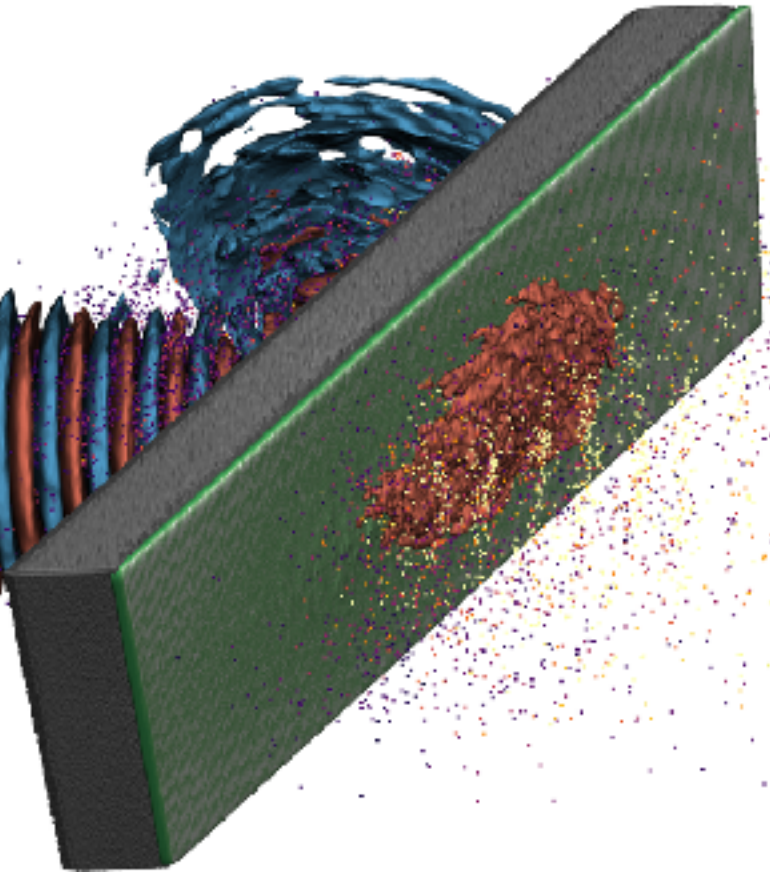
Challenges of accelerating ions with lasers at extreme intensities

5th European Advanced Accelerator Concepts Workshop
21st September 2021

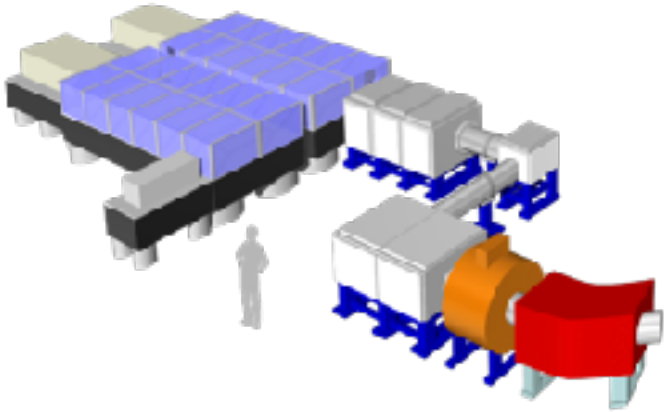


N.P. Dover[1,2], T. Ziegler[3], H. Sakaki[2], M. Garten[3], I. Goethel[3], Ko. Kondo[2], H.F. Lowe[2], M.A. Alkhimova[4], S. Assenbaum[3], C. Bernert[3], S. Bock[3], E.J. Ditter[1], O.C. Ettlinger[1], A.Ya. Faenov[5,4], M. Hata[5], G.S. Hicks[1], N. Iwata[5], H. Kiriyama[2], J. K. Koga[2], A. Kon[2],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

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

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** (up to ~100 MeV)
  - **Highly divergent**
  - **Typically broadband energy**
- Complementary technology to existing methods, with new applications



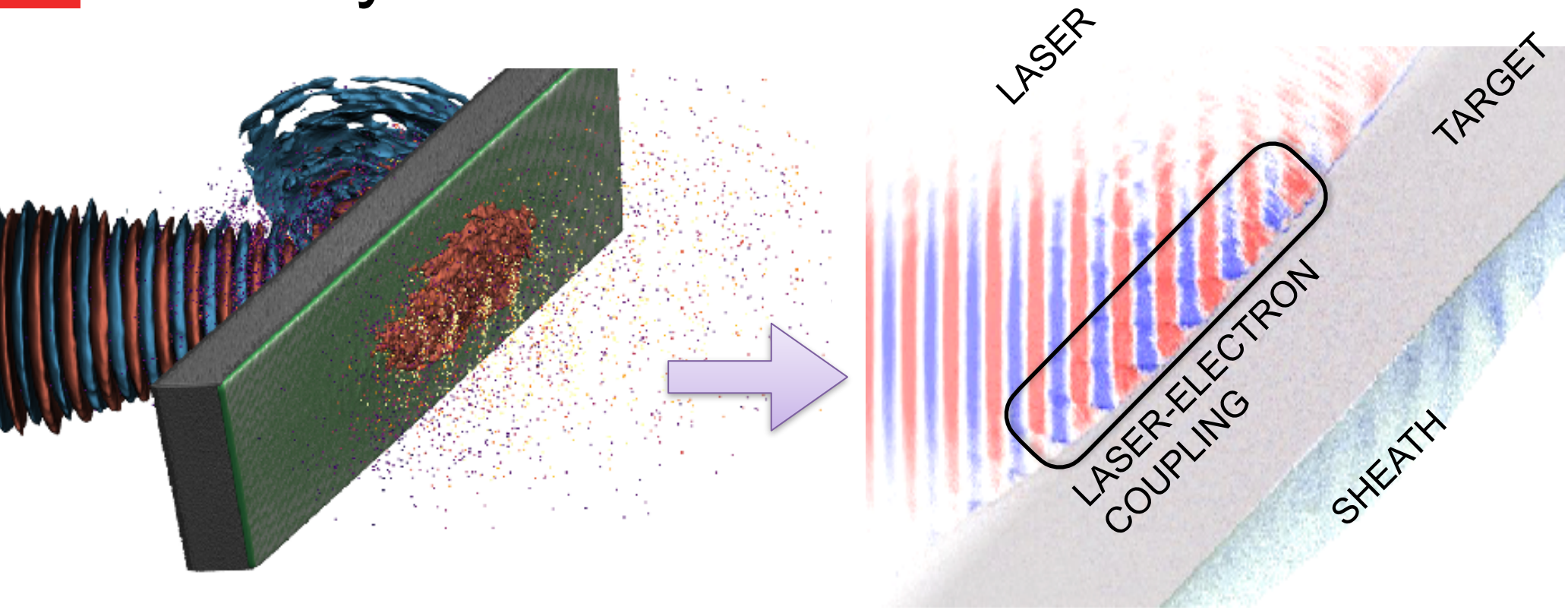
Applications in science:

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

Applications in society:

- Materials processing
- Radiobiology/therapy

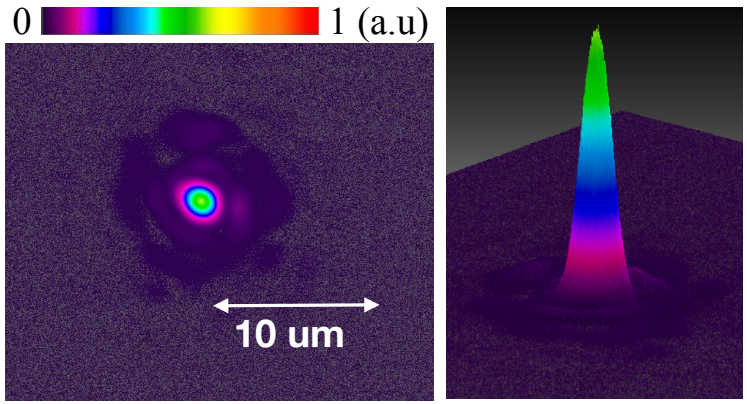
Laser-solid interactions at ultra-high intensity



- Only a few laser facilities operating with intensities > 10^{21} Wcm^{-2}
- Fundamental questions:
  - What is the dominant mechanism for laser-electron coupling?
  - How important is the prepulse/rising edge?
  - How do existing ion acceleration schemes scale to higher intensities?

Ultrahigh laser intensities at J-KAREN-P and DRACO-PW

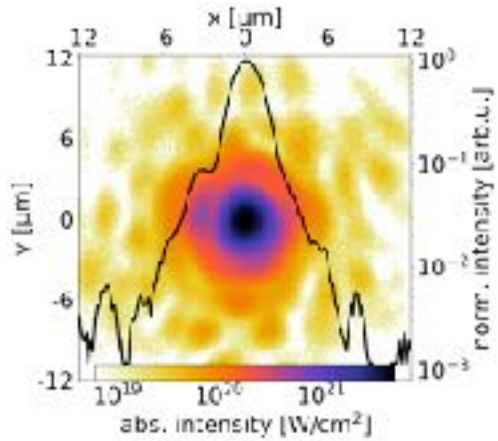
J-KAREN-P



- Laser energy ~10 J *on target* with ~45 fs FWHM
- Spot size ~1.5 μm FWHM
- Intensity ≈ 3-4x10^{21} W/cm^2 ($a_0 \approx 40$)

Pirozhkov et al. Opt. Expr. ***25****, (2017);*
Kiriyama et al. Opt. Lett. ***43****, (2018)*

DRACO-PW



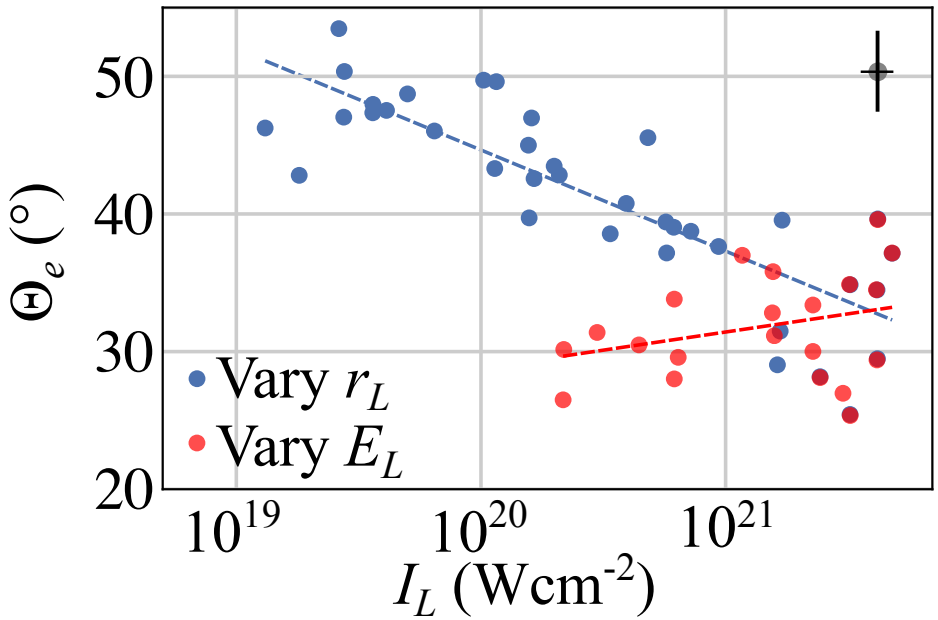
- Laser energy ~21 J *on target* with ~30 fs FWHM
- Spot size ~2.5 μm FWHM
- Intensity ≈ 5x10^{21} W/cm^2 ($a_0 \approx 50$)

Schramm et al., J. Phys.: Conf. Ser. ***874,*** *012028 (2017)*

- Using inherent contrast (no plasma mirrors)
- Allows “repetitive” operation, depending on target replenishment

Measuring ultra-intense laser driven electron beam parameters

Tape target,
5 μm steel,
45° a.o.i.



- Parametric scans of *laser energy* and *laser focal spot* to understand intensity scaling of electron divergence and temperature
  - Beam collimation *increases* with *decreasing focal size*

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

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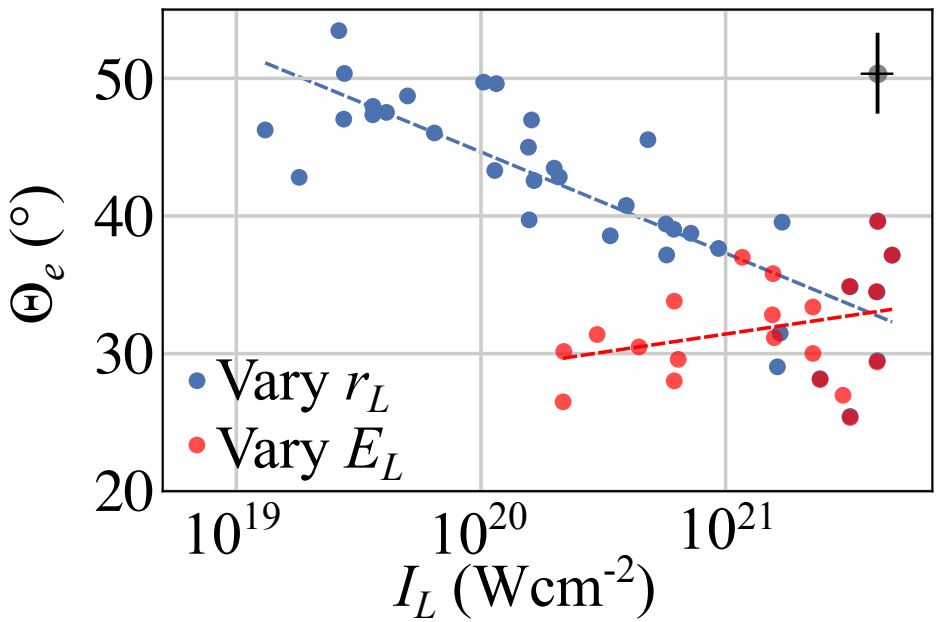
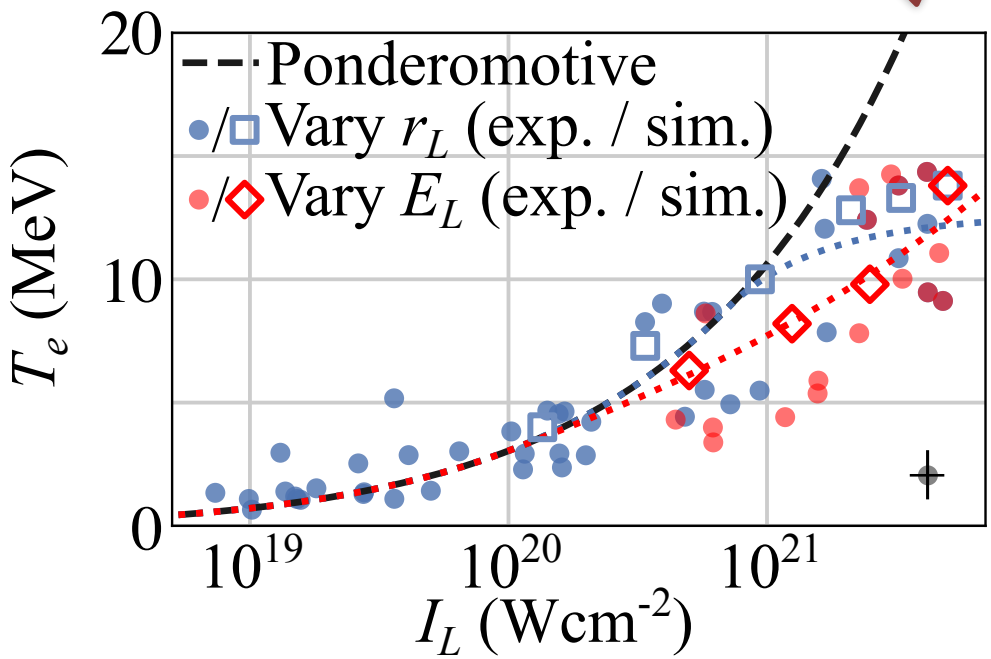
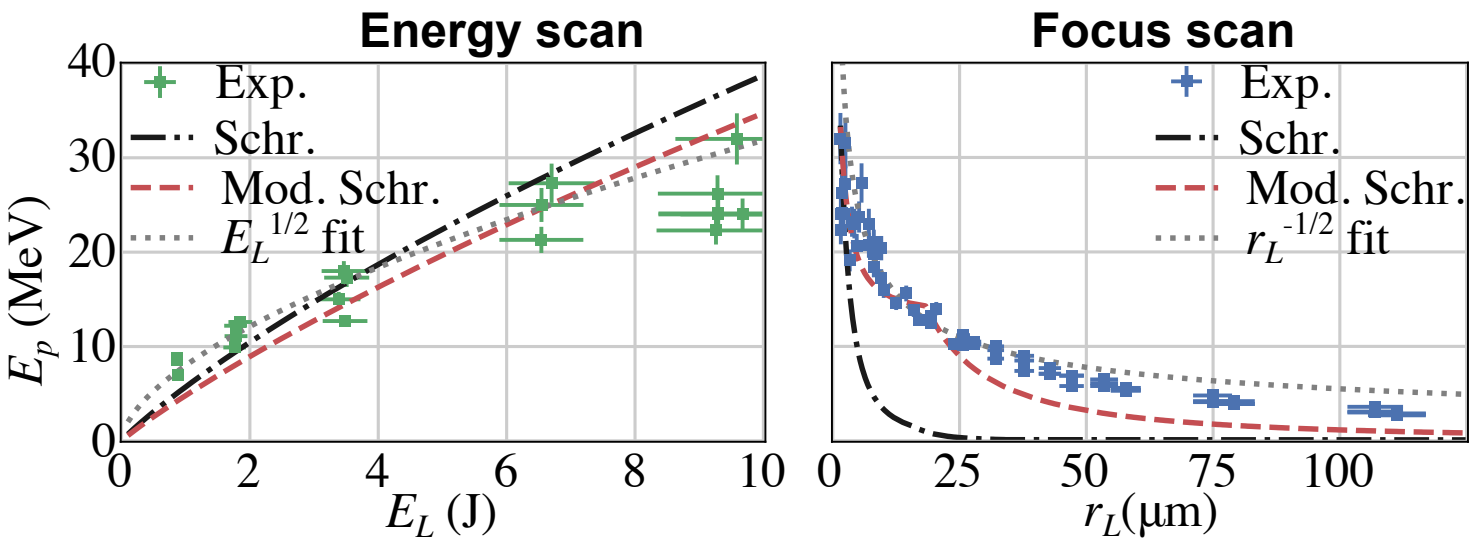




