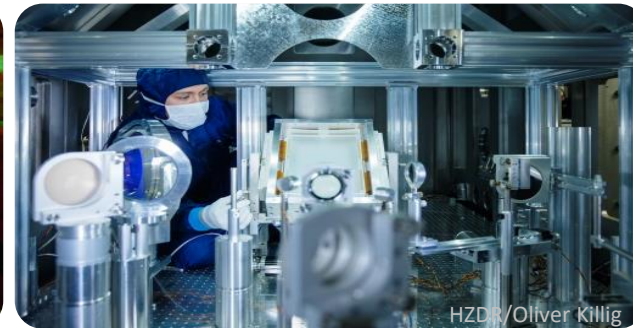
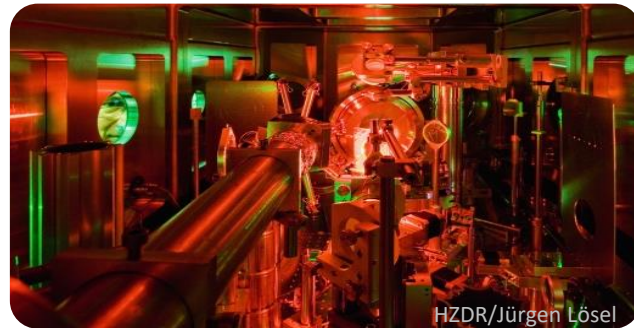
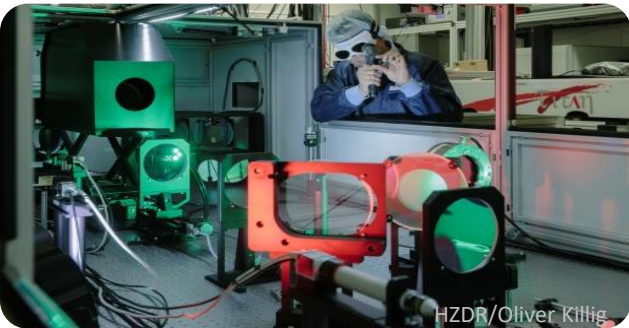


High energy proton acceleration at DRACO-PW and radiobiological applications

6th European Advanced Accelerator Concepts Workshop, La Biodola Bay, Isola d'Elba (Italy), 2023

21.09.2023



Josefine Metzkes-Ng

Young Investigator Group *Application-oriented laser-plasma accelerators*

Institute of Radiation Physics

Helmholtz-Zentrum Dresden – Rossendorf

HZDR



Acknowledgements

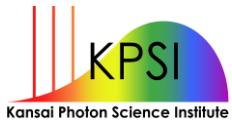


K. Zeil & T. Kluge and teams for laser-driven ion acceleration experiment & theory

J. Metzkes-Ng and team for realization of application experiments

E. Beyreuther & J. Pawelke and team for radiobiological studies

S. Assenbaum, C. Bernert, F.-E. Brack, C. Bernert, S. Bock, E. Bodenstein, K. Brüchner, M. Bussmann, A. Corvino, T. E. Cowan, M. Garten, L. Gaus, R. Gebhardt, I. Goethel, U. Helbig, L. Huang, A. Hübl, S. Kraft, M. Krause, F. Kroll, E. Lessmann, M. Löser, S. Meister, T. Miethlinger, L. Obst-Hübl, J. Pietzsch, I. Prencipe, T. Püschel, M. Reimold, M. Rehwald, C. Richter, H.-P. Schlenvoigt, M. Siebold, M. E. P. Umlandt, M. Vescovi, L. Yang, T. Ziegler, U. Schramm



N. Dover, H. Kiriya, A. Kon, M. Nishuichi



C. B. Curry, F. Fiuza, M. Gauthier, S. Göde, S. H. Glenzer, J. B. Kim,

C. Schoenwaelder, F. Treffert

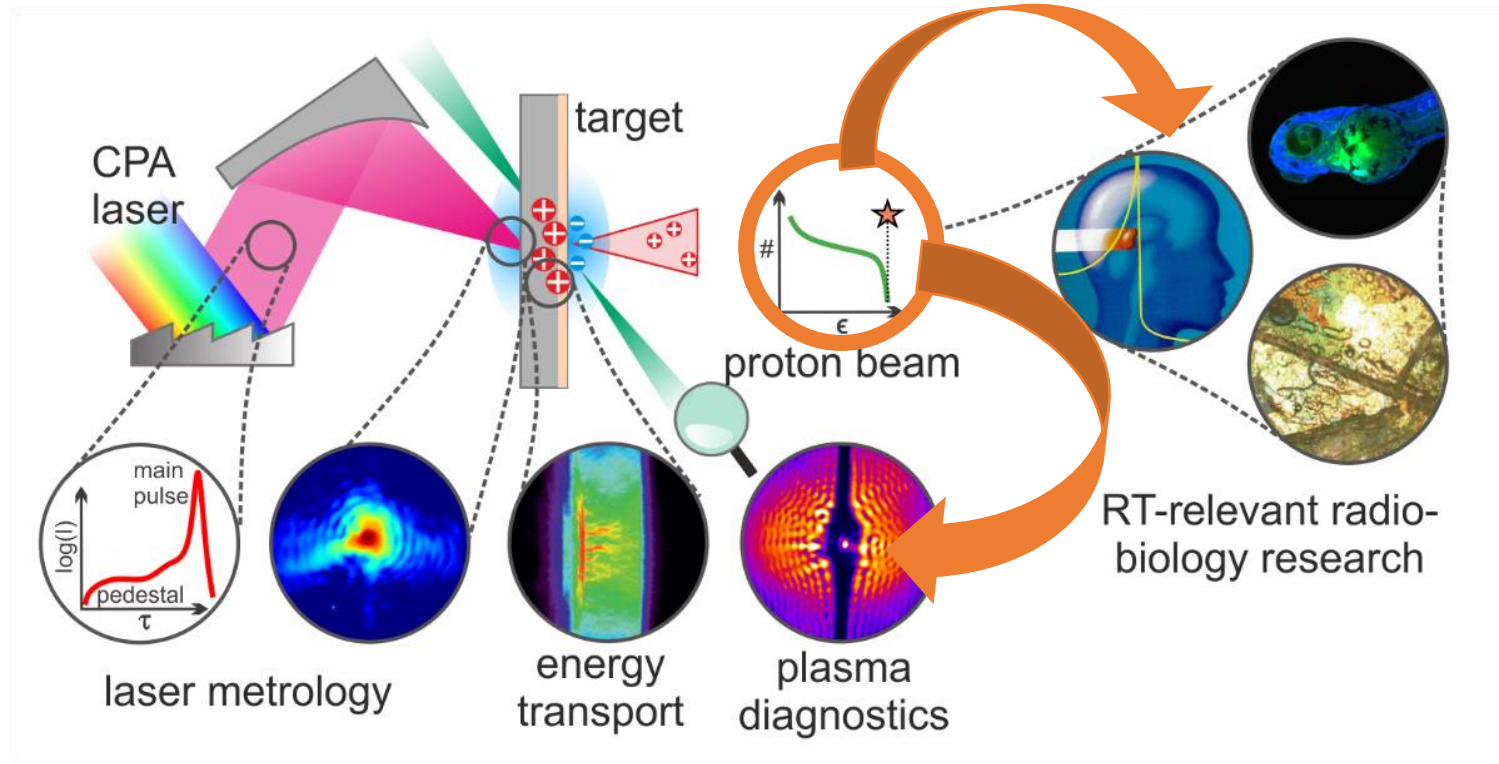
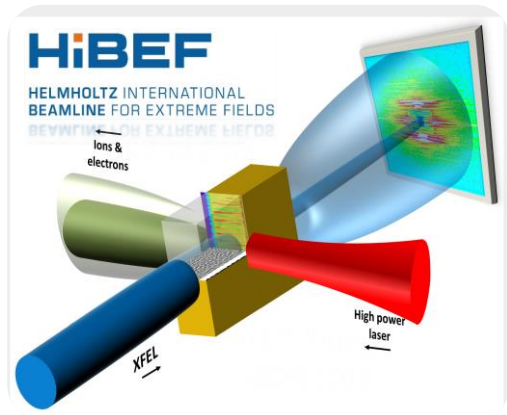
Motivation

High power laser solid matter interaction for plasma-based proton acceleration



PICon GPU

Scalable particle-in-cell simulations on many-core hardware with the free and open source code



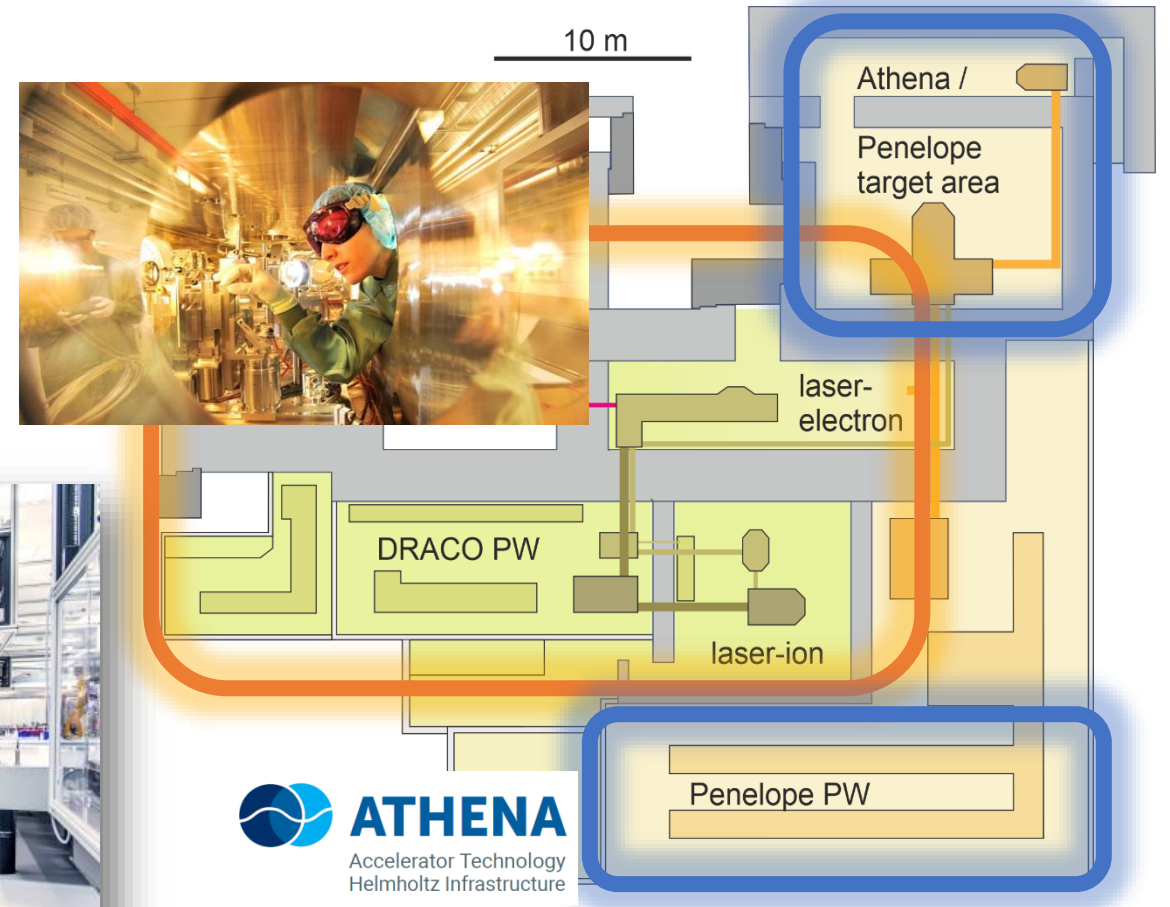
1. Achieving highest proton energies beyond TNSA
2. Stable laser-driven proton beams for ultra-high dose rate radiobiology

