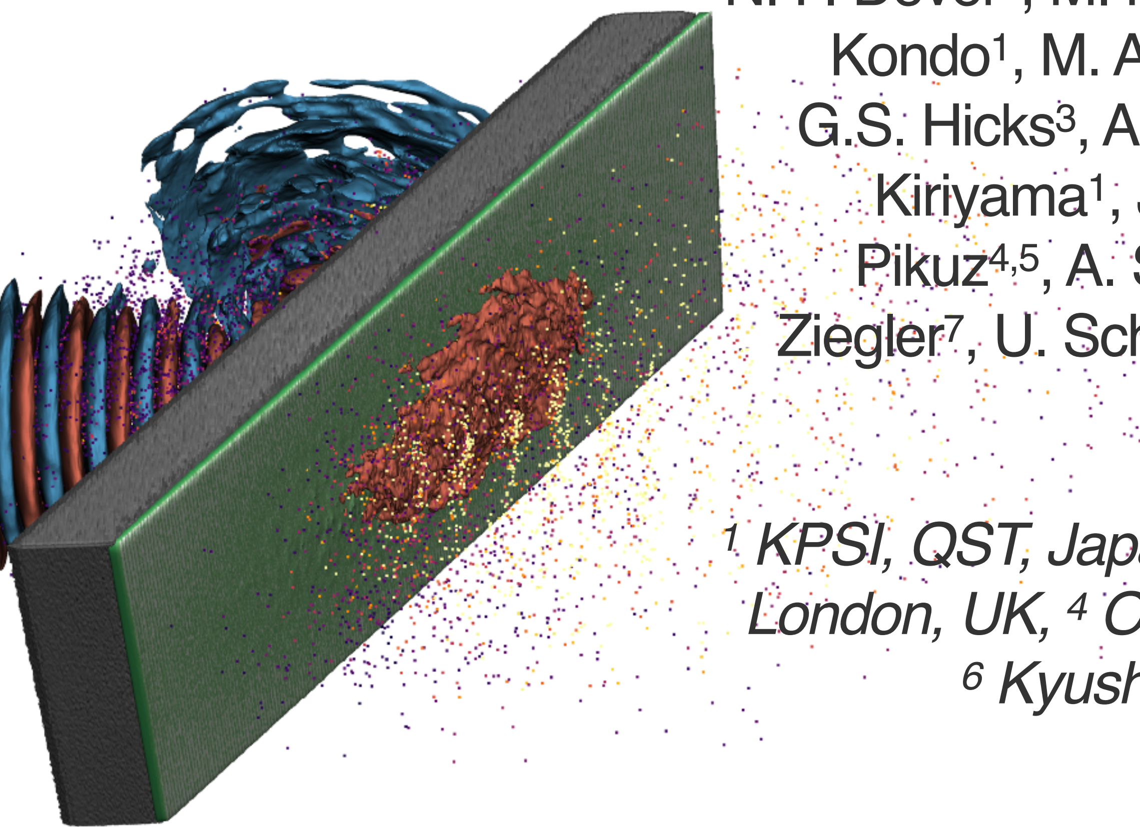
Effect of small focus on electron heating and proton acceleration in ultra-relativistic laser-solid interactions

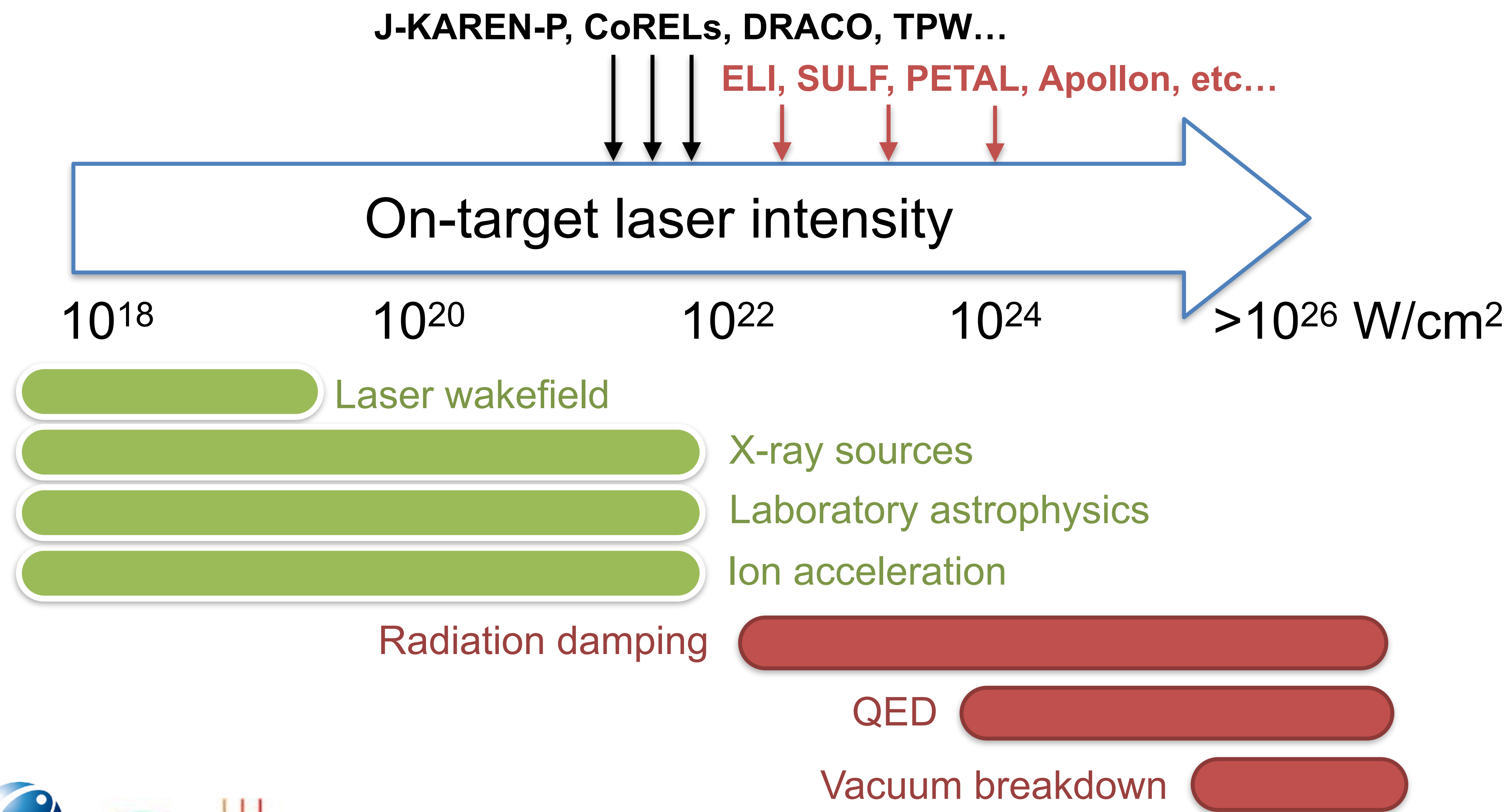
June 12th 2019, OPTO 2019

N. P. Dover[1], M. Nishiuchi[1], H. Sakaki[1], H. F. Lowe[1], Ko. Kondo[1], M. A. Alkhimova[2], E. Ditter[3], O.C. Ettlinger[3], G.S. Hicks[3], A. Ya. Faenov[4,5], M. Hata[4], N. Iwata[4], H. Kiriyama[1], J. K. Koga[1], A. Kon[1], T. Miyahara[6], T. A. Pikuz[4,5], A. S. Pirozhkov[1], A. Sagisaka[1], K. Zeil[7], T. Ziegler[7], U. Schramm[7], Y. Sentoku[4], Y .Watanabe[6], M. Kando[1], K. Kondo[1]

