Modeling Underdense Plasma Photocathode Experiments

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This work is part of the FACET E-210 Trojan Horse collaboration.

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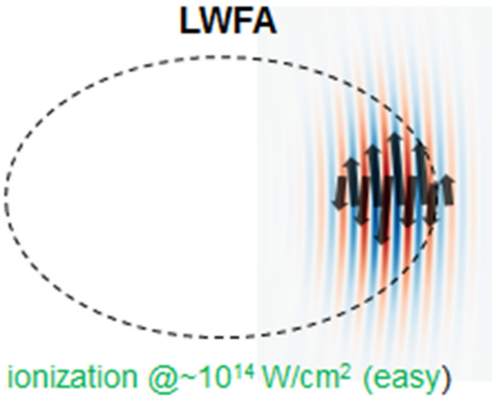
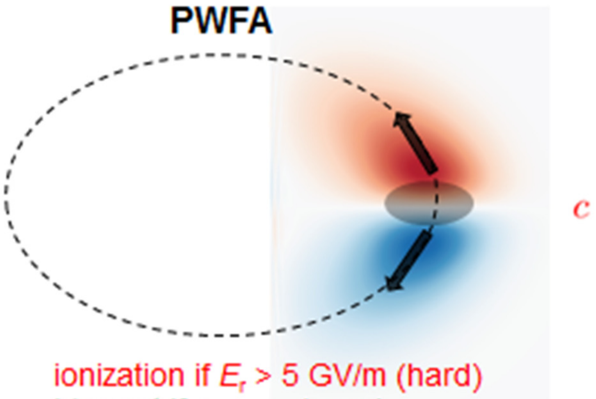
Plasma Photocathode is a Hybrid of LWFA and PWFA Concepts



$v_g = c\left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} < c$

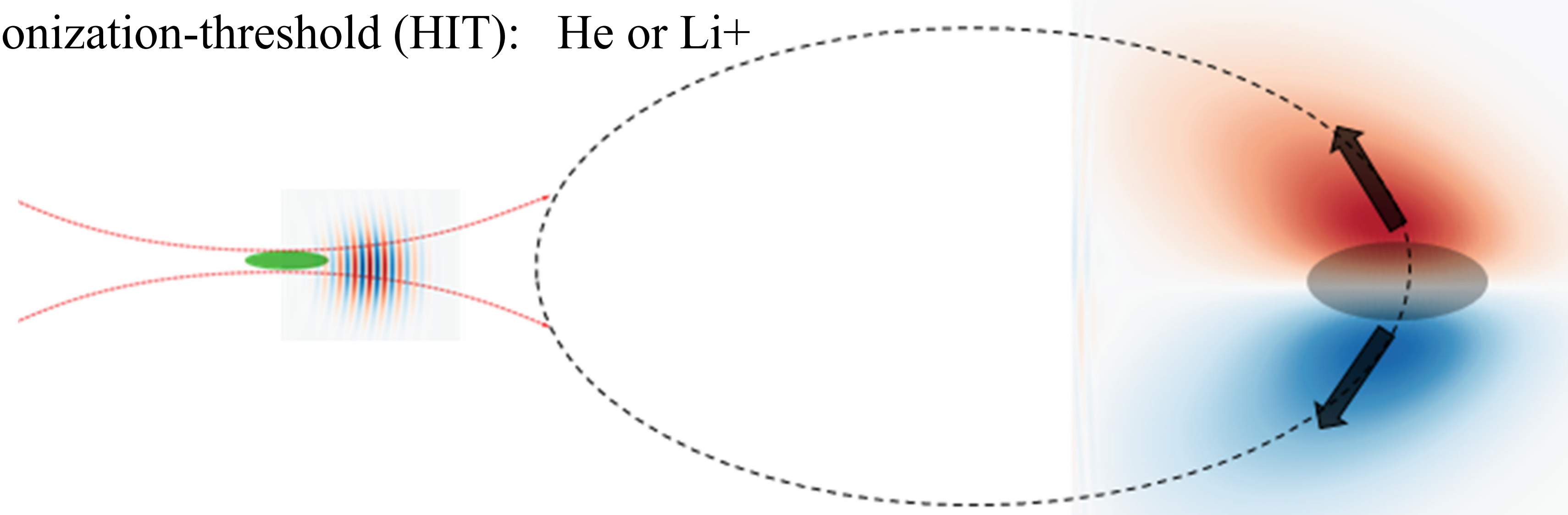
ionization @~10^{14} W/cm² (easy)
bubble @~10^{18} W/cm² (hard)