High power lasers at HZDR

Driving advanced accelerator research

Draco – accelerator research (e⁻/p⁺) & application

- commercial Ti:Sapphire dual-beam laser system
 - 150 TW (4 J in 30 fs routinely on target) @ 10 Hz
 - ~PW (> 20 J on target in 30 fs) @ 1 Hz



PENELOPE – prototype driver for radiobiology with protons

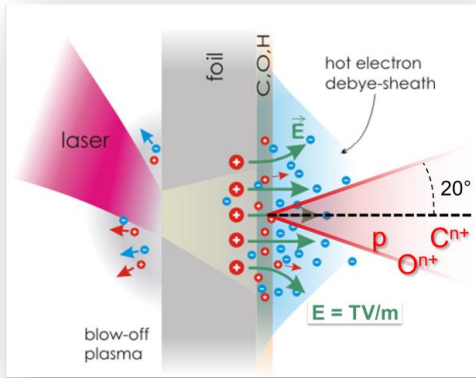
- diode-pumped, energy-efficient 150 J / 150 fs laser @ 1Hz
- lighthouse project for proton/ion acceleration within ATHENA

Accessing different proton acceleration schemes via target density tailoring

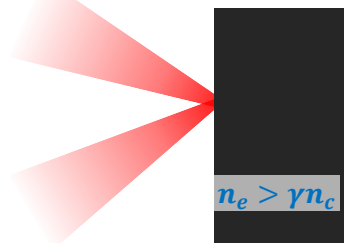
Acceleration regimes

TNSA

Snively (2000), Clark (2000), Wilks (2001)



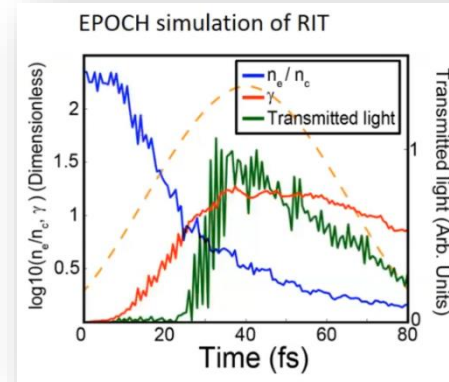
mirror-like behaviour
pulse mostly reflected



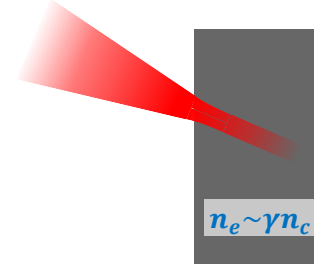
typ. $> 10^{23} \text{ cm}^{-3}$
dense, opaque target

Relativistic transparency

Henig PRL (2009), Yin POP (2011), D'Humieres POP (2015),
Higginson Nat. Comm. (2018), McKenna, Gonzales-Izquierdo et al.
SPIE (2021) & ApplSci (2018)



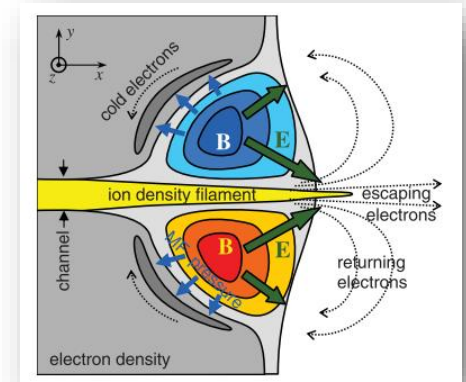
pulse mostly absorbed,
volumetric interaction



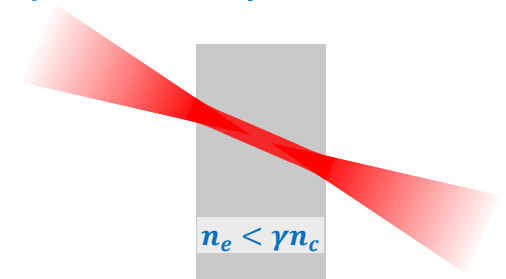
$1.7 \times 10^{21} \text{ cm}^{-3} = n_{\text{critical}} [800\text{nm}]$
near-critical density

Magneto vortex acceleration

Bulanov & Esirkepov PRL (2007)



pulse mostly transmitted



typ. $< 10^{20} \text{ cm}^{-3}$
transparent target

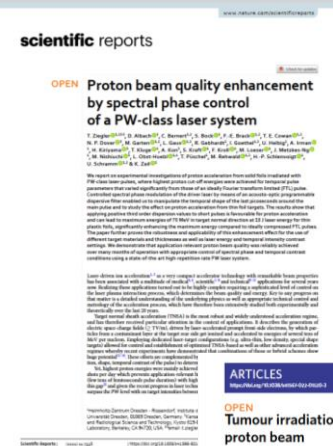
Accessing different proton acceleration schemes via target density tailoring

Experimental realization

TNSA

Relativistic transparency

Magneto vortex acceleration



Formvar foils

- stable acceleration performance up to 70 MeV
- application: *in vivo* irradiations of mice
- proton acceleration up to 150 MeV

laser intensity contrast & dispersion management



Florian Krull^{1,2}, Florian-Emanuel Brack^{1,2}, Constantin Bernert^{1,2}, Stefan Bock^{1,2}, Elisabeth Bellenkötter^{1,2}, Kerstin Brückner^{1,2}, Thomas E. Cowan^{1,2}, Lemart Gauer^{1,2}, René Gebhardt^{1,2}, Uwe Hahn^{1,2}, Leonhard Karawitz^{1,2}, Thomas Kluge^{1,2}, Stephan Kraft^{1,2}, Maximilian Krause^{1,2,3}, Elisabeth Leemann^{1,2}, Umar Masood^{1,2}, Sebastian Meister^{1,2}, Josefine Metzkes-Ng^{1,2}, Alanaj Nossaj^{1,2}, Jörg Pawellek^{1,2}, Jens Petzsch^{1,2}, Thomas Plehn^{1,2}, Maximilian Reimold^{1,2}, Martin Reimold^{1,2,3}, Christian Richter^{1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137,138,139,140,141,142,143,144,145,146,147,148,149,150,151,152,153,154,155,156,157,158,159,160,161,162,163,164,165,166,167,168,169,170,171,172,173,174,175,176,177,178,179,180,181,182,183,184,185,186,187,188,189,190,191,192,193,194,195,196,197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212,213,214,215,216,217,218,219,220,221,222,223,224,225,226,227,228,229,230,231,232,233,234,235,236,237,238,239,240,241,242,243,244,245,246,247,248,249,250,251,252,253,254,255,256,257,258,259,260,261,262,263,264,265,266,267,268,269,270,271,272,273,274,275,276,277,278,279,280,281,282,283,284,285,286,287,288,289,290,291,292,293,294,295,296,297,298,299,300,301,302,303,304,305,306,307,308,309,310,311,312,313,314,315,316,317,318,319,320,321,322,323,324,325,326,327,328,329,330,331,332,333,334,335,336,337,338,339,340,341,342,343,344,345,346,347,348,349,350,351,352,353,354,355,356,357,358,359,360,361,362,363,364,365,366,367,368,369,370,371,372,373,374,375,376,377,378,379,380,381,382,383,384,385,386,387,388,389,390,391,392,393,394,395,396,397,398,399,400,401,402,403,404,405,406,407,408,409,410,411,412,413,414,415,416,417,418,419,420,421,422,423,424,425,426,427,428,429,430,431,432,433,434,435,436,437,438,439,440,441,442,443,444,445,446,447,448,449,450,451,452,453,454,455,456,457,458,459,460,461,462,463,464,465,466,467,468,469,470,471,472,473,474,475,476,477,478,479,480,481,482,483,484,485,486,487,488,489,490,491,492,493,494,495,496,497,498,499,500,501,502,503,504,505,506,507,508,509,510,511,512,513,514,515,516,517,518,519,520,521,522,523,524,525,526,527,528,529,530,531,532,533,534,535,536,537,538,539,540,541,542,543,544,545,546,547,548,549,550,551,552,553,554,555,556,557,558,559,560,561,562,563,564,565,566,567,568,569,570,571,572,573,574,575,576,577,578,579,580,581,582,583,584,585,586,587,588,589,590,591,592,593,594,595,596,597,598,599,600,601,602,603,604,605,606,607,608,609,610,611,612,613,614,615,616,617,618,619,620,621,622,623,624,625,626,627,628,629,630,631,632,633,634,635,636,637,638,639,640,641,642,643,644,645,646,647,648,649,650,651,652,653,654,655,656,657,658,659,660,661,662,663,664,665,666,667,668,669,670,671,672,673,674,675,676,677,678,679,680,681,682,683,684,685,686,687,688,689,690,691,692,693,694,695,696,697,698,699,700,701,702,703,704,705,706,707,708,709,710,711,712,713,714,715,716,717,718,719,720,721,722,723,724,725,726,727,728,729,730,731,732,733,734,735,736,737,738,739,740,741,742,743,744,745,746,747,748,749,750,751,752,753,754,755,756,757,758,759,760,761,762,763,764,765,766,767,768,769,770,771,772,773,774,775,776,777,778,779,780,781,782,783,784,785,786,787,788,789,790,791,792,793,794,795,796,797,798,799,800,801,802,803,804,805,806,807,808,809,810,811,812,813,814,815,816,817,818,819,820,821,822,823,824,825,826,827,828,829,830,831,832,833,834,835,836,837,838,839,840,841,842,843,844,845,846,847,848,849,850,851,852,853,854,855,856,857,858,859,860,861,862,863,864,865,866,867,868,869,870,871,872,873,874,875,876,877,878,879,880,881,882,883,884,885,886,887,888,889,890,891,892,893,894,895,896,897,898,899,900,901,902,903,904,905,906,907,908,909,910,911,912,913,914,915,916,917,918,919,920,921,922,923,924,925,926,927,928,929,930,931,932,933,934,935,936,937,938,939,940,941,942,943,944,945,946,947,948,949,950,951,952,953,954,955,956,957,958,959,960,961,962,963,964,965,966,967,968,969,970,971,972,973,974,975,976,977,978,979,980,981,982,983,984,985,986,987,988,989,990,991,992,993,994,995,996,997,998,999,1000}

Recent progress in the development of proton therapy for cancer treatment has been driven by the realization of laser-driven proton beams. These beams offer several advantages over conventional proton beams, including compact size, high energy, and the potential for on-site production. However, the development of laser-driven proton beams is still in its early stages, and several challenges remain. One of the main challenges is the low energy and low current of the proton beams. To overcome this, researchers have developed various techniques, such as using formvar foils and relativistic transparency. In this article, we report on the development of a laser-driven proton beam with a density of $1.7 \times 10^{21} \text{ cm}^{-3}$, which is near-critical density. This density allows for the production of a proton beam with a high energy and high current, which is suitable for cancer treatment. The results show that the proton beam has a high energy of up to 150 MeV and a high current of up to 10 pA. This is a significant improvement over conventional proton beams, which typically have a low energy of up to 70 MeV and a low current of up to 1 pA. The results also show that the proton beam has a high stability and a high reproducibility, which is essential for cancer treatment. The results are discussed in the context of the development of laser-driven proton beams for cancer treatment.

