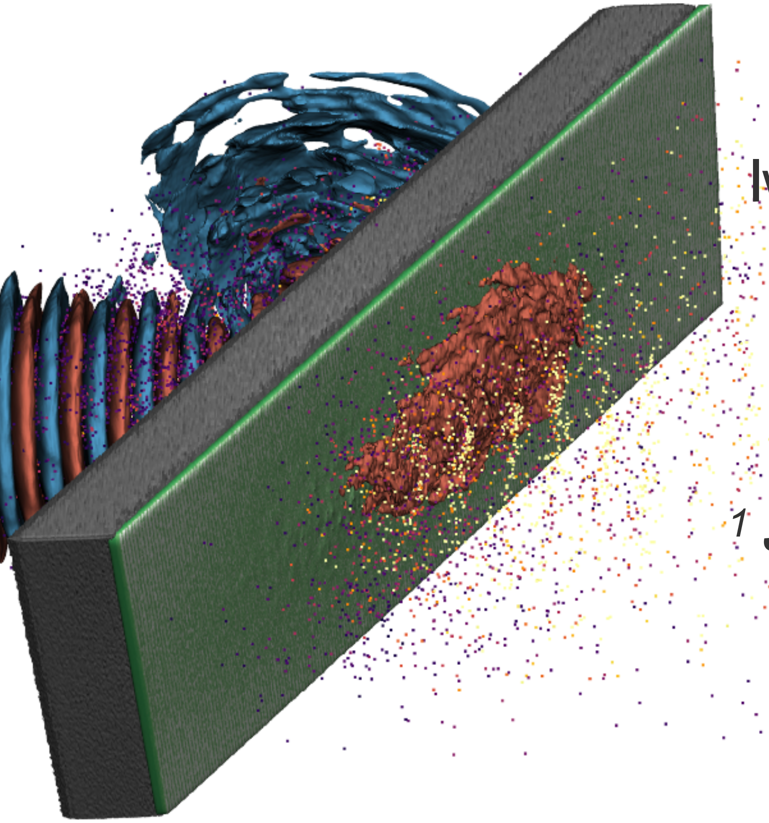
Energetic ion generation at the ultra-high laser intensity frontier

JAI-fest

11 December 2020, Remote e-conference



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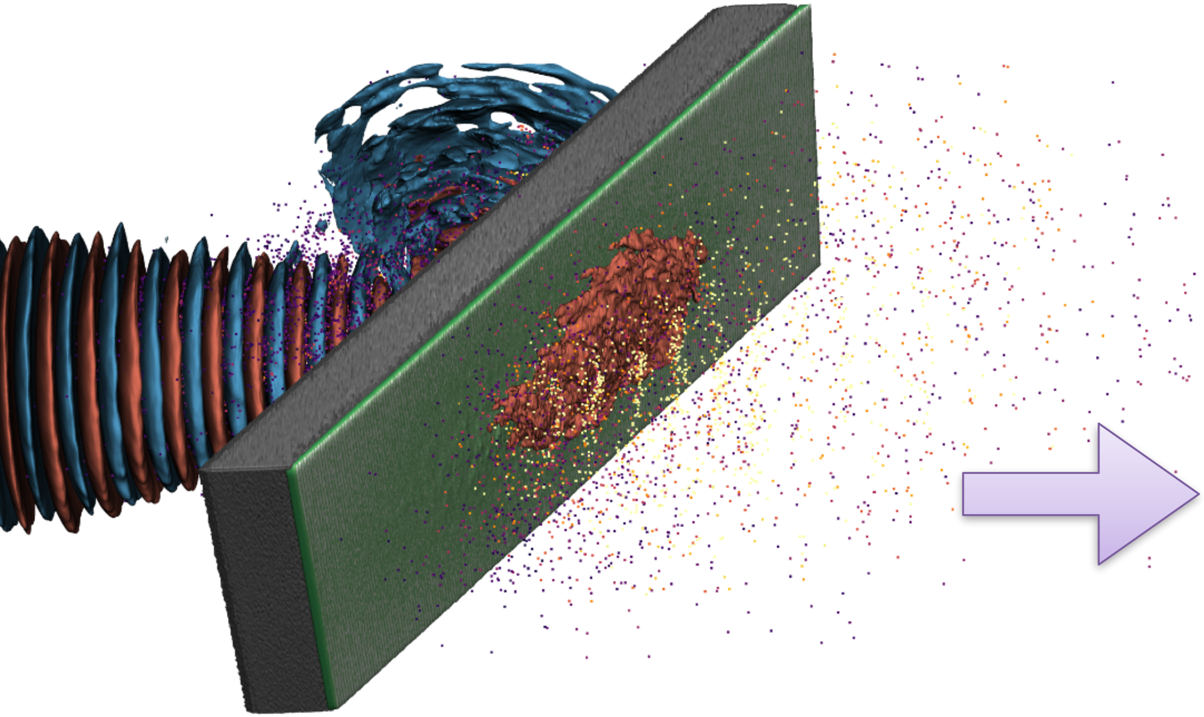
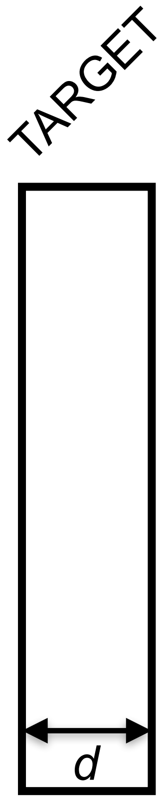
Optimising sheath acceleration from intense-laser solid interactions





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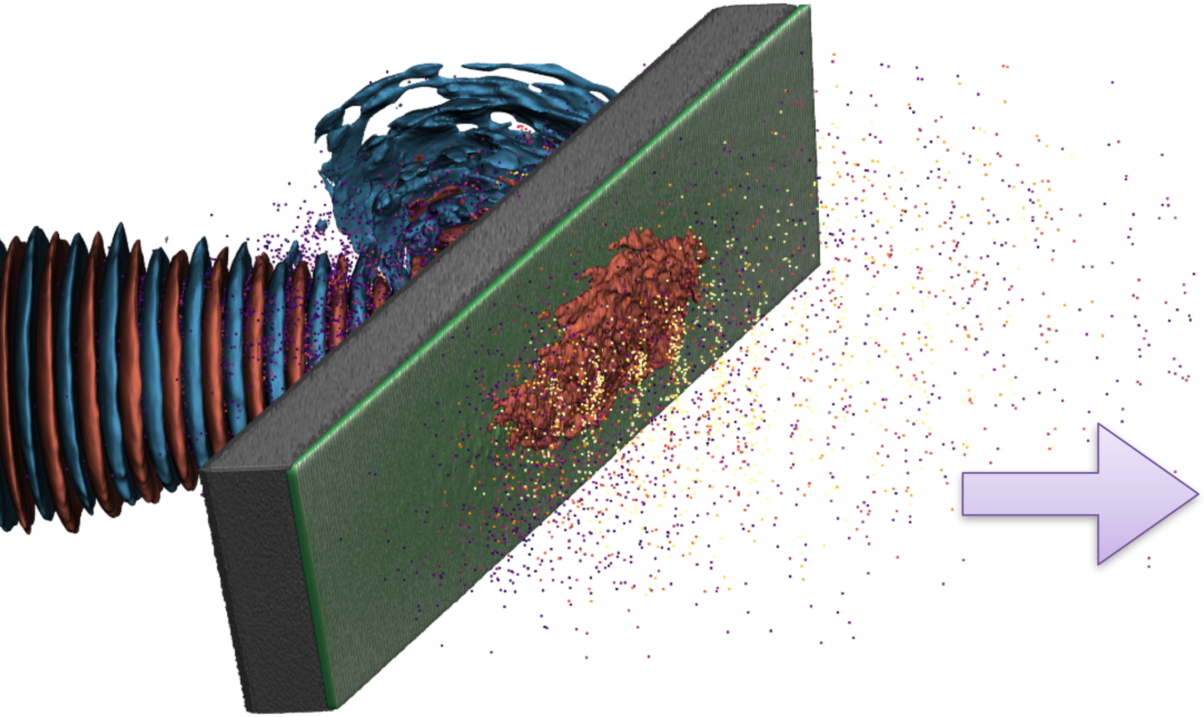

