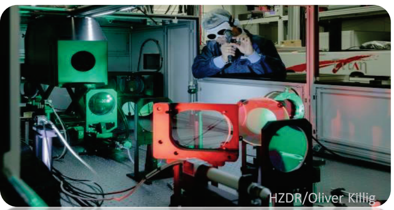
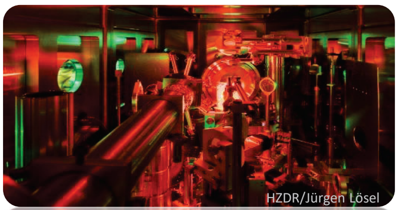
# Laser-Driven Proton Acceleration – Schemes and Diagnostics

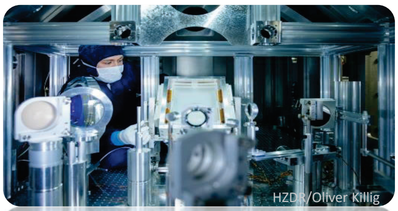
ELI Summer School

2.–6. September 2024

Szeged, Hungary








Karl Zeil

Group leader for laser-driven ion acceleration

Institute of Radiation Physics

Helmholtz-Zentrum Dresden – Rossendorf


HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF


+ 5 further research locations (Germany/France)

## Department of Laser Particle Acceleration

**development & application of high power lasers for plasma-based particle acceleration since 2007**


1st *in vivo* irradiation study with laser-driven protons (2022)

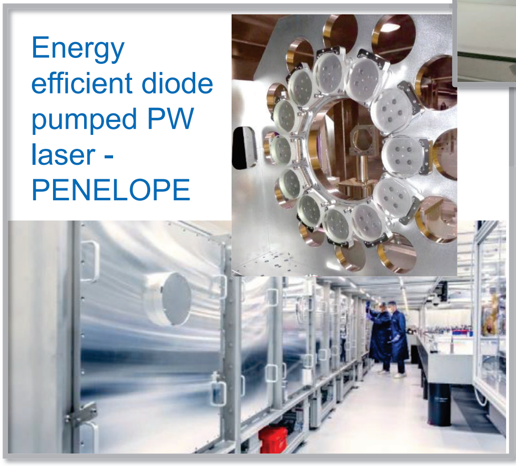
1st seeded free-electron laser driven by a compact laser plasma accelerator (2023)

Record energy from a laser driven proton source (2024)


Karl Zeil I k.zeil@hzdr.de I www.hzdr.de

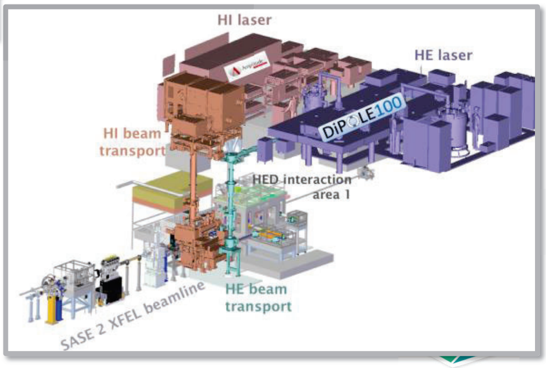
# HZDR High-power lasers

150 TW / PW dual beam facility DRACO



Energy efficient diode pumped PW laser - PENELOPE

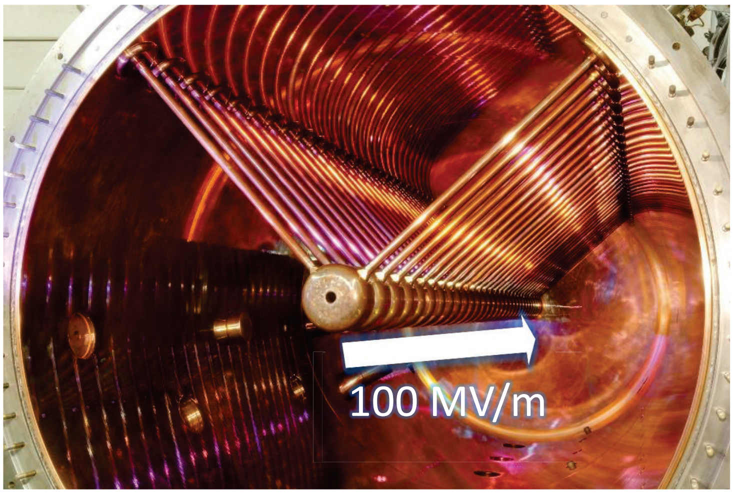
RELAX @ EuXFEL



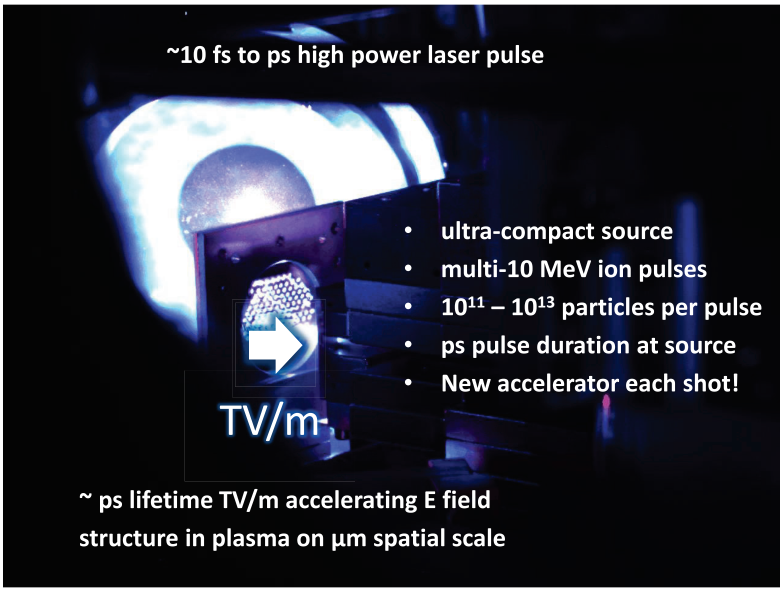
# Outline

1. **An introduction to laser-driven ion acceleration**
   - Ion acceleration via Target Normal Sheath Acceleration
   - Ion detection methods
   - Applications
   - Advanced acceleration schemes
2. **A current research project:** Characterizing Laser Transmission in the Relativistically Induced Transparency Regime for PW Laser-Driven Proton Acceleration

