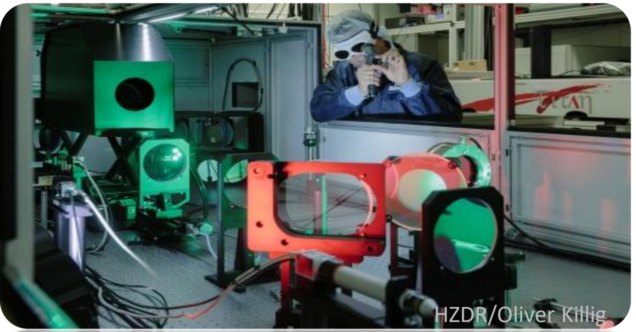
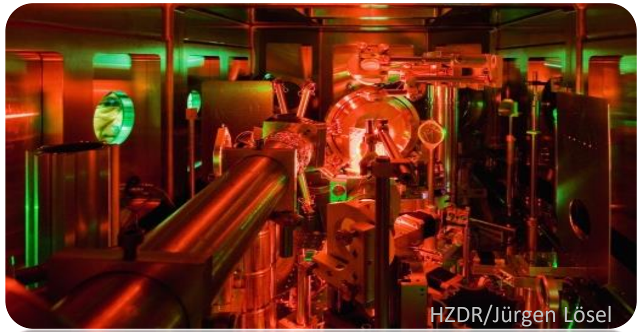
High energy proton acceleration at DRACO-PW and radio-biological applications





Karl Zeil
Helmholtz-Zentrum Dresden-Rossendorf

20th Advanced Accelerator Concepts Workshop (AAC'22)
November 7, 2022

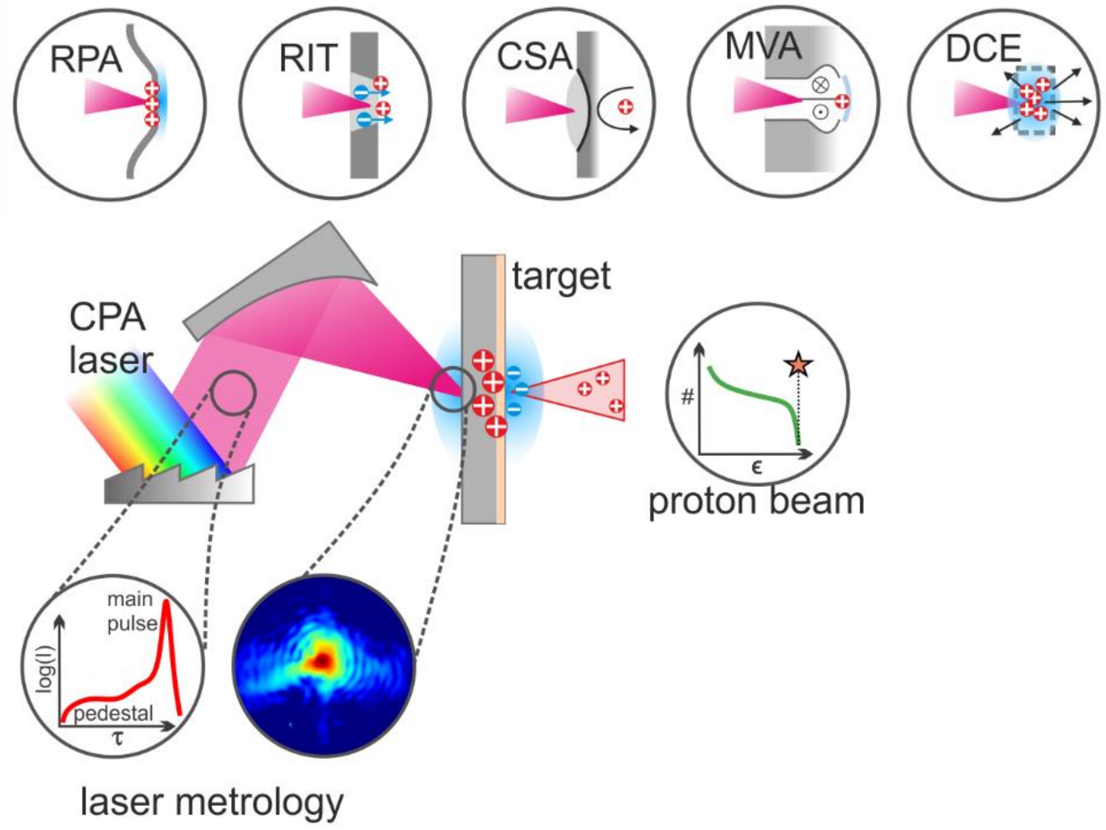
HZDR

MT ARD

ATHENA
The Helmholtz-Project for Laser-Plasma-Acceleratio

OncoRay
National Center for Radiation Research in Oncology Dresden

Development of a high repetition-rate, high energy plasma accelerator for ions

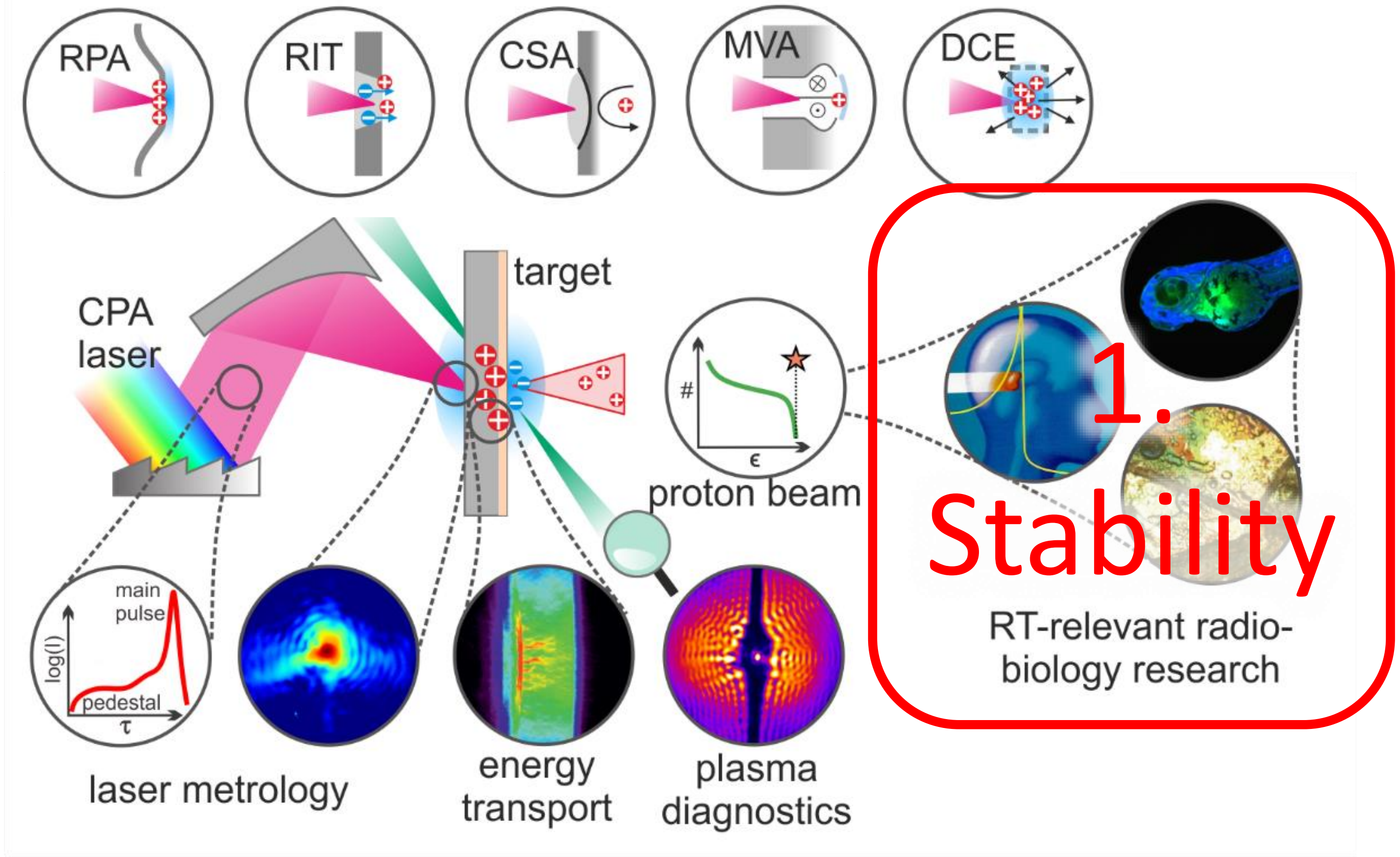


Energy scaling – two challenges:

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

2020 Roadmap on plasma accelerators
New Journal of Physics 23, 031101 (2021)

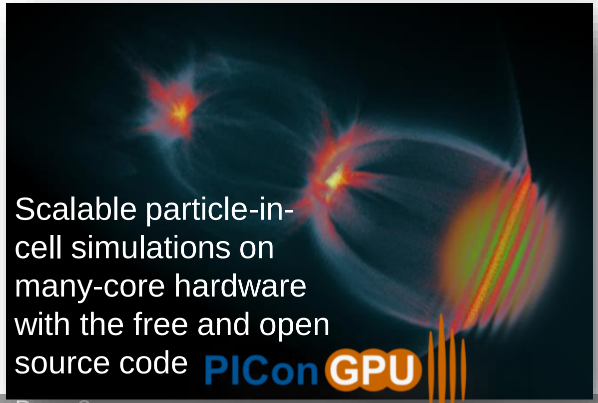
Development of a high repetition-rate, high energy plasma accelerator for ions

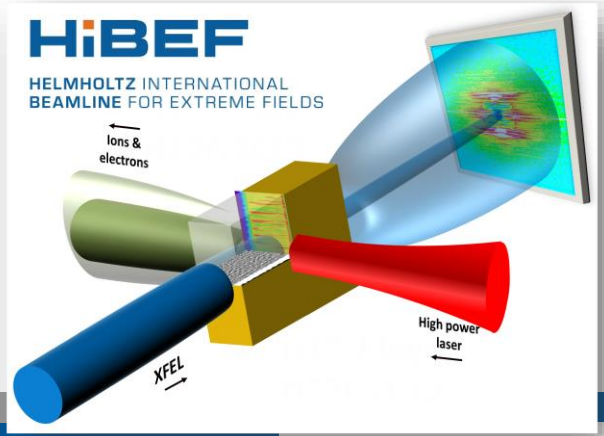


Energy scaling – two challenges:

1. Technological limits for larger laser systems:
   - Advanced accelerator schemes: from surface to volumetric interaction
   - Indirect, highly non-linear processes (instabilities) → high sensitivity on input parameters
2. Limited predictability of simulations
   - microscopic understanding
   - control and knowledge of laser parameters on target