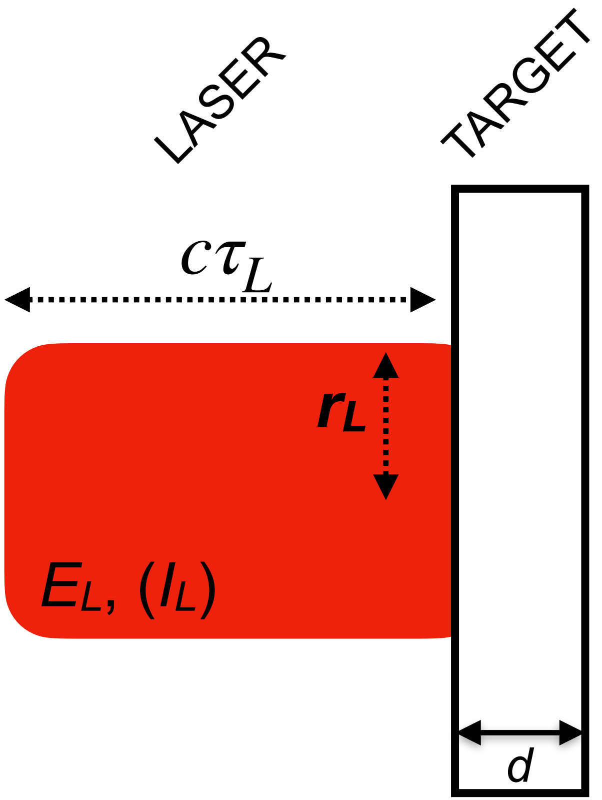

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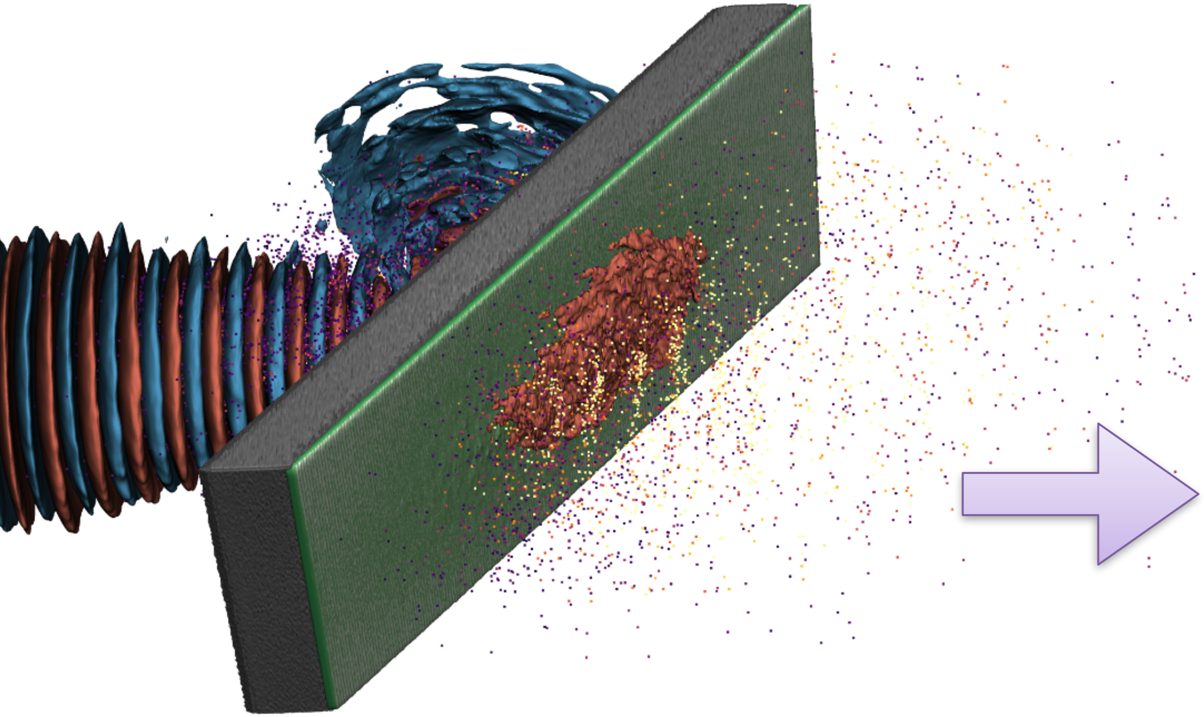
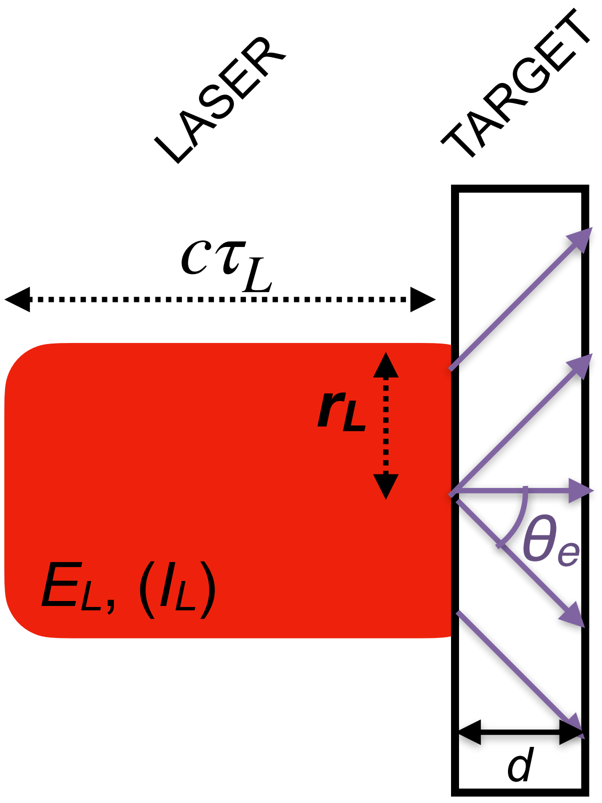
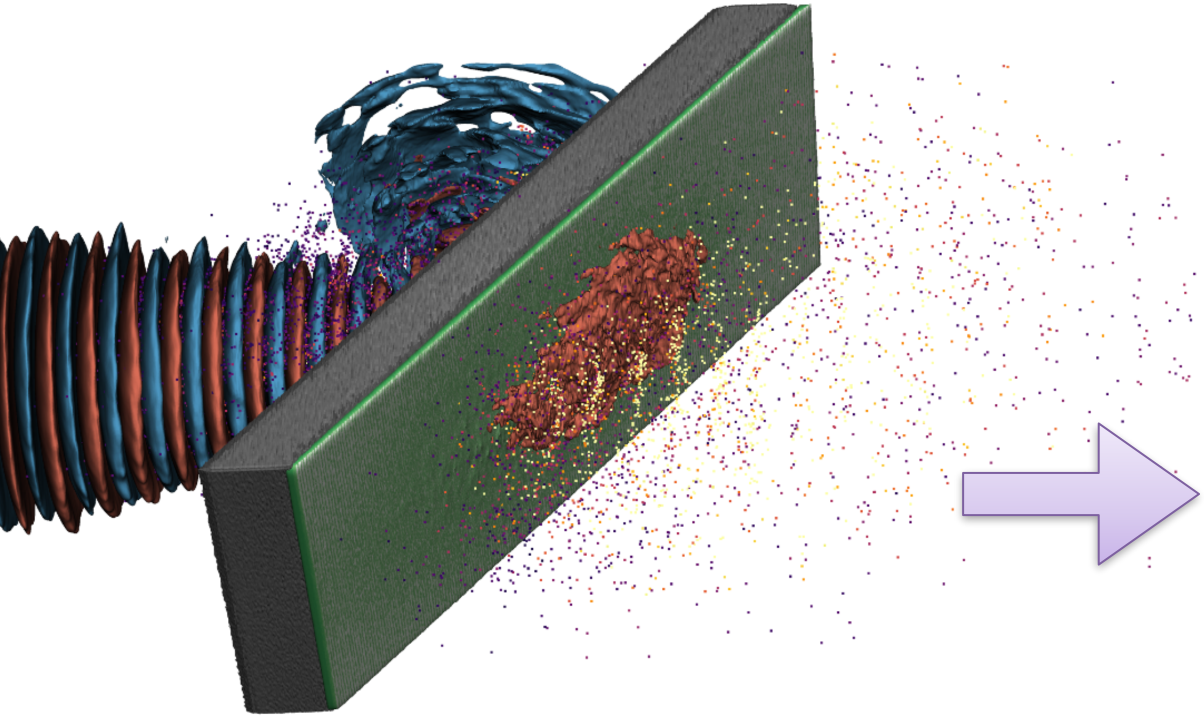
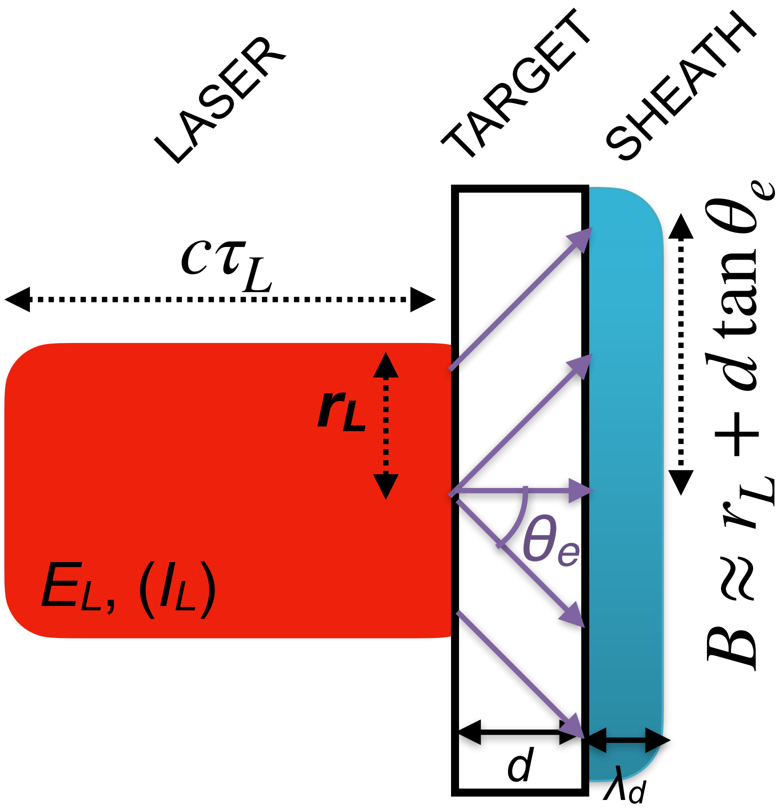




Electrons: N_e, T_e, θ_e

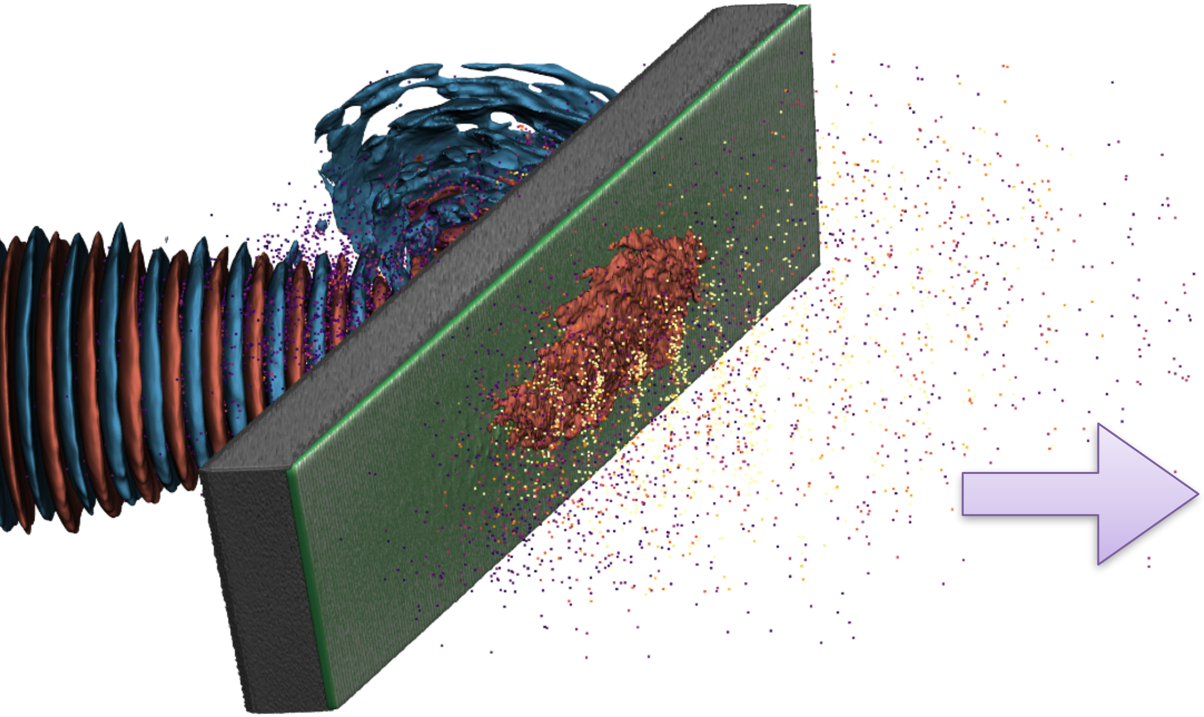
Optimising sheath acceleration from intense-laser solid interactions

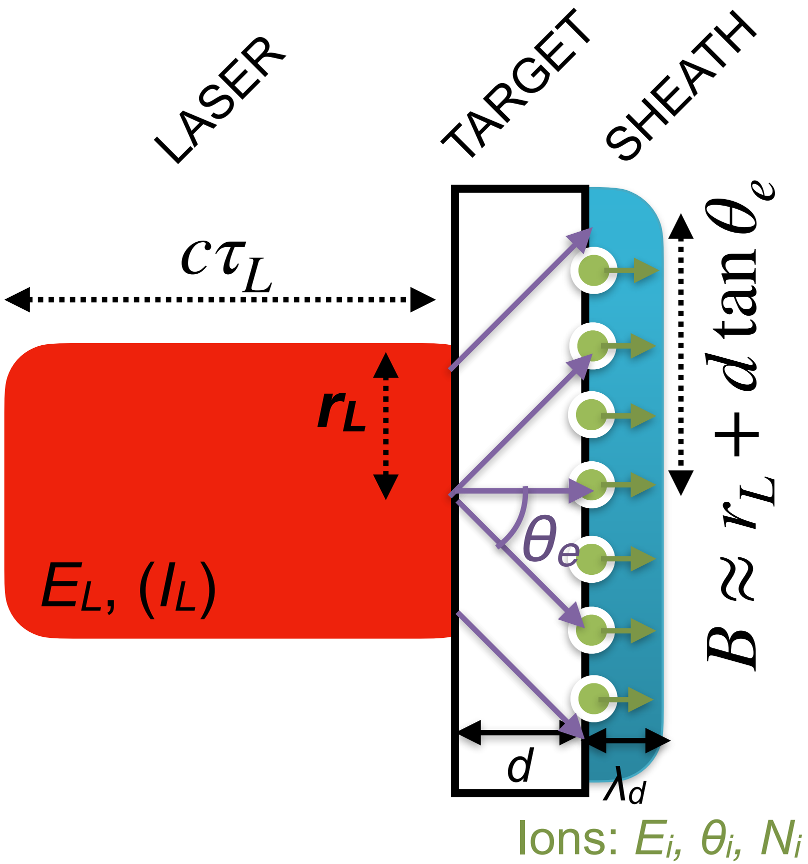




Sheath: n_e, B, λ_{D}, τ_S

Optimising sheath acceleration from intense-laser solid interactions





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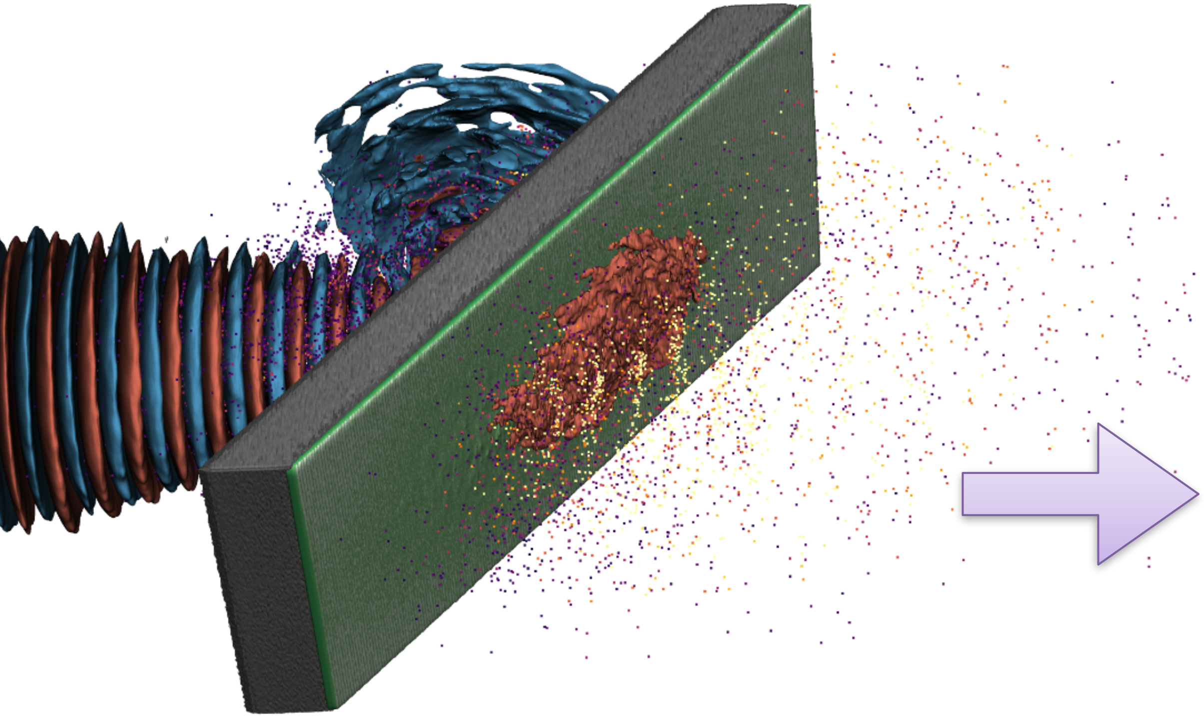
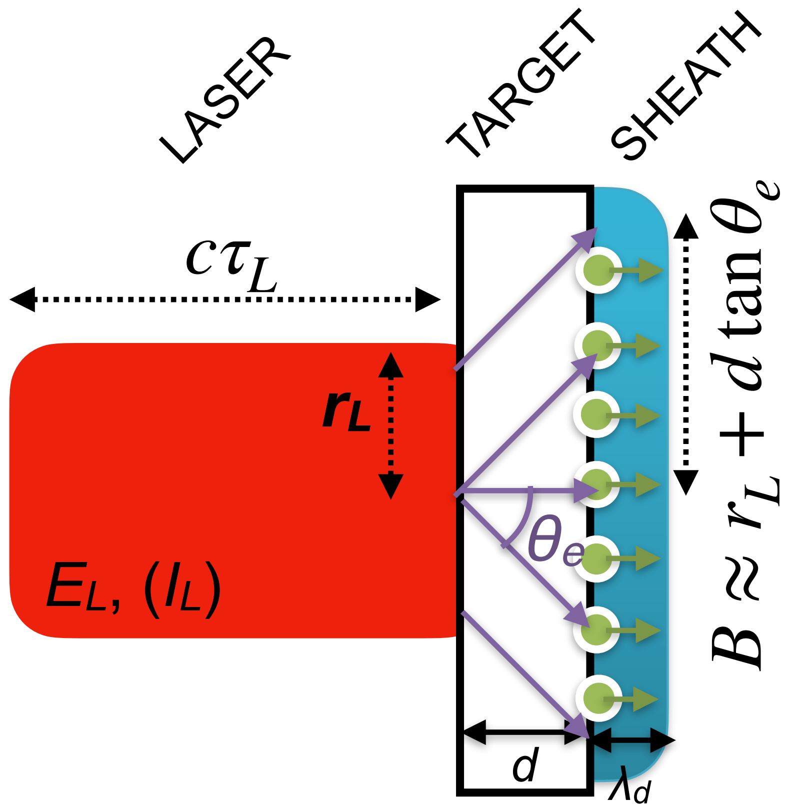
Optimising sheath acceleration from intense-laser solid interactions

