Simulations of Plasma Wakefield Acceleration at FACET and Beyond

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Collaboration with FACET E200 Team and Special Thanks to Viktor Decyk, Frank Tsung, Chengkun Huang, and Thomas Antonsen

SciDAC
Scientific Discovery through Advanced Computing

PICKSC

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Plasma Based Accelerator Research is at the Forefront of Science

Plasma simulation has greatly impacted on PBA research.

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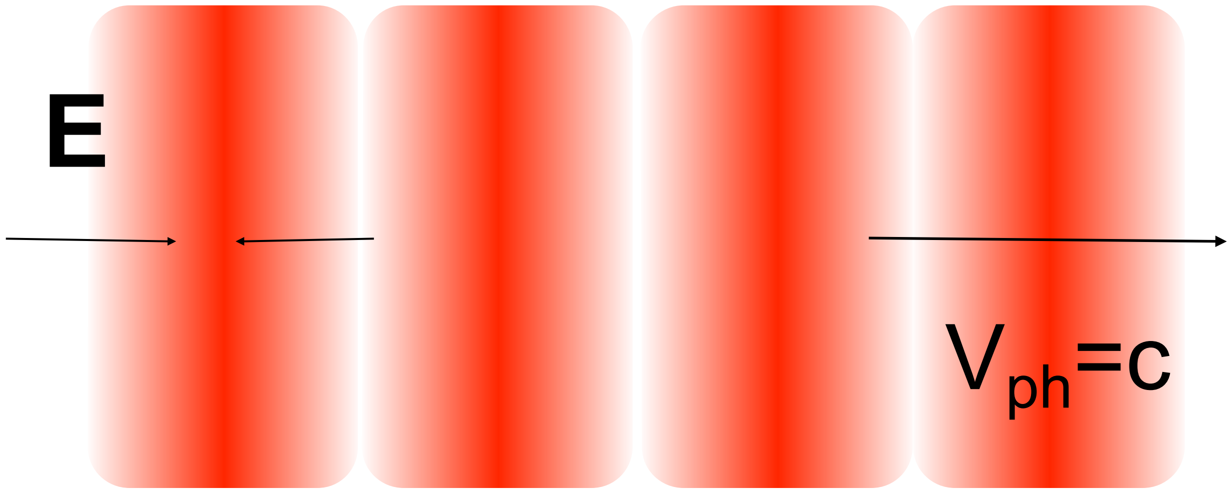
Why Plasma?



1-D plasma density wave

Gauss' Law

$$\nabla \bullet E \sim ik_p E = -4\pi e n_1$$

$$k_p = \omega_p / V_{ph} \approx \omega_p / c$$

$$n_1 \sim n_o$$

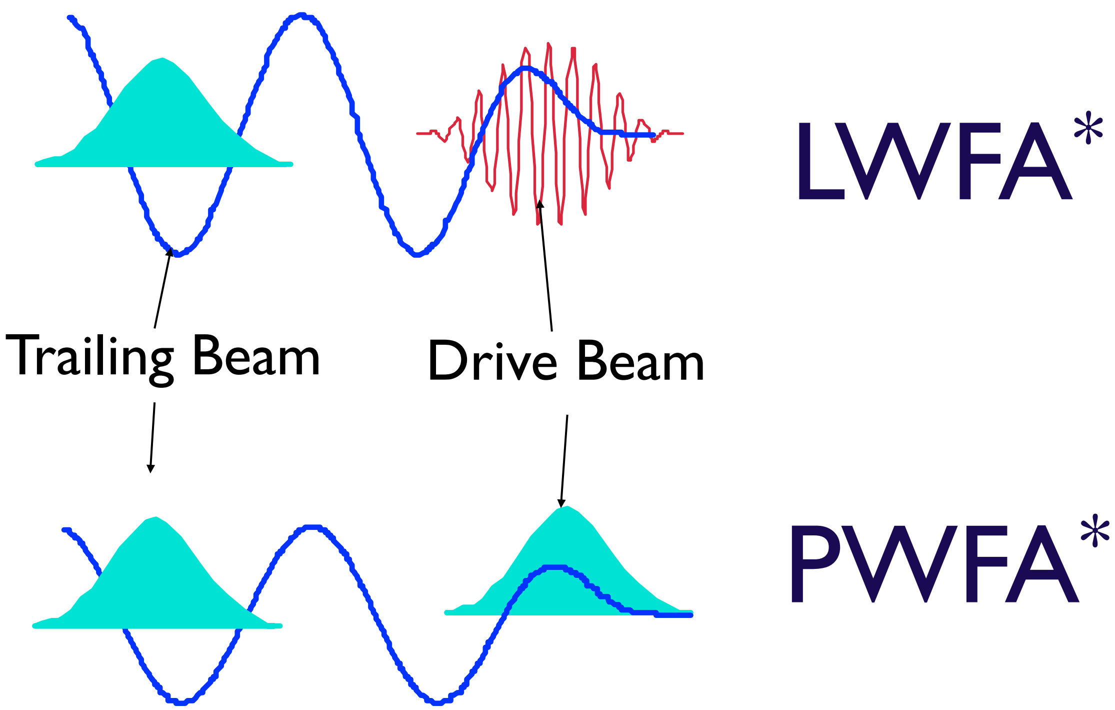
$$\Rightarrow eE \sim 4\pi e n_o e^2 c / \omega_p = mc\omega_p$$

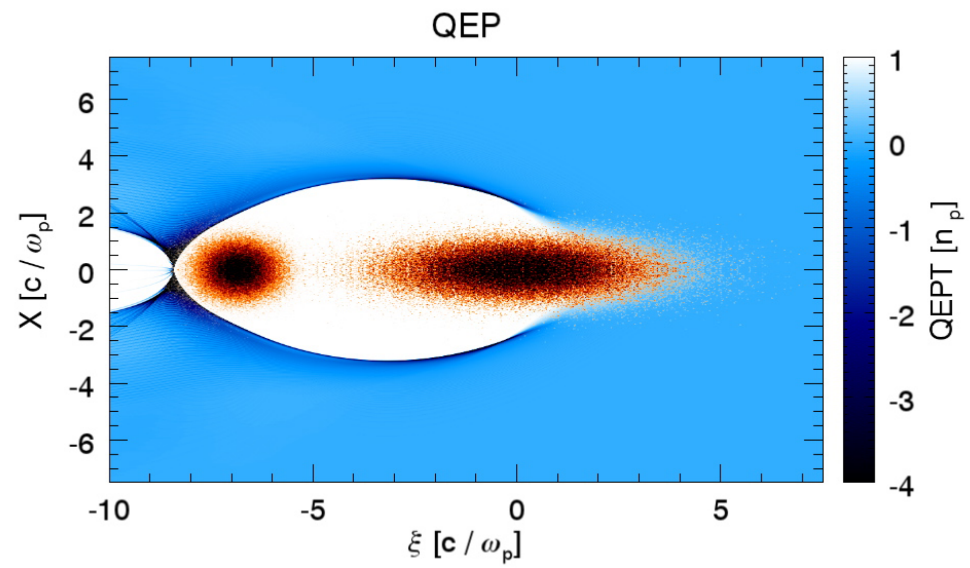
$$or \quad eE \sim \sqrt{\frac{n_o}{10^{16} cm^{-3}}} 10\, GeV/m$$

~1000 times larger than the conventional accelerators

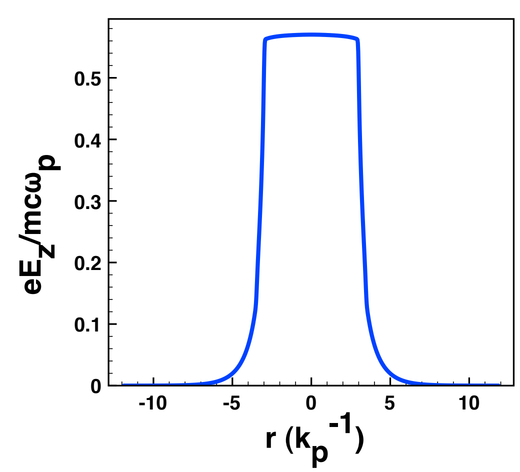
How to Make a Plasma Wake Field?

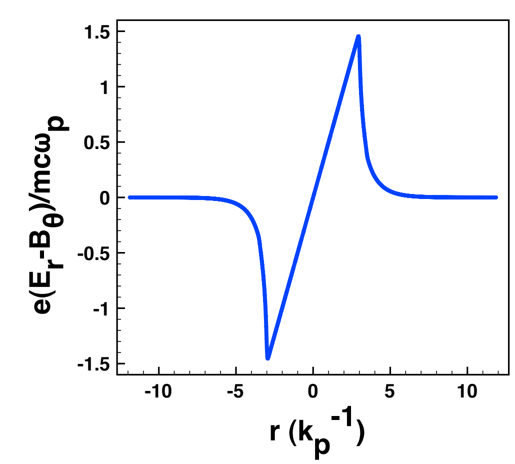
Nonlinear Process





Blow-out Regime[1,2]





- Wake: phase velocity = driver velocity (V_g or V_{beam})

LWFA: Tajima and Dawson 1979
PWFA: Chen, Dawson et al., 1985

***J. B. Rosenzweig, et. al., Phys. Rev. A 44, R6189 (1991)**
***W. Lu, et. al., Phys. Rev. Lett. 96, 165002 (2006)**

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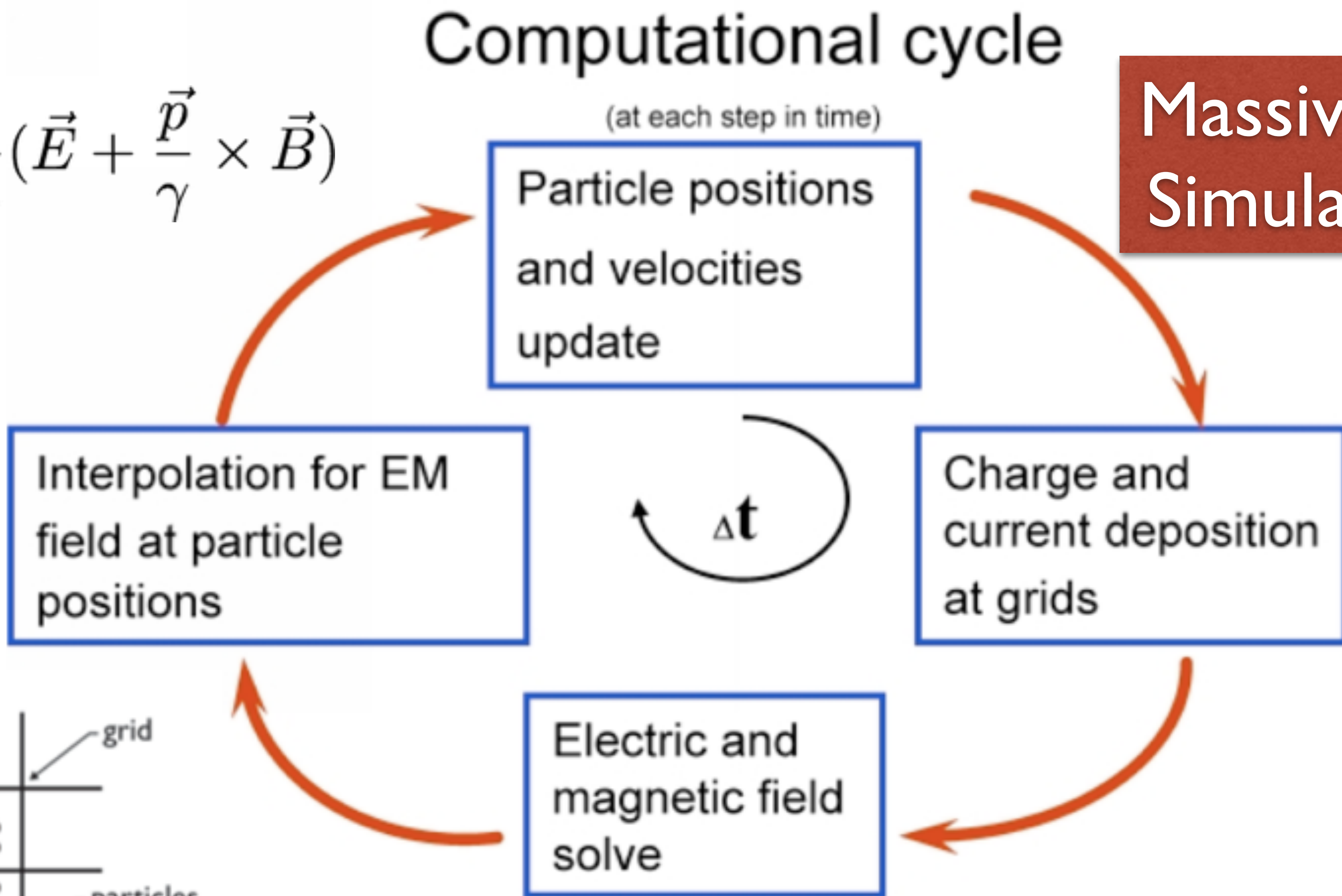
How to Simulate Plasma Based Accelerator?

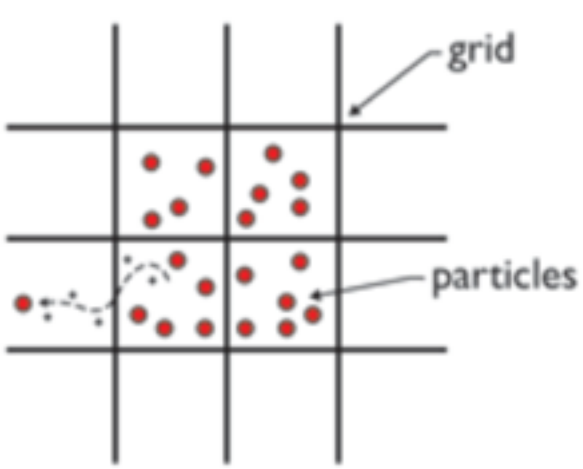
Particle-In-Cell Simulation

$$\frac{d\vec{p}}{dt} = \frac{q}{m}\left(\vec{E} + \frac{\vec{p}}{\gamma} \times \vec{B}\right)$$



Massively Parallel Simulation Code

$$\begin{cases} \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{J} \\ \nabla \cdot \vec{E} = \rho \\ \nabla \cdot \vec{B} = 0 \end{cases}$$



Spatial Domain

* J. Dawson, Review of Modern Physics, Vol. 55, No. 2, April 1983.
* C. K. Birdsall, L.A. Bruce, Plasma physics via computer simulations. New York: McGraw-Hill, 1985.

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Simulation of PBA

Beam Particles: 10^{10}

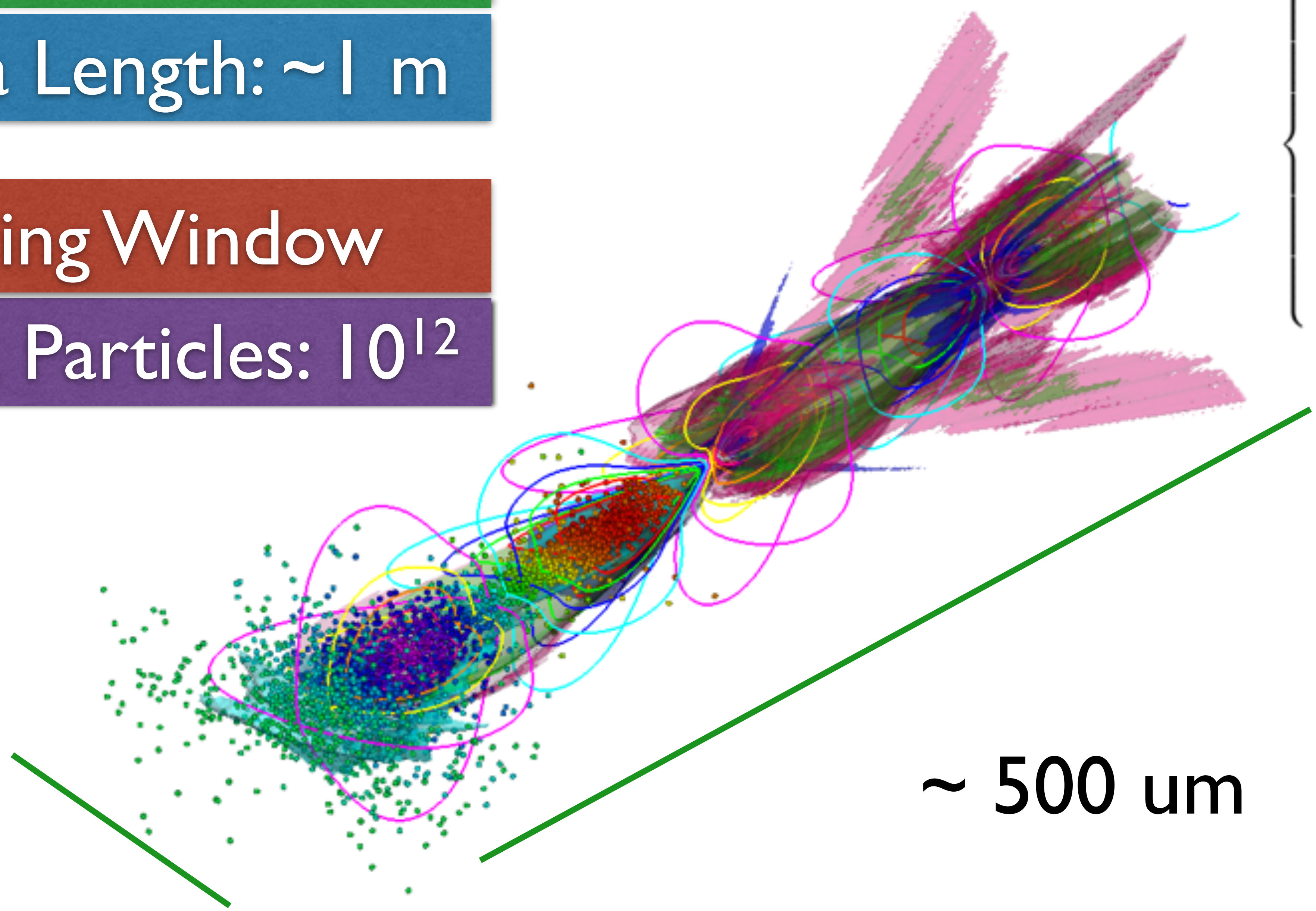
Plasma Length: ~1 m

Moving Window

Plasma Particles: 10^{12}

Maxwell's Eqns

$$\begin{cases} \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} = \dfrac{\partial \vec{E}}{\partial t} + \vec{J} \\ \nabla \cdot \vec{E} = \rho \\ \nabla \cdot \vec{B} = 0 \end{cases}$$



