Plasma-based acceleration: Fundamental issues for designing a collider

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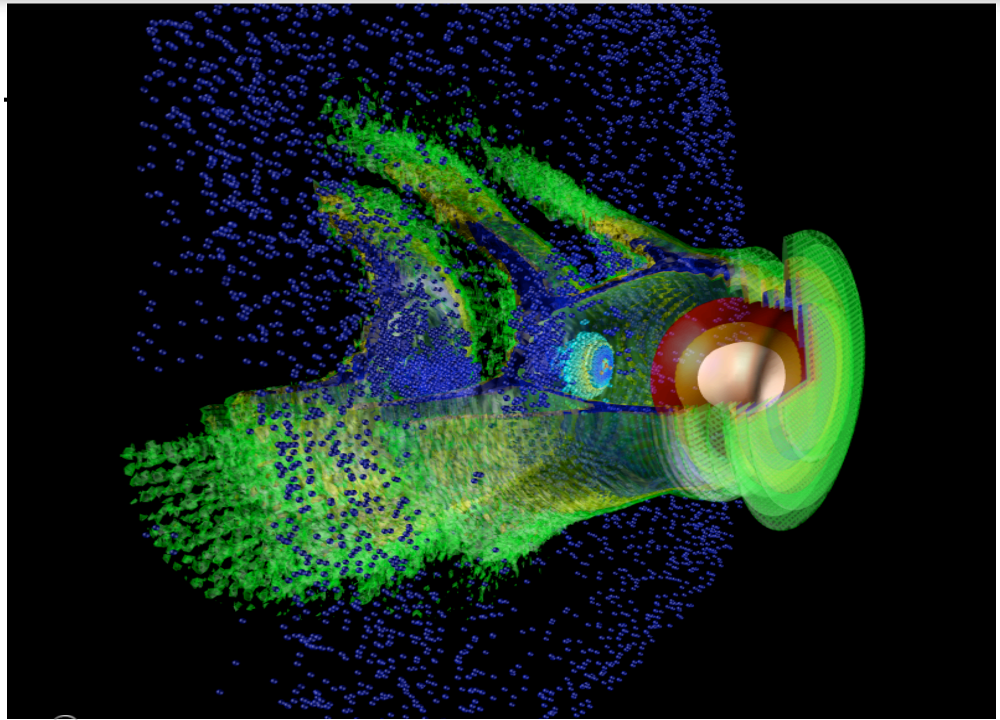

Work supported by DOE and NSF

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And E-167 and FACET team (M.Hogan and P. Muggli et al.).

Large Hadron Collider (LHC)at CERN

Terascale Physics

14 Trillion Volts (*CM*) *pp*

27 km circumference

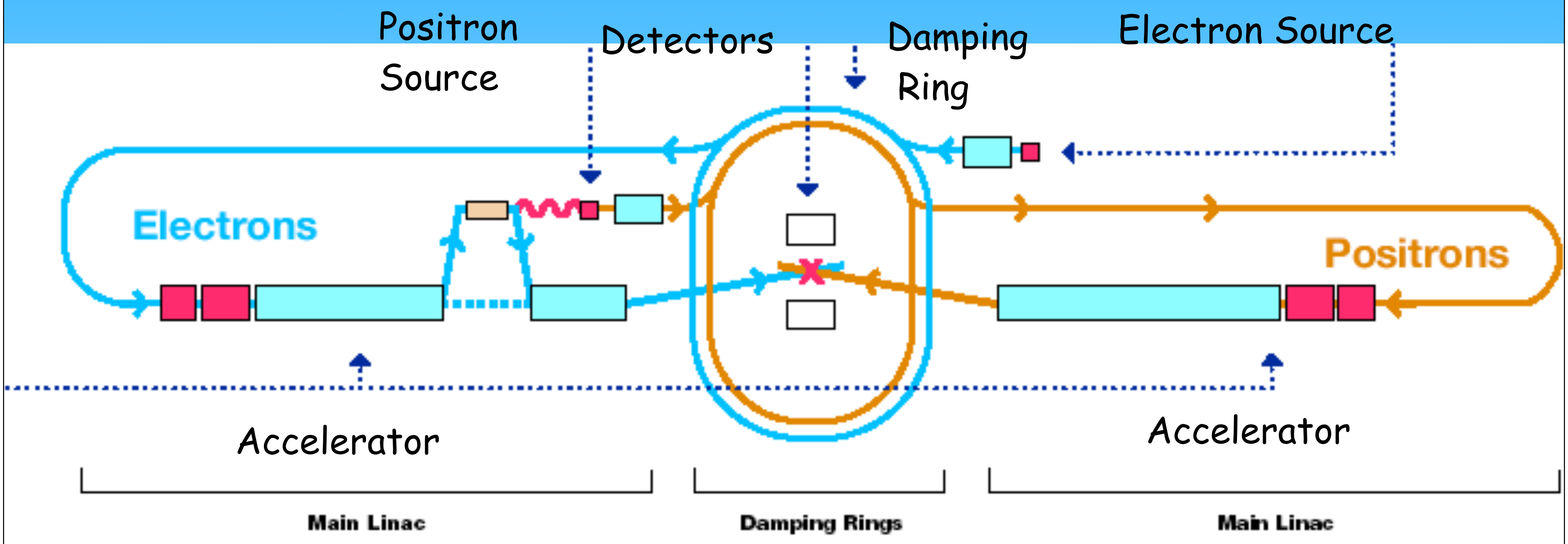
$6 Billion+?

What is next?

Thinking big

Accelerators like the future LHC require long tunnels and powerful bending magnets.

International Linear Collider



Positron Source

Detectors

Damping Ring

Electron Source

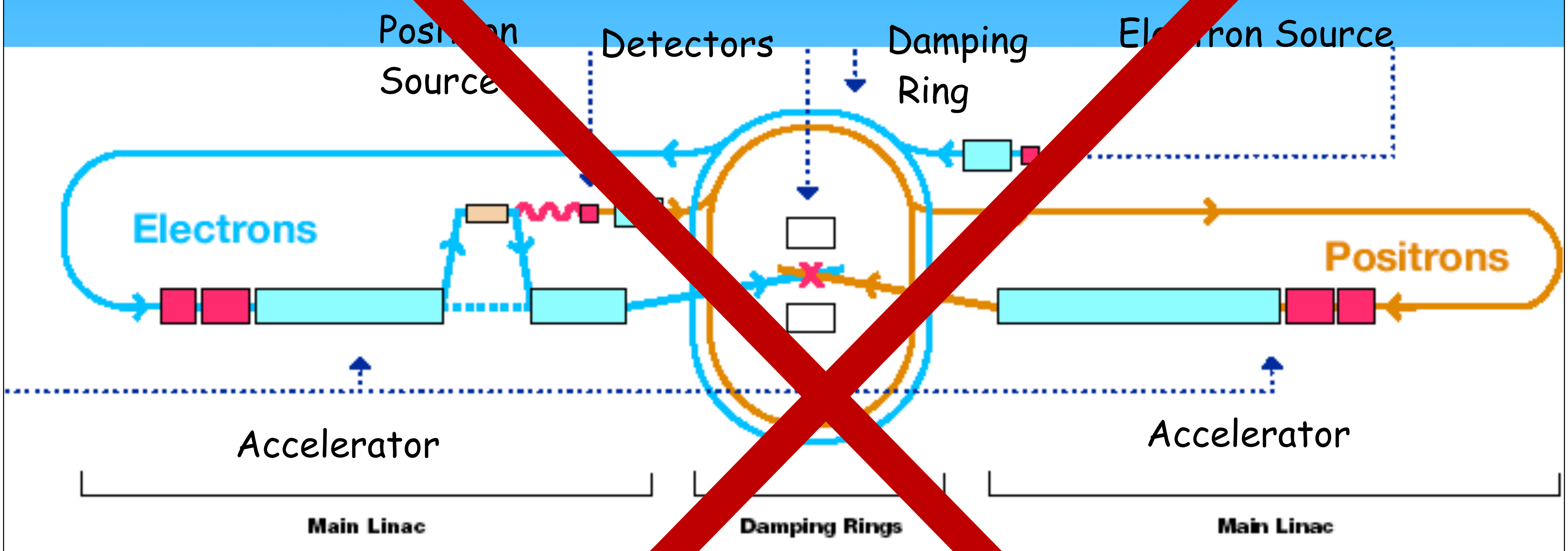
Accelerator

Accelerator

Origin of mass
Extra dimensions of space
More fundamental particles

31 km
500 GeV CM
$????

International Linear Collider



Positron
Source

Detectors

Damping
Ring

Electron Source

Accelerator

Accelerator

Origin of mass
Extra dimensions of space
More fundamental particles

[illegible]1 km
50[illegible] GeV CM
$?[illegible]?

Particle Accelerators

Why Plasmas?

Conventional Accelerators

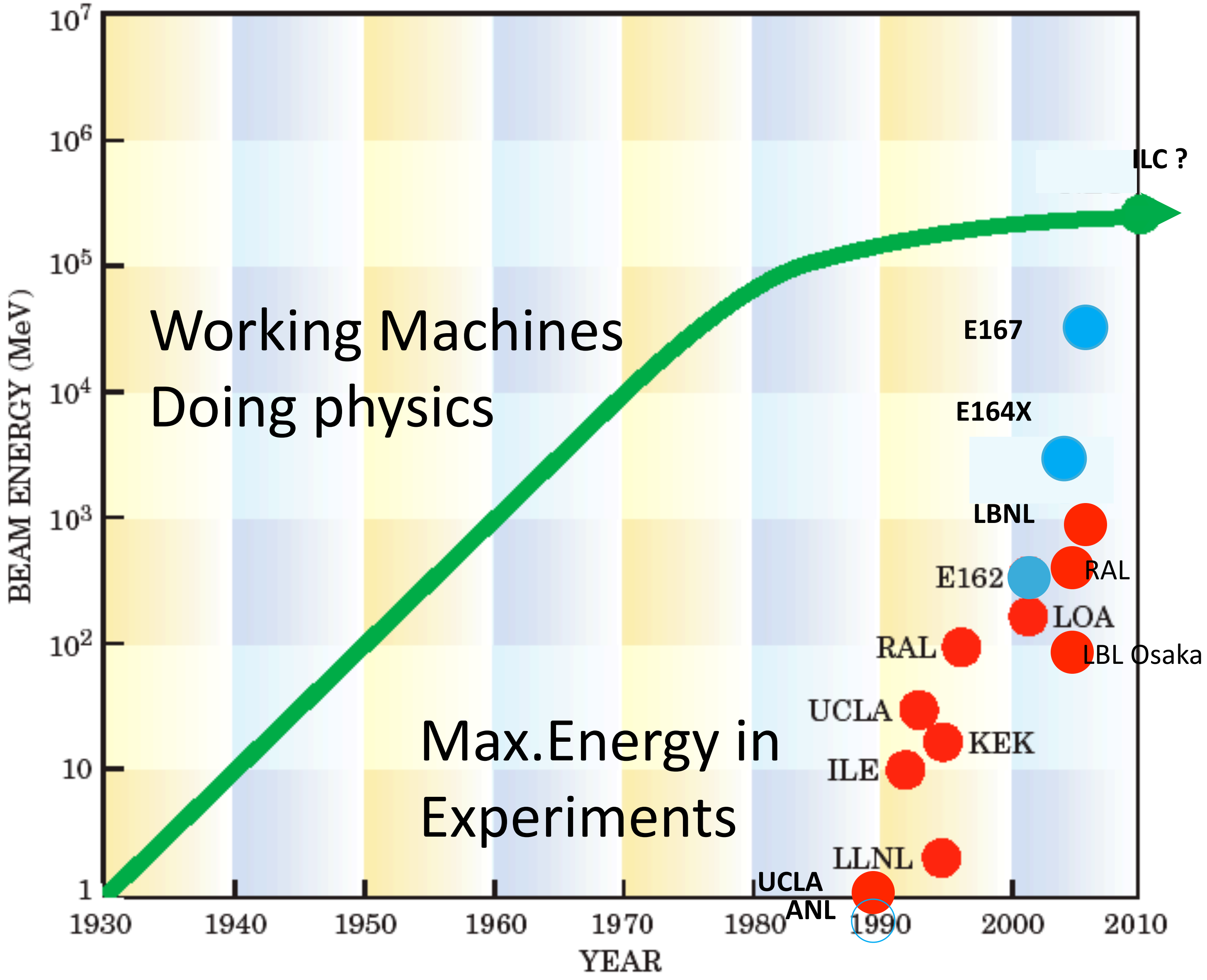
- Limited by peak power and breakdown
- 20-100 MeV/m
  - **20km /0.8 TeV**

Plasma

- No breakdown limit
- 10-100 GeV/m

Plasma Accelerator Progress

“Accelerator Moore’s Law”



Plasma-based acceleration is rich in science:
Today I will talk about some of the issues for designing an accelerator

