Science and Applications of Plasma-Based Accelerators

Health and industrial applications

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767. WE-Heraeus-Seminar

WILHELM UND ELSE
HERAEUS-STIFTUNG

HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

Science and Applications of Plasma-Based Accelerators

Health and industrial applications (and research)

Establishing ***laser accelerated proton beam*** *performance for dose controlled irradiation studies*

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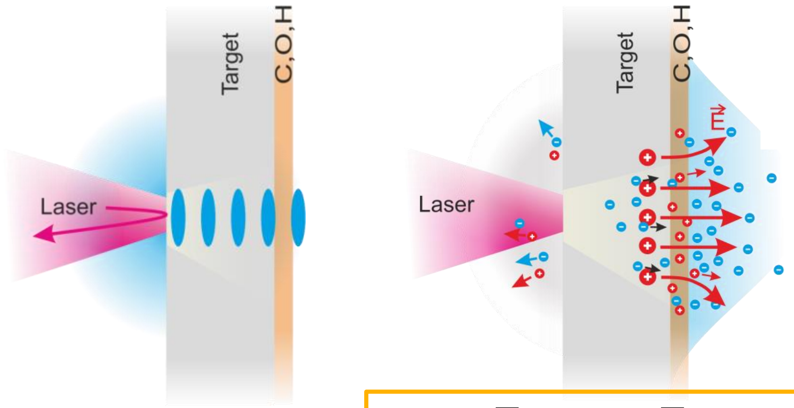
Motivation (in the early times of laser plasma acceleration)

- compact (cheap) accelerator to replace clinical proton therapy source
  [T. Bortfeld, J. Loeffler, Nature 2017: shrink accelerators, sharpen beams, broaden coverage]

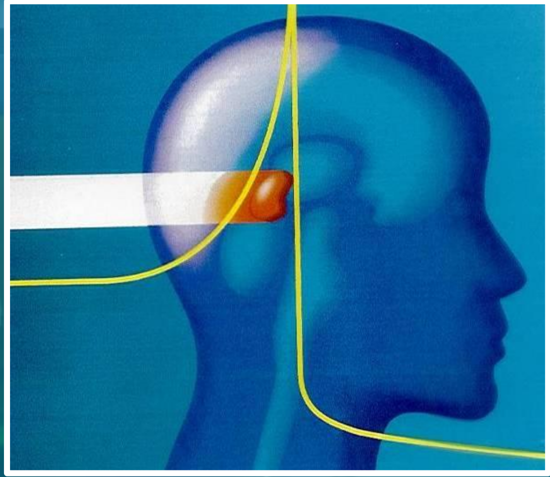
Target normal sheath acceleration



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

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

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



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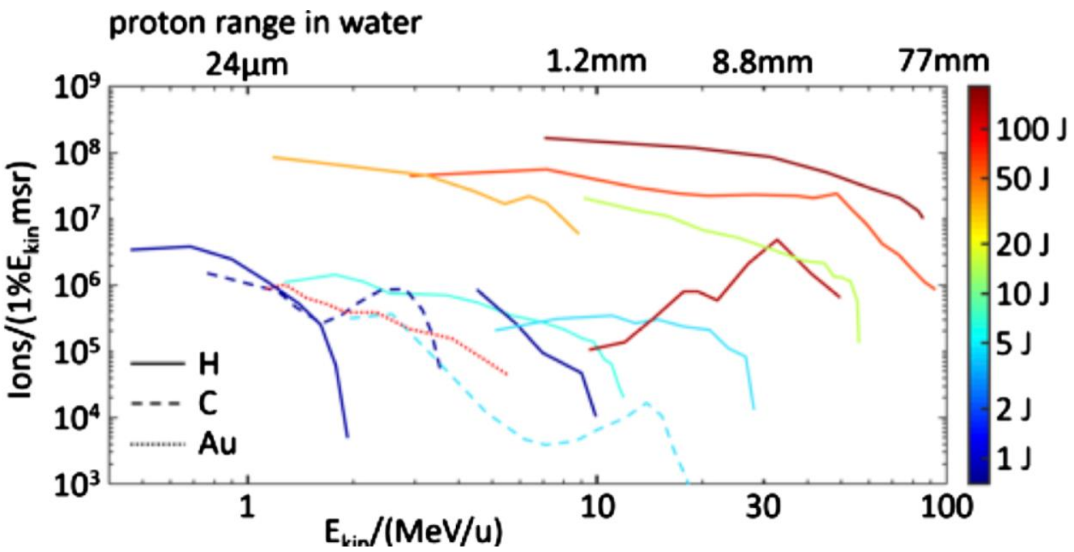
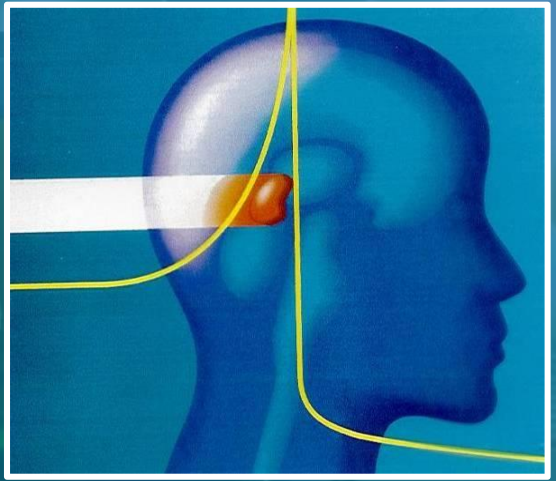


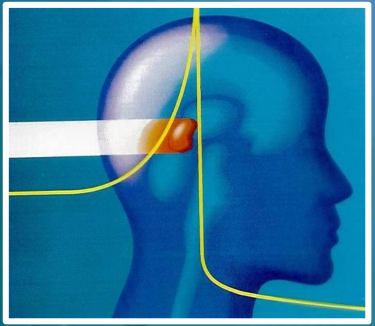


updates on https://alpa.physik.uni-muenchen.de/

Motivation revisited and requirements

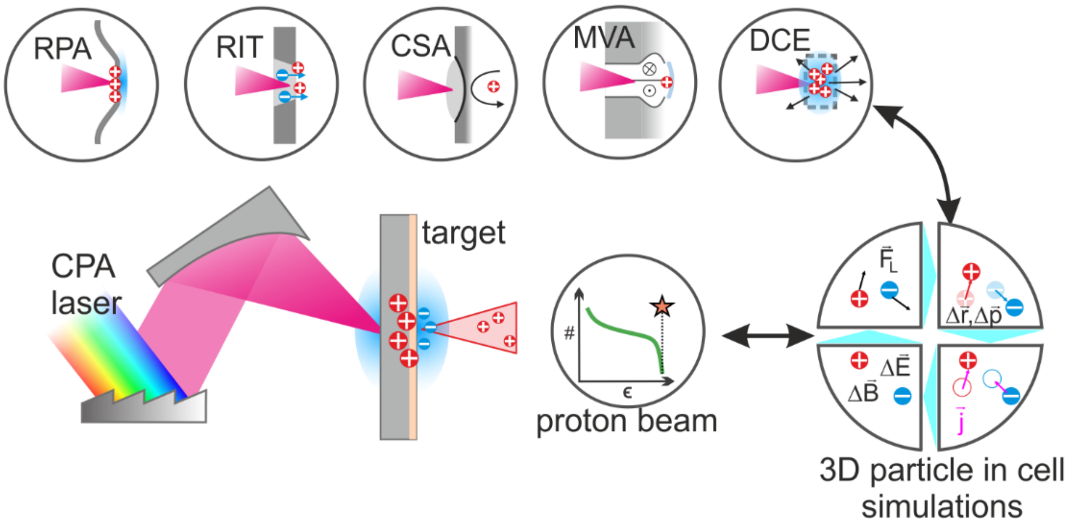
- *Sufficient energy to penetrate volume of interest (>30 MeV protons for animal studies)*
- *Sufficient particle yield (pulse dose rate and average = repetition rate)*
- *Stability (laser accelerator availability on demand)*

- *Dedicated beam transport (and filtering) to target*
- *Absolute dose control and metrology in 3D*
- *Radiobiology expertise and infrastructure (including reference irradiation)*



-> extreme dose rates (10s of Gy in nanosecond pulse)
-> broad energy range -> single pulse depth dose shaping
-> exploit unprecedented source characteristics for translational research

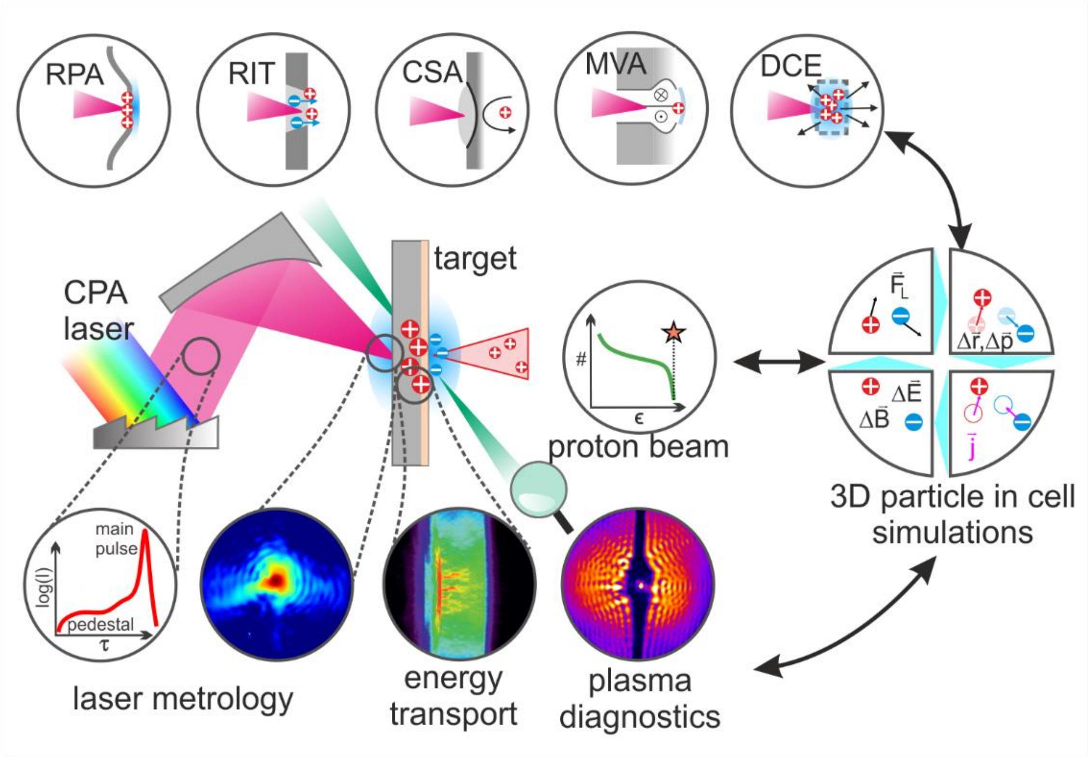
Upscaling of laser accelerated proton beam energies …



