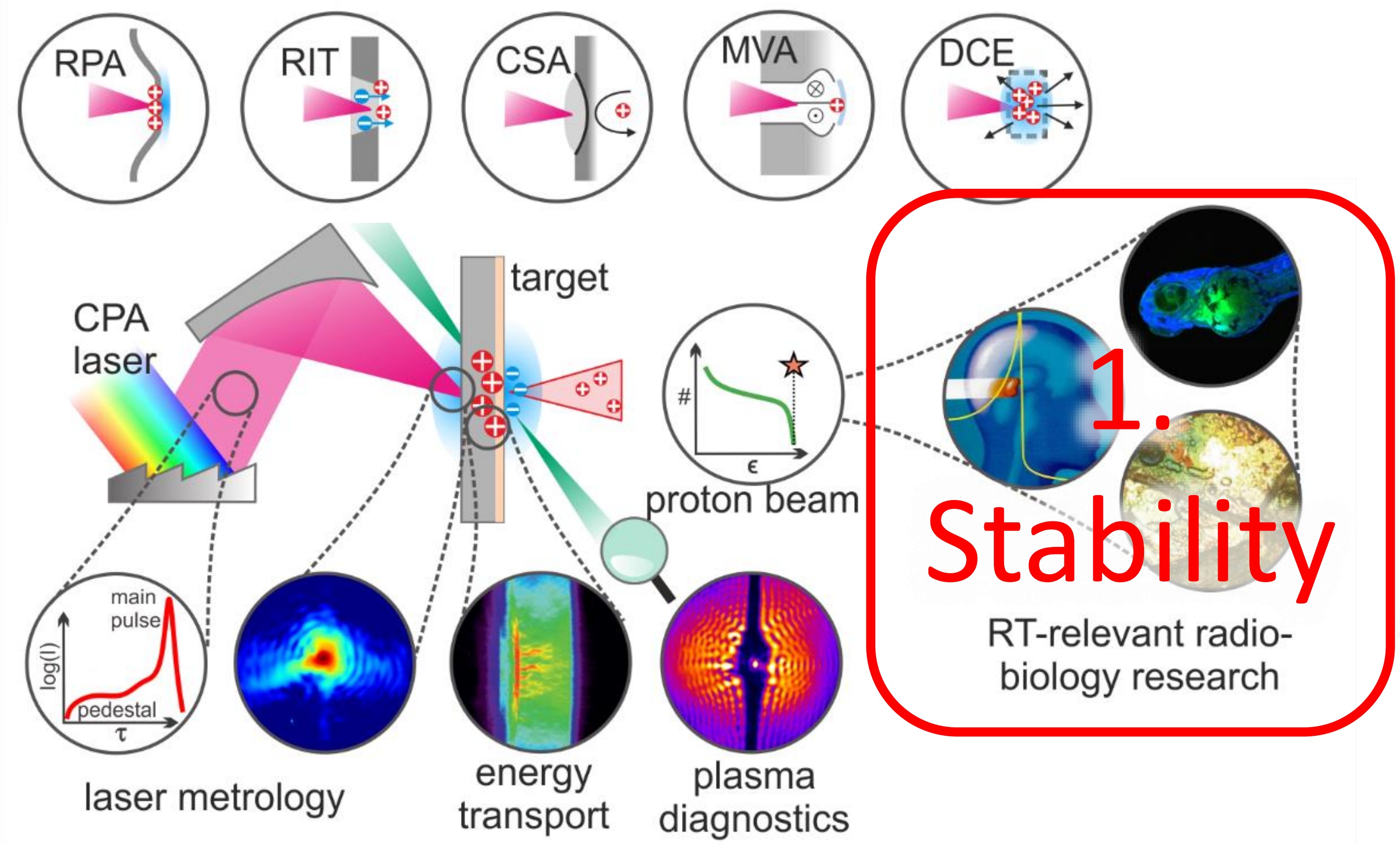


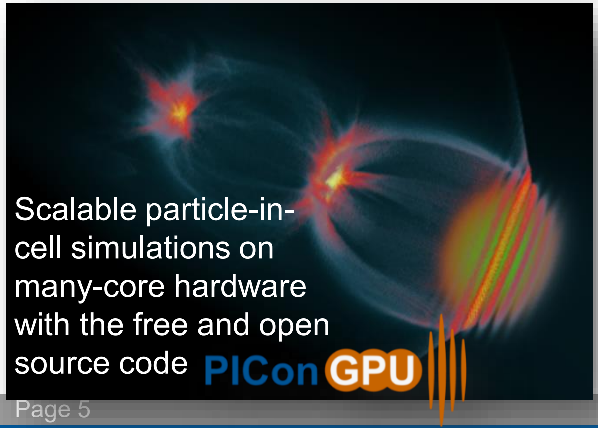
Energy scaling – two challenges:

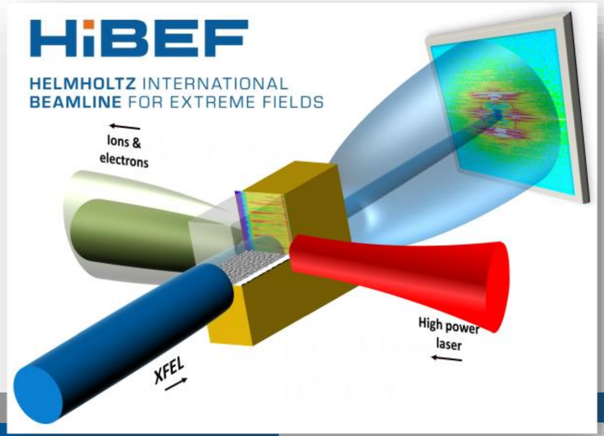
1. Technological limits for larger laser systems:
   - ➢ Advanced accelerator schemes
   - ➢ Indirect, highly non-linear processes (instabilities) → high sensitivity on input parameters



Laser-driven proton acceleration – Overview



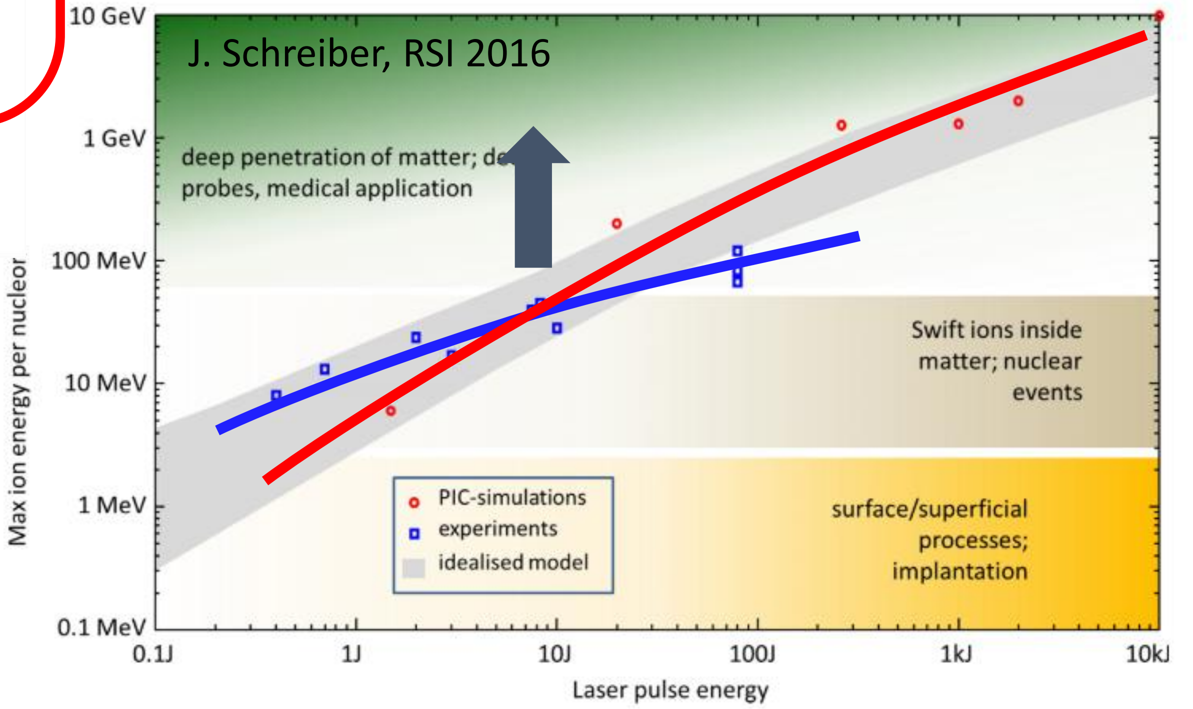




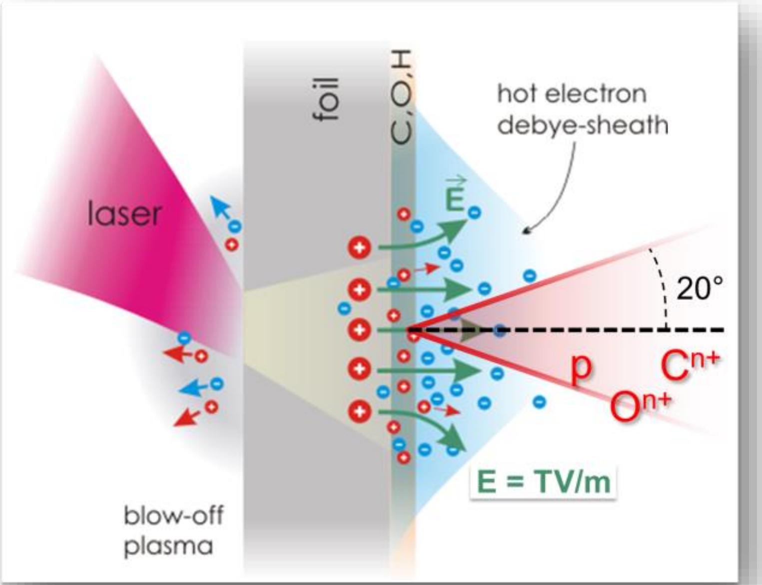
Energy scaling – two challenges:

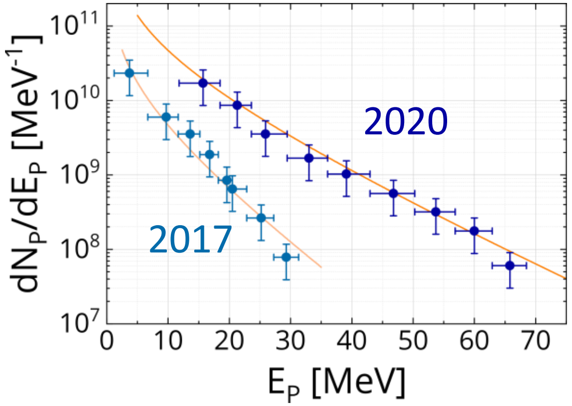
1. Technological limits for larger laser systems:
   - Advanced accelerator schemes
   - Indirect, highly non-linear processes (instabilities) → high sensitivity on input parameters
   - Looking inside the plasma
2. Limited predictability of simulations