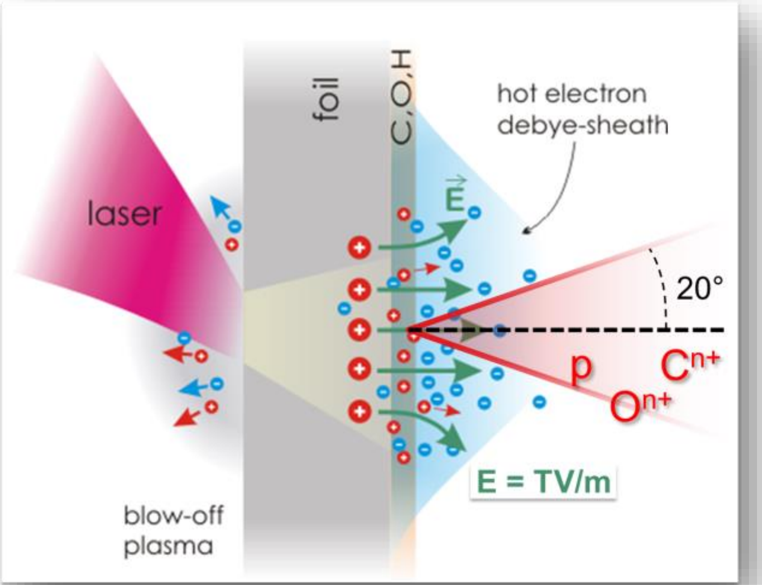
2. Upscaling

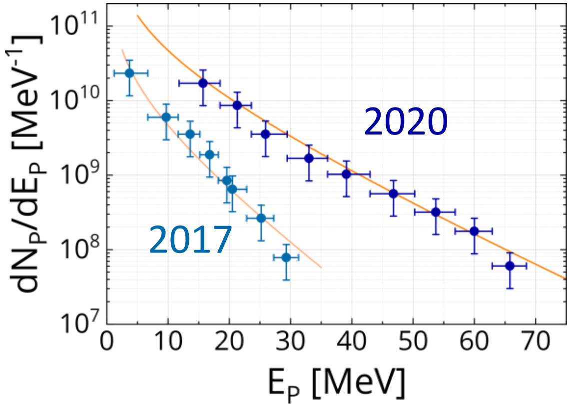


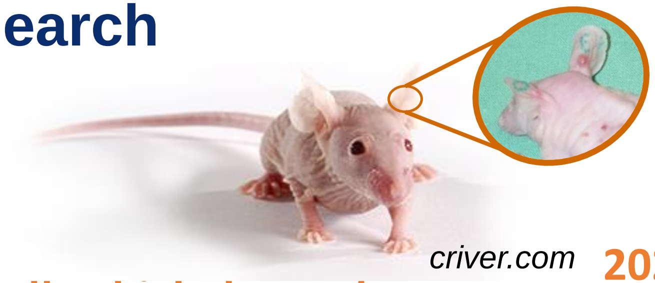


2020 Roadmap on plasma accelerators
New Journal of Physics 23, 031101 (2021)

Laser-driven proton acceleration for radiobiological research

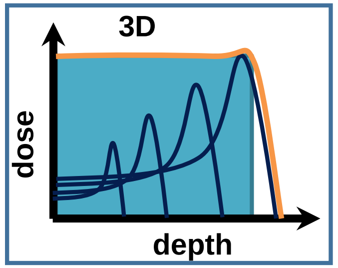






2020

ultra-high dose rate radiobiology @ HZDR

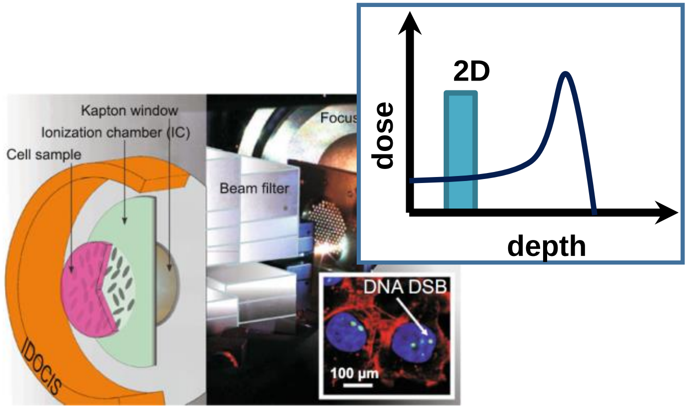


> 2015

Ti:Sa PW lasers

> 2009

in vitro radiobiology



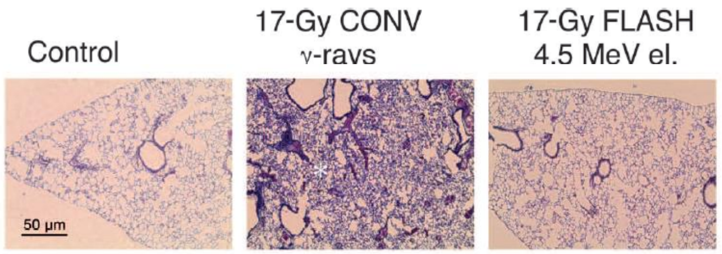
2005 to 2010

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

2000

~ 60 MeV protons at Nova PW (TNSA)

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



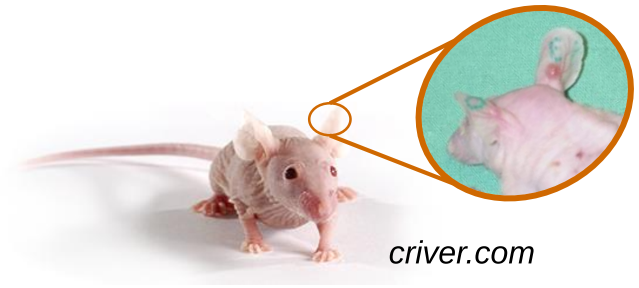
Favaudon et al. Sci. Transl. Med. 2014

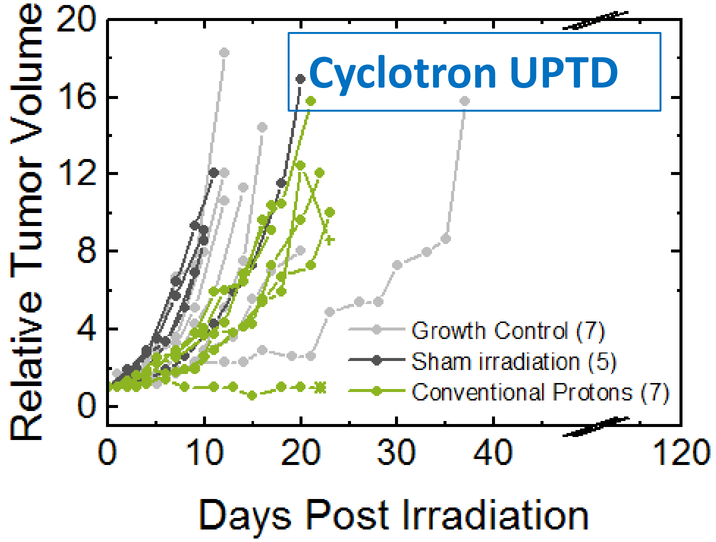
compact accelerators for radiotherapy **ultra-high dose rate** translational radiobiology

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





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

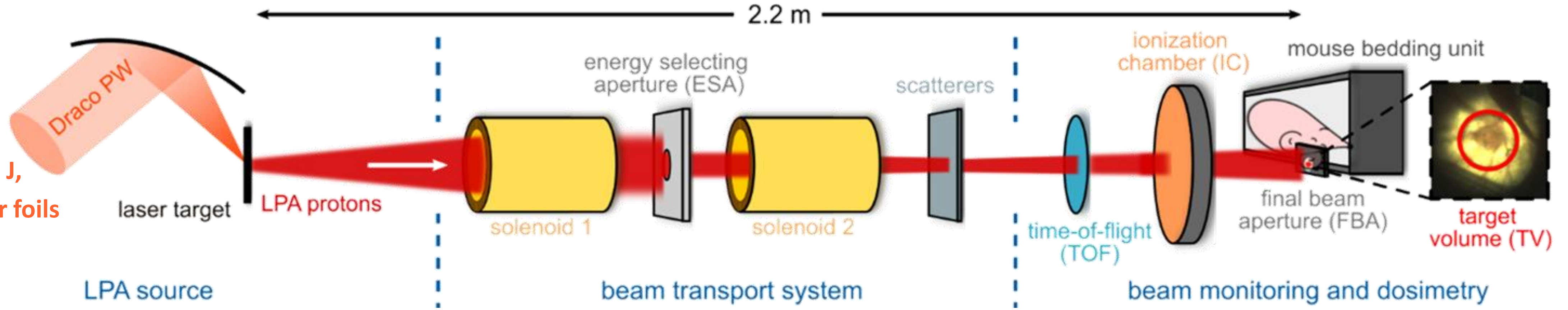
	Draco PW	UPTD
mean dose		3.9
single dose accuracy (2σ)		14%
dose homogeneity lateral/depth (2σ)		9%/2%
mean dose rate		3.6 Gy/min
peak dose rate		-

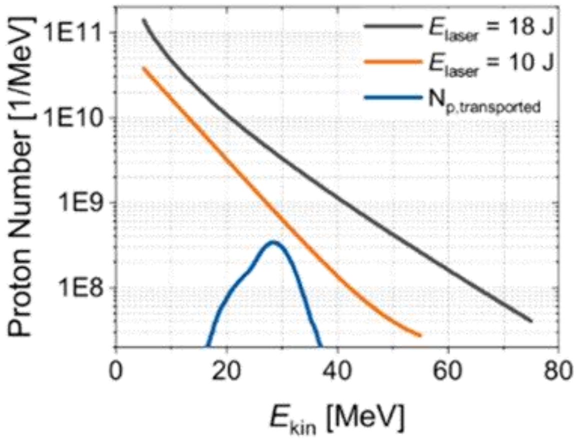
K. Brüchner et al., Radiat. Onc., Vol. 9 (2014)
Animal study approval DD24-5131/338/35

Small animal pilot study with laser-driven proton pulses

Setup at Draco PW

τ = 30 fs, E_L = 18 J,
200 nm Formvar foils





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

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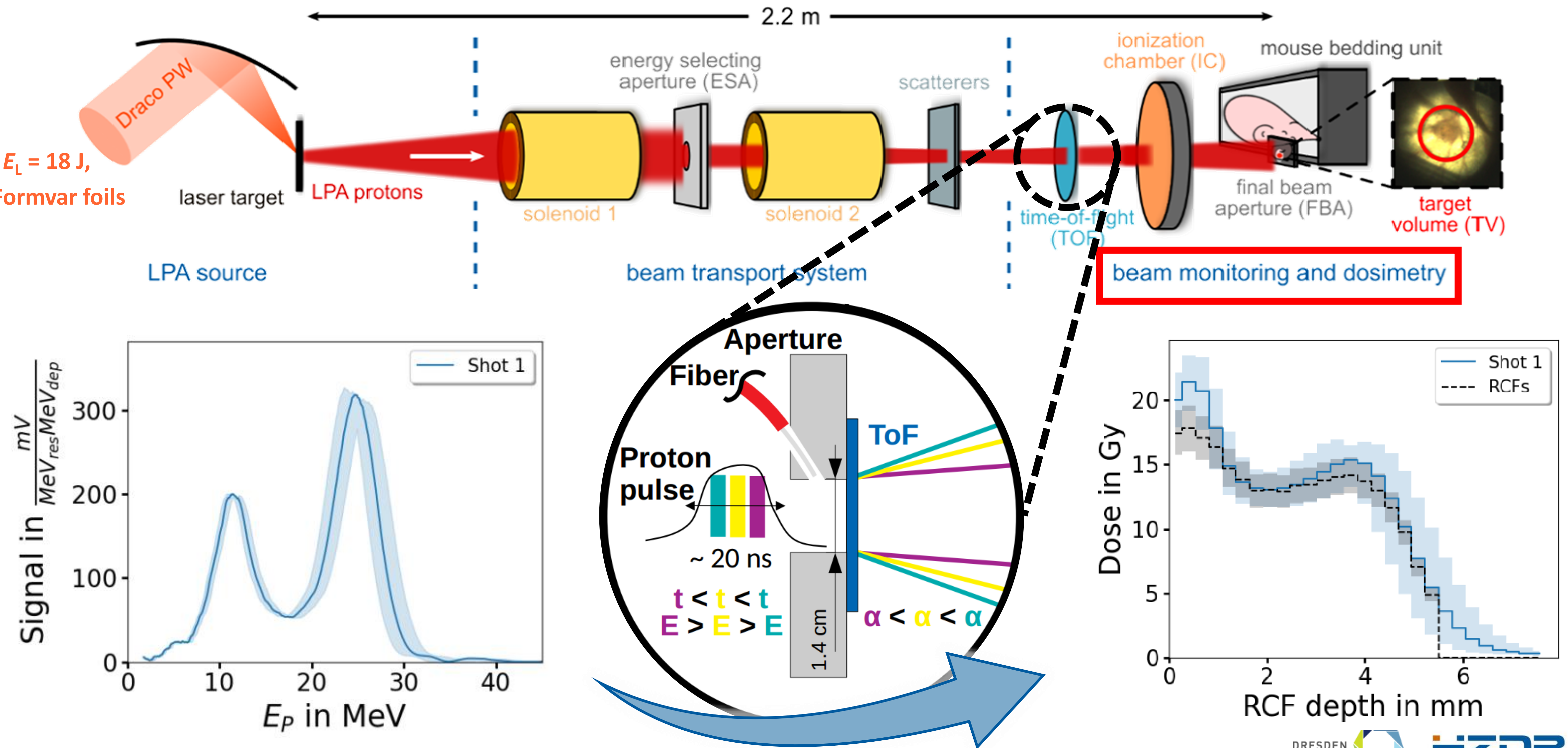