solid H₂

- proton acceleration up to 80 MeV

density tuning via single prepulses



Ultra-short pulse laser acceleration of protons to 80 MeV from cryogenic hydrogen jets tailored to near-critical density

typ. $> 10^{23} \text{ cm}^{-3}$
dense, opaque target

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

typ. $< 10^{20} \text{ cm}^{-3}$
transparent target

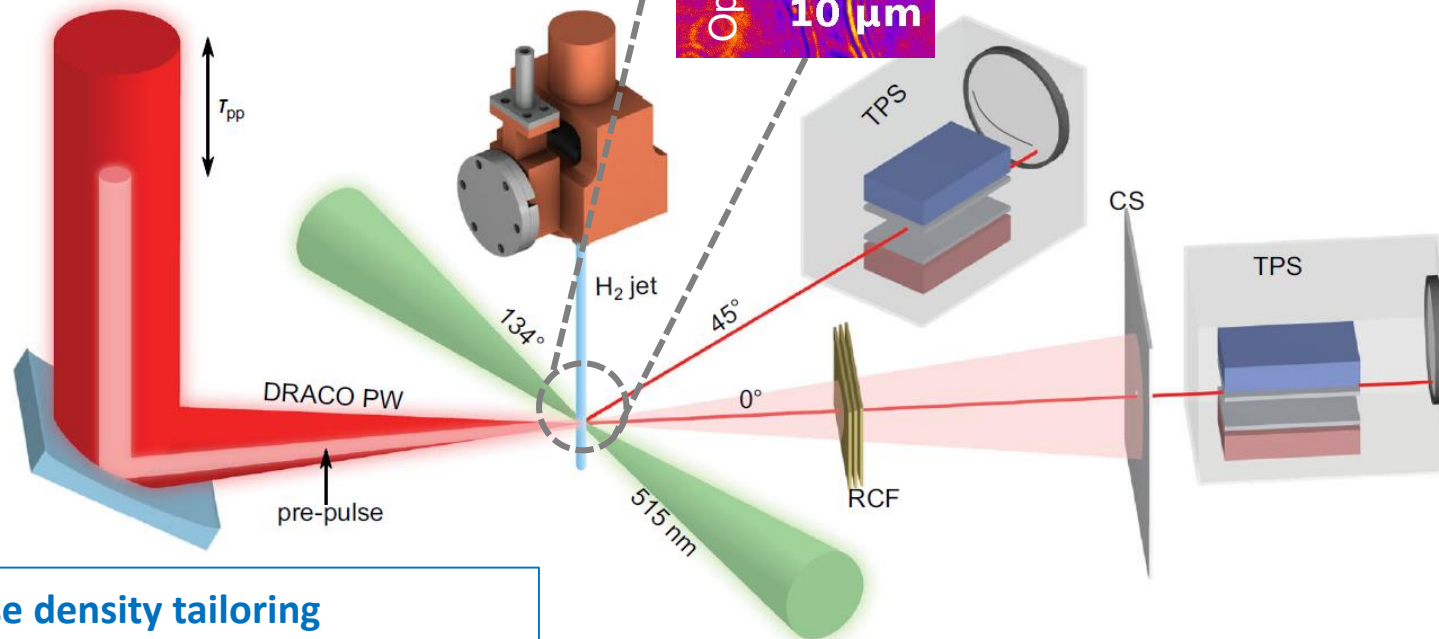
Efficient proton acceleration from a solid hydrogen target

Experimental realization

DRACO PW

- 18 J, 30 fs, 800 nm, $\sim 2.6 \mu\text{m}$ focus
→ $I \sim 5.4 \times 10^{21} \text{ W/cm}^2$
- enhanced laser contrast (PM cleaned)

- pure proton source → application & modeling
- $30 n_c$ @ 800 nm ($5 \times 10^{22} \text{ e-/cm}^3$)
- high repetition rate capability w/o debris
- free-standing geometry → diagnostic access
- flexible geometry and gas mixture



Prepulse density tailoring

- 55 fs, 800 nm, $\sim 30 \times 19 \mu\text{m}^2$ focus
→ $I \sim 6 \times 10^{17} \text{ W/cm}^2$
- variable delay

- off-harmonic (515/1030 nm) optical probing
w 160 fs probe pulse

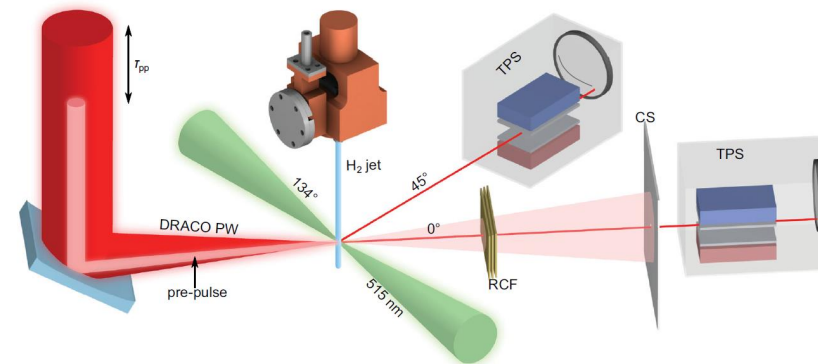
M. Rehwald et al., Nat Com 14, 4009 (2023)
J. B. Kim et al., RSI 87, 11E292 (2016)
C. B. Curry et al., J Vis Exp 159, e61130 (2020)
T. Ziegler et al., PPCF 60 074003 (2018)
M. Löser et al., Opt Exp 29, 9119 (2021)
C. Bernert et al., Sci Rep 12, 7287 (2022)

Efficient proton acceleration from a solid hydrogen target

Results – optimum acceleration regime

prepulse-only geometry characterization

prepulse + DRACO PW

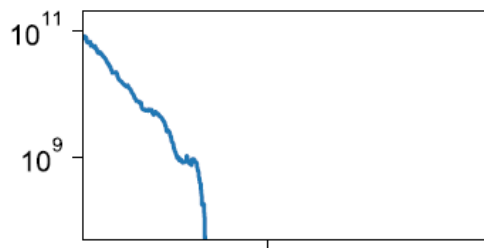
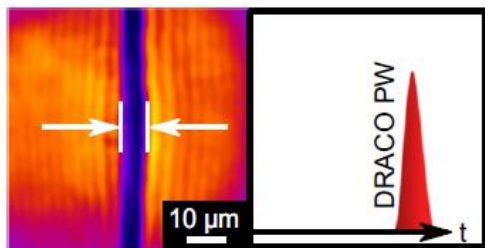


Shadow diameter

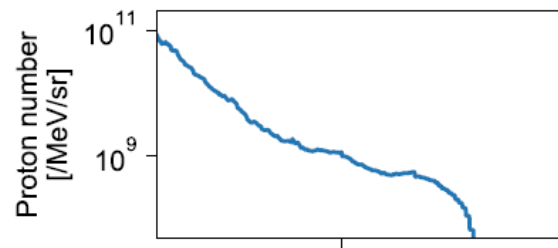
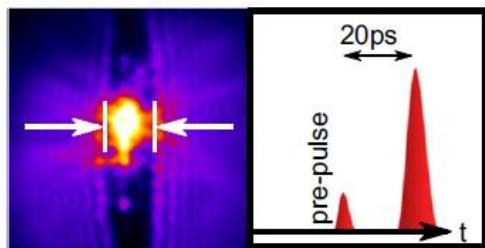
Shadowgraphy images

Proton spectra

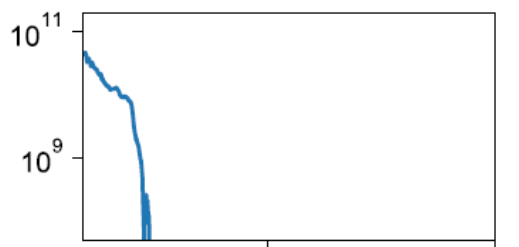
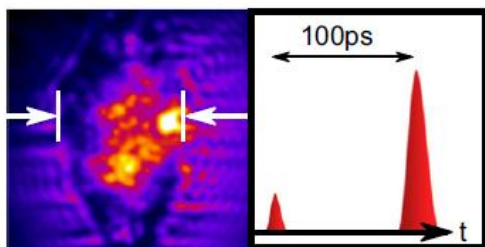
5 μm



11 μm



28 μm



50 100
Proton energy [MeV]



Member of the Helmholtz Association

Josefine Metzkes-Ng | j.metzkes-ng@hzdr.de | www.hzdr.de

Efficient proton acceleration from a solid hydrogen target

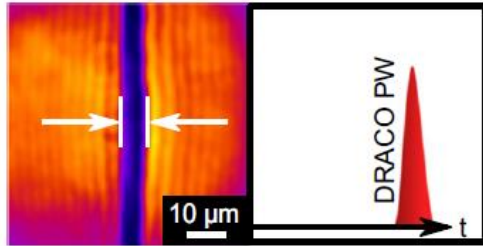
Results – target density & shape characterization

prepulse-only geometry characterization

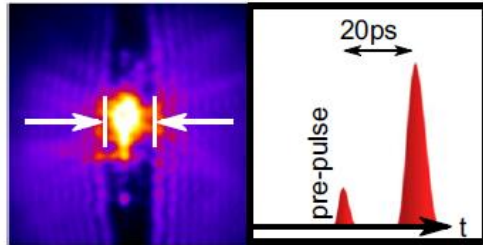
Shadow diameter

Shadowgraphy images

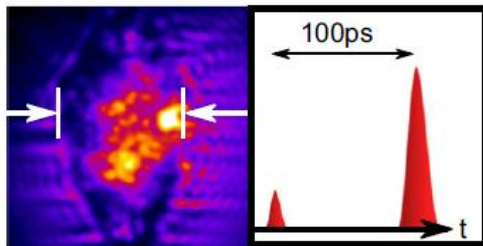
5 μm



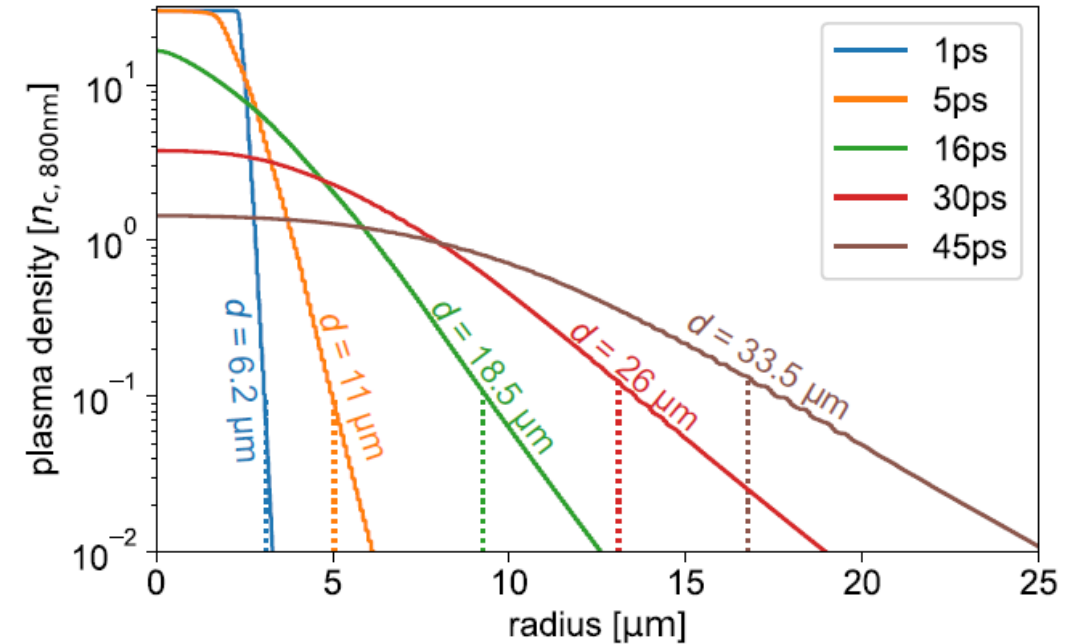
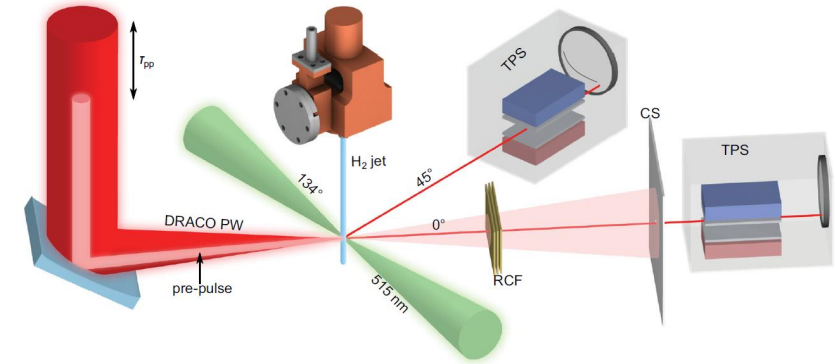
11 μm