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

- from surface to efficient volumetric interaction
- microscopic understanding (instabilities, …)
- links between simulation and experiment, predictive capability, diagnostics
- control (and knowledge) of laser parameters on target

Upscaling of laser accelerated proton beam energies …



- from surface to efficient volumetric interaction
- microscopic understanding (instabilities, …)
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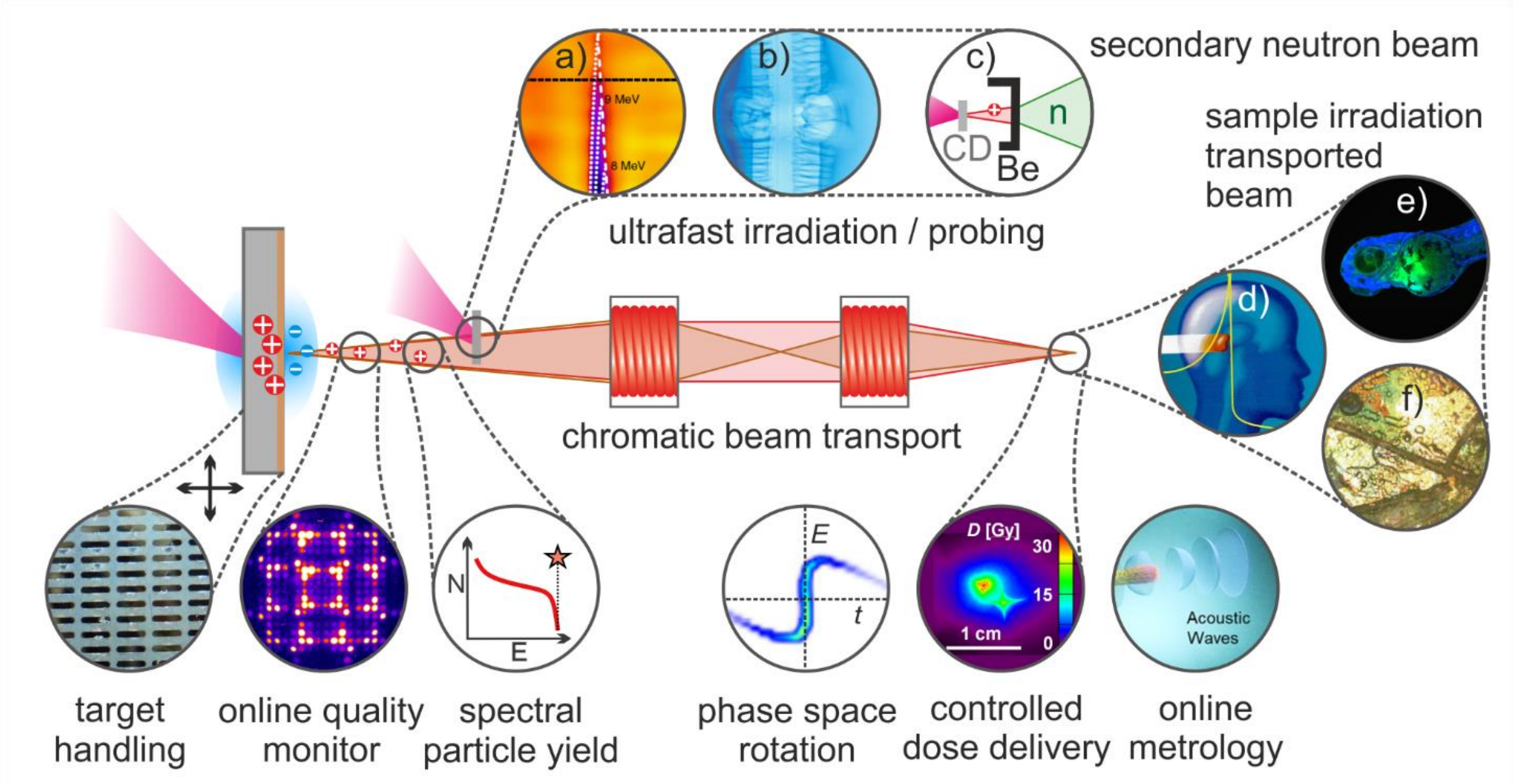
Exploit applications matching unique ion beam parameters …



For details and references … New Journal of Physics 23, 031101 (2021)

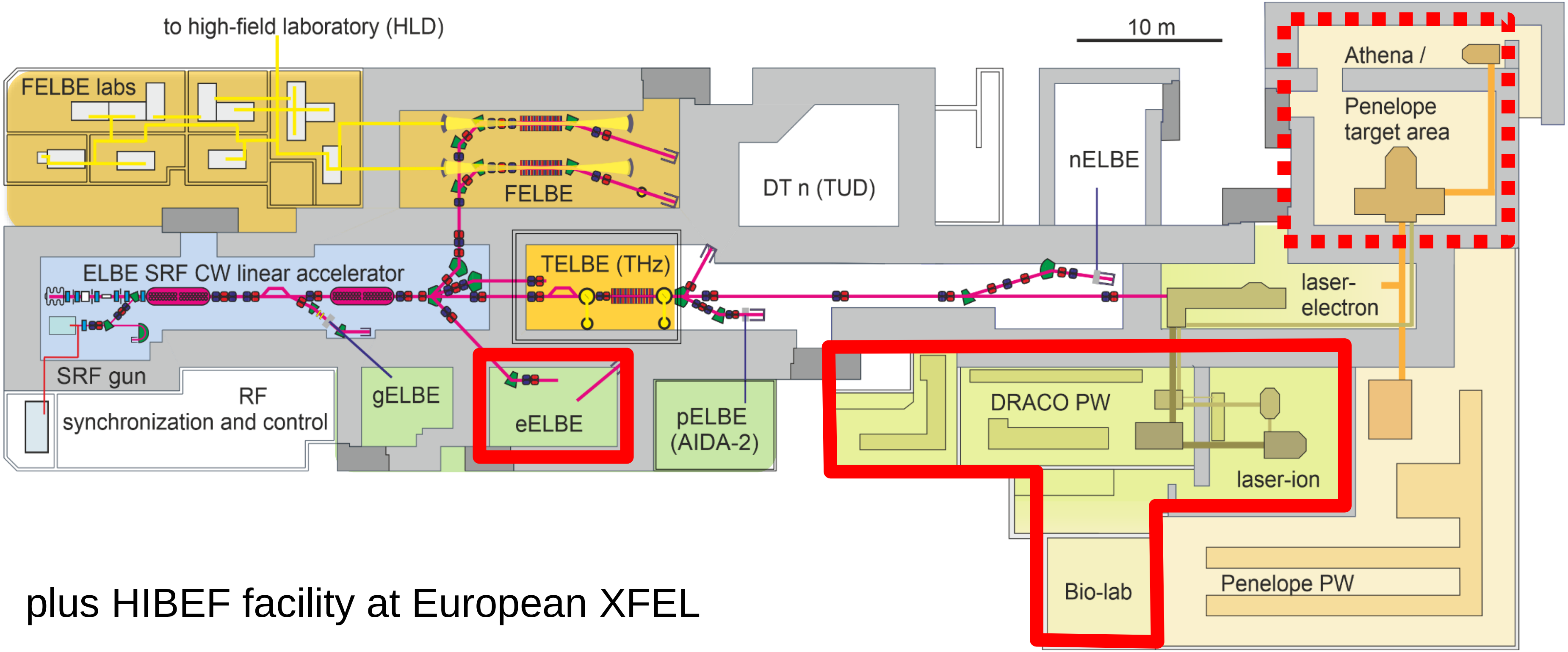
From compact radio-therapy accelerators to sources for translational radiobiology at extreme dose rates

(summing up 10 years of development at theDresden PW facility DRACO)

- *Proton energy and spectral stability*
- *Targetry for high repetition rates*
- *Beam transport and metrology*
- *Demonstration experiment (mouse tumor irradiation) as a benchmark for laser plasma accelerator development*

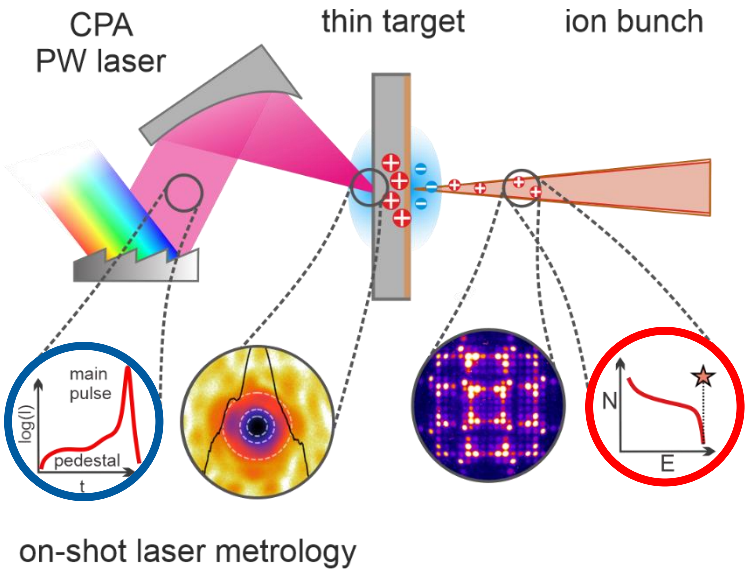
ELBE Center for high power radiation sources