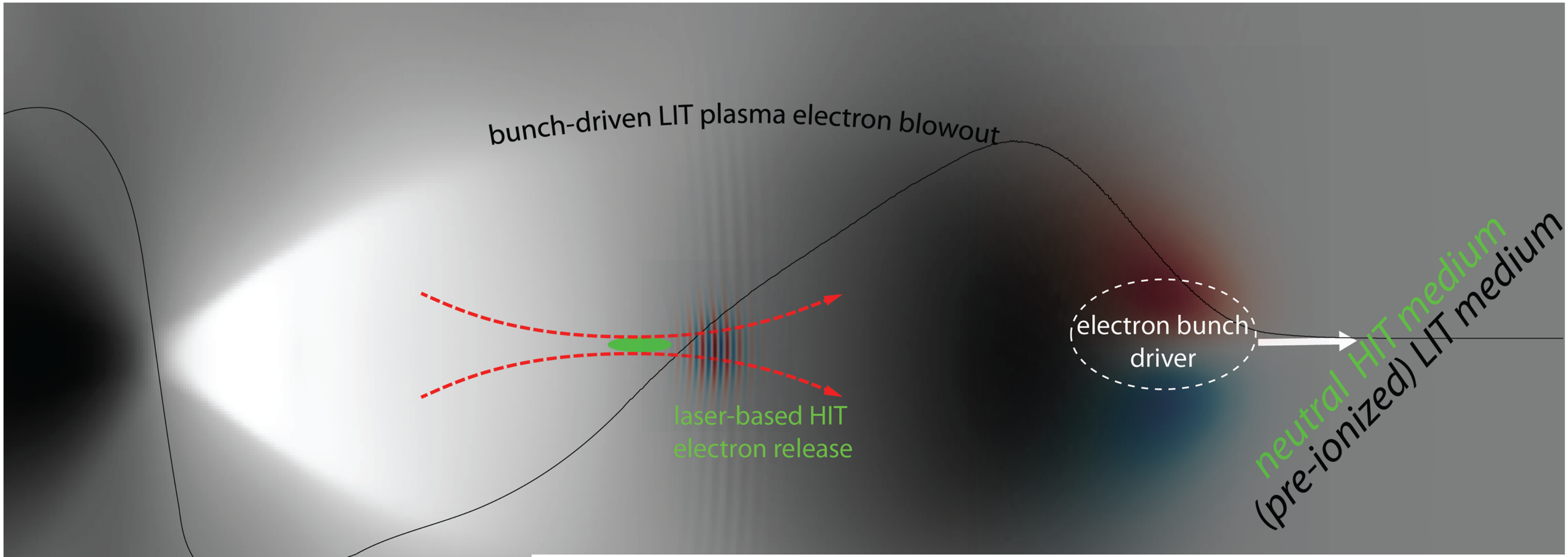
ionization if E_r > 5 GV/m (hard)
blowout if $n_b > n_e$ (easy)

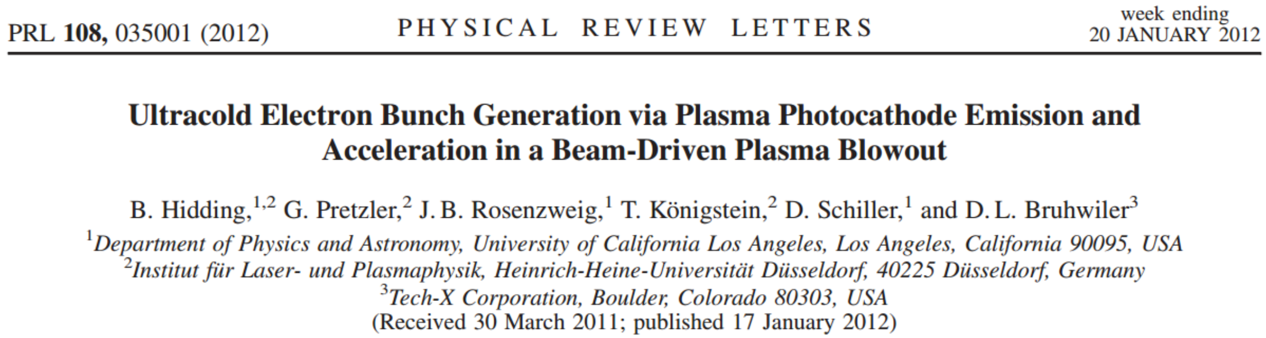
Combine both in media w/ at least two components:

Low-ionization-threshold (LIT): H or Li
High-ionization-threshold (HIT): He or Li+



Plasma Photocathode: putting the pieces together





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Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

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What's needed:

- LIT/HIT medium
- electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout

Simulated with VSim 6.0 at NERSC.

