SciDAC plasma-based team:

- W.B.Mori — UCLA
  - F.S.Tsung
  - CK. Huang
  - V.K.Decyk
- D.Bruhwiler — TechX
  - D.Dimitrov
- E.Esarey — LBNL
  - B.Shadwick
  - G.Fubiani
- T.Katsouleas — USC
  - S.Deng

Advanced accelerator effort is highly leveraged: Big bang for the buck

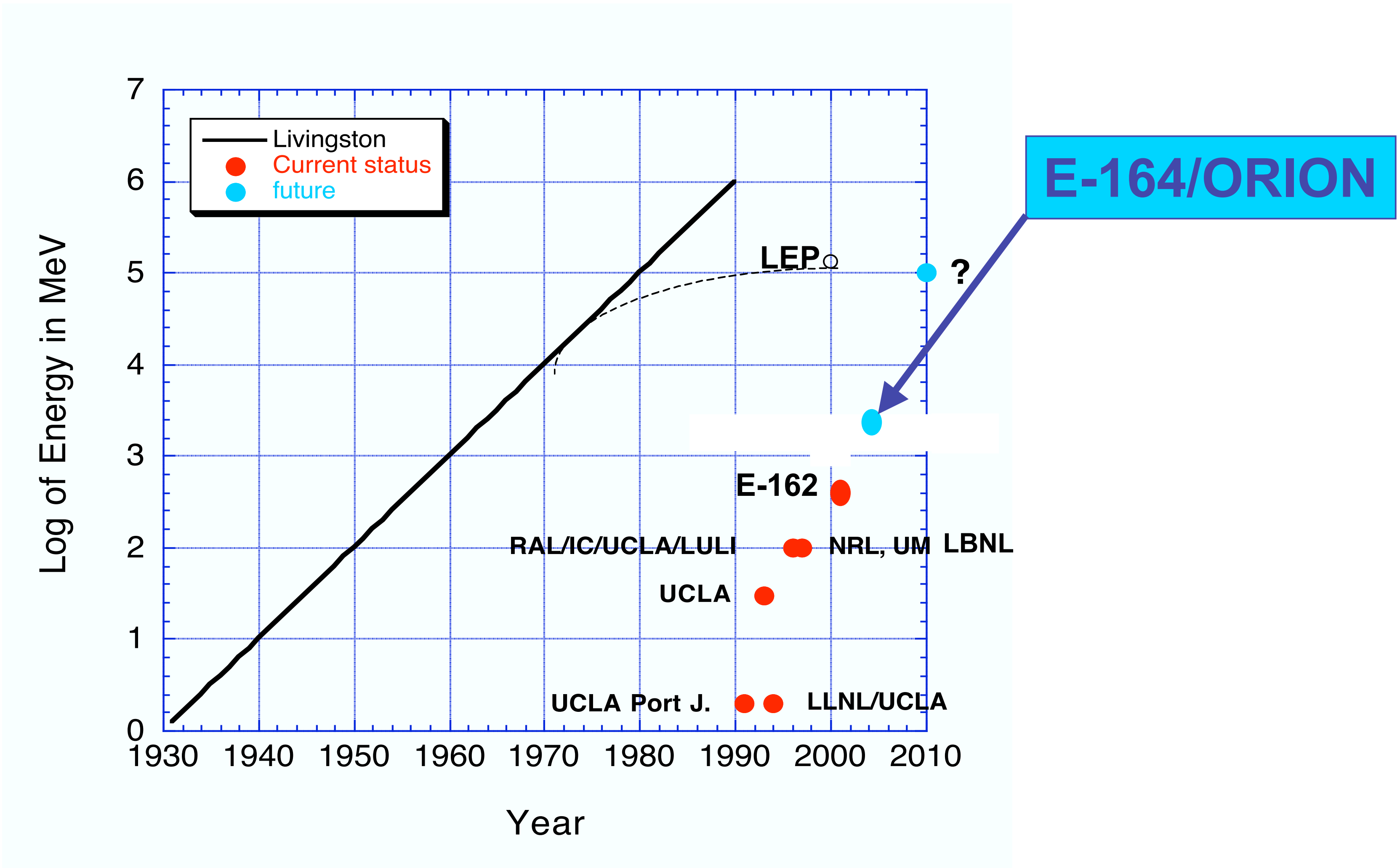
Institution	2002	2003
UCLA	60K (125K)	70K (144K)
Tech-X	50K	60K
USC	20K	25K
LBNL	20K	25K

Why and what is plasma-based acceleration

Long term future of High-Energy physics requires the need for new high-gradient technology

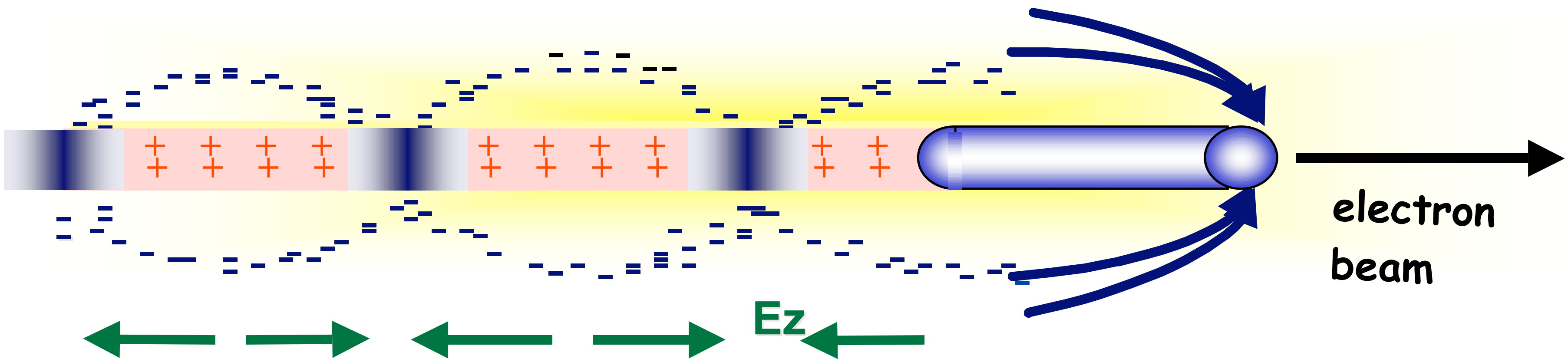
Gradients from 1GeV/m to 100 TeV/m are possible from relativistic plasma waves

Experimental progress



Physical Principles of the Plasma Wakefield Accelerator

- Space charge of drive beam displaces plasma electrons



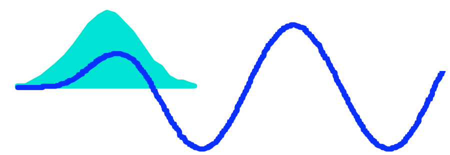
- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude N_b / σ_z^2 $\quad (for\ 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_o}})$
- Transformer ratio $E_{z\,acc.} / E_{dec.beam}$

Concepts For Plasma Based Accelerators

Pioneered by J.M.Dawson

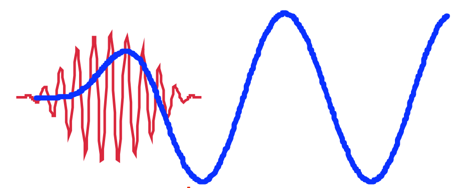
- Plasma Wake Field Accelerator(PWFA)

  A high energy electron bunch



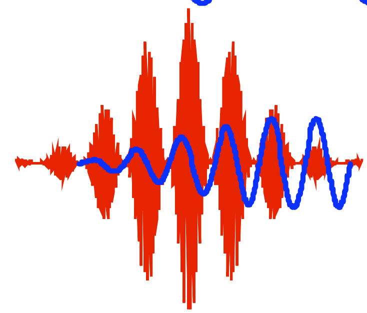
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



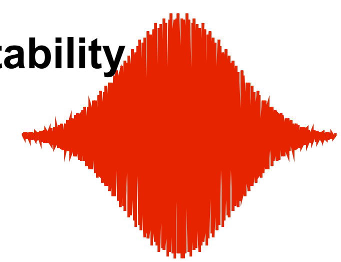
- Plasma Beat Wave Accelerator(PBWA)

  Two-frequencies, i.e., a train of pulses

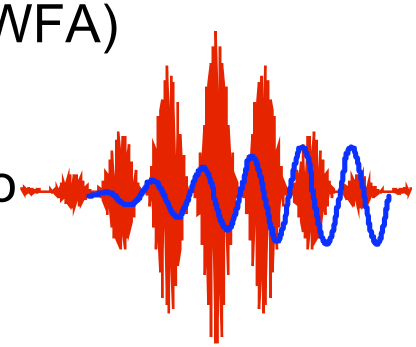


- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability



evolves to



Mission

Develop high fidelity parallelized software (at least two distinct codes): primarily particle based models

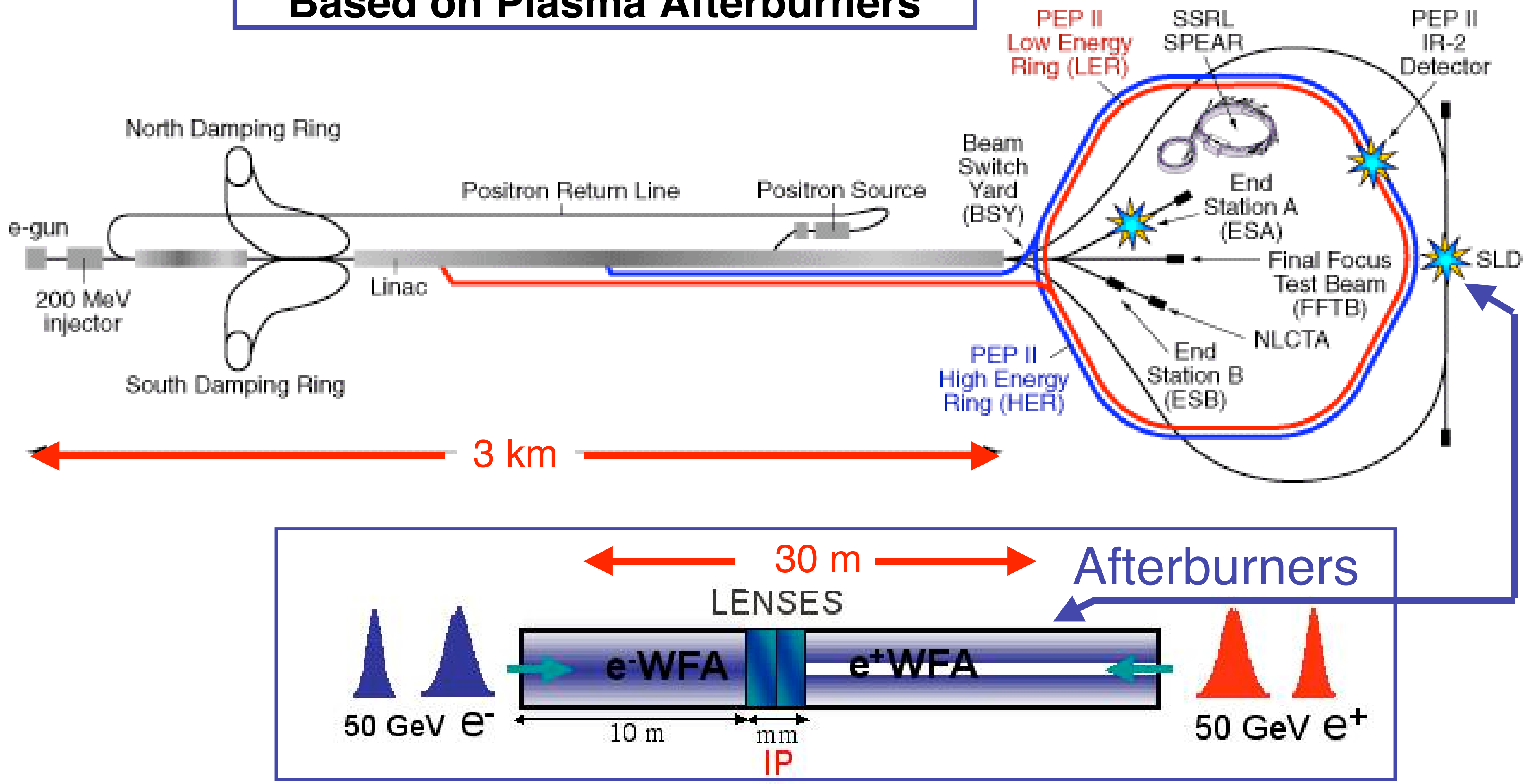
Model the full-scale of current experiments ~100MeV - 1GeV

Enable full-scale modeling of 100+ GeV plasma-based colliders

Transfer plasma models to conventional accelerator modeling

Enable scientific discovery

A goal is to build a virtual accelerator:
A 100 GeV-on-100 GeV e^-e^+ Collider
Based on Plasma Afterburners



Computational challenges for modeling plasma-based acceleration (1 GeV Stage): 1000hours/GFlop

Beam-driven wake*	Fully Explicit
Δz	$\leq .05\ c/\omega_p$
Δy, Δx	$\leq .05\ c/\omega_p$
Δt	$\leq .02\ c/\omega_p$
# grids in z	≥350
# grids in x, y	≥150
# steps	$\geq 2 \times 10^5$
$N_{particles}$	$\sim .25\text{-}1. \times 10^8$ (3D)
Particles x steps	$\sim .5 \times 10^{13}$ (3D) - ≥ 10,000 hrs at ~.1 GFlops

*Laser-driven GeV stage requires on the order of $(\omega_o/\omega_p)^2$=1000 x longer, however, the the resolution can usually be relaxed.

Community of parallel PIC codes and algorithms exist: PIC codes make "minimal" physics approximations

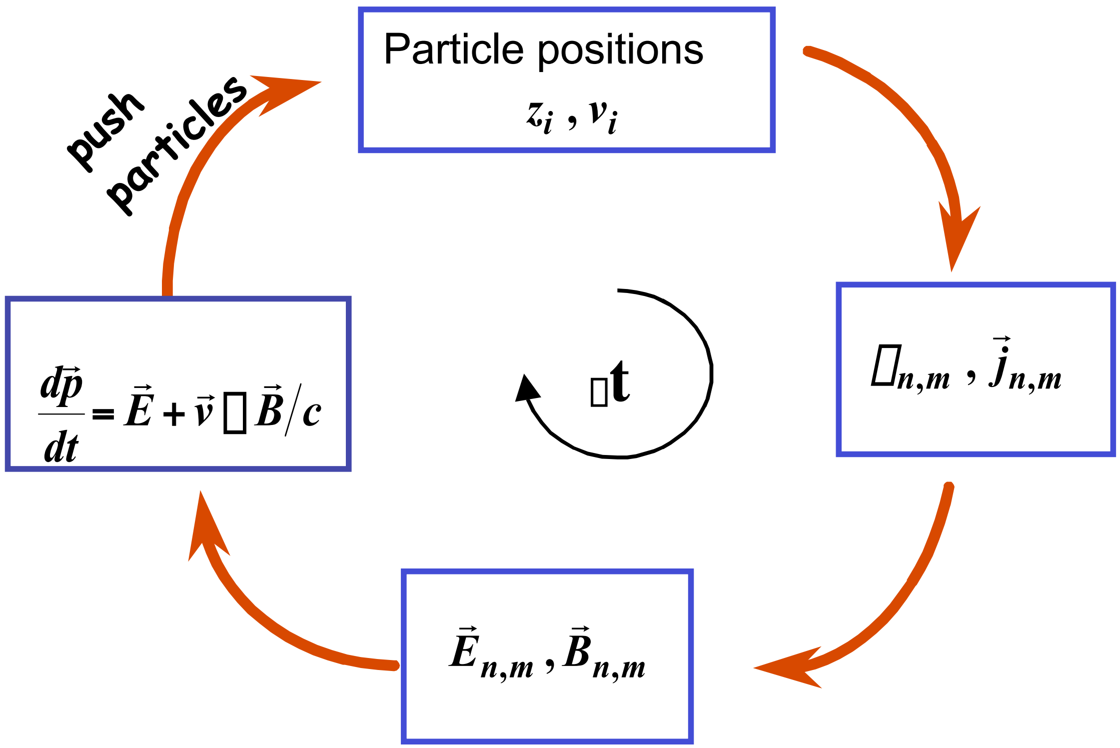
- Parallel Full PIC
  - OSIRIS
  - Vorpal/OOPIC
- Parallel quasi-static PIC
  - quickPIC
- Fluid (quasi-static and full)

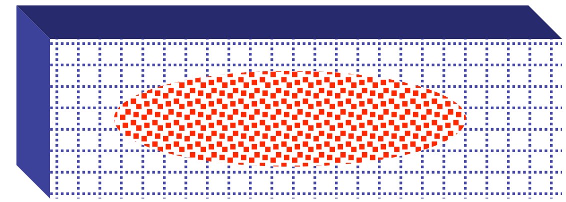
  - To model a plasma stage including beam loading will require particle models

What Is a Fully Explicit Particle-in-cell Code?