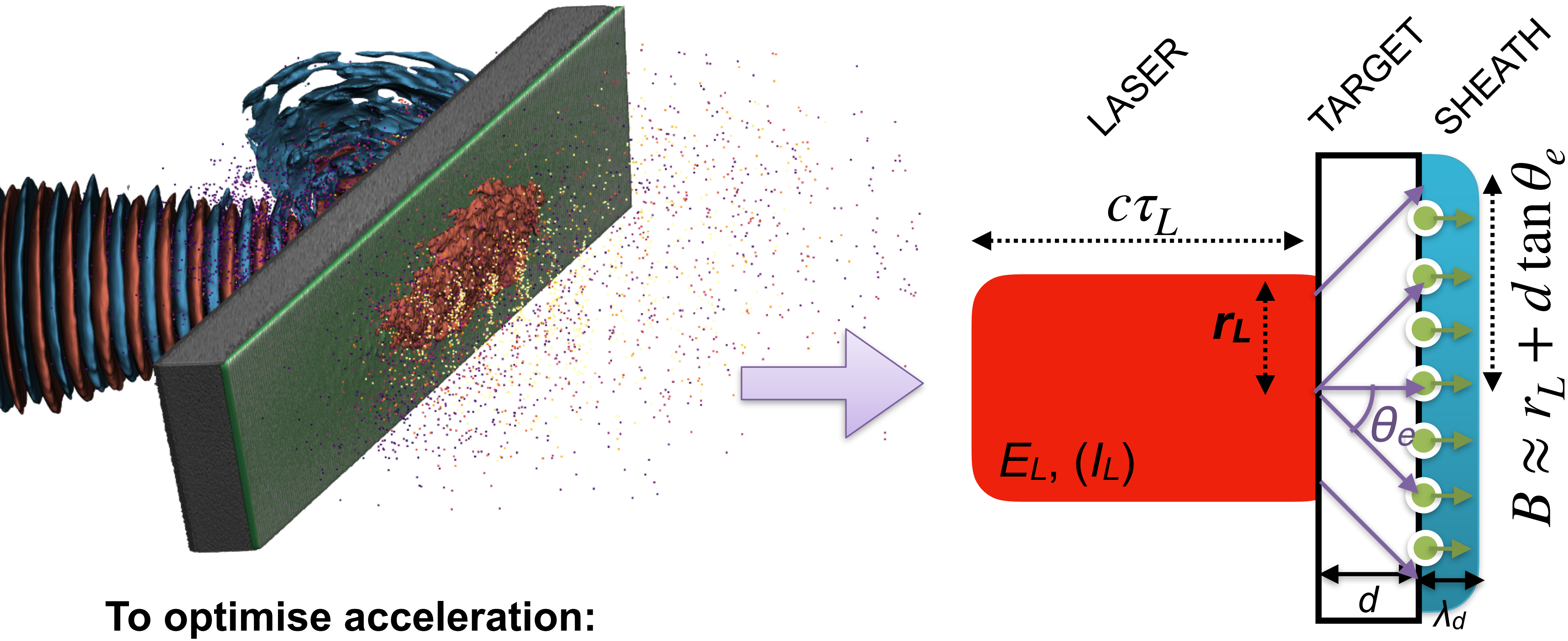
[1] KPSI, QST, Japan, [2] MEPhI, Russia, [3] Imperial College London, UK, [4] Osaka University, Japan, [5] RAS, Russia, [6] Kyushu University, Japan, [7] HZDR, Germany



Lasers are reaching ever-higher intensities



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

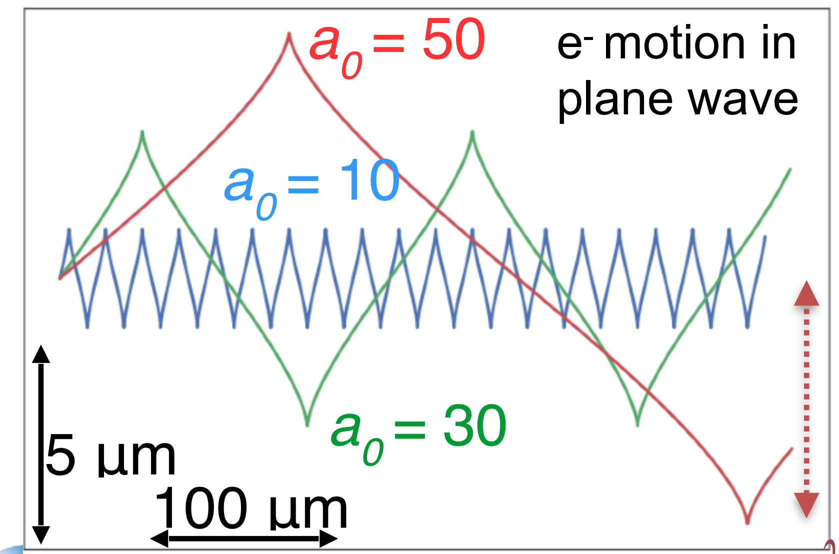
QST
KPSI
Kansai Photon Science Institute

How might electron heating scale?