Particle Accelerators

Requirements for a High Energy Physics Collider

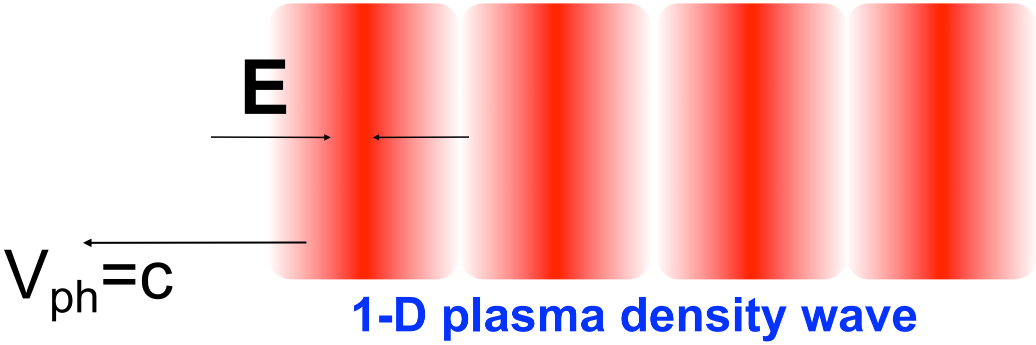
- High Energy
  - ~TeV
- High Luminosity (event rate)
  - $L = fN^2/4\pi\sigma_x\sigma_y$
  - ~nC of charge at 10 kHz: ~kJ per bunch and 20 MW of average power in beam (So Driver needs more!)
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma \sim .1 - 10\%$
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad
- Low Cost (one-tenth of $10B/TeV)
  - Gradients > 100 MeV/m
  - Efficiency > few %

Particle Accelerators

Requirements for an X-RAY FEL

- Moderate Energy
- High peak current (N/σ_z ~10 kA)
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma$ ~ .1 - 1%
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y$ < 1 mm-mrad

Simple Wave Amplitude Estimate



1-D plasma density wave

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

Gauss' Law

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

$$n_1 \sim n_o$$

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

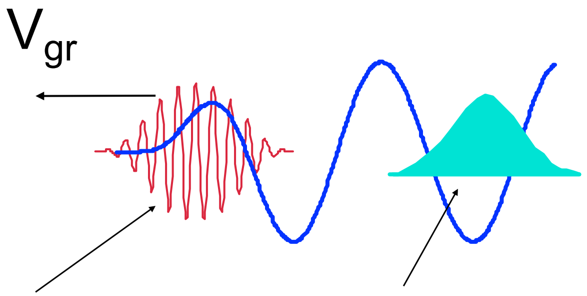
$$or \quad eE \sim \sqrt{\frac{n_o}{10^{16} cm^{-3}}} \underline{10\, GeV/m}$$

Create a plasma wave wake:
Wake Behind a Motor Boat

How does one excite a relativistic plasma wave wake:Concepts for plasma based accelerators*

- Laser Wake Field Accelerator

  A single short-pulse of photons

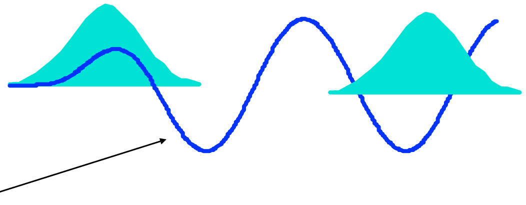


V_{gr}

- Drive beam
- Trailing beam

- Plasma Wake Field Accelerator (PWFA)

  A high energy electron bunch



- 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

PROLOGUE or EPILOGUE

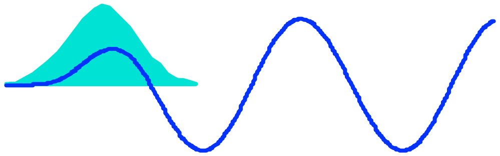
John M. Dawson
1930-2001

“This is a story **of Science as a Living Thing** taking unexpected turns in directions that were never foreseen. Science must have goals, but it must also have the freedom to follow up interesting and unexpected results when they turn up. This is what excites the good young researcher and it is in their hands that our future rests.”

John Dawson AIP Conf. Proc. 560 p 3 (2000)
Personal Recollections on the Development of Plasma Accelerators and Light Sources

Quasi-static approximation

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.

Use appropriate variables

- Transform from:

$$(z, x, y; t)$$

- Transform to:

$$(\xi = z - v_\phi t, x, y; s = z)$$

Meaning of new variables

- $\xi = z - v_\phi t$ is the distance from front of the driver
- $s = z$ is the distance the driver has propagated into the plasma

Mathematical meaning of quasi-static approximation

$$\partial_s << \partial_\xi$$

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-potenial

$$\psi = (\phi - A_z)$$

Don't choose a gauge where

$$\phi = A_z$$

Forces on relativistic particle

$$F_z = -\partial_\xi \psi$$

$$F_\perp = -\nabla_\perp \psi$$

A Panofsky Wenzel Theorem for plasma wakefields

Relationship between accelerating and focusing forces

Forces come from a single potential:

$$F_\perp = -\nabla_\perp \psi$$

$$F_z = -\partial_\xi \psi$$

From which it follows (and vice versa):

$$\nabla_\perp F_z = \partial_\xi F_\perp$$

- Some ideal properties for an accelerating structure are that:
  - The accelerating fields do not depend on the transverse coordinate: Low energy spread
  - The focusing fields to not depend on the axial coordinate: emittance preservation
- If one is met so is the other
- THEOREM IS TRUE FOR LINEAR AND NONLINEAR WAKES

Linear theory for **particle beam** and **laser** drivers

What are the wakefields produced by a laser or a particle beam?
For wide beams (spot sizes comparable or larger to the wavelength of the wake) there are no differences!

Linearized equation for plasma density (valid for wide and narrow beams):

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_0} = \omega_p^2\left(\frac{n_b}{n_0} - k_p^2\nabla^2\frac{a_0^2}{4}\right)$$

Normalized vector potential of the laser:

$$a_0 \equiv \frac{eA_0}{mc^2} = .85 \times 10^{-9}\sqrt{I_{W/cm^2}}\lambda_{\mu m}$$

Normalized electron plasma and beam (it can be + or -) densities:

$$\frac{n_1}{n_0} \qquad \frac{n_b}{n_0}$$

For wide beams the equation for the wake potential is simple:

$$\frac{\partial^2}{\partial\xi^2}\overline{\psi} + k_p^2\overline{\psi} = -k_p^2\frac{n_b}{n_0} + k_p^2\overline{\phi}_p$$

Ponderomotive potential or radiation pressure:

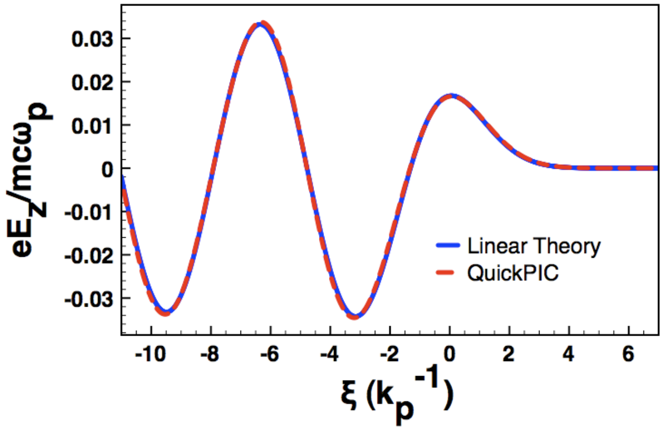
$$\overline{\phi}_p \equiv \frac{a_0^2}{4} \qquad \overline{\psi} \equiv \frac{e\psi}{mc^2}$$

Note: Transverse profile of the wake follows that of the driver!

Solution for wake is easily calculated via Greens functions

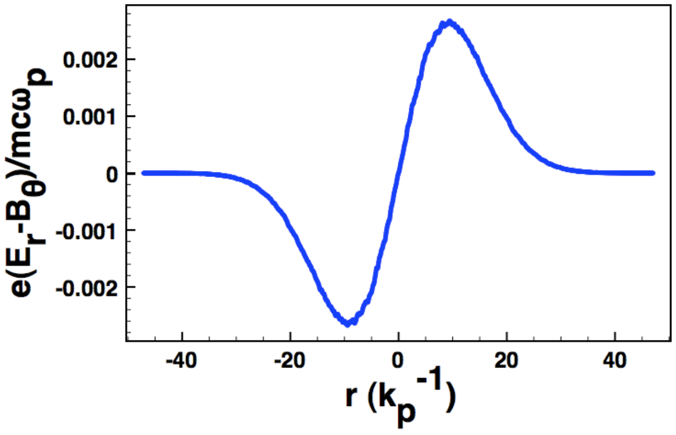
$$\bar{\psi}(x_\perp,\xi) = k_p \int_\xi^\infty d\xi' \sin\left[k_p(\xi-\xi')\right]\left(\frac{-n_b(x_\perp,\xi)}{n_0} + \bar{\phi}_p(x_\perp,\xi)\right)$$

Accelerating field



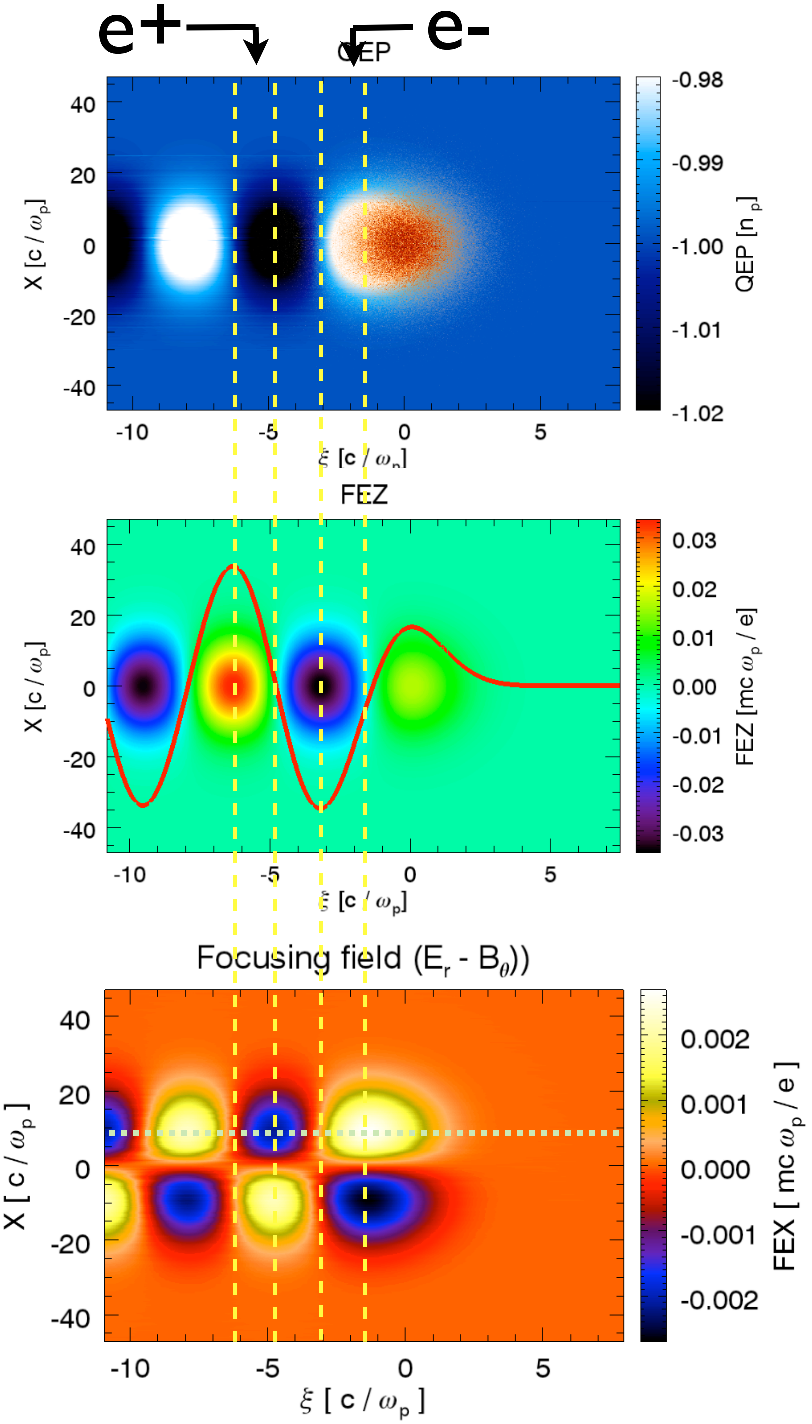
$$F_z = -\partial_\xi \psi$$

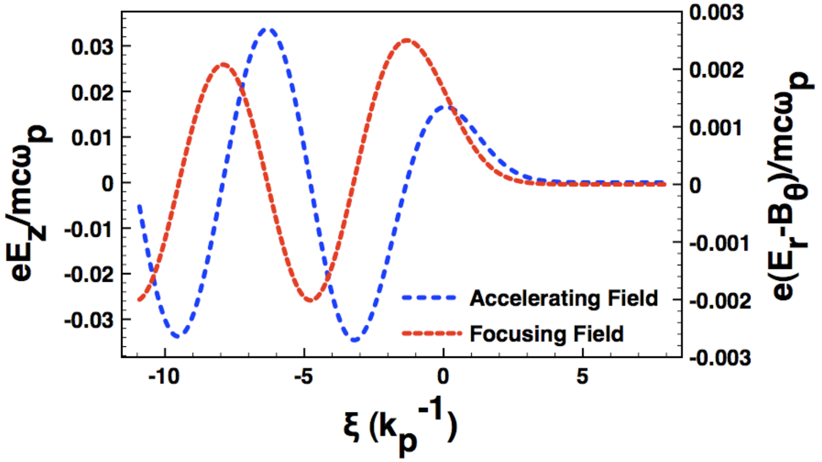
Focusing field



$$F_\perp = -\nabla_\perp \psi$$

Focusing and accelerating fields are $\frac{\pi}{2}$ out of phase

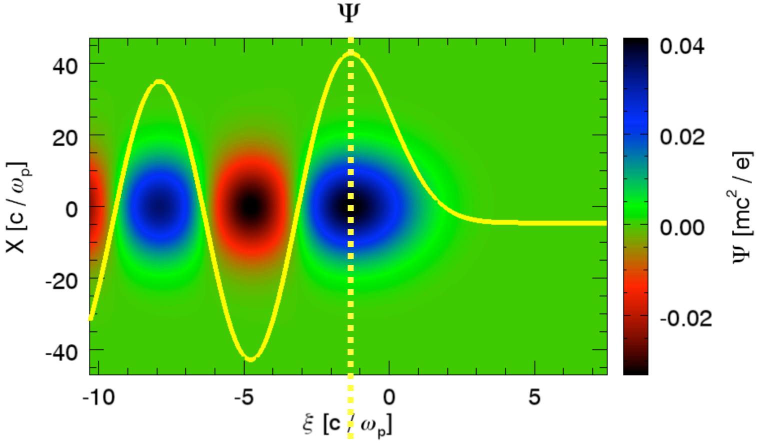




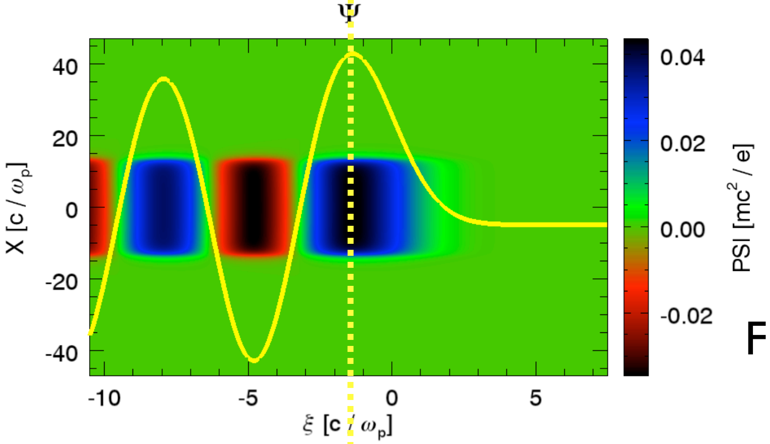
Only half of the accelerating phase can be used.

