8 years of beam-driven wakefield simulation –

lessons learned, reduced models & future plans

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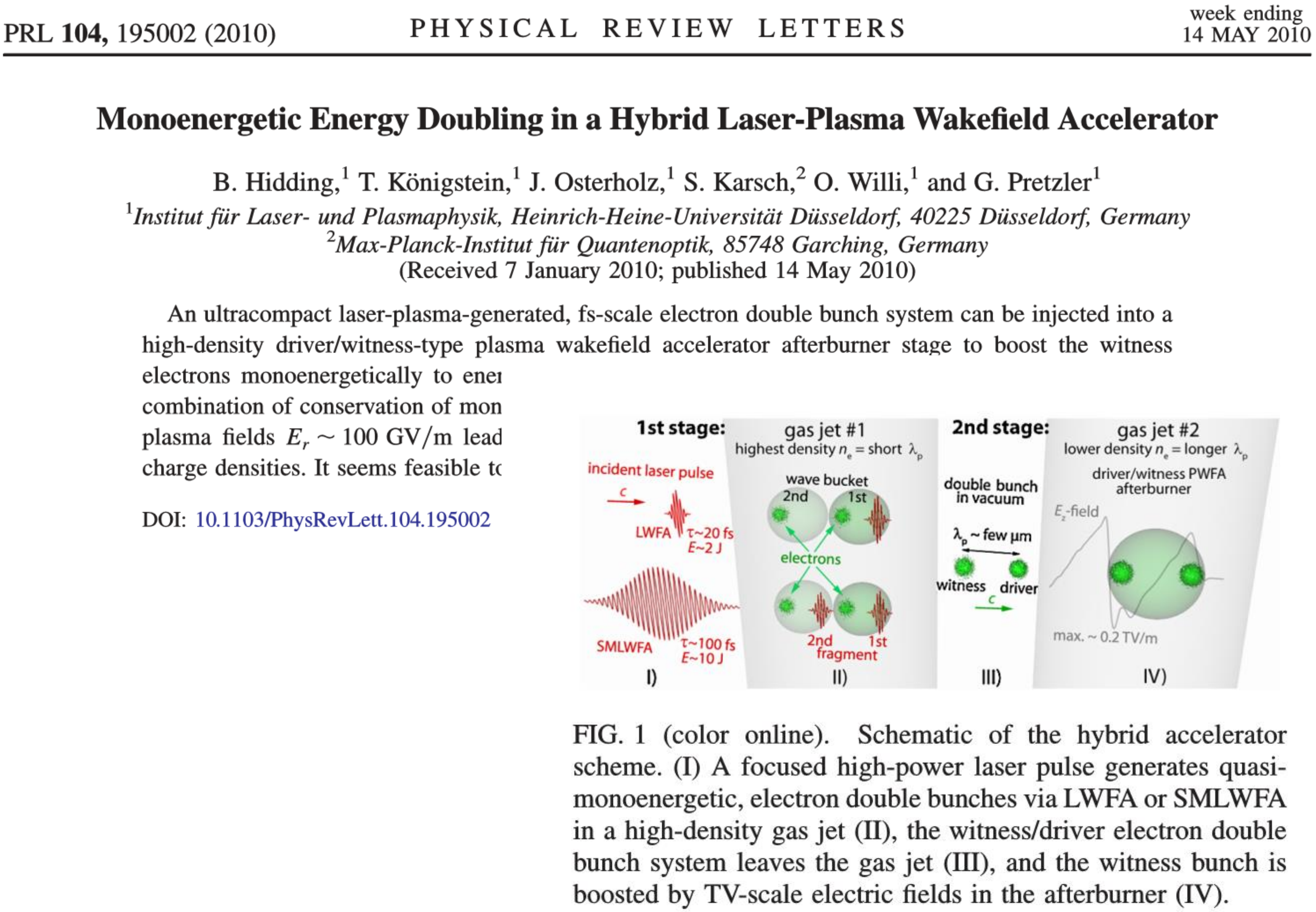
RadiaBeam Technologies[&] UCLA[#] Lawrence Berkeley Lab[%]

FACET - II Science Workshop

20 October 2017 – SLAC – Menlo Park, CA



PRL **104,** 195002 (2010) PHYSICAL REVIEW LETTERS week ending 14 MAY 2010

Monoenergetic Energy Doubling in a Hybrid Laser-Plasma Wakefield Accelerator

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(Received 7 January 2010; published 14 May 2010)

An ultracompact laser-plasma-generated, fs-scale electron double bunch system can be injected into a high-density driver/witness-type plasma wakefield accelerator afterburner stage to boost the witness electrons monoenergetically to ene
combination of conservation of mon
plasma fields $E_r \sim 100$ GV/m lead
charge densities. It seems feasible t

DOI: 10.1103/PhysRevLett.104.195002

FIG. 1 (color online). Schematic of the hybrid accelerator scheme. (I) A focused high-power laser pulse generates quasi-monoenergetic, electron double bunches via LWFA or SMLWFA in a high-density gas jet (II), the witness/driver electron double bunch system leaves the gas jet (III), and the witness bunch is boosted by TV-scale electric fields in the afterburner (IV).

2010: Simulating hybrid LWFA/PWFA with OOPIC

- XOOPIC at UC Berkeley (1992)
  - 2D (xy & rz), X11 GUI on Linux
- OOPIC Pro at Tech-X (1999)
  - PWFA (rz) and LWFA (xy)
- Numerical approximations:
  - 2D geometry
    - xy (slab) required for LWFA
    - rz (cylindrical, noisy) for PWFA
  - simple particle shapes, 4 ppc
  - low resolution
    - 16 cells per laser wavelength

Verboncoeur *et al*., Comp. Phys. Comm. **87**, 199 (1995).

Bruhwiler *et al*., Phys. Rev. ST/AB **4**, 101302 (2001).

Bruhwiler *et al*., Phys. Plasmas **10**, 2022 (2003).

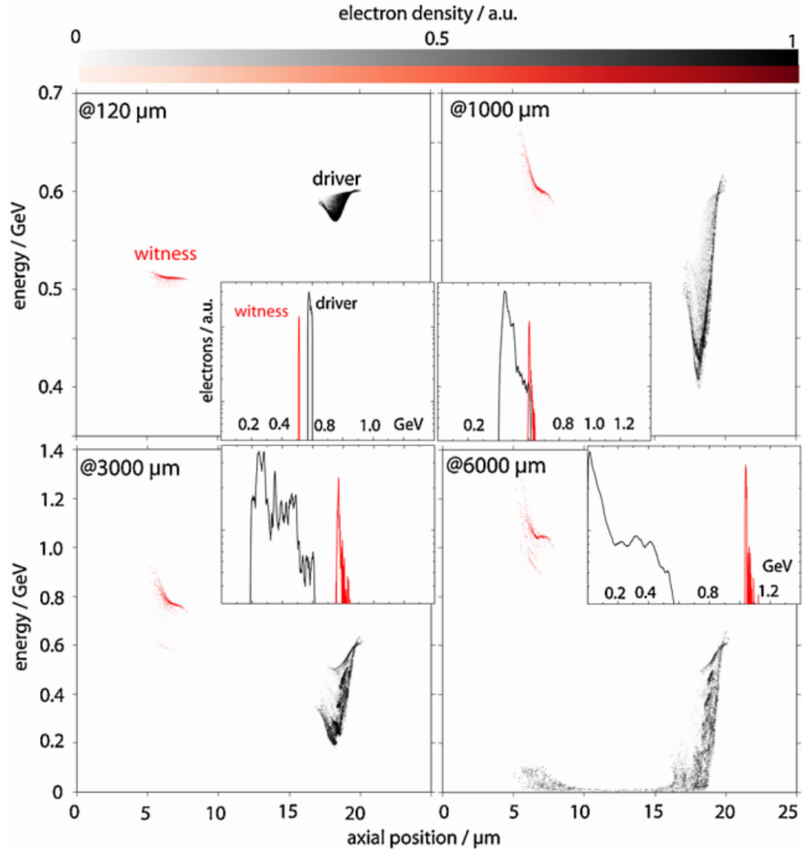
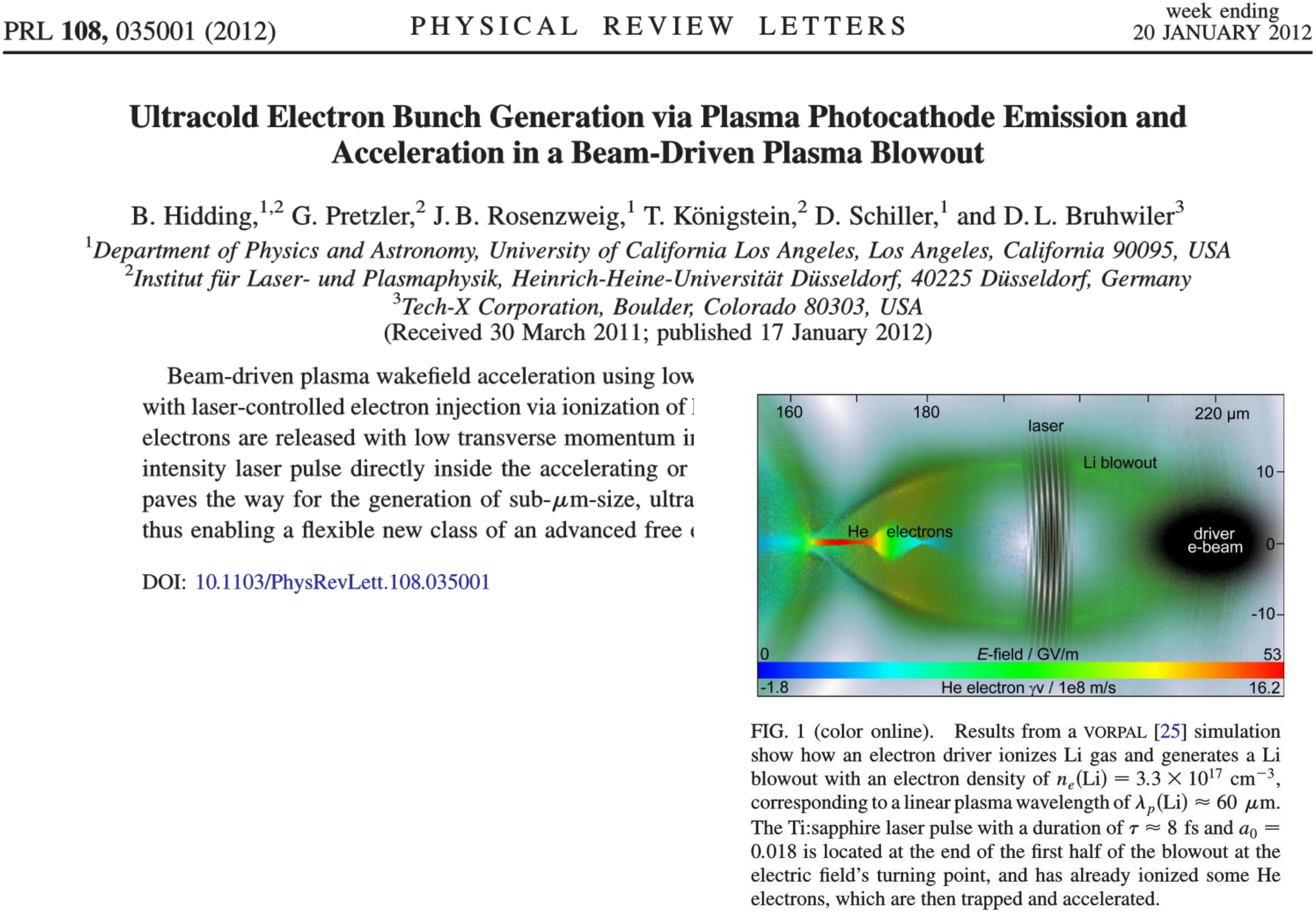


FIG. 3 (color online). Snapshots of driver/witness energy-position phase space during acceleration. The witness energy is boosted from 0.5 GeV to over 1 GeV in a distance of only $L_{\rm acc} \approx 6$ mm due to the ultrahigh accelerating field set up by the driver ploughing through the plasma. The monochromaticity of the witness is maintained, as shown by the electron spectra (insets).