- Parametric scans of *laser energy* and *laser focal spot* to understand intensity scaling of electron divergence and temperature
  - Beam collimation *increases* with *decreasing focal size*
  - Beam temperature *higher* for *larger focal size* (at same intensity)

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

Parametric scan of proton energy scaling

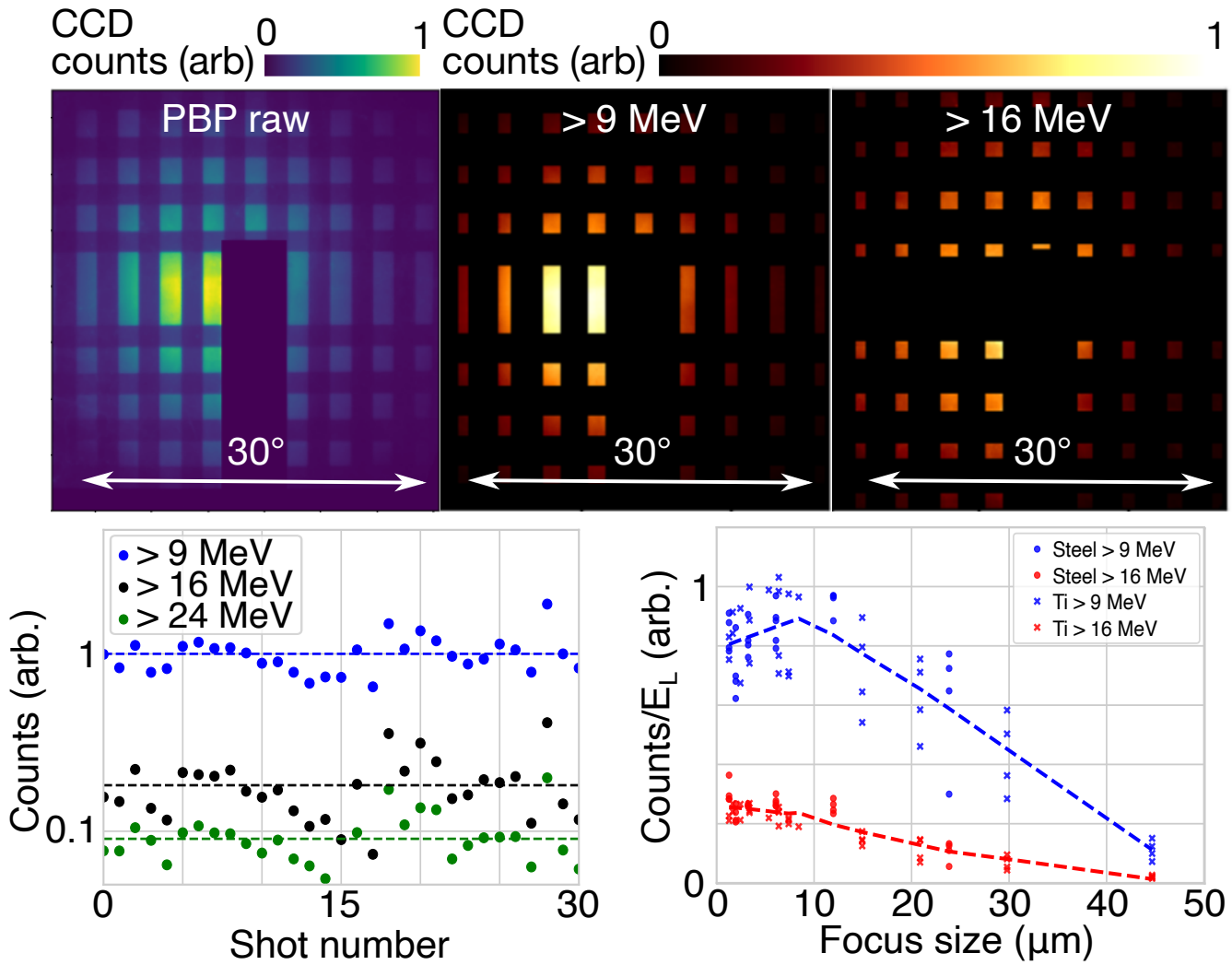


- Same parametric scans of *energy* and *focal spot* reveal scaling with laser energy ($\propto E_L^{1/2}$, $\propto I_L^{1/2}$) and spot size ($\propto r_L^{-1/2}$, $\propto I_L^{1/4}$)
  - Widely used models fail badly for larger focal spot sizes
  - Introduced an ad-hoc modification of Schreiber model including acceleration time lengthened by refluxing within sheath extent

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

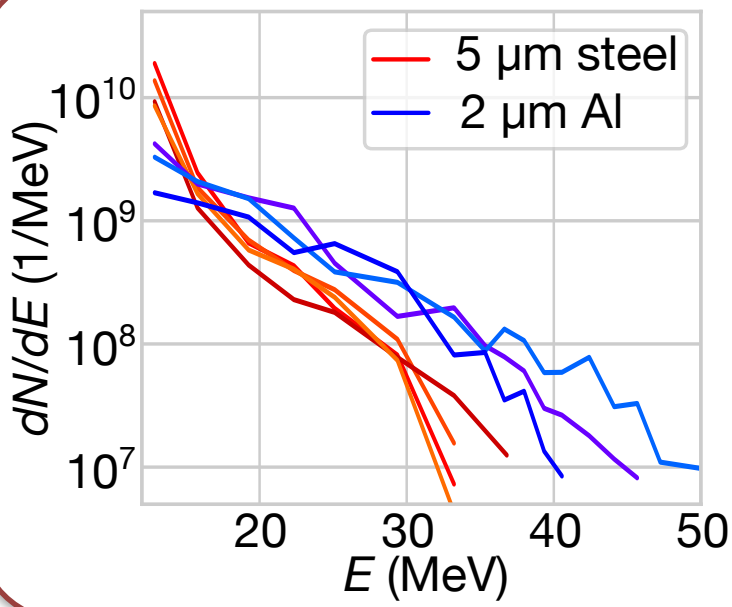
Stable proton generation at 0.1 Hz from tape target

- Maximum energies up to 40 MeV with smooth spatial profile
- Consecutive shots shows fluctuations ~25% of flux



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

Boost to ion energies when using thinner targets



- Using thinner targets boosts ion energies from sheath acceleration
- 50 MeV beams from 2 μm aluminium
- < 1 μm targets pre-expanded by laser prepulse - different ion acceleration mechanisms?

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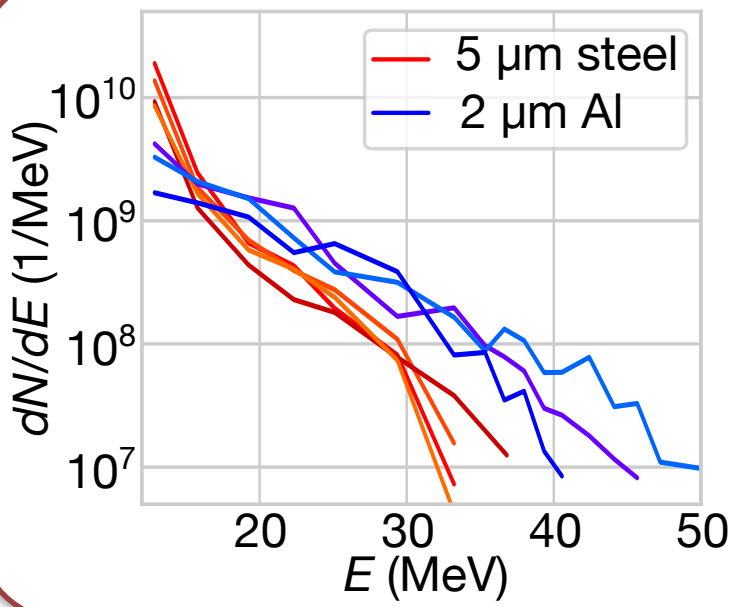

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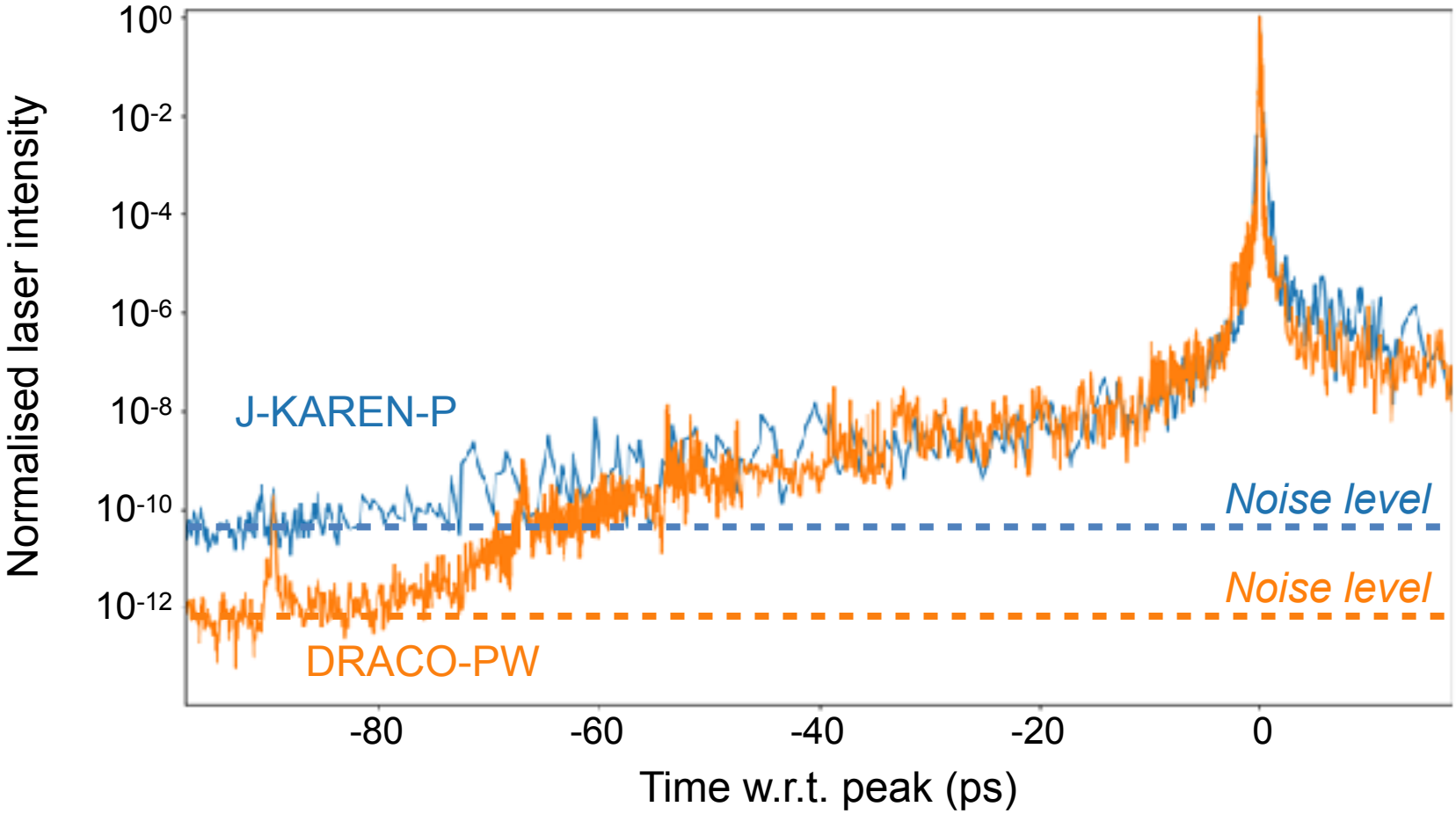
Ultrathin targets - move beyond sheath acceleration

- Radiation pressure acceleration - typically ultrahigh contrast, sub-100 nm targets, circular polarisation, normal incidence…
- Acceleration during relativistic induced transparency - optimised when target turns transparent at peak of the pulse (*Yin LPB 2006, Henig PRL 2009, etc.*)

Prepulse plays a significant role in shaping the target



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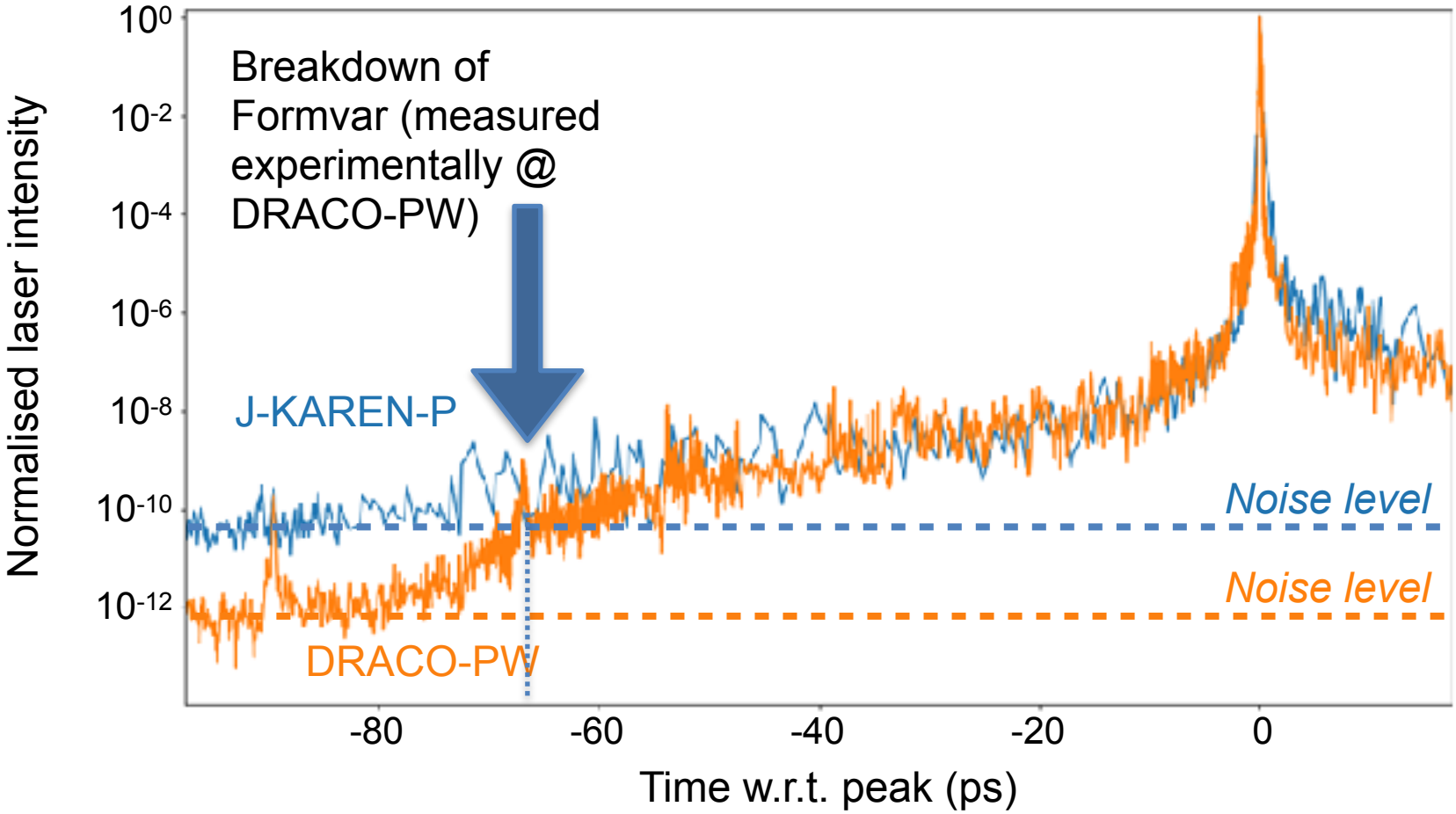