T. Ziegler *et al.*, Sci Rep 11 (2021); F.-E. Brack *et al.*, Sci Rep 10 (2020), F. Kroll *et al.* Nature Physics (2022), M. Reimold *et al.* in review

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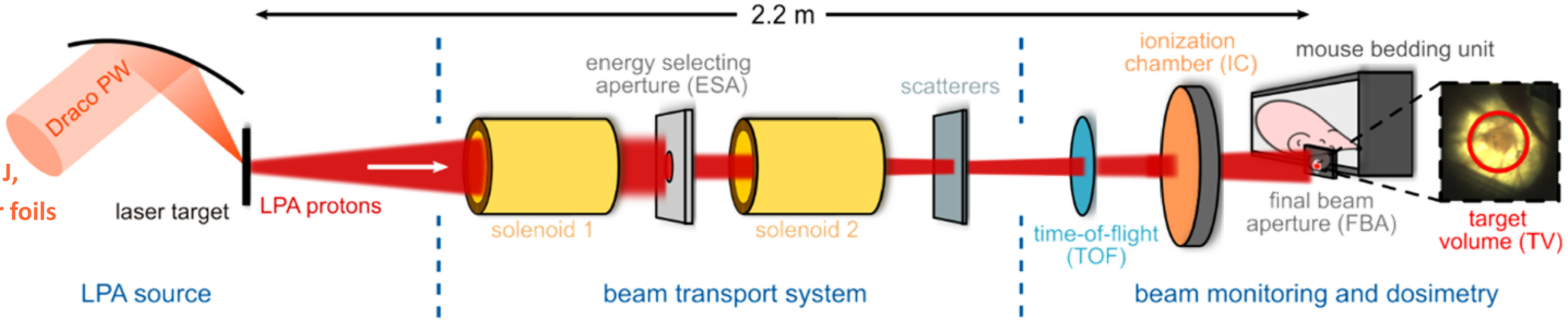
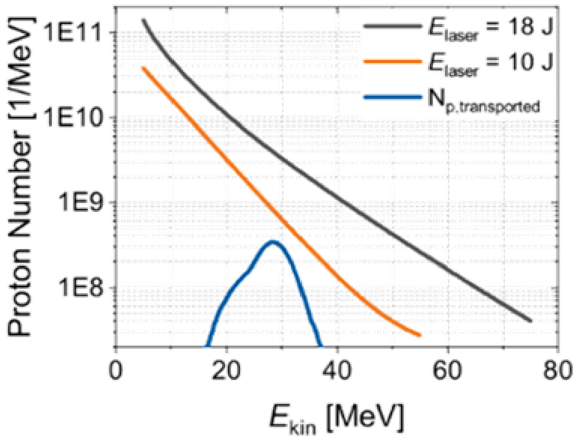
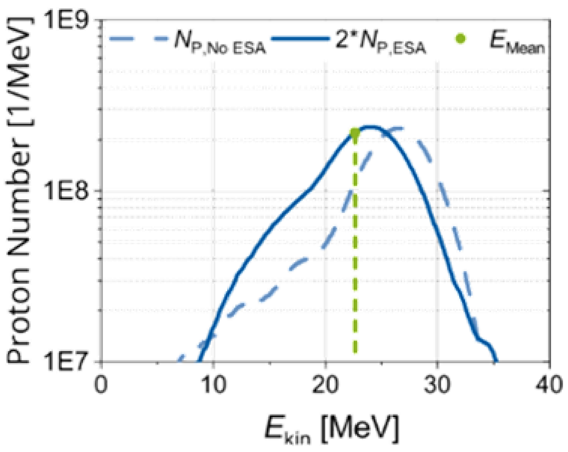
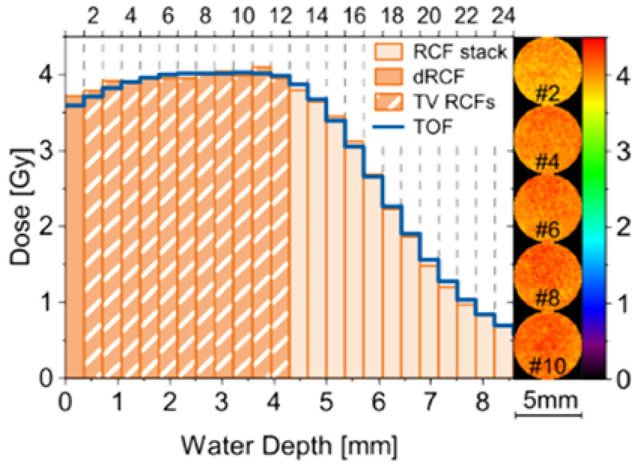






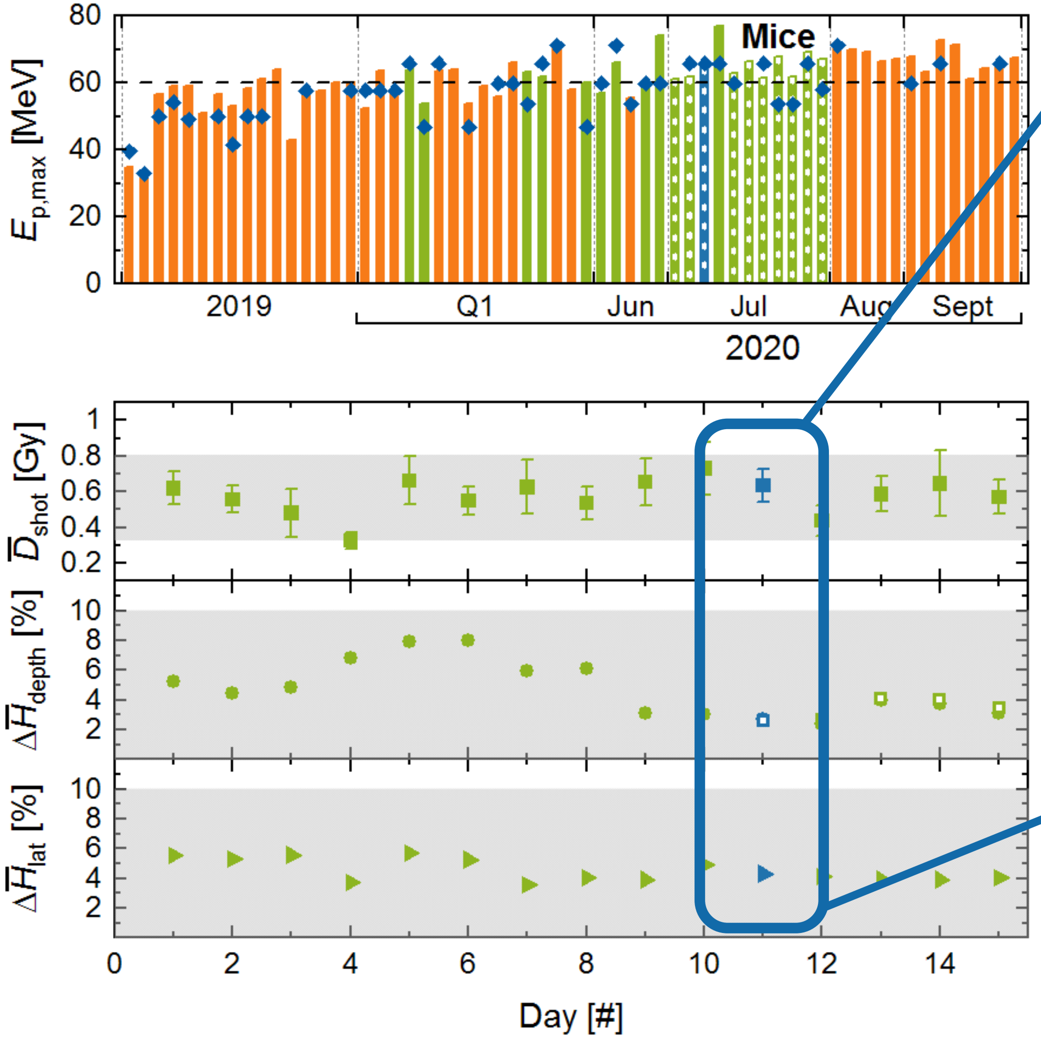


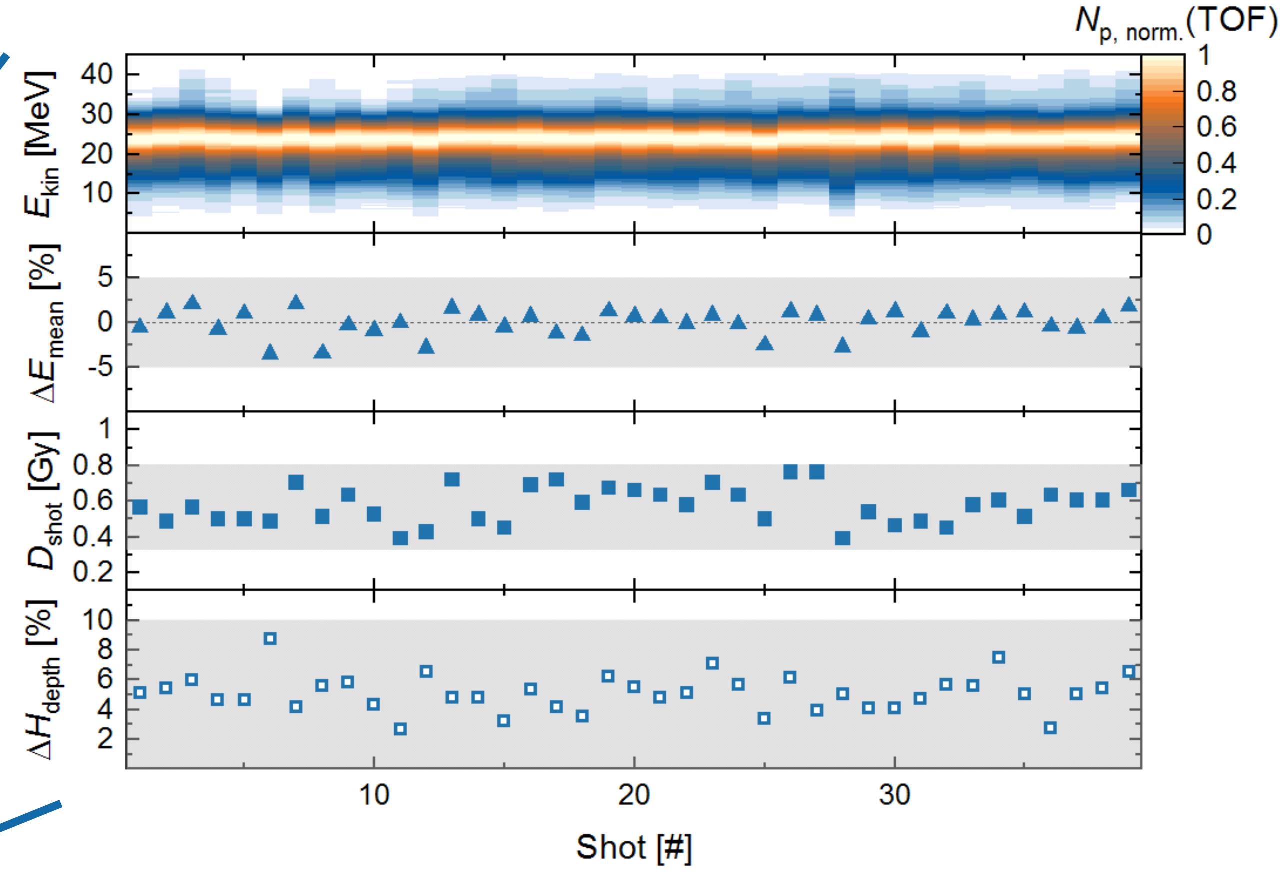
platform enables single-shot delivery of mm-scale 3D tumor-conform dose distributions making perfect use of the broadband LPA proton spectrum

