Efficient laser proton acceleration in the near critical density regime

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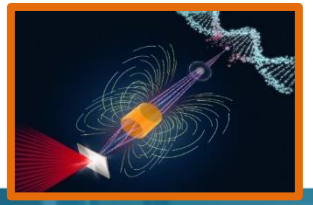
HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

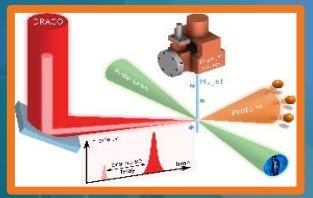
European Advanced Accelerator Conference, La Biodola Bay 2025

Efficient laser proton acceleration in the near critical density regime

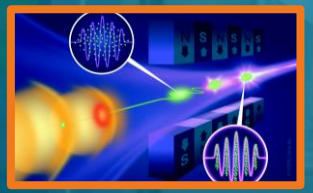


Nat. Phys. 18 (2022)

Nat. Phys. 20 (2024)



Nat. Com. 14 (2023)



Nat. Phot. 17 (2023)

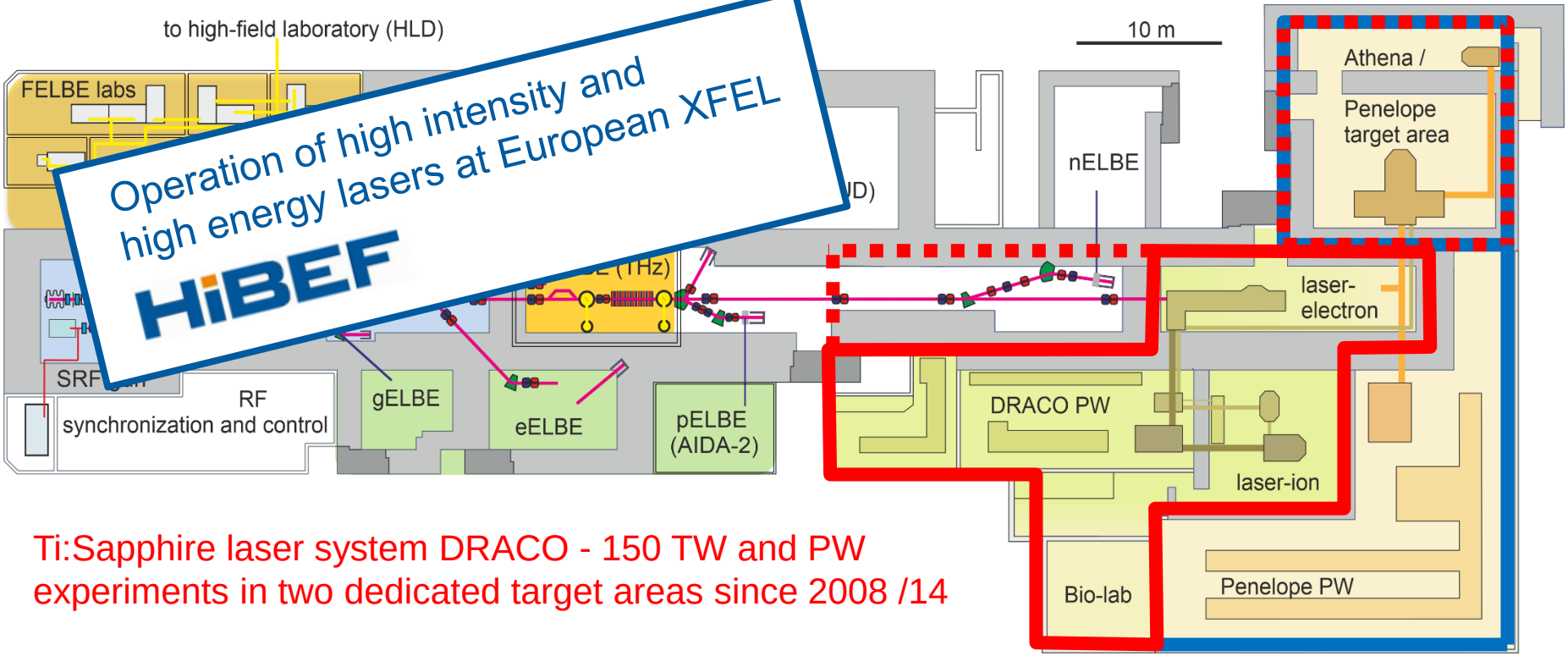
Application oriented optimization criteria:

repetition rate, maximum energy, spectrum, transport properties, conversion efficiency …

Ideally, find the perfect target that matches realistic laser parameters
(by means of refined diagnostics, simulations, …)

ELBE Center for high power radiation sources

advanced plasma accelerator R&D in a 24/7 accelerator user facility



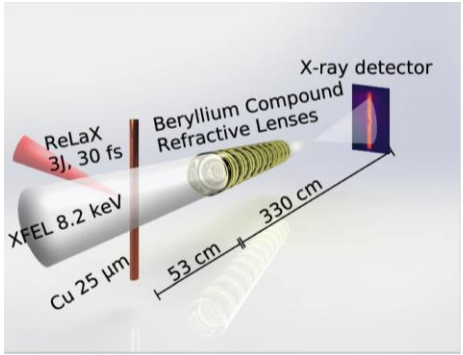
Operation of high intensity and high energy lasers at European XFEL

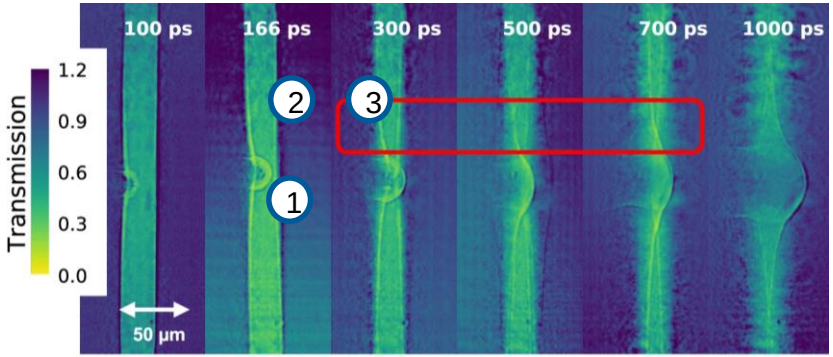
HiBEF

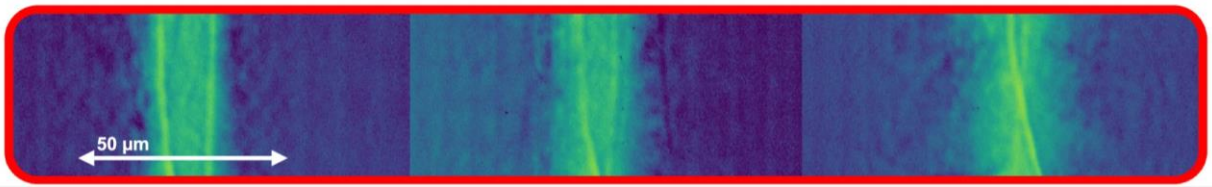
Ti:Sapphire laser system DRACO - 150 TW and PW
experiments in two dedicated target areas since 2008 /14

Short pulse laser driven wire compression

- Finding novel HED / IFE (inertial fusion energy) relevant processes in relativistic plasmas
- Probing micron-scale effects in compressed matter via high resolution phase contrast imaging







1) Initial laser impact and spherical shock

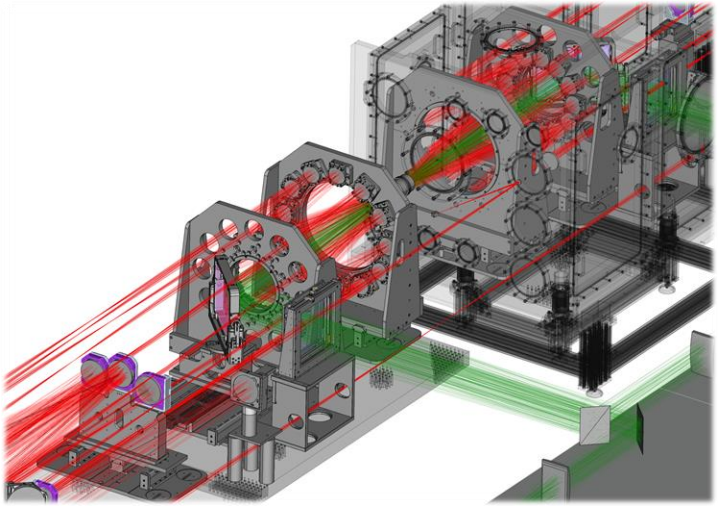
2) Surface return current to compensate charge loss