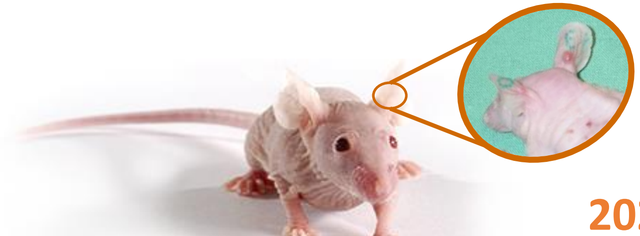
2. Upscaling



Laser-driven proton acceleration for radiobiological research







criver.com

2000

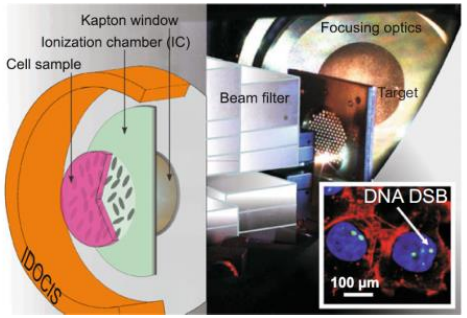
~ 60 MeV protons at Nova PW (TNSA)

2005 to 2010

20 MeV protons at ~100 TW Hz rep rate Ti:Sa systems

> 2009

in vitro radiobiology



> 2015

Ti:Sa PW lasers

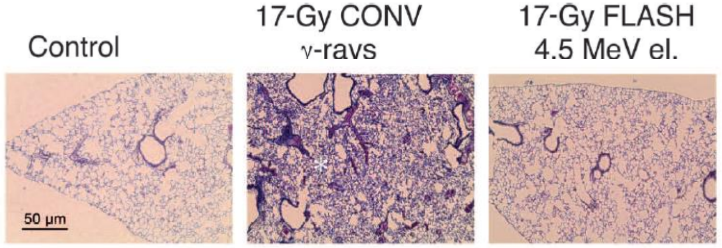
2017

proof-of-principle *in vivo* radiobiology

2020

ultra-high dose rate radiobiology @ HZDR

Radiation toxicity of RT: **ultrahigh dose-rate FLASH** irradiation increases the differential response between normal and tumor tissue in mice

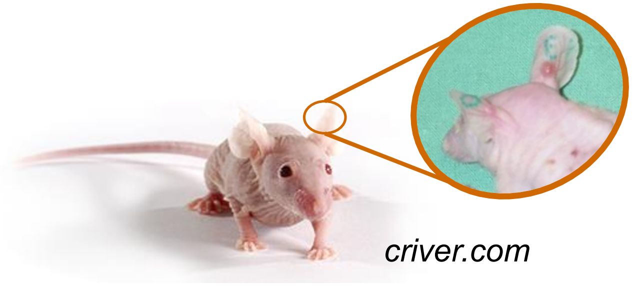


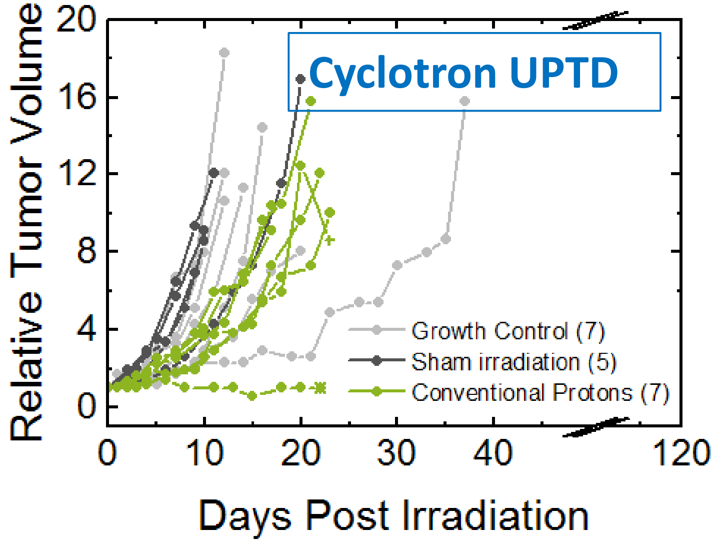
Favaudon et al. Sci. Transl. Med. 2014

compact accelerators for radiotherapy **ultra-high dose rate** translational radiobiology

Small animal pilot study with laser-driven proton pulses

Preparation of comparative *in vivo* radiobiological studies for dose rate effect studies





Radiobiological model & requirements:

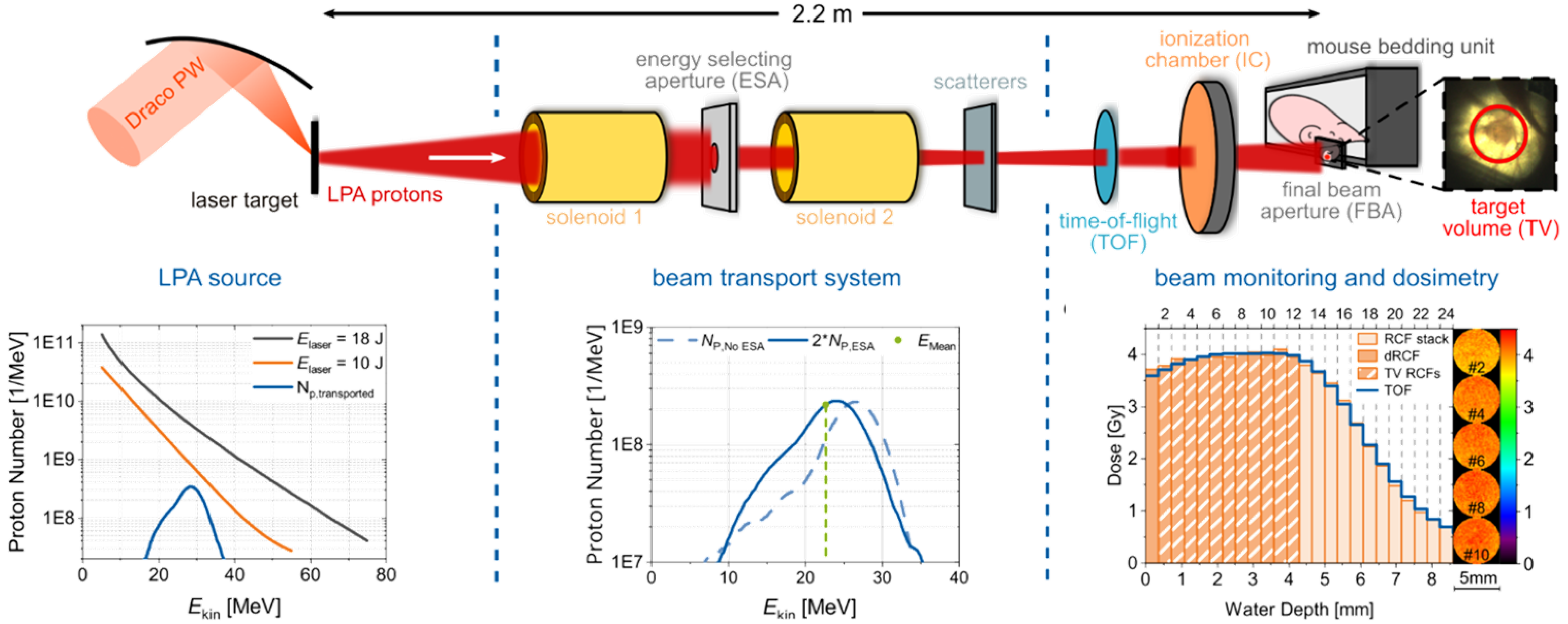
- radiobiological endpoint: tumor-growth delay of mouse ear tumor
- irradiated volume Ø 5 mm, 5 mm depth
- 4 Gy < +/- 10%
- homogeneity < 10% dev. dose deposition at 4 Gy (< 10% sample-to-sample variation)
- 2 cohorts (Draco PW & UPTD) with 5 treatment groups each

	Draco PW	UPTD
mean dose		3.9
single dose accuracy (2σ)		14%
dose homogeneity lateral/depth (2σ)		9%/2%
mean dose rate		3.6 Gy/min
peak dose rate		-

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

Small animal pilot study with laser-driven proton pulses

Setup at Draco PW

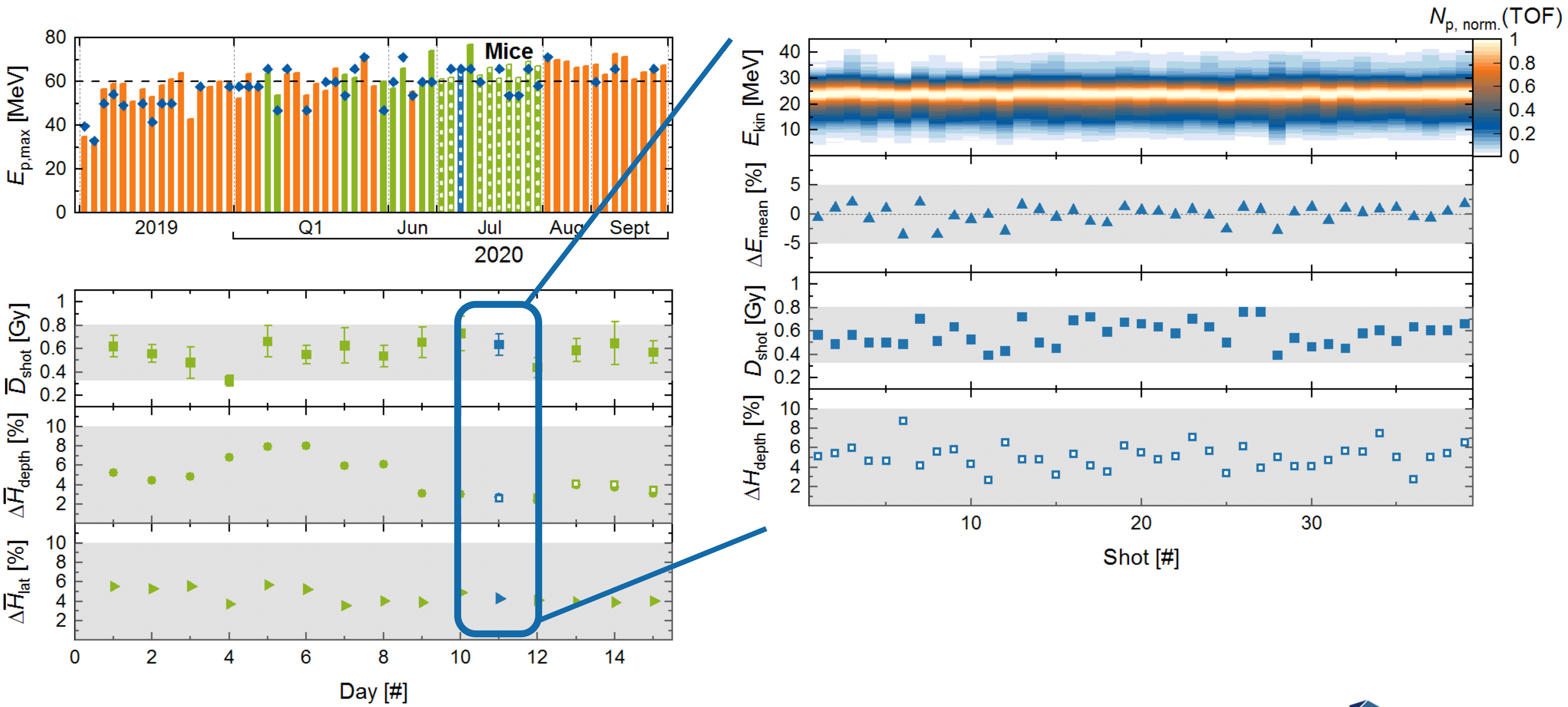


platform enables single-shot delivery of mm-scale 3D tumor-conform dose distributions making perfect use of the broadband LPA proton spectrum

