High-performance computing in plasma-based acceleration

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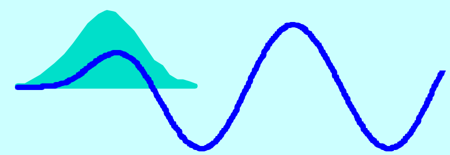
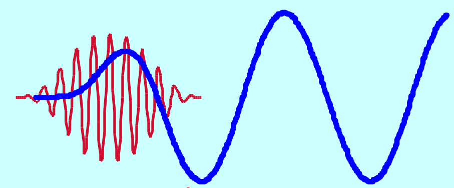
Concepts For Plasma Based Accelerators

Pioneered by J.M.Dawson

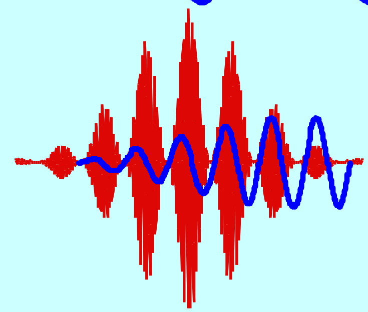
- Plasma Wake Field Accelerator(PWFA)
  A high energy electron bunch



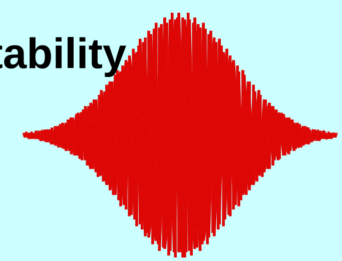
- Laser Wake Field Accelerator(LWFA)
  A single short-pulse of photons



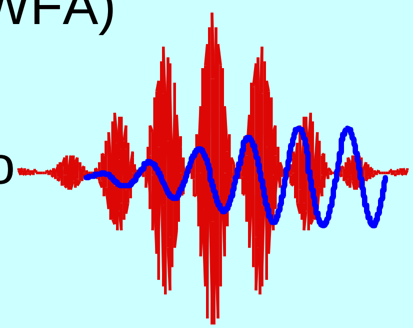
- Plasma Beat Wave Accelerator(PBWA)
  Two-frequencies, i.e., a train of pulses



- Self Modulated Laser Wake Field Accelerator(SMLWFA)
  Raman forward scattering instability