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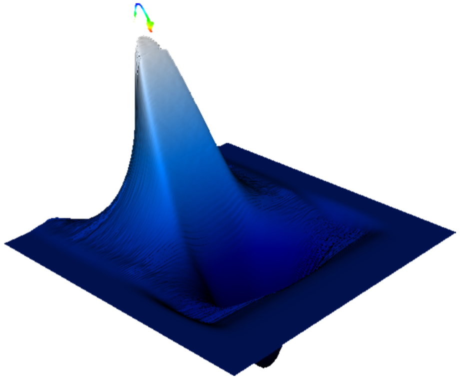
Proof of principle experiment will be conducted at SLAC / FACET



E-210: Trojan Horse collaboration

E-210: Trojan Horse Underdense Photocathode Plasma Wakefield Acceleration

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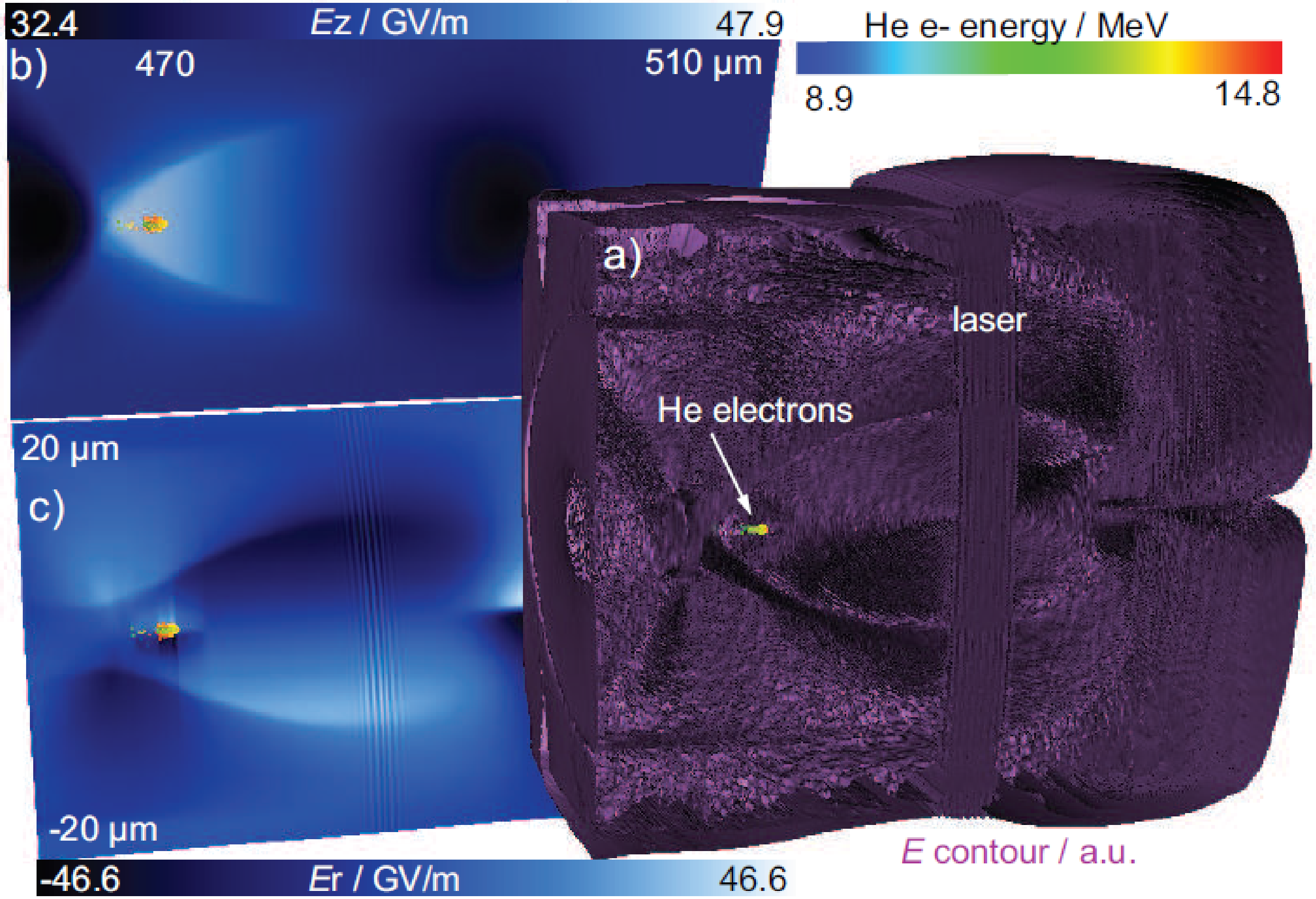
Pros:

- stable electron driver beam, can self-ionize
- High energy bunch: 23 GeV
- 10-TW Laser system to be installed for preionization (E-200 expt.) and E-210 expt.

Cons:

- Laser-jitter to master clock ~ +/- 40 fs
- Electron beam jitter < 1 ps
- Needs 2 km accelerator

The massively parallel simulations are very resource intensive



- inherently 3D physics
- 2 gases with ionization physics
- must resolve laser wavelength (0.8 μm)
- cm-scale propagation distances

Large-scale simulations are essential for detailed physics

Ionization threshold of Li: 5 eV

$E_{r,\max} \approx 27\,\mathrm{GV/m}$

Ionization threshold of He: 25 eV

$E_0 \approx 72\,\mathrm{GV/m}$

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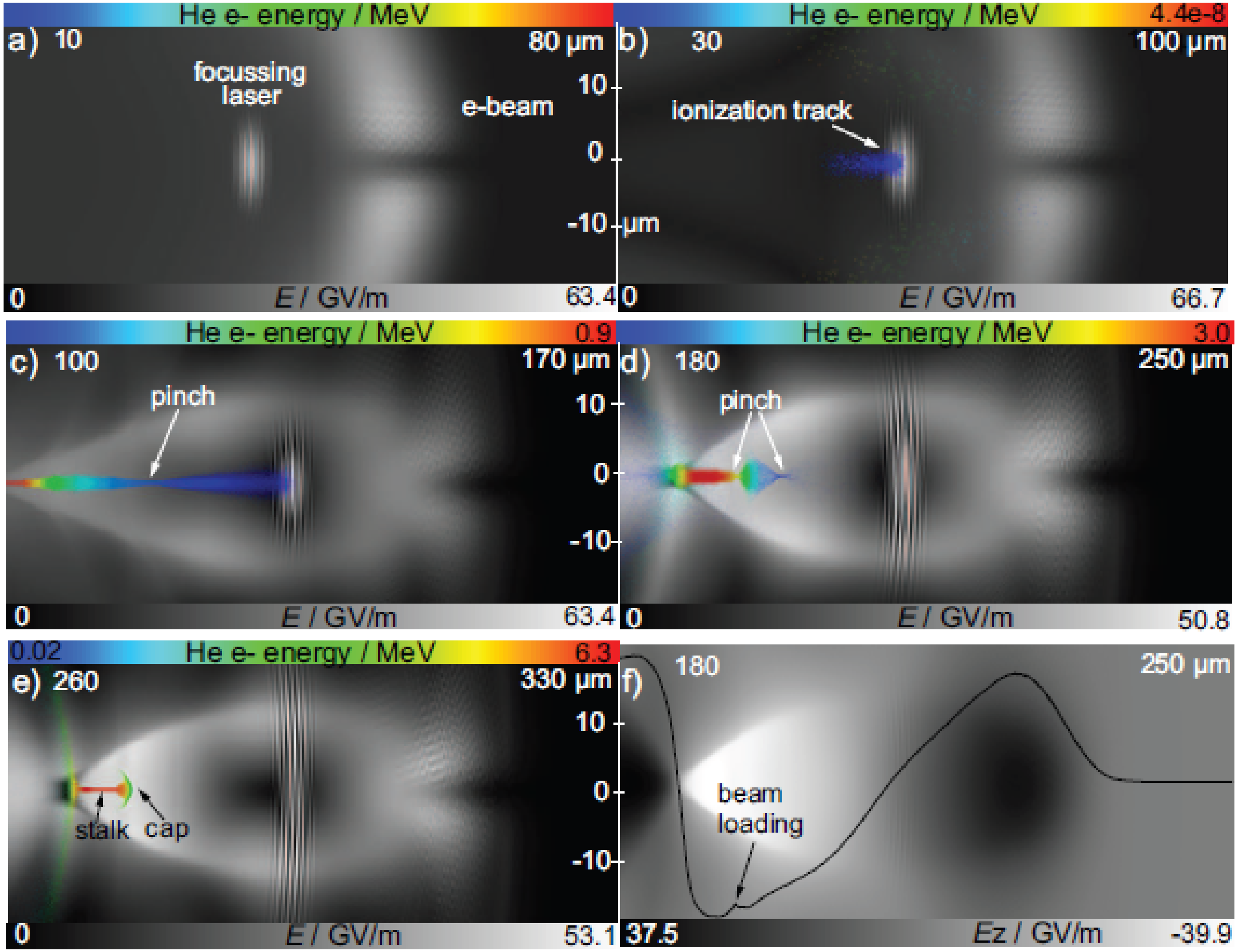
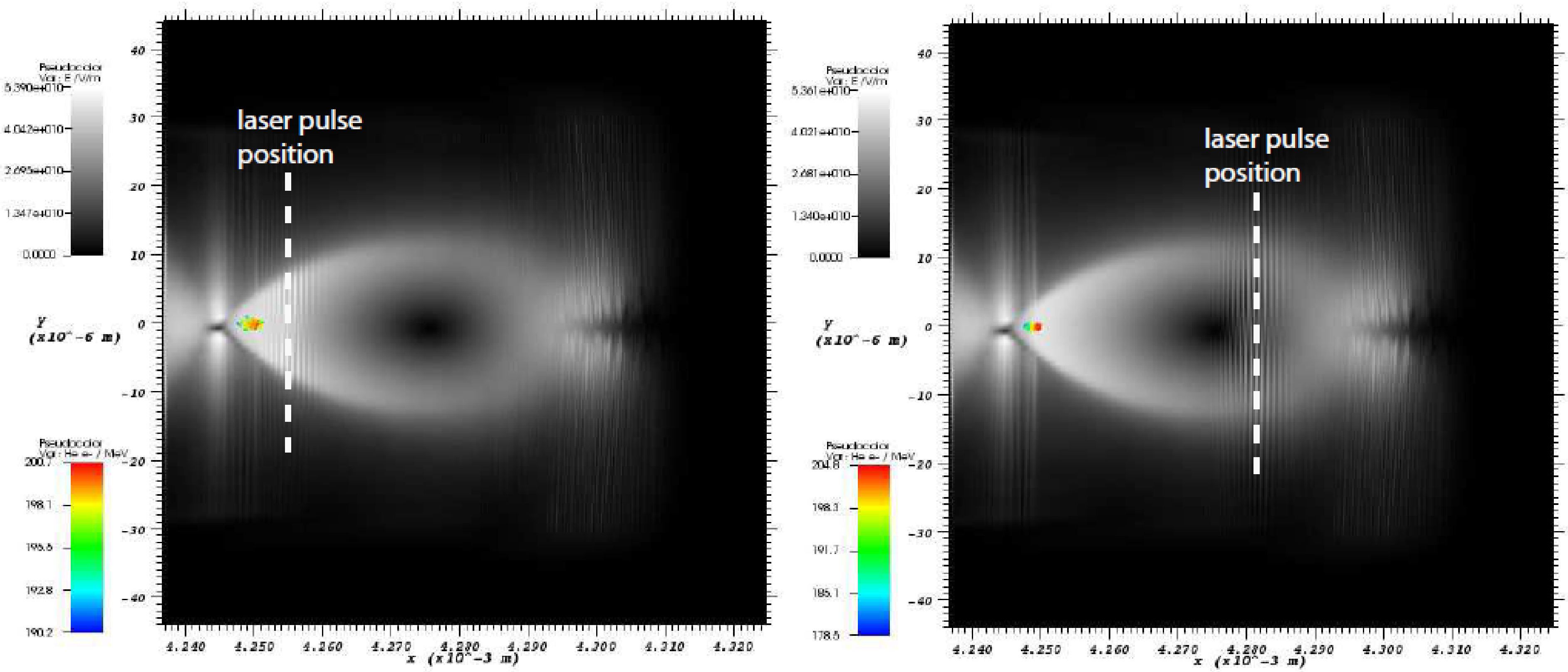