PRL **108,** 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

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

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(Received 30 March 2011; published 17 January 2012)

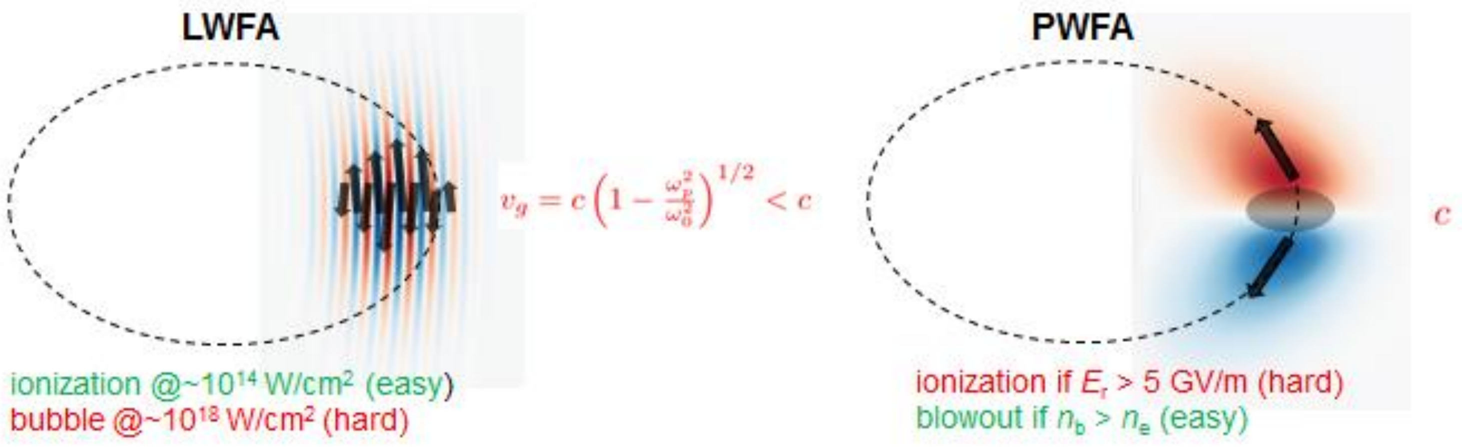
Beam-driven plasma wakefield acceleration using low
with laser-controlled electron injection via ionization of
electrons are released with low transverse momentum i
intensity laser pulse directly inside the accelerating or
paves the way for the generation of sub-μm-size, ultra
thus enabling a flexible new class of an advanced free

DOI: 10.1103/PhysRevLett.108.035001

FIG. 1 (color online). Results from a VORPAL [25] simulation show how an electron driver ionizes Li gas and generates a Li blowout with an electron density of $n_e(\mathrm{Li}) = 3.3 \times 10^{17}\ \mathrm{cm}^{-3}$, corresponding to a linear plasma wavelength of $\lambda_p(\mathrm{Li}) \approx 60\ \mu\mathrm{m}$. The Ti:sapphire laser pulse with a duration of $\tau \approx 8$ fs and $a_0 = 0.018$ is located at the end of the first half of the blowout at the electric field's turning point, and has already ionized some He electrons, which are then trapped and accelerated.

"Trojan Horse" aka "Plasma Photocathode"

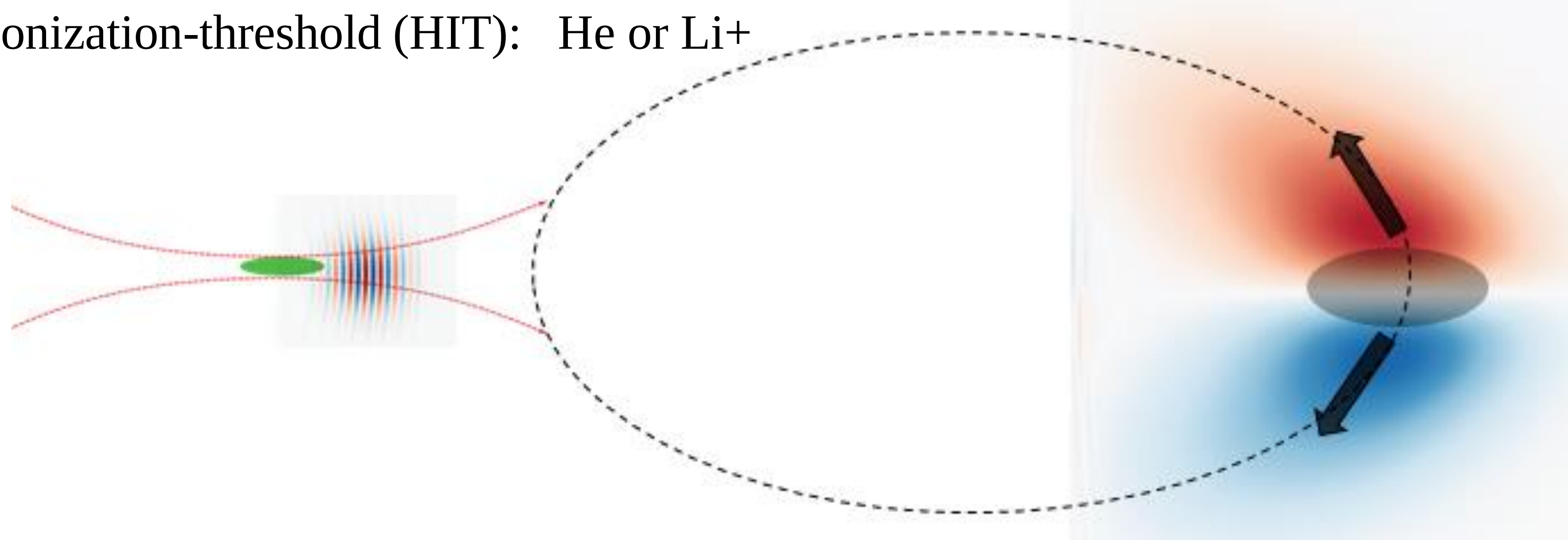
– *hybrid of LWFA and PWFA Concepts*



Combine both in media w/ at least two components:

Low-ionization-threshold (LIT): H or Li

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



Simulating Trojan Horse with VORPAL/VSim

- VORPAL/VSim at Tech-X Corp.
  - 2000: development started at CU
  - 2004: “dream beams” Nature paper
  - 2D & 3D Cartesian PIC

- Numerical aspects:
  - 2D Cartesian (slab) geometry
  - low resolution
    - 16 cells per laser wavelength
  - noise suppression
    - quadratic particle shapes
    - spatial 1-2-1 current smoothing
  - tunneling ioniz. w/ multiple species
    - ‘static fluid’ treatment of neutral gas
    - careful handling of ion macroparticles

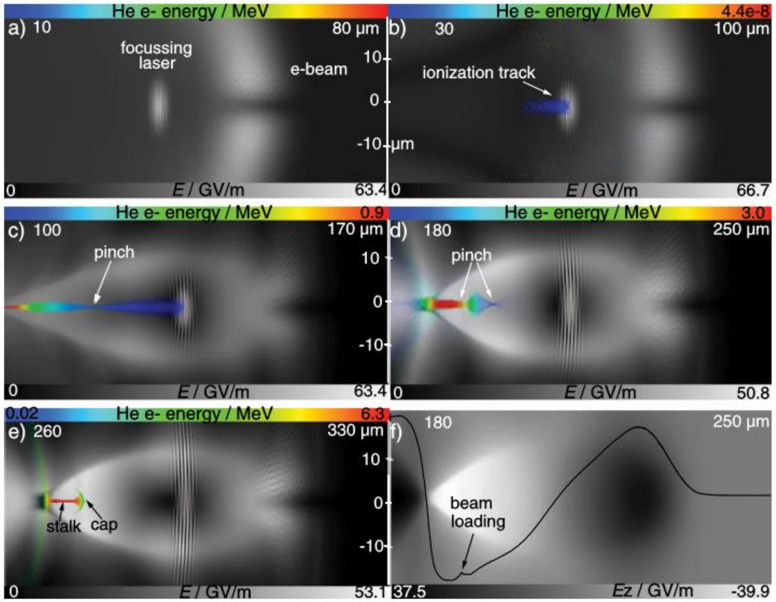


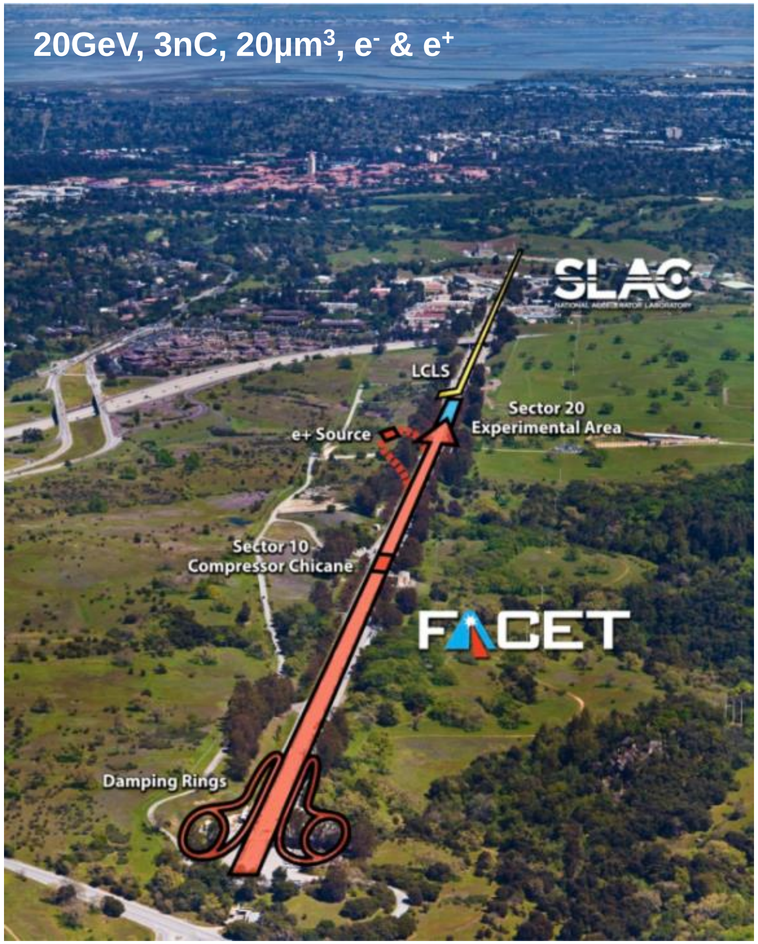
FIG. 2 (color online). Injection of He electrons at the beginning of the interaction. Snapshots (a) to (e) show *E* generated by the Li blowout and the laser pulse, and the He electrons which are born inside the Li blowout due to ionization by the focused laser pulse, while (f) shows only E_z and a lineout on axis, corresponding to (d).

VORPAL

Nieter and Cary,
J. Comp. Phys. **196**, 448 (2004).

E210 Trojan Horse Experiment at
FACET – the premier facility for PWFA

Hidding, Rosenzweig & the E-210 team.



20GeV, 3nC, 20µm^3, e$^-$ & e$^+$

Timeline:
- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

“E210: Trojan Horse PWFA“ experiment approved in 2011

A National User Facility:
- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

✓Mono-energetic e- acceleration

✓High efficiency e$^-$ acceleration (*Nature* **515**, Nov. 2014)

✓First high-gradient e$^+$ PWFA (*Nature* **524**, Aug. 2015)

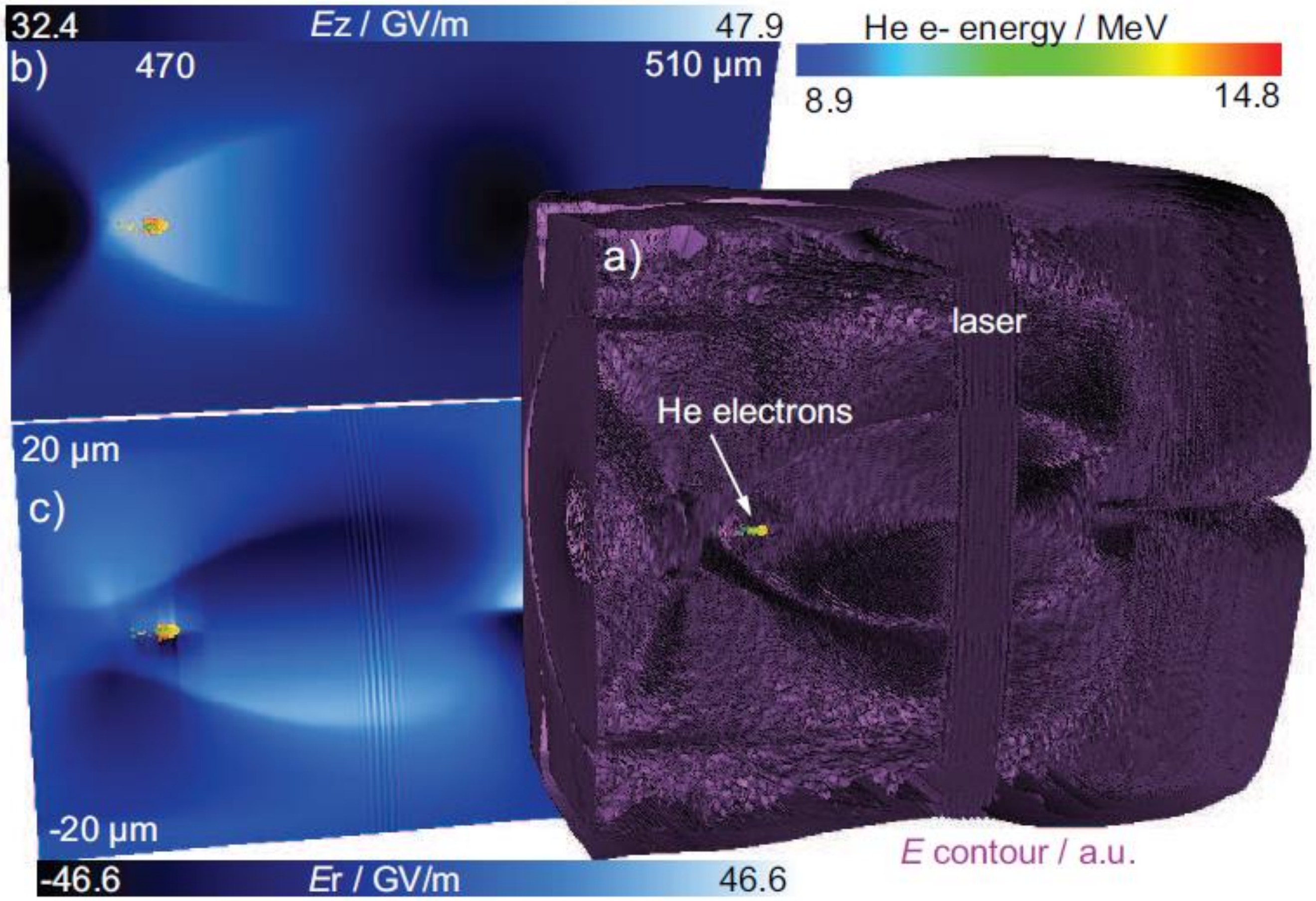
E210: Multi-institutional, cross-continental collaboration of academia (Strathclyde—UCLA—Hamburg—Oslo—Texas—Boulder), research centers (SLAC—DESY) and industry (RadiaBeam—Tech-X—Radiasoft)

PI‘s B. Hidding (Strathclyde) & J.B. Rosenzweig (UCLA)

2012-2017, experiments at FACET ramping up from 2013-2016

3D simulations resource intensive – need reduced models

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



VORPAL

NERSC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 031303 (2013)

Hybrid modeling of relativistic underdense plasma photocathode injectors

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(Received 6 November 2012; published 25 March 2013)

The dynamics of laser ionization-based electron inj
cathode concept is analyzed analytically and with partic
few-cycle laser pulse that liberates electrons through b
accelerator on the final electron phase space is describe
theory as well as nonadiabatic Yudin-Ivanov (YI) ionizat
in the combined laser and plasma wave fields. The phot
equations of motion. They experience the analytically
derived plasma wakefields. It is shown that the mini
bunches released in mulit-GV/m-scale plasma wake
unprecedented values, combined with the dramatical
production, pave the way for highly compact yet ultra
and light source applications.