28 μm



optical raytracing
hydrodynamic expansion modeling



M. Rehwald et al., Nat Com 14, 4009 (2023)

C. Bernert et al., Sci Rep 12, 7287 (2022)

L. Yang et al., under review

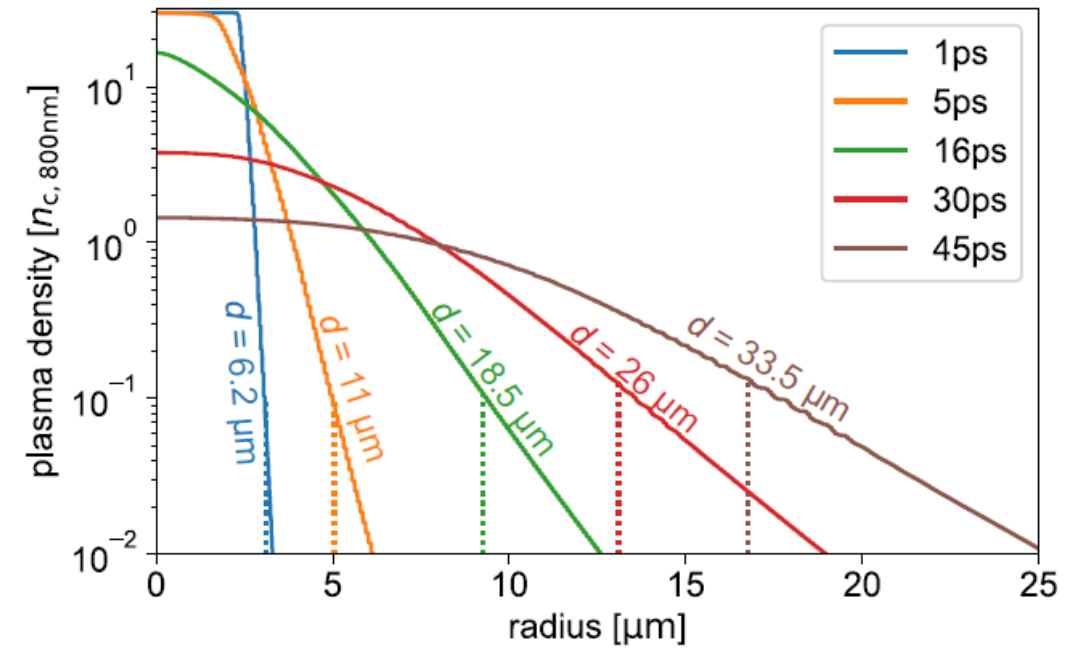
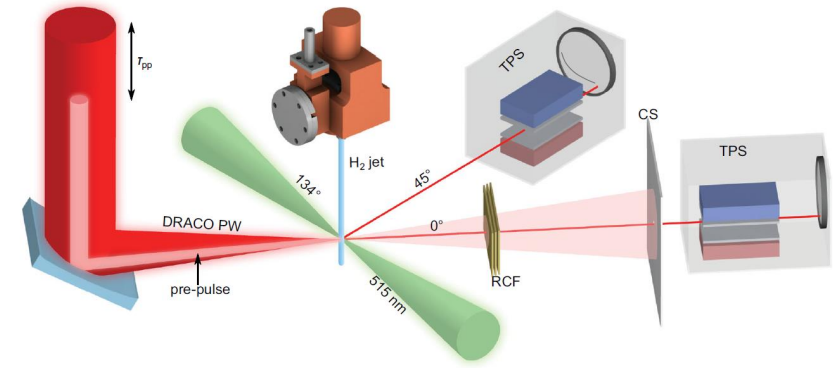
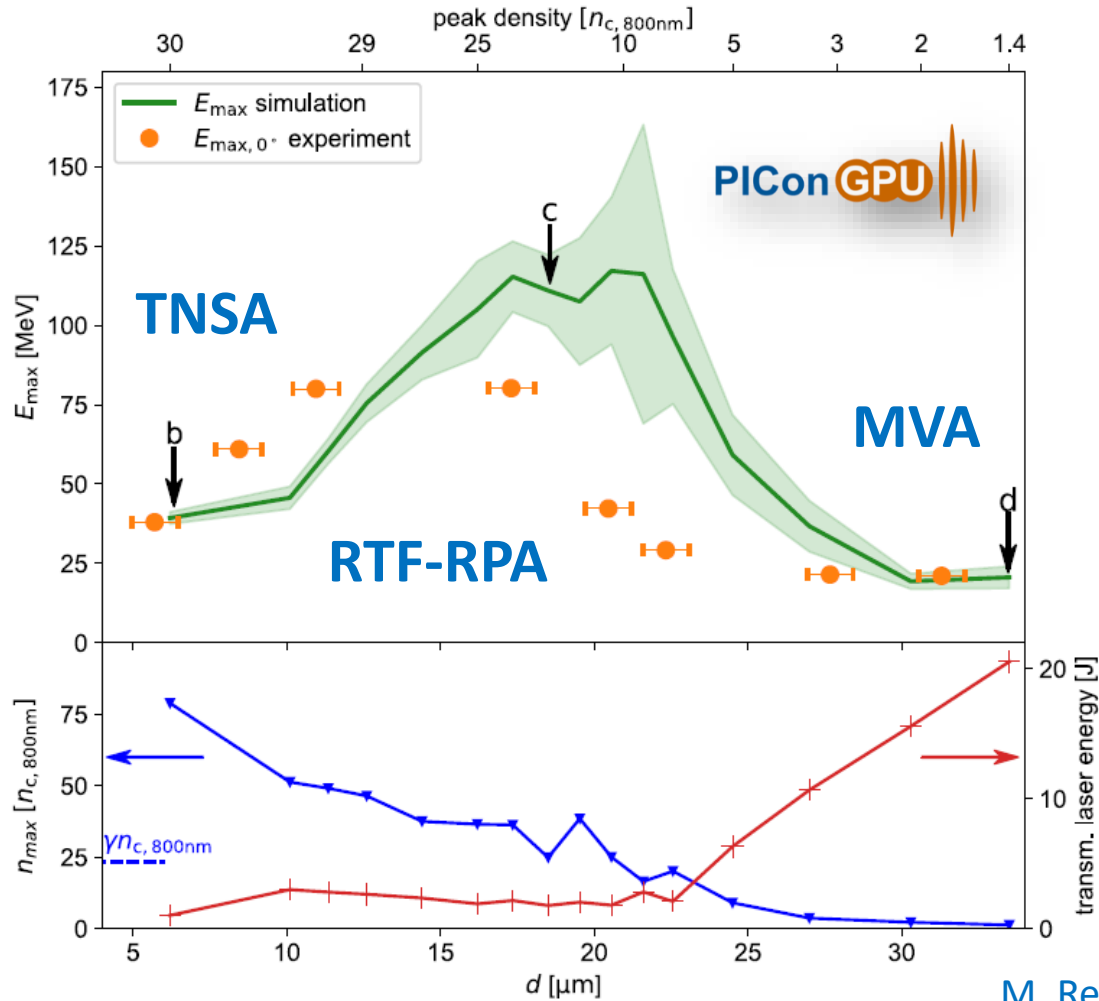


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Efficient proton acceleration from a solid hydrogen target

Results – target density & shape characterization



M. Rehwald et al., Nat Com 14, 4009 (2023)

C. Bernert et al., Sci Rep 12, 7287 (2022)

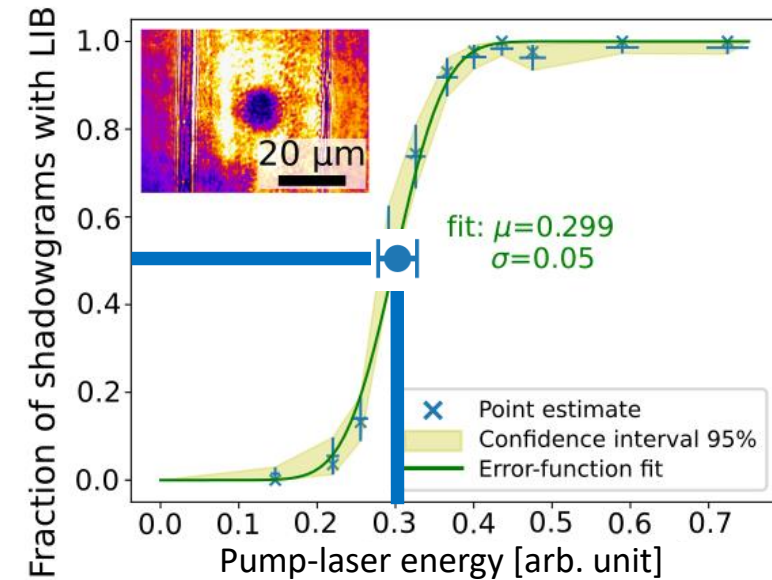
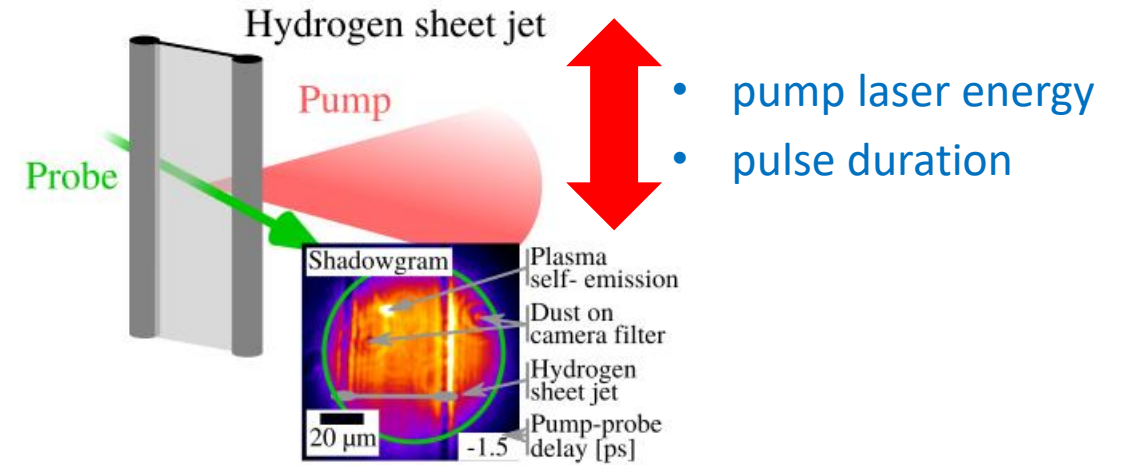
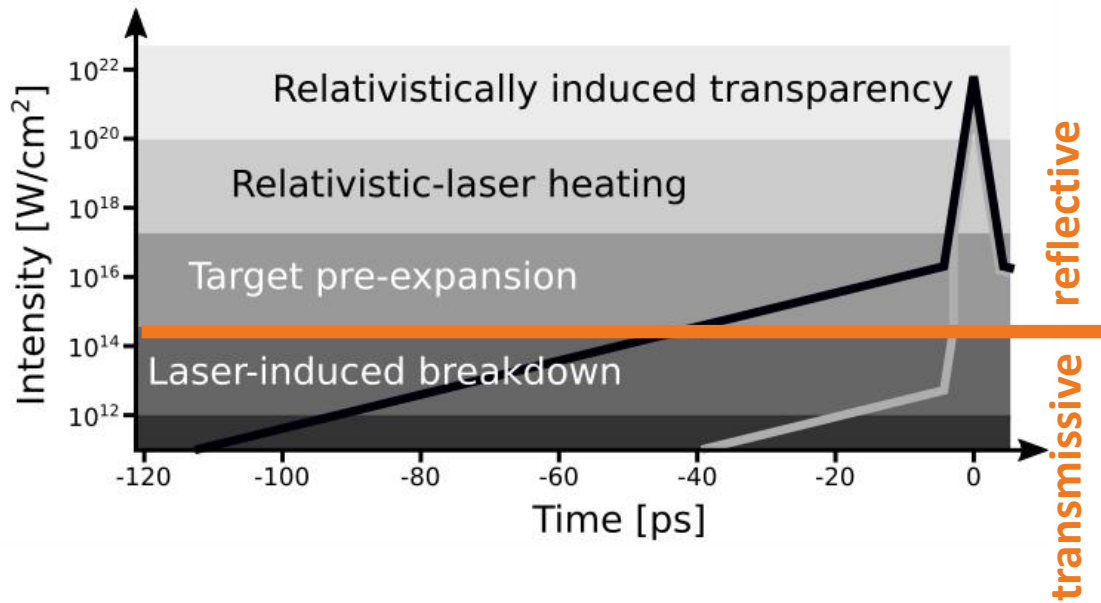
L. Yang et al., under review



