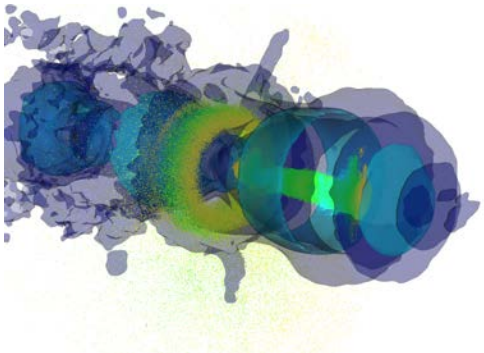
Exaflop, Petawatt, and Terabar physics

B. Polllock et al. PRL 2015



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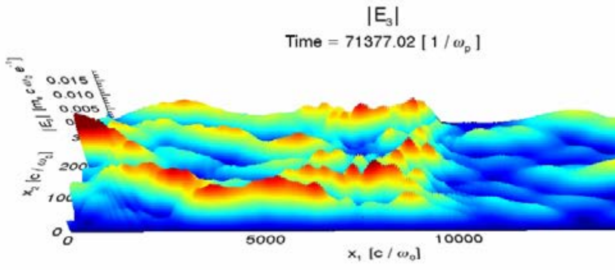
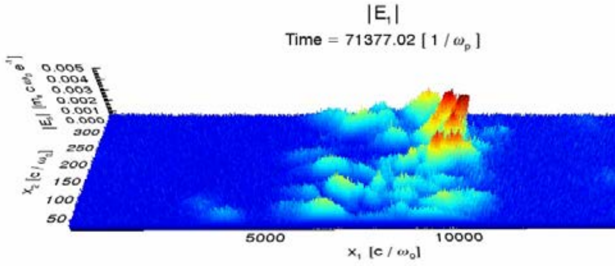
Many thanks to PICKSC members, FACET, LLNL etc





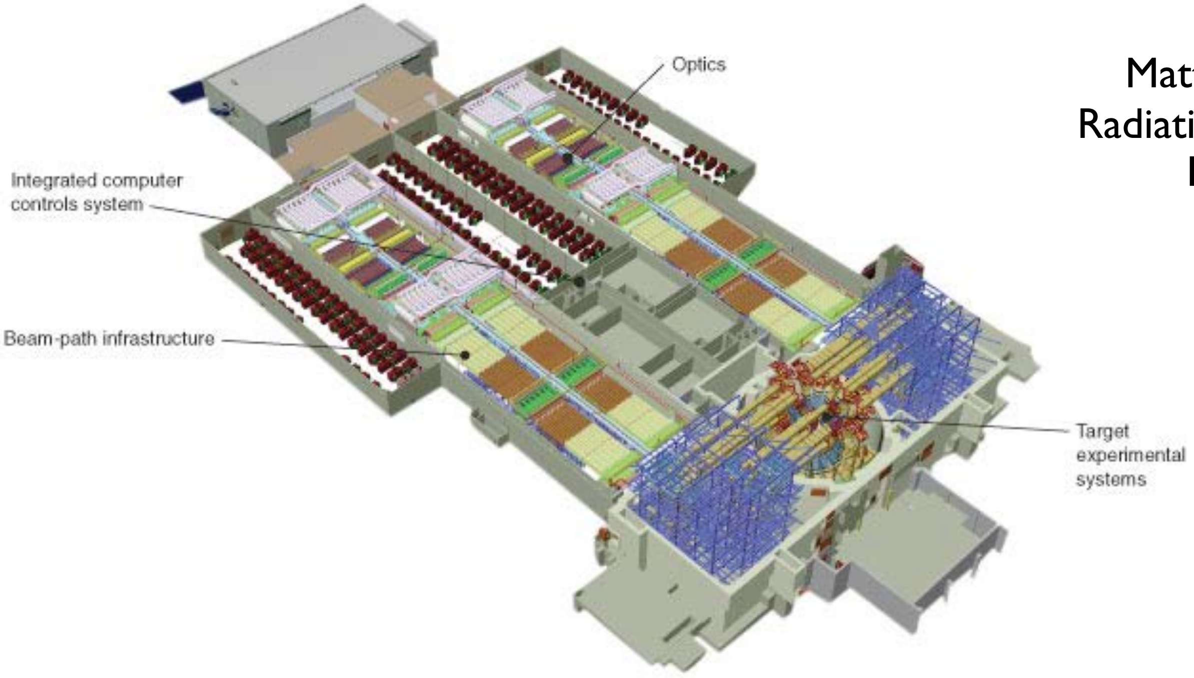
Today's tools for scientific discovery can be large, complex, and expensive: Accelerators

LCLS: 4th generation

LHC: "Last" generation?

Today’s tools for scientific discovery can be large, complex, and expensive:

National Ignition Facility: 1.8 MJ, ~4ns, 192 beams



Matter Temperature > 10^8 K
Radiation Temperature >3.5 10^6 K
Densities >10^3 g/cm3
Pressures >.1Tbar
.5PW

NSF, DOE, NASA, NNSA invests in computers that cost ~$250,000: Large, complex, and expensive

Blue Waters - Cray XE/XK hybrid

24140 XE Compute Nodes

2× 16 core AMD 6276 @ 2.3 GHz

R_{peak} *7.1 PFlop/s*

3072 XK Compute Nodes

1× 16 core AMD 6276 @ 2.3 GHz

1 × Nvidia Tesla K20 GPU

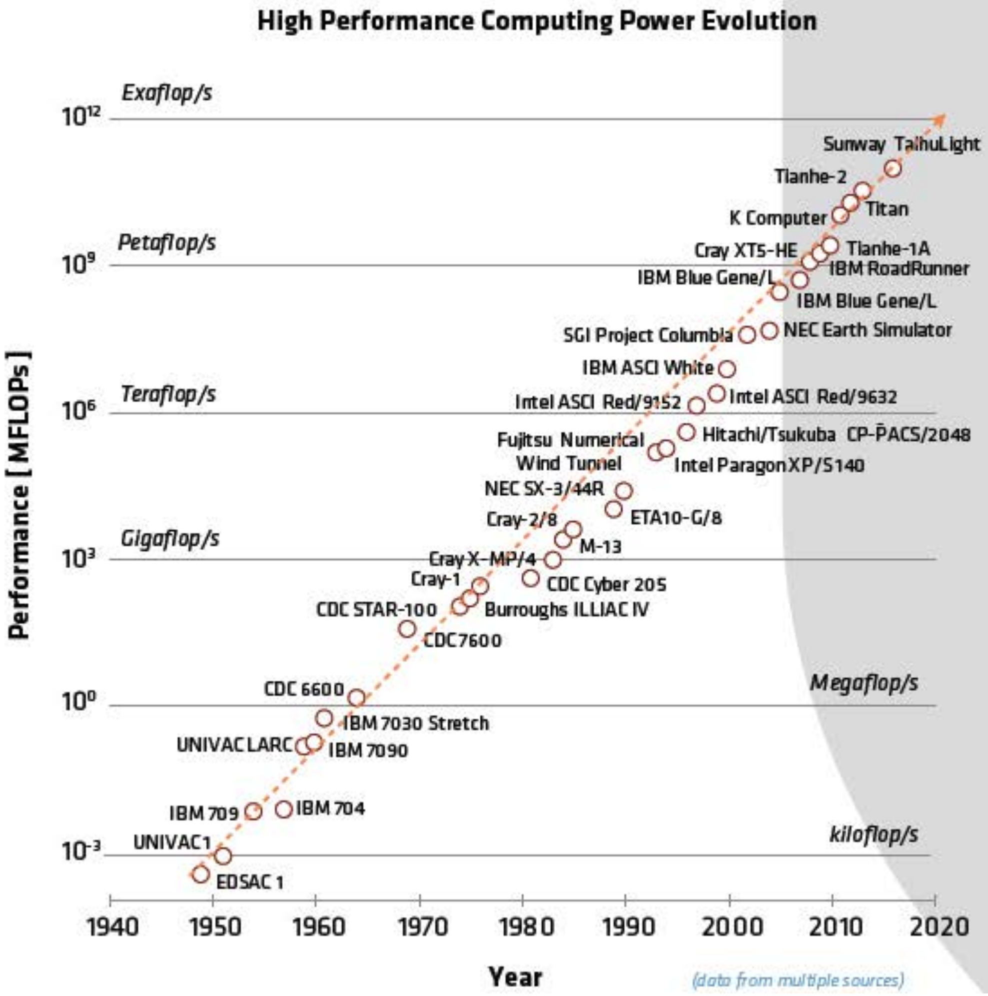
R_{peak} *4.51 PFlop/s*

$R_{peak\ aggr}$ ***11.61 Pflop/s***

Progress in science is often driven by riding up a Moore's Law curve. Need to be using the previous generation of that tool.

You just don't wake up one day and say you want to use the LHC, NIF, or a leadership class computer.

Computing Power (R)Evolution



Sunway Taihulight
- 40 960 compute nodes

Node Configuration
- 1× SW26010 manycore processor
  - 4×(64+1) cores @ 1.45 GHz
- 4× 8 GB DDR3

Total system
- 10 649 600 cores
- 1.31 PB RAM

Performance
- R_{peak} 125.4 Pflop/s
- R_{max} 93.0 Pflop/s

High Performance Computing Power Evolution (data from multiple sources)

Progress in science is often driven by grand challenge questions coupled with discovery driven research and advances in tools for discovery.

Let me show show two in high energy density plasma physics.

Large Hadron Collider: 30 km in circumference, $10 Billion +

What is next? Use plasma waves?

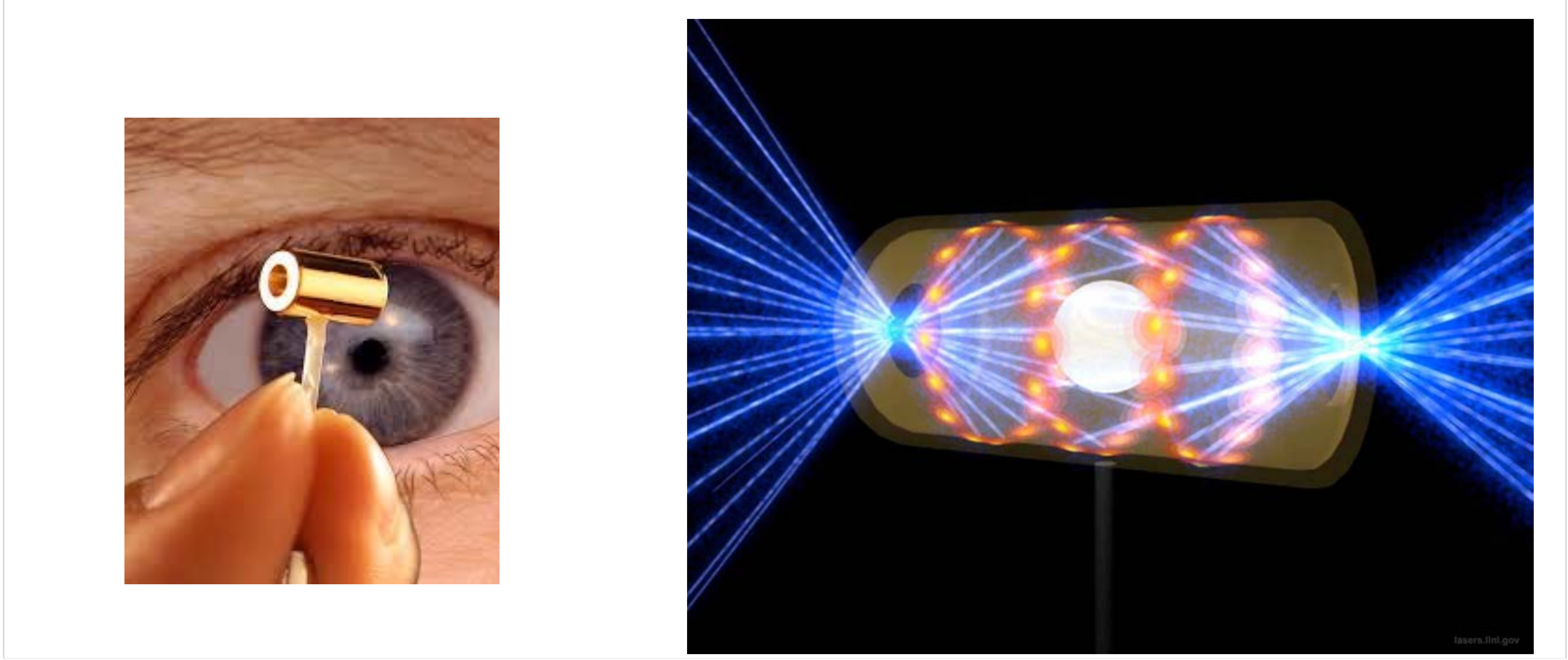
PLASMA BASED ACCELERATION

Can fusion ignition be achieved?

National Ignition Facility (NIF) is a 1.8 MJ, 192 laser facility that was built to demonstrate fusion ignition, $3.5 Billion +

Can the laser-plasma interactions be mitigated or controlled?

NONLINEAR OPTICS OF PLASMAS


lasers.llnl.gov

What is high energy density plasma physics?

Why are both plasma-based acceleration and the nonlinear optics of plasmas considered high-energy density plasma research?

- High energy density, means high pressure
  - What is a high pressure?
    - MBar? GBar?
  - Need a dimensionless parameter
    - In plasma physics an important parameter is the number of particles in a Debye sphere (which is directly related to the ratio of the kinetic energy of an electron to the potential energy between particles). It measures the discreteness of the plasma.

$$\frac{4\pi}{3} n\lambda_d^3 \equiv N_D = 2.1\times 10^3 \frac{T_{keV}^2}{P_{MBar}^{1/2}}$$

  - When the pressure exceeds ~1 MBar then the discrete nature of the plasma becomes important:
    - N_D is not “infinite”

- Discreteness makes developing computational methods difficult

What is high energy density plasma physics?

Why are both plasma-based acceleration and the nonlinear optics considered high-energy density plasma research?

- High energy density means high pressure
  - What is a high pressure?
    - MBar? GBar?
- An intense laser or particle beam can have a high energy density (high intensity).

$$\mathcal{E} = \frac{E^2 + B^2}{8\pi} \qquad \mathcal{I} = c\mathcal{E} = c\frac{E^2}{4\pi}$$

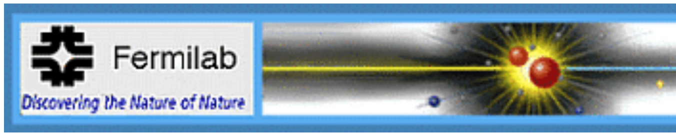
  - It turns out that for radiation pressures corresponding to ~GBar that a laser (or particle beam) causes individual electrons to move at relativistic energies.

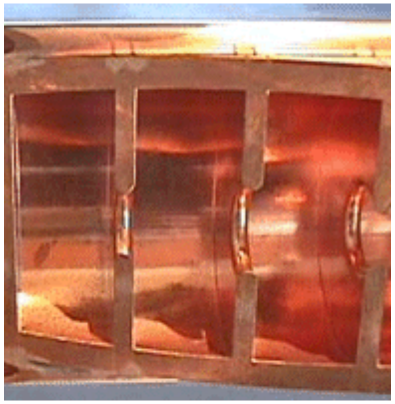
- Relativistic particles and trajectory crossing make computational modeling difficult

A major driver for HEDP remains the goal of reducing the size and cost of expensive particle accelerators

Accelerators


Aerial View of SLAC






Thinking big
Accelerators like the future LHC require long tunnels and powerful bending magnets.

Energy, efficiency, charge, beam quality are the important metrics.

UCLA

Plasma based acceleration has been a driver for the field of short-pulse laser and beam plasma interactions which is at the forefront of basic science

UCLA

The synergy between simulation and experiment has "accelerated" the rate of discovery

VORPAL

OSIRIS

QUICKPIC

Each article contained experimental results whose interpretation was supported from simulations.

Particle Accelerators

Why Plasmas?

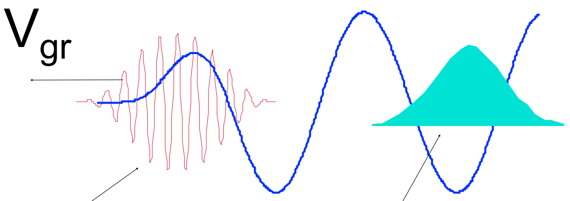
Conventional Accelerators	Plasma
Limited by peak power and breakdown	No breakdown limit
20-100 MeV/m – **20km /0.8 TeV**	10-100 GeV/m
	Based on plasma wave wakefields (“longitudinal plasma waves”

Create relativistic plasma waves as wakefields: “Fast boats”

Create relativistic wakefield using lasers or particle beams: Concepts for plasma based accelerators*

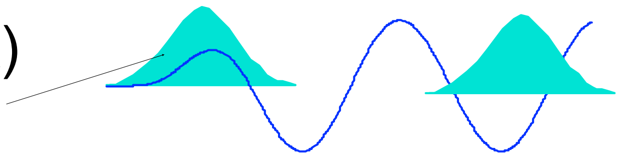
- Laser Wake Field Accelerator (LWFA)

  A single short-pulse of photons



- Trailing beam
- Drive beam

- Plasma Wake Field Accelerator (PWFA)



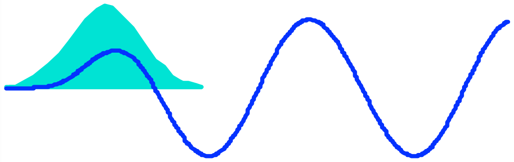
- Wake: phase velocity = driver velocity

(V_{gr} or V_b)

***Both proposed by John Dawson**
LWFA: Tajima and Dawson 1979
PWFA: Chen, Dawson et al., 1985

Use waveframe or quasi-static variables

Sprange, Esarey, and Ting 1990



For a fixed driver shape the wake can be calculated. The wake only changes if the driver shape changes. The driver's shape changes very slowly.