- "Ponderomotive temperature" calculated from maximum transverse momentum of electron in plane wave

$$p_{y,max} = a_0 m_e c \qquad T_e = (\gamma_y - 1) m_e c^2 \sim a_0 m_e c^2$$

- Neglects plasma fields, longitudinal momentum etc… other models also used
- <u>All models depend only on laser intensity</u>



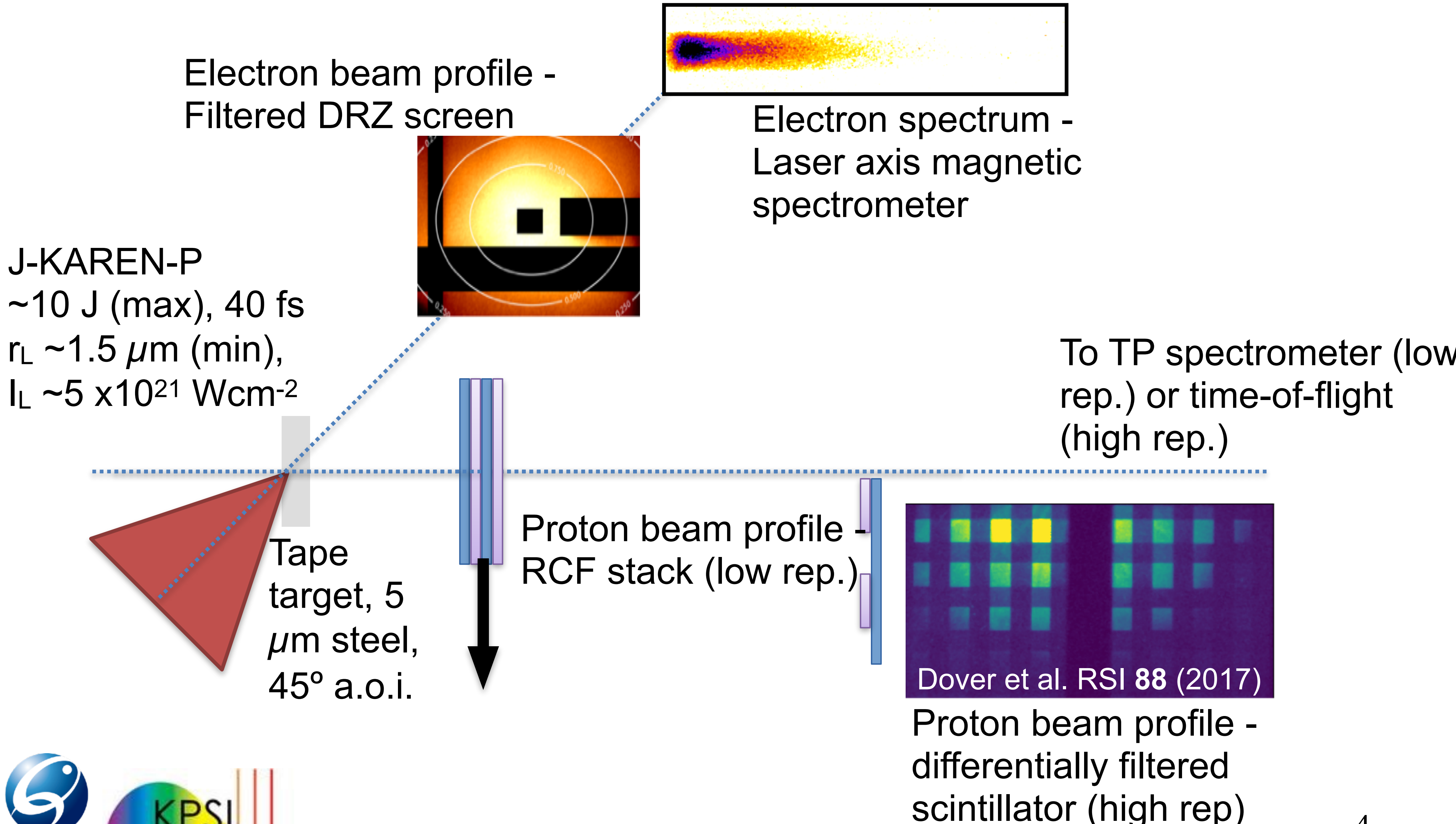
$$y_0 = a_0 \lambda_L / 2\pi$$

- Unclear how electron heating behaves at ultrahigh intensity, and therefore unclear how ion acceleration will scale!
- **Experiment aims:**
  - **Investigate electron heating at ultra-high intensity**
  - **Optimise proton generation**