Investigating ionization dynamics with a solid hydrogen target

Laser-induced breakdown of cryogenic hydrogen

- modeling requires input on onset of plasma evolution
- temporal evolution of laser intensity on targets
 - determines target pre-expansion (density profile)
 - governs acceleration regime & performance

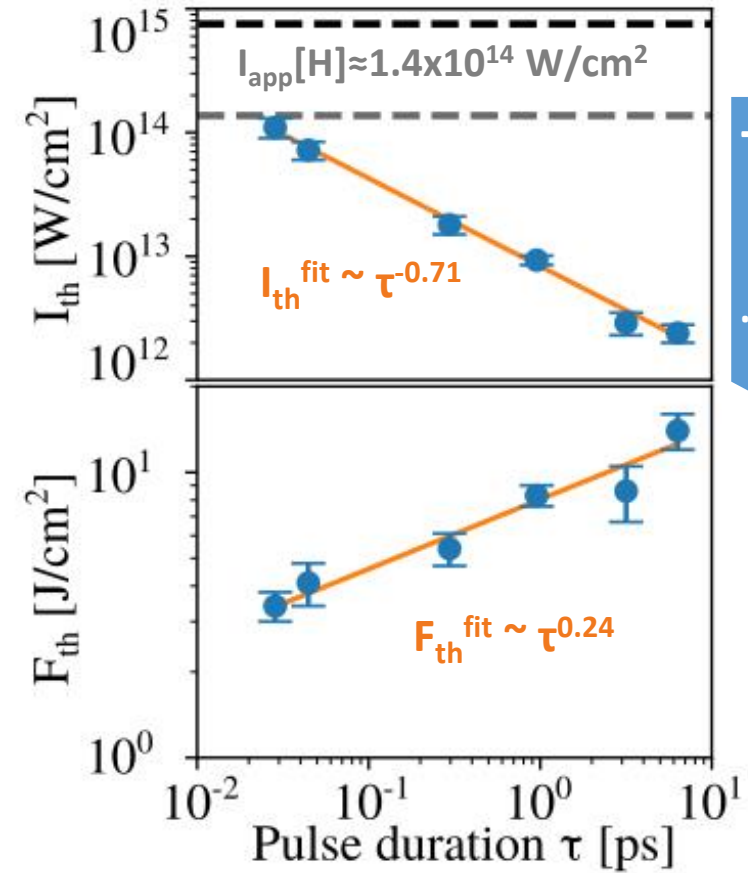
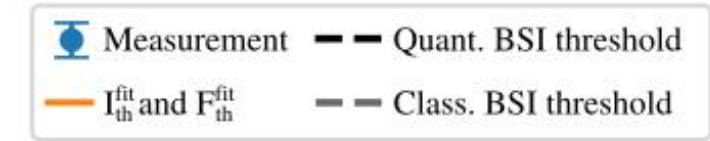
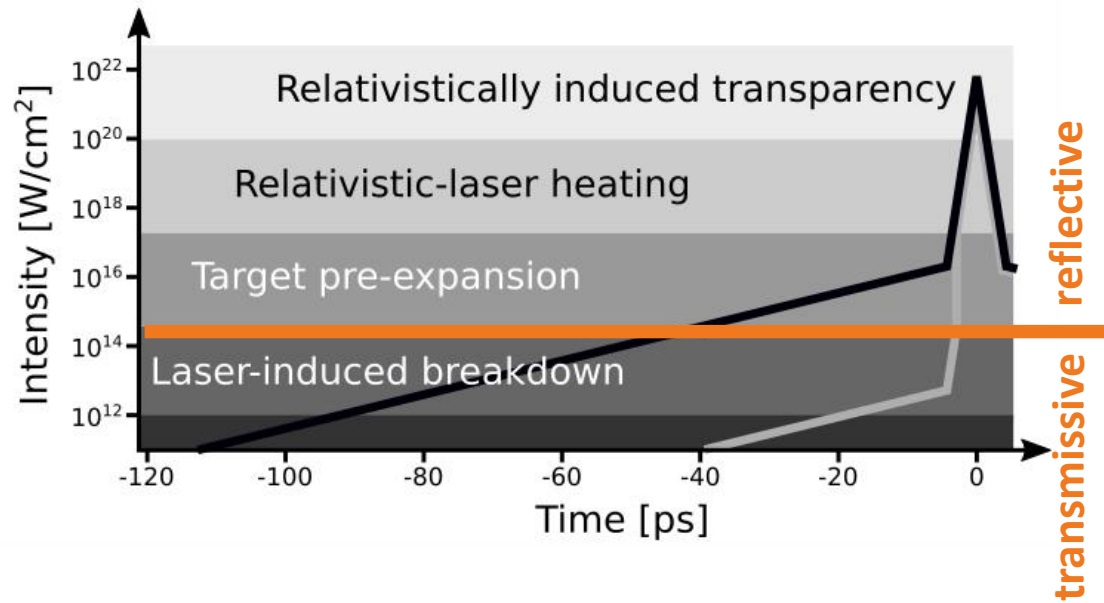


C. Bernert et al., Phys Rev Appl 19, 014070 (2023)

Investigation ionizing dynamics with a solid hydrogen target

Laser-induced breakdown of cryogenic hydrogen

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- temporal evolution of laser intensity on targets
 - determines target pre-expansion (density profile)
 - governs acceleration regime & performance



C. Bernert et al., Phys Rev Appl 19, 014070 (2023)



Member of the Helmholtz Association

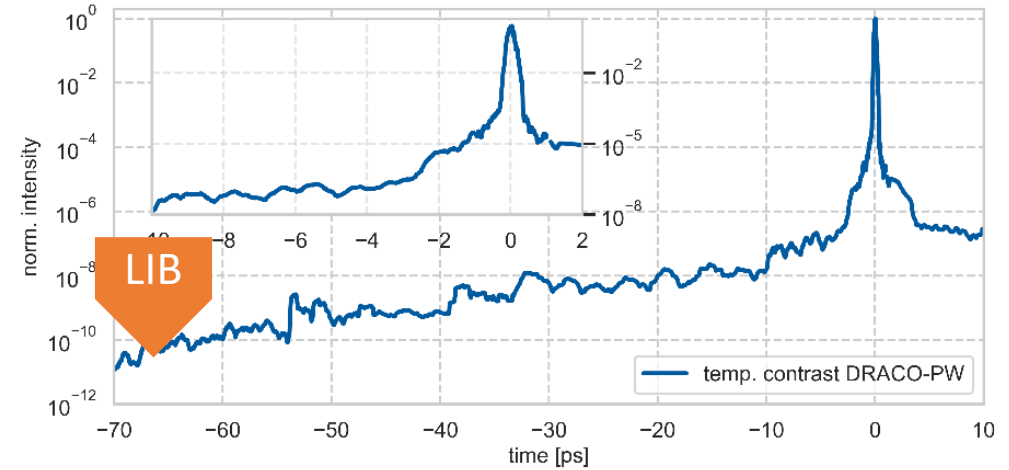
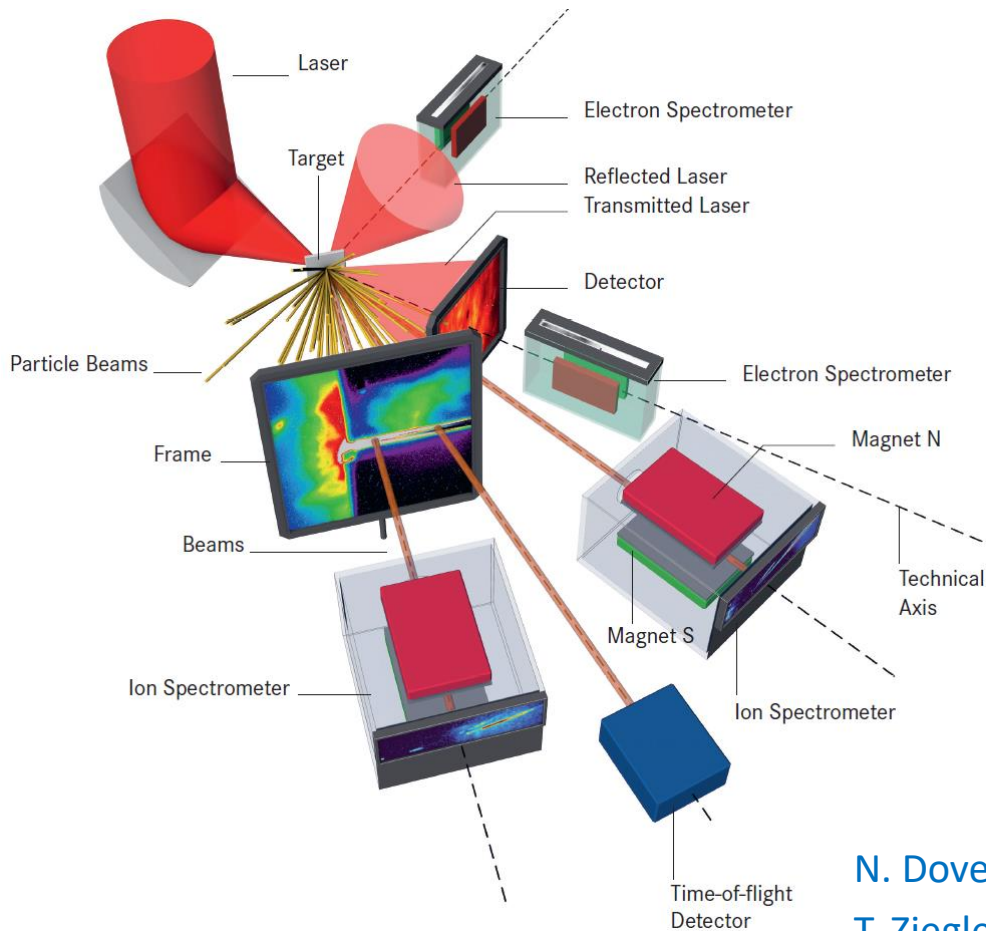
Josefine Metzkes-Ng | j.metzkes-ng@hzdr.de | www.hzdr.de

