

Stable acceleration of proton beams to energies beyond 80 MeV at rep-rated laser systems

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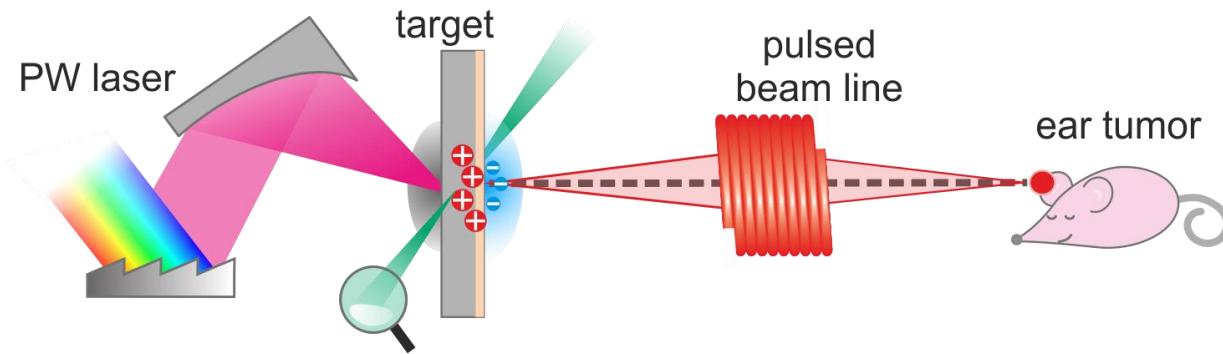
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4) John Adams Institute for Accelerator Science, Imperial College London, London, United Kingdom

5th European Advanced Accelerator Concepts Workshop



Laser-driven proton sources for high-dose rate radiobiology

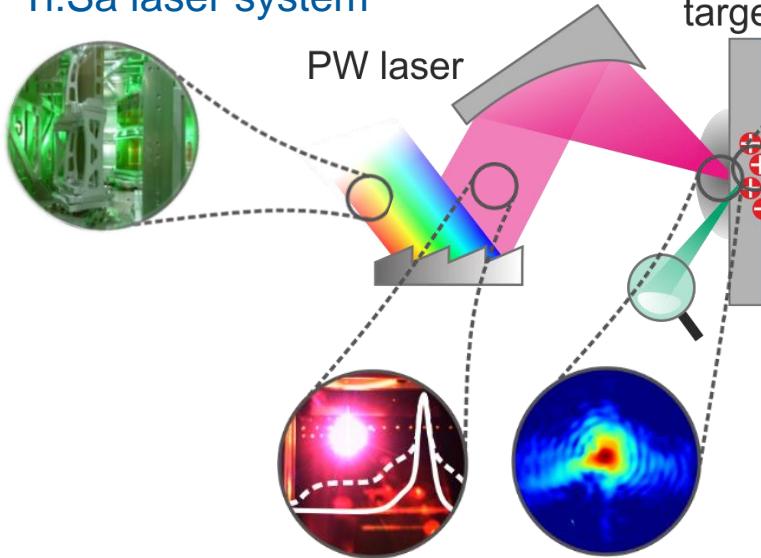


major hurdles for a laser-driven plasma accelerator:

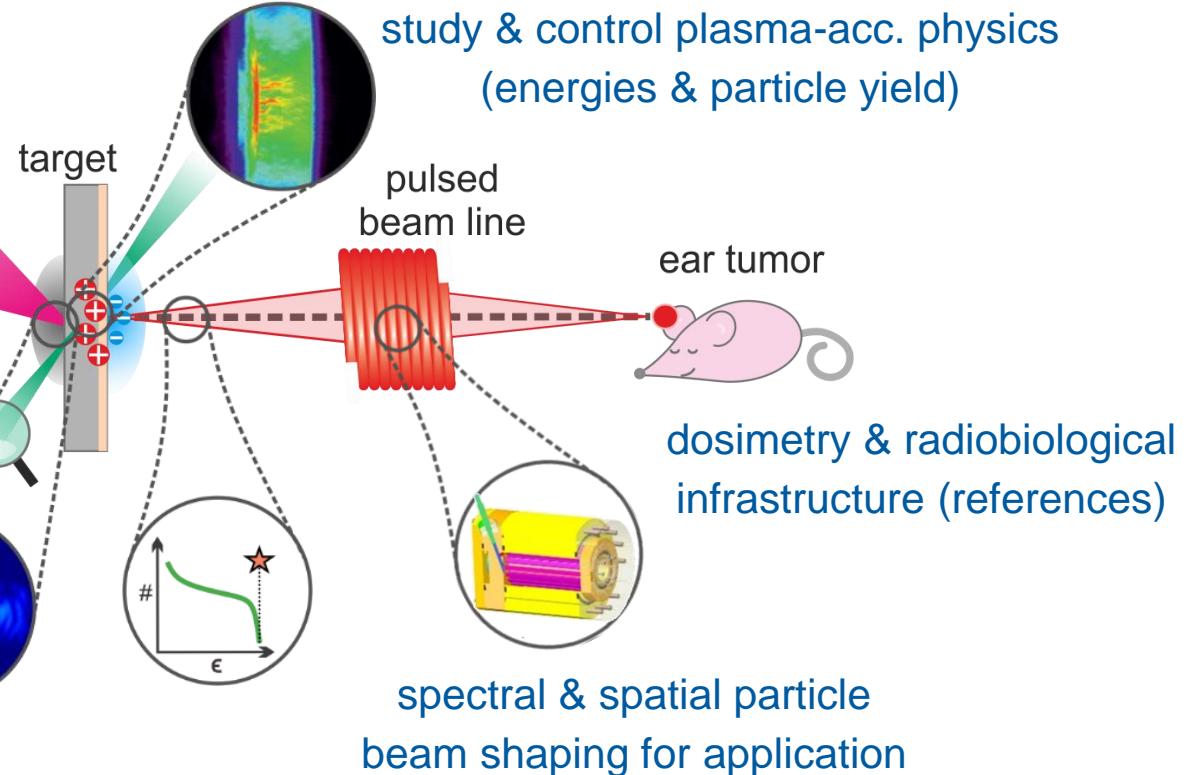
performance, instrumentation, readiness and stability level