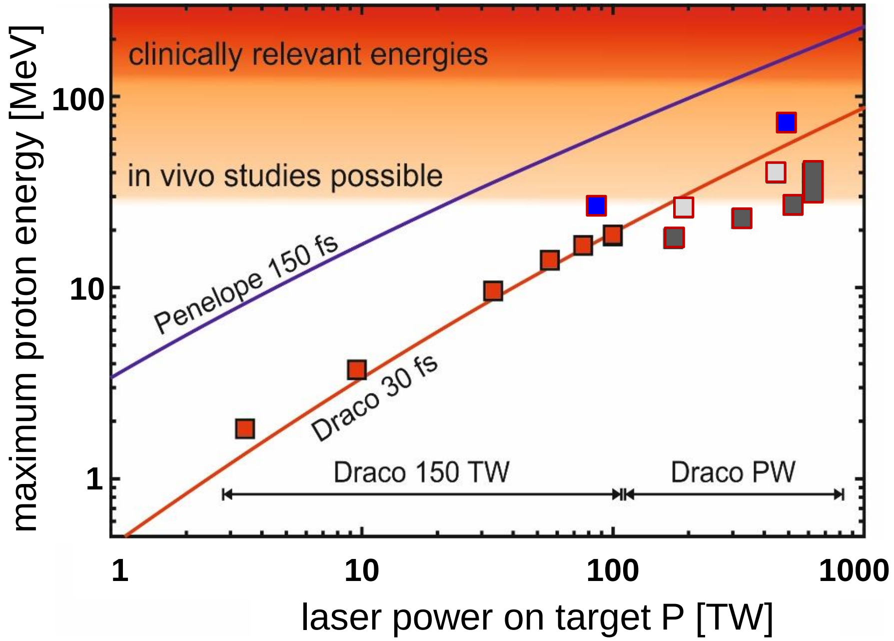
a user facility and advanced accelerator R&D



plus HIBEF facility at European XFEL

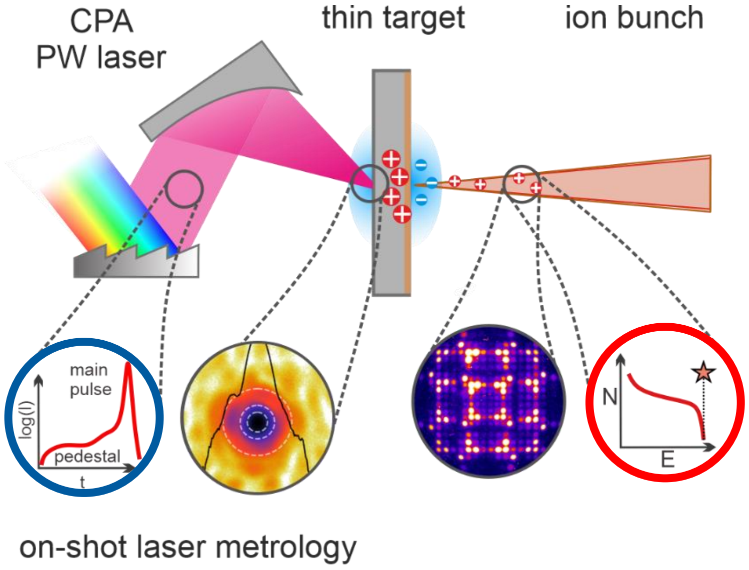
Upscaling of laser accelerated proton beam energies …

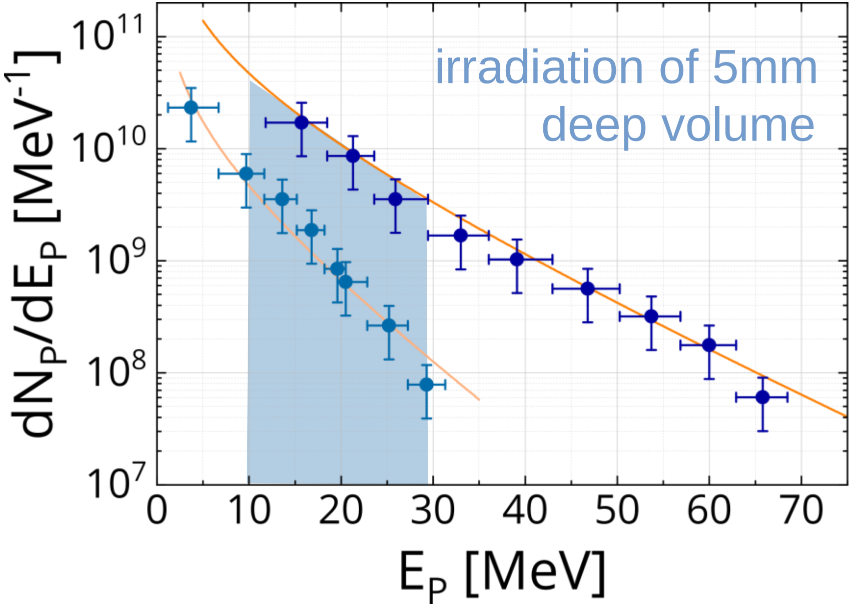




- increased laser energy
- dedicated targetry - 100nm class plastic foils and contrast cleaning
- improved and monitored laser and plasma control on target

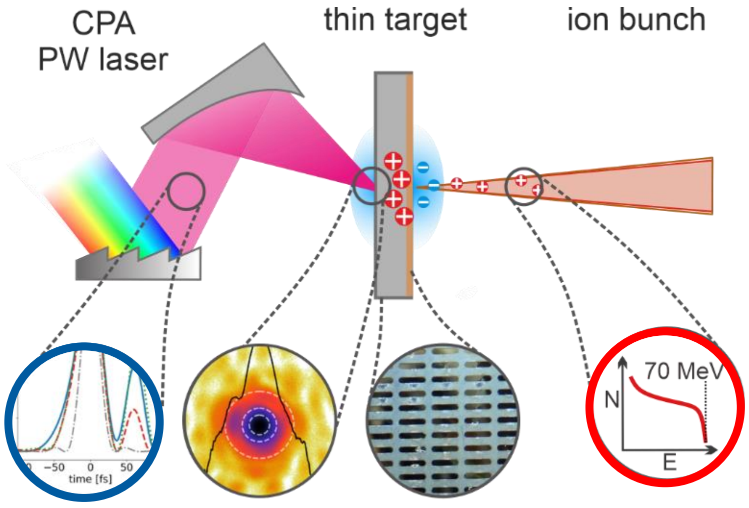
Upscaling of laser accelerated proton beam yields …





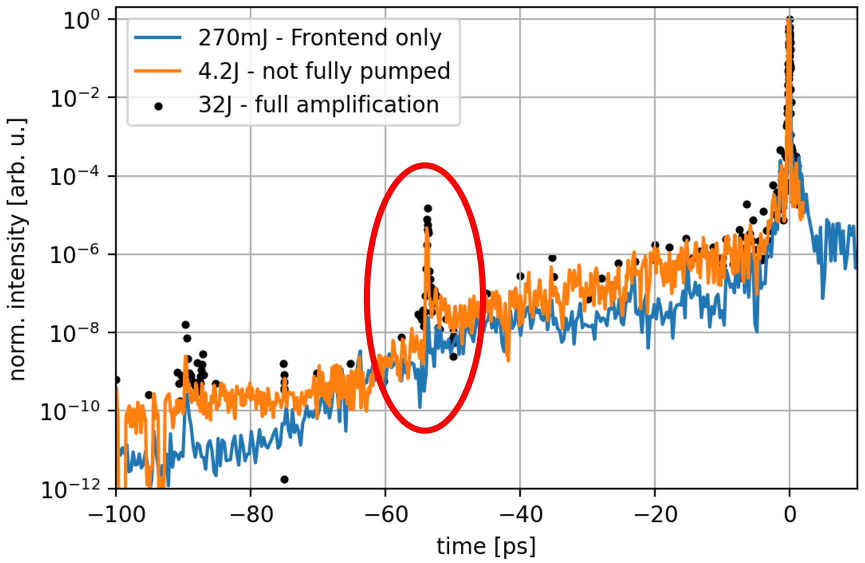
- reduced sensitivity to cut-off fluctuation
- reproducible depth dose profile and control

