HZDR

FIRST RESULTS WITH THE NOVEL PETA-WATT LASER ACCELERATION FACILITY IN DRESDEN

U. Schramm

Helmholtz-Zentrum Dresden-Rossendorf

MT ARD

oncooptics

OncoRay ZIK Radiation Research in Oncology

Partner von DRESDEN concept exzellenz-dresden.de

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Advanced accelerator research embedded in independent national programs (Helmholtz Association)

MT ARD

Accelerator research and development
(DESY, HZDR, GSI, KIT, HI-Jena, HIB)

- *cw superconducting rf accelerators and radiation sources*
- *plasma accelerators (from acceleration to accelerators)*

oncooptics

OncoRay ZIK Radiation Research in Oncology

Translational research in radiation oncology (HZDR, DKFZ)

- *real-time diagnostics / dosimetry*
- *clinical impact of carbon vs proton therapy*
- *advanced accelerators*

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Laser plasma interaction basics

100TW (30 fs) pulse focused

$I=10^{21}$ W/cm^2 $E=10^{14}$ V/m

oscillating transverse fields

Laser plasma interaction basics

100TW (30 fs) pulse focused

$I=10^{21}$ W/cm^2 $E=10^{14}$ V/m

oscillating transverse fields

$$\vec{F} = e\vec{E} + e\,\vec{v} \times \vec{B} \qquad \left(B_0 = E_0/c\right)$$

ponderomotive push ~grad (I)

„relativistic“ laser plasma

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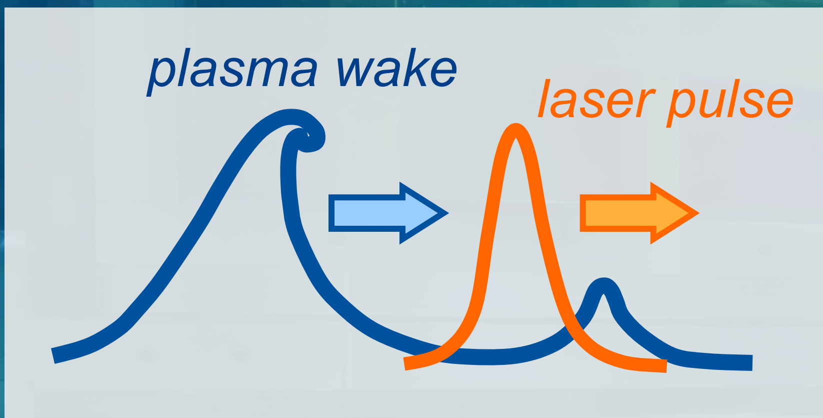
transparent medium (gas)



Co-moving wakefield
-> electron acceleration

typical scales:
GeV/cm for $5x10^{18}$ e/cm^3

opaque medium (thin foil)

Quasi-static field
-> ion acceleration

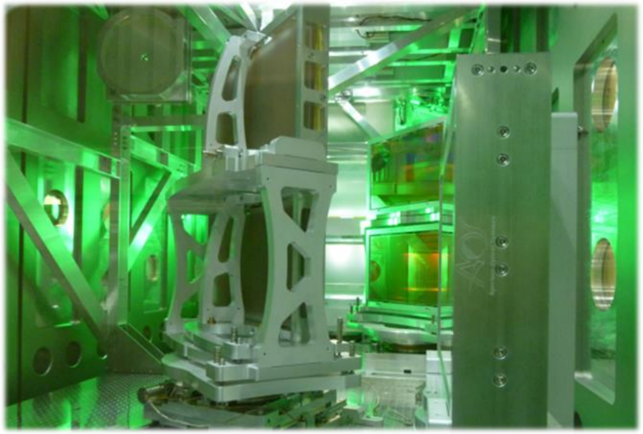
MeV/um on few micron scales

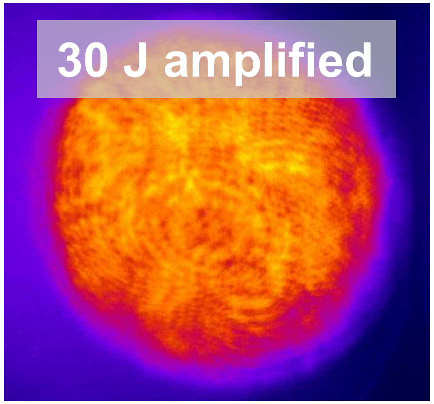
Lasers for advanced accelerator research

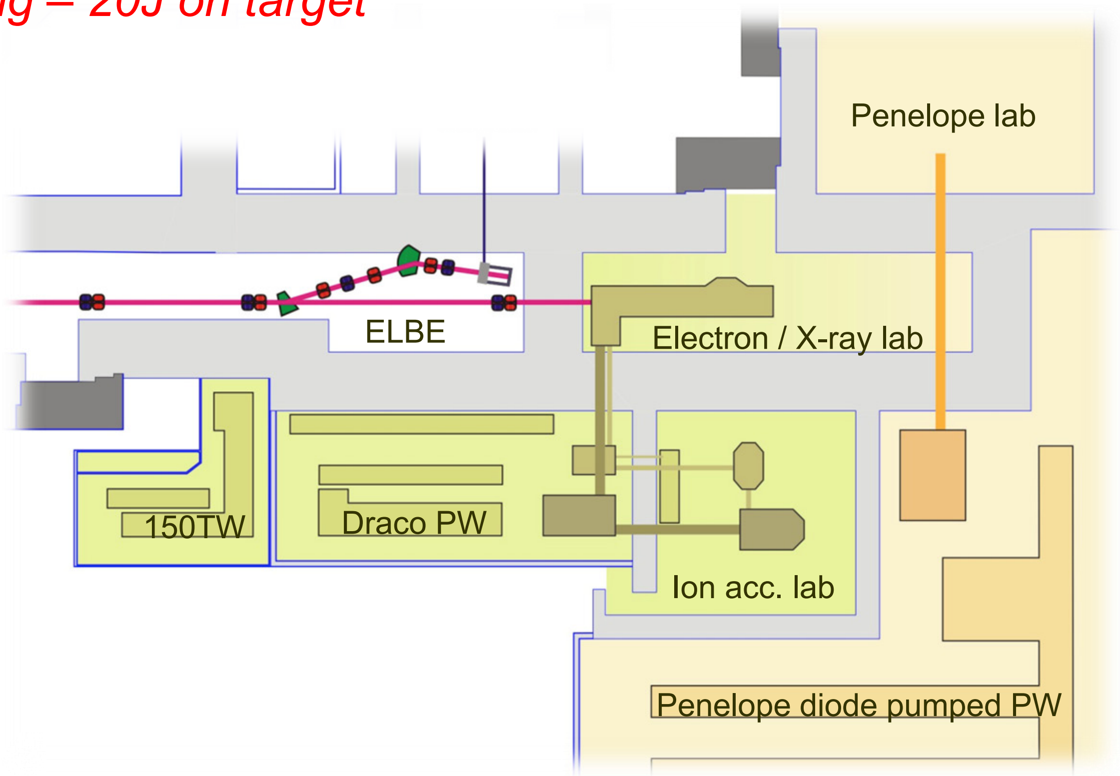
- Diode pumped 150J / 150fs laser Penelope
  amplification to >10J operational

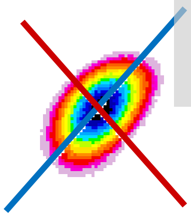
- Draco Ti:Sapphire laser dual-beam:

  150TW (4J in 30fs routinely on target)
  PW (30J on target in 30fs)
  commissioning ongoing – 20J on target





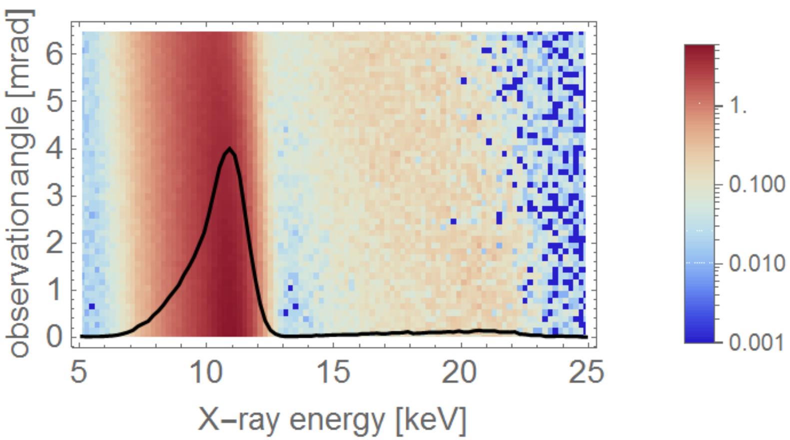




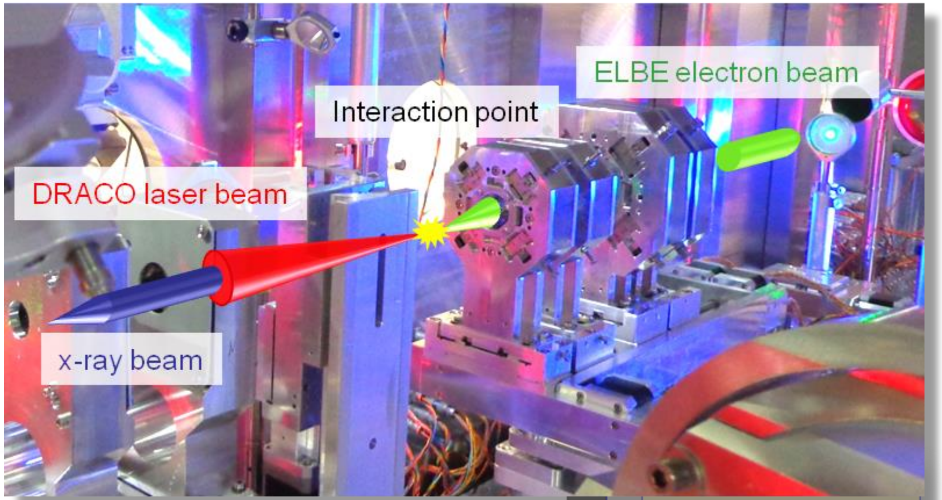
Focus 3-4 μm FWHM
(F/2.5 90deg), ~35fs

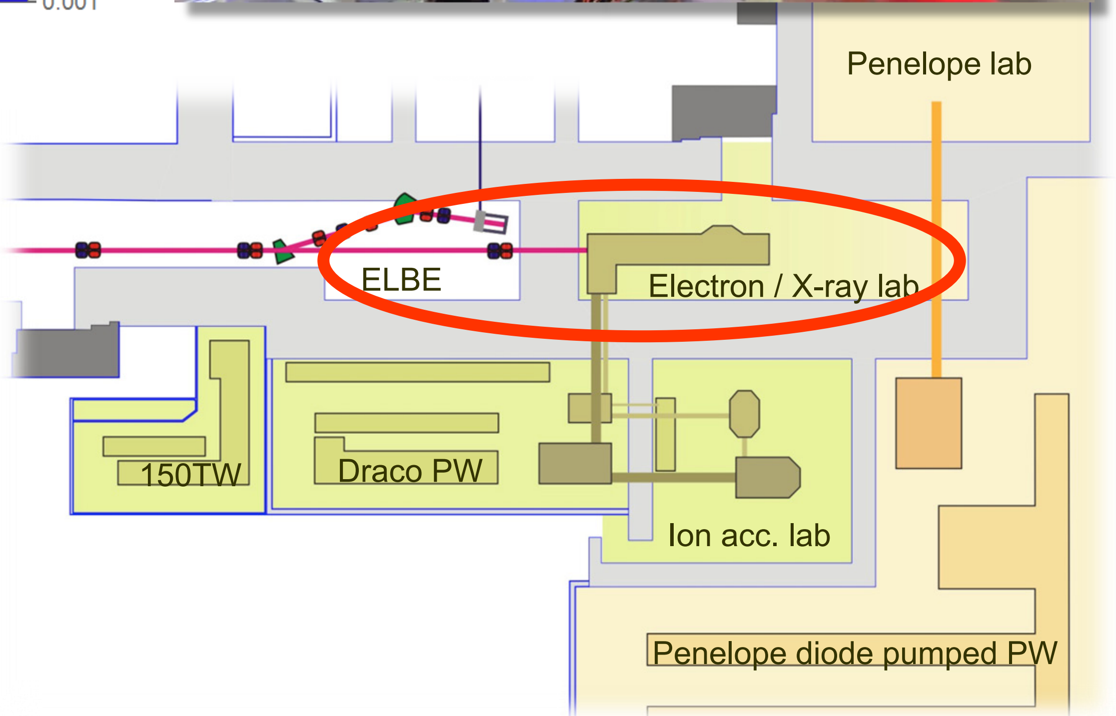
→ **$I \approx 6 \cdot 10^{21}$ W/cm²**

Nonlinear Thomson scattering



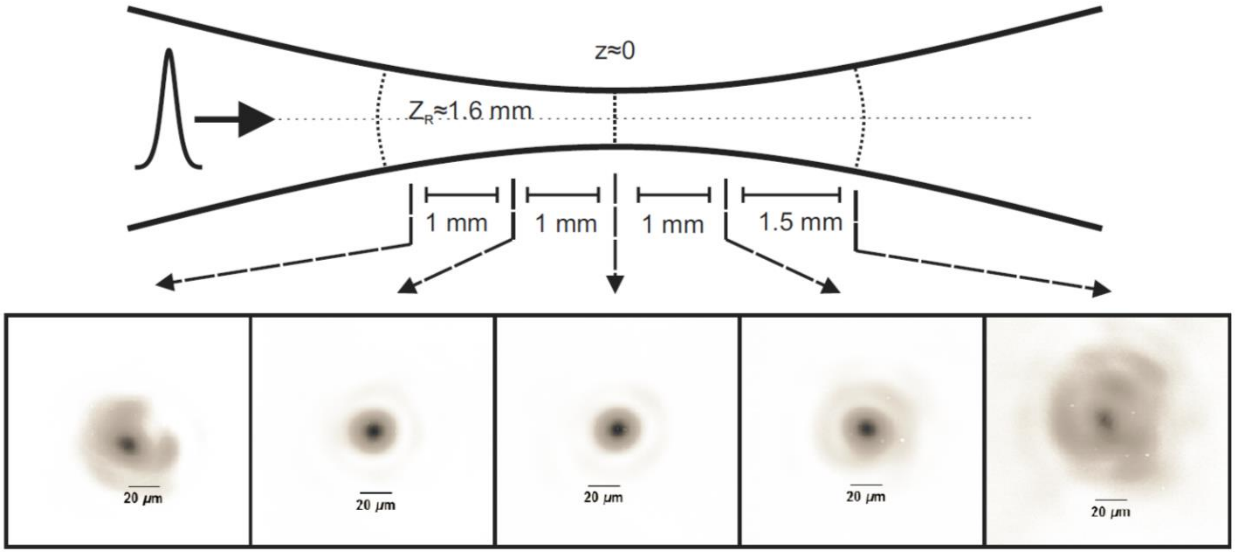
J. Krämer, et al., MOPVA011

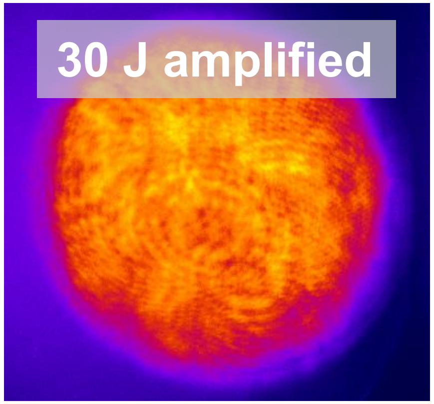




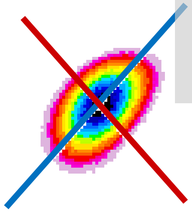
- Draco Ti:Sapphire laser dual-beam

Quality control *online single-shot* and *on-target* and *full power* is essential