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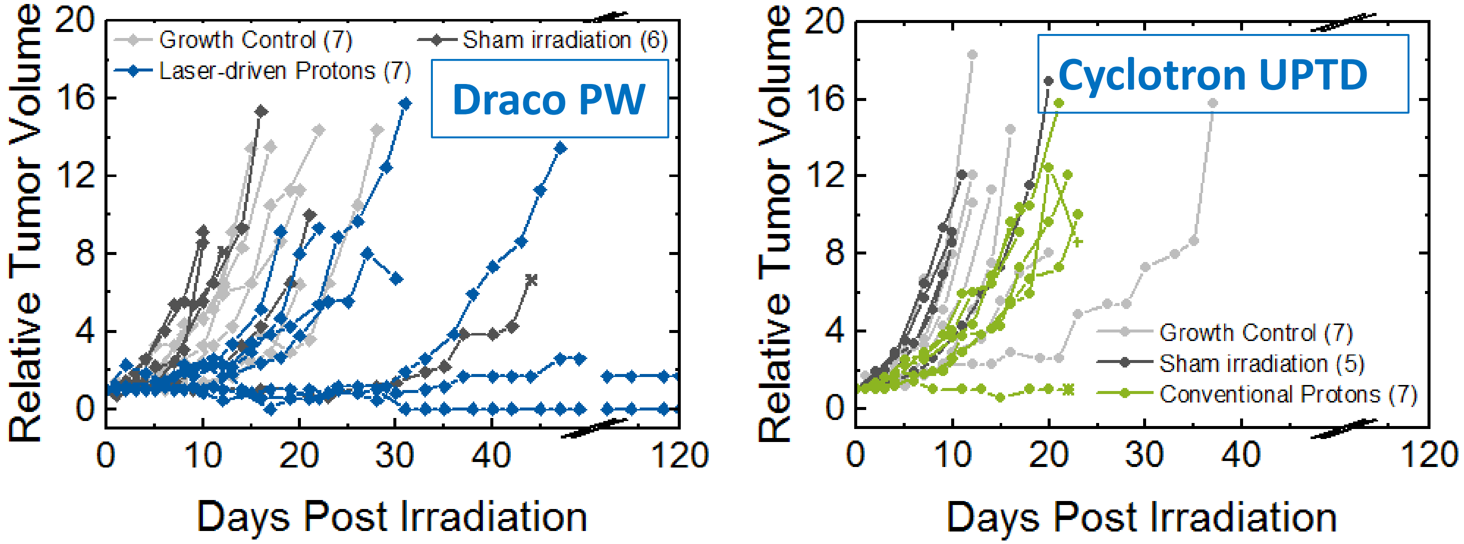
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

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	-

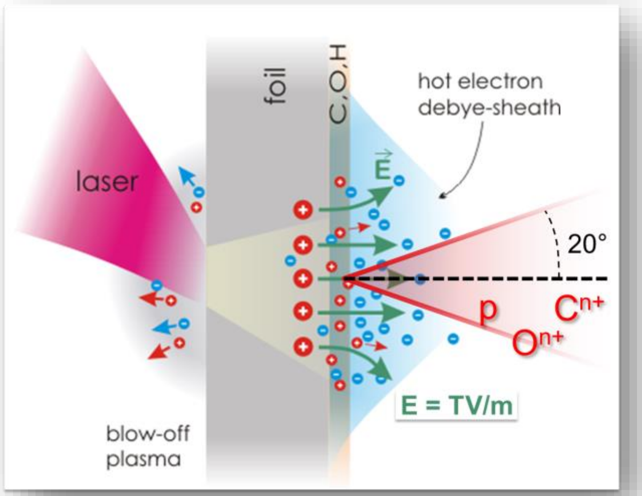
F. Kroll, et al., Nature Physics 18, 316 (2022)

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

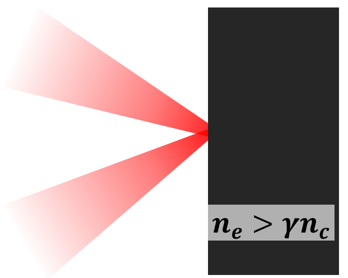
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Tailoring the target (plasma) density profile as decisive parameter

TNSA

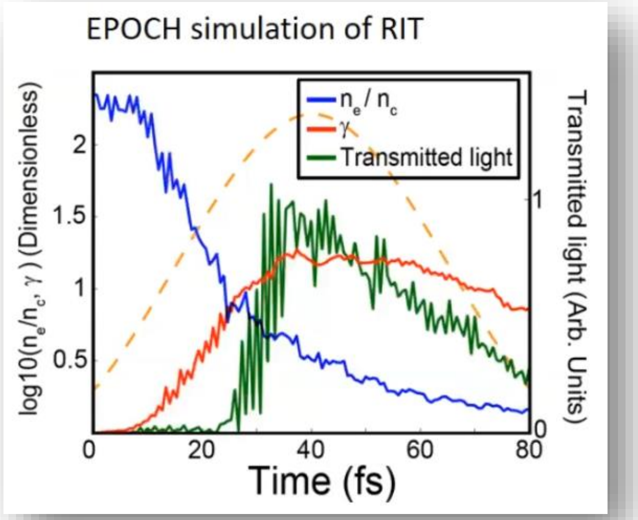


mirror-like behaviour
pulse mostly reflected

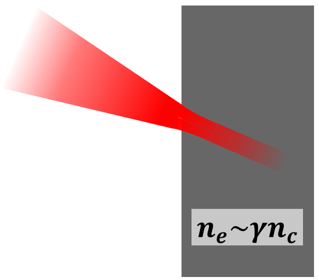


Relativistic transparency

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

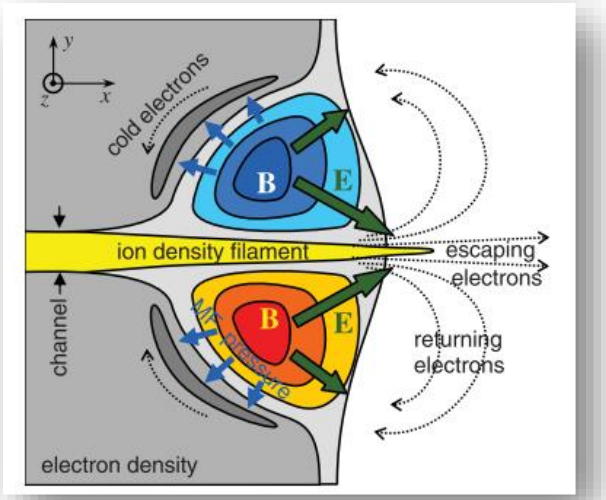


pulse mostly absorbed

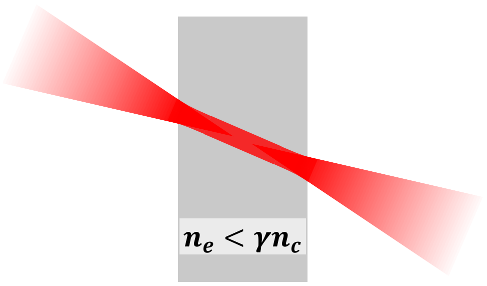


Magneto vortex acceleration

Bulanov & Esirkepov PRL (2007)



pulse mostly transmitted



Target density

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

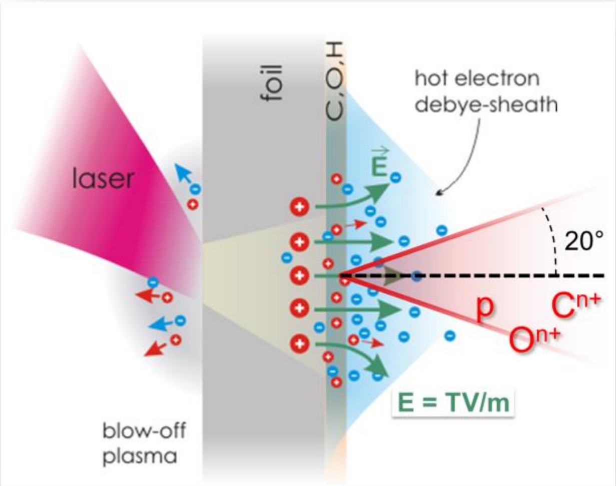
1.7 x 10^{21} cm^{-3} =$n_{critical}$[800nm]
near-critical density

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

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

Tailoring the target (plasma) density profile as decisive parameter

TNSA



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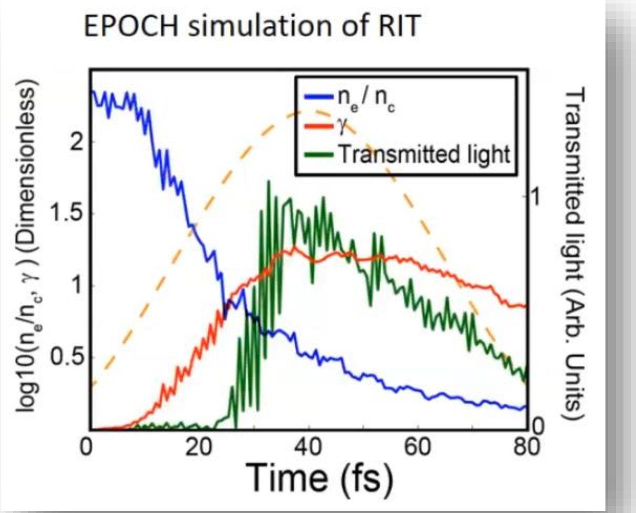

Magneto vortex acceleration

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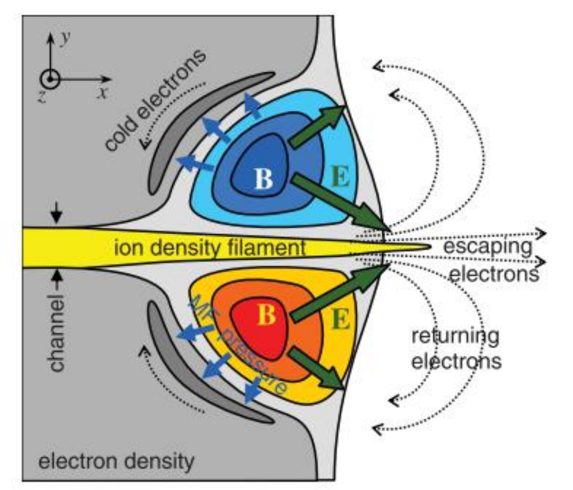

Solid H_2

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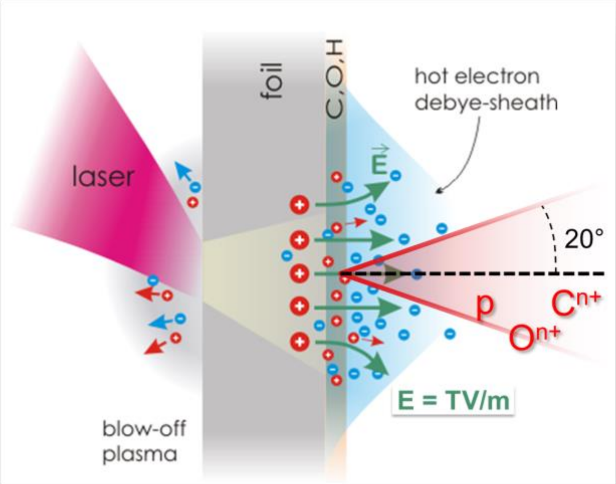
TNSA



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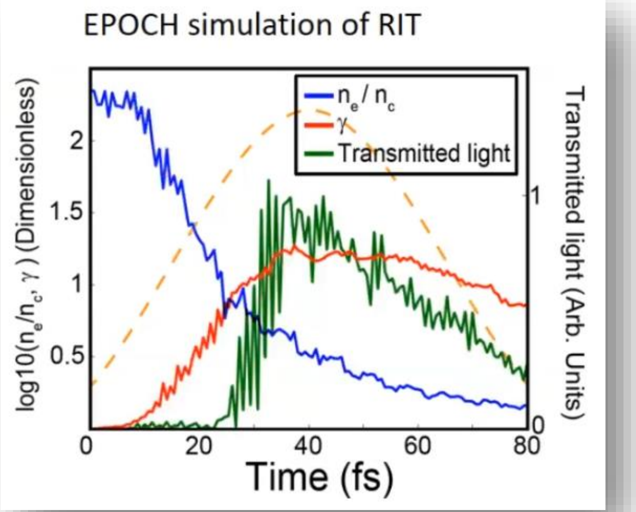