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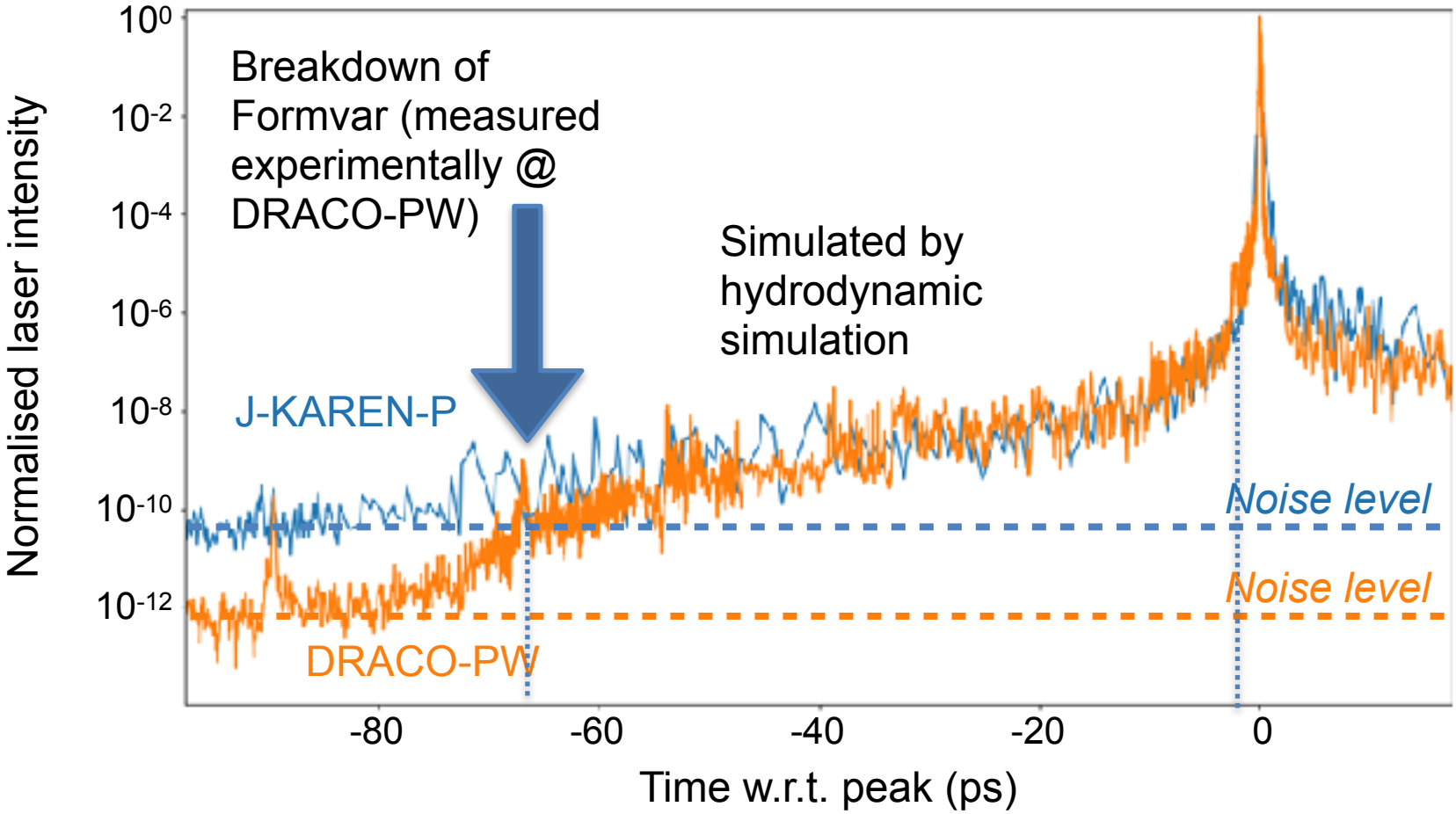

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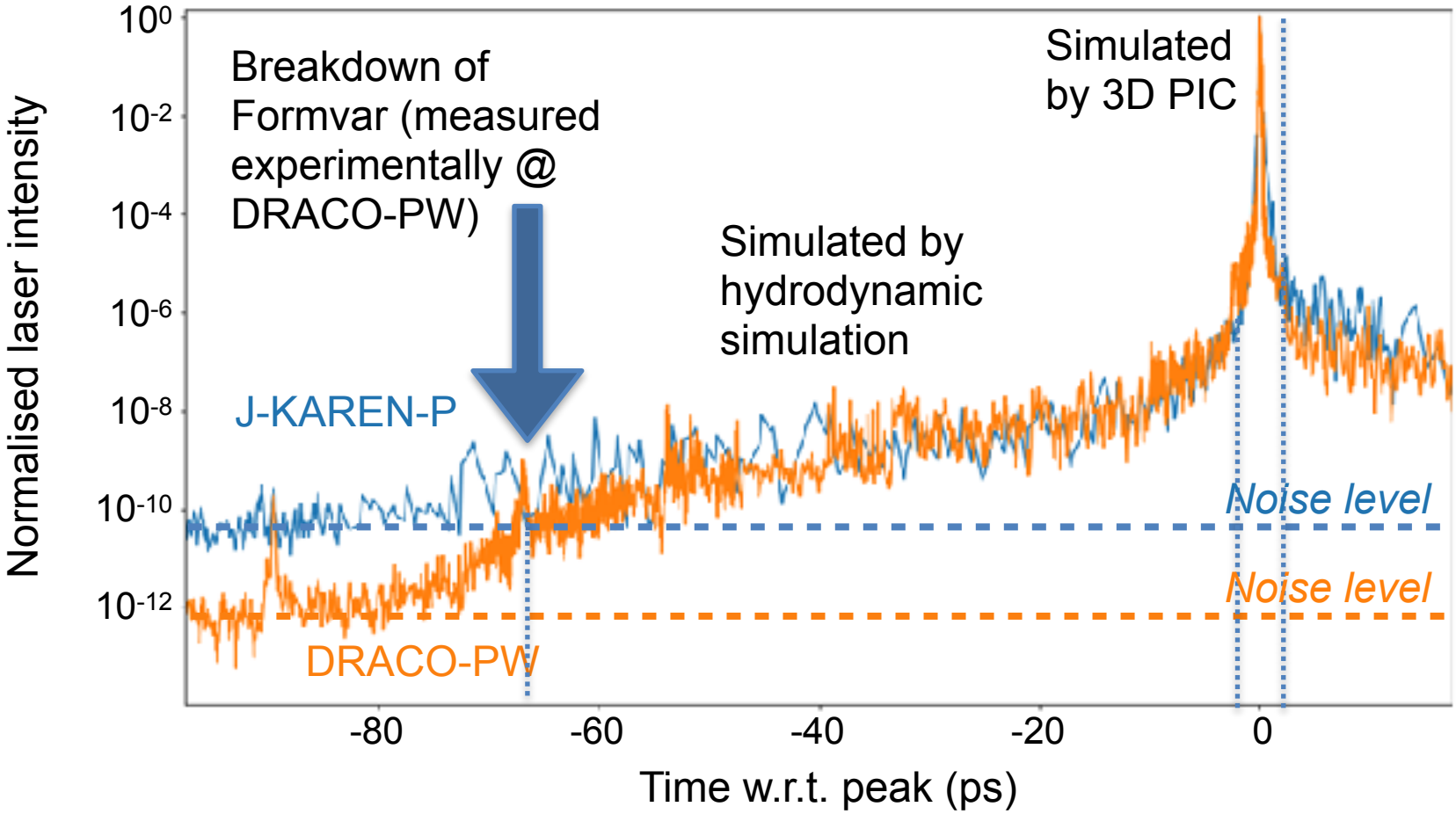
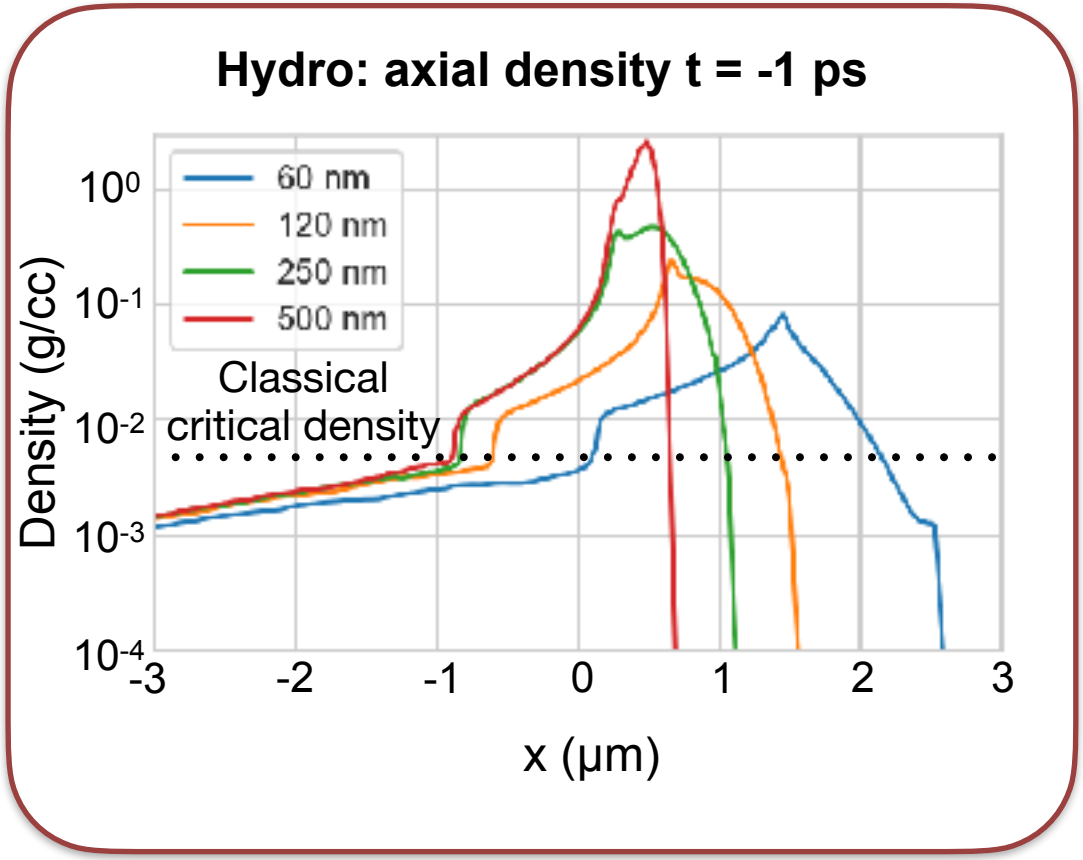


Fluid/3D PIC simulations of ps rising edge



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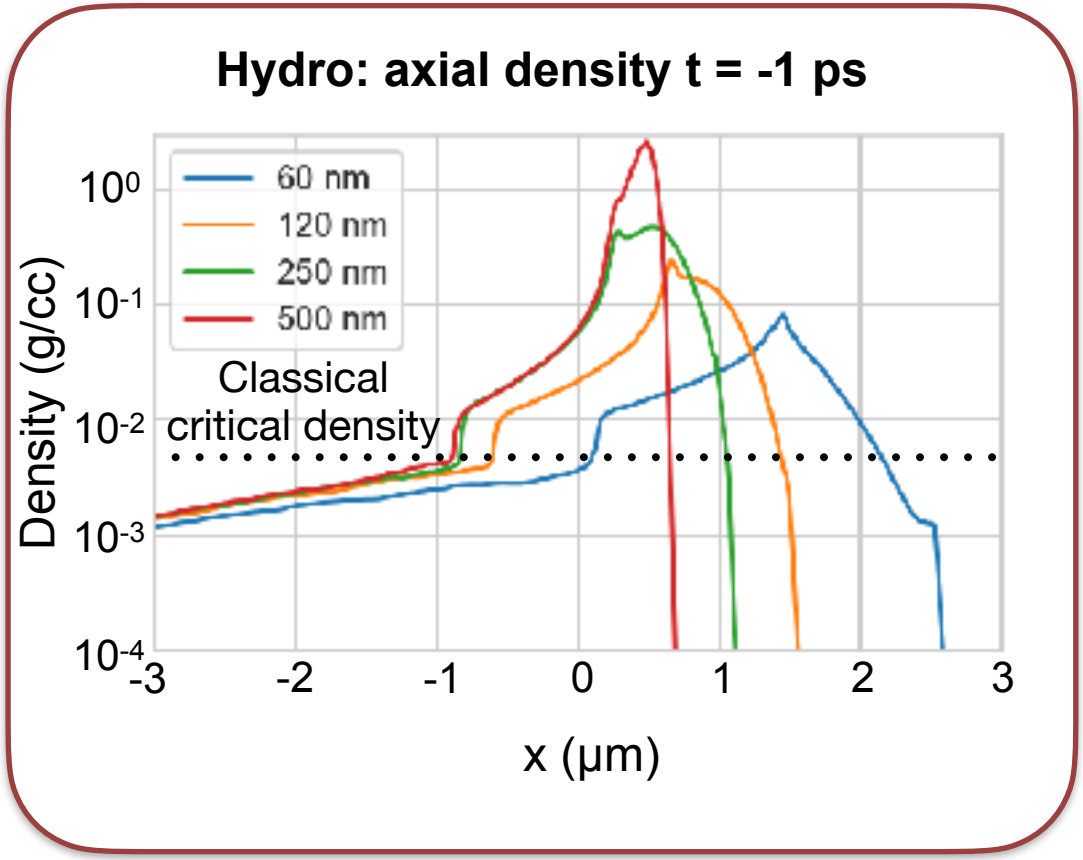
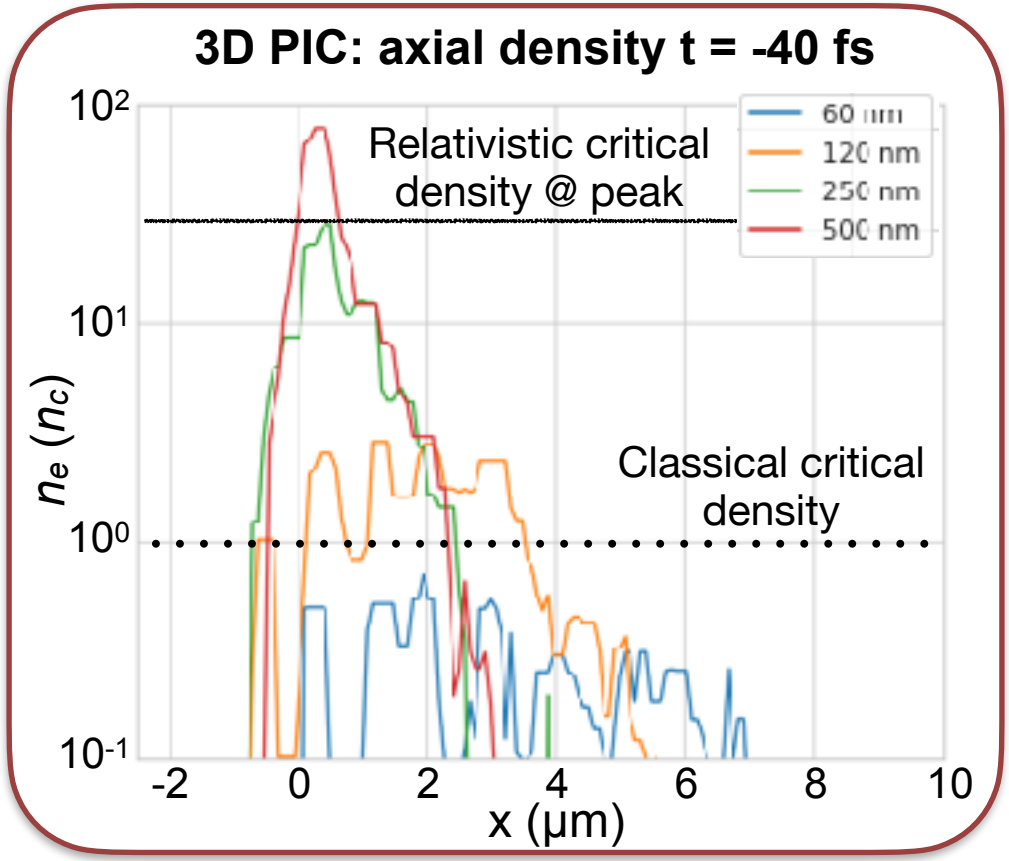
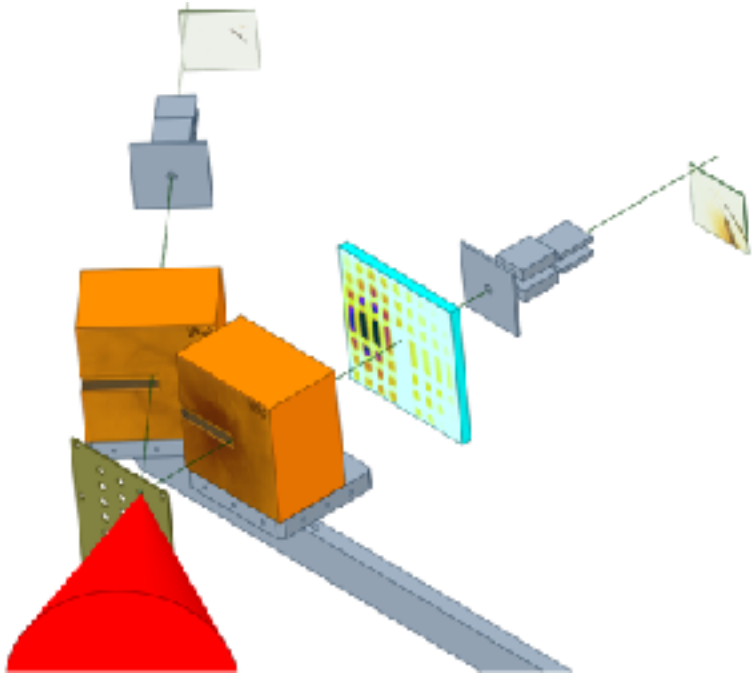