T. Ziegler *et al.*, Sci Rep 11 (2021); F.-E. Brack *et al.*, Sci Rep 10 (2020), F. Kroll *et al.* Nature Physics (2022)

Small animal pilot study with laser-driven proton pulses

Accelerator readiness and stability benchmarked via application-specific parameters



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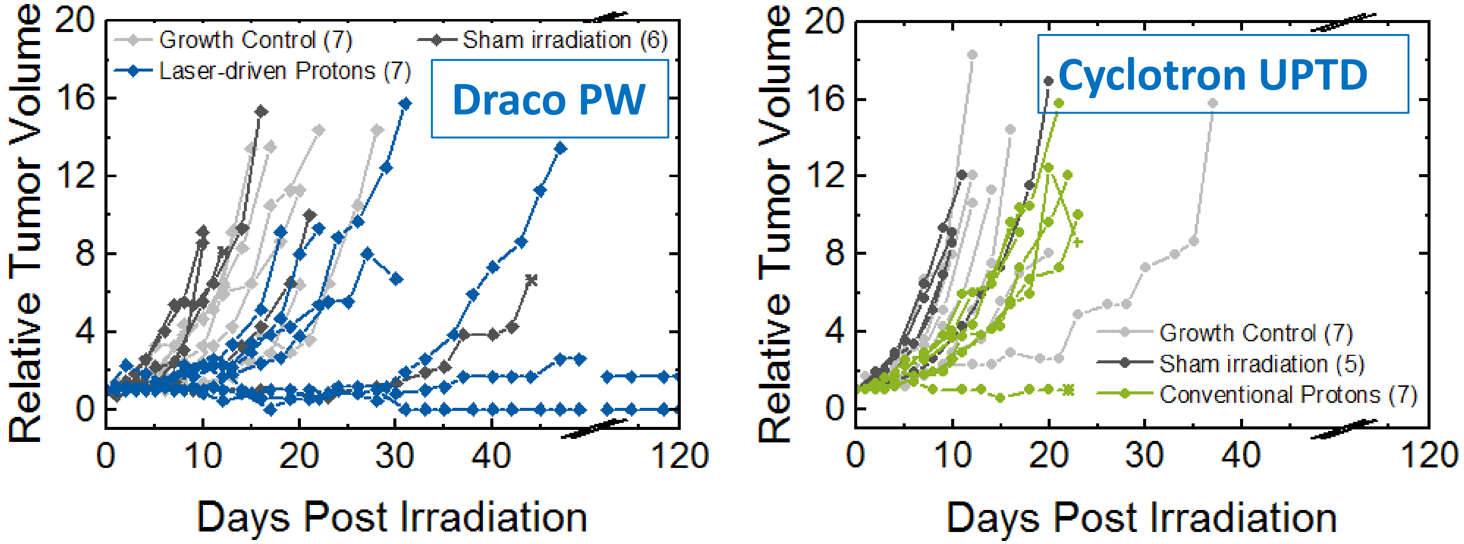
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Small animal pilot study with laser-driven proton pulses

Preparation of comparative *in vivo* radiobiological studies for dose rate effect studies

- **model-conform dose delivery**
  ✓ … mitigation of LPA-inherent spectral intensity fluctuations
- **accelerator readiness and stability**
  ✓ … stable daily accelerator performance over weeks enabling a bio-driven schedule
- **radiobiological pilot study**
  … meaningful dose-effect data via
  ✓ … on-demand proton LPA source operation
  … precise dose delivery & dosimetry
  … complex *in vivo* sample preparation, irradiation & follow-up

- Interesting radiation induced (4 Gy) effect observed, but no significant conclusion because of too small sample number



	Draco PW	UPTD
mean dose	3.9	3.9
single dose accuracy (2σ)	8%	14%
dose homogeneity lateral/depth (2σ)	9%/< 9%	9%/2%
mean dose rate	1.2 – 2.2 Gy/min	3.6 Gy/min
peak dose rate	10^8 Gy/s	-

F. Kroll Nature Physics 2022

Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Upscaling the energy: Enhanced acceleration with near-critical density targets

DRESDEN concept HZDR
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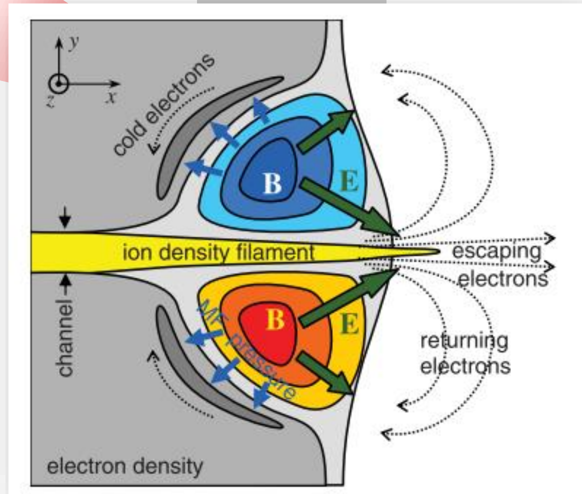
Tailoring the target (plasma) density profile as decisive parameter

Magneto vortex acceleration

Bulanov & Esirkepov PRL (2007)

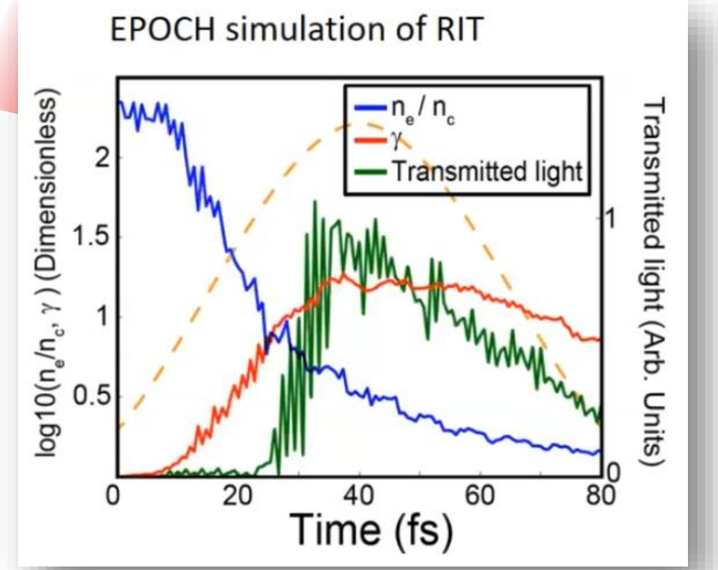
Transparent target



Relativistic transparency

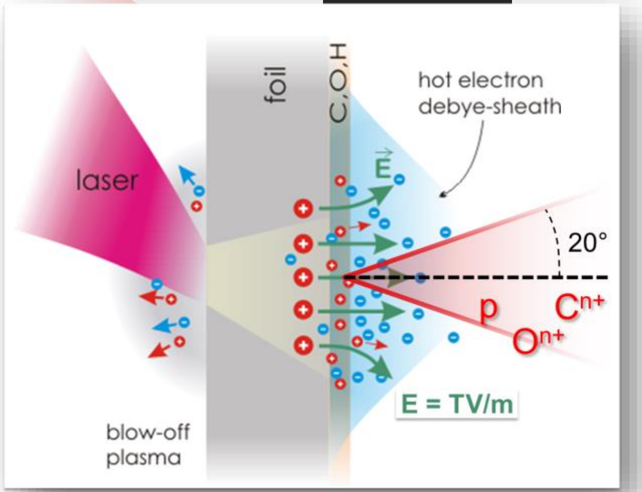
Yin POP (2011), D'humieres POP (2015), Higginson Nat. Comm. (2018), McKenna, Gonzales-Izquierdo et al. SPIE (2021) & ApplSci (2018)