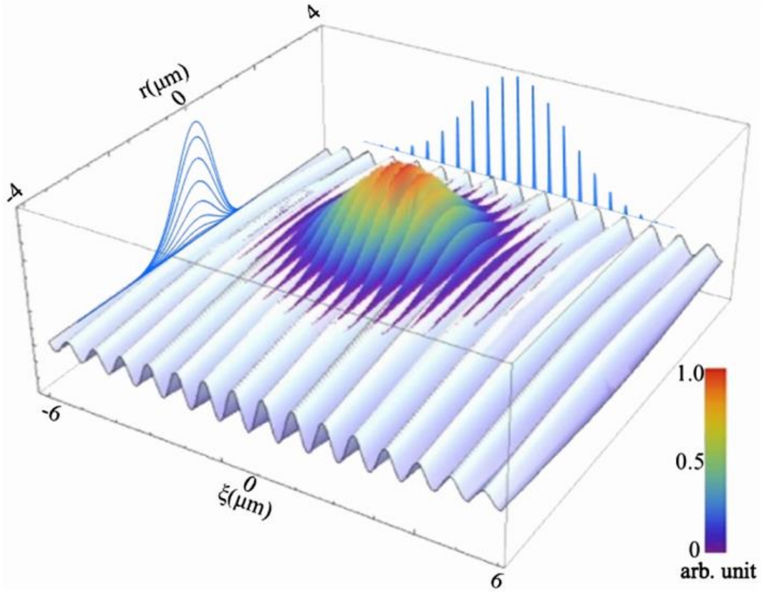


FIG. 2. Visualization of laser-triggered ionization photoelectron yield. The color-coded elevation is the normalized ionization probability rate distribution inside the laser pulse, while the laser pulse profile is shown at the base. The probability distribution is also projected to show longitudinal and axial characteristics.

Hybrid simulations of Trojan Horse

- Numerical aspects:
  - 3D Cartesian geometry
    - short-time simulation with VSim
  - tracking ionized electrons in 3D fields
    - wake fields are assumed quasistatic
  - explore alternate ionization algorithms
    - ADK is very approximate
    - YI alg. yields different brightness

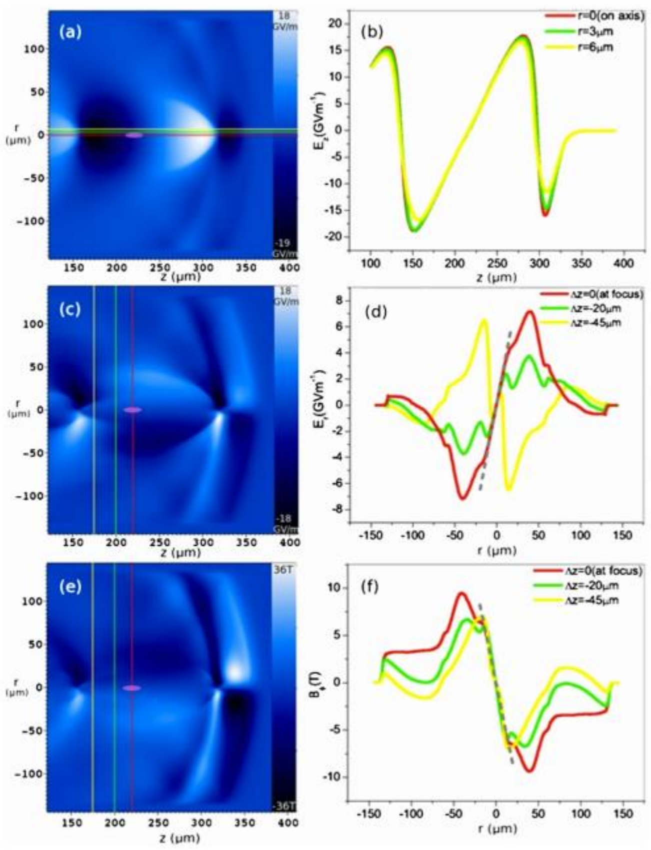


FIG. 3. VORPAL simulation results of the plasma wakefields acting on the released electrons. The left three figures (a), (c), (e) are color plots of the spatial distribution and intensity of wakefields E_ξ, E_r, B_ϕ, respectively, while the right three figures (b), (d), (f) are lineout plots of the fields at the indicated positions. While the corresponding simulation did not include the laser pulse, the laser pulse position of the laser pulse assumed in the numero-analytical analysis is indicated by the reddish ellipse.

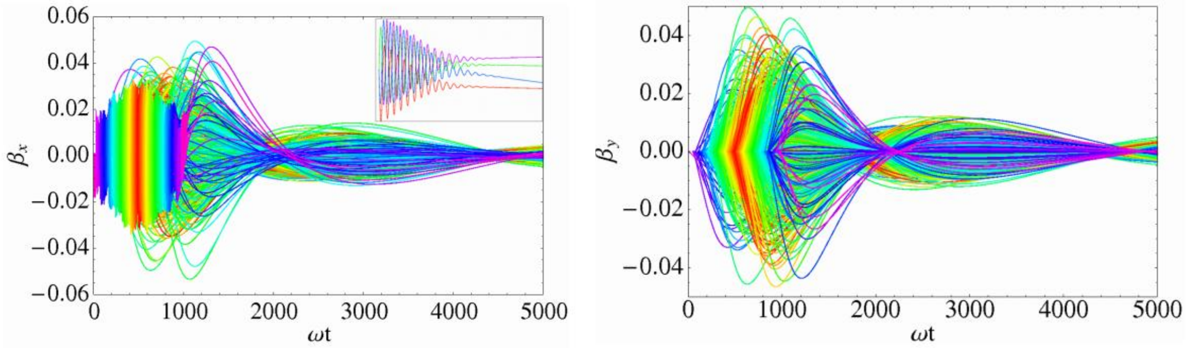
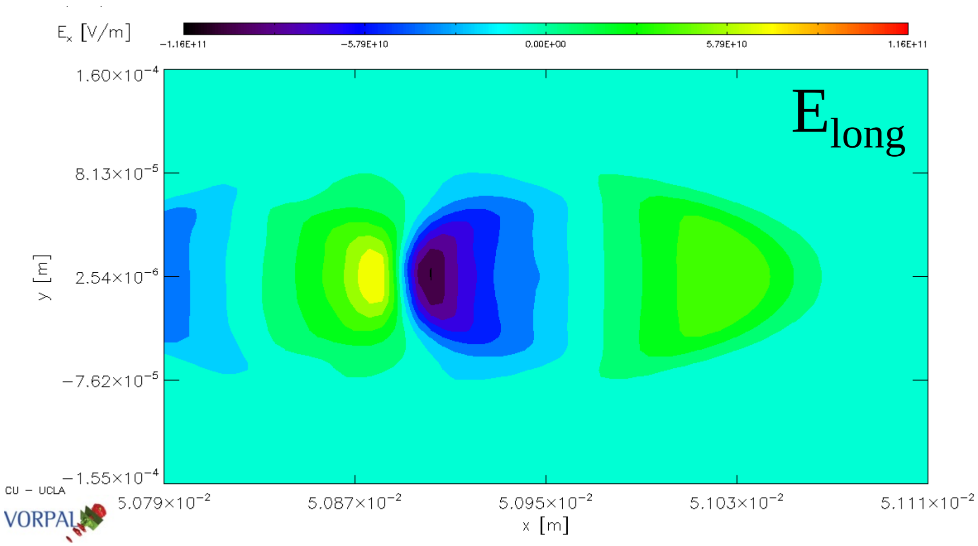


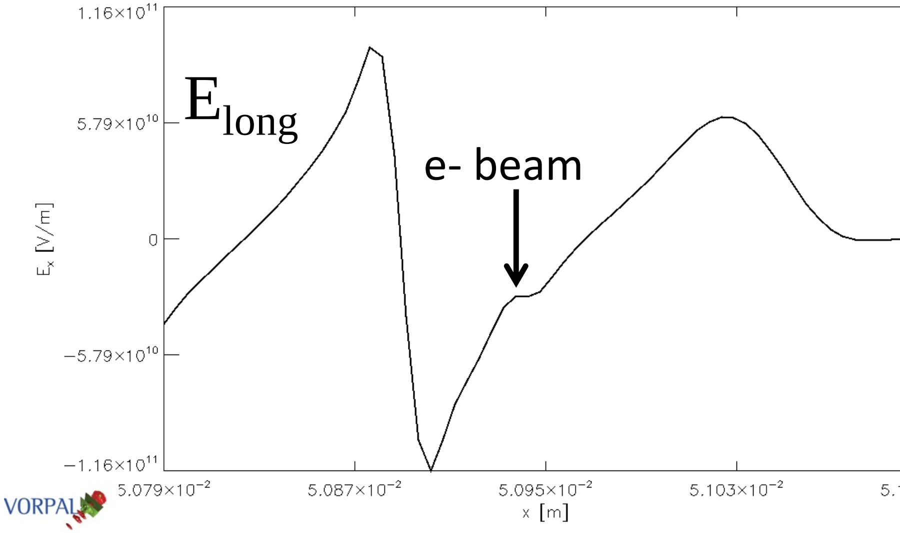
FIG. 4. Electron motion in x (polarization) and y direction are shown in plots at top and bottom, respectively. The inset is a close-up of ponderomotive motion tracks. The tracks are color coded according to electron density from red (maximum) to magenta (minimum).

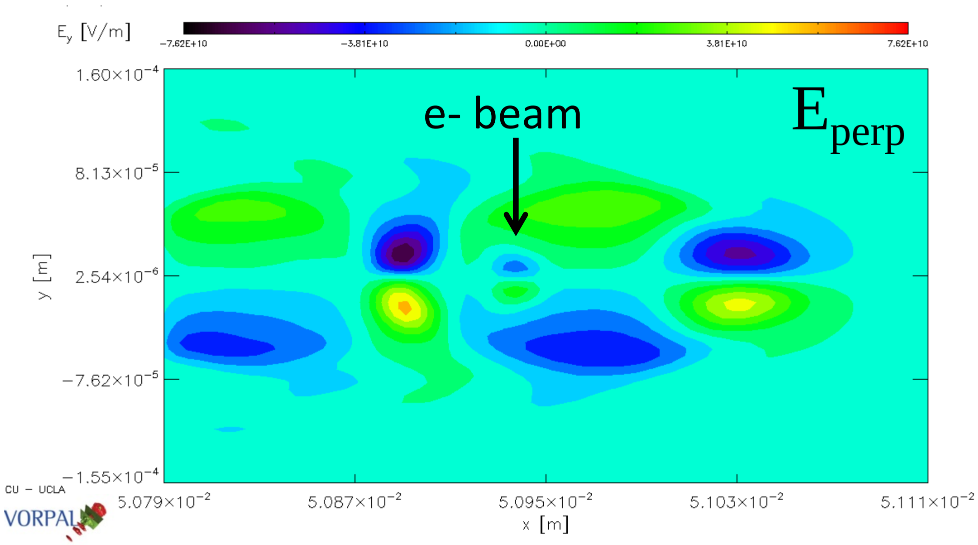
Approach for low-resolution 3D TH simulations

- 2D Cartesian geometry is highly problematic
  - laser and beam evolution is not correct; wakefield is not correct
  - low-resolution 3D is much better than high-resolution 2D
- Don’t resolve the laser pulse
  - use an analytic paraxial approximation for a 3D laser pulse
    - typically, the laser pulse is treated as an envelope
    - with care, one can make use of the time & space resolved fields
- We developed very sophisticated VSim input files
  - inject the laser pulse from any angle, with specified phase (i.e. timing)
    - multiple laser pulses, envelope or explicit (colinear geometry only)
  - static domain decomposition to accommodate macro-particles
    - macro-particle density is highest near the central axis
  - several flavors of resolution (low to high)
    - transition easily from fast parameter scans to heroic parallel simulations
  - different driver shapes (Gaussian, triangle) and representations
    - current profile (fast, non-evolving); full PIC