~ 500 um

~ 500 um

All particles move self-consistently

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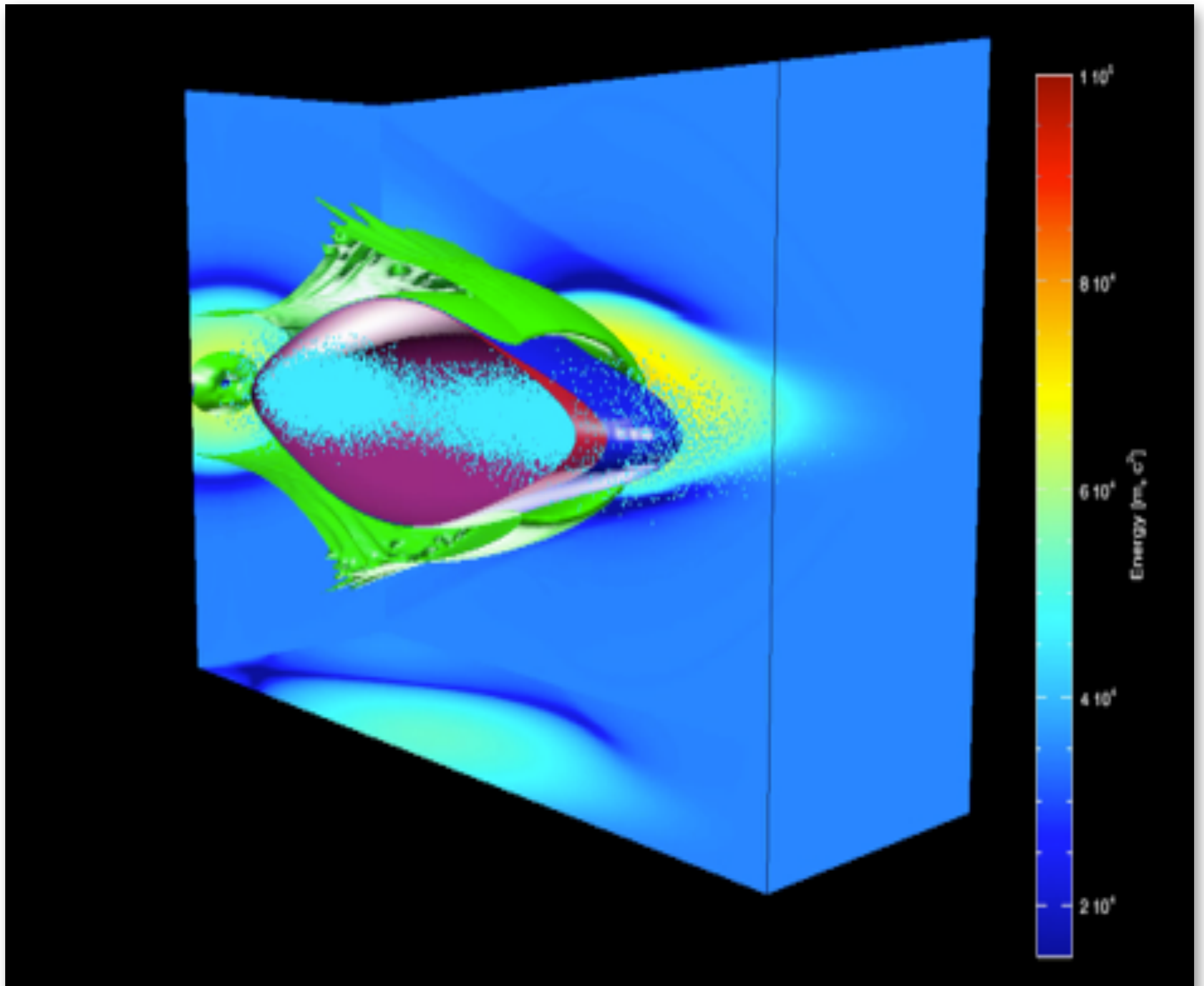
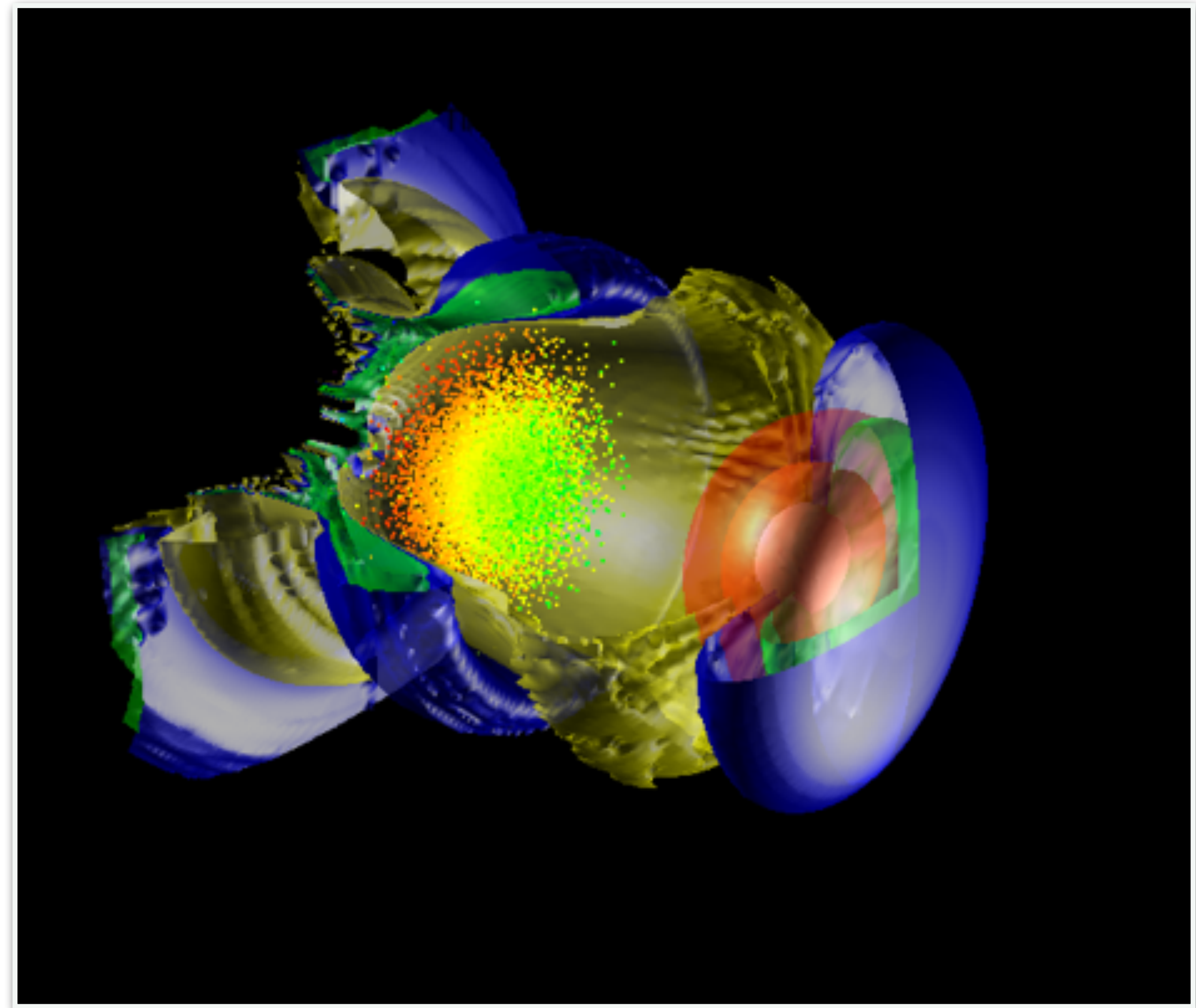
Simulation of PBA



QuickPIC simulation of two-bunch electron-driven PWFA.

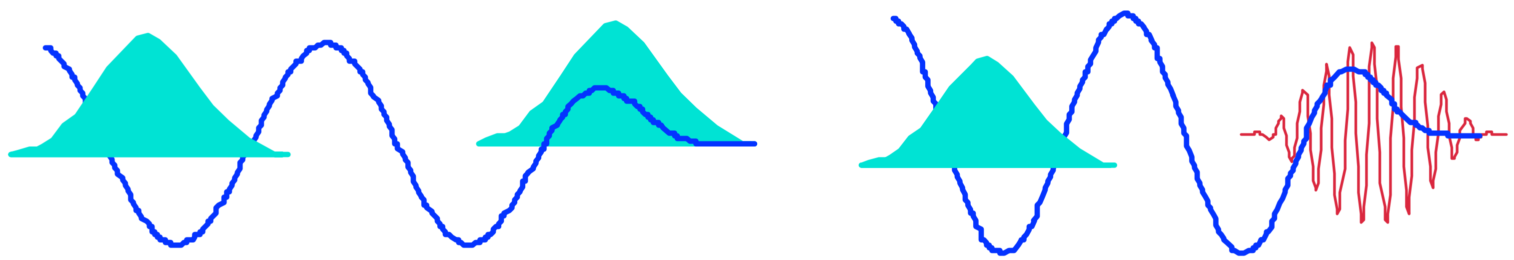


QuickPIC simulation of LWFA with a beam load.

The drive beam evolves in a much longer time scale than the plasma particles.

QuickPIC

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



Full PIC(Osiris): $dt \sim 0.05\omega_p^{-1}$ Courant Condition

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

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

1000 Times Faster

[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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Math Behind QuickPIC

(x, y, z; t)

↓

(x, y, ξ=ct-z, s=z)

↓

$\partial_s << \partial_\xi$

↓

Plasma: (x, y; ξ)

↓

Beam: (x, y, ξ, s)

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

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

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

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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.

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

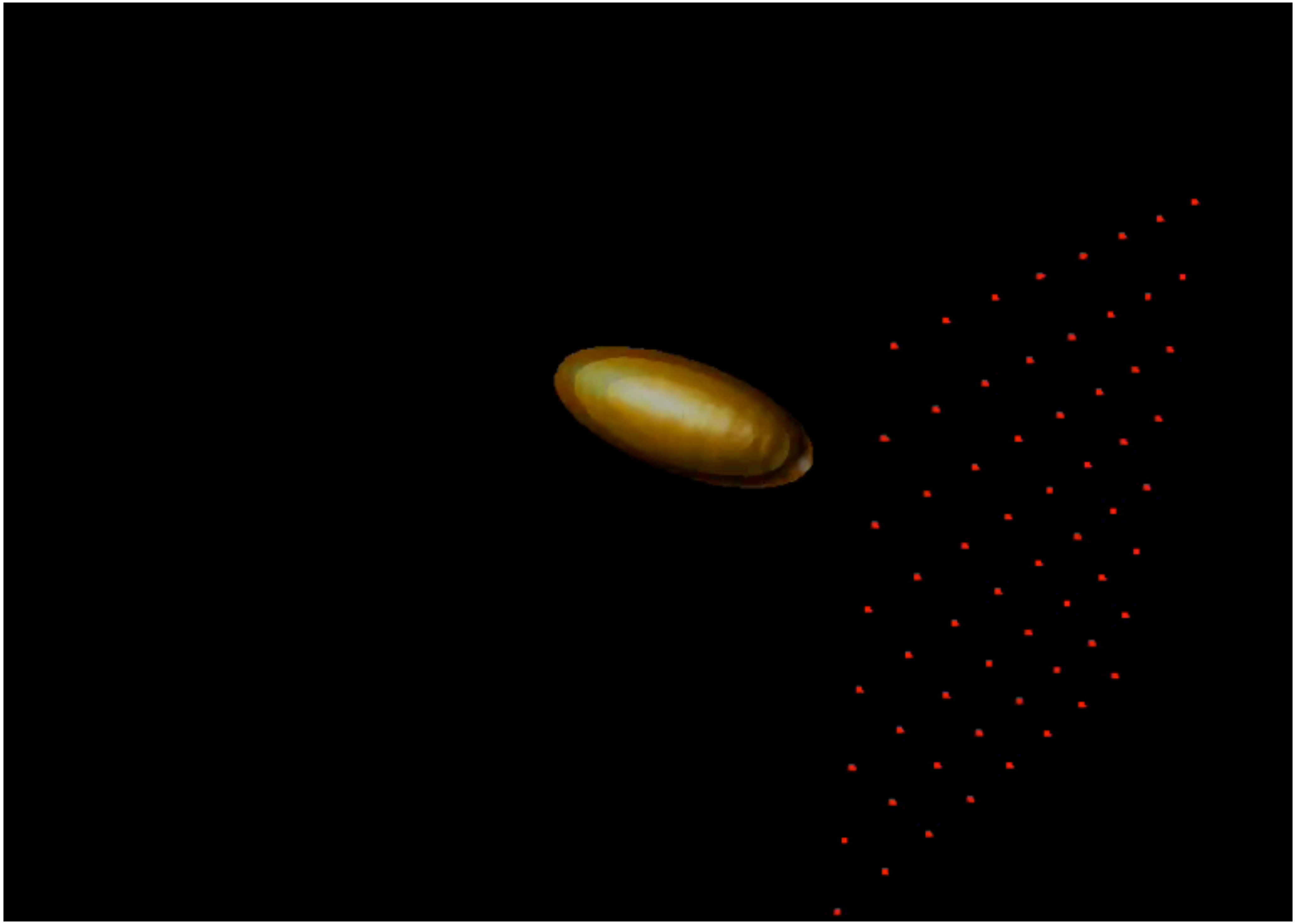
$$\frac{\partial}{\partial \xi} \int (\rho - J_z) d\vec{x}_\perp + \int \nabla_\perp \cdot \vec{J}_\perp d\vec{x}_\perp = 0$$

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

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

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

How QuickPIC Works



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

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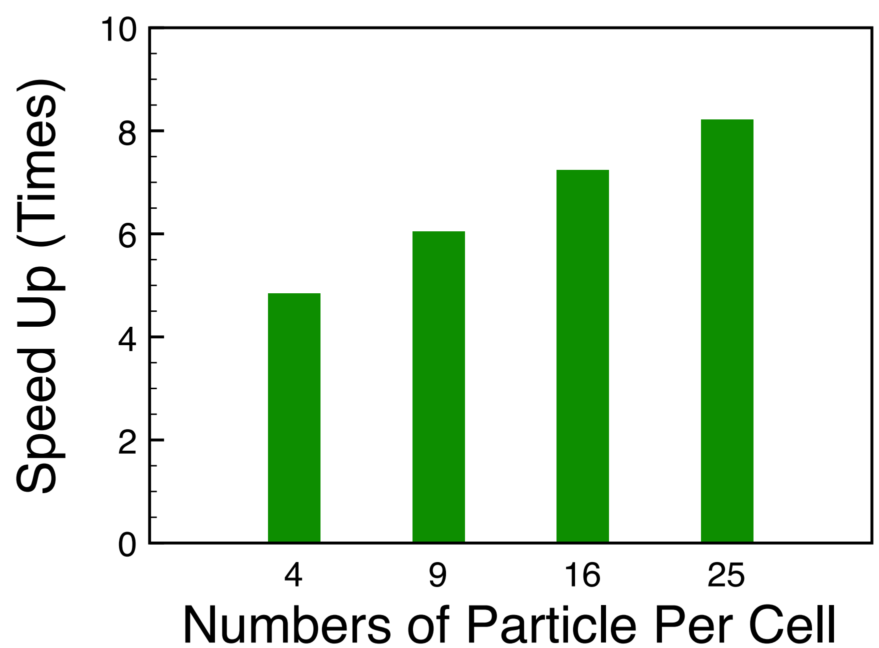
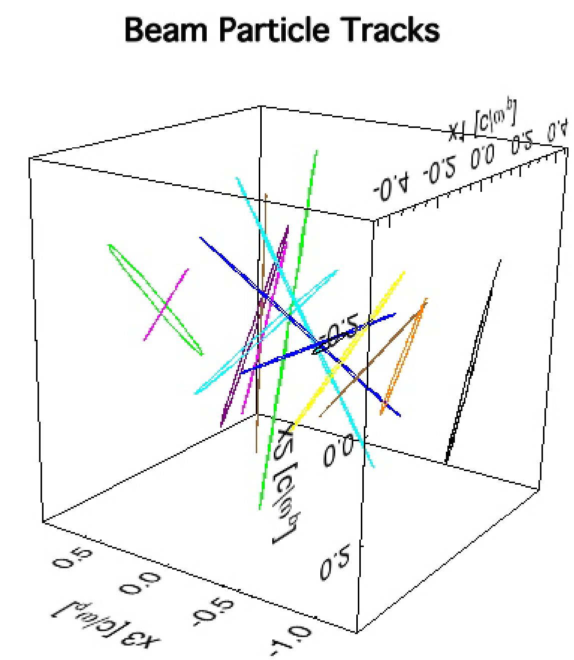
Current Status of QuickPIC