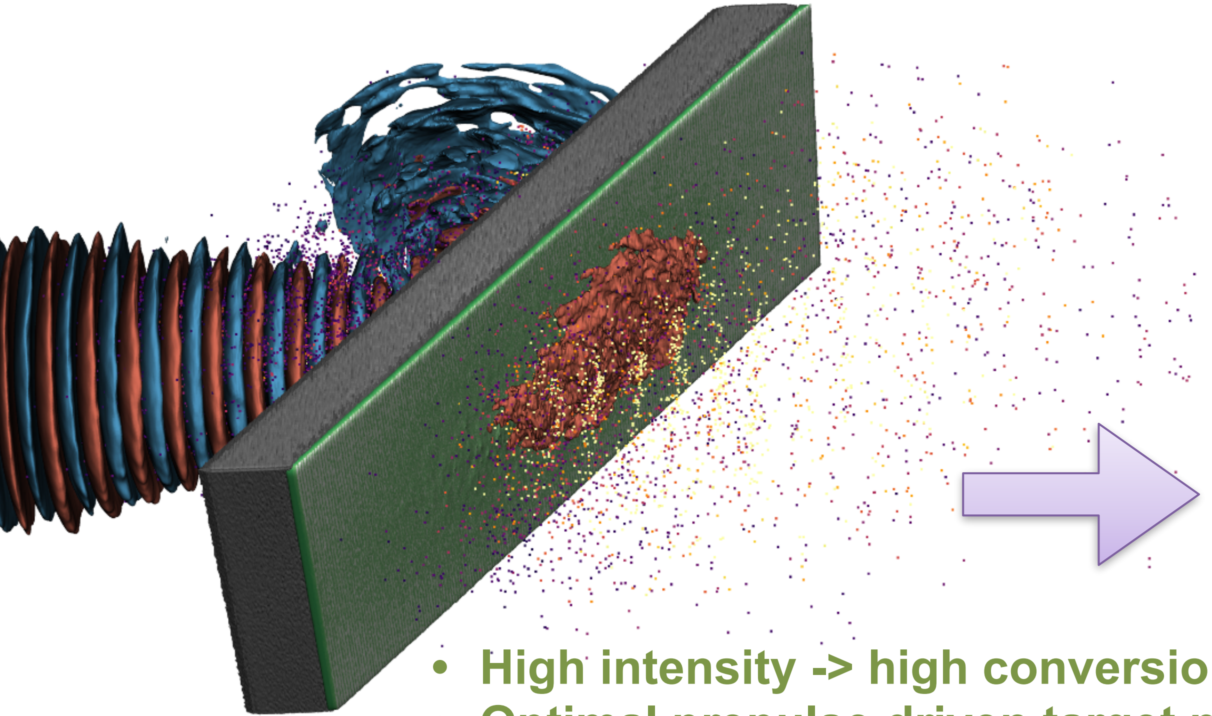


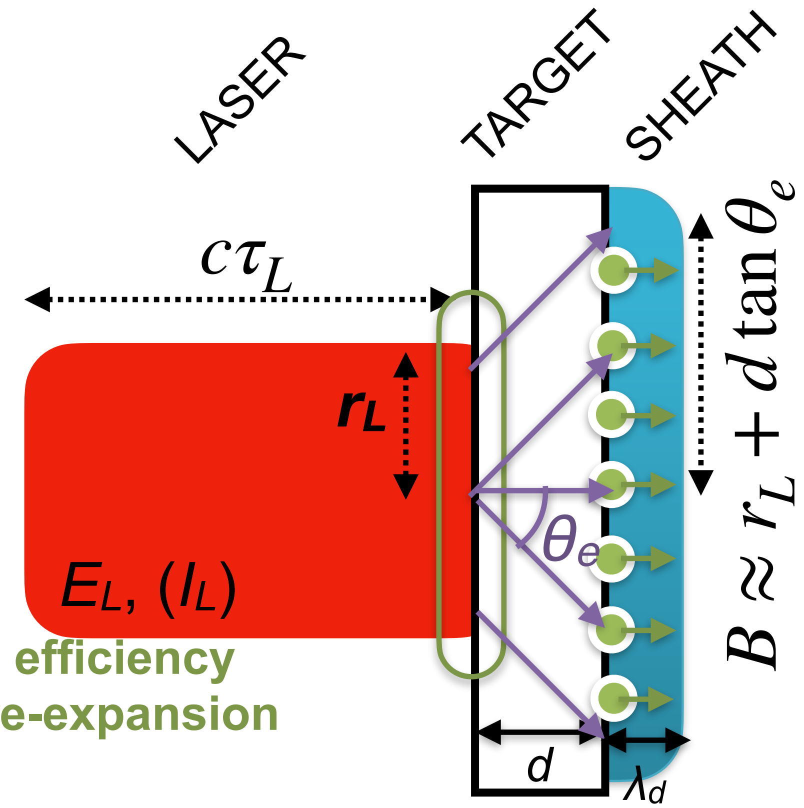


To optimise acceleration:

1) High conversion efficiency of laser to energetic electrons at front surface
2) Efficient transport of electrons from front surface to rear surface
3) Tight & long confinement of electrons in sheath at rear surface

Optimising sheath acceleration from intense-laser solid interactions





- **High intensity -> high conversion efficiency**
- **Optimal prepulse driven target pre-expansion**

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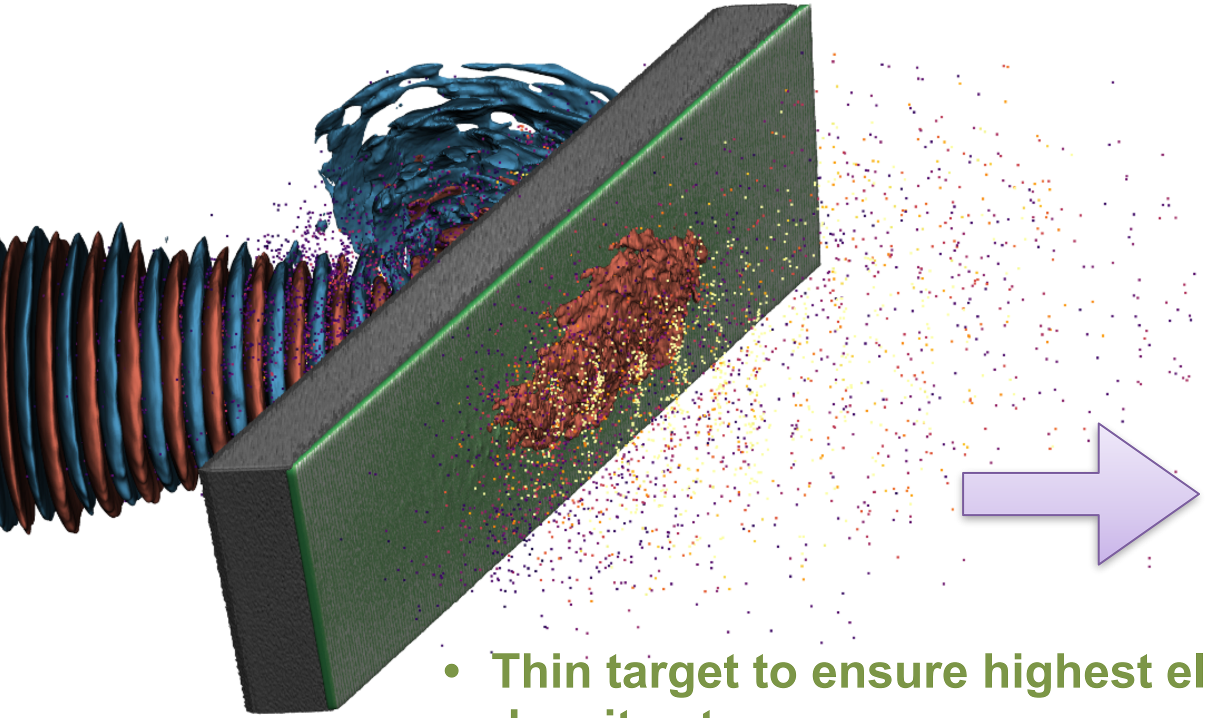

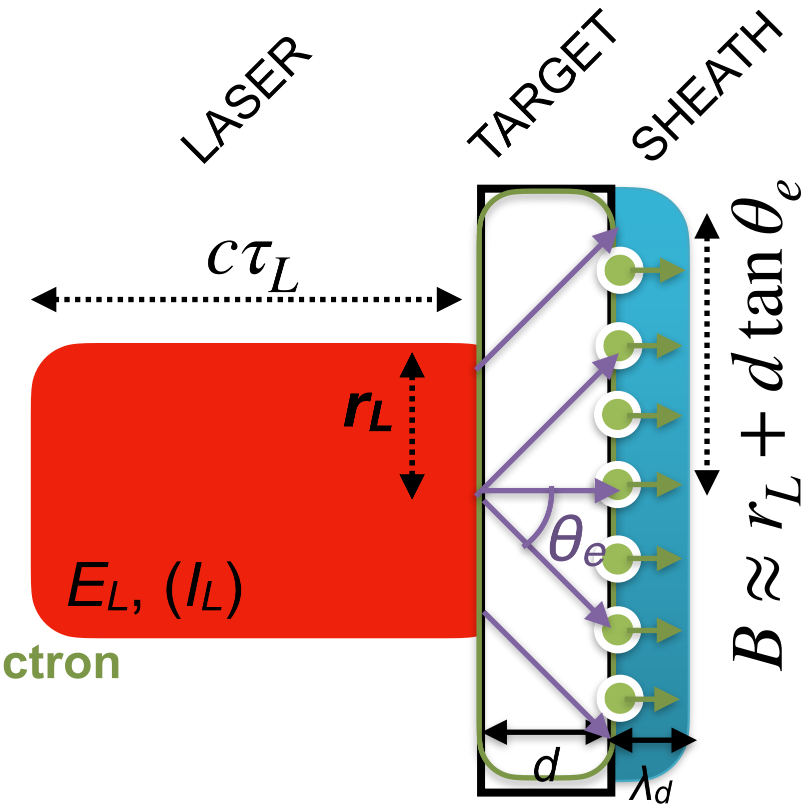

- **Thin target to ensure highest electron density at rear**

To optimise acceleration:

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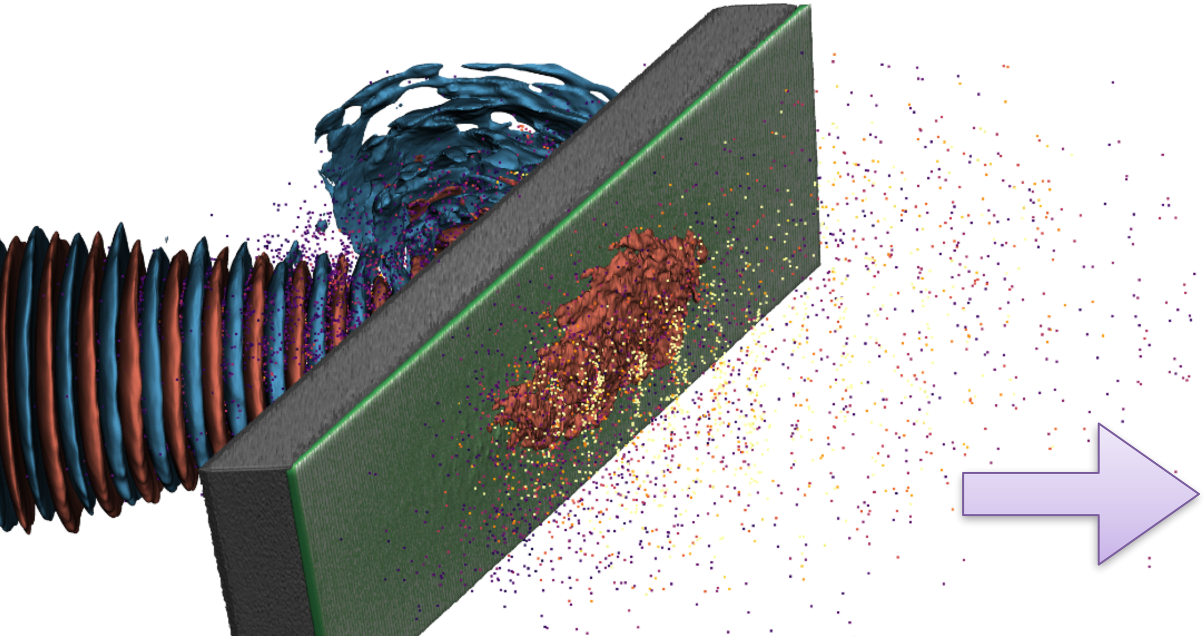