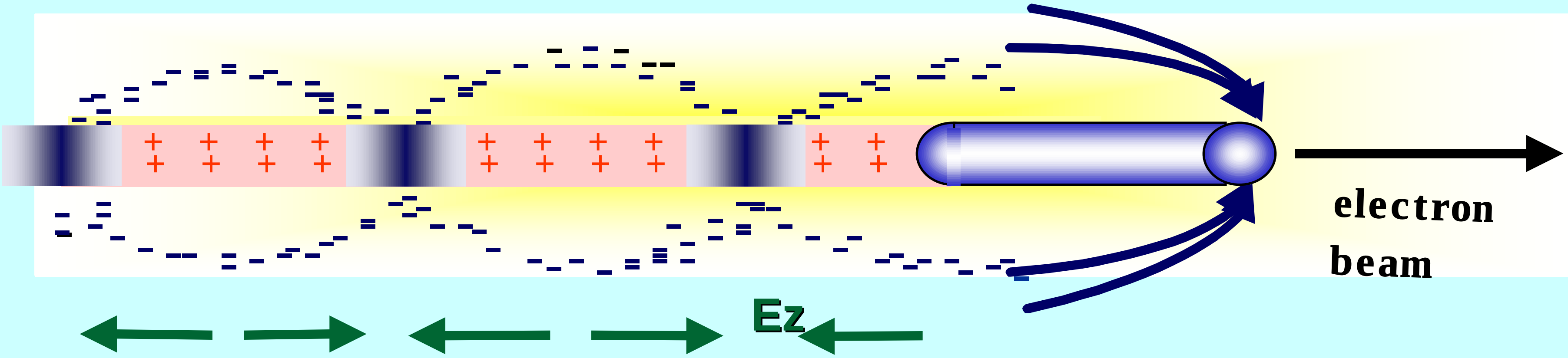


evolves to



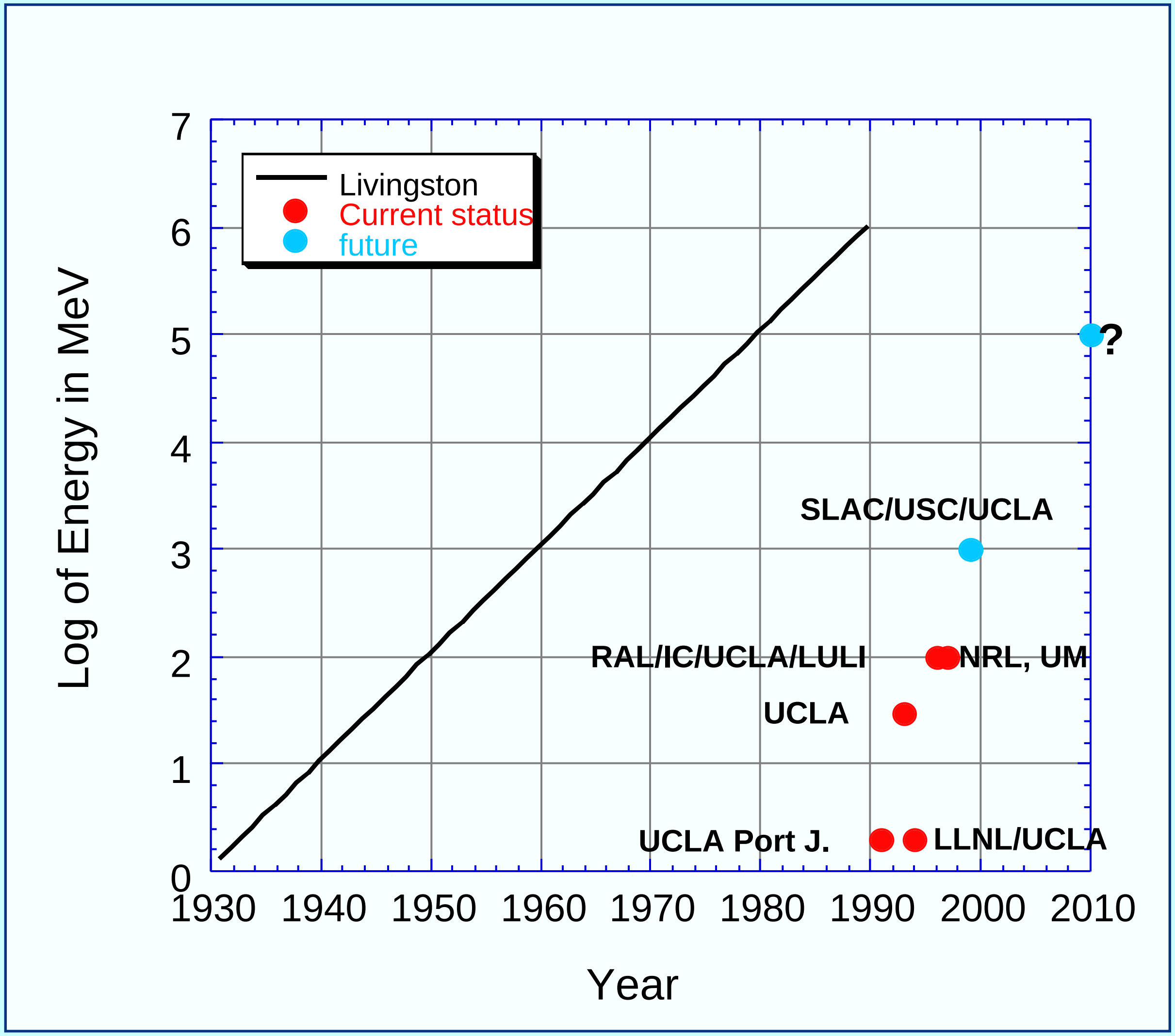
Physical Principles of the Plasma Wakefield Accelerator

- 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 $\propto N_b / \sigma_z^2$ $\quad (for\ 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_o}})$
- Transformer ratio $E_{zacc.} / E_{dec.beam}$