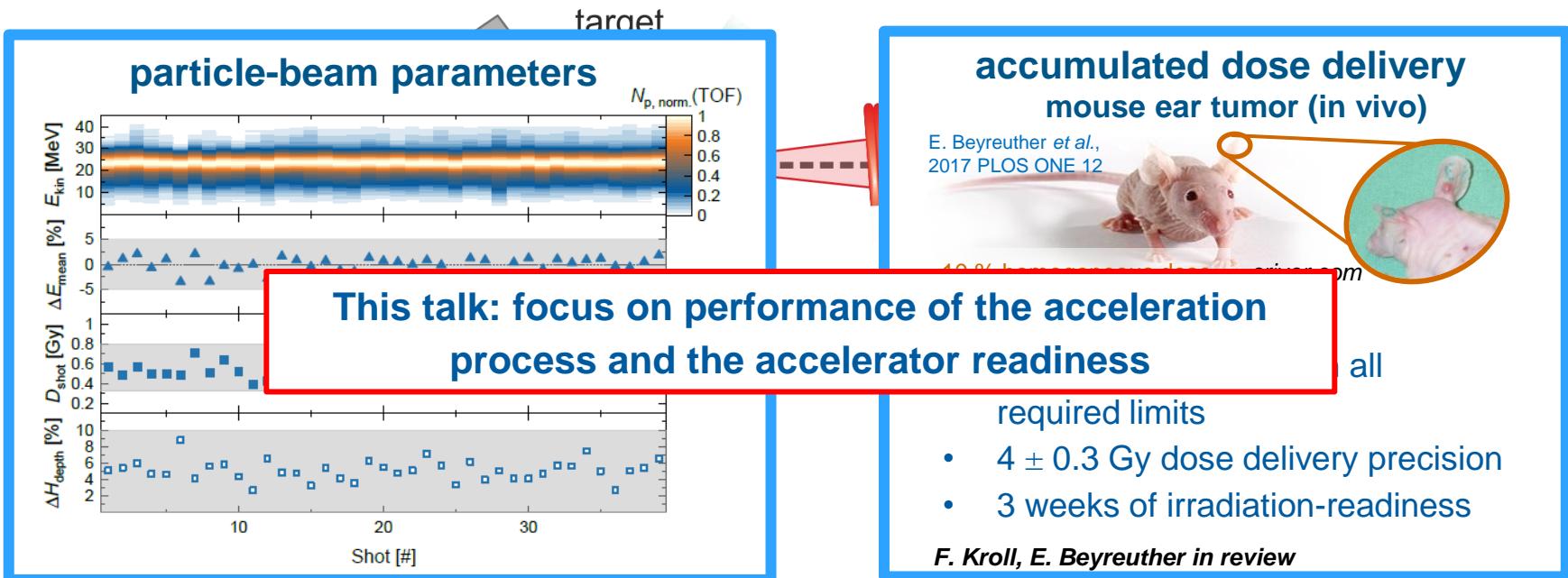
Laser-driven proton sources for high-dose rate radiobiology

PW-class double-CPA
Ti:Sa laser system

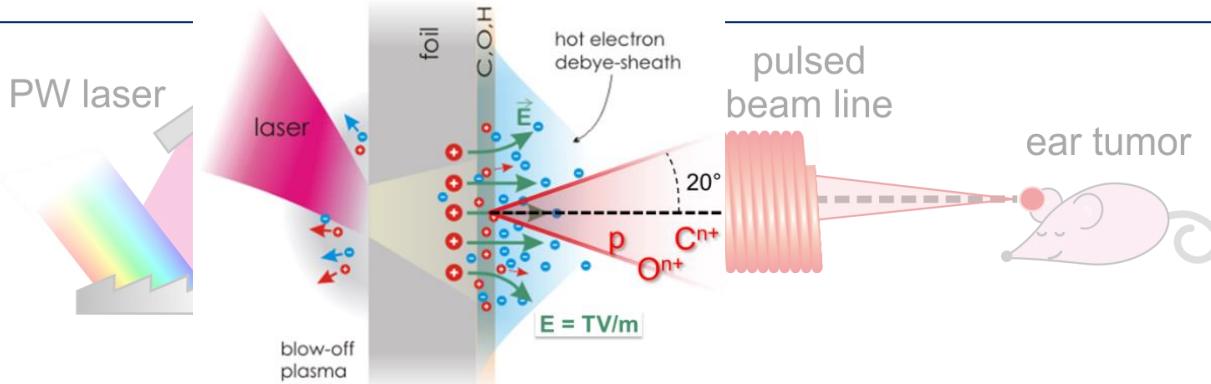


laser metrology & control
→ preserve laser-system quality





Controlling the plasma acceleration



- TNSA as established, intensively studied & robust scheme
- advanced & hybrid schemes promise to enhance performance:
 - for very thin targets
 - at near critical densities

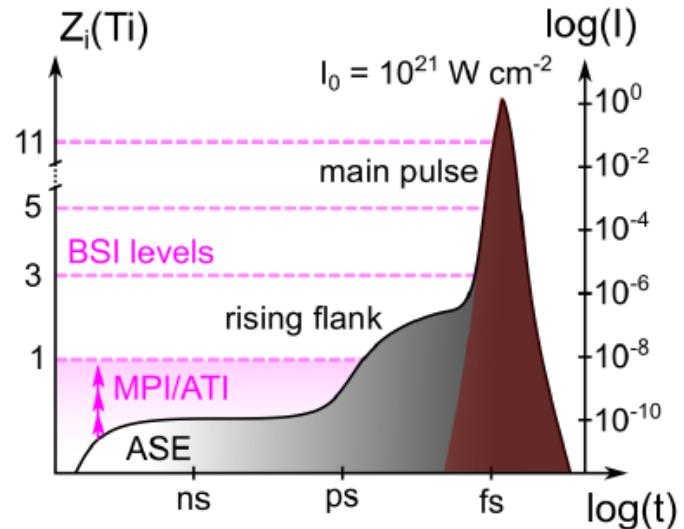
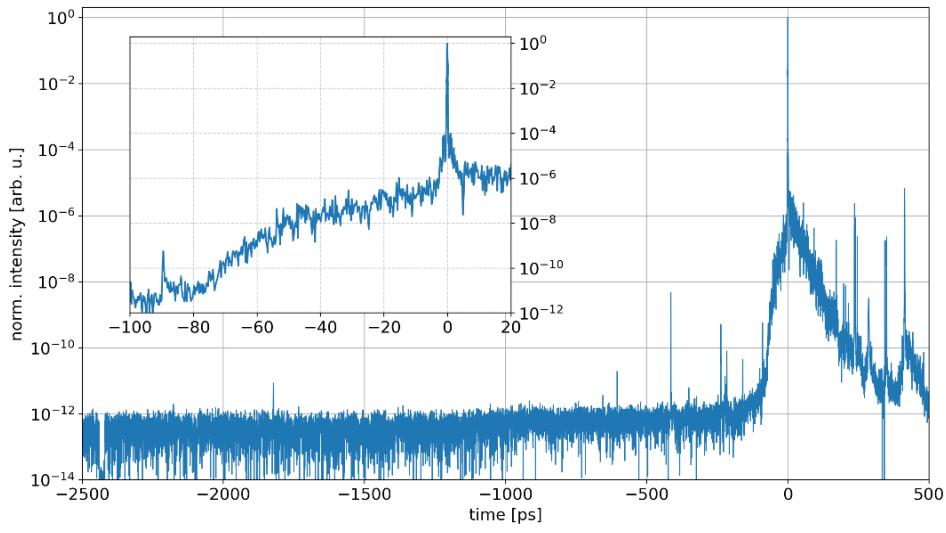
1st part