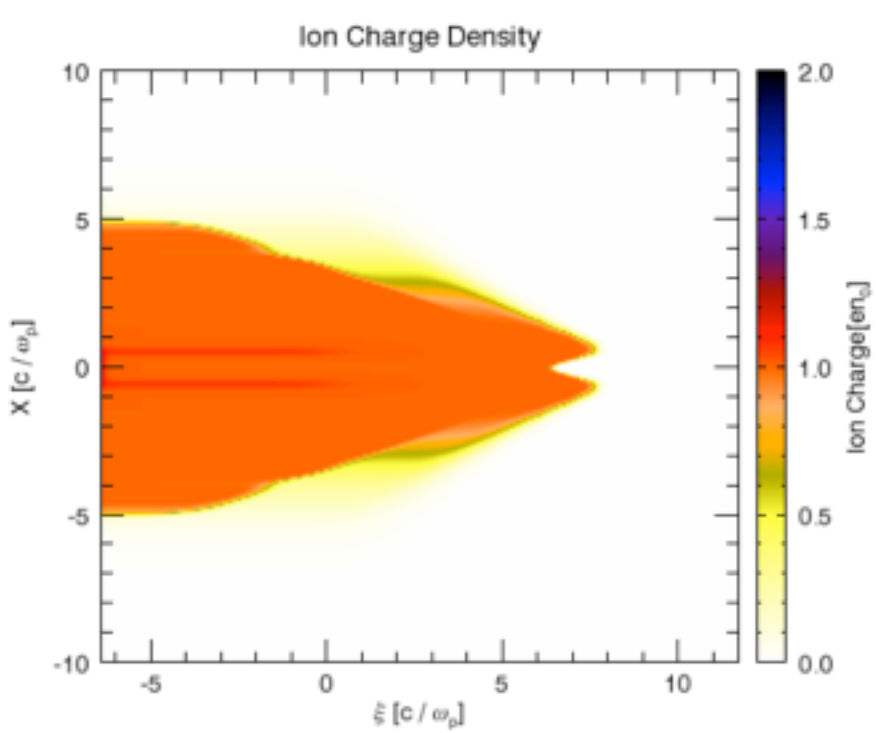
1. Improved Iteration Loop



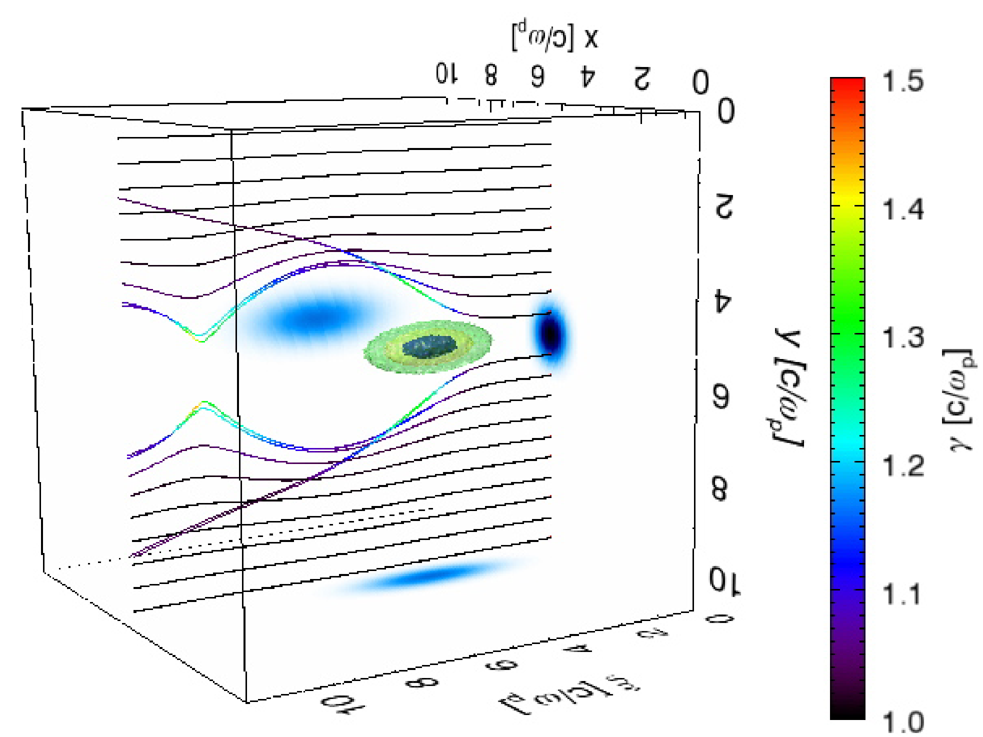
3. Beam Particle Tracking



2. Multiple Field Ionization Module



4. Plasma Particle Tracking



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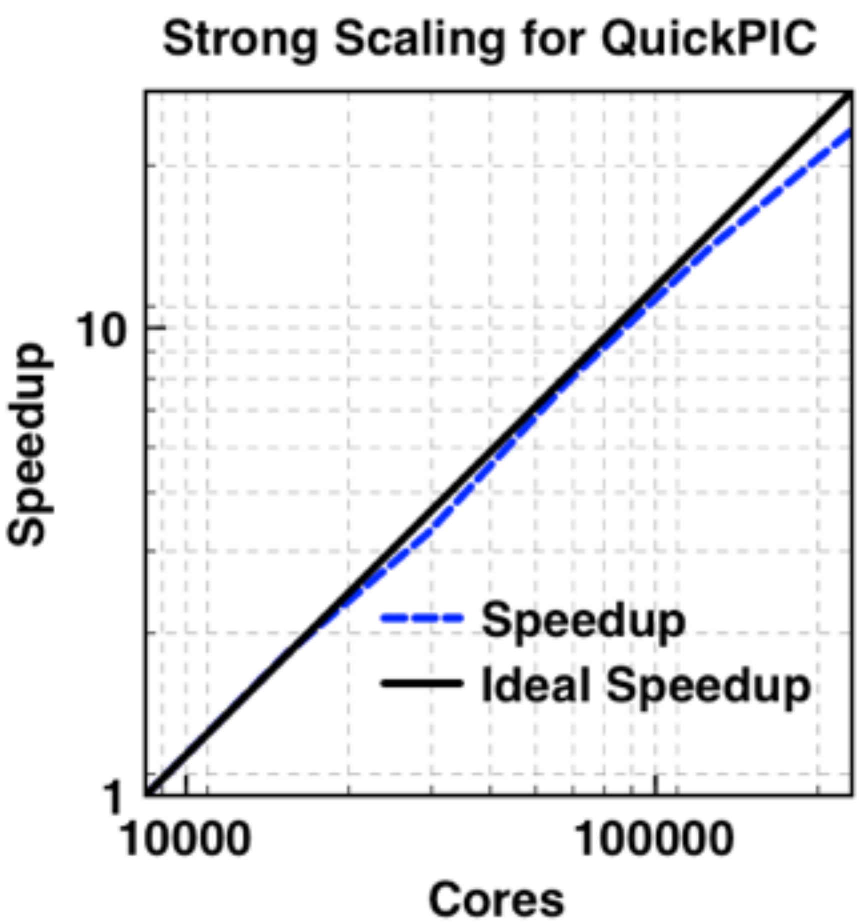
Current Status of QuickPIC



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

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Current Status of QuickPIC

On-Going Work:
MPI+OpenMP
GPU Acceleration
Python version
Open Source Project

SUPPORT

PICKSC

UPIC 2.0
SKELETON CODES

*http://picksc.idre.ucla.edu

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Research Using QuickPIC

Many research papers use QuickPIC as the simulation tool.

2007
FFTB

2014
FACET

2015
FACET

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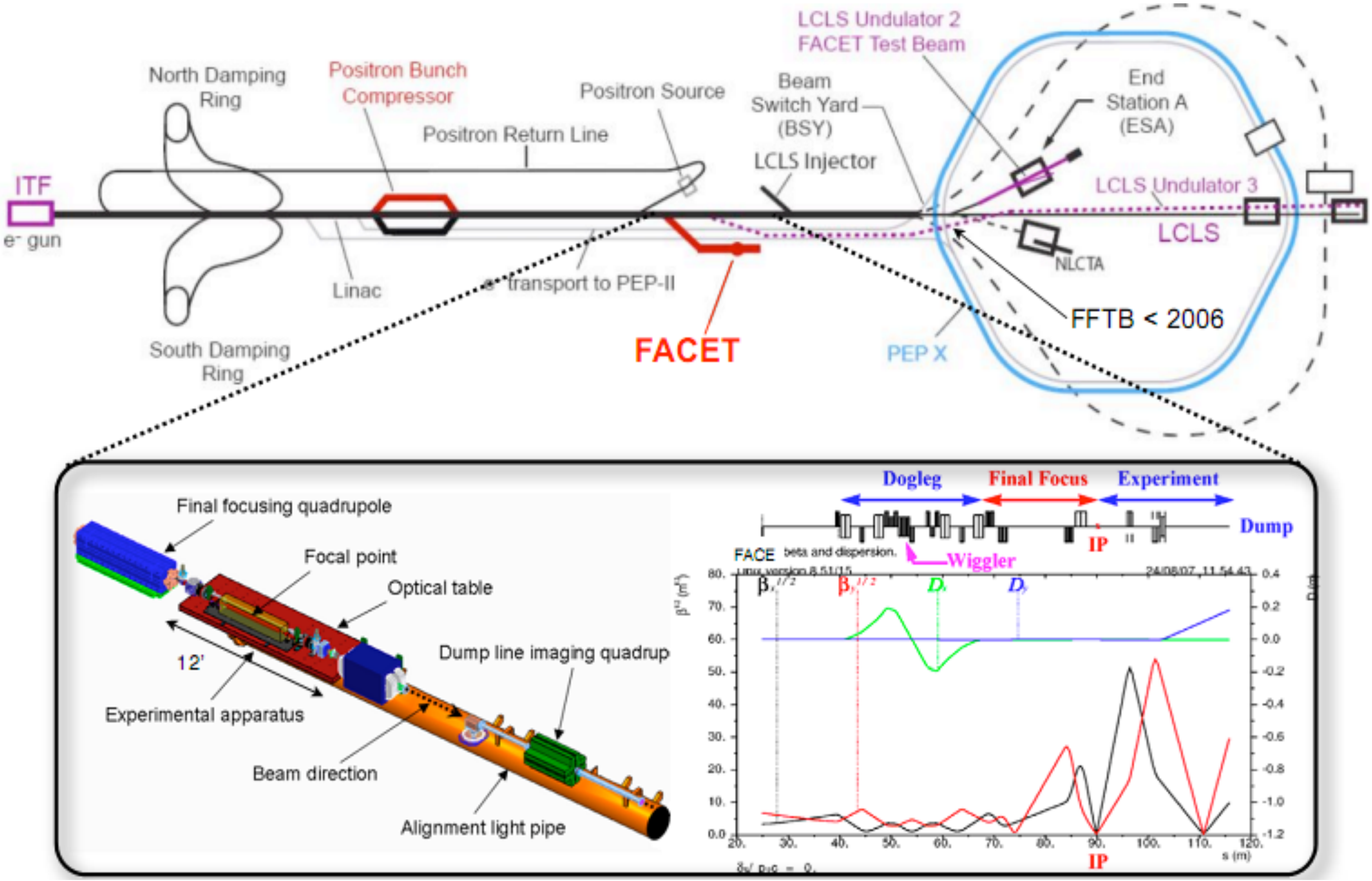
FACET

Facility for Advanced Accelerator Experimental Tests



FACET provides high-energy, high peak current e^- & e^+ beams for PWFA experiments at SLAC.

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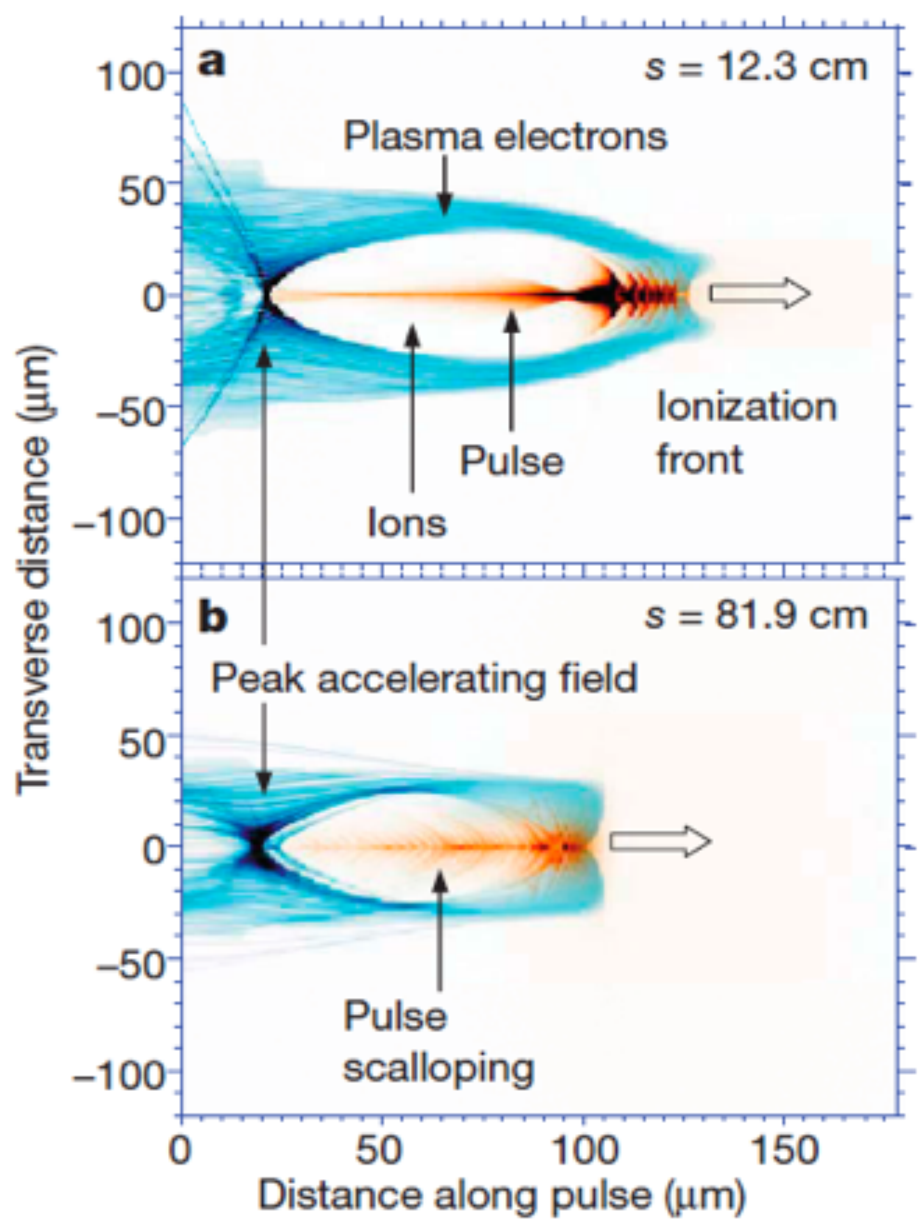
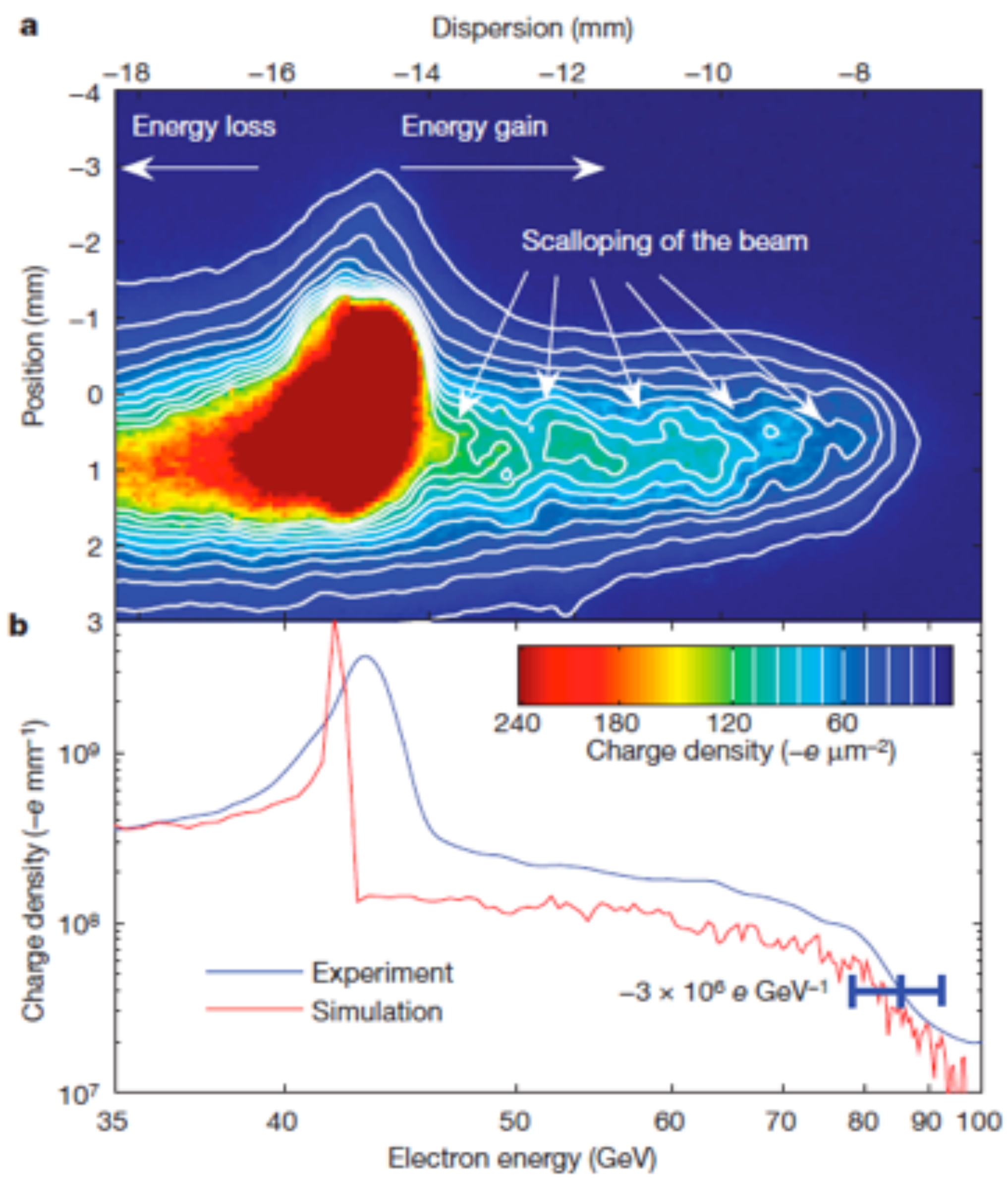
Demonstrate Ultra-High Gradient Acceleration Over 1Meter Long

Plasma Wake Field Acceleration





* Ian Blumenfeld, et. al., Nature 445, 741 (2007)

Former Experiments on FFTB at SLAC demonstrated a more than 50 GeV/m accelerating gradient can be produced in PWFA over a meter long scale.

Demonstrate High Energy Transfer From a Drive Bunch to a Trailing Bunch: Design Experiment

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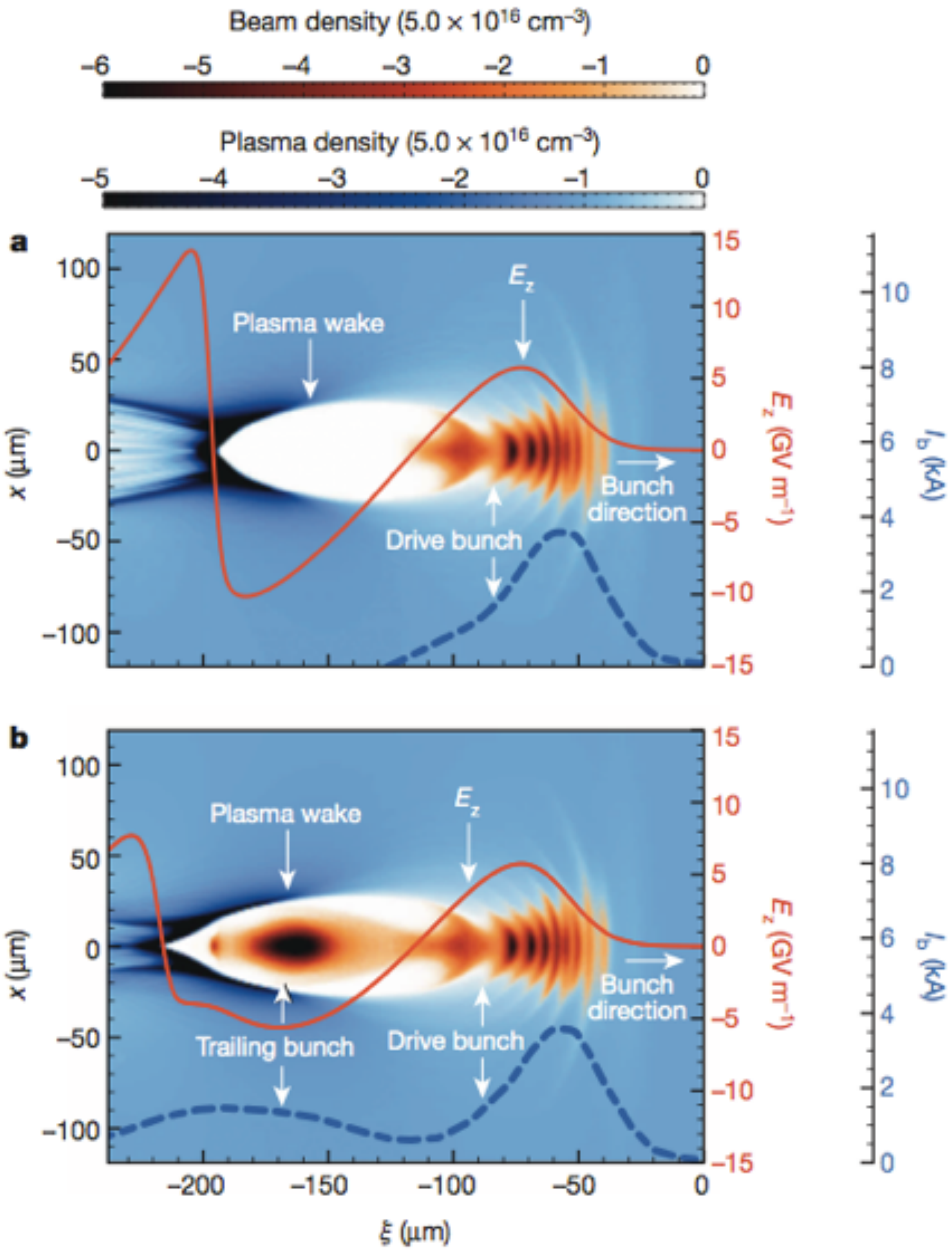