Near critical density target



TNSA

Dense, opaque target



Solid H_2

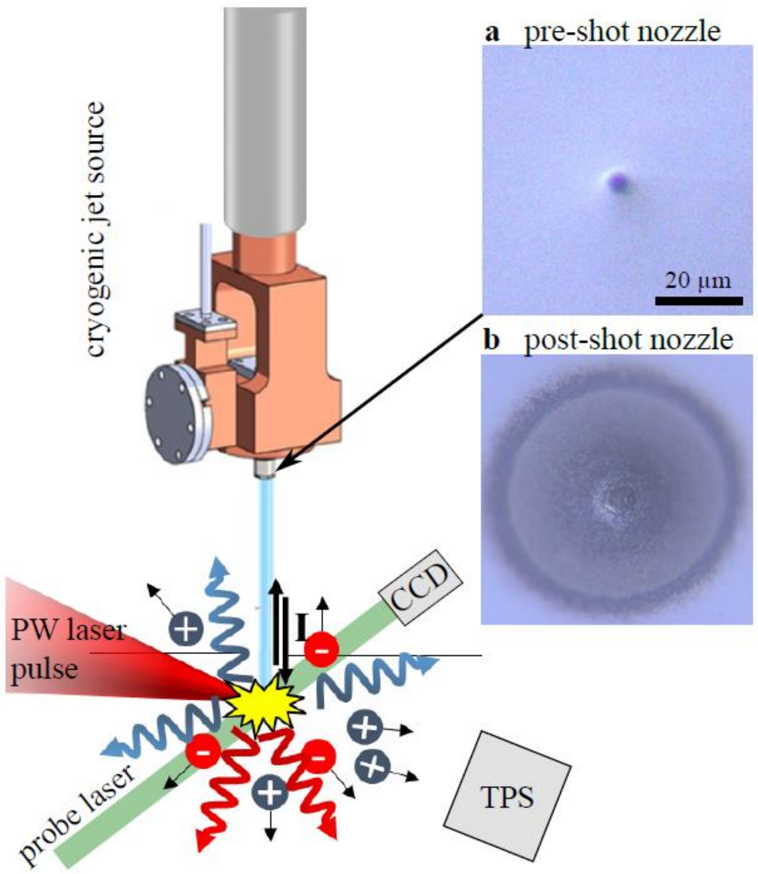
Target density

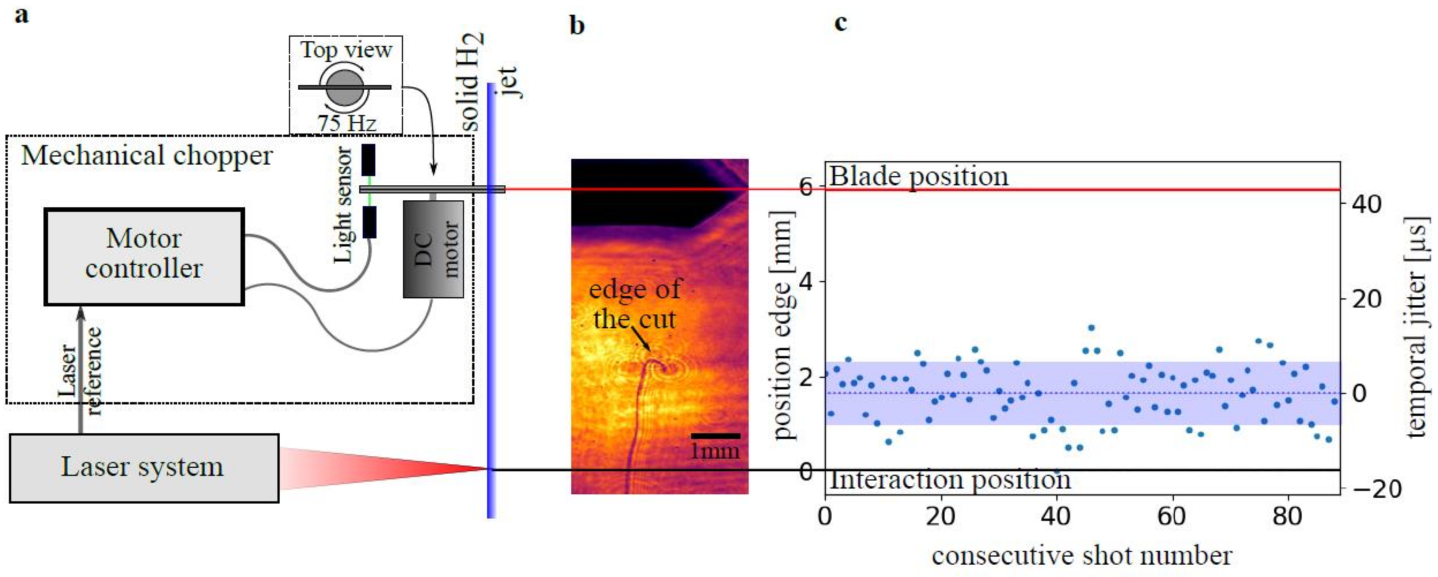
typ. < 10^{20} cm^{-3}
under-critical density

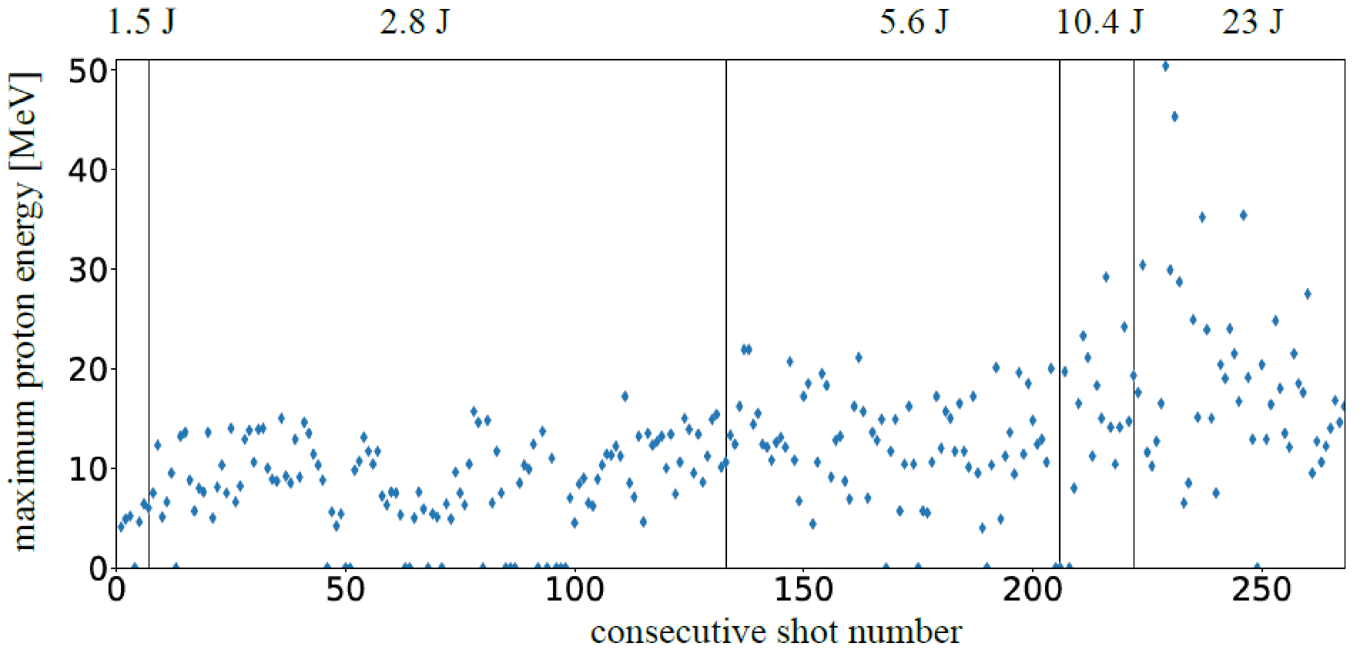
1.7 x 10^{21} cm^{-3} = $n_{critical}$[800nm]
near-critical density

typ. > 10^{23} cm^{-3}
over-critical density

Towards high-repetition rate with cryogenic jets using a mechanical chopper

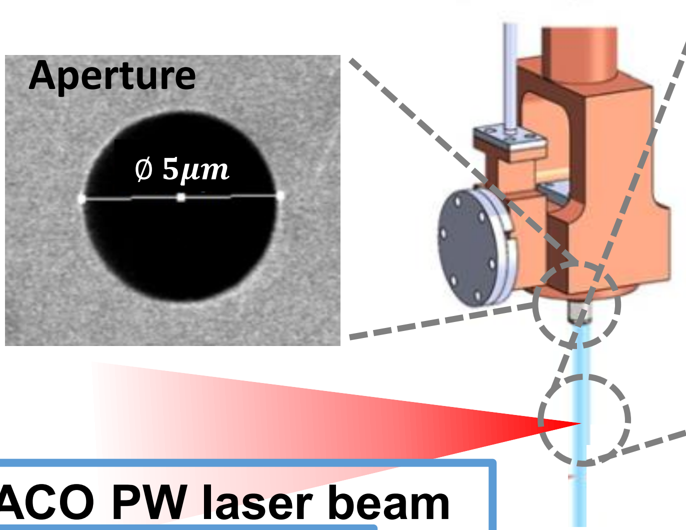


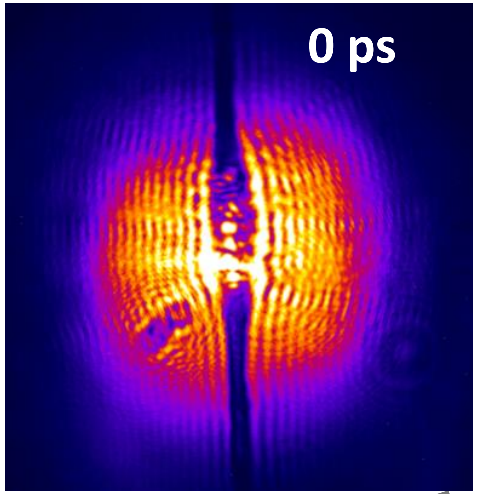


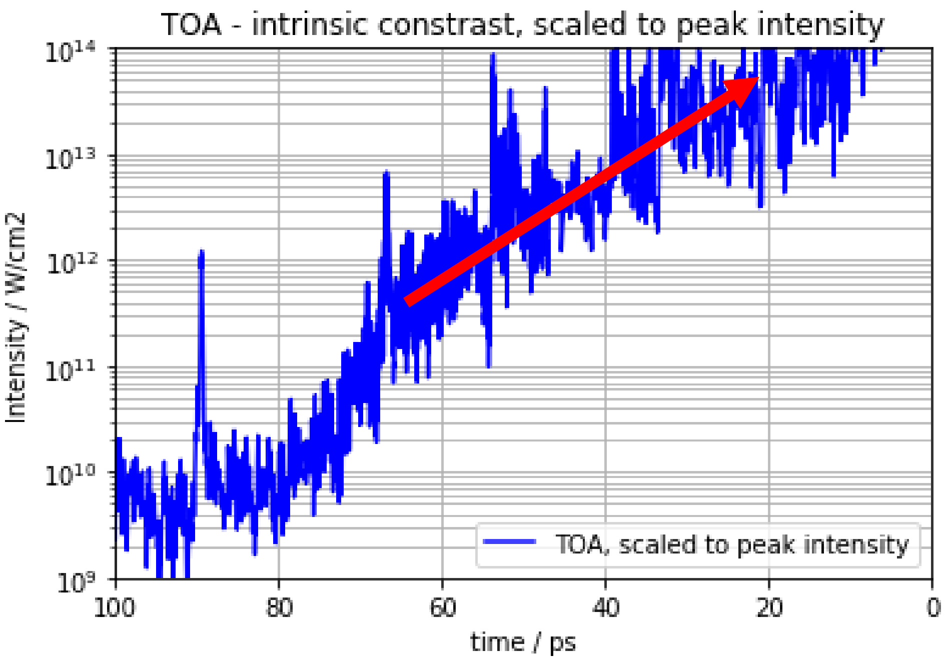


Cryogenic hydrogen jets – pre-expansion

Cryogenic hydrogen jet source



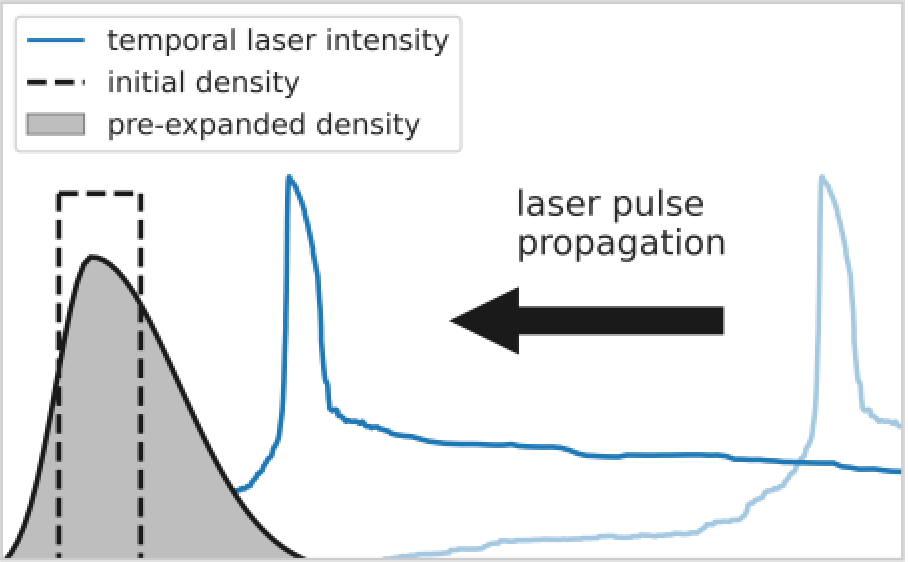




DRACO PW laser beam

22J, 30fs, intrinsic contrast focused to ~3µm spot size → $6.6 \times 10^{21} W/cm^2$