Formalism for electrons and positrons is the "same": Just switch the sign of nb.

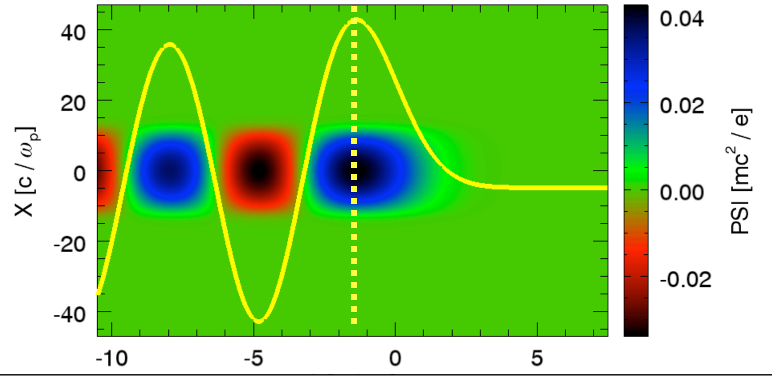
The transverse profile of wakefield potential is the same as that of a wide particle beam or laser



Gaussian-red



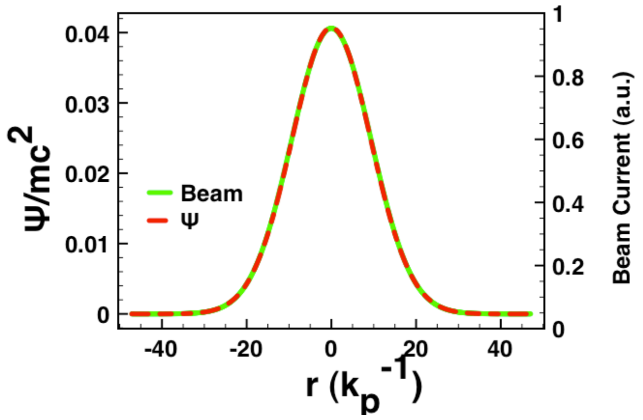
Flat-top-blue



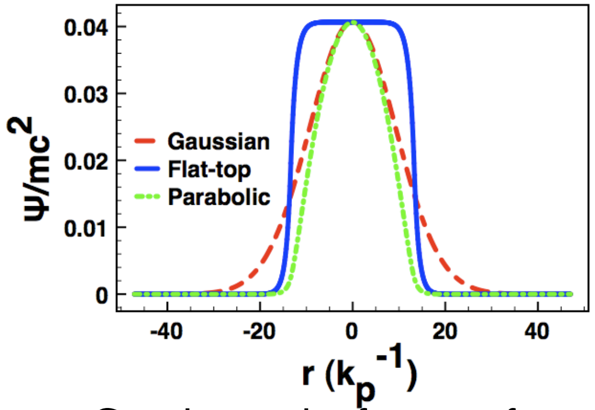
Parabolic-green

Example: e- driver

Transverse Profile of Ψ and Beam Current



Transverse lineout of Ψ with Different Beam Current



Can design the focusing force and transverse profile of Ez for a SINGLE particle if the beam shape can be preserved.

Linear theory tells us we need a poweful laser or particle beam to make large wakes

For example, if a0 ~1or nb/n0 ~.25, if the pulse length is matched to the plasma frequency, and if the spot size is ~half the wakes wavelength then:

For a laser this corresponds to:

$$P \approx 110TW(\frac{\tau_{pulse}}{100fs})^2$$

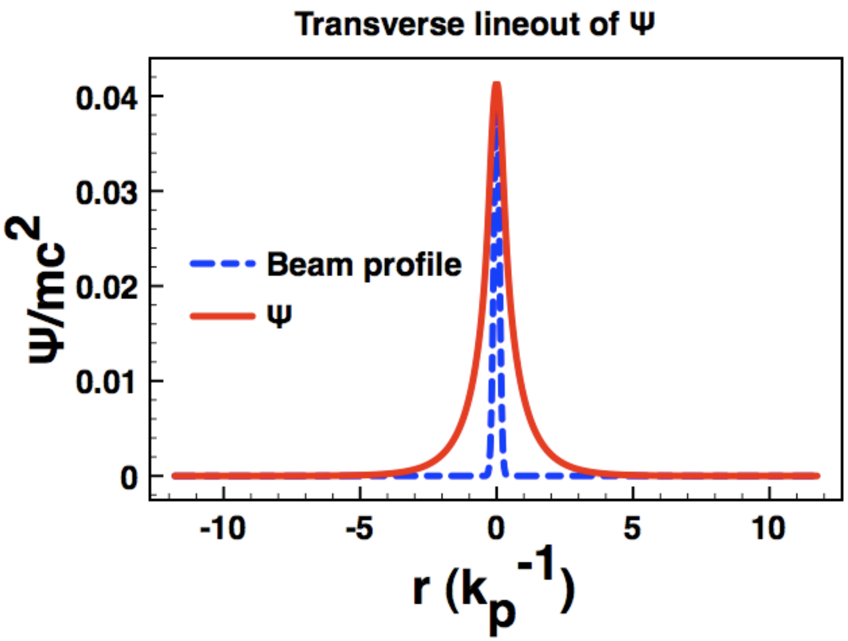
For a particle beam: this corresponds to:

$$\frac{Q}{\tau_{pulse}} \approx \frac{50nCoul}{100fs}(\ 50kA)$$

Linear theory for arbitrary transverse profiles is still straightforward for both a particle beam and a laser driver-- The wake potential is now given by:

$$\overline{\psi}(\xi, r, \phi) = -\int_{\xi}^{\infty} k_p d\xi' sin(k_p\left[\xi - \xi'\right]) \left[\overline{\phi}_p(\xi'\phi', r') + \int_0^{2\pi} \frac{d\phi'}{2\pi} \int_0^{\infty} dr' r' K_0\left(k_p|\bar{r} - \bar{r'}|\right) \frac{n_b(\xi', \phi', r')}{n_0}\right]$$

However, there is a very important difference between the wake of a narrow particle beam and that of a laser: The wake of a very narrow particle beam still extends out to a skin depth. (There is no reason to use a very narrow laser!)



For a fixed amount of charge you can always make nb/n0 large by decreasing the spot size of a beam

The wake amplitude for a narrow beam depends on the normalized charge per unit length:

$$\Lambda \equiv \frac{n_b}{n_0} k_p^2 \sigma_r^2 \approx 2 \frac{N}{2 \times 10^{10}} \frac{20_{\mu m}}{\sigma_z} = \frac{I}{24kA}$$

Linear theory works when $\Lambda < 1$ and $\frac{n_b}{n_0} < 10$ for e- beams

and when $\Lambda < 1$ and $\frac{n_b}{n_0} < 1$ for e+ beams.

UCLA

What happens if Λ or $\overline{\phi}_p$>1 ?

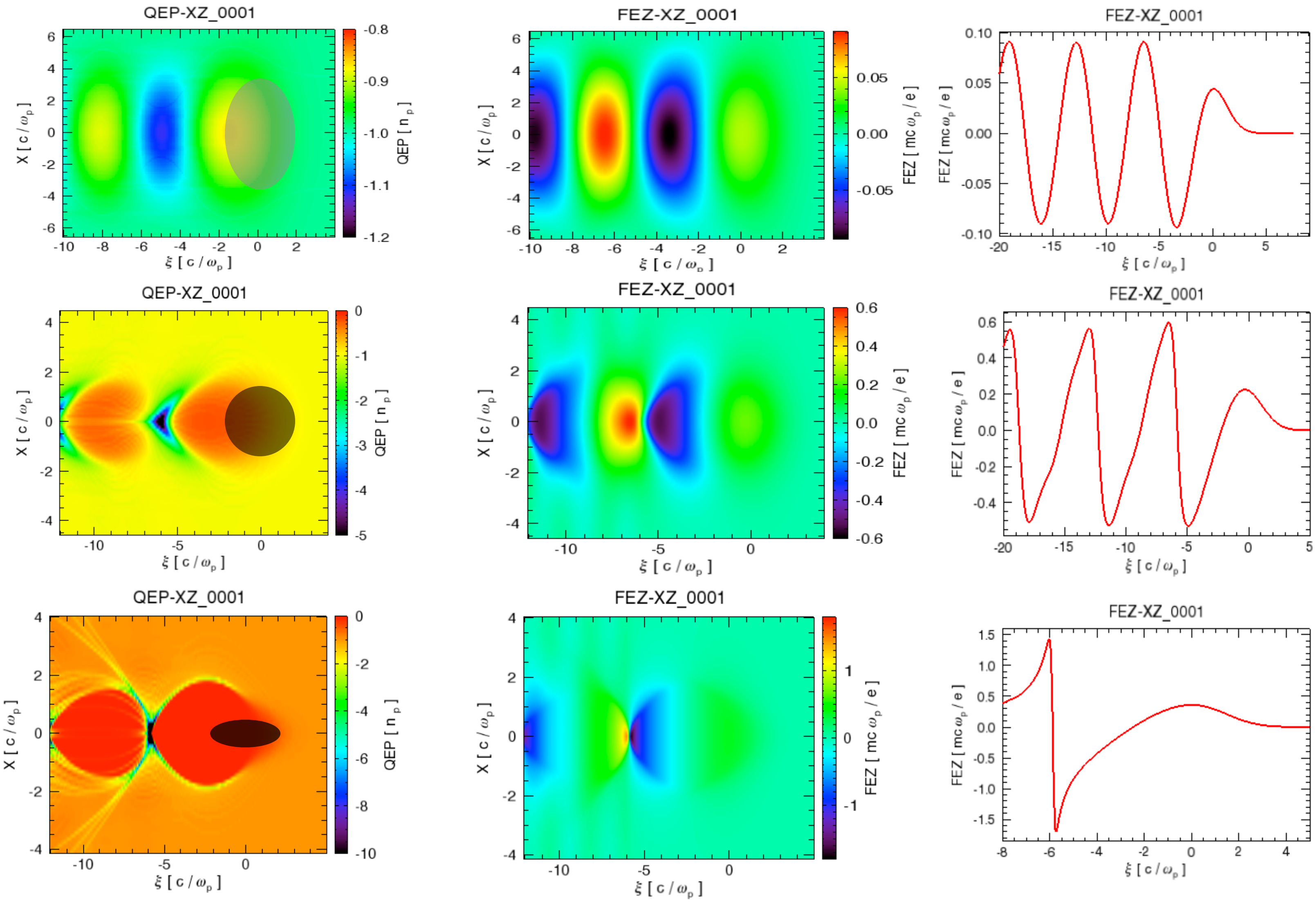
$k_p R_b \approx 2\sqrt{\Lambda}$ for $k_p \sigma_z \approx 1$

ne psi Ez

$k_p \sigma_r = 2.8$

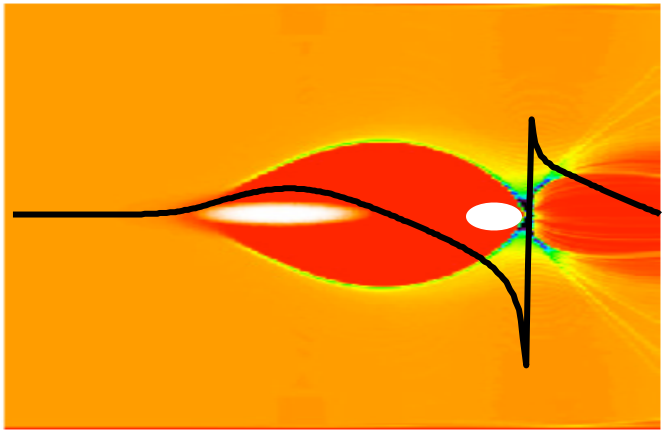
$k_p \sigma_r = 1.0$

$k_p \sigma_r = 0.38$

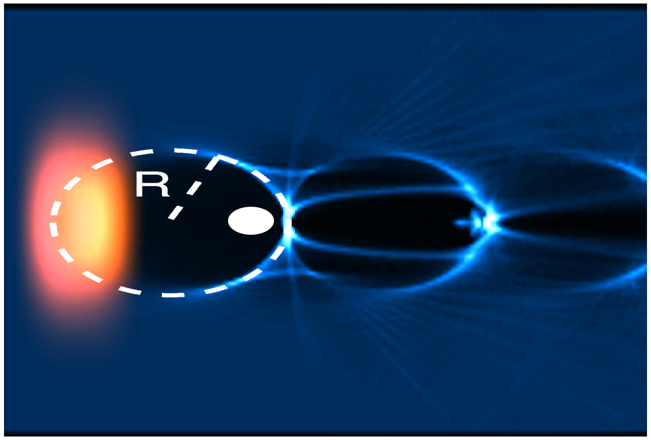


Very intense lasers also create similar looking nonlinear wakes

Driven by an electron beam



Driven by a laser pulse



Called blowout or bubble

Need a nonlinear description of these wakes

Very stable wakes!