Computational cycle

(at each step in time)





- Maxwell’s equations for field solver
- Lorentz force updates particle’s position and momentum

Typical simulation parameters:

~10^7-10^9 particles
~10^4 time steps
~1-100 Gbytes
~10^2-10^4 cpu hours

SciDAC collaborative approach

- Multiple codes
- Benchmarking against each other and against reduced numerical models and analytic theory
- Validation against experiment
  - E-162/E-164
  - L'OASIS
- Modeling future experiments
  - E-164/E-164x
  - L'OASIS
- A path towards a virtual accelerator
- SCIENTIFIC DISCOVERY ALONG THE WAY

Parallel Code Development

OSIRIS: full PIC

Vorpal/OOPIC: full PIC

quickPIC: reduced PIC

UPIC: parallel PIC framework

OSIRIS.framework

Basic algorithms are mature and well tested

- **Fully relativistic**
- **Choice of charge-conserving current deposition algorithms**
- **Boris pusher for particles, finite field solver for fields**
- **2D cartesian, 2D cylindrical and 3D cartesian**
- **Arbitrary particle initialization and external fields**
- **Conducting and Lindmann boundaries for fields; absorbing, reflective, and thermal bath for particles; periodic for both**
- **Moving window**
- **Launch EM waves: field initialization and/or antennas**
- **Launch particle beam**
- **particle sorting and ion subcycling**
- **Extended diagnostics using HDF file output:**
  - Envelope and boxcar averaging for grid quantities
  - Energy diagnostics for EM fields
  - Phase space, energy, and accelerated particle selection diagnostics for particles

Ionization modules are being added: Both in 2D and 3D

Ionization modules were added in 2D (slab and cylindrical) and 3D

Monte Carlo impact ionization model was used: particles are born at rest

Monte Carlo field ionization model was used: particles are born at rest

Various cross sections and tunnel rates are being tested: benchmarking with the help of OOPIC

Effort was made to improve speed and maintaing parallel efficiency:

2D 128x128 with 16 particles/cell per processor and V_{th}=.1c

CPU #	Speed □s/ps	Push %	BCpart	BCcurr	Field Solve	BC Field	other	Efficiency
1	2.1	95	4.2	.03	.56	.03	.19	100
4	2.13	95	3.89	.09	.59	.1	.31	99.48
16	2.2	92.8	4.91	.53	.71	.38	.68	95.82
64	2.3	89.3	6.87	1.28	.57	1.09	1.09	91.82
256	2.29	88.7	6.97	1.29	.55	1.39	1.15	92.16
512	2.37	85.2	7.42	1.27	.54	1.87	3.72	88.52
1024	2.45							85

Speed in 3D: 3.2□s/ps with 80%efficiency on 512 processors
And 60% on 1024 processors

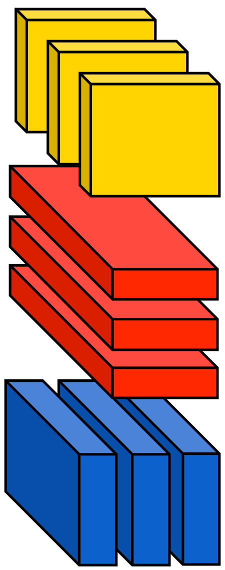
OSIRIS Algorithms

Domain Decompositions

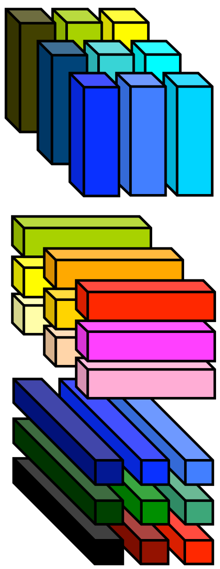
- ***OSIRIS*** **currently allows distribution of the simulated space into evenly partitioned domains along any axis**

- **next steps in extending the code will be to introduce an uneven distribution of domains and dynamic load balancing: follow concepts in PLIB**

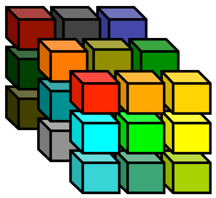
1D Decomposition



2D Decomposition



3D Decomposition

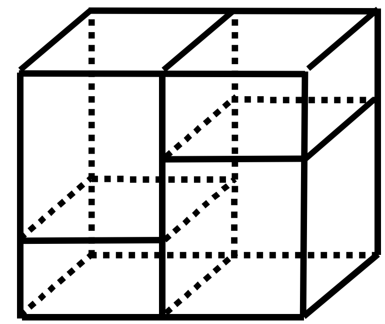


VORPAL – Multi-dimensional hybrid code

- Achieves great flexibility with negligible run-time penalty
  - Multi-dimensional (2D or 3D, with Cartesian geometry)
    - can switch from 2D to 3D with same code and input file
    - enabled by “generic programming” paradigm of C++
  - Runs in serial or parallel (using MPI)
    - flexible 2D and 3D domain decomposition
    - good scaling up to 500 processors has been demonstrated
  - Cross-platform: Linux, IBM SP, Windows, Solaris
- Combines multiple fluid and PIC algorithms seamlessly
  - finite-difference time domain (FDTD) on structured Yee mesh
  - Particle-in-Cell
    - standard Boris particle push
    - charge-conserving current deposition
  - Cold fluid algorithms
    - multiple flux-corrected transport (FCT) algorithms for positive density

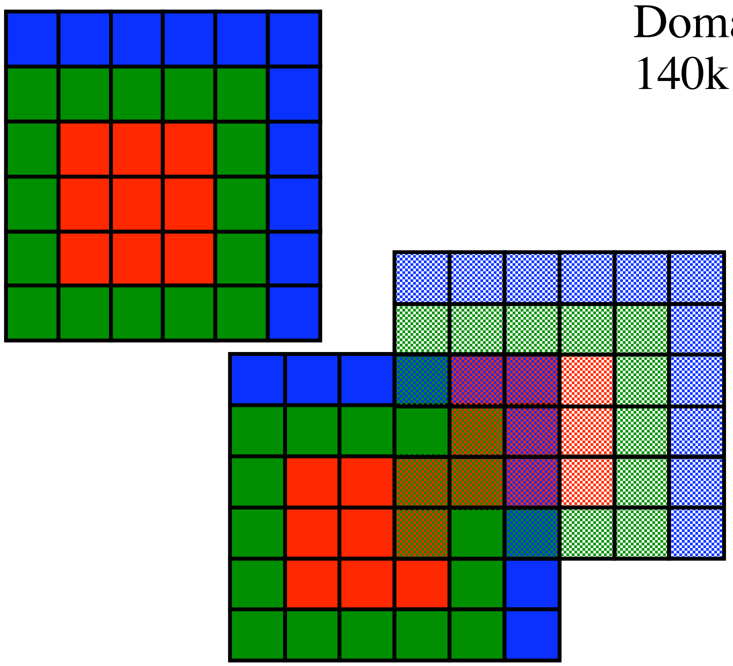
VORPAL's flexible domain decomposition allows full load balancing, good scaling

- Beowulf: 1.2GHz Athlons, fast ethernet
- Have seen good scaling on 128-256 SP processors

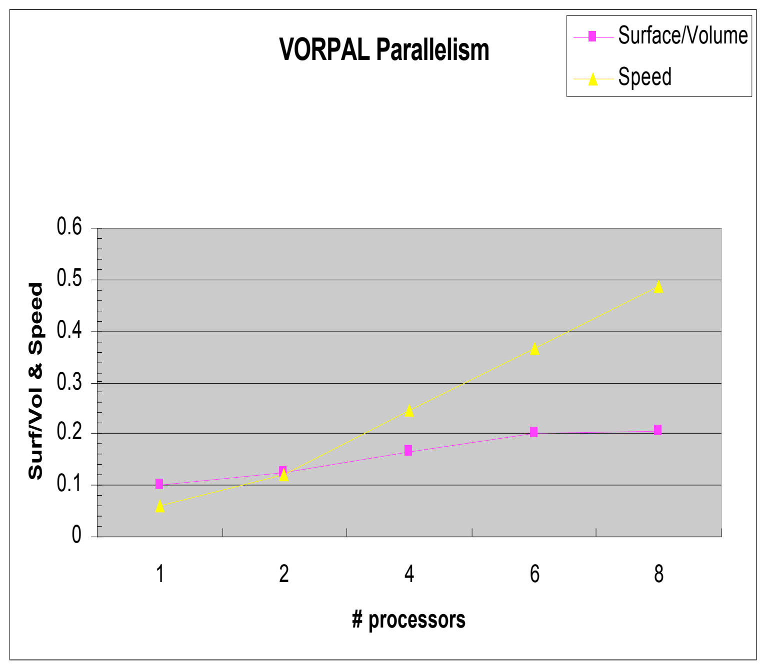


General decomposition *allows* load balancing

Domains down to 45x25x25 with 140k particles, 20% surf/vol



Set theory based messaging



Moving Ionization Algorithms from OOPIC to VORPAL

- OOPIC is a 2-D (x-y & r-z) electromagnetic PIC code
  - Includes Monte Carlo collision (MCC) models
    - These enabled rapid implementation of relativistic electron-impact and field-induced tunneling ionization algorithms
  - Uses MPI for parallel computing (1-D domain decomposition)
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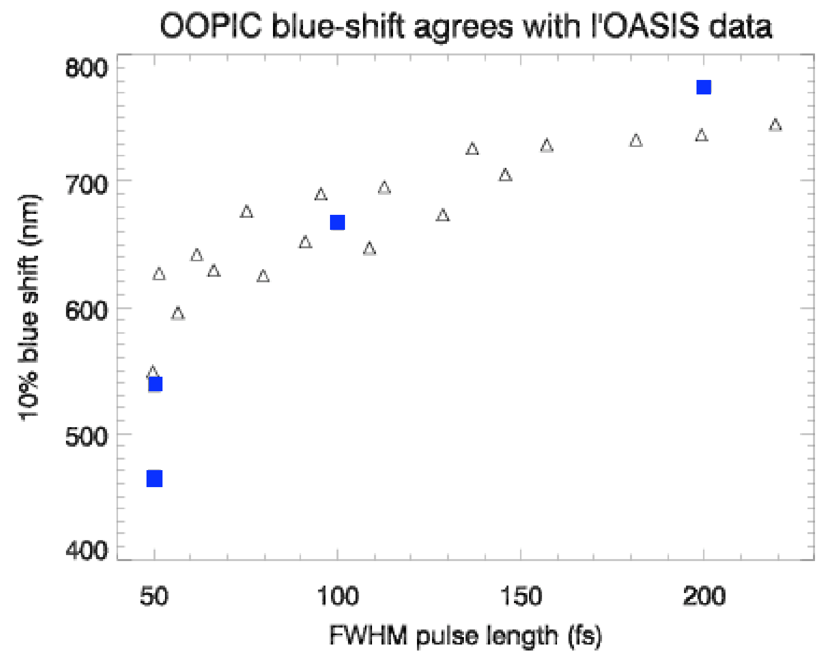
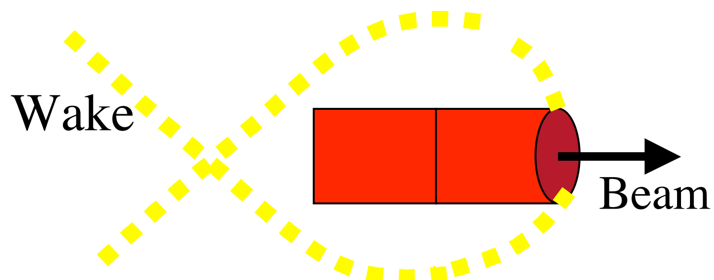
- OOPIC ionization algorithms have been validated against data from the l'OASIS lab at LBNL:



quickPIC

- Quasi-static approximation: driver evolves on a much longer distances than wake wavelength
  - Frozen wakefield over time scale of the bunch length
  - 

  - => □ and/or x_R >> $□_z$ (very good approximation!)

Basic equations for approximate QuickPIC

- **Quasi-static or frozen field approximation converts Maxwell's equations into electrostatic equations**

Maxwell equations in Lorentz gauge

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)\mathbf{A} = \frac{4\pi}{c}\mathbf{j}$$

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)\phi = 4\pi\rho$$

Quasi-static approx.

$$\partial_t A = \partial_\xi A(z - ct)$$

Reduced Maxwell equations

$$-\nabla_\perp^2 \mathbf{A} = \frac{4\pi}{c}\mathbf{j}$$

$$-\nabla_\perp^2 \phi = 4\pi\rho$$

Local--ϕ,A at any z-slice depend only on ρ,j at that slice!