Use appropriate variables

- Transform from:

$$(z, x, y; t)$$

- Transform to:

$$(\xi = z - v_\phi t, x, y; s = z)$$

Meaning of new variables

- $\xi = z - v_\phi t$ is the distance from front of the driver
- $s = z$ is the distance the driver has propagated into the plasma

Mathematical meaning of quasi-static approximation

$$\partial_s << \partial_\xi$$

Important potential and forces inside wake with $(c \approx v_\phi)$

Let the wake move at c and make the quasi-static approximation

$$E_z = -\partial_z \phi - 1/c \; \partial_t A_z$$

$$F_z \approx -q\partial_\xi(\phi - A_z)$$

$$\vec{F}_\perp = q\left(\vec{E}_\perp + (\vec{v_b} \times \vec{B})_\perp\right)$$

$$\vec{v_b} = \hat{z}c$$

$$F_\perp \approx q(-\nabla_\perp(\phi - A_z))$$

Psuedo-potenial

$$\psi = (\phi - A_z)$$

Don't choose a gauge where

$$\phi = A_z$$

Forces on relativistic particle

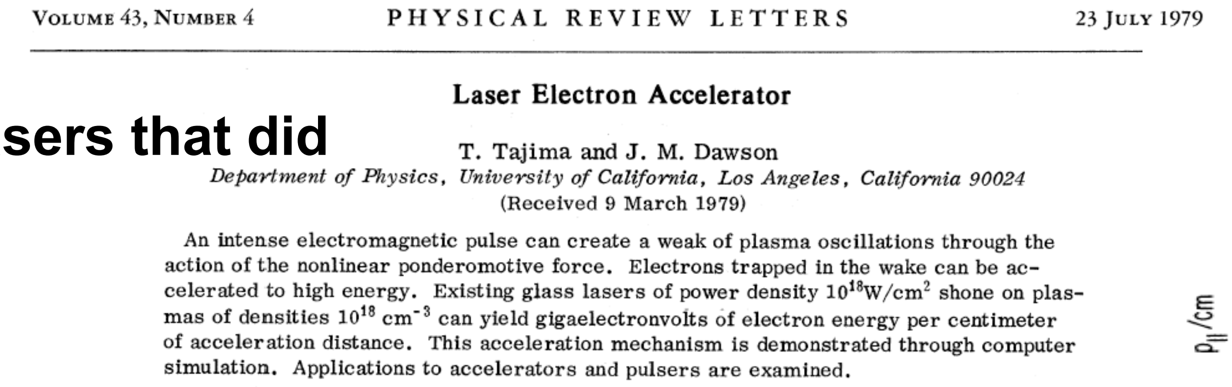
$$F_z = -\partial_\xi \psi$$

$$F_\perp = -\nabla_\perp \psi$$

Humble beginning of a new subject area!

Required lasers that did not exist

1979



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

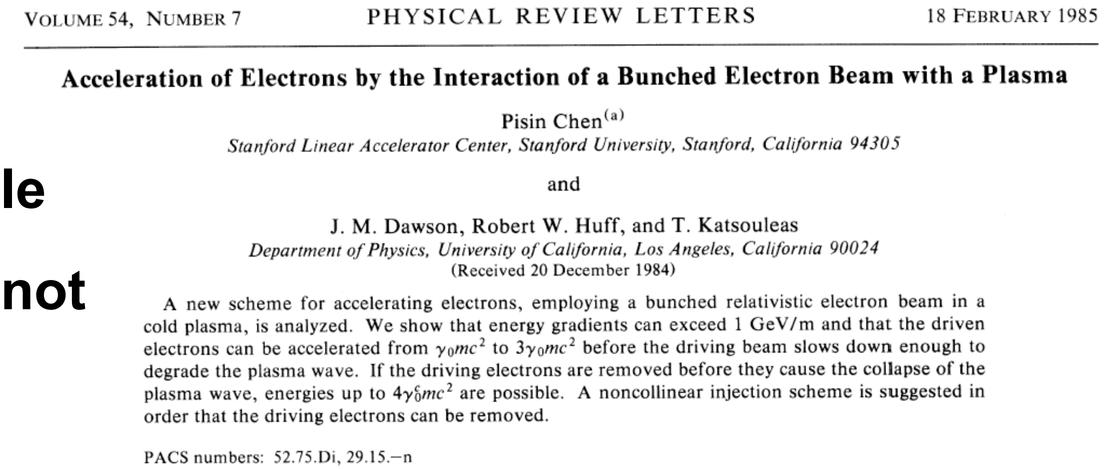
T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Required particle beams that did not exist 1986



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

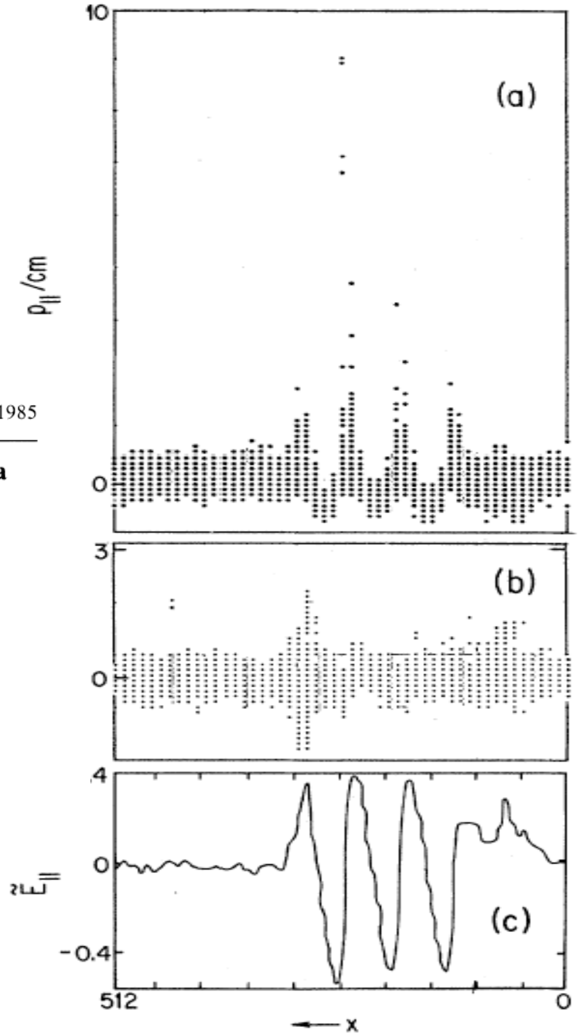
J. M. Dawson, Robert W. Huff, and T. Katsouleas

Department of Physics, University of California, Los Angeles, California 90024

(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

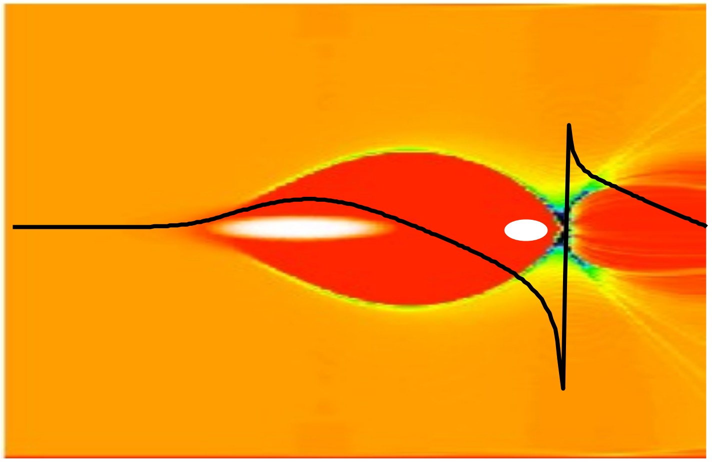
PACS numbers: 52.75.Di, 29.15.−n



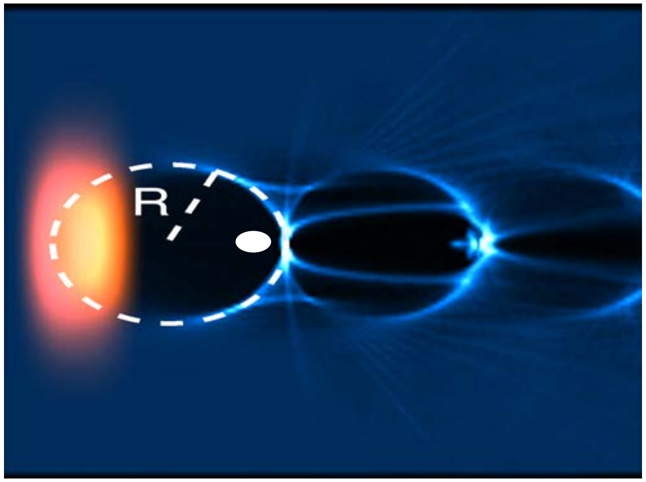
The simulations of Tajima and Dawson would take <1 second on my laptop!
~5000 particles for 500 time steps

Today: short pulse drivers and nonlinear 3D wakes

Driven by an electron beam



Driven by a laser pulse



Called blowout or bubble (Rosenzweig et al. 1990, Mori et al. 1992, Puhkov and Meyer-ter-Vehn 2002, Lu et al. 2006, 2007)

Need a nonlinear description of these wakes (Not till Lu et al. 2006)

Ideal for accelerating electrons/not for positrons

Very stable wakes!

Experimental progress in the last decade has been in this regime.

Wake is described by an equation for the radius of the bubble: $\frac{dr_b}{d\xi}$

Relativistic blowout regime for blowout radius and for large maximum radius the trajectory of rb is a circle: Bubble
Lu et al.PRL 16, 16500 [2006]

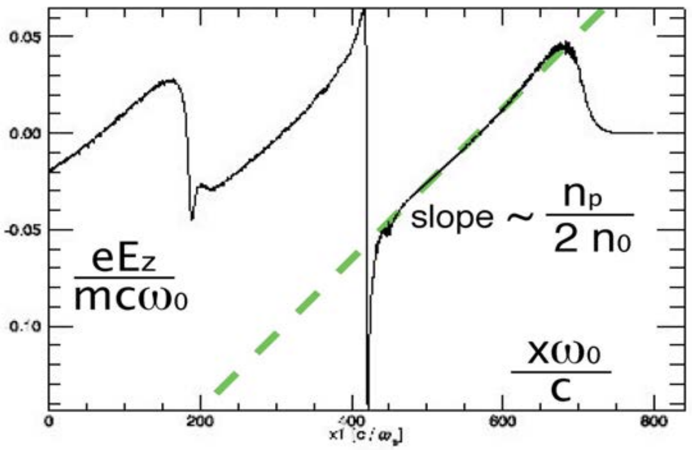
$$\overline{\psi} \approx k_p^2 \frac{r_b^2(\xi) - r^2}{4}$$

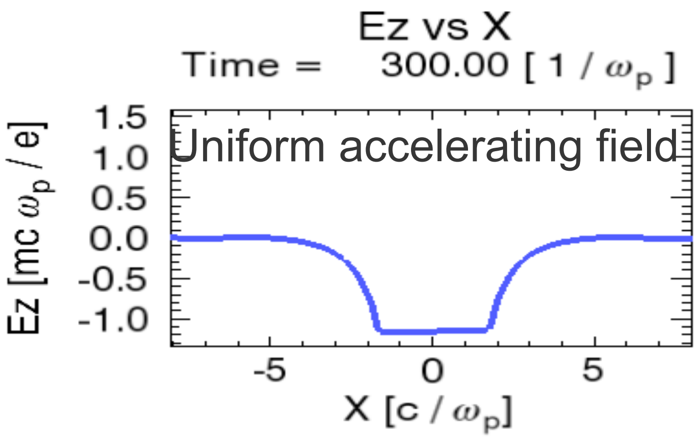
$$\frac{eE_z}{mc\omega_p} = \frac{r_b}{2}\frac{dr_b}{d\xi} \approx \frac{1}{2}\xi$$

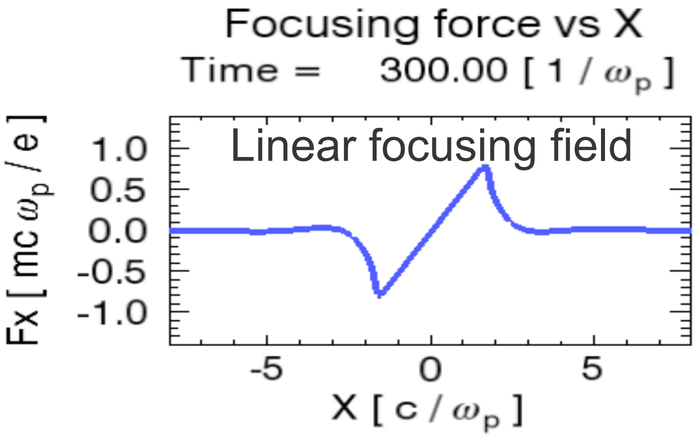
$$\frac{eE_M}{mc\omega_p} \approx \frac{1}{2}k_p R_b \approx \sqrt{\Lambda}$$

Bubble radius :

$k_p R_b \approx 2\sqrt{\Lambda}$ or $k_p R_b \approx 2\sqrt{a_0}$

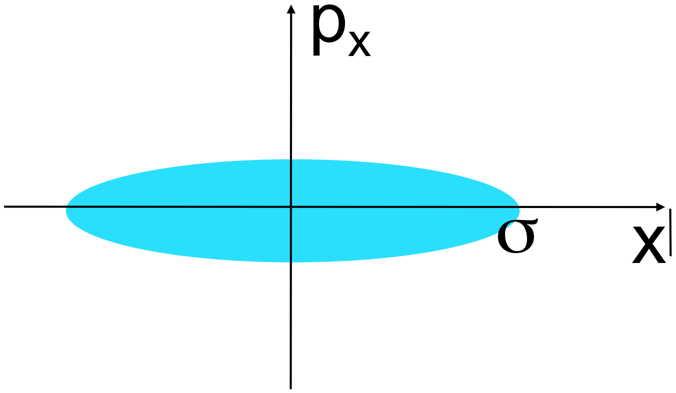






Transverse Dynamics and Beam Quality

- Emittance **ε_n** = phase space area and a measure of its ability to get focused:



- The spot size of a beam in vacuum evolves as:

$$\sigma_r = \sqrt{(1+(\frac{z}{\beta^*})^2)} \quad \text{where} \quad \beta^* = \frac{\sigma_r^2}{\epsilon_n}\gamma$$

- Inside a plasma wake a single particle oscillates as:

$$\frac{dP_\perp}{dt} = q(-\nabla_\perp \psi)$$

- If the focusing force is “linear” AND radial in the transverse coordinates then

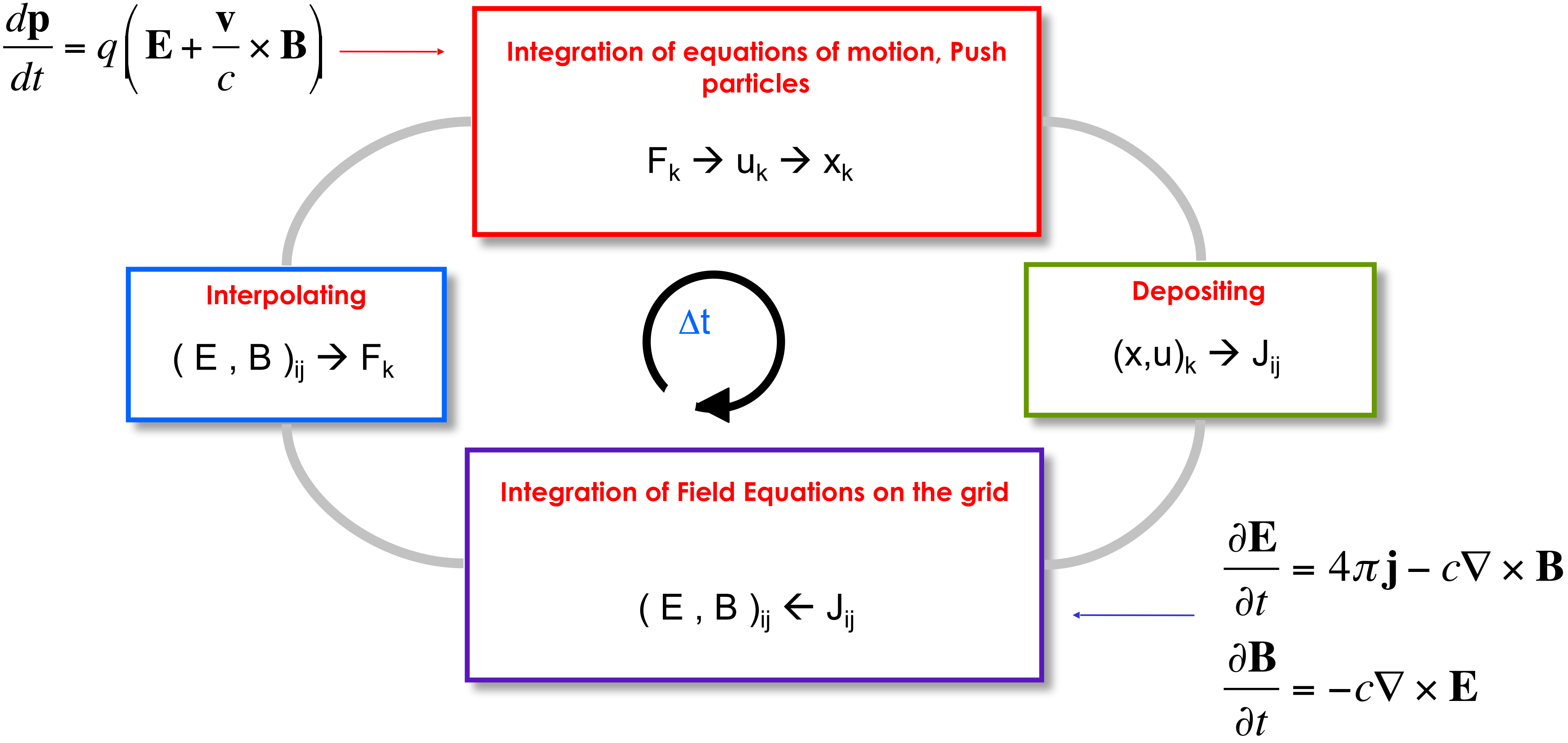
$$\frac{d^2 x_\perp}{dt^2} + \omega_\beta^2 x_\perp = 0$$

$$k_\beta \equiv \frac{\omega_\beta}{c} \qquad k_\beta = \alpha \frac{k_p}{\sqrt{2\gamma}}$$

What computational method do we use to model HEDPincluding discrete effects?

The Particle-in-cell method

Not all PIC codes are the same!



$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)$$

Integration of equations of motion, Push particles

$F_k \rightarrow u_k \rightarrow x_k$

Interpolating

$(E, B)_{ij} \rightarrow F_k$

Δt

Depositing

$(x,u)_k \rightarrow J_{ij}$

Integration of Field Equations on the grid

$(E, B)_{ij} \leftarrow J_{ij}$

$$\frac{\partial \mathbf{E}}{\partial t} = 4\pi \mathbf{j} - c\nabla \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

What is the PIC model?