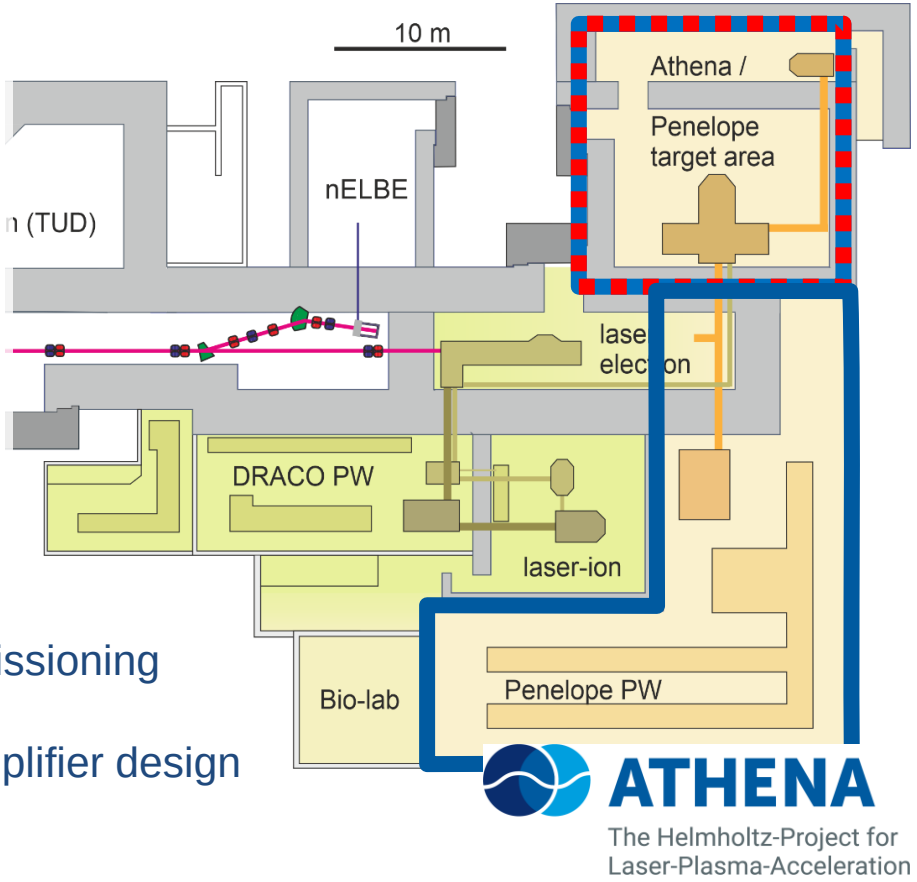
3) Heated surface ablation driving wire implosion

- Establishing a unique new platform for IFE research (strongly coupled to German fusion initiative and interlinked with HZDRs core laser plasma accelerator activities)

A. Laso Garcia et al., Nature Commun. ***15****, 7896 (2024)*

Penelope laser / Athena @ ELBE Center



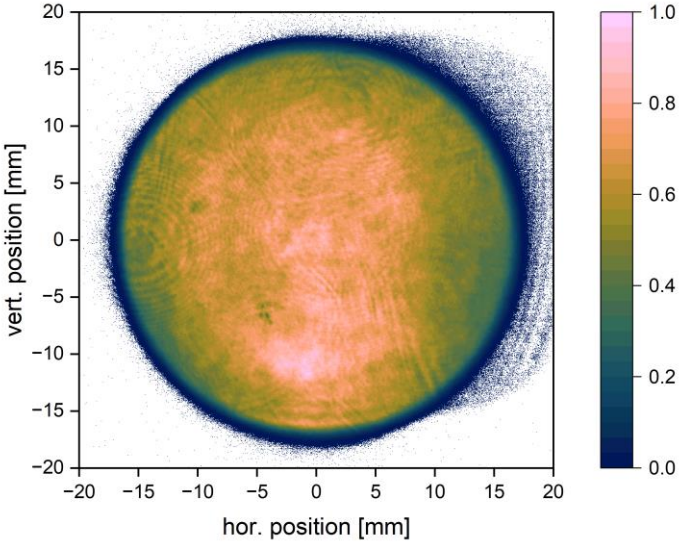


Diode laser pumped PW laser Penelope in commissioning
10 J stage opertional (goal 150J / 150 fs)
12 pass fully imaged He cooled Yb:CaF_2 main amplifier design
multi-beam experimental areas

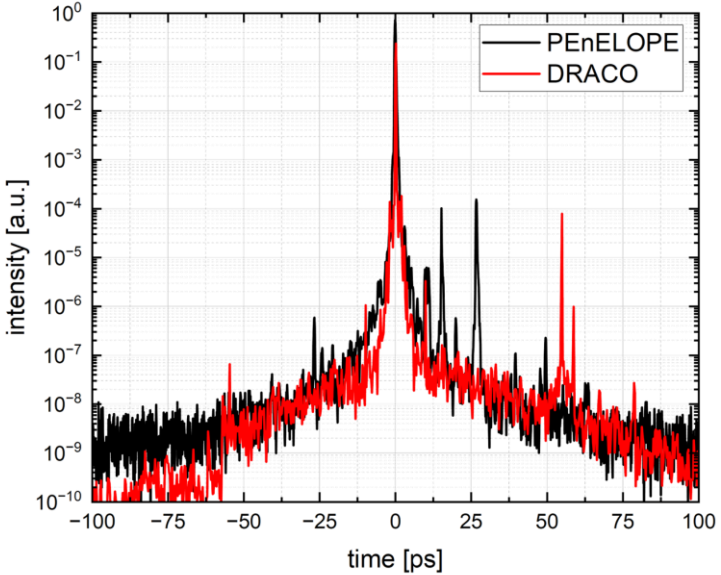
ATHENA
The Helmholtz-Project for
Laser-Plasma-Acceleration

Penelope commissioning … (CPA amplification)