2nd part

ion-acc. is complex indirect, nonlinear process

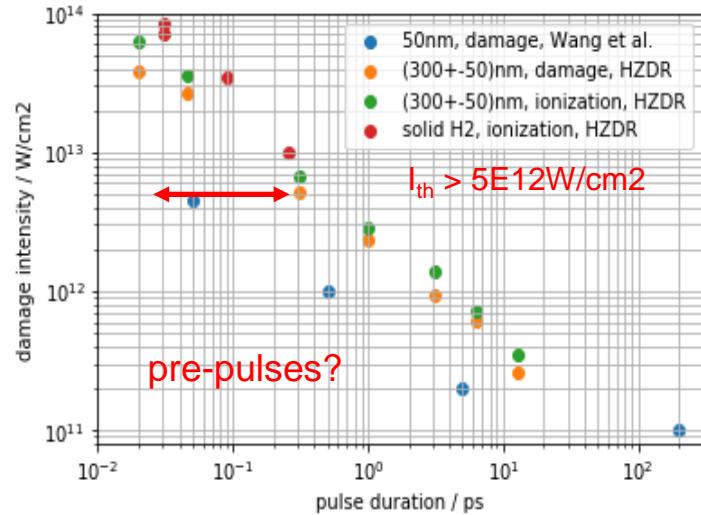
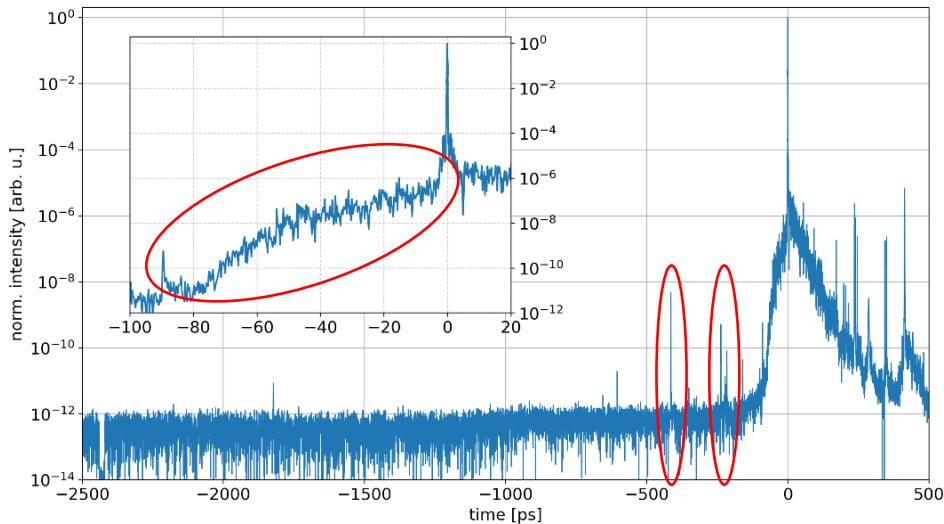
→ high sensitivity on input parameters → control of temporal pulse contrast

Control of temporal laser-pulse contrast



- temporal pulse contrast: ratio of peak intensity to the intensity at a certain time
- ideally: delta-distribution
- reality: ASE influence (ns-timescale) + uncompressed coherent light (ps-timescale) + pre-pulses & post-pulses

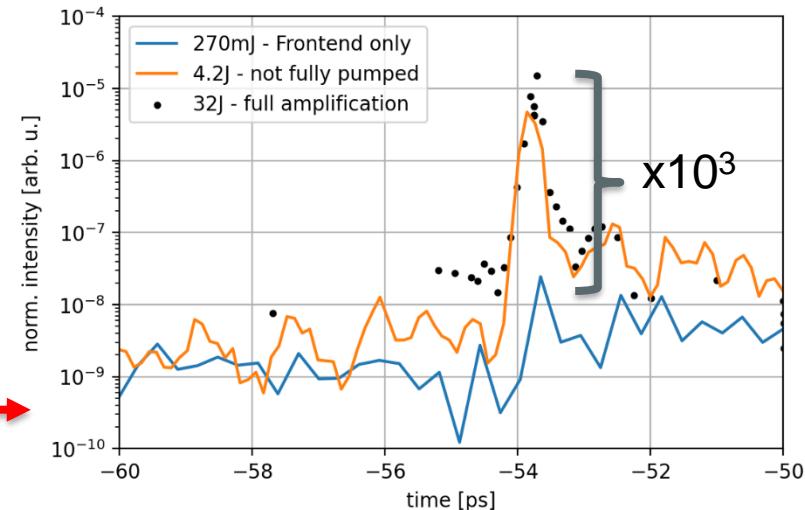
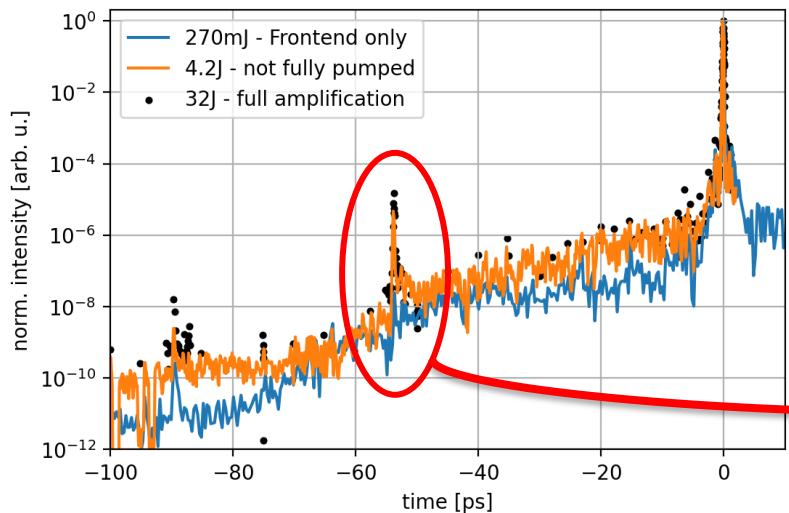
Control of temporal laser-pulse contrast