Field structure in Blowout/Bubble regime is described by the wake potential.

Just need an understanding of electrostatic for infinitely long systems

Field equations in Lorentz gauge

$$(\frac{1}{c^2}\partial_t^2 - \nabla^2)\vec{A} = \frac{4\pi}{c}\vec{J}$$

$$(\frac{1}{c^2}\partial_t^2 - \nabla^2)\phi = 4\pi\rho$$

Make quasi-static approximation

$$-\nabla_\perp^2\vec{A} = \frac{4\pi}{c}\vec{J}$$

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

Wake potential follow "2D electrostatic" equation

$$-\nabla_\perp^2\psi = 4\pi(\rho - \frac{J_z}{c})$$

Acceleration and focusing fields:

$$F_z = -\partial_\xi\psi$$

$$F_\perp = -\nabla_\perp\psi$$

Inside bubble there only ions so use Gauss's Law for cylinders

$$F_\perp = -2\pi e^2 n_0 x_\perp$$

Need an equation for the radius of the bubble: $\frac{dr_b}{d\xi}$

Relativistic blowout regime for blowout radius and for large maximum radius the trajectory of rb is a circle: Bubble
Lu et al.PRL 16, 16500 [2006]

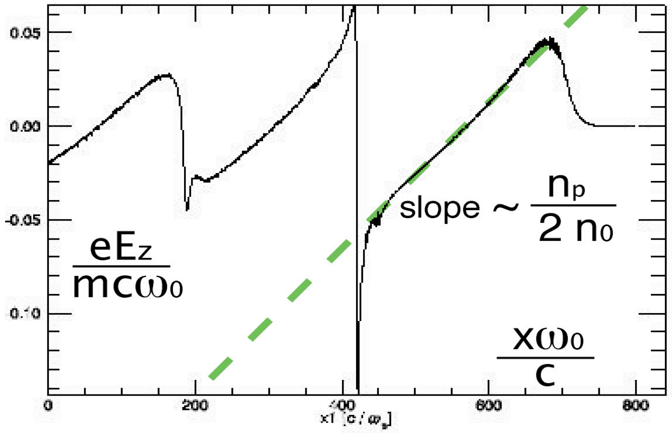
Bubble radius :

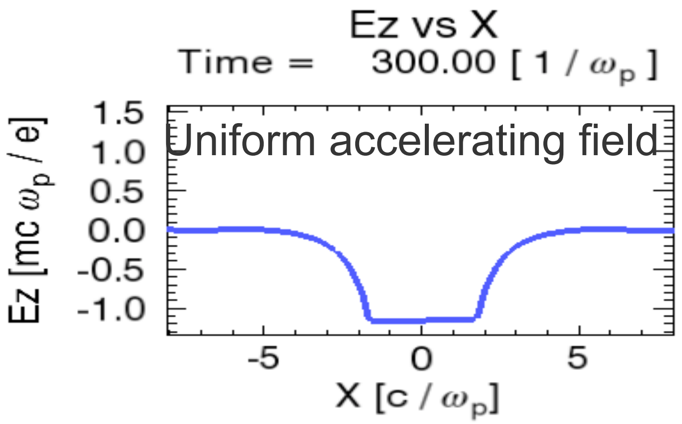
$$k_p R_b \approx 2\sqrt{\Lambda} \text{ or } k_p R_b \approx 2\sqrt{a_0}$$

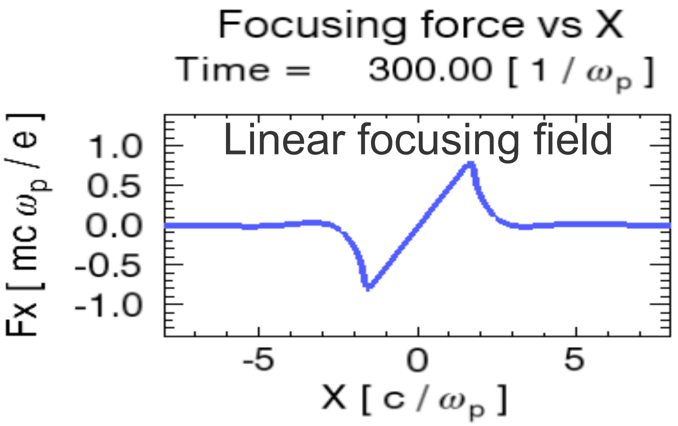
$$\overline{\psi} \approx k_p^2 \frac{r_b^2(\xi) - r^2}{4}$$

$$\frac{eE_z}{mc\omega_p} = \frac{r_b}{2}\frac{dr_b}{d\xi} \approx \frac{1}{2}\xi$$

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

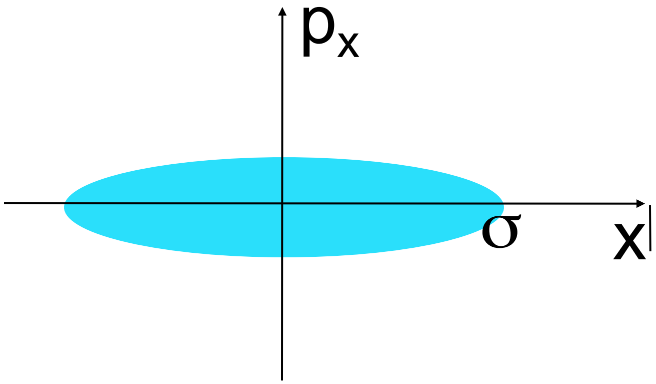






Transverse Dynamics and Beam Quality

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



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

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

- Inside a plasma wake a single particle oscillates as:

$$\frac{dP_\perp}{dt} = q(-\nabla_\perp \psi)$$

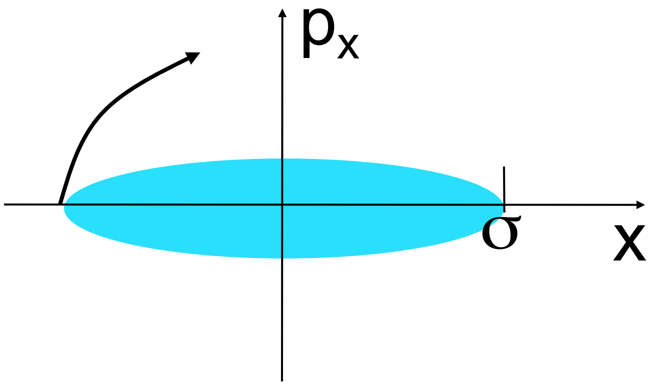
- If the focusing force is “linear” in the transverse coordinate then

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

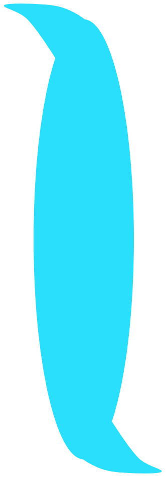
$$k_\beta \equiv \frac{\omega_\beta}{c} \qquad k_\beta = \alpha \frac{k_p}{\sqrt{2\gamma}}$$

Transverse Dynamics and Beam Quality

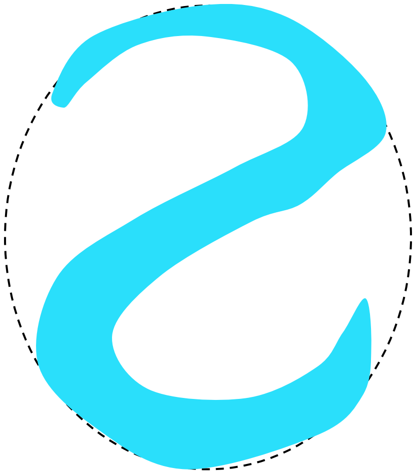
- Emittance ε_n = phase space area and a measure of its ability to get focused:



Plasma focusing causes beam to rotate in phase space



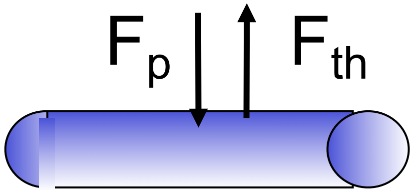
1/4 betatron period (tails from nonlinear F_p)



Several betatron periods (effective area increased)

- Matching: Focusing length k_β^{-1} = Beam diffraction length β_*

$$\boxed{\sigma^2 = \varepsilon_n \sqrt{\frac{2}{\gamma}}\,\frac{c}{\omega_p}}$$



  - And a Gaussian beam remains Gaussian with a fixed spot size
  - No emittance growth
  - A nonlinear Focusing force has a matched profile that is different than Gaussian

Now we are ready to analyze beam loading: What is beam loading?

- The placing of a bunch charge on an accelerating structure to extract energy with high efficiency, small energy spread, and emittance preservation.

- This involves understanding:
    - how much charge can be loaded.
    - where to place the charge.
    - and how to shape the charge.

- ***The best properties for the LOADED wake are (while the beam is matched):***

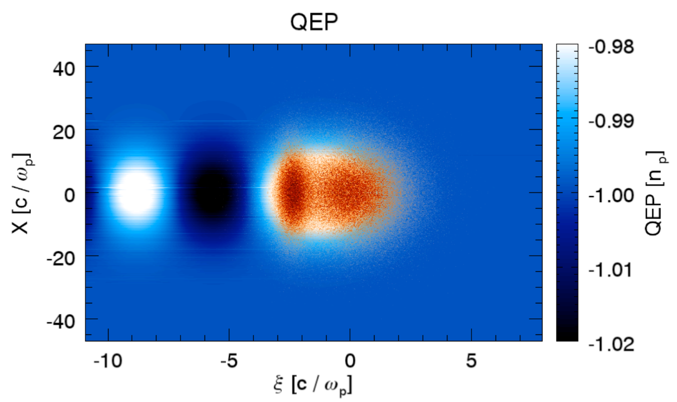
$$\partial_\xi F_z = 0 \qquad \partial_\xi F_\perp = 0$$

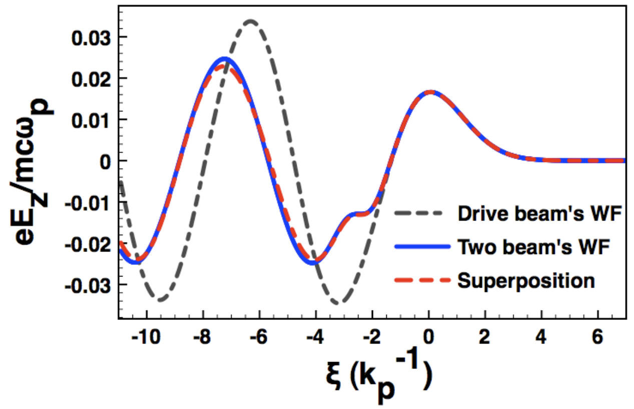
$$\nabla_\perp F_\perp = C_{onstant} \qquad \nabla_\perp F_z = 0$$

We now have all the tools needed to investigate beam loading in linear regime

$$\bar{\psi}(\xi,r,\phi) = -\int_{\xi}^{\infty} k_p d\xi' sin(k_p\left[\xi-\xi'\right])\left[\bar{\phi}_p(\xi'\phi',r') + \int_0^{2\pi}\frac{d\phi'}{2\pi}\int_0^{\infty} dr' r' K_0\left(k_p|\bar{r}-\bar{r'}|\right)\frac{n_b(\xi',\phi',r')}{n_0}\right]$$

$n_b = n_d + n_t$ where **d** stands for driver and **t** stands for trailing. If there is a laser driver then $n_d = 0$. The challenge is to get the wake fields inside the trailing beam that provide good beam quality while at the same time to get the trailing beam to absorb the wakes energy (wake behind the two bunches is less than behind the driver).





The wake potential (and forces) inside the trailing beam depend on its longitudinal and transverse profiles. The profiles you want depend on the relative position: Phase slippage, driver distortion, and trailing bunch distortion make this challenging.