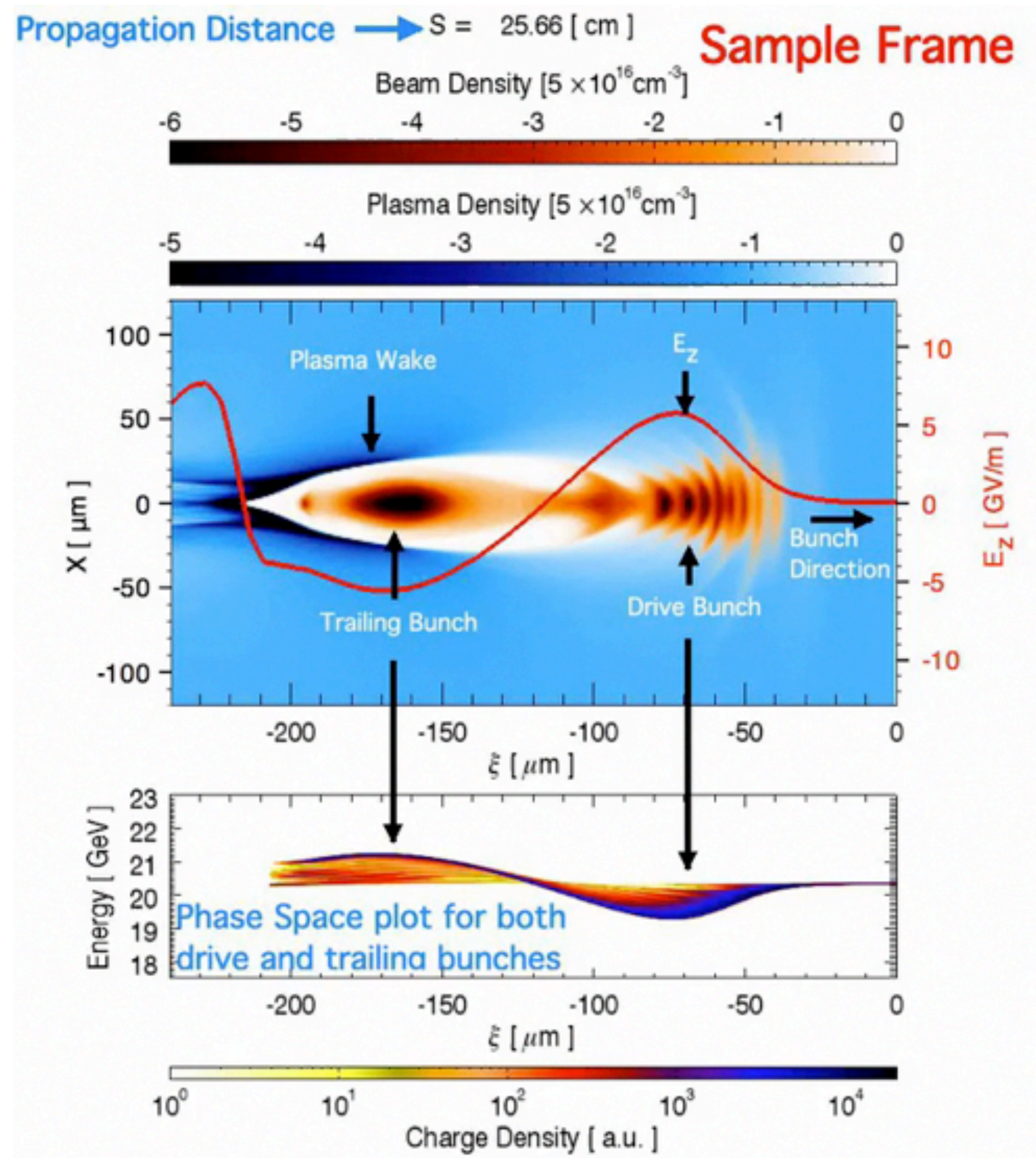

*T. Katsouleas et al., Part. Accel (1987)

**W. Lu, PRL(2006) and M. Tzoufras, PRL (2008)

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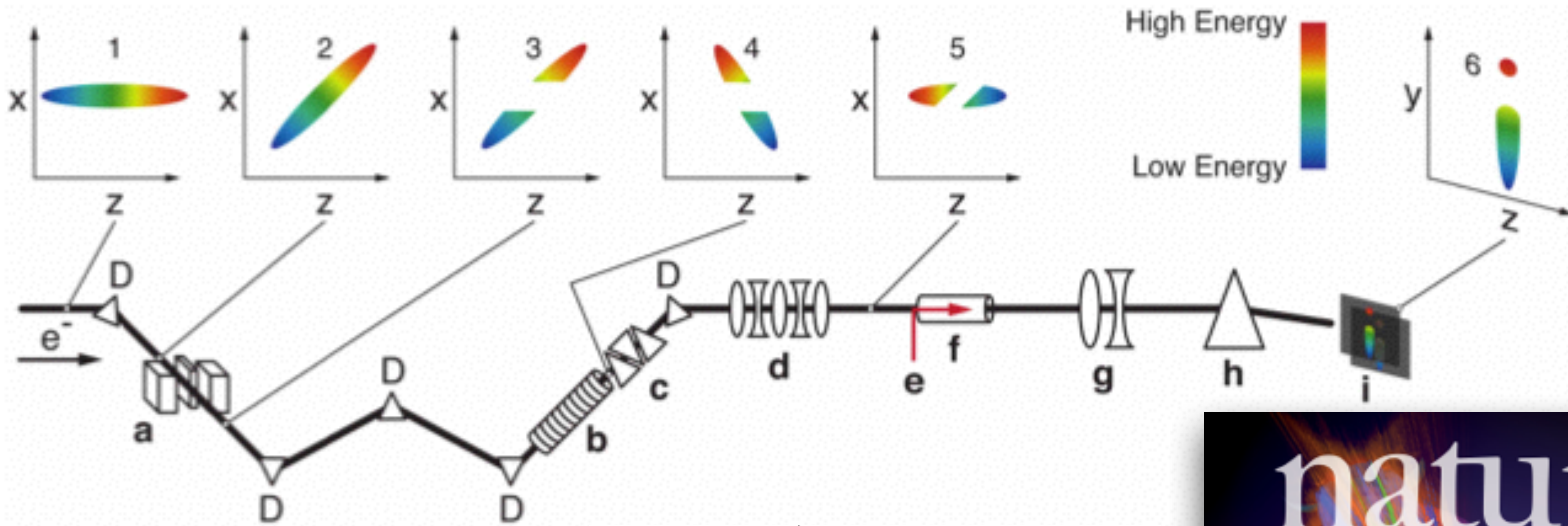
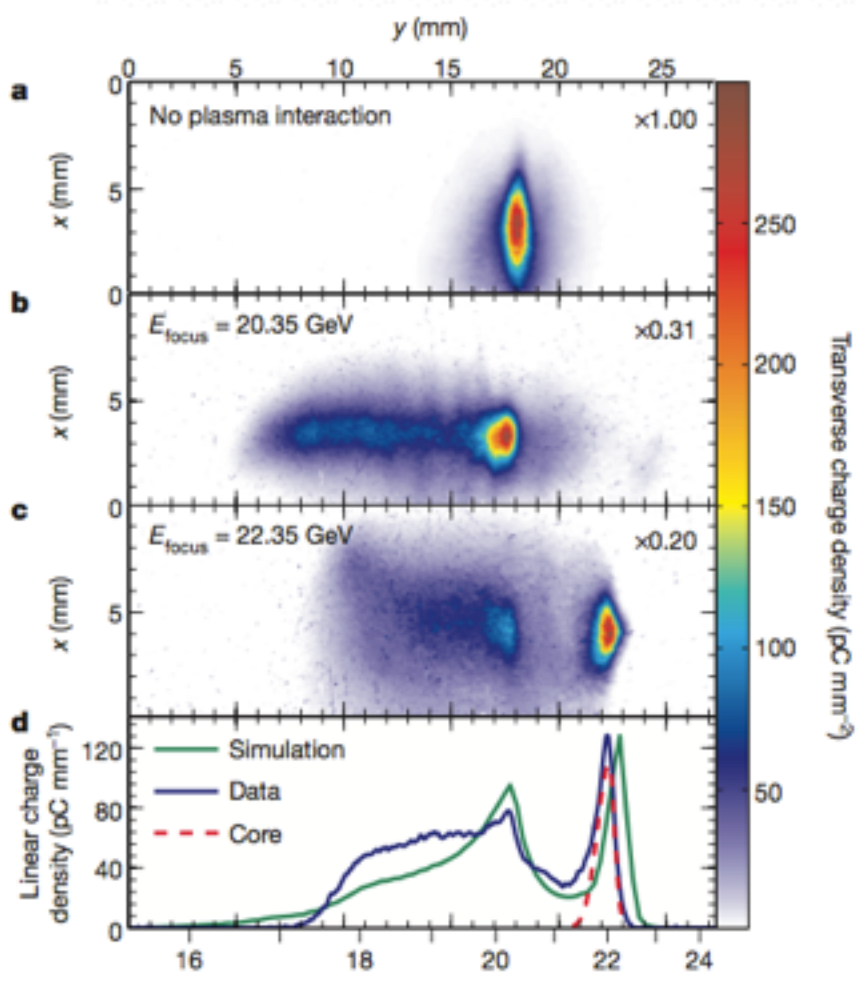
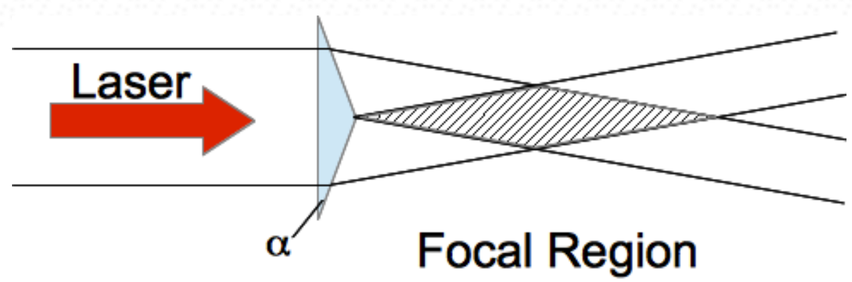
Two-Bunch e⁻ PWFA





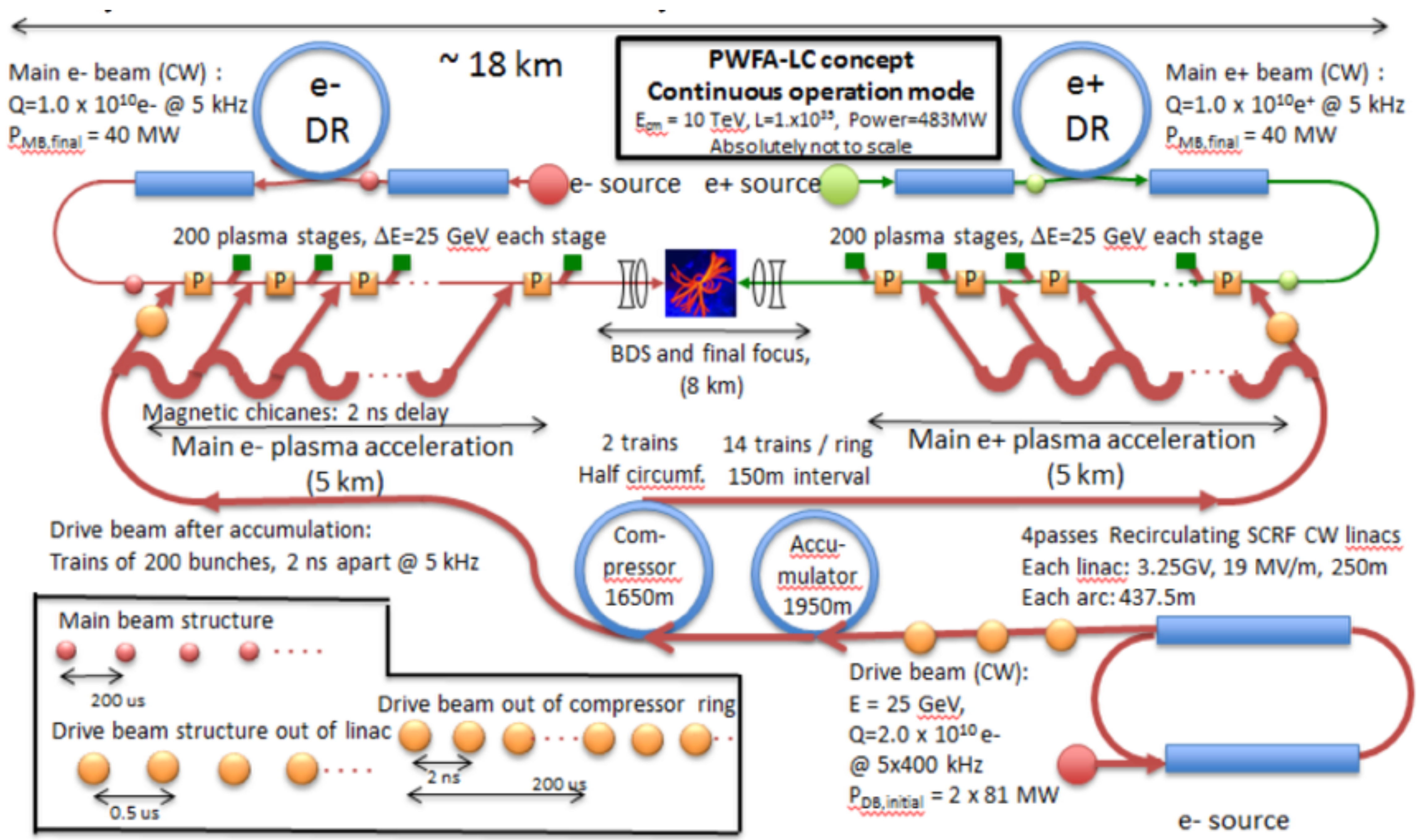


Head Erosion
For FACET BEAM

*W. An et. al, 16 101301, PRSTAB (2013)

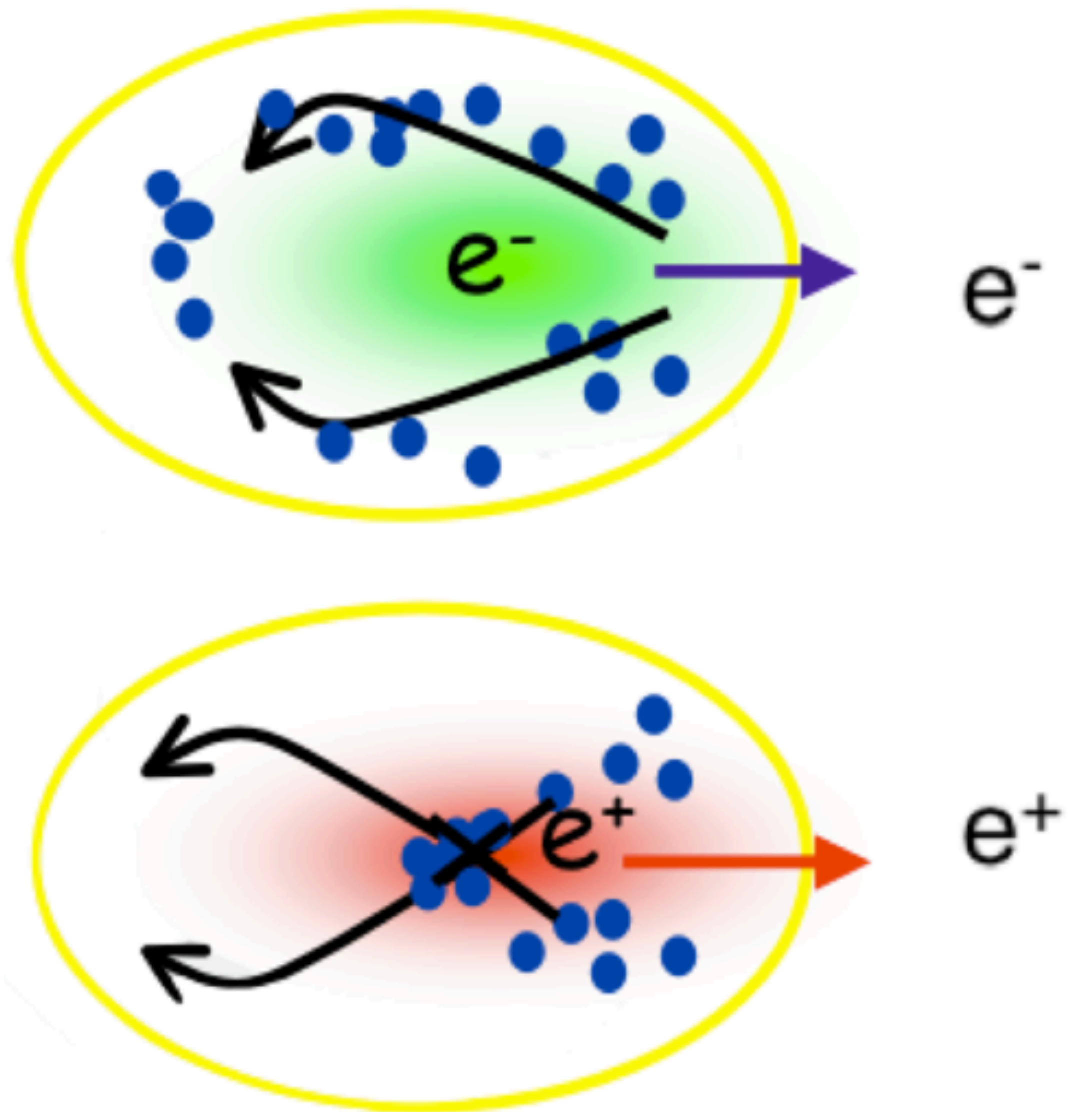
*M. Litos et. al, 515, 92 Nature (2014)

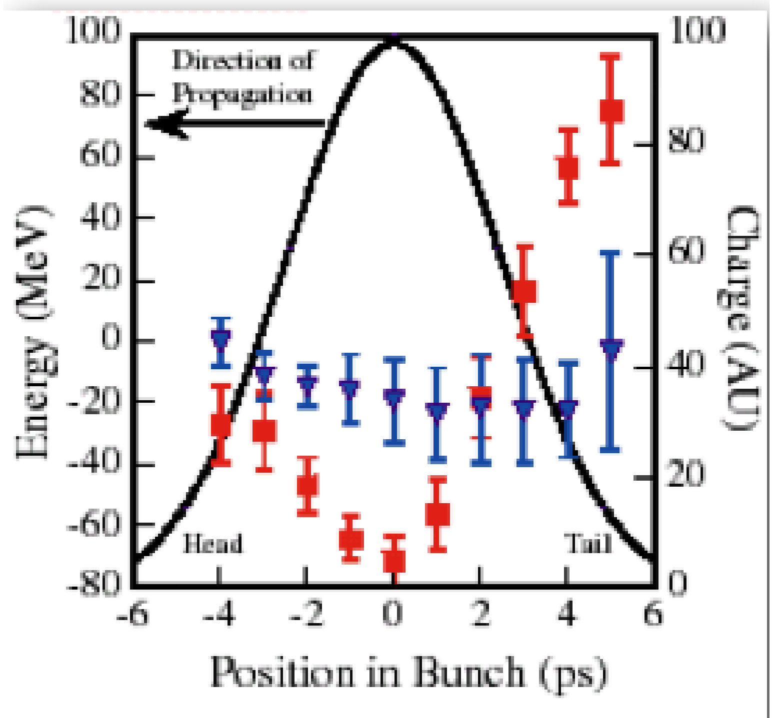
A Collider Requires Positrons



* E. Adli et al., IPAC 2014

The e^+-Plasma Interaction Differs from the e^--Plasma Interaction

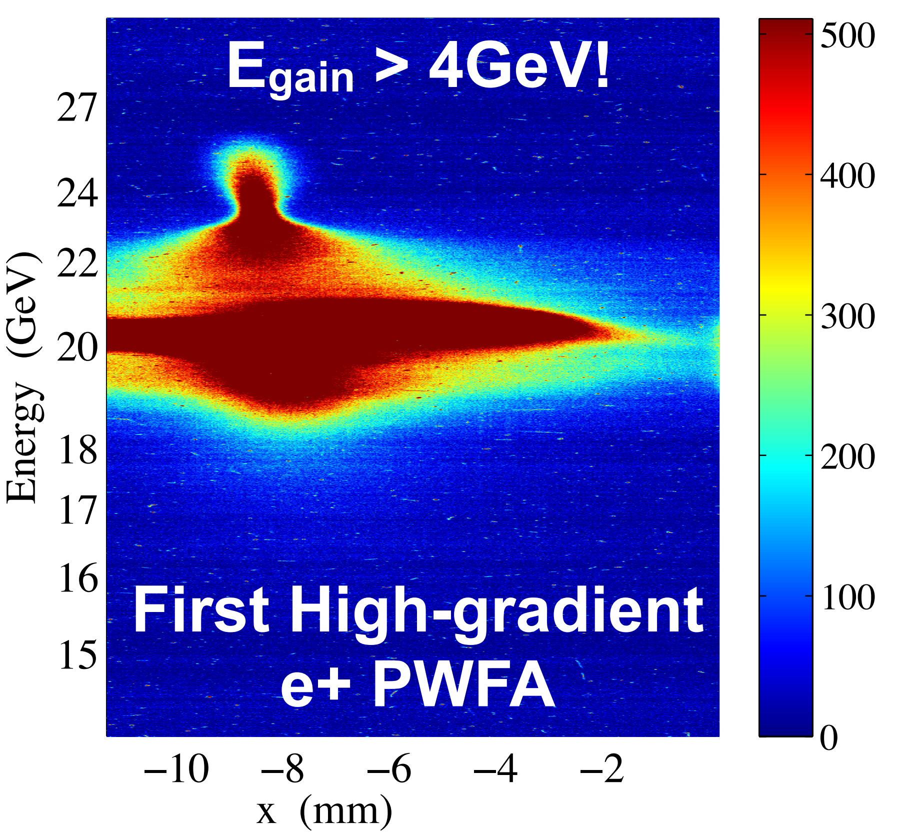




Phys. Rev. Lett. 90, 214801 (2003)