- $\mathbf{j} = \mathbf{j}_b + \mathbf{j}_e \approx \mathbf{j}_b = c\rho_b \hat{z}$ $\quad (\mathbf{A} = A_{//}\hat{z})$

- $\psi = \phi - A_{//}$

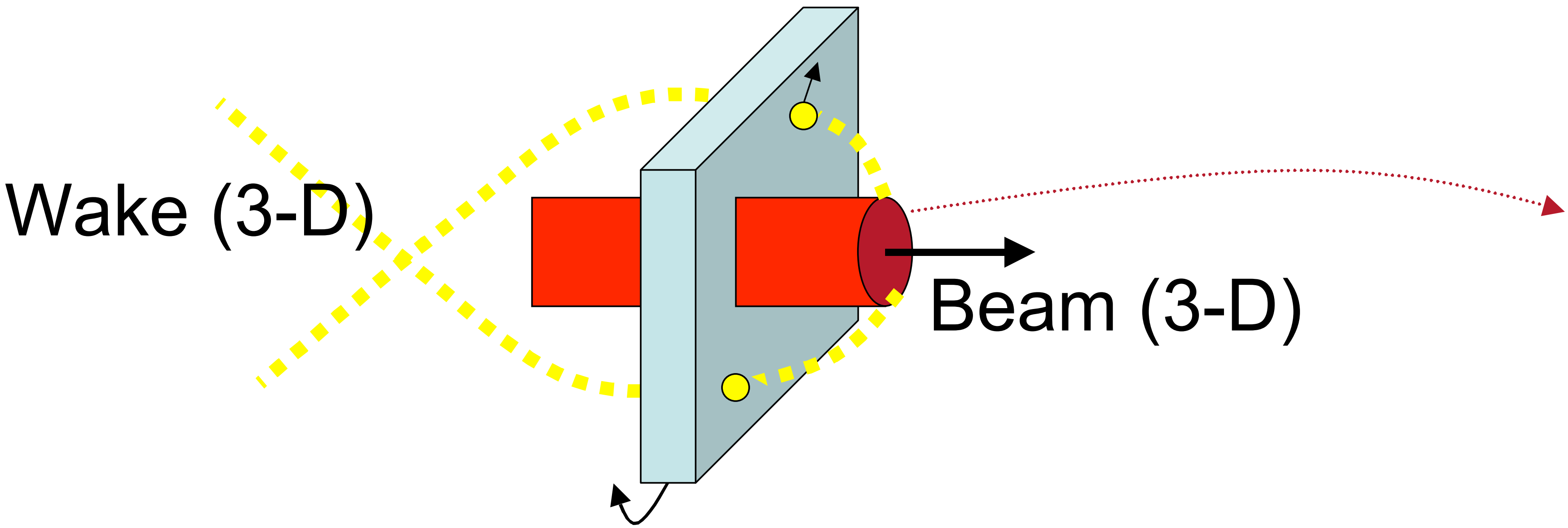
Forces:

plasma: $F_{e\perp} = -e\nabla_\perp\phi$

beam: $F_{b\perp} = -e\nabla_\perp\psi$

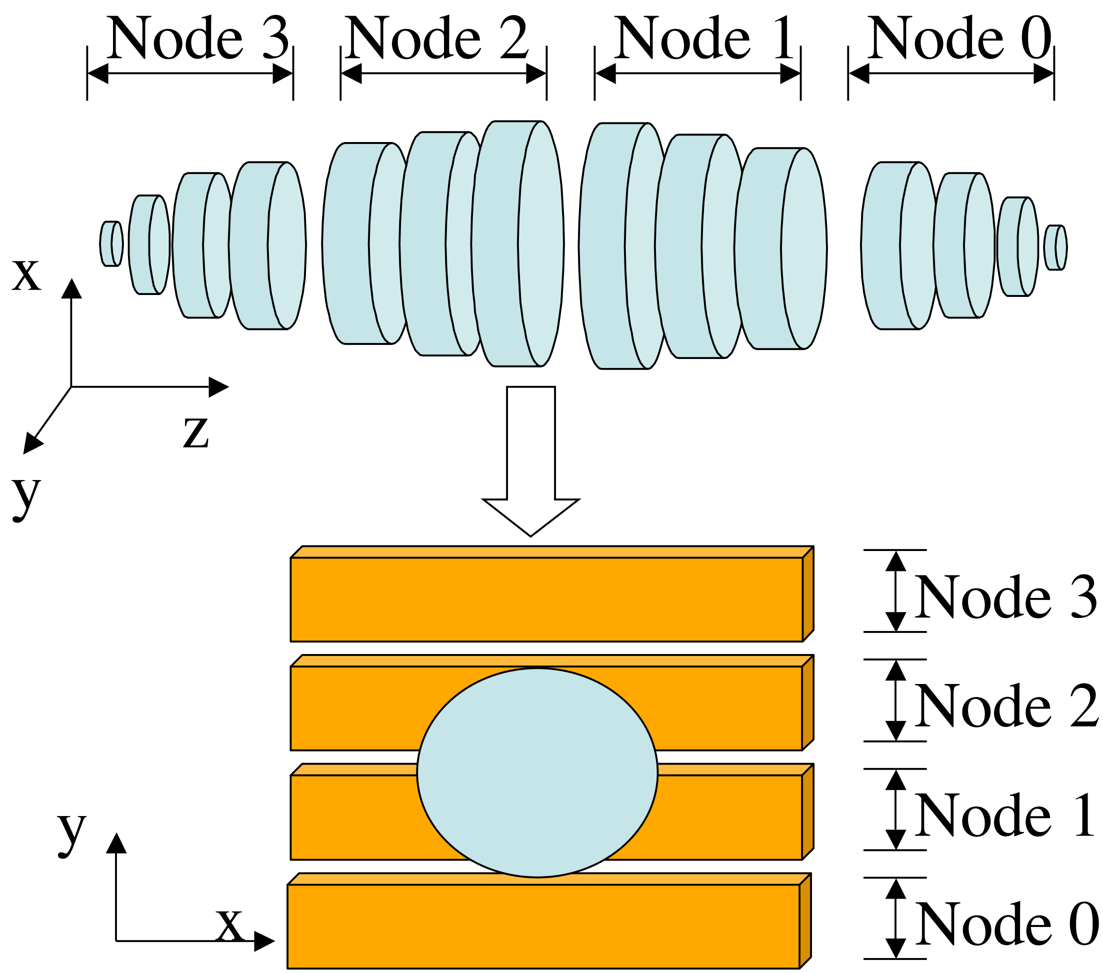
QuickPIC loop (based on UPIC):

2-D plasma slab



1. *initialize beam*
2. *solve* $\square_{\square}^{2}\square = \square, \square_{\square}^{2}\square = \square_{e} \; \square \; F_{p}, \square$
3. *push plasma, store* □
4. *step slab and repeat* 2.
5. *use* □ *to giant step beam*

Parallelization of QuickPIC



Benchmarking

Full PIC: OSIRIS and OOPIC

- ***particle drivers***
- ***laser drivers***

Full PIC vs. quasi-static PIC: OSIRIS and quickPIC

- ***particle drivers***

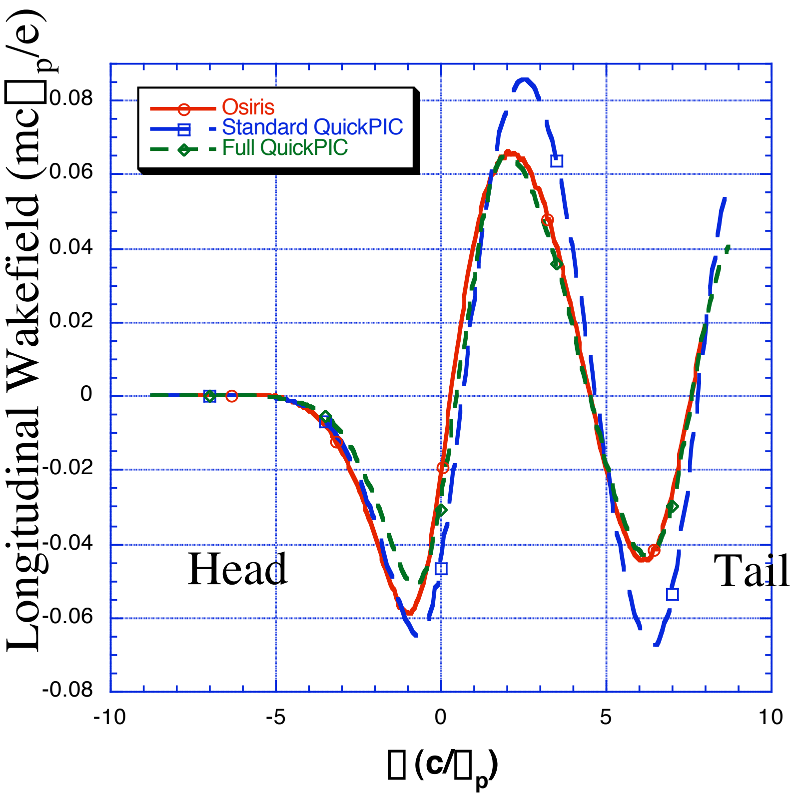
PIC vs. Fluid:

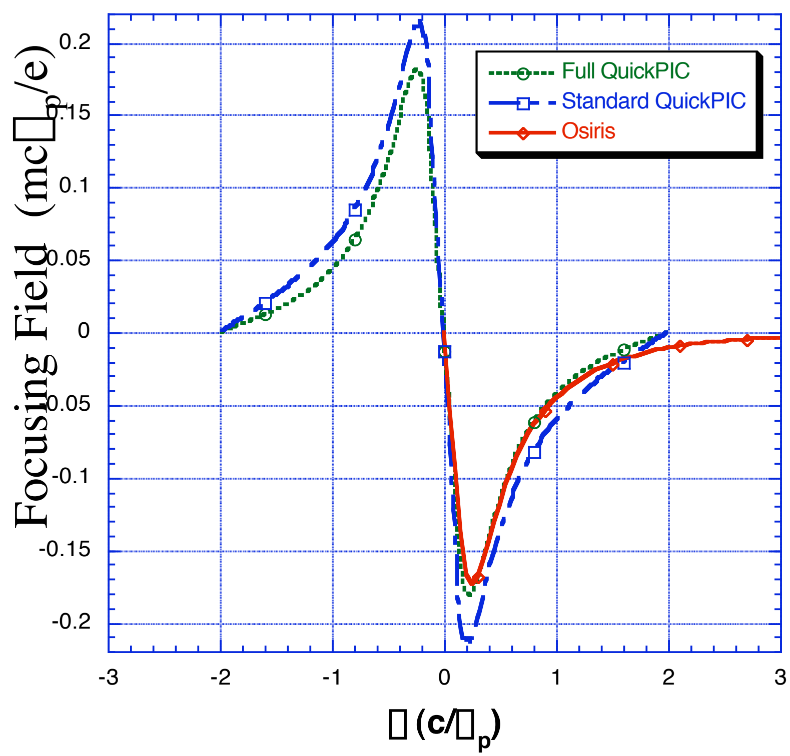
- ***Laser drivers***
- ***particle drivers***

Simulation against theory

- ***trapping mechanism in all optical injection***

quickPIC vs. OSIRIS
Positron driver

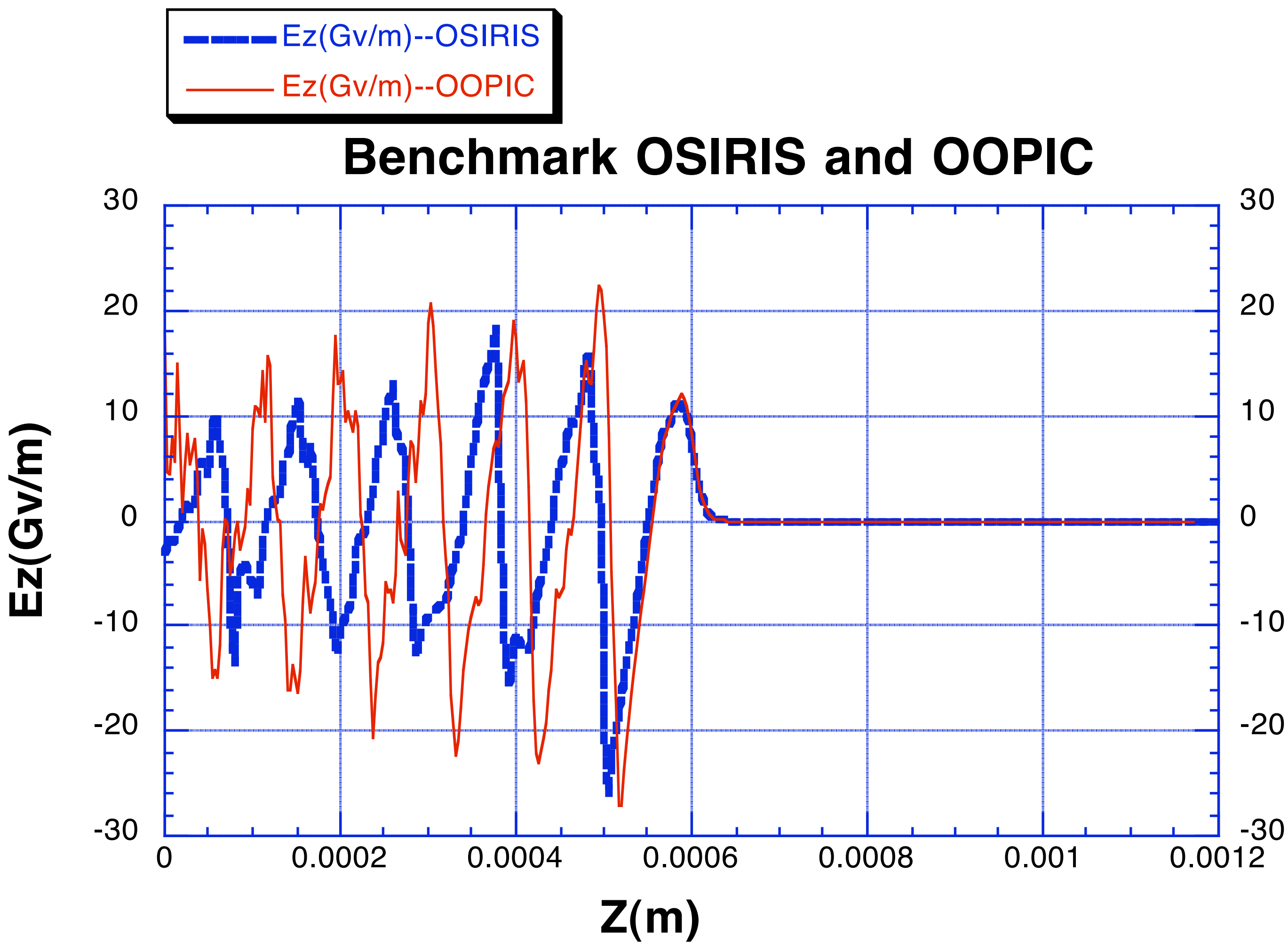




Plasma density = 2.1E14 cm^{-3}, Beam Charge = 1.8E10 e^{+}

Wakefield and focusing field from QuickPIC agree well with those from Osiris, and it is >100 times faster!.

Benchmarking (2D) field ionization routines: OOPIC and OSIRIS

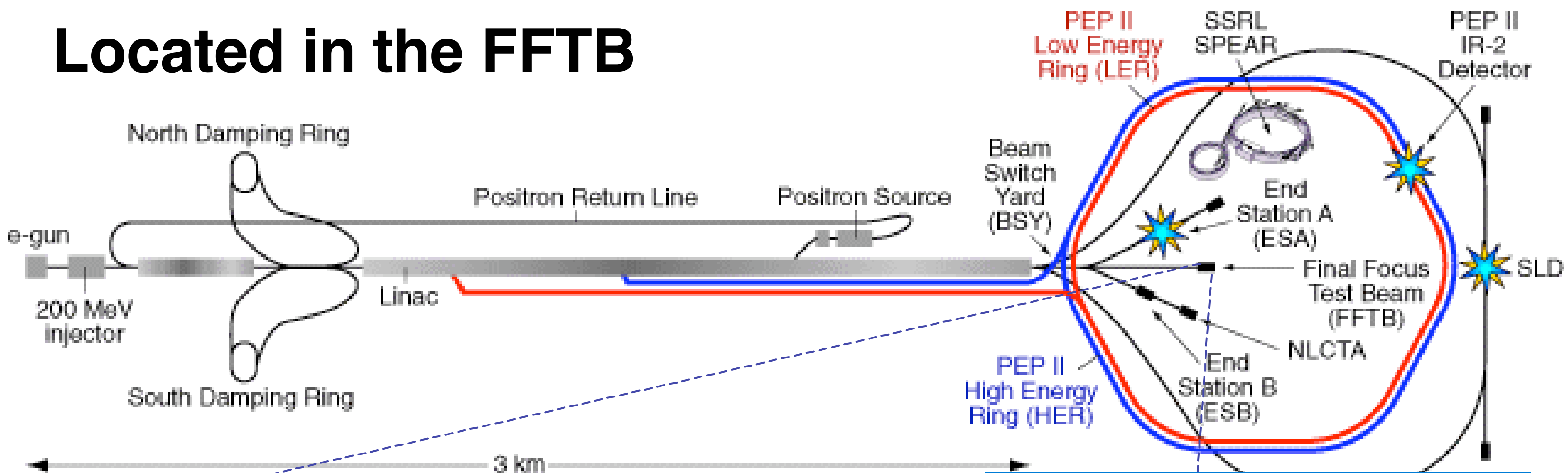


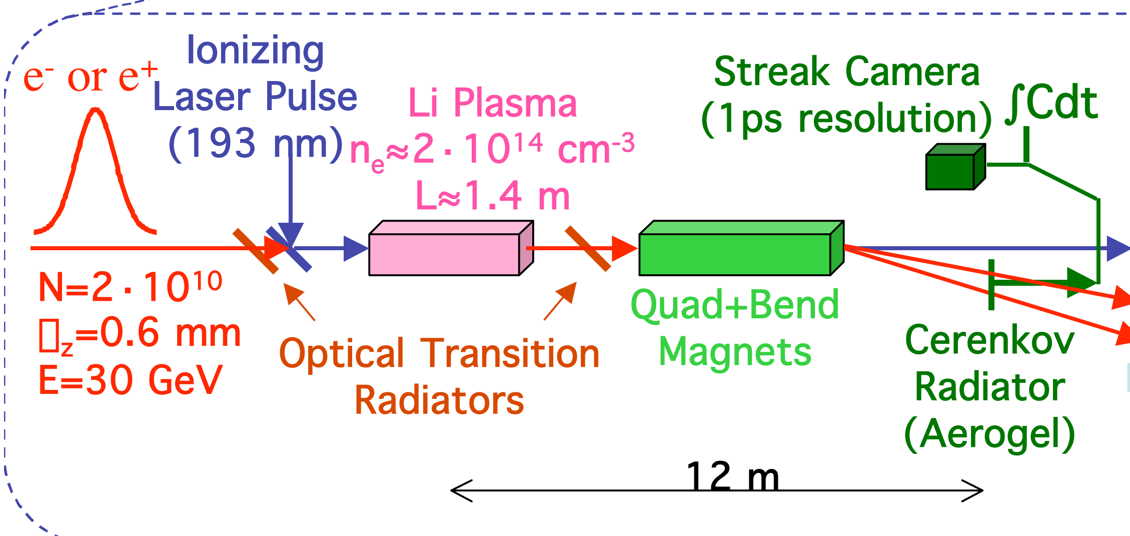
Modeling experiments:
Code validation and interpretation of physics

