Exaflop, Petawatt, and Terabar physics

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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 > $3.5 \times 10^6$ K
Densities > $10^3$ g/cm$^3$
Pressures > .1 Tbar
.5 PW
NSF, DOE, NASA, NNSA invests in computers that cost ~$250,000: Large, complex, and expensive

Blue Waters - Cray XE/XK hybrid

24,140 XE Compute Nodes
2× 16 core AMD 6276 @ 2.3 GHz
\( R_{\text{peak}} \) 7.1 PFlop/s

3,072 XK Compute Nodes
1× 16 core AMD 6276 @ 2.3 GHz
1 × Nvidia Tesla K20 GPU
\( R_{\text{peak}} \) 4.51 PFlop/s

\( R_{\text{peak \ agg}} \) 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

High Performance Computing Power Evolution

- **Sunway TaihuLight**
  - Node Configuration:
    - 1x SW26010 manycore processor
    - 4x(64+1) cores @ 1.45 GHz
    - 4x 8 GB DDR3

- Total system:
  - 10,649,600 cores
  - 1.31 PB RAM

- Performance:
  - $R_{\text{peak}}$ 125.4 Pflop/s
  - $R_{\text{max}}$ 93.0 Pflop/s

(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 two in high energy density plasma physics.
Large Hadron Collider: 30 km in circumference, $10\text{ Billion} +$

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
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 \(\sim 1\) 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).

\[
\mathcal{E} = \frac{E^2 + B^2}{8\pi} \quad \mathcal{I} = c\mathcal{E} = c\frac{E^2}{4\pi}
\]

- It turns out that for radiation pressures corresponding to \(\sim\) 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.

Energy, efficiency, charge, beam quality are the important metrics.
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.
The synergy between simulation and experiment has “accelerated” the rate of discovery.

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

### Why Plasmas?

<table>
<thead>
<tr>
<th>Conventional Accelerators</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Limited by peak power and breakdown</td>
<td>• No breakdown limit</td>
</tr>
<tr>
<td>• 20-100 MeV/m – 20km /0.8 TeV</td>
<td>• 10-100 GeV/m</td>
</tr>
</tbody>
</table>

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

- 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.

<table>
<thead>
<tr>
<th>Use appropriate variables</th>
<th>Meaning of new variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Transform from:</td>
<td>• ( \xi = z - v_\phi t ) is the distance from front of the driver</td>
</tr>
<tr>
<td>(( z, x, y; t ))</td>
<td>• ( S = z ) is the distance the driver has propagated into the plasma</td>
</tr>
<tr>
<td>- Transform to:</td>
<td>Mathematical meaning of quasi-static approximation</td>
</tr>
<tr>
<td>(( \xi = z - v_\phi t, x, y; s = z ))</td>
<td>( \partial_s \ll \partial_\xi )</td>
</tr>
</tbody>
</table>
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-potential**

\[
\psi = (\phi - A_z)
\]

**Don’t choose a gauge where**

\[
\phi = A_z
\]

**Forces on relativistic particle**

\[
F_z = -\partial_\xi \psi
\]

\[
F_\perp = -\nabla_\perp \psi
\]
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 (Rosenzwieg 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:

\[
\frac{d r_b}{d \xi} \approx k_p^2 \frac{r_b^2(\xi) - r^2}{4}
\]

\[
\frac{eE_z}{mc \omega_p} = \frac{r_b}{2} \frac{d r_b}{d \xi} \approx \frac{1}{2} \xi
\]

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

Relativistic blowout regime for blowout radius and for large maximum radius the trajectory of \( r_b \) is a circle: Bubble

Lu et al. PRL 16, 16500 [2006]

Bubble radius:

\[
k_p R_b \approx 2\sqrt{\Lambda} \quad \text{or} \quad k_p R_b \approx 2\sqrt{a_0}
\]
Transverse Dynamics and Beam Quality

- Emittance $\varepsilon_n$ = phase space area and a measure of its ability to get focused:

\begin{align*}
n \sigma_X = 0.5 & \\
n \frac{\sigma_X}{\sigma_Y} = c & \\
\end{align*}

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

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

- 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

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

\begin{align*}
k_\beta & \equiv \frac{\omega_\beta}{c} \quad k_\beta = \alpha \frac{k_p}{\sqrt{2\gamma}}
\end{align*}
What computational method do we use to model HEDP including discrete effects?