Operation of „soft cryo“ cooled (170K) 10J head at 0.1 Hz

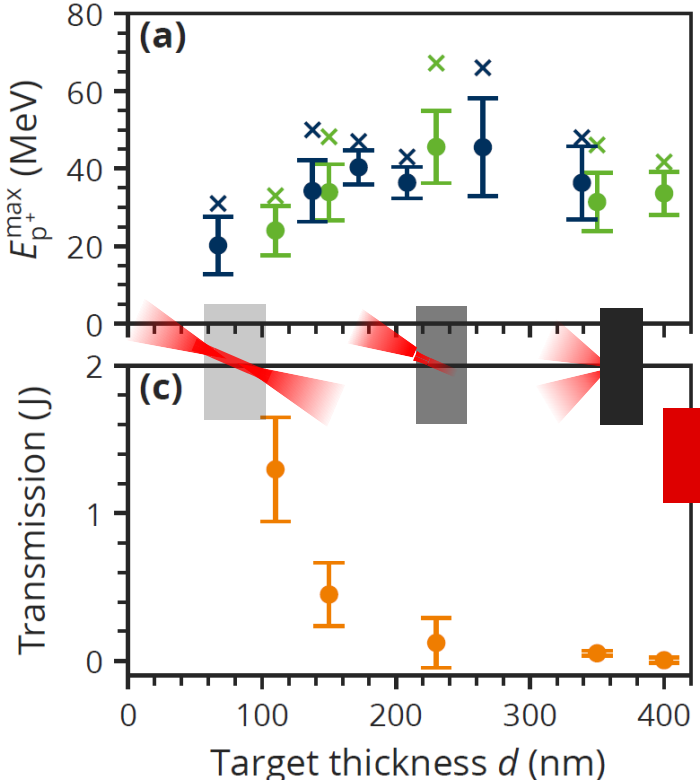


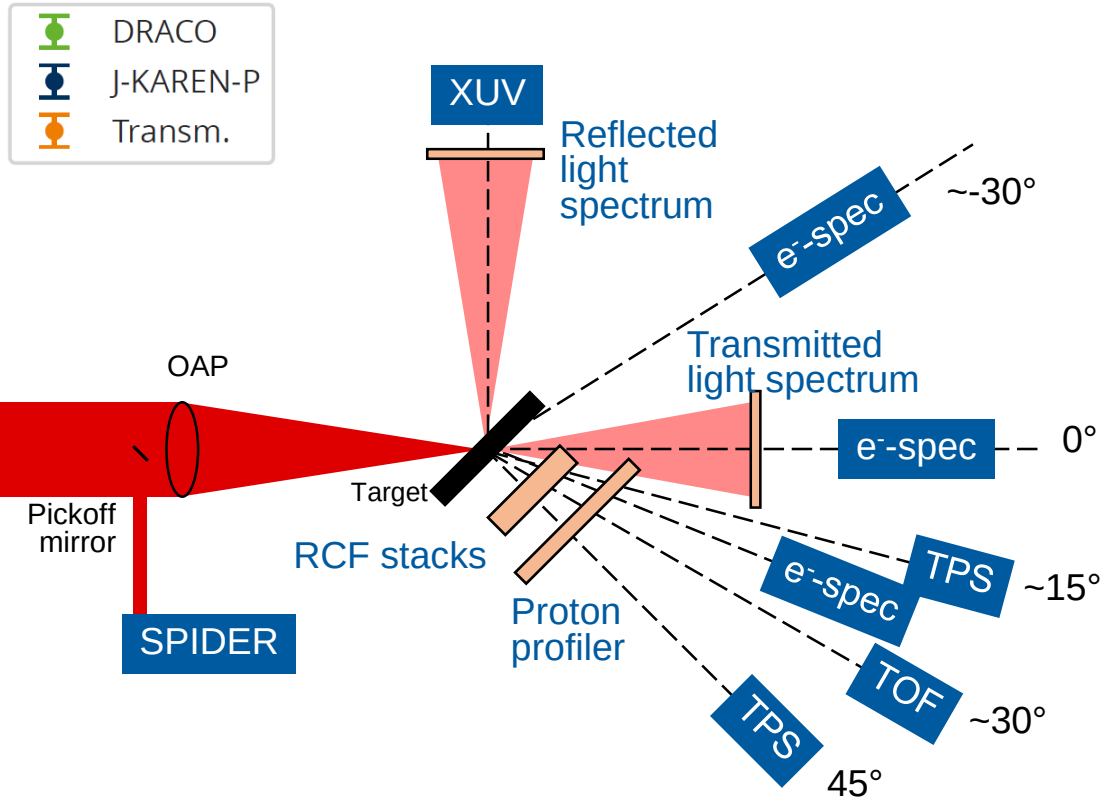
Preliminary pulse contrast (no cleaning yet)



(complex temperature / gain relation to be solved for 1 Hz)

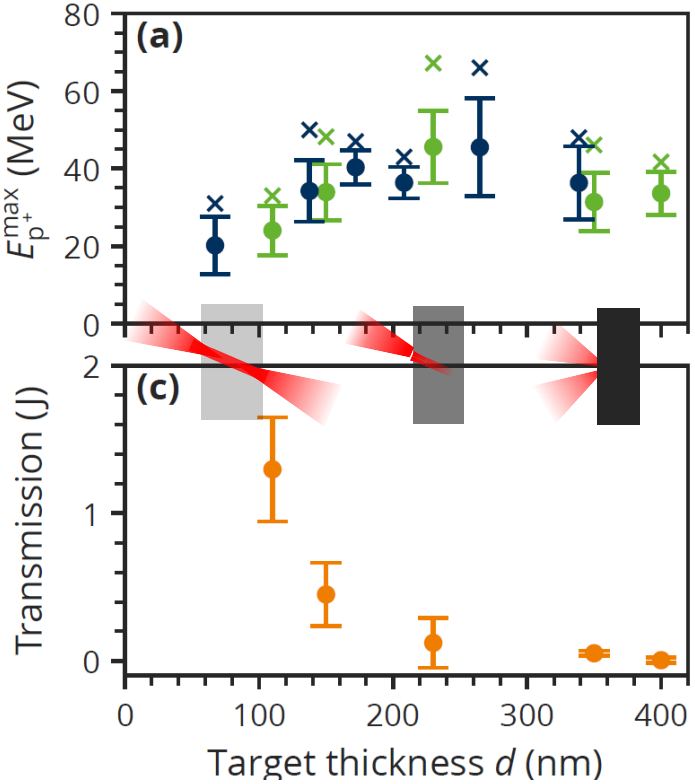
PW (30fs) experiments with variation of target thickness