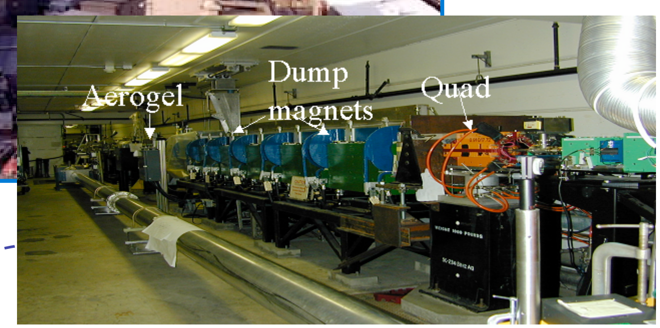
- Plasma wakefield accelerator(PWFA)
  - E-157/E-162
    - electron acceleration/focusing
    - positron acceleration/focusing
- Laser wakefield accelerator(LWFA/SMLWFA)
  - L'OASIS(LOA)
    - Blue shifts
    - self-trapped electrons

E-162 Plasma Wakefield Expt.

Located in the FFTB



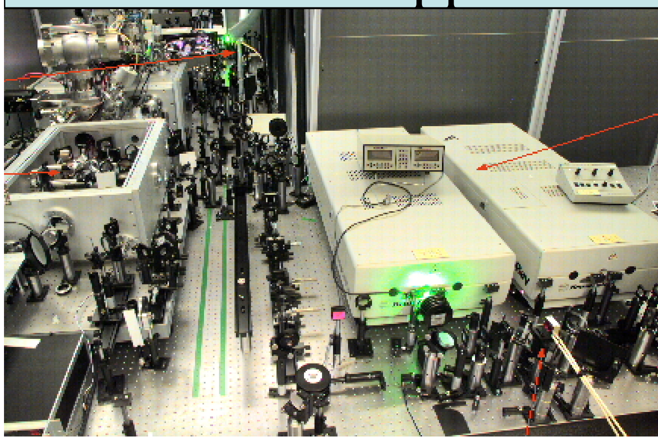




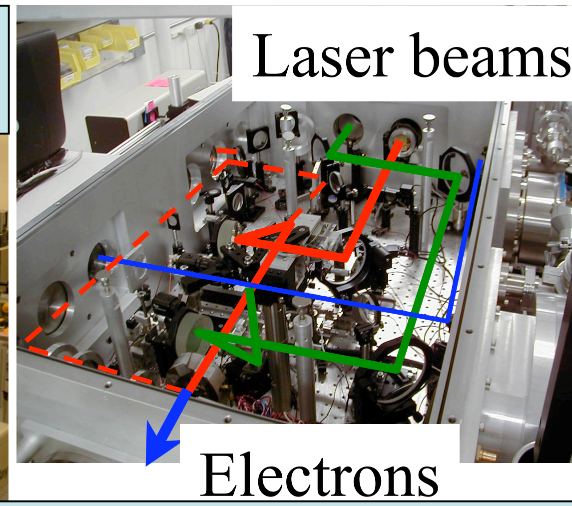
Laser-plasma accelerator R&D at l'OASIS lab

- Test bed for R&D concepts towards 1 GeV module of a laser accelerator and applications
- Facility includes 10 TW, 50 fs laser system @ 10 Hz (100 TW under development)
- Laser, plasma and beam diagnostics; radiation shielded experimental bays
- Training ground for students and postdocs

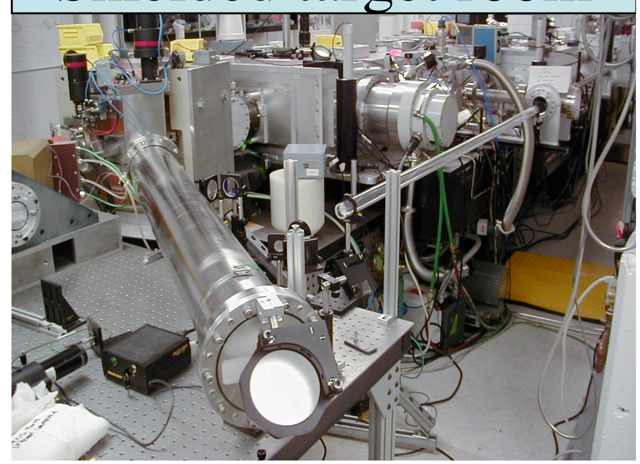
10 TW Ti:sapphire

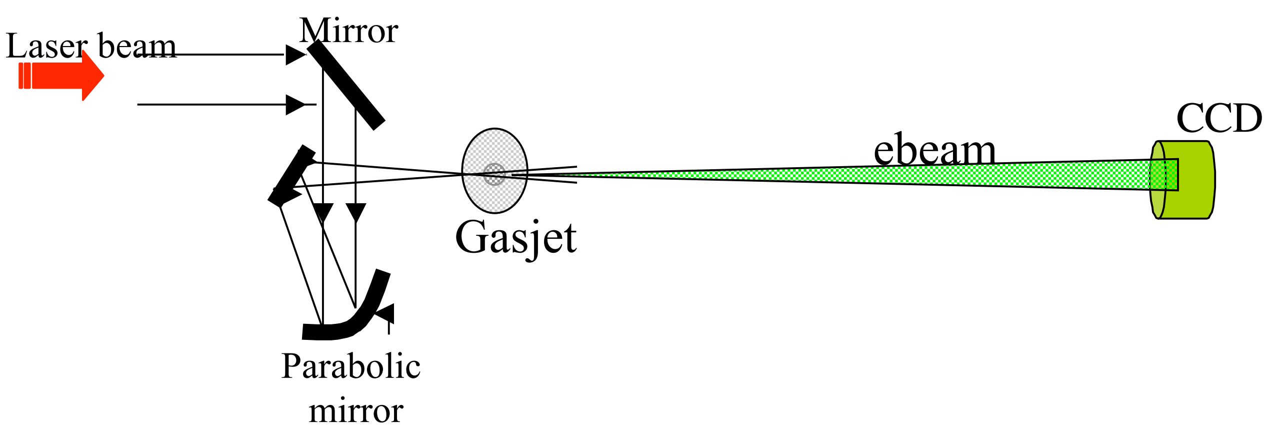


100 TW Ti:sapphire
Under construction



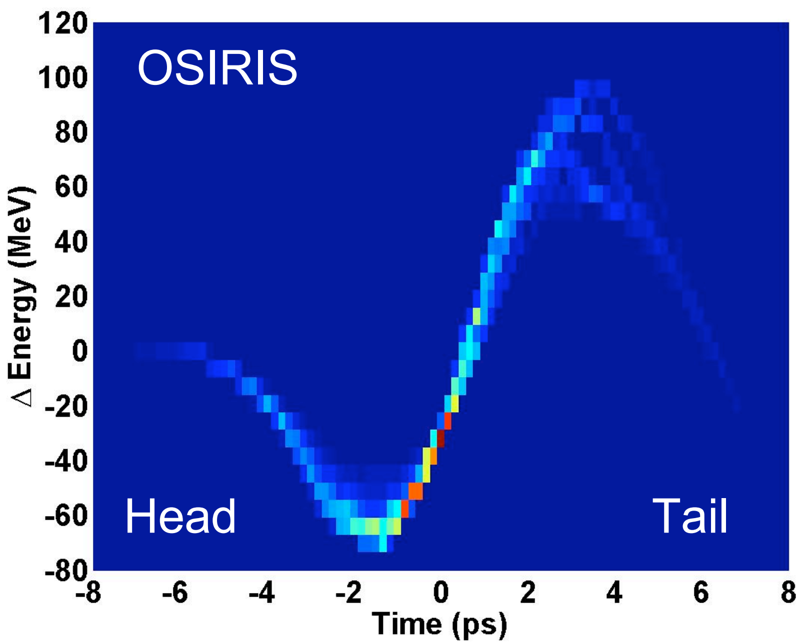
Shielded target room

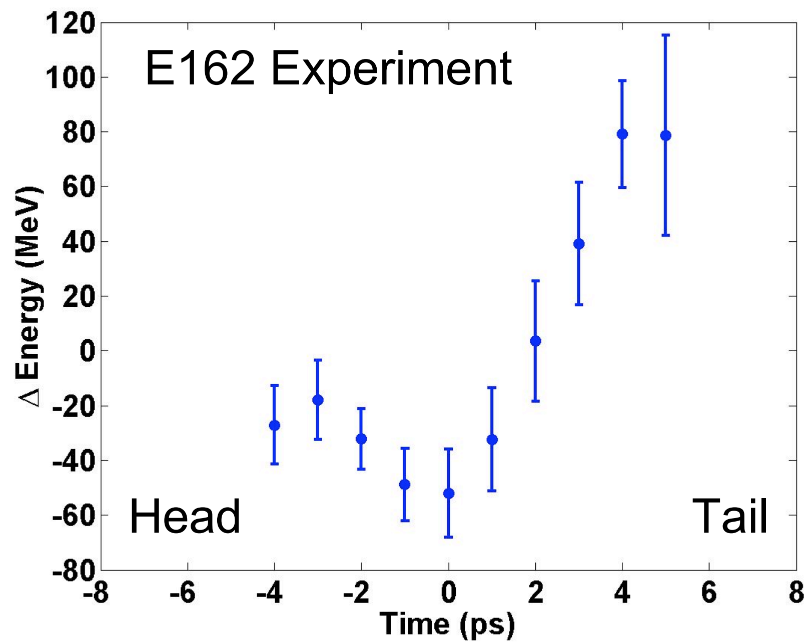




Excellent agreement between simulation and experiment of a 28.5 GeV positron beam which has passed through a 1.4 m PWFA

	Peak Energy Loss	Peak Energy Gain
OSIRIS Simulation Prediction:	64 MeV	78 MeV
Experimental Measurement:	65±10 MeV	79±15 MeV





5×10^8 e^+ in 1 ps bin at +4 ps

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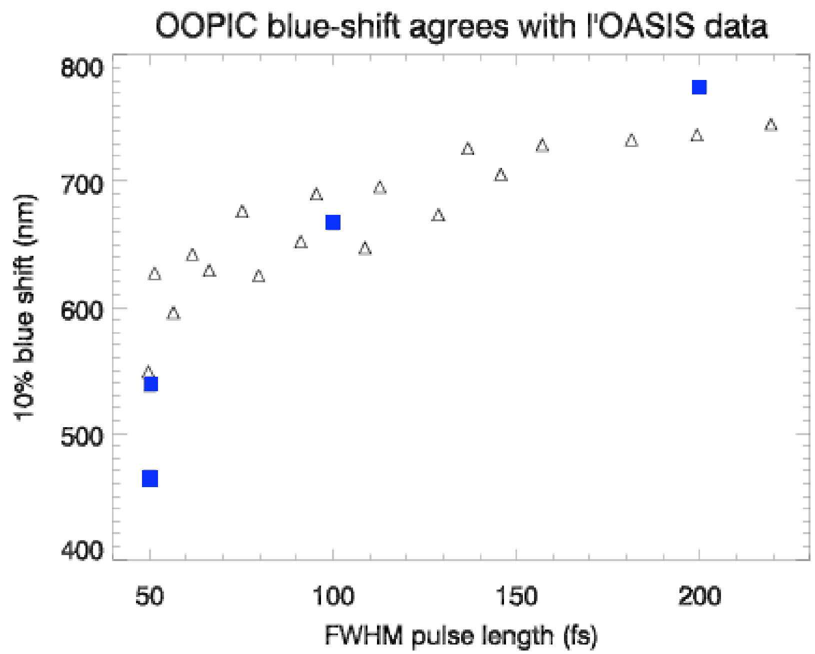
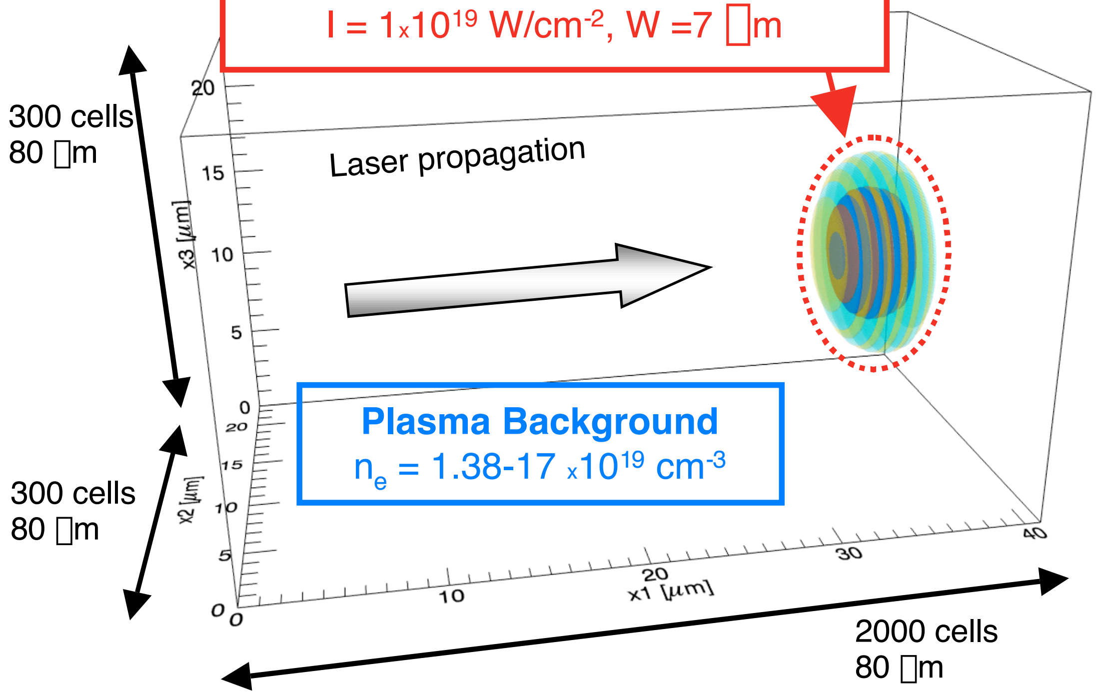