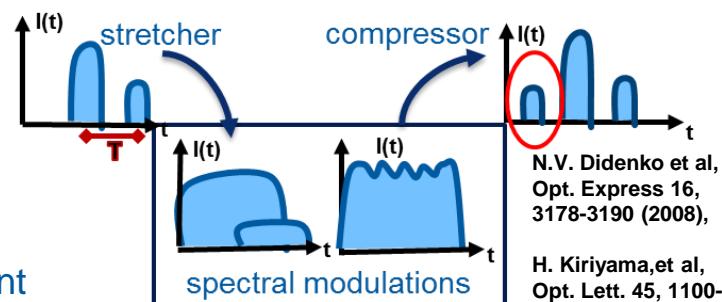
D. Wang et al., HPLSE (2020), S. Assenbaum in preparation

- identify and understand role of short pulse pre-pulses and pedestal for ionization process
- established optical probing technique @ HZDR → pulse duration dependence ionization measurements
- pre-pulse level crucial → detailed check needed

Control of temporal laser-pulse contrast at full energy



- difference between pumped and unpumped main amplifiers (pedestals + pre-pulses)
- modulation of propagating field structure by non-linear phase
- ionization threshold reached → suppress with intensity dependent filter-system → plasma-mirror



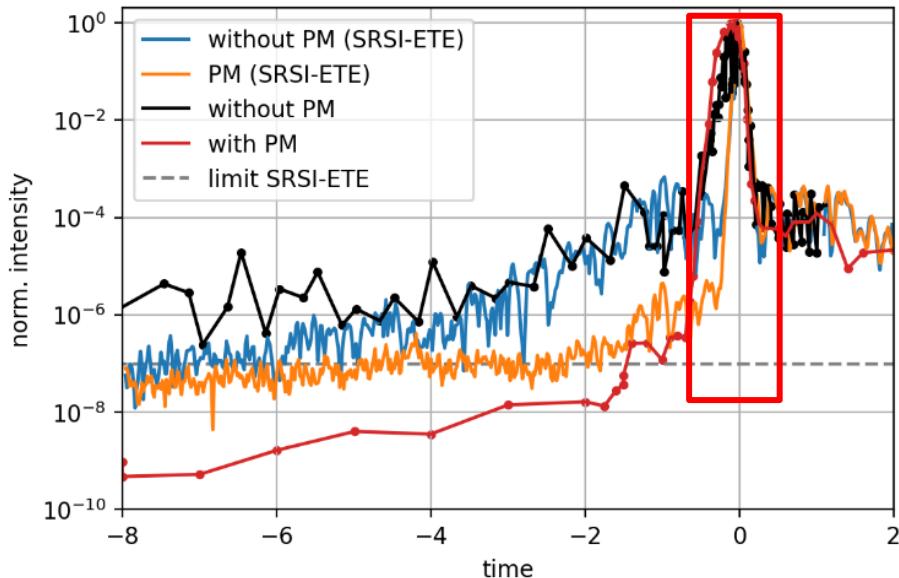
N.V. Didenko et al,
Opt. Express 16,
3178-3190 (2008),

H. Kiriyama, et al,
Opt. Lett. 45, 1100-
1103 (2020)

Plasma-mirror (PM) implementation for contrast cleaning

- cleaning quality of PM (experiment data)
→ $2.1 \text{e-}4$ (TOAC) vs $2.3 \text{e-}4$ (photometer)
→ pre-pulse reduction
- temporal contrast level after PM:
 - $< 1\text{e-}13$ @ -100ps
 - $\sim 1\text{e-}10$ @ -10ps
 - $\sim 1\text{e-}07$ @ -1ps
- trigger point PM: $\sim -600\text{fs}$

SRSI-ETE: T. Oksenhendler et al., Opt. Exp. (2017)



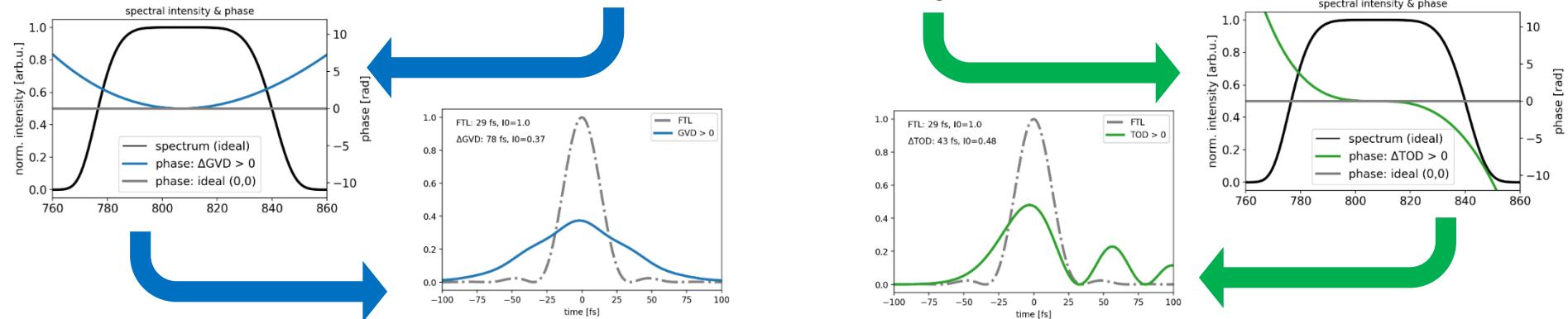
- almost perfect starting conditions for stable acc. process
- plasma dynamic restricted to last ps
- start to modify even the sub-ps regime