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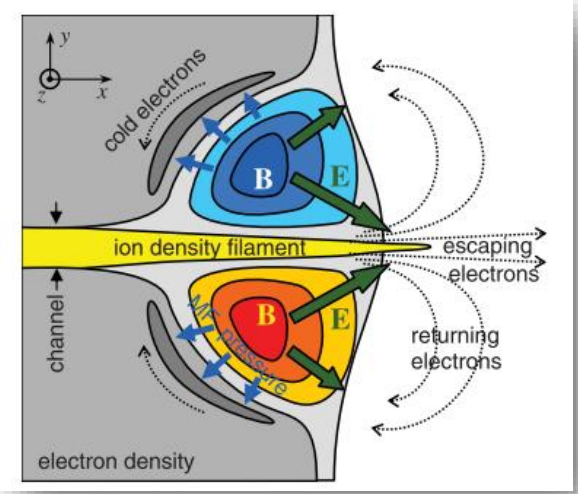
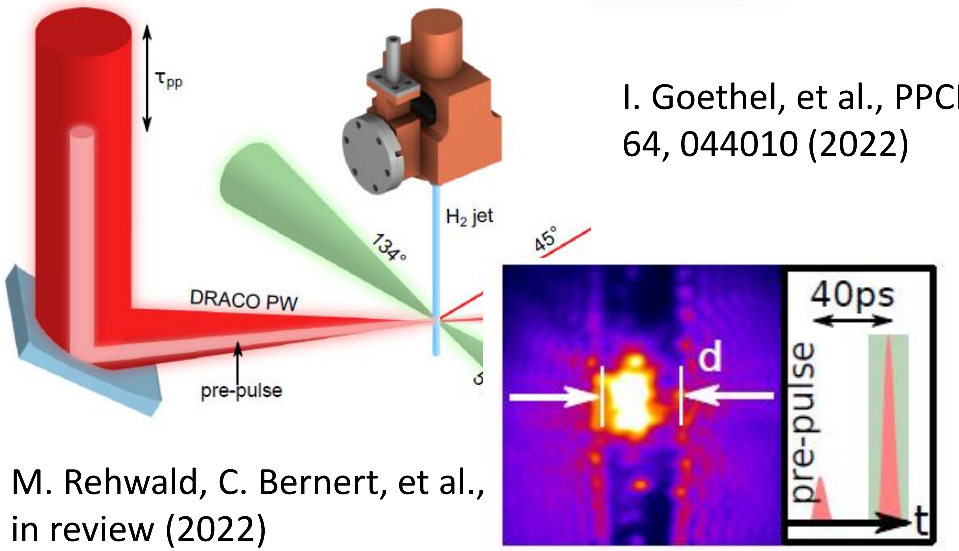


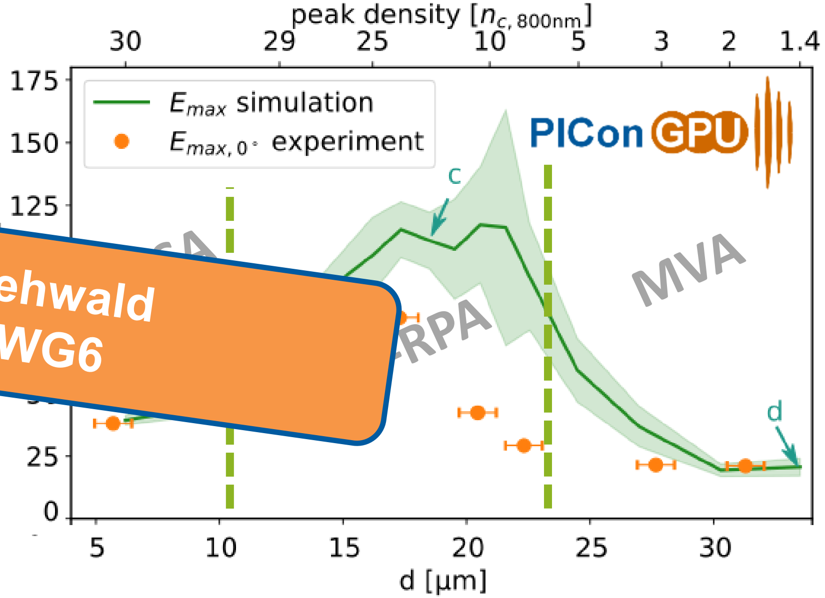


I. Goethel, et al., PPCF 64, 044010 (2022)

M. Rehwald, C. Bernert, et al., in review (2022)

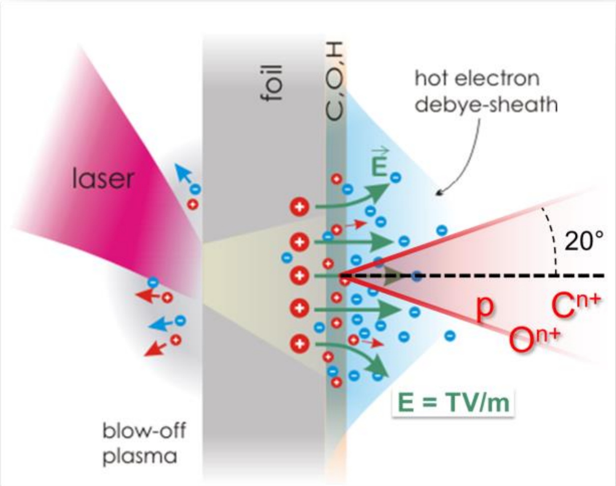
- On-shot hydrogen target density ...
- suppor... with d... rated target
- enabling quantitative simulation

Martin Rehwald
Tue @ WG6



Tailoring the target (plasma) density profile as decisive parameter

TNSA



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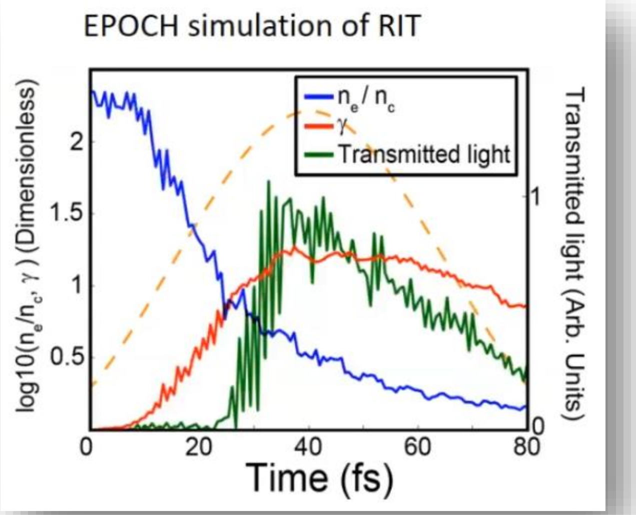
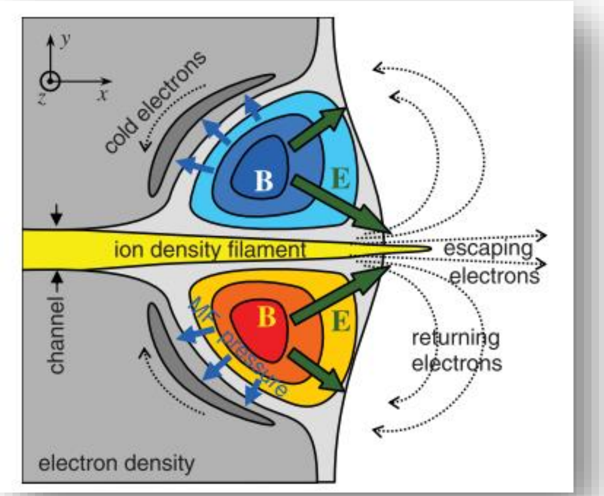
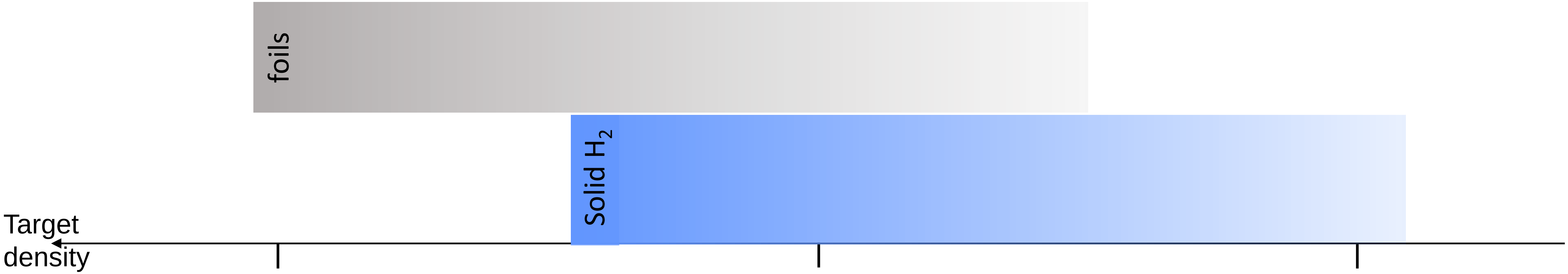


Magneto vortex acceleration

Bulanov & Esirkepov PRL (2007)





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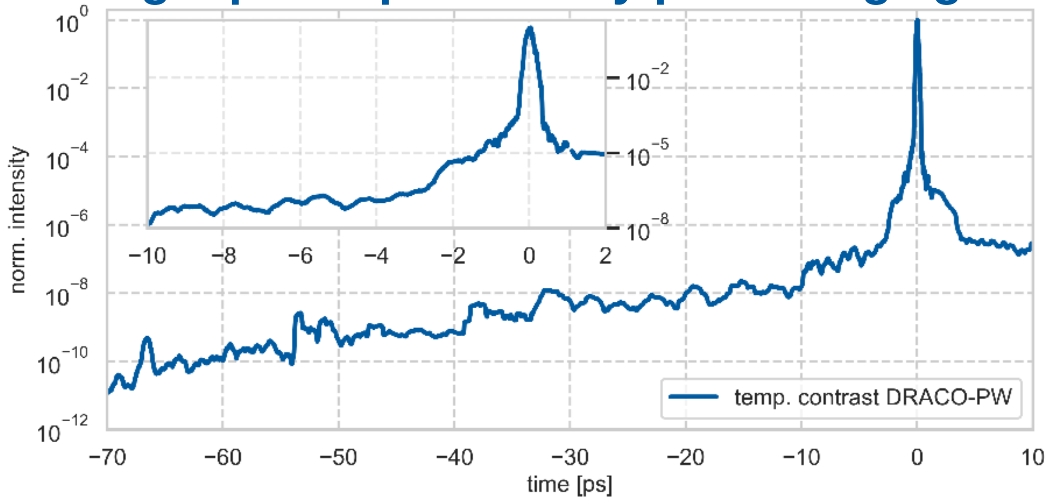
Dense, opaque target

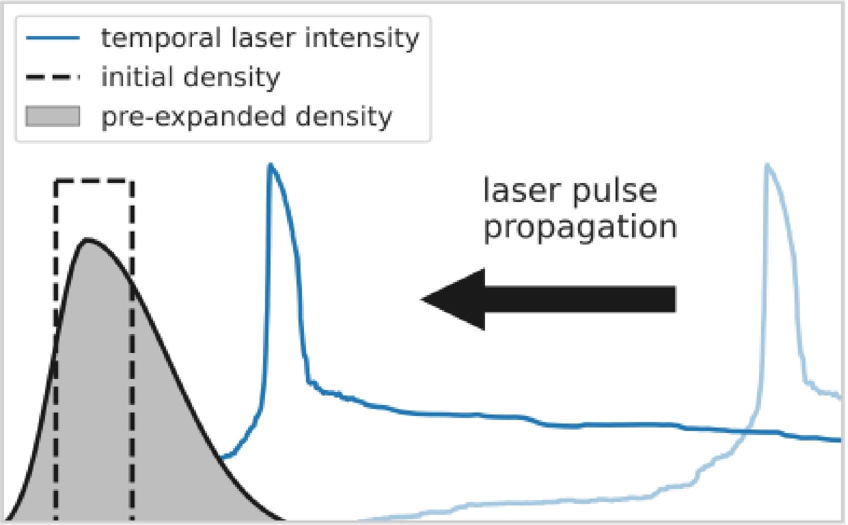
1.7 x 10^{21} cm^{-3} = $n_{critical}$[800nm]
near-critical density

