Needs and challenges for modeling PWFA: Near term and and Beyond

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www.picksc.idre.ucla.edu

PICKSC PLASMA SIMULATION UCLA

SciDAC Scientific Discovery through Advanced Computing

INSIGHT
Sustainable ecosystems and society

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

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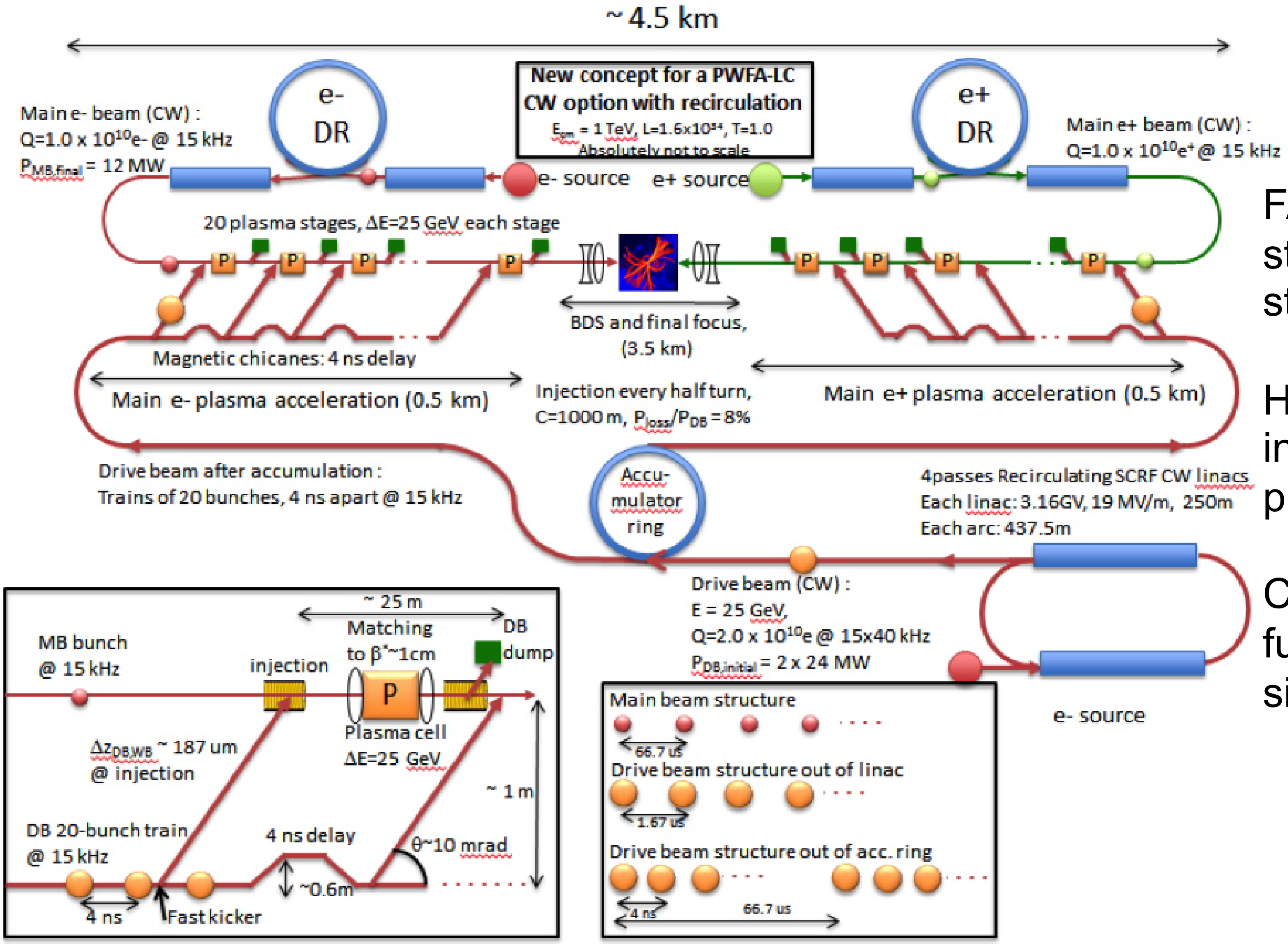
What is the goal?

PWFA Linear Collider



FACET(II) aimed at studying one and two stages.

High fidelity simulations including emittance preservation.

Can parameters of a future collider be simulated?

* Taken from E. Adli et al. arXiv:1308.1145, 2013

Components of a PWFA-LC "design"

The following issues need to be considered in PWFA-LC research:

1. Optimum shape for a driver
2. Acceleration in a single stage: Self-consistent beam loading scenarios.
3. Drive and trailing beam instabilities
4. Coupling between stages: Gaps based on beam optics etc.
5. Final focus (Oide limit etc.)
6. IP (disruption/beamstrahlung)

Particle-in-cell modeling can help with much of this.

Simulations will be critical for near and long term PWFA linear collider research

- Need simulation tools that can support the design of near term experiments such as those at FACET II.
- Need simulation tools that can aid in interpreting near term experiments such as those at FACET II.
- Need simulation tools that can simulate new physics concepts, e.g., 3D down ramp injection and matching sections.
- Need simulation tools that can simulate physics of a PWFA-LC including the final focus.
- Need simulation tools that aid in helping to design a self-consistent set of parameters for a PWFA-LC.