Strehl ration on target 0.9



Focus 3-4 µm FWHM
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→ I ≈ 6·10^{21} W/cm^2

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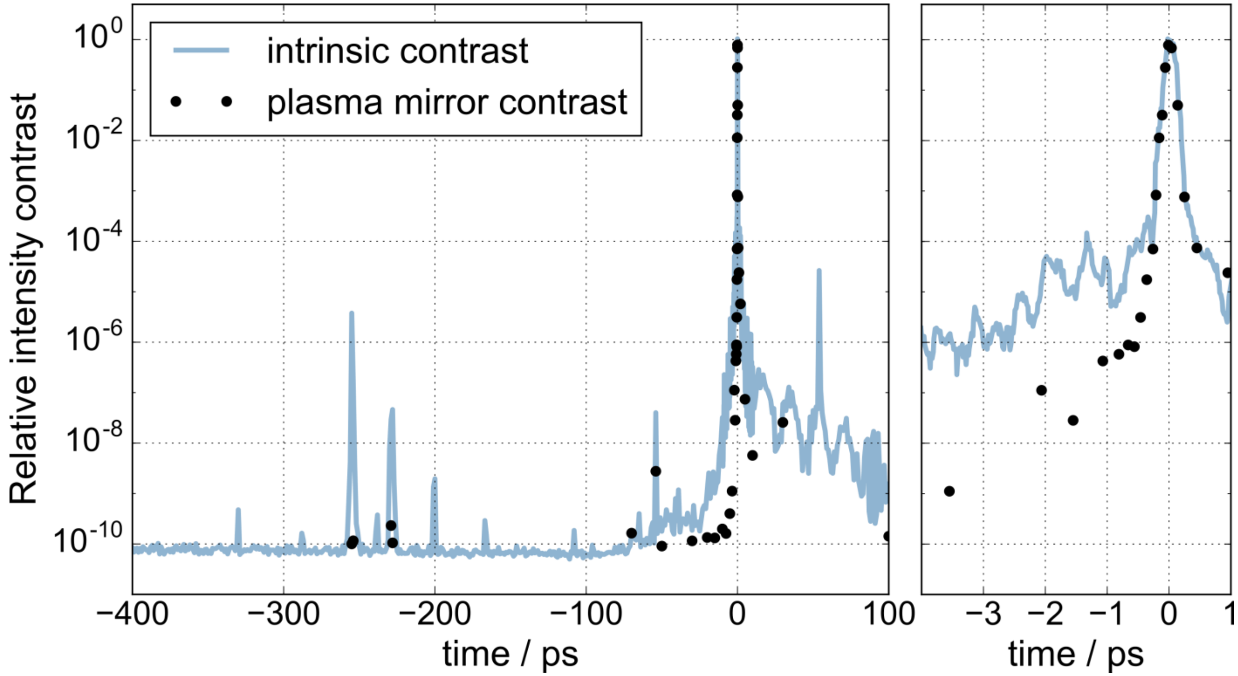
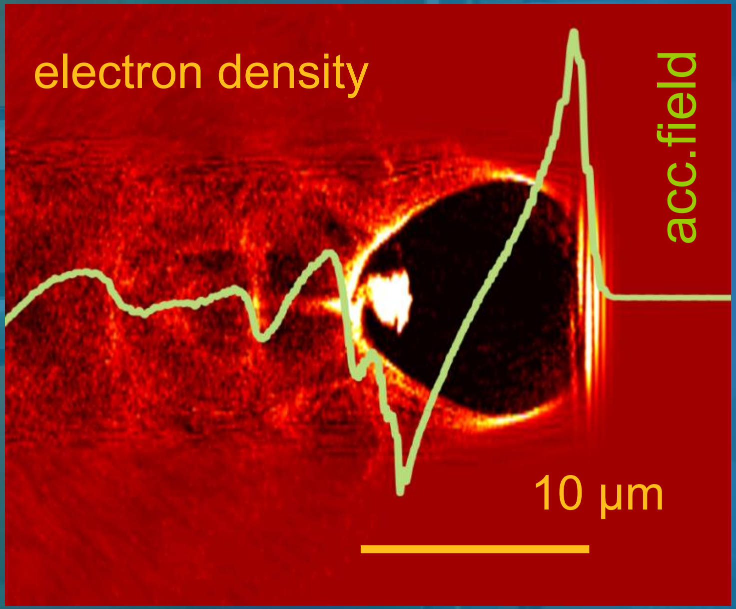


Single recollimating plasma mirror (T=80%, x0.001 suppression)

Laser wakefield acceleration with nC-class bunch charge

- nonlinear wakefield
- nonlinear injection
- beam loading

- and stable laser conditions

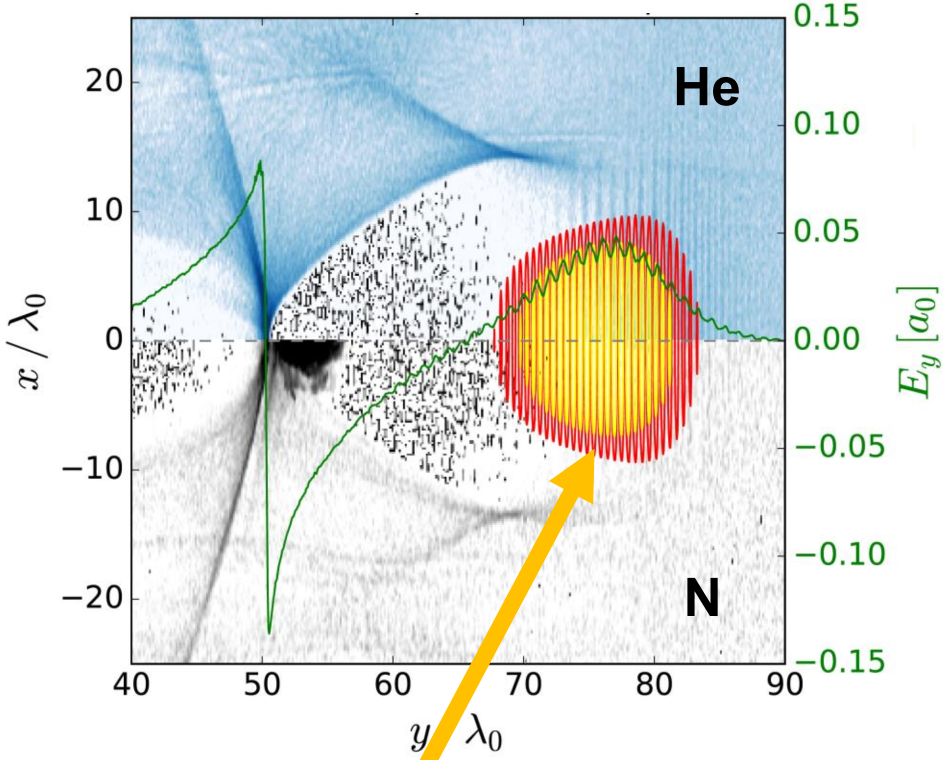


may lead to stable high quality bunches

Self truncated ionization injection

- the accelerating medium is doped by a high-Z gas
- inner shell electrons only ionized at the peak of the laser

Species	Ionisation energy (eV)
He^{1+}	24.6
He^{2+}	54.4
N^{1+}	14.5
N^{2+}	29.6
N^{3+}	47.4
N^{4+}	77.5
N^{5+}	97.9
N^{6+}	552
N^{7+}	667



Ionized only near the laser peak intensity

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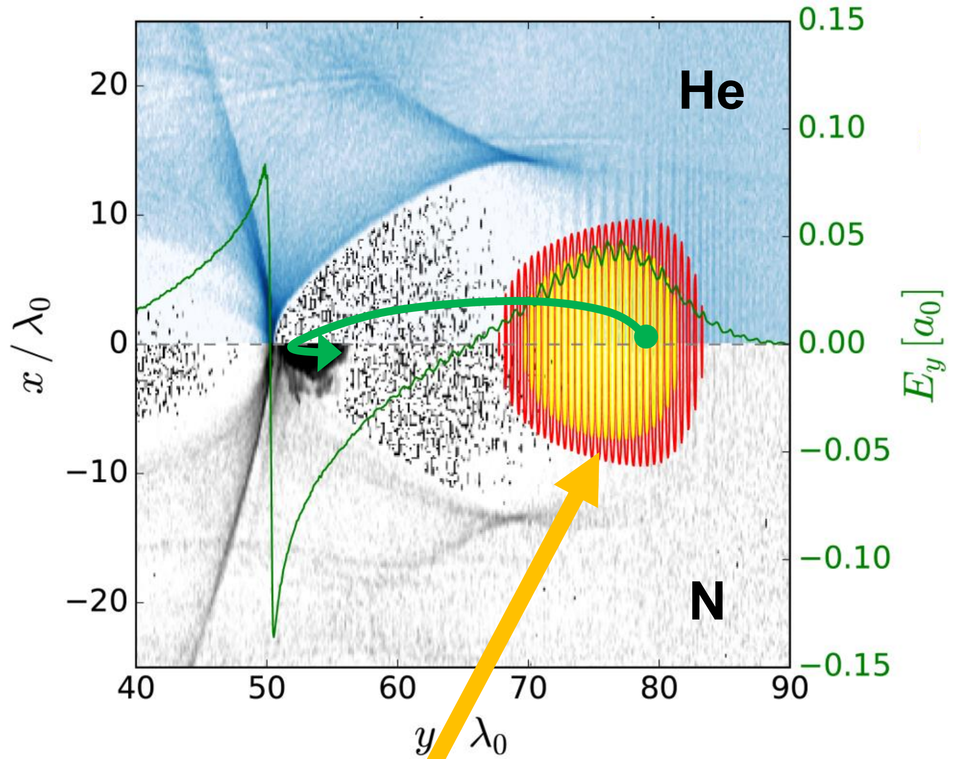

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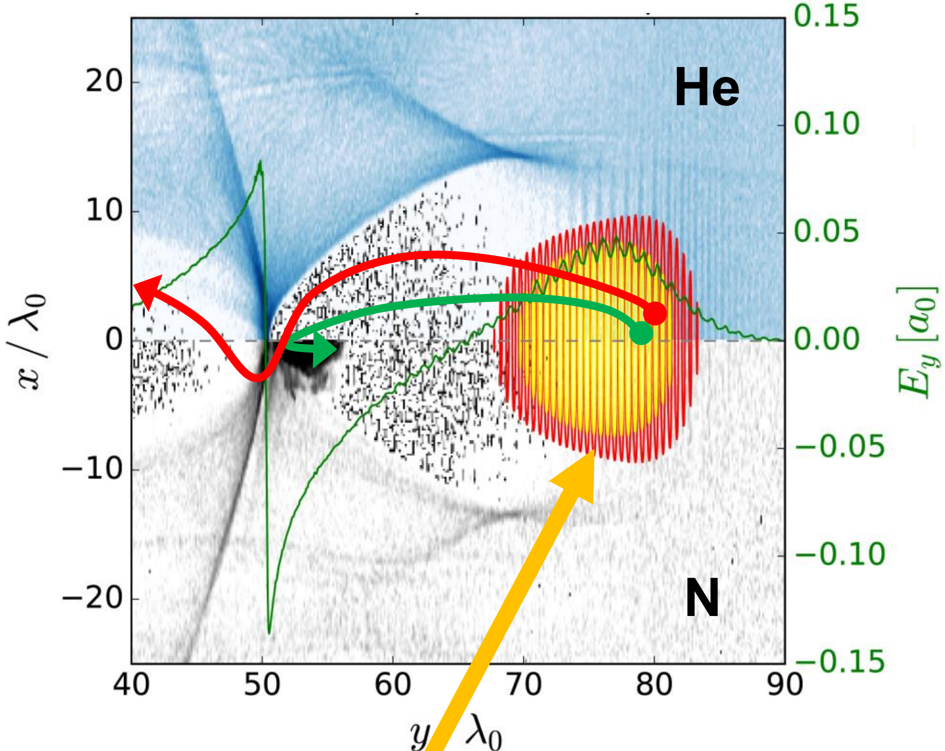


Ionized only near the laser peak intensity

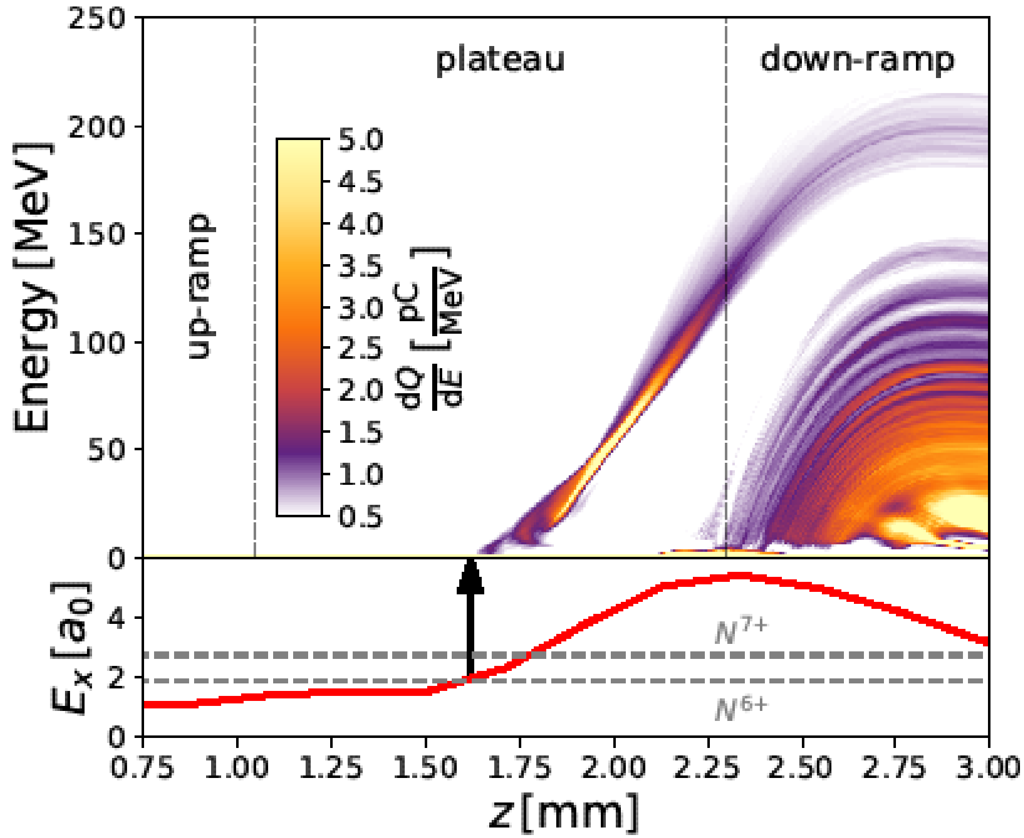
Self truncated ionization injection

- Injection can be limited by using an **unmatched laser spot**
- Laser modulation influences the wake,
  thus changing the wake pseudo-potential difference

PIConGPU

picongpu.hzdr.de

(real beam propagation, ionization, 3D)