Is it an efficient way of modeling the Vlasov equation?
No, it is a Klimontovich description for finite size (macro-particles)

- Mathematical model for PIC

- Klimontovich equation of macro-particles

Maxwell's equations

$$\frac{D}{Dt}F = 0$$

$$F(\vec{x},\vec{v};t) = \sum_i^N S_p(\vec{x}-\vec{x}_i(t))\delta(\vec{v}-\vec{v}_i(t))$$

$$\left[\frac{D}{Dt} \equiv \partial_t + \vec{v}\cdot\nabla_x + \vec{a}\cdot\nabla_v\right]$$

$$\vec{a} \equiv \frac{d}{dt}\vec{v} = \frac{q}{m}\left(\vec{E} + \frac{\vec{v}}{c}\times\vec{B}\right)$$

$$\vec{J}(\vec{x},t) = \int d\vec{v}\; q\vec{v}\; F(\vec{x},\vec{v},t)$$

$$\frac{\partial}{\partial t}\vec{B} = -\nabla\times\vec{E}$$

$$\frac{\partial}{\partial t}\vec{E} = \nabla\times\vec{B} - \frac{4\pi}{c}\vec{J}$$

OSIRIS 4.0 (began in late 1990s from LLNL funding)

Osiris 3.0

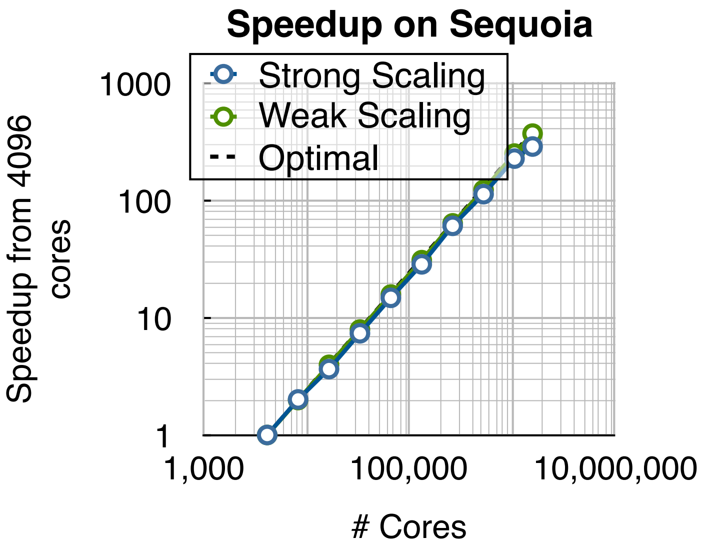
TÉCNICO LISBOA

UCLA

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium

  ⇒ UCLA + IST



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- Collisions
- Field ionization
- QED module
- Particle splitting/merging
- Quasi-3D
- Boosted frame
- GPGPU support
- Xeon Phi support

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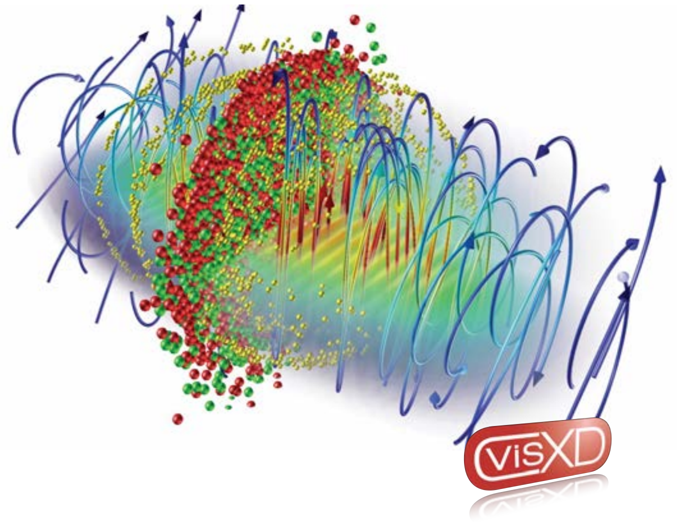
http://picks.idre.ucla.edu/



accessible through MoU

QuickPIC: A PIC code based on quasi-static approximation

$$\vec{E}_\perp + \hat{z} \times \vec{B}_\perp = -\nabla_\perp \cdot \psi$$

$$\nabla_\perp^2 \psi = -(\rho - J_z)$$

$$\nabla_\perp^2 \vec{B}_\perp = \hat{z} \times (\frac{\partial}{\partial \xi}\vec{J}_\perp + \nabla_\perp \cdot J_z)$$

$$\nabla_\perp^2 B_z = -\nabla_\perp \times \vec{J}_\perp$$

$$\nabla_\perp^2 E_z = \nabla_\perp \cdot \vec{J}_\perp$$

plasma: $$\frac{d\vec{p}}{d\xi} = \frac{q/m}{1 - v_z}\left[\vec{E} + \vec{v} \times \vec{B}\right]$$

Iteration Required! Coupled with equation of motion.

$$\frac{\partial}{\partial \xi}(\rho - J_z) + \nabla_\perp \cdot \vec{J}_\perp = 0$$

$$\frac{\partial}{\partial \xi}\int(\rho - J_z)d\vec{x}_\perp + \int \nabla_\perp \cdot \vec{J}_\perp d\vec{x}_\perp = 0$$

$$\frac{\partial}{\partial \xi}Q(1 - v_z) = 0 \quad *$$

For each plasma particle: Q varies along ξ according to its v_z

* P. Mora and T. Antonsen, Phys. Plasmas 4, 217 (1996)

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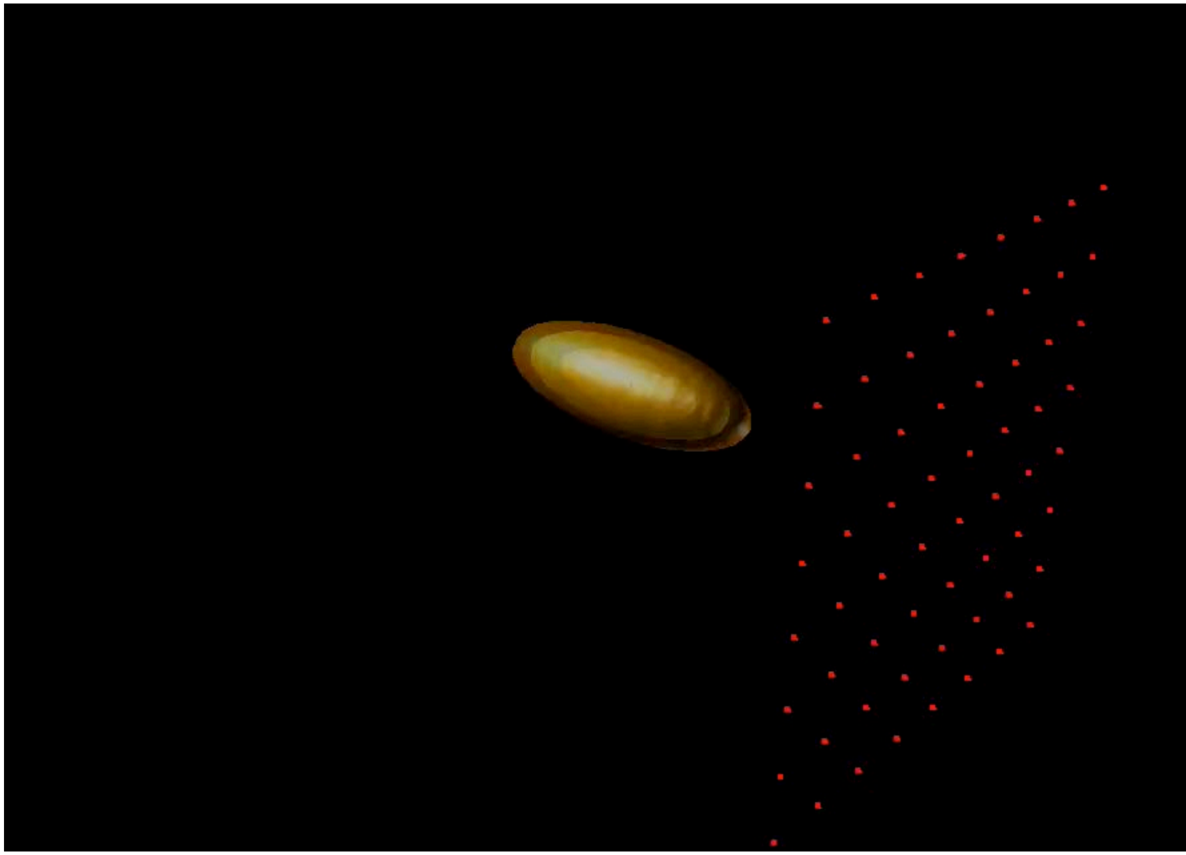
QuickPIC: 3D Quasi-static PIC Opensource



Fully parallelized and scaled to 100,000+ cores

Requires predictor corrector,
has some similarities with a Darwin code.

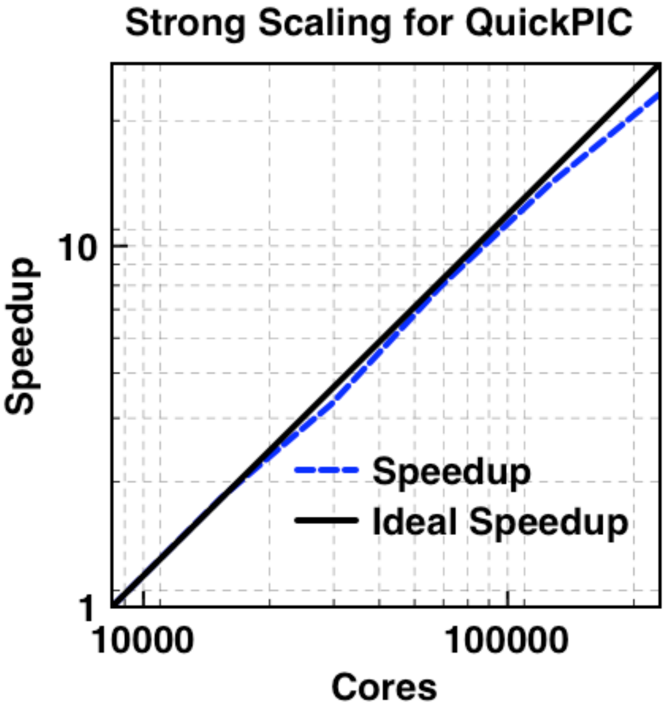
C-K. Huang et al., 2006
W. An et al., 2014

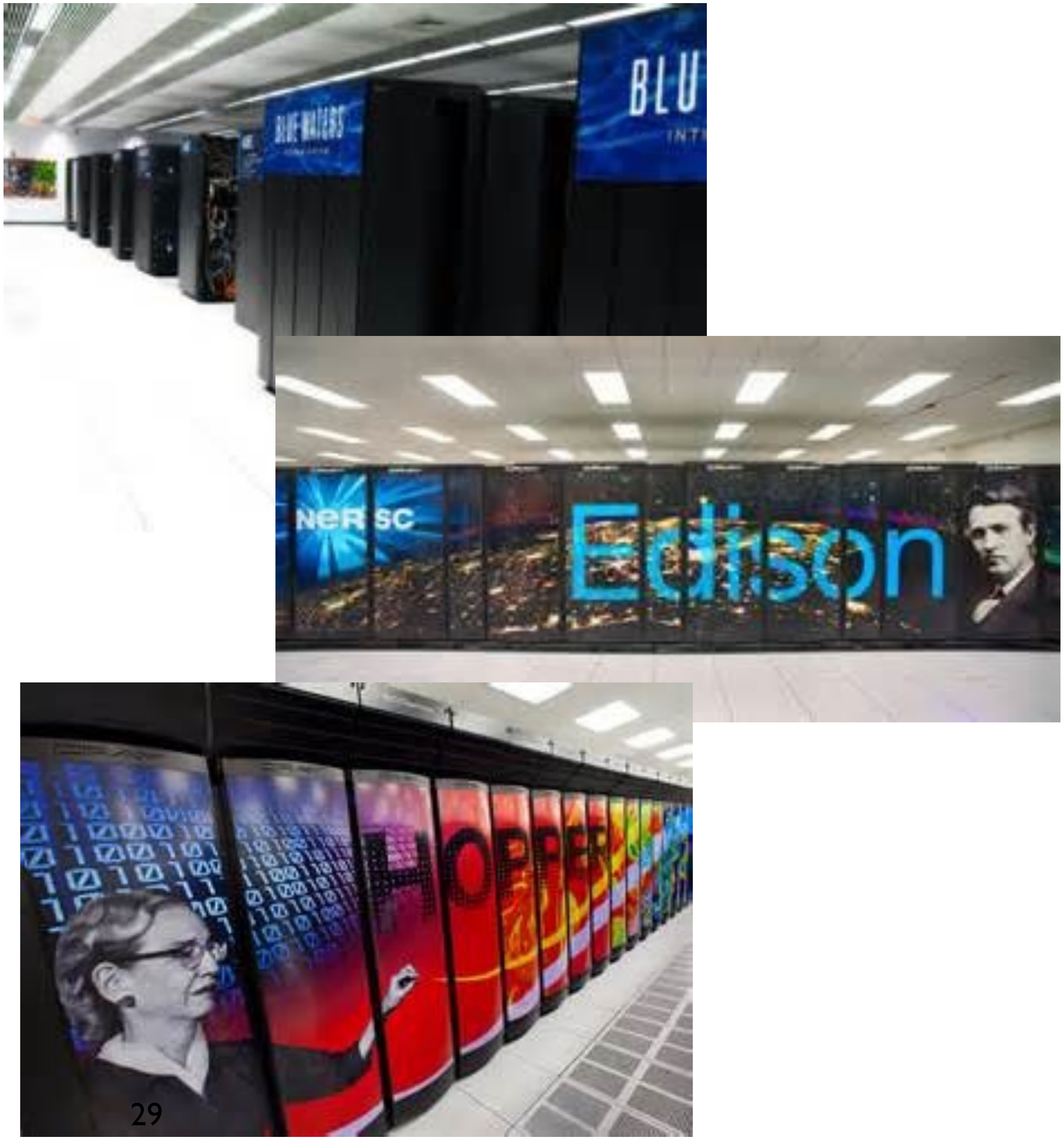
Recently HIPACE

Embeds a parallelized 2D PIC code inside a 3D PIC code based on UPIC Framework.

Current Status of QuickPIC

Opensource





Time for pushing one particle for one step using a single processor (double precision): ~770 ns

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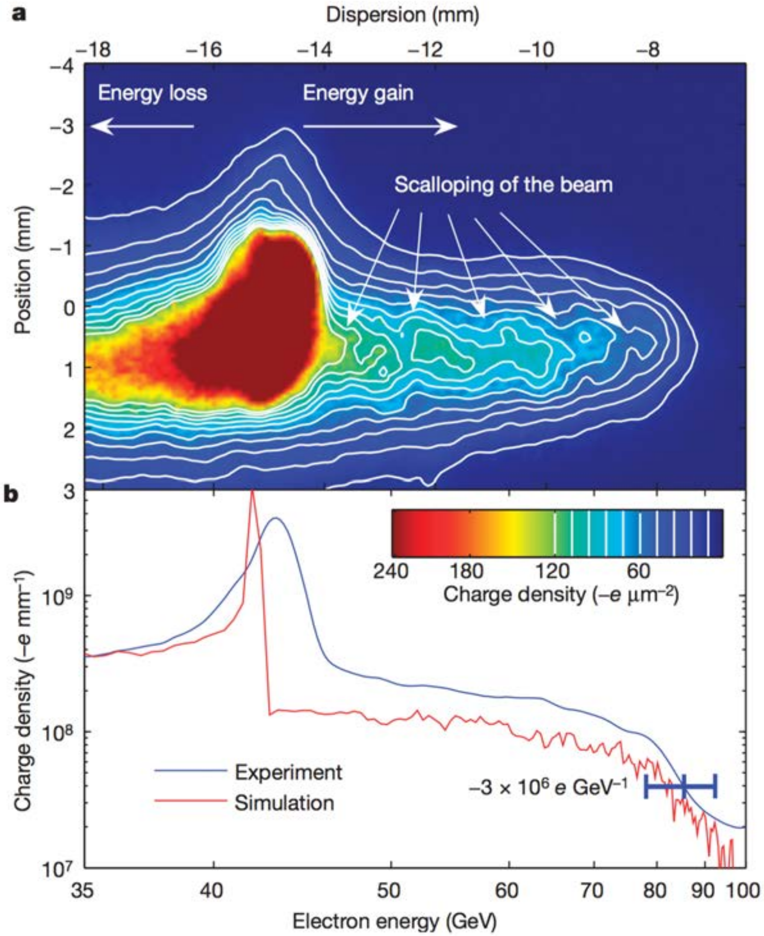
Example of synergy at FFTB: 42 GeV energy gain in less than 1 meter!

Can high gradients be sustained over 1 meter?