Simulations will be critical for near and long term PWFA linear collider research

- Simulations tools need to be continually improved and validated.
- Simulation tools need to run on entire ecosystem of resources.
- Simulation and analysis tools need to be easy to use.
- Relationship between code developers/maintainers and users is critical (best practices are not always easy to document).

osiris 3.0 (OSIRIS 4.0 is now the development branch)

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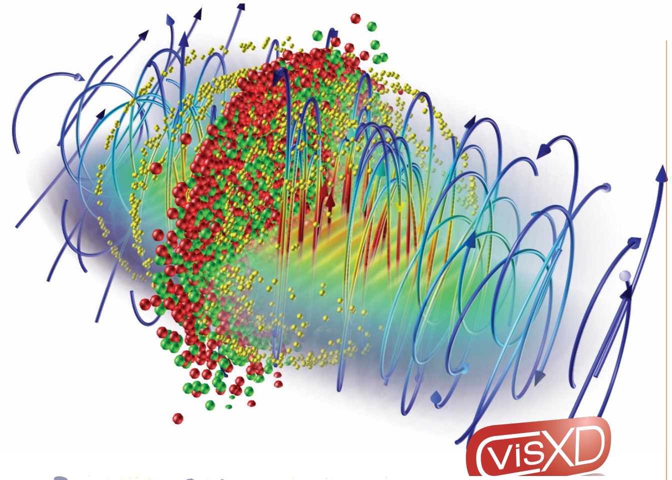
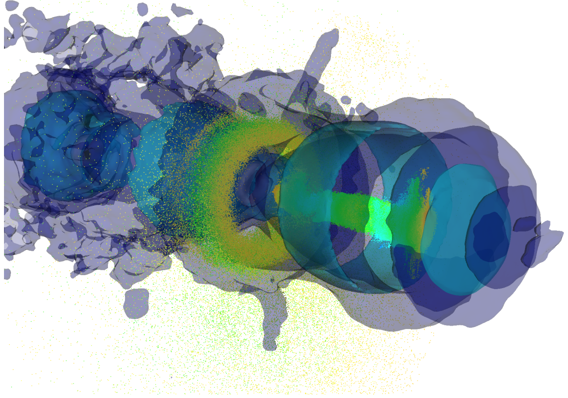
osiris framework

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



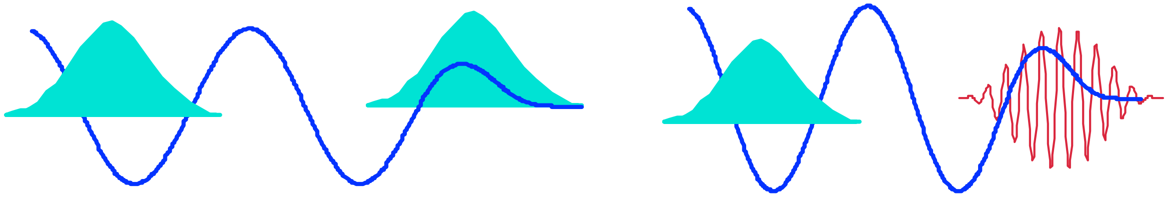


code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- PGC
- Radiation reaction
- QED module
- Particle splitting/merging
- Quasi-3D
- Boosted frame/-NCI
- Customized solvers
- Multi-speckle antenna
- GPGPU support
- Xeon Phi support

Quasi-static: QuickPIC

QuickPIC[1,2] is a 3D parallel Quasi-Static PIC code, which is developed based on the framework UPIC[3].



Full PIC(Osiris): $dt \sim 0.02\omega_p^{-1}$ Courant Condition

QS PIC(QuickPIC): $dt \sim 20.0\omega_p^{-1}$ Free of CC and of NCI!

$\sim \sqrt{\gamma}$ of the beam $\quad \sim \omega_0/\omega_p$

Ideal for PWFA
No self-trapping

1000 Times Faster

2D QS codes: LCODE and WAKE

[1] C. Huang et al., J. Comp. Phys. 217, 658 (2006).
[2] W. An et al., J. Comp. Phys. 250, 165 (2013).
[3] V. K. Decyk, Computer Phys. Comm. 177, 95 (2007).

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Equations in QuickPIC

Quasi-Static Approximation*

Radiationless: No NCR and NCI

(x, y, z; t)
↓
(x, y, ξ=ct-z, s=z)
↓
$\partial_s << \partial_\xi$
↓
Plasma: (x, y; ξ)
↓
Beam: (x, y, ξ, s)

$$\begin{cases} \nabla\times\vec{E} = -\dfrac{\partial\vec{B}}{\partial t} \\ \nabla\times\vec{B} = \dfrac{\partial\vec{E}}{\partial t} + \vec{J} \\ \nabla\cdot\vec{E} = \rho \\ \nabla\cdot\vec{B} = 0 \end{cases} \qquad \begin{cases} \nabla_\perp\times\vec{E} = -\dfrac{\partial}{\partial\xi}(\vec{B} - \hat{z}\times\vec{E}) \\ \nabla_\perp\times\vec{B} - \vec{J} = \dfrac{\partial}{\partial\xi}(\vec{E} + \hat{z}\times\vec{B}) \\ \nabla_\perp\cdot\vec{E} - \rho = \dfrac{\partial}{\partial\xi}\hat{z}\cdot\vec{E} \\ \nabla_\perp\cdot\vec{B} = \dfrac{\partial}{\partial\xi}\hat{z}\cdot\vec{B} \end{cases}$$

$$\frac{\partial}{\partial z} = -\frac{\partial}{\partial\xi} + \frac{\partial}{\partial s} \quad , \quad \frac{\partial}{\partial t} = \frac{\partial}{\partial\xi}$$