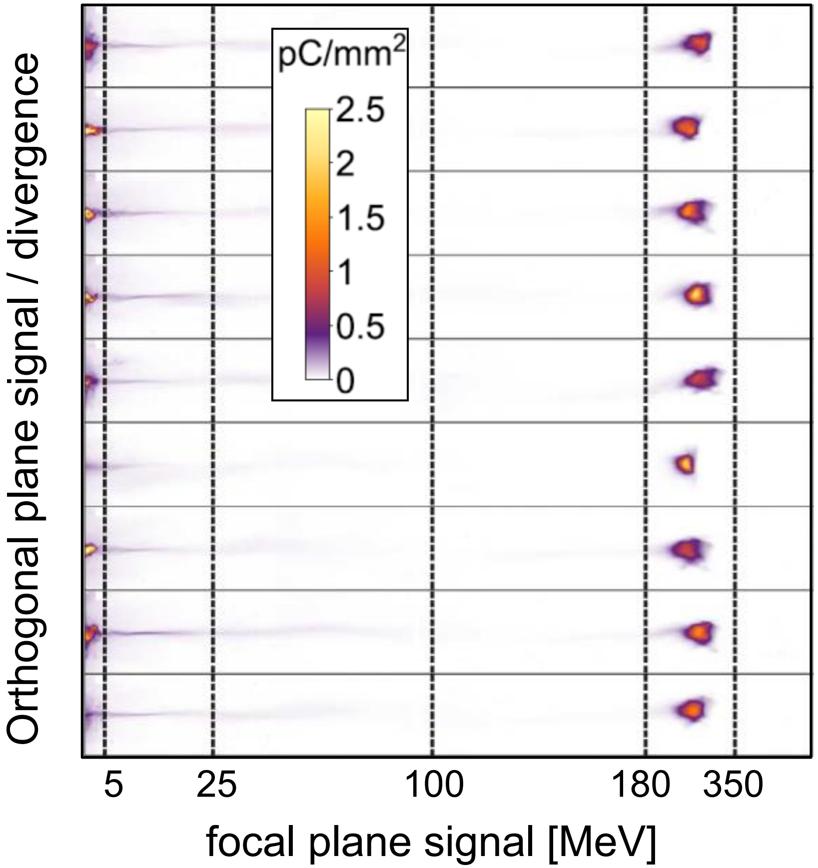


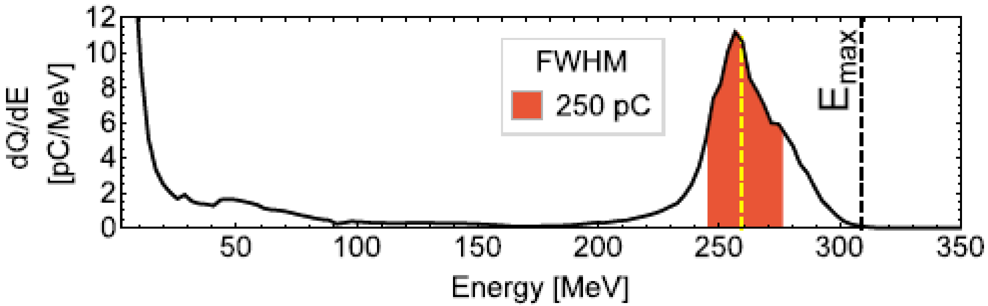
- **Injection only when**:
  - Laser max energy is high enough
  - pseudo-potential difference allows trapping

High peak current LWFA

nC-level charge in peaked low background distribution

2.5 J, 30 fs, plasma density 3.1×10^{18} cm^{-3} , mixed He + 1% N_2

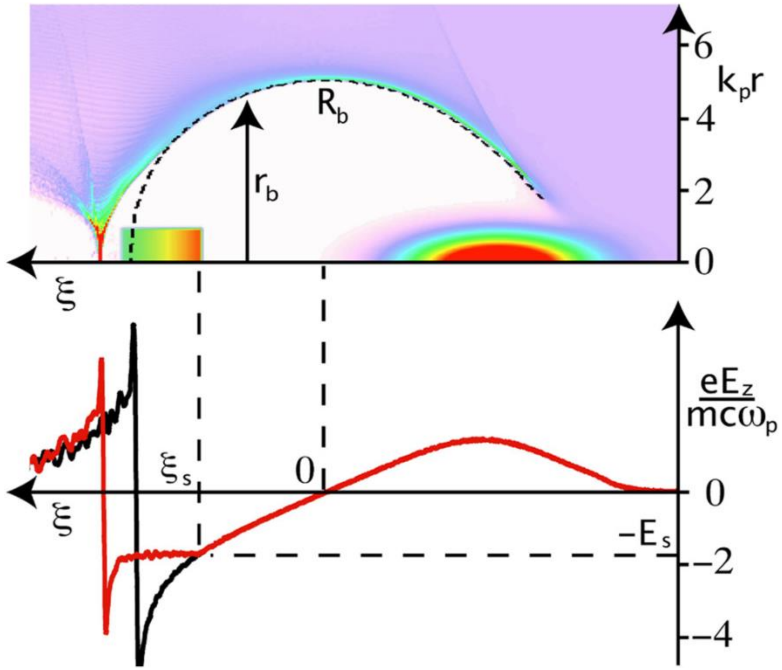




Parameters	Mean ± Shot-to-shot jitter
Mean peak energy	250 MeV ± 22.5 MeV
Charge in fwhm	250 pC ± 40 pC
Abs. energy width	36 MeV ± 11 MeV
Divergence	7 mrad ± 1 mrad

Charge induced beam loading

- Injection of an optimum bunch shape with a **specific charge Q_s**



- Charge scaling at the **optimum loading condition**

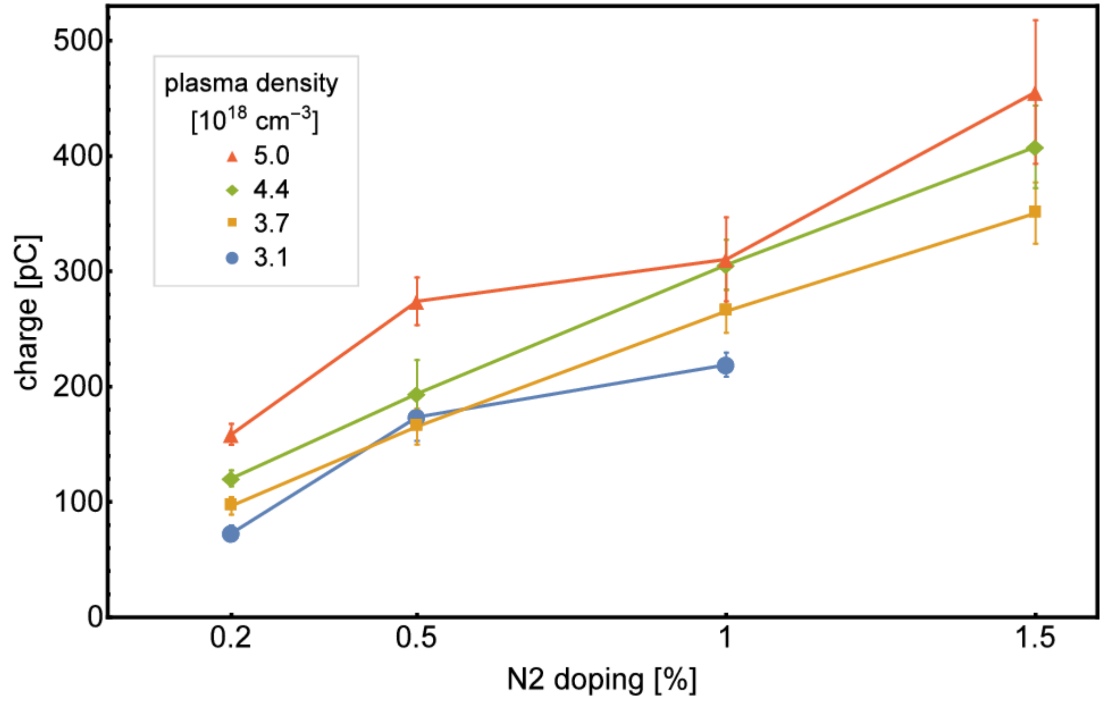
$$\frac{Q_s}{1\text{nC}}\frac{eE_s}{mc\omega_p} \simeq 0.047\sqrt{\frac{10^{16}\,\text{cm}^{-3}}{n_p}}(k_p R_b)^4$$

$$Q_s \propto \sqrt{P}$$

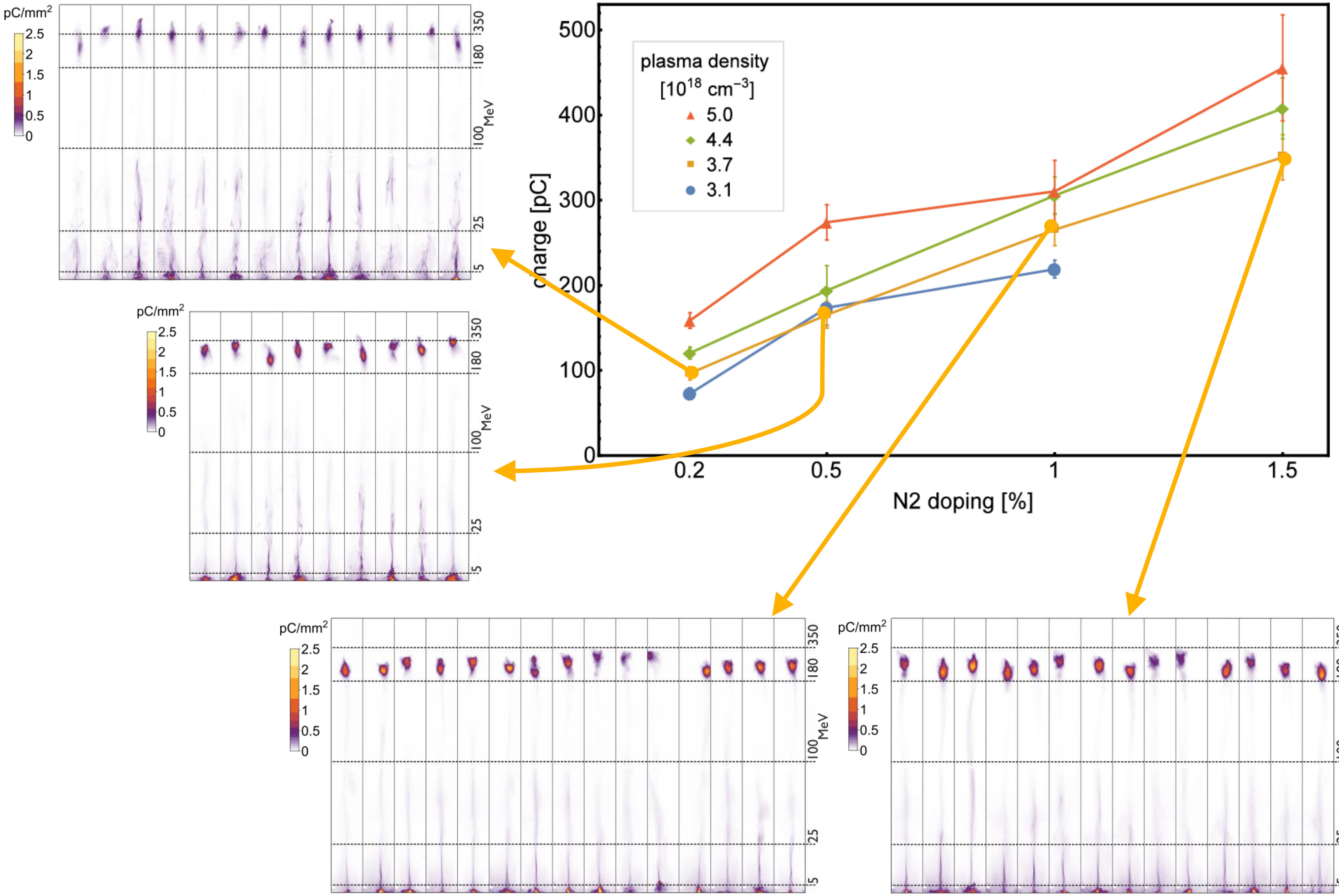
Tzoufras,*et al.*, PRL. 101,145002(2008)

Charge tuning via Nitrogen doping

- We need to **tune** the **injected charge** at **equal plasma dynamics** in order to study beam loading effects