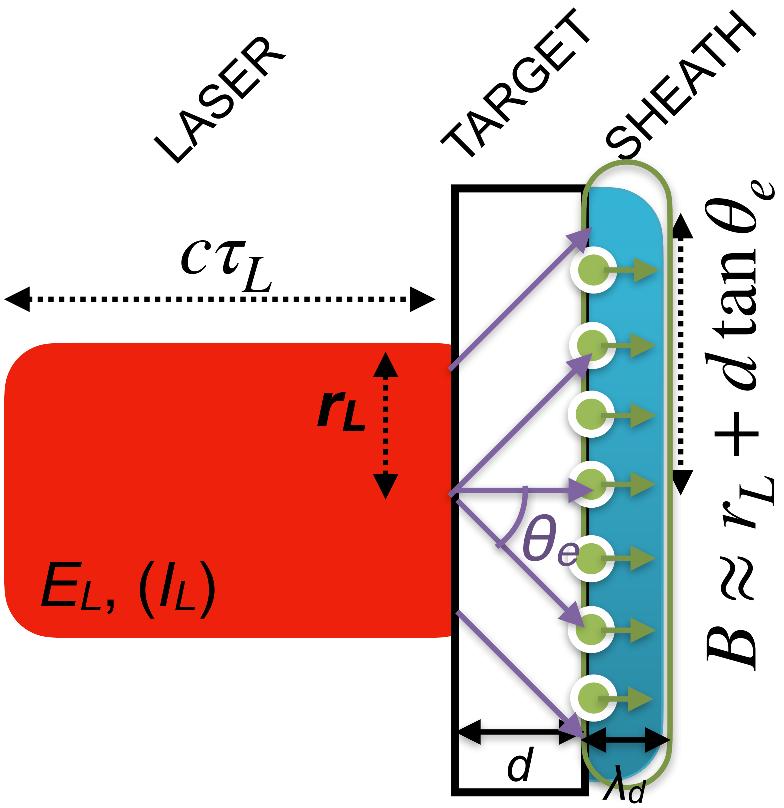

- **Suppress pre-expansion of rear surface - high contrast!**

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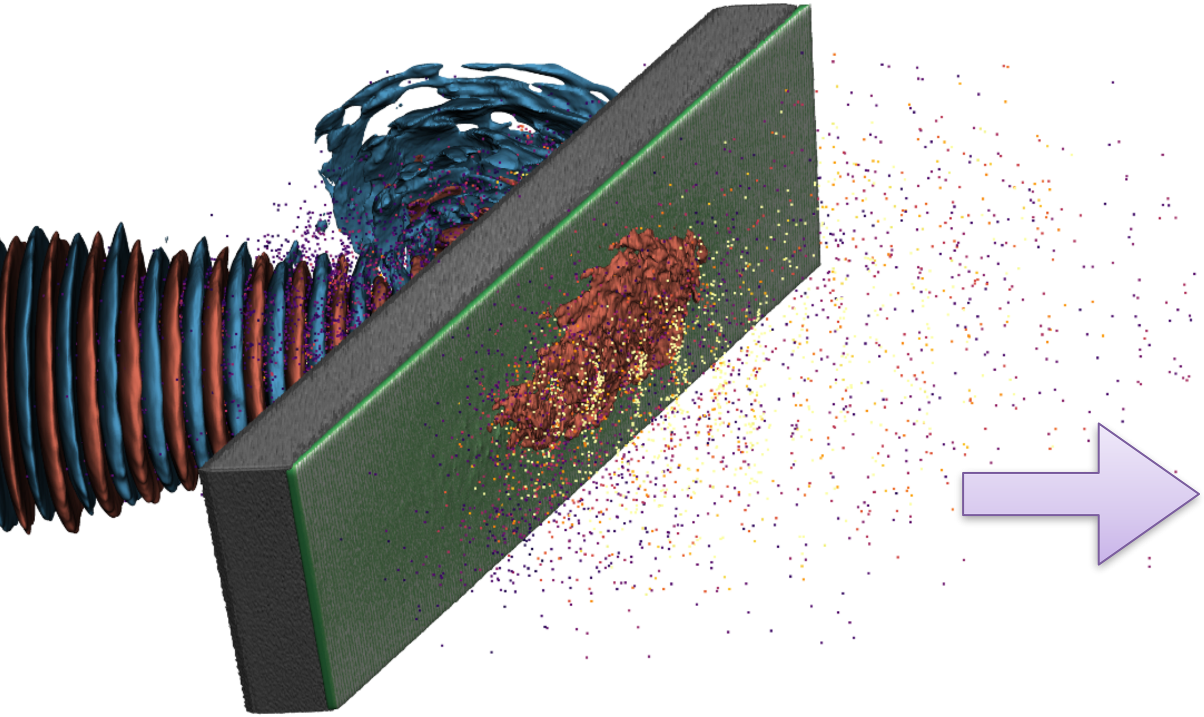

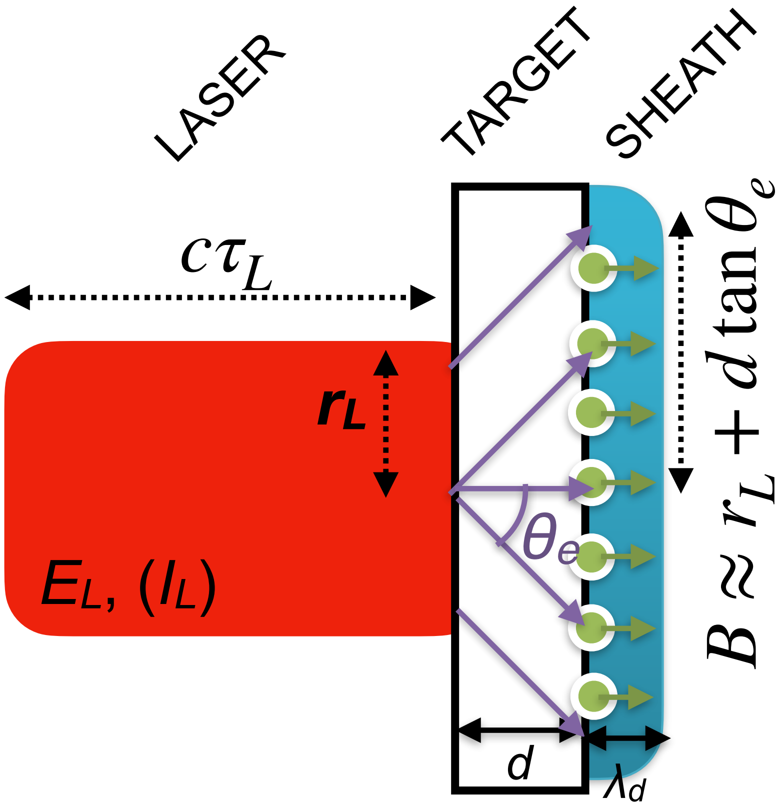

Electron heating & dynamics key to understanding sheath acceleration

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High intensity laser driven ion sources

- High intensity laser driven ion sources have unique features:
  - **Extremely high peak current** (ultra-short generation time)
  - **High energy from source** (maximum recorded is ~100 MeV)
- They also have some challenges:
  - **Highly divergent**
  - **Typically broadband energy**
- Many applications require high average flux… this means repetitive operation

Applications in science:

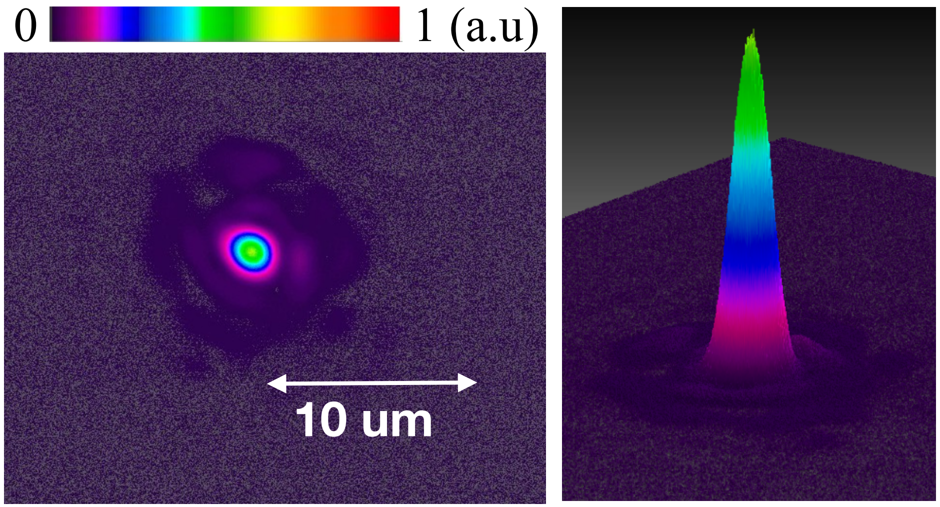
- Radiography of high energy density physics experiments
- Generation of warm dense matter
- Injector for next-generation accelerator

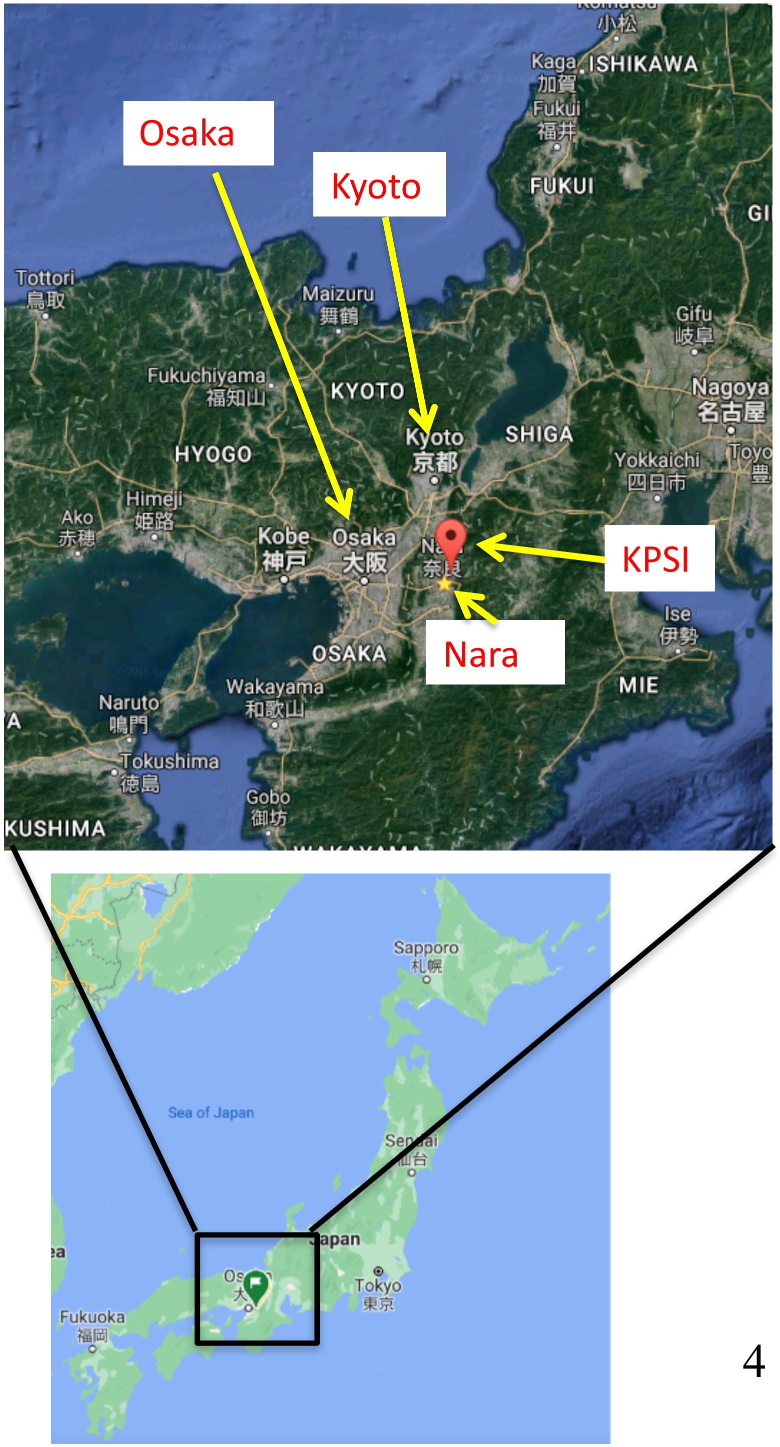
Applications in society:

- Ultrafast material response
- Material processing
- Radiobiology/therapy

High field science with J-KAREN-P

- Hybrid OPCPA/ Ti:Sapphire system
- ~15 J, ~40 fs at 0.1 Hz at target
- Intensity up to ≈ 5×10^{21} W/cm^2 ($a_0 \approx 50$)





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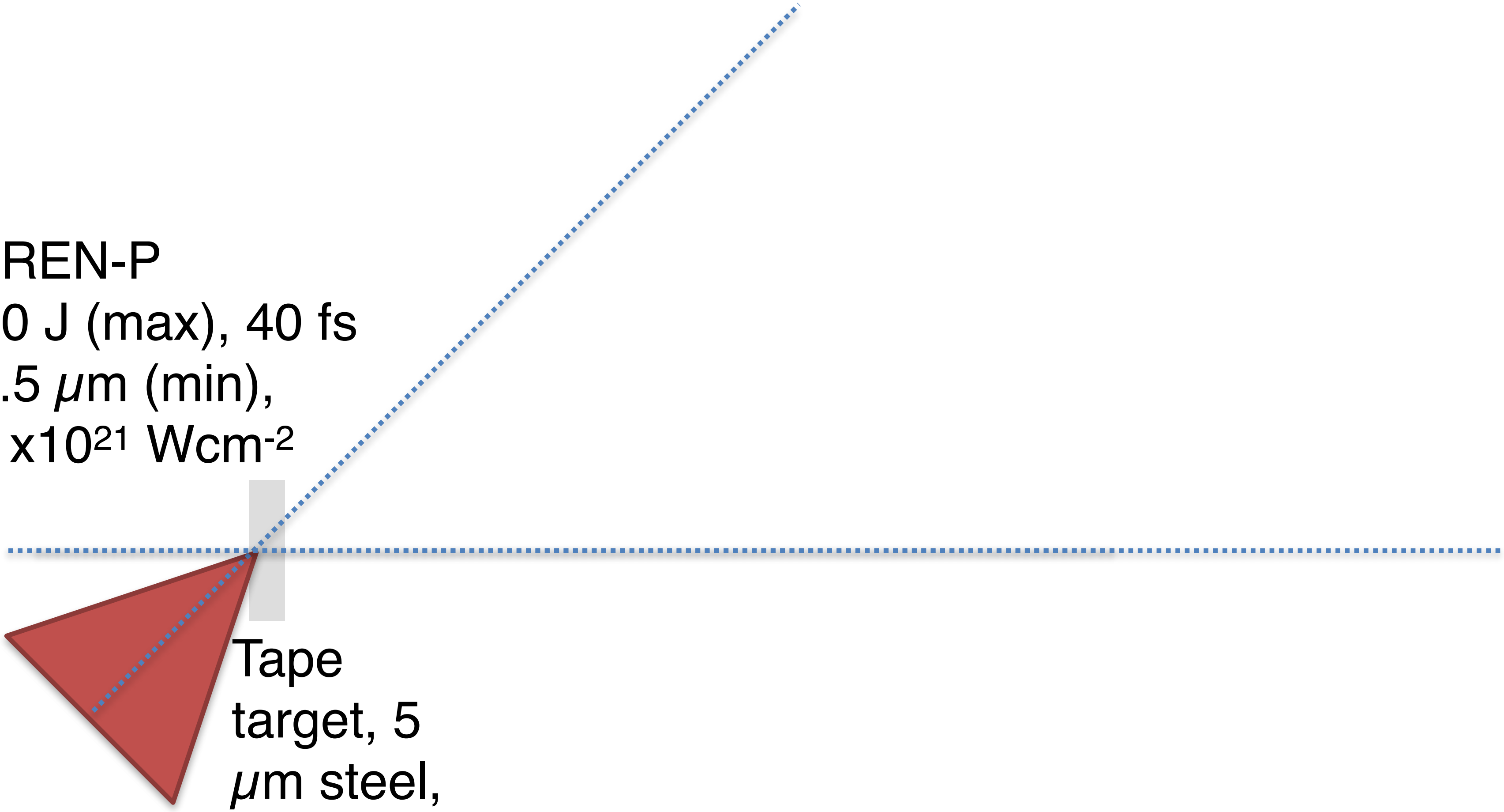
KPSI Kansai Photon Science Institute

Kiriyama et al. Opt. Lett. ***43****, 2018*

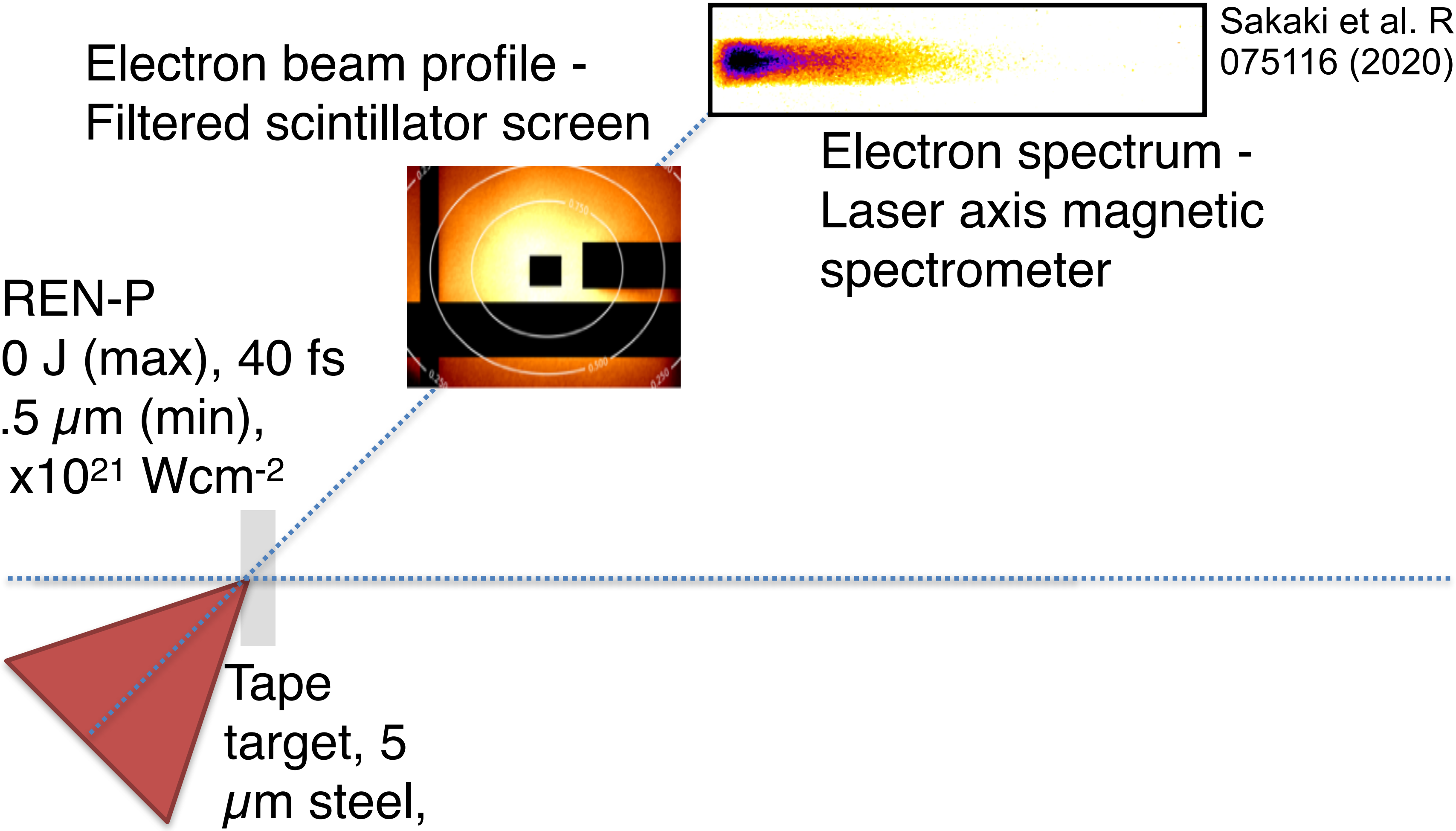
J-KAREN-P experimental setup



J-KAREN-P
E_L~10 J (max), 40 fs
r_L ~1.5 μm (min),
I_L ~5 x10^{21} Wcm^{-2}

Tape
target, 5
μm steel,
45° a.o.i.

J-KAREN-P experimental setup



Electron beam profile -
Filtered scintillator screen

Sakaki et al. RSI **91,** 075116 (2020)

Electron spectrum -
Laser axis magnetic
spectrometer

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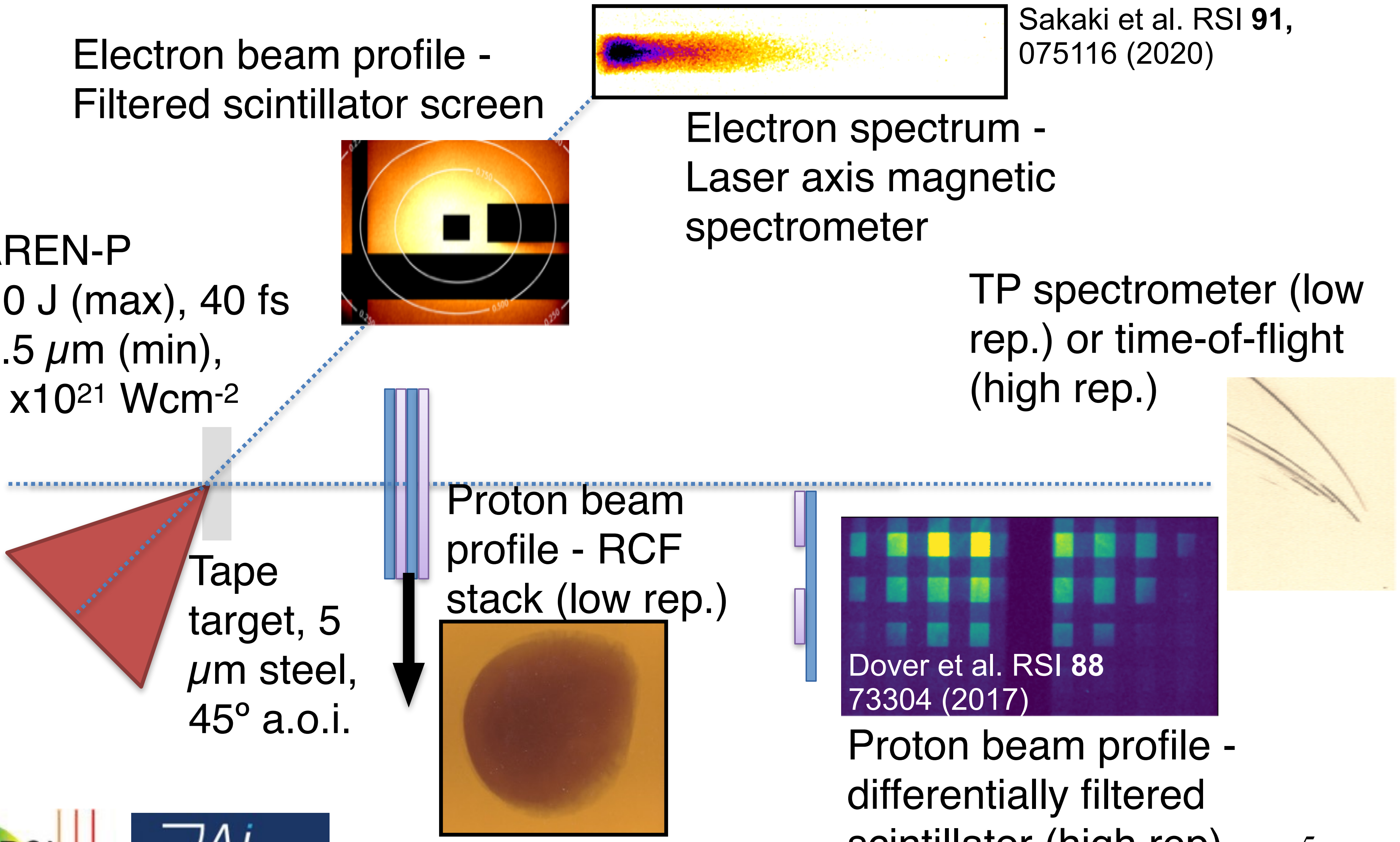

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J-KAREN-P
E_L~10 J (max), 40 fs
r_L ~1.5 μm (min),
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TP spectrometer (low rep.) or time-of-flight (high rep.)