*P. Sprangle, et al., PRA 41, 4463 (1990)

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

Equations in QuickPIC

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

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

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

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

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

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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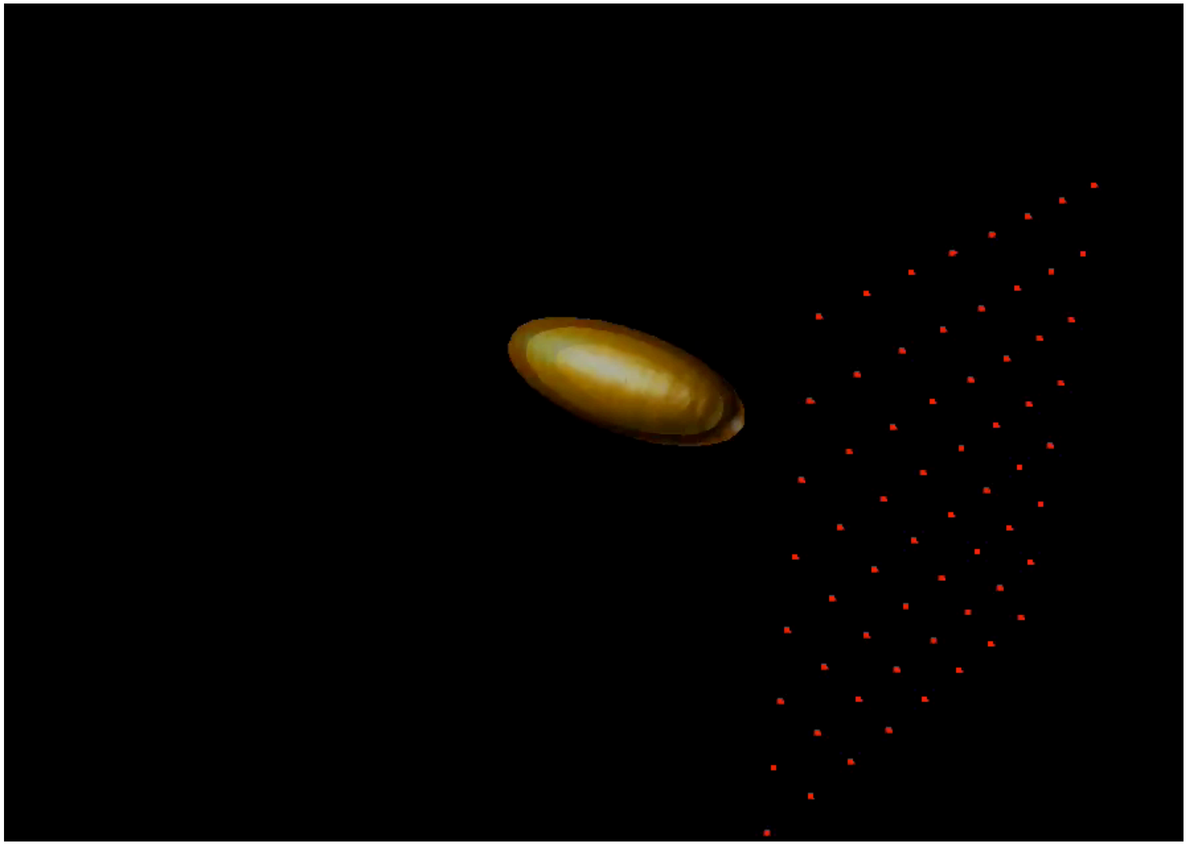
QuickPIC:
A 3D quasi-static PIC code

Fully parallelized and scaled to 100,000+ cores

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

Open Source:
Goto PICKSC web page

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



Recently HIPACE (not fully 3D)