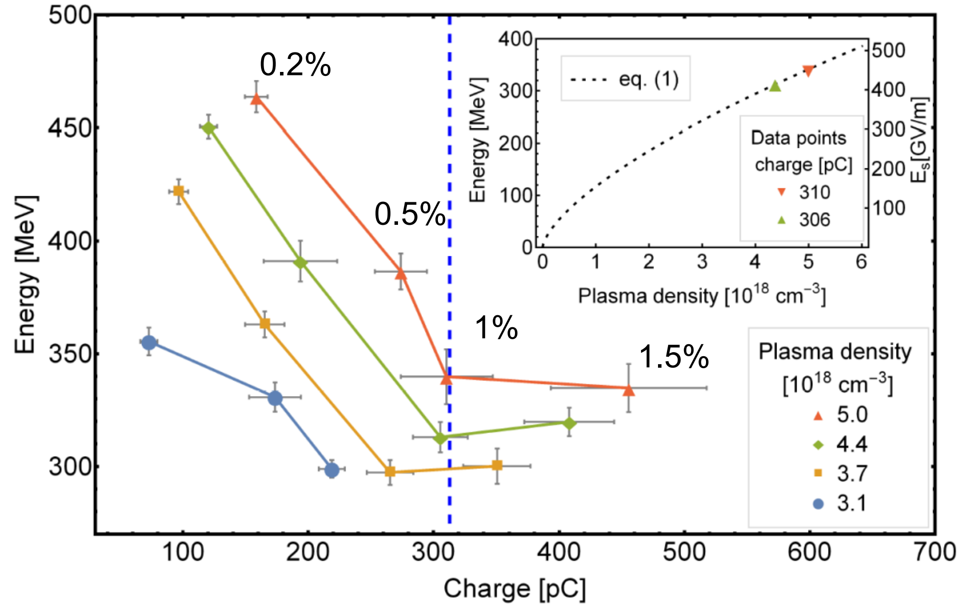
Charge tuning via Nitrogen doping

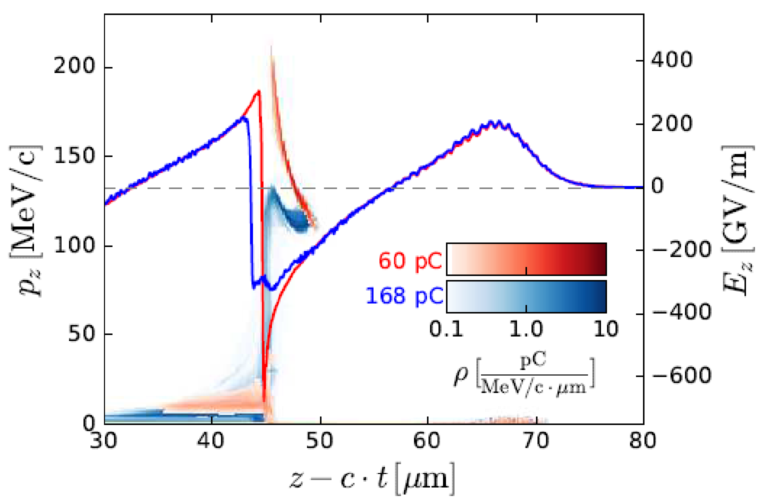


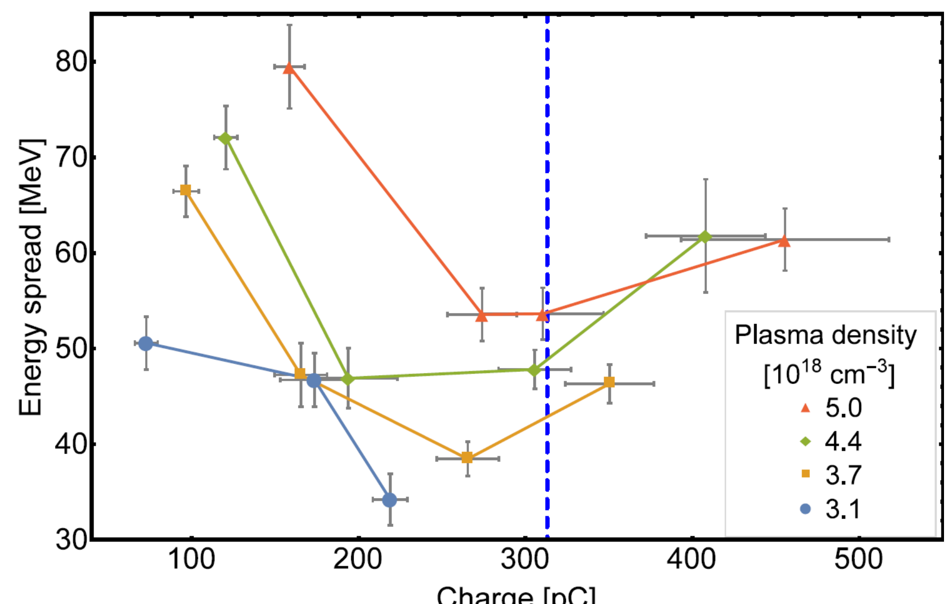
Beam loading improved beam quality

Beam energy dependence

- Increasing charge
  → energy and **energy spread decrease**







Beam loading improved beam quality

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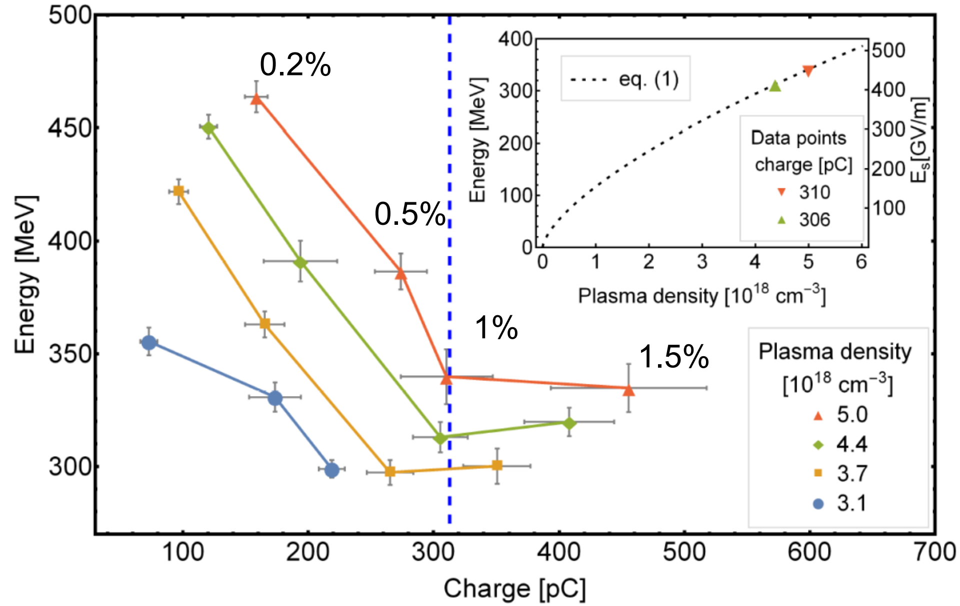
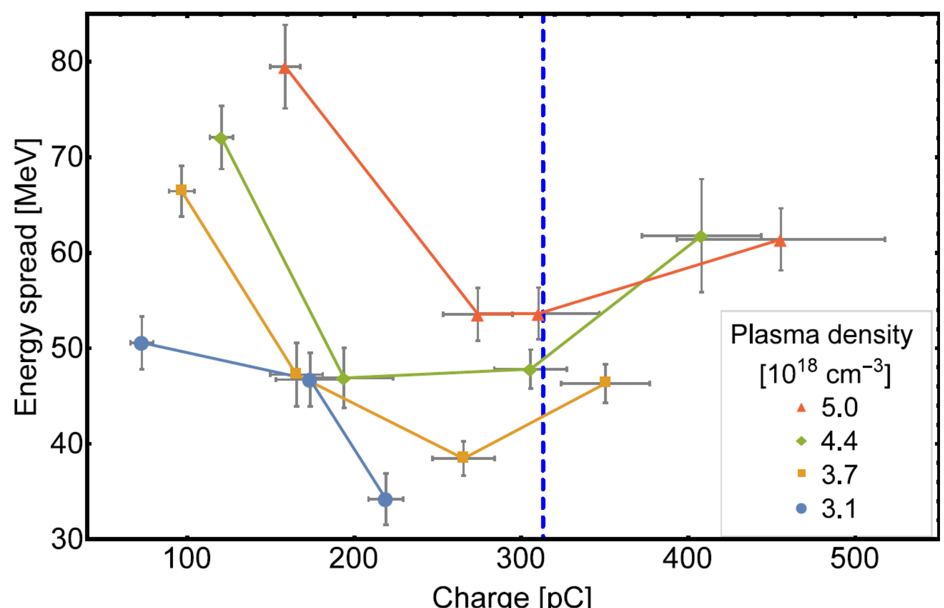
Beam energy dependence

- Increasing charge
  → energy and **energy spread decrease**

- **Optimum loading**:
  → minimum energy spread
  @ 300 pC, ~ 6 fs → up to **50 kA**

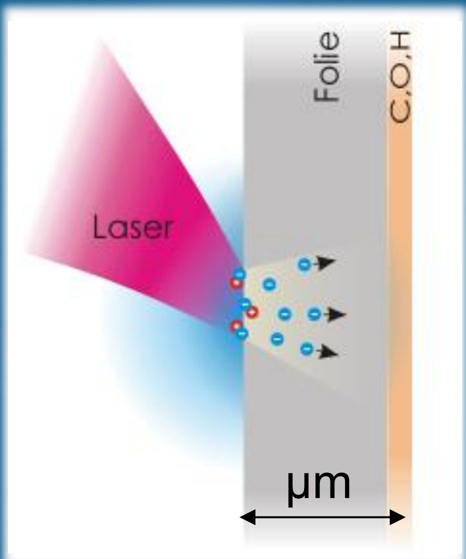




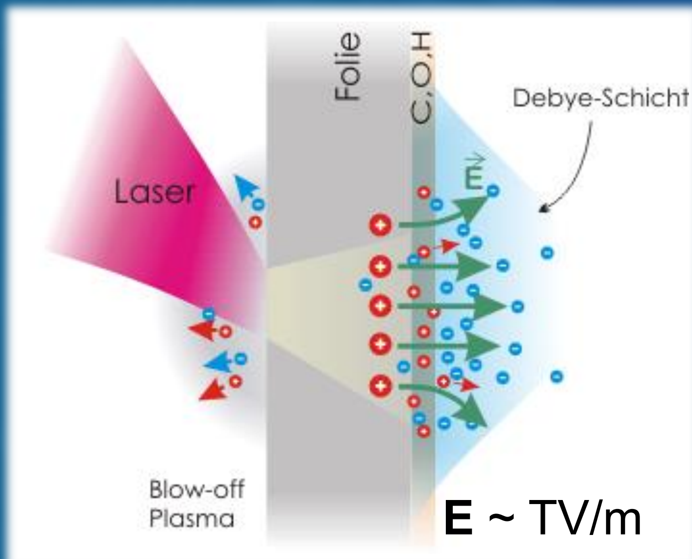
A. Köhler, et al., TUPIK004
O. Zarini, et al., TUPIK005
T. Heinemann, et al., TUPIK010

Ion acceleration - TNSA

laser absorption and electron acceleration
(fs-scale)

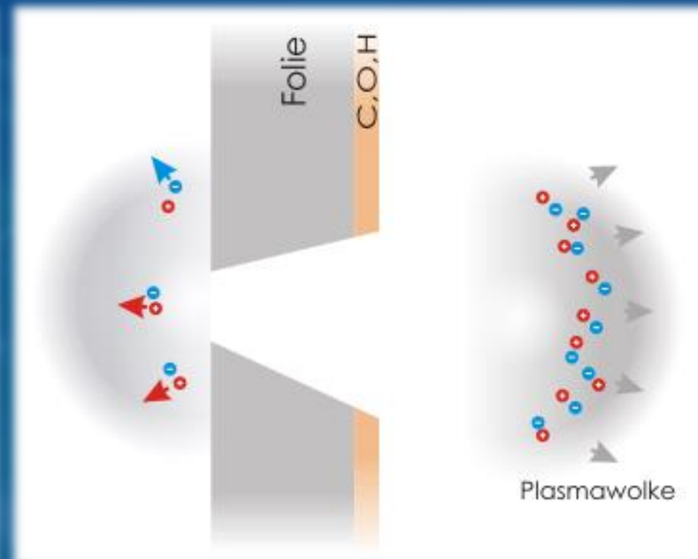


electron transport and Debye-sheath formation



expansion of the plasma

(ps-scale)



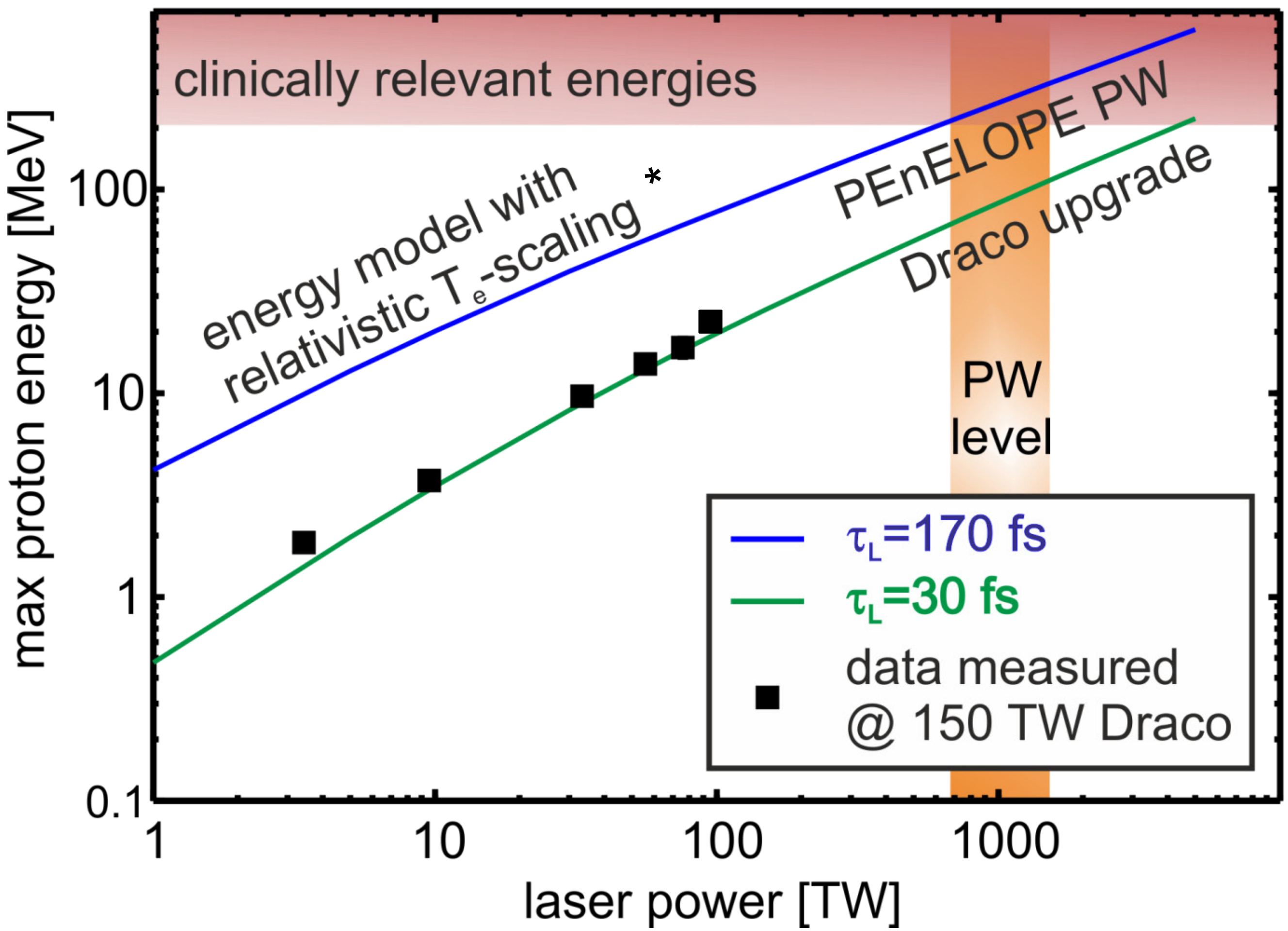
$$T_h\,(I_L) \sim \mathrm{MeV}$$

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

$$E \propto \frac{k_B T_h}{\lambda_D} \propto \frac{k_B T_h}{\sqrt{\frac{k_B T_h}{n_h}}}$$

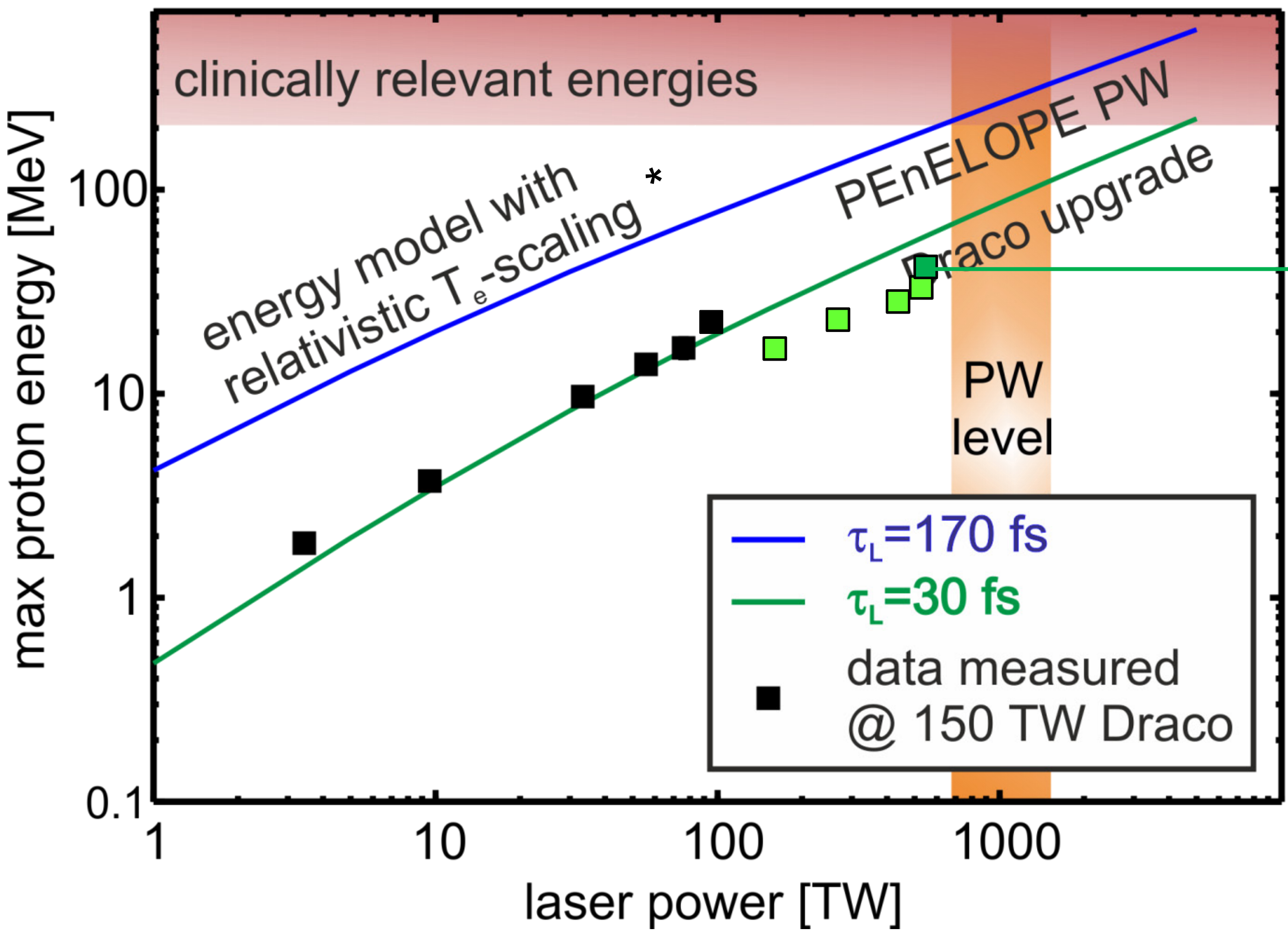
$$\vec{E} \propto \nabla n_h / n_h$$

Proton energy scaling (TNSA, lin. pol.)