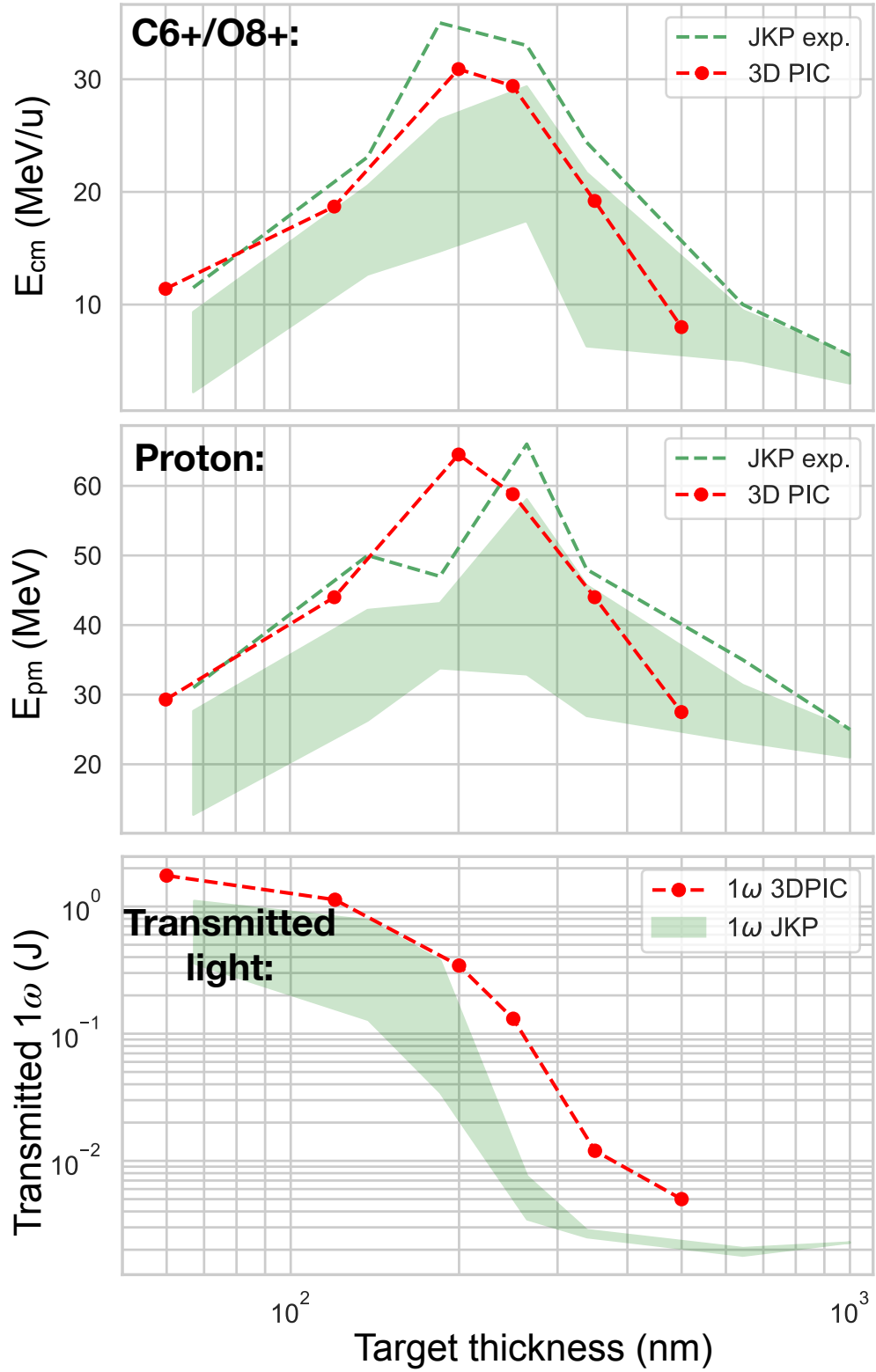
Just before main pulse:

- <120 nm underdense
- ~250 nm ~relativistic critical density
- >500 nm >> relativistic critical density

Experimental observation of optimum thickness



- Maximum energy of proton (~60 MeV) and carbon (~30 MeV/u) at *t*≈250 nm
- Optimum thickness corresponds to start of increase in laser transmission



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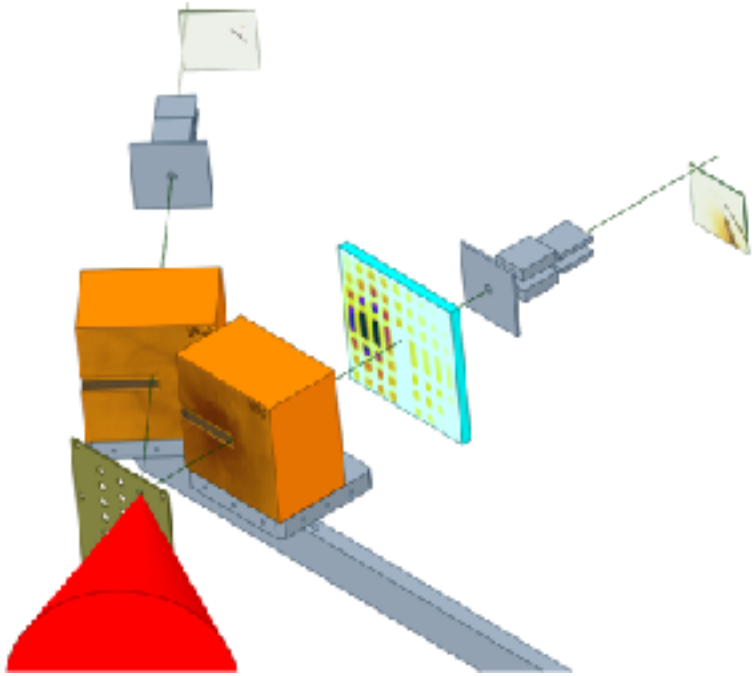

- Maximum energy of proton (~60 MeV) and carbon (~30 MeV/u) at $t \approx 250$ nm
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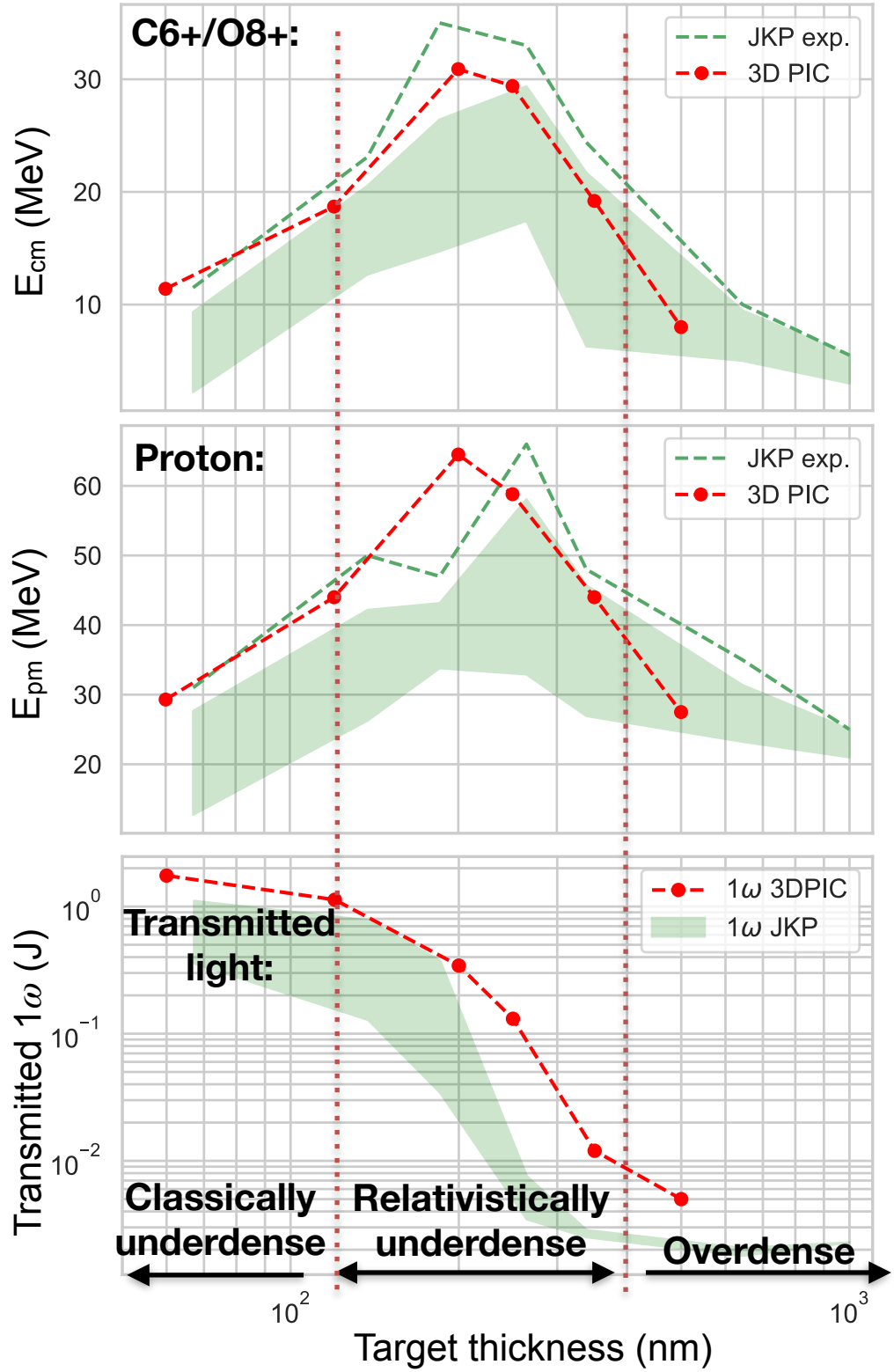
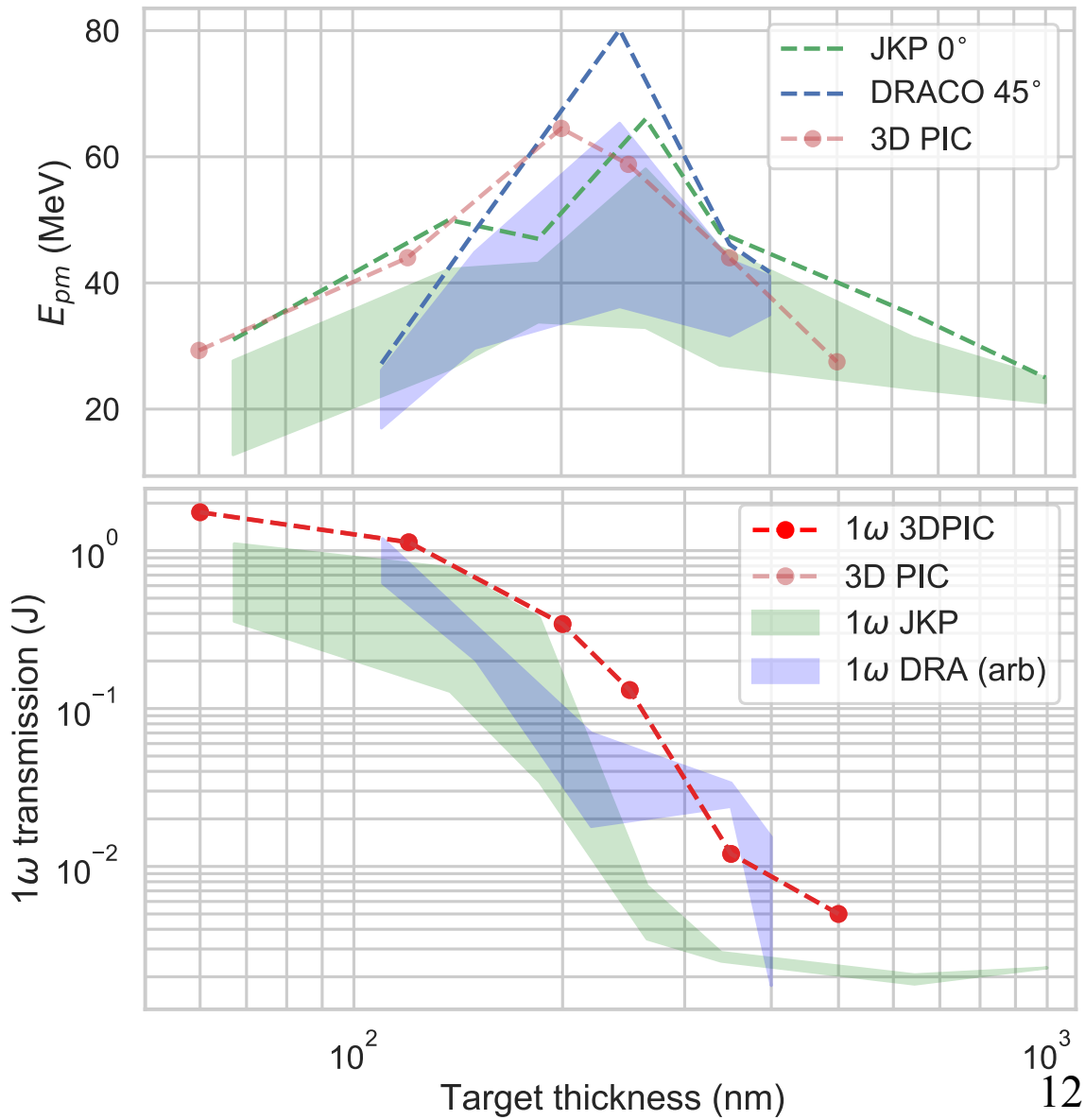
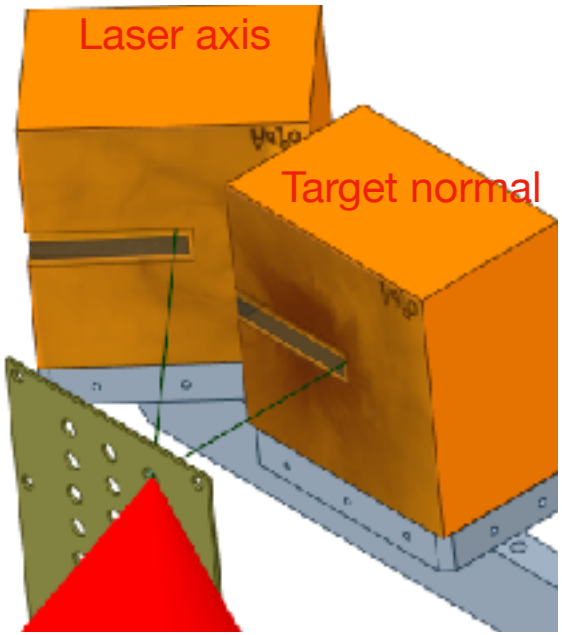


Behaviour is consistent with DRACO-PW experiments

- Formvar thickness scan also performed at DRACO-PW
- Remarkably similar behaviour in proton acceleration and laser transmission, **optimum performance ~250 nm**
- Suggests similar performance achieved by matching **laser intensity** and **contrast**



Beam profiles of generated energetic proton beams



	60 nm		250 nm		780 nm	
	Laser axis	Target normal	Laser axis	Target normal	Laser axis	Target normal
10 MeV						
18 MeV						
27 MeV						
39 MeV						
52 MeV						