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

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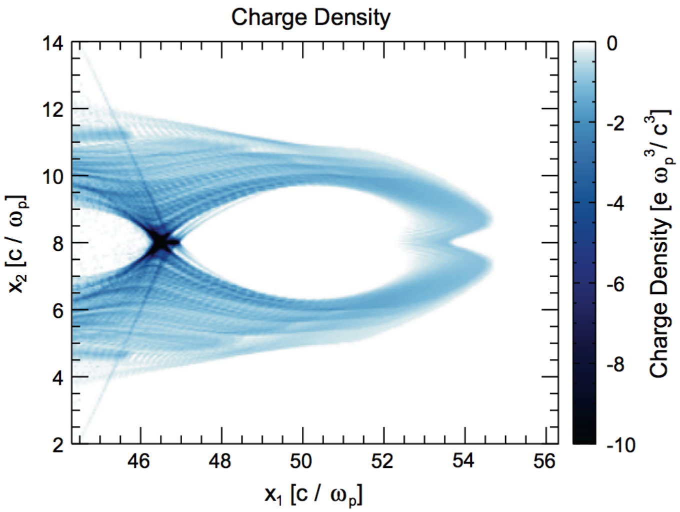
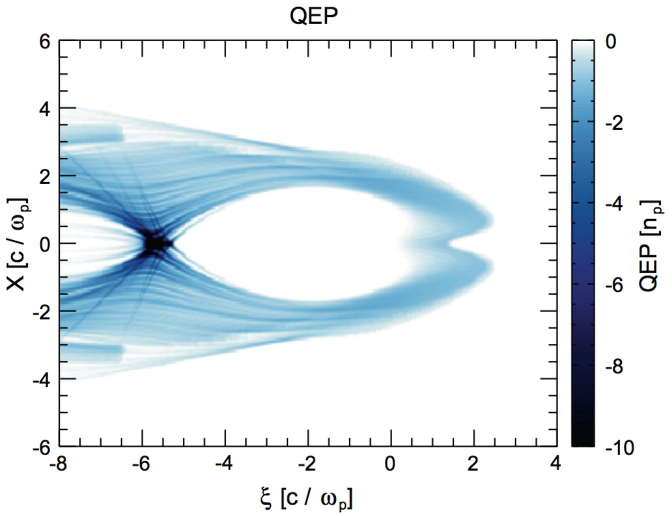
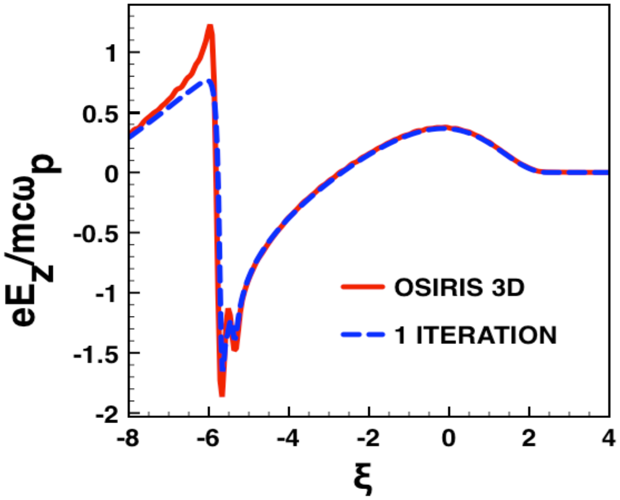
Comparison of Osiris 3D and QuickPIC