Enhancing proton energies with pre-expanded foil targets and thickness scanning

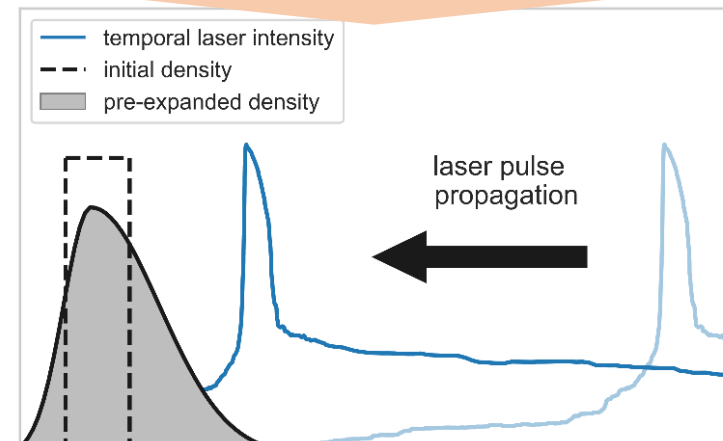
Experimental realization

DRACO PW

- 22.4 J, 30 fs, $\sim 2.3 \mu\text{m}$ focus
- $I \sim 6.5 \times 10^{21} \text{ W/cm}^2$



hydrodynamic expansion modeling FLASH



N. Dover et al., Light Sci Appl 12, 71 (2023)

T. Ziegler et al., under review

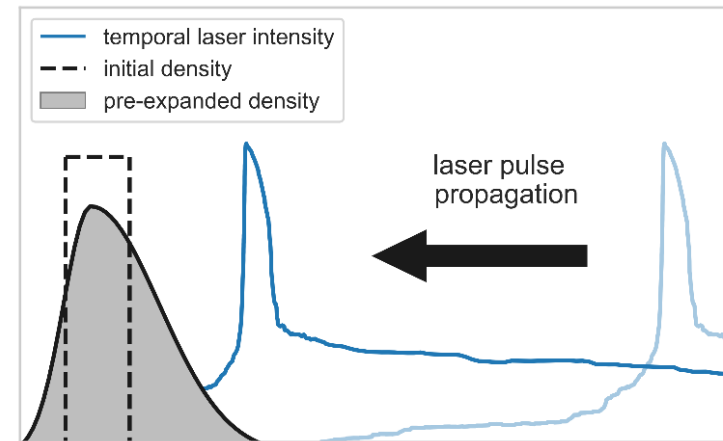
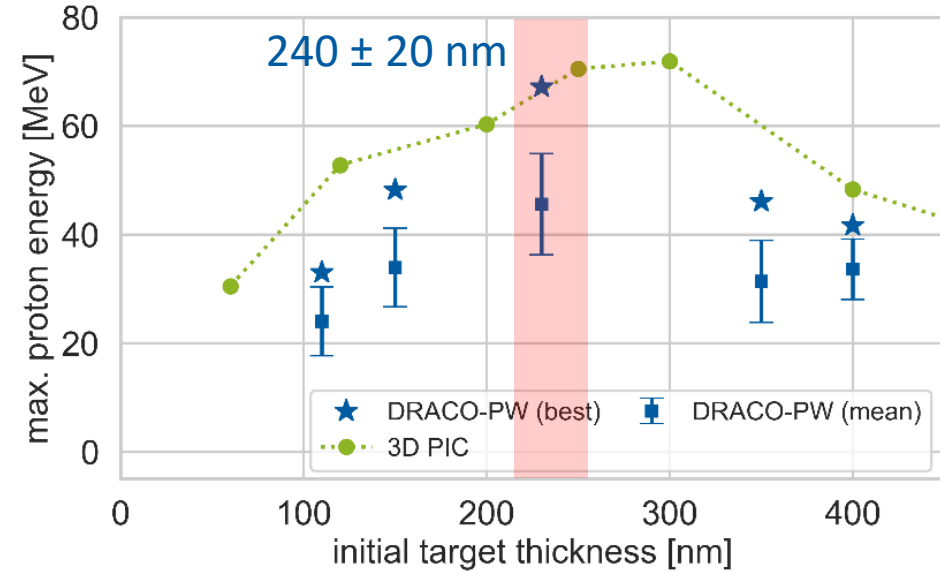
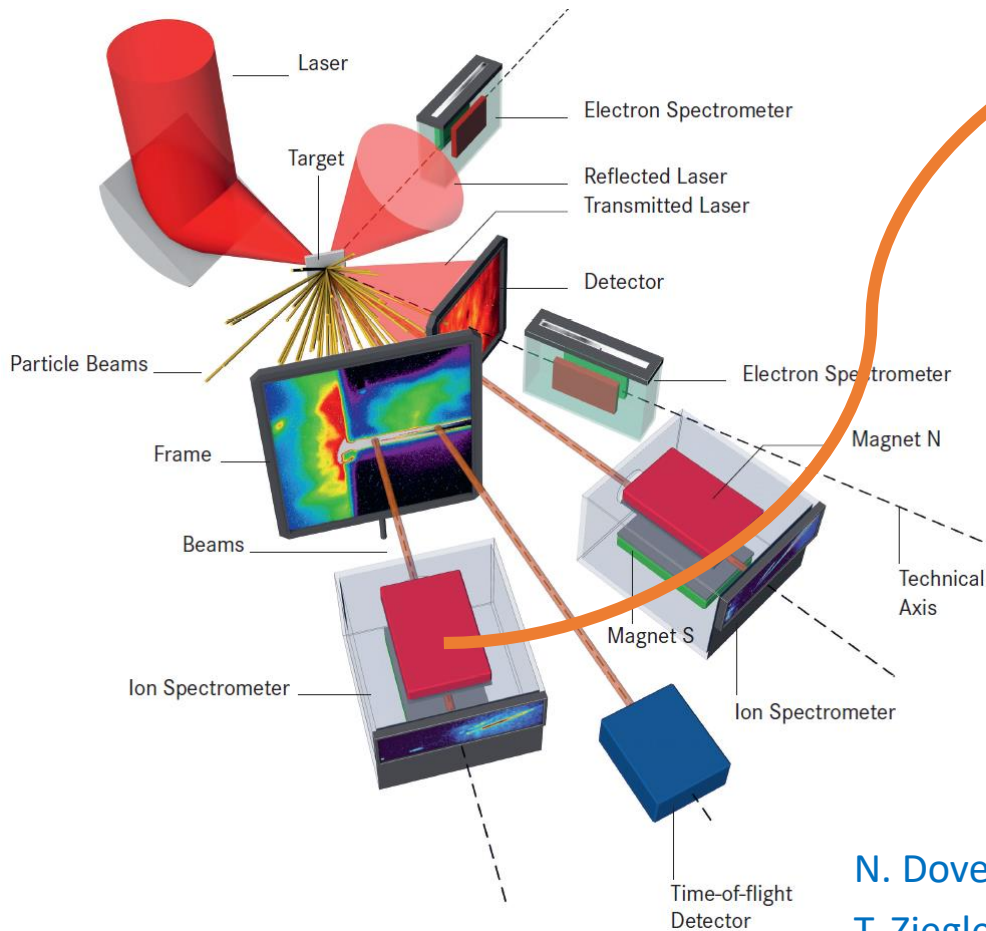


Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental results

DRACO PW

- 22.4 J, 30 fs, $\sim 2.3 \mu\text{m}$ focus
- $I \sim 6.5 \times 10^{21} \text{ W/cm}^2$



N. Dover et al., Light Sci Appl 12, 71 (2023)

T. Ziegler et al., under review

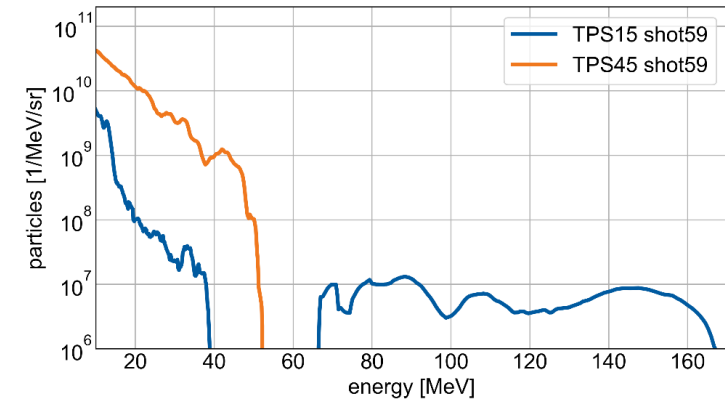
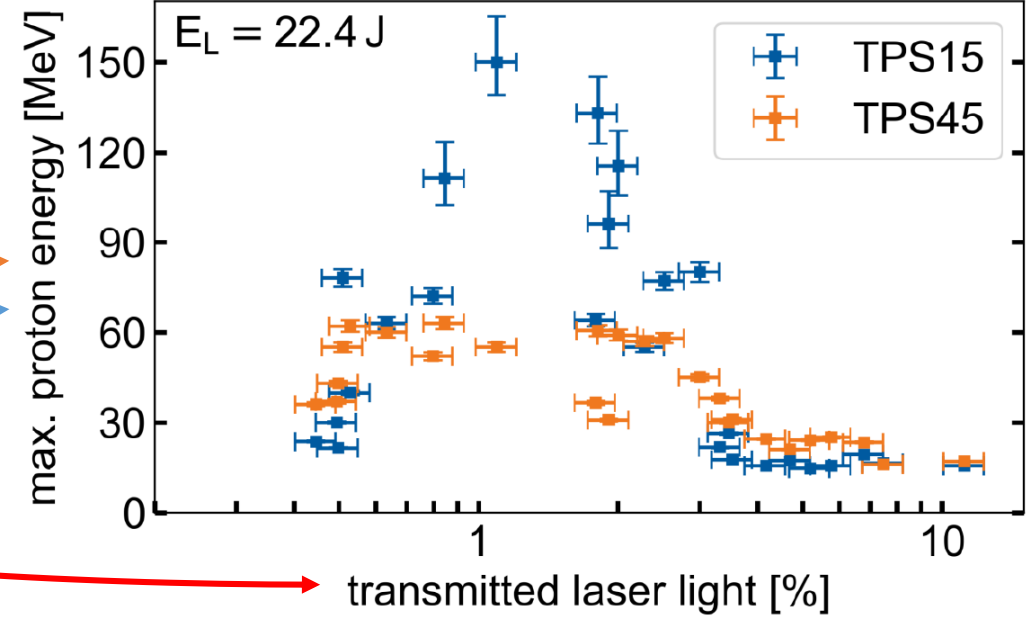
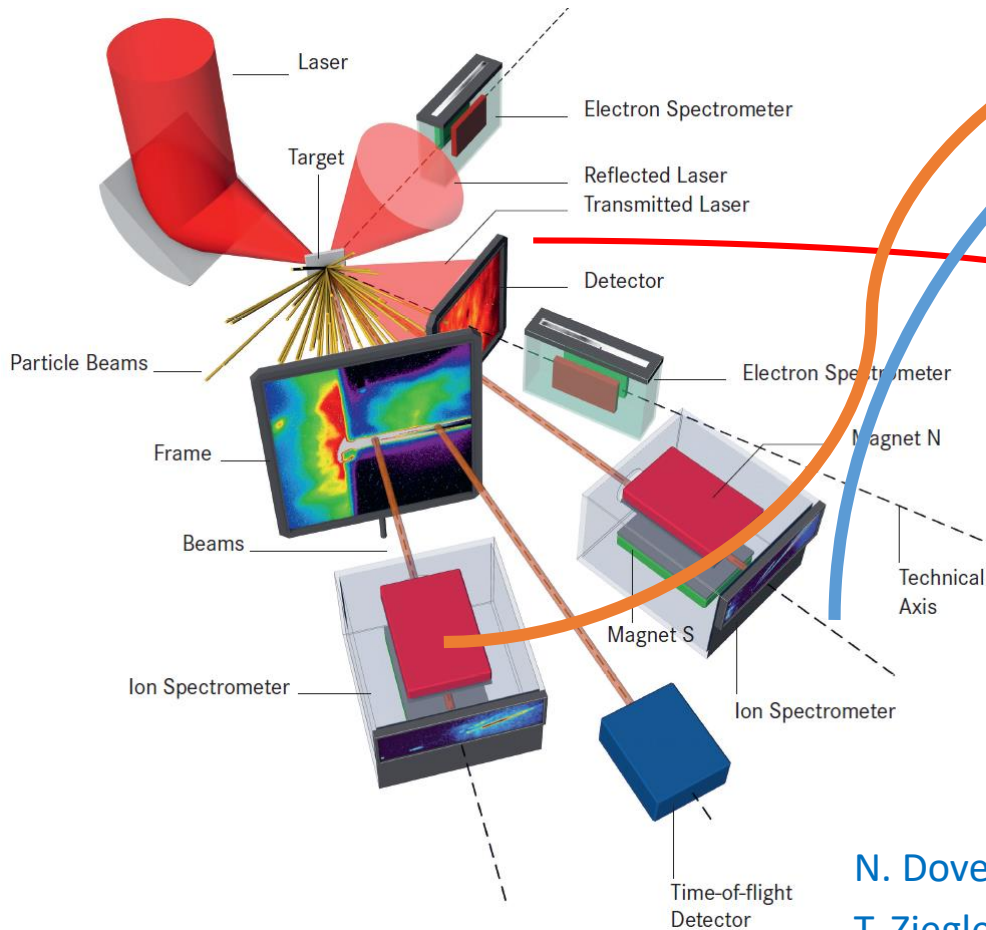