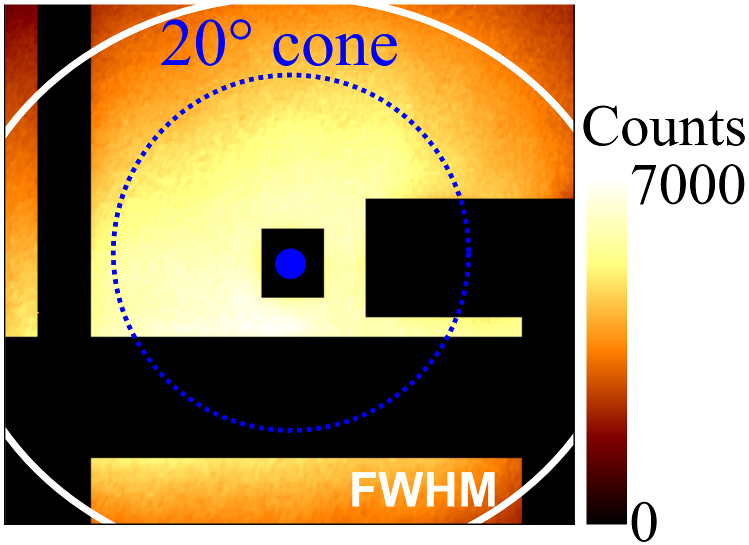
QST

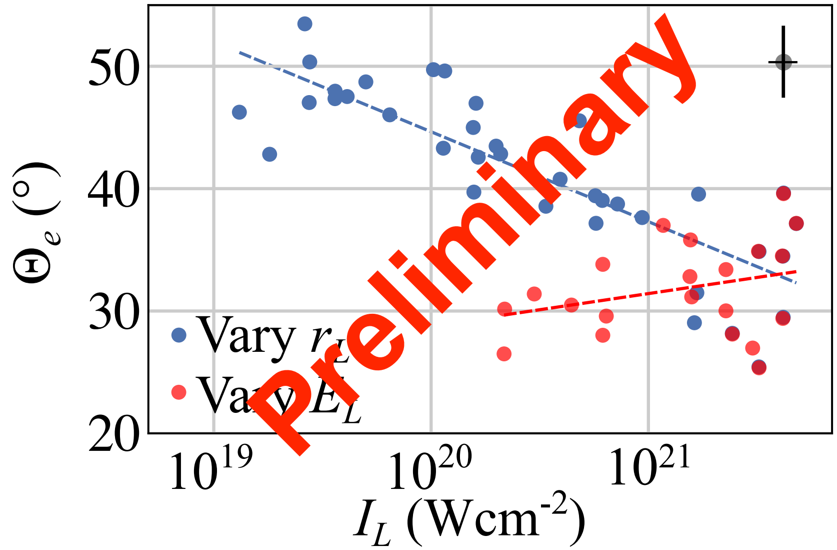
KPSI Kansai Photon Science Institute

J-KAREN-P experimental setup

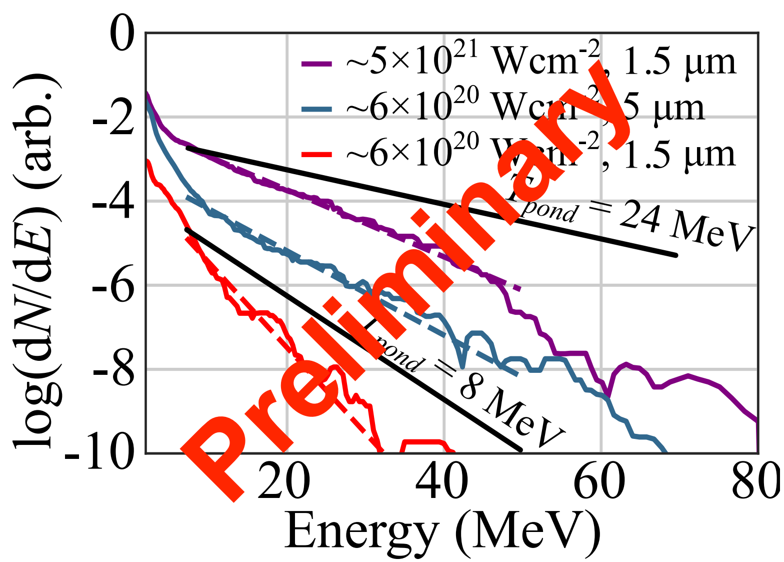


Laser-axis electron beam generated at ultra-high intensities

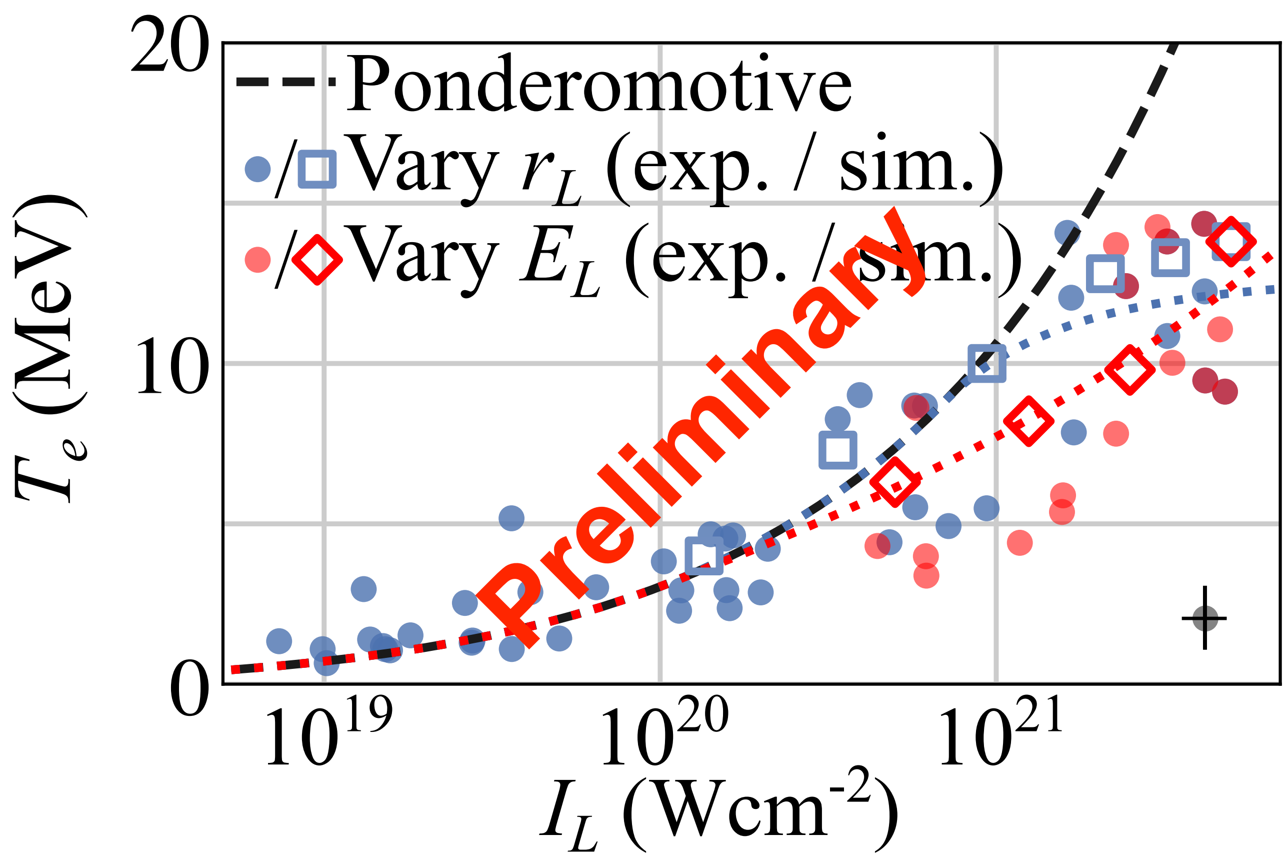




- Electron beam directed along laser axis (pointing varies +/- 5º)
- Vary intensity by changing laser energy and focusing - Electrons least divergent for small focal spot sizes
- Focal spot dependence of T_e



Sub-ponderomotive electron temperature increase with intensity

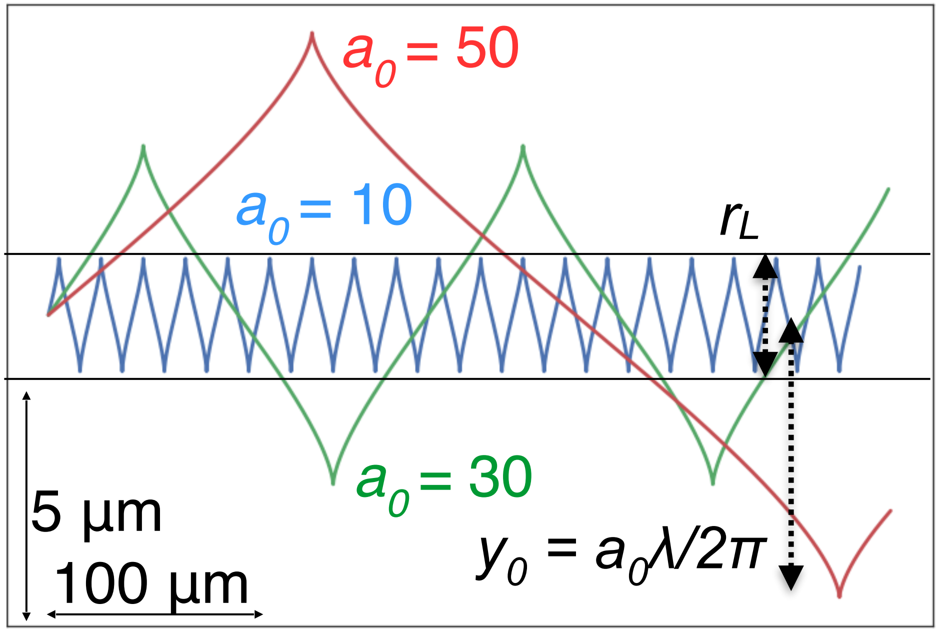


- At low intensities (large spot size), electron temperature T_e follows ponderomotive scaling
- At highest intensities, scaling worsens
- **Suppression for smaller spot sizes at same intensity**