Future prospects for plasma-based acceleration are exciting



High-performance computing in plasma-based acceleration

- Develop an ***accurate*** suite of particle based codes for modeling plasma-based acceleration.
- Use these codes to study:
  - » Plasma wakefield acceleration: energy doublers
  - » Laser wakefield acceleration
  - » Beat wave acceleration
  - » All optical injectors
  - » Plasma lensing
  - » Beam loading/ efficiency
  - » New ideas and plasma engineering
- Develop a virtual accelerator

SciDAC team has generated a hierarchy of parallel particle codes

I.OSIRIS (UCLA/USC) fully explicit :

$\Delta x < \lambda / 2\pi$

$\Delta t < \Delta x$

3D PIC, parallelized, and moving window

II.XOOPIC/VORPAL (UCB/Tech-X/CU-Boulder/LBNL) fully explicit:

$\Delta x < \lambda / 2\pi$

$\Delta t < \Delta x$

2D PIC, parallelized, ionization, 3D fluid, and moving window

III. quickPIC (UCLA/USC): Quasi-static (frozen field) and no axial dynamics (concept developed by Whittum and by Mora and Antonsen)

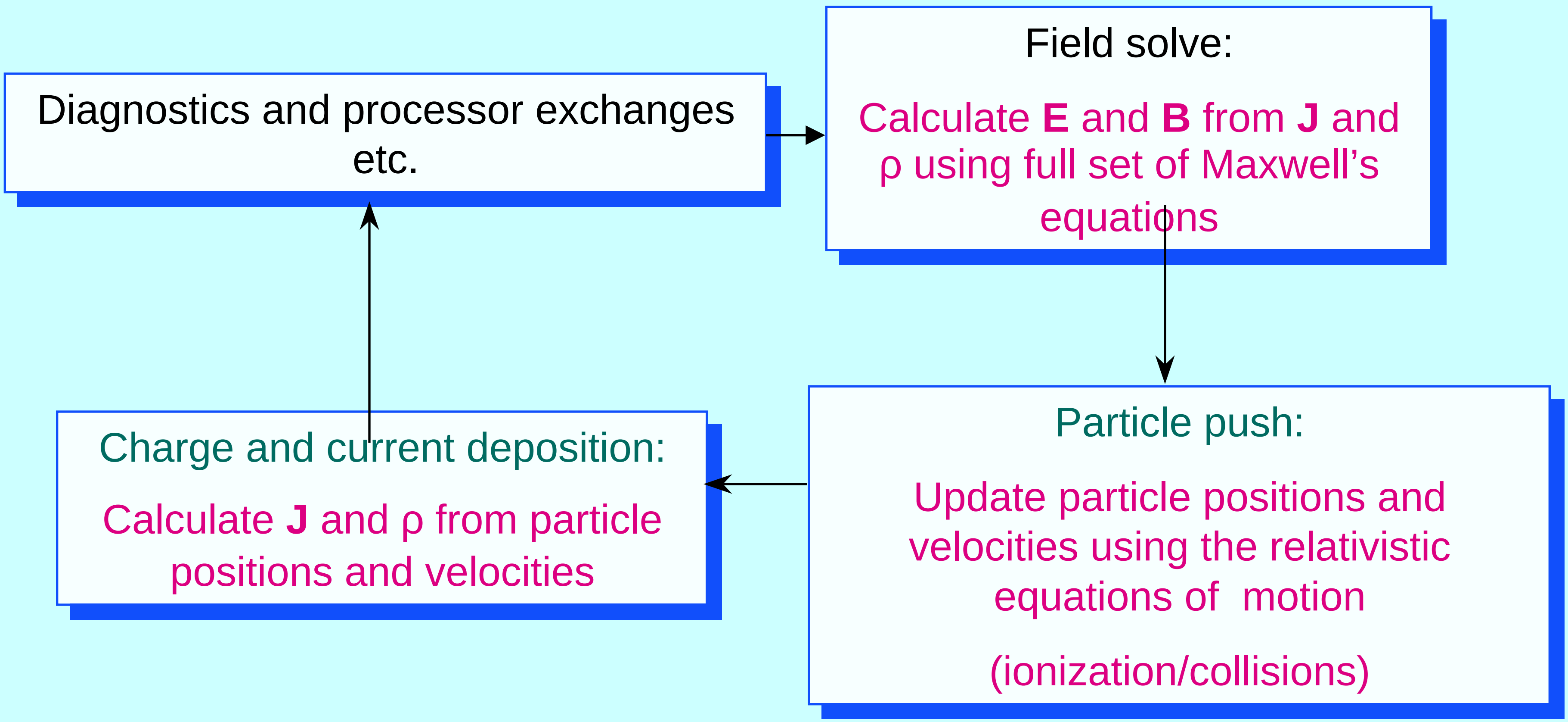
$\Delta x < \lambda_p / 2\pi$

$\Delta t < 1/\omega_B$

3D and parallelized. (Currently for beam drivers, but will be extended to include all quasi-static equations into our parallel structure.)

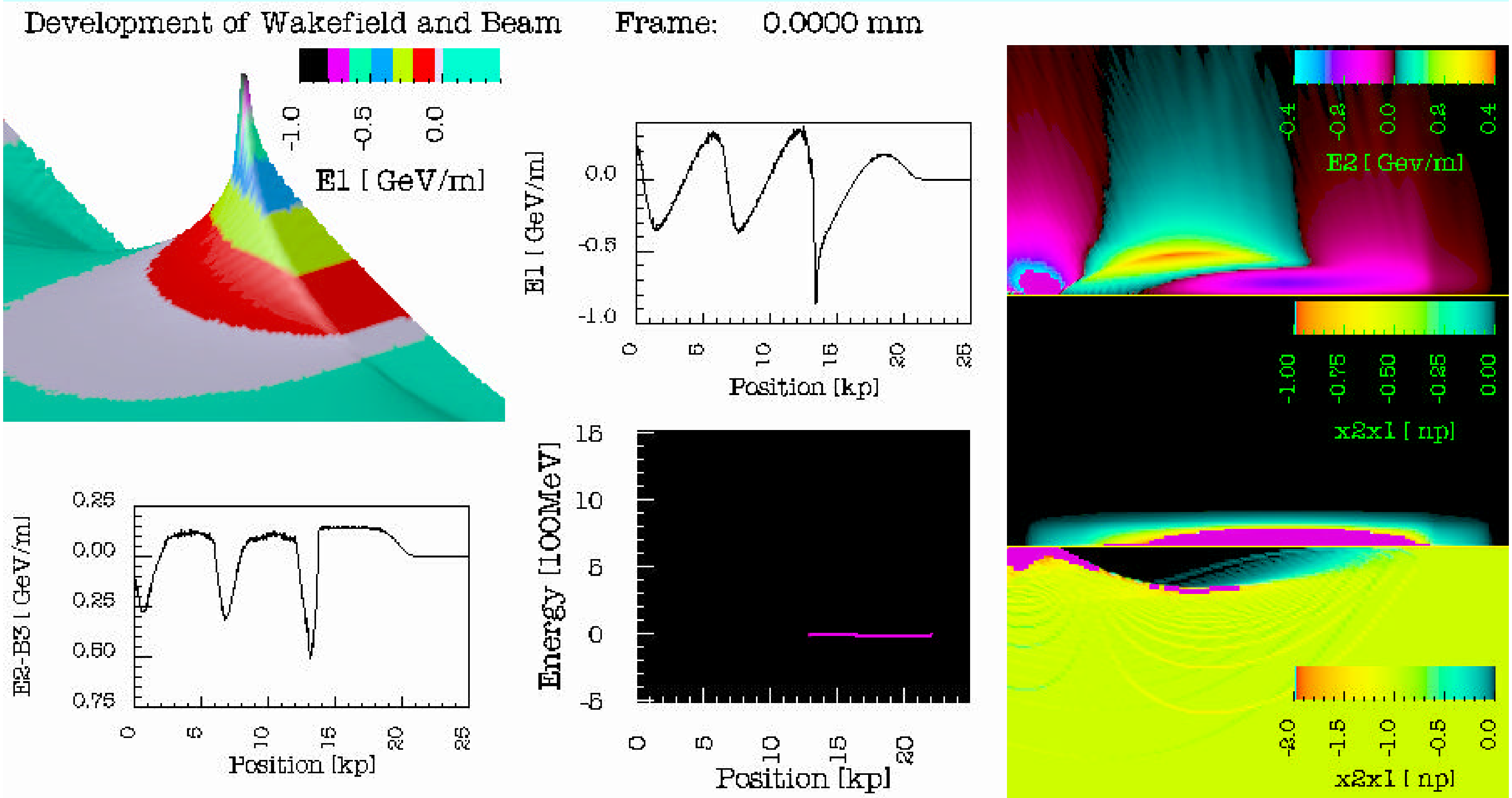
The team will build from this mature base