… through improved laser (contrast) metrology …



monitored laser pulse tailoring

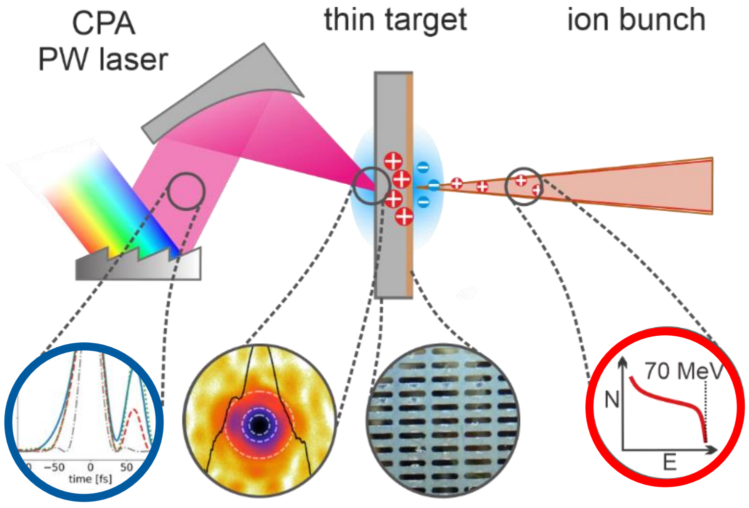
intensity contrast at full energy



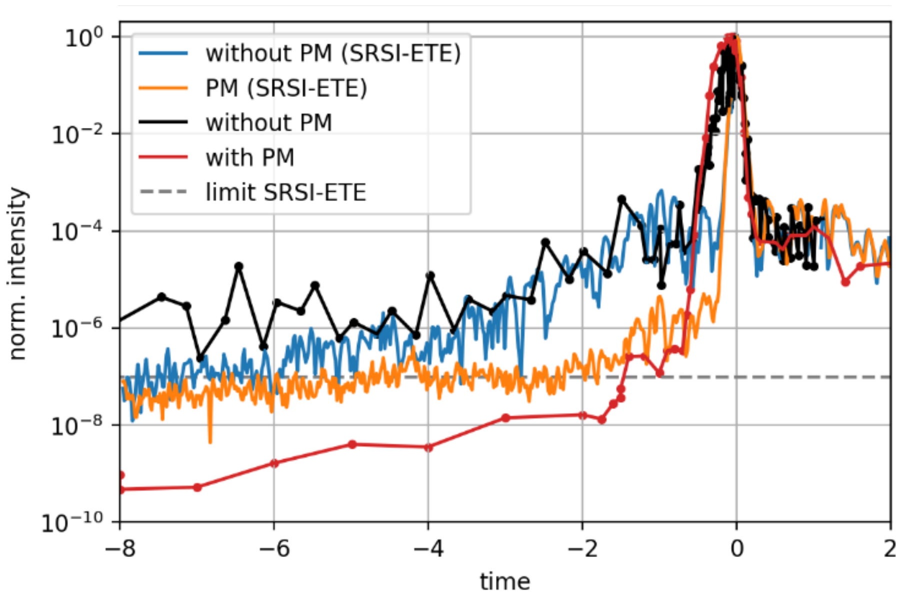
… and single plasma mirror cleaning

T. Ziegler, C. Bernert, et al., in preparation
T. Oksenhendler, et al., Optics Express 25, 12588 (2017)
L. Obst, et al., Plasma Physics and Controlled Fusion 60, 054007 (2018)

… through improved laser (contrast) metrology and PM pulse cleaning …



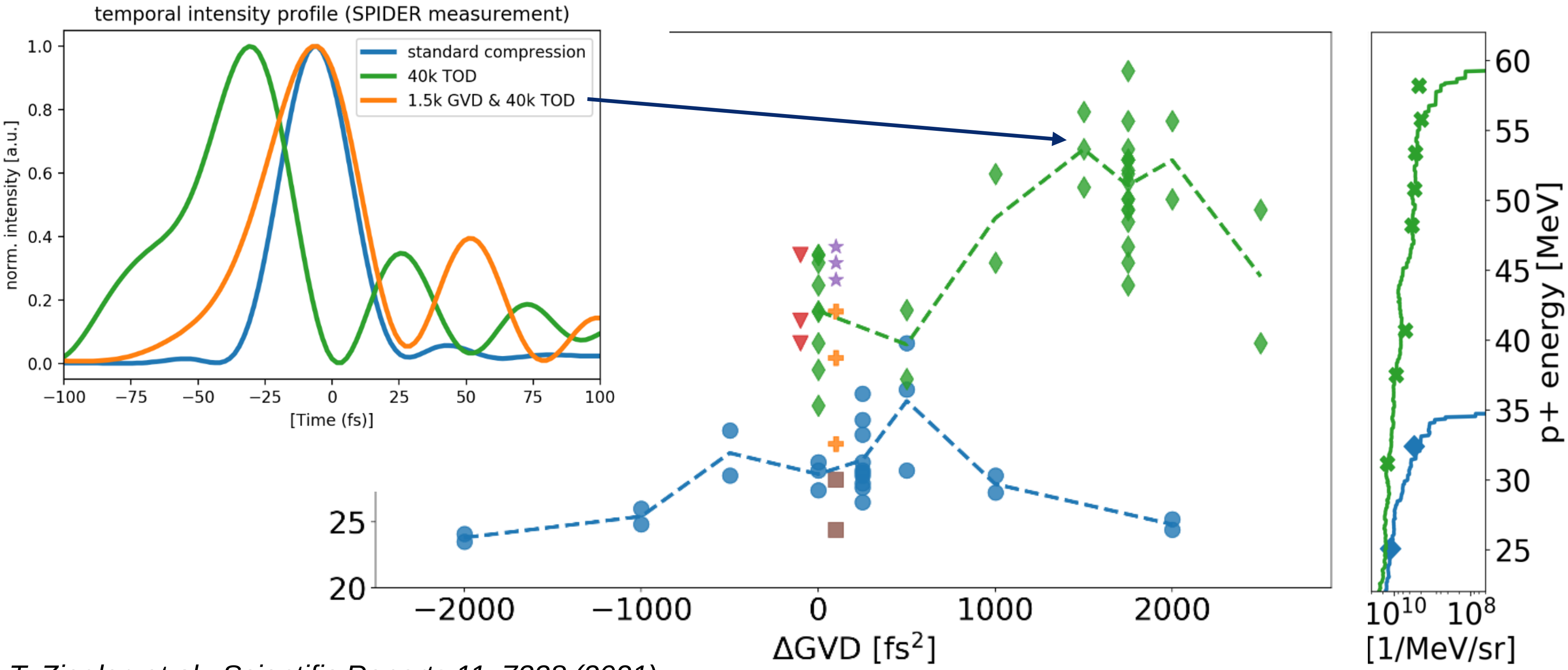
monitored laser pulse tailoring



- empirical GVD and TOD optimization for best TNSA performance
- optimizes the pulse shape and dynamic at ps scales for final spectrum

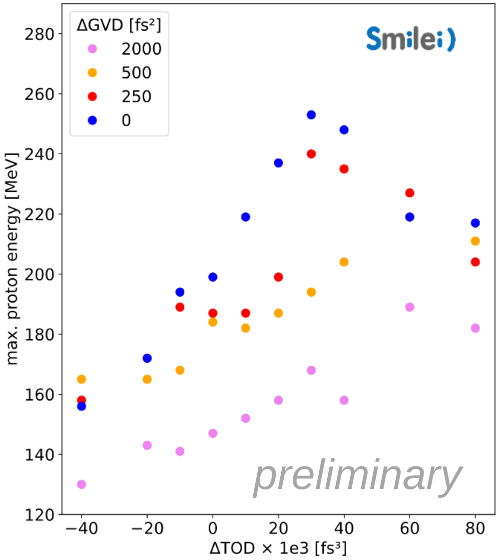
… and active dispersion (compression) management

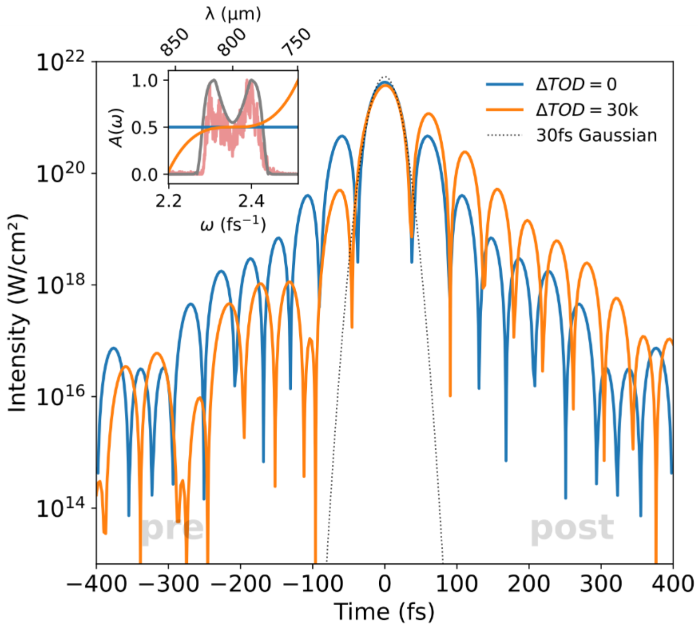
(typically 15J (PM cleaned) on few 100nm plastic targets)



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

… consistent with optimized (*non-idealized*) TNSA

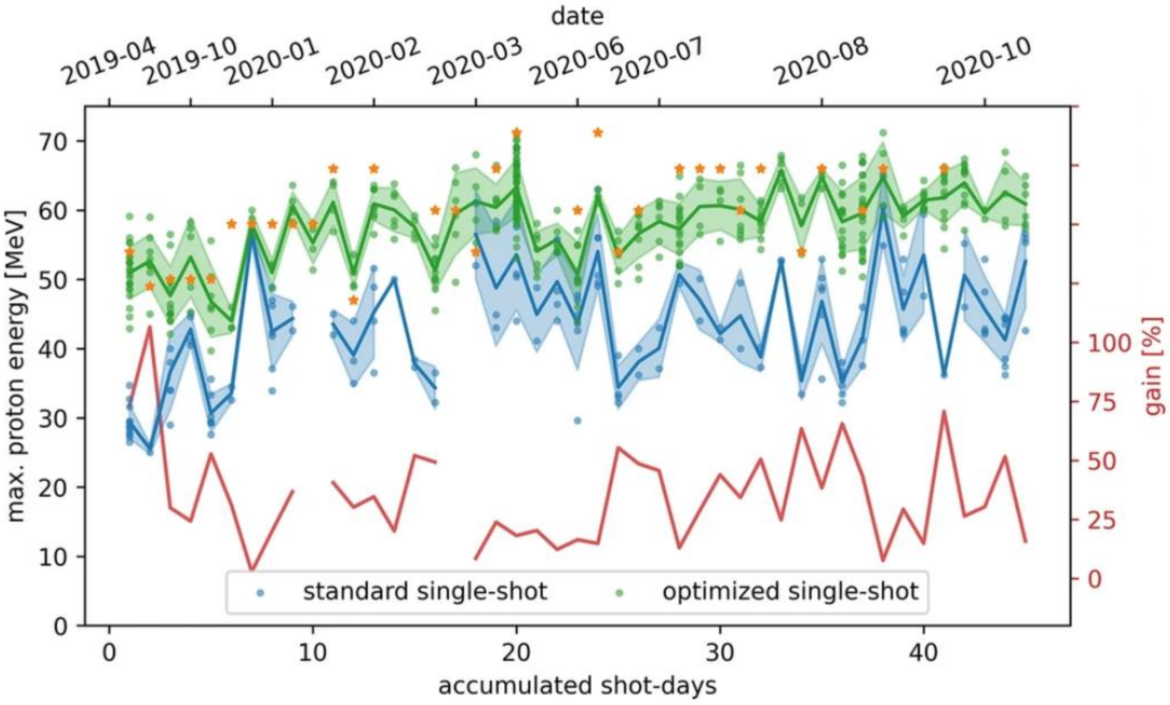




- empirical GVD and TOD optimization for a given spectrum on target for best TNSA performance (best back-side plasma gradient)