Full scale 3D LWFA and SMLWFA simulations:
L'OASIS parameters

State-of- the- art ultrashort laser pulse

λ_0 = 800 nm, Δt = 35 fs

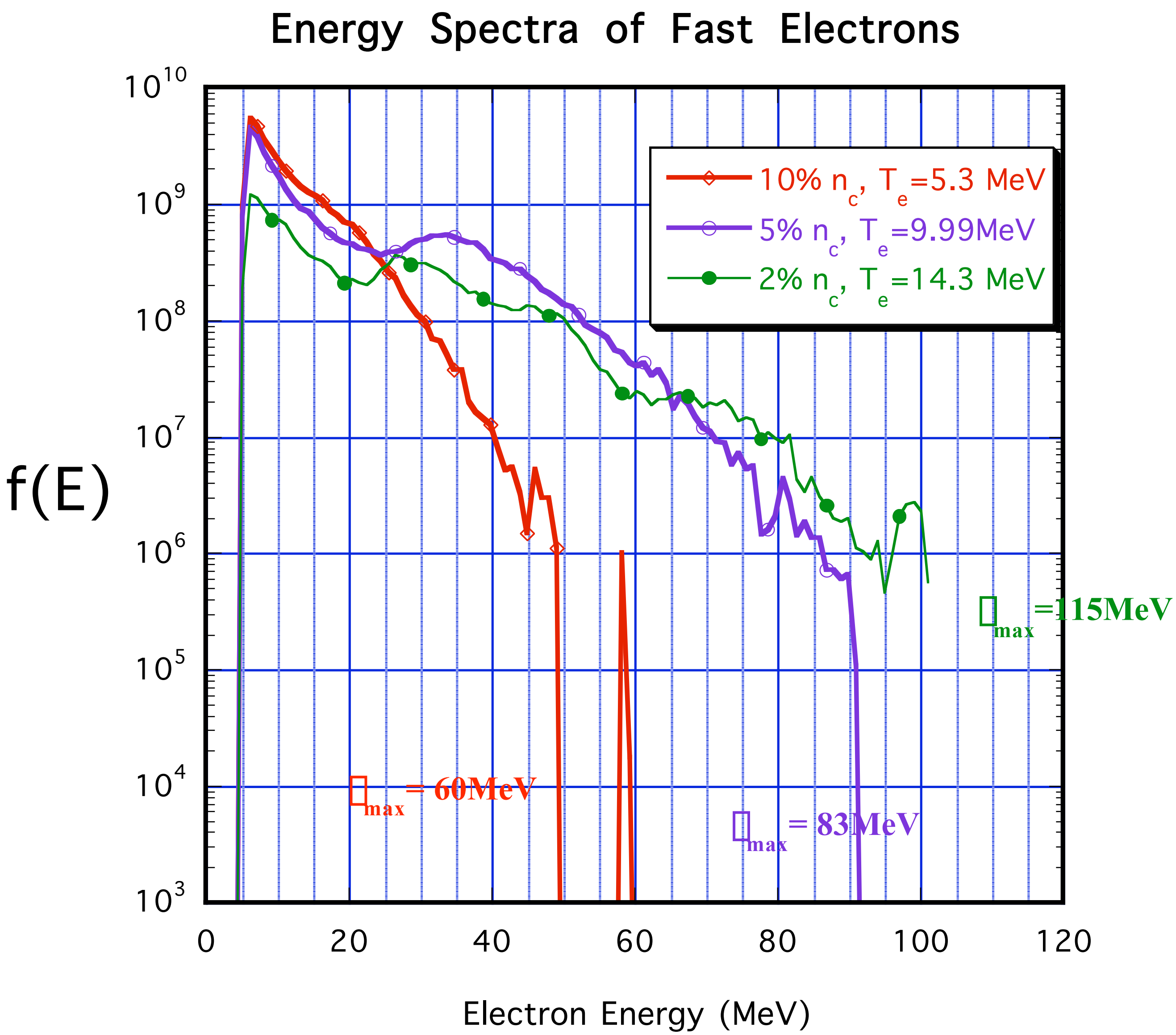
I = 1×10^{19} W/cm^{-2}, W =7 μm



- Simulation Parameters
  - Laser:
    - a_0 = 3
    - ω_l/ω_p = 3 to 15
  - Particles
    - 1x2x2 particles/cell
    - 200 million total
- The parameters are similar to those at LOA and LBNL

Simulation ran for ~10000 time steps
(~3 Rayleigh lengths)

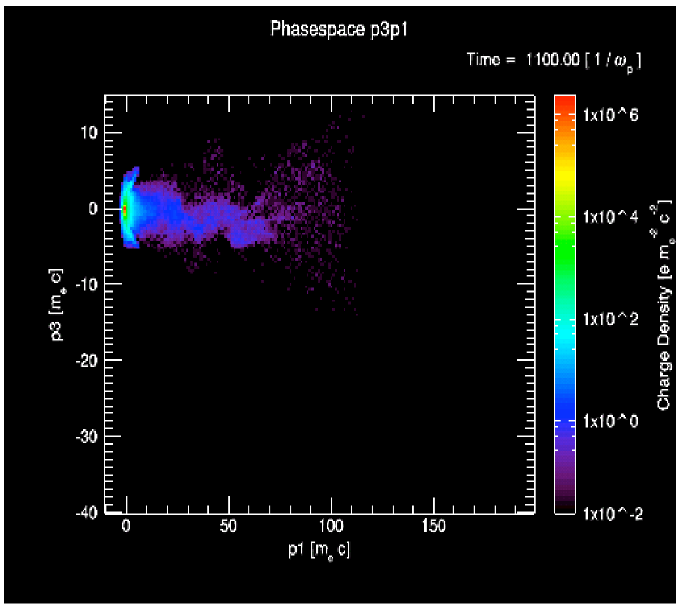
Electron spectra is **consistent** with results from LOA



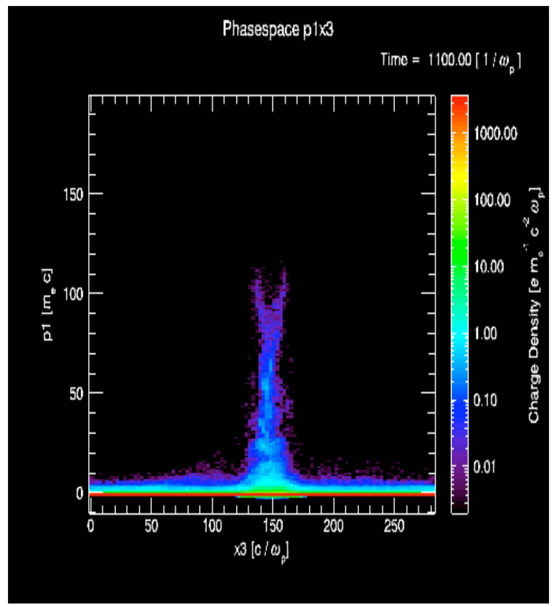
In 3D the electrons have an asymmetric spot size in the plasma:

laser effects acceleration

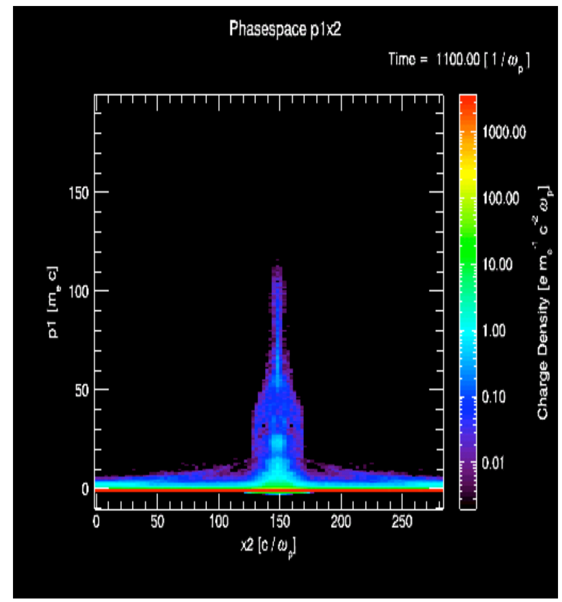
what happens when they exit the plasma? (Electrostatic PIC combined with semi-analytical model: Fubiani)



p3 vs. p1



p1 vs. x3



p3 vs. x2

Modeling planned experiments: Providing guidance

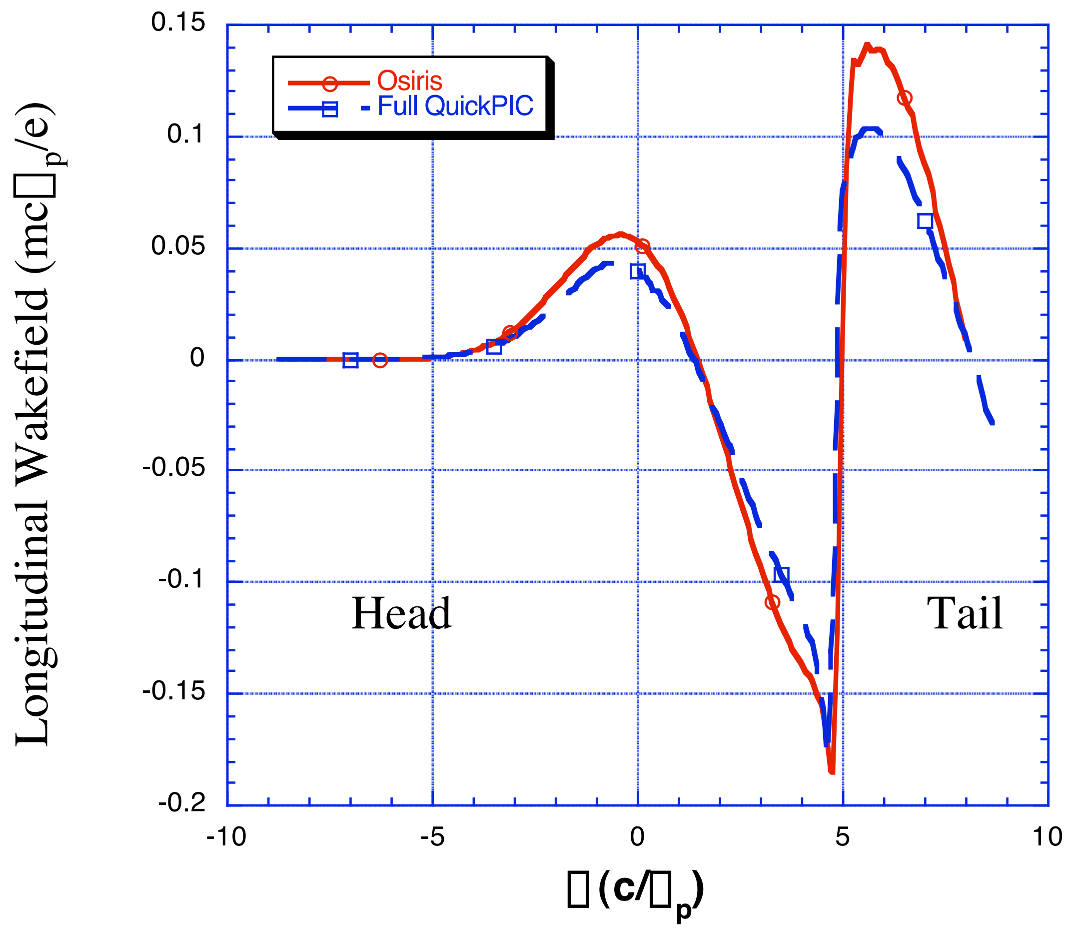
Plasma wakefield accelerator(PWFA)

- *E-164/E-164x*
  - *high-gradient electron acceleration*
  - *bunch length scaling*
  - *ionization*

Laser wakefield accelerator(LWFA/SMLWFA)