Particle-in-cell (PIC) code flow chart



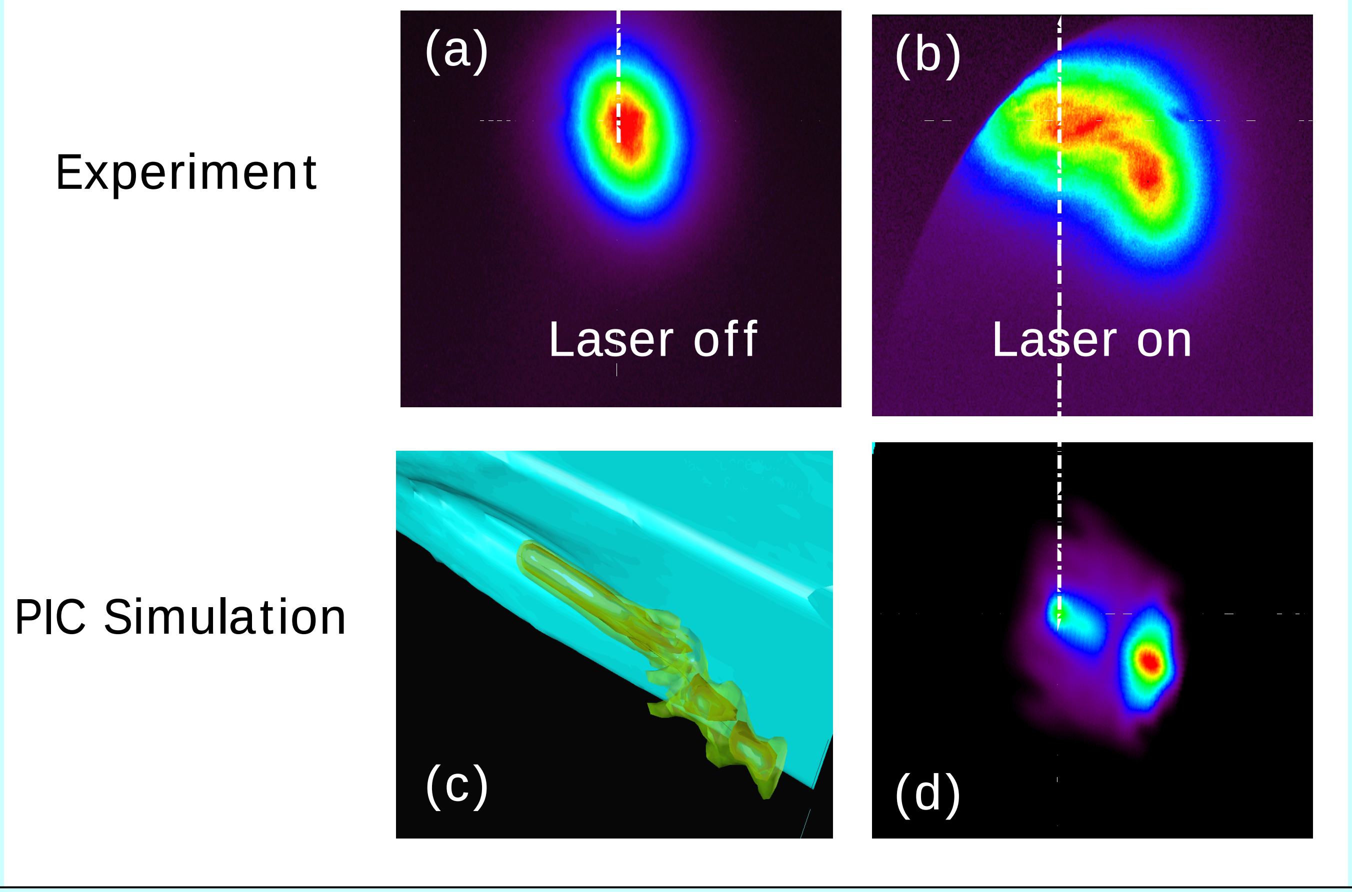
Plasma Wakefield Accelerator

Dynamics of the Beam and the Accelerating Field



High-performance full-scale 3D modeling
P.Muggli et al., Nature 411, 32 2001

Direct comparison between the experiment and a full-scale PIC simulation using OSIRIS of the refraction of a 30 GeV electron beam at a plasma vacuum interface



Results are from the E-157 collaboration:SLAC/UCLA/USC

Computational challenges for modeling plasma-based acceleration

γbeam = 60000	Fully Explicit
Δx	$\leq .05\ c/\omega_p$
$\Delta y/\Delta z$	$\leq .05\ c/\omega_p$
Δt	$\leq .02\ c/\omega_p$
N_x	≥ 500
N_y/N_z	≥ 200
ITMAX	$\geq 2 \times 10^5$
$N_{particles}$	$\sim 1 \times 10^8$ (3D) $\sim 1 \times 10^6$ (2D)
particle steps	$\sim 2 \times 10^{13}$ (3D) - $\geq 1 \times 10^5$ hrs $\sim 2 \times 10^{11}$ (2D) - $\geq 3 \times 10^2$ hrs

Table 1. A summary of the computing requirements for modeling 1GeV stages.

Hierarchy of codes: ponderomotive guiding center

Such a code is fully explicit except for the addition of a laser envelope which is included into the pusher as a relativistically correct ponderomotive force

$$\frac{d\vec{P}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) - \frac{1}{4}\frac{q}{\gamma}\nabla|a|^2 \quad \text{where } \gamma = \sqrt{1 + P^2 + \frac{|a|^2}{2}}$$

The evolution of the laser is described via a paraxial type wave equation with a source term obtained by weighting a contribution from each particle:

$$\left(2i\omega\partial_\tau - 2\partial_{\tau\xi} - {}^{2}\right) a = \chi\, a$$