T. Ziegler, et al., Scientific Reports 11, 7338 (2021), M. Garten, et al., in preparation

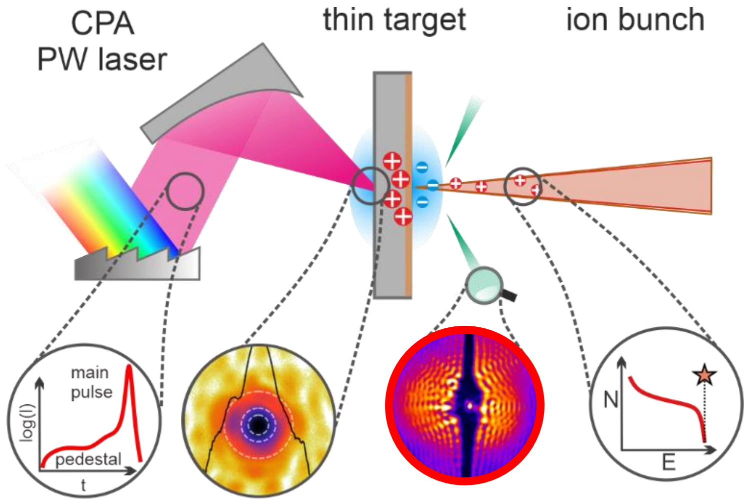
Stable laser proton accelerator operation over months @ >60 MeV



- empirical GVD and TOD optimization improves and stabilizes TNSA performance
- measured / cross-checked with RCF stacks, TP spectromter, TOF
- **ready for applications**

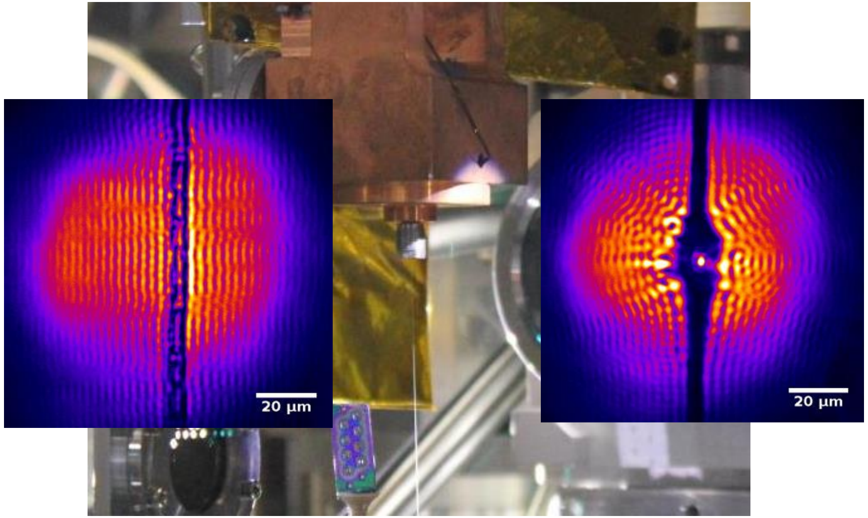
T. Ziegler, et al., Scientific Reports 11, 7338 (2021)

short interlude - proton acceleration in near critical density targets



on-shot laser and plasma metrology

cryogenic hydrogen jet targets with off-harmonic probing



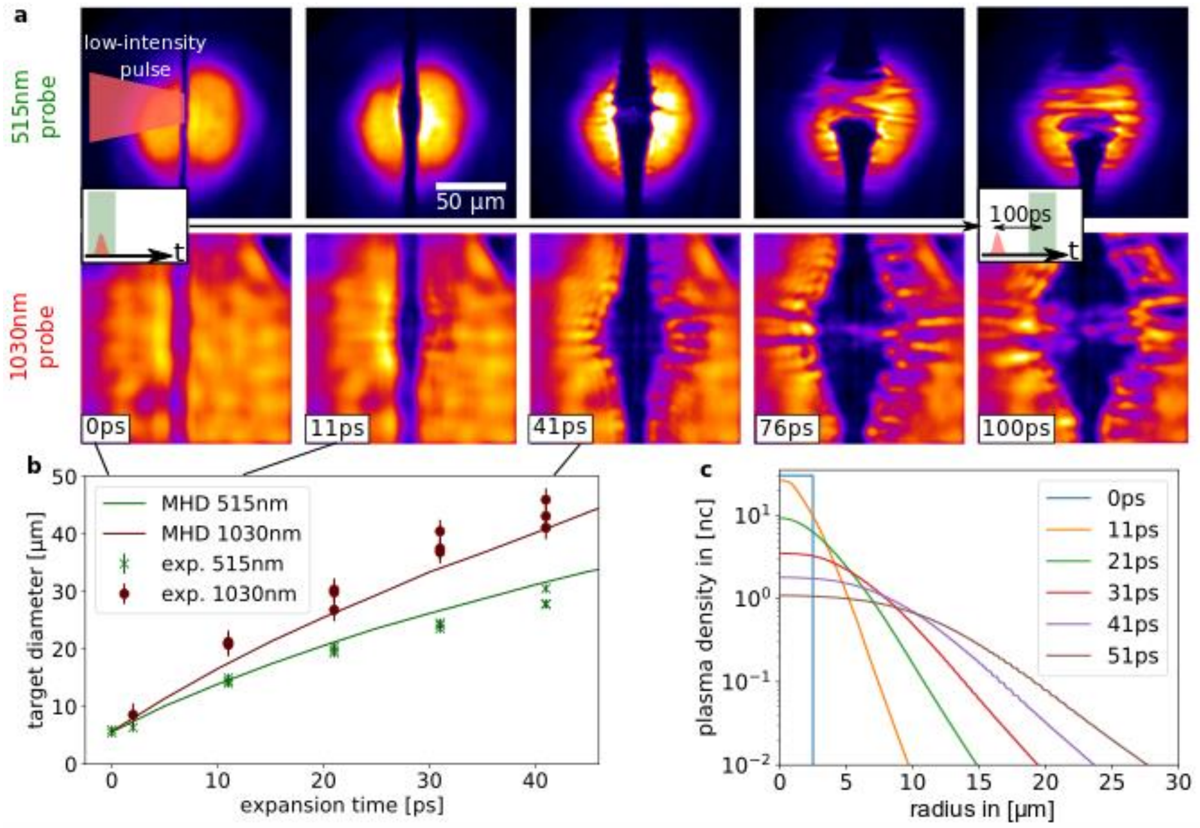
S. Goede et al., *PRL 118, 194801 (2017)*
L. Obst et al., Sci. Rep. 7, 10248 (2017)
M. Gauthier, et al., APL 111, 114102 (2017)
L. Obst, et al., Nat. Comun. 9, 5292 (2018)

M. Loeser, et al, Optics Express 29, 9199 (2021)
T. Ziegler, et al., PPCF 60, 074003 (2018)
C. Bernert, et al., Sci. Rep. 12, 7287 (2022)

European XFEL SLAC

On-shot plasma characterization by bi-colour high resolution probing

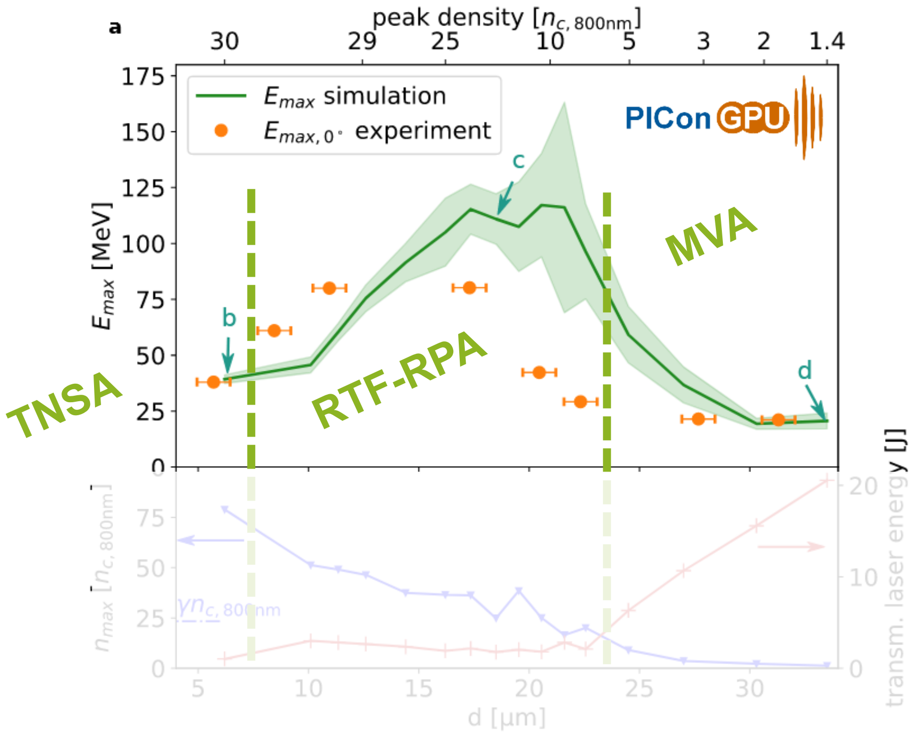
- enabling controlled plasma density tailoring and predictive simulation input