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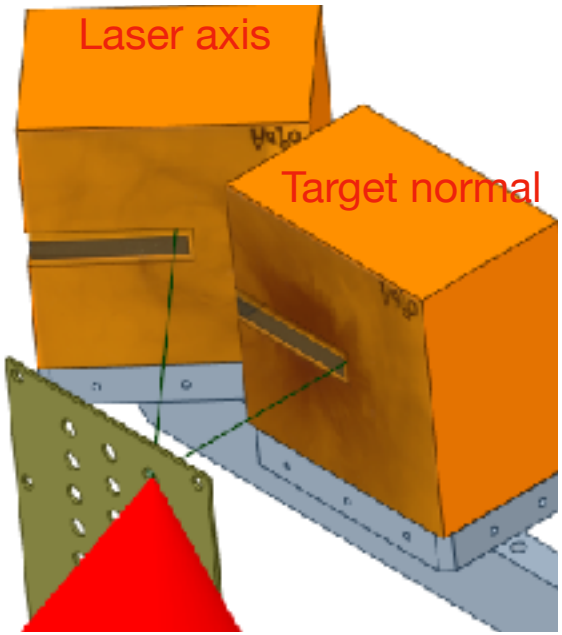

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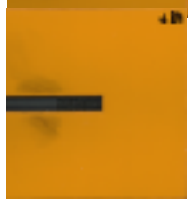
27 MeV						
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52 MeV						

"Overdense"

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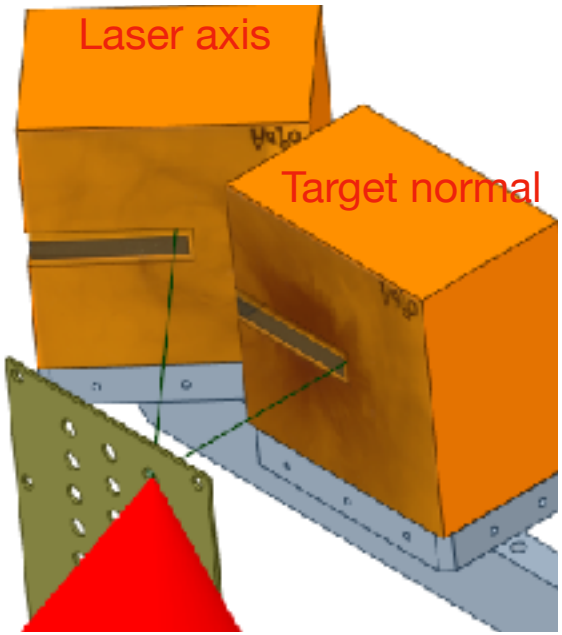

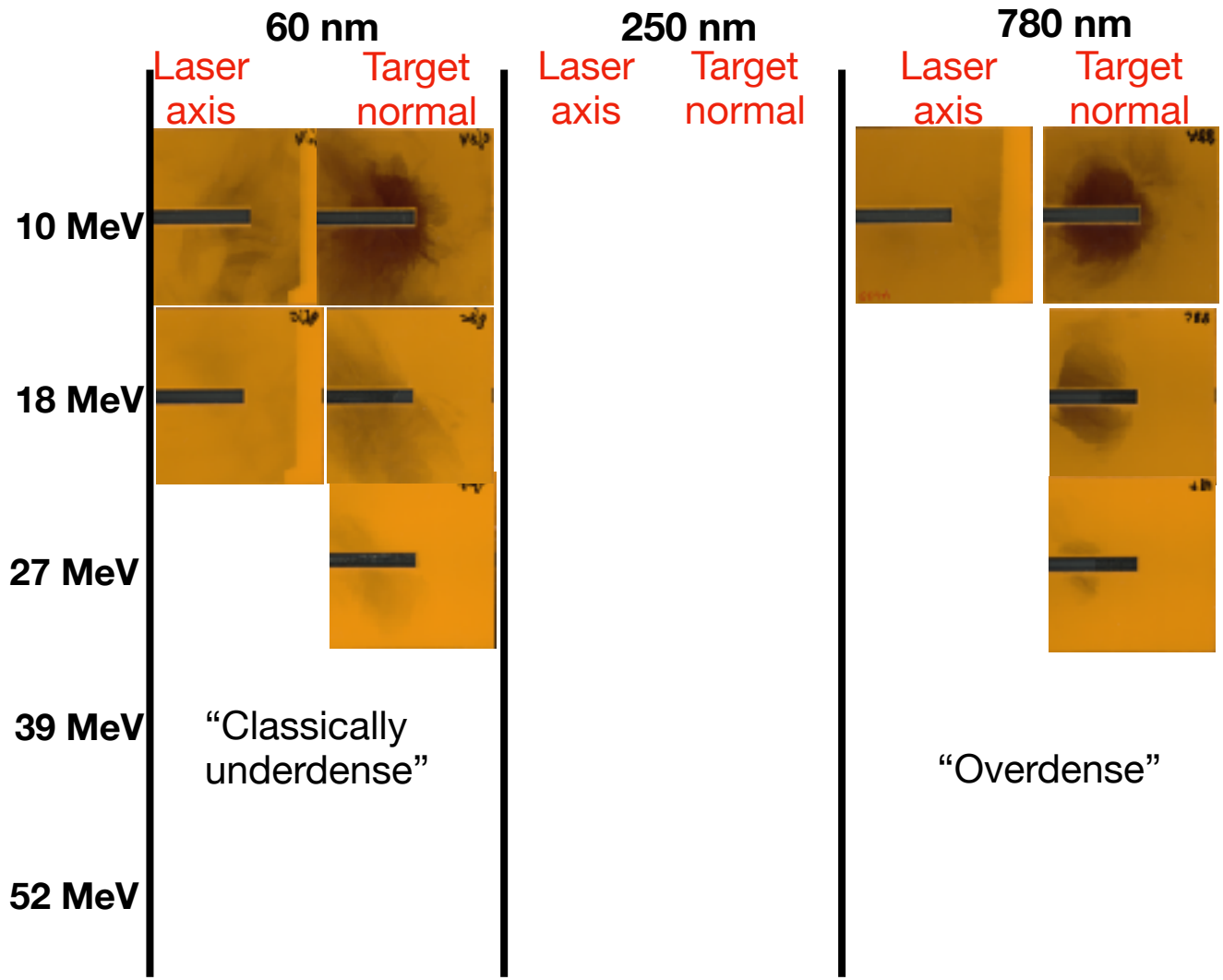

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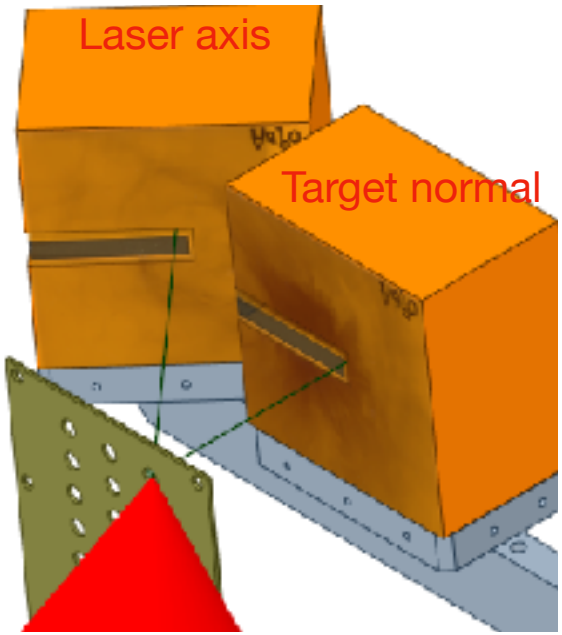

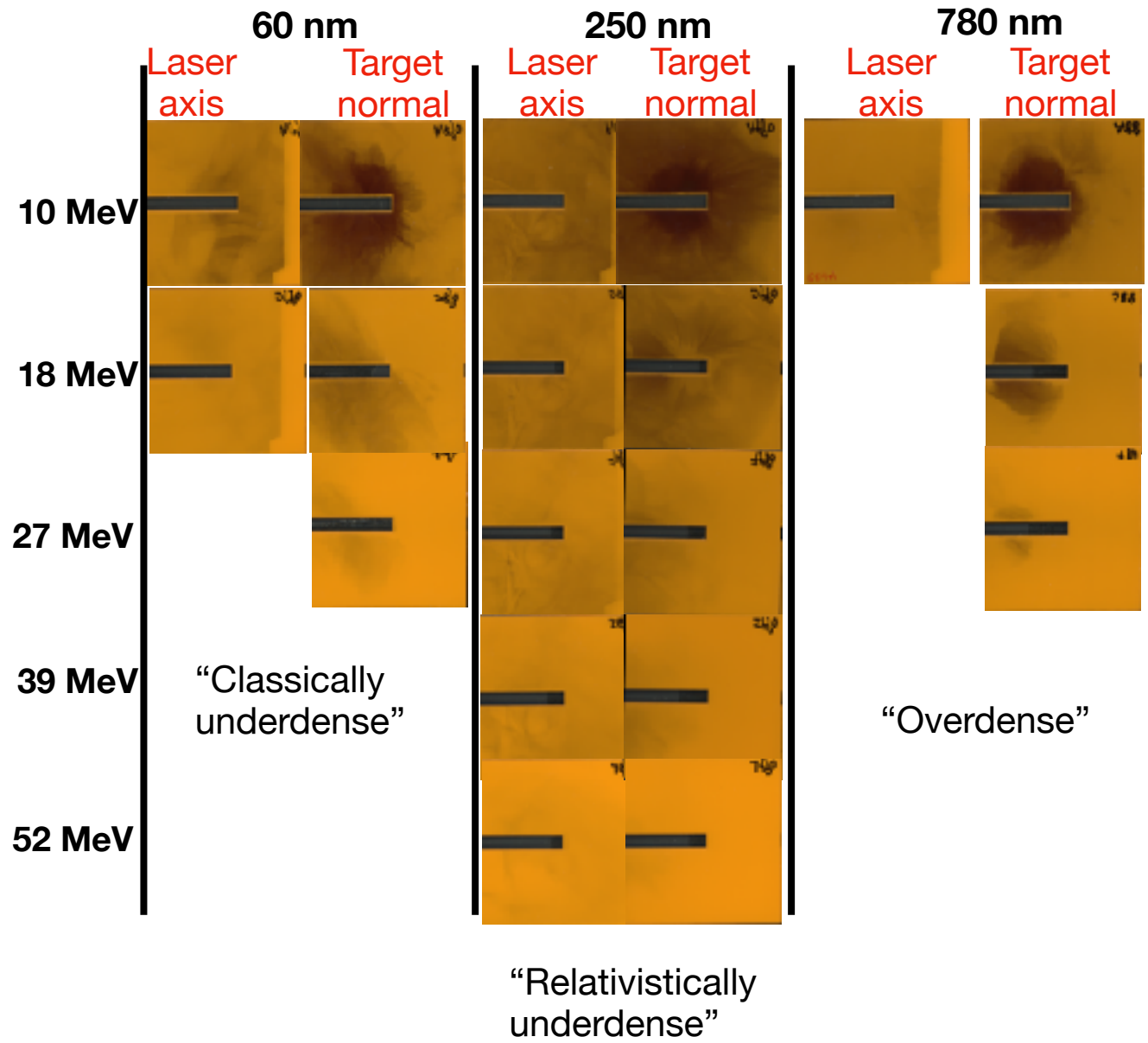

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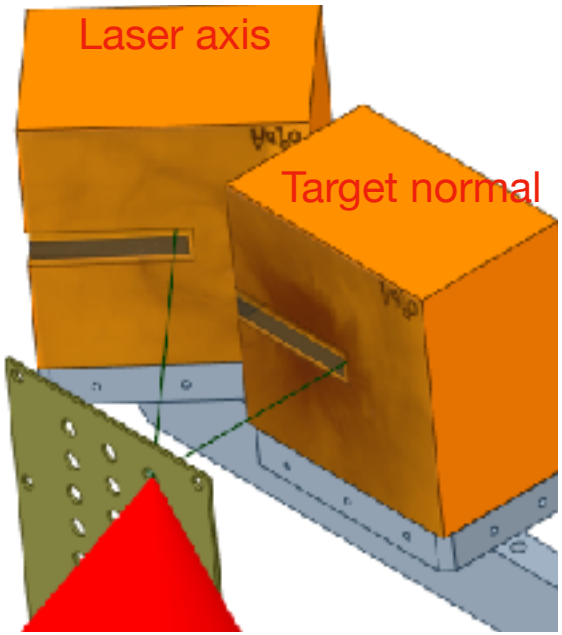
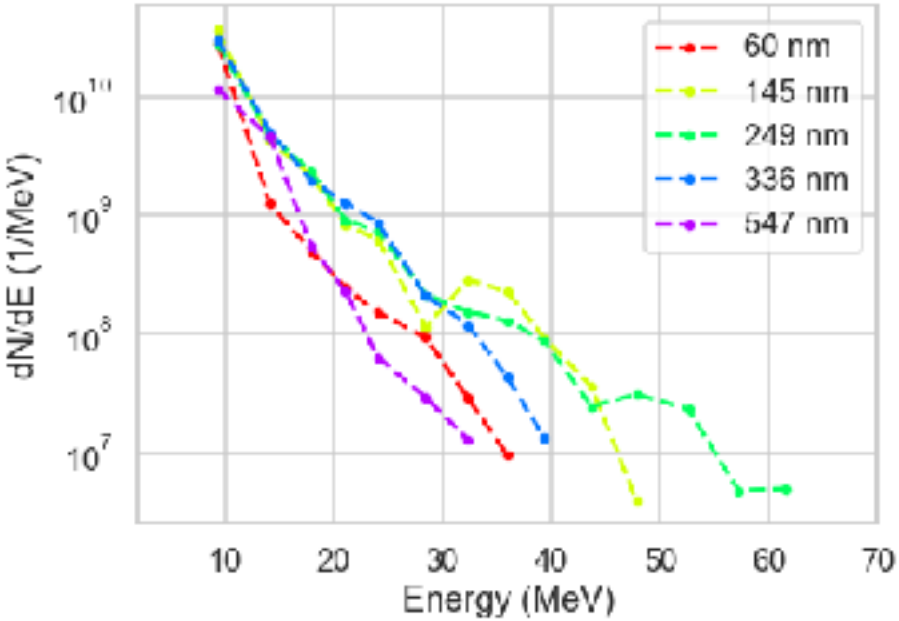
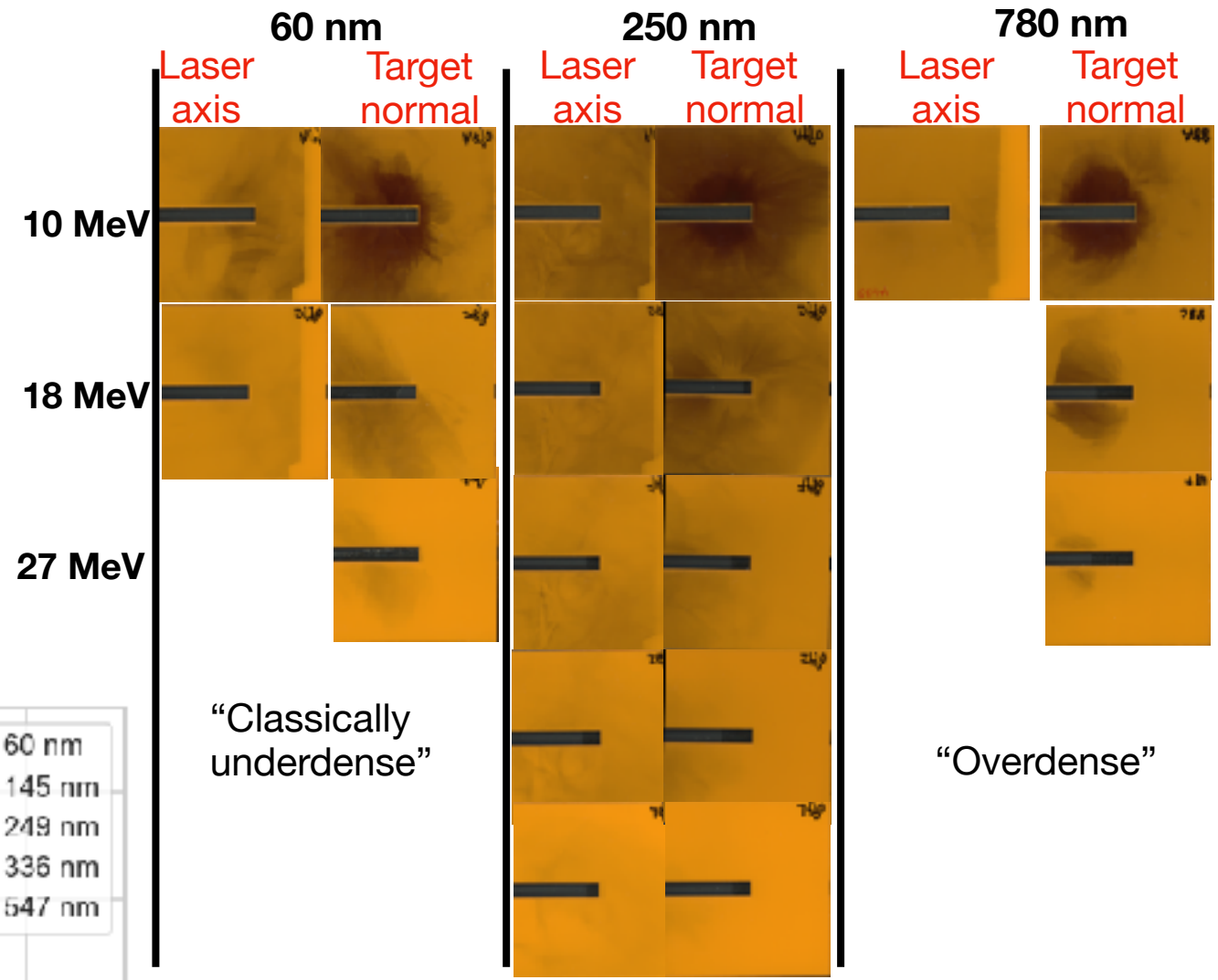
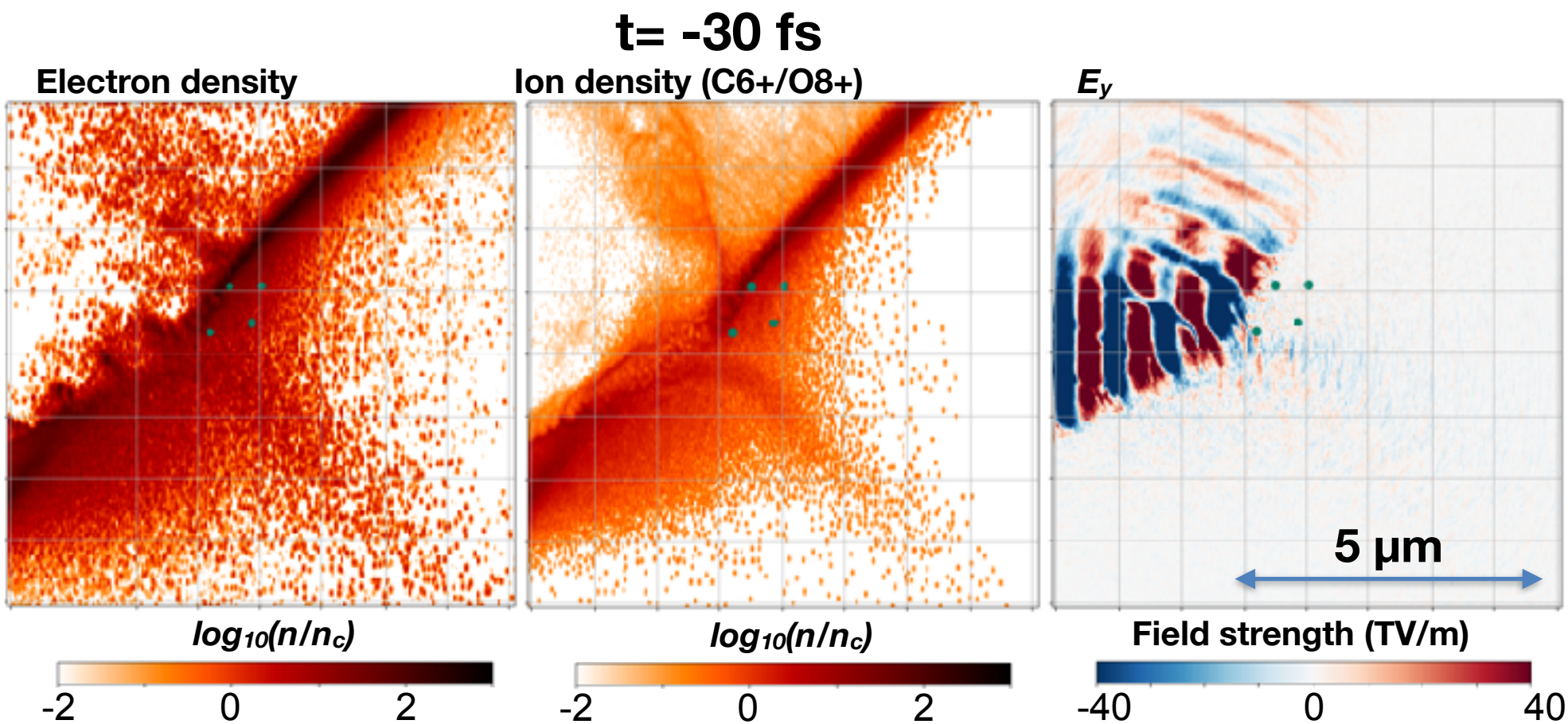