QST KPSI Kansai Photon Science Institute

Suppression of T_e due to small focal spots

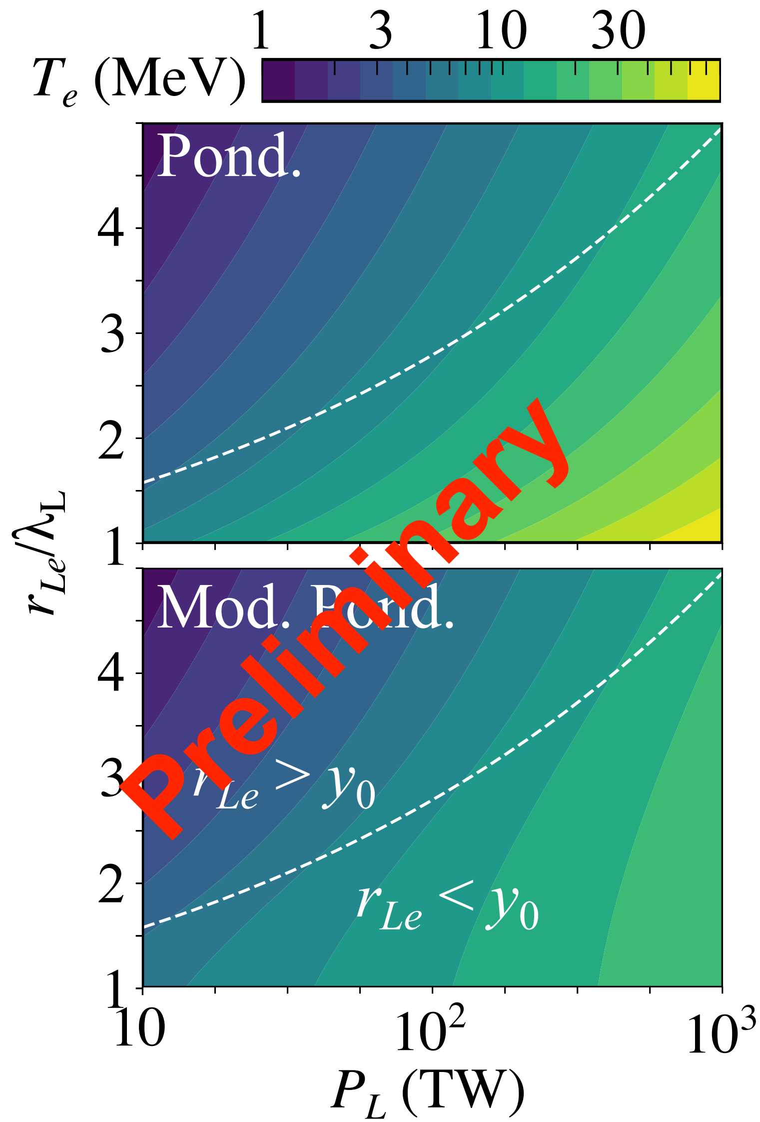
Electron in plane wave, vary a_0



Modified scaling:

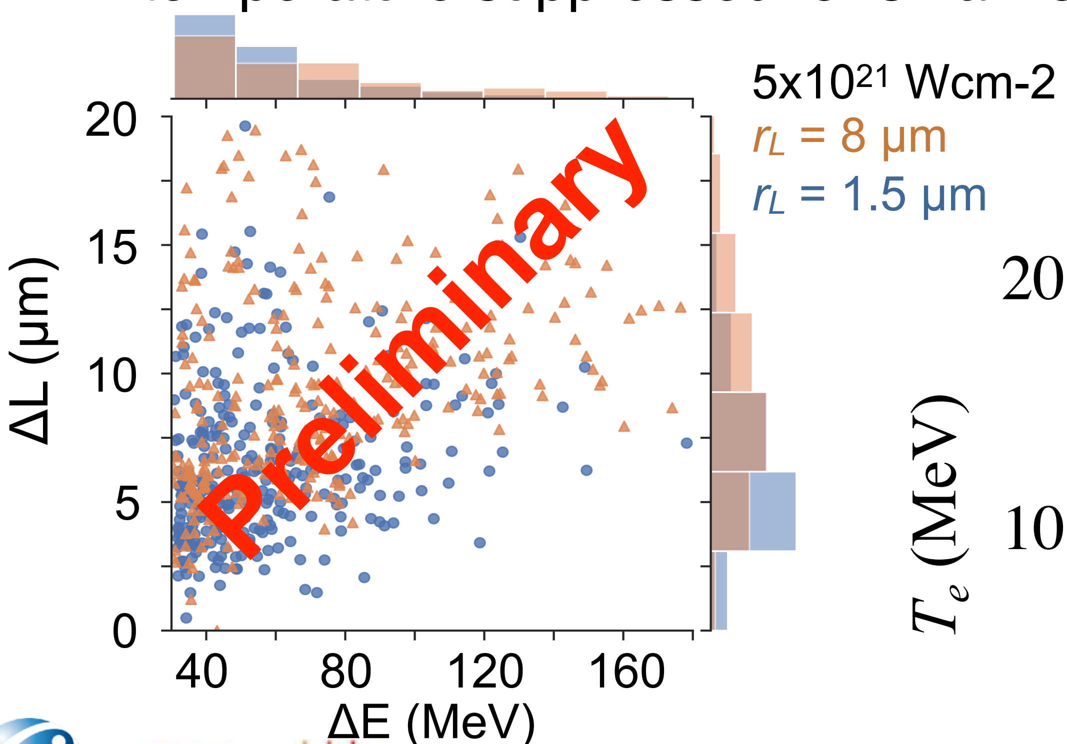
$r_L > y_0$: $p_{y,max} = a_0 m_e c$

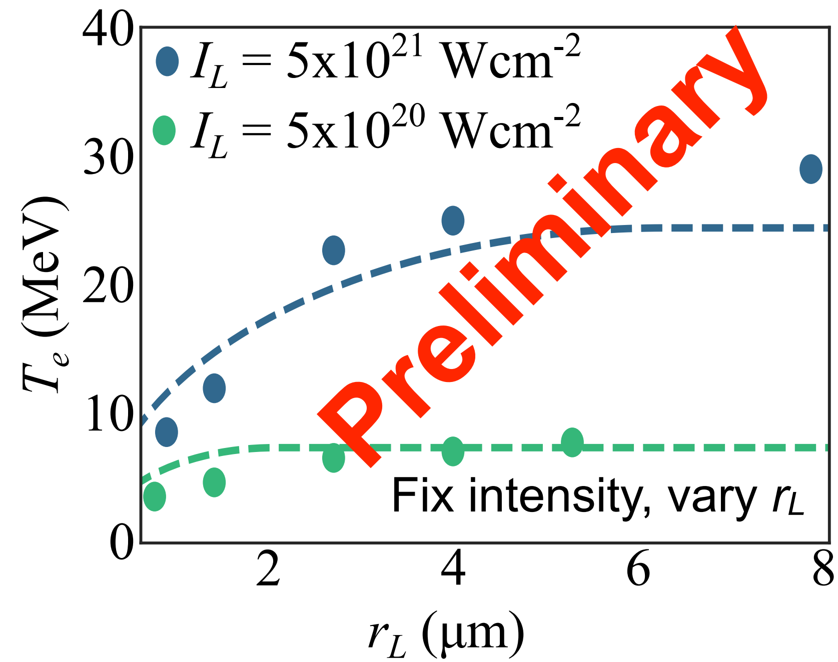
$r_L < y_0$: $p_{y,max} = a_0 m_e c \left(1 - \left(\frac{r_L}{y_0} - 1\right)^2\right)^{1/2}$

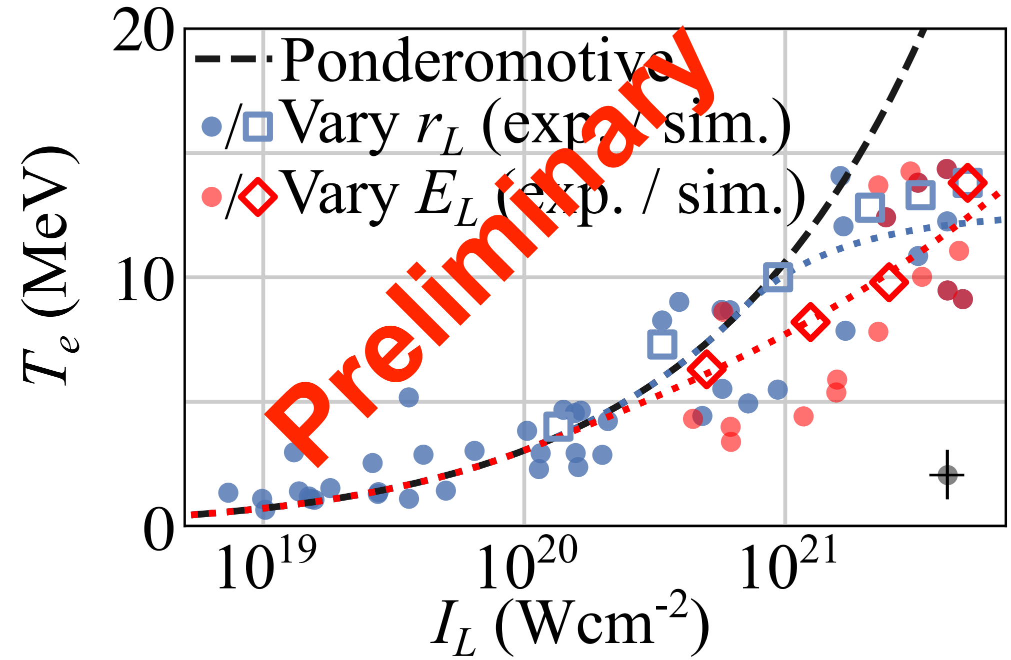


2D PIC reveals electron temperature suppression

- PIC to self-consistently include plasma fields & dynamics -> 2D PIC simulations using EPOCH2D code
- For a fixed intensity, electron temperature suppressed for small focus



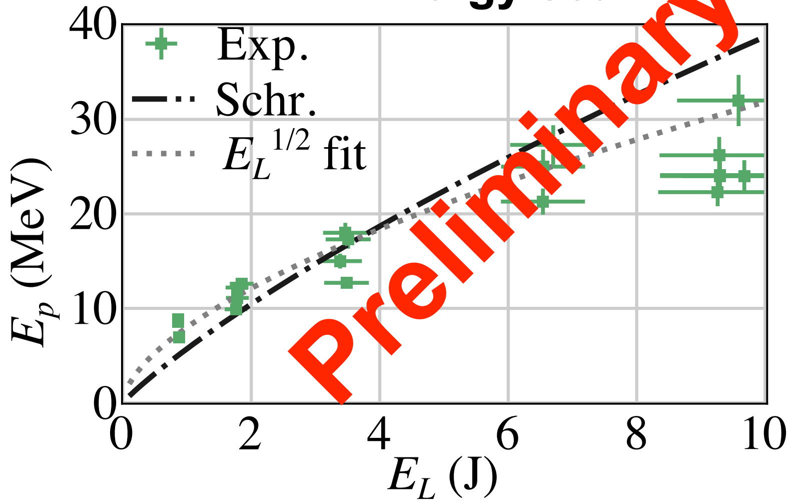




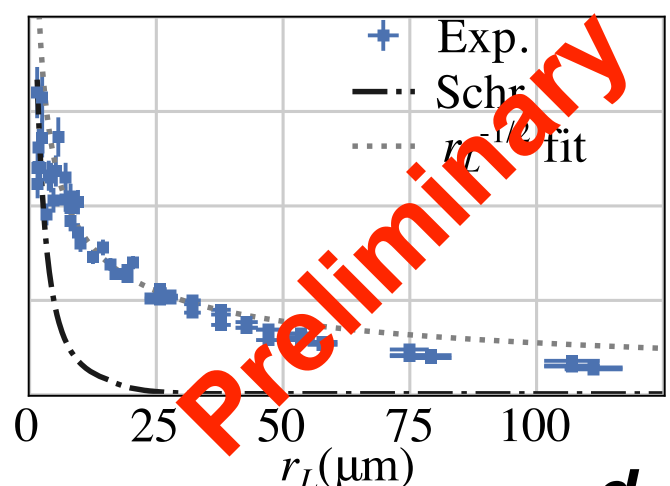
Parametric scan to measure proton energy scaling