Beam Loading

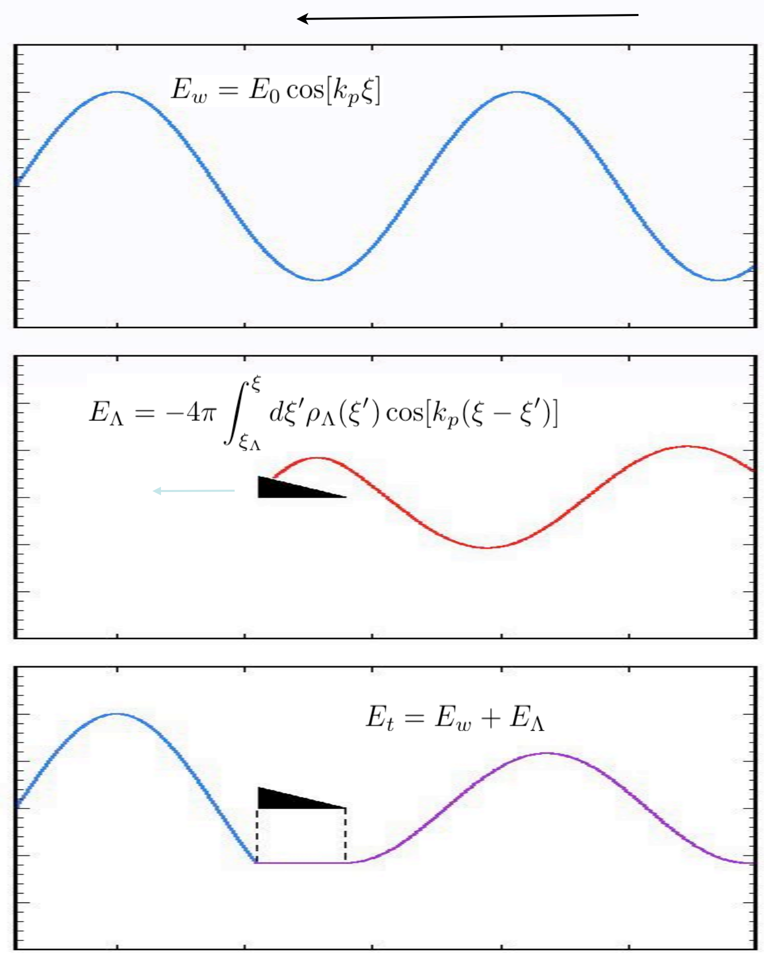
linear regime

- In the linear regime one superimposes the wake by trailer to the wake by the driver to find the total wakefield [1].

- Bunch shaping for no energy spread: Triangular.

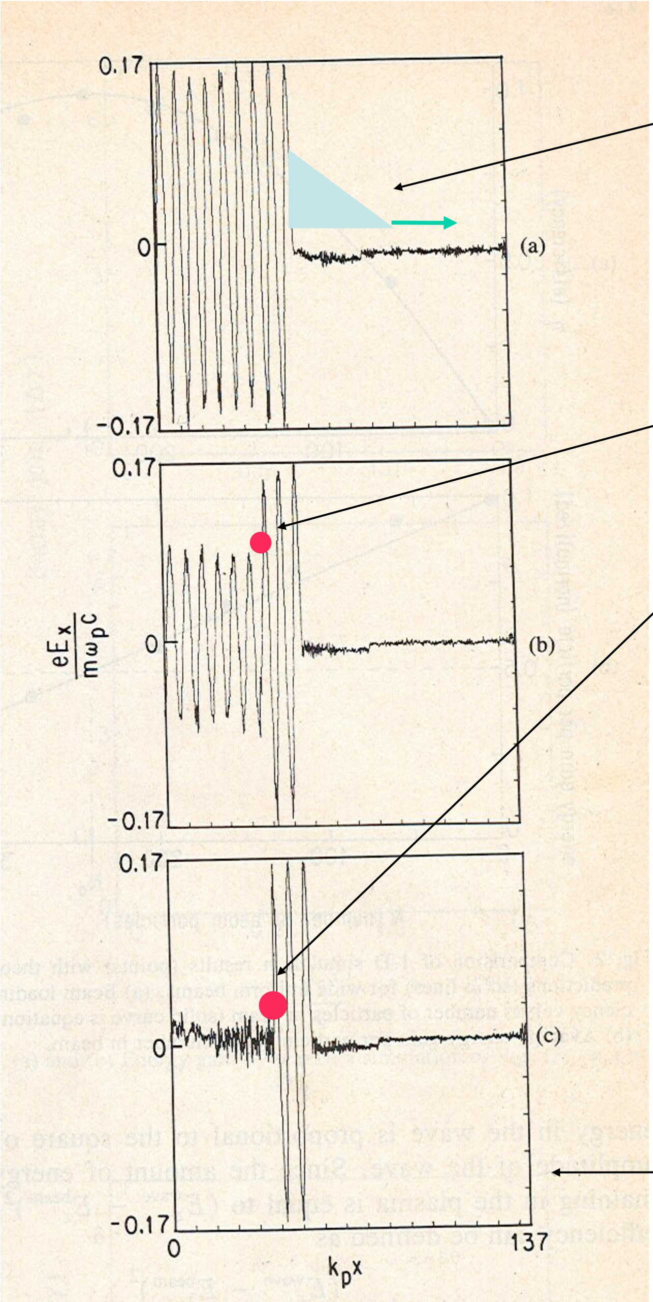
- The total charge can be found by requiring that all of the energy in the wake is absorbed. You can look at the wake left behind or you can look at the force on the particle.

- Works for electron and positron loads.



[1] T. Katsouleas, S. Wilks, P. Chen, J. M. Dawson, J. J. Su - Part. Accel, 1987

Original simulation results: 1987



Katsouleas, Wilks et al., 1987

Drive beam (laser or particle beam)
Note that wedge gives nearly constant decelerating field

Properly phased trailing beam of particles: Loads wake

- In linear theory just use superposition:
  Add wakes =>

$$\boxed{N_{\max} \approx 10^{11} \frac{n_1}{n_o} \sqrt{\frac{10^{16} cm^{-3}}{n_o}}}$$

(for spot size c/ω_p)

$$eE_z cN = \frac{E_z^2}{8\pi} Ac$$

- 100% energy extraction (though V_{gr}=0)
- 100% energy spread

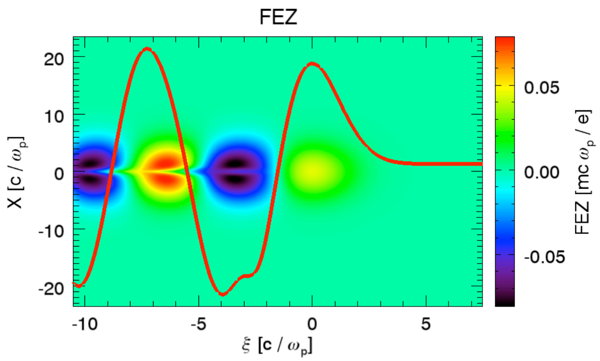
Efficiency: Linear theory

- Need to absorb the wake including in the transverse direction: Energy in wake behind the trailing bunch must be a large fraction of that in front of the bunch

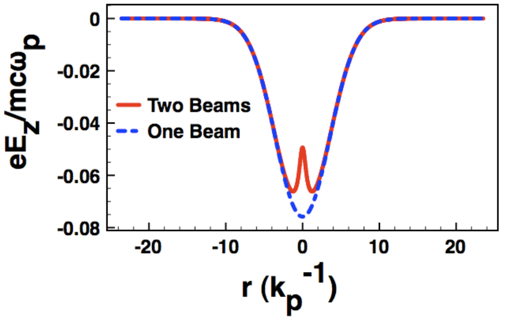
$$\frac{\int d\xi k_p \int dx_\perp \frac{<E_z^2+E_r^2>}{8\pi}\Big|_{after}}{\int d\xi k_p \int dx_\perp \frac{<E_z^2+E_r^2>}{8\pi}\Big|_{before}} \equiv R$$

$$\eta \equiv 1 - R$$

$$\eta = 1 - \frac{\psi_a^2 A_a}{\psi_b^2 A_b}$$



Transverse lineout of Ez at the center of trailing beam



- If the trailing bunch is wide then its spot size needs to be equal to the drivers spot size.
- Recall a narrow trailing bunch can absorb energy out to a radius of c/wp. So one can use a narrow trailing bunch and a driver with a spot size ~c/wp.
- Note: You can get good efficiency at the expense of the gradient: You make the wake small after (and hence inside) the bunch.

What did linear theory tell us?

UCLA

- Emittance preservation (spot size matching), high efficiency, low energy spread can be achieved by using:
  a. very narrow beam loads and c/wp wake spot sizes, with shaped current profiles

  b. very wide drive and witness beams and shaped (longitudinally and transversely) shaped witness beams.

- The accelerating and transverse fields within the trailing beam depend on both the witness beam and driver profiles:
  - Need to shape the witness beam
  - Phase slippage is an issue

- ***Narrow beams with high charge themselves make nonlinear wakes.***

Efficient beam loading requires nC of charge which create nonlinear wakes they are narrow

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:

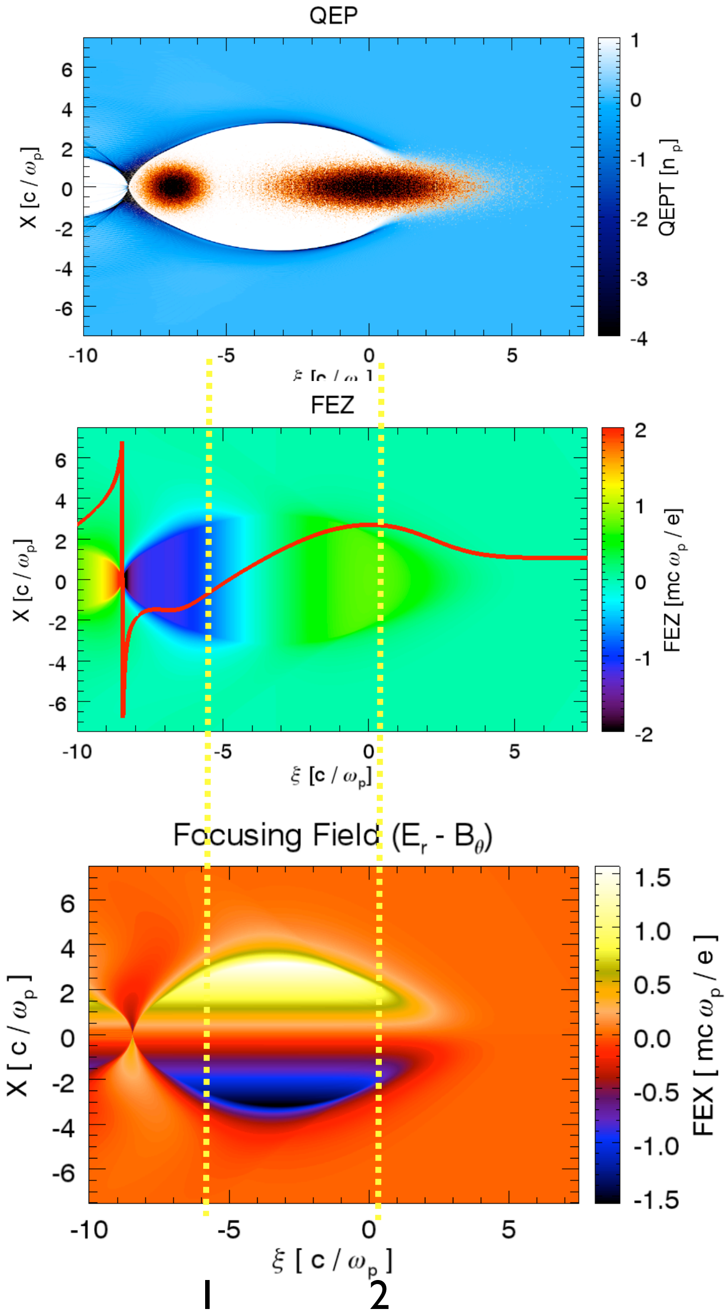
$$\frac{n_b}{n_0} = 1.4\times10^4\frac{N}{1\times10^{10}}\frac{\mu m - rad}{\sqrt{\epsilon_{Nz}\epsilon_{Ny}}}\sqrt{\frac{Energy}{250GeV}}\frac{1}{\alpha}$$

For collider parameters:

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

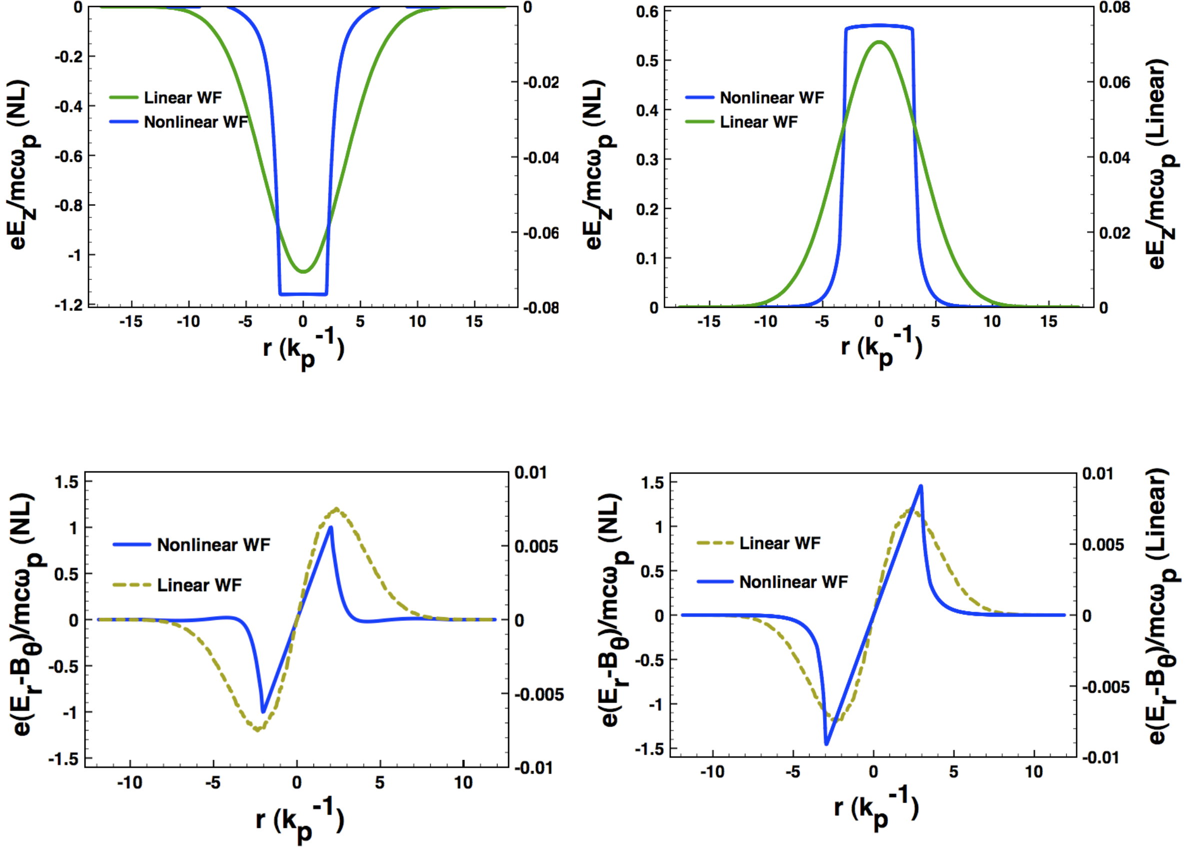
Ion motion, which can degrade the accelerating and focusing fields, occurs when nb/no~M/m