- Pedestal starting @ 67 ps shapes target density profile



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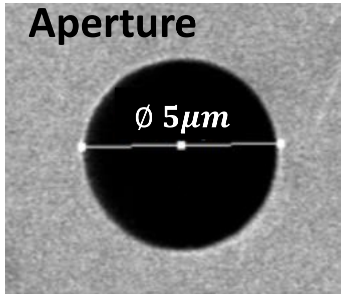
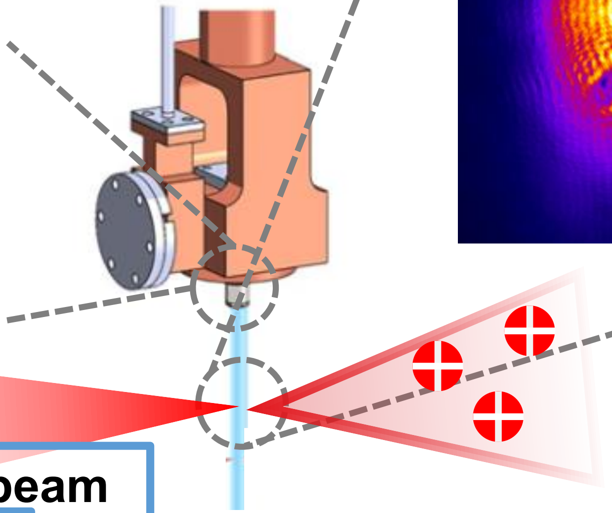
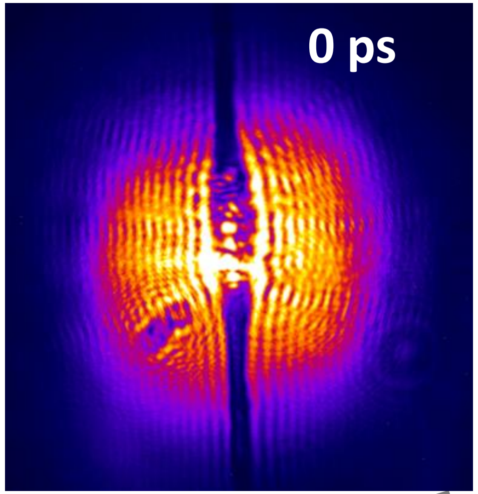
Cryogenic hydrogen jets – pre-expansion

SLAC European XFEL

Cryogenic hydrogen jet source



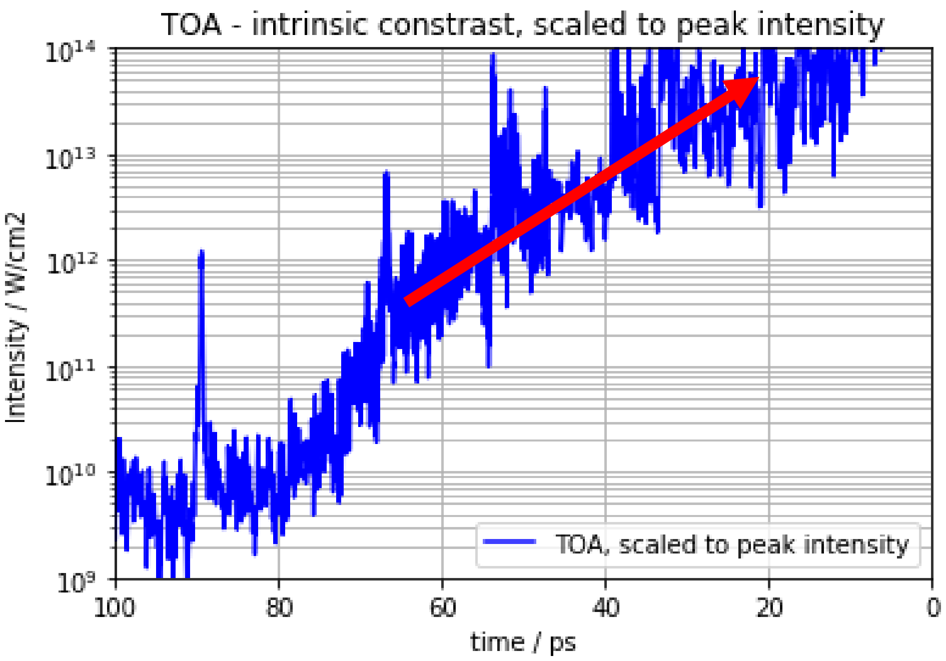


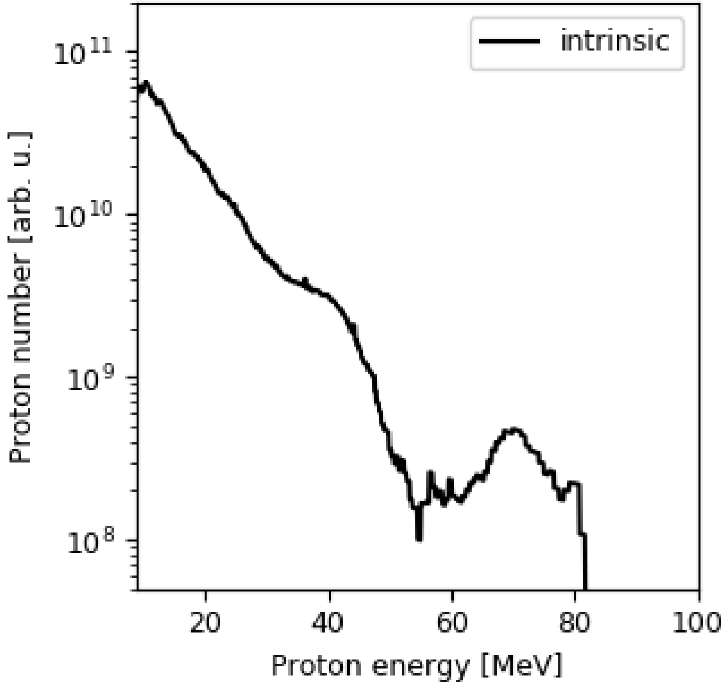


DRACO PW laser beam

22J, 30fs, intrinsic contrast focused to ~3µm spot size → 6.6 x 10^{21}W/cm^2

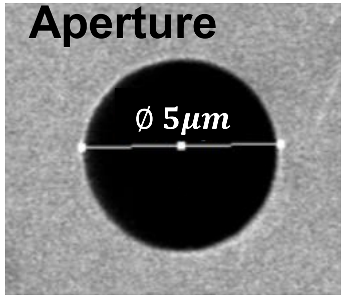
- Pedestal starting @ 67 ps shapes target density profile
- 80 MeV observed in the best shot
- Effect? Density tailoring?

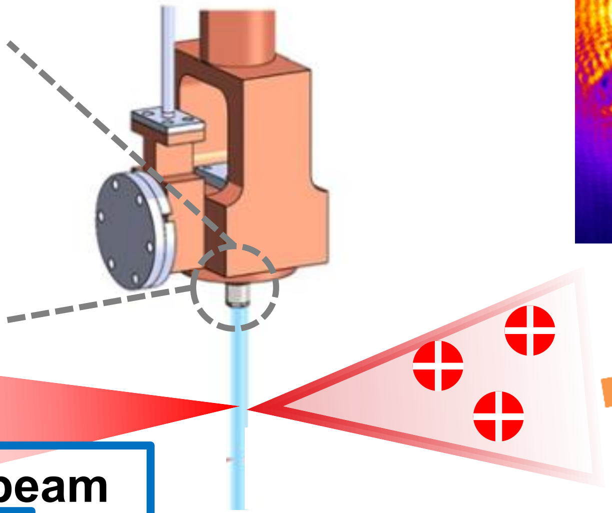


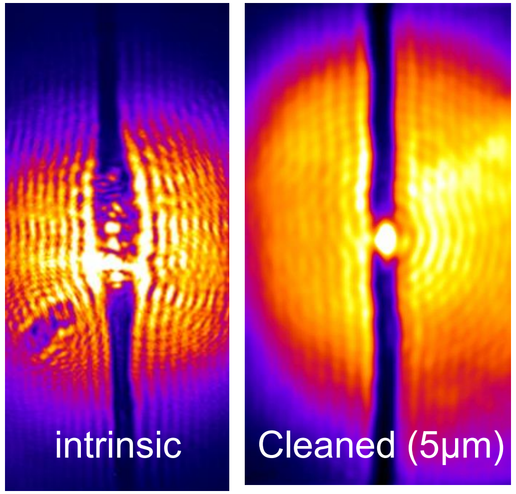


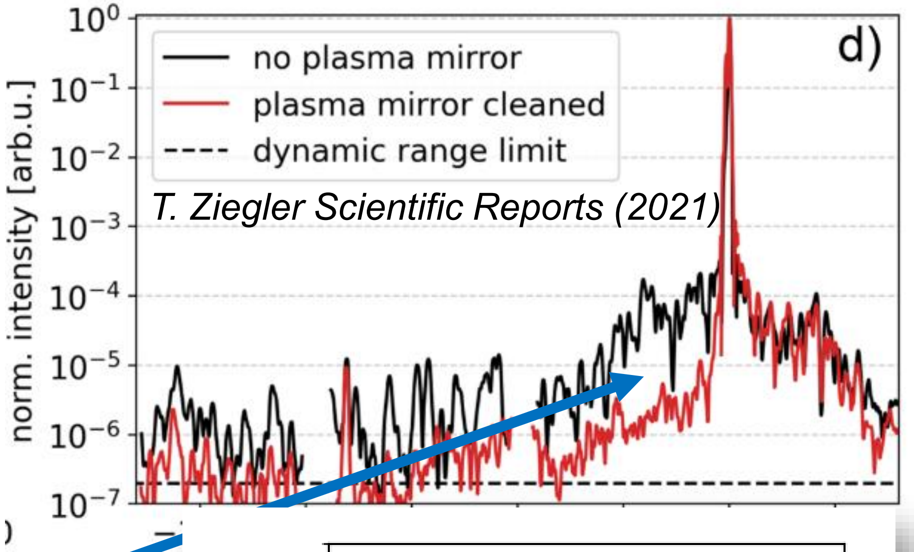
Cryogenic hydrogen jets – tailoring the density profile