Spectral phase influences the temporal pulse shape (theory)

$$E(\omega) = \text{FT } E(t)$$

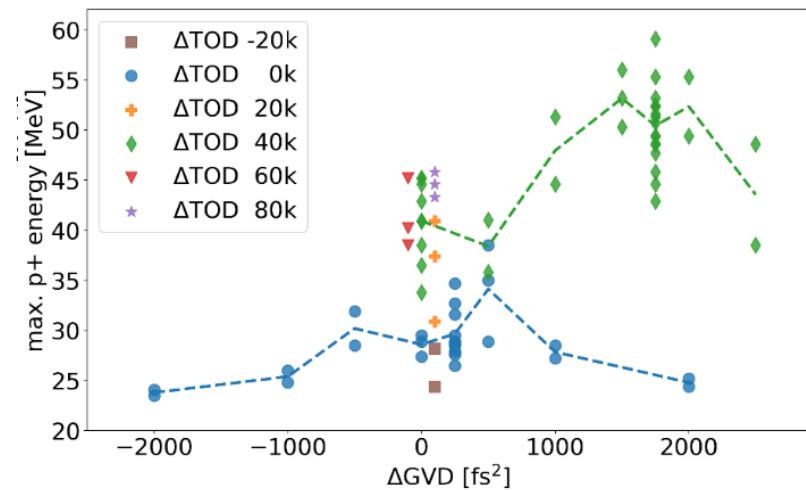
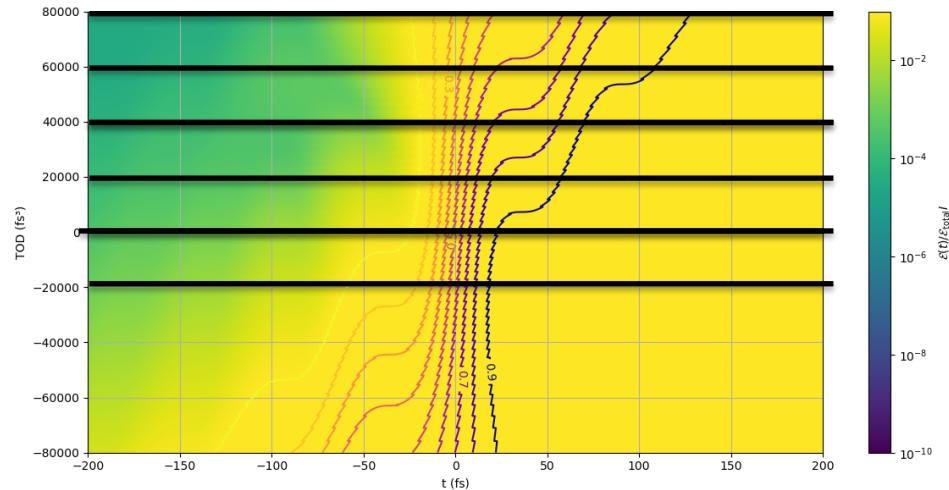
$$E(\omega) = A_0(\omega) \cdot \exp[i(\Phi(\omega) + \omega t)]$$

$$\Phi(\omega) = \Phi_0 + \tau(\omega - \omega_z) + \frac{\Delta GVD(\omega_z)}{2}(\omega - \omega_z)^2 + \frac{\Delta TOD(\omega_z)}{6}(\omega - \omega_z)^3 + \dots$$



- Laser pulse = Fourier-synthesized object with large bandwidth containing many laser modes
- ideally all frequencies in phase (e.g. by implementing AOPDF's) → shortest pulse
- frequency component manipulation as tool to change the temporal structure

Spectral phase influences p+ acceleration performance

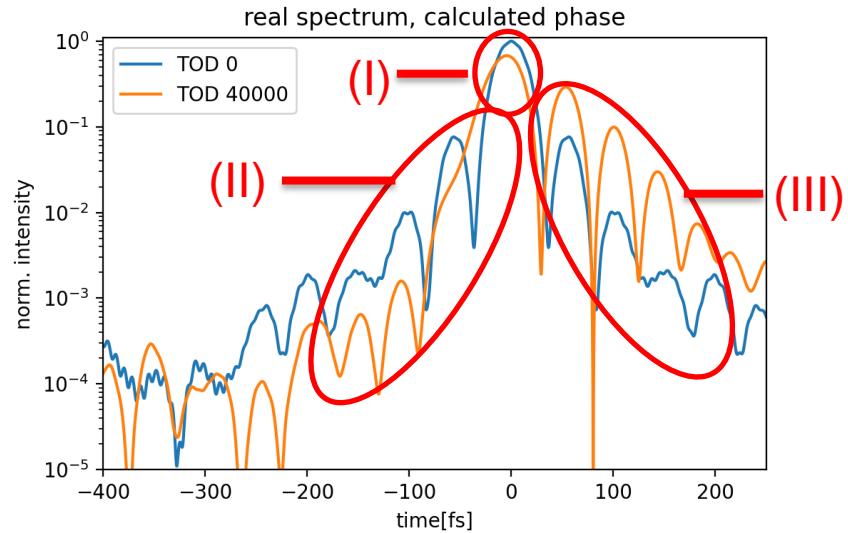
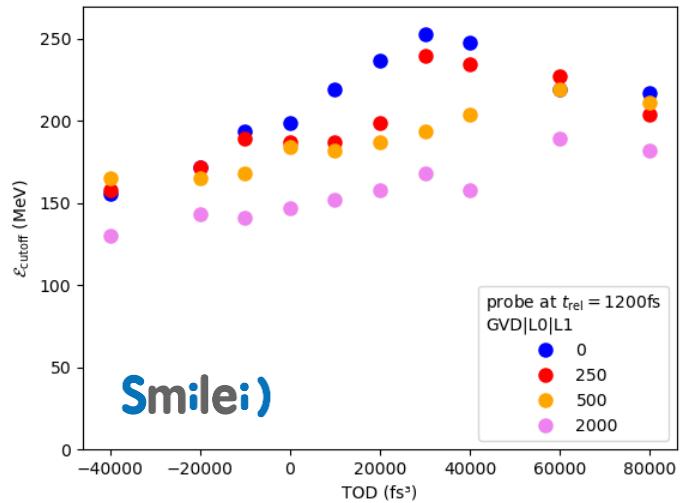


- symmetry-break of temporal energy distribution achieved by manual TOD modification
- idea: shift energy from pre- to post-pulse area
→ steeper rising edge while slight intensity reduction
- positive TOD values lead to higher energies and particle yields