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

Energy scan

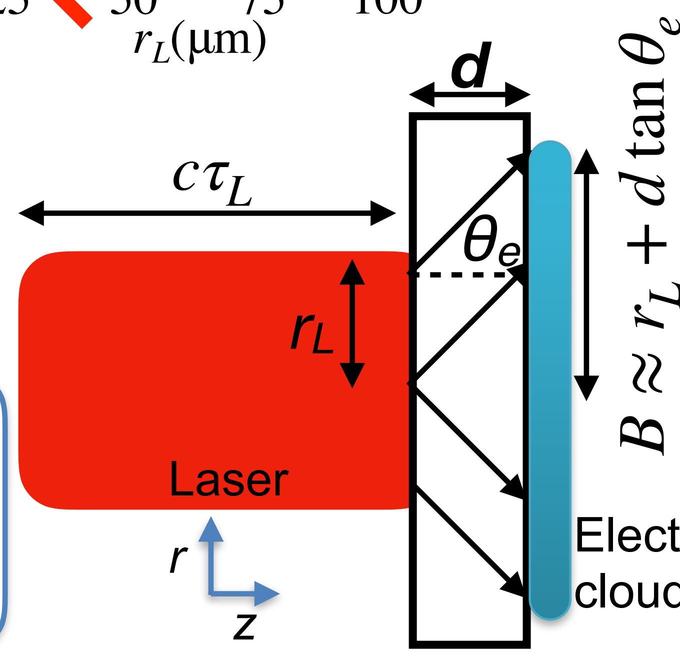


Focus scan

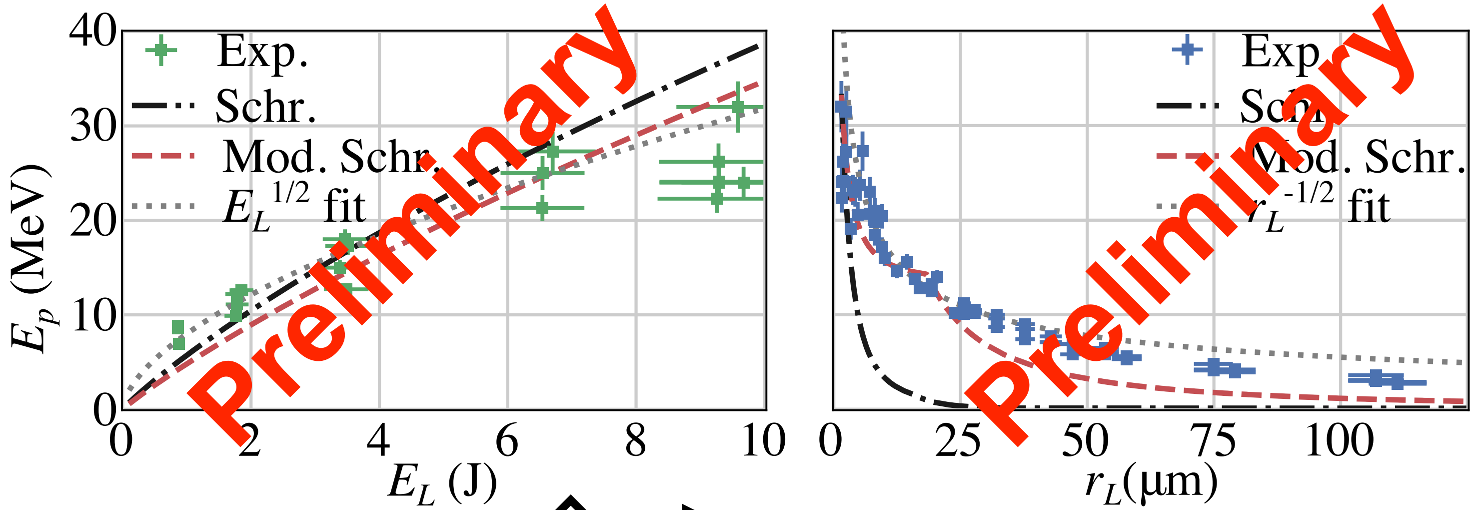


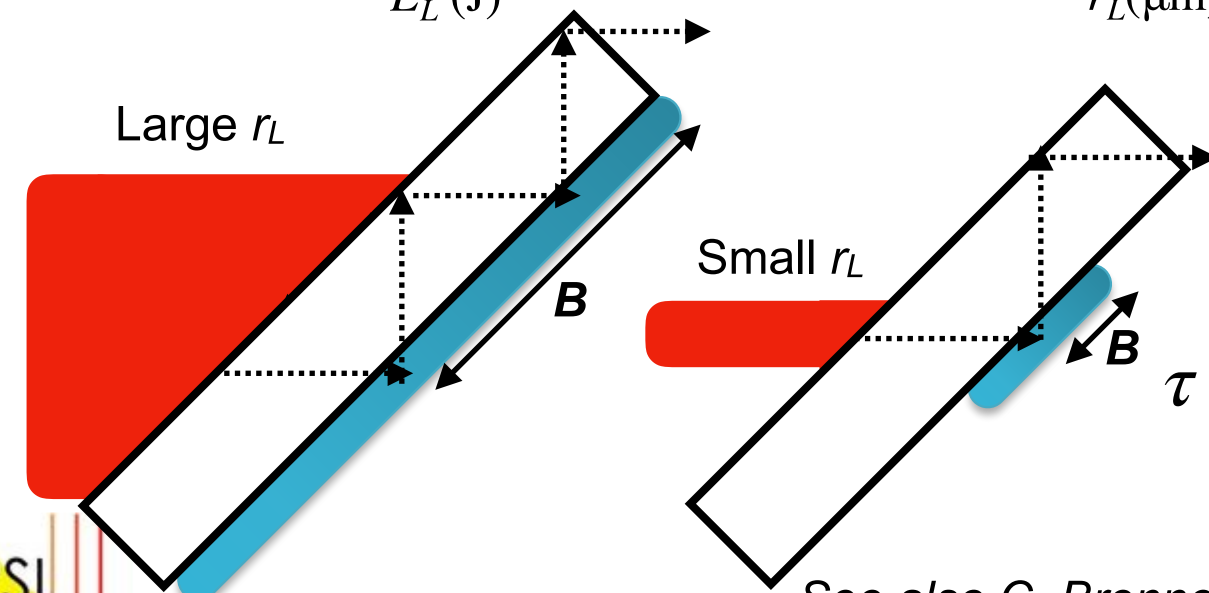
- Schreiber model shows good agreement for energy scan using realistic conversion efficiencies (~50%)
- Very poor agreement with focal scan!