FFTB

Profile Monitor CMOS:LI20:3490 25–Jun–2014 00:47:49



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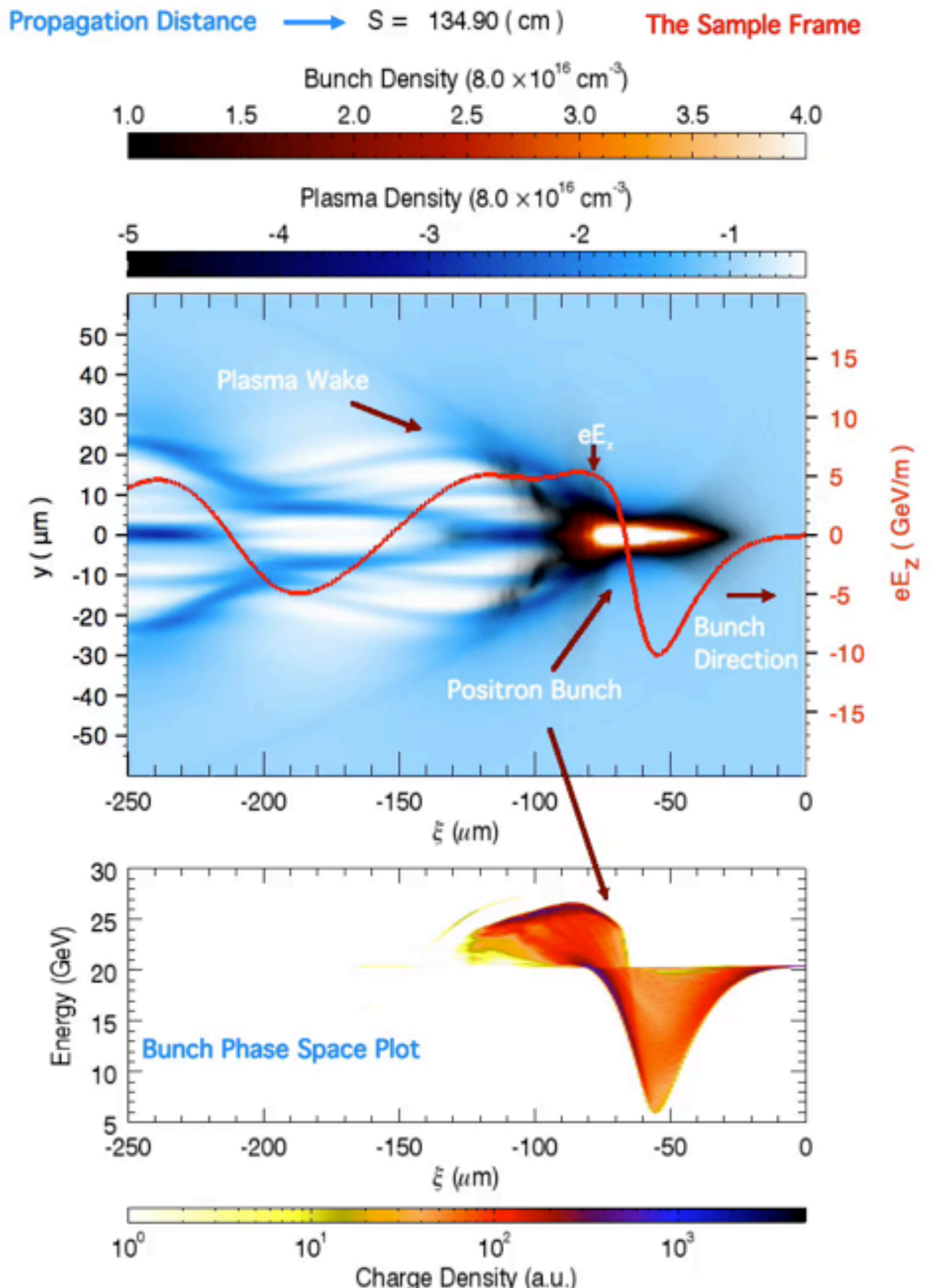
Generation of Mono-Energetic e^+ with High Gradient

Drive Beam: σ_r = 70.0 μm , σ_z = 30.0 μm , N_2 =1.4 x 10^{10}, ε_N =(50,200) mm·mrad

Plasma Density: 8.0 x 10^{16} cm^{-3} (1.5 meters long)

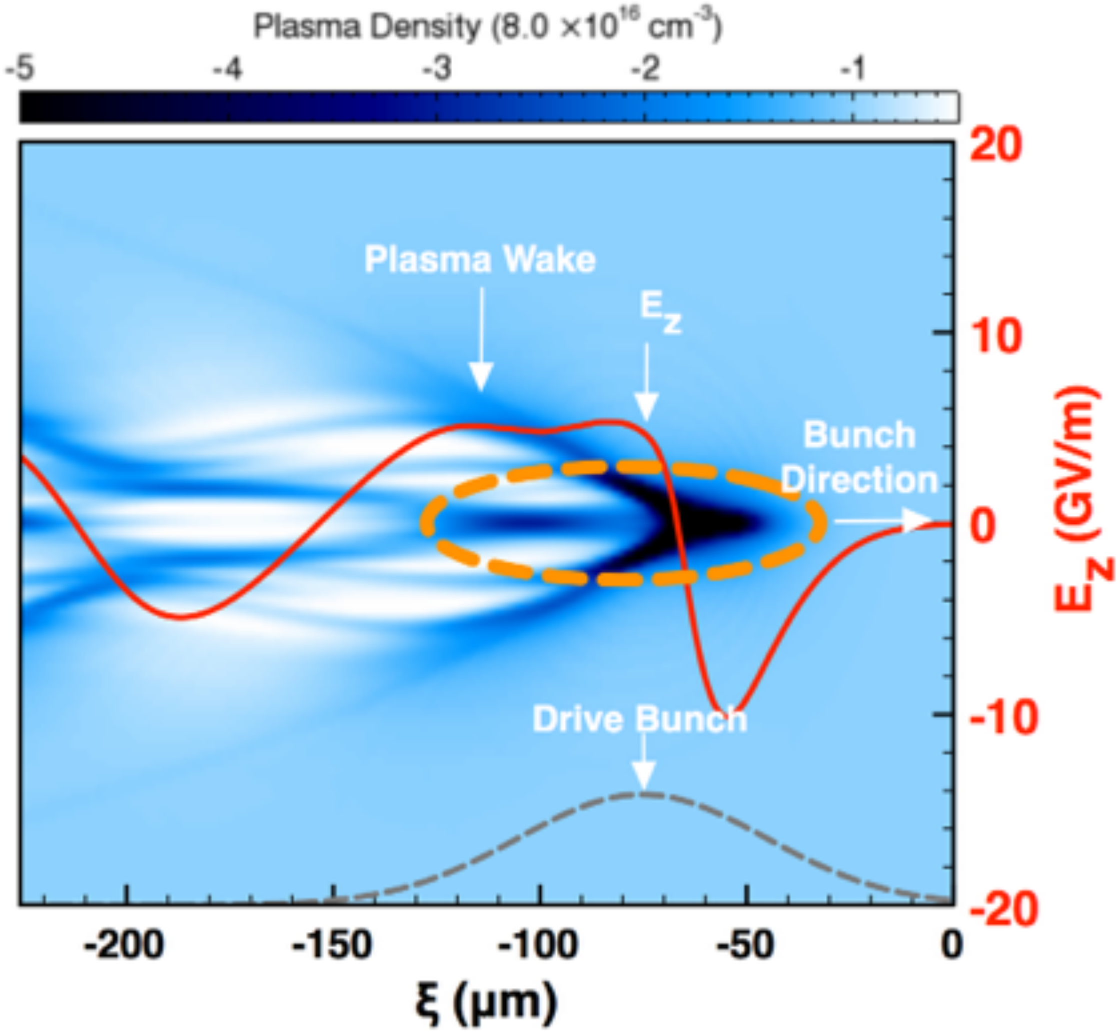
*S. Corde et. al, 524, 442 Nature(2015).

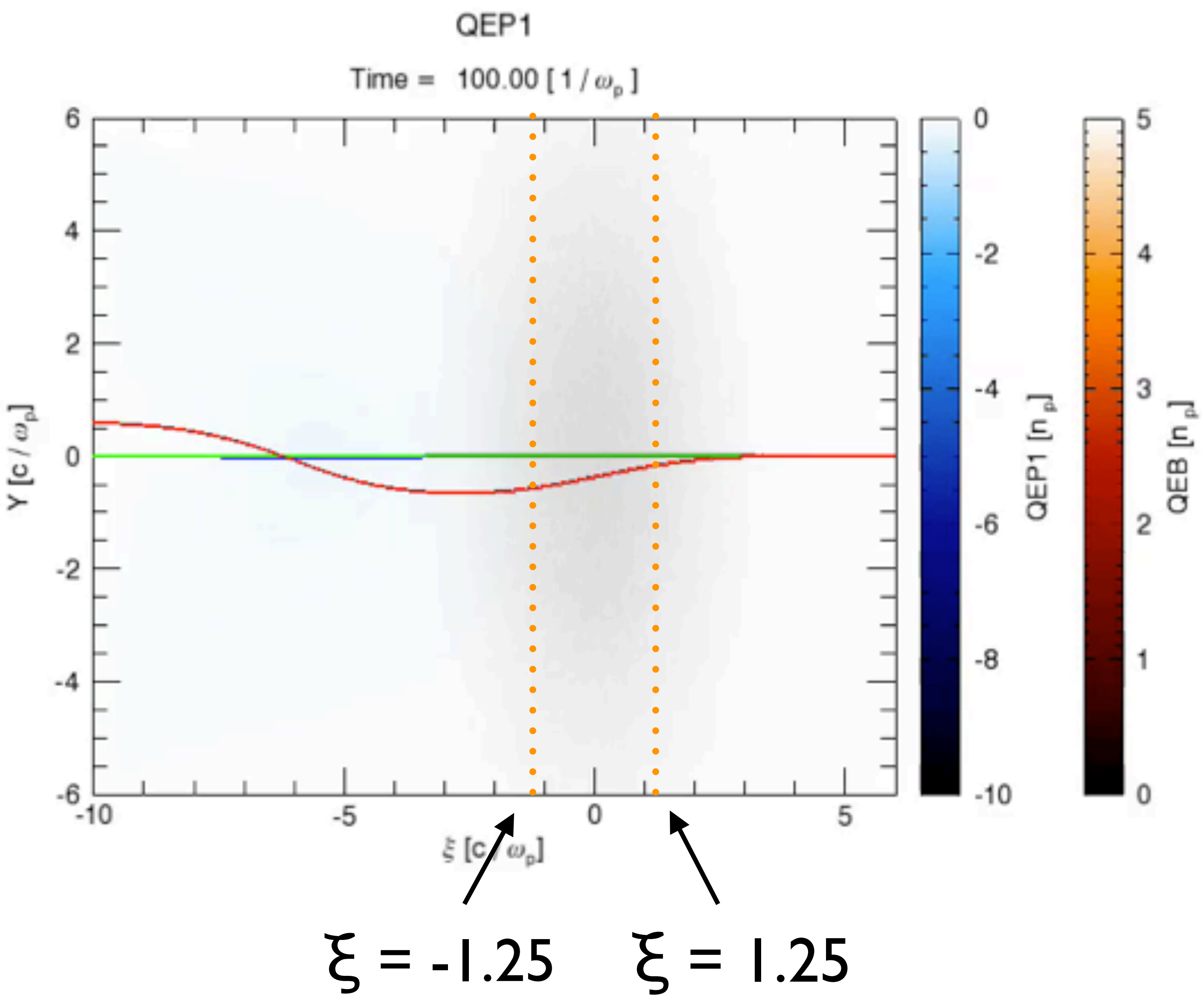


Generation of Mono-Energetic e^+ with High Gradient

Drive Beam: σ_r = 70.0 μm , σ_z = 30.0 μm , N =1.6 x 10^{10} , ε_N =**(50,200) mm·mrad**

Plasma Density: 8.0 x 10^{16} cm^{-3} (1.3 meters long including two 15 cm long density ramps)





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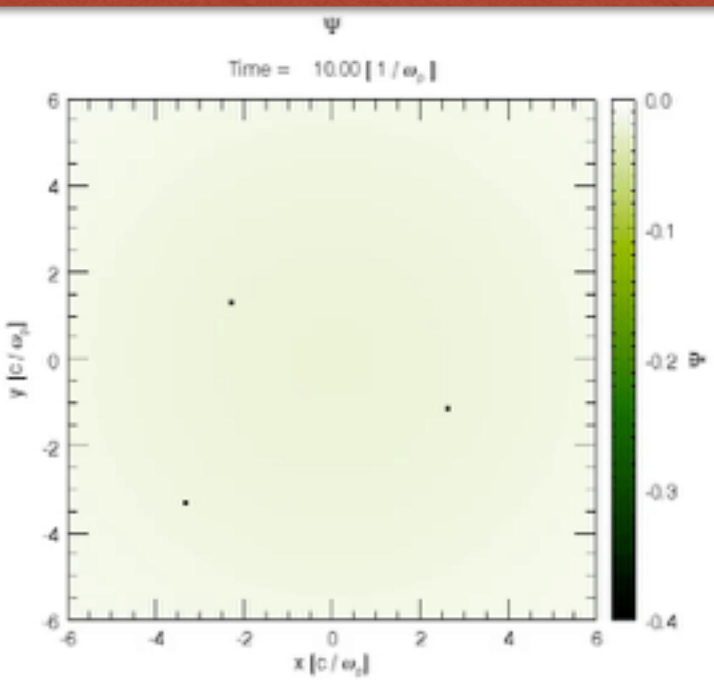
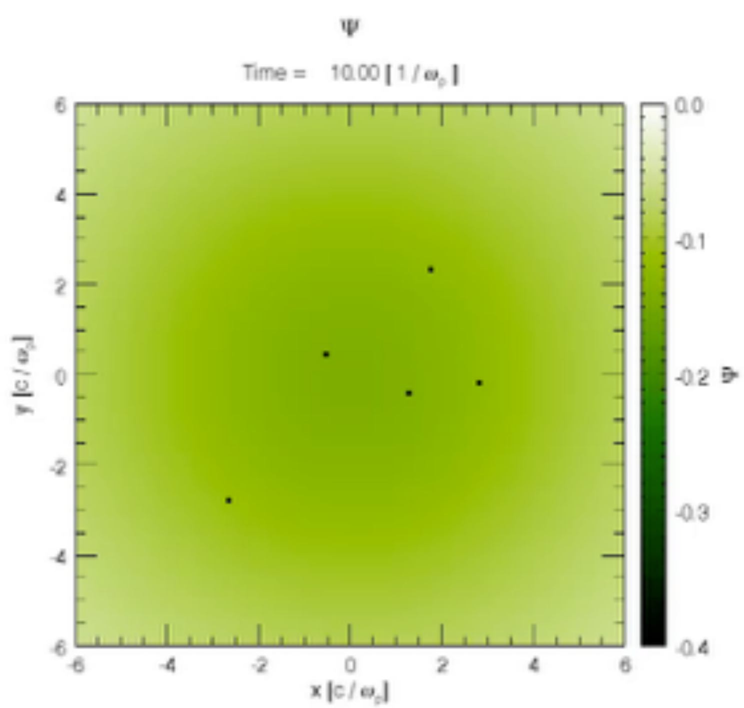
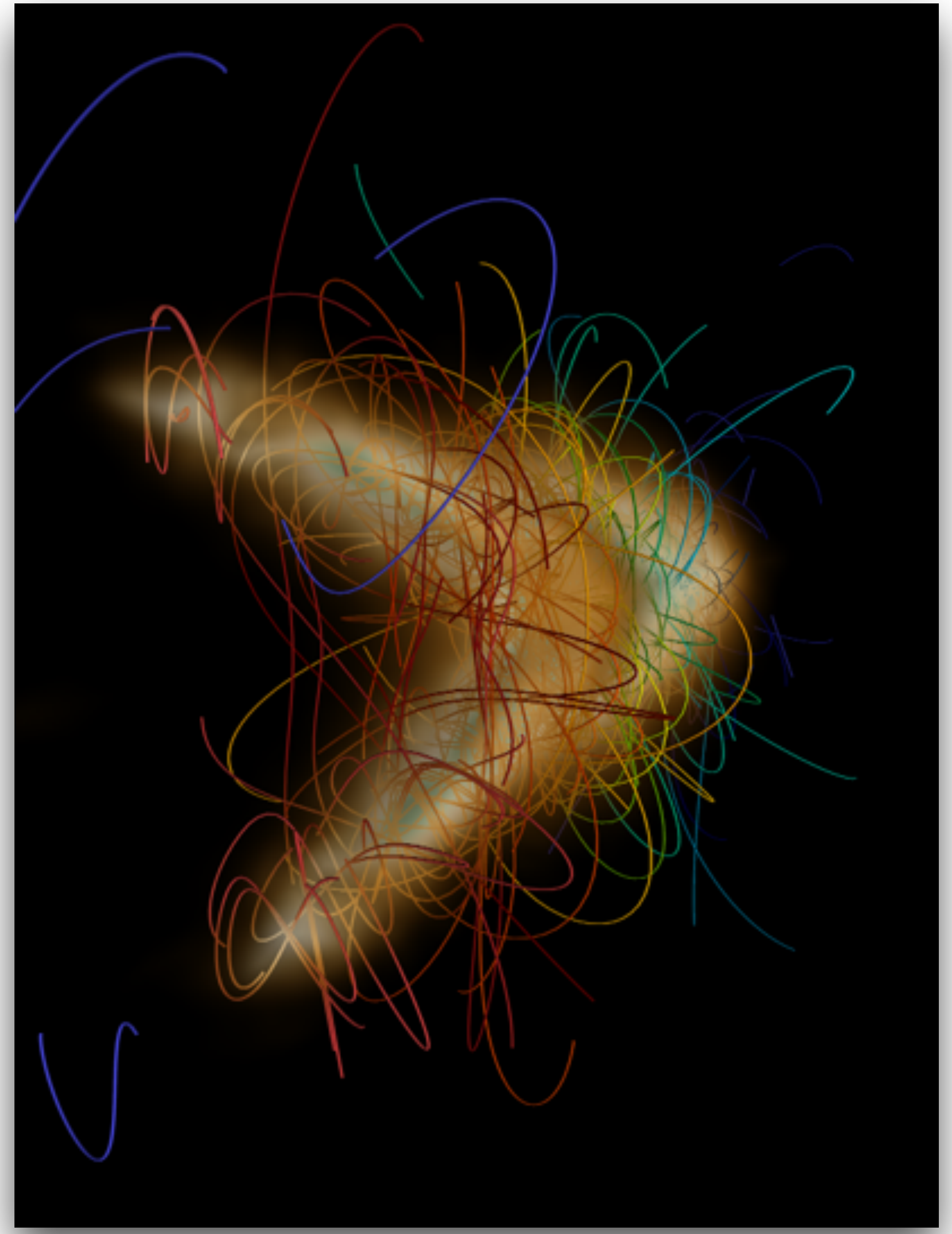
The Pseudo Potential ψ