Draco PW

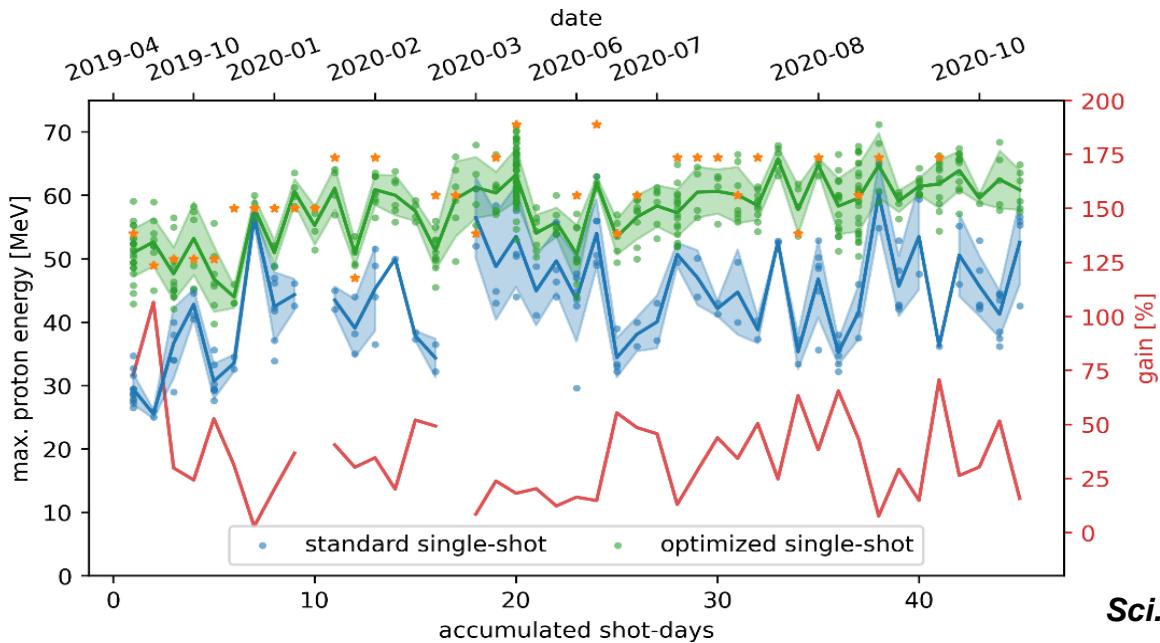
- $\tau = 30$ fs
- $E_L = 18$ J (on target)
- $I_{peak} = 5 \cdot 10^{21}$ W/cm² (after PM)
- $\sim 200\text{-}400$ nm Formvar foils

PIC results + physical picture of acc. process



- PIC simulation (Smilei & PIConGPU) reproduce general trend ... BUT:
 - ...still not clear how the whole plasma dynamics is changed by such a pulse shape
 - microscopic picture really complicated
- next step: disentangle different parts individually to find differences in the acceleration dynamic
 - analysis still ongoing

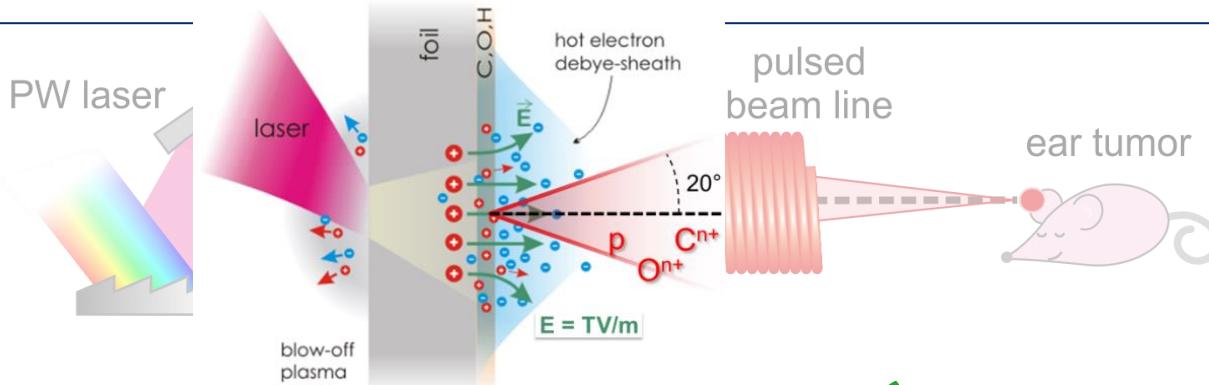
Demonstration of accelerator readiness



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

- TNSA acceleration for state-of-the-art PW-class laser system optimized
- routine operation with >60 MeV cut-off energy over month
- stable beam generation enabled radiobiology *in vivo* studies