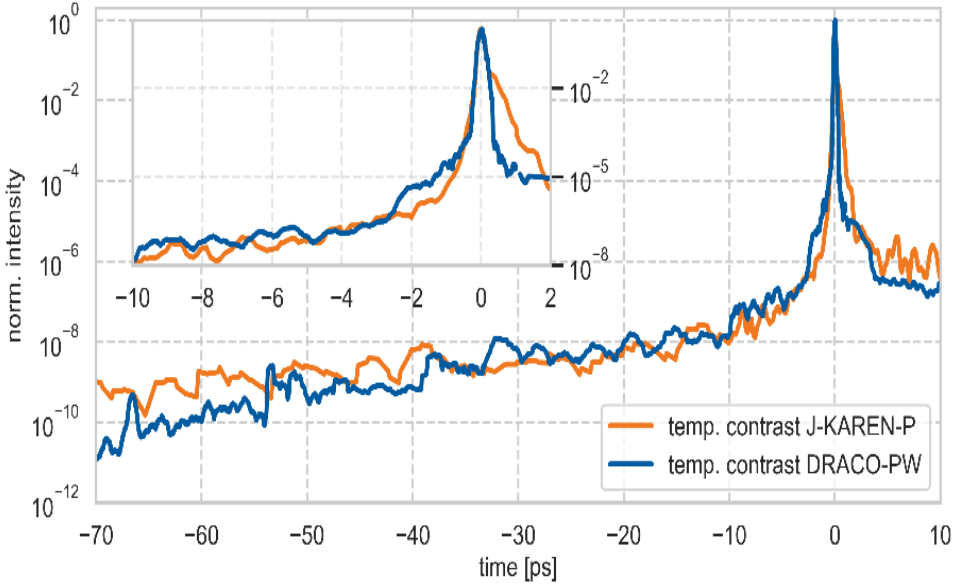




N. Dover, T. Ziegler, et al.
Light: Science and Appl. 12, 71 (2023)

PW (30fs) experiments with thin (~100nm) targets





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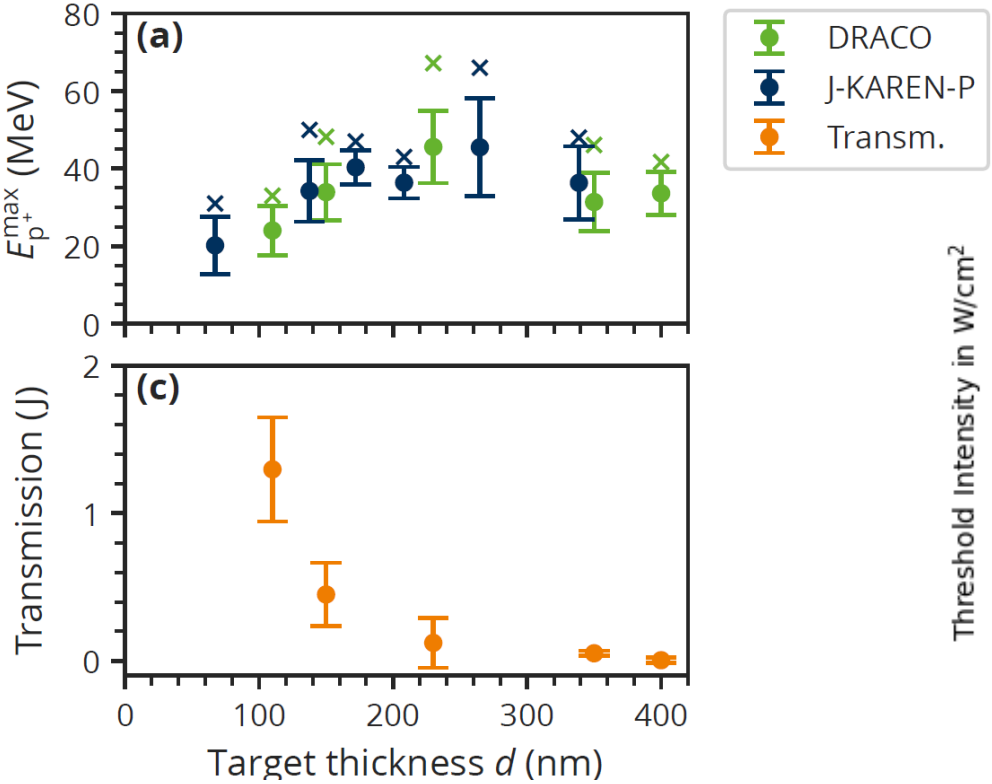
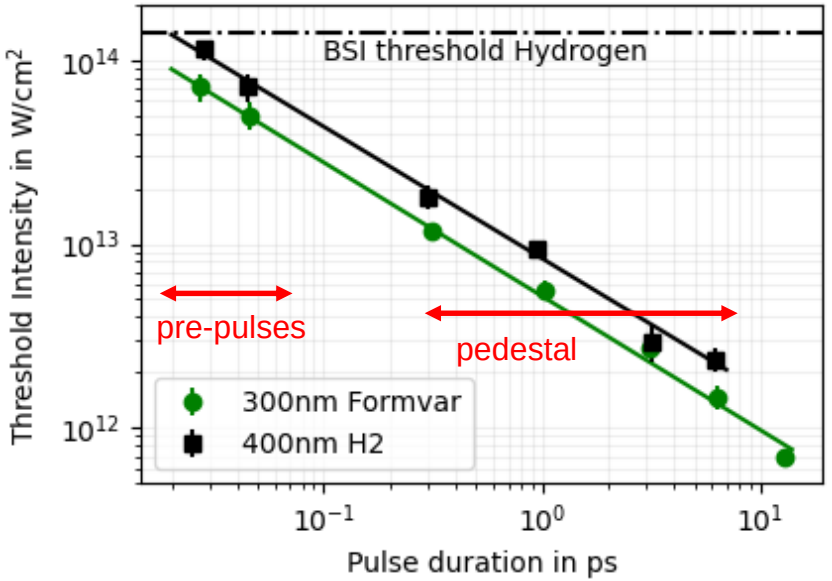
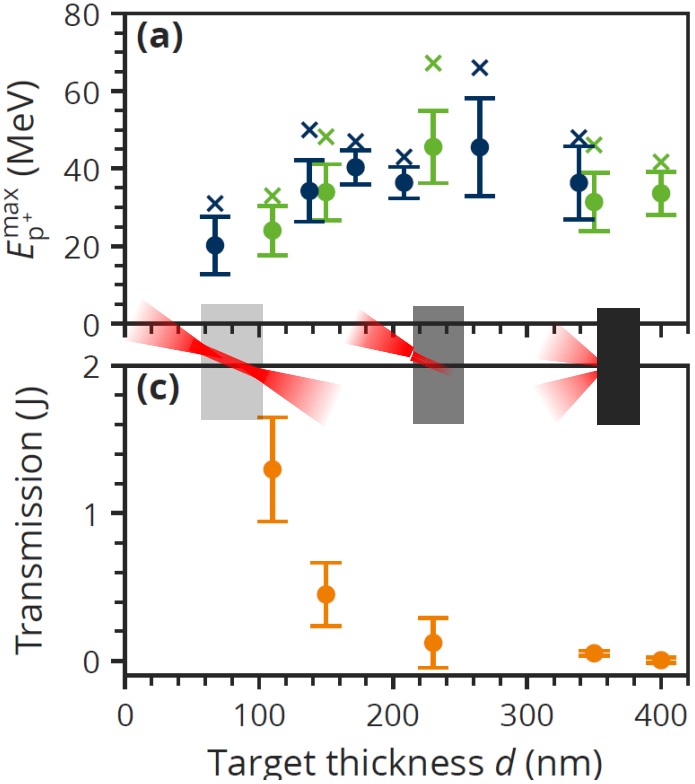


dielectric breakdown and heating exposure-time dependent

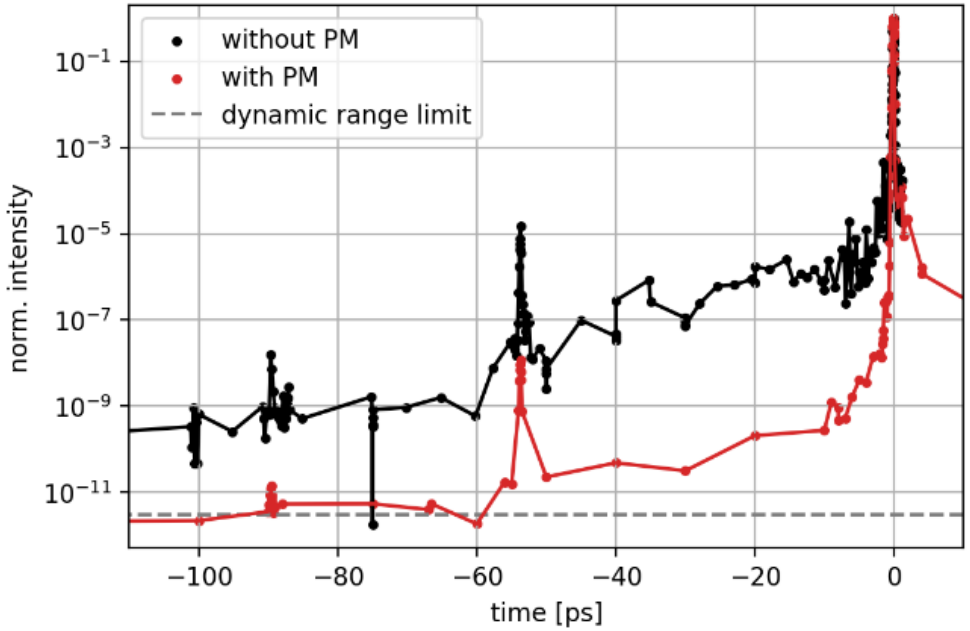


S. Assenbaum, PPCF 67, 015032 (2025)
C. Bernert et al., Phys. Rev. Appl. 19, 014070 (2023)

PW (30fs) experiments with thin (~100nm) targets



improved PM contrast
(full energy)



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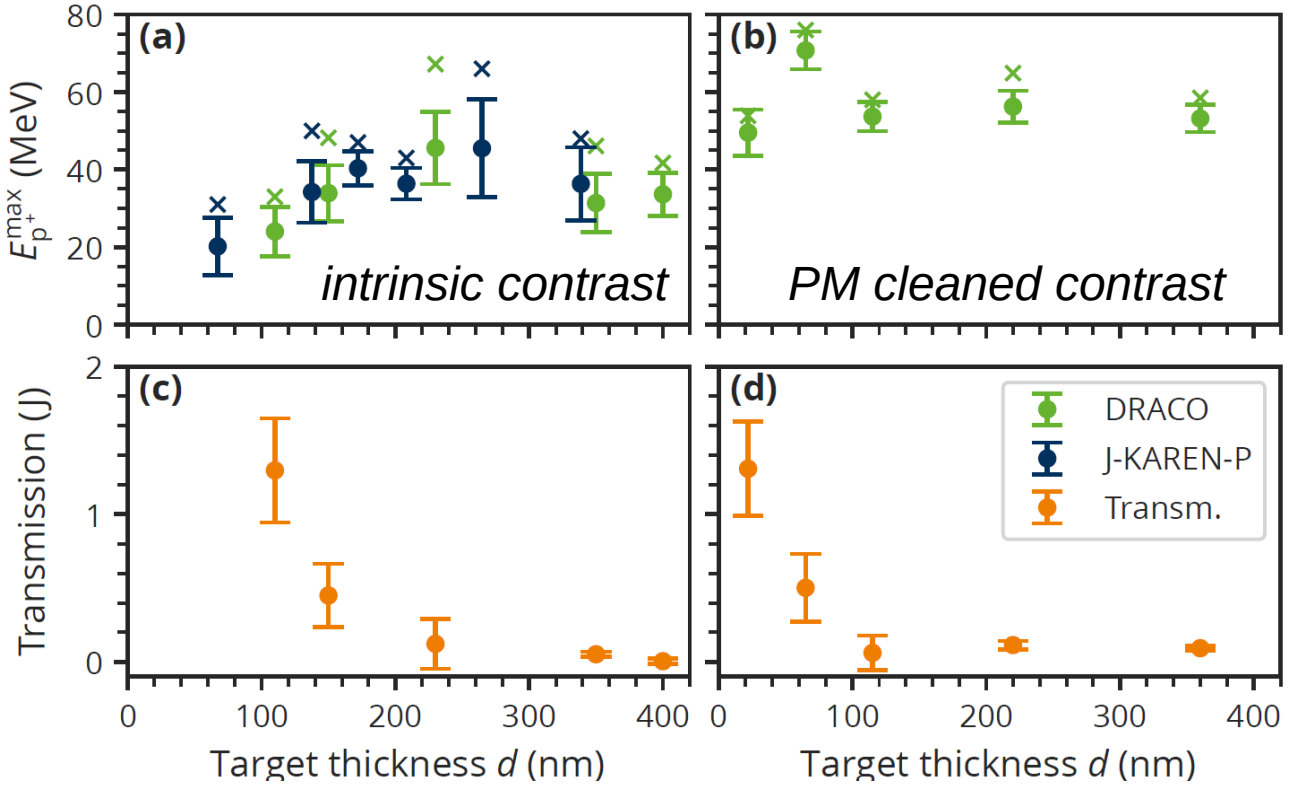
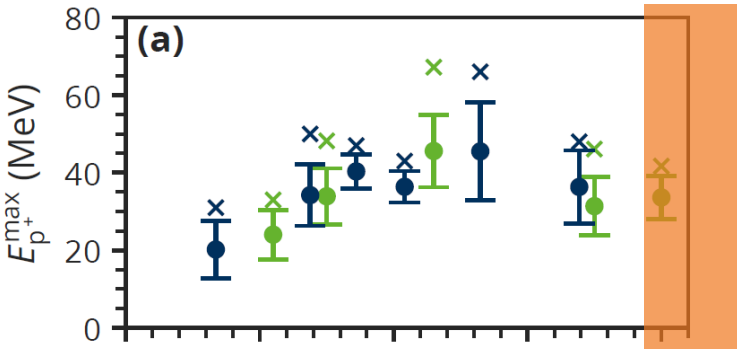
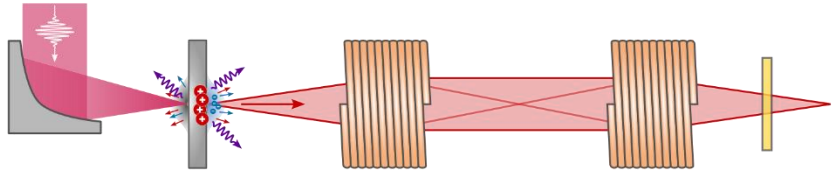