## Laser-driven acceleration of ions in a nutshell…



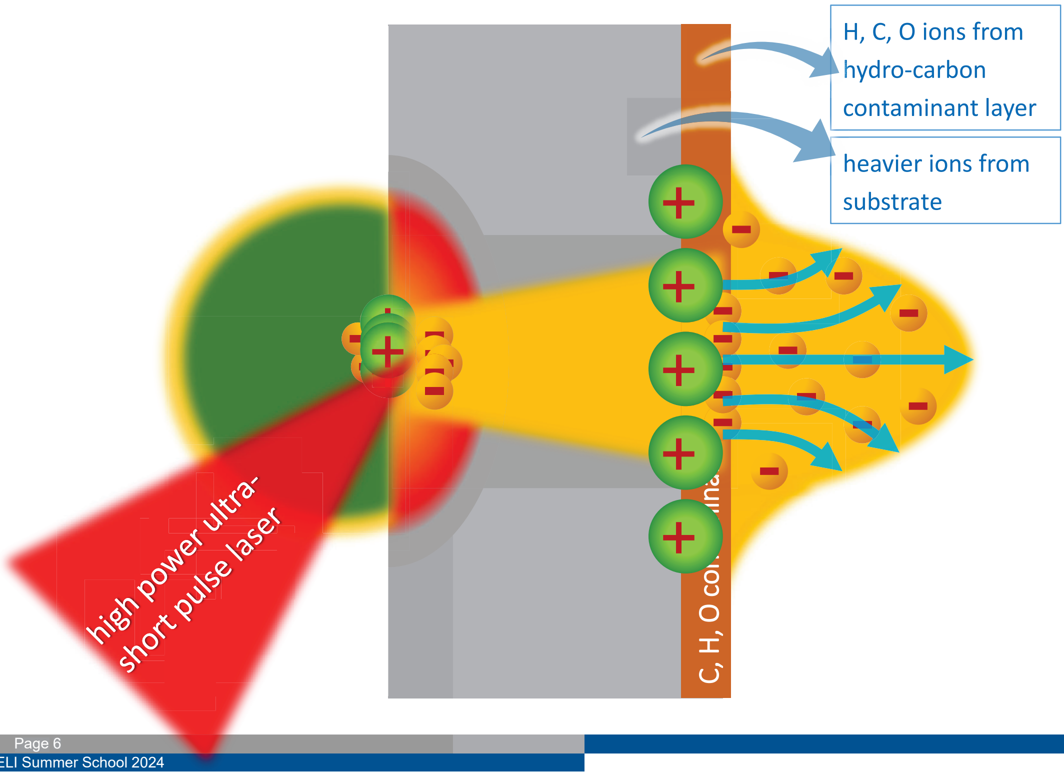

UNILAC accelerator at GSI, Germany

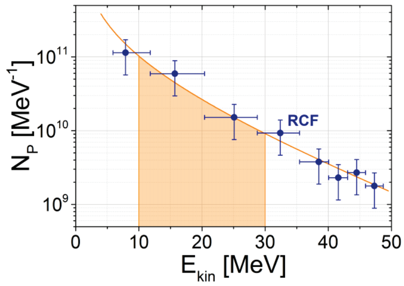


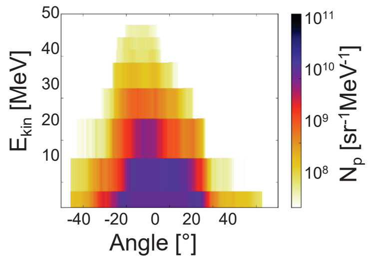

Laser-driven ion accelerator

# Laser-driven acceleration of ions – Target normal sheath acceleration

## A more detailed view

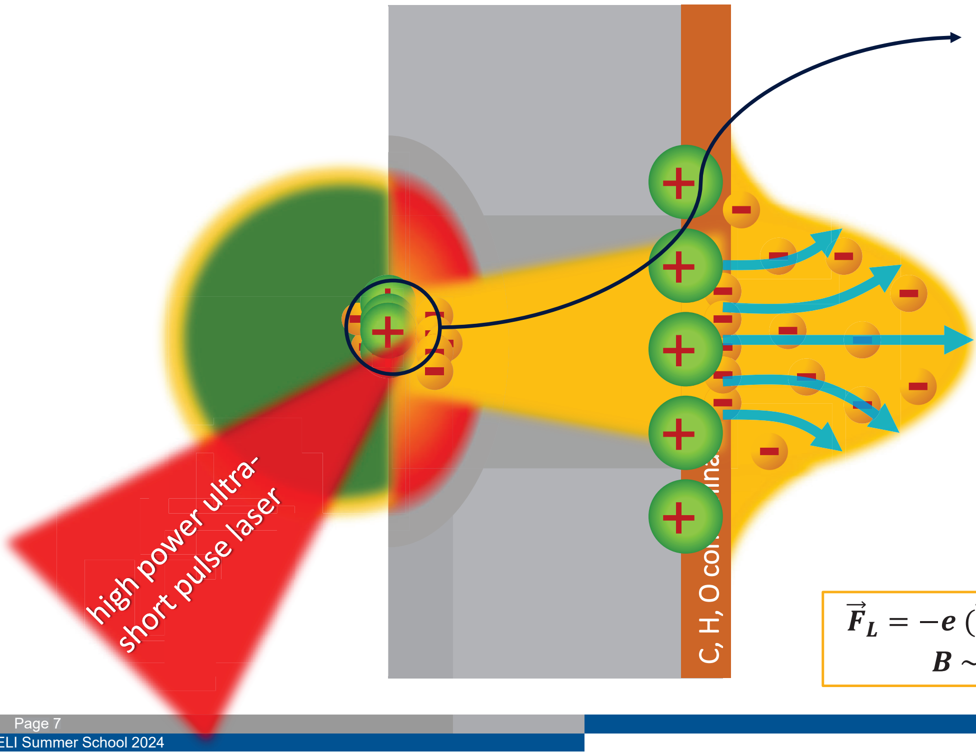


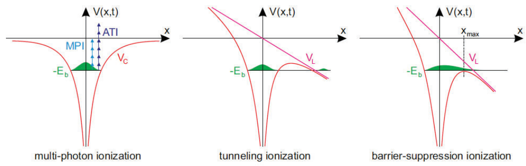



# Laser-driven acceleration of ions – Target normal sheath acceleration

## Laser intensity requirements



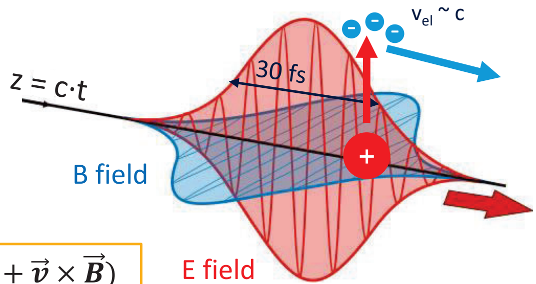

- **Plasma generation → ionization**




I = $10^{10}$ W/cm²  …  $10^{16}$ W/cm²

- **Electron acceleration**

I > $10^{18}$ W/cm² → relativistic intensities




$$\vec{F}_L = -e\,(\vec{E} + \vec{v} \times \vec{B})$$
$$B \sim {}^{E}/_{c}$$



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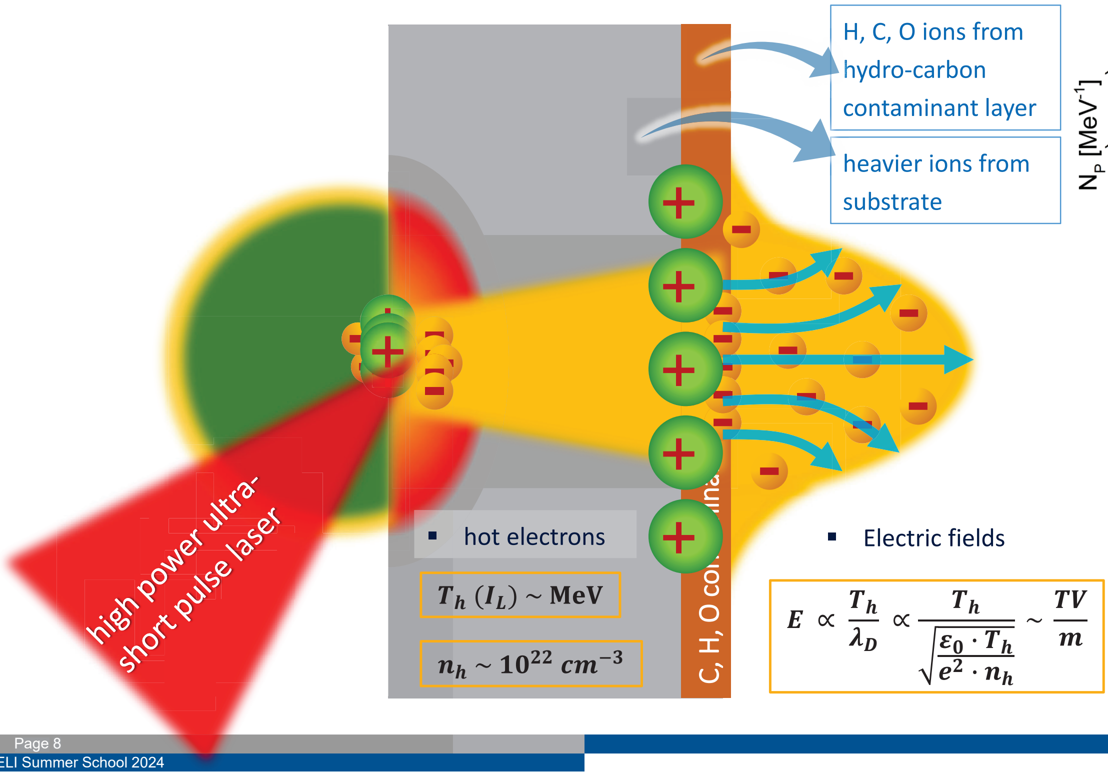
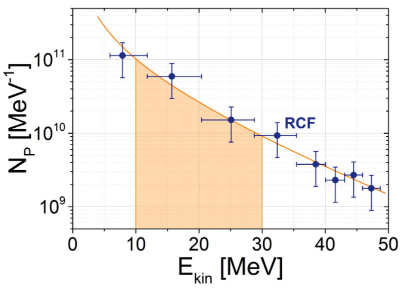
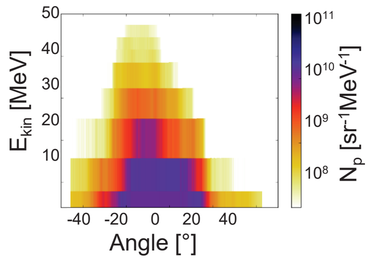