Simulations show relativistic transparency breakthrough at peak of pulse



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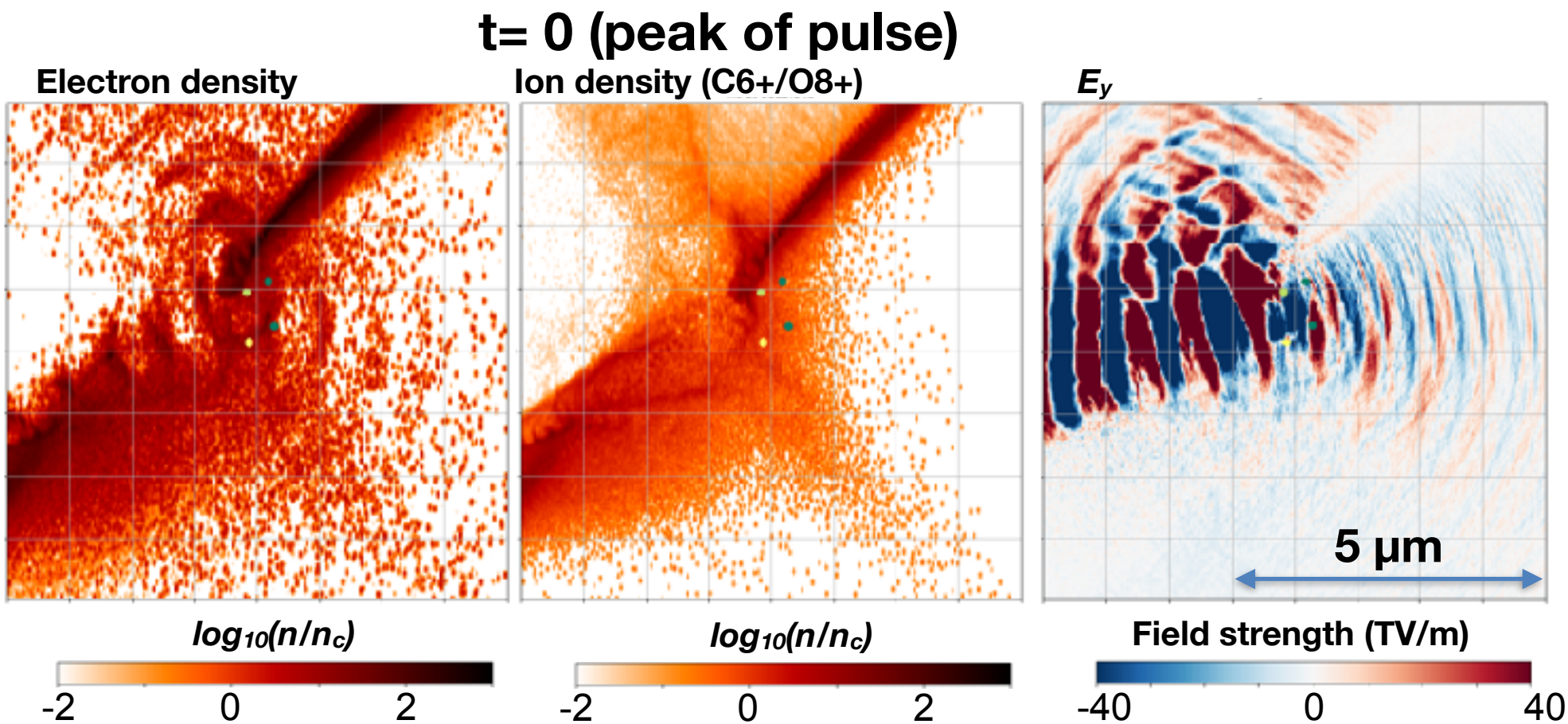

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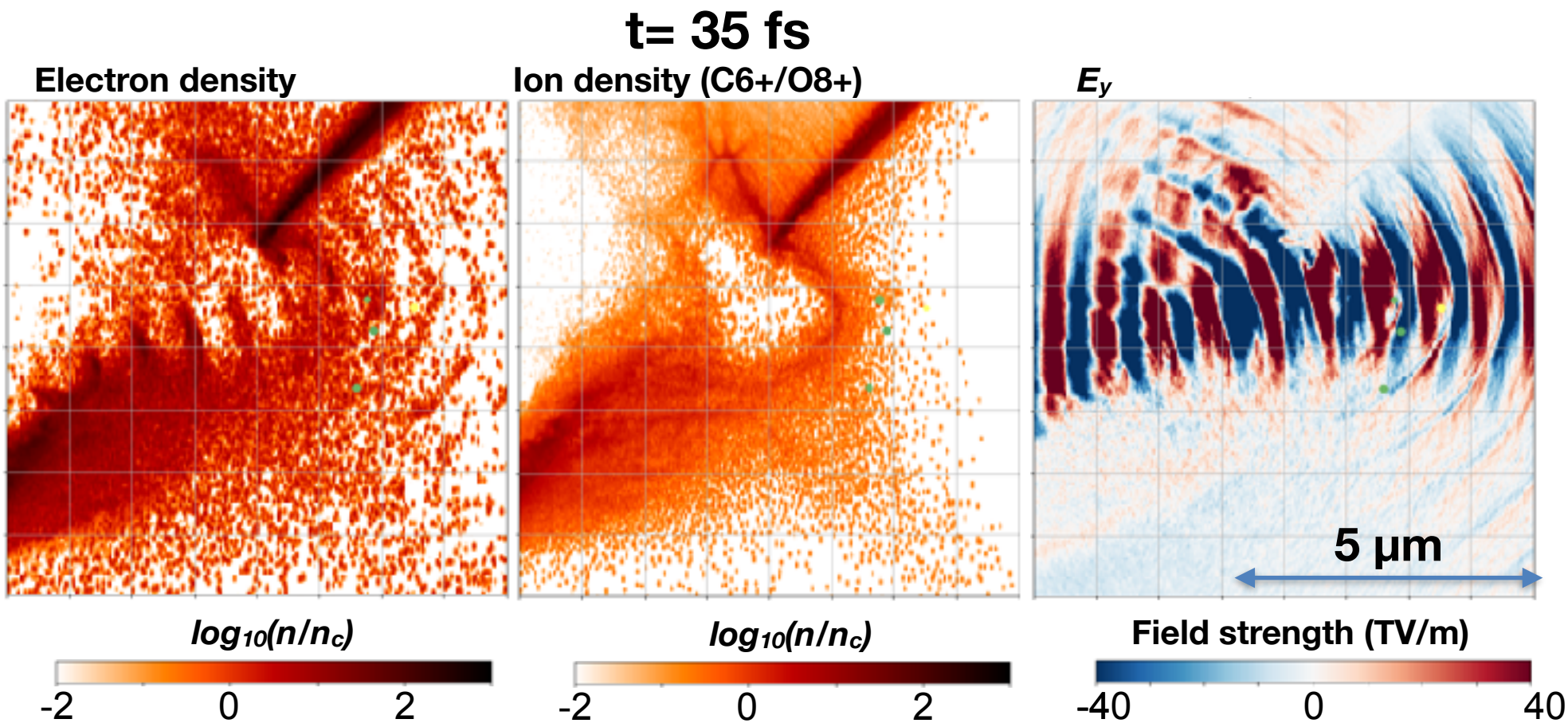
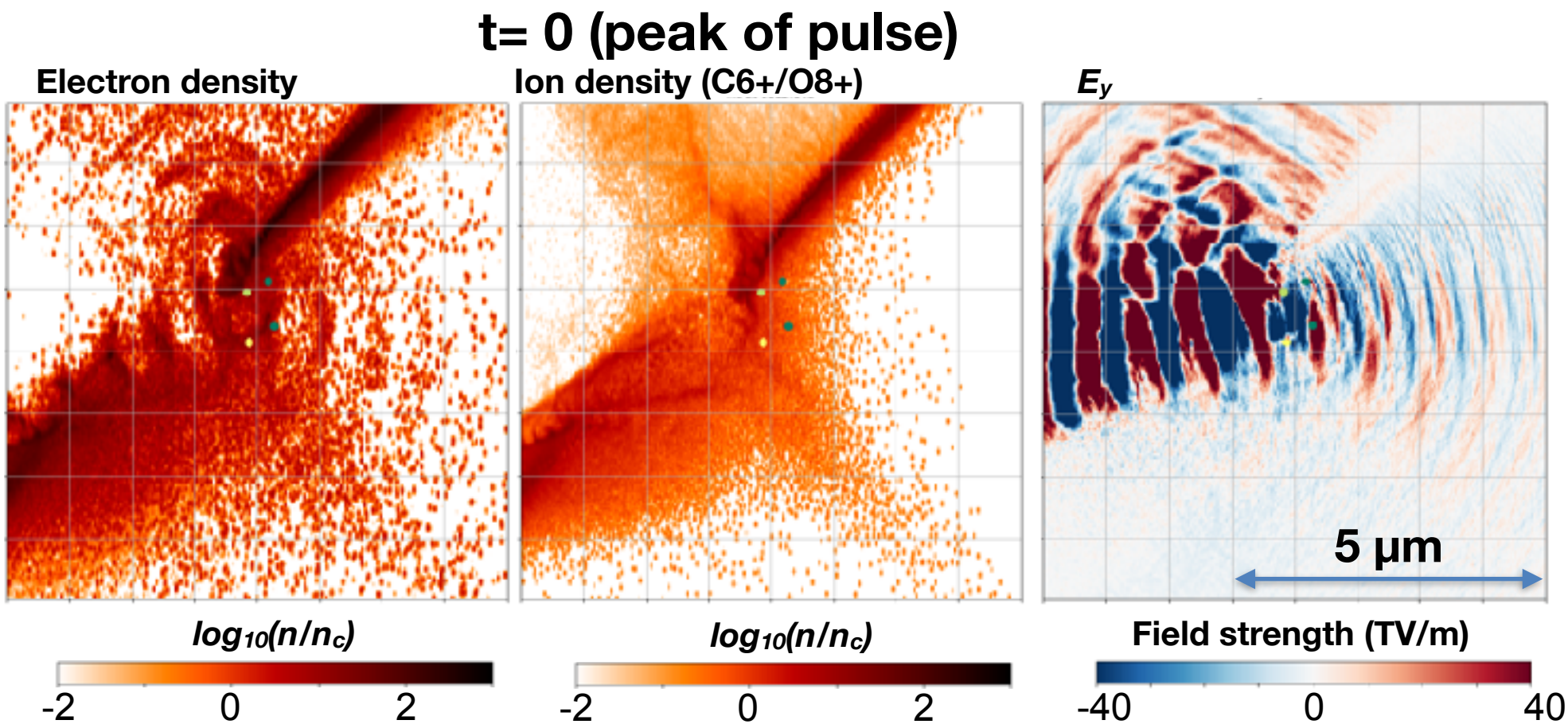


Identification of highest energy ion generation mechanism from 3D PIC



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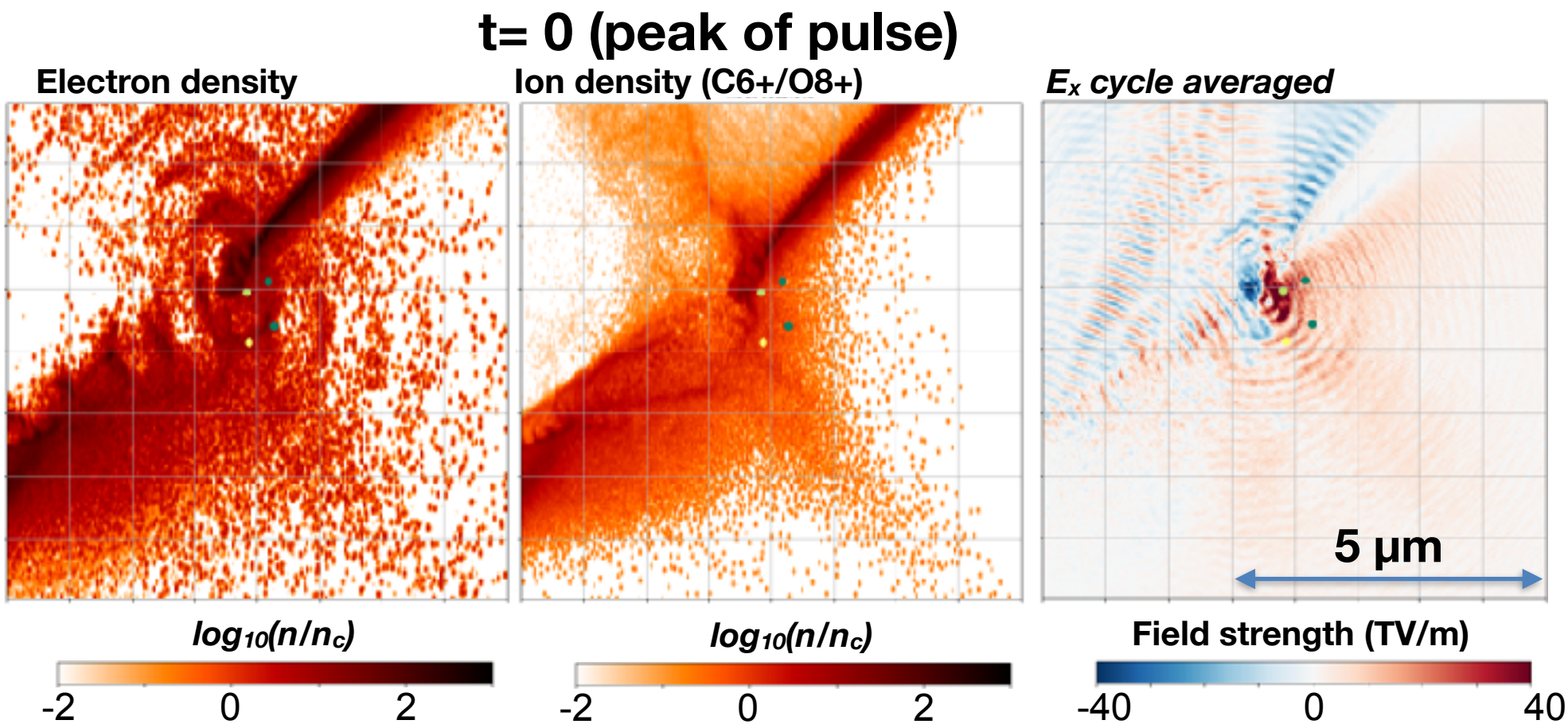