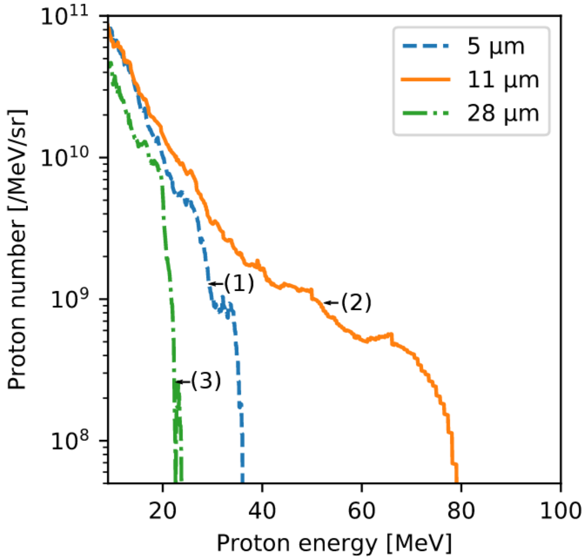


M. Rehwald, C. Bernert, et al., in review (2022)

On-shot hydrogen target density tailoring

- enabling quantitative simulation suggesting transition from TNSA via RTF-RPA to MVA
- supporting up to 80 MeV with **debris-free and rep-rated target**





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

On-shot hydrogen target density tailoring (work in progress)

- enabling quantitative simulation suggesting transition from TNSA via RTF-RPA to MVA
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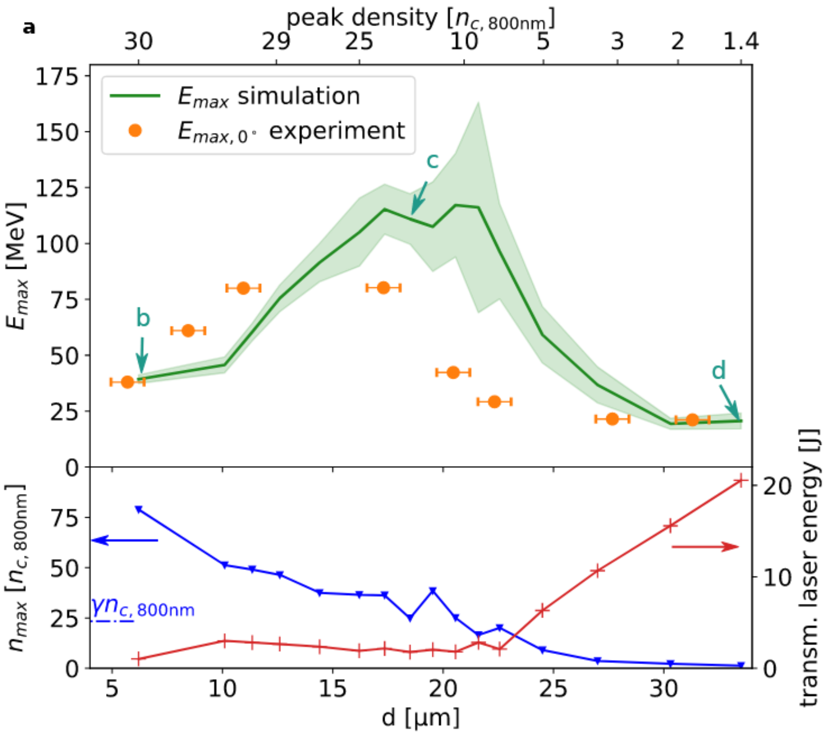
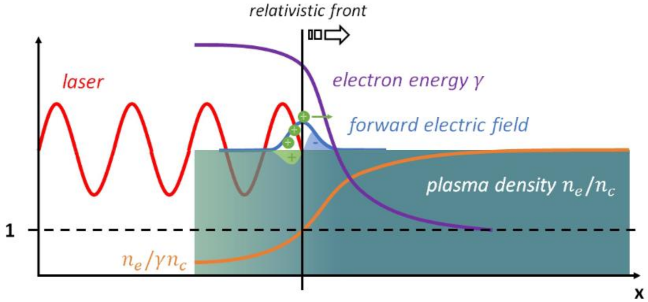


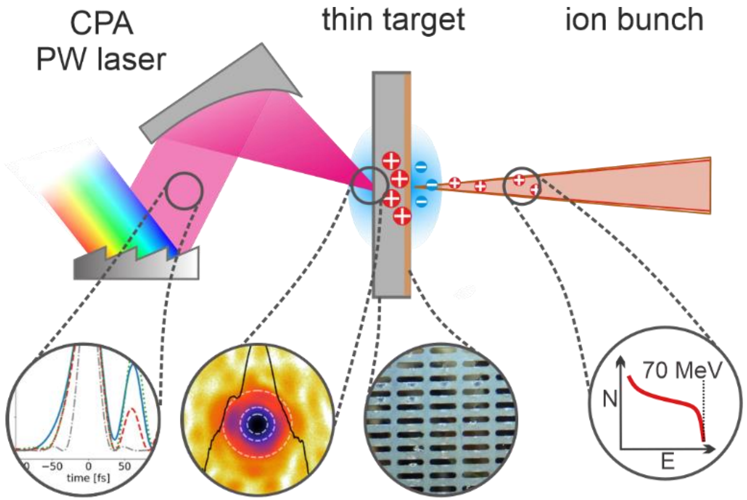
RTF-RPA = Relativistic Transparency Front - RPA

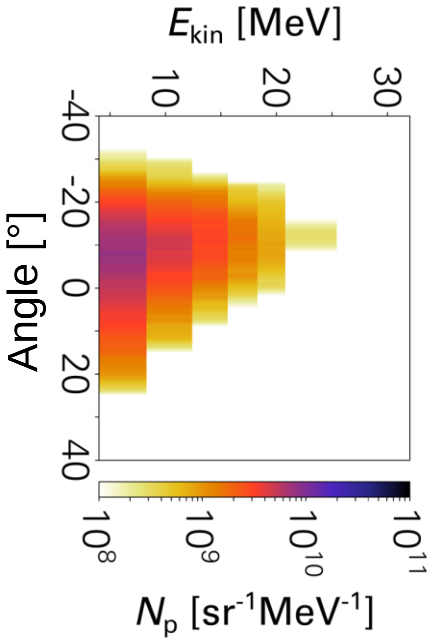
synchronized acceleration of ions at the moving (intensity dependent) relativistic critical density front



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

Controlled dose delivery (= beam transport) for applications

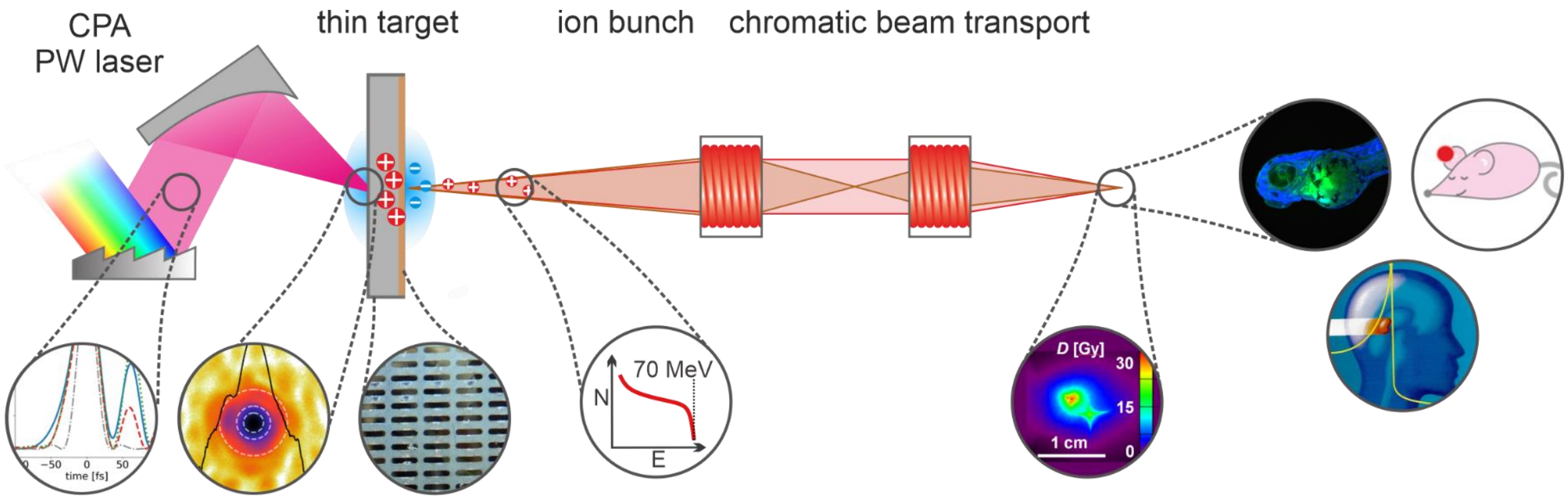




pulsed magnet beamline for

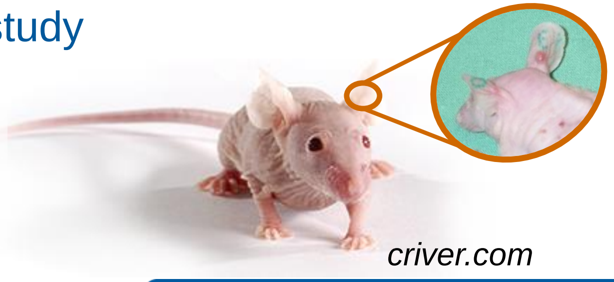
- high angular acceptance
- efficient beam transport
- spectral control (active filter)
- controlled depth dose delivery