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

Enhancing ion energies with relativistically transparent targets

target pre-expansion by preceding light



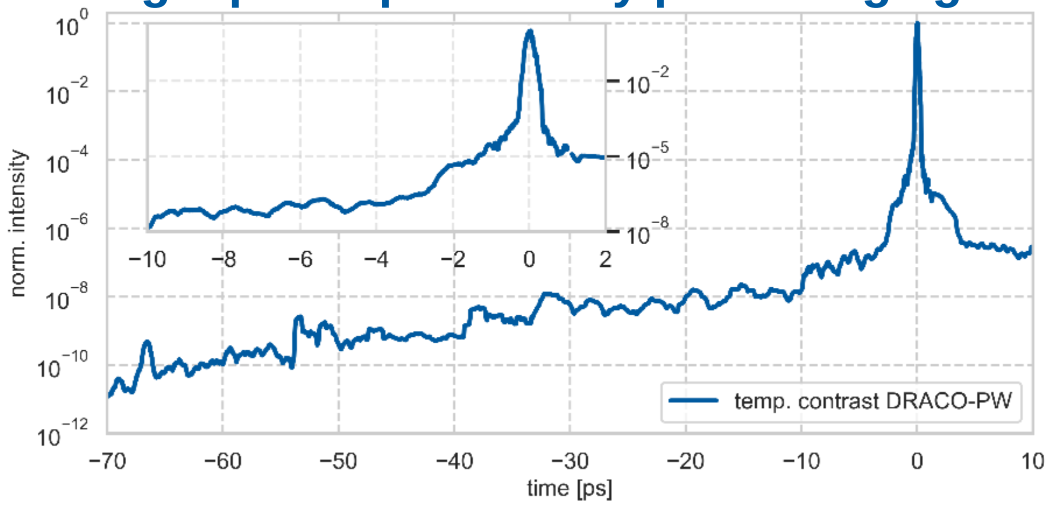


- **targets can get relativistic transparent during interaction**

  → increase absorption + coupling into ions + energies

Enhancing ion energies with relativistically transparent targets

target pre-expansion by preceding light

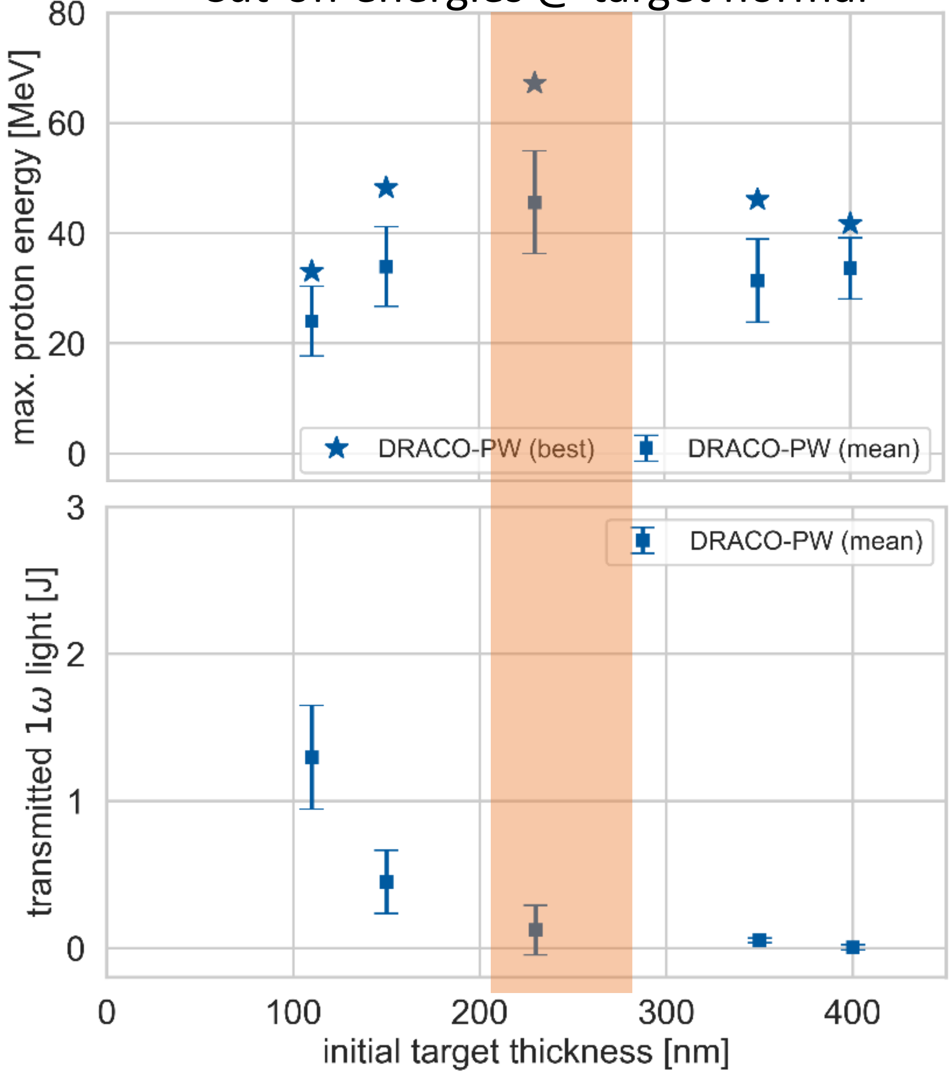


- targets can get relativistically transparent during interaction

  → increase absorption + coupling into ions + energies

- enhanced proton energies at optimal thickness
- onset of transparency at optimal thickness
- observation of forward acceleration

Cut-off energies @ target normal



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

Experimental setup

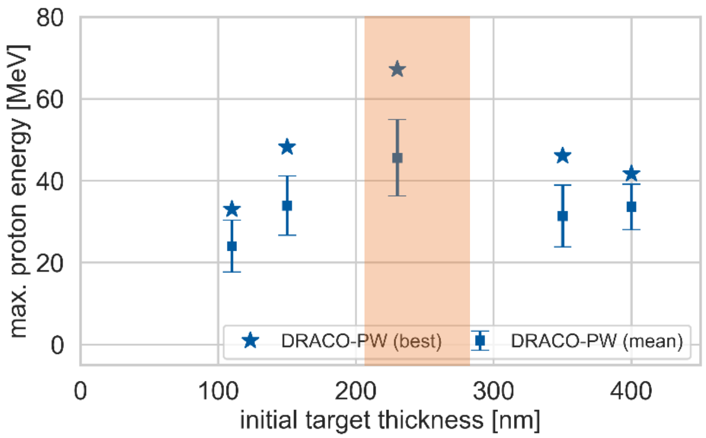
DRACO-PW

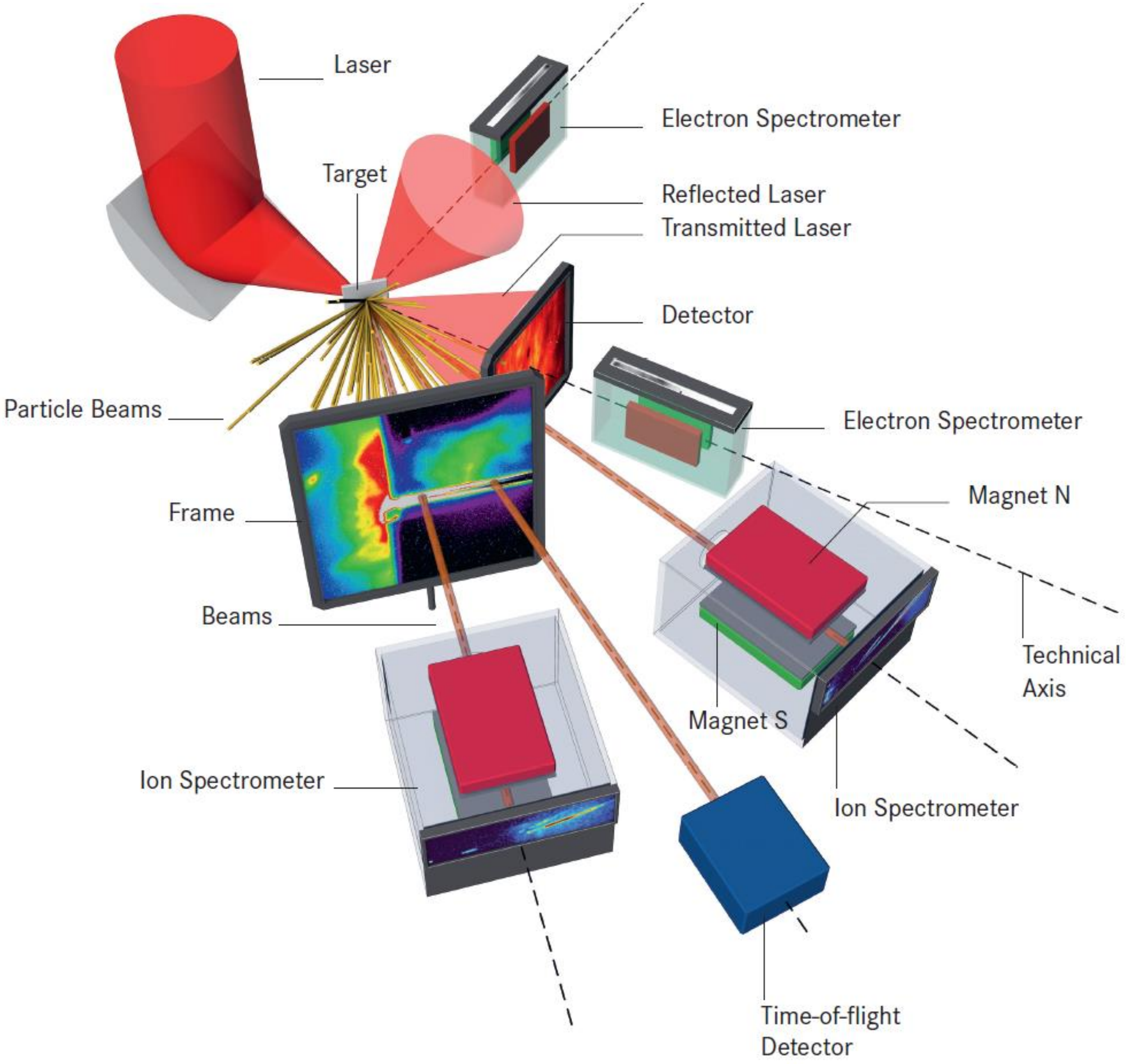
E_L = 22.4 J (on target), τ = 30 fs

F/2.3 OAP → 2.3 µm (FWHM)