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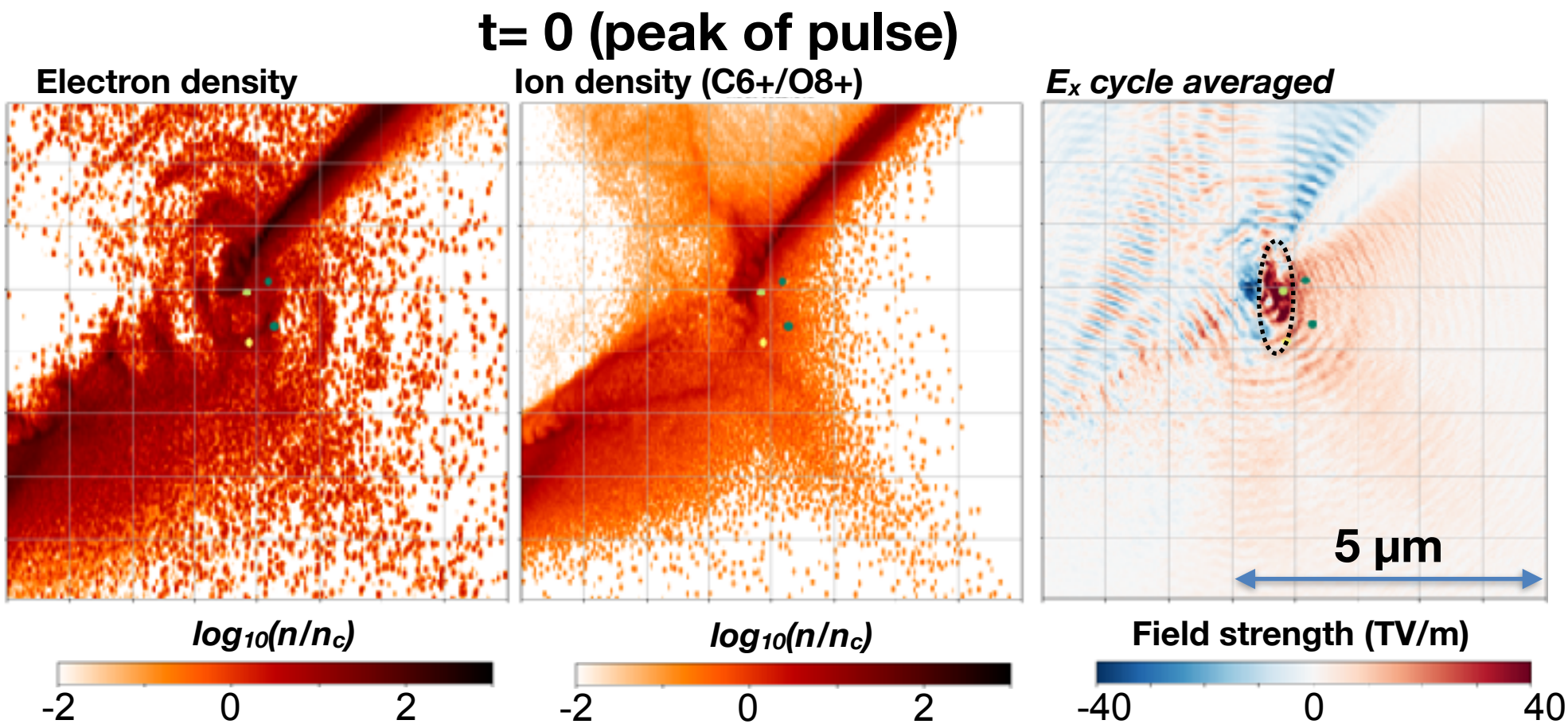

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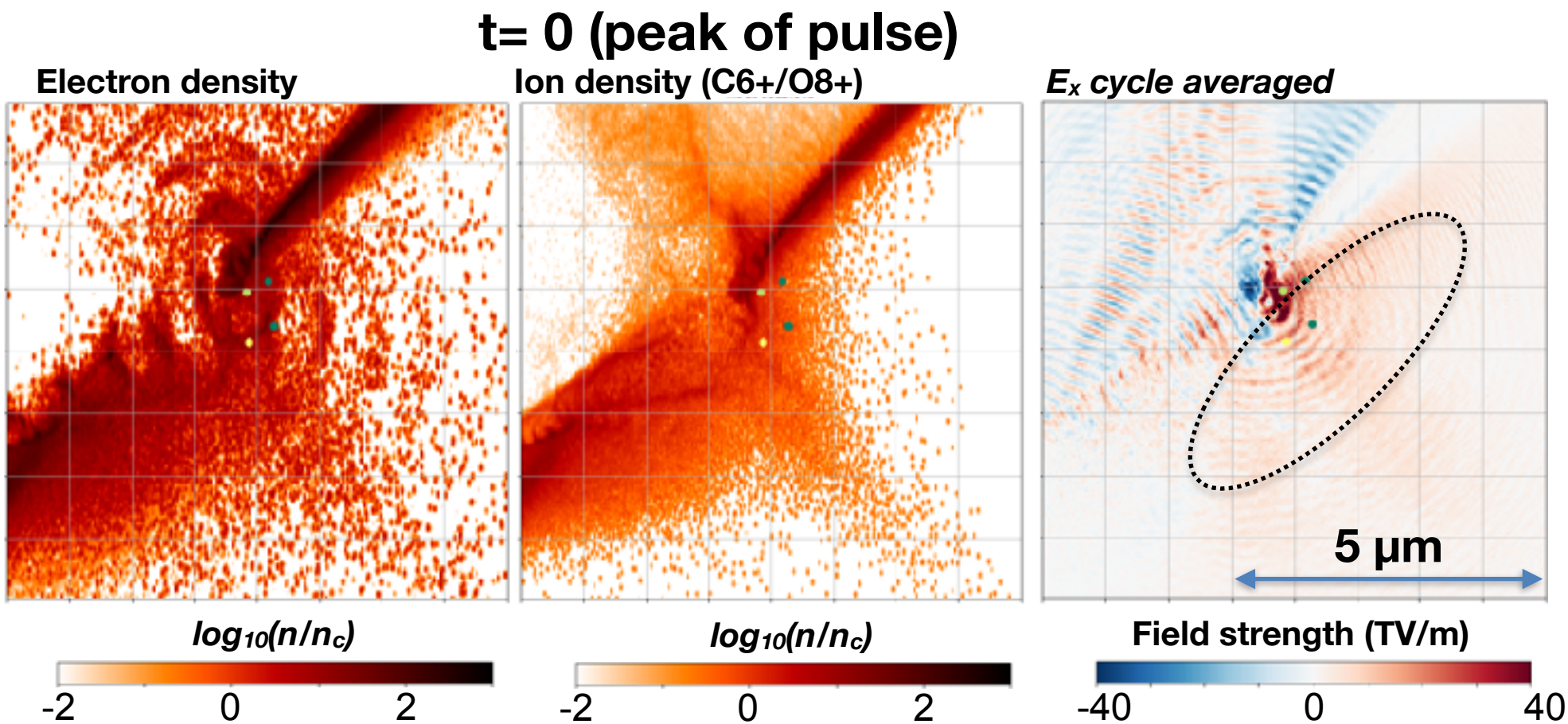

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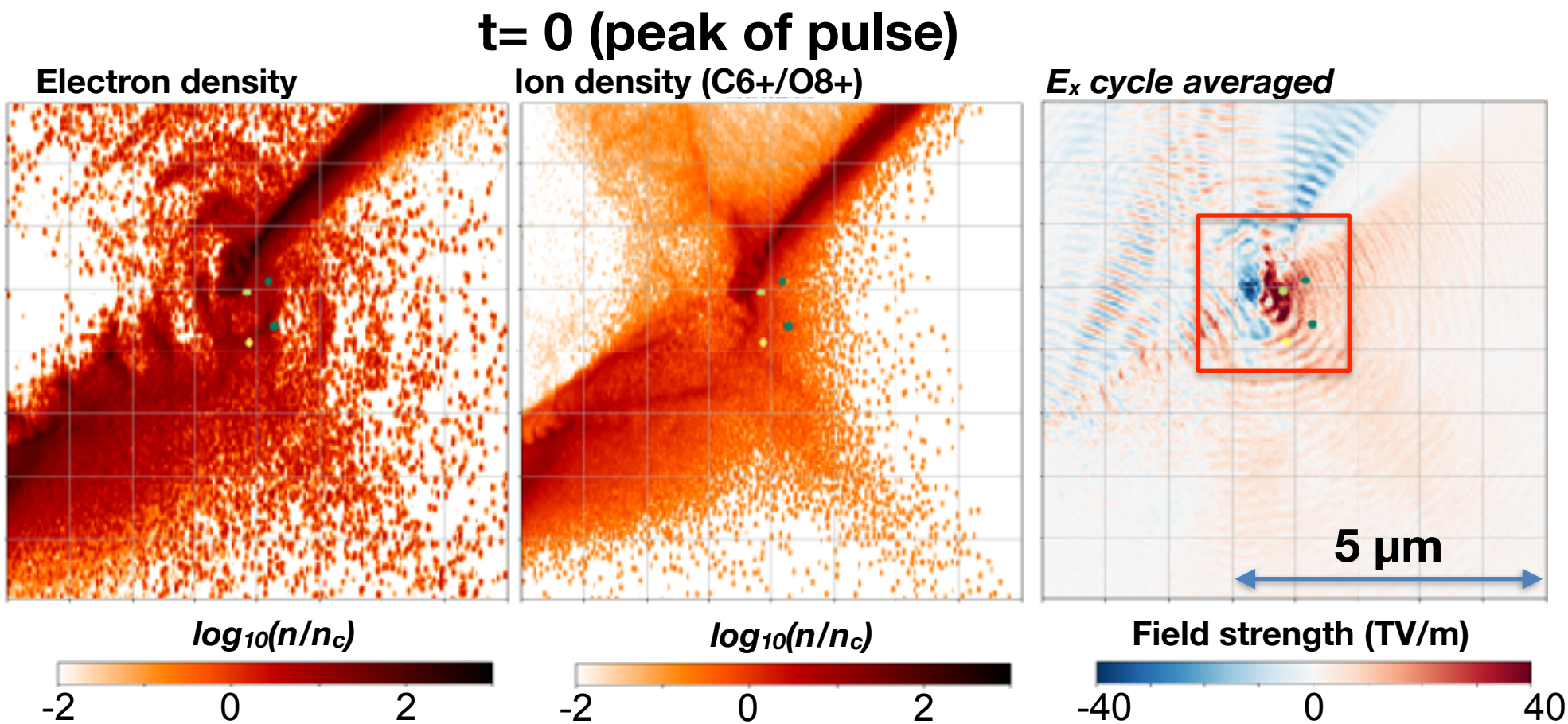
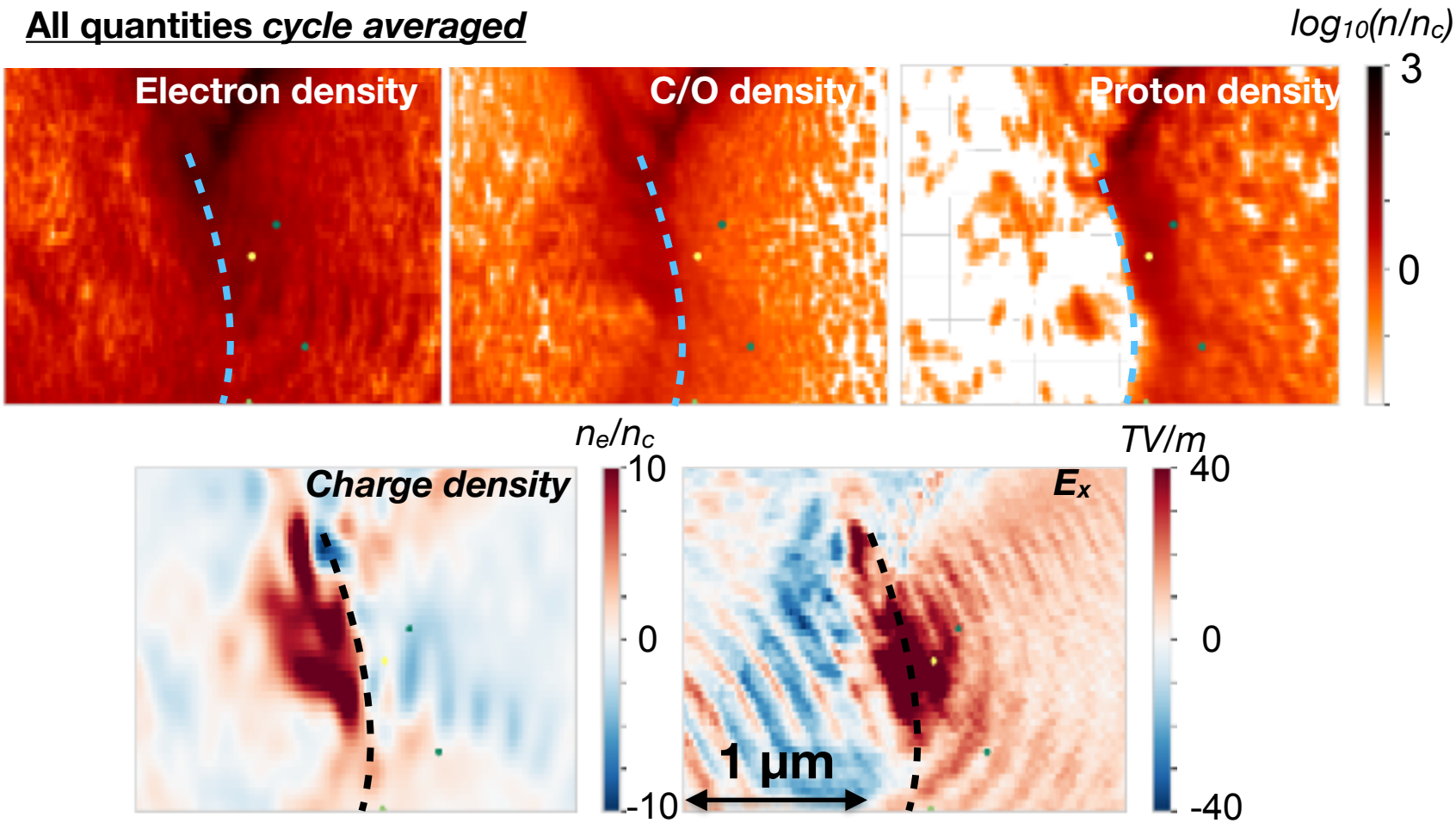


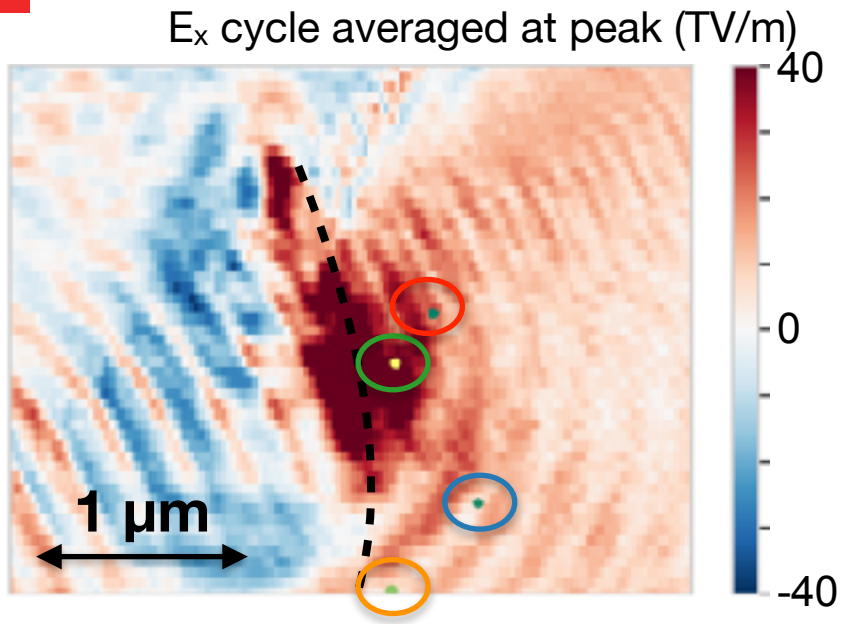
Microscopic view of space charge generation at region of strongest ion acceleration