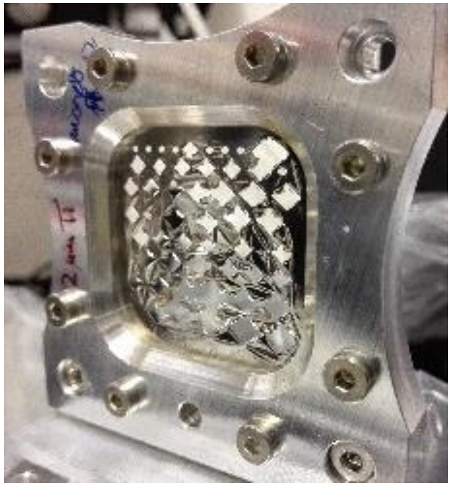


*T. Kluge et al., PRL 107 (2011), 205003

Proton energy scaling (TNSA, lin. pol.)



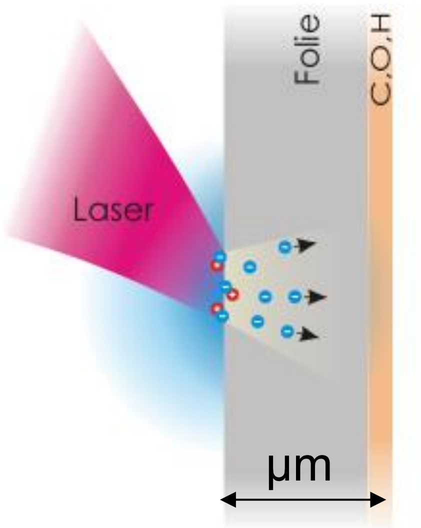
>40 MeV p from 1 µm Ti-foil with 20J on target



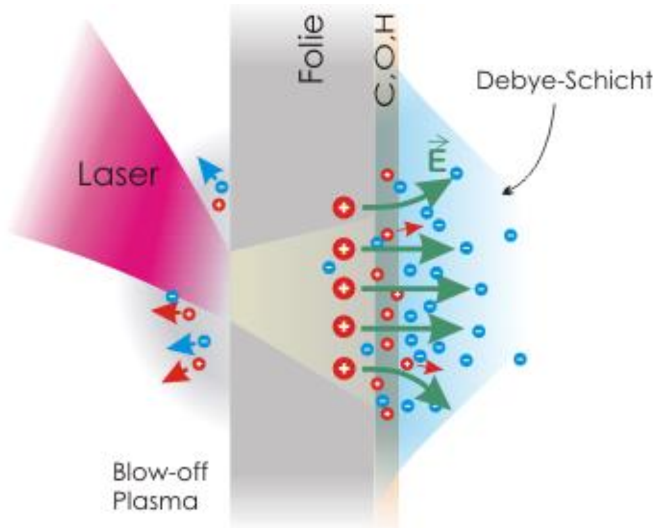
**T. Kluge et al., PRL 107 (2011), 205003*

Thin targets (more localized source)

Laser absorption and
Elektronen acceleration
(fs-scale)



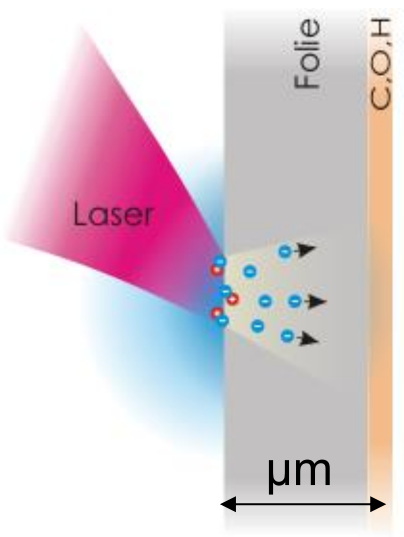
Electron transport and
Debye-sheath formation



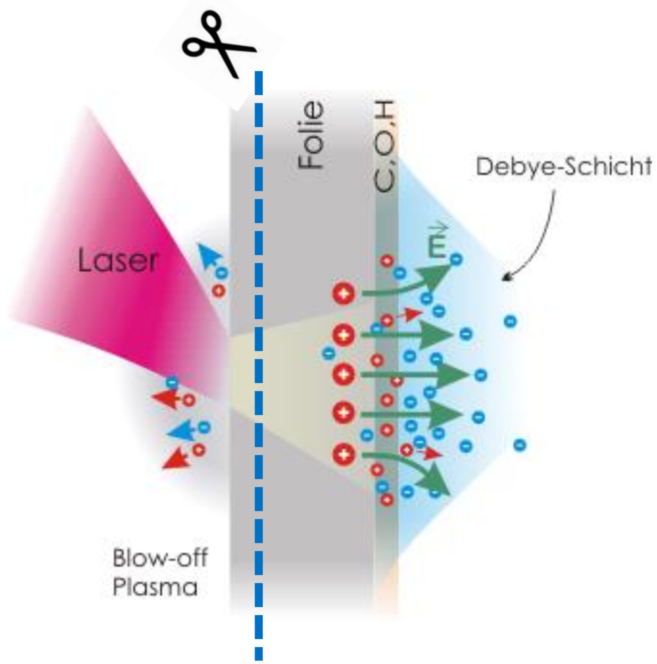
Control electron generation … pulse contrast
… local shape
… density distribution (foams)

Thin targets (more localized source)

Laser absorption and Elektronen acceleration **(fs-scale)**



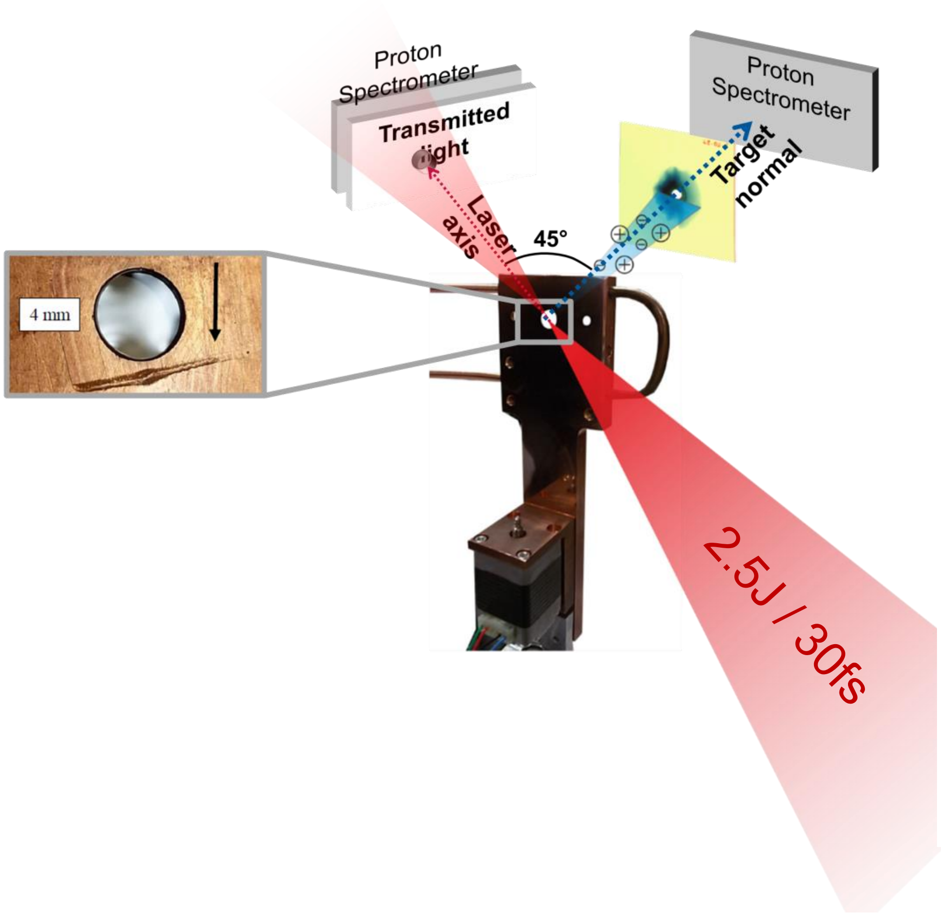
Electron transport and Debye-sheath formation

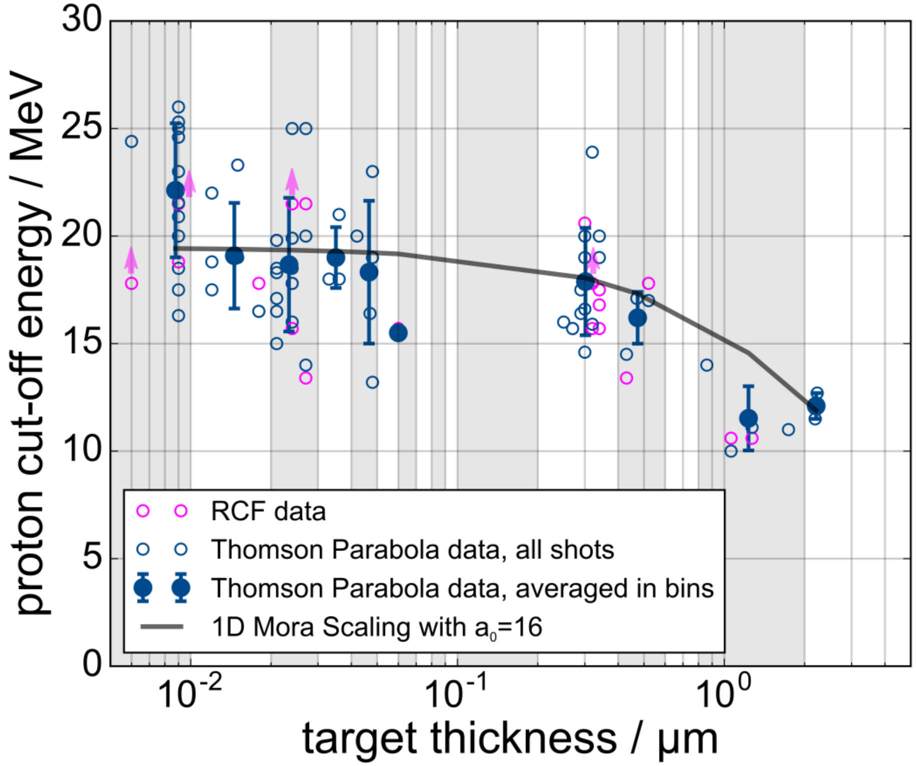


Control electron transport (bulk)

Enhanced TNSA with ultra-thin foils

Variable thickness (perfect surface) liquid crystal target





-> onset of (relativistic) transparency

-> up to 10 MeV per Joule energy

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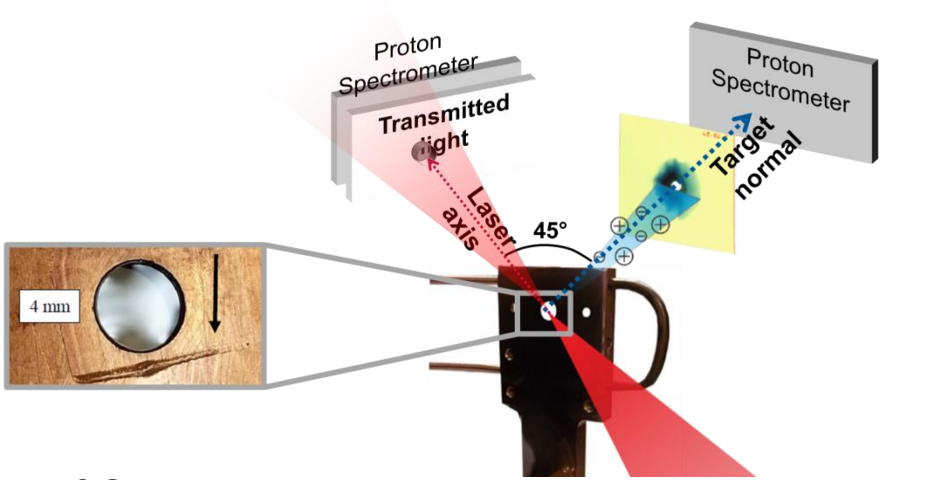
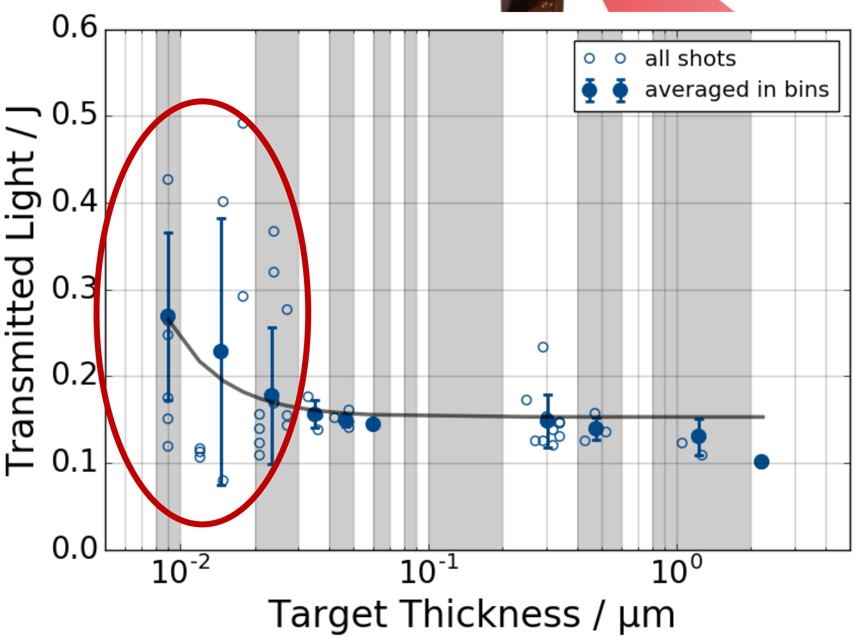
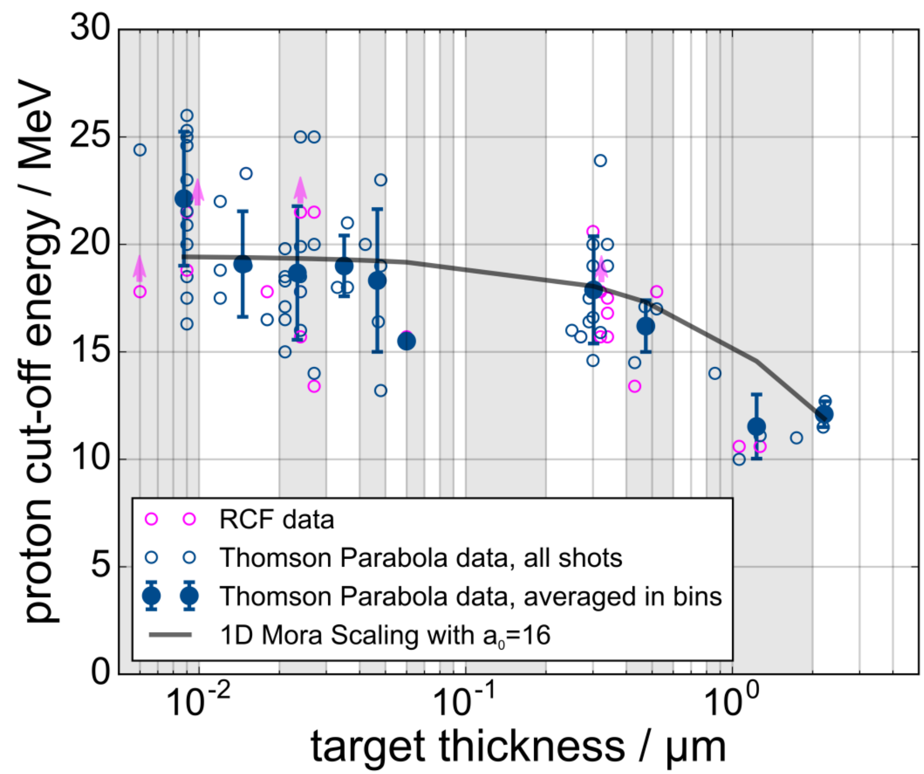
Variable thickness (perfect surface) liquid crystal target