Simulations show high tolerance for beam/laser timing jitter



$\pm$ 43 fs

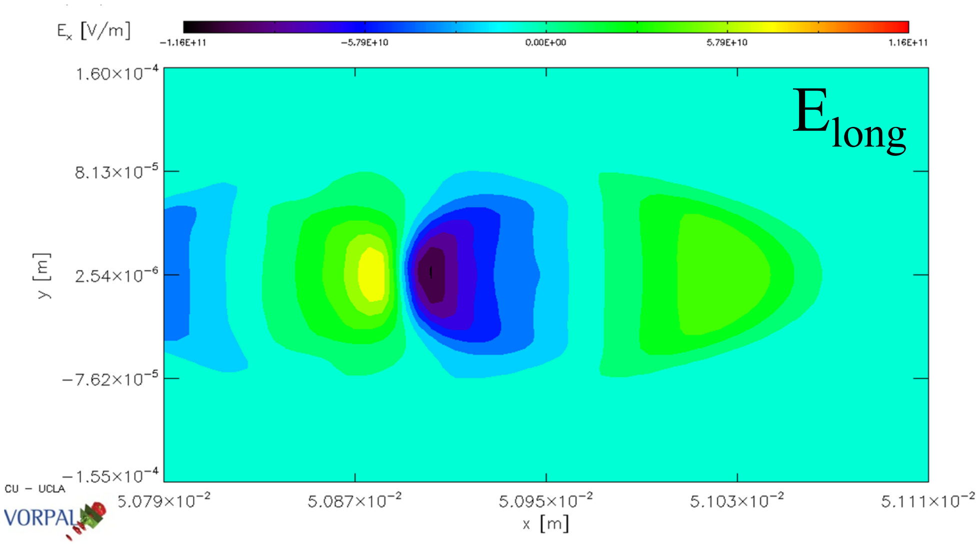
- Even if the laser pulse delay is off by +- 43 fs (13 μm), one sees trapping & acceleration.
- Acc. field increases quasi-linearly towards end of blowout. Released electrons fall behind relative to blowout, are always trapped at end of blowout where acc. field is maximum
- SLAC: +-100/20 fs jitter between electron driver and laser pulse reported

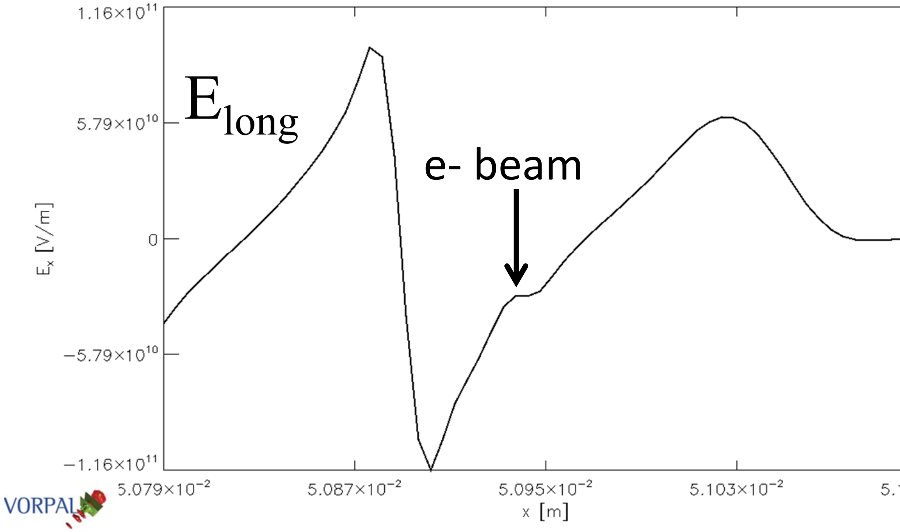
3D, Very-Low-Resolution simulations of Trojan Horse