Example: Low-resolution 3D VSim runs w/ E-210 parameters







- 300 pC of trapped charge
  - beam loading
- transversely unmatched beam
  - strong betatron oscillations
- ~1.5 GeV in 0.5 cm
  - ~2% $\delta E/E$
- ~0.5 mm mrad, $\varepsilon_{N,rms}$
- ~100 kA peak current

IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **47** (2014) 234010 (12pp) doi:10.1088/0953-4075/47/23/234010

Ultrahigh brightness bunches from hybrid plasma accelerators as drivers of 5th generation light sources

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Published 24 November 2014

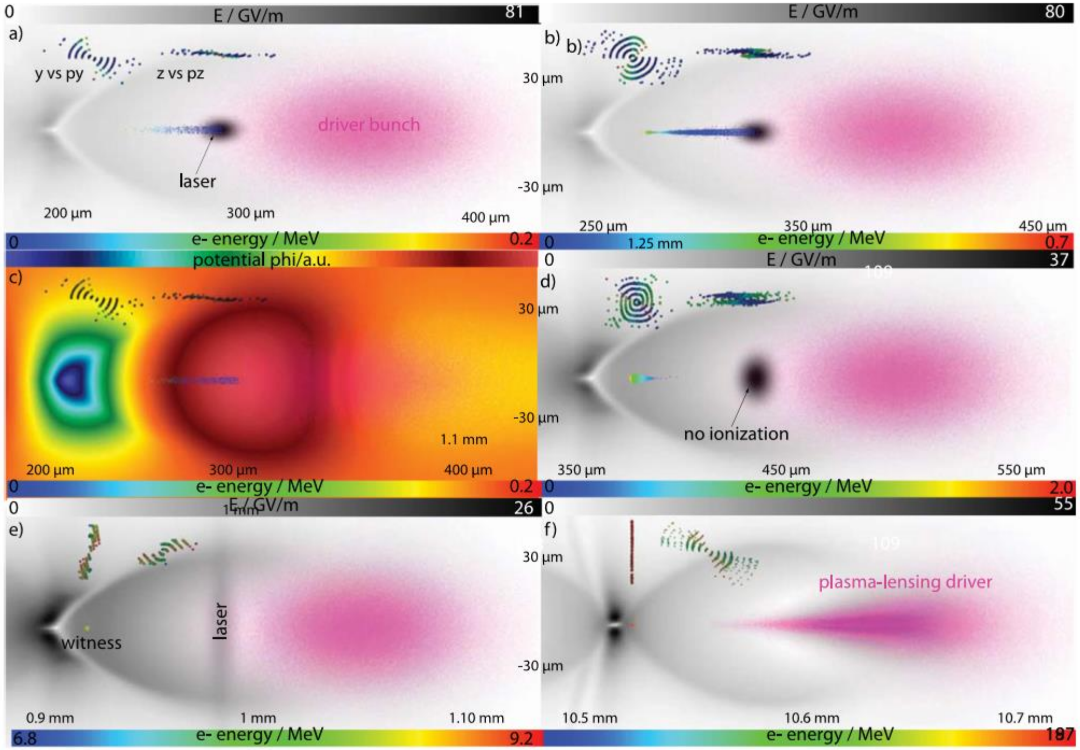

Figure 4. 3D PIC simulation results with VORPAL/VSim. The Gaussian drive bunch (pink) moves to the right and sets up the H plasma wave. He is ionized by the strongly focused laser pulse at the wave's trapping potential maximum, releasing electrons in figures (a)–(c) until it is diffracted to below the He ionization threshold. Then the witness bunch is fully formed and compresses longitudinally (d) and is then further accelerated (e)–(f). The insets show the He electrons' transverse phase space distribution y versus p_y and z versus p_z, respectively.

PRL **113,** 264801 (2014) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2014

Planar-Dielectric-Wakefield Accelerator Structure Using Bragg-Reflector Boundaries

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K. Kusche,[3] B. Naranjo,[1] B. O'Shea,[1] P. Stoltz,[4] C. Swinson,[3] A. Valloni,[1] and J. B. Rosenzweig[1,*]
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(Received 24 June 2014; published 30 December 2014)

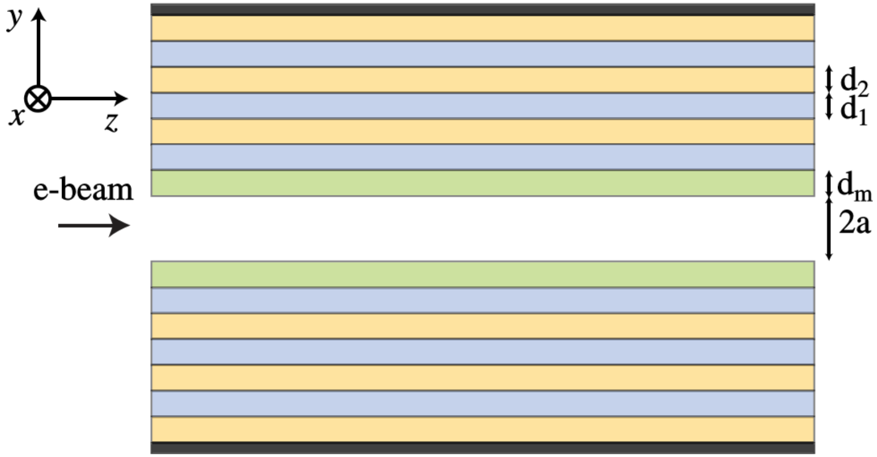

FIG. 1 (color online). Sketch of the DWA structure with Bragg-reflector boundaries. The thickness of the matching layer is d_m, and alternating dielectric layers have thickness of d_1 and d_2, respectively. The total beam gap is $2a$.

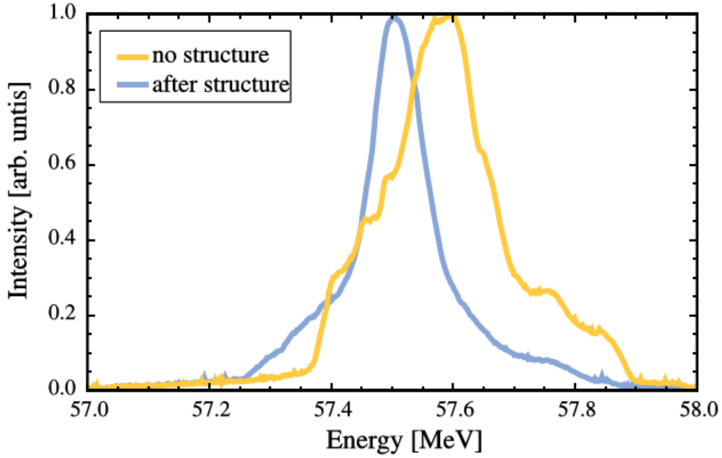

FIG. 3 (color online). The normalized measured beam energy profile (yellow), unaffected by the structure, shows an energy spread ~120 keV (~0.2%) whereas the beam going through the structure (blue) shows an energy spread ~60 keV (~0.1%) and a mean central energy shift of ~70 keV consistent with simulations.

Simulating beam-driven Bragg structures with VSim

- Numerical aspects:
  - 3D Cartesian geometry
    - initial runs in 2D
  - drive beam modeled via current profile
    - fast, low noise (no particles)
    - non-evolving beam
  - high transverse resolution
    - to capture dielectric slab thicknesses
    - simple 2nd-order algorithm for dielectrics
      - alternate between ***E*** and ***D***

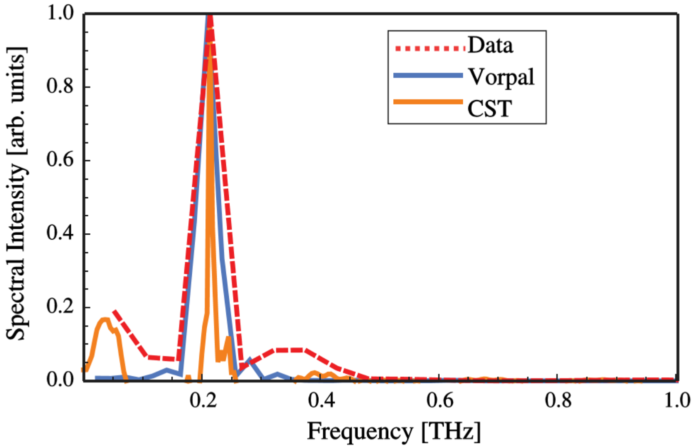

FIG. 5 (color online). Comparison of simulation results with data (dashed red). VORPAL (blue), and CST (orange) yield the same resonant mode for the Bragg DWA structure.

VORPAL

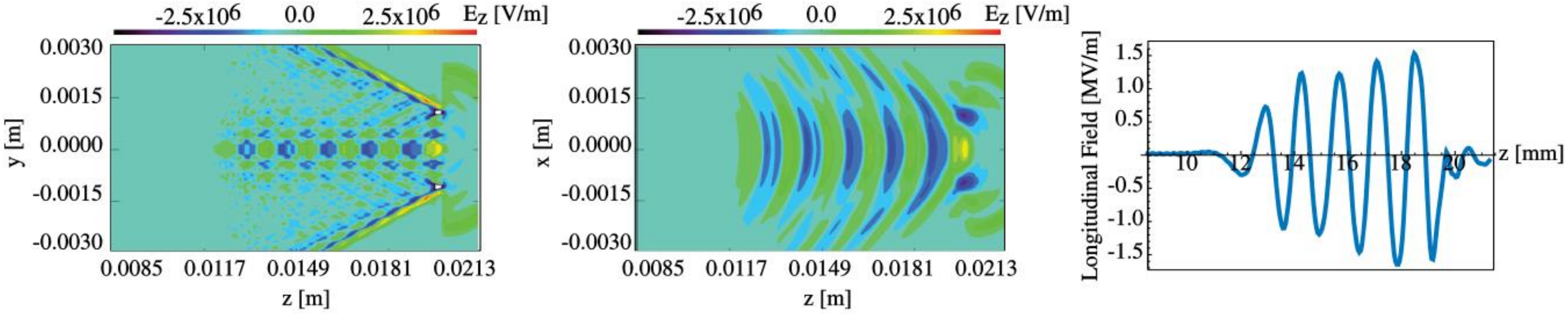

FIG. 4 (color online). Simulated longitudinal field contour plot using experimental parameters from VORPAL shows a peak field of ~1.5 MV/m, displayed as a function of vertical coordinate (bisecting Bragg layers)—left, and horizontal coordinate (parallel to Bragg layers)—middle. The longitudinal projection of E_z on axis is shown on the right. The electron beam travels in the positive-z direction.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 081304 (2015)

Optical plasma torch electron bunch generation in plasma wakefield accelerators

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(Received 27 February 2015; published 3

A novel, flexible method of witness electron bunch generati
described. A quasistationary plasma region is ignited by a focus
plasma wave. This localized, shapeable optical plasma torch ca
blowout during passage of the electron driver bunch, leading to
trajectories and to controlled injection. This optically steered inj
compared to hydrodynamically controlled gas density transition

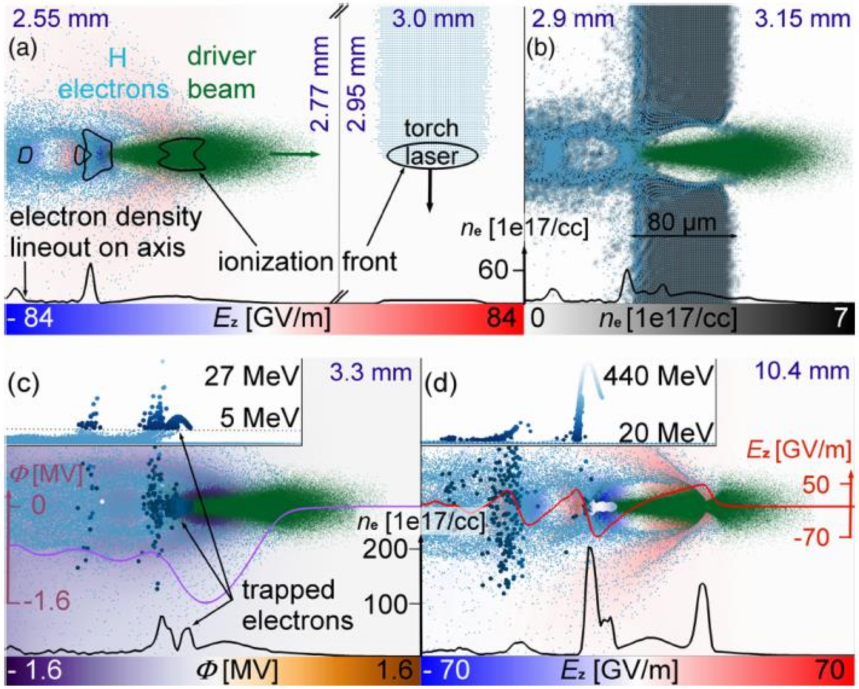


FIG. 3. Optical plasma torch injection for case (i). In (a) the plasma torch is generated in the path of the drive beam, and in (b) the torch is crossed, leading to blowout amplification and injection. The injected hydrogen electrons are shown in (c) and (d) after $z \approx 10.4$ mm of acceleration, where maximum energies of $E \approx 440$ MeV are reached.