- *L'OASIS(LOA)*
  - *all optical injection*
  - *acceleration in channels*

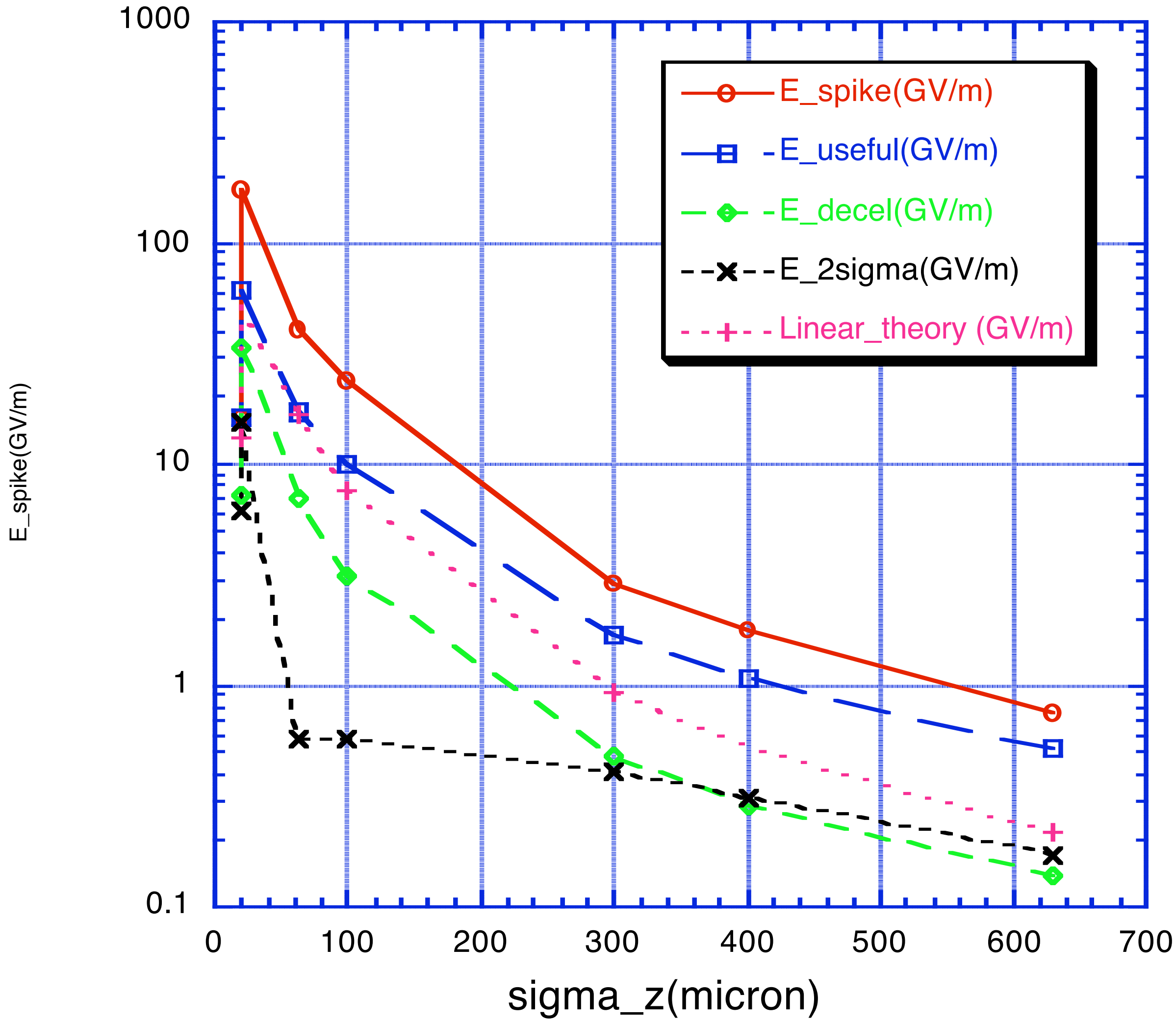
Benchmarking



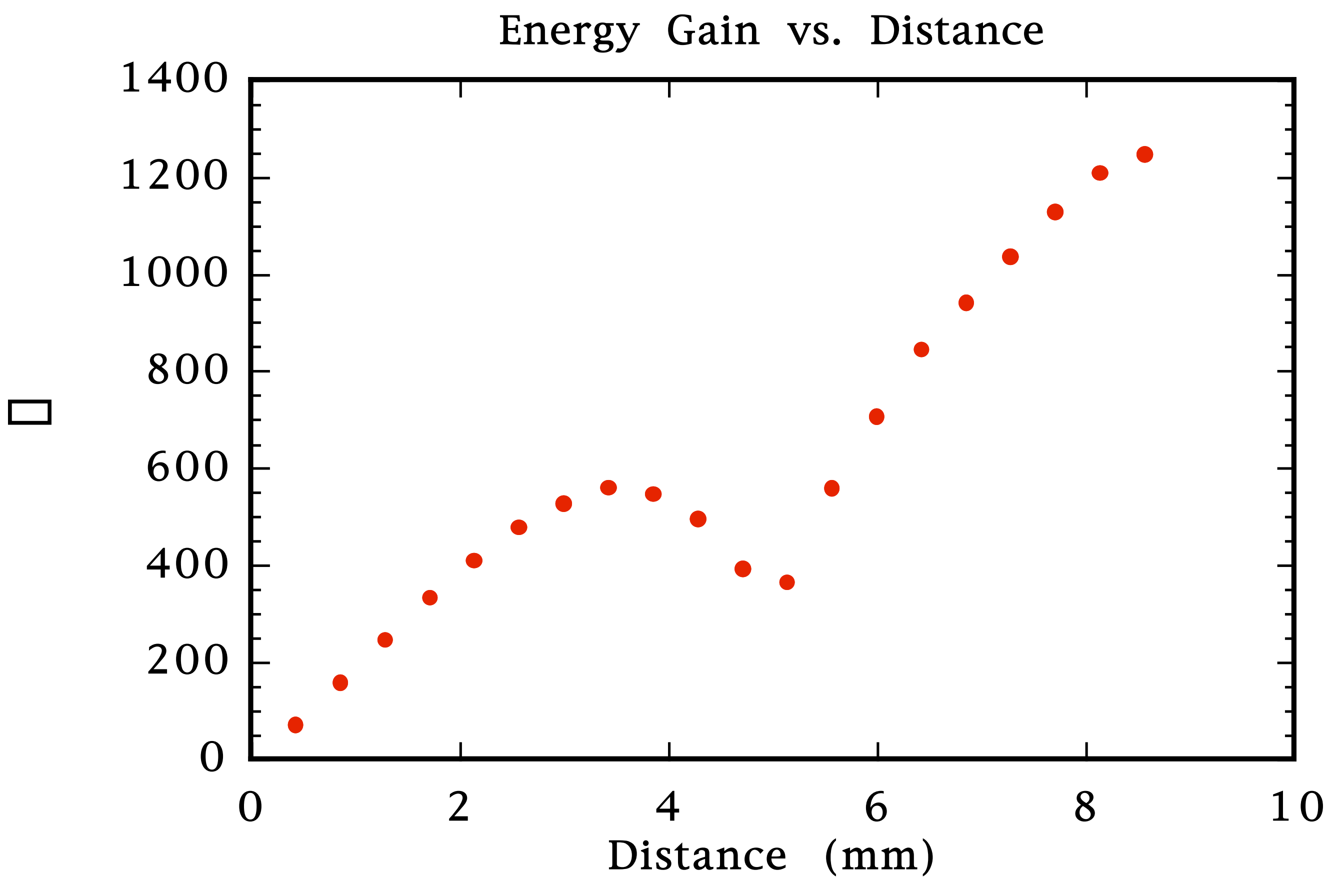
Result from benchmark run with plasma density = 2.1E14 cm^{-3}, beam charge = 1.8E10 e^{-}. QuickPIC run with periodic boundary, Osiris run with conducting boundary.

Bunch length scaling:
E164 and Afterburner parameters

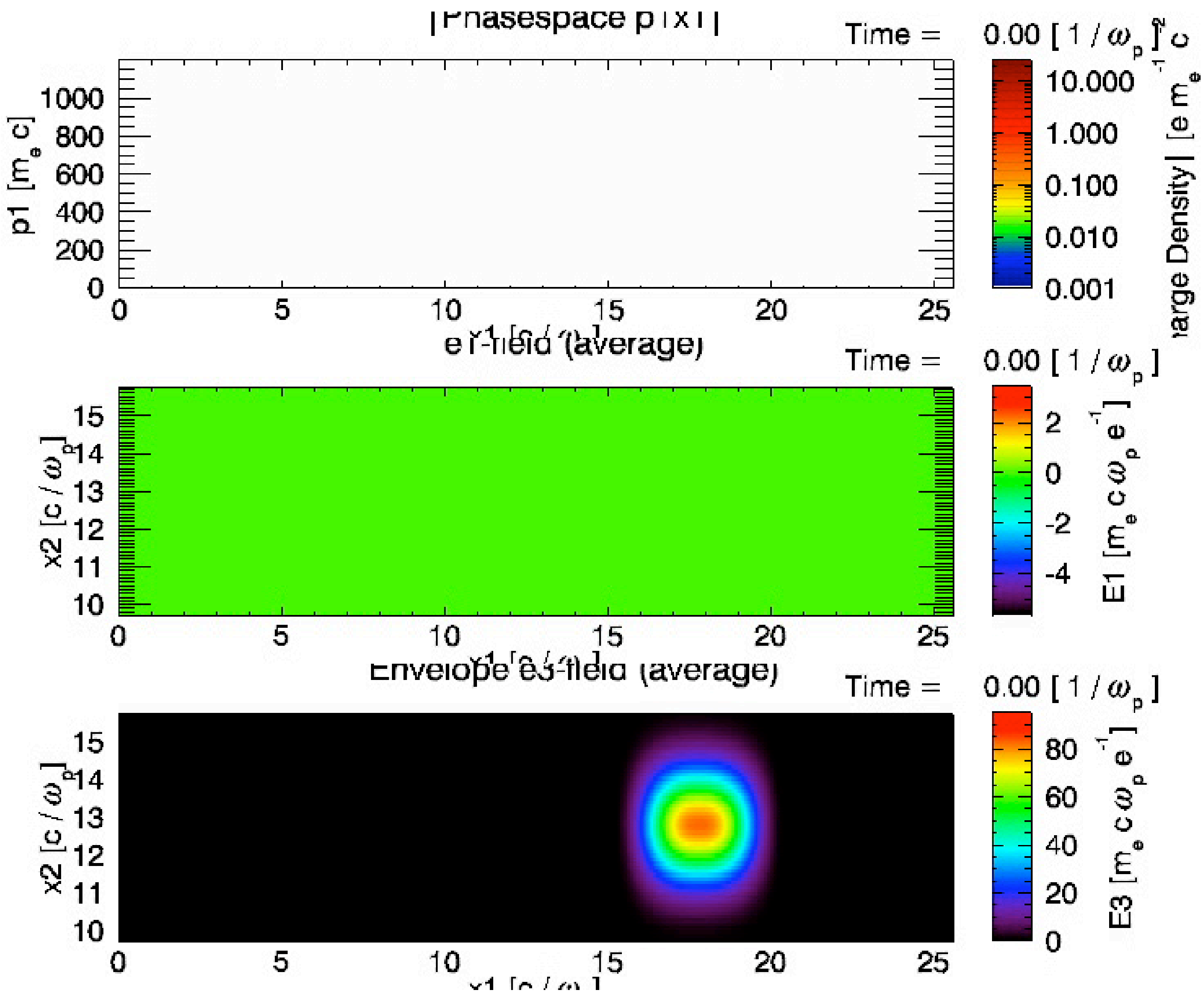
Sigma_r=25 micron



Pulse distortion leads to a second phase of acceleration



Modeling a 5TW 50 fs laser propagating through 60 Raylengths in a plasma channel



Fluid Code: Laser pulse in a channel

- 2D Fluid-Maxwell Code
  - Relativistic and nonlinear
  - No averaging: laser oscillations resolved
  - Moving window
- Detailed comparisons to particle codes in progress

- Example: Laser pulse in a plasma channel
  - Wakefield generation
  - Laser pulse energy depletion
  - Frequency red-shifting
- Parameters: Achievable at the l'OASIS lab

$$L_{\mathrm{FWHM}} = 30\ \mathrm{fs},\ \lambda_0 = 0.8\ \mu\mathrm{m},\ r_0 = 12\ \mu\mathrm{m},\ Z_R = 565\ \mu\mathrm{m},\ P = 4.84\ \mathrm{TW}$$

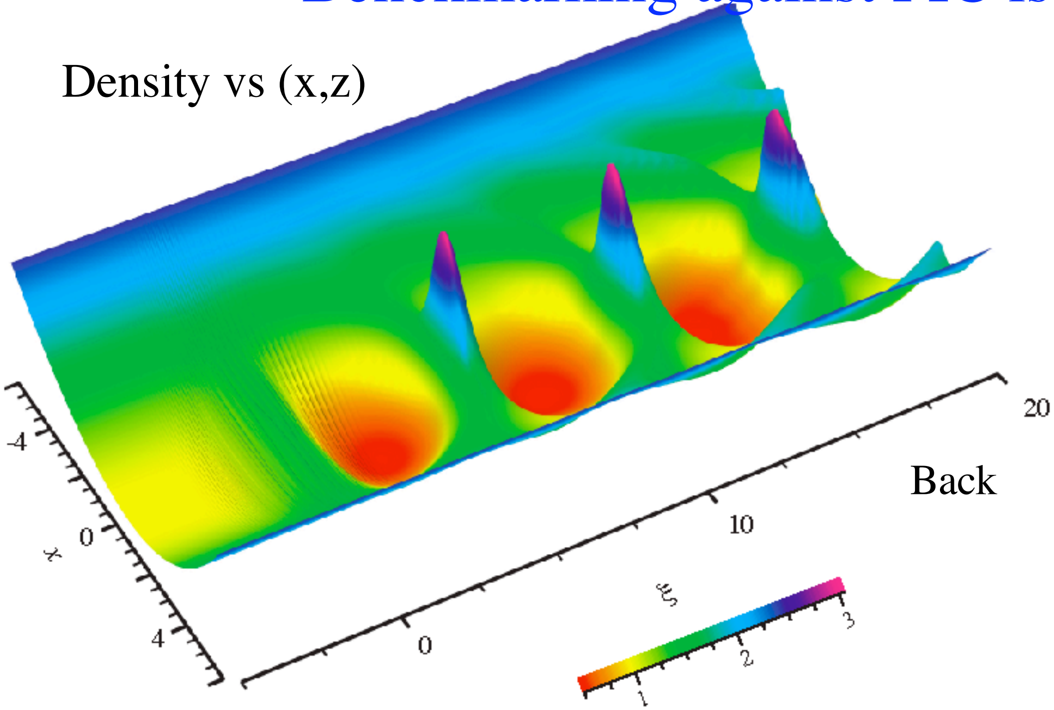
$$\lambda_p = 24\ \mu\mathrm{m},\ n_0 = 4.35 \times 10^{18}\ \mathrm{cm}^{-3},\ \Delta n_c = 7.84 \times 10^{17}\ \mathrm{cm}^{-3}$$

$$L_{\mathrm{D}} = 2.16\ \mathrm{cm},\ E_0 \approx 133\ \mathrm{GV\,m}^{-1},\ E_z\big|_{\max} = 41.3\ \mathrm{GV\,m}^{-1}$$

Laser Wakefields in Plasma Channel

Benchmarking against PIC is beginning

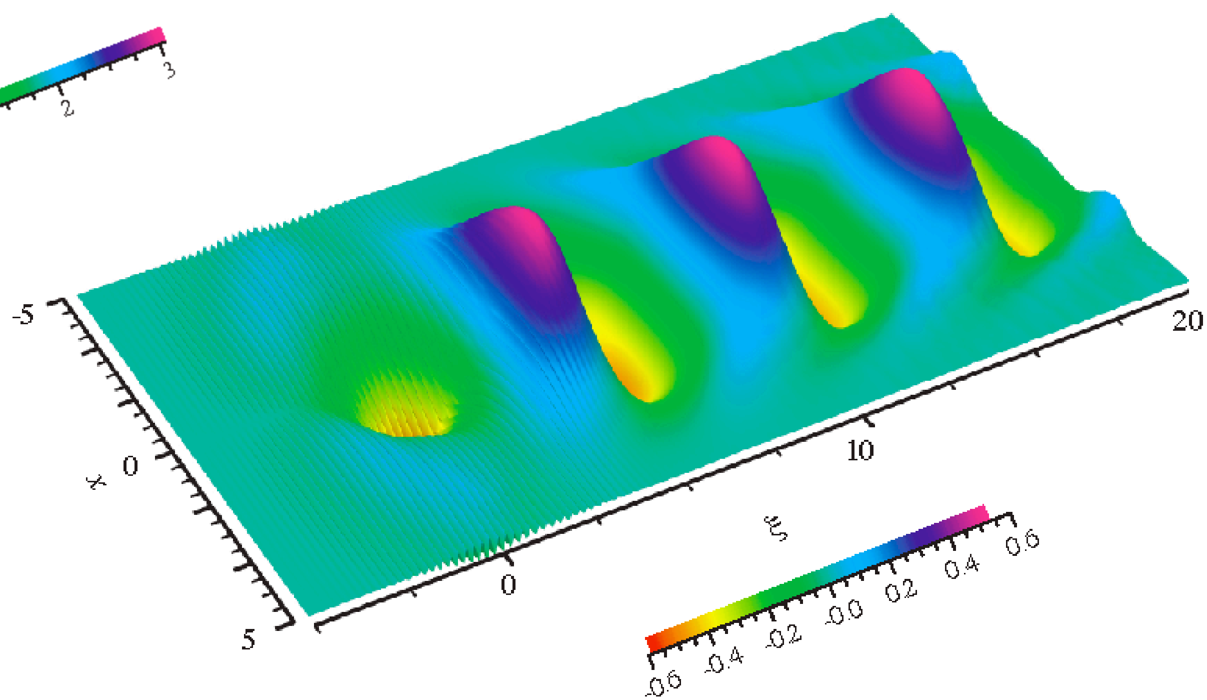
Density vs (x,z)



Nonlinear plasma wave

$\omega_p t = 240$ (0.9 mm)

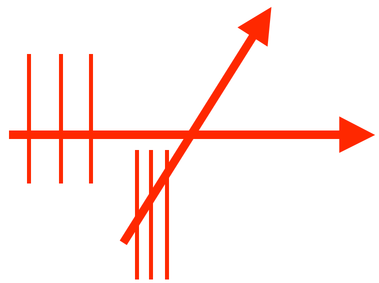
Longitudinal Electric Field vs (x,z)



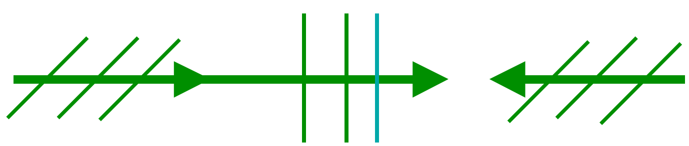
Research focus: How can one inject particles into accelerating region of phase space?