Cryogenic hydrogen jet source

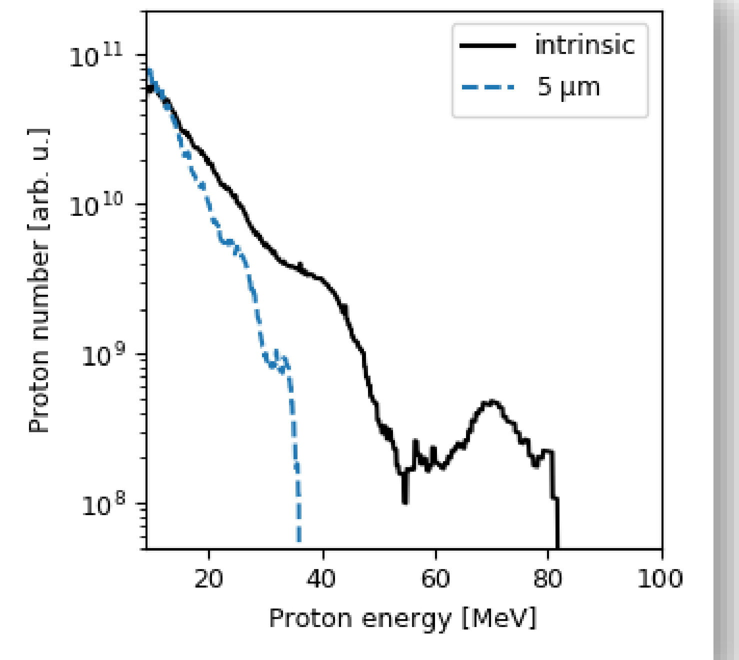








- Pre-pulse reduction by >100

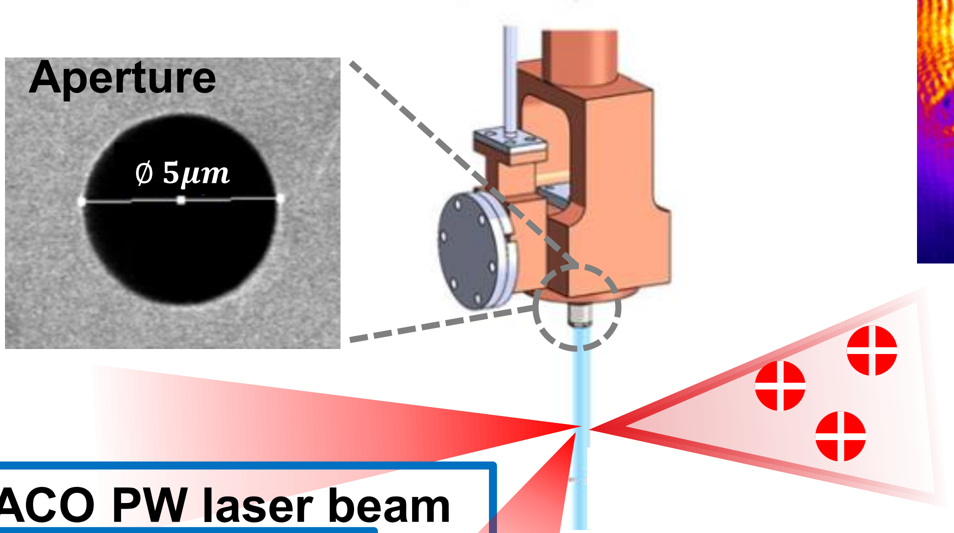


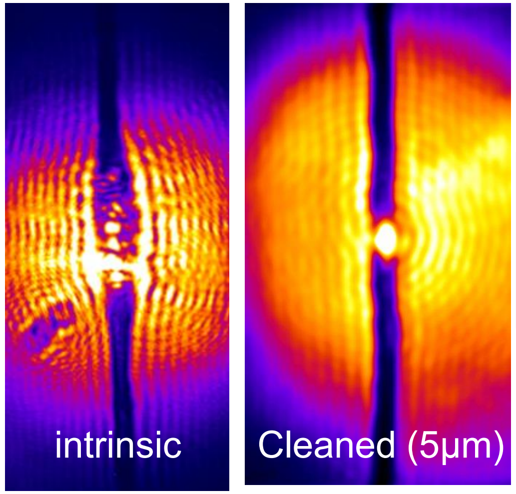
DRACO PW laser beam

18J, 30fs, cleaned contrast focused to ~3μm spot size → 5.4 x 10^{21}W/cm^2

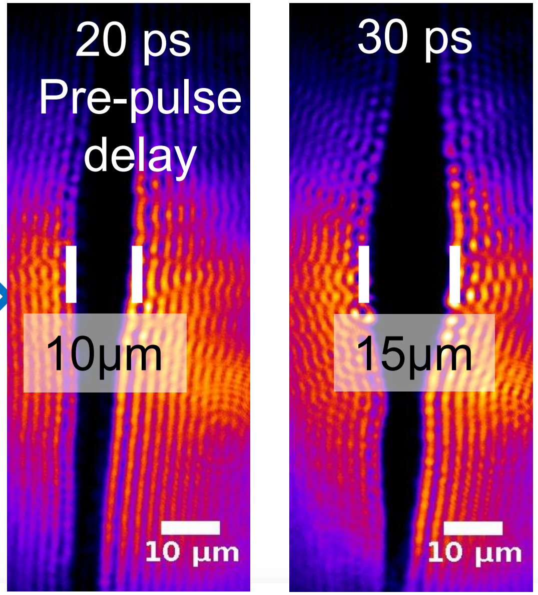
Cryogenic hydrogen jets – tailoring the density profile

Cryogenic hydrogen jet source





Controlled pre-expansion

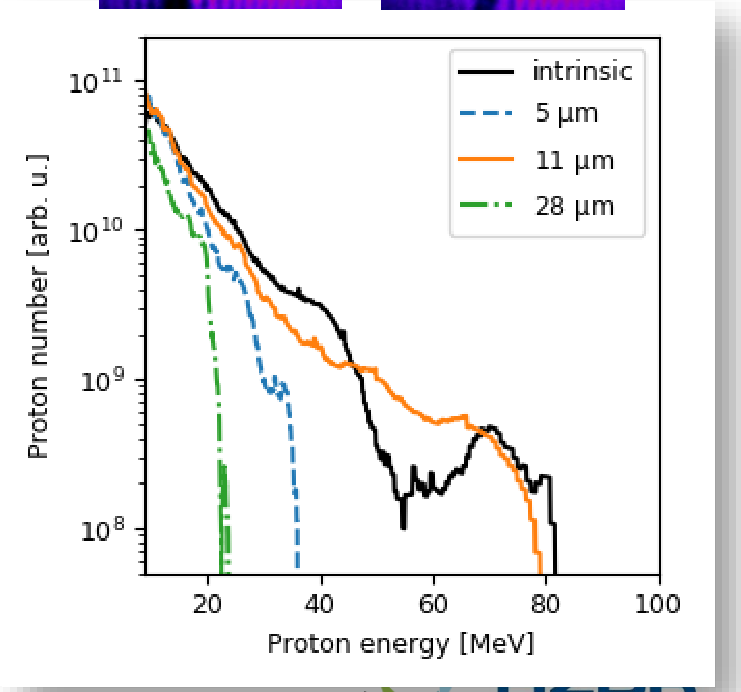


DRACO PW laser beam

18J, 30fs, cleaned contrast focused to ~3μm spot size
→ 5.4 x 10^{21}W/cm^2

Heating laser pulse
(5 x 10^{17} W/cm^2)
Variable delay

- Optimum with a **twofold energy increase**



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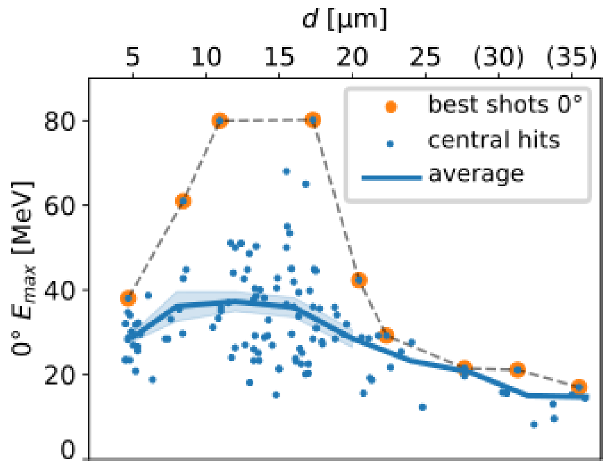
Cryogenic hydrogen jets – tailoring the density profile