ξ = 1.25



ξ = -1.25





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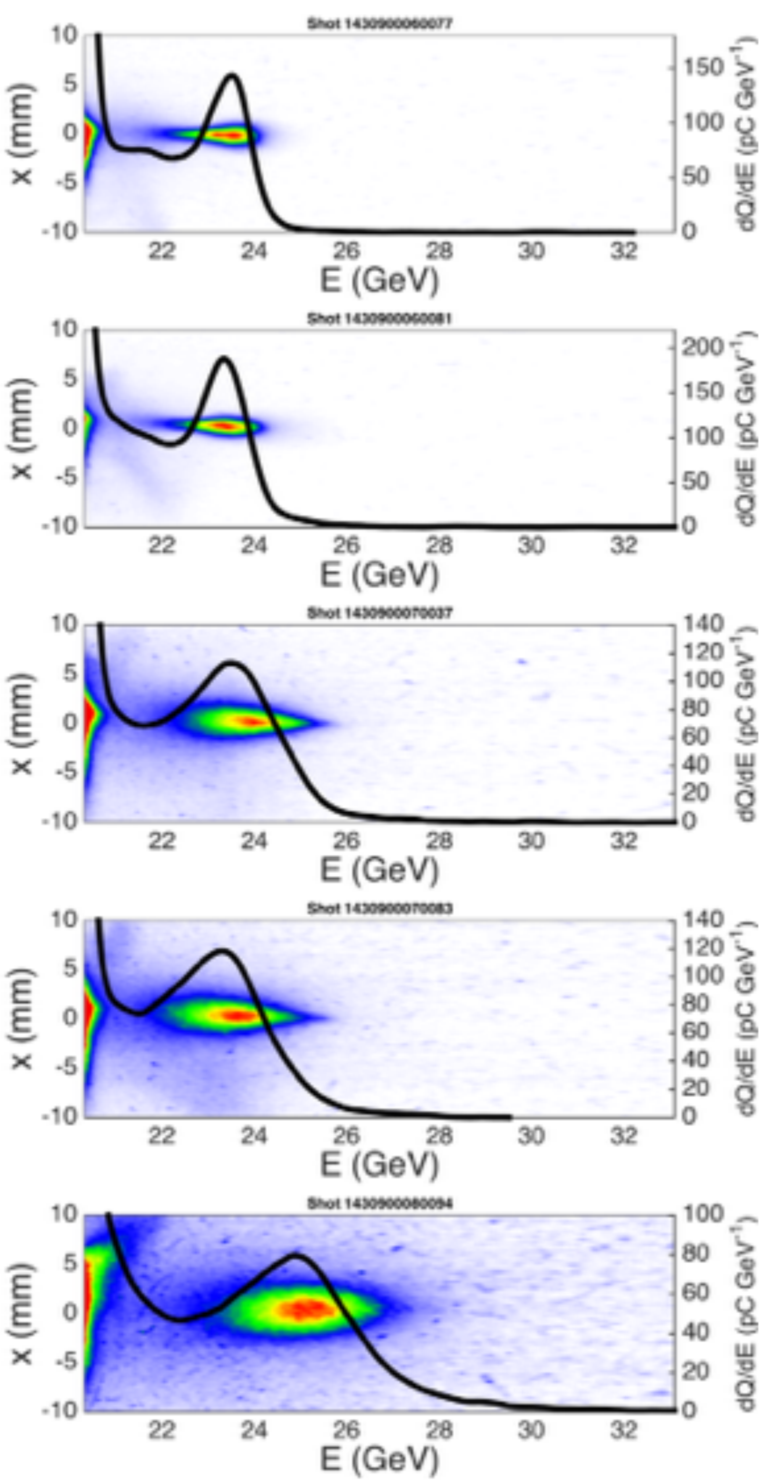
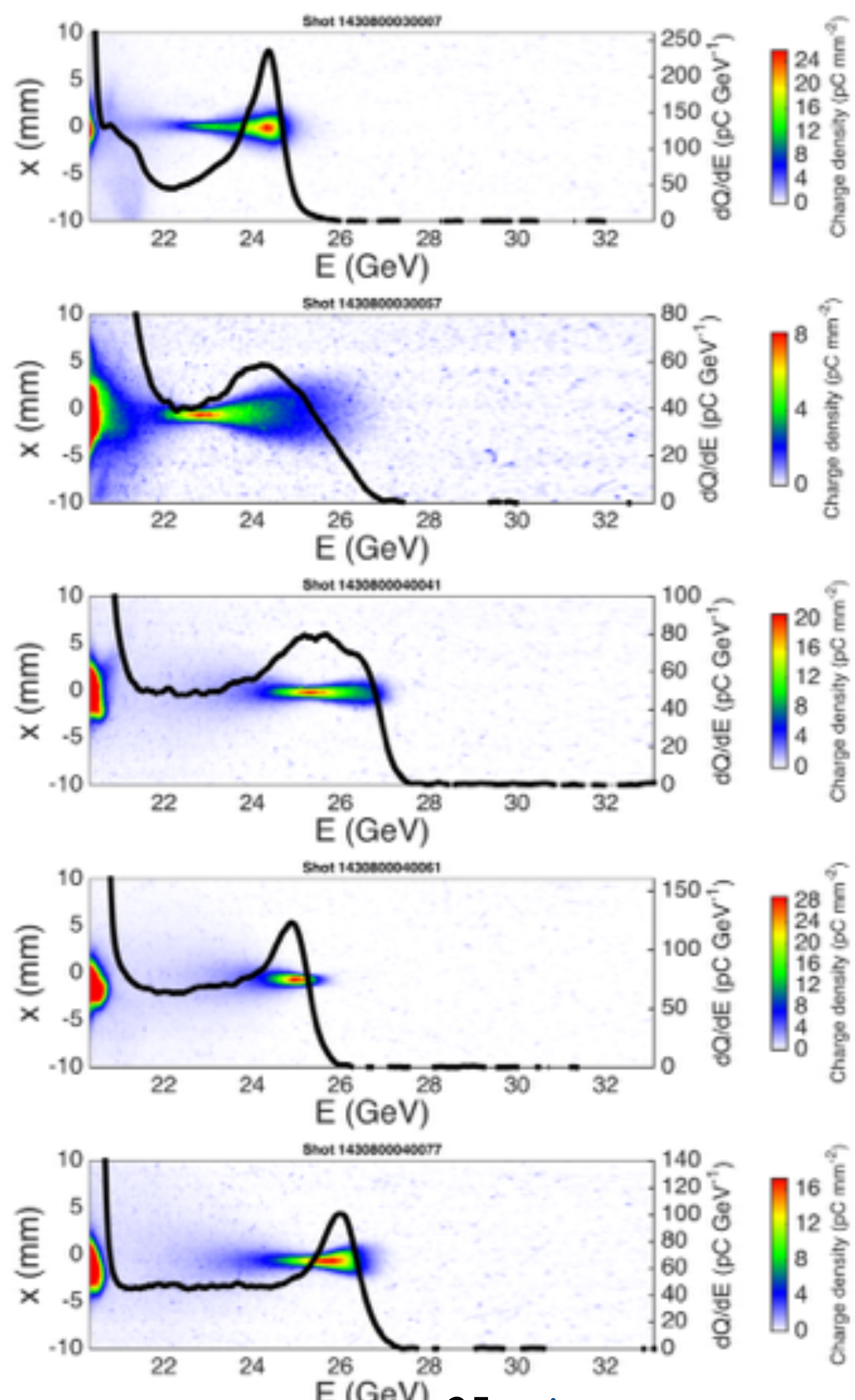
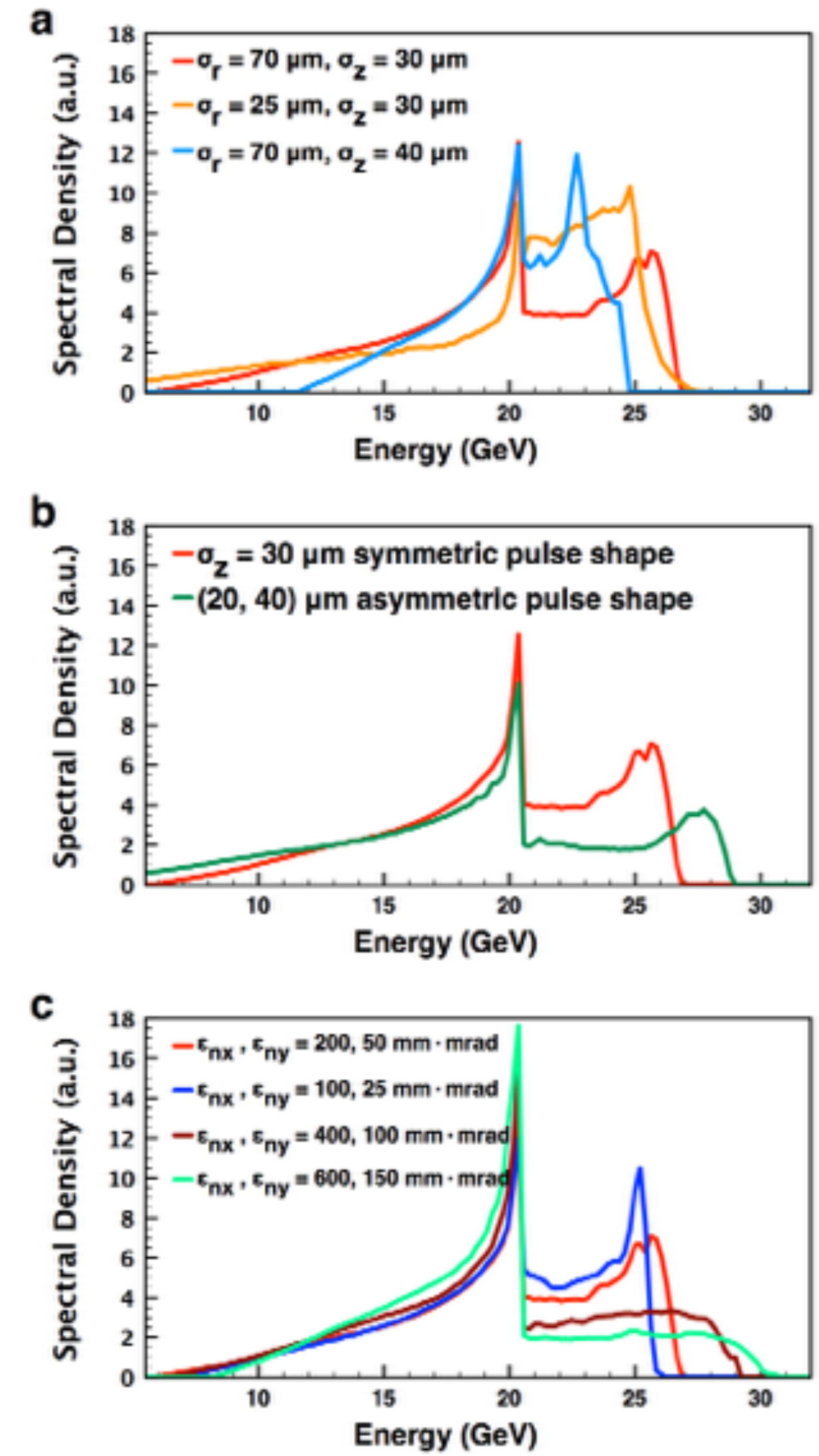
Generation of Mono-Energetic e^+ with High Gradient

Spectrometer dipole at 20.35
QS from 22.85 to 27.85 Ge



Spectrometer dipole at 40.7 GeV
QS from 22.85 to 25.35 GeV





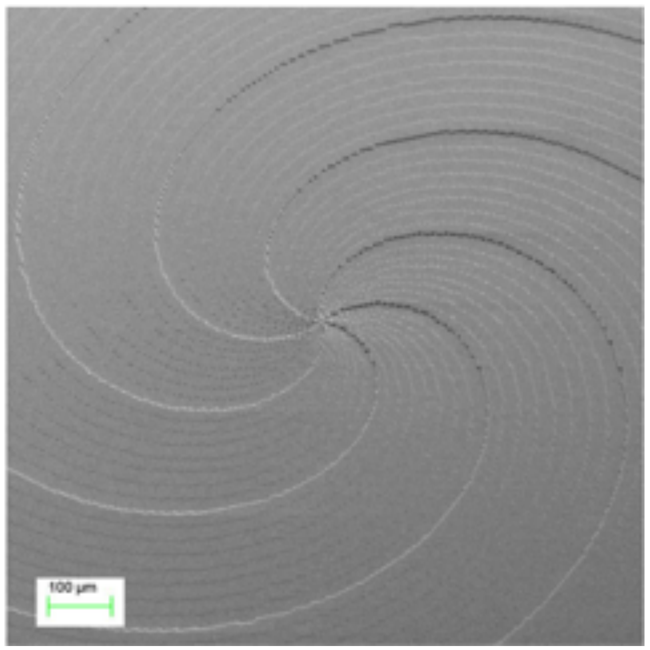
*S. Corde et. al, 524, 442 Nature(2015).

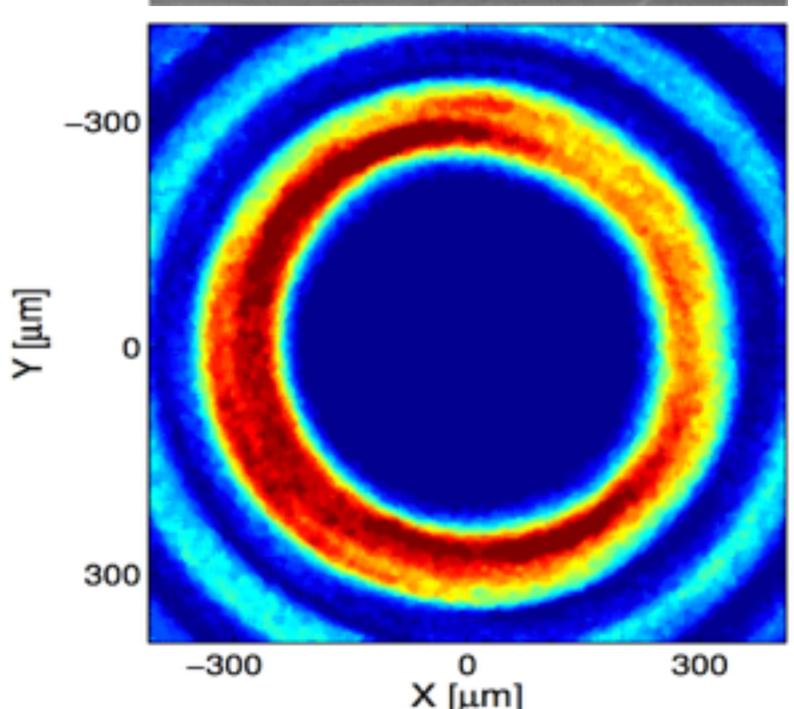
Other Research at FACET

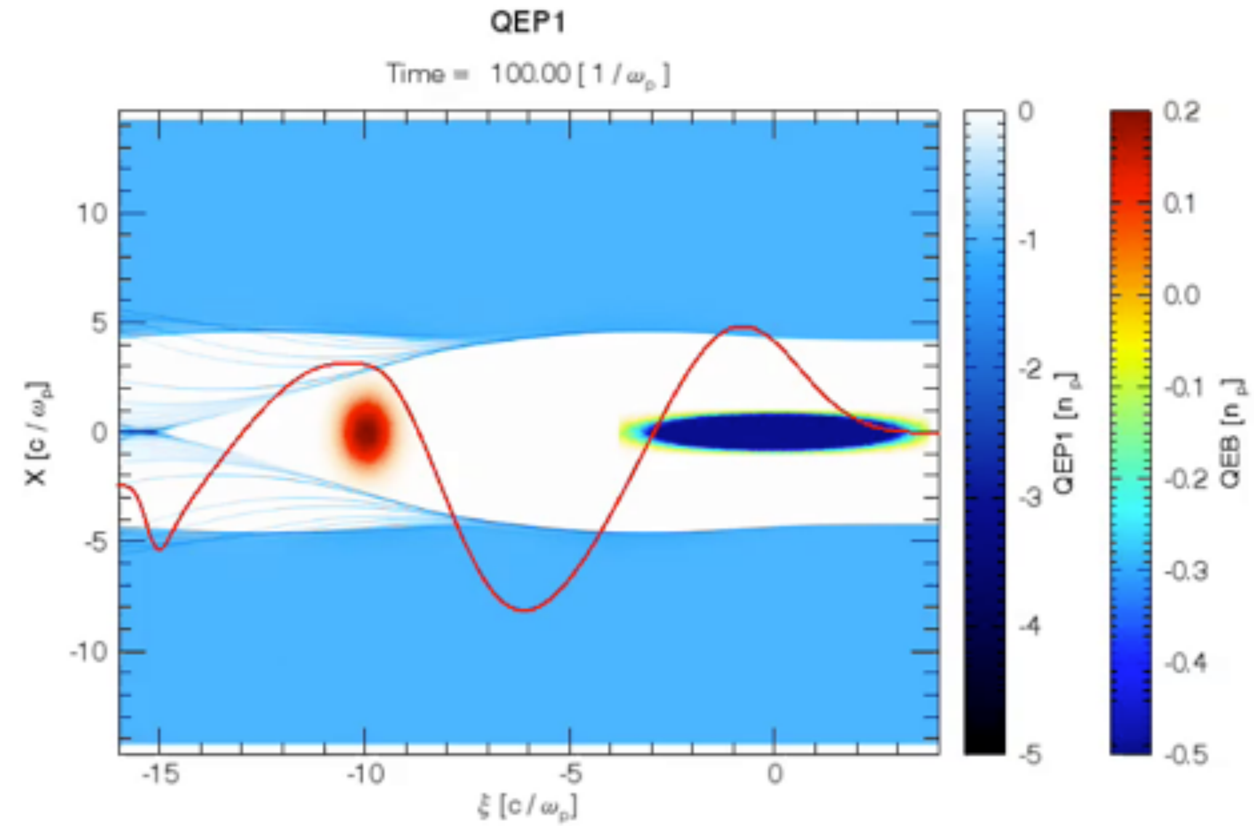
Another Way to Accelerate Positron

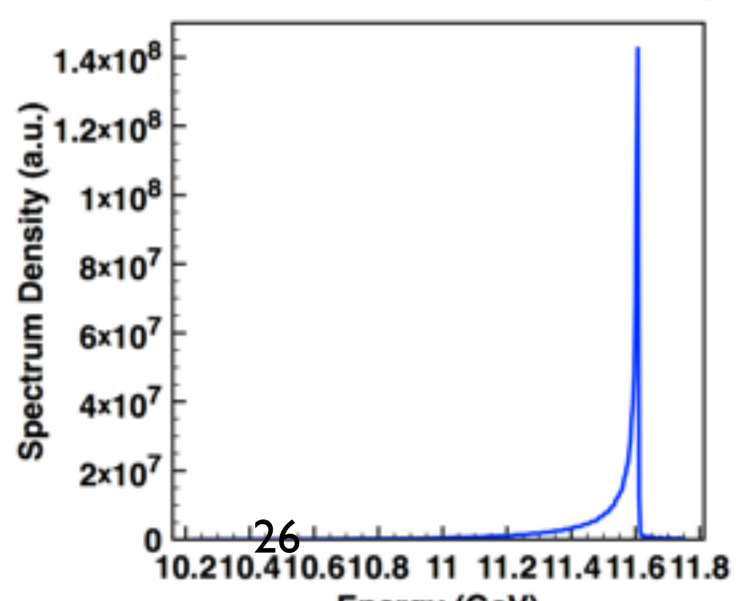
Plasma Hollow Channel

Kinoform









1.6 GeV Energy Gain for in 1 meter
0.2% Energy Spread
(Initial E.S. is 0)

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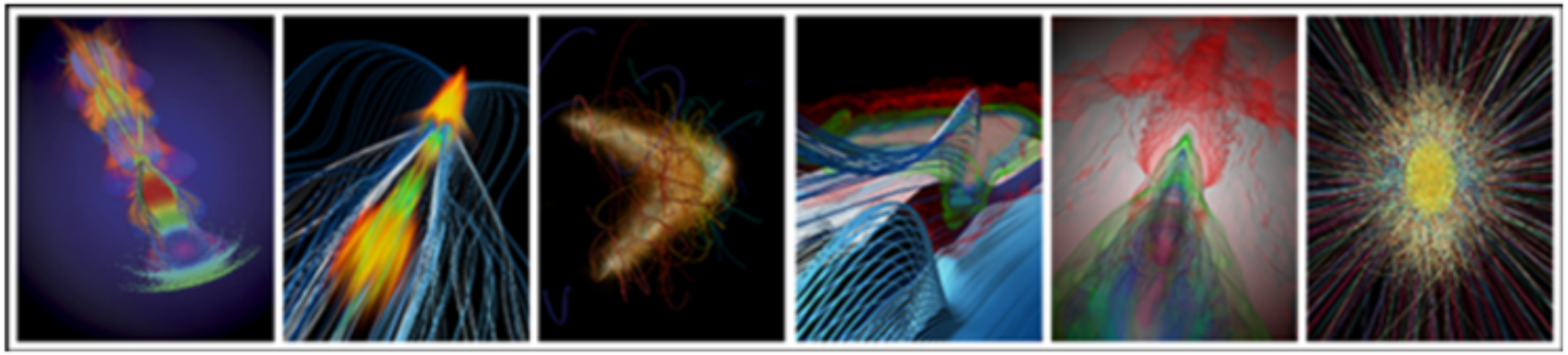
Going Beyond Current Experimental Capabilities