# Laser-driven acceleration of ions – Target normal sheath acceleration

## A more detailed view

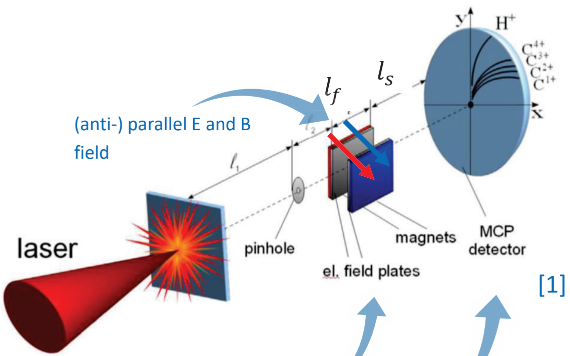


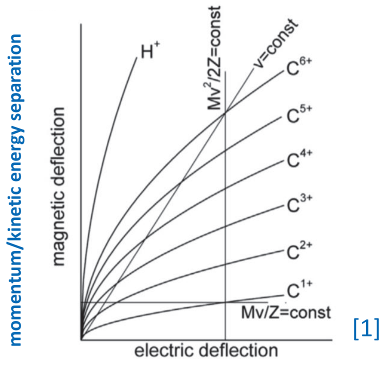



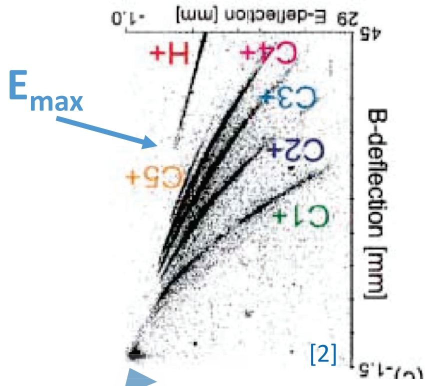



# Ion detection methods

## Thomson parabola spectrometer




$$x = \frac{q \cdot E}{m \cdot v^2} \cdot \left(\frac{1}{2} l_f^2 + l_f \cdot l_s\right)$$

$$y = \frac{q \cdot B}{m \cdot v} \cdot \left(\frac{1}{2} l_f^2 + l_f \cdot l_s\right)$$

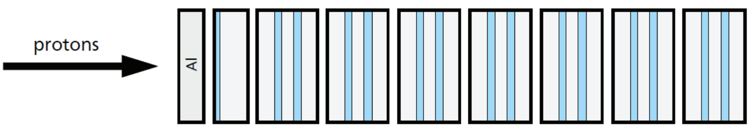
[for $l_f$ << radius of curvature]

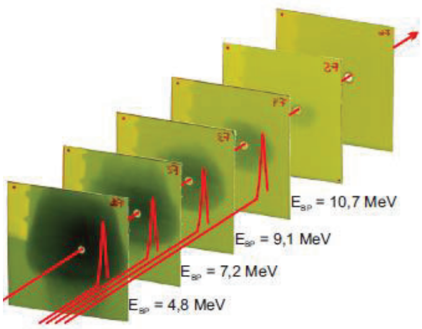

[1] P. R. Bolton et al. **Instrumentation for diagnostics and control of laser-accelerated proton (ion) beams**, Phys. Med. 30, 255 (2014)
[2] M. Hegelich et al. **MeV Ion Jets from Short-Pulse-Laser Interaction with Thin Foils**, PRL 89, 085002 (2002)

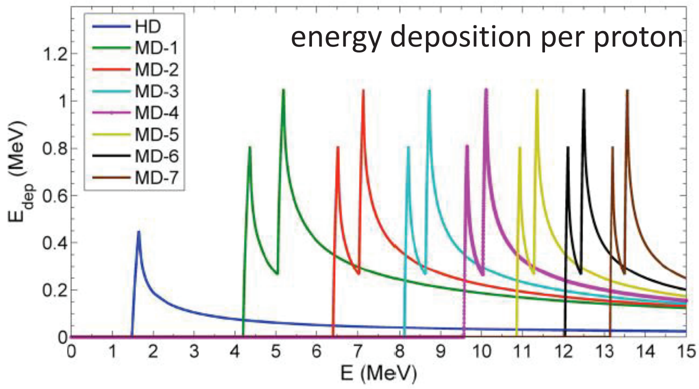
# Ion detection methods

## Radiochromic film stack - spectroscopy

- spectral resolution through energy dependent dose depth profile of ions
- calculation of energy loss
- deconvolution of depth dose profile