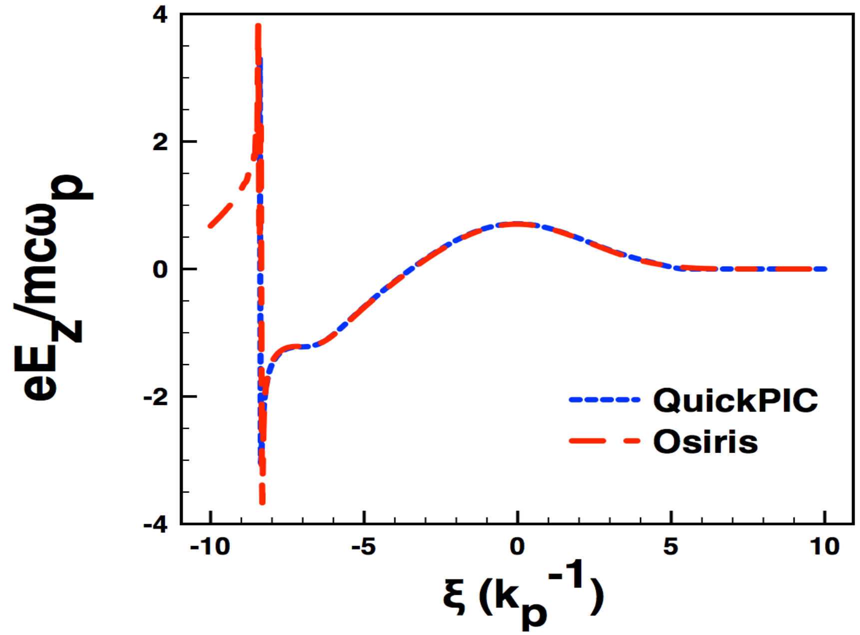
PWFA using field ionized plasma







PWFA-LC using preformed plasma



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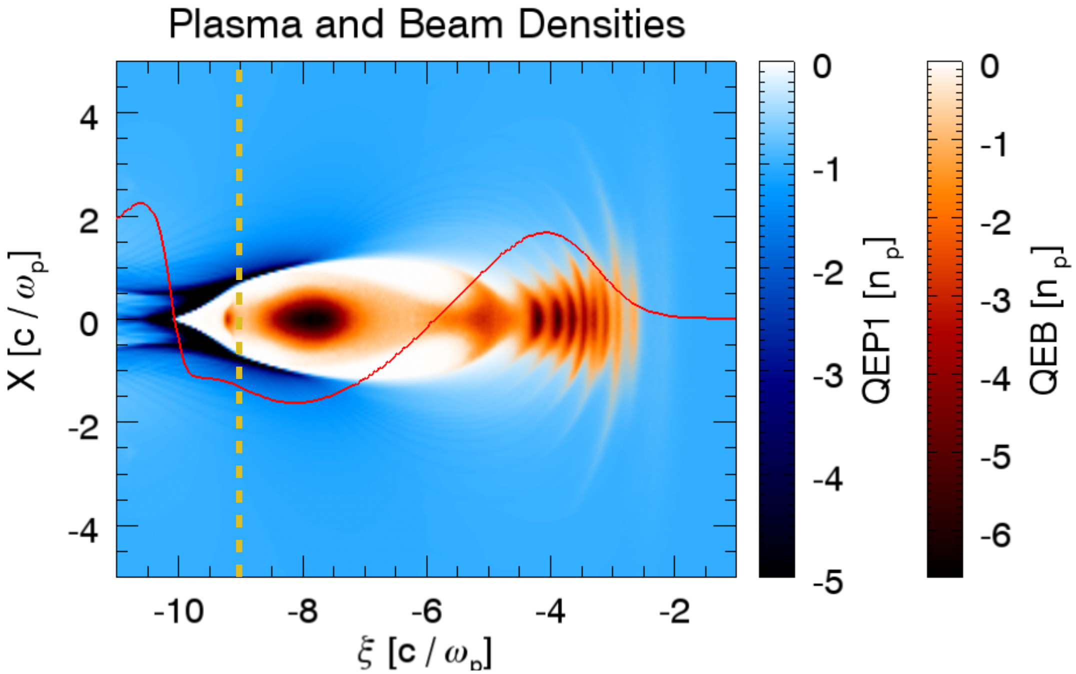
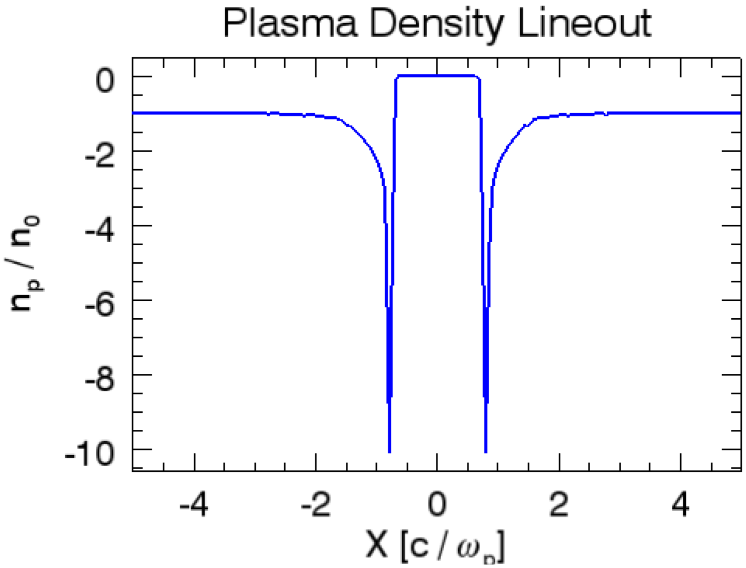
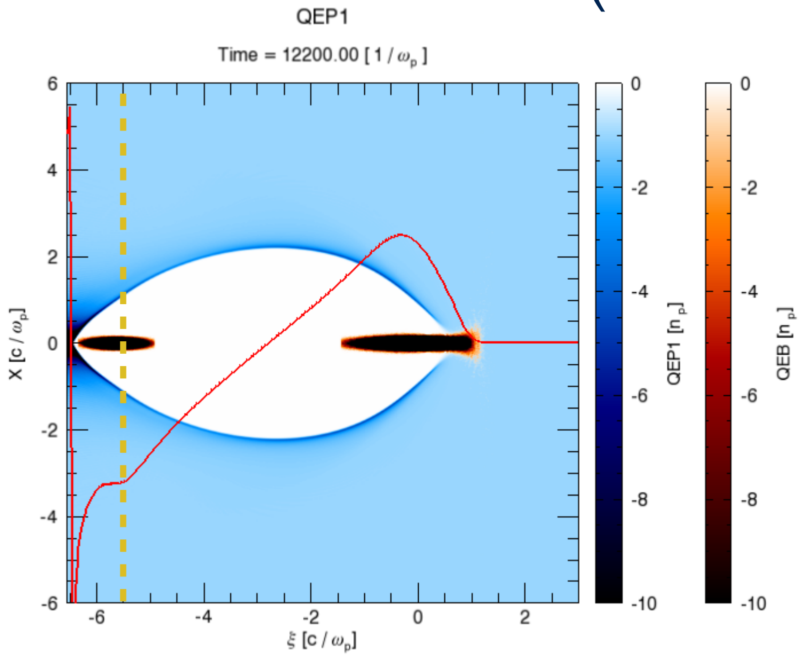
FACET & FACET II Simulations: Routine

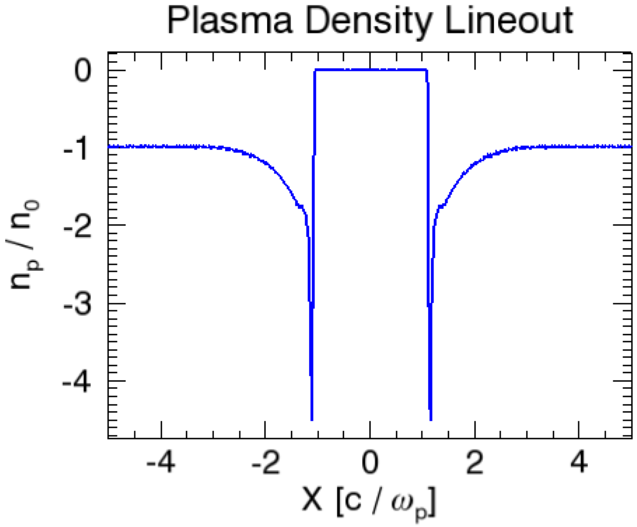
FACET Two-Bunch





FACET II Two-Bunch(Low ε_N)