Similar behaviour (improved control with PM and, if needed, heating)

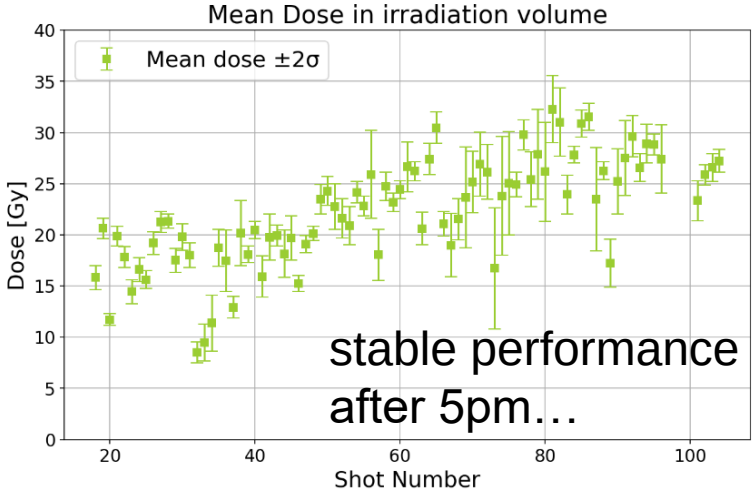
N. Dover, T. Ziegler, et al.
Light: Science and Appl. 12, 71 (2023)

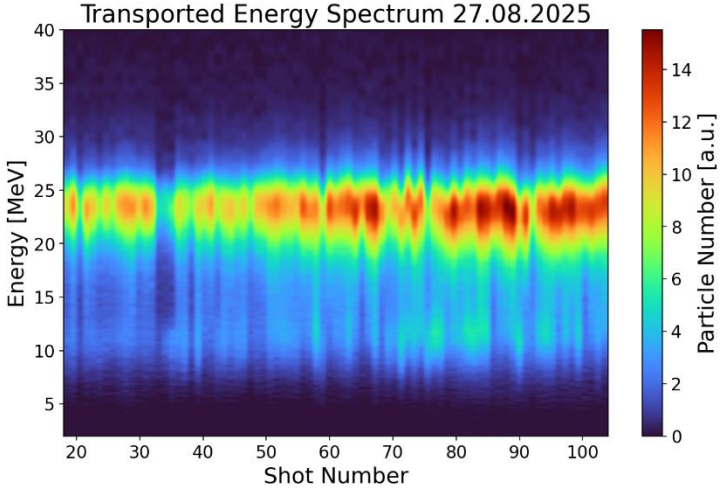
Short TNSA interlude …





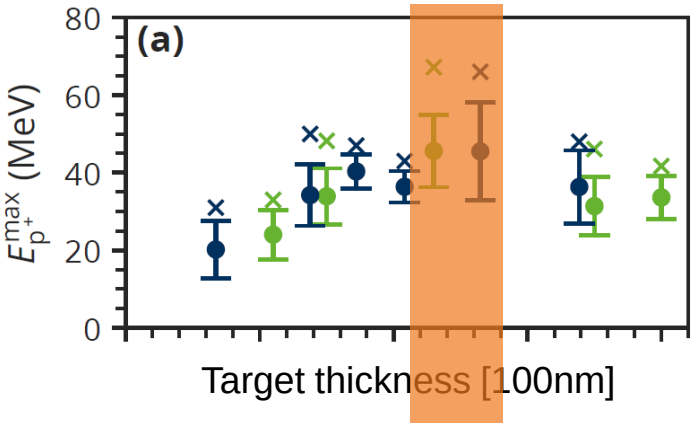
Revival of solenoid beamline
and 65 MeV operation (optimized dispersion)
with calibrated online detectors



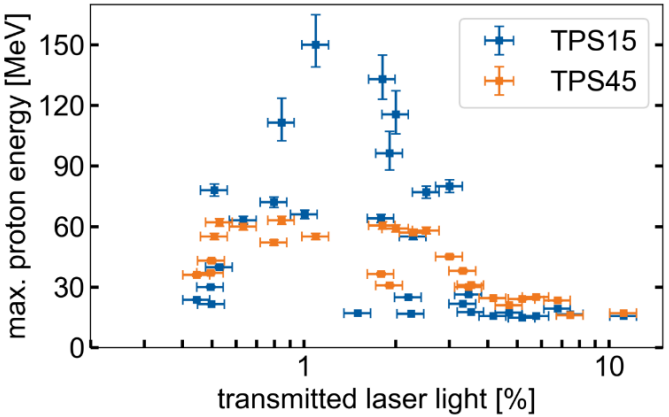


J. Metzkes.Ng, et al., Sci. Rep. 13, 20611 (2023) *F. Kroll, et al., Nat. Phys. 18, 316 (2022)*

Acceleration regimes …

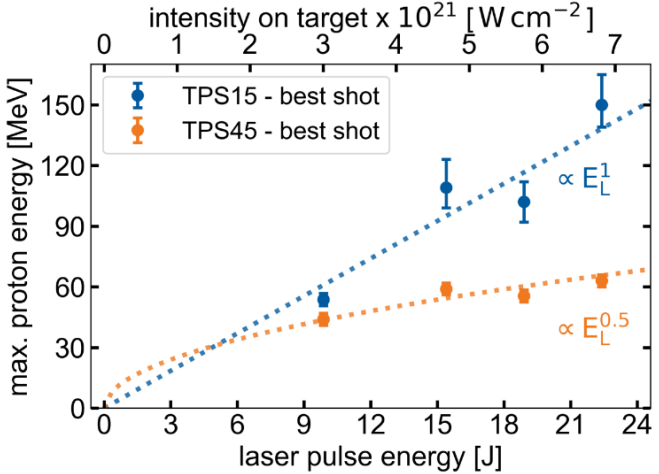


High energies in forward direction (transmission sorted data)



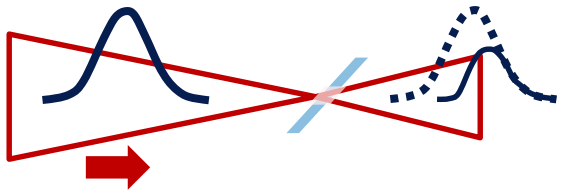
through combination of cascade of acceleration mechanismsn (and only accessible with simulation support)

can one learn more from transmitted / reflected light?