Investigating multiple methods for optical inject, those of others and ours

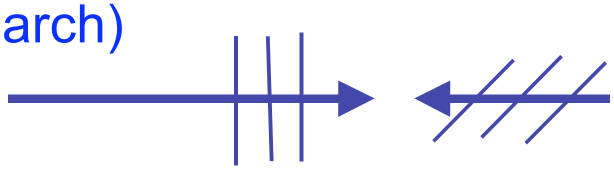
- LILAC



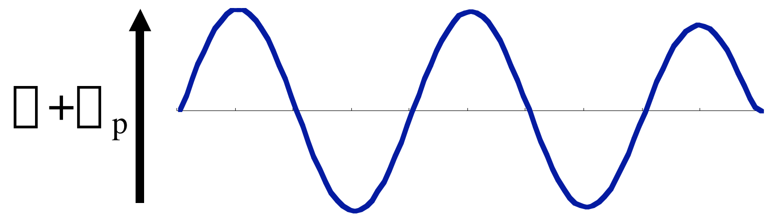
- Beat wave (LBNL)

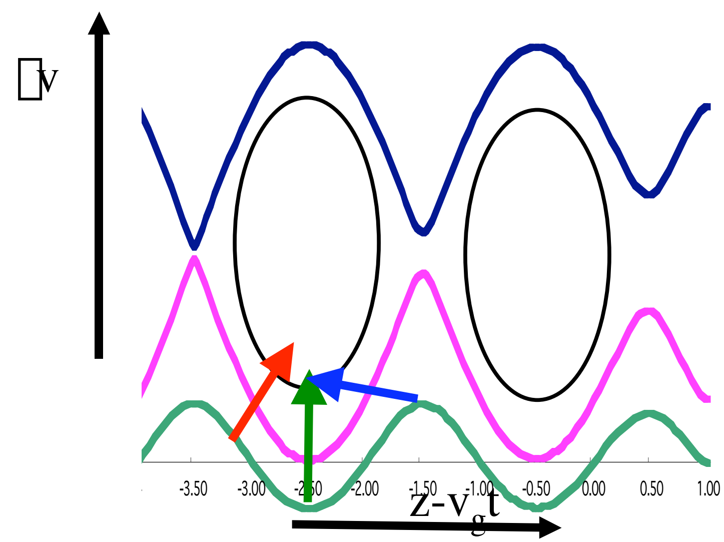


- Phase kick (result of this research)



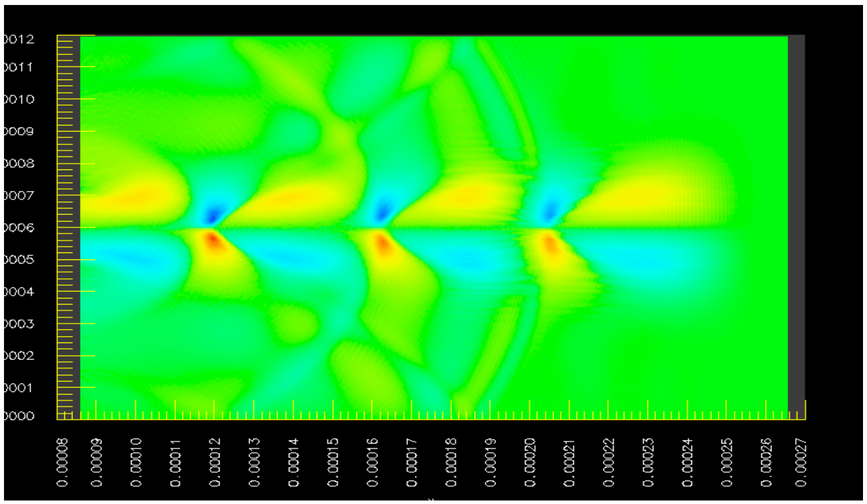
All require moving particles to accelerating/focused region in phase space



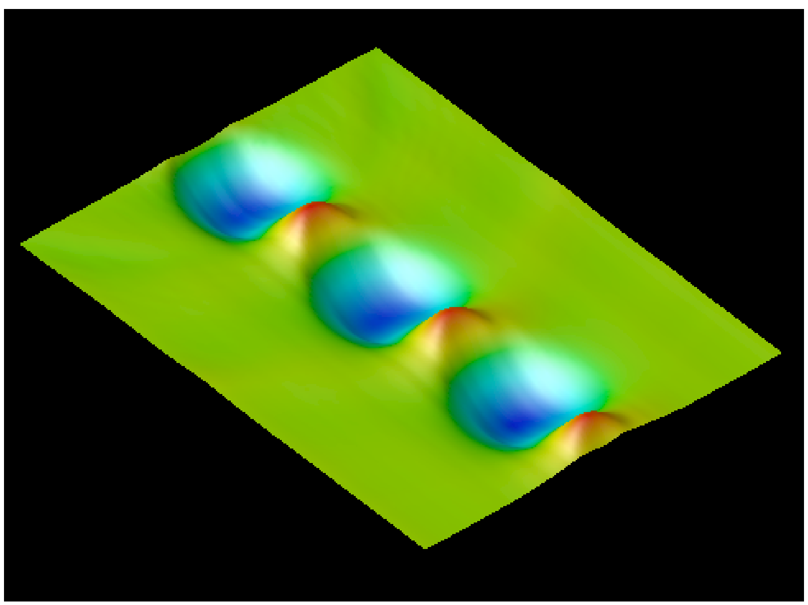


Discovery: The expansion of the focusing region for nonlinear wakes improves trapping mechanism

E_y



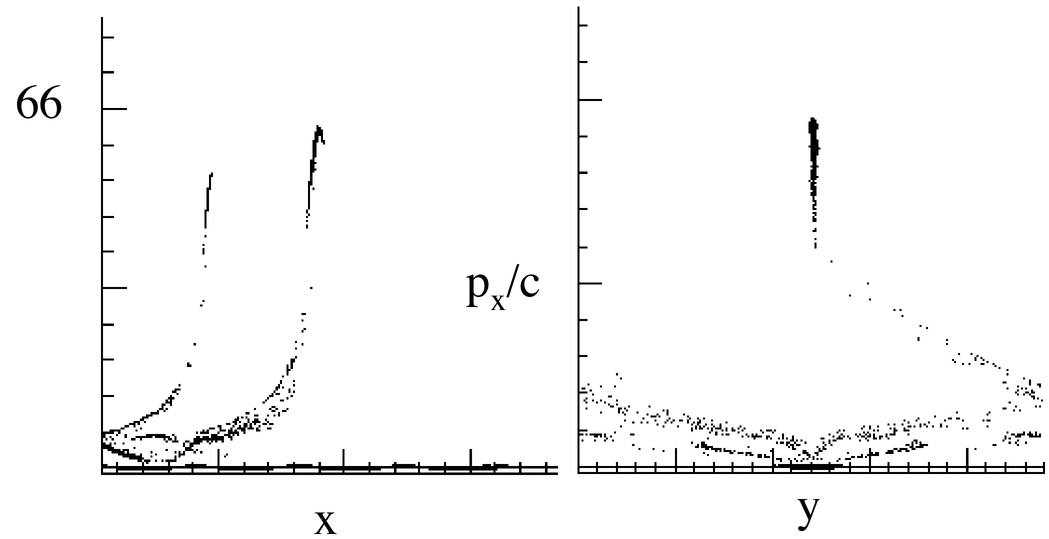
[illegible]



- Focusing region greatly expanded
- Focusing trajectories exists for positive potential
- Consequence: small phase kick can trap particles

Simulations show that focusing collimation forms the beam

- Region of negative potential energy is focusing
- Region of negative phase relative to minimum is accelerating
- Particles stay in this region while accelerating provided they are inside the F/D transition invariant curve
- Place large population of particles just inside this curve and dynamics forms beam after 1/4 of synchrotron (bounce) oscillation



Laser propagates along x

Overplotting shows beams worse than they are
Simulations showing secondary beams

Beyond planned experiments: Afterburner modeling

Nonlinear wakes

preformed

self-ionized

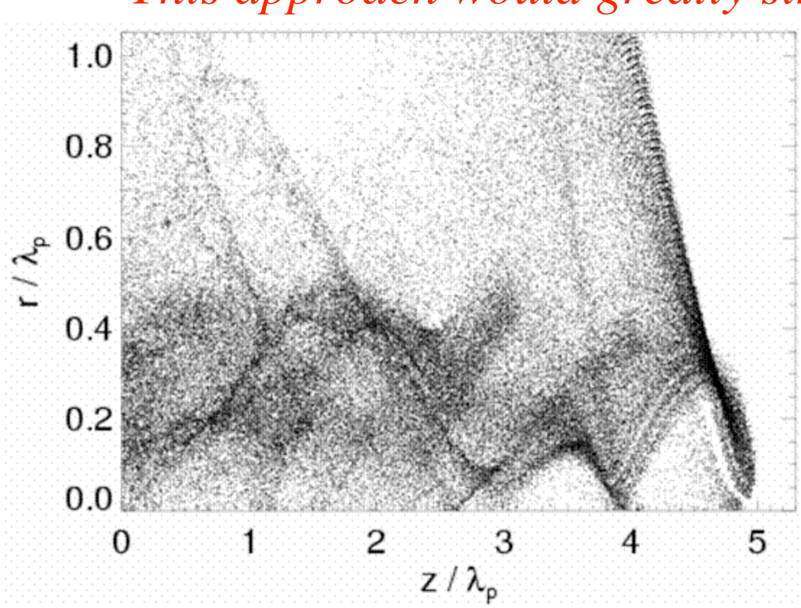
Nonliear beamloading

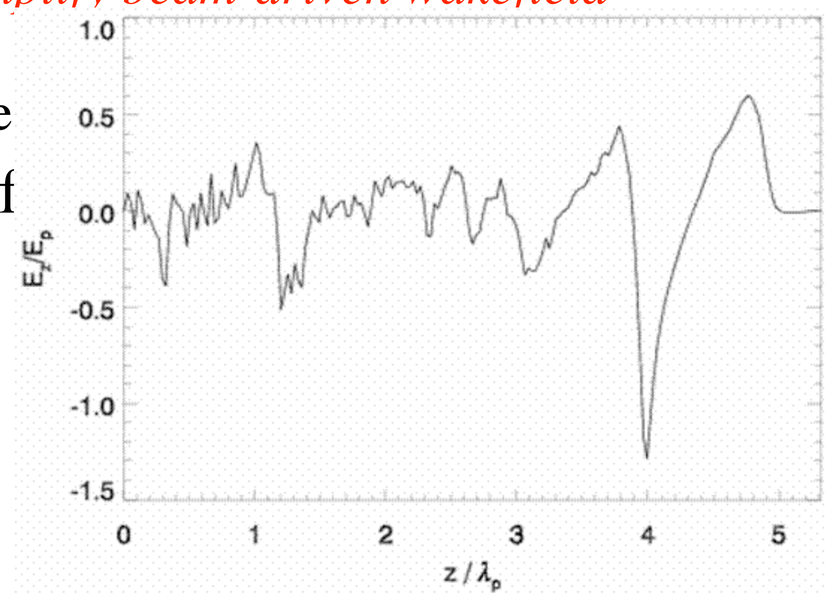
Stability: hosing

Final focusing

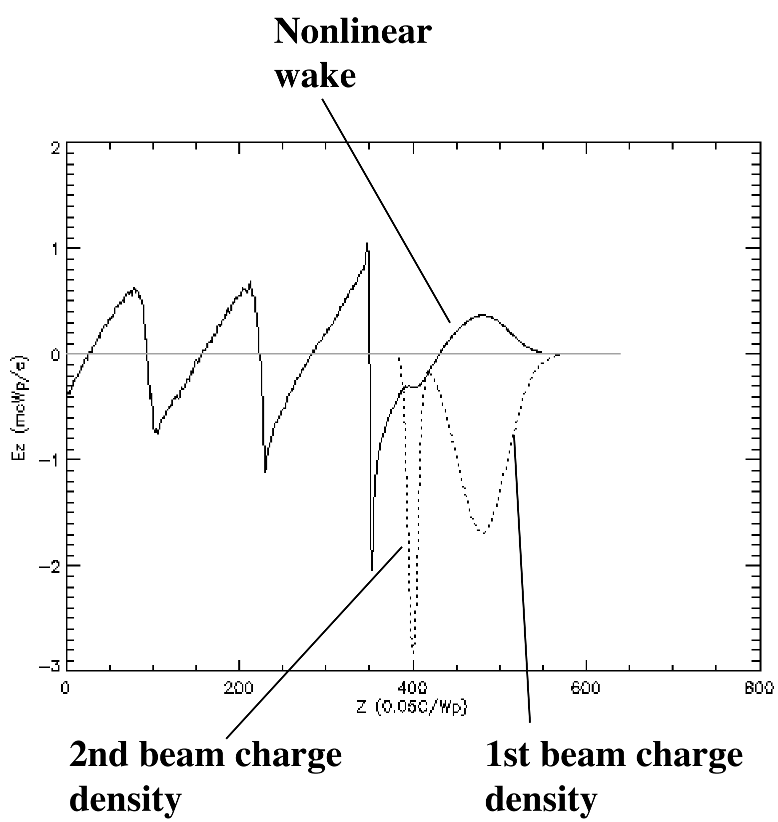
OOPIC shows that a PWFA e- driver can ionize neutral Li

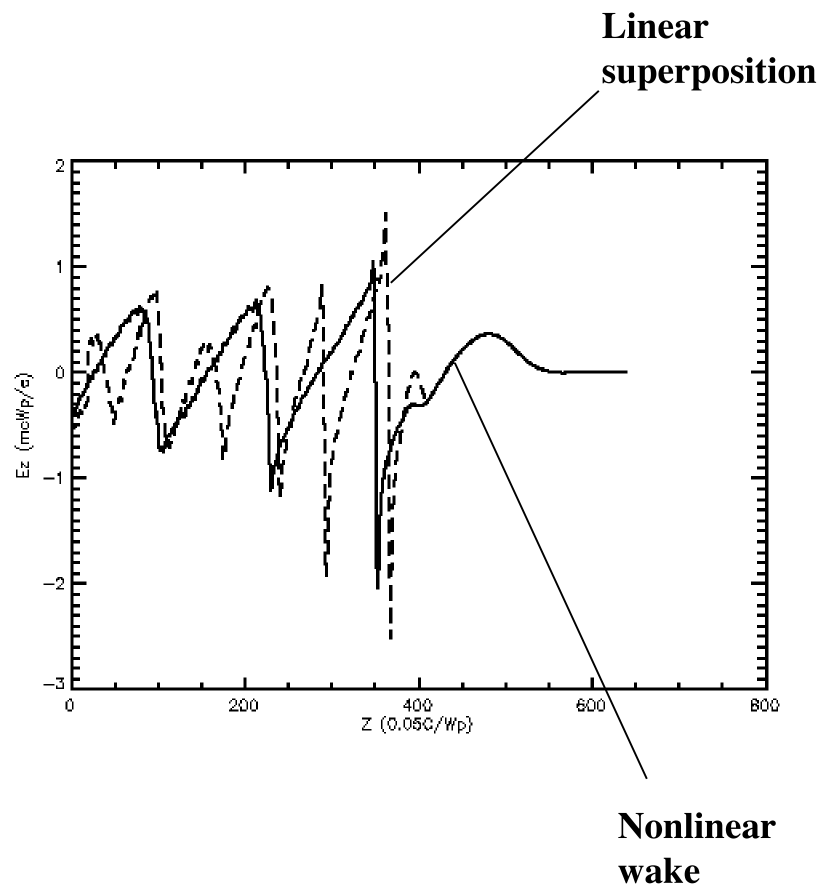
- OOPIC simulations show that tunneling ionization plays a key role in the PWFA afterburner concept
  - The self-fields of the bunch can ionize Li or Cs
  - High particle density (i.e. large self-fields) is required to drive a strong wake
- In Li, a shorter afterburner drive beam could ionize the plasma by itself
  - *This approach would greatly simplify beam-driven wakefield*