radiasoft

Simulating plasma torch injection with VSim

- Numerical aspects:
  - 3D Cartesian geometry
  - many options for particle layout
    - neutral (macroparticles or ‘fluid’)
    - preionized
    - careful arrangement on mesh
    - many species to choose from
  - many options for ionization processes
    - singly-charged ion macroparticles
      - can be ignored
      - can be created & further ionized
    - different species handled differently
  - each species managed separately
    - different ions, charge states
    - e-’s are tagged by origin (or not)

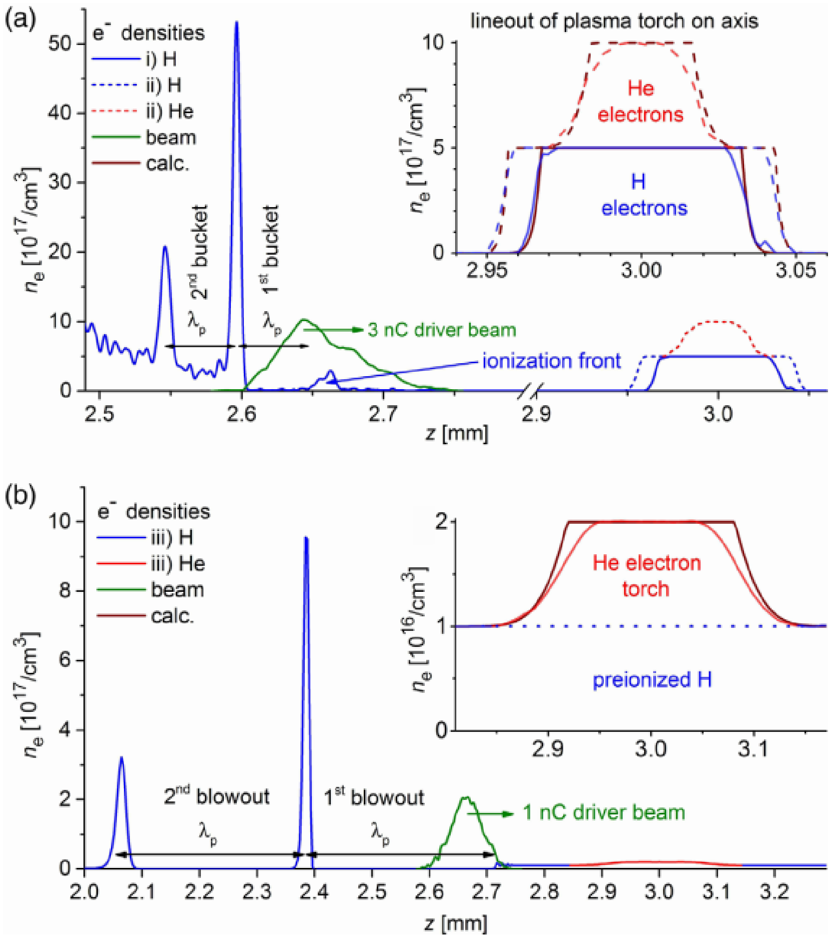


FIG. 2. On-axis density lineouts for cases (i) and (ii), where hydrogen and helium are neutral (a), and (iii), where hydrogen is preionized (b). The electron bunch driver (green) propagates to the right, and the torch is produced by a laser pulse with $a_0 = 0.015$ in case (i) and $a_0 = 0.025$ in case (ii) and (iii). The zoomed insets show the plasma torch profile obtained via numero-analytical ADK calculations (brown) compared to densities obtained in the simulation (blue/red).

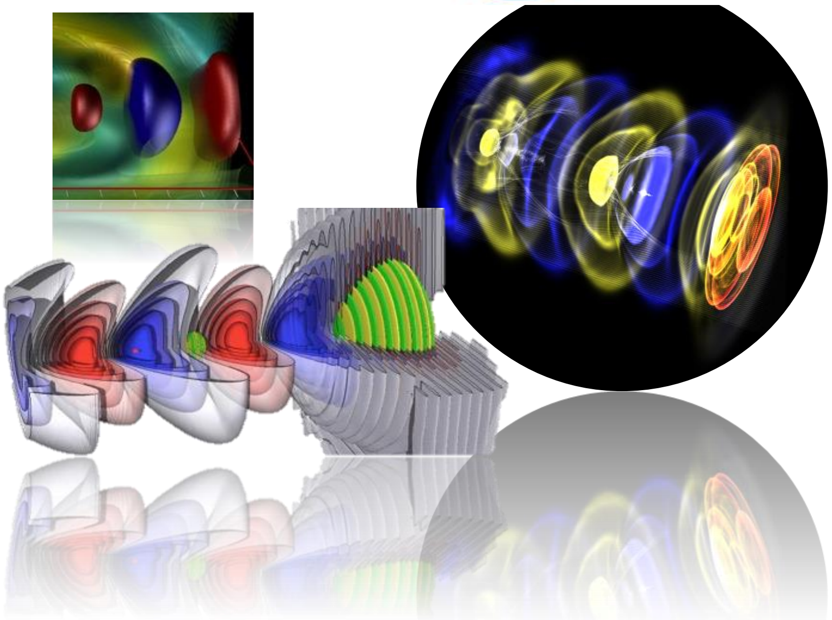
LBNL “BLAST” simulation toolset

for 3-D modeling of plasma accelerators (and more)

blast.lbl.gov

BLAST

BERKELEY LAB ACCELERATOR SIMULATION TOOLKIT



State-of-the-art simulation tools*:

- *Multiphysics framework*: **Warp**.
- *PIC optimized library*: **PICSAR**.
- *New PIC-AMR code*: **WarpX**.

Multiphysics:

- beams, plasmas, lasers, field ionization, …

Advanced algorithms:

- boosted frame, PSATD, PML, AMR, rel. particle pusher, NCI suppr. (Galilean fr.), Python steering, …

High-performance computing:

- parallel (MPI, OpenMP), portable vectorization, OpenPMD HFD5 I/O., …

*open source: Warp (warp.lbl.gov), PICSAR (picsar.net), WarpX (public release in 2018).

Simulating shaped Trojan Horse e- beams with Warp

- Designer beams:
  - reproducing in Warp the VSim input file capabilities described above
  - 3 ionizing Trojan Horse laser pulses are used in combination
    - nonlinear optimizer is used with Warp to achieve trapezoidal longitudinal profile

Cook, Bruhwiler, Lehe, Vay *et al*., Phase I DOE/HEP SBIR final report (2016), DE-SC0013855.

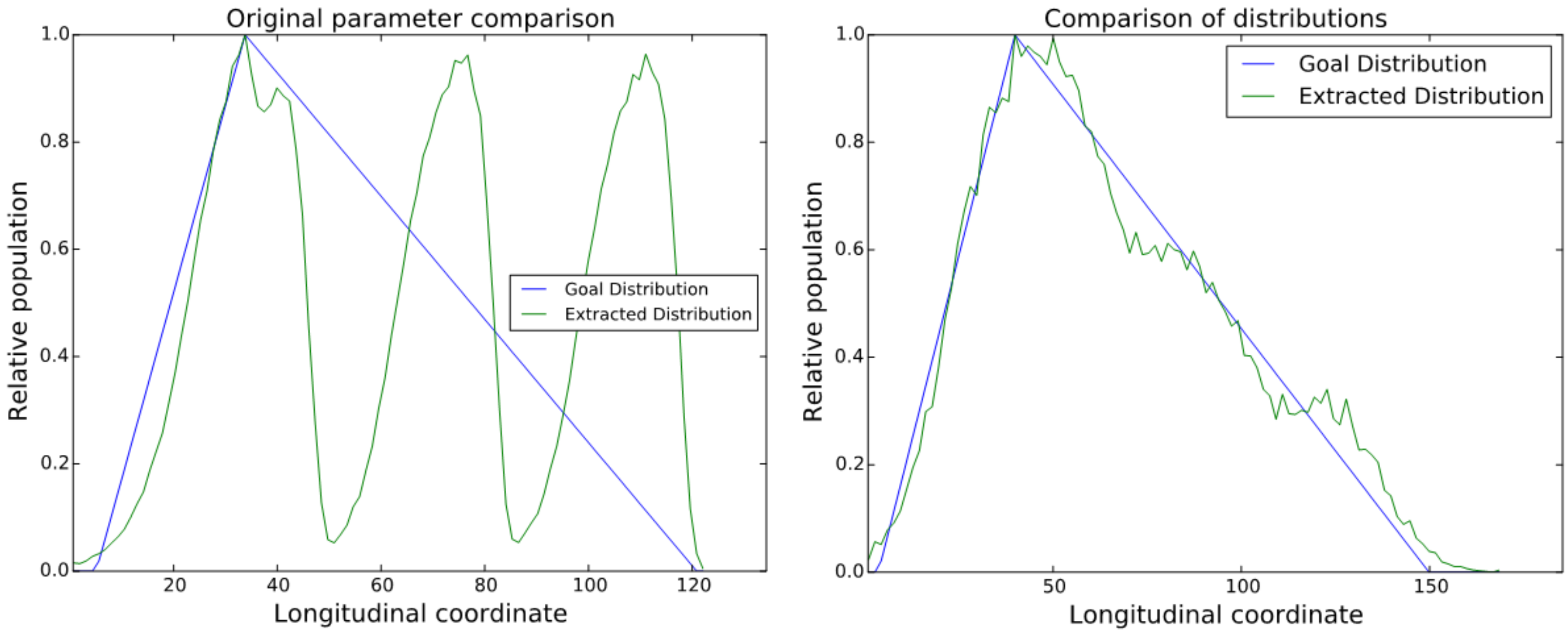


Figure 3: At left, the original laser parameters without optimization produce a disjointed longitudinal electron profile. At right, the use of an optimizer to iteratively improve several sets of physical parameters produces a witness bunch profile approximating the trapezoidal distribution with linear ramp length greater than 3 times the tail length.

FBPIC (Fourier-Bessel Particle-In-Cell)

- Spectral quasi-cylindrical Particle-In-Cell algorithm
  (azimuthal mode decomposition)
- Runs on GPU and (multi-core) CPU
- Open-source: github.com/fbpic/fbpic
  Documentation: fbpic.github.io

Several useful features for plasma acceleration:

- Intrinsic mitigation of Numerical Cherenkov Radiation (NCR)
- Support for boosted-frame technique
- Calculation of initial space-charge fields
- Field ionization physics (ADK model)

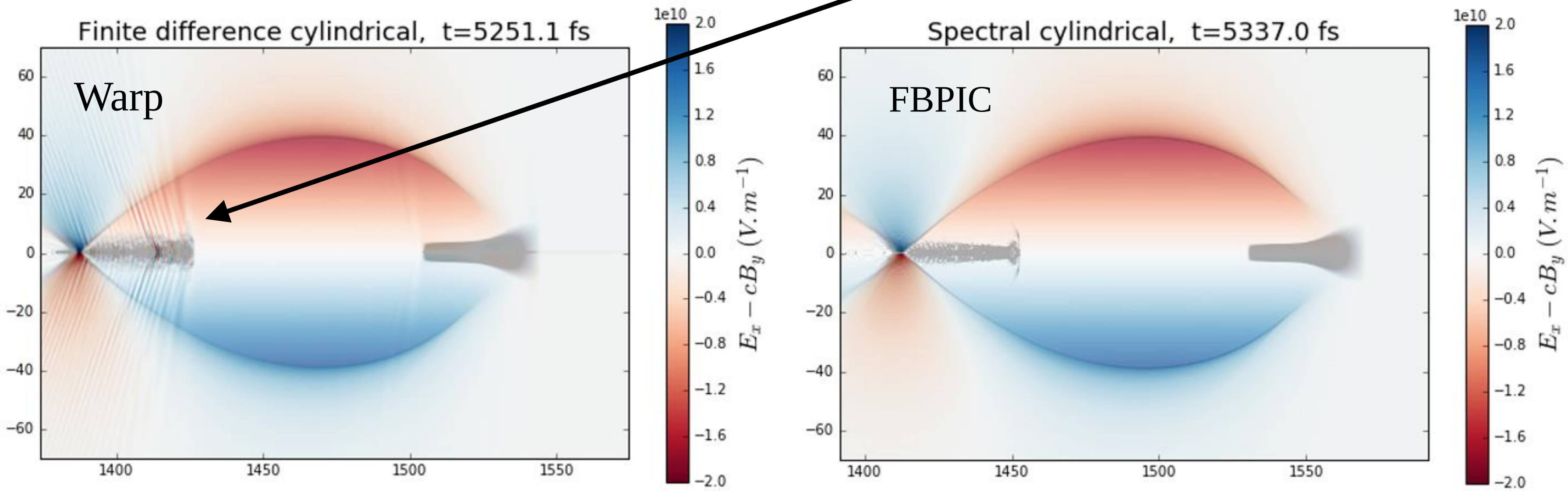
Primarily developed at LBNL and CFEL, Hamburg

Suppressing NCI in r-z geometry w/ FBPIC

- Numerical aspects:
  - 3D Cartesian geometry
  - many options for particle layout
    - neutral (macroparticles or ‘fluid’)

Cook, Bruhwiler, Lehe, Vay *et al.*, Phase I DOE/HEP SBIR final report (2016), DE-SC0013855.