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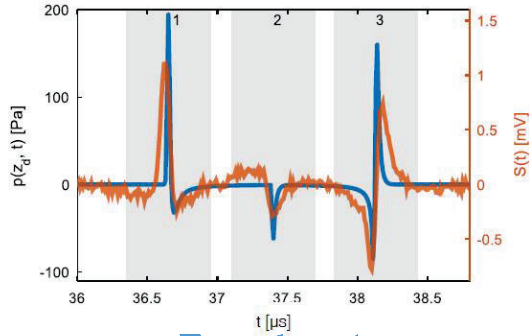
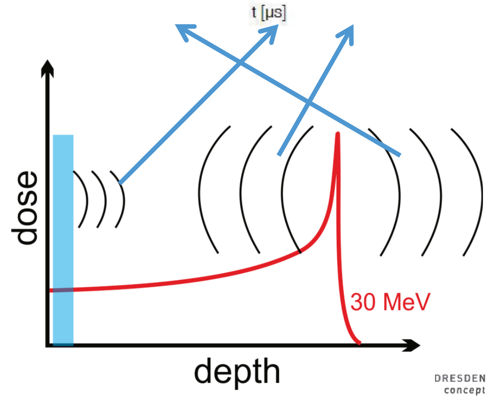
# Ion detection methods

## I-beat: ultrasonic single bunch measurement

D. Haffa et al., Scientific Reports, (2019), 6714, 9(1)

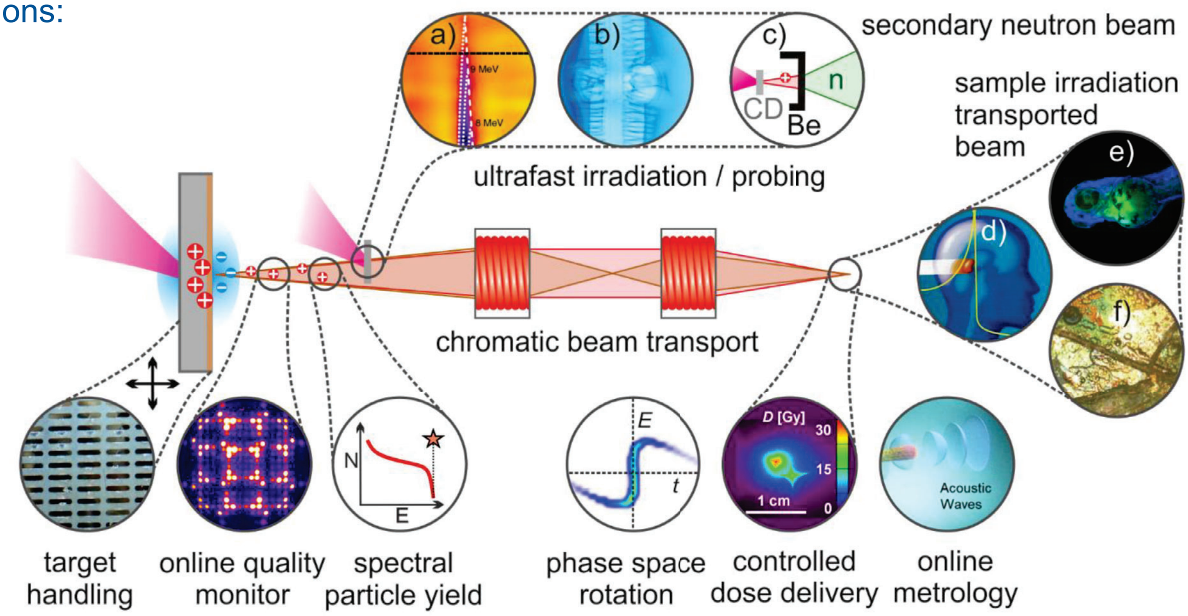

**Ion-Bunch Energy Acoustic Tracing (I-BEAT)**




- ion bunch instantaneously deposit its energy
- acoustic waves (pressure) are generated
- measured by the transducer
- reconstruction necessary

# Laser-driven proton acceleration – Identifying the most impactful field of research

Applications:

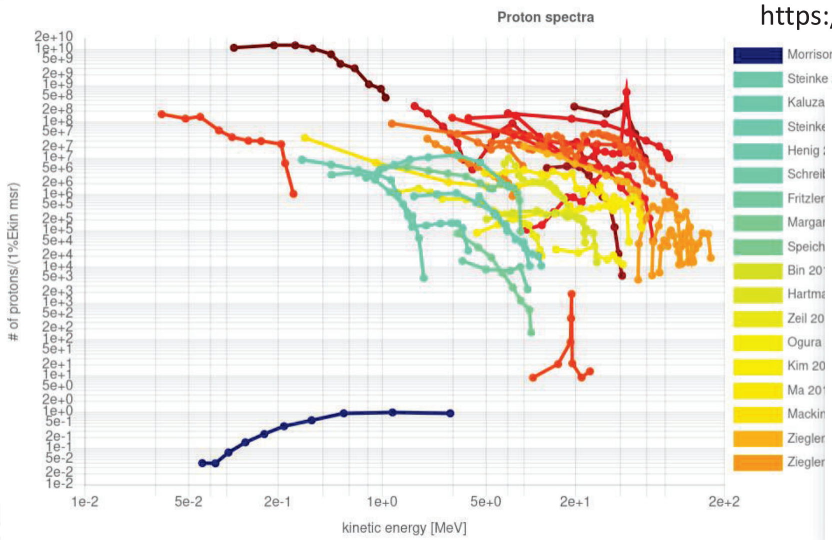


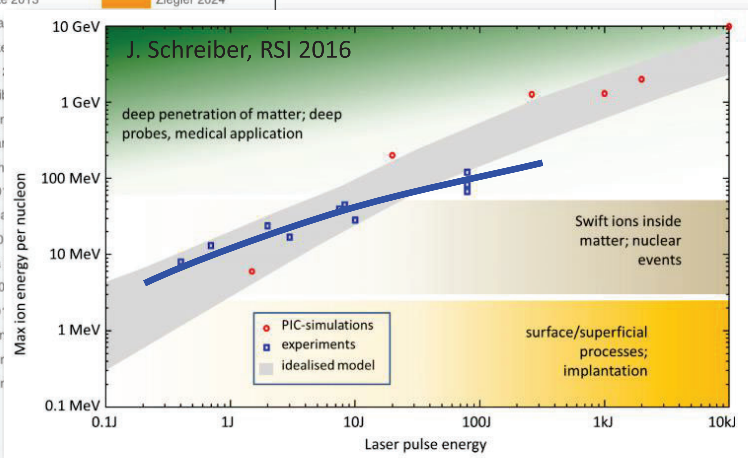

**reliable high energy (> 100 MeV) proton beams with sufficient repetition rate and tunable spectral intensity**

2020 Roadmap on Plasma Accelerators, NJP 2021

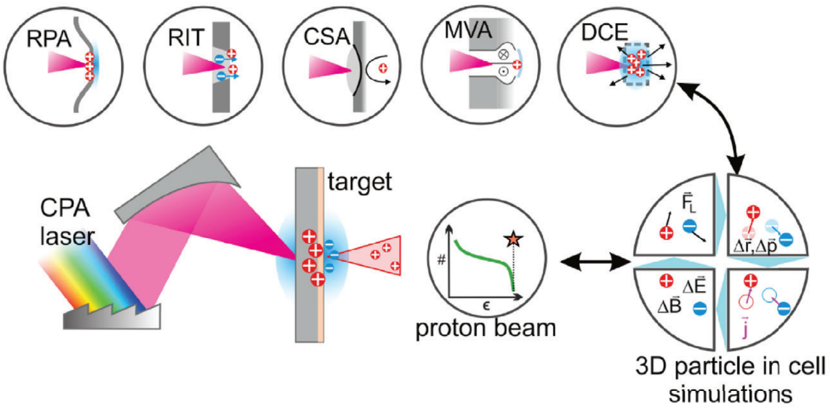
# The road to high proton energies


Prof. Jörg Schreiber:
https://www.alpa.physik.uni-muenchen.de/protons.html



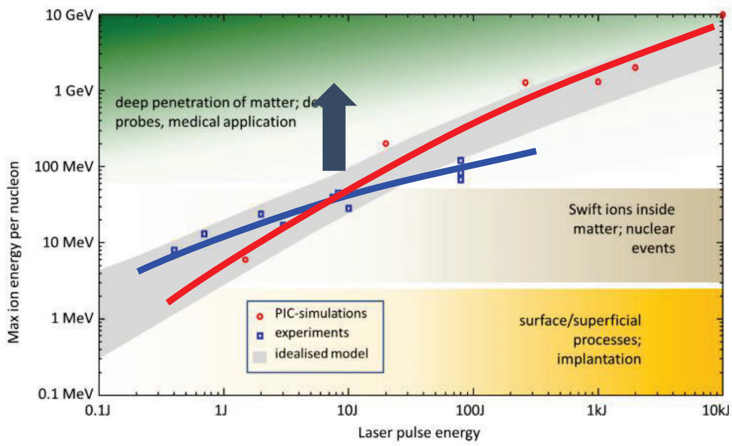



# Laser-driven proton acceleration – Advanced acceleration schemes




**Energy scaling – two challenges:**

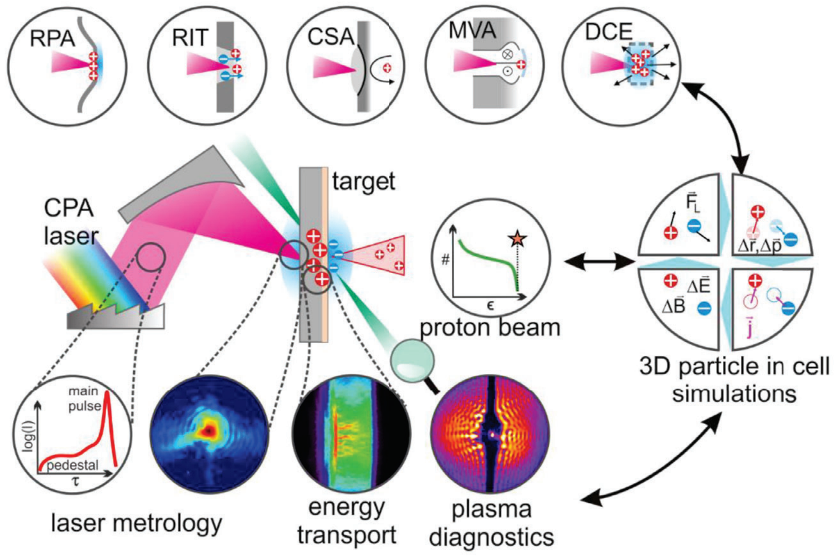
1. Technological limits for larger laser systems:
   - increase of efficiency: from back-illuminated photo anode to bulk acceleration in quasi co-moving schemes
   - Indirect, highly non-linear processes (instabilities) → high sensitivity on input parameters




2. Limited predictability of simulations: need of realistic input & all physics to be covered

2020 Roadmap on Plasma Accelerators, NJP 2021

# Laser-driven proton acceleration – Advanced acceleration schemes




**Energy scaling – two challenges:**

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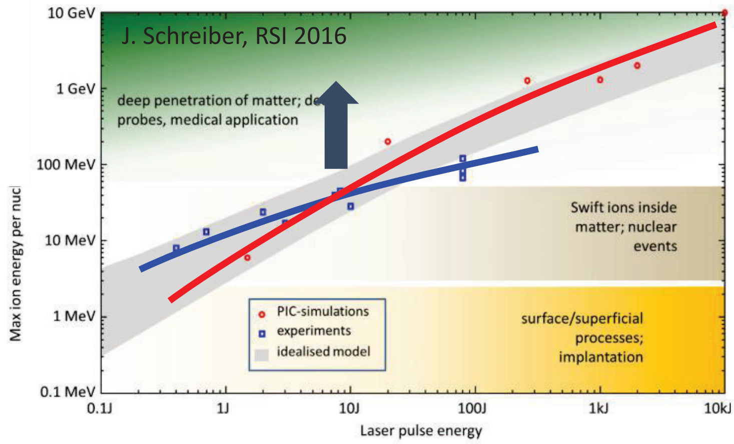
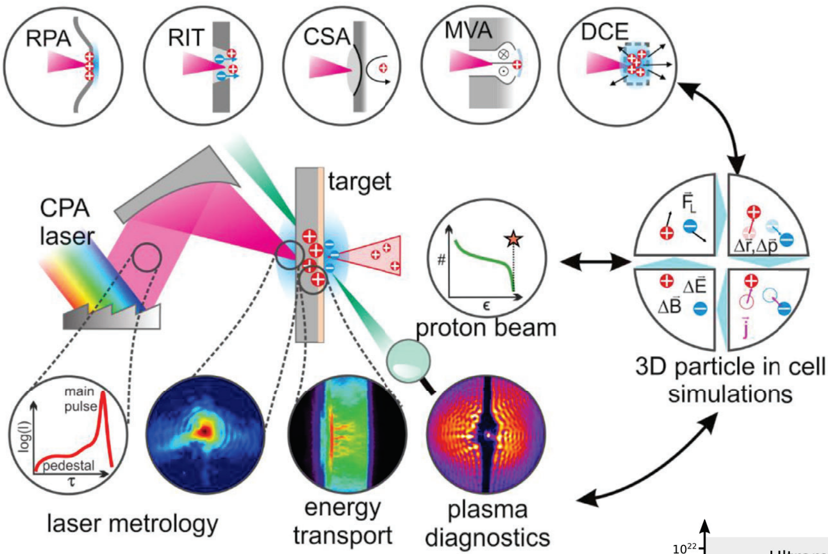



2020 Roadmap on Plasma Accelerators, NJP 2021

# Laser-driven proton acceleration – Advanced acceleration schemes

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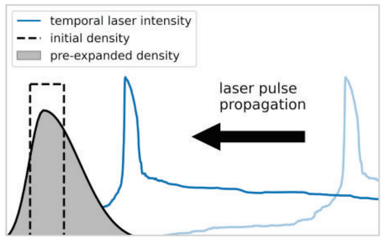
It is all about the temporal laser pulse contrast …

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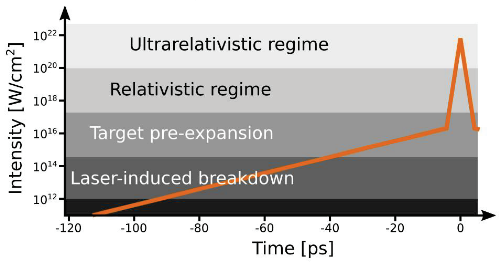