Blumenfeld et al., 2007

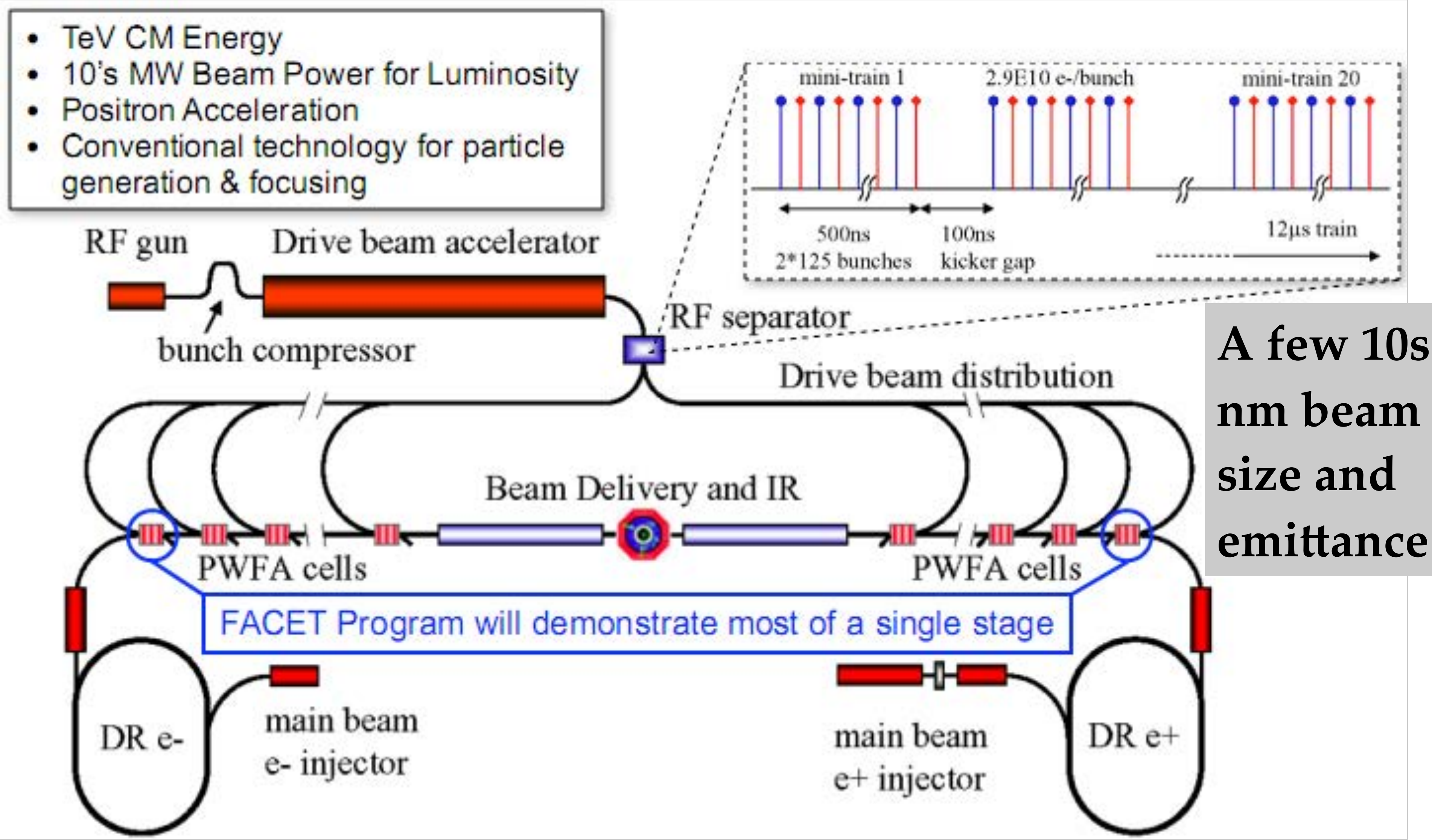


43 GeV electron beam
1.8 x 10^10 particles ~25kA
10^17cm-3 plasma

QuickPIC simulations explained what limited the acceleration length

SLAC
NATIONAL ACCELERATOR LABORATORY
New SLAC National Accelerator Laboratory logo

PWFA-based collider concept (no ILC)



- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing

FACET Program will demonstrate most of a single stage

A few 10s nm beam size and emittance

a 19 Stages PWFA-LC with 25GeV energy gain per stage

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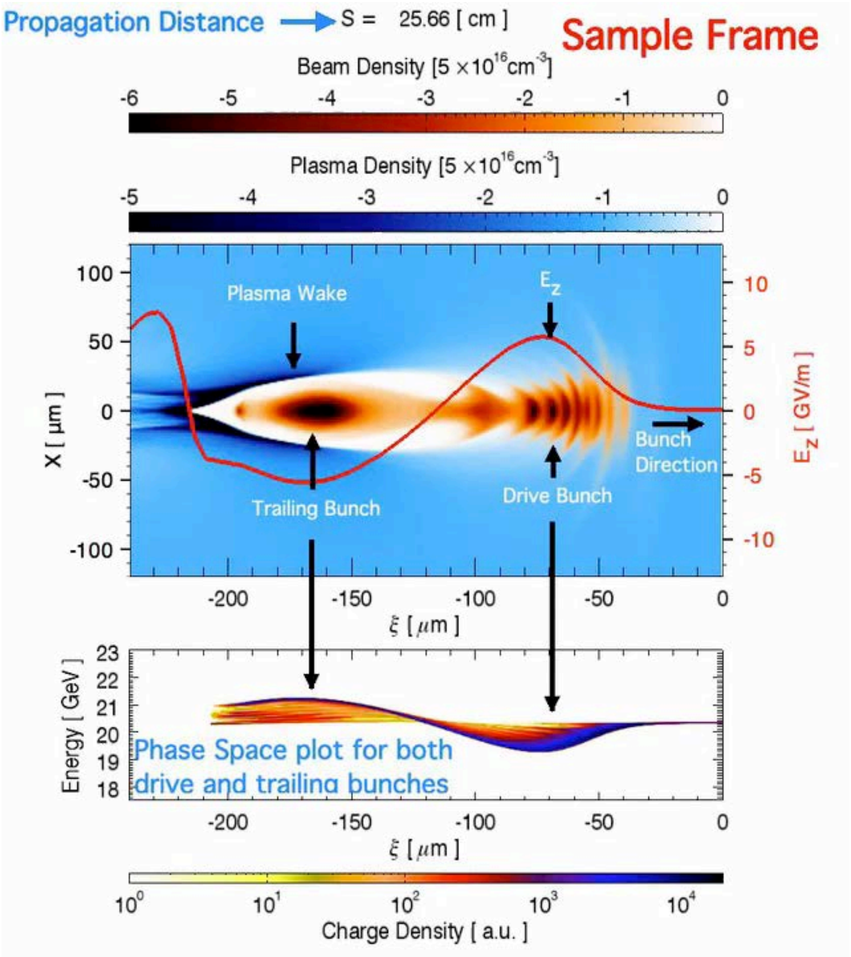
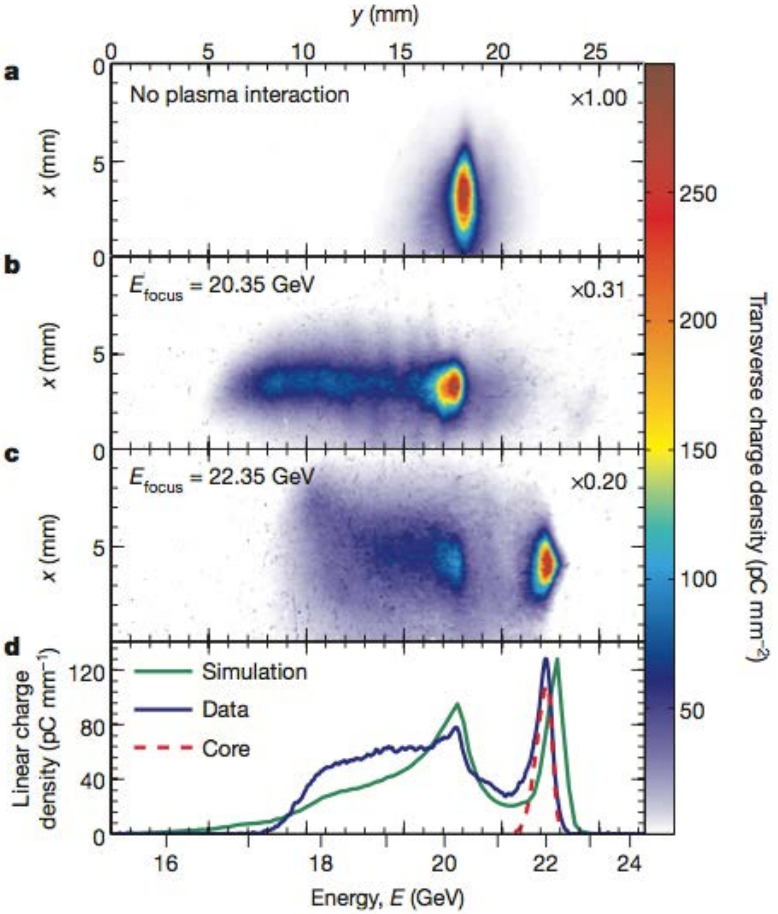
Another example at FACET: Synergy demonstrated efficient beam loading of wake

Litos et al, 2014





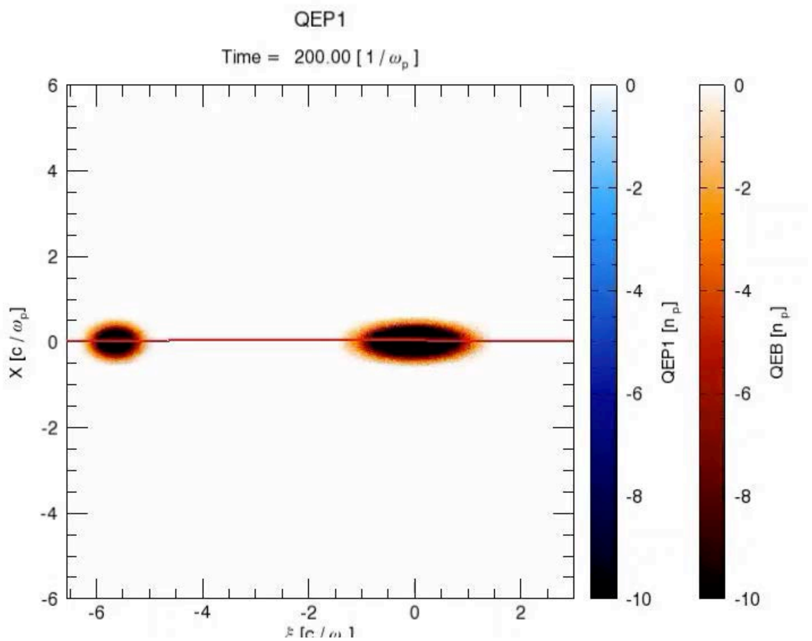
QuickPIC and OSIRIS simulations helped to design and interpret the experiment.

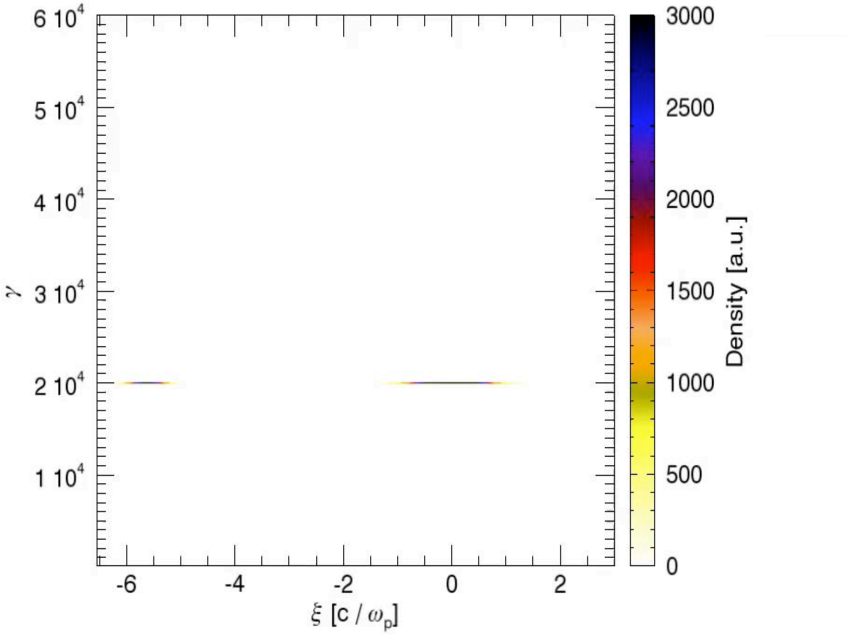
FACET II (proposed) with QuickPIC

Drive Beam: E = 10 GeV, I_{peak}=15 kA
σ_r = 21.17 µm, σ_z = 12.77 µm ,
N =1.0×10^{10} (1.6 nC),
ε_N = 10 µm

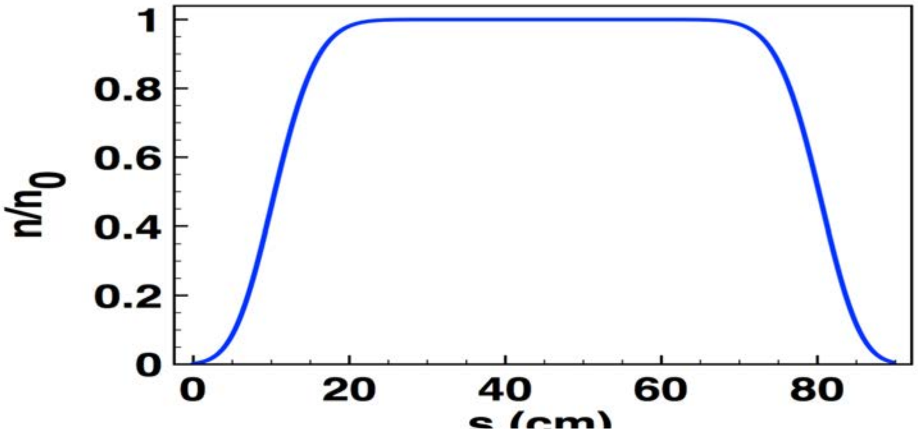
Trailing Beam: E = 10 GeV, I_{peak}=9 kA
σ_r = 21.17 µm, σ_z = 6.38 µm ,
N =0.3×10^{10} (0.48 nC),
ε_N = 10 µm

Distance between two bunches: 150 µm
Plasma Density: 4.0×10^{16} cm^{-3} (with ramps)





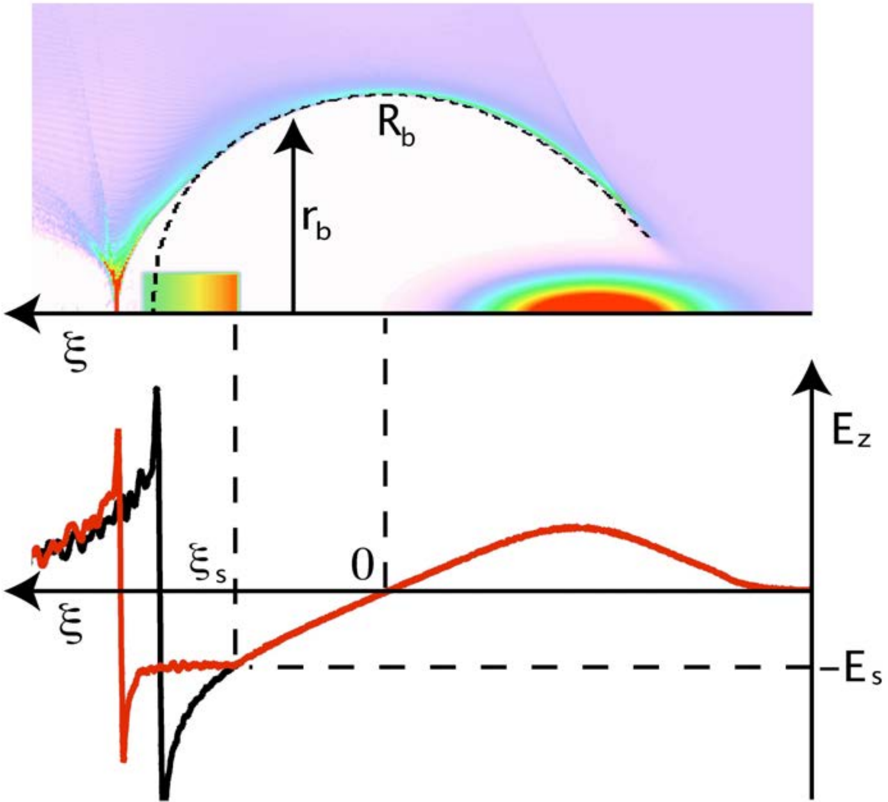
Plasma Density Profile

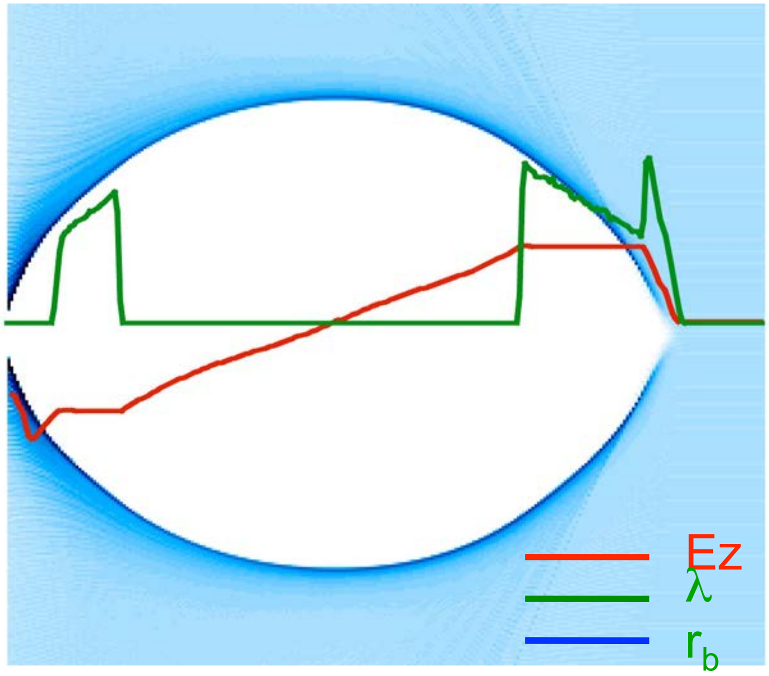


Grand challenge research problem to develop self-consistent beam loading scenarios: Stable high gradient acceleration while maintaining beam quality

Nonlinear beam loading and shaping bunches

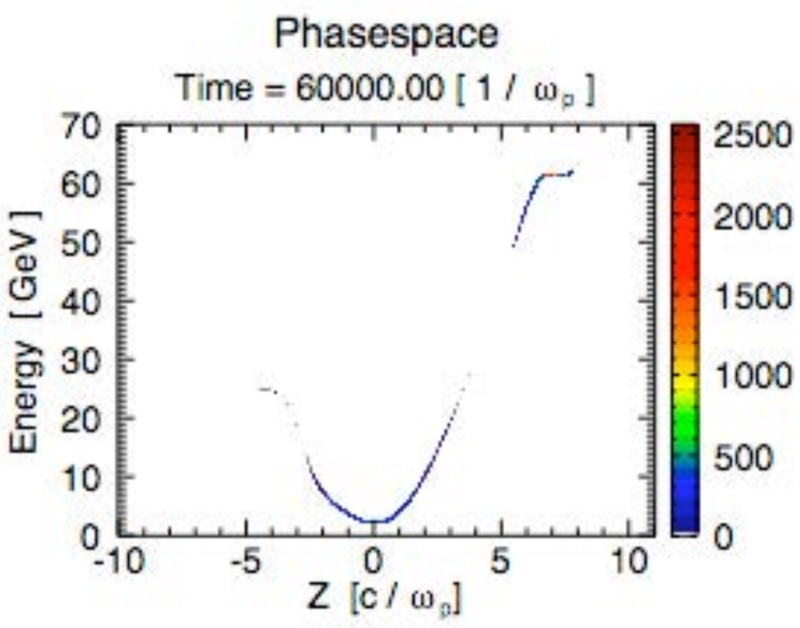
M. Tzoufras et al. PRL 2008

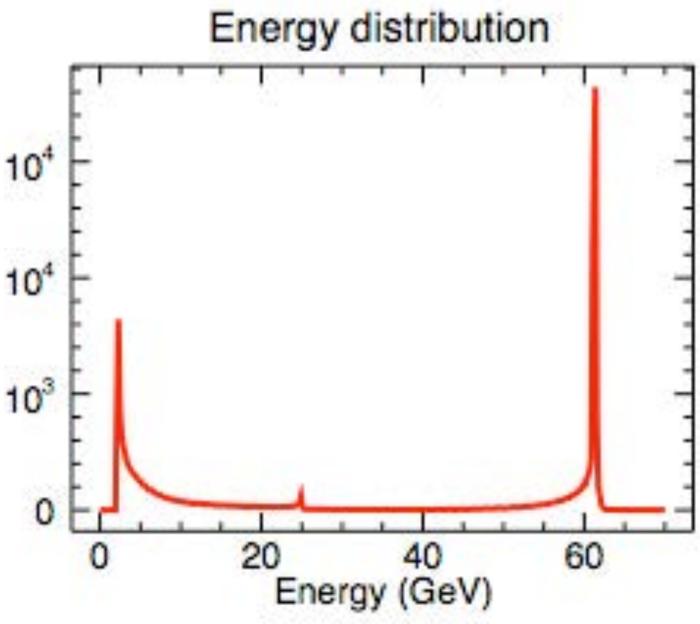


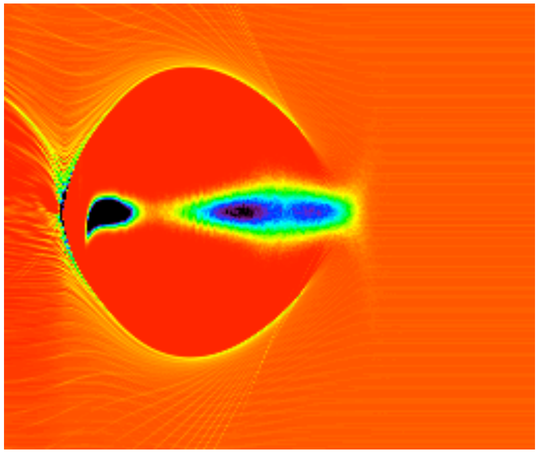


- Theory allows for designing highly efficient stages that maintain excellent beam quality.
- Theory allows for understanding how standard beams absorb energy of nonlinear wakes.
- This regime cannot work for positrons.