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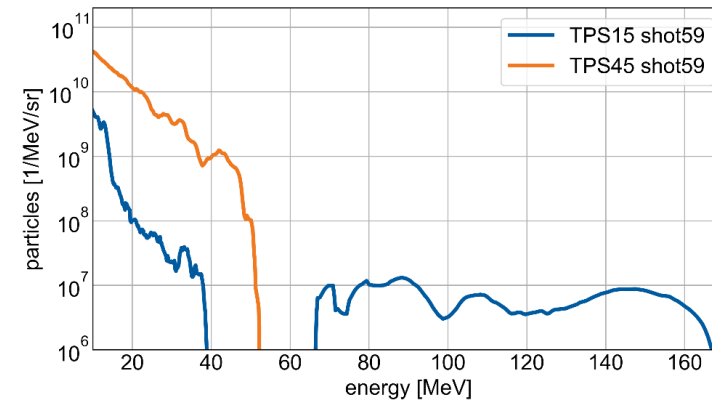
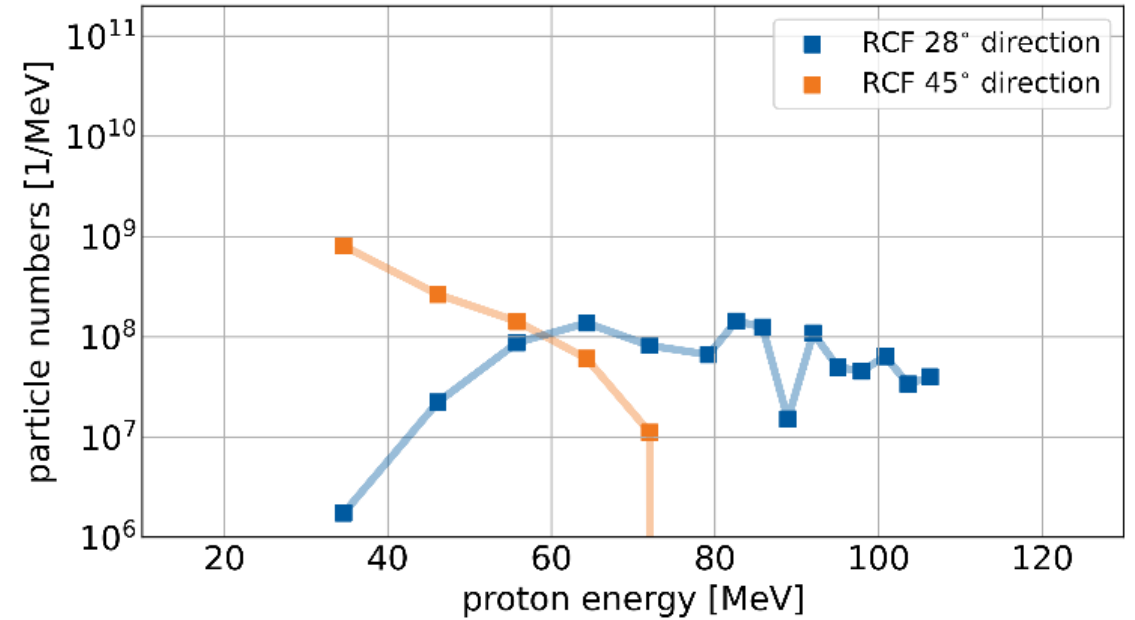
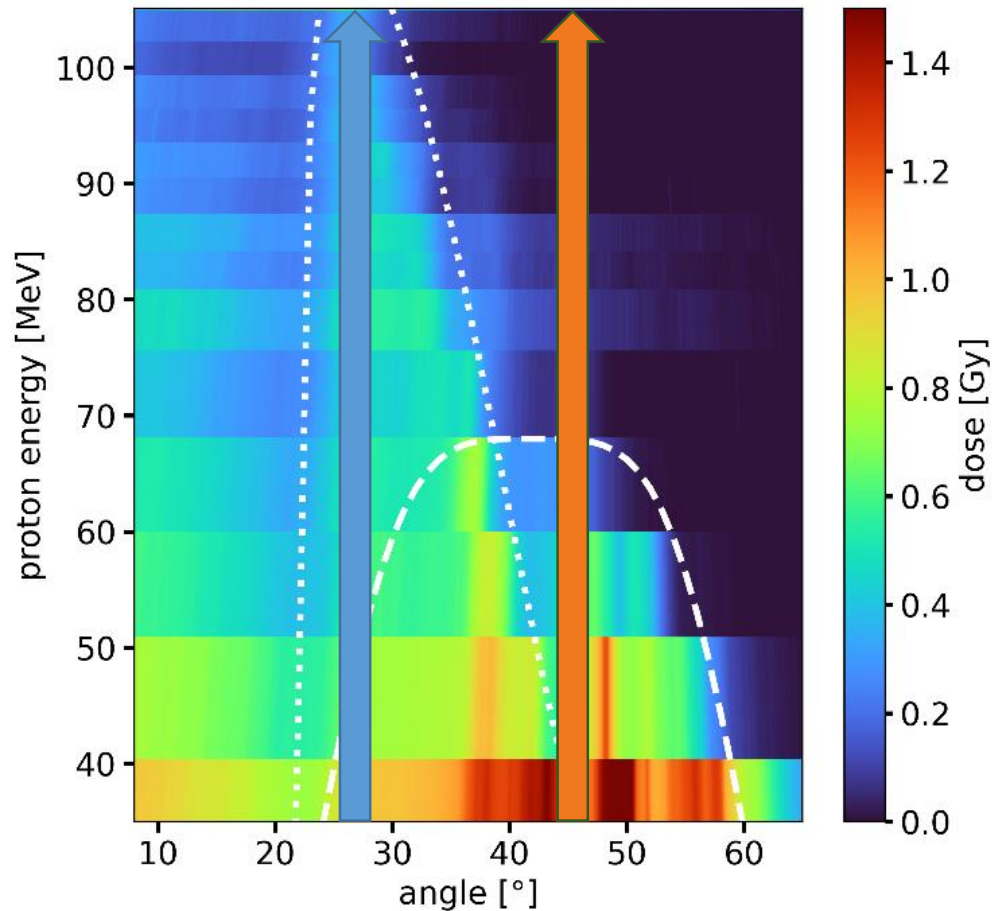
N. Dover et al., Light Sci Appl 12, 71 (2023)

T. Ziegler et al., under review



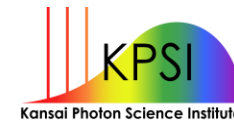
Enhancing proton energies with pre-expanded foil targets and thickness scanning

Experimental results



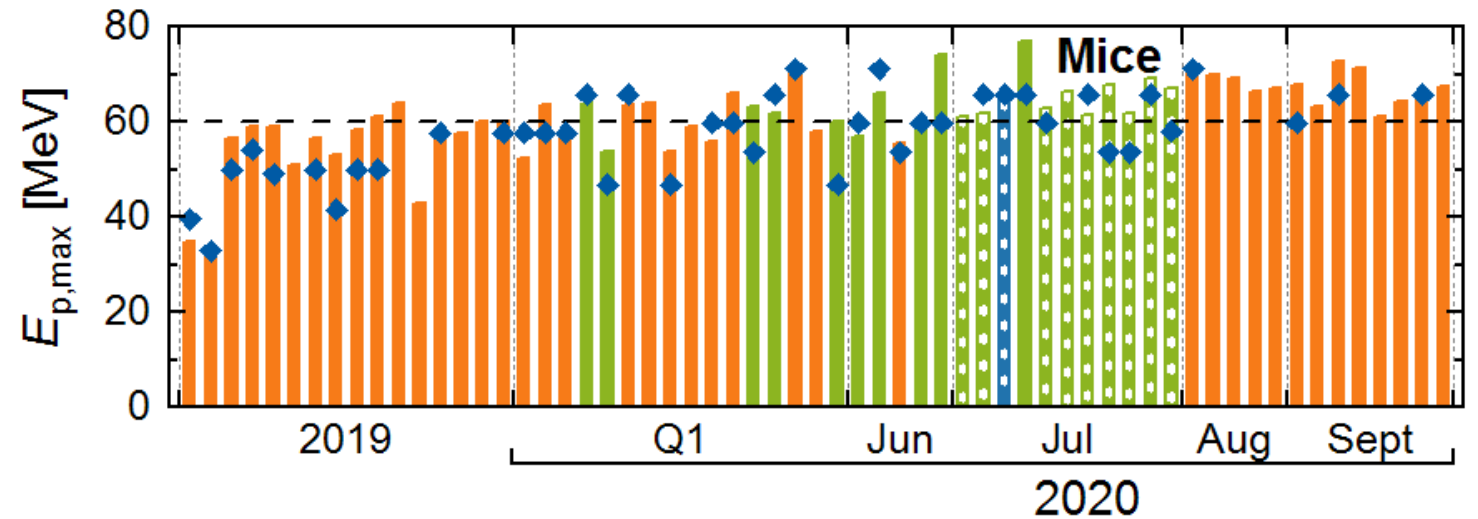
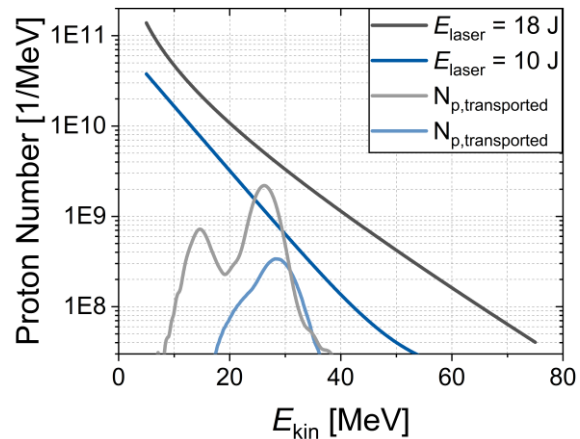
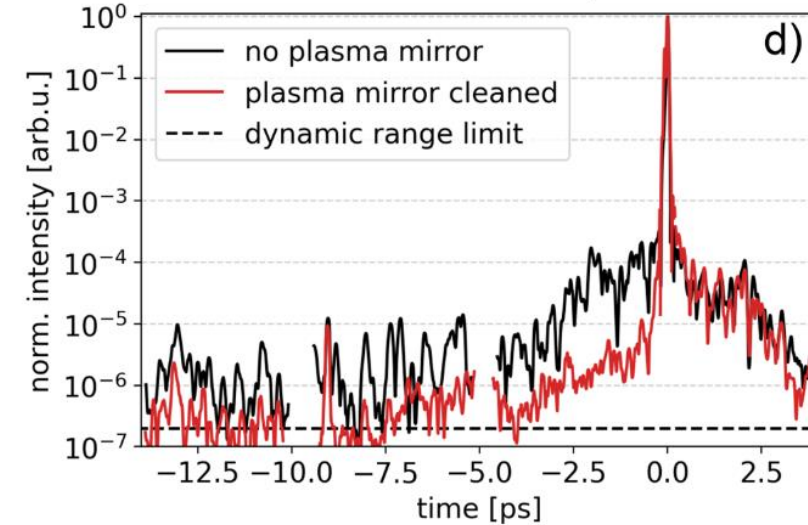
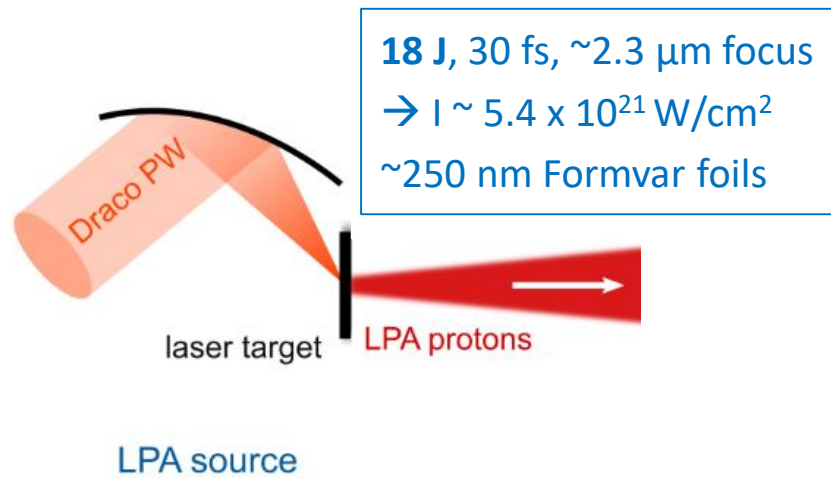
- **bi-modal feature (low + high energy component)**
- **high-energy feature with reduced divergence**