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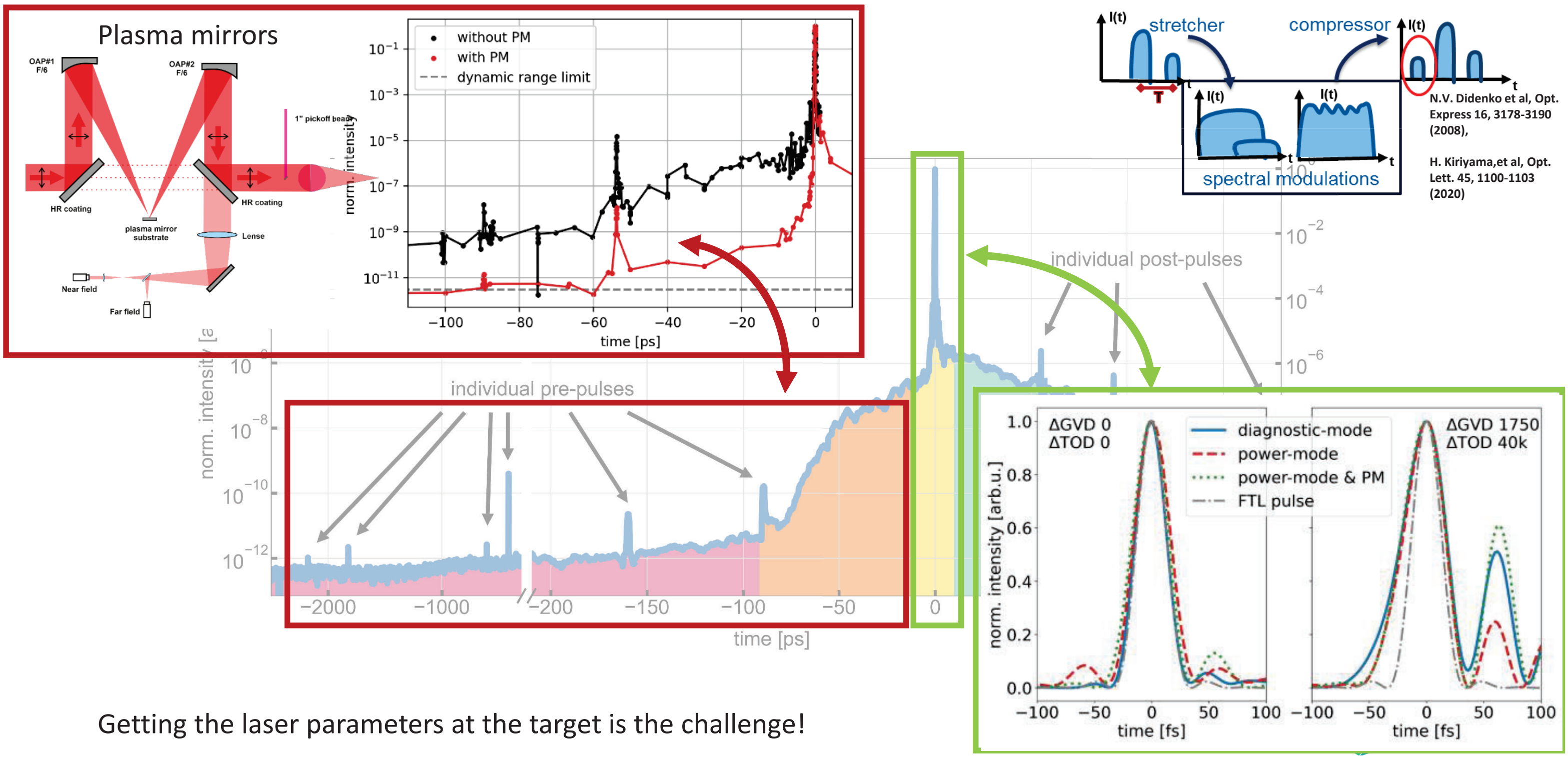
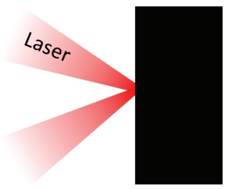
# Temporal laser contrast – the most important control parameter




Getting the laser parameters at the target is the challenge!

# Target Density dynamics and energy absorption




Dense, opaque target

Mirror-like behavior, pulse mostly reflected

$\omega_p > \omega_L$

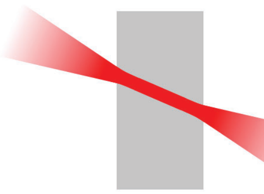
$n_e > \gamma n_c$

Near critical density target

Pulse mostly absorbed

$\omega_p \sim \omega_L$

$n_e \sim \gamma n_c$



Transparent target

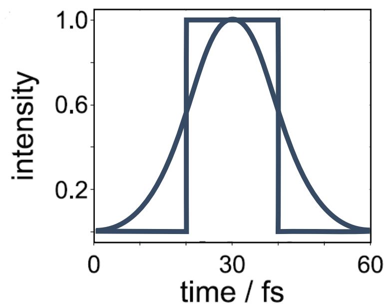
Pulse mostly transmitted

$\omega_p < \omega_L$

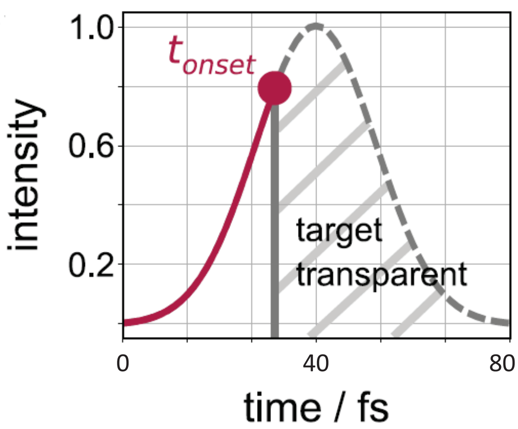
$n_e < \gamma n_c$

Plasma frequency $\omega_p(t) = \sqrt{\frac{n_e(t)e^2}{\gamma(t)\, m_e \varepsilon_0}}$

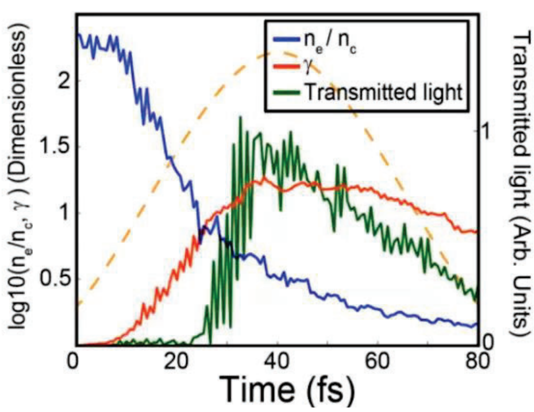
Relativistic laser pulses → $\gamma(t) = \sqrt{1 + \frac{a_0(t)^2}{2}}$



# Relativistically Induced Transparency




EPOCH simulation of RIT

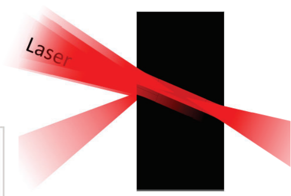


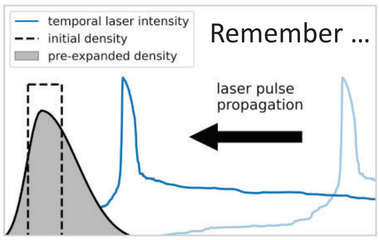

$$\gamma(t) = \sqrt{1 + \frac{a_0(t)^2}{2}}$$

Transparent target / Most energy absorbed at:

$\omega_p \lessapprox \omega_L$

$m_e \rightarrow \gamma m_e \rightarrow \frac{m_e}{m_c} \lessapprox \gamma$




Obst-Hübl; PhD thesis (2019) | McKenna, Gonzales-Izquierdo *et al.*; SPIE (2021) & ApplSci (2018)



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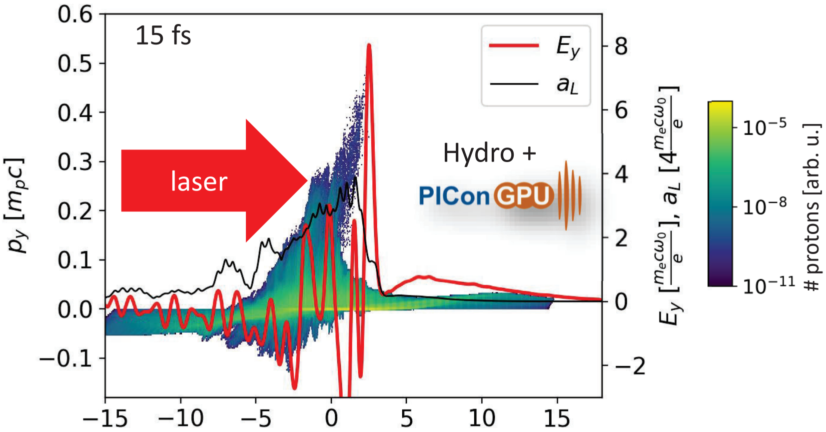
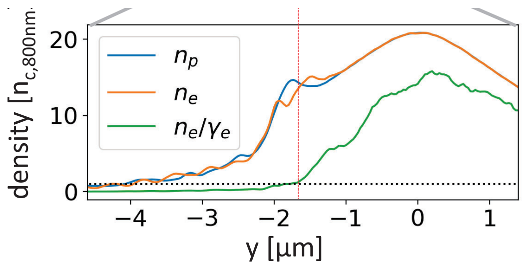
# Proton acceleration at the relativistic transparency front

## Phase space evolution of a pre-expanded hydrogen target



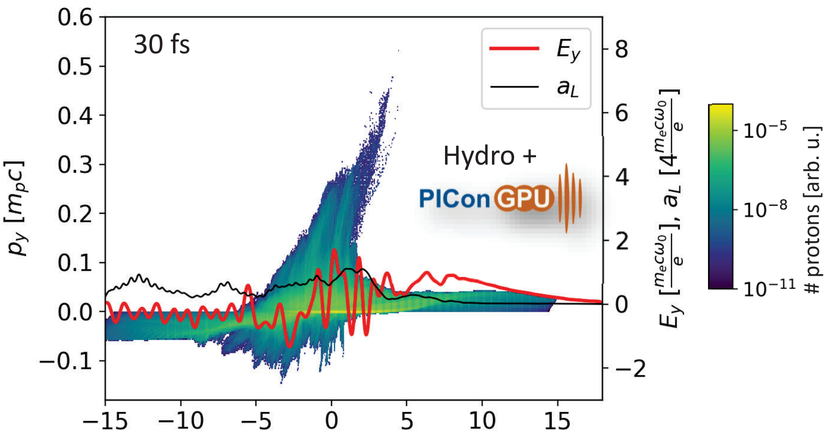



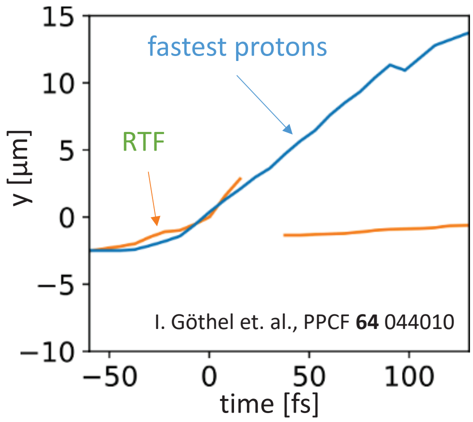

- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk

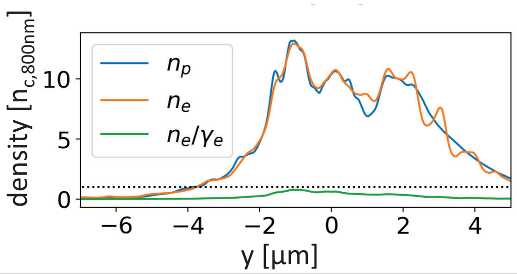
M. Rehwald et. al., *Nature Communications 2023*

# Proton acceleration at the relativistic transparency front

## Phase space evolution of a pre-expanded hydrogen target



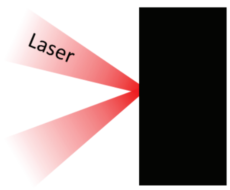



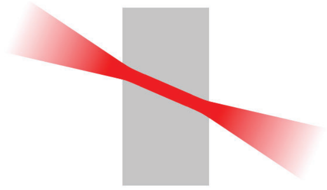



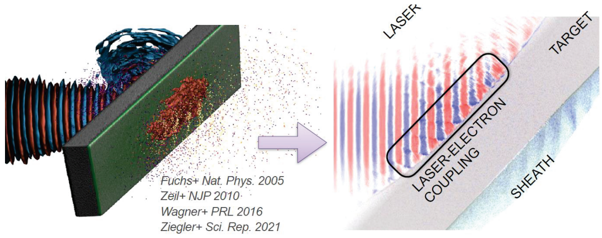

- Reflection of the laser pulse at the relativistic transparency front (RTF)
- Protons moving with the RTF are accelerated within the target bulk
  → **quasi co-moving accelerating field structure**

M. Rehwald et. al., *Nature Communications 2023*

# Summarizing acceleration schemes …

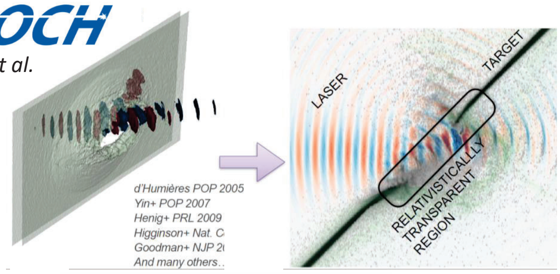


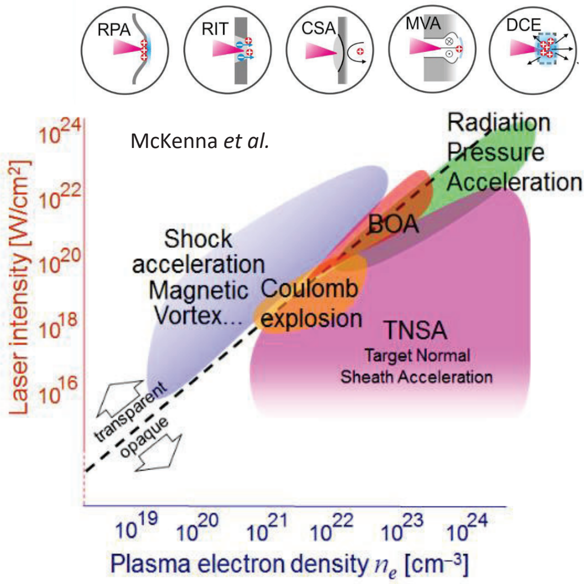



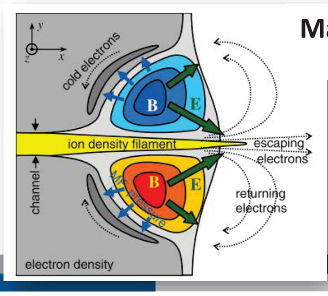



EPOCH

Dover *et al.*




**Magneto vortex acceleration**

*Bulanov & Esirkepov PRL (2007)*

**Induction of overlap/cascades of mechanisms becomes obvious ….**

## Outline

1. **An introduction to laser-driven ion acceleration**
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2. **A current research project:** Characterizing Laser Transmission in the Relativistically Induced Transparency Regime for PW Laser-Driven Proton Acceleration