$$\chi = -\sum \frac{q}{\gamma}$$

Hierarchy of codes: quickPIC

We start from the wave equations in the Lorentz gauge

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

We make the quasi-static approximation by defining the variables ξ=t-z,s=z,and $\psi=\phi-A_z$ and assume d/ds=0 giving

$$-\nabla^2\vec{A} = \frac{4\pi}{c}\vec{J} \qquad -\nabla^2\phi = 4\pi\rho$$

For highly relativistic beams the total current can be approximated by J=zρ_bc

$$-\nabla^2\psi = \rho_e + \rho_i$$

The momenta of the plasma and the beam can be obtained via

$$\left(1 - v_{\parallel}\right)\frac{dP_p}{d\xi} = \nabla\phi \qquad \frac{dP_b}{ds} = \nabla\psi$$

$$\gamma - P_{zp} = 1 + \psi \qquad P_{zp} = \frac{1 + P_p^2 - (1+\psi)^2}{2(1+\psi)} \qquad q_i = \frac{q_{oi}}{1 - v_{\parallel}}$$

High-performance computing in plasma-based acceleration

- Goals:
  - **Fast and parallel algorithm design**
    - **Single processor speed:**
      - **Field solve, push, deposition**
    - **Dynamic load balancing**
  - **Accurate physics output**
    - **3D**
    - **Ionization**
    - **Appropriate boundary conditions**
  - **New parallel reduced description PIC codes**
    - **Ponderomotive guiding center**
    - **Quasi-static**
  - **Robust and easy to use diagnostic and visualization packages**
  - **Modular code that can be interfaced to model plasma elements (e.g., lenses, energy doublers….) in more conventional accelerator codes.**
- We will come up with a modified set of milestones in the breakout session