Nonlinear wakefield is IDEAL for accelerating/focusing electrons
Trailing beam does not modify focusing fields of wake



Trailing beam

Drive beam



$$\partial_\xi F_z = 0$$

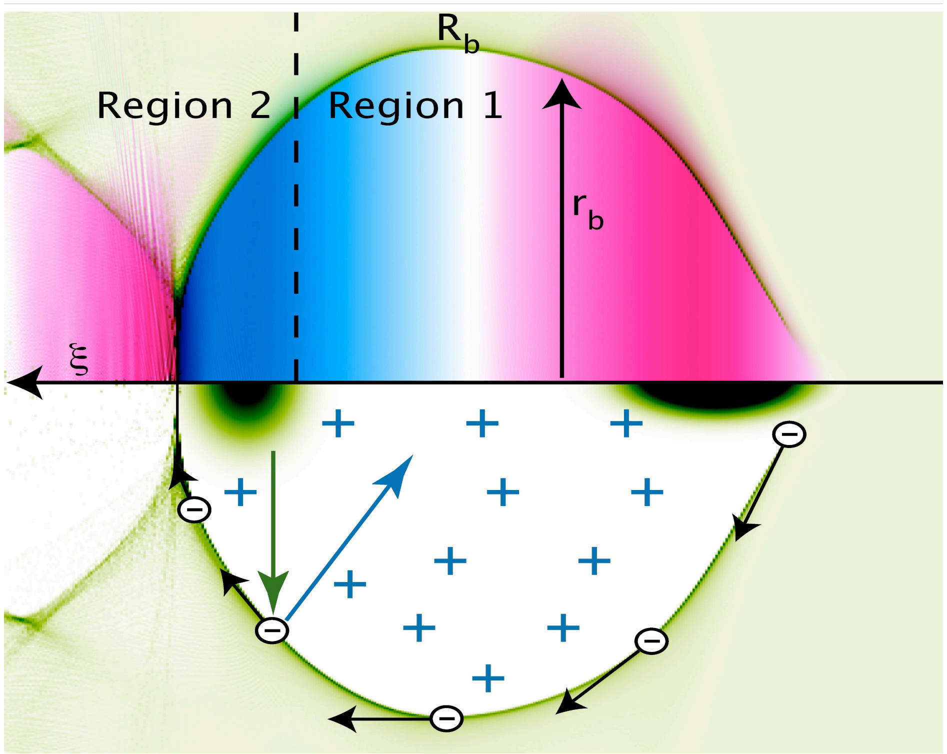
$$\nabla_\perp F_\perp = C_{onstant}$$

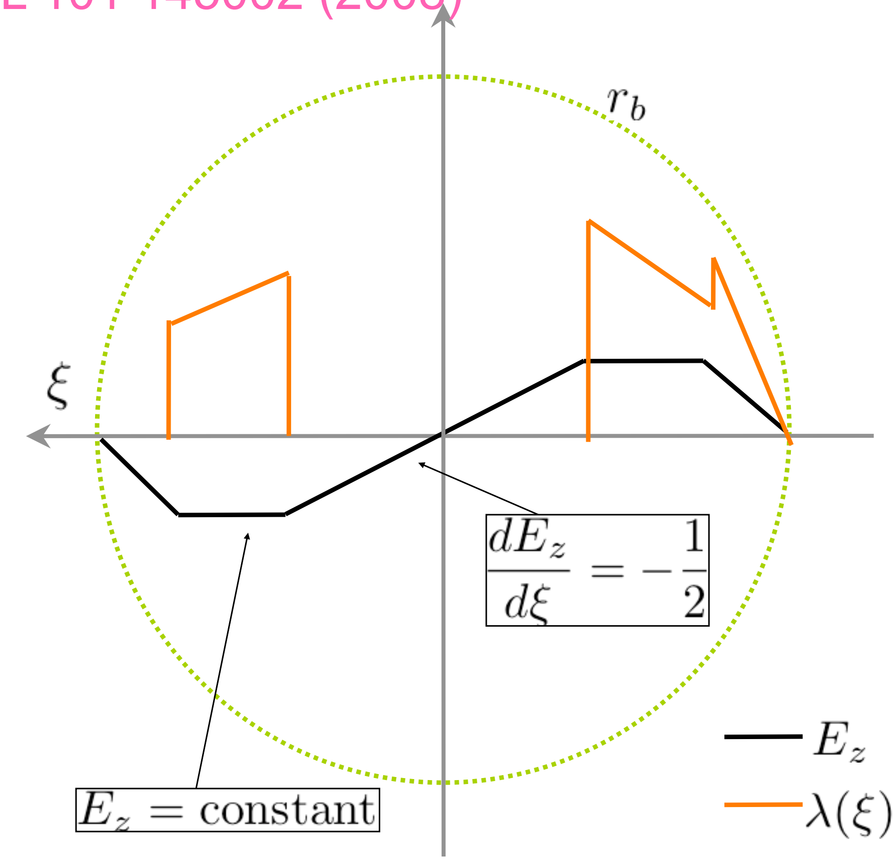
$$\partial_\xi F_\perp = 0$$

$$\nabla_\perp F_z = 0$$

Nonlinear beam loading: Solve equation for $R_b(\xi)$

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





$$\text{For } \frac{r_b}{R_b} \ll 1 \rightarrow \begin{cases} r_b \frac{d^2 r_b}{d\xi^2} + 2\left[\frac{dr_b}{d\xi}\right]^2 + 1 = \frac{4\lambda(\xi)}{r_b^2} \\ E_z = \frac{1}{2} r_b \frac{dr_b}{d\xi} \end{cases}$$

These equations are integrated for a trapezoidal $\lambda(\xi)$ to obtain $E_z(\xi)$ and $r_b(\xi)$. This allows us to design accelerators with 100% beam-loading efficiency that conserve the energy spread.

Efficiency

Very high efficiency can be achieved in the nonlinear regime because the spot size also is reduced when energy is absorbed!

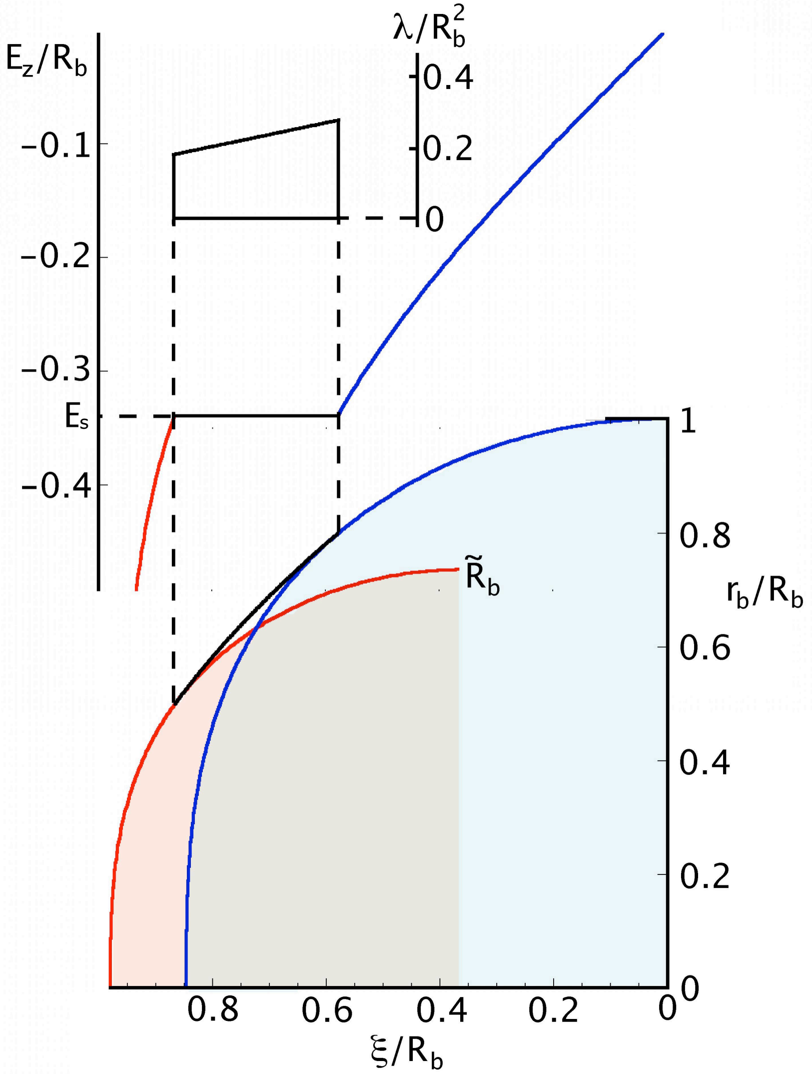
- There is a tradeoff between maximum charge and maximum energy

$$\frac{Q_s \times E_s}{mc^2/r_e} = \frac{1}{4^3} \times (k_p R_b)^4$$

$$\frac{Q_l \times E_l}{mc^2/r_e} = \frac{1}{8\pi}\left(\frac{n_1}{n_0}\right)^2 \times \sin^2(k_p \zeta_0)$$

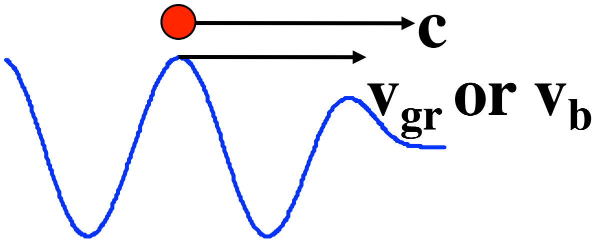
- **For nonlinear beam loading the efficiency approaches 100%, while E_z is constant in z and r.**

$$\eta_b = 1 - (\widetilde{R}_b/R_b)^4 = \frac{\widetilde{Q}_s}{Q_s}$$



Let me switch gears as we near the end and discuss some basic concepts and terms regarding what limits the acceleration distance

Dephasing



$$(c - v_g)L_{dph} = \lambda_p/4$$

$$v_g \approx c(1 - \frac{1}{2}\frac{\omega_p^2}{\omega_o^2})$$

$$\Rightarrow L_{dph}\frac{\omega_p}{c} = \pi\frac{\omega_0^2}{\omega_p^2}$$

order 10 cm
x $10^{16}/n_o$

or

$$\Rightarrow L_{dph}\frac{\omega_p}{c} = \pi\gamma_b^2$$

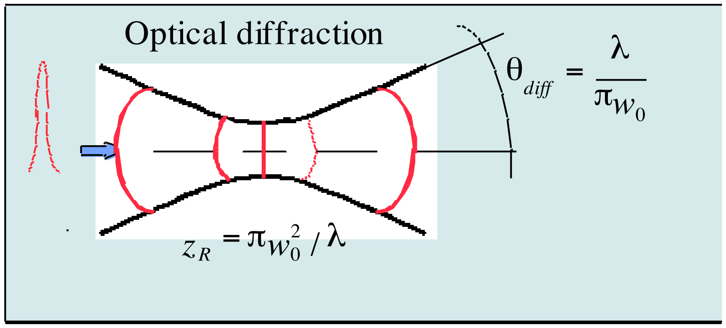
Generally not a problem for a particle beam

Diffraction

- Laser: $$L_{dif} \cong \pi L_R = \pi^2 w_0^2 / \lambda = \frac{\pi}{2}\frac{\omega_o}{\omega_p}\left(w\frac{\omega_p}{c}\right)^2 \frac{c}{\omega_p}$$

order mm!