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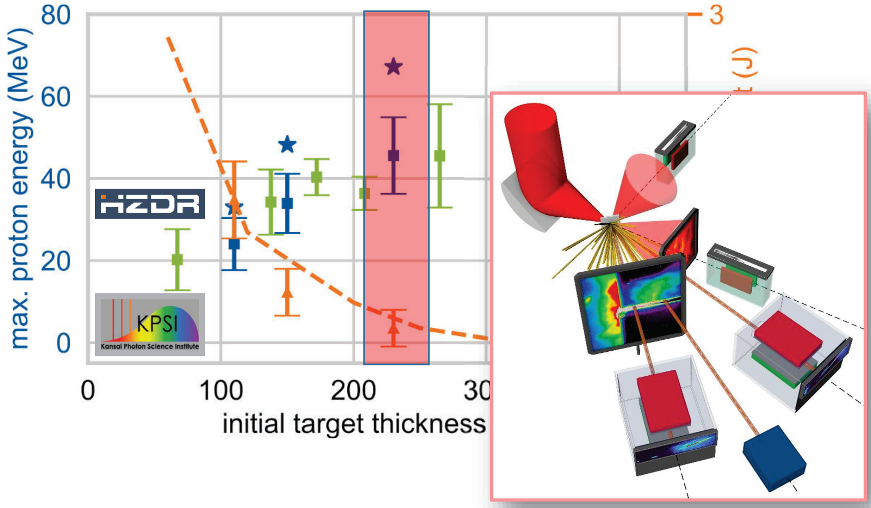
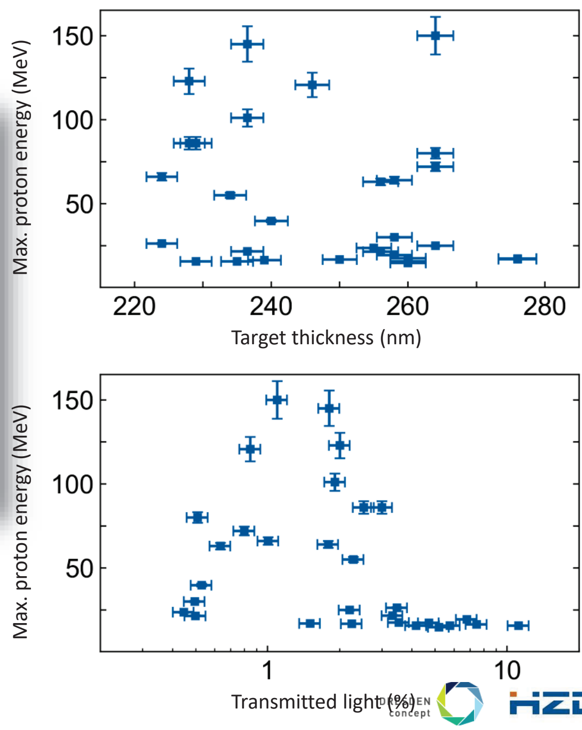
# Optimal target thickness and onset of transparency



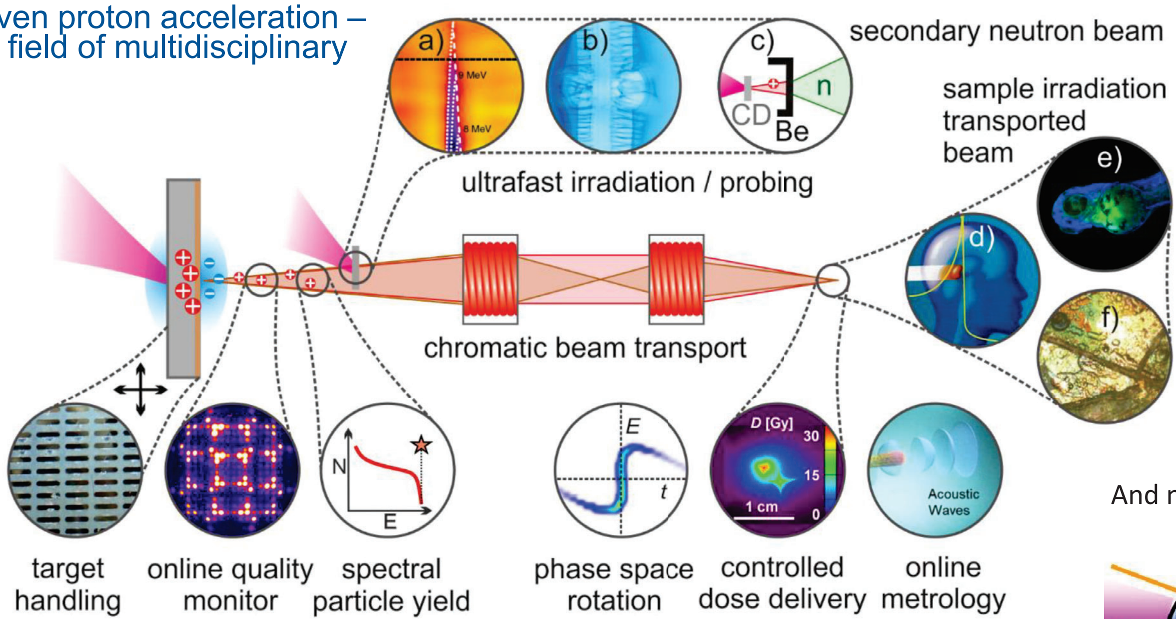




d'Humieres, E. *et al.*; Phys. Plasmas (2005)
Yin, L. *et al.*; Phys. Plasmas (2011)
Higginson, A *et al.*; Nat. Commun. (2018)
Gonzales-Izquierdo, B. *et al.*; Appl. Sci. (2018)

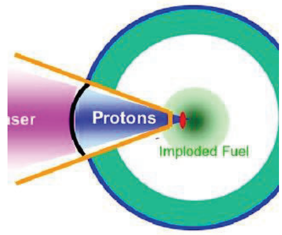
Dover, N.P., Ziegler, T. *et al.*; Light Sci. Appl. (2023)
Ziegler, T. *et al.*; Nat. Phys. (2024)

## Summary & outlook

Laser-driven proton acceleration – attractive field of multidisciplinary research




And now fusion …?




**reliable proton beams with sufficient repetition rate, tunable spectral intensity and high conversion efficiency**

2020 Roadmap on Plasma Accelerators, NJP 2021


Thank you for your attention!