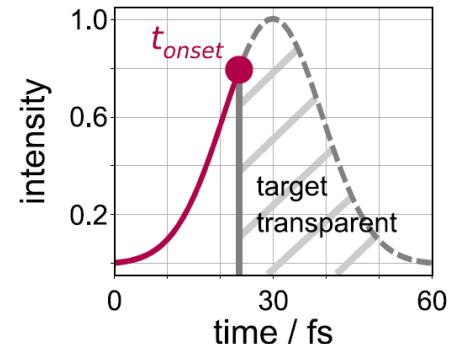
Controlling the plasma acceleration



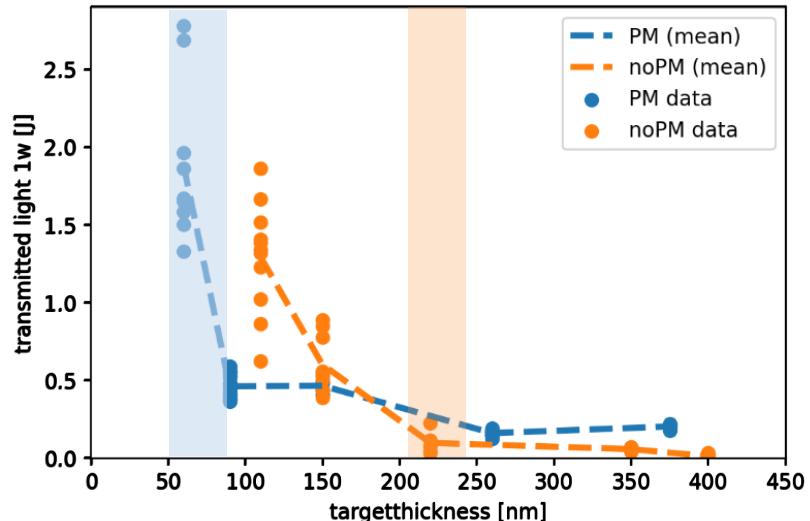
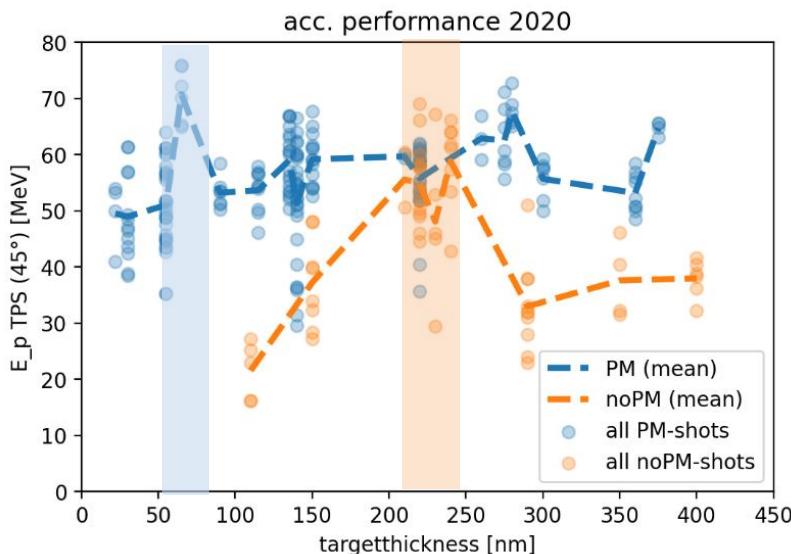
- TNSA as established, intensively studied & robust scheme ✓
- advanced & hybrid schemes promise to enhance performance:
 - for very thin targets
 - at near critical densities



- theoretically clear, but experimentally hard to achieve
- problem: complex interplay between laser and temporal evolution of plasma density profile ... again!



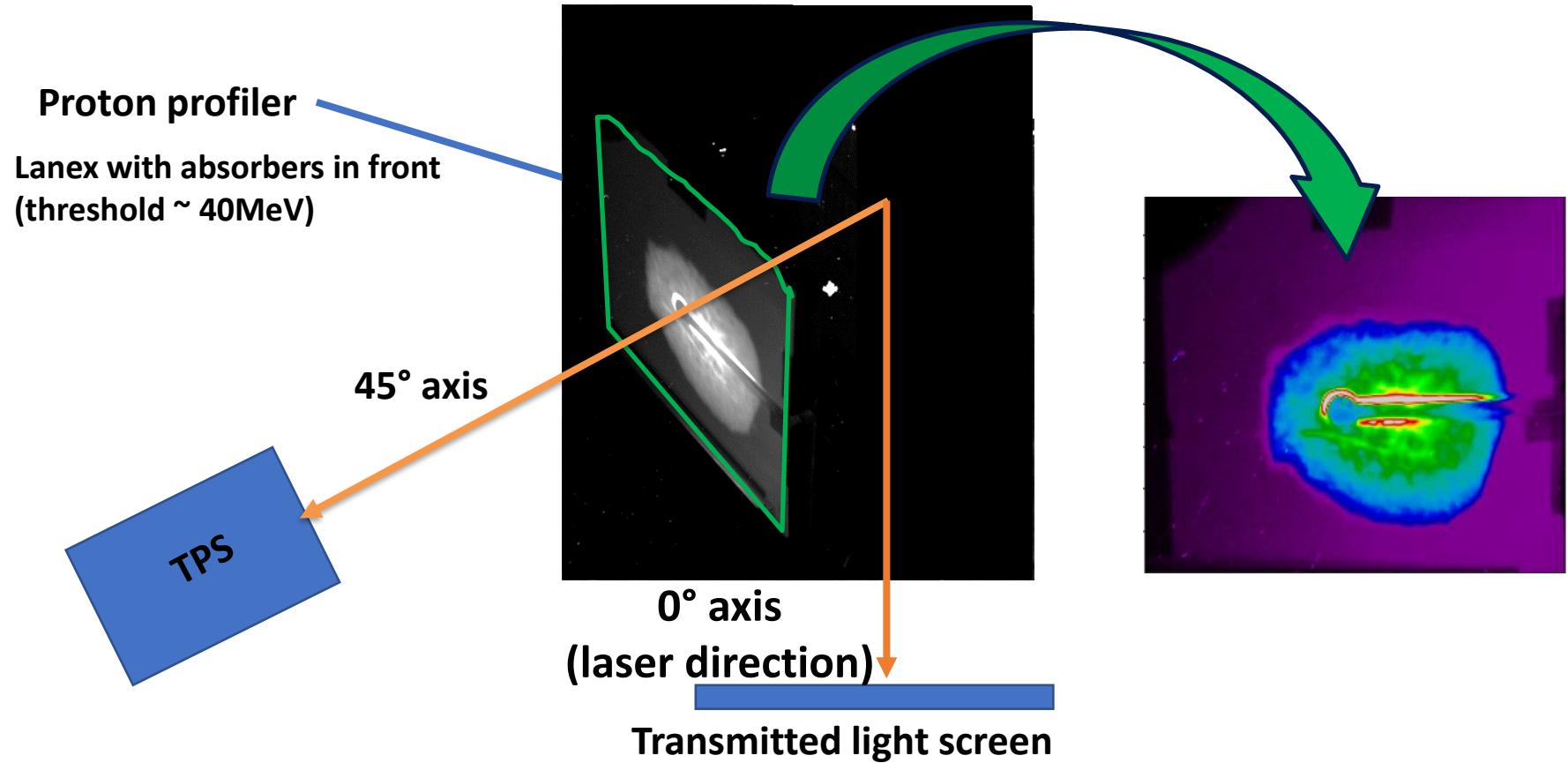
Relativistically induced transparency (RIT) regime