The Particle-in-cell method
Not all PIC codes are the same!

\[
\frac{dp}{dt} = q \left( E + \frac{v}{c} \times B \right)
\]

Integration of equations of motion, Push particles

\[ F_k \rightarrow u_k \rightarrow x_k \]

Interpolating

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

\( \Delta t \)

Depositing

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

Integration of Field Equations on the grid

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

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

\[
\frac{\partial B}{\partial t} = -c \nabla \times E
\]
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

\[
\frac{D}{Dt} F = 0
\]

\[
F(\vec{x}, \vec{v}; t) = \sum_{i}^{N} S_{p}(\vec{x} - \vec{x}_i(t)) \delta(\vec{v} - \vec{v}_i(t))
\]

\[
\frac{D}{Dt} \equiv \partial_{t} + \vec{v} \cdot \nabla_{x} + \vec{a} \cdot \nabla_{v}
\]

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

Maxwell’s equations

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

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

\[
\frac{\partial}{\partial t} \vec{E} = \nabla \times \vec{B} - \frac{4\pi}{c} \vec{J}
\]
OSIRIS 4.0 (began in late 1990s from LLNL funding)

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST

Ricardo Fonseca:
ricardo.fonseca@tecnico.ulisboa.pt

Adam Tableman:
tableman@physics.ucla.edu

Frank Tsung:
tsung@physics.ucla.edu

http://
epp.tecnico.ulisboa.pt/
http://picks.idre.ucla.edu/

accessible through MoU

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

Speedup on Sequoia

- Strong Scaling
- Weak Scaling
- Optimal

# Cores

Speedup from 4096 cores
QuickPIC: A PIC code based on quasi-static approximation

\[ \vec{E}_\perp + \hat{z} \times \vec{B}_\perp = -\nabla_\perp \cdot \psi \]
\[ \nabla_\perp^2 \psi = -(\rho - J_z) \]
\[ \nabla_\perp^2 \vec{B}_\perp = \hat{z} \times \left( \frac{\partial}{\partial \xi} \vec{J}_\perp + \nabla_\perp \cdot \vec{J}_\perp \right) \]
\[ \nabla_\perp^2 B_z = -\nabla_\perp \times \vec{J}_\perp \]
\[ \nabla_\perp^2 E_z = \nabla_\perp \cdot \vec{J}_\perp \]

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

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

For each plasma particle:
\[ Q(1 - v_z) = 0 \]

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
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^{17}cm^{-3} plasma

QuickPIC simulations explained what limited the acceleration length
PWFA-based collider concept (no ILC)

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

A few 10s nm beam size and emittance

RF gun \rightarrow Drive beam accelerator

bunch compressor

RF separator

Drive beam distribution

Beam Delivery and IR

PWFA cells

FACET Program will demonstrate most of a single stage

DR e- \rightarrow main beam e- injector

DR e+ \rightarrow main beam e+ injector

A 19 Stages PWFA-LC with 25GeV energy gain per stage
Another example at FACET:
Synergy demonstrated efficient beam loading of wake

QuickPIC and OSIRIS simulations helped to design and interpret the experiment.
Drive Beam: $E = 10$ GeV, $I_{\text{peak}} = 15$ kA
$\sigma_r = 21.17 \, \mu m$, $\sigma_z = 12.77 \, \mu m$
$N = 1.0 \times 10^{10} \, (1.6 \, nC)$,
$\varepsilon_N = 10 \, \mu m$

Trailing Beam: $E = 10$ GeV, $I_{\text{peak}} = 9$ kA
$\sigma_r = 21.17 \, \mu m$, $\sigma_z = 6.38 \, \mu m$
$N = 0.3 \times 10^{10} \, (0.48 \, nC)$,
$\varepsilon_N = 10 \, \mu m$

Distance between two bunches: 150 µm
Plasma Density: $4.0 \times 10^{16} \, \text{cm}^{-3}$ (with ramps)
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.
Drive beam energy is 25 GeV
Output beam energy is ~60 GeV

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

Trailing beam is very tightly focused. Electric field in trailing beam ~10 TeV/cm.
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 spots size is “matched”:

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

\[ k_p w_0 \simeq k_p R_b \simeq 2 \sqrt{a_0} \]

\[ v_{etch} \simeq \frac{c n_p}{n_c} \]

Lu et al. 2007
Phenomena that are Relevant to the Study of LWFAs

- 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.