Numerical Cerenkov Instability (NCI) is observed



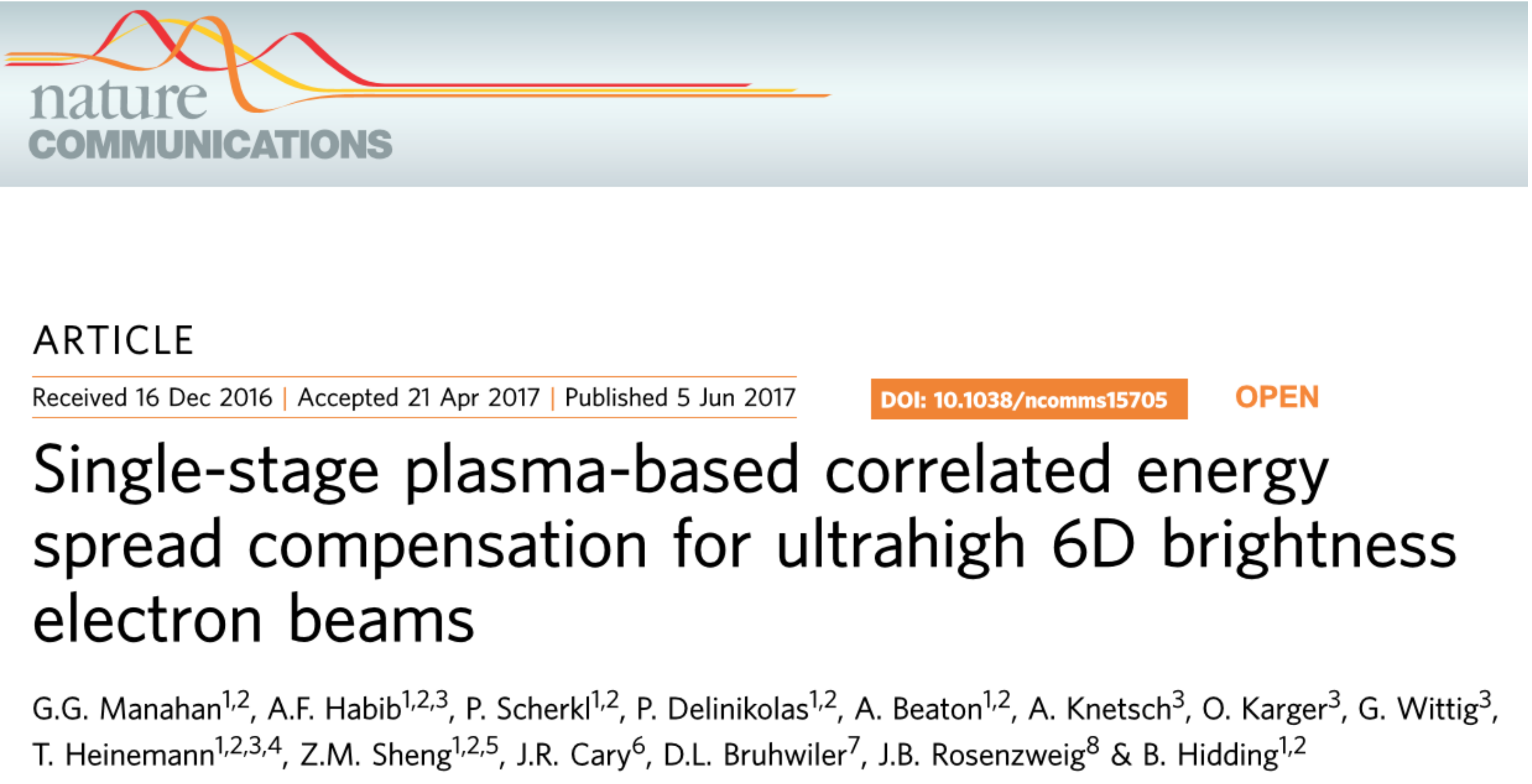
Finite difference cylindrical, t=5251.1 fs

Warp

Spectral cylindrical, t=5337.0 fs

FBPIC

Figure 19: A comparison of a 2D PWFA simulations. At least, the FDTD cylindrical solver in R-Z geometry shows significant evidence of numerical Cherenkov radiation, produced by the injected witness bunch as well as at the head and tail of the bubble. At right use of a spectral cylindrical solver eliminates the numerical Cherenkov and produces a cleaner representation of the electrical field.



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Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams

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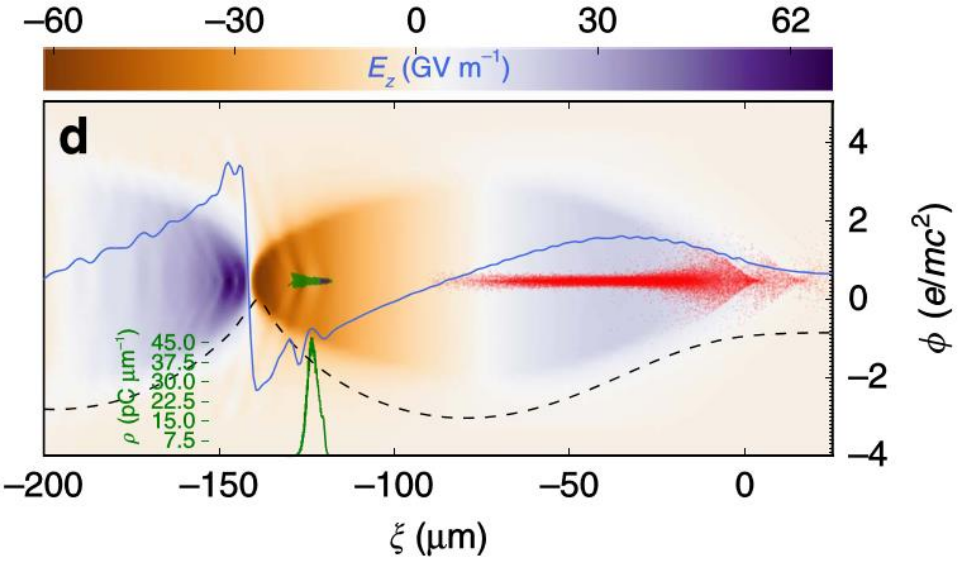
Plasma photocathode wakefield acceleration combines energy gains of te
generation of ultralow emittance electron bunches, and opens a path to
orders of magnitude larger than state-of-the-art. This holds great p
accelerator building blocks and advanced light sources. However, an in
the enormous electric field gradients inherent to plasma accelerators is s

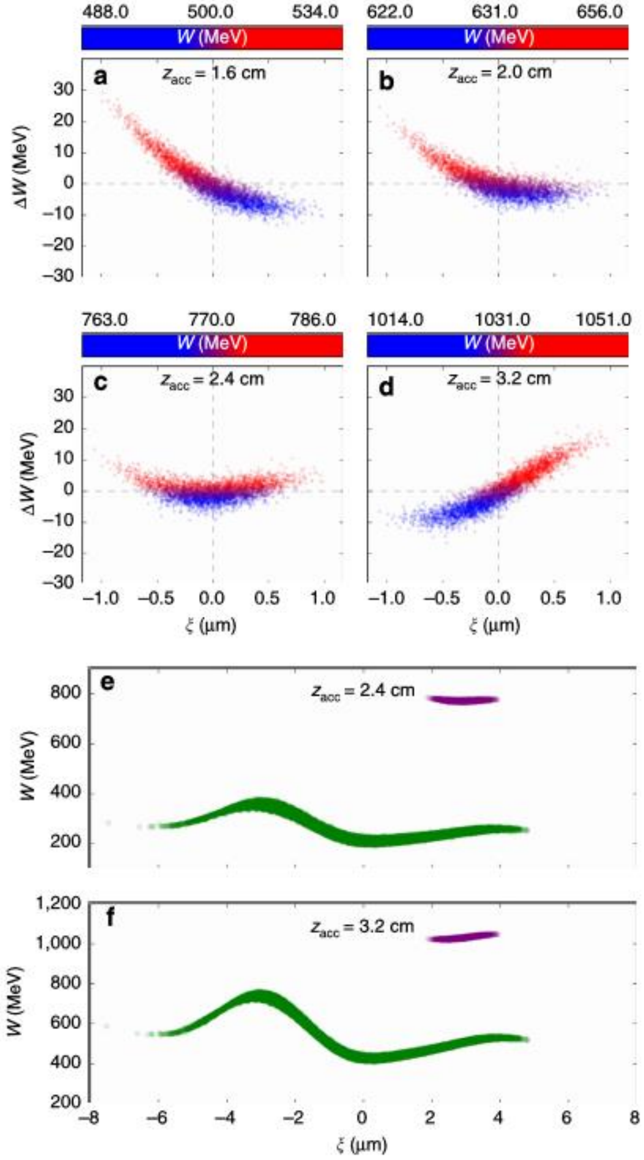


radiasoft

Simulating TH-based dechirping of the witness bunch, using VSim

- Numerical aspects:
  - As the witness beam achieves new levels of brightness, we are observing signs of NMI
    - the 'magic time step' is used, which helps

Godfrey and Vay, J. Comp. Phys. **267**, 1 (2014).



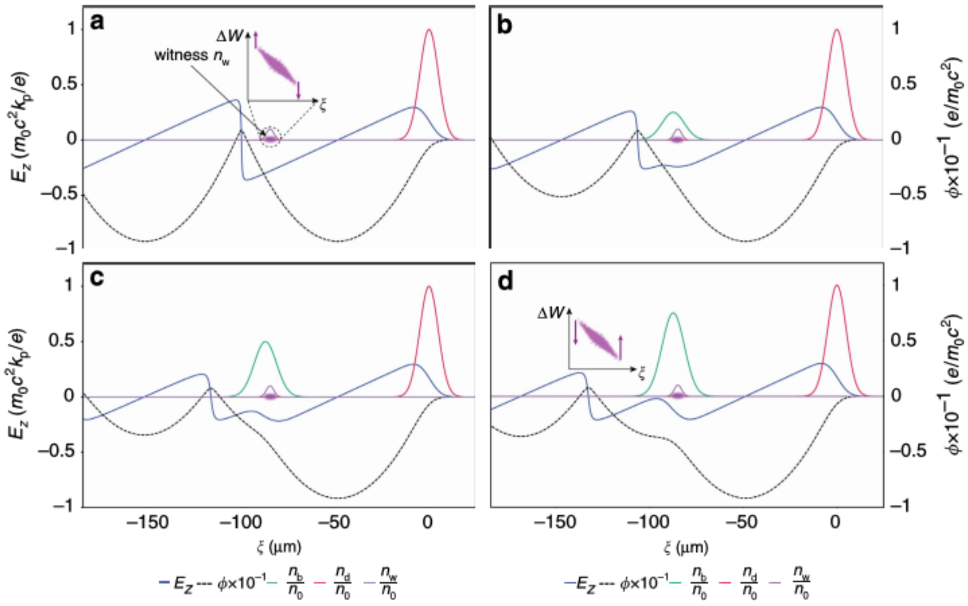


Figure 1 | Beamloading of the plasma wake in 1D nonlinear regime. On-axis longitudinal electric field E_z (blue line) and electrostatic potential ϕ (dashed black line) in a plasma wave of density $n_0 = 1.1 \times 10^{17}$ cm^{-3}, driven by a non-evolving electron beam (red curve), propagating to the right. Adding an electron escort beam (green curve) with charge density n_b can load the wake and flatten or reverse the electric longitudinal field locally: (**a**) unloaded case ($n_b = 0$), where the position of the witness bunch n_w (purple curve) and its resulting energy chirp is indicated schematically, (**b**) $n_b/n_0 = 0.5$, (**c**) $n_b/n_0 = 1.0$ and (**d**) $n_b/n_0 = 1.5$. The results are obtained using the 1D nonlinear fluid model description. The electron witness bunch position and size (purple) is indicated, thus visualizing the electric accelerating field which would be sampled by the witness. The insets in (**a**,**d**) are the longitudinal phase spaces of the witness bunch, indicating the phase rotation for the (**a**) unloaded and (**d**) loaded cases.

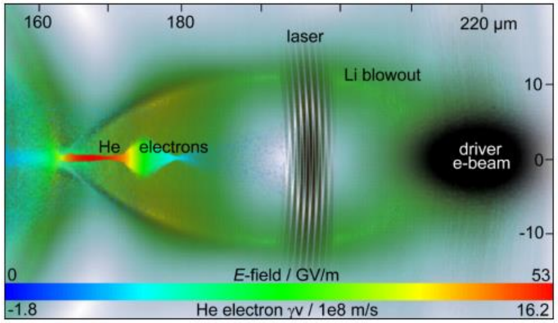
Plasma photocathodes

E-210: Trojan Horse collaboration

Hybrid concept: Use laser pulses to inject high-quality electrons in beam-driven plasma wakefield acceleration

Hidding, Rosenzweig & the E-210 team; multiple papers are in preparation.

- ☐ **Two modes of operation:**
  - ☐ **Plasma torch: optically controlled, ultraflexible density downramp injection**
    - **(hydrodynamic) density downramp injection was long proposed for PWFA (Suk et al., PRL 86, 1011 (2001) but until E210 only shown for LWFA.**
    - Plasma torch goes a step further and avoids hydrodynamics completely: “next-**generation** density downramps” which e.g. can have ultrasharp scale lengths (Wittig et al., **PRSTAB 18, 081304 (2015)**
    - **Density downramps are interesting in its own right, reinforced plans at FACET-II and DESY, for example**
  - ☐ **Trojan Horse: implant tunable, ultracold electron population directly within blowout, promises emittance (nm rad-scale) and brightness improved by orders of magnitude**
    - **Idea proposed in 2011 and led to E210: Trojan Horse programme (Hidding et al., PRL 108, 035001, 2012)**
    - **Requires fs, µm-scale spatiotemporal alignment of laser and electron beam**
    - **Preionized plasma channel width a (technical) bottleneck**



Modeling “Capillary Trojan Horse” concept with Warp

- New hybrid concept:
  - replace the plasma with a cylindrical dielectric
    - or planar geometry…
  - neutral H or He gas inside
- Simpler than standard TH
  - only one plasma species
- Otherwise, very similar
  - e- drive beam
  - ionizing laser pulse

F.H. O’Shea *et al.*, Phase I DOE/HEP SBIR project (2017), DE-SC0017690.