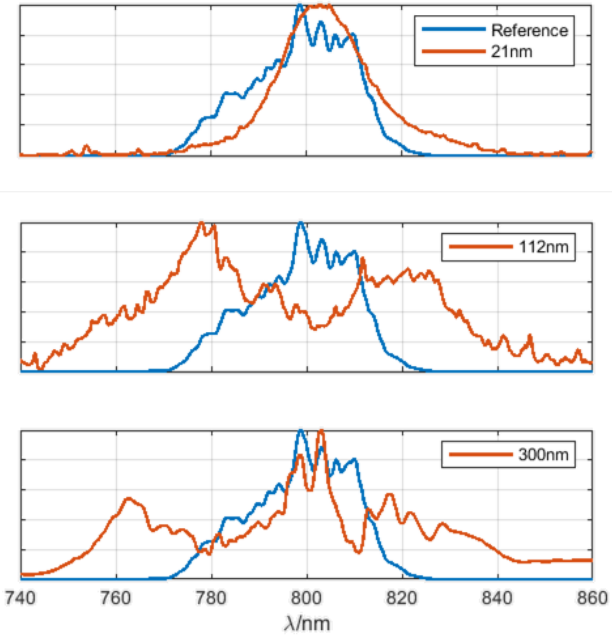
T. Ziegler, et al. Nature Physics 20, 1211 (2024)

Transmitted (and reflected) light studies

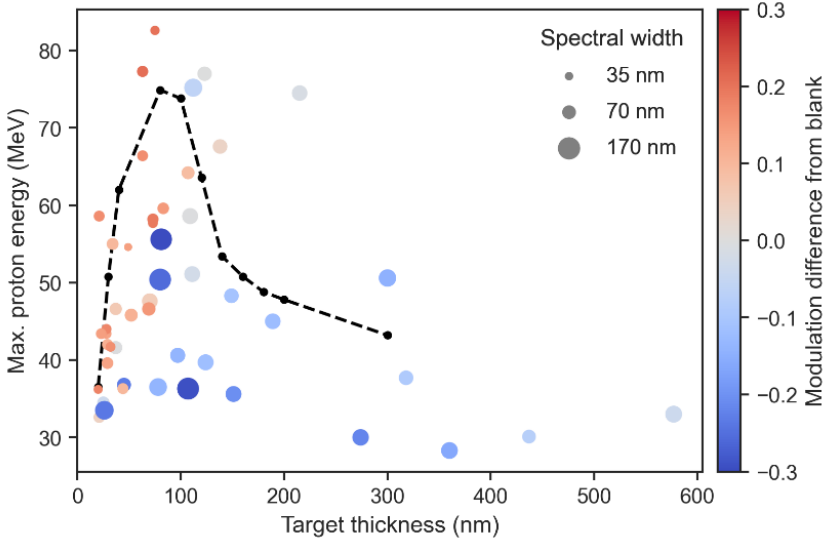


J-KAREN-P (KPSI): 40fs, 3×10^{21} W cm^{-2}
plasma mirror contrast, formvar foils ($230n_c$)

Thickness / structured

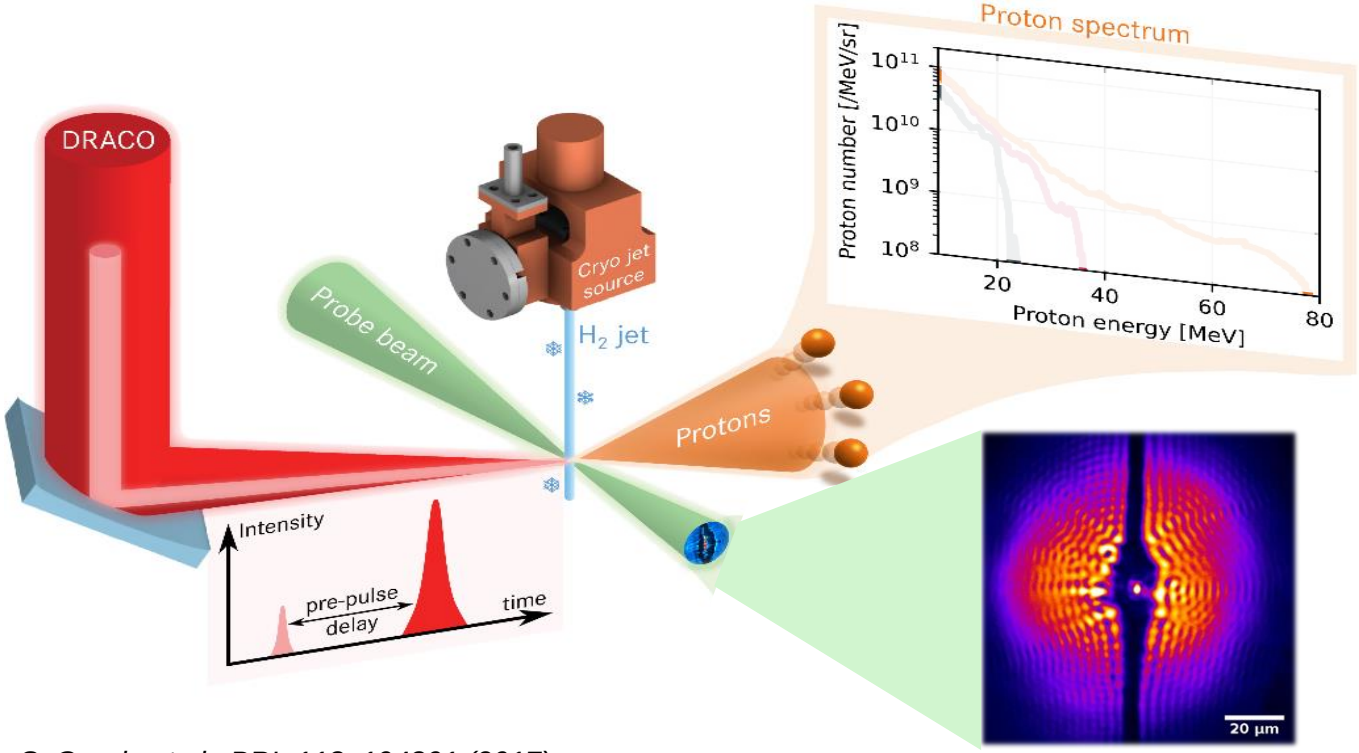


Transmission / smooth



RIT and density change represents shutters
Favors transmission at laser peak

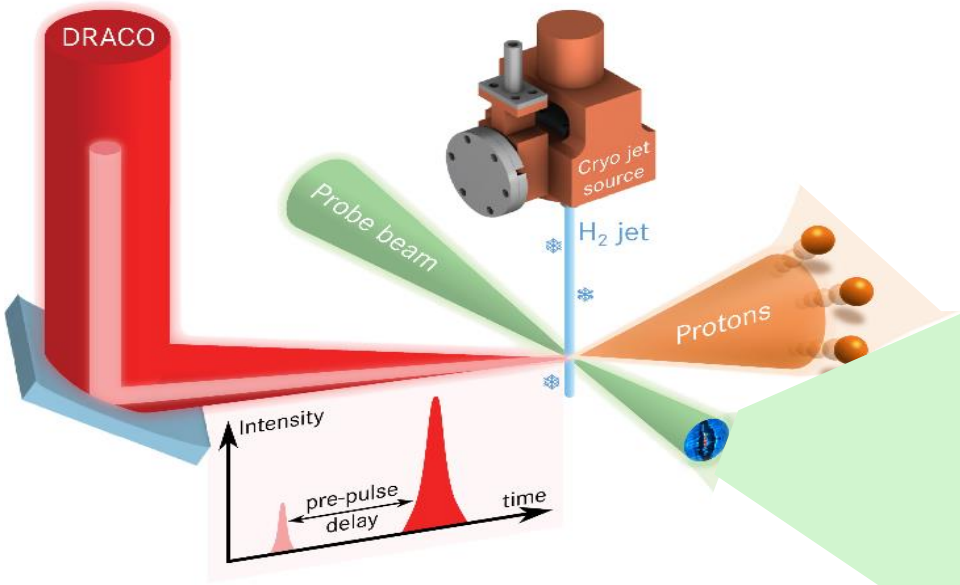
Proton acceleration in solid hydrogen targets