Model a single stage of a PWFA-LC design including beam loading







Drive beam energy is 25 GeV
Output bean energy is ~60GeV

1% Energy spread
Efficiency from drive to trailing bunch ~48%!

Trailing beam is very tightly focused. Electric field in trailing beam ~10 TeV/cm.

What about laser drivers?

Nonlinear self-guided blowout regime for LWFA

- The ponderomotive force of the laser pushes the electrons out of the way.
- The ion channel supports huge and ideal accelerating and focusing fields.
- Electrons are self or externally injected at the tail of the ion channel.
- Beam loading flattens wake.

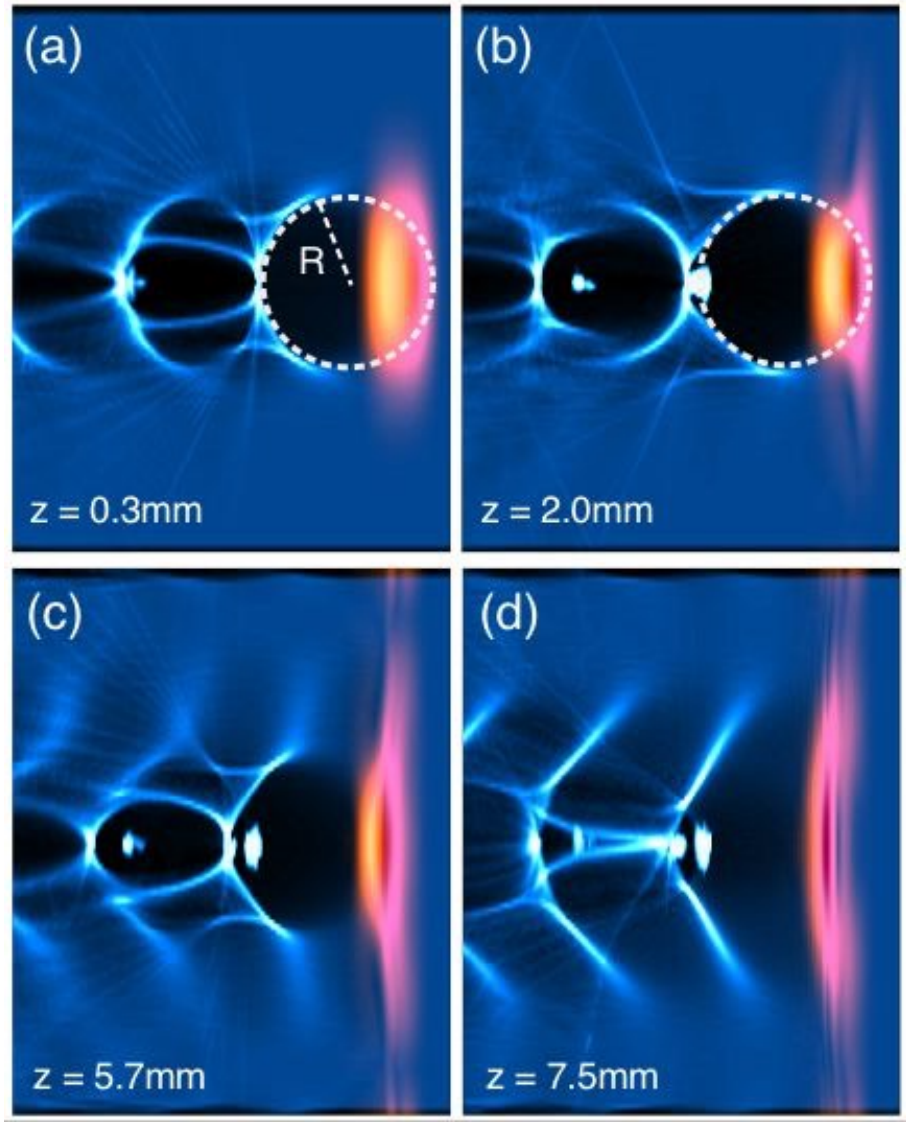
➔ The laser's spotsize is "matched":

➔ Local pump depletion: The front of the laser etches back:

$$k_p w_0 \simeq k_p R_b \simeq 2\sqrt{a_0}$$

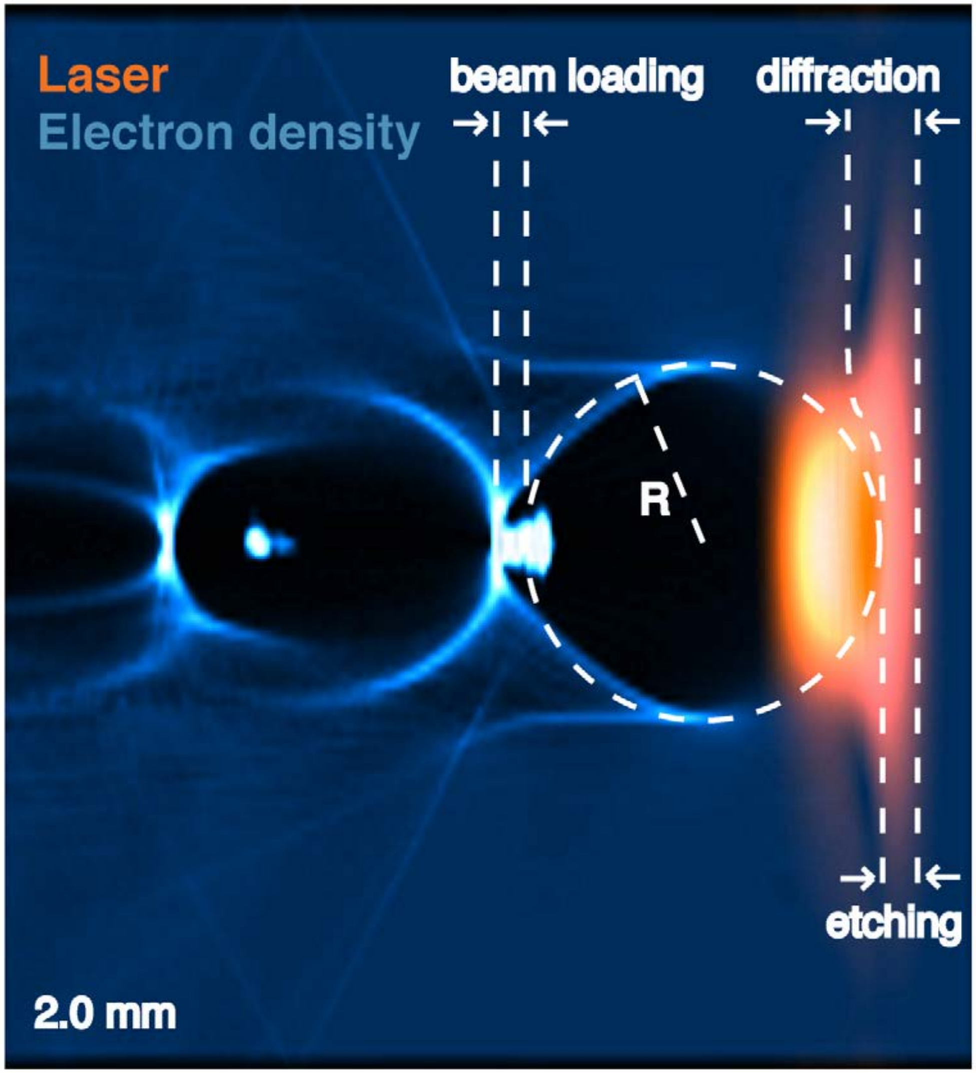
$$v_{etch} \simeq c\frac{n_p}{n_c}$$

Lu et al. 2007



The Laser Wakefield Accelerator

Phenomena that are Relevant to the Study of LWFAs

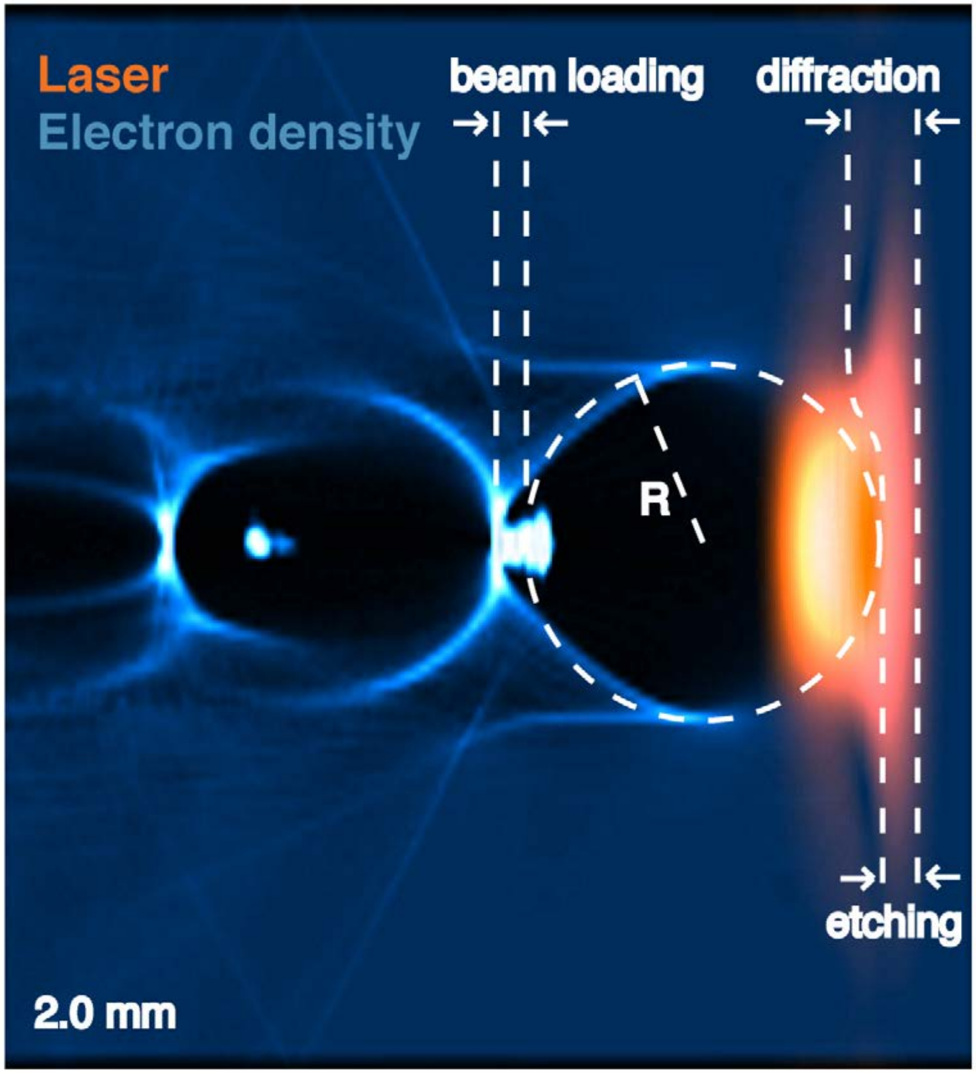


(Courtesy of Lu et al.)

- The front of the laser pulse loses energy to the plasma and etches back (pump depletion)
- Electrons are self or externally injected in the back of the ion channel, slightly distorting the wake in their region (beam loading)
- The front of the laser, once depleted of most of it's energy, diffracts

The Laser Wakefield Accelerator

Phenomenological Scaling Law[†]



(Courtesy of Lu et al.)

- Given that the laser has a matched spot size, a scaling law can be derived
- The maximum accelerating distance is estimated as

$$L_d \simeq \frac{2}{3}\left(\frac{\omega_0}{\omega_p}\right)^2 W_0$$

- The particle energy estimated as

$$\Delta E = \frac{2}{3}mc^2\left(\frac{\omega_0}{\omega_p}\right)^2 a_0$$

[†] W. Lu et al., PRSTAB 10 (2007) 061301

The Laser Wakefield Accelerator

- Lu et al. results in an expression for the estimated energy of the trapped particles given the power of a laser, the plasma density, and the laser wavelength

$$\Delta E[\mathrm{GeV}] \simeq 1.7\left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3}\left(\frac{10^{18}}{n_p[\mathrm{cm}^{-3}]}\right)^{2/3}\left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{4/3}$$

- **How far does it scale?**

[†] W. Lu et al., PRSTAB 10 (2007) 061301

UCLA Useful to rewrite in terms of the laser energy

We Explore the Implications of the Scaling Laws Given a Fixed Energy Laser

Optimal density and pulse length for a laser of fixed energy:

$$E_L = \alpha P \tau,$$

Assuming a matched spot size, we can adjust the relative pulse length as a free parameter:

$$\tau = \mathcal{F} 2 \sqrt{a_0} \omega_p^{-1}$$

We may recast the scaling laws equations as a function of the laser energy, pulse length, and amplitude:

$$\Delta E = \frac{2}{3} \frac{m_e c^2}{\alpha^{2/3}} \left[\frac{4\omega_0}{\mathcal{A}} \right]^{2/3} \frac{E_L^{2/3}}{\mathcal{F}^{2/3} a_0^{4/3}}.$$

[*A* = 17 GW]

Logically, there is a lower bound to the pulse length that can be determined empirically

A. Davidson, PhD Disseration UCLA 2016

Pushing the Theory Further

by Scaling to Higher Acceleration Distances

estimated CPU hours (3D)	P (TW)	n_p (cm^{-3})	W_0 (μm)	L_d (cm)	a_0	ΔE (GeV) Estimated	ΔE (GeV) Simulated
100,000	200	1.5×10^{18}	19.5	1.5†	4.0	1.58	1.55†
430,000	324	1.0×10^{18}	22.0	2.62	4.44	2.52	???
3,200,000	649	5.0×10^{17}	31.7	7.37	4.44	5.28	???
26,000,000	1298	2.5×10^{17}	44.8	20.8	4.44	10.57	???
120,000,000	2162	1.5×10^{17}	57.8	44.8	4.44	17.6	???
340,000,000	3280	1.0×10^{17}	71.2	83.8	4.44	26.7	???

We implement the quasi-3D geometry to attain hundreds of times of speedup

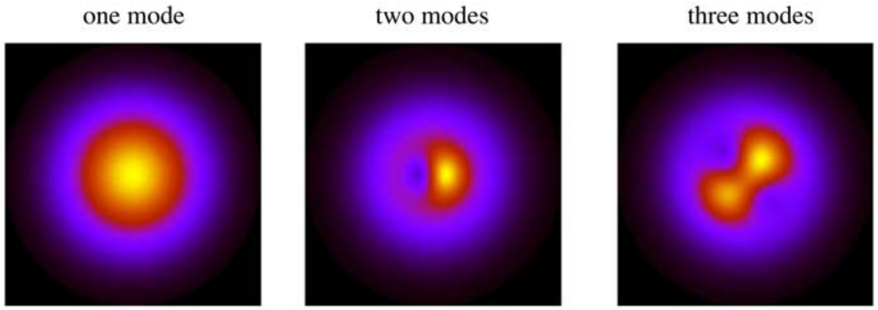
†Lu et al. Conducted this simulation over 0.75cm, not the entire L_d

New reduced models:
3D simulations of LWFA and PWFA (e and p) can be expensive, but quasi-3D simulations are now possible!

- 2D cylindrical r-z simulations can get the geometric scaling correct: Used extensively for PWFA
- Laser pulses are radially polarized in r-z simulations, so cylindrical r-z simulations not used for LWFA studies.
- In many 3D simulations the drivers and wake develop only lower order azimuthal modes.
- Expand in azimuthal mode number and truncate expansion! [1]: This is PIC in r-z and gridless in phi [2]
- We have now incorporated the ability to expand the fields into an arbitrary number of azimuthal modes into OSIRIS. Made improvements to [1] including rigorous charge conserving algorithm [2]. As part of OSIRIS, algorithm scales to 1,000,000+ cores and can model laser, beams, and beam loading. Allows rapid parameter scans.

[1] A.F. Lifshitz et al., JCP 228, pp.1803 (2009).

[2] A. Davidson et al., JCP 281 pp.1063 (2015).

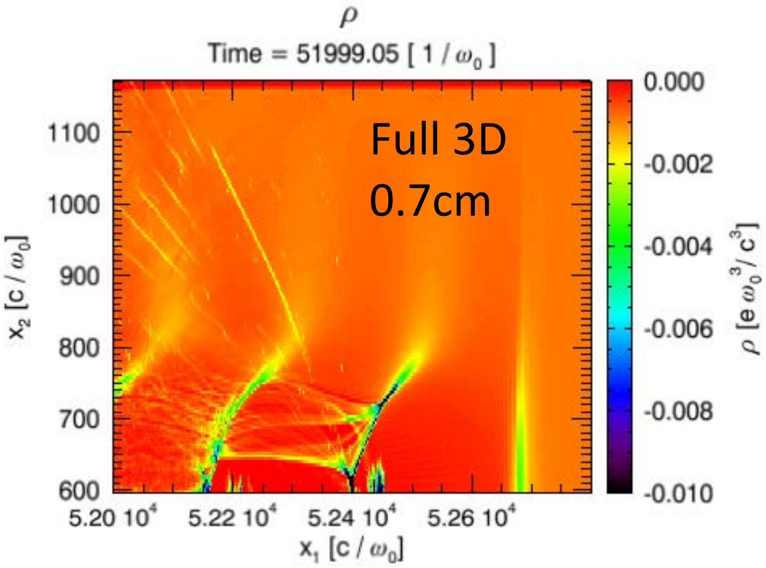


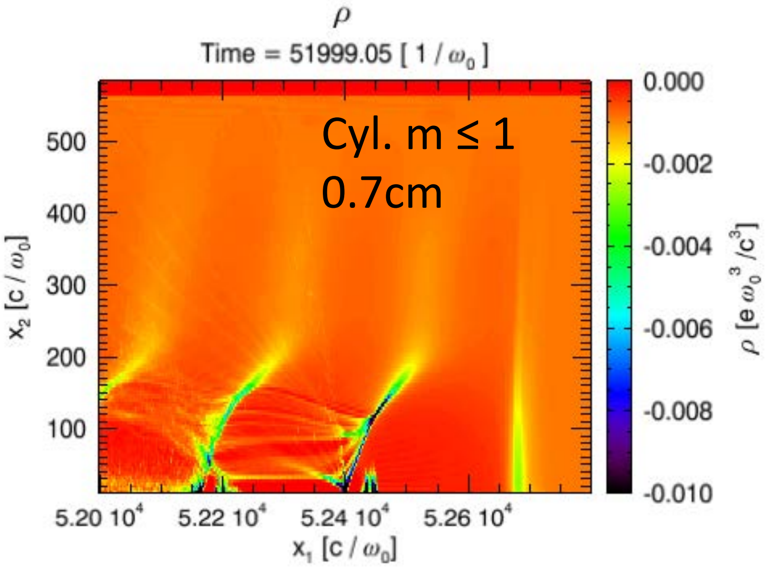
Can reduce simulation time by factors of 100s.