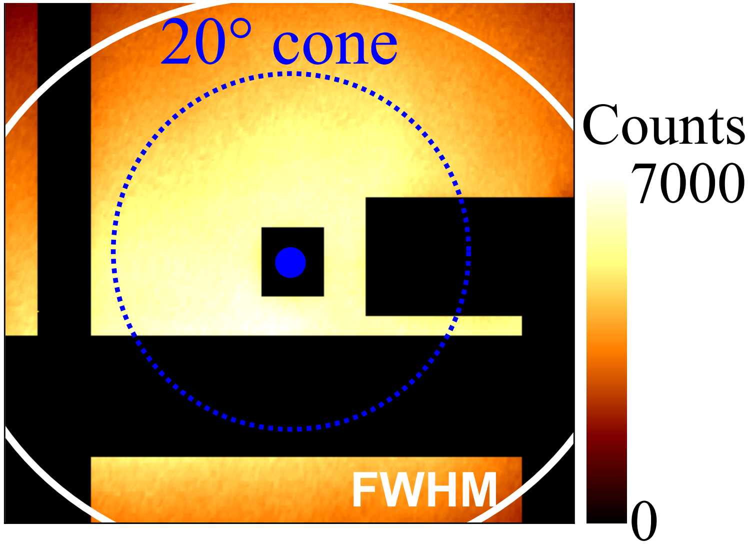
Tape target, 5 μm steel, 45° a.o.i.

Proton beam profile - RCF stack (low rep.)

Dover et al. RSI **88** 73304 (2017)

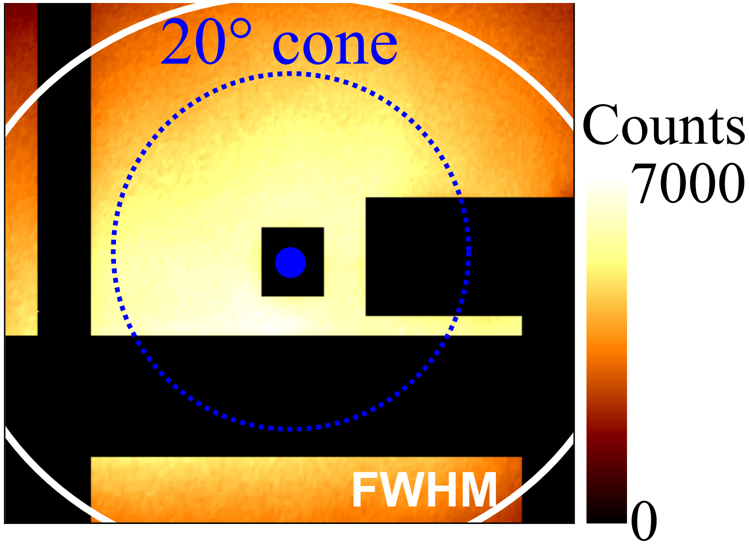
Proton beam profile -
differentially filtered
scintillator (high rep)

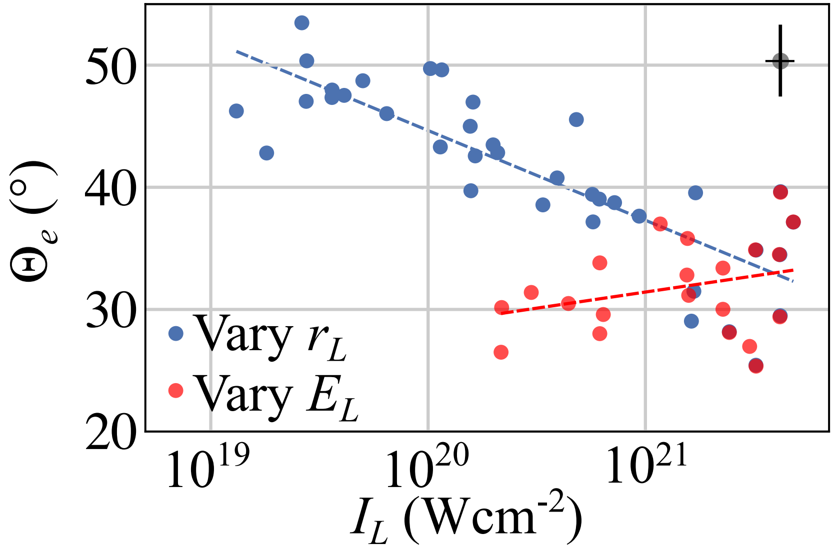
Laser-axis electron beam generated at ultra-high intensities



- Electron beam always directed along laser axis (pointing varies +/- 5º)

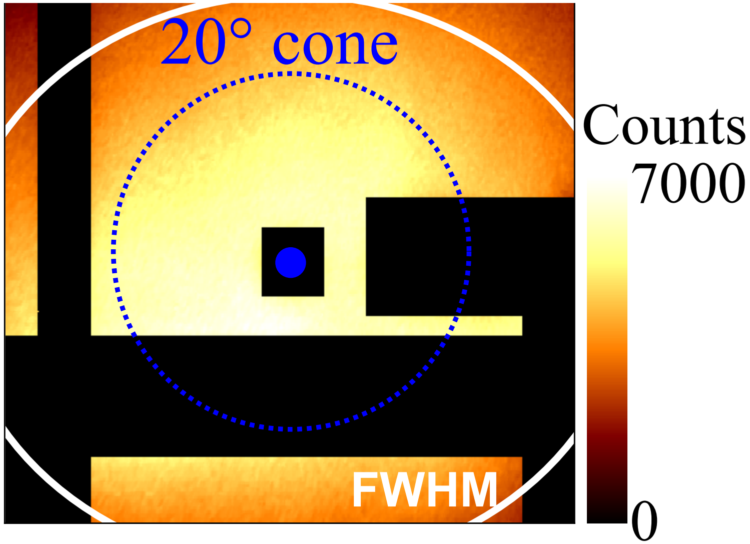
Laser-axis electron beam generated at ultra-high intensities

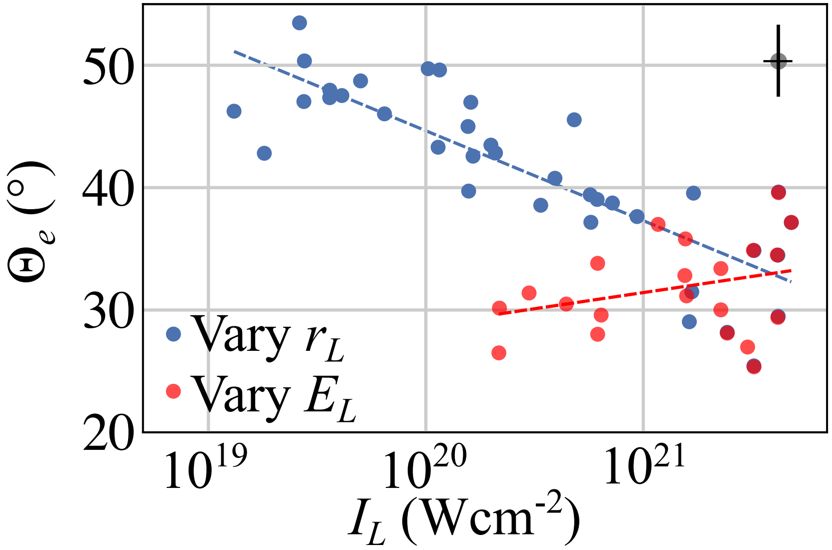




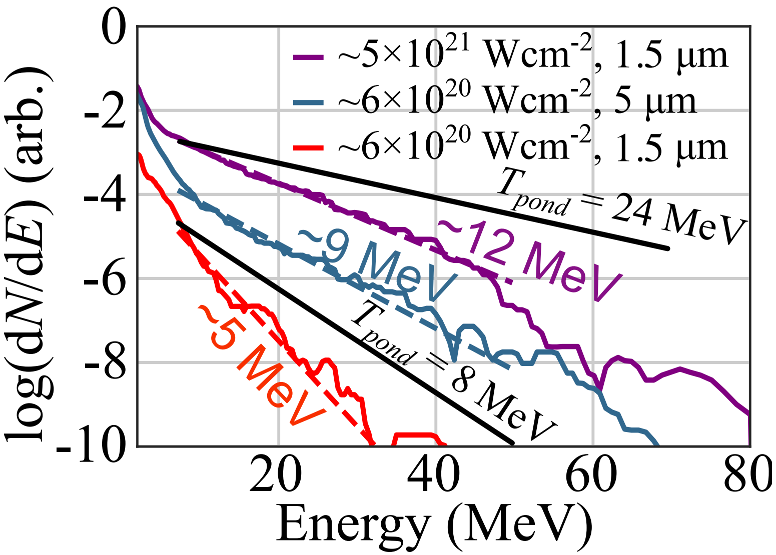
- Electron beam always directed along laser axis (pointing varies +/- 5º)
- Vary intensity by changing laser energy and focusing - Electrons least divergent for small focal spot sizes

Laser-axis electron beam generated at ultra-high intensities

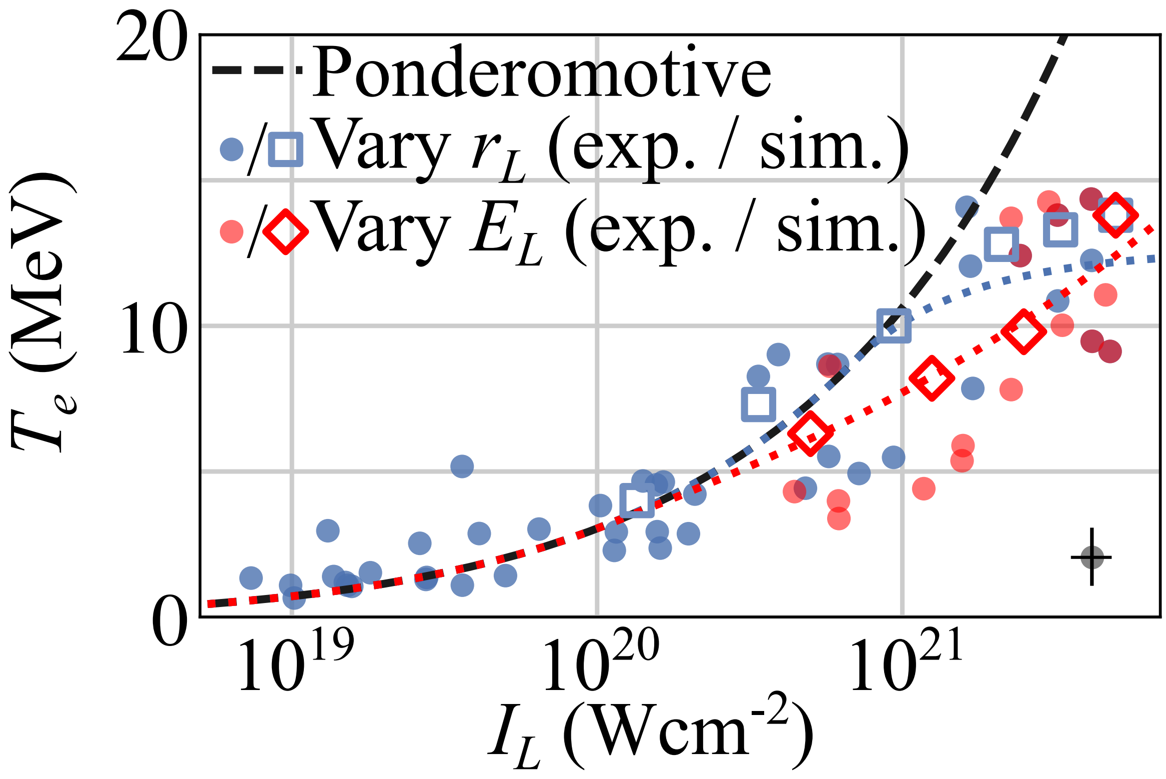




- Electron beam always directed along laser axis (pointing varies +/- 5º)
- Vary intensity by changing laser energy and focusing - Electrons least divergent for small focal spot sizes
- Focal spot dependence of T_e



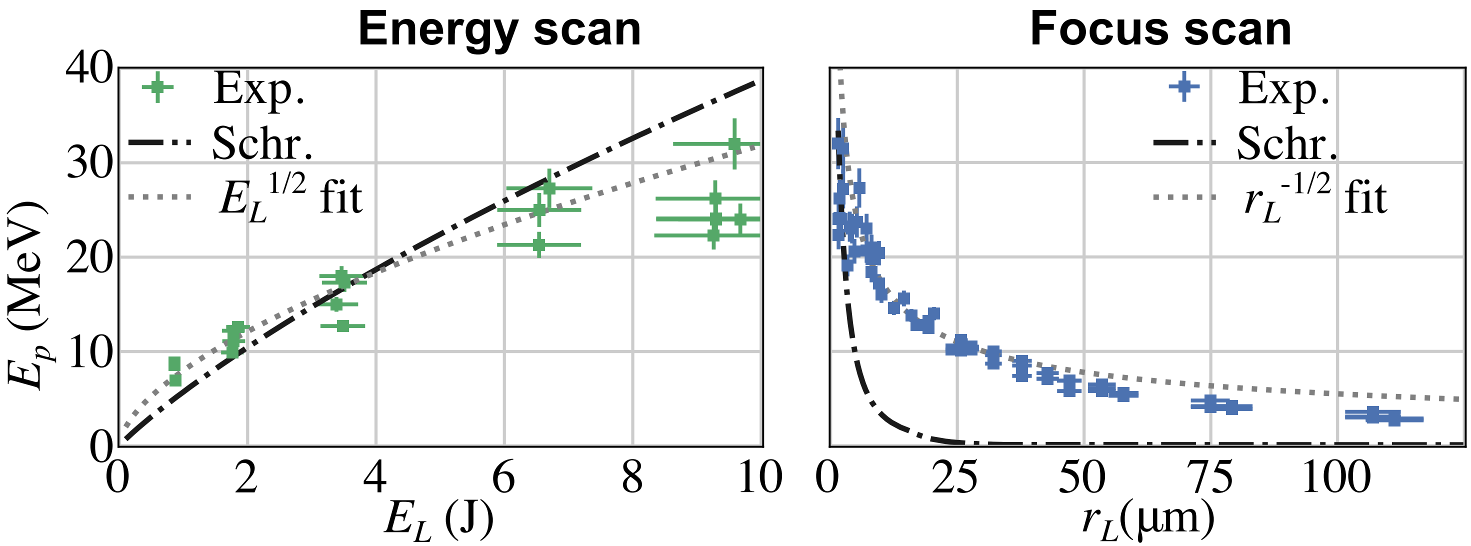
Sub-ponderomotive electron temperature increase with intensity