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Osiris and QuickPIC:

Rough estimates for near term experiments

Total Number of Particle Pushes

	Osiris 3D (8ppc)	QuickPIC (8ppc)
FACET II	7×10^{15}	1×10^{13}
PWFA-LC	1×10^{21}	5.6×10^{16}

Total CPU-Hours: assuming no load imbalance

	Osiris 3D (8ppc)	QuickPIC (8ppc)
FACET II	5.9×10^{5}	2.8×10^{3}
PWFA-LC	8.7×10^{10}	1.5×10^{7}

Exascale is not needed for FACET II

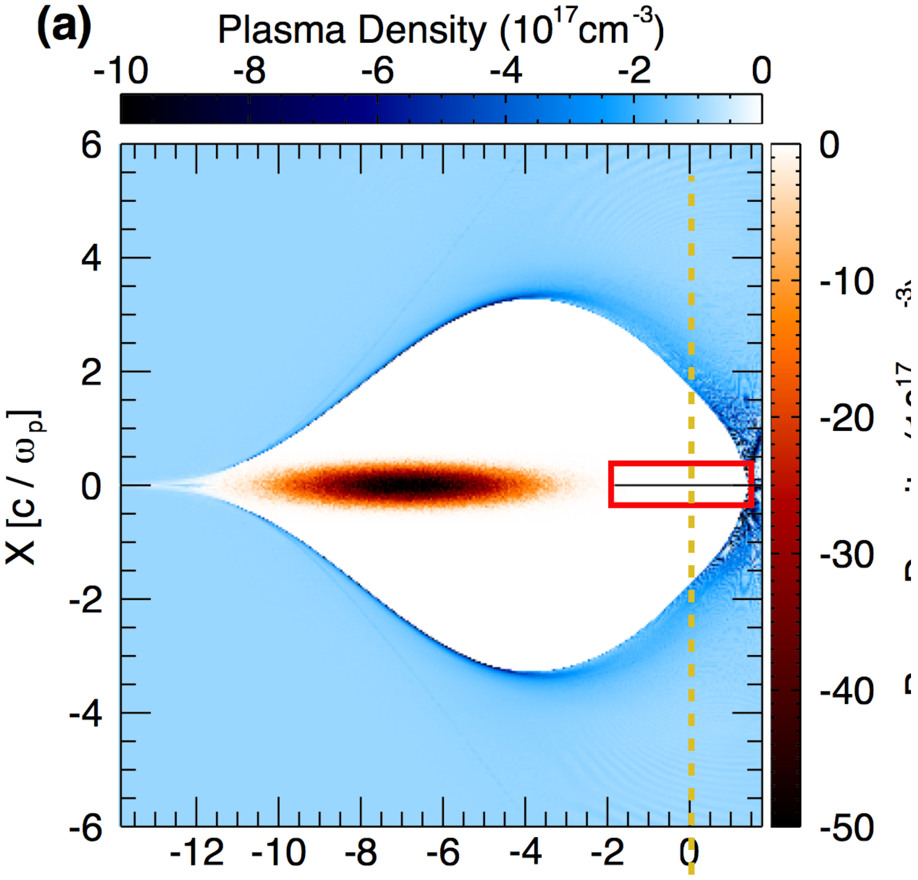
PWFA-LC Stage: Matched beams lead to ion motion

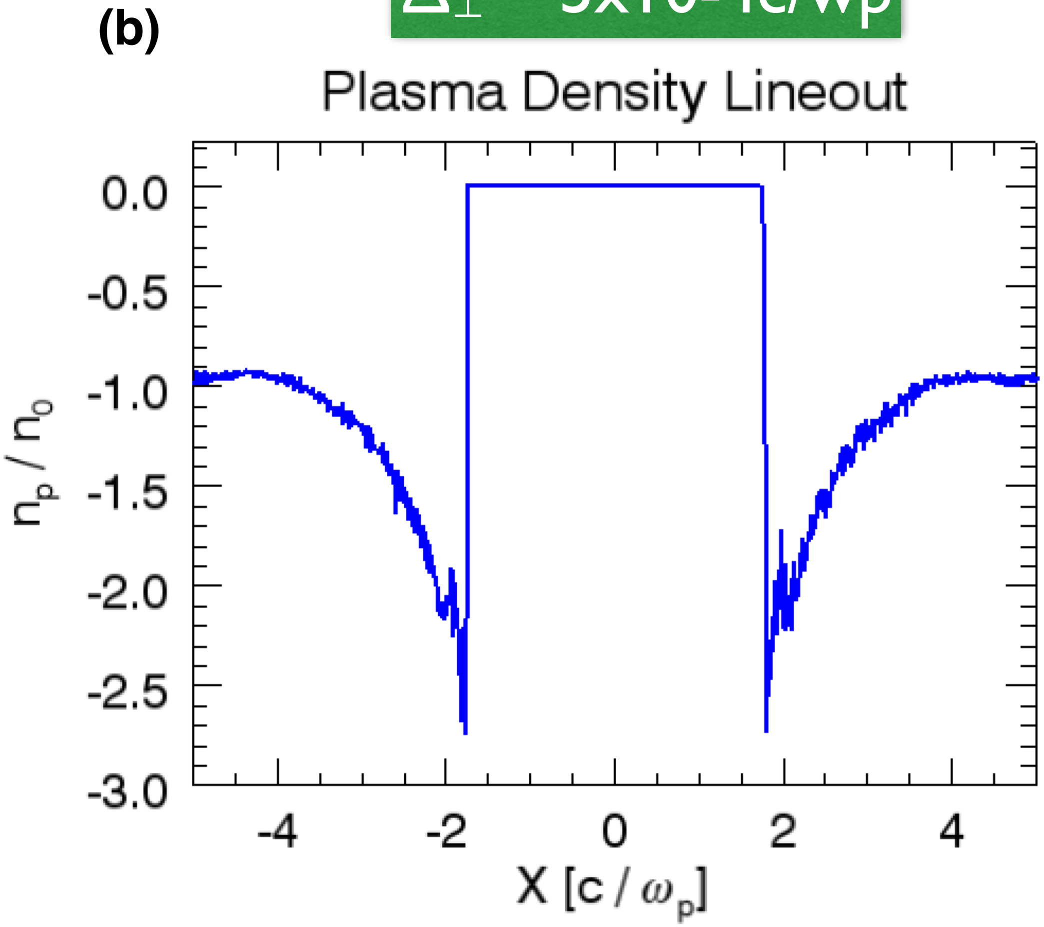
Drive Beam : σ_r = 3.45 μm , σ_z = 30.0 μm , N_1 = 3.0 x 10^{10} , ε = **100 mm·mrad**