FACET-II
Science Opportunities Workshops

12-16 October, 2015
SLAC National Accelerator Laboratory
Menlo Park, CA

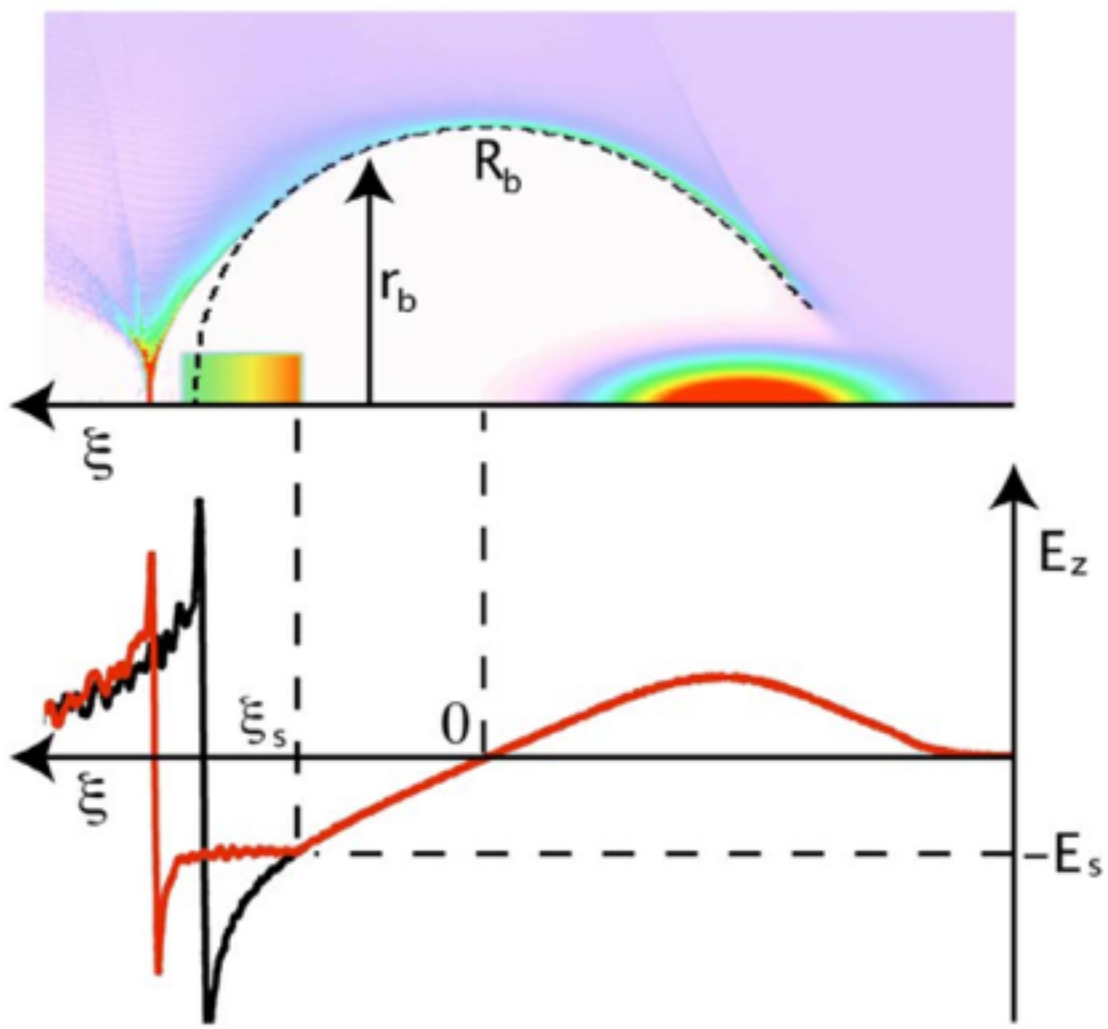
FACET-II is a new user facility that will provide unique capabilities to develop advanced acceleration and coherent radiation techniques with high-energy electron and positron beams. FACET-II provides a major upgrade over current FACET capabilities and the breadth of the potential research program will make it truly unique.

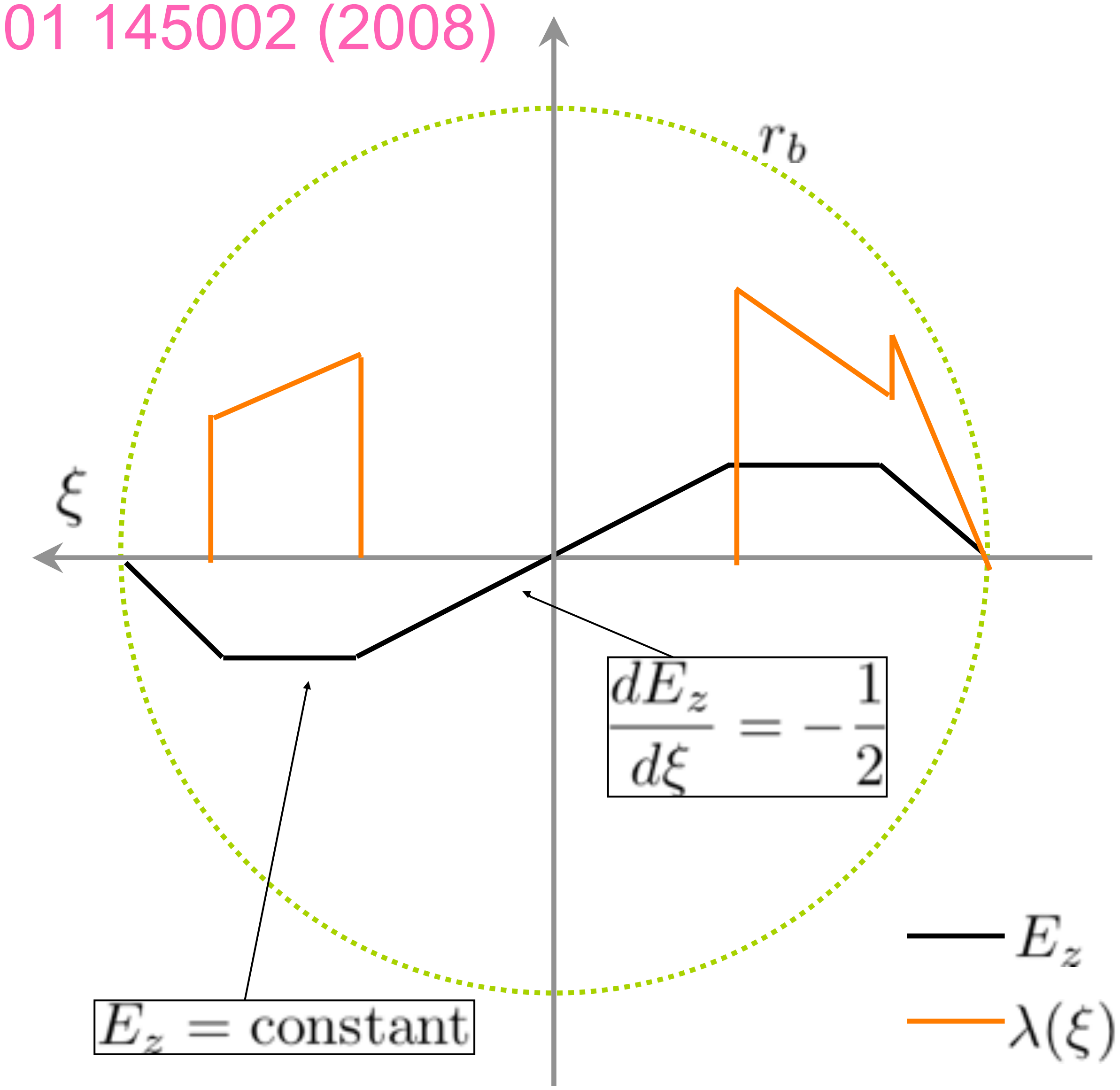
Even High Efficiency and High Quality Beam Aiming to the Future Linear Collider.

Beam Loading Scenarios
&
Ion Motion

High Efficiency PWFA through Nonlinear Beam Loading and Shaped Bunches

M. Tzoufras et al., PRL 101 145002 (2008)





- **Theory allows for designing highly efficient stages that maintain excellent beam quality.**
- **Simulation for PWFA-LC showed ~ 50% energy transfer efficiency with <1% energy spread**
- **BUT…….**

Matched Beams Lead to Ion Collapse that Degrades Emittance

Trailing beam density:

$$n_b = \frac{N}{(2\pi)^{3/2}\sigma_r^2\sigma_z}$$

Efficient beam loading and high luminosity:

$$N = 1 \times 10^{10}$$

Matching:

$$\sigma_r^2 = \sqrt{\frac{2}{\gamma}} k_p^{-1}\epsilon_N$$

Energy spread:

$$\sigma_z = \alpha\frac{c}{\omega_p} \qquad (\Lambda > 1)$$

Leads to:

$$\frac{n_b}{n_0} = 1.4 \times 10^4 \frac{N}{1 \times 10^{10}} \frac{\mu m - rad}{\sqrt{\epsilon_{Nz}\epsilon_{Ny}}} \sqrt{\frac{Energy}{250GeV}} \frac{1}{\alpha}$$

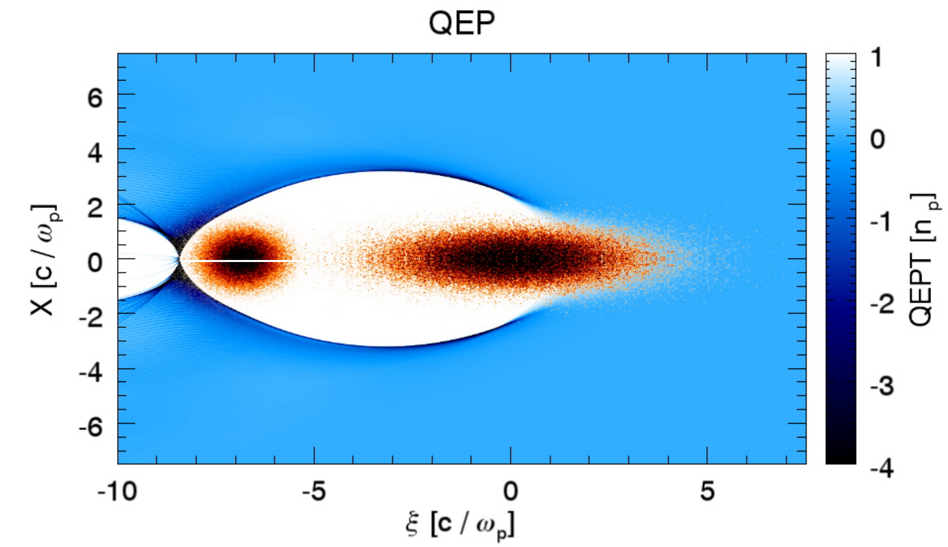
For collider parameters:

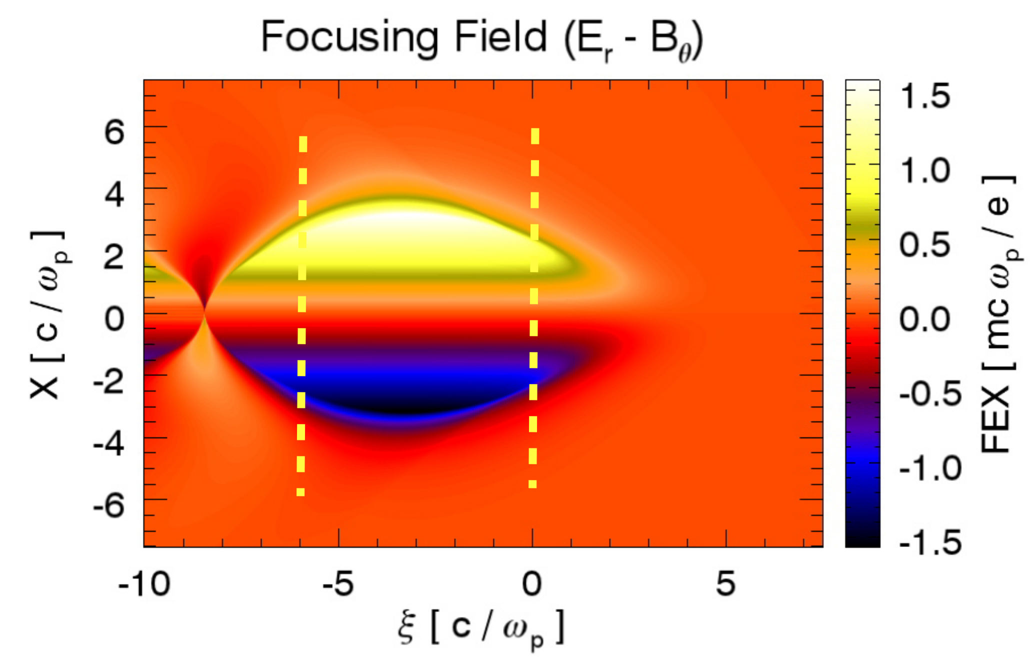
$$\frac{n_b}{n_0} \approx 10^4 - 10^5$$

Ion motion, which can degrade the accelerating and focusing fields, occurs when nb/no~M/m

Ion Motion in PWFA

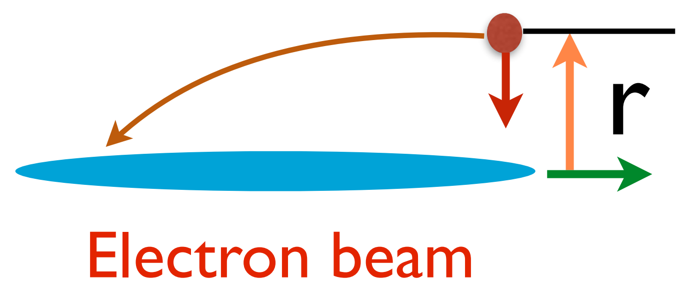
Blowout PWFA





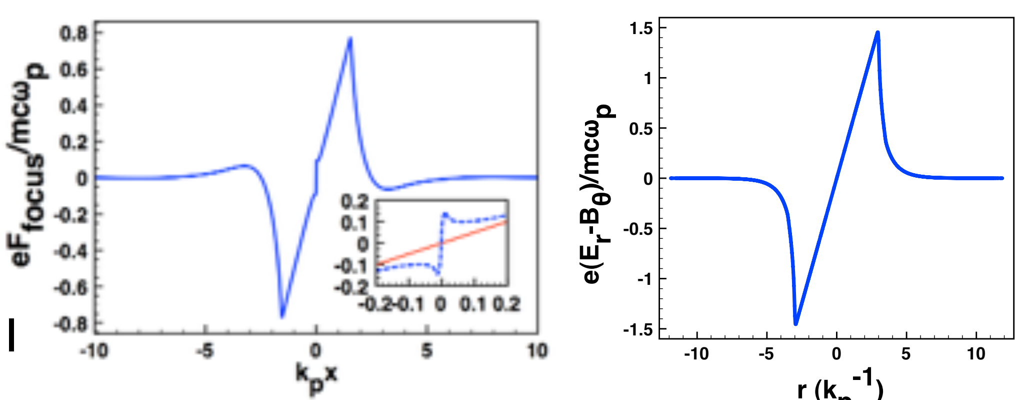
Ions collapse!