- At low intensities (large spot size), electron temperature T_e follows ponderomotive scaling
- At highest intensities, scaling worsens
- **Suppression for smaller spot sizes at same intensity**
- Due to the laser focus being too small - electron leaves focal region too quickly to reach high energies

For more details: Dover *et al.*, Phys. Rev. Lett. **124**, 084802 (2020)

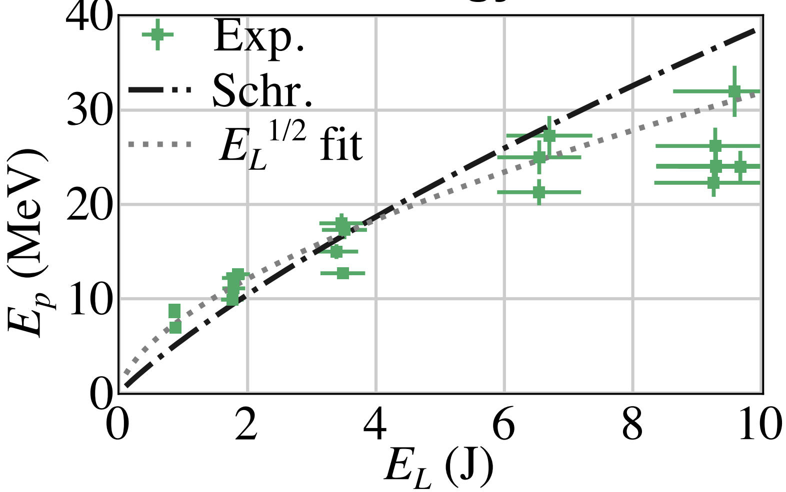
Parametric scan to measure proton energy scaling



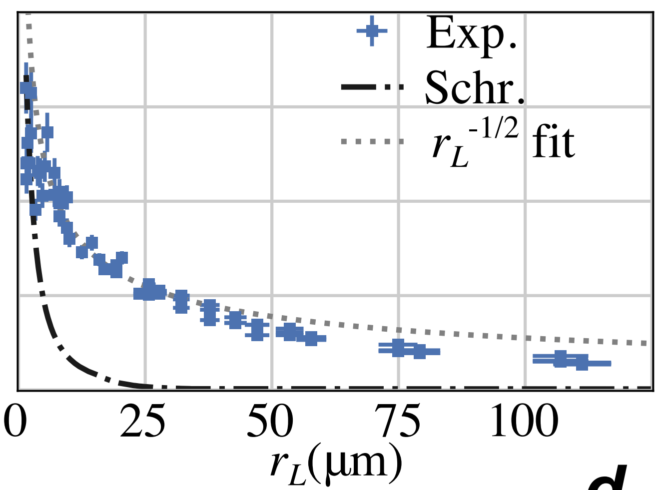
Parametric scan to measure proton energy scaling

$\eta = 1.2\text{x}10^{-15}\, I_L^{3/4}$ [Wcm^{-2}]
up to max $\eta = 0.5$
$\tau = \tau_L$
Θ_e, T_e from experiment

Energy scan



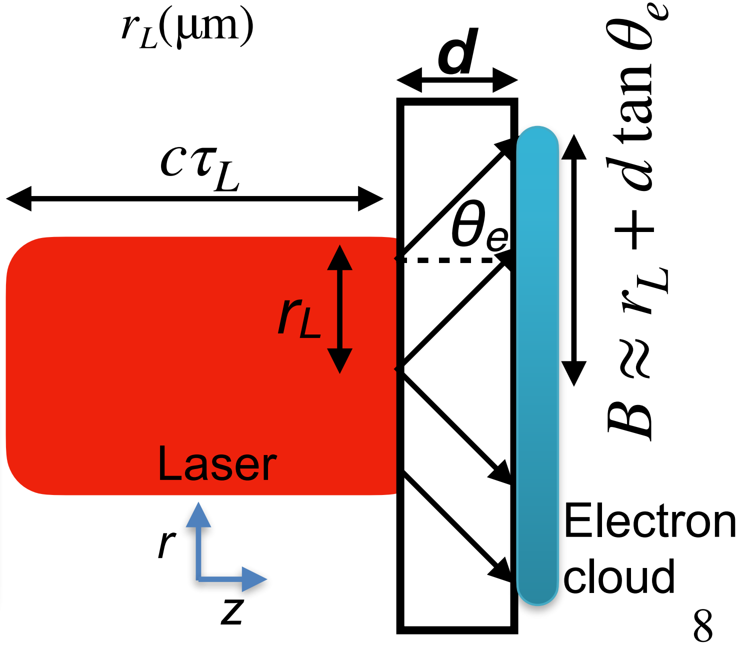
Focus scan



- Schreiber model shows good agreement for energy scan using realistic conversion efficiencies (~50%)
- Very poor agreement with focal scan!

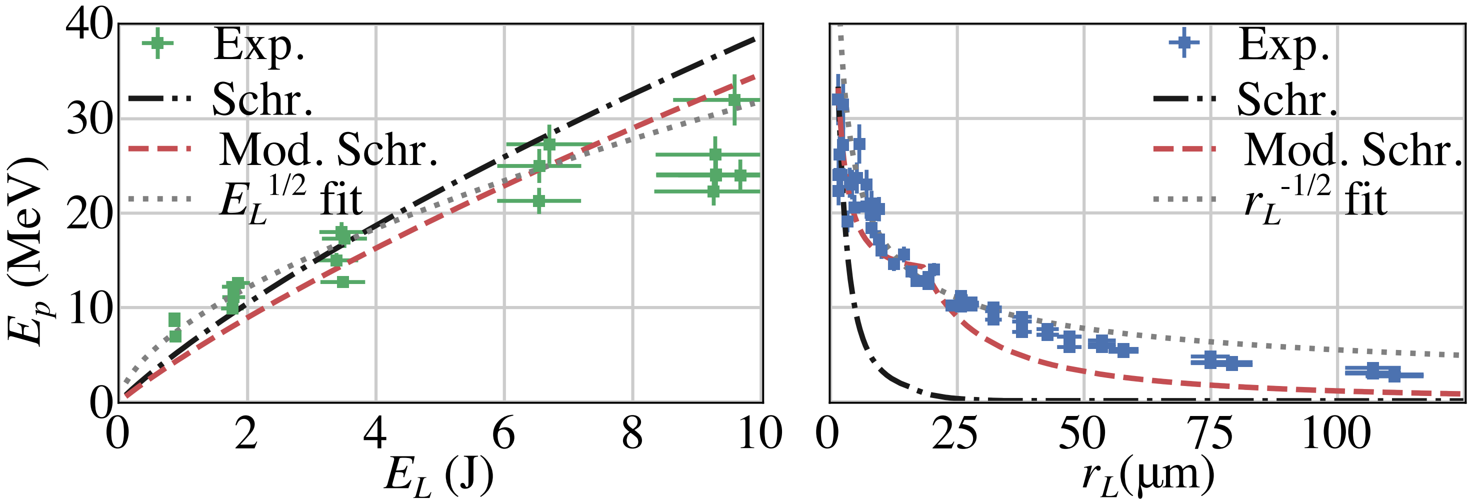
Schreiber model:

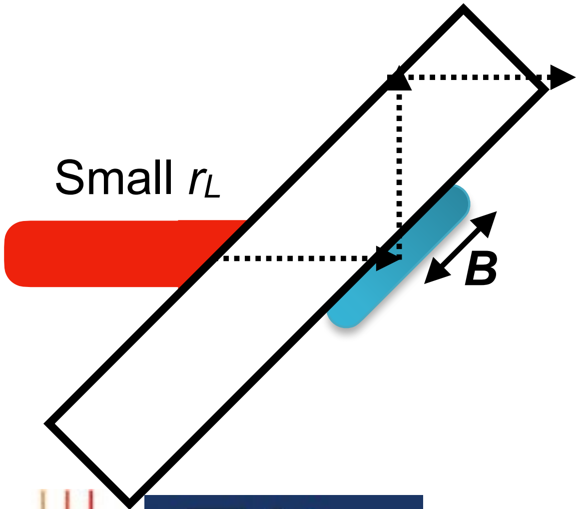
- Calculate static sheath potential from e$^-$ parameters
- integrate over time τ_L



(See Schreiber *et al.* PRL **97**, 045005 (2006))