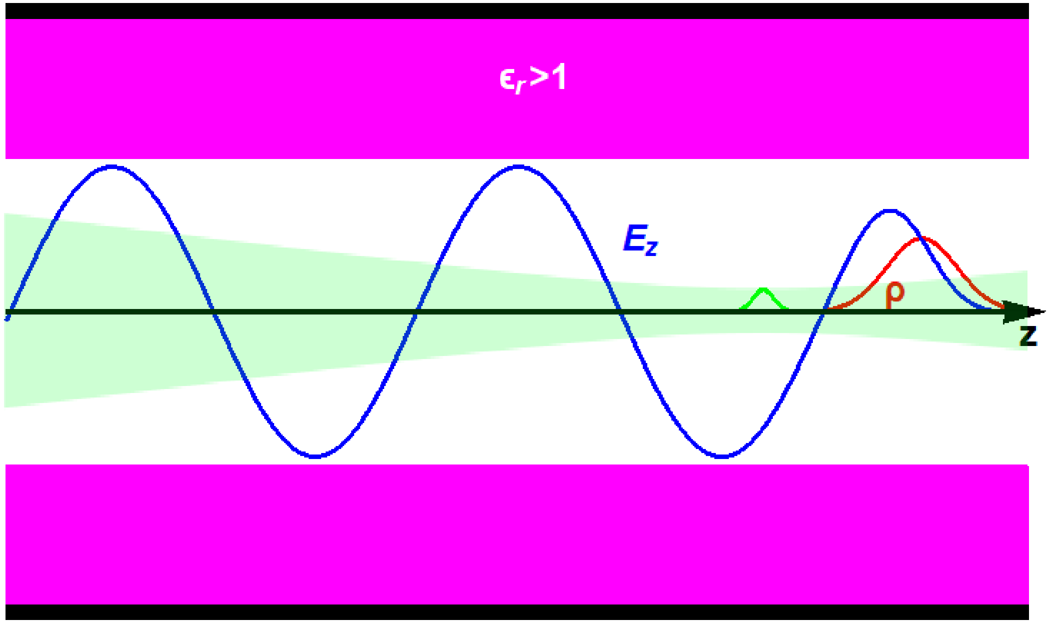


Figure 3: Illustration of the Capillary Trojan Horse plasma cathode technique for producing ultracold electron beams. Here, a drive beam (red line) excites a longitudinal wakefield (blue line) inside a dielectric (magenta) surrounded by a metal boundary (black). A co-propagating laser (light green) ionizes a tenuous gas at the laser focus that is positioned to expose the newly liberated electrons to large accelerating field (>100 MV/m).

Modeling "Capillary Trojan Horse" concept with Warp

F.H. O'Shea *et al.*, Phase I DOE/HEP SBIR project (2017), DE-SC0017690.

- Numerical aspects:
  - starting with 2D Cartesian in planar structure
  - dielectric wakefield is represented by an analytic function
  - laser pulse is not resolved
  - we've started exploring the parameter space
    - laser pulse energy and length
    - resolution, PPC, …

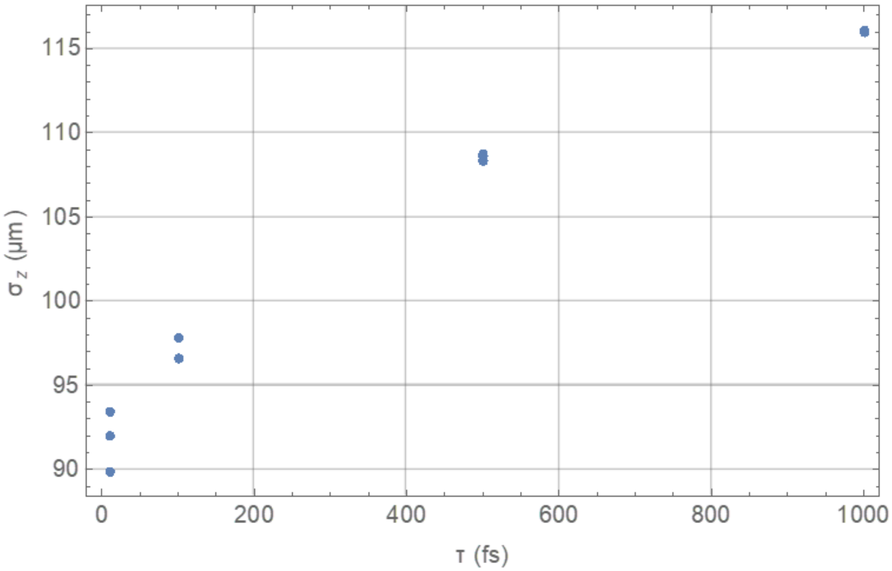


Figure 1: Length of electron beam created through ionization injection in neutral gas as a function of ionization laser pulse length.

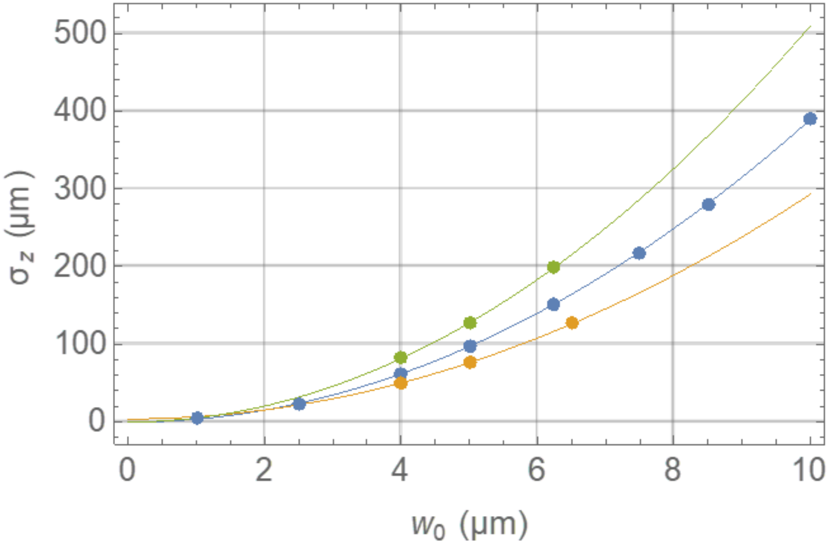


Figure 2: Electron beam length as a function of laser waist size for three different laser pulse energies.

Partial list of EM PIC codes for plasma accelerators

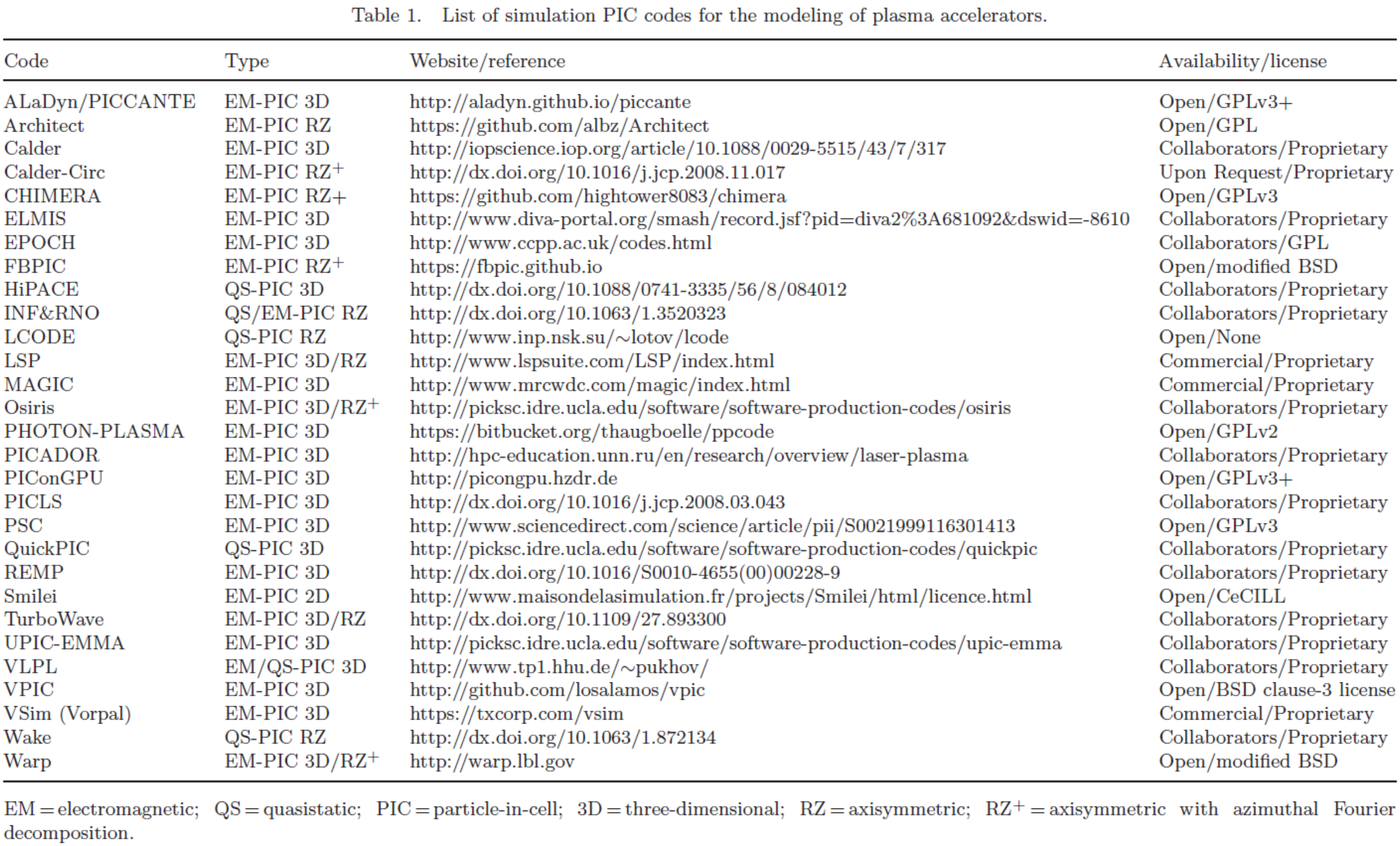


Table 1. List of simulation PIC codes for the modeling of plasma accelerators.