(but overcome w/ channels or relativistic self-focusing)

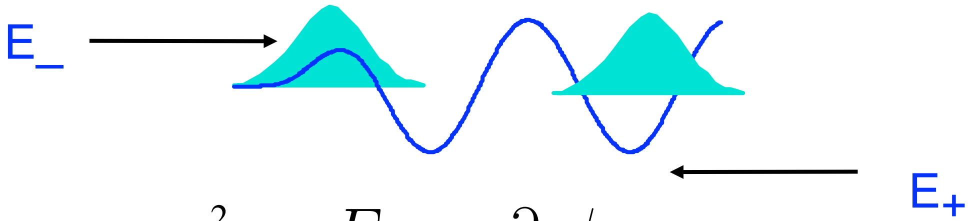


- Particle beam: $$L_{dif} \cong \pi\beta^* = \pi^2 w_0^2 / \varepsilon$$

where ε is the emittance (unnormalized) of the beam

order meter
So not an issue

Pump depletion: Transformer ratio



$$eE_{-}L_{pd} = \gamma_b mc^2 \qquad E_{-} = \partial_\xi \psi_{-}$$

$$\Delta W = eE_{+}L_{pd}$$

$$\Rightarrow \Delta W = \frac{E_{+}}{E_{-}}\gamma_b mc^2$$

$$\frac{E_{+}}{E_{-}} \equiv \text{Transformer ratio} \equiv \mathrm{R}$$

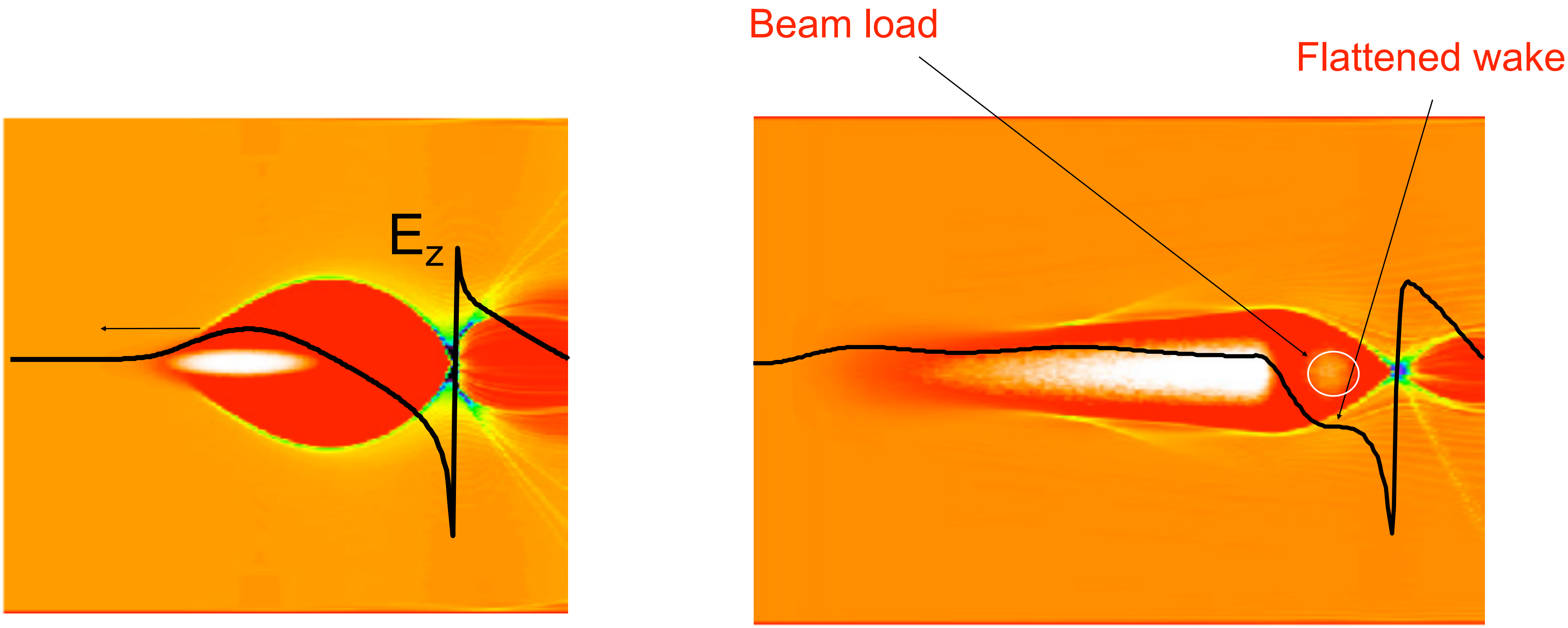
Linear theory: For a symmetric bunch R = 2

You want particles in bunch to slow down together:

$$E_{-} = \partial_\xi \psi_{-} = Constant$$

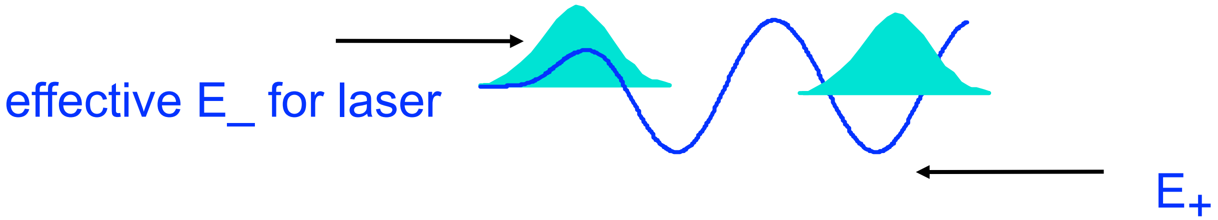
High transformer ratio used a wedge shaped beam

Blowout regime



High transformer ratio also leads to constant decelerating field

Pump depletion: Same idea for a laser



Action of light pulse is conserved: Photon number is conserved

As laser energy is depleted the frequency (group velocity) of each photon decreases: Photon deceleration

$$\frac{1}{\omega_0}\partial_s \omega_0 = -\frac{1}{2}\frac{\omega_p^2}{\omega_0^2}\partial_\xi \psi$$

Pump depletion occurs when the laser frequency drops to $\omega_p << \omega_0$

$$L_{pd} \approx 2\frac{\omega_0^2}{\omega_p^2}\frac{1}{\psi_-}\frac{c}{\omega_p}$$

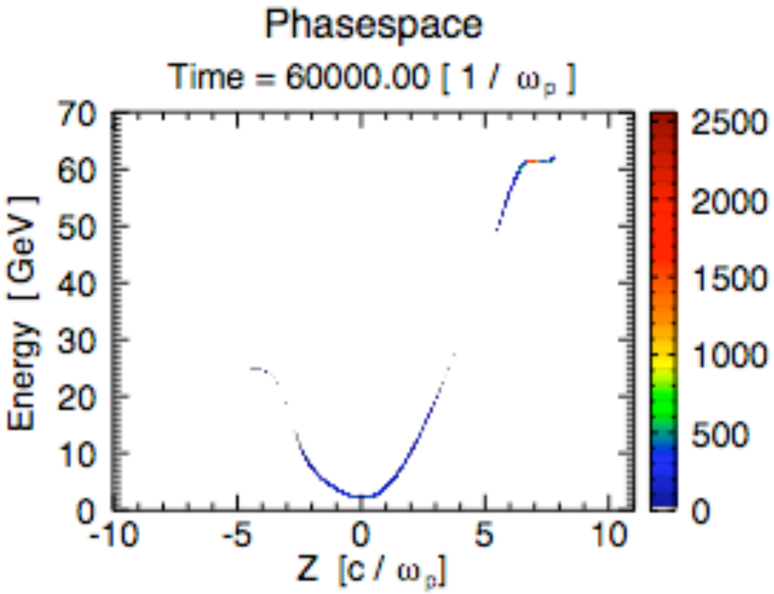
You want photons in bunch to slow down together:

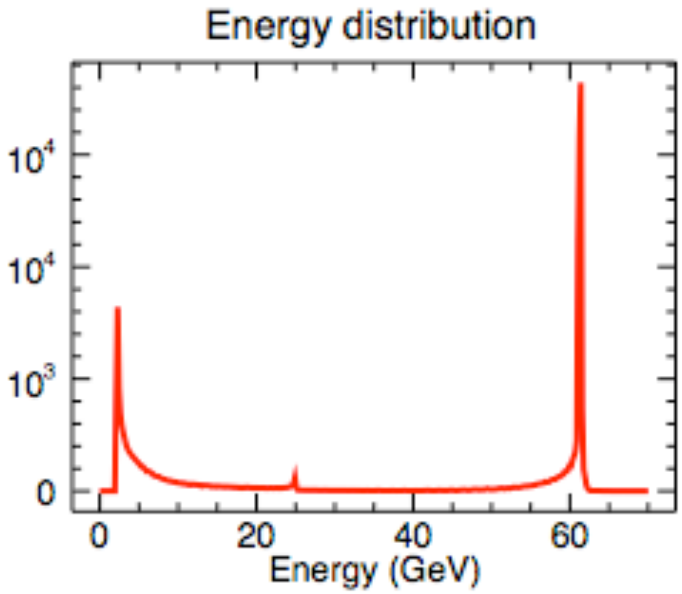
$$E_- = \partial_\xi \psi_- = Constant$$

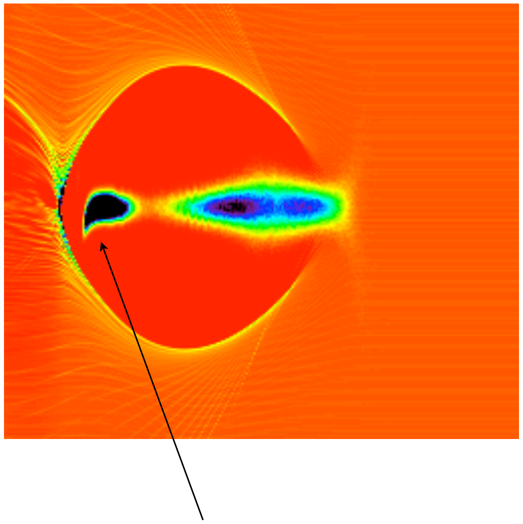
You want pump depletion to be the limiting factor to the acceleration length for high efficiency.

A high efficiency 25 GeV PWFA stage

Preionized







Hosing: A talk
for another day

$n_p =$ $1\times10^{17}\,cm^{-3}$

$N_{driver} =$ 2.9×10^{10}, $\sigma_r = 3\ \mu$, $\sigma_z = 30\ \mu$, Energy = 25 GeV

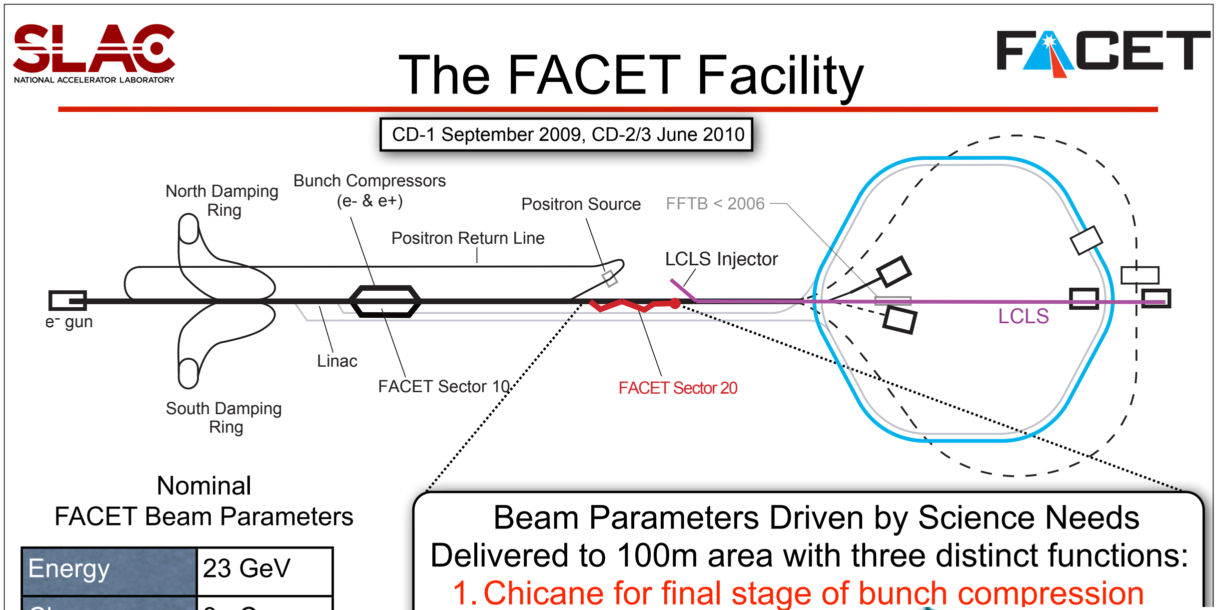
$N_{trailing} =$ 1.0×10^{10}, $\sigma_r = 3\ \mu$, $\sigma_z = 10\ \mu$, Energy = 25 GeV

Spacing= 110 μ

$R_{trans} = -E_{acc}/E_{dec} > 1$ (Energy gain exceeds 25 GeV per stage)

1% Energy spread

Efficiency from drive to trailing bunch ~48%!