For example from 10,000,000s

of core hours to 80,000 core hours!

Excellent agreement between 3D & quasi-3D OSIRIS for original Lu et al.





- This geometry has been tested against and shown to “reproduce” known 3D Cartesian simulations†.

Geometry	Charge [pC] (1cm)	ex [π mm mrad]	ey [π mm mrad]	Max Energy [GeV]
Full 3D Cartesian	*340*	*27*	*30*	*1.57*
Cyl. Mode ≤ 1	*328*	*43*	*43*	*1.55*

[†] W. Lu, M. Tzoufras, C. Joshi, F. Tsung, W. Mori, J. Vieira, R. Fonseca, L. Silva, Generating multi-gev electron bunches using single stage laser wakefield acceleration in a 3d nonlinear regime, Physical Review Special Topics - Accelerators and Beams 10 (061301).doi:http://link.aps.org/doi/10.1103/PhysRevSTAB.10.061301.

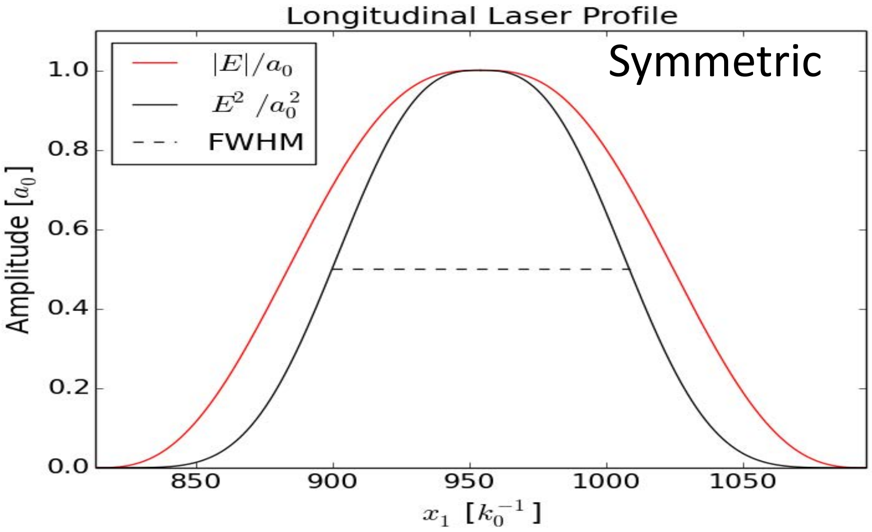
Scaling Laws in Nonlinear Regime

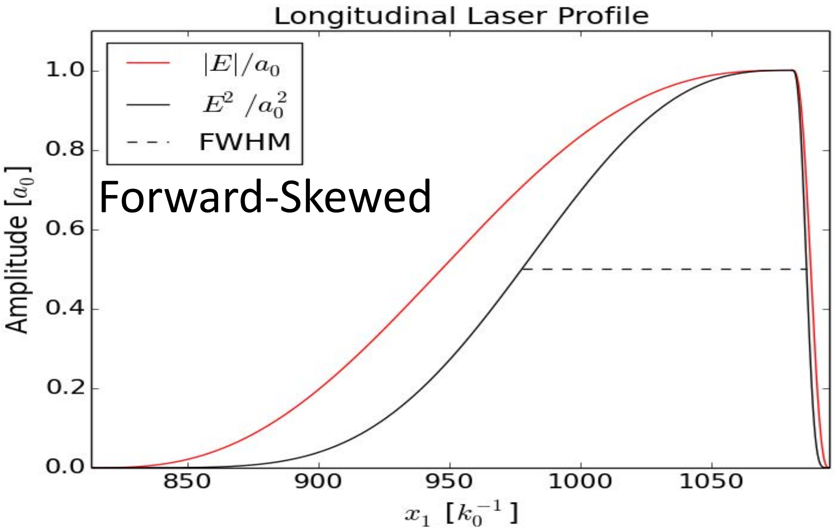
Faster Methods Means Physics in Farther Regimes

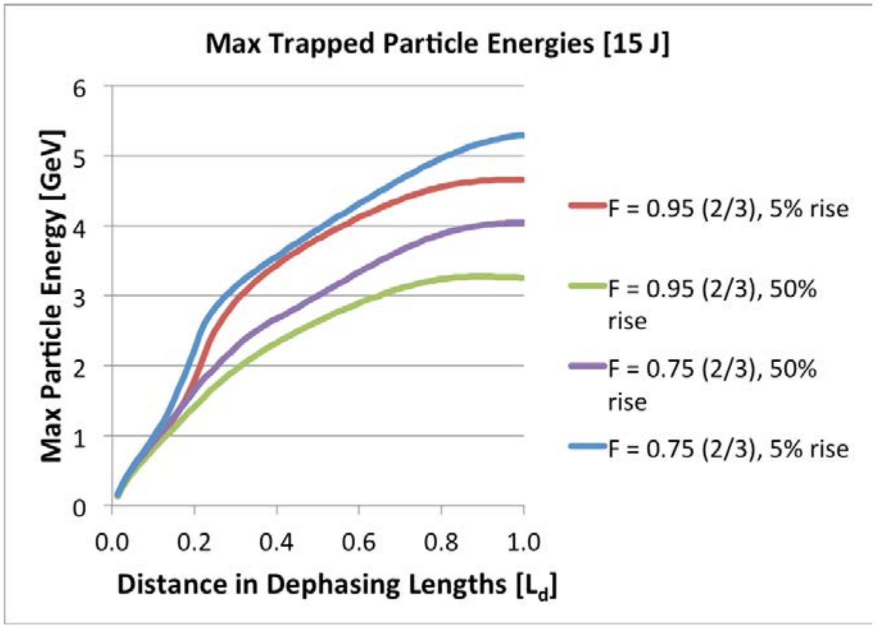
Laser Energy (J)	**P (TW)**	**n_p (cm^{-3})**	**W_0 (μm)**	**L_d (cm)**	**a_0**	**ΔE (GeV) Estimated**	**ΔE (GeV) Simulated**
6	200	1.5×10^{18}	19.5	1.5†	4.0	1.58	1.55†
16	**324**	**1.0×10^{18}**	**22.0**	**2.62**	**4.44**	**2.52**	**3.46**
47	**649**	**5.0×10^{17}**	**31.7**	**7.37**	**4.44**	**5.28**	**6.63**
133	**1298**	**2.5×10^{17}**	**44.8**	**20.8**	**4.44**	**10.57**	**13.6**
290	2162	1.5×10^{17}	57.8	44.8	4.44	17.6	???
542	3280	1.0×10^{17}	71.2	83.8	4.44	26.7	???

Capabilities of a Fixed Energy Laser

Longitudinal Profile Adjustment







- Best results I found so far, by combining a skewed profile with optimized pulse length:
  - 15 J Laser : **5.3 GeV**
  - 30 J Laser : **8.1 GeV**
- Note that for the 15 J case, this is twice the estimated energy of 2.52 GeV using default parameters

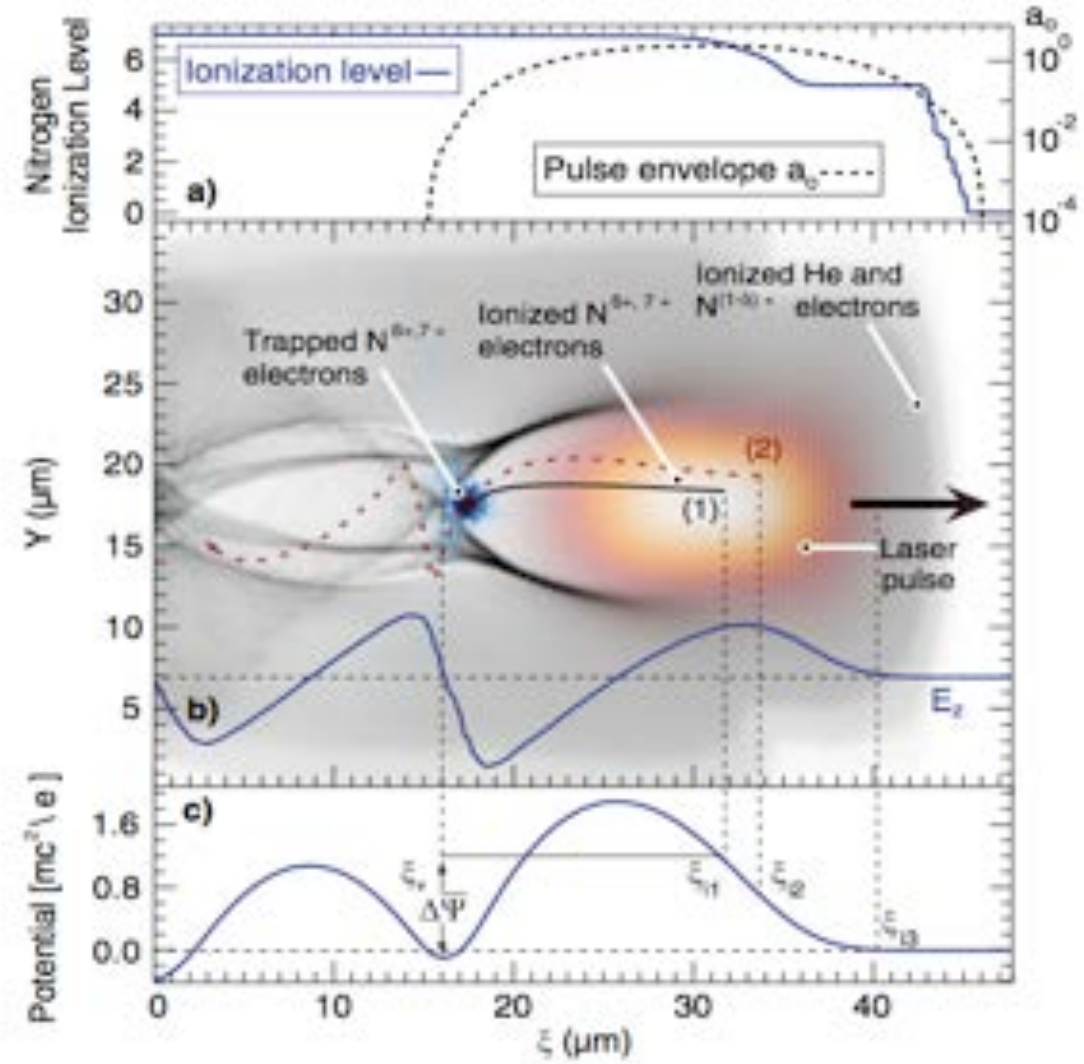
Grand challenge research problem is generation of ultra-low emittance beams and the manipulation of six dimensional phase space

Easier to inject electrons into wake when they are "born" inside wake.

Create electrons inside the wake (e.g., ionization).

Easier to satisfy trapping condition:

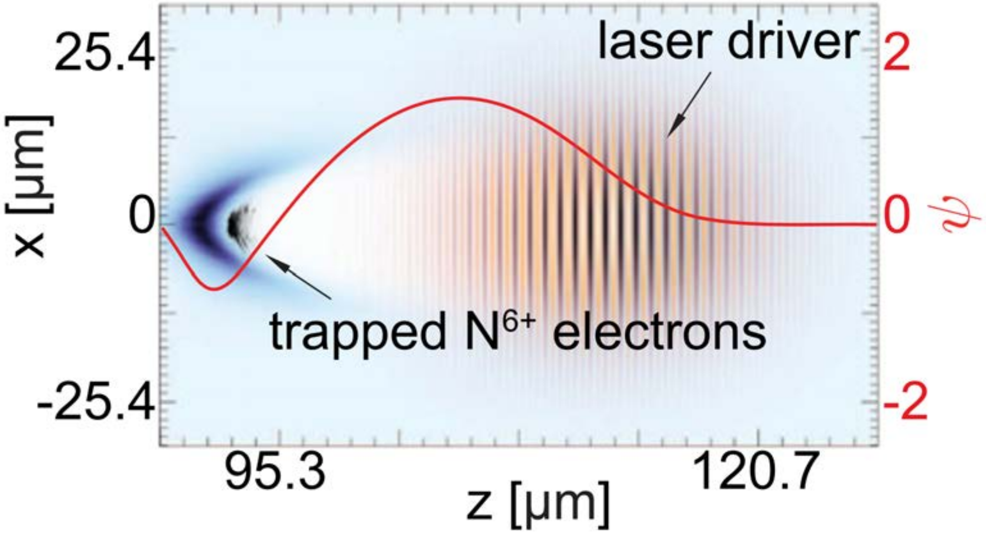
$$\Delta\psi \equiv \psi_{final} - \psi_{init} < -1$$



Pak et al. PRL 2009

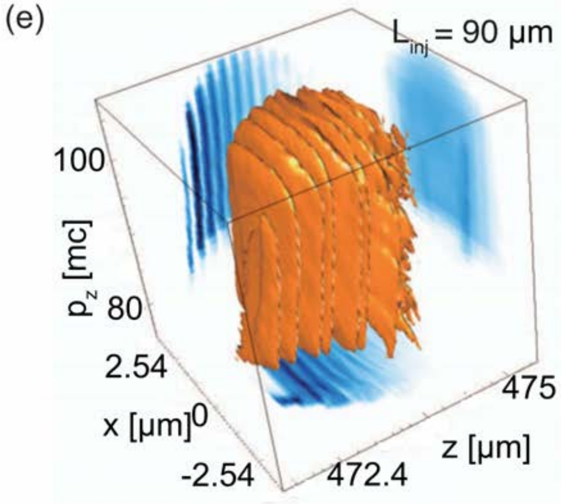
Many recent papers on using ionization injection

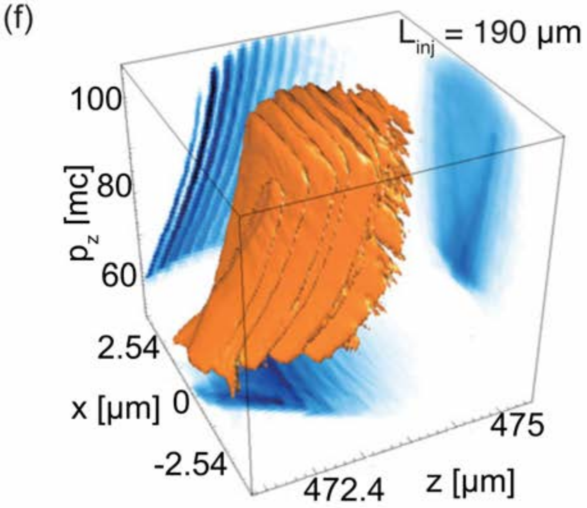
Ionization injection can generate nano-bunched electron beams



63.5 x63.5x 38.1 **μm^3 with**
500 x 500 x 1500 cells

Laser parameters:
800 nm/a0=2/w0 =14 μm/pulse length of 26 fs,
Plasma density:
2 x10^18 cm–3





X. Xu, et al. Physical Review Letters 2016

Ultrabright e^- bunch generation using down ramp injection: PWFA or LWFA driven

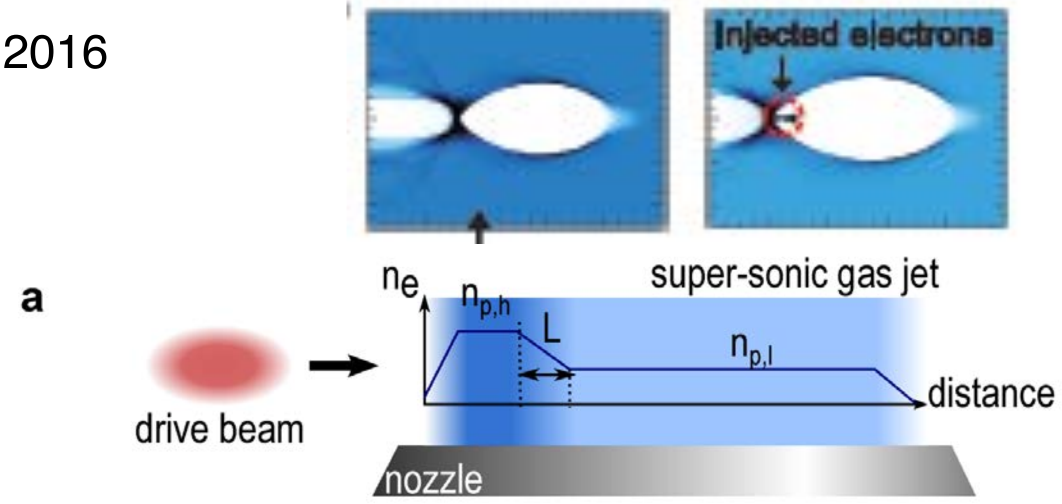
X. Xu, F. Li, et al. UCLA/Tsinghua submitted 2016