Trailing Beam: σ_r = 0.1 μm (0.006 k_p^{-1}), σ_z = 10.0 μm, N_2 = 1.0 x 10^{10}, ε = **0.1 mm·mrad**

Distance between two beams : 115 μm; Plasma Density : 1.0 x 10^{17} cm^{-3}

$\Delta_\perp$ = 5x10-4c/wp





$$16384x16384x1024 = N_xN_yN_z$$

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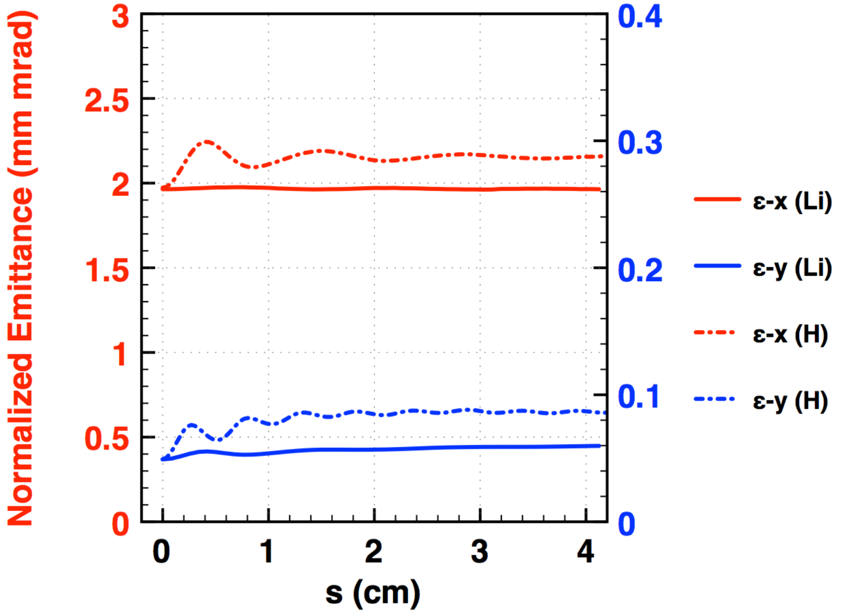
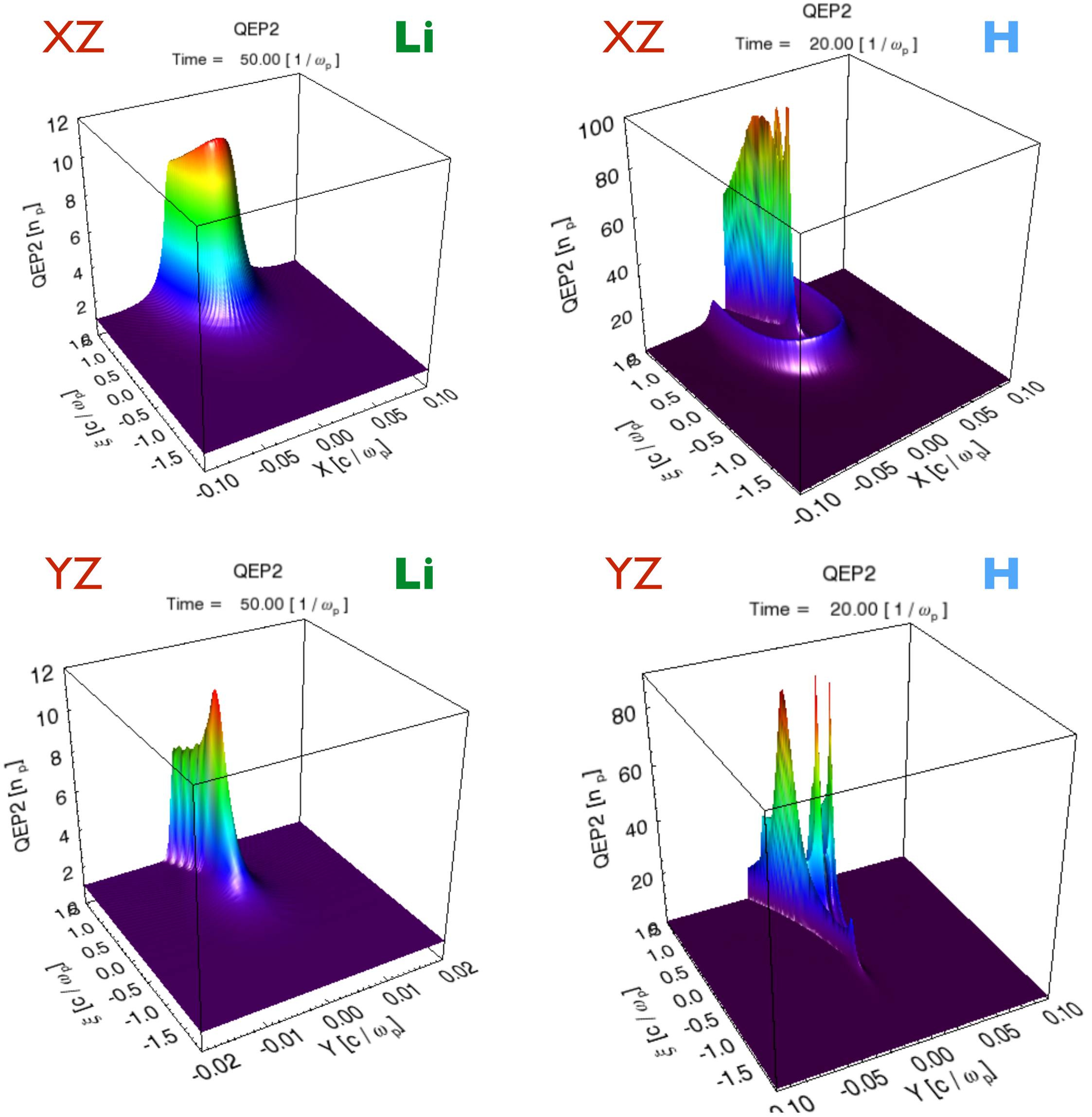
Ion Motion Driven by Asymmetric Trailing Beam