The Ohio State University







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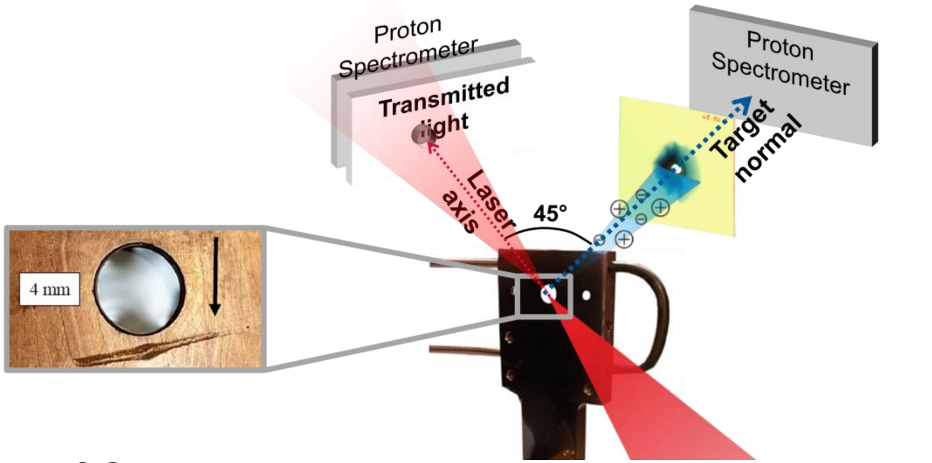

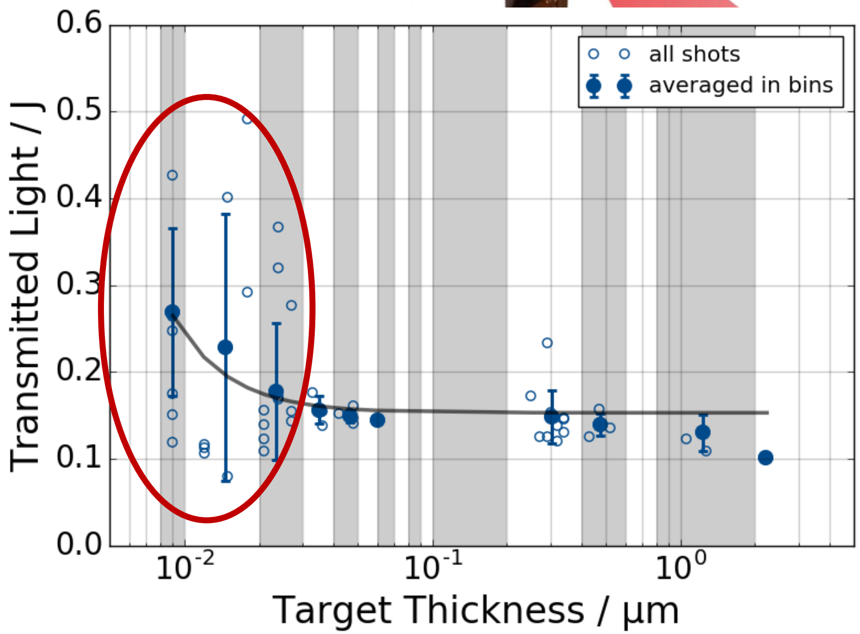

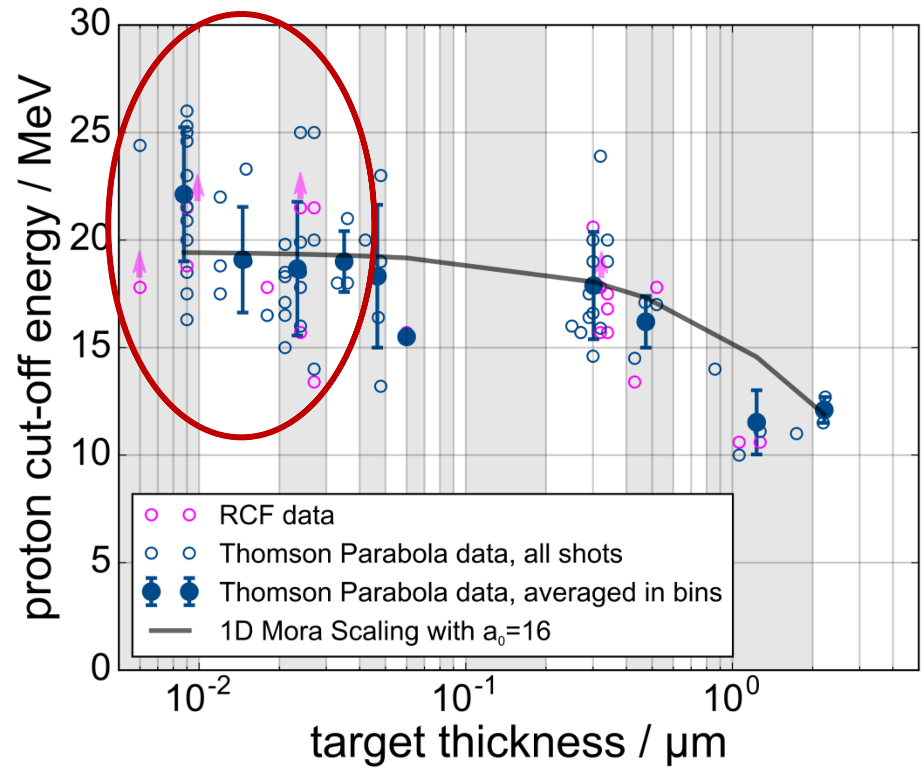

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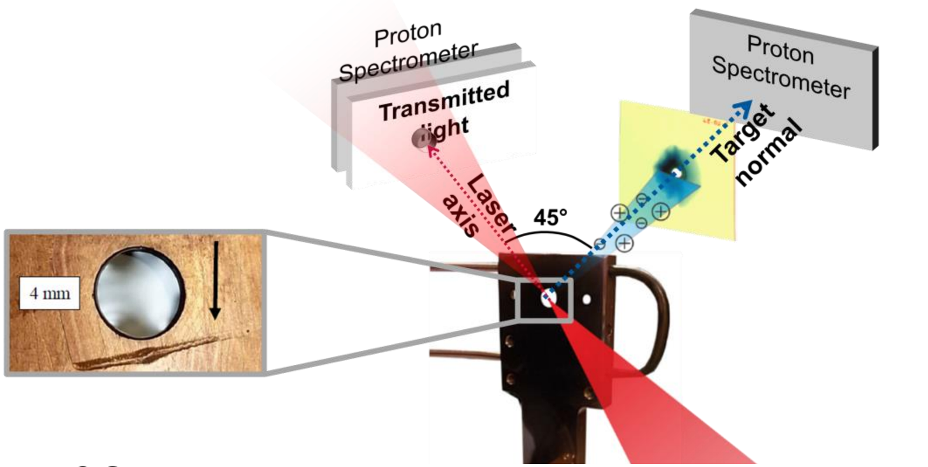

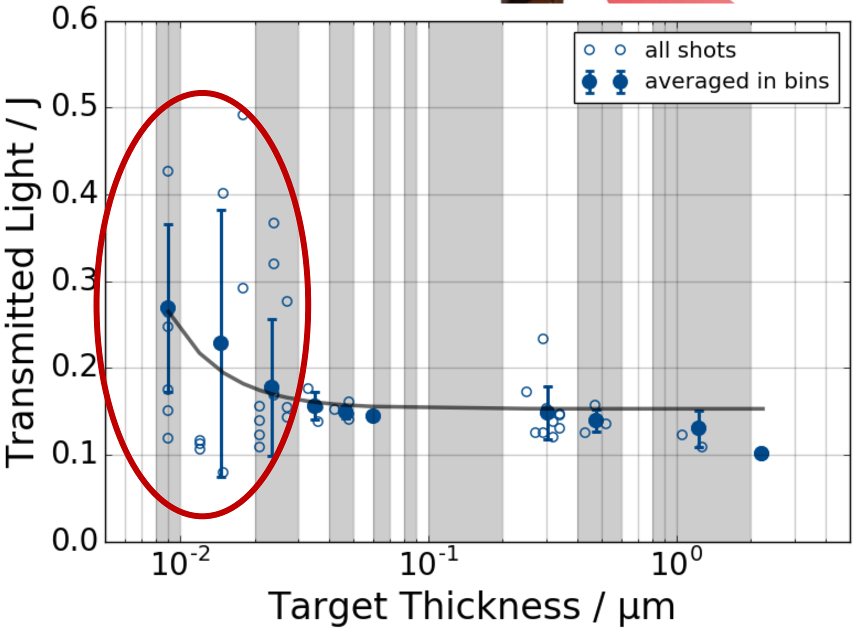

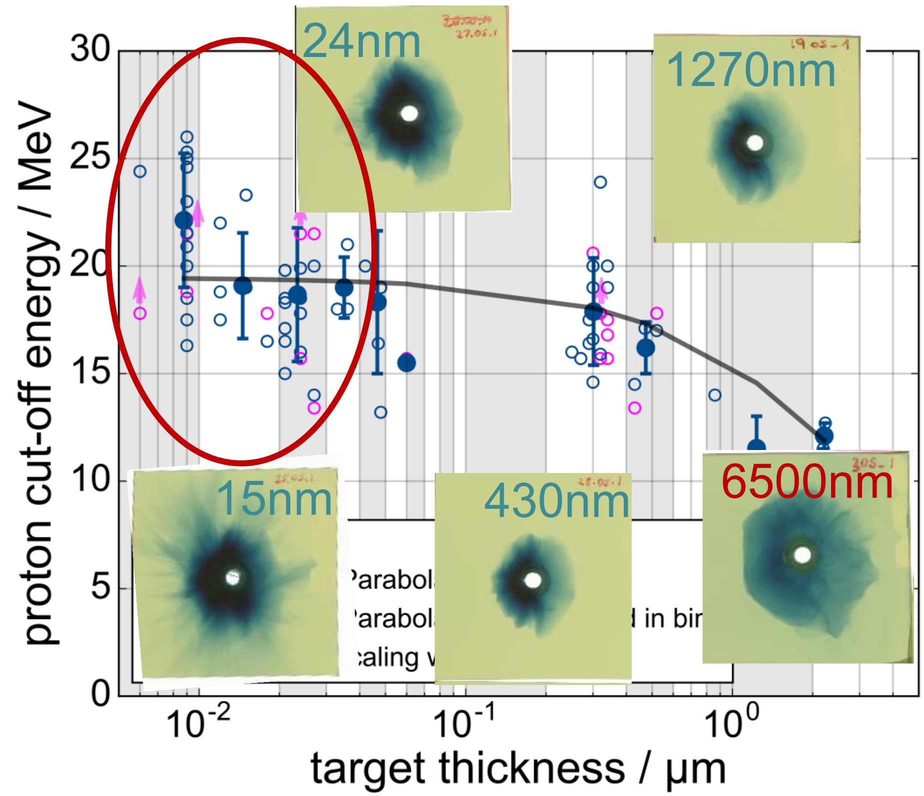

-> onset of (relativistic) transparency

-> up to 10 MeV per Joule energy

How can we increase the average yield

high repetition rate lasers
continuous target support
debris mitigation

For "best performance" 10 MeV / Joule seems to be a "limit", enhancement multiplication open challenge

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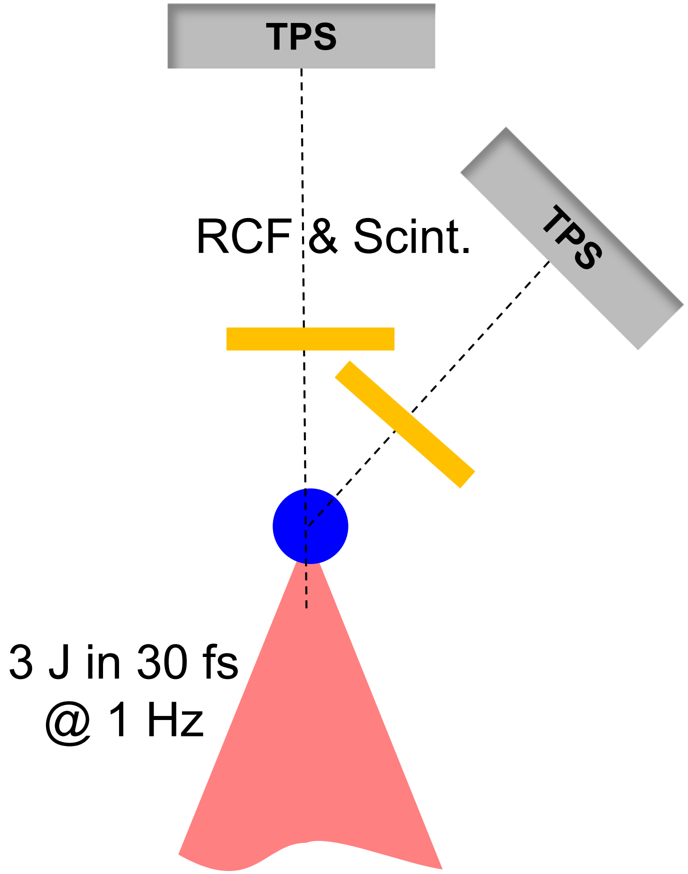
Cryogenic hydrogen target