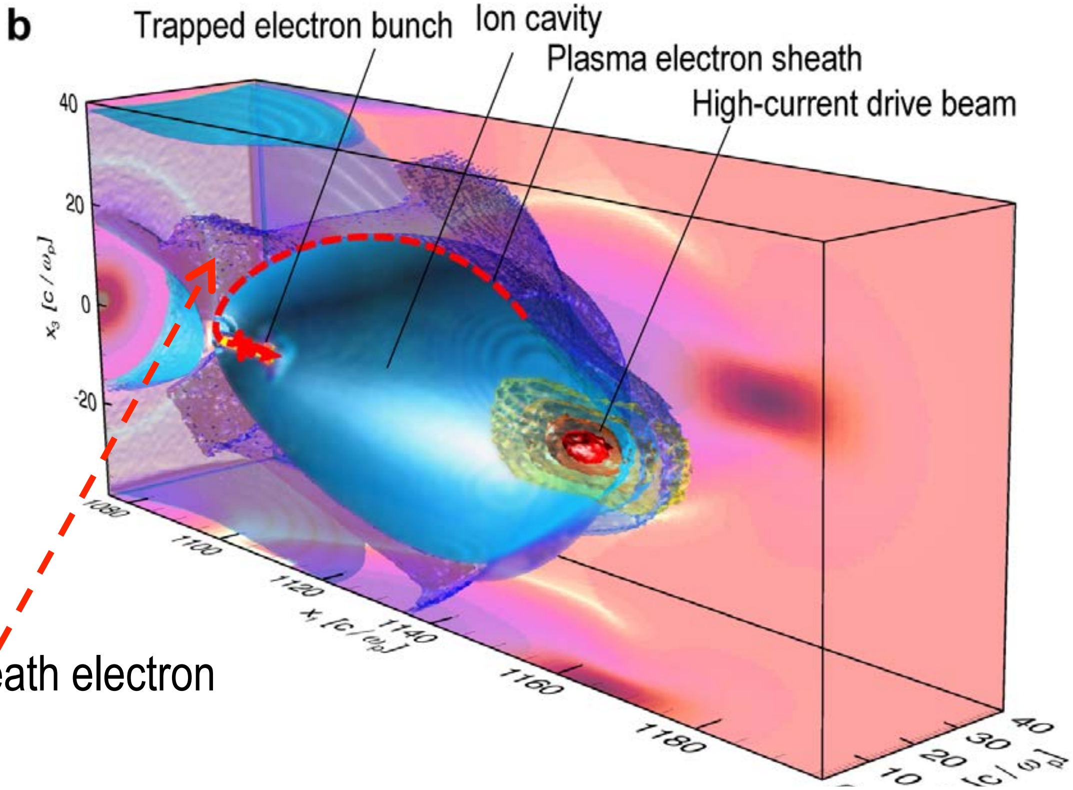
- **Could drive a compact XFEL**
- Beam-driven plasma acceleration in blowout regime can produce such beam via density transition: ~1nC

Output Beam

ε_n<50nm rad, I~10 kA, ΔE<3 MeV,

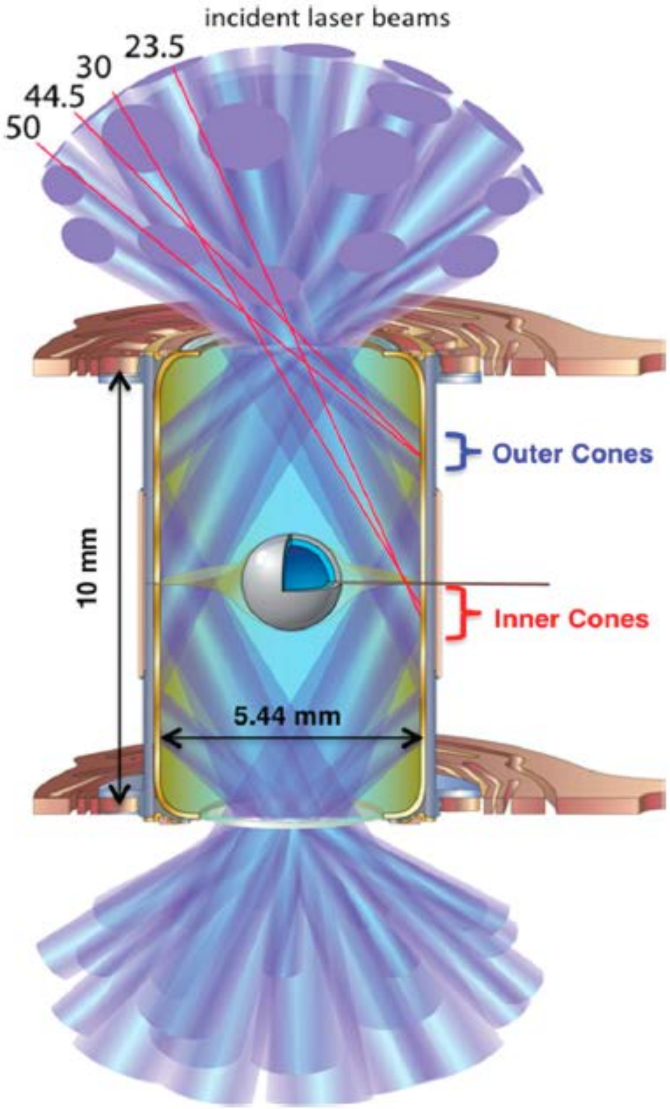
$B_n>10^{21}$A m^{-2} rad^{-2} may be possible





trapped sheath electron trajectory

NIF this is incredibly complicated with much fundamental science



1.8 MJ into holhraum
but just ~10s KJ into compressed fuel

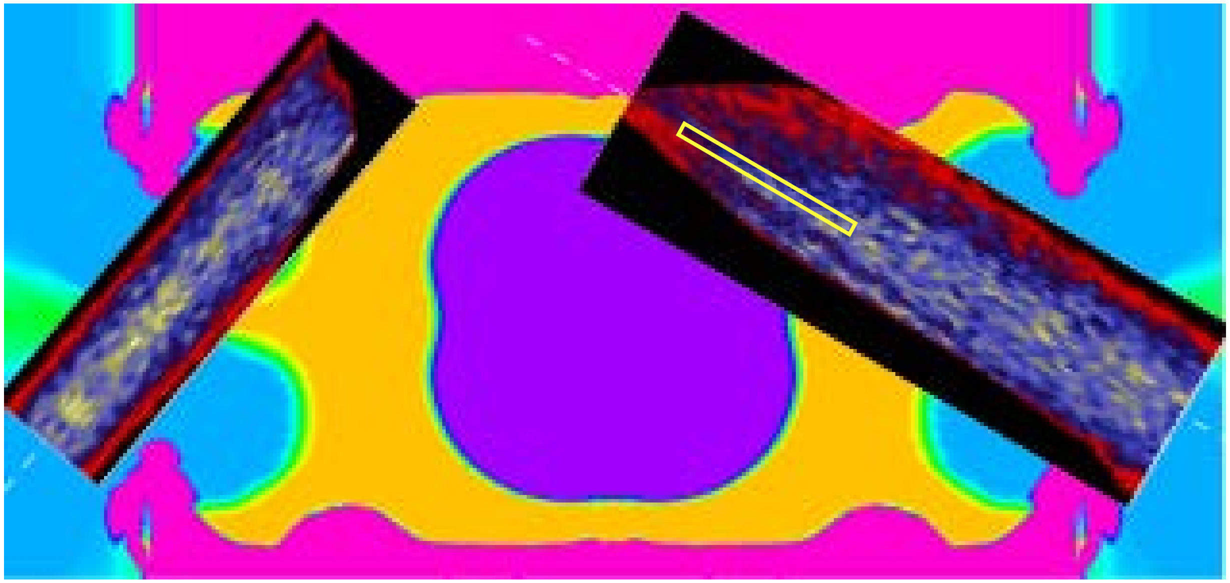
Requires very symmetric compression
Requires very symmetric x-ray drive
Requires correct time dependence to this drive

Lasers must hit where they are aimed!

Hinkel et al., PoP (2011)

NONLINEAR OPTICS OF PLASMAS

But lasers propagate through long regions of tenuous on NIF. They can “scatter” into other light waves and electron plasma and ion acoustic waves. This is **very** complicated. Beams cross paths and beams are broken up into “speckles” (Gaussian beamlets) to minimize the instabilities.



Colors correspond to different ranges of density (and material).

Inner Boxes: pF3D simulations of speckled laser beams
Inner yellow box is the size that a fully kinetic simulation can model.

Hinkel et al., PoP (2011)

After 40 years of research, and the evolution of software and computers, it is now possible to carry out full kinetic simulations and data analysis of a meaningful volume and time duration of a NIF (laser fusion) beam propagating through a plasma.

Example: Stimulated Raman Scattering (no magnetic fields)

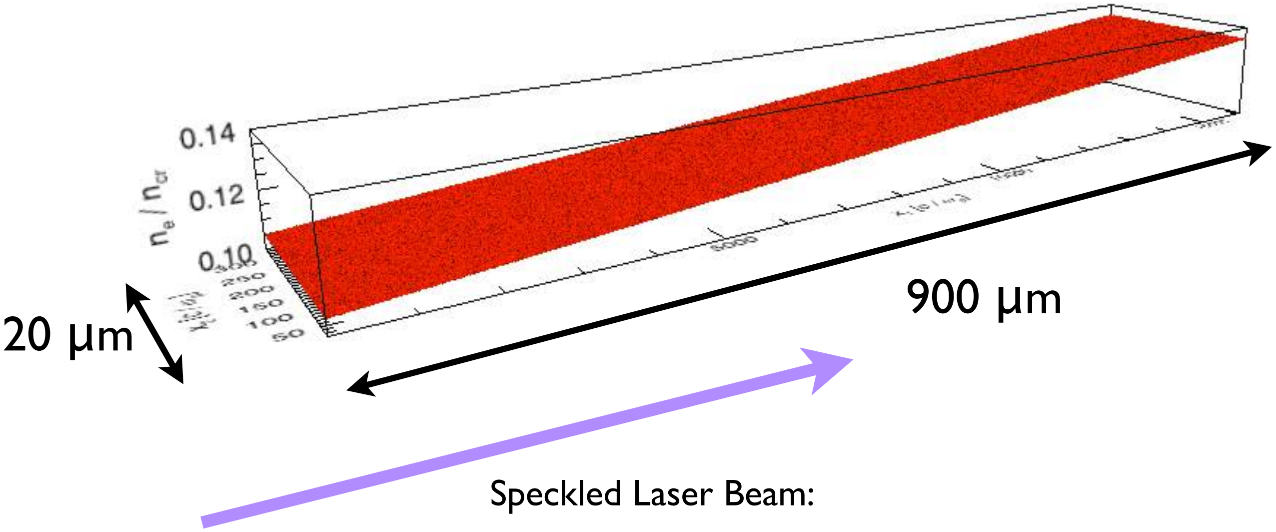
VPIC and OSIRIS

Multi-speckle SRS

2D plasma simulated for 16 ps:

T_e = 2.75 keV

linear density gradient, n_e/n_{cr} = 0.105 to 0.135



Speckled Laser Beam:

λ = 351nm

$I_{avg} = 10^{15}$ W/cm^2

5 speckles long x 7 speckles wide

Domain:

6.4 million cells

16 billion particles

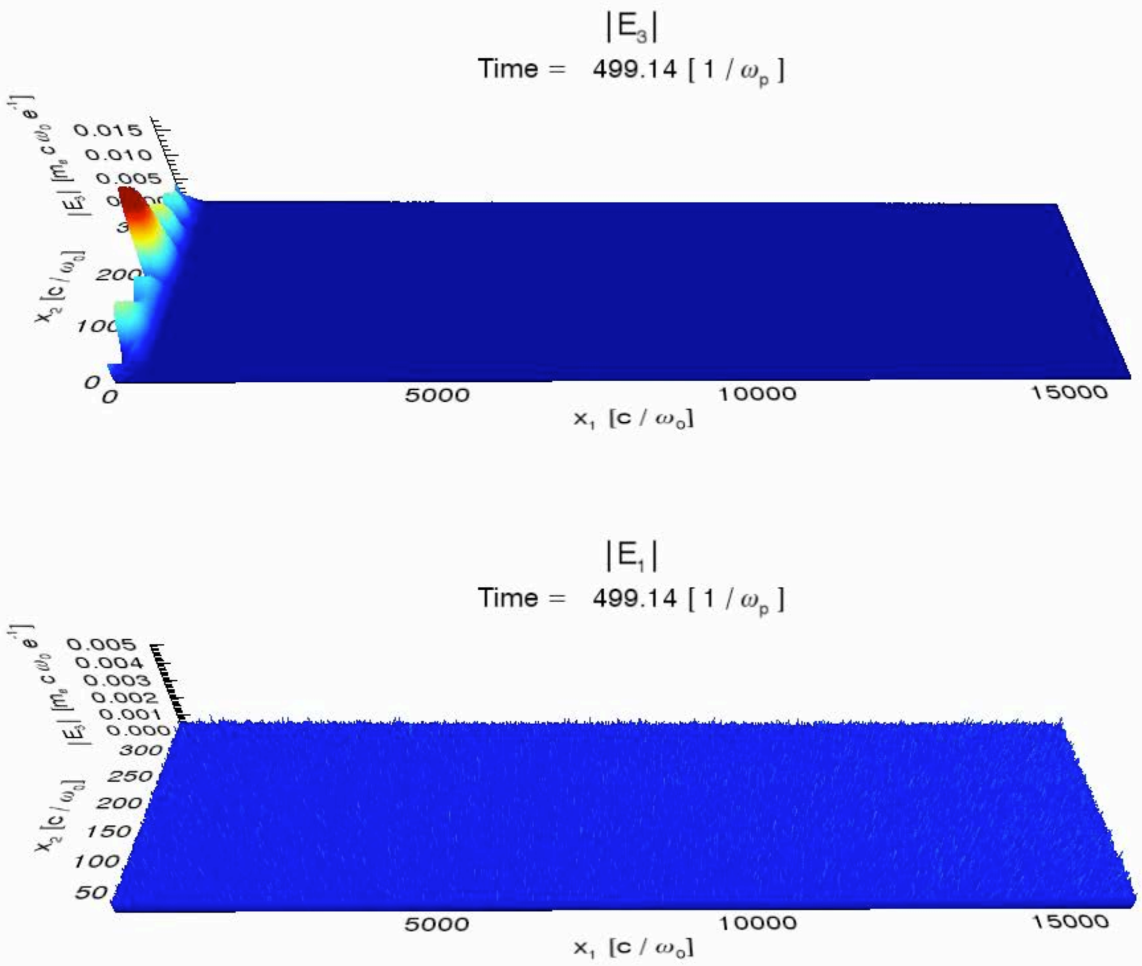
450,000 time steps

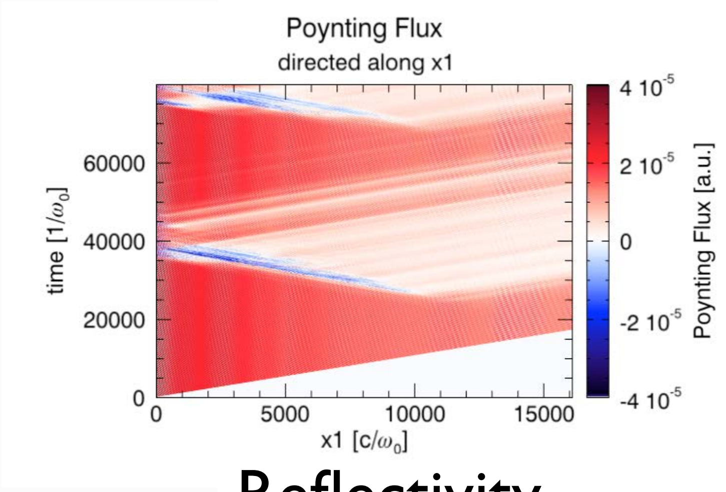
Computational:

32768 processors on Blue Waters

880,000 CPU hours

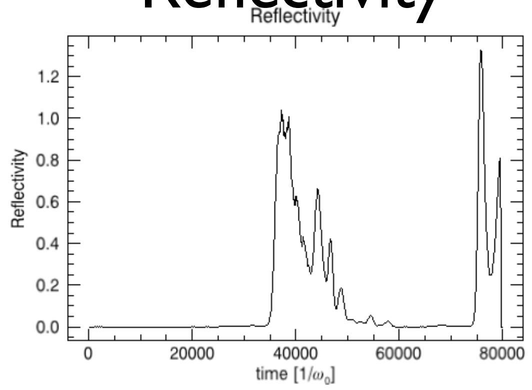
Multi-speckle (~35) fully kinetic simulations: Reflectivity is bursty: ~1,000,000 CPU Hours





Reflectivity

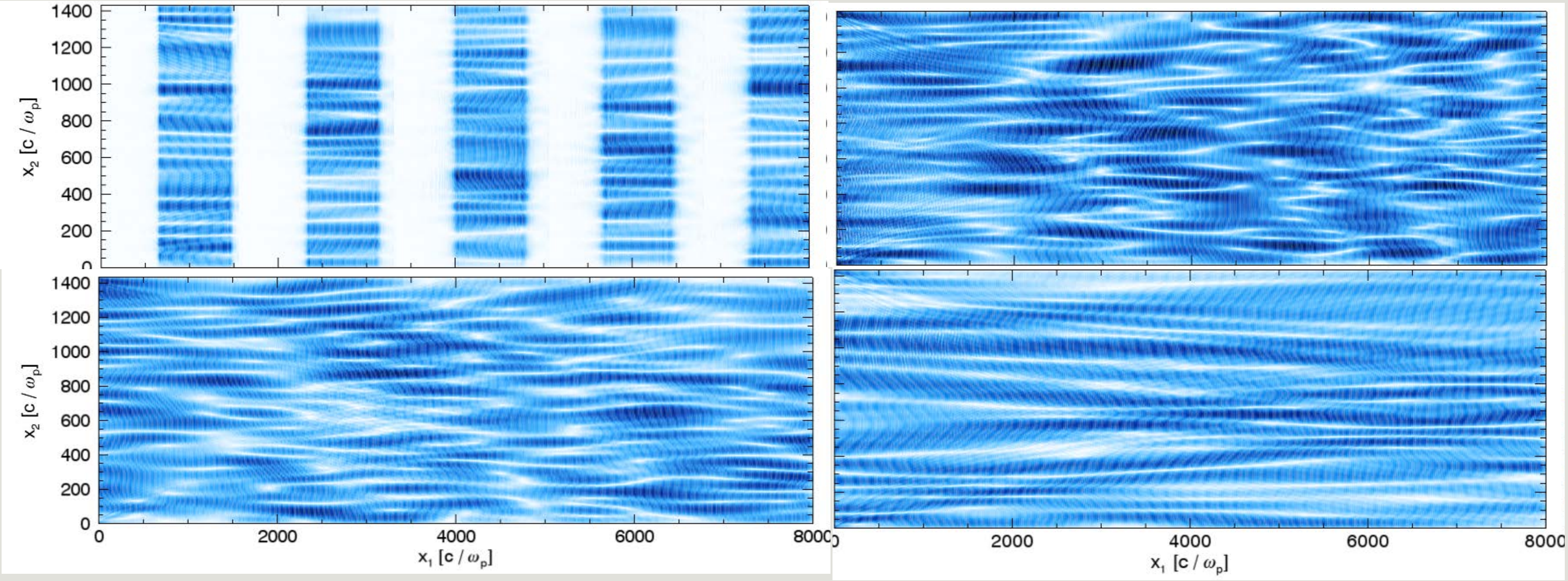
1.3



Examples of speckle patterns generated by OSIRIS with different smoothing techniques

STUD

Multi-FM SSD



ISI

RPP

Simulation parameters

Particle-per-cell: 256	256[1]
Grid: 44750×4772, 10740×2386	36864 × 4096
Electron temperature: 3.0 keV	2.6 keV
Intensity: $5\sim10\times10^{14}W/cm^2$	$2\sim5\times10^{14}W/cm^2$