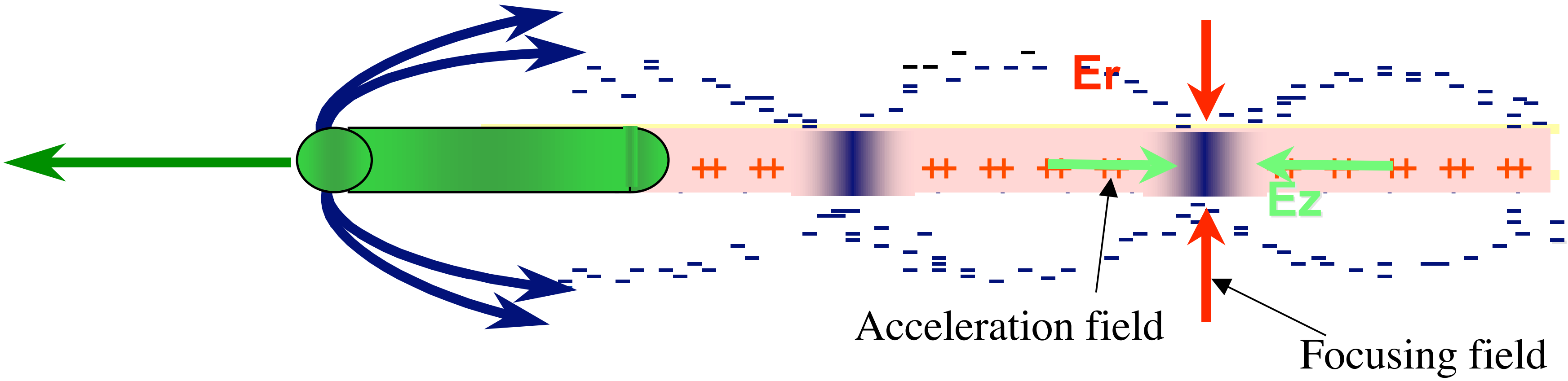


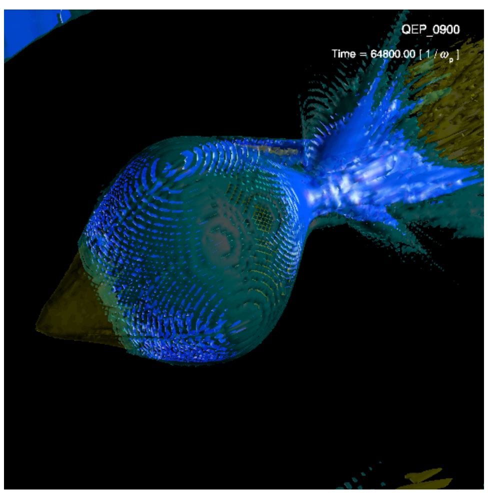
1+1 ≠ 2:
Superpostion cannot be used for nonlinar beamloading



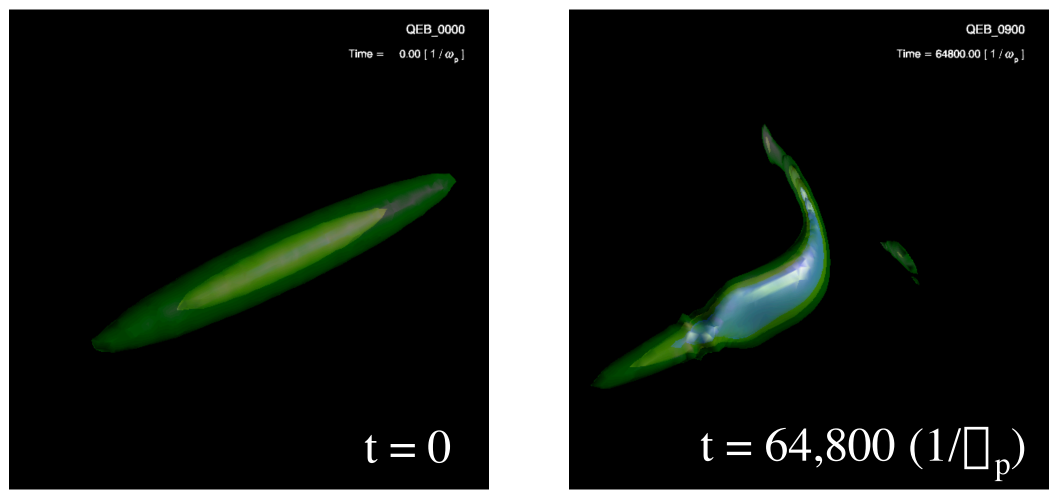


Hosing can be studied for afterburner parameters using quickPIC





3D image of the plasma charge density under blow-out regime



Electron drive beam hoses as it propagate over a long distance in the plasma

Connections to other areas in accelerator modeling

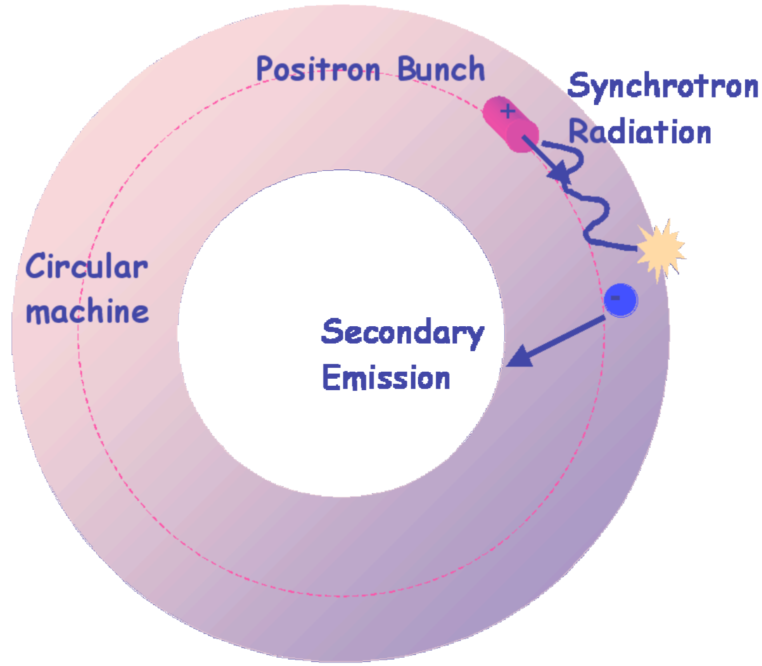
electron-cloud modeling using plasma codes: quickPIC

Beam-Beam codes use parts of UPIC:

UPIC is a parallel PIC Framework (it incluces PLIB)which is a general computer science component to this project

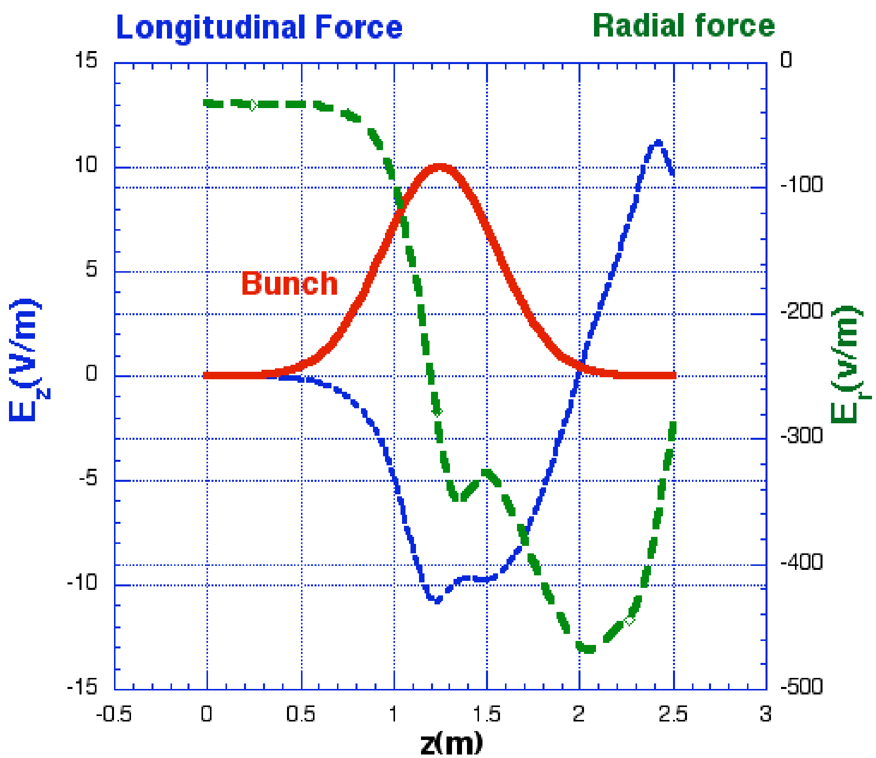
Plasma Modeling of Electron Cloud Instability

- **E-cloud formation(Positron): synchrotron radiation+secondary emission**
- **E-cloud formation(Proton): halo scraping+secondary**
- **Observed in circular accelerators like:CERN-SPS and SLAC-PEP and KEKB**
- **Major concern in LHC Design, Fermilab upgrade**

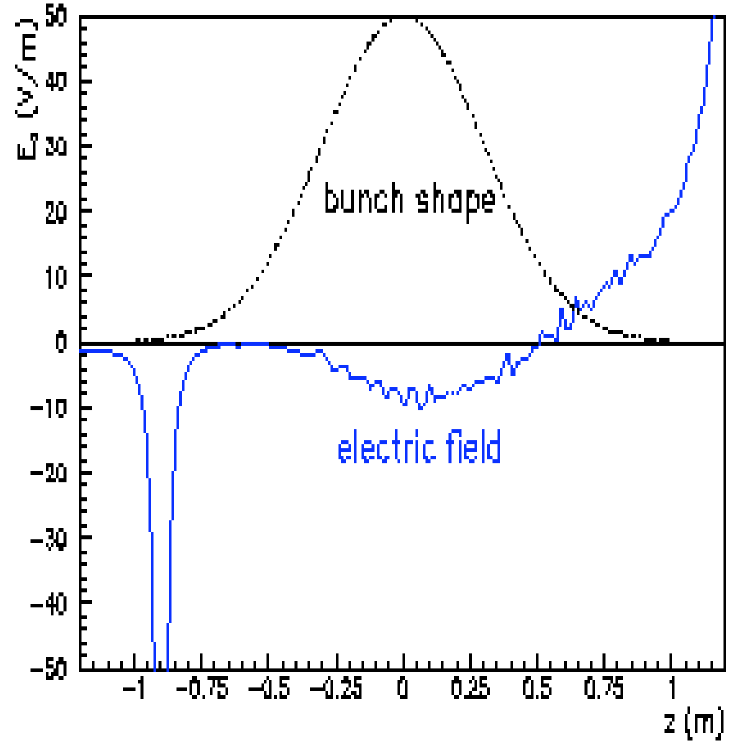


- **e-cloud is a non-neutral plasma -- well suited to plasma wakefield PIC models**
- **Previous cloud models-- single node workstations**
  - **treat cloud as a single kick once per orbit**
  - **No image forces from beam pipe**
  - **No benchmarks-- poor agreement with experiments**

Code Comparison



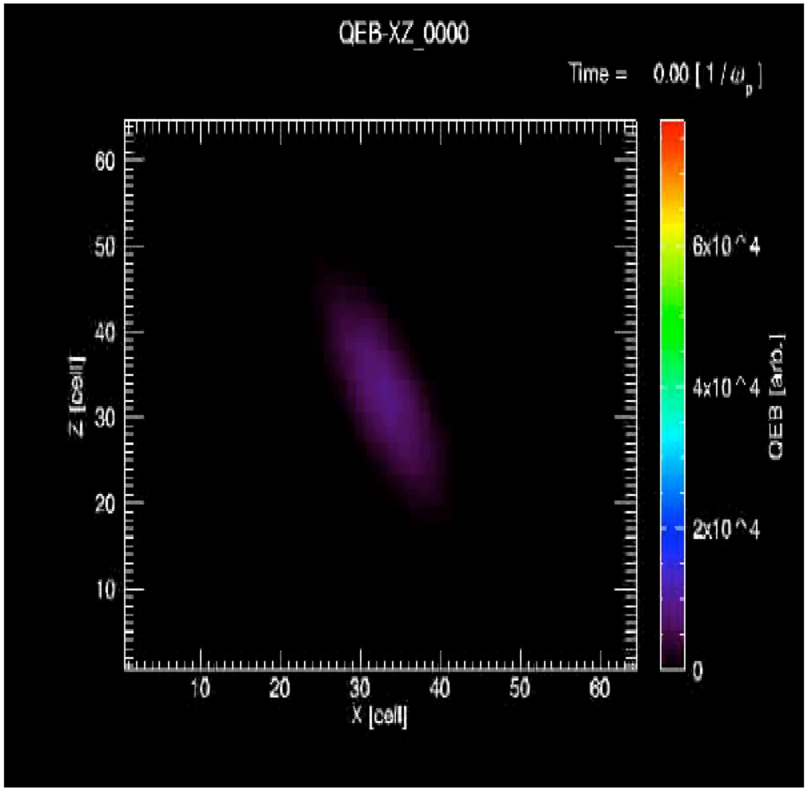
Transverse and Longitudinal wakes vs. z (From QuickPIC)



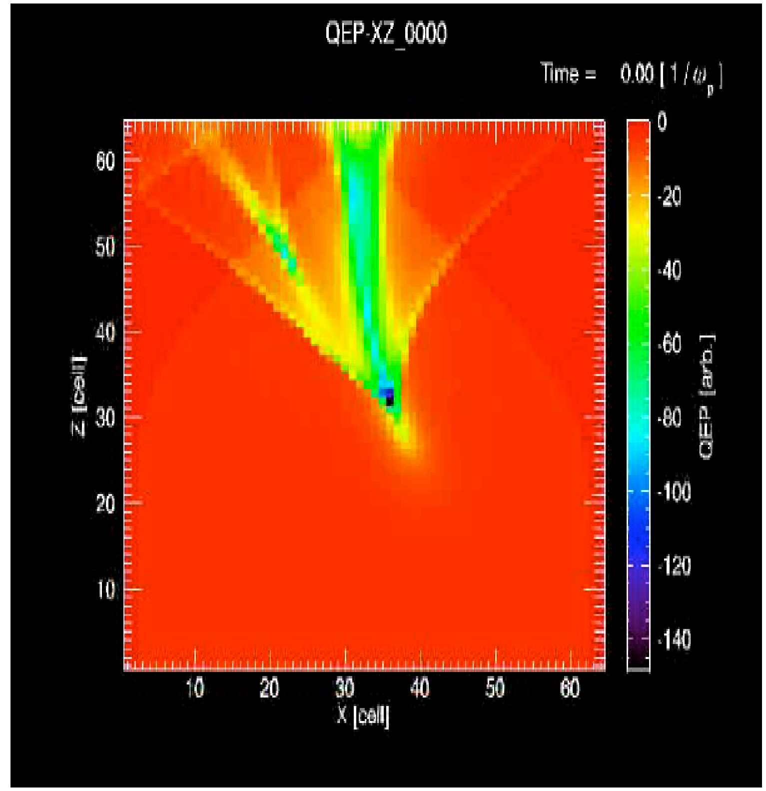
Longitudinal wake vs. z unphysical divergence!

(From HEAD-TAIL)

QuickPIC Model of Beam & Cloud Evolution Through 40Km of SPS Proton Ring at CERN (6 turns)



Beam Density



Cloud Density

Recently 700km (100 turns) was modeled

Connections with ISIC's

APDEC:
Parallel Poisson solvers for elliptical conductors
for applying quickPIC to e-cloud
Modeling gas jets
Laser-plasma experiments

Strong educational component: Includes those directly funded and those who are closely coupled to the effort

Graduate students:

CK.Huang, W.Lu, R.Narang (UCLA)

S.Deng, A.Z.Ghalam

G.Fubiani (LBNL)

J.Regele (UofColorado)

Young researchers:

F.S.Tsung (UCLA)

C.Nieter (UofColorado)

R.Giaconne

SciDAC has greatly accelerated progress:

Collaboration, computational resources, applied math

Code development:

- ***benchmarking of codes against each other***
- ***cooperation of ionization routine development***
- ***rapid construction of new codes:***
  - ***Vorpal***
  - ***quickPIC for e-cloud***

Collaboration in science:

- ***electron-cloud***
- ***all-optical injection collaborative effort***

Enabling computational resources :

- ***Full-scale modeling of SMLWFA experiments***
- ***Full-scale modeling of E-162***
- ***Modeling of LWFA in a channel***