Trailing Beam: σ_z = 10.0 μm , N = 1.0 x 10^{10} ,
σ_x = 0.463 μm , ε_{Nx} = **2.0 mm·mrad** , σ_y = 0.0733 μm , ε_{Ny} = **0.05 mm·mrad**
Y = 48923.7 (25 GeV), Plasma Density : 1.0 x 10^{17} cm^{-3}

$\sigma_x / \Delta_\perp = 75.9$
$\sigma_y / \Delta_\perp = 12.0$





In Li, the emittance in x does not change, and in y direction it only increase by 20%.

In H, the emittance in x increase by 10%, and in y direction it increases by 70%.

Osiris and QuickPIC: Rough estimates

Total Number of Particle Pushes

	Osiris 3D (8ppc)	QuickPIC (8ppc)
FACET II	7 x 10^{15}	1 x 10^{13}
PWFA-LC	1 x 10^{21}	5.6 x 10^{16}

Total CPU-Hours: assuming no load imbalance

	Osiris 3D (8ppc)	QuickPIC (8ppc)
FACET II	5.9 x 10^{5}	2.8 x 10^{3}
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Exascale is not needed for FACET II

If ion motion does not lead to emittance growth then lower resolution simulations are possible

LC examples can be simulated with ~10-50 times less resources

Quasi-static is ideal for PWFA modeling if self-injection is absent: NO NCR and NCI

- Incomplete list of future algorithmic development:
  - Adaptive mesh refinement
  - Adaptive particle loading:Vary Npcell and/or particle merging and splitting
  - Dynamic load balancing
  - Adaptive 2d and 3d time steps
  - Intel Phi and GPUs
  - Radiation reaction (basic model is implemented) and QED effects based on OSIRIS 4.0 packages
  - Full 3D and quasi-3D OSIRIS are still useful for PWFA research: requires customized field solver for NCI mitigation

Challenges (Opportunities): From a talk at LBNL Workshop

- PWFA and LWFA research are now focused on collider concepts that have multiple stages (10-100) that are each ~1meter in length.
- The challenges fall into a variety of areas:
  - Driver (particle beams and/or lasers)
    - Need development and design such they have a low cost for high average power and are efficient.
    - May need to develop methods to shape them (axially, transversely, chirp them etc.)
    - There analogies but also key differences.
- Interstage transport of the particle beams (emittance preservation) and injection of new drive beams.
- Final focus and interaction point: Oide limit, disruption, beamstrahlung, QED (OSIRIS?)

In my opinion the biggest challenge remains developing self-consistent beam loading scenarios for electrons and positrons (they don't have to be the same, e.g., use electron beam to accelerate electrons in blowout regime and lasers to accelerate positrons in a hollow channel) in a single stage.

  - There are many options with decisions that are inter-related.
  - Any scenario needs to be tested self-consistently over meter distances (including the evolution of the driver).
  - It is my sense that the two scenarios being discussed most seriously are: 1. Nonlinear wakes in the blowout regime and 2. Linear wakes in a fully or nearly hollow channel.