All quantities *cycle averaged*



- Relativistic transparency -> ponderomotive blowout of electrons
- Remaining ions results in strong *transient* space charge field, moving with peak of ion density

Particle tracking shows ion energy boost from blown out ion core



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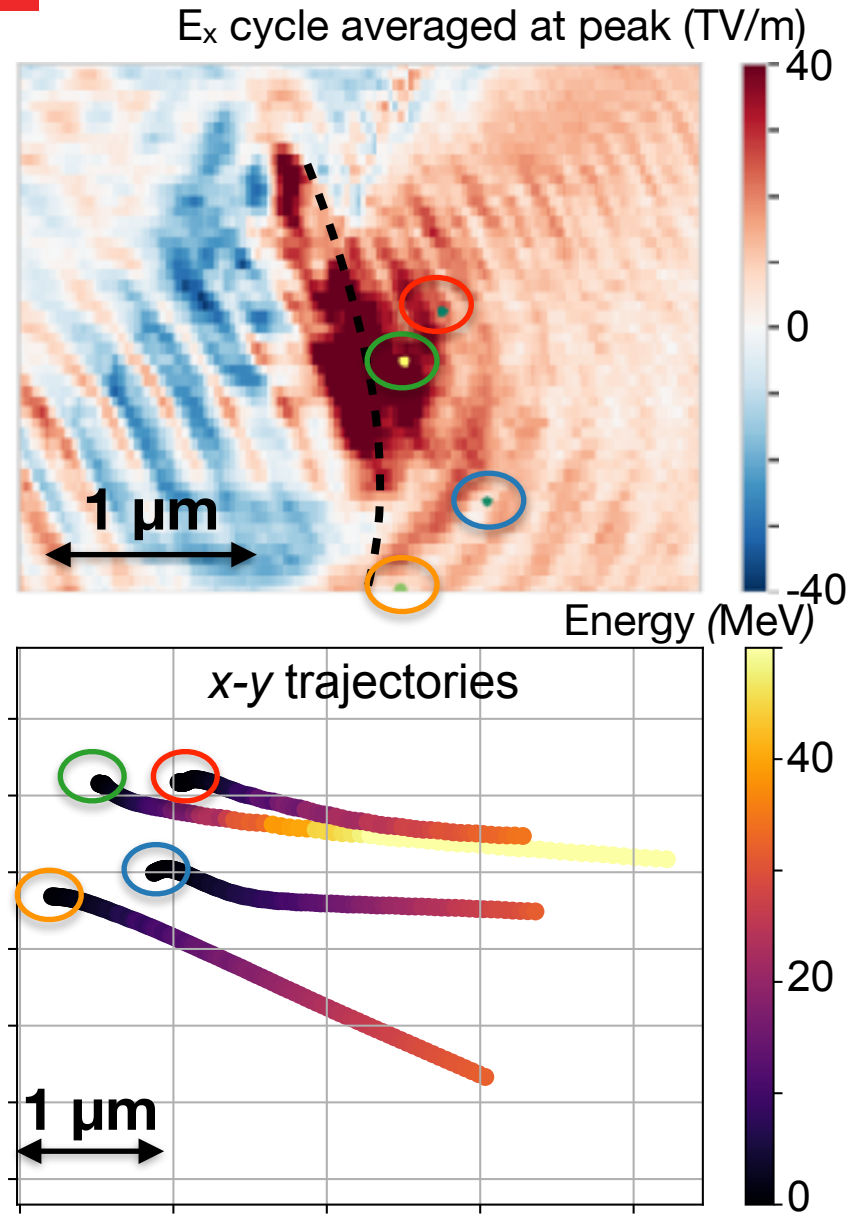

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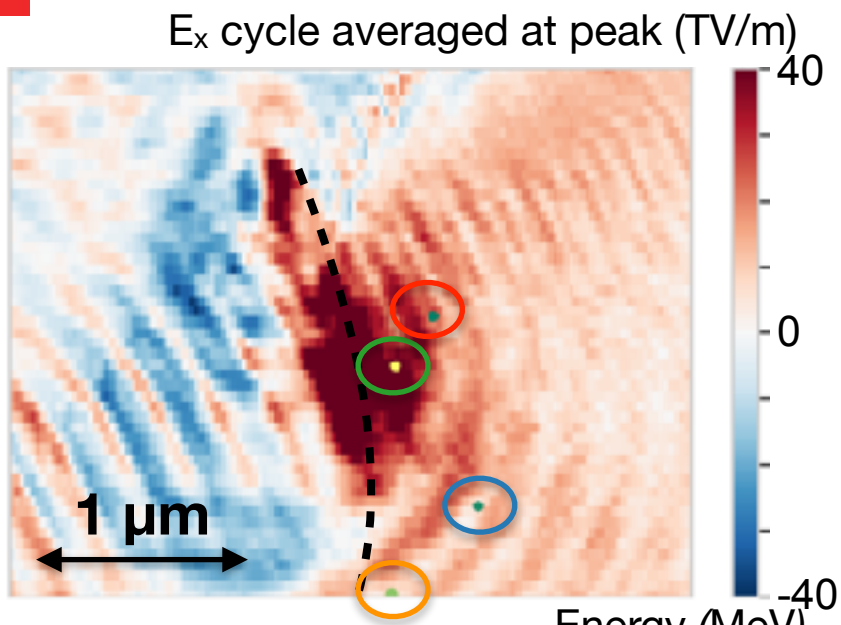
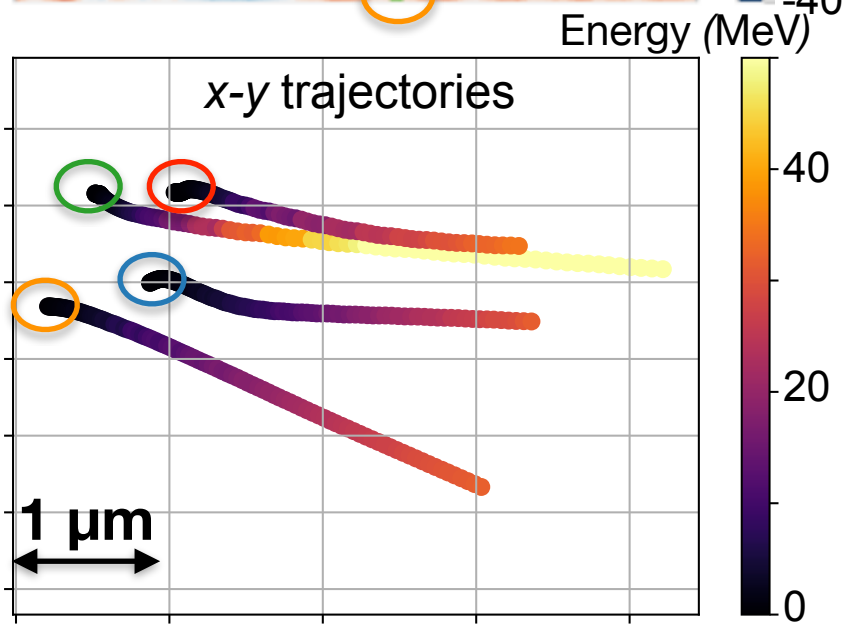
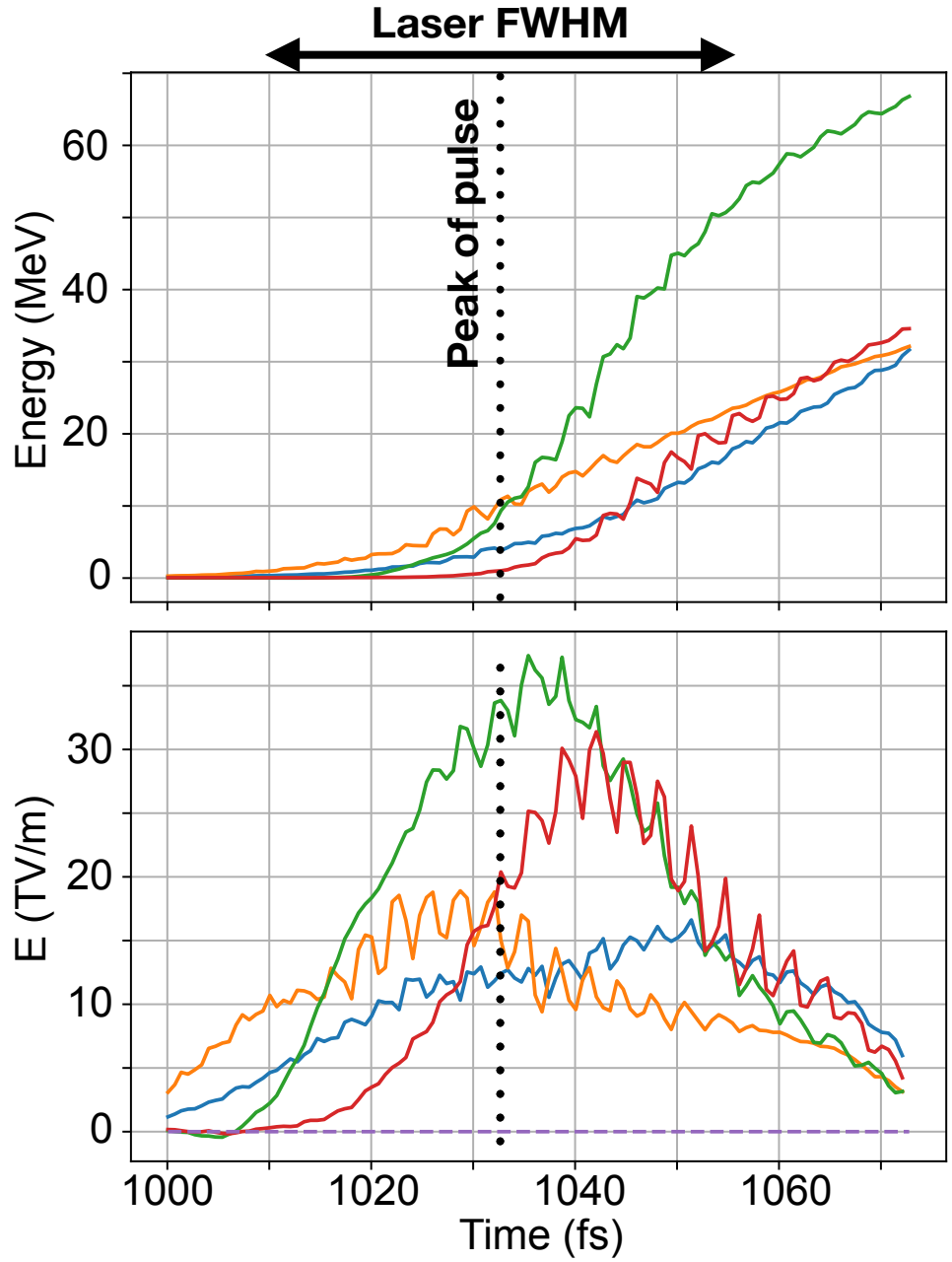
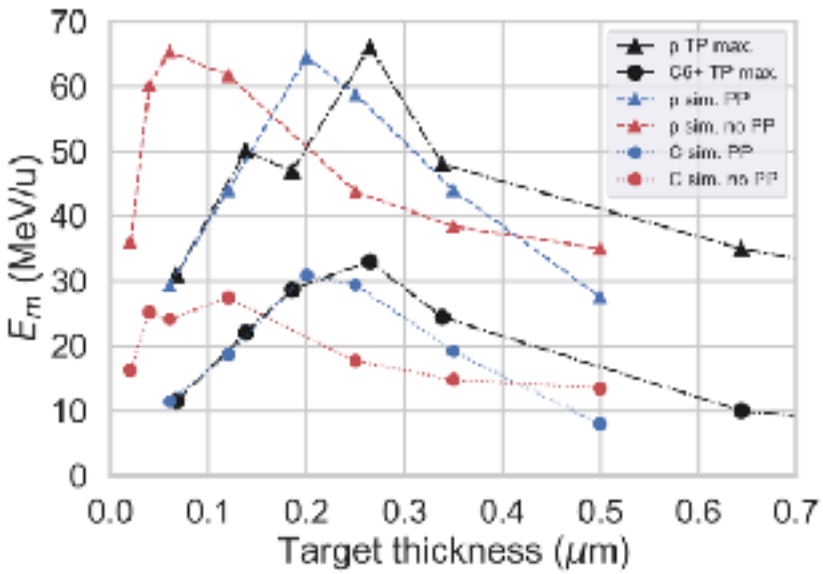






Removing prepulse shifts optimum thickness to thinner targets



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- Similar acceleration mechanism and peak energies, but with thinner optimum thickness

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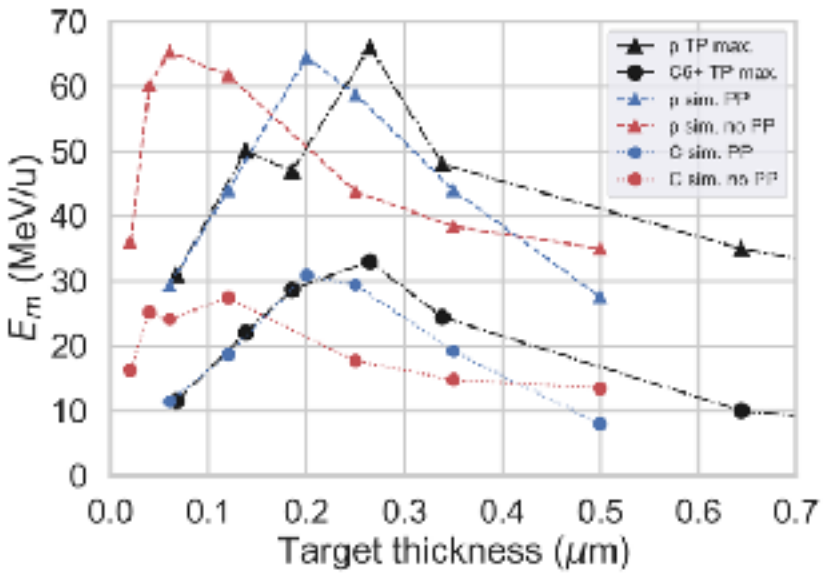

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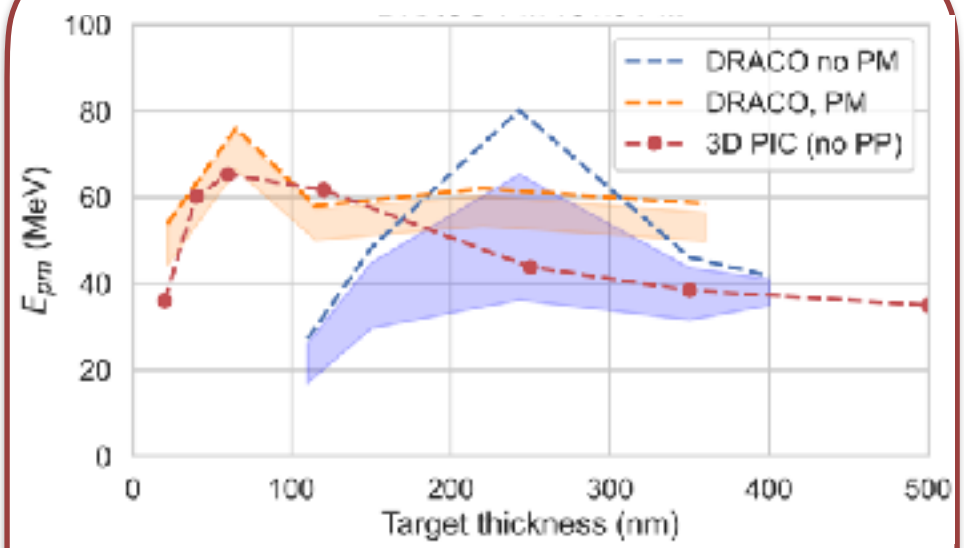

- Used DRACO-PW system with contrast enhancing PM (>4 orders improvement)
- Behaviour matches simulation prediction
- Acceleration regime optimised by matching target thickness to prepulse

Summary

- Delivery of high energy ion beams on *repetitive* high power laser systems operating at ultra-high intensities (~>60 MeV protons, ~> 30 MeV/nucleon O^{8+}/C^{6+} with laser energies ~10 J)
- Role of prepulse is vital in determining optimum target thickness
- Data reproduced robustly on two world-leading laser systems
- Work ongoing at J-KAREN-P and DRACO-PW to improve performance of ion acceleration process

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