Controlled dose delivery with pulsed solenoids



in vivo 3D irradiation (mouse ear tumor)
proof-of-concept study

homogeneous dose
within 5×5×5 mm³
< 10% dose fluctuation
4 Gy in ~minute



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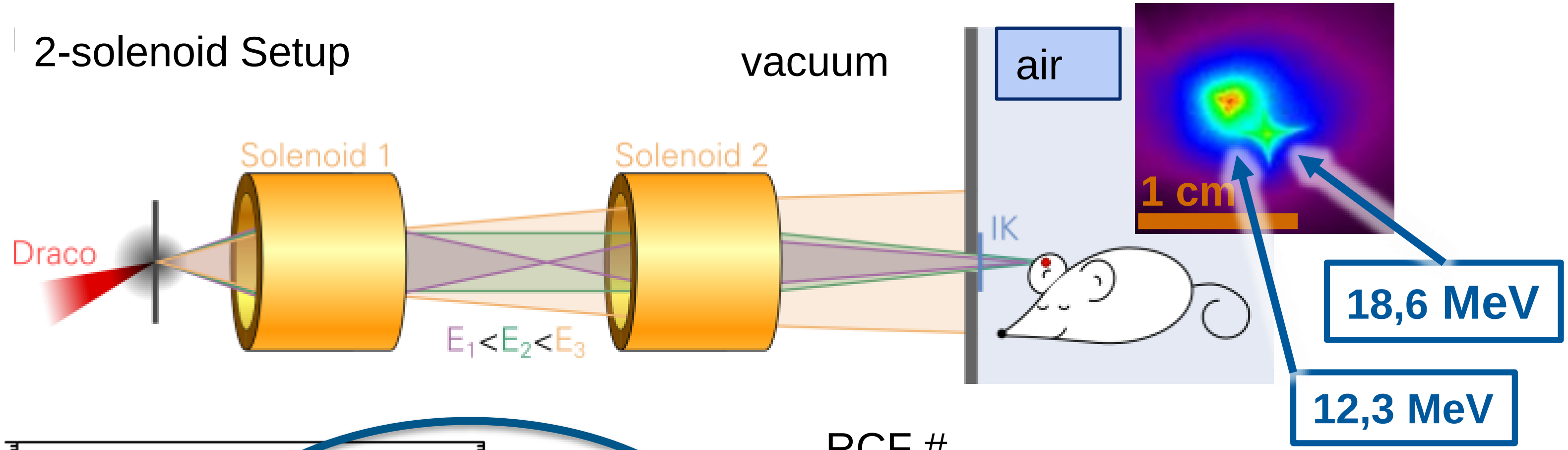
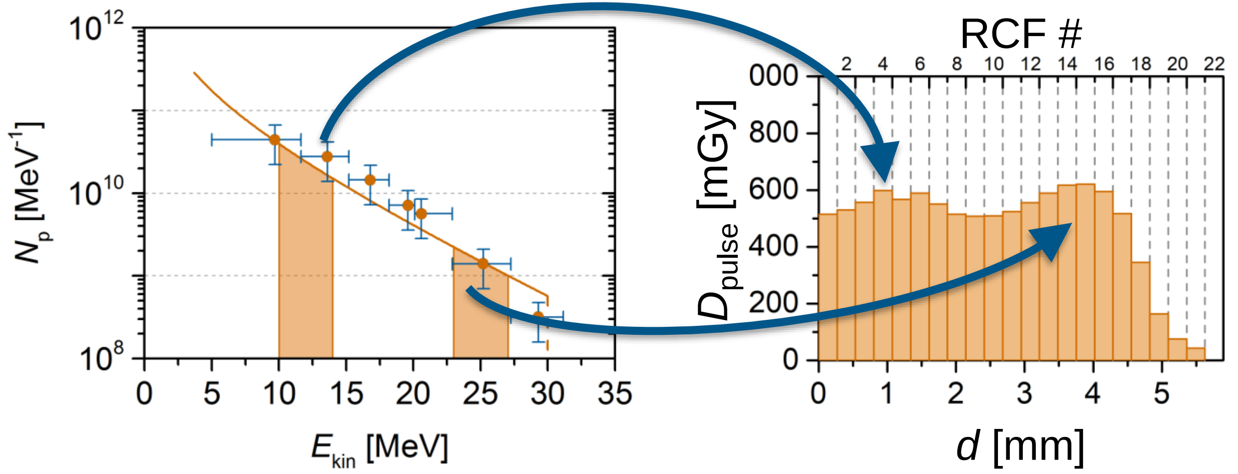
F. Brack, et al., Scientific Reports 10, 9118 (2020)
S. Busold, et al., (LIGHT), Sci. Rep. 5, 12459 (2015)
D. Haffa, et al., Sci. Rep. 9, 6714 (2019)
U. Masood, et al., Phys. Med. Biol. 62, 5531 (2017)
F. Albert, et al., New J. Physics 23, 031101 (2021)

E. Beyreuther et al., PLOS ONE 12 (2017)

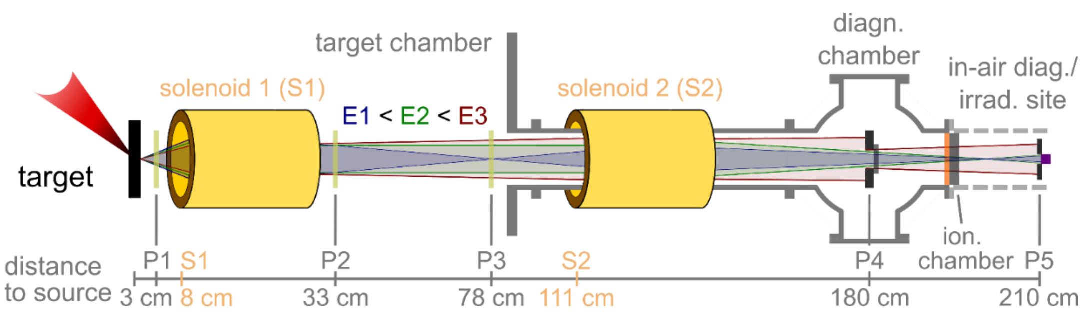
Single pulse depth dose control …



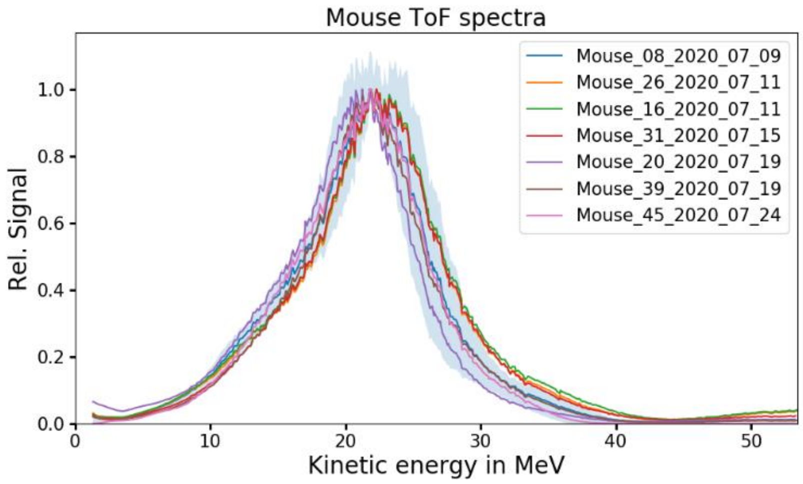


F. Brack, et al., Scientific Reports 10, 9118 (2020)

… through on-shot metrology …



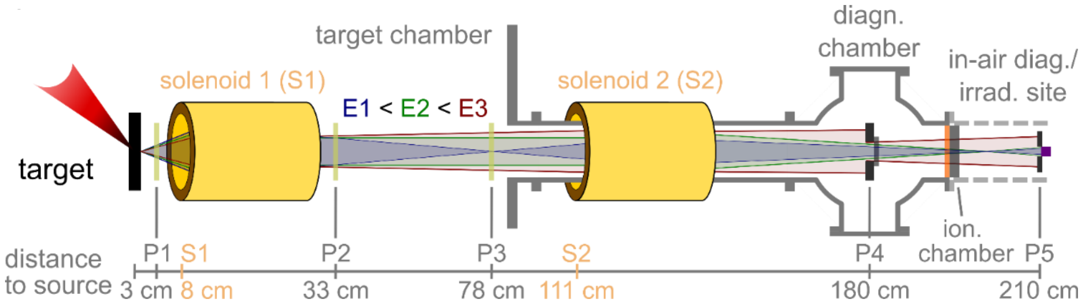
- offline (RCF) optimization
- online performance monitoring (TOF)
- complex online / offline dosimetry



Thin scintillator based TOF (time of flight) detector enables on-shot monitoring of proton spectrum and indirectly dose