Modified sheath acceleration model for large foci

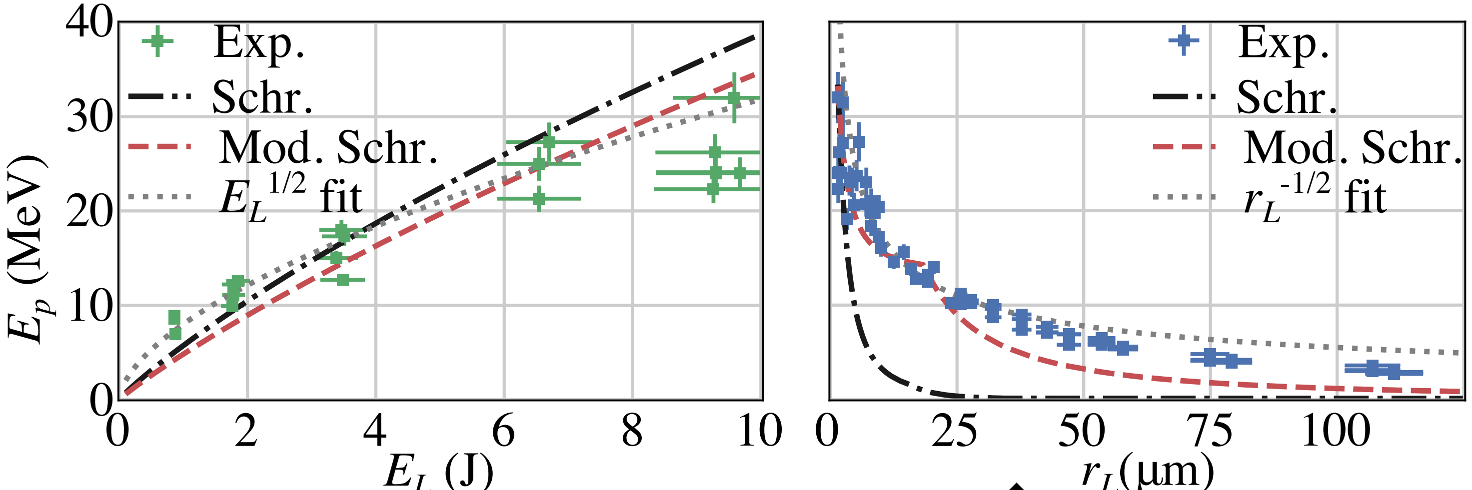


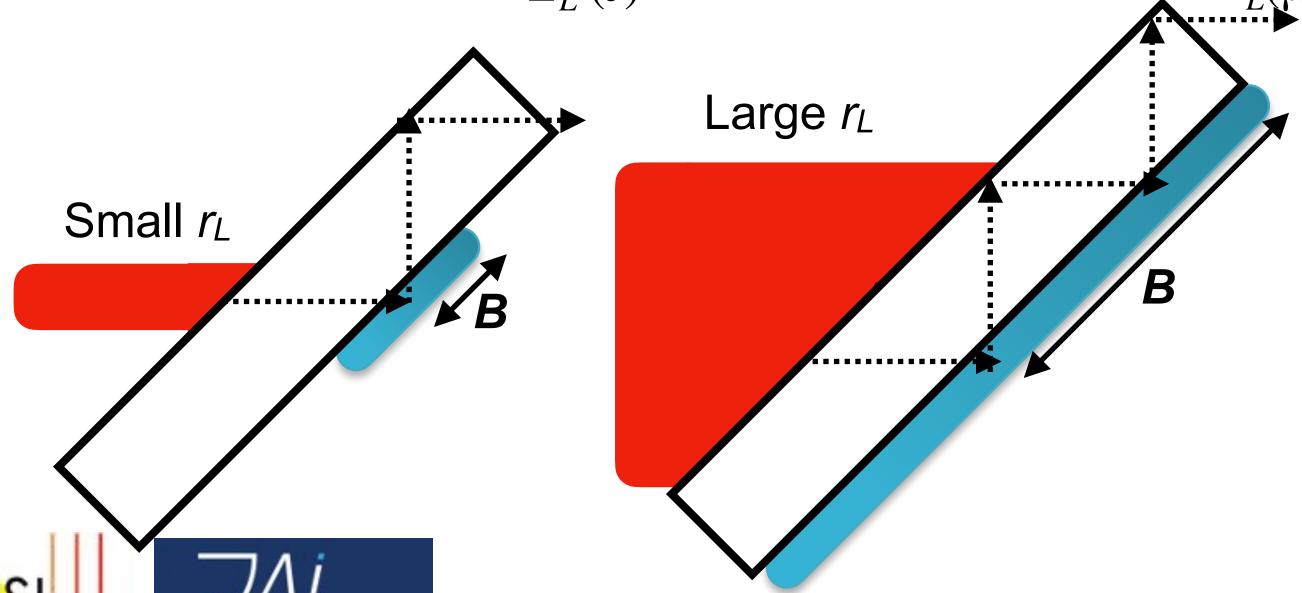


Small r_L

B

Modified sheath acceleration model for large foci





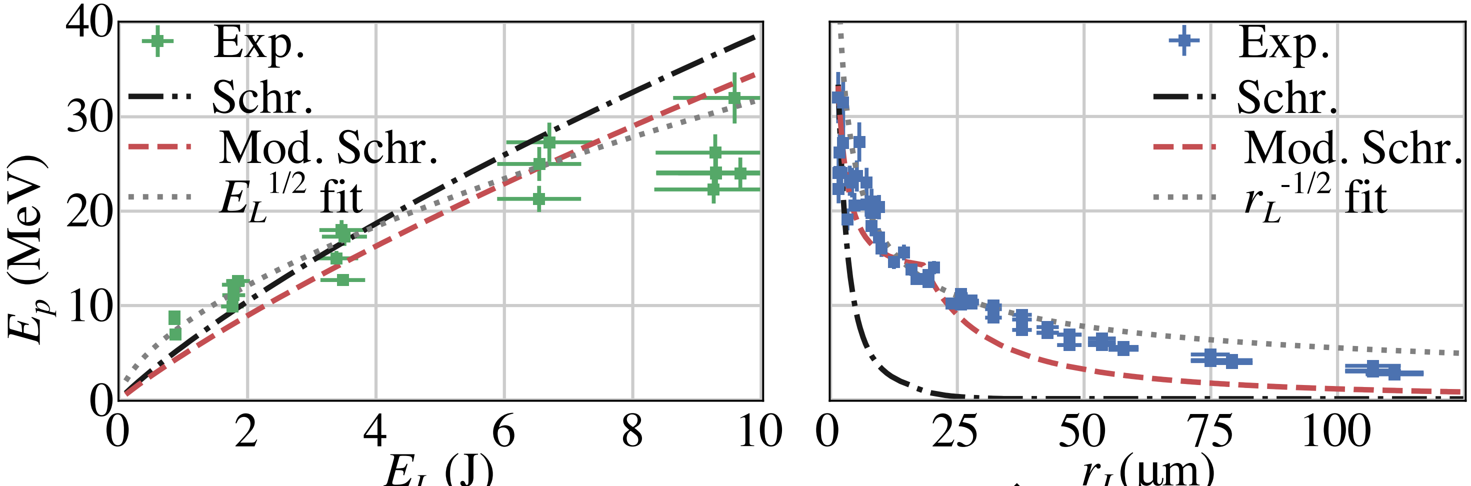
Increase in acceleration time

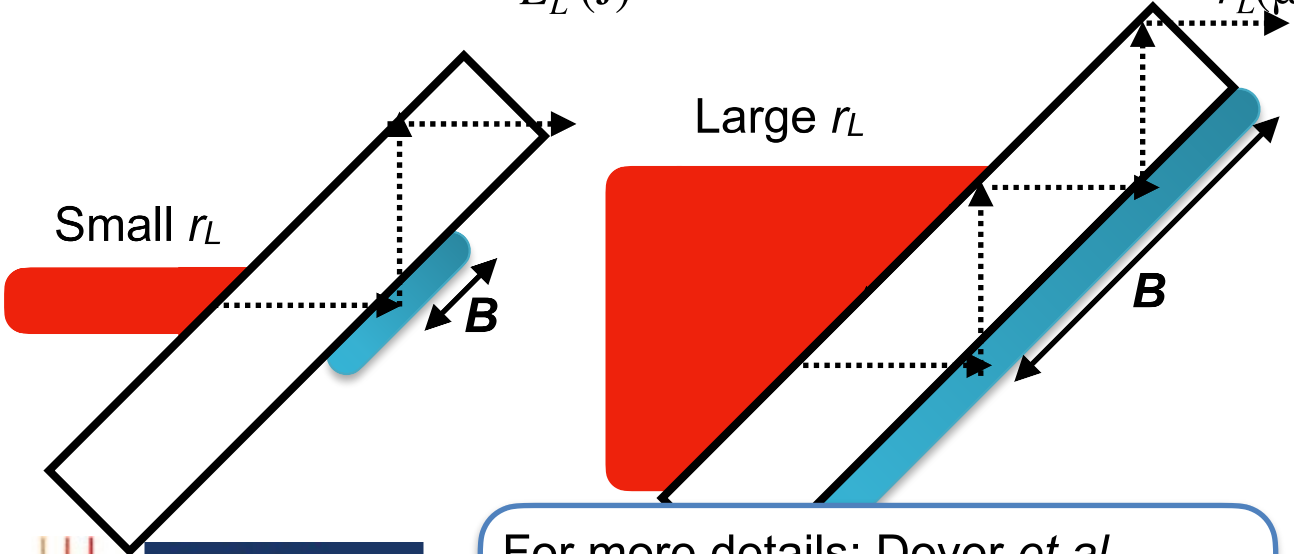
$$\tau = \tau_L$$

$$\tau = (\tau_L^2 + \tau_{esc}^2)^{1/2}$$

$$\tau_{esc} \approx \frac{2B}{c}$$

Modified sheath acceleration model for large foci





Increase in acceleration time

$$\tau = \tau_L$$

$$\Downarrow$$

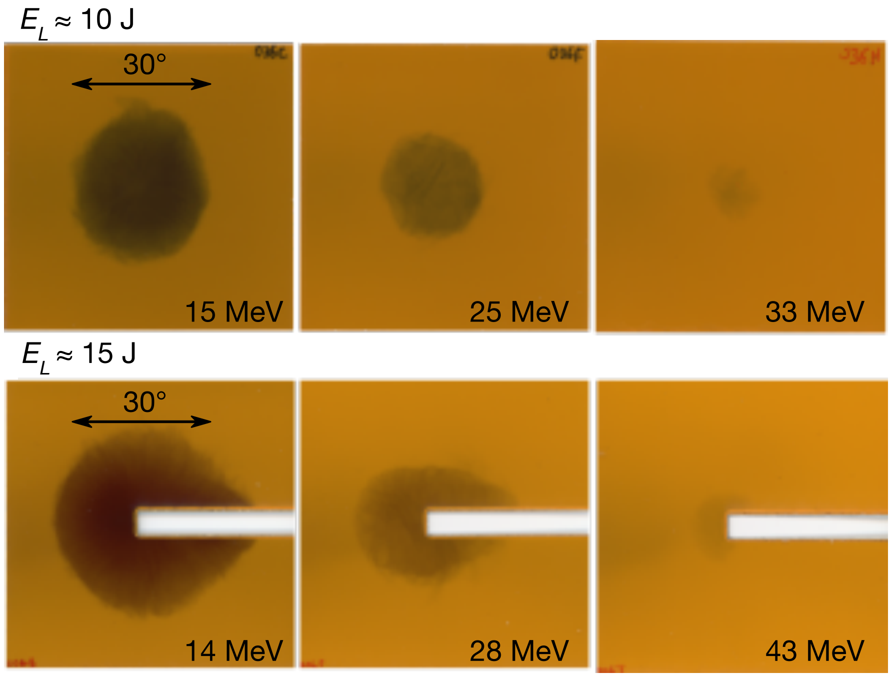
$$\tau = (\tau_L^2 + \tau_{esc}^2)^{1/2}$$

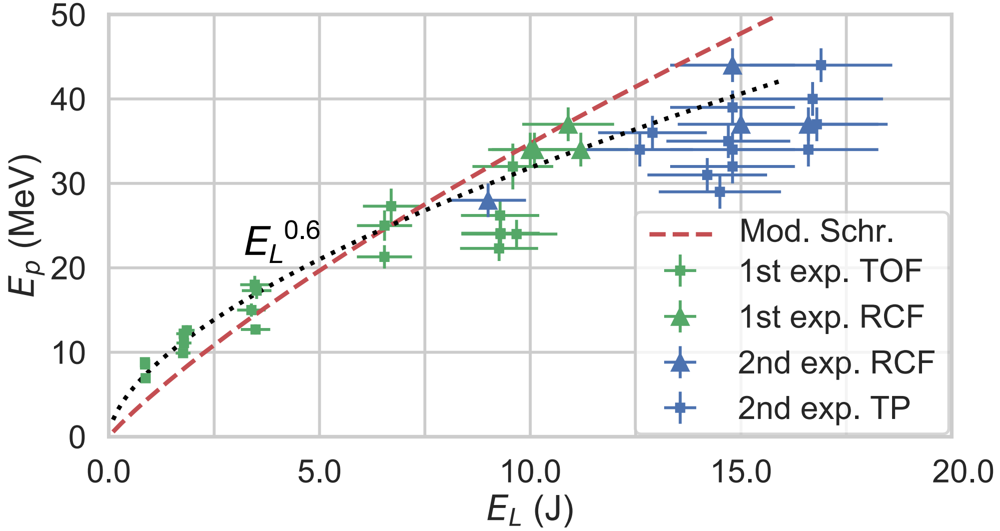
$$\tau_{esc} \approx \frac{2B}{c}$$

For more details: Dover *et al.*, Phys. Rev. Lett. **124**, 084802 (2020)

J-KAREN-P beamline upgrade: laser energies up to 15 J

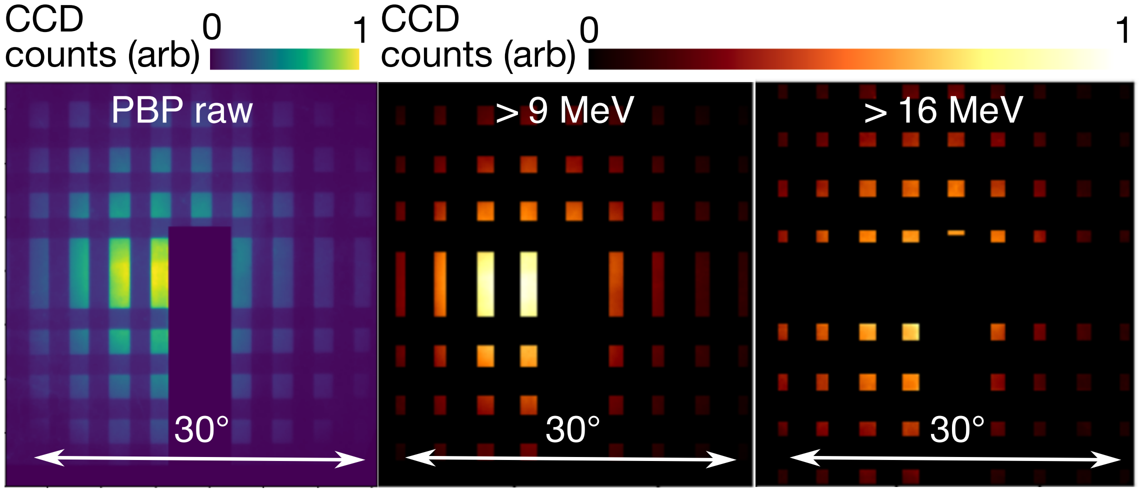
- Improvements in laser near field allowed increase of laser energy to ~15 J
- Increased maximum energy up to ~40 MeV at 0.1 Hz
- Consistent with previous experiment, despite change in laser contrast

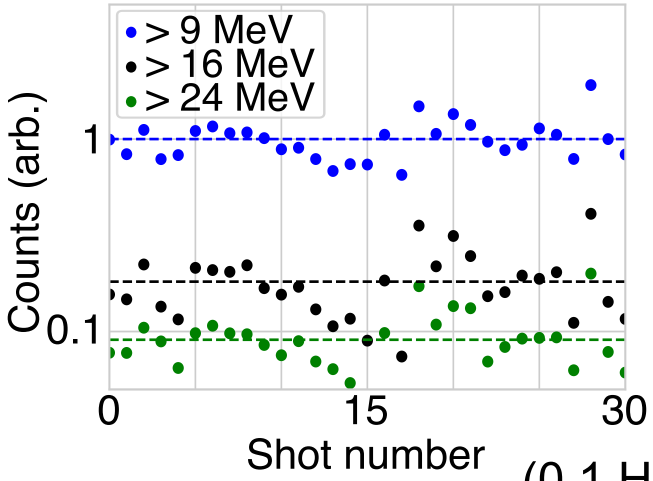




Stable proton generation at 0.1 Hz from tape target

- Using 5 μm tape target (steel or titanium)
- Consecutive shots shows fluctuations ~25% of flux
- Enormous peak currents possible, but beams difficult to transport to applications





	Beam > 12 MeV	15 MeV, ΔE = 1%E, 1 msr
	~2x10^{10} particles	~3x10^{6} particles
	~3 nC	~0.5 pC
	~50 mJ	~7 μJ
	~30 kA (peak)	*~5 A (peak)*
(0.1 Hz)	~0.3 nA (avg.)	~50 fA (avg.)
(10 Hz)	~30 nA (avg.)	~5 pA (avg.)

Dover *et al.*, High Energ. Dens. Phys. **37**, 100847 (2020)

Summary

- Investigated electron heating and ion acceleration at intensities > 10^{21} W/cm^2
- Saturation of electron temperature with ultra-intense tightly focused spots, limiting potential energy gain
- Investigated scaling of sheath acceleration of protons, showing increasing laser energy most effective way to boost energies
- Developed repetitive proton source with energies up to 40 MeV