C frame



$$\frac{n_b}{n_p} \gg \frac{m_{ion}}{m_e} \Rightarrow \Delta\phi \gg 1$$

* J. B. Rosenzweig et al. Phys. Rev. Lett., 95:195002, 2005



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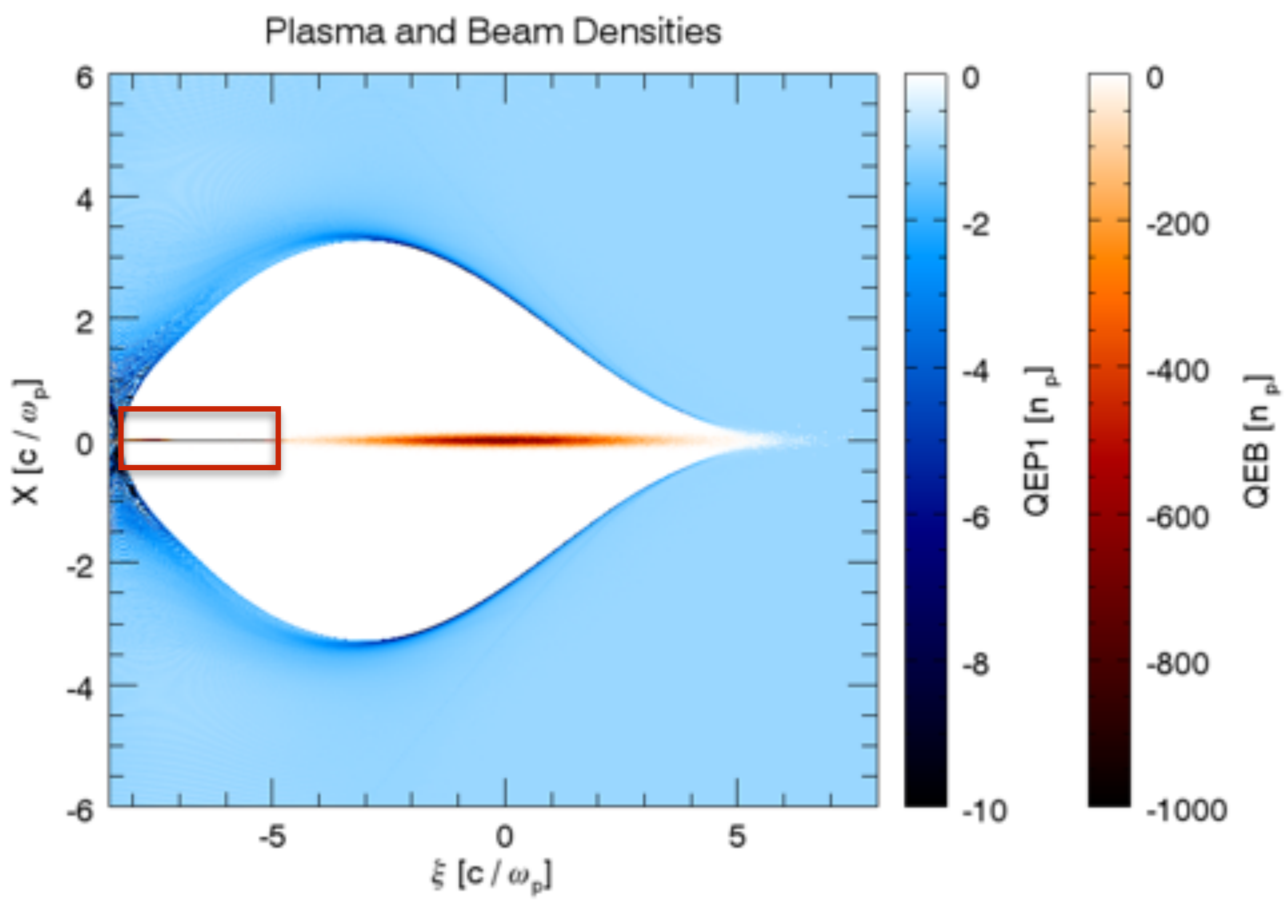
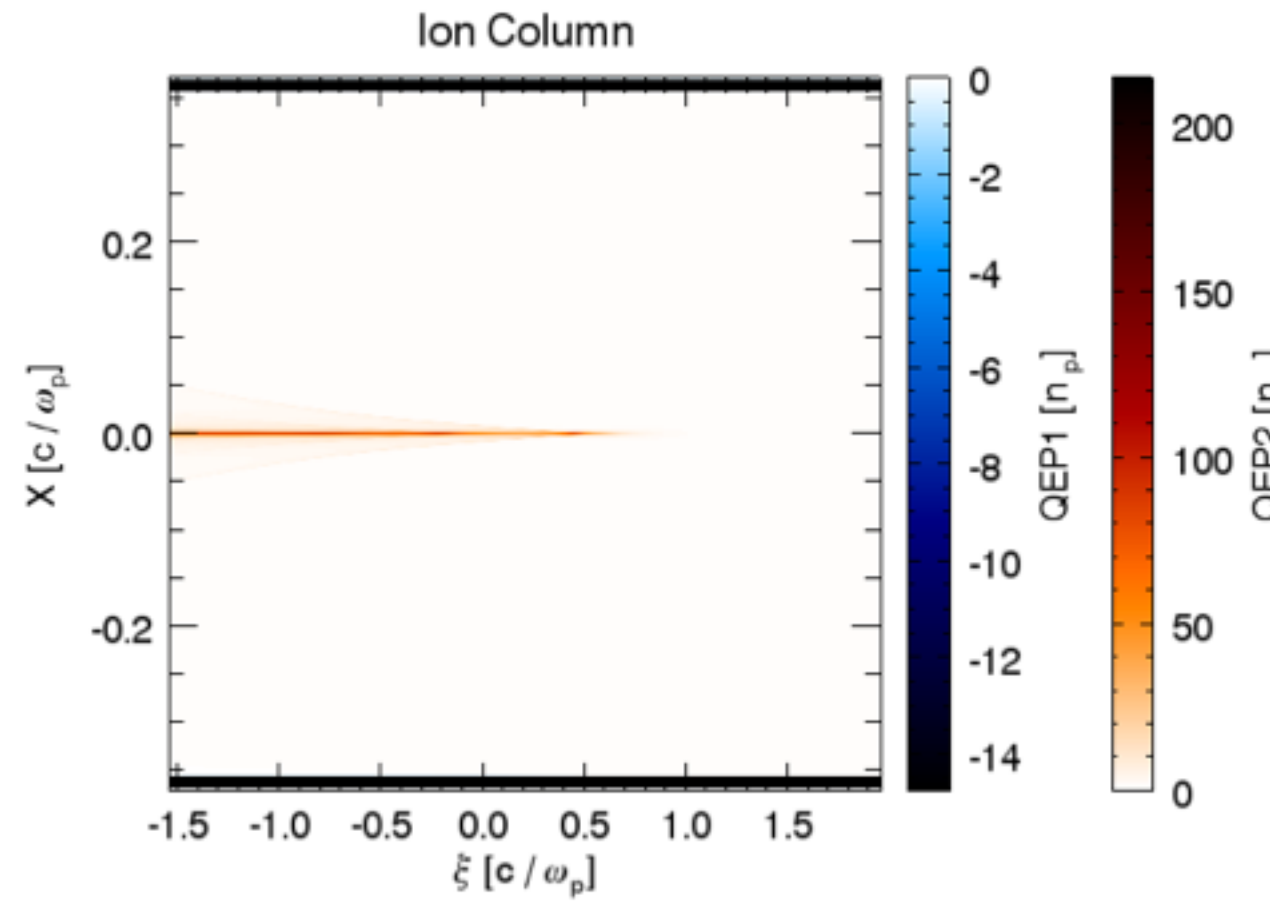
Ion Motion in PWFA

Big Challenge





400 μm x 400 μm x 300 μm Box

16384 x 16384 x 2048 Cells

$\Delta_\perp \approx 25$ nm

12 μm x 12 μm x 60 μm Box

4096 x 4096 x 512 Cells

$\Delta_\perp \approx 3$ nm

Ion Motion Driven by Asymmetric Trailing Beam

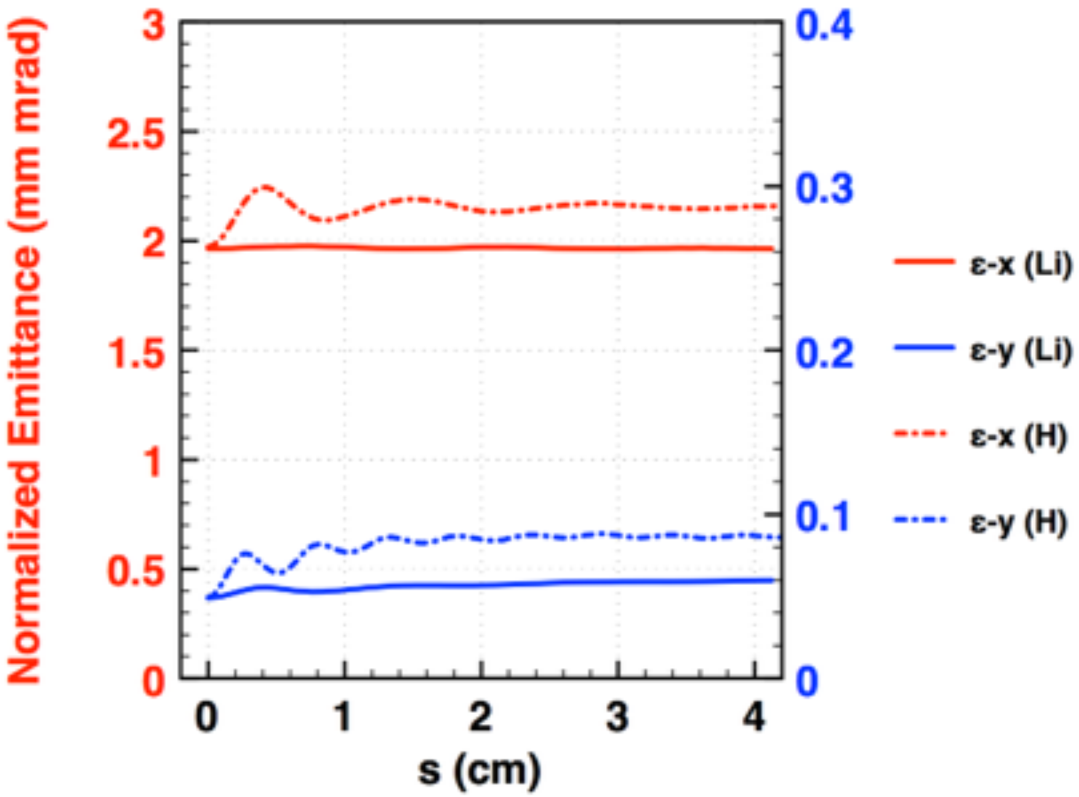
Trailing Beam: σ_z = 10.0 μm , N = 1.0 x 10^{10} ,

σ_x = 0.463 μm , ε_{Nx} = **2.0 mm·mrad** , σ_y = 0.0733 μm , ε_{Ny} = **0.05 mm·mrad**

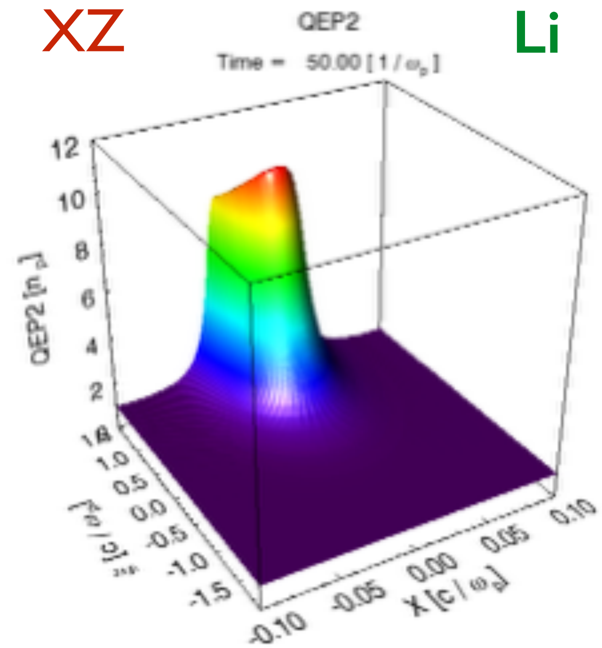
Y = 48923.7 (25 GeV), Plasma Density : 1.0 x 10^{17} cm^{-3}

$\sigma_x / \Delta_\perp$ = 75.9

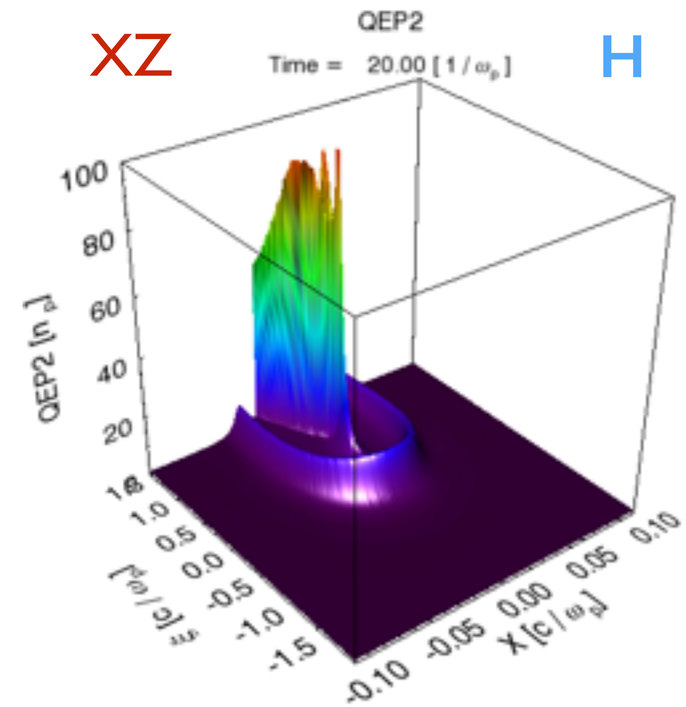
$\sigma_y / \Delta_\perp$ = 12.0



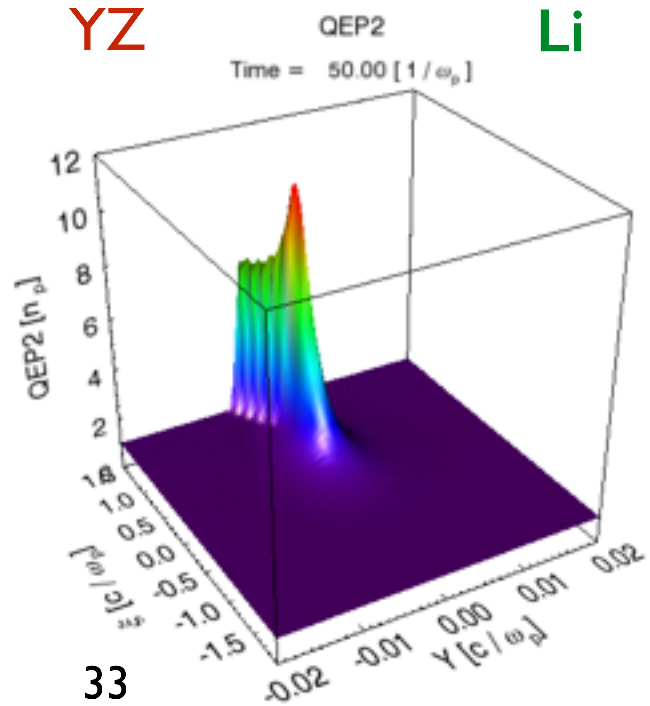
XZ Li



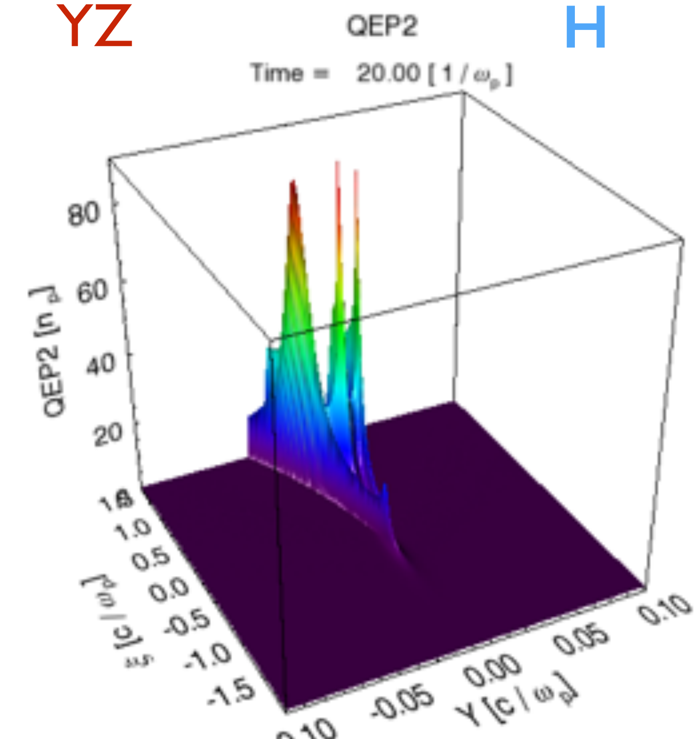
XZ H



YZ Li



YZ H



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%.

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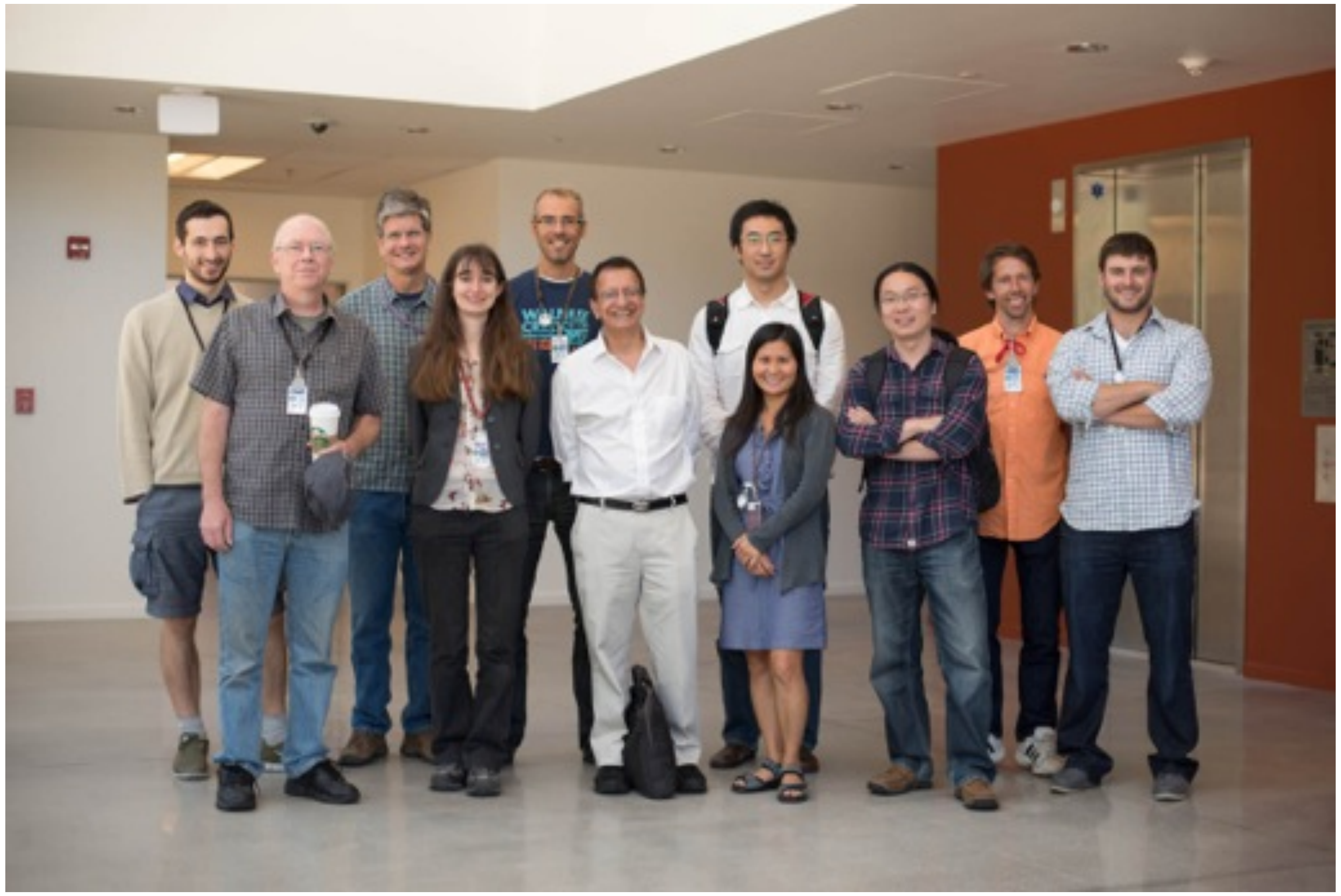
FACET E200 Collaboration

E. Adli, J. Allen, W. An, C.I. Clarke, C.E. Clayton, S. Corde, J.P. Delahaye, A.S. Fisher, J. Frederico, S. Gessner, S.Z. Green, M.J. Hogan, C. Joshi, M. Litos, W. Lu, K.A. Marsh, W.B. Mori, N. Vafaei-Najafabadi, D. Walz, V. Yakimenko



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laboratoire d'optique appliquée

Summary

High energy gain and high efficiency acceleration of both e^- and e^+ in the PWFA have been demonstrated in the experiments at FACET.

QuickPIC simulation results for these experiments show a good agreement with the experimental results. The simulation study also provides us more detailed information that can help us explore the unknown and guide our future experiments.