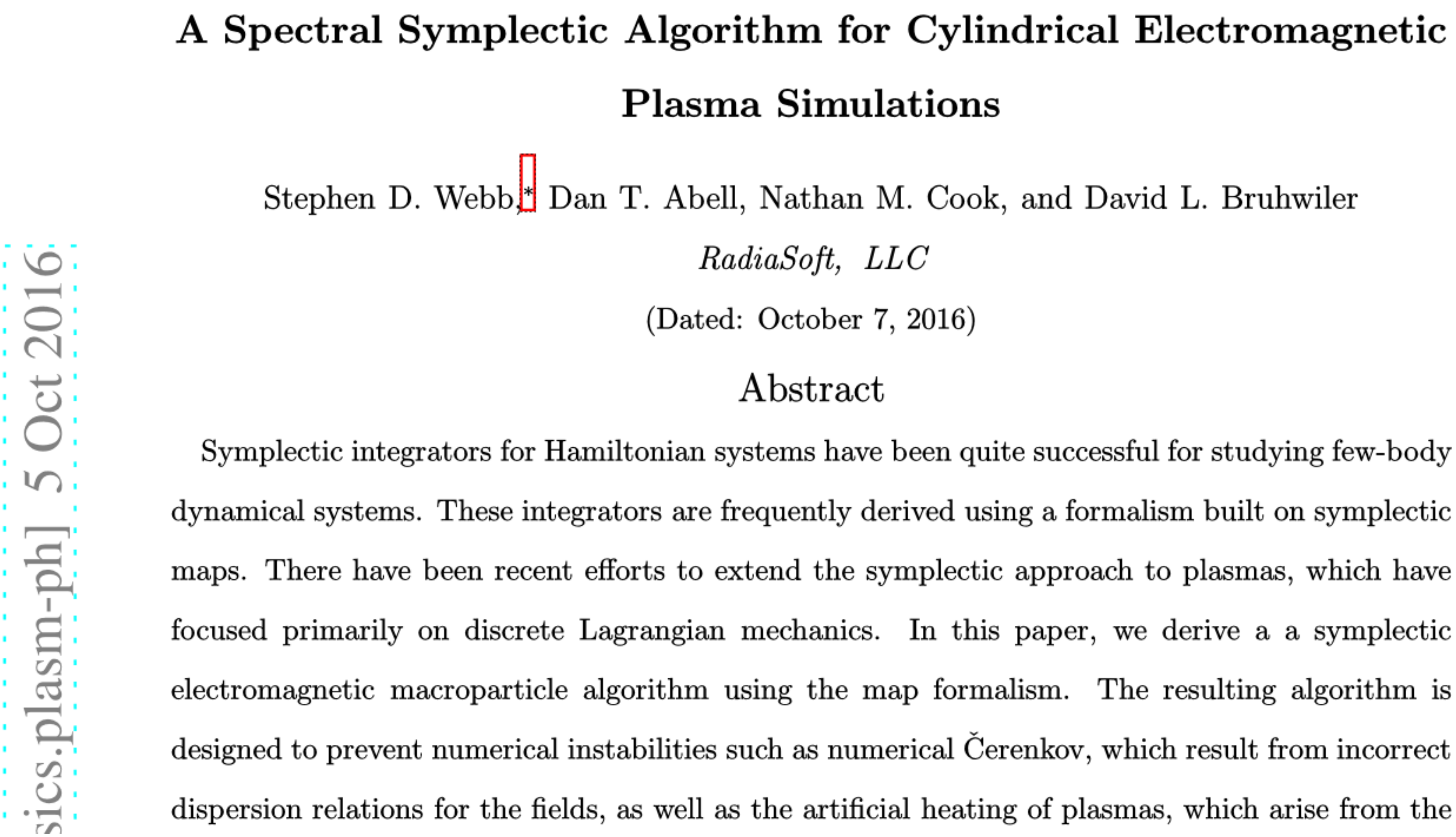
Code	Type	Website/reference	Availability/license
ALaDyn/PICCANTE	EM-PIC 3D	http://aladyn.github.io/piccante	Open/GPLv3+
Architect	EM-PIC RZ	https://github.com/albz/Architect	Open/GPL
Calder	EM-PIC 3D	http://iopscience.iop.org/article/10.1088/0029-5515/43/7/317	Collaborators/Proprietary
Calder-Circ	EM-PIC RZ$^+$	http://dx.doi.org/10.1016/j.jcp.2008.11.017	Upon Request/Proprietary
CHIMERA	EM-PIC RZ+	https://github.com/hightower8083/chimera	Open/GPLv3
ELMIS	EM-PIC 3D	http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A681092&dswid=-8610	Collaborators/Proprietary
EPOCH	EM-PIC 3D	http://www.ccpp.ac.uk/codes.html	Collaborators/GPL
FBPIC	EM-PIC RZ$^+$	https://fbpic.github.io	Open/modified BSD
HiPACE	QS-PIC 3D	http://dx.doi.org/10.1088/0741-3335/56/8/084012	Collaborators/Proprietary
INF&RNO	QS/EM-PIC RZ	http://dx.doi.org/10.1063/1.3520323	Collaborators/Proprietary
LCODE	QS-PIC RZ	http://www.inp.nsk.su/~lotov/lcode	Open/None
LSP	EM-PIC 3D/RZ	http://www.lspsuite.com/LSP/index.html	Commercial/Proprietary
MAGIC	EM-PIC 3D	http://www.mrcwdc.com/magic/index.html	Commercial/Proprietary
Osiris	EM-PIC 3D/RZ$^+$	http://picksc.idre.ucla.edu/software/software-production-codes/osiris	Collaborators/Proprietary
PHOTON-PLASMA	EM-PIC 3D	https://bitbucket.org/thaugboelle/ppcode	Open/GPLv2
PICADOR	EM-PIC 3D	http://hpc-education.unn.ru/en/research/overview/laser-plasma	Collaborators/Proprietary
PIConGPU	EM-PIC 3D	http://picongpu.hzdr.de	Open/GPLv3+
PICLS	EM-PIC 3D	http://dx.doi.org/10.1016/j.jcp.2008.03.043	Collaborators/Proprietary
PSC	EM-PIC 3D	http://www.sciencedirect.com/science/article/pii/S0021999116301413	Open/GPLv3
QuickPIC	QS-PIC 3D	http://picksc.idre.ucla.edu/software/software-production-codes/quickpic	Collaborators/Proprietary
REMP	EM-PIC 3D	http://dx.doi.org/10.1016/S0010-4655(00)00228-9	Collaborators/Proprietary
Smilei	EM-PIC 2D	http://www.maisondelasimulation.fr/projects/Smilei/html/licence.html	Open/CeCILL
TurboWave	EM-PIC 3D/RZ	http://dx.doi.org/10.1109/27.893300	Collaborators/Proprietary
UPIC-EMMA	EM-PIC 3D	http://picksc.idre.ucla.edu/software/software-production-codes/upic-emma	Collaborators/Proprietary
VLPL	EM/QS-PIC 3D	http://www.tp1.hhu.de/~pukhov/	Collaborators/Proprietary
VPIC	EM-PIC 3D	http://github.com/losalamos/vpic	Open/BSD clause-3 license
VSim (Vorpal)	EM-PIC 3D	https://txcorp.com/vsim	Commercial/Proprietary
Wake	QS-PIC RZ	http://dx.doi.org/10.1063/1.872134	Collaborators/Proprietary
Warp	EM-PIC 3D/RZ$^+$	http://warp.lbl.gov	Open/modified BSD

EM = electromagnetic; QS = quasistatic; PIC = particle-in-cell; 3D = three-dimensional; RZ = axisymmetric; RZ$^+$ = axisymmetric with azimuthal Fourier decomposition.

J.-L. Vay and R. Lehe, "Simulations for Plasma and Laser Acceleration",
Reviews of Accelerator Science and Technology **9**, 165 (2016).

Future Plans

- *Ongoing simulation of E-210 experiment*
  - *better understand the experimental data*
  - *papers are in preparation*
- *Continued exploration of new beam-driven ideas*
  - *assist in development of plans for FACET-II & other facilities*
  - *support "capillary Trojan horse"*
- *Codes*
  - *VSim will continue to be used by those with access*
    - *highly-productive work flow*
  - *Ongoing use of Warp – moving to WarpX*
    - *2D and 3D Cartesian, manycore, pseudospectral solvers (no NCI)*
  - *Begin using FBPIC*
    - *2D cylindrical with azimuthal modes, manycore, spectral solvers*
- *New symplectic EM algorithm with r-z spectral solver*



A Spectral Symplectic Algorithm for Cylindrical Electromagnetic Plasma Simulations

Stephen D. Webb,* Dan T. Abell, Nathan M. Cook, and David L. Bruhwiler
RadiaSoft, LLC

(Dated: October 7, 2016)

Abstract

Symplectic integrators for Hamiltonian systems have been quite successful for studying few-body dynamical systems. These integrators are frequently derived using a formalism built on symplectic maps. There have been recent efforts to extend the symplectic approach to plasmas, which have focused primarily on discrete Lagrangian mechanics. In this paper, we derive a a symplectic electromagnetic macroparticle algorithm using the map formalism. The resulting algorithm is designed to prevent numerical instabilities such as numerical Čerenkov, which result from incorrect dispersion relations for the fields, as well as the artificial heating of plasmas, which arise from the

$$\mathcal{H} = \underbrace{\sum_j \sqrt{\left(p_j^{(r)} - w_j \frac{q}{c}\sum_\sigma I_\sigma^{(r)}(\mathbf{x}_j)\right)^2 + \left(p_j^{(z)} - w_j \frac{q}{c}\sum_\sigma I_\sigma^{(z)}(\mathbf{x}_j)\right)^2 + \frac{p_j^{(\theta)2}}{r_j^2} + w_j^2 m^2 c^2}}_{\mathcal{H}_{p-c}}$$

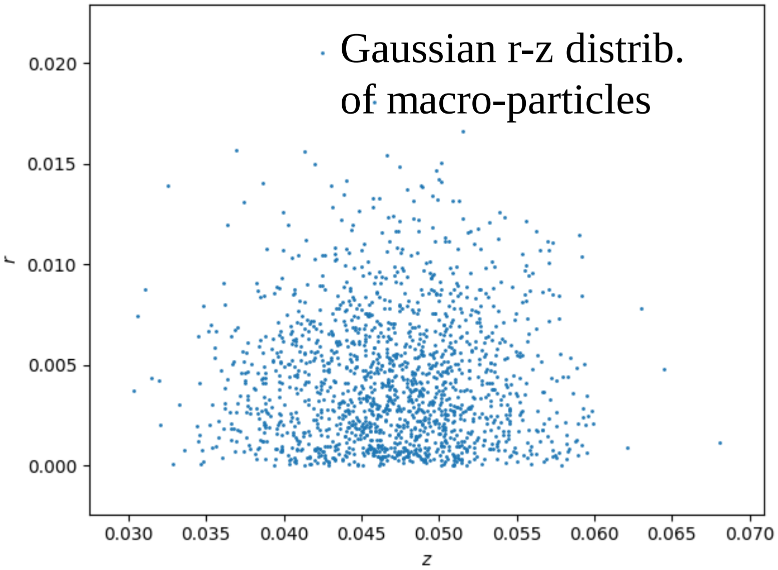
$$+ \underbrace{\sum_\sigma \frac{\mathcal{P}_\sigma^{(0)2}}{2\mathcal{M}_\sigma} + \frac{\mathcal{P}_\sigma^{(\omega)2}}{2\mathcal{M}_\sigma} + \frac{1}{2}\mathcal{M}_\sigma \Omega_\sigma^2 Q_\sigma^{(\omega)2}}_{\mathcal{H}_{EM}}$$

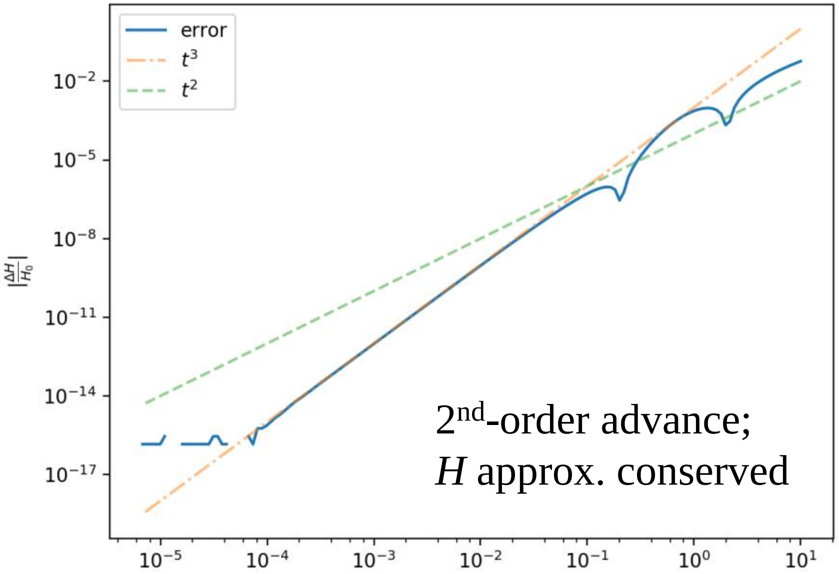
Webb *et al.*, “A Spectral Symplectic Algorithm for Cylindrical Electromagnetic Plasma Simulations (2016); https://arxiv.org/abs/1609.05095

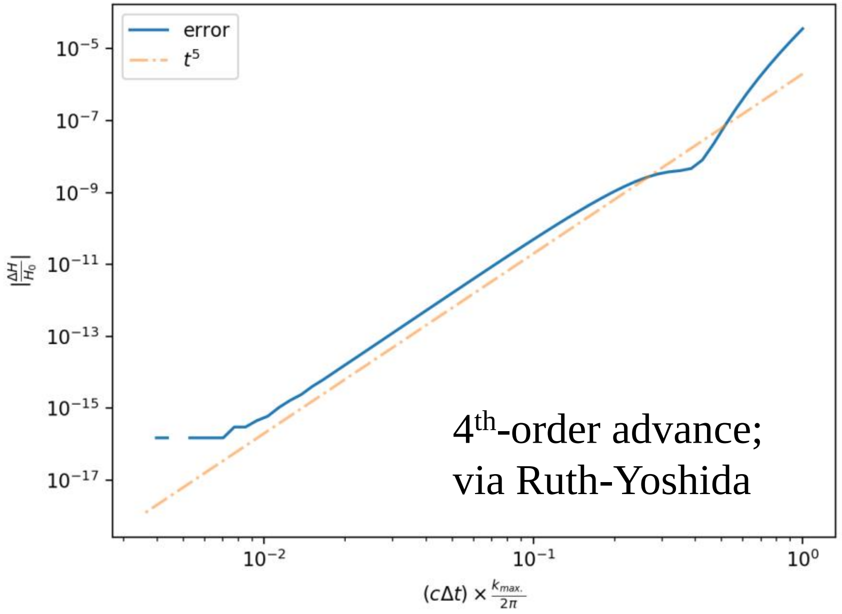
Explicit maps for charged particle & field dynamics

Beam/field update is a sequence of explicit maps:

$$\begin{aligned}\mathscr{N} = \mathscr{M}^{(EM)}(\Delta\tau/2)\mathscr{M}^{(\theta)}(\Delta\tau/2)\times \\ \mathscr{A}^{(z)}\mathscr{D}^{(z)}(\Delta\tau/2)\left[\mathscr{A}^{(z)}\right]^{-1}\times \\ \mathscr{A}^{(r)}\mathscr{D}^{(r)}(\Delta\tau)\left[\mathscr{A}^{(r)}\right]^{-1}\times \\ \mathscr{A}^{(z)}\mathscr{D}^{(z)}(\Delta\tau/2)\left[\mathscr{A}^{(z)}\right]^{-1}\times \\ \mathscr{M}^{(\theta)}(\Delta\tau/2)\mathscr{M}^{(EM)}(\Delta\tau/2)\end{aligned}$$


Gaussian r-z distrib.
of macro-particles


2nd-order advance;
H approx. conserved


4th-order advance;
via Ruth-Yoshida

Acknowledgments (8 years)

U.S. DEPARTMENT OF
ENERGY
Office of Science

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FACET
E-210: Trojan Horse collaboration

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NERSC