---

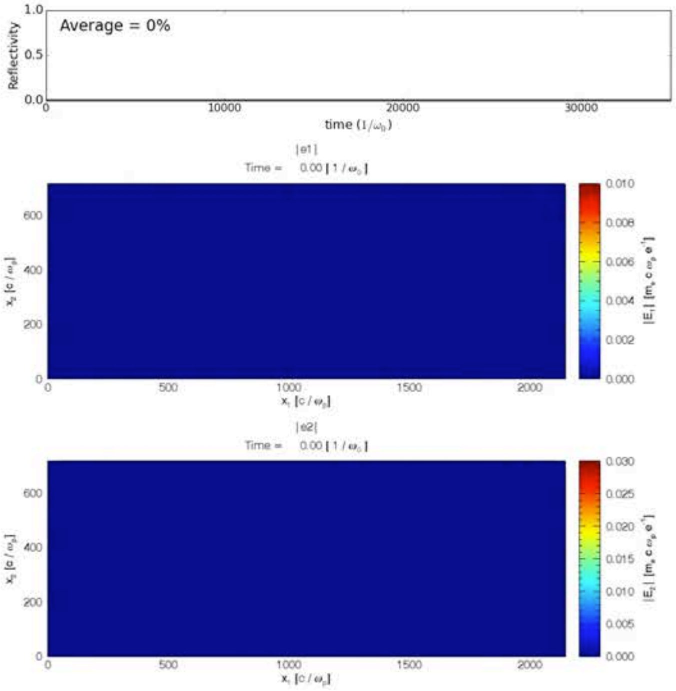
1) Albright, B. J., Yin, L., & Afeyan, B. Physical Review Letters, 113(4), 45002. (2014)

LPI Simulation Results — Temporal bandwidth can reduce LPI

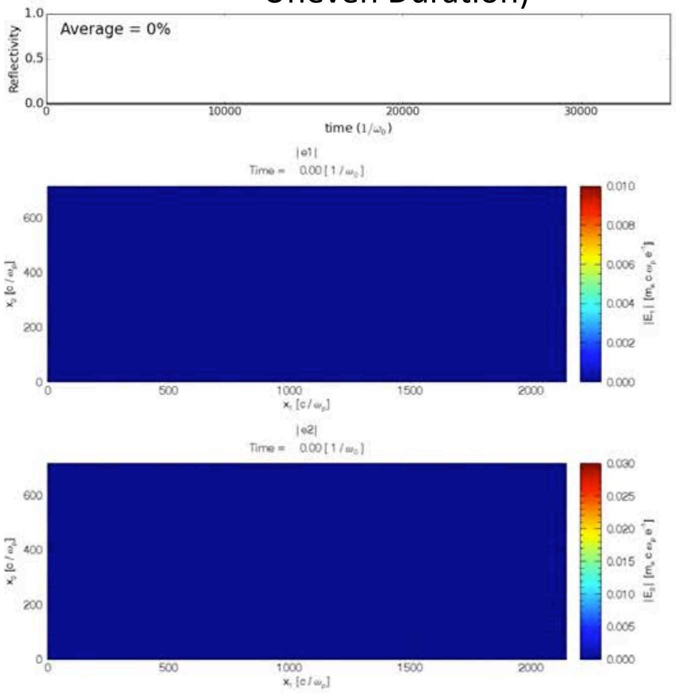
Temporal bandwidth can reduce SRS growth

- Small simulations (90k core-hours each) to identify interesting parameters before starting full simulations (<1 million core-hours each)
    - 15 speckles across and ~120 microns long, I=10^15
    - ~100 million grids and ~10 billion particles each.
- Incorporating polarization smoothing can further reduce SRS reflectivity
- These are very preliminary: Wide parameter space needs to be studied.

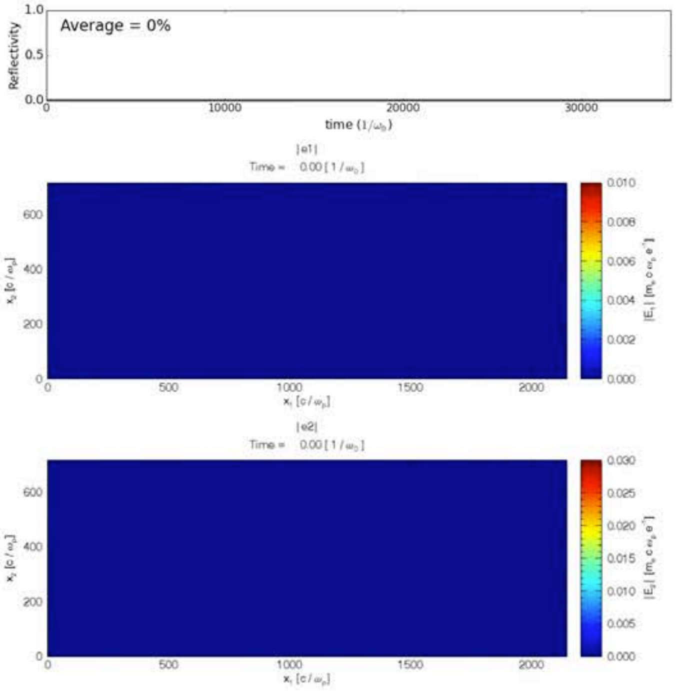
RPP



STUD (Spike Train of Uneven Duration)



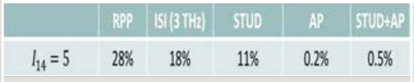
ISI



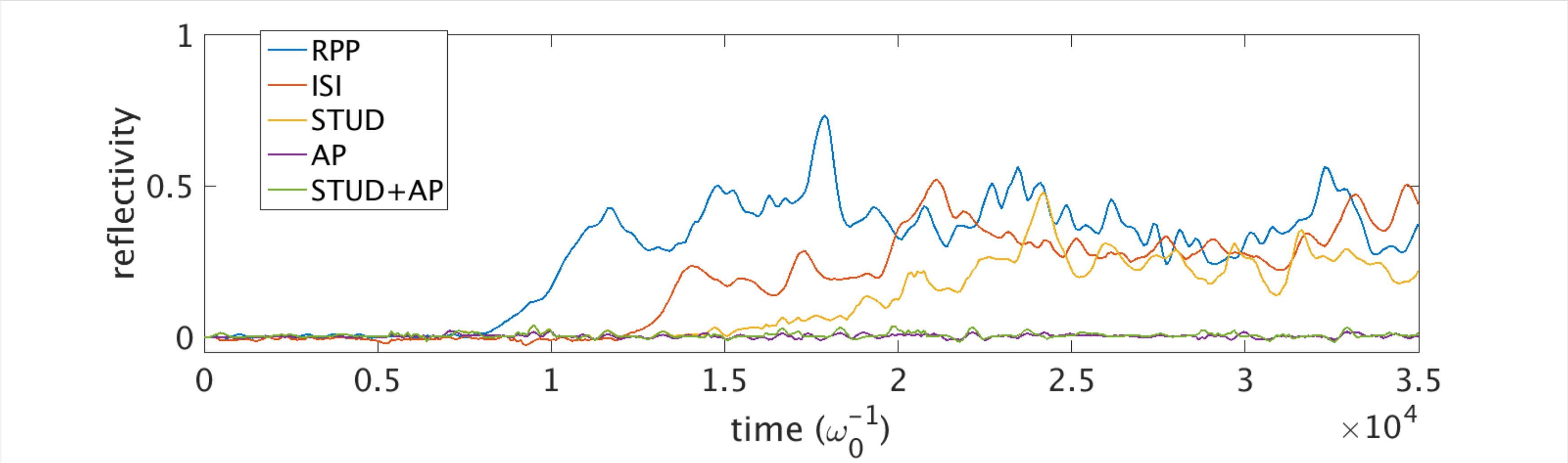
long-scale-length simulations with $I_{14} = 5 \; (L_{INT} \gg L_{HS})$

$n \in [0.125, 0.135] n_c$, $T_e = 3\ keV$, box size $500 \times 80 \mu m$, $L_{HS} = 90 \mu m$, $L_{spike} = 40 \mu m$

- $I_{14} = 5$, $L_{INT} = 450 \mu m$, $G = 56$

	RPP	ISI (3 THz)	STUD	AP	STUD+AP
	28%	18%	11%	0.2%	0.5%

	RPP	ISI (3 THz)	STUD	AP	STUD+AP
$I_{14} = 5$	28%	18%	11%	0.2%	0.5%



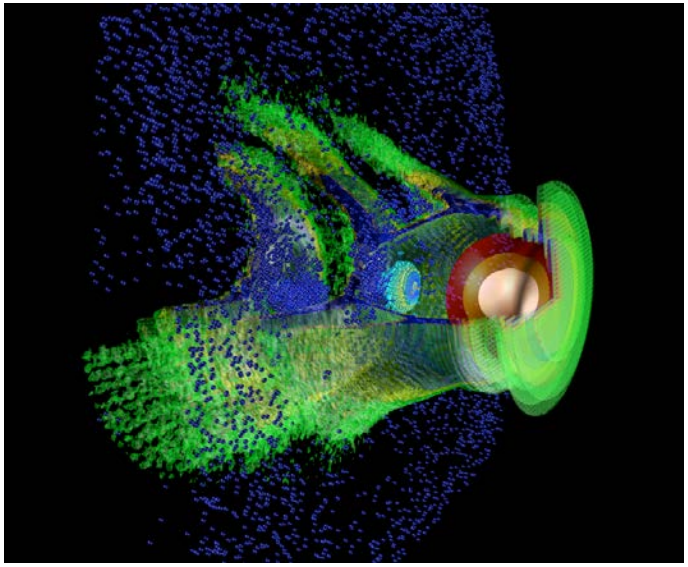
Exascale may permit 3D PIC simulations of LPI. Will require code development including new numerical methods and algorithms for new hardware

	2D multi-speckle along NIF beam path	3D, 1 speckles	3D, multi-speckle along NIF beam path
Speckle scale	50 x 8	1 x 1 x 1	20 x 20 x 5
Size (microns)	150 x 1500	9 x 9 x 120	56 x 56 x 900
Grids	9,000 x 134,000	500 x 500 x 11,000	1,700 x 1,700 x 80,000
Particles	300 billion (256/cell)	300 billion (64/cell)	10 trillion (64/cell)
Steps	470,000 (15 ps)	540,000 (15 ps)	540,000 (15 ps)
Memory Usage*	1.5 TB	1.5 TB	1 PB
core-hours	8 million	13 million	1 billion (2 months on Blue Waters; Exascale

Estimates are sensitive to resolution and number of particles

The UCLA Particle-in-Cell and Kinetic Simulation SoftwareCenter (PICKSC)

The mission of the Particle-in-Cell and Kinetic Simulation Software Center (PICKSC) at UCLA is to support an international community of PIC and plasma kinetic software users, developers, and educators, and to increase the use of this software for accelerating the rate of scientific discovery.

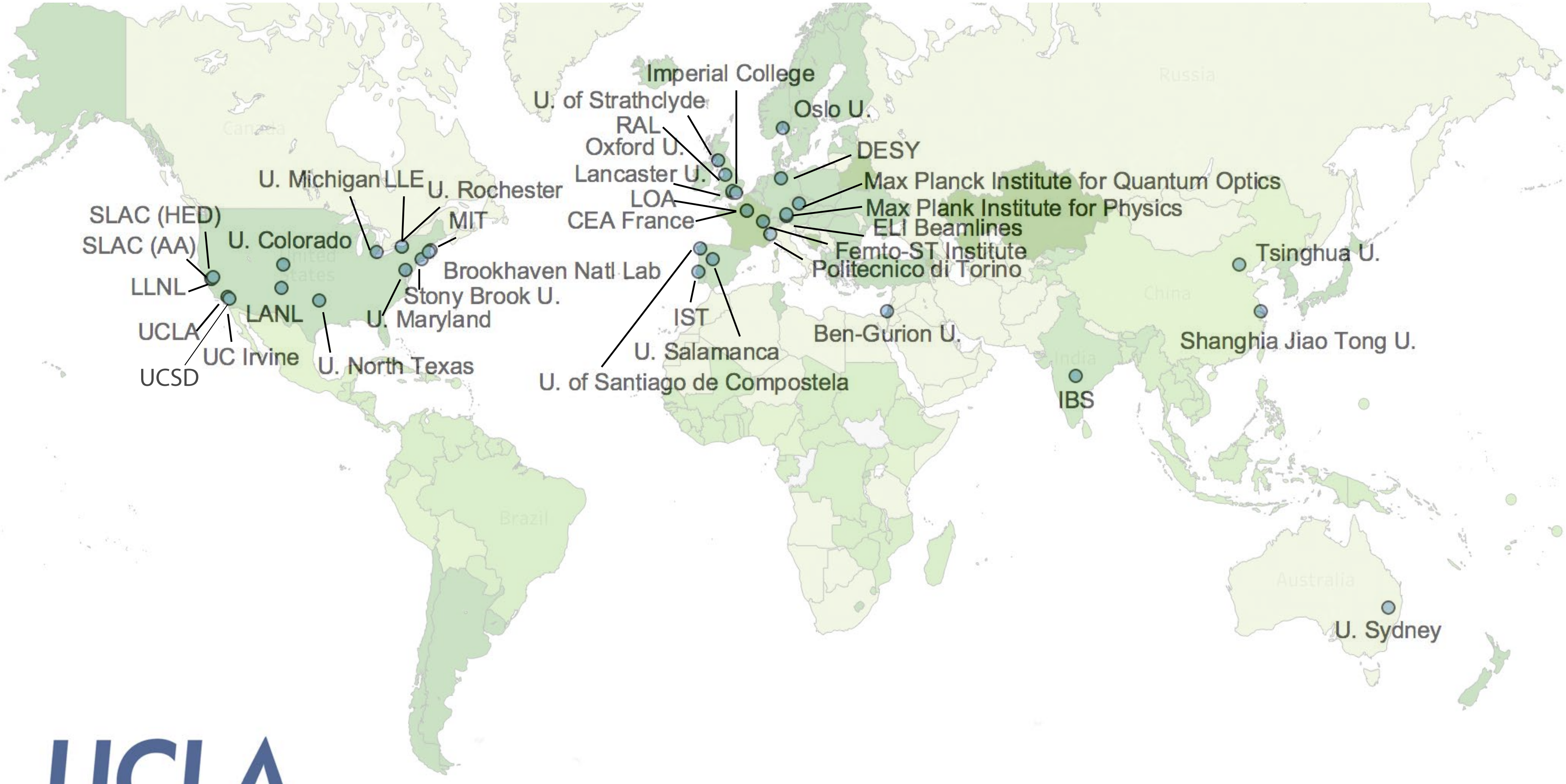


OSIRIS, QuickPIC, UPIC, OSHUN

http://picksc.idre.ucla.edu

E-mail me if you would like more information about available software: Mori@physics.ucla.edu

OSIRIS and QuickPIC access and use is international: Used in AA and HEDP research



UCLA

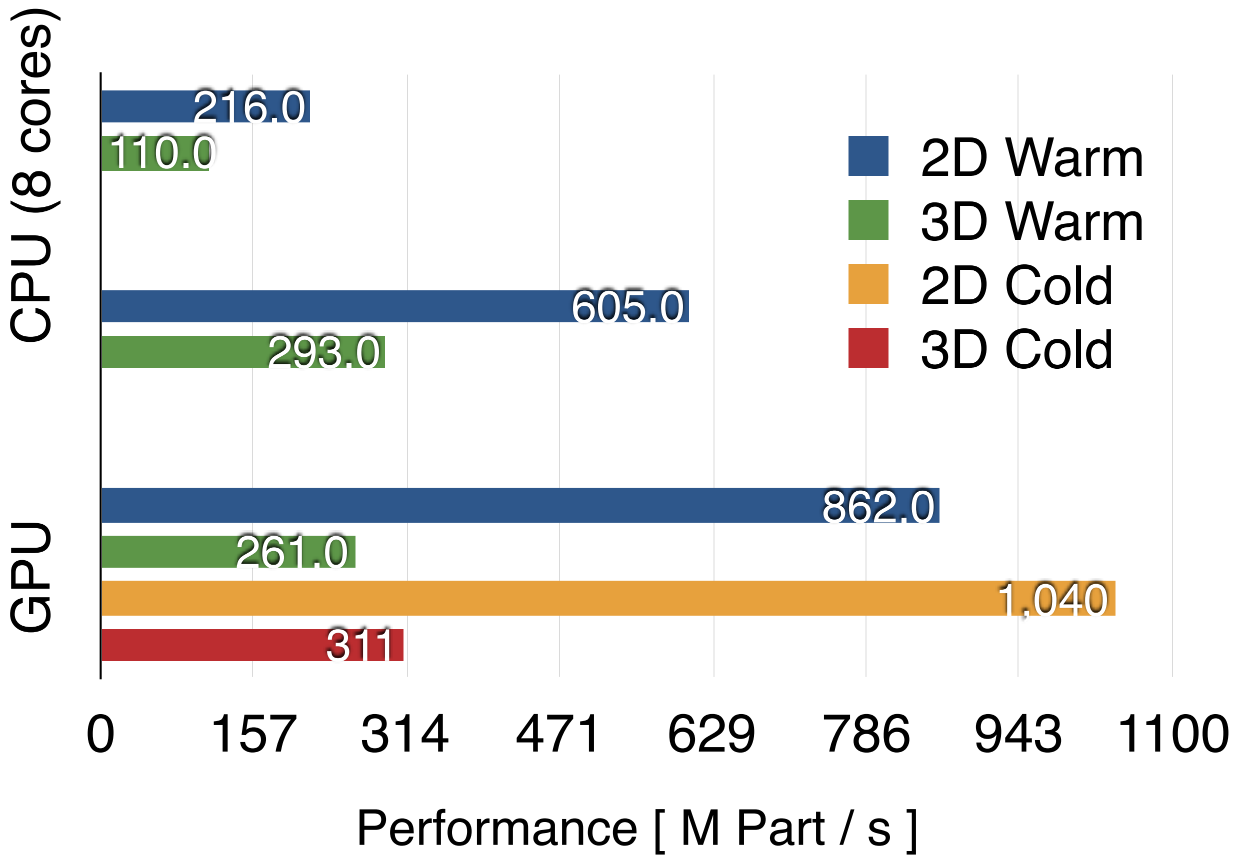
PICKSC

PLASMA SIMULATION UCLA

NSF

U.S. DEPARTMENT OF ENERGY

Take advantage of many core



OSIRIS is GPU and Intel Phi enabled

HEDLP is rich in big and discovery driven science.

There is a close synergy between experiment and simulation.

Kinetic software continues to advance forward.

Preparing for exascale requires learning how to run on petascale.

Plasma based acceleration is making rapid progress.

A roadmap for research for a linear collider application is underway. The modeling capability and concepts for a paper study could be available within the next decade.

A compact XFEL is a realistic goal within the next decade.

Ignition on NIF will occur within the next ?????