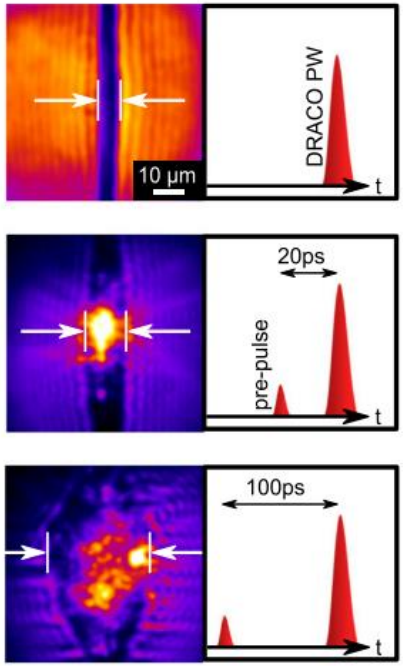
S. Goede et al., PRL 118, 194801 (2017)
L. Obst et al., Sci. Rep. 7, 10248 (2017)
M. Gauthier, et al., APL 111, 114102 (2017)
L. Obst, et al., Nat. Comun. 9, 5292 (2018)
M. Rehwald, et al., Nat. Commun. 14, 4009 (2023)

M. Loeser, et al, Optics Express 29, 9199 (2021)
C. Bernert, et al., Sci. Rep. 12, 7287 (2022)
C. Bernert, et al., Phys. Rev. Appl. 19, 014070 (2023)

Proton acceleration in solid hydrogen targets

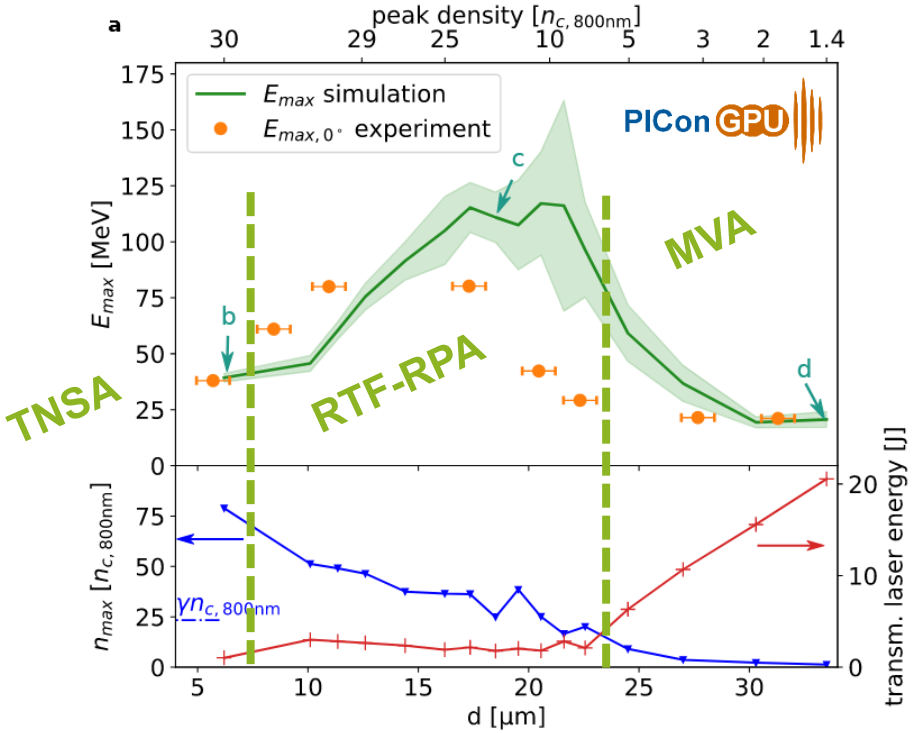


- exploit controlled target expansion for density tailoring



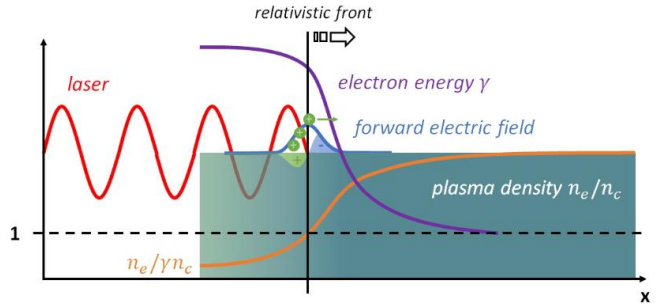
Scanning through acceleration regimes

quantitative 3D simulation suggests transition from TNSA via RTF-RPA to MVA



RTF-RPA = Relativistic Transparency Front - RPA

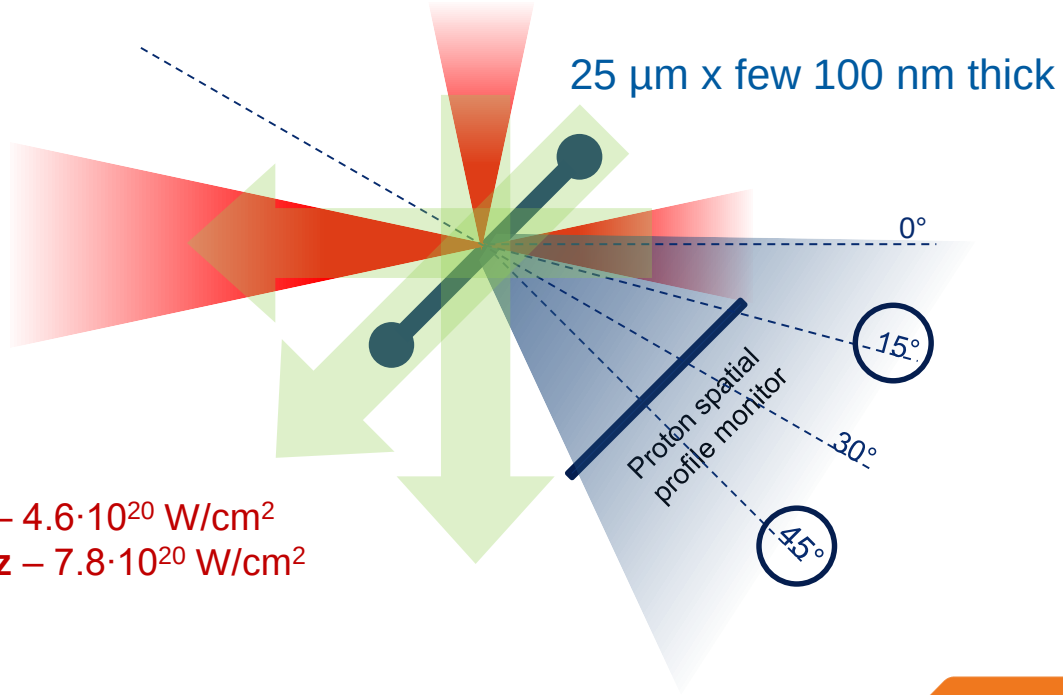
synchronized acceleration of ions at the moving (intensity dependent) relativistic critical density front



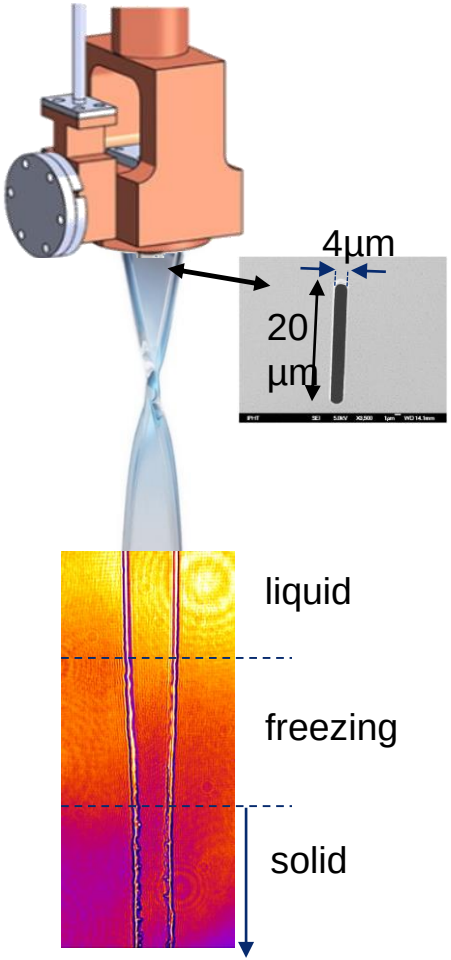
M. Rehwald, et al., Nat. Commun. 14, 4009 (2023)
I. Goethel, et al., PPCF 64, 044010 (2022)