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



Modified sheath acceleration model for large foci





Increase in acceleration time

$$\tau = \tau_L$$

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

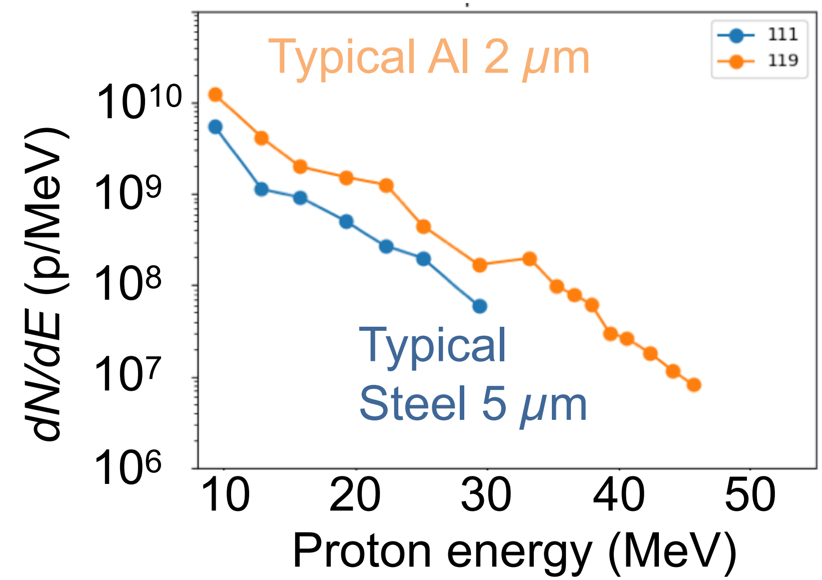
$$\tau_{esc} \approx \frac{2B}{c}$$

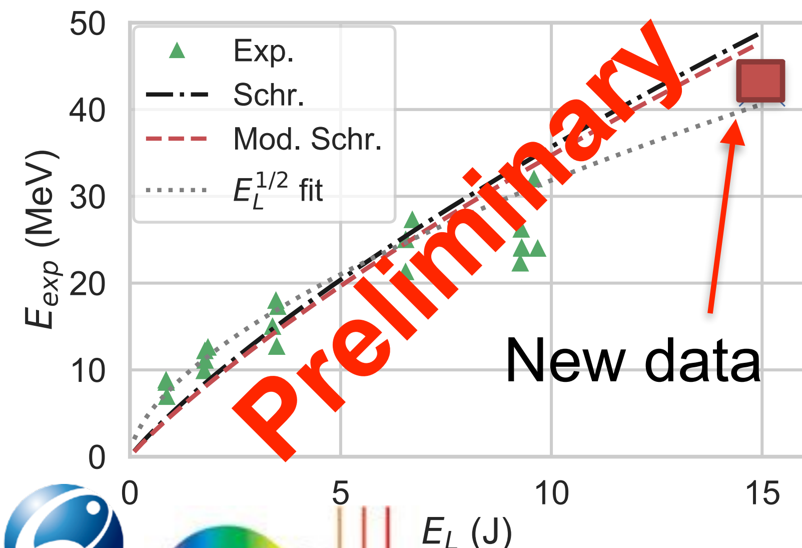
*See also C. Brenner PPCF **56** (2014)*

QST KPSI Kansai Photon Science Institute

Sheath acceleration at high repetition & future prospects - energy

- Smooth > 30 MeV beams at 0.1 Hz
- Thinner targets -> higher flux up to ~50 MeV
- Technological challenge @ high repetition rate

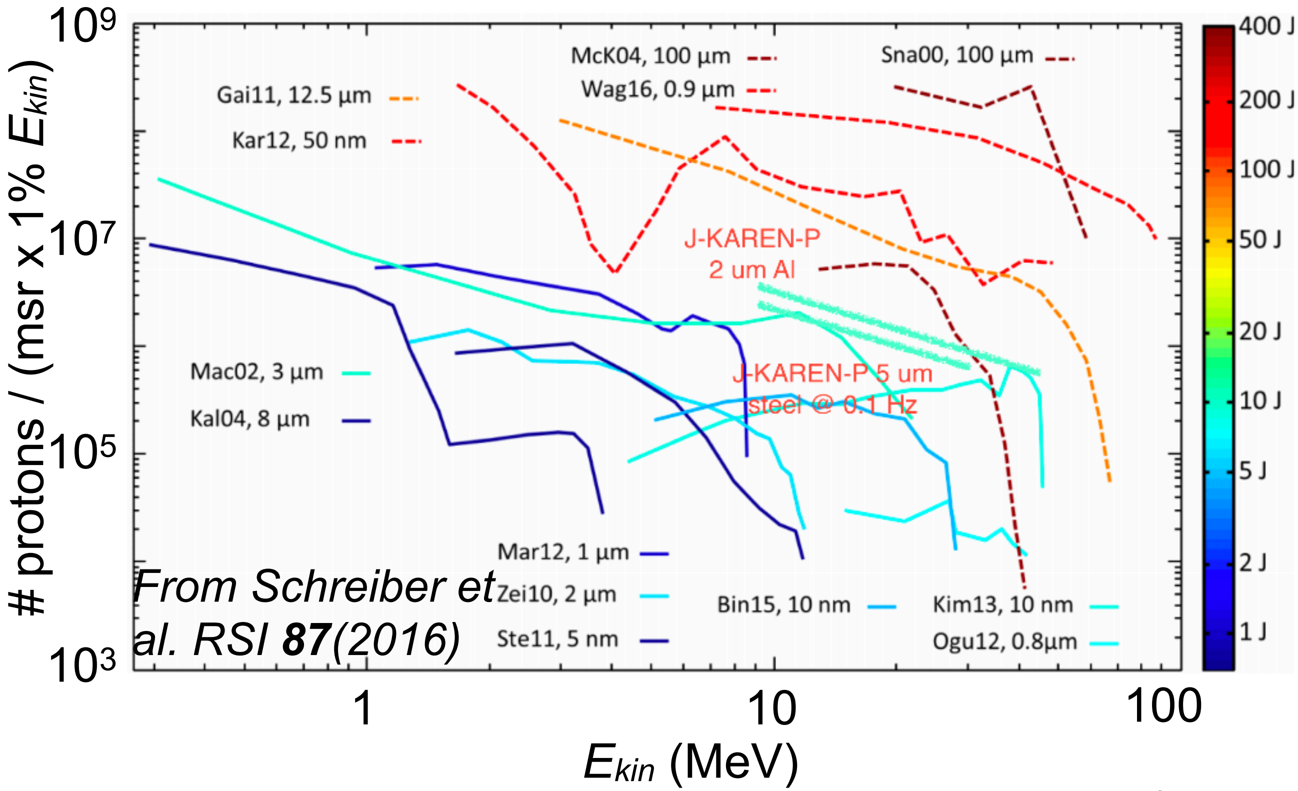




- Subsequent experimental campaign enabled increase in laser energy to ~15 J on target
- Steel 5 μm target resulted in >40 MeV protons

QST
KPSI
Kansai Photon Science Institute

Sheath acceleration at high repetition & future prospects - current



- Higher currents require high repetition rates and high energy
- Significant challenges in targetry, debris, radiation shielding

- Enormous peak currents possible!
- Beams difficult to transport to applications

	Beam > 10 MeV	1 msr, 1% E_{kin} @ ~10 MeV
	~10^{11} particles	~10^7 particles
	~10 nC	~ 1 pC
	~100 kA (peak)	*~10 A (peak)*
(0.1 Hz)	~1 nA (avg.)	~100 fA (avg.)
(10 Hz)	~100 nA (avg.)	~10 pA (avg.)

QST
KPSI Kansai Photon Science Institute

Summary

- Investigated acceleration of ions in sheath fields generated by electrons heated by ultra-intense lasers
- Saturation of electron temperature with ultra-intense tightly focused spots, limiting potential energy gain
- Repetitive proton acceleration scales up to 30-40 MeV, with poor scaling with reducing focal spot size
- Working towards a high flux & high energy repetitive source of protons (and ions) for applications

QST KPSI Kansai Photon Science Institute