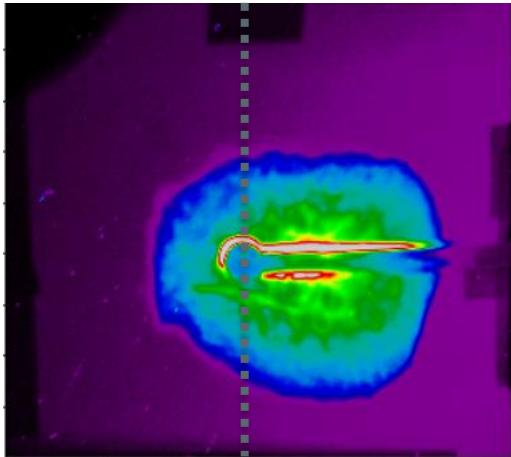
- enhanced proton energies at optimal thickness
- onset of transparency (transmitted light increases) at optimal thickness
- optimum shifted to thicker values for worse laser contrast
- study influence of PM/noPM differences + comparison to other laser systems

next talk by N. Dover

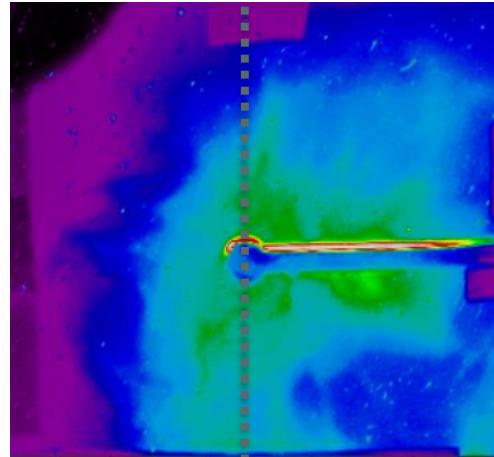
Relativistically induced transparency (RIT) regime



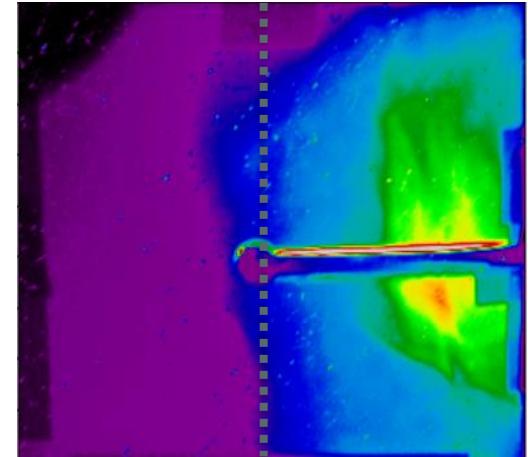
Relativistically induced transparency (RIT) regime



150nm, PM contrast



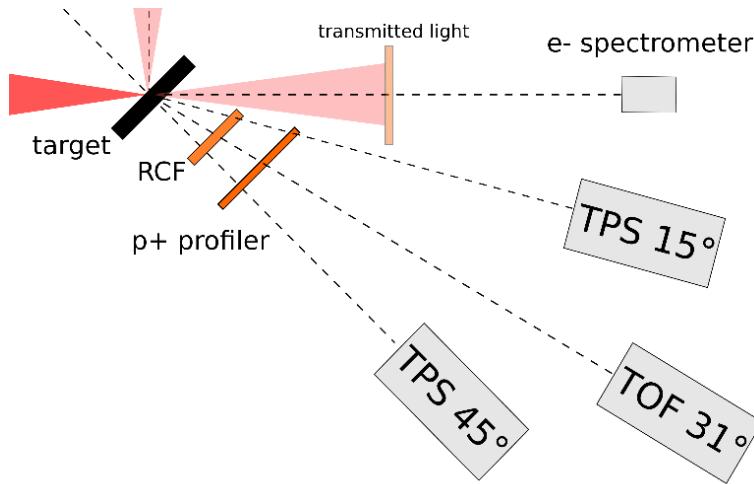
350nm, noPM contrast



230nm, noPM contrast

- PM contrast, no transmission: confined proton beam profile, close to target-normal direction
- noPM contrast, no transmission: distorted beam profile, close to target-normal direction
- noPM contrast, onset of transparency: distorted beam profile, shift towards laser axis

Relativistically induced transparency (RIT) regime



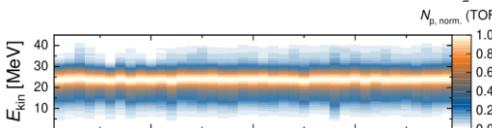
- repeated experiments woPM at optimal thickness → close to transparency
- added a lot of complementary particle diagnostics
- confirmed: highest energies not in target-normal direction
- fluctuations quite high but promising results with respect to maximum energy

Summary

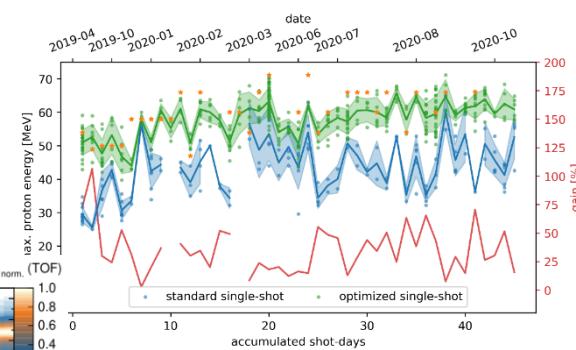
- First dose-controlled in-vivo irradiation of mice with a laser-driven proton source by:

- absolute control over temporal pulse properties of the laser
- TNSA optimization for stable generation of >60MeV proton beams

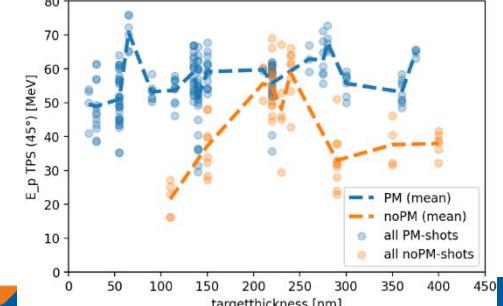
→ proof of accelerator readiness



10 % homogeneous dose
within $5 \times 5 \times 5 \text{ mm}^3$



acc. performance 2020



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, L. Gaus, S. Kraft, A. Nossula, M.E.P. Umlandt, M.
Rehwald, M. Reimold, H.-P. Schlenvoigt, S. Bock, R. Gebhardt, U. Helbig, T. Püschel,
D. Albach, M. Löser, U. Schramm, T. Cowan, et al.

N. P. Dover, A. Kon, M. Nishiuchi, H. Kiriyama et al

Thank you!