I_{peak} = 6.5·10^{21} W/cm² (a0=55)

targets: 240±20 nm Formvar foils





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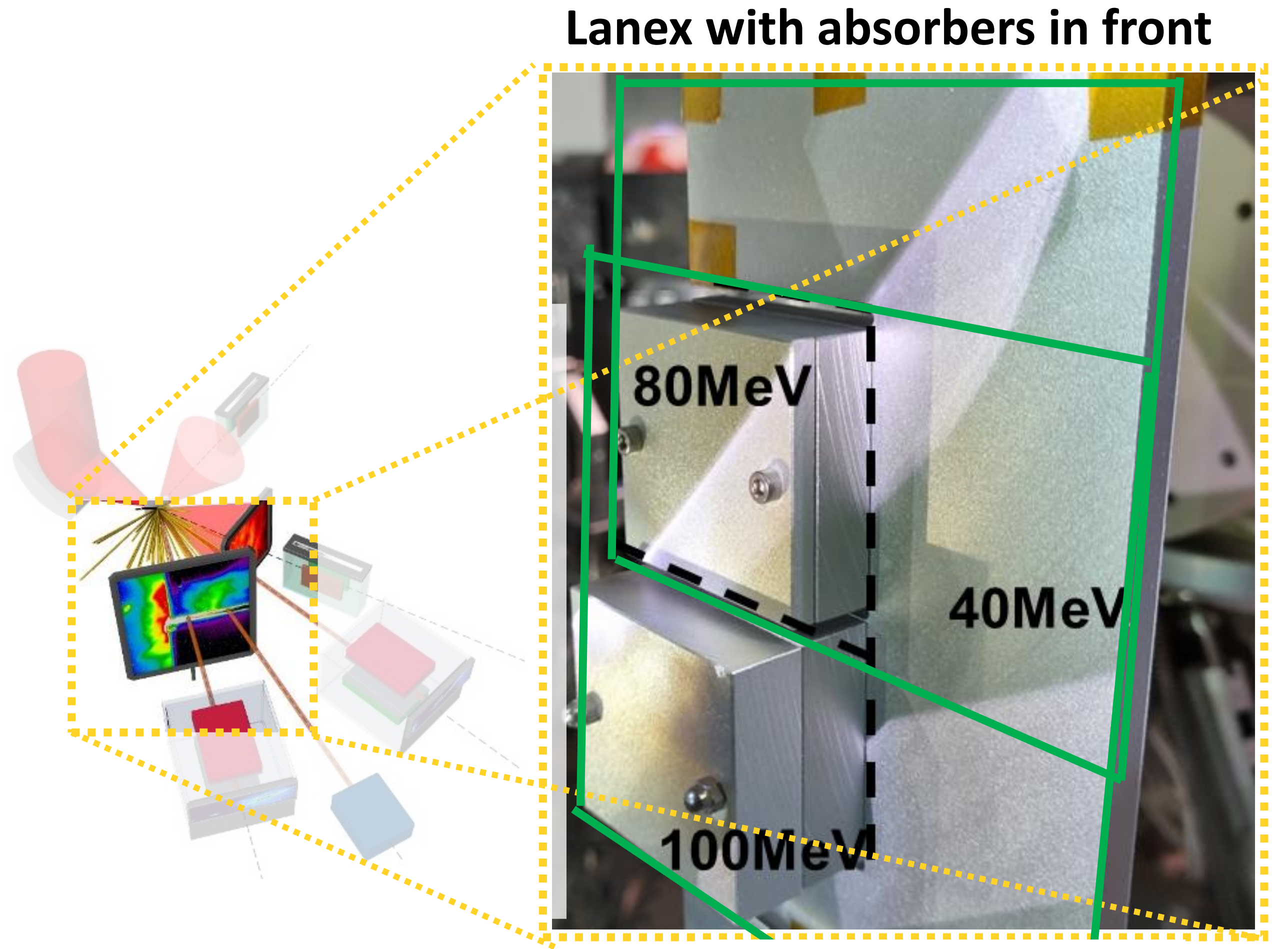
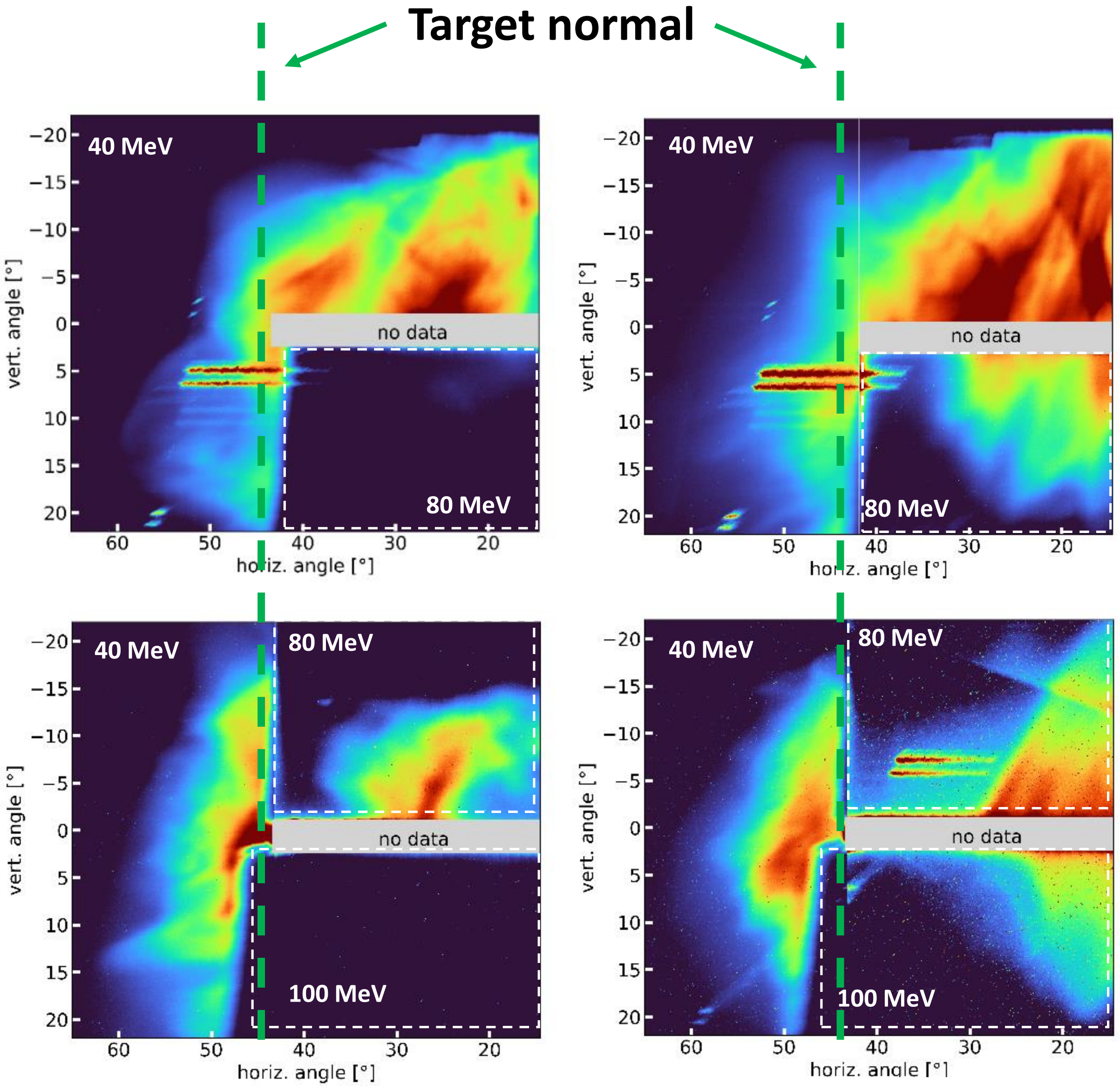
Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

Profiler: shift of acceleration direction towards laser axis



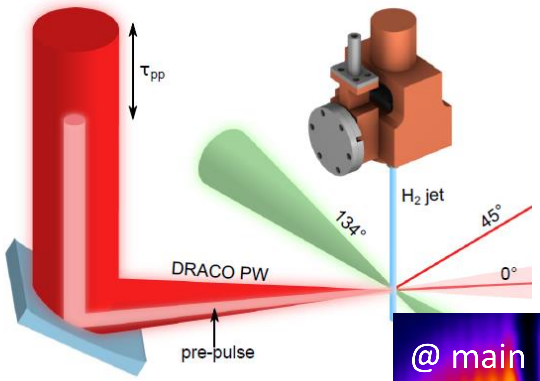


- **highest energies in forward direction**

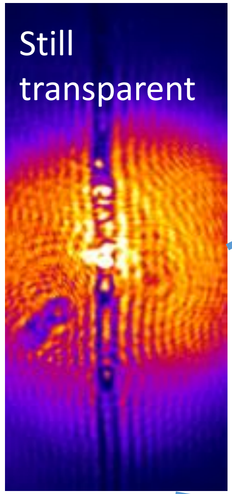
T. Ziegler, et al. unpublished

Microscopic understanding and robust performance

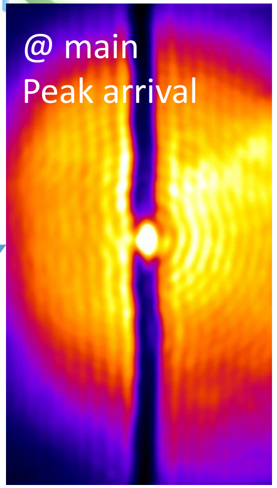
Characterization of the laser induced breakdown



C. Bernert et al. SciRep 12, 7278 (2022) & C. Bernert et al. Phys. Rev. Applied, under review (2022)

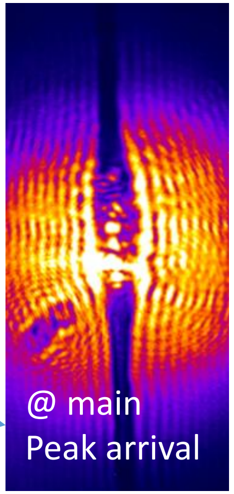


2 ps



High, PM cleaned contrast

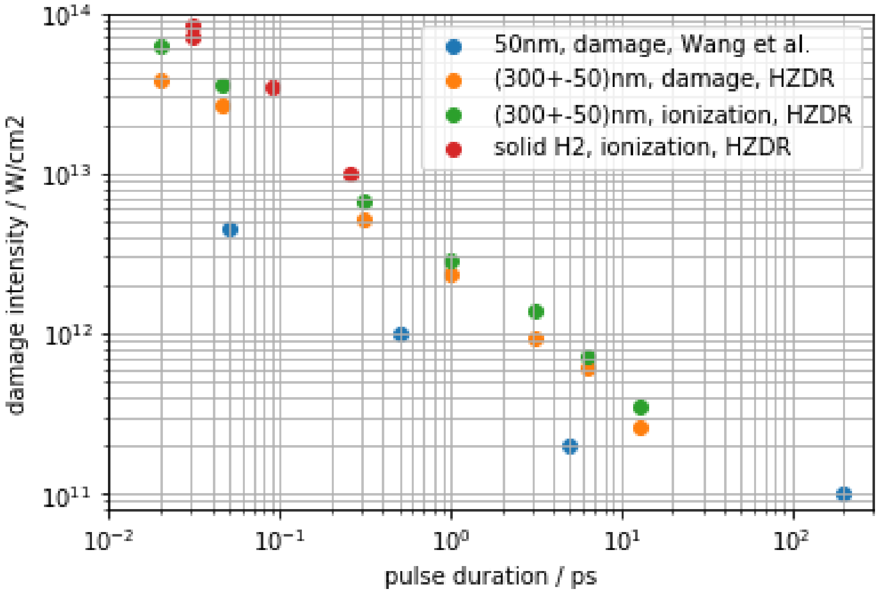
Low, intrinsic contrast



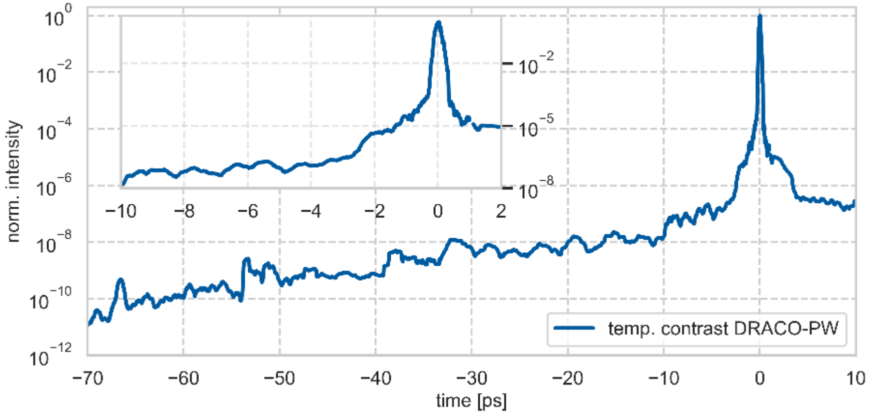
ca. 70 ps

We can characterize the start of the interaction at full energy laser shots,

… precisely measure the threshold intensities at low intensities,



… and correlate to the full energy temporal laser contrast (what is real).