Proton energy

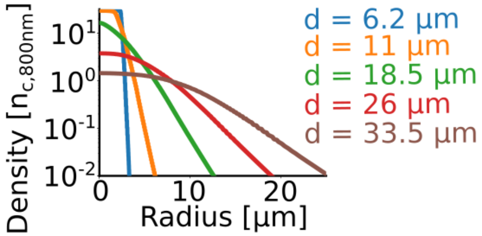


Directionality

Transmitted light

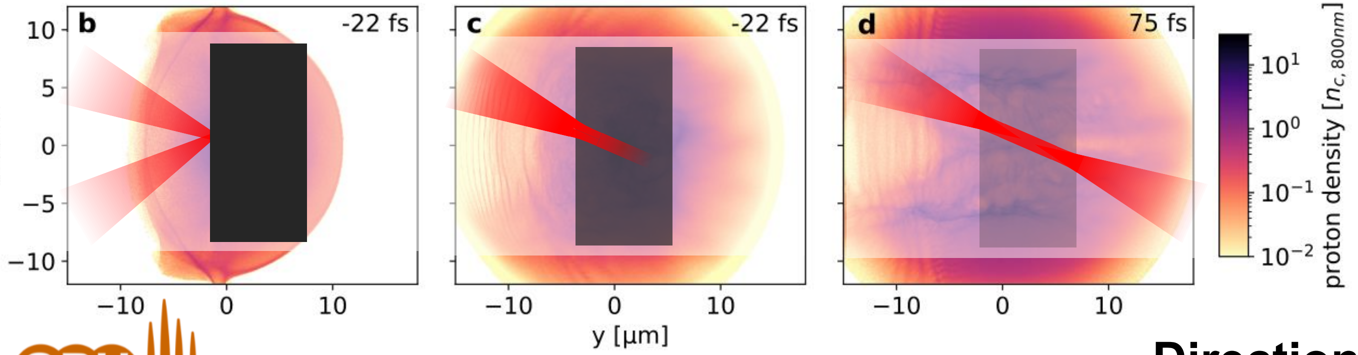
Diameter ↔ Density

probing assisted MHD

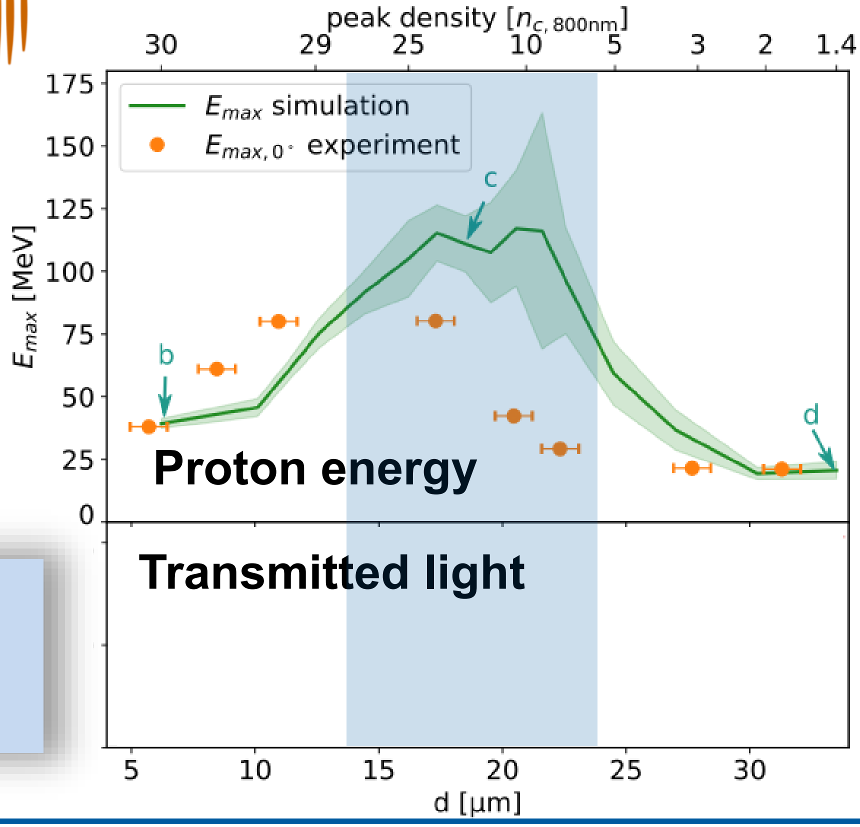


- Highest proton energies by **RTF-RPA**

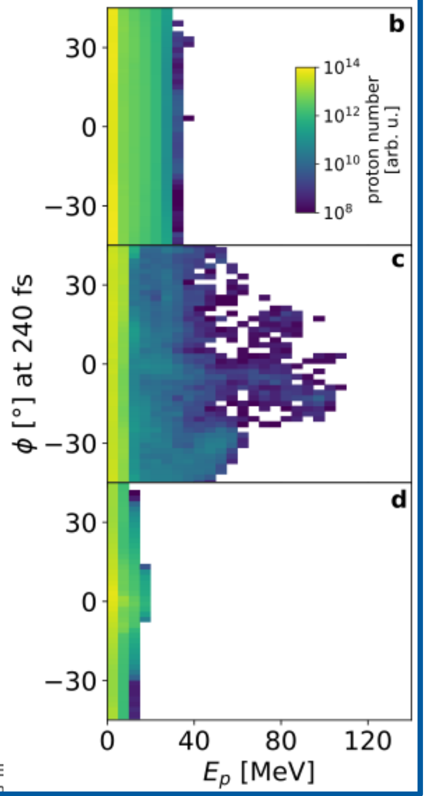
Top view



PIConGPU

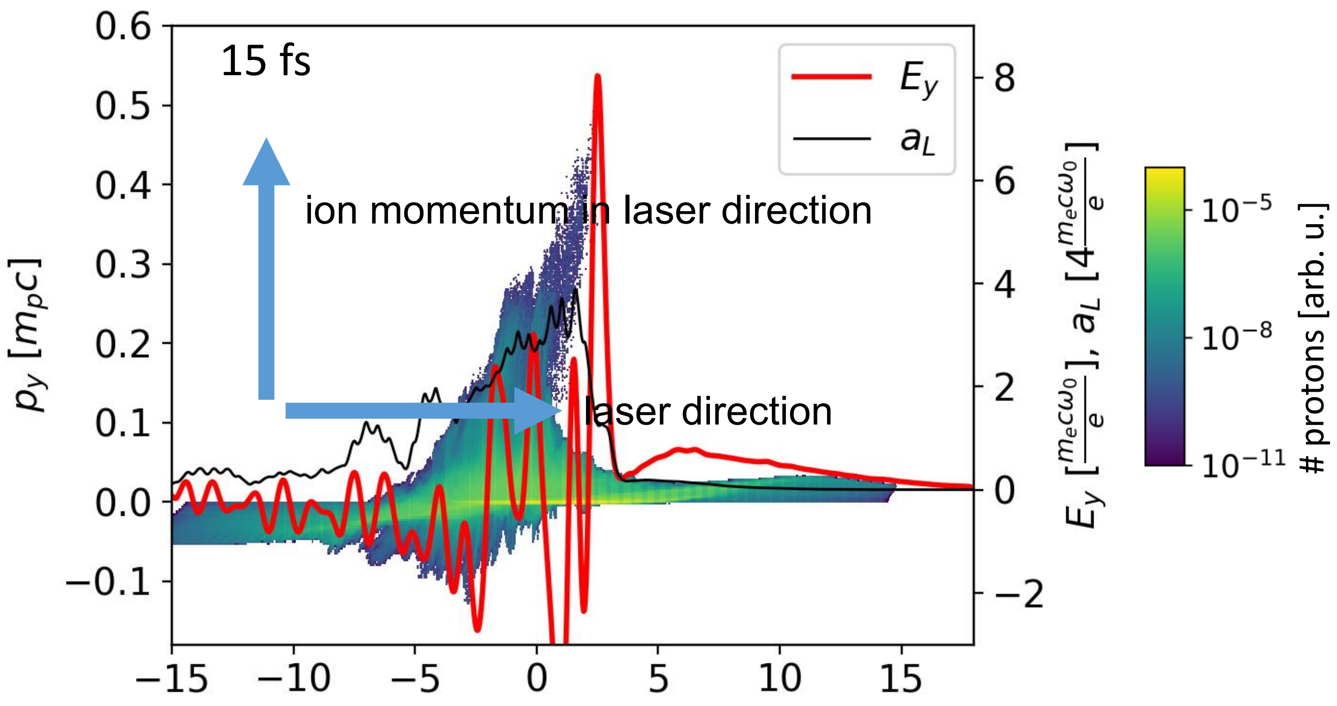


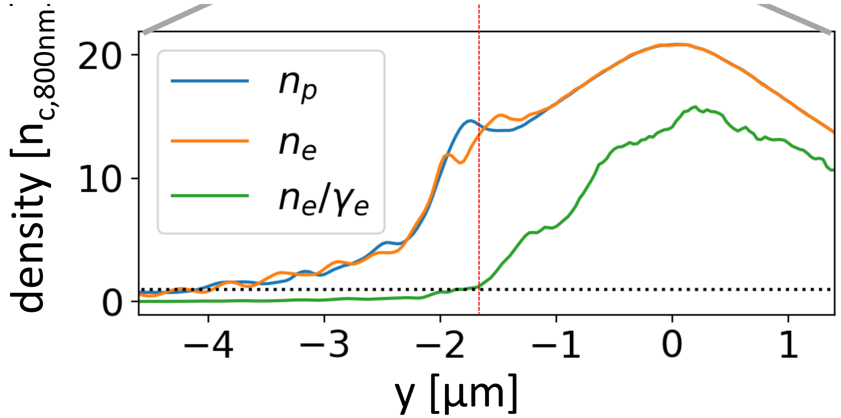
Directionality



Optimized laser ion acceleration at the relativistic transparency front (RTF-RPA)

Phase space evolution





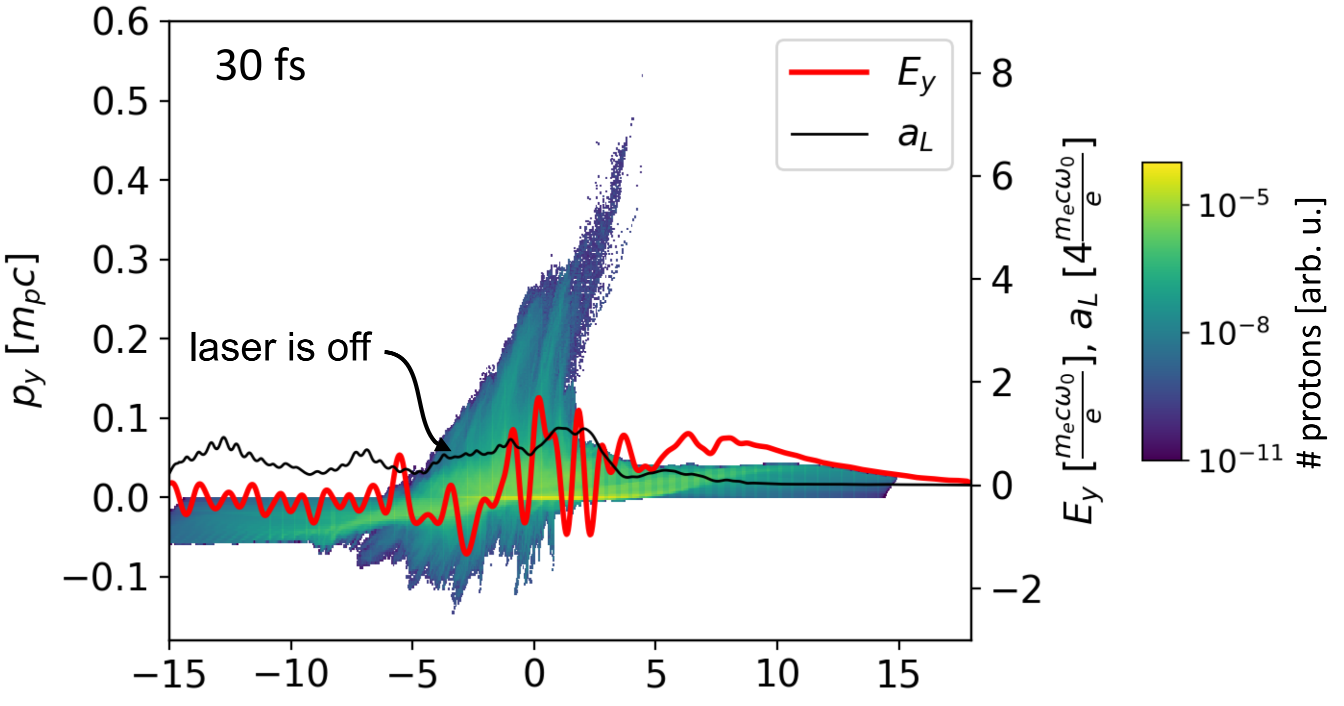
- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk

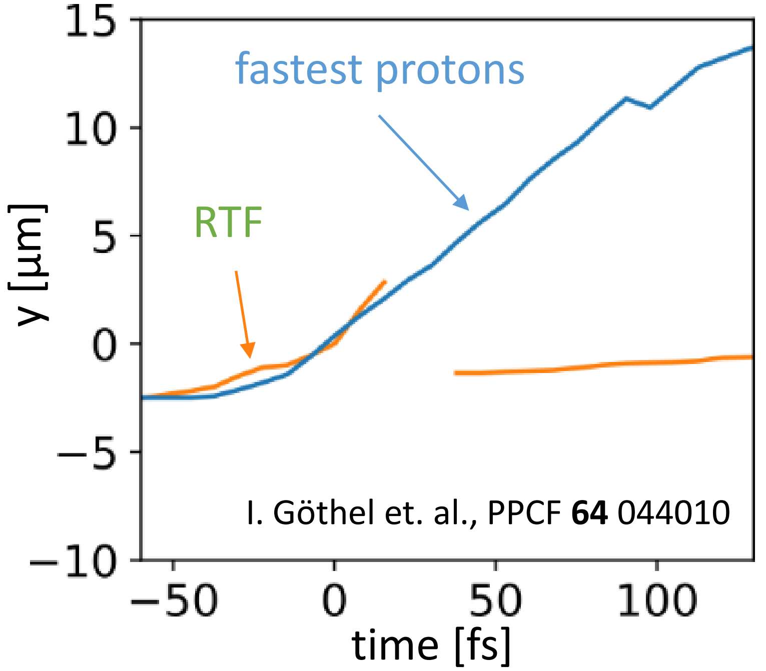
M. Rehwald et. al., *in review*

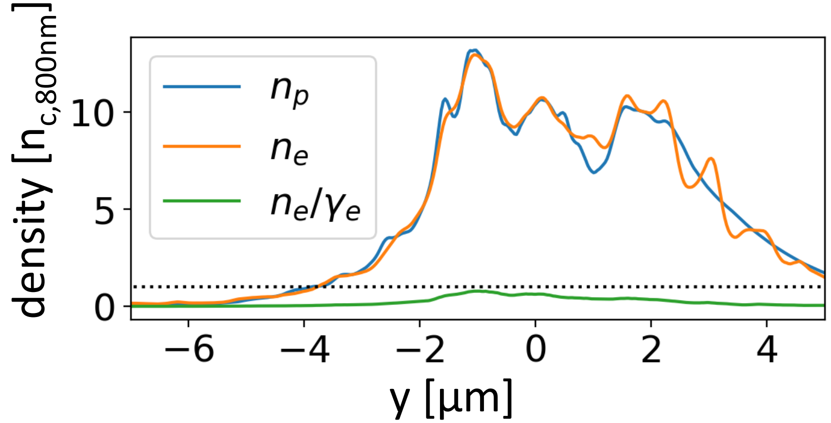
Member of the Helmholtz Association
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Optimized laser ion acceleration at the relativistic transparency front (RTF-RPA)