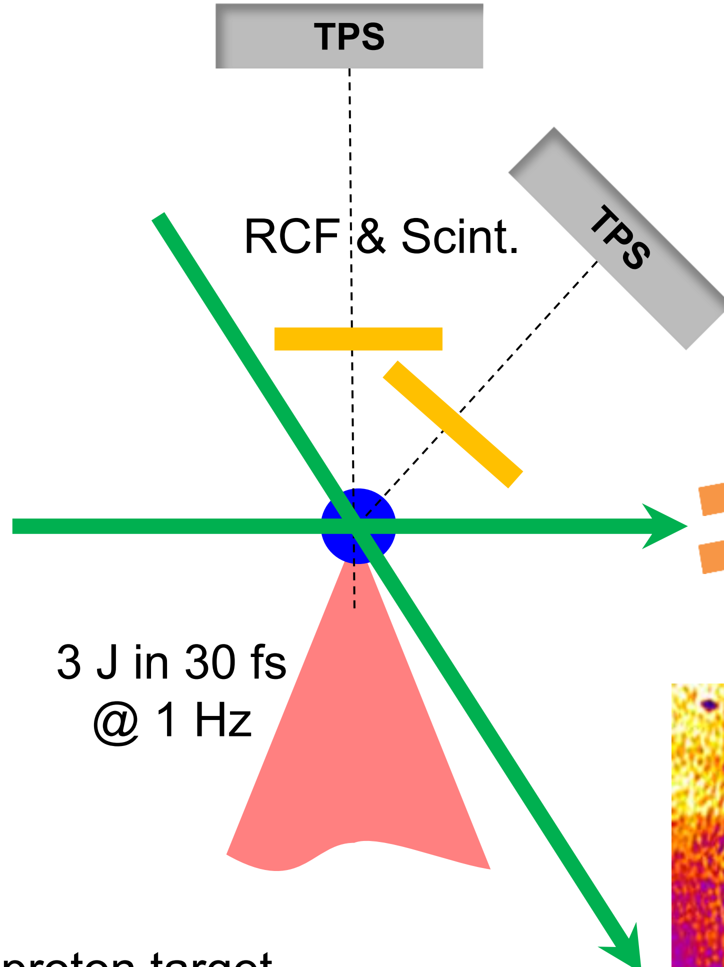


S. Goede et al., PRL in press

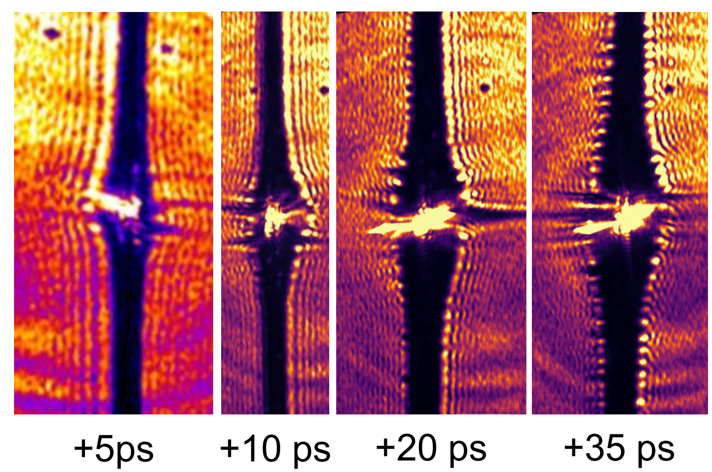
- debris-free pure proton target
- Flow speed ~ 100 m/s
  → Repetition rate > 1 Hz
- Different geometries and gases

Cryogenic hydrogen target

S. Goede et al., PRL in press

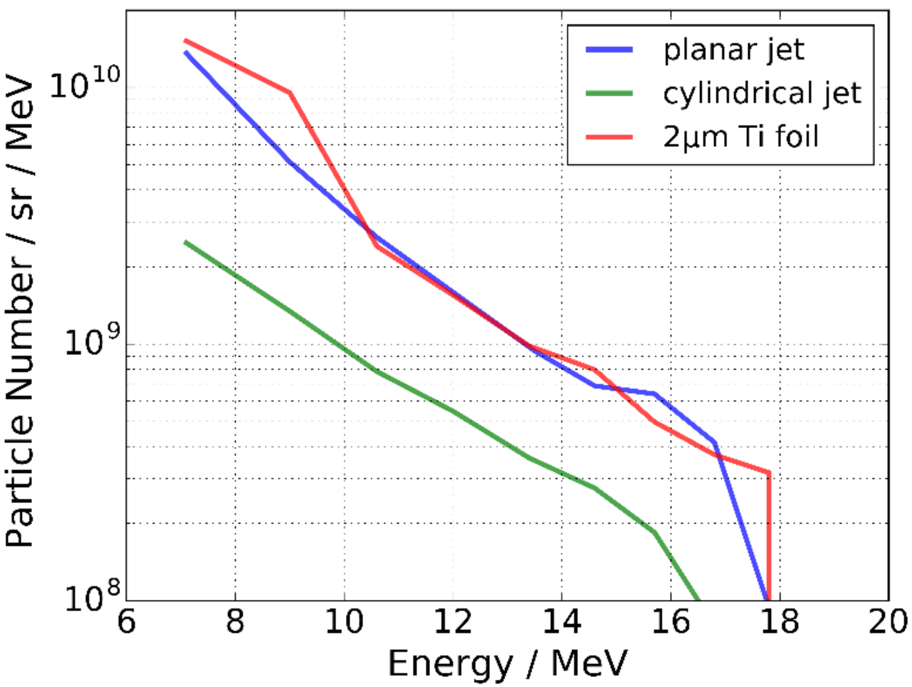


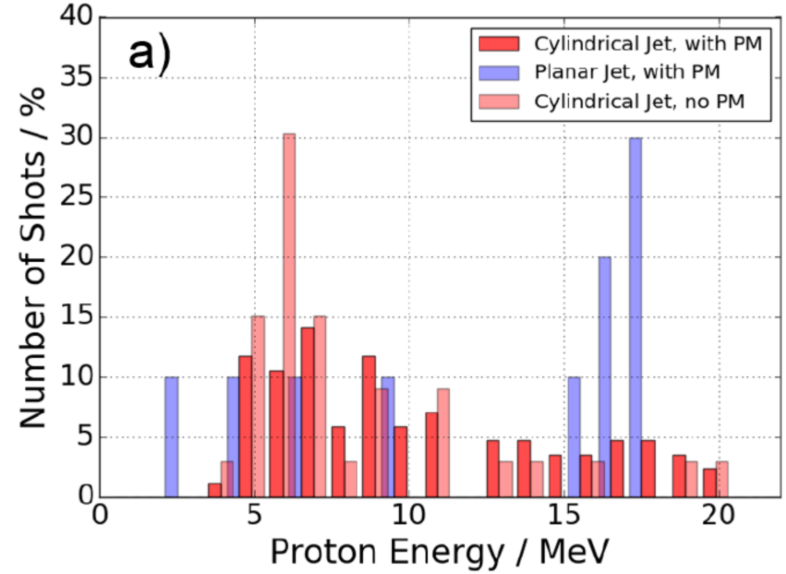
- transversal ***and*** longitudinal
- auxiliary phase locked ps-probe laser @ 515 nm, 1.6 ps

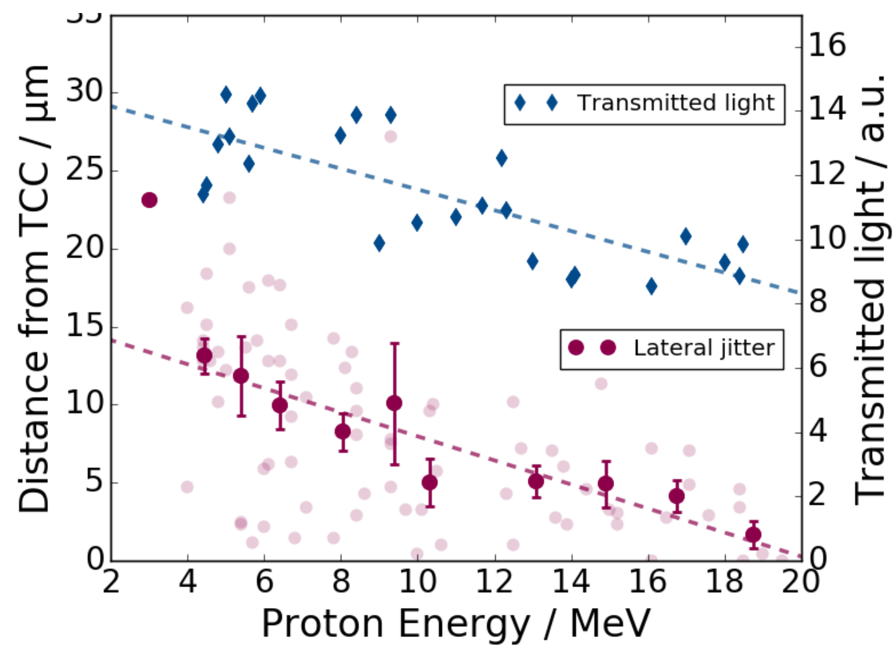


- debris-free pure proton target
- Flow speed ~ 100 m/s
  → Repetition rate > 1 Hz
- Different geometries and gases

TNSA with frozen hydrogen jets

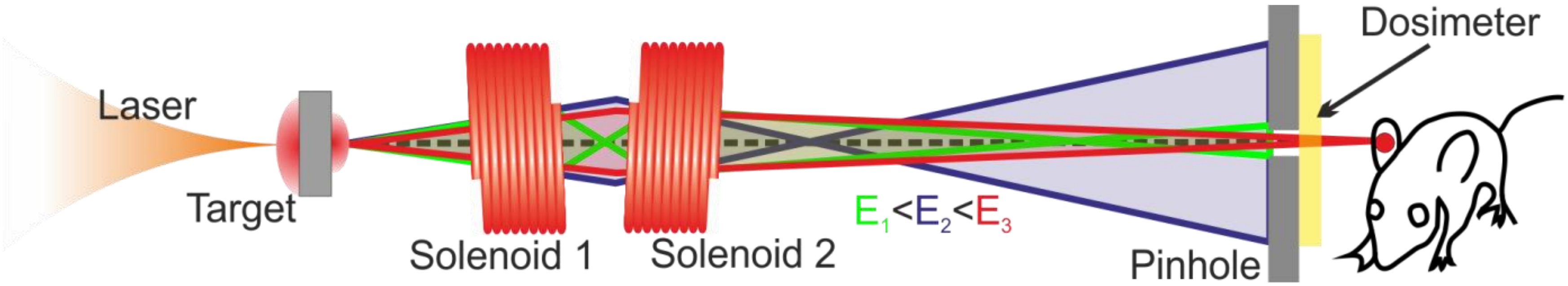




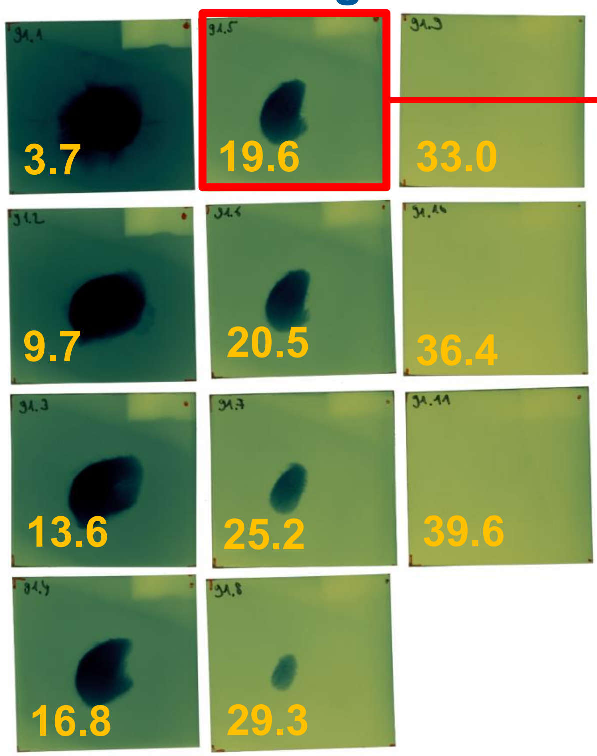


- stability challenging
- pure beam with competitive energy
- debris-free
- 1Hz operation demonstrated
- heavy ions (He)