(Courtesy of Lu et al.)
The Laser Wakefield Accelerator

Phenomenological Scaling Law†

• Given that the laser has a matched spot size, a scaling law can be derived

• The maximum accelerating distance is estimated as

\[ L_d \approx \frac{2}{3} \left( \frac{\omega_0}{\omega_p} \right)^2 W_0 \]

• The particle energy estimated as

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

(Courtesy of Lu et al.)

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

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

• How far does it scale?

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

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

\[ [A = 17 \text{ GW}] \]

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

A. Davidson, PhD Dissertation UCLA 2016
By Scaling to Higher Acceleration Distances

Pushing the Theory Further by Scaling to Higher Acceleration Distances

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

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.


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†.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Charge [pC] (1cm)</th>
<th>ex [π mm mrad]</th>
<th>ey [π mm mrad]</th>
<th>Max Energy [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full 3D Cartesian</strong></td>
<td>340</td>
<td>27</td>
<td>30</td>
<td>1.57</td>
</tr>
<tr>
<td><strong>Cyl. Mode ≤ 1</strong></td>
<td>328</td>
<td>43</td>
<td>43</td>
<td>1.55</td>
</tr>
</tbody>
</table>

# Scaling Laws in Nonlinear Regime

Faster Methods Means Physics in Farther Regimes

<table>
<thead>
<tr>
<th>Laser Energy (J)</th>
<th>P (TW)</th>
<th>$n_p$ (cm$^{-3}$)</th>
<th>$W_0$ ($\mu$m)</th>
<th>$L_d$ (cm)</th>
<th>$a_0$</th>
<th>$\Delta E$ (GeV) Estimated</th>
<th>$\Delta E$ (GeV) Simulated</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>200</td>
<td>$1.5 \times 10^{18}$</td>
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<tr>
<td>542</td>
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<td>83.8</td>
<td>4.44</td>
<td>26.7</td>
<td>????</td>
</tr>
</tbody>
</table>
• 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


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

Osiris 3.0

63.5 x63.5x 38.1 μm^3 with 500 x 500 x 1500 cells
• Could drive a compact XFEL

• Beam-driven plasma acceleration in blowout regime can produce such beam via density transition: \(\sim 1\text{nC}\)

Output Beam

\(\varepsilon_n < 50\text{nm rad, } I \sim 10\text{ kA, } \Delta E < 3\text{ MeV,}\)

\(B_n > 10^{21}\text{A m}^{-2}\text{ rad}^{-2}\text{ may be possible}\)
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
2D plasma simulated for 16 ps:

\[ T_e = 2.75 \text{ keV} \]

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

Domain:
- 6.4 million cells
- 16 billion particles
- 450,000 time steps

Computational:
- 32768 processors on Blue Waters
- 880,000 CPU hours

Speckled Laser Beam:

\[ \lambda = 351 \text{nm} \]

\[ I_{avg} = 10^{15} \text{W/cm}^2 \]

5 speckles long x 7 speckles wide
Multi-speckle (≈35) fully kinetic simulations: Reflectivity is bursty: ≈1,000,000 CPU Hours
Examples of speckle patterns generated by OSIRIS with different smoothing techniques
### Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle-per-cell</td>
<td>256</td>
</tr>
<tr>
<td>Grid</td>
<td>44750×4772, 10740×2386</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>3.0 keV</td>
</tr>
<tr>
<td>Intensity</td>
<td>5∼10×10^{14} W/cm^2</td>
</tr>
</tbody>
</table>

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

$n \in [0.125, 0.135] n_c, \ T_e = 3 \text{ keV}$, box size $500 \times 80 \mu m, \ L_{\text{HS}} = 90 \mu m, \ L_{\text{spike}} = 40 \mu m$
- $I_{14} = 5, \ L_{\text{INT}} = 450 \mu m, \ G = 56$

<table>
<thead>
<tr>
<th>RPP</th>
<th>ISI (3 THz)</th>
<th>STUD</th>
<th>AP</th>
<th>STUD+AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPP</td>
<td>ISI (3 THz)</td>
<td>STUD</td>
<td>AP</td>
<td>STUD+AP</td>
</tr>
<tr>
<td>$I_{14} = 5$</td>
<td>28%</td>
<td>18%</td>
<td>11%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

![Graph showing reflectivity over time](image-url)
Exascale may permit 3D PIC simulations of LPI. Will require **code development** including new numerical methods and algorithms for new hardware.

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

Estimates are sensitive to resolution and number of particles.
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
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 ??????