Flat hydrogen jet foil-like conditions

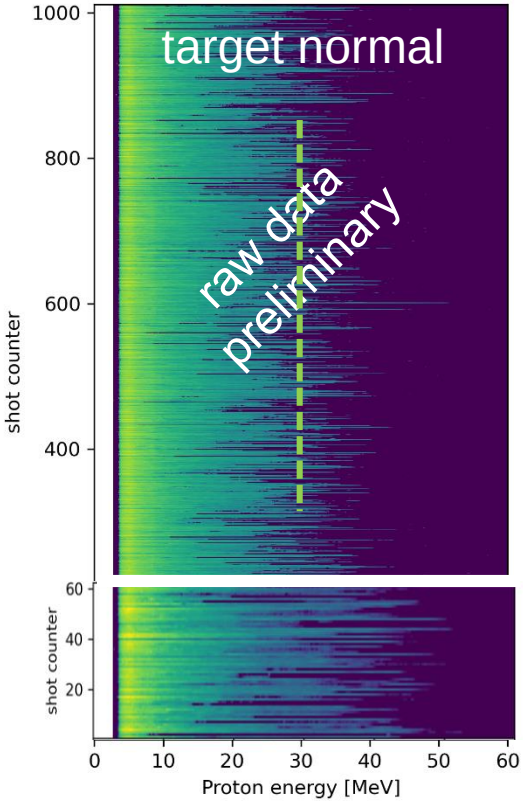
- improves hit probability
- improves emission (direction and spread)
- extensive probing and diagnostics …



1.6J, 1 Hz – $4.6 \cdot 10^{20}$ W/cm^2
2.7J, 0.2 Hz – $7.8 \cdot 10^{20}$ W/cm^2

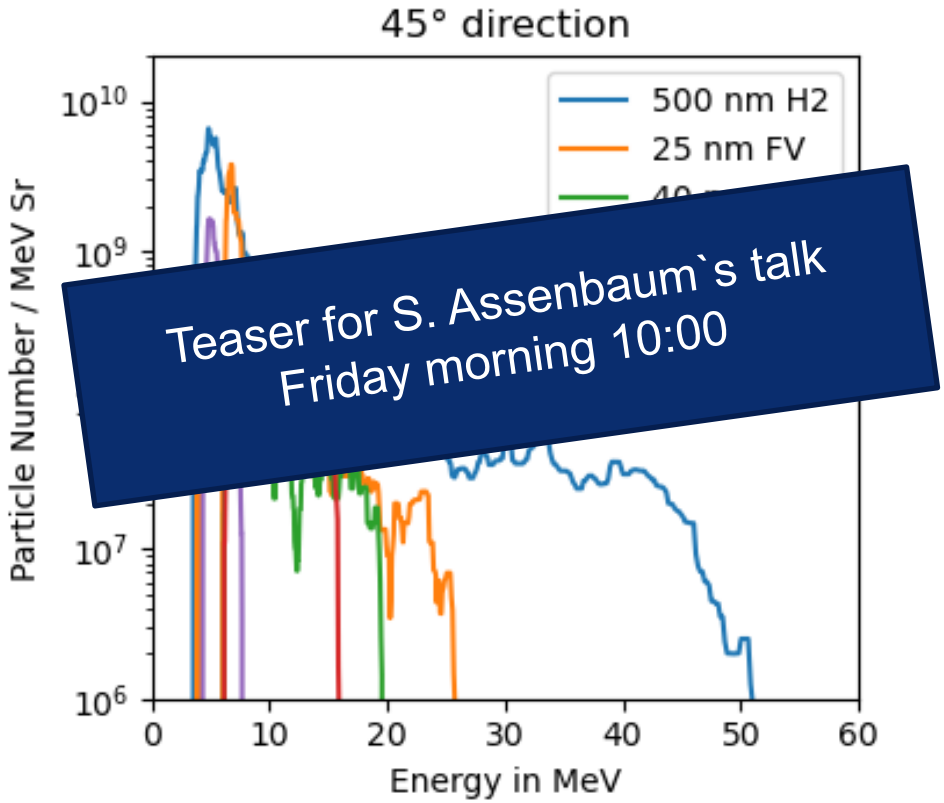


Flat hydrogen jet foil-like conditions - *preliminary results*



median cut-off
30 MeV
@ 1.6 J / 1 Hz

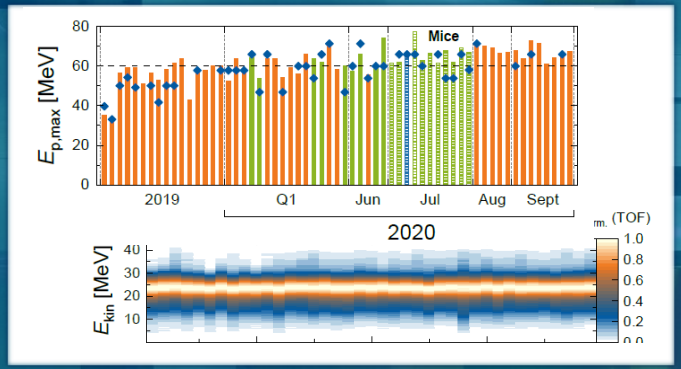
median cut-off
42 MeV
@ 2.7 J / 0.2 Hz



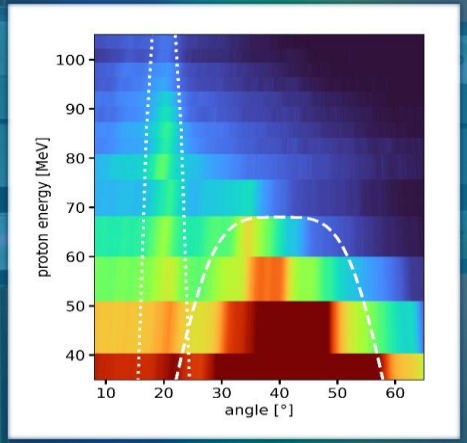
Teaser for S. Assenbaum`s talk
Friday morning 10:00

Plasma accelerator take-away message – pilot studies demonstrate system readiness – TNSA beaten with intrinsic laser setting – FELs shown

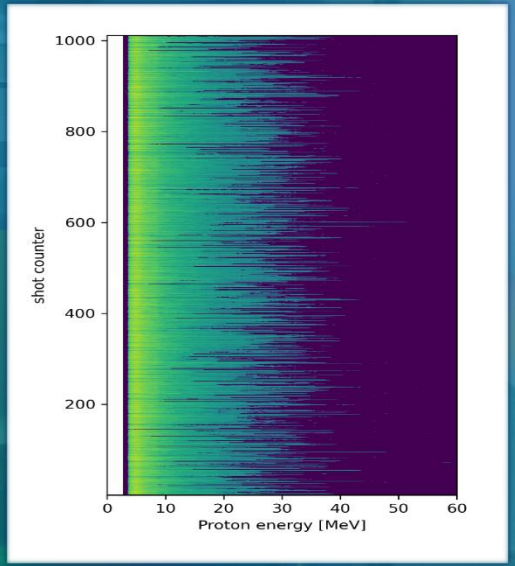
- long and short term stability



- energy to penetrate volume



- cryogenic hydrogen serving target rep rate



Laser beam quality on target is essential in all aspects

- **K. Zeil, J. Metzkes-Ng**, F. Kroll, **S. Assenbaum, C. Bernert,** F. Brack, **M. Rehwald,** M. Reimold, H.P. Schlenvoigt, **E. Umlandt**, J. Schilz, **M. Vescovi,** T. Ziegler, et al.
- A. Irman, J. Couperus, V. Chang, A. Ghaith, M. Laberge, P. Ufer, S. Schöbel, et al.,
- T. Kluge, A. Debus, M. Bussmann, R. Pausch, K. Steiniger, I. Göthel, P. Ordyna, et al.
- E. Beyreuther, J. Pawelke, M. Krause, et al.,
- D. Albach, S. Bock, R. Gebhardt, U. Helbig, M. Löser, T. Püschel, M. Siebold, et al.
- U. Schramm, T. Cowan, R. Sauerbrey

- N. Dover, M. Nishiuchi, A. Kon, H. Kyriama et al. / M. Gauthier, F. Fiuza, S. Glenzer, et al. / S. Goede, et al. / V. Malka, et al. / M.E. Couprie, M. Labat, et al.

European XFEL

SOLEIL SYNCHROTRON

WEIZMANN INSTITUTE OF SCIENCE

KPSI Kansai Photon Science Institute

SLAC

HZDR