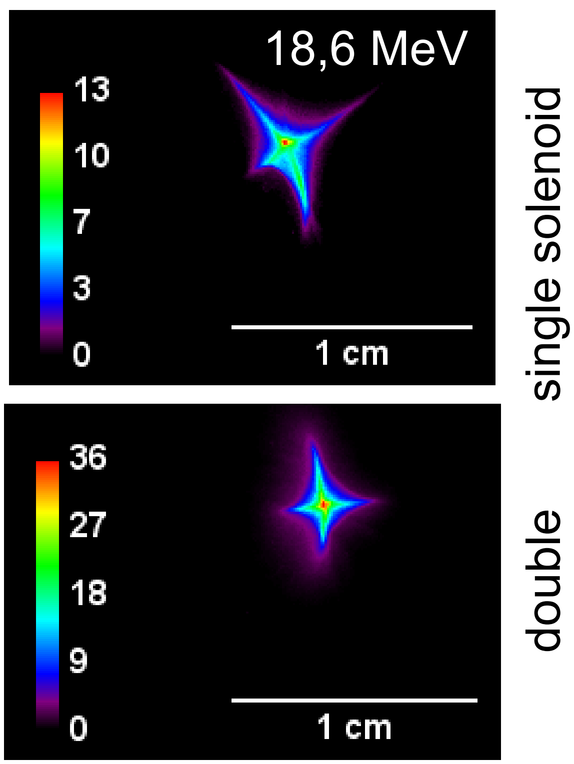
Capture and transport of TNSA beams

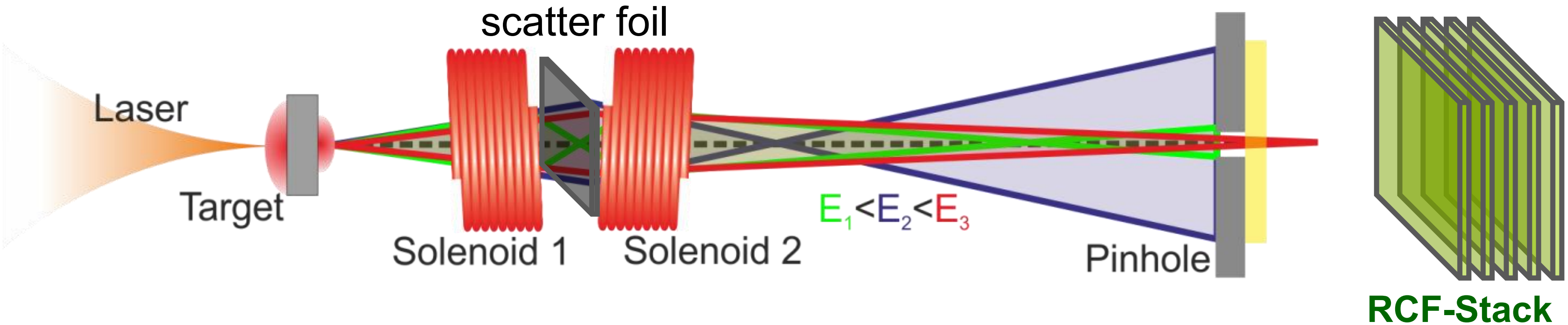


20 J on Ti- target

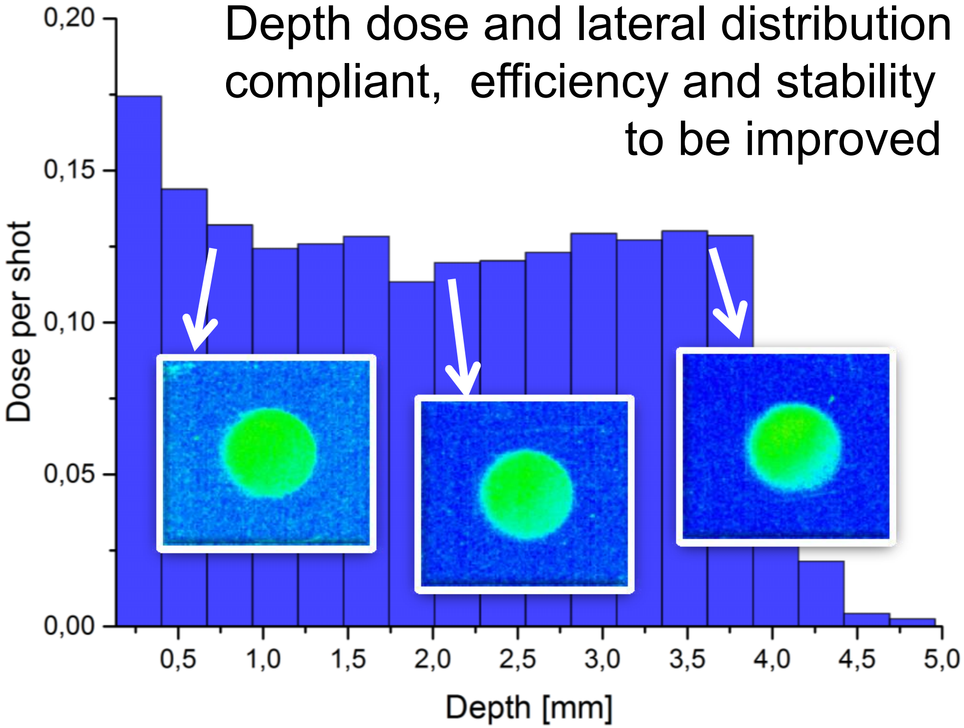


proton focus

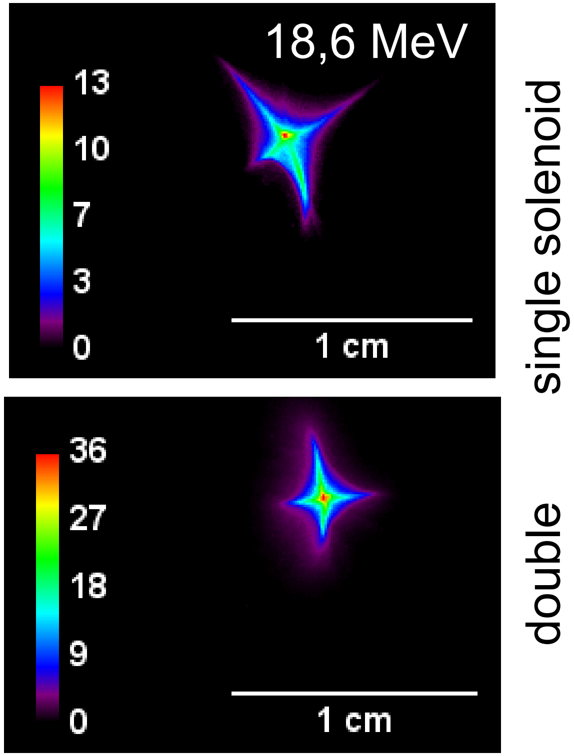




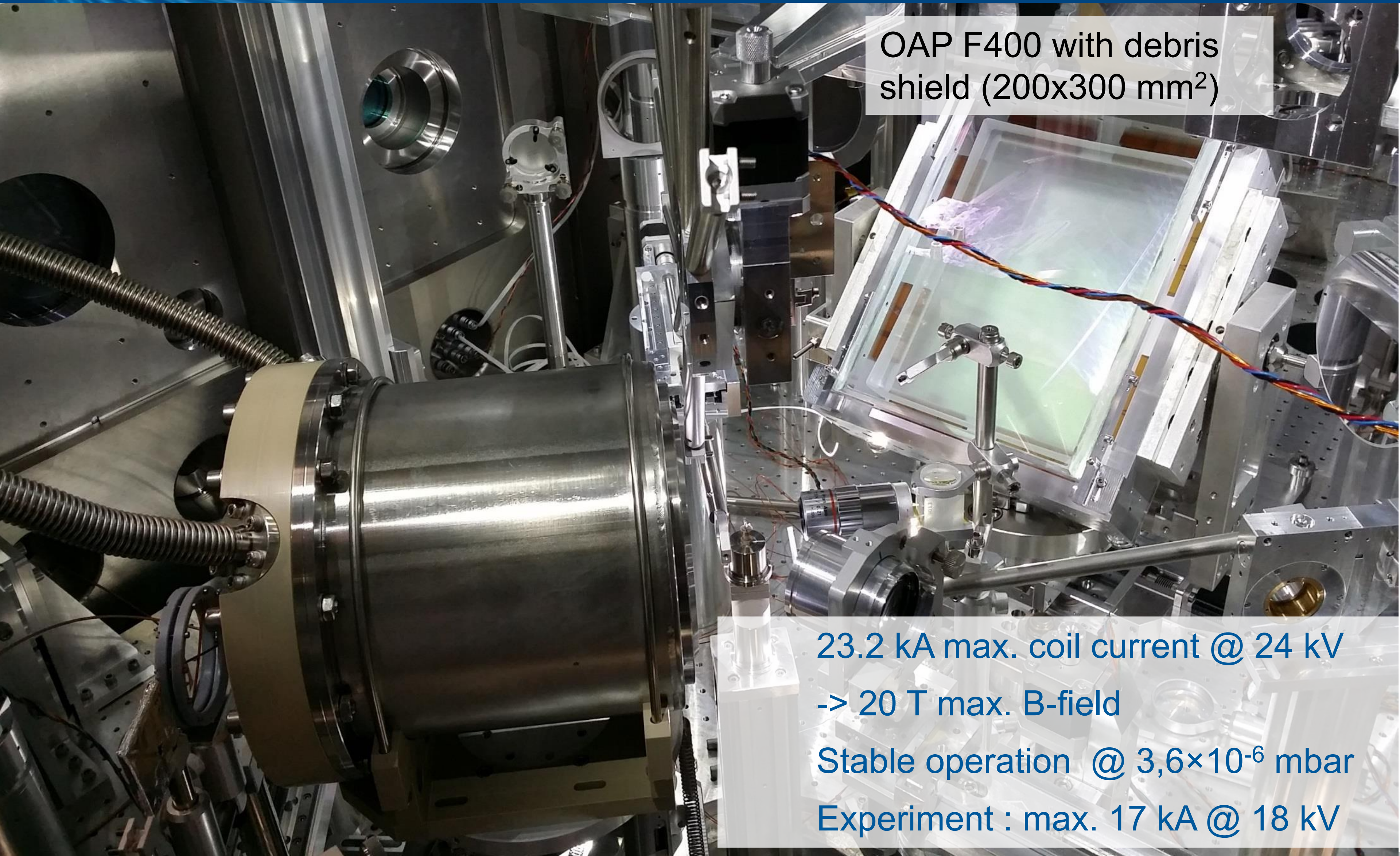
proton focus



Depth dose and lateral distribution compliant, efficiency and stability to be improved



Capture and transport of TNSA beams

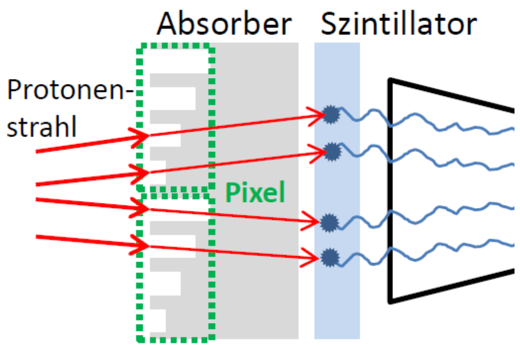


Pixel detector: J. Metzkes, et al, RSI 87, 083310 (2016)

Capture and transport of TNSA beams

OAP F400 with debris shield (200x300 mm²)

5x5mm² „pixel“ (9 energies)



23.2 kA max. coil current @ 24 kV

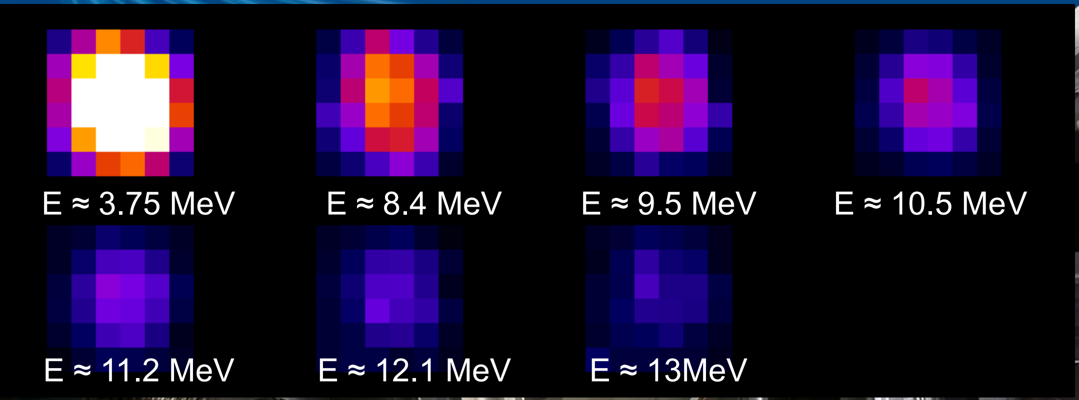
-> 20 T max. B-field

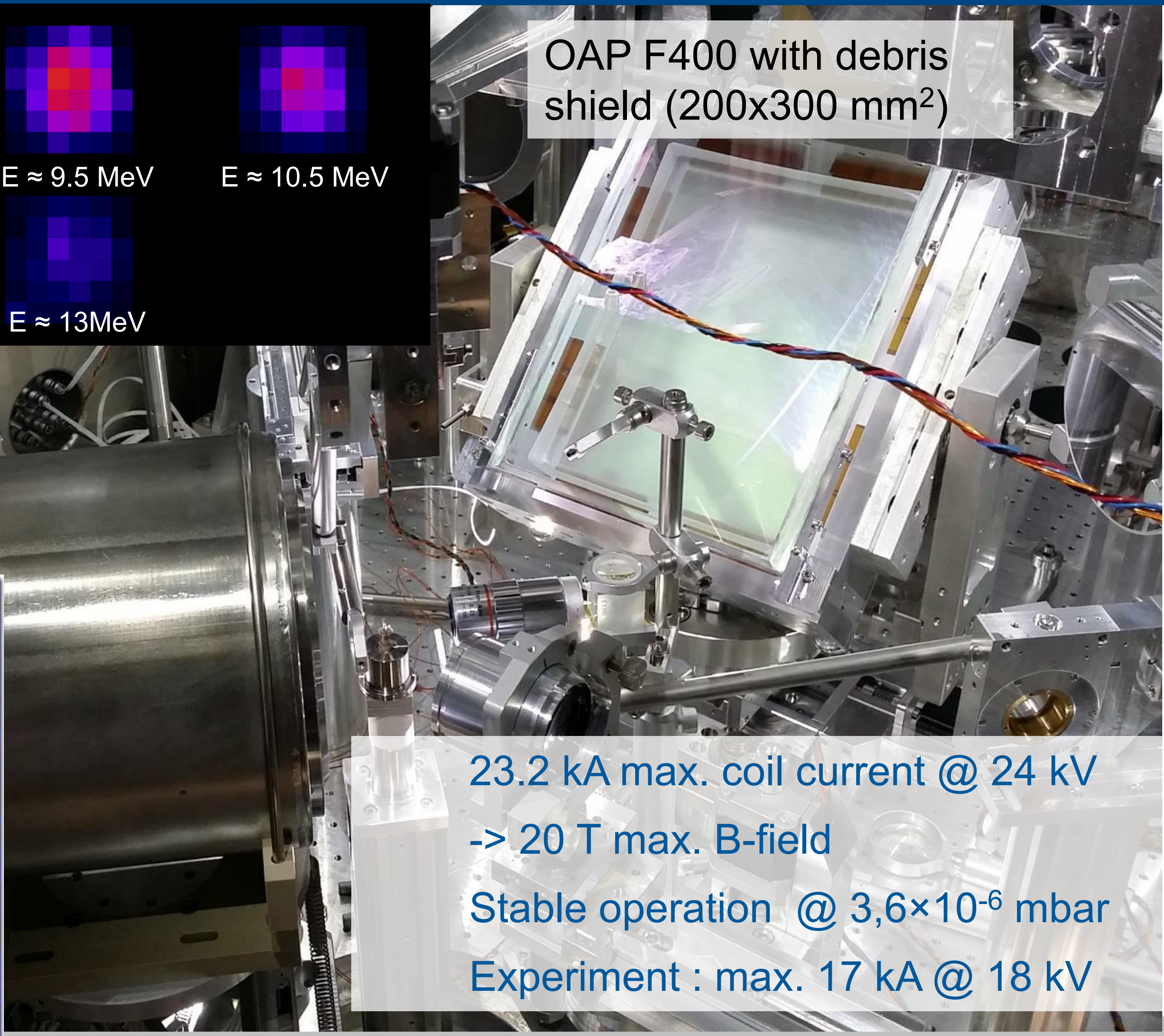
Stable operation @ 3,6×10^{-6} mbar

Experiment : max. 17 kA @ 18 kV

Pixel detector: J. Metzkes, et al, RSI 87, 083310 (2016)

Capture and transport of TNSA beams





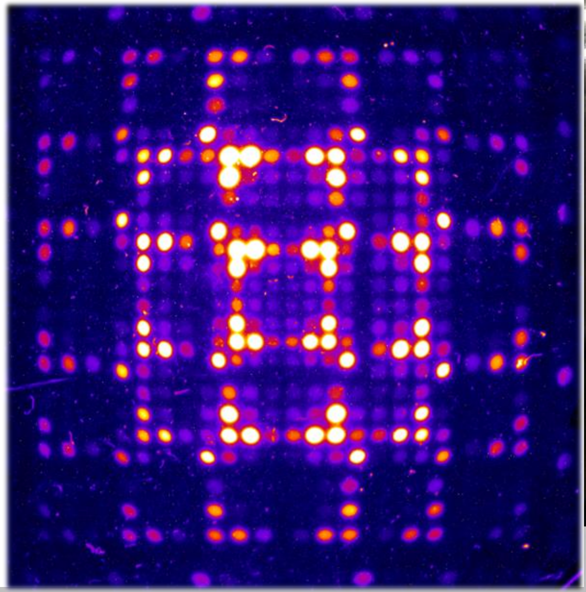
OAP F400 with debris shield (200x300 mm^2)

23.2 kA max. coil current @ 24 kV

-> 20 T max. B-field

Stable operation @ 3,6×10^{-6} mbar

Experiment : max. 17 kA @ 18 kV



Pixel detector: J. Metzkes, et al, RSI 87, 083310 (2016)

- Dresden Petawatt operational,
  yet many open projects at 100 TW level

- Unprecedented peak curents (nC-class charge) by
  ionizuation injection with strong beam loading
  -> PWFA driver …

A. Köhler, et al., TUPIK004
O. Zarini, et al., TUPIK005
T. Heinemann, et al., TUPIK010

- Ion / Proton acceleration at 10 MeV / Joule (25 MeV max)
  with various schemes

- K. Zeil, J. Metzkes, S. Kraft, F. Kroll, L. Obst, M. Rehwald, H.P. Schlenvoigt, et al.
- A. Irman, J. Couperus, J. Krämer, A. Köhler, T. Kurz, O. Zarini, et al.
- M. Bussmann, A. Debus, A. Hübl, T. Kluge, R. Pausch, K. Steiniger, et al.
- M. Siebold, D. Albach, S. Bock, R. Gebhardt, U. Helbig, M. Löser, et al.
- U. Schramm, T. Cowan, R. Sauerbrey

D. Schumacher, P. Poole, et al., The Ohio State University

S. Göde, F. Fiuza, C. Rödel, S. Glenzer, et al., SLAC, European XFEL

MT ARD