Phase space evolution



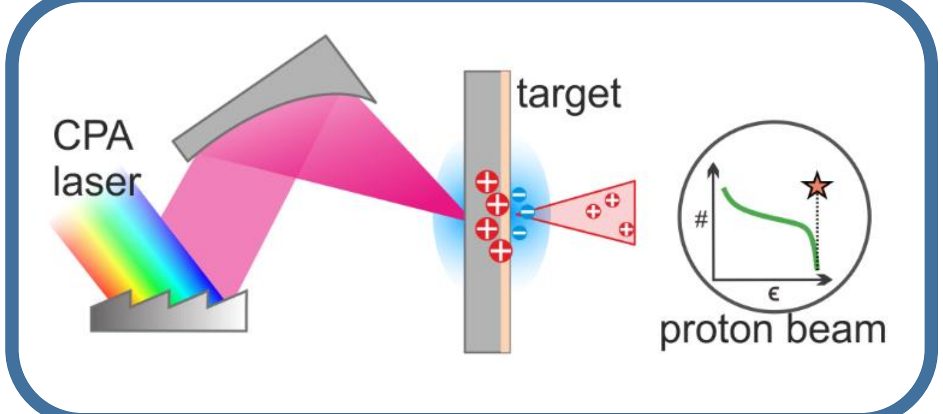




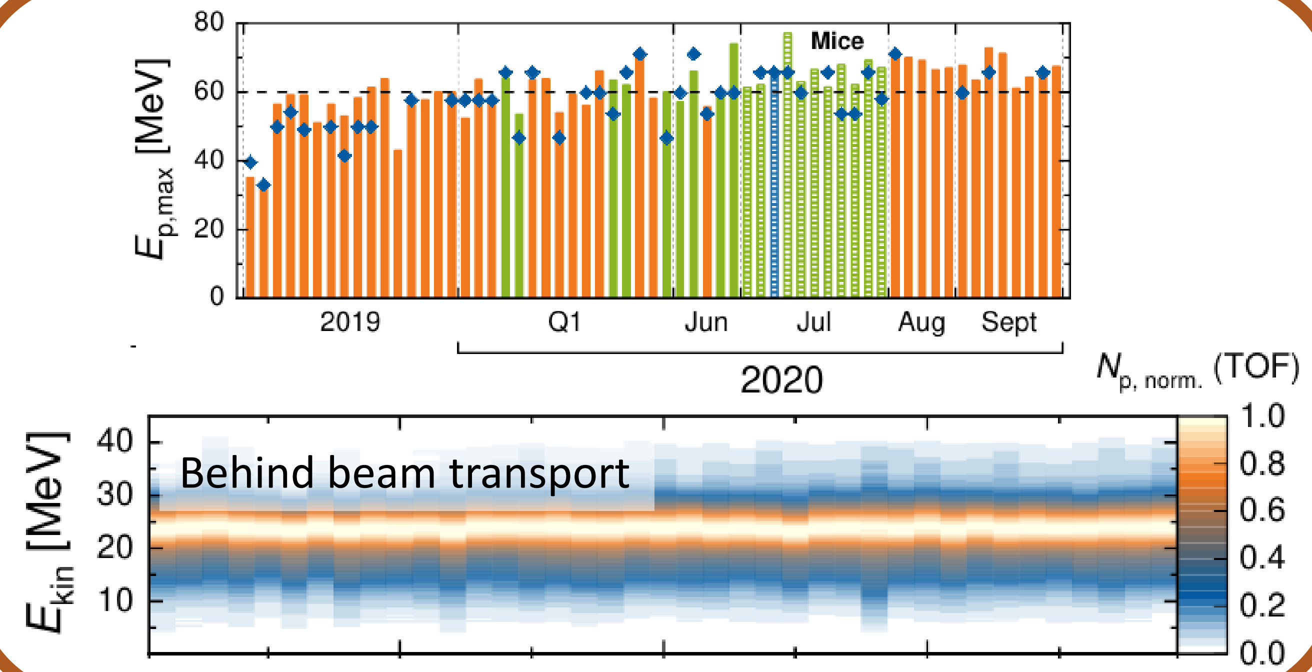
- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk
  → **quasi co-moving accelerating field structure**

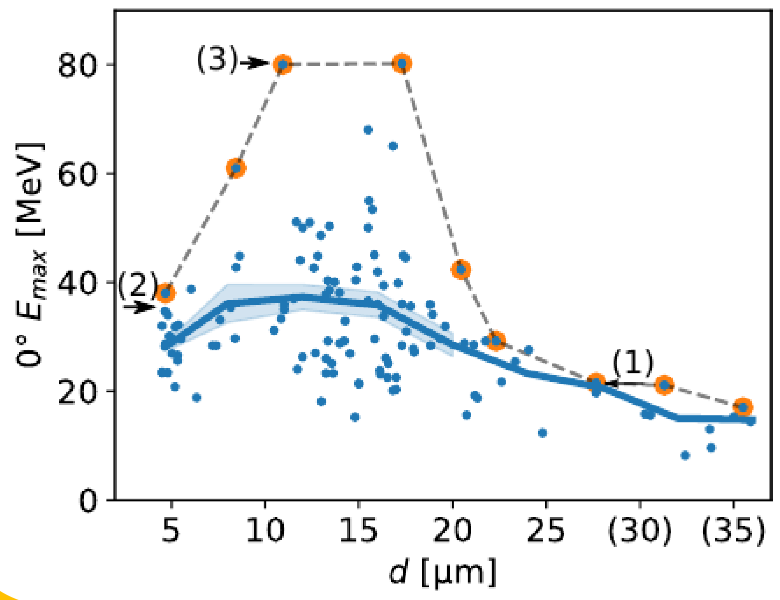
M. Rehwald et. al., *in review*

Summary



- Stable beam generation >60MeV and accelerator readiness demonstrated
- First animal irradiation → platform ready for translational research with laser-driven protons
- Enhanced acceleration with near-critical density targets beyond 80 MeV with rep-rated jet target





Member of the Helmholtz Association
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Big Thanks to the Team and Collaborators

Laser radiooncology | **Laser particle acceleration**

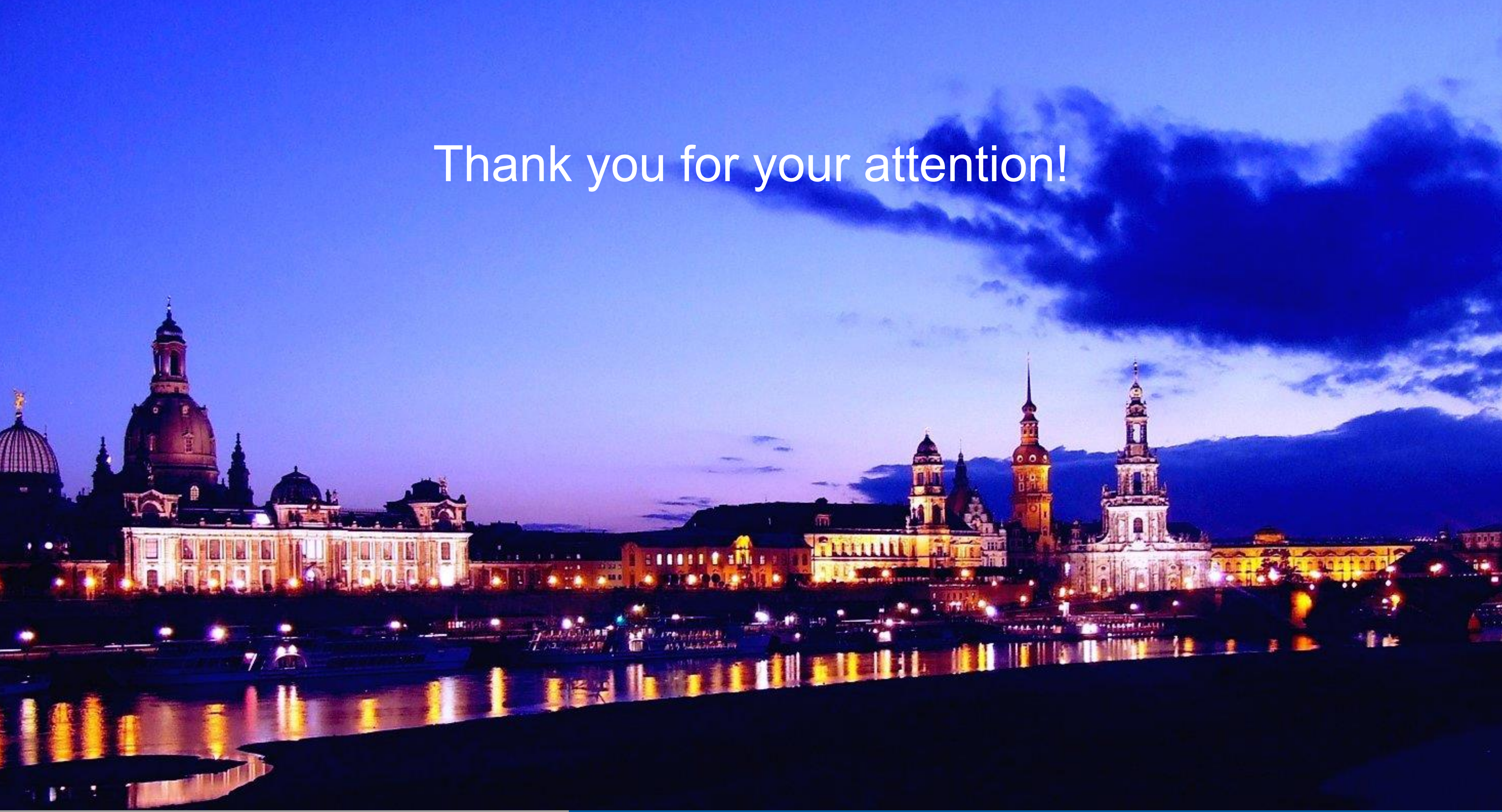
J. Pawelke, E. Beyreuther, K. Brüchner, E. Bodenstein, L. Karsch, E. Lessmann, M. Krause, E. Troost, N. Cordes, C. Richter, et al.
K. Zeil, J. Metzkes-Ng, F. Kroll, C. Bernert, E. Beyreuther, L. Gaus, S. Kraft, A. Nossula, M.E.P. Umlandt, M. Rehwald, M. Reimold, H.-P. Schlenvoigt, M. Sobiella, T. Ziegler, S. Bock, R. Gebhardt, U. Helbig, T. Püschel, U. Schramm, T. Cowan, et al.
High-field laboratory Dresden (HLD) and HZDR workshop; R. Szabo, et al. (ELI-ALPS); J. Jansen, et al. (DKFZ)

SLAC / European XFEL: S. Glenzer, C. Curry, M. Gauthier, J. Kim, F. Fiuza, S. Goede et al.

KPSI (Kansai Photon Science Institute): M. Nichiuchi, H. Kyriama, N. Dover, A. Kon

Weizmann Institute of Science: V. Malka, D. Levy, E. Kroupp (Whelmi)

Thank you for your attention!



Karl Zeil I k.zeil@hzdr.de I www.hzdr.de