M. Reimold, et al, in preparation (2022)

Single pulse depth dose control through on-shot metrology …



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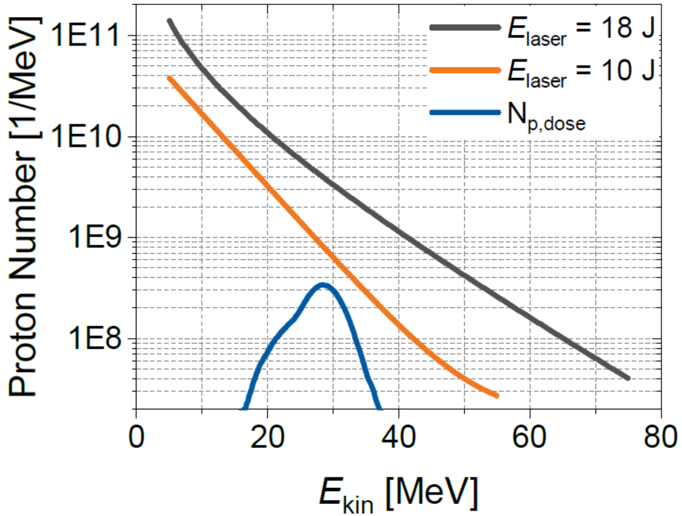
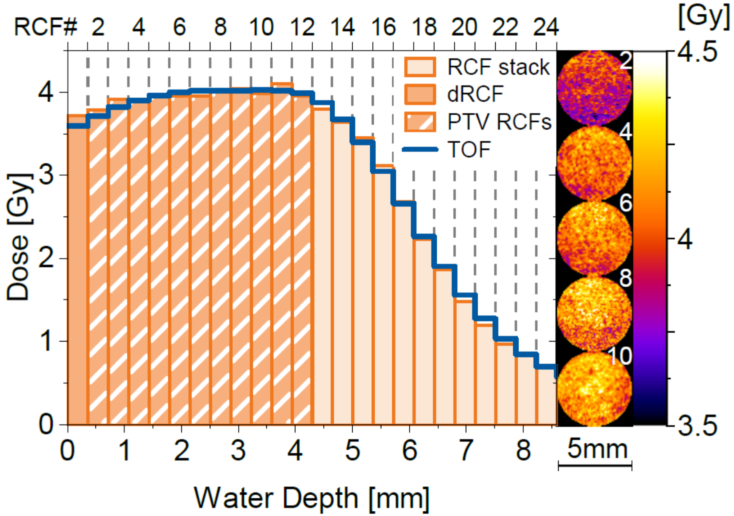
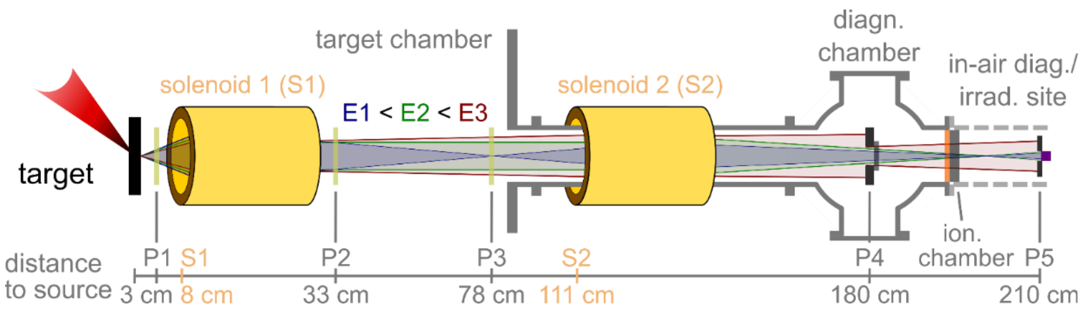


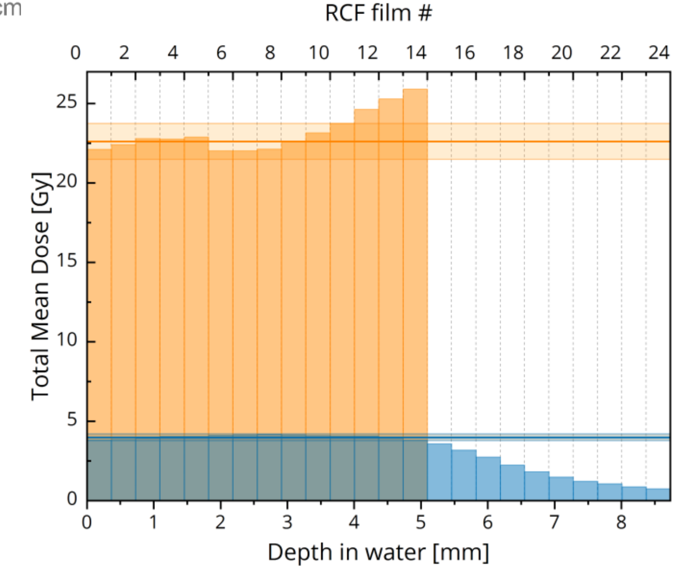


F. Kroll, et al., Nature Physics 18, 316 (2022)

First in-vivo proton irradiation study



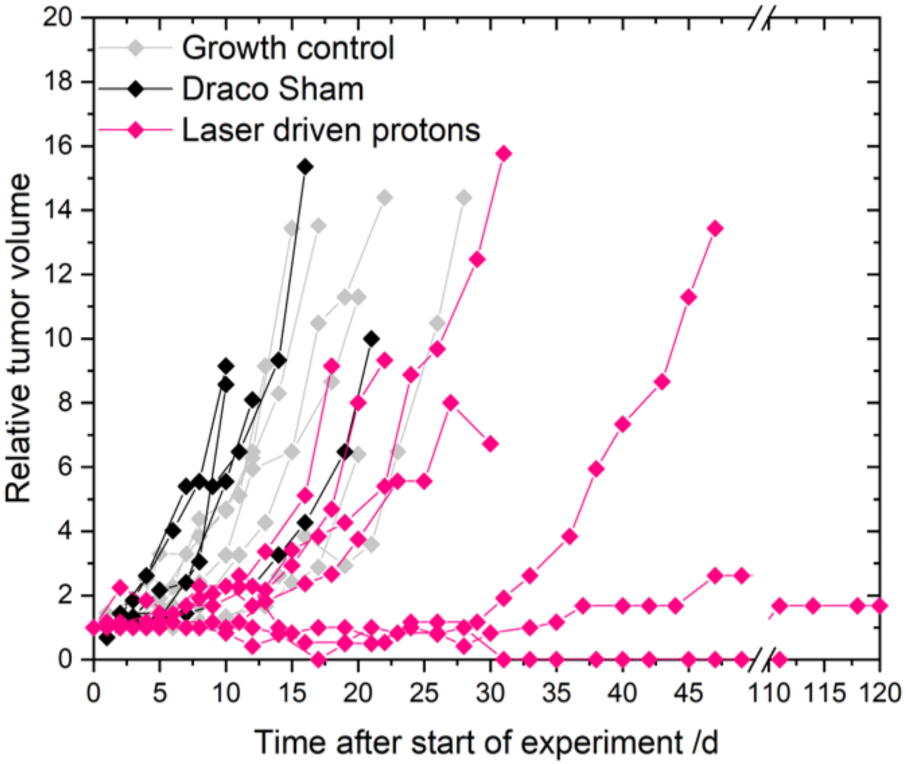
transfering intense poly-chromatic proton pulse into flat and laterally homogeneous depth-dose



Two modes of operation:

- Controlled dose at highest precision (mouse experiment, accumulated shots)
- Maximum dose rate (up to 25 Gy/shot) enabling FLASH irradiation studies (zebra fish experiment)

First in-vivo proton irradiation study with laser accelerated protons

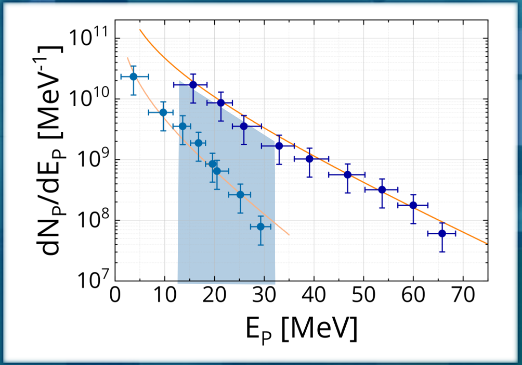


- Full-scale pilot study in a small animal model with a laser proton beam
- Radiation induced (4 Gy) effect observed
- In total 47 mice at HZDR (Draco 4 Gy | Draco 0 Gy | X-ray 4 Gy | X-ray 0 Gy | Controll) + same number for reference at clinical beam
- Long-term survival unexpected, yet requiring higher statistics …

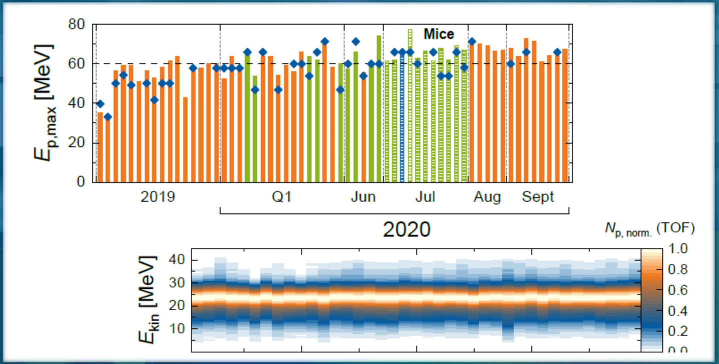
F. Kroll, et al., Nature Physics 18, 316 (2022)

High dose-rate applications at DRACO-PW take away message - pilot study demonstrates system readiness

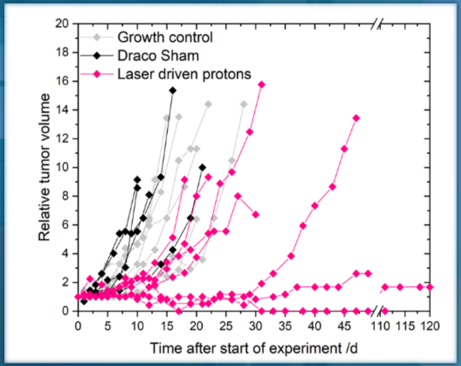
- energy to penetrate volume



- stability



- model – growth delay



- beam transport, energy selective shaping, monitoring, **online and absolute dosimetry**
- capability to handle ~100 mice with reference irradiation (x-ray, proton)
- FLASH performance level demonstrated and Zebra-fish studies ongoing

- **K. Zeil**, **J. Metzkes-Ng**, **F. Kroll**, S. Assenbaum, C. Bernert, F. Brack, S. Kraft, L. Obst-Huebl, M. Rehwald, M. Reimold, H.P. Schlenvoigt, T. Ziegler, et al.
- **A. Irman**, J. Couperus, et al.,
- **T. Kluge**, **A. Debus**, M. Bussmann, R. Pausch, K. Steiniger, I. Göthel, M. Garten, et al.
- **J. Pawelke, E. Beyreuther**, L. Karsch, M. Krause, et al.,
- M. Siebold, D. Albach, S. Bock, R. Gebhardt, U. Helbig, M. Löser, T. Püschel, et al.

- U. Schramm, T. Cowan, R. Sauerbrey

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