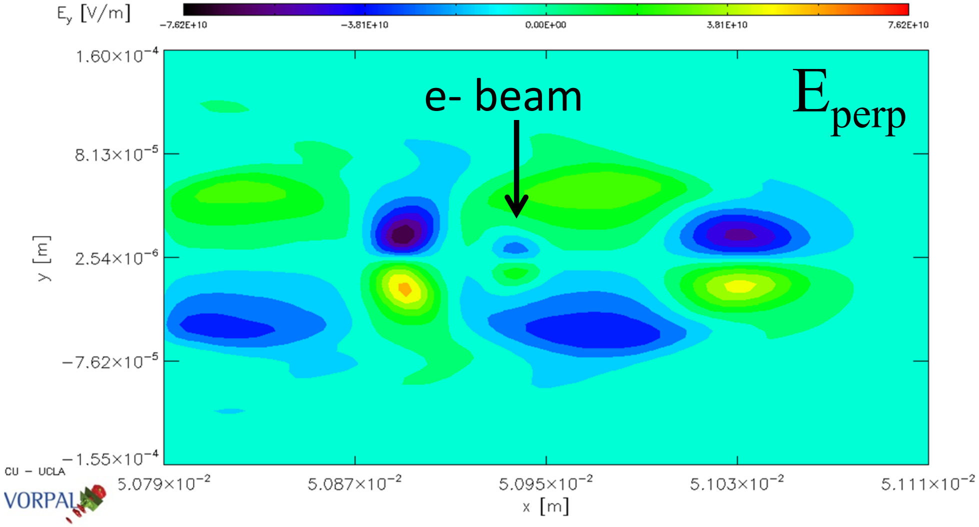
- Physical parameters:
  - Q = 3 nC; <E> = 27 GeV
  - Long.: x_{rms} = 15 μm; Xverse: $y_{rms} = z_{rms}$ = 20 μm
  - Li, Li+ density: 1.7 x 10^{17} cm^{-3}; 0.5 cm propagation
- Simulation domain & mesh parameters:
  - $L_{x,y,z}$ = 320 μm; dx, dy, dz = 5 μm; $N_{x,y,z}$ = 64
  - 70 proc-hours
- Avoid resolving the laser wavelenth
  - paraxial approximation is used to represent the laser envelope
  - time-averaged ADK algorithm is used for ionization physics
- Caveats
  - laser-induced transverse emittance is lost
  - accelerated beam is not resolved (space charge, beam loading)
    - serious problem in any case; especially transverse resolution

Sample results from very-low-resolution runs

for the experiment; we choose high charge at expense of emittance







- 300 pC of trapped charge; beam loading
- Transversely unmatched; betatron osc.'s
- ~1.5 GeV in 0.5 cm; ~2% δE/E
- ~0.5 mm mrad, norm. rms emittance
- ~100 kA peak current

+/- 20% variations of drive beam dimensions

resulting % variations of accelerated beam

- strong sensitivity to drive beam length
- weak sensitivity to drive beam radius
- trapped charge is very robust

	E	Q	$\delta E/E$	L_{rms}	$\varepsilon_{norm,rms}$	I_{peak}
L_{rms}	30%	1%	80%	100%	100%	50%
R_{rms}	1%	0%	3%	3%	3%	2%

drive beam parameters are varied by +/- 20%

- fast, 3D results will be really powerful
  - 1000x faster than resolved 3D simulations
  - parameter scans for experimental design
  - exploration of completely new concepts
- 2D simulation results are problematic
- more testing and benchmarking is required

Summary and Outlook

- Key features of the plasma photocathode concept (aka Trojan Horse)
  - Arbitrary control of injection, directly into accelerating phase
  - Extremely low transverse momentum --> low divergence & emittance
  - unprecedented bunch transversal size ~150 nm
  - ultra-high controllability and tunability via laser and density tuning
  - unprecendented emittance
  - unprecedented brightness

- Upcoming Proof-of-concept experiment at FACET!

- New ideas presently being explored by the collaboration
  - driving an free electron laser (FEL)
  - coherent betatron oscillations
  - Energy/bunch size/duration transformer
  - bunch shaping (inject ion laser at arbitrary angles through blowout)
  - multiple pulses (bunch shaping, two-color FEL)

- Idea pursued independently by Lu, Mori & collaborators, using OSIRIS
  - Xu *et al.*, *Phase Space Dynamics of Ionization Injection…* (2013), arXiv.
  - Li *et al.*, *…Transverse Colliding Lasers in … PWFA* (2013), arXiv.
  - The concept builds on a rich history of research in LWFA, PWFA, ionization injection

Acknowledgements

3D simulations were conducted with the parallel VSim framework, version 6.0.

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E-210: Trojan Horse collaboration

We thank all members of the FACET E-210 Trojan Horse collaboration.

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