T. Ziegler et al., under review



Stable proton beam generation with ultra-high intensity contrast

Experimental realization



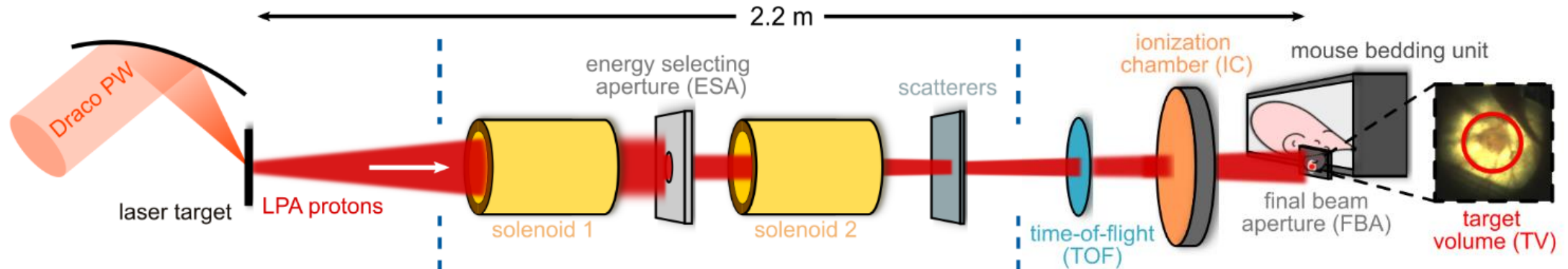
F. Kroll et al., Nat Phys 18, 316 (2022)

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

- Thomson parabola (bar) and RCF (diamond) proton E_{max}
- longterm stable operation > 60 MeV

Ultra-high dose rate radiobiology at DRACO PW

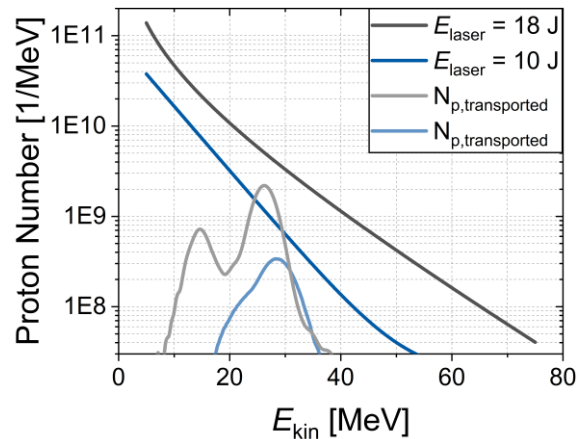
ALBUS-2S beamline



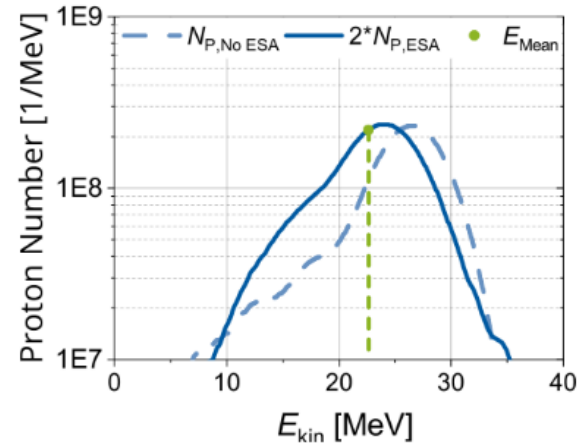
LPA source

beam transport system

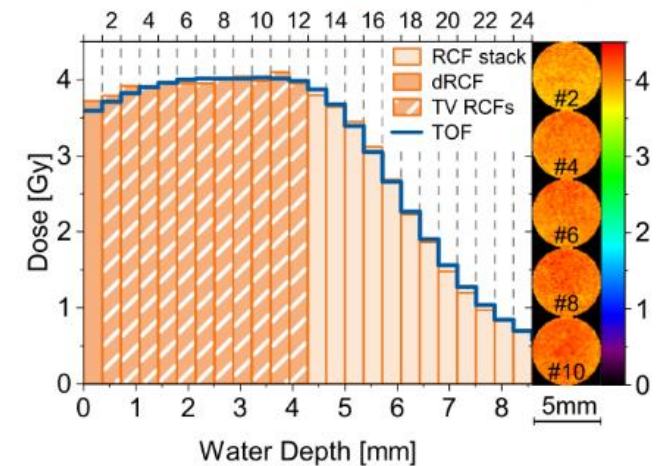
beam monitoring and dosimetry



c



d



F. Kroll et al., Nat Phys 18, 316 (2022)

F.-E. Brack et al., Sci Rep 10, 9118 (2020)

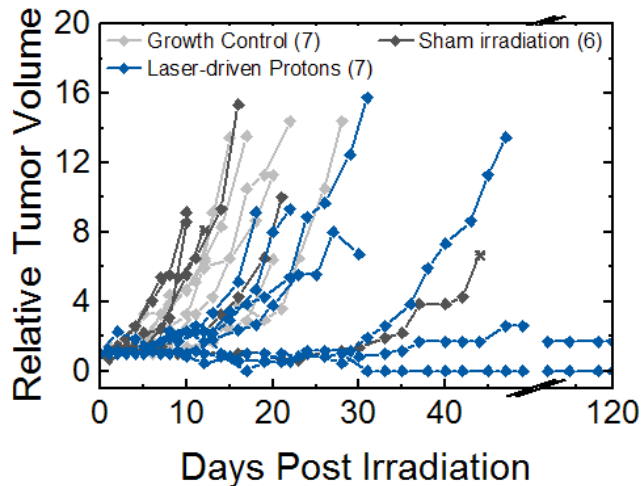
Worldwide-first pilot *in vivo* studies with LPA protons



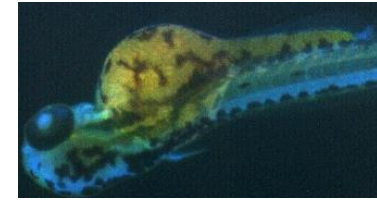
criver.com

- **mouse model** (3D *in-vivo* tumour tissue)
- **pulse accumulation for precise dose delivery**
- **endpoint: tumour-growth delay**
- **4 Gy dose, < 10% precise total dose delivery**

K. Brüchner et al., Radiat. Onc., Vol. 9 (2014)
 M. Oppelt et al., Radiat Environ Biophys (2015)
 Animal study approval DD24-5131/338/35

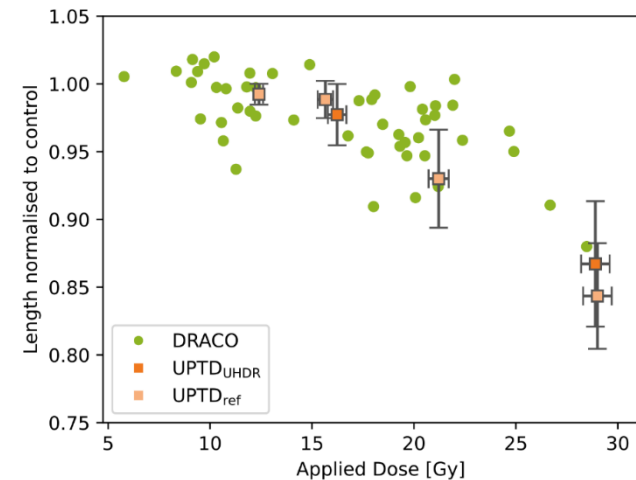


F. Kroll et al., Nat Phys 18, 316 (2022)



- **zebrafish embryo** (normal tissue, FLASH)
- **single-shot ultra-high dose rate delivery**
- **endpoint: morphological changes, etc.**
- **dose escalation > 10 Gy**

J. Pawelke et al., Radiotherapy and Oncology 158 (2021), 7-12
 E. Beyreuther et al., Radiotherapy and Oncology 139 (2019), 46-50
 E. R. Szabo et al., PLOS ONE 13 (2018)11, e0206879



J. Metzkes-Ng et al., under review

Accelerator readiness:
 LPA capabilities for radiobiological applications confirmed

Summary

Proton acceleration from cryogenic solid hydrogen

80 MeV proton acceleration

M. Rehwald et al., Nat Com 14, 4009 (2023)

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

Off-harmonic optical probing

T. Ziegler et al., PPCF 60 074003 (2018)

M. Löser et al., Opt Exp 29, 9119 (2021)

C. Bernert et al., Sci Rep 12, 7287 (2022)

Laser-induced breakdown

C. Bernert et al., Phys Rev Appl 19, 014070 (2023)

Proton acceleration from thin plastic foils

Proton acceleration in the transparency regime

N. Dover et al., Light Sci Appl 12, 71 (2023)

Highest proton acceleration in a cascaded acceleration regime

T. Ziegler et al., under review

Stable efficient proton acceleration for applications

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

Radiobiological studies with LPA protons

Radiobiological in vivo studies with LPA protons

F. Kroll et al., Nat Phys 18, 316 (2022)

J. Metzkes-Ng et al., under review

Source-to-sample proton bunch characterization for applications

M. Reimold et al., Sci Rep 12, 21488 (2022)

M. Reimold et al., Phys Med Biol 68 185009, (2023)

M. Reimold et al., HPLSE (accepted) (OCTOPOD)

A. Corvino et al., under review (miniSCIDOM)

Thank you for your attention!