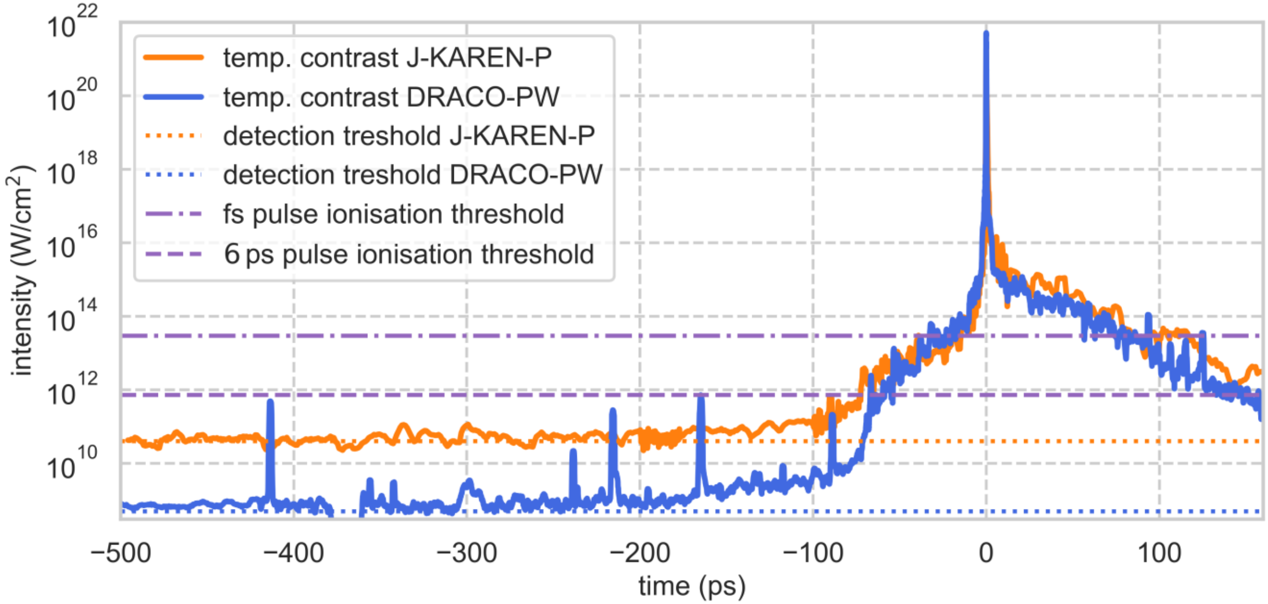


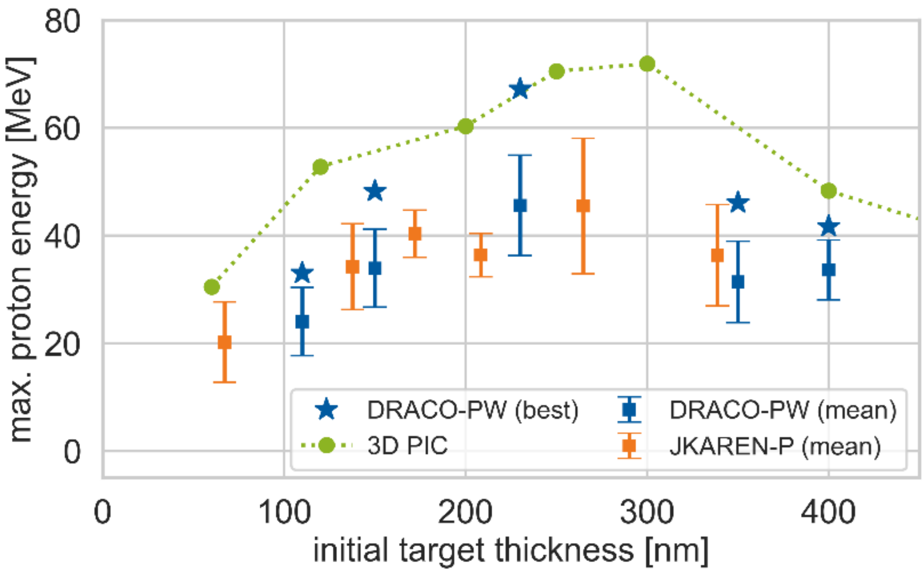
→ Input for start-to-end simulation frameworks based on MHD and 3DPIC.

Microscopic understanding and robust performance

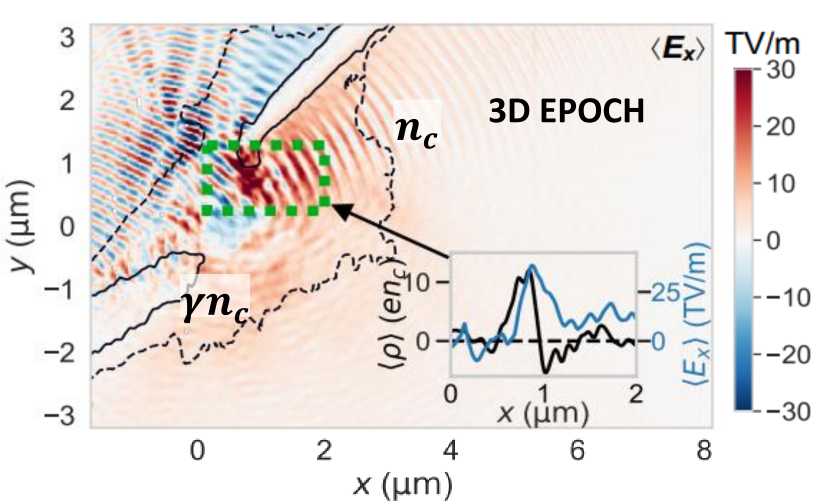
Comparing pre-expanded thin foil studies at two laser systems w/o PM

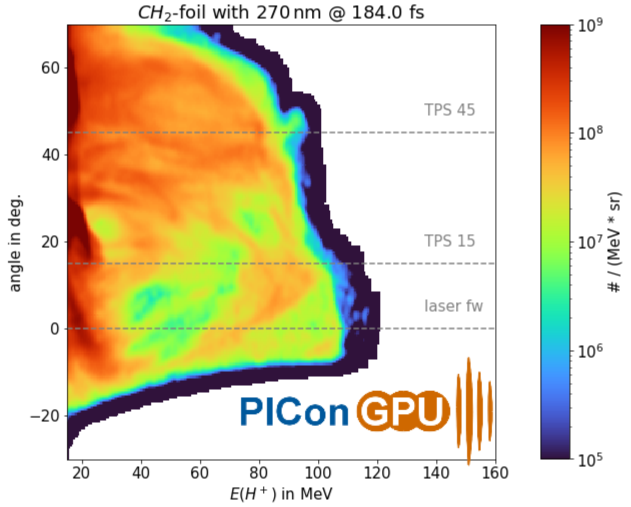
Coordinated laser and plasma diagnostics provide similar results





... and enable the establishment of start-to-end simulation framework based on MHD sims and two 3D PIC codes.

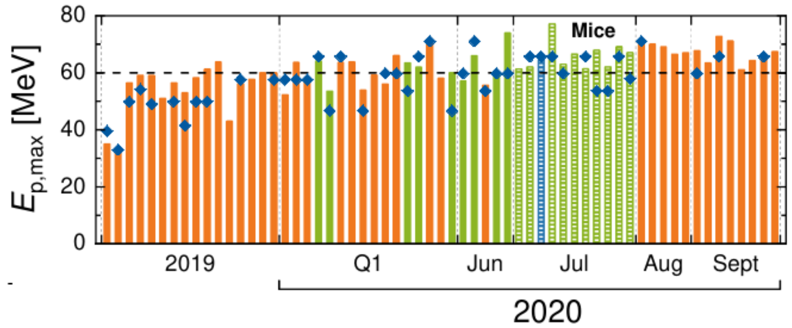


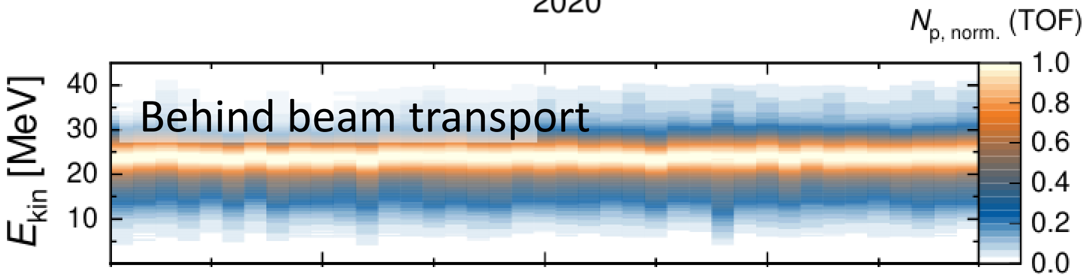


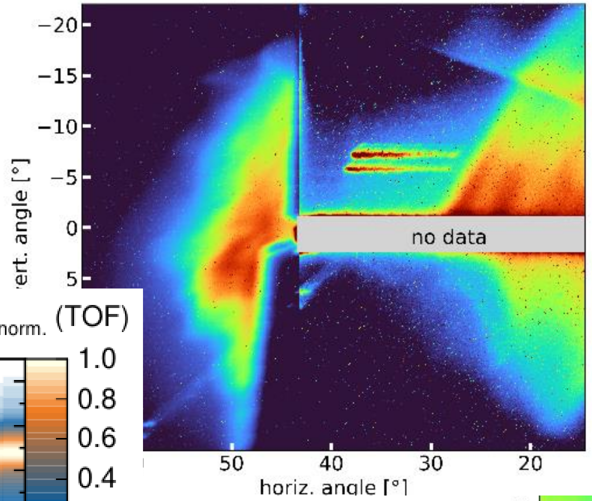
N. Dover, T. Ziegler, et al. in review (2022)

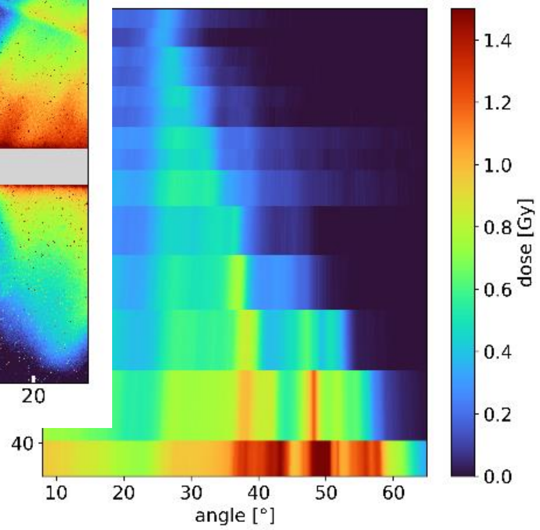
Conclusion

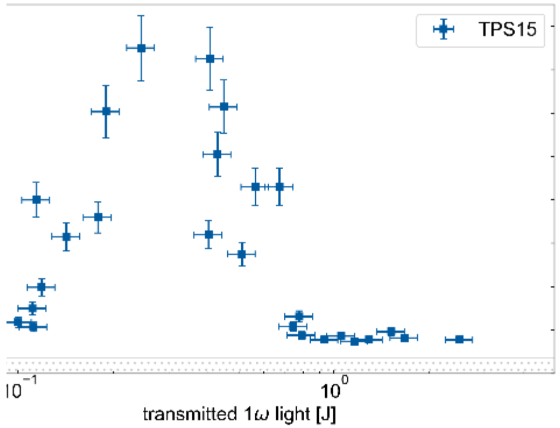
1. Stable TNSA beam performance enabled first volumetric in-vivo irradiation of mice
2. Combining multiple detector systems based on different principles to confirm energies >100 MeV in pre-expanded foils
3. High energy, bandwidth limited pulses from rep-rate capable laser system
4. Understand and mitigate strong fluctuation is work in progress











Big Thanks to the Team and Collaborators

Laser radiooncology

Laser particle acceleration

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K. Zeil, J. Metzkes-Ng, F. Kroll, S. Assenbaum, C. Bernert, F. Brack, E. Beyreuther, L. Gaus, S. Kraft, A. Nossula, M.E.P. Umlandt, M. Rehwald, M. Reimold, M. Vescovi, H.-P. Schlenvoigt, M. Sobiella, T. Ziegler, T. Kluge, I. Goethel, S. Bock, R. Gebhardt, U. Helbig, T. Püschel, U. Schramm, T. Cowan, et al.
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Thank you for your attention!