The FACET Facility

CD-1 September 2009, CD-2/3 June 2010

Nominal
FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Sigma z	14 µm
Sigma r	10 µm
Peak Current	22 kAmps
Species	e^- & e^+

Beam Parameters Driven by Science Needs
Delivered to 100m area with three distinct functions:

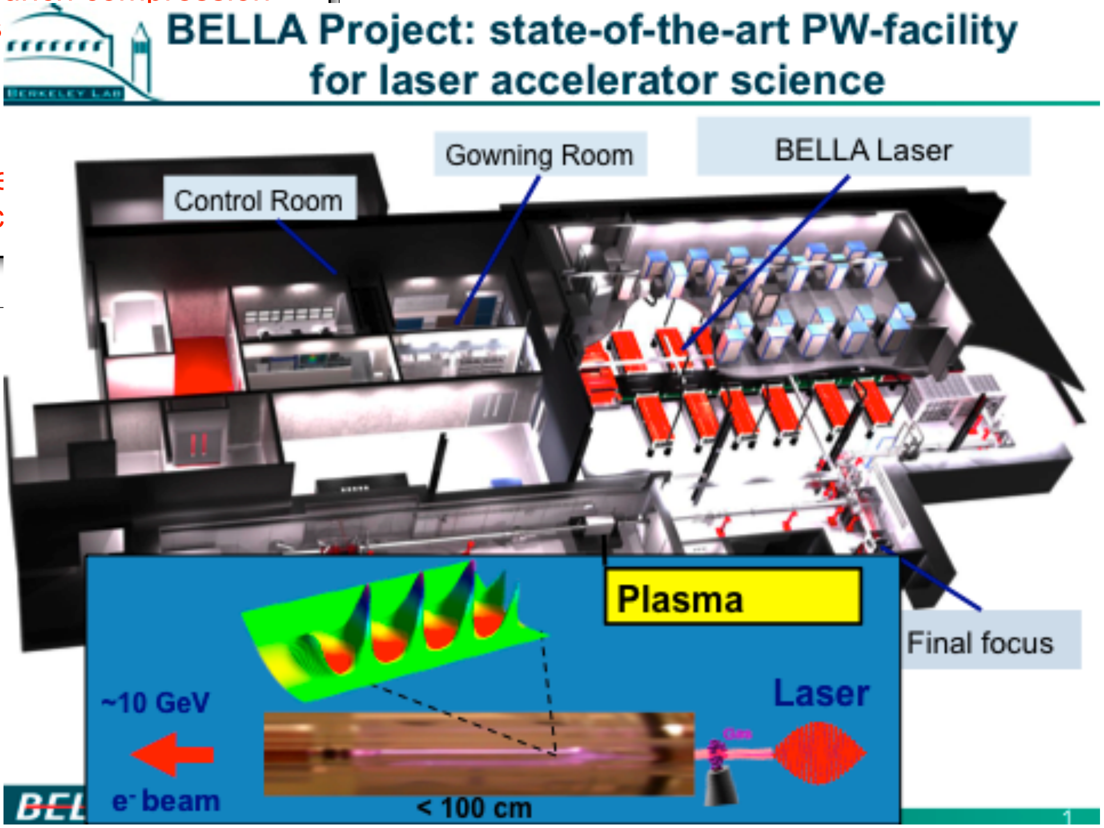
1. Chicane for final stage of bunch compression
2. Final Focus for small spots
3. Experimental Area(s)

Advantageous location:

- Preserves e+ capability
- No bypass lines or interfere
- Linac setup virtually identic

M.J. Hogan, AAC2010, June 14, 2010 Page 1

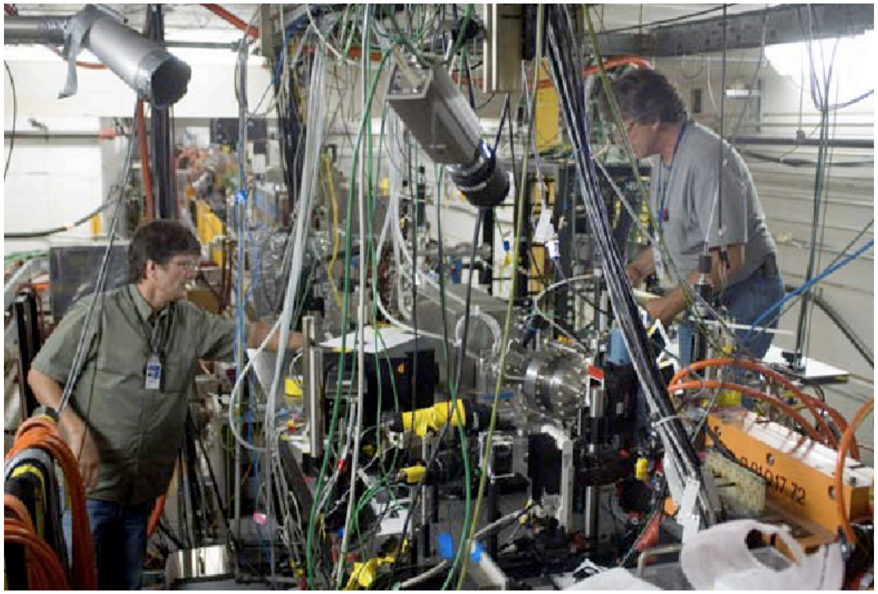
Two new facilities are being built for studying key physics of plasma-based acceleration related to colliders: Study a single stage of a multi-stage accelerator



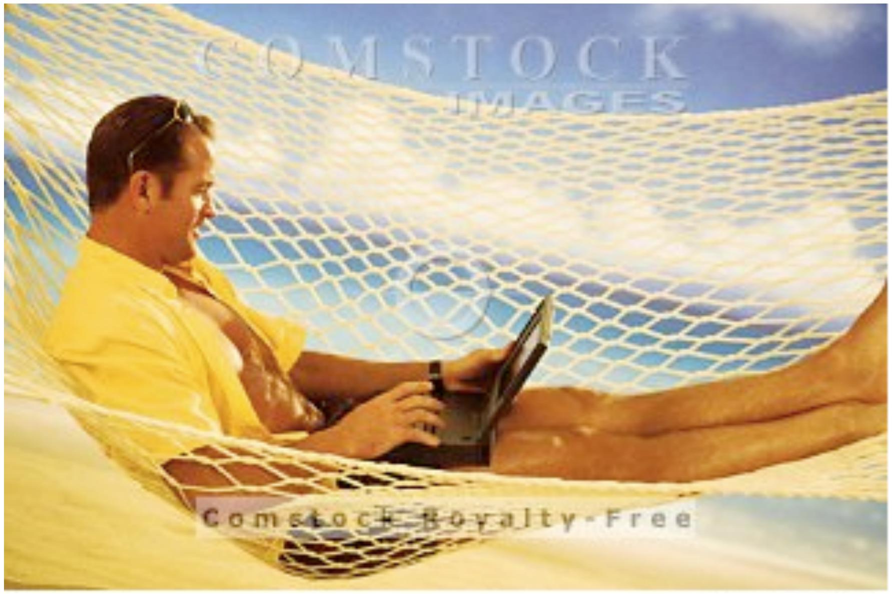
BELLA Project: state-of-the-art PW-facility for laser accelerator science

The plasma based accelerator ecosystem also includes university facilities such as here Michigan which are aimed at studying basic physics

The past required and the future will require a close connection between experiments and simulations



Life of an experimentalist



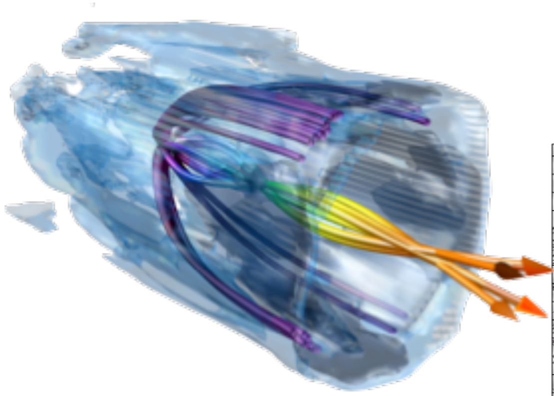
Life of a simulationist

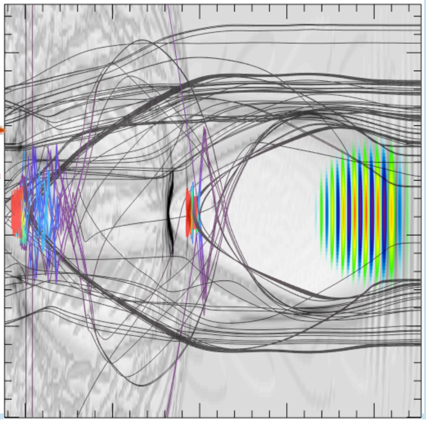
My experimental colleagues view of
the world

Massively parallel PIC codes for advanced accelerator modeling at UCLA: Unique capabilities

OSIRIS

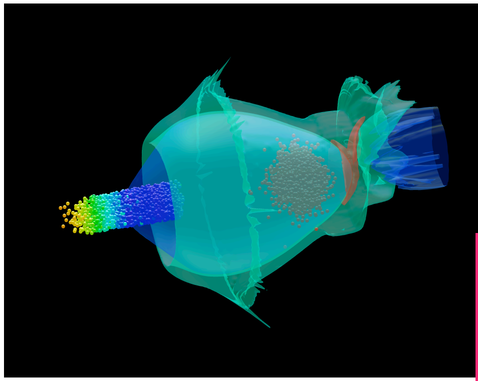
- **3D Fully Relativistic Electromagnetic PIC code**
- **Massively Parallel (scales well up to 300,000 cpus)**
- **Optimized, dynamic Load Balancing, higher order particle shapes, Open EM boundary conditions, Ionization, Binary Collision Module, Parallel I/O, Boosted Frame, Hybrid model for high densities**
- **4 INCITE Grants, chosen for 2011 DOE Joule Metric Challenge**
- **Development institutions**
  - UCLA and IST
  - See http://plasmasim.physics.ucla.edu/

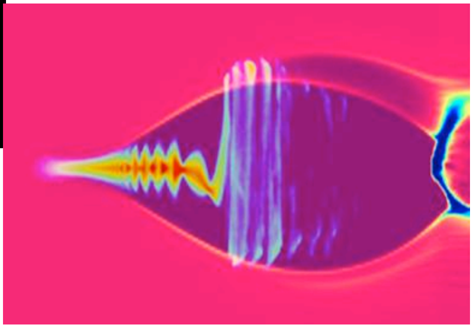




QuickPIC

- **3D Quasi-static fully nonlinear PIC code**
- **Ponderomotive guiding center + envelope model**
- **Can be 100+ times faster than conventional PIC with no loss in accuracy**
- **Scales to 10,000s of processors**
- **2 INCITE Grants**
- **Development institutions**
  - UCLA, IST, and U. Maryland
  - See http://plasmasim.physics.ucla.edu/





Speed ups from advanced architectures

SIMD units

VM

SSE/

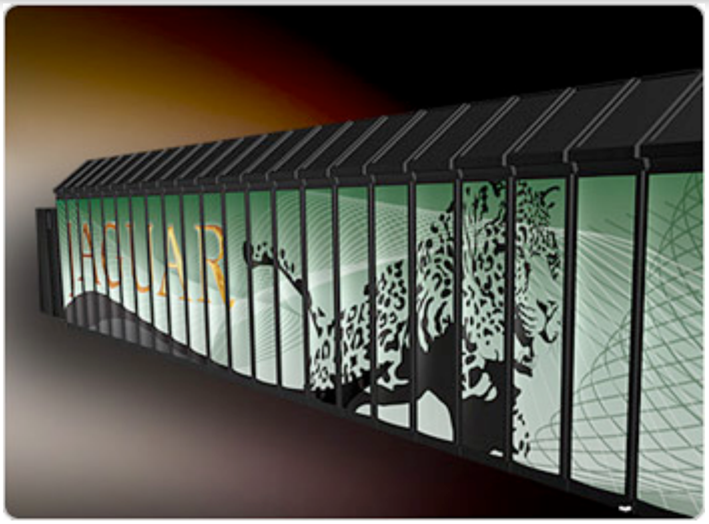
GPGPUs

CUD

STREA

- SIMD
- GPGPU
- Ultra-Massively Parallel: 10^5 + cores

FZ Jülich Jugene
IBM BlueGene/P
#5 - TOP500 Jul/10
294912 cores
R_{max} 825 TFlop/s



Jaguar
#1 - TOP500 Jul/10
224,256 cores
R_{max} 1.7 PFlop/s

DAWSON2
300 Tflop/s GPU based cluster
Exclusively for UCLA Plasma Simulation Group!
(Just constructed with picture taken 4/12/11)

Summary and predictions for the next 10 years

- Very exciting time for plasma-based acceleration. Much recent progress has been made due to the advent of 100TW, 50 fs lasers, the compression of the SLAC beam to 100fs, AND the development of advanced codes together with Petaflop computers. LWFA produce GeV beams and PWFA has shown doubled the energy of 42 GeV electrons in less than 1 meter!
- Both PWFA and LWFA research is now focused on collider concepts that have multiple stages (10-100) that are each ~1meter in length. Two new facilities are being built to study single stages: FACET for PWFA and BELLA (30J/30fs) for LWFA
- Prediction: LWFA will make GeV+ beams with ~.1nC of charge, ~1% energy spread, and normalized emittances of ~mm-mr within the next 5 years and with sufficient R&D funding could be developed into a driver for a compact XFEL within the next 10 years.
- Prediction: PWFA will show 25 GeV energy gain of nC of charge in less than 1 meter while keeping the energy spread ~1% and maintaining the emittance.
- Prediction: Simulations will allow real time steering of experiments: We will reduce the throughput of a simulation from 1,000,000 hours to minutes or seconds: Hardware, CS, Algorithms, New methods..
- Prediction: Simulations will allow the design of optimum laser and beam profiles, energy chirps, plasma profiles etc. as well as the design of complete concepts for such stages including beam loading scenarios.

Synchrotron Radiation:The ultimate limit

$$P_{loss} = \frac{2}{3}\frac{e^2}{c}\gamma^6\left(\left[\dot{\vec{\beta}}\right]^2 - \left[\vec{\beta}\times\dot{\vec{\beta}}\right]^2\right)$$

$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}}1.5x10^{-5}(\frac{\mathrm{E}}{50GeV})^2(\frac{n}{10^{16}})^{3/2}(\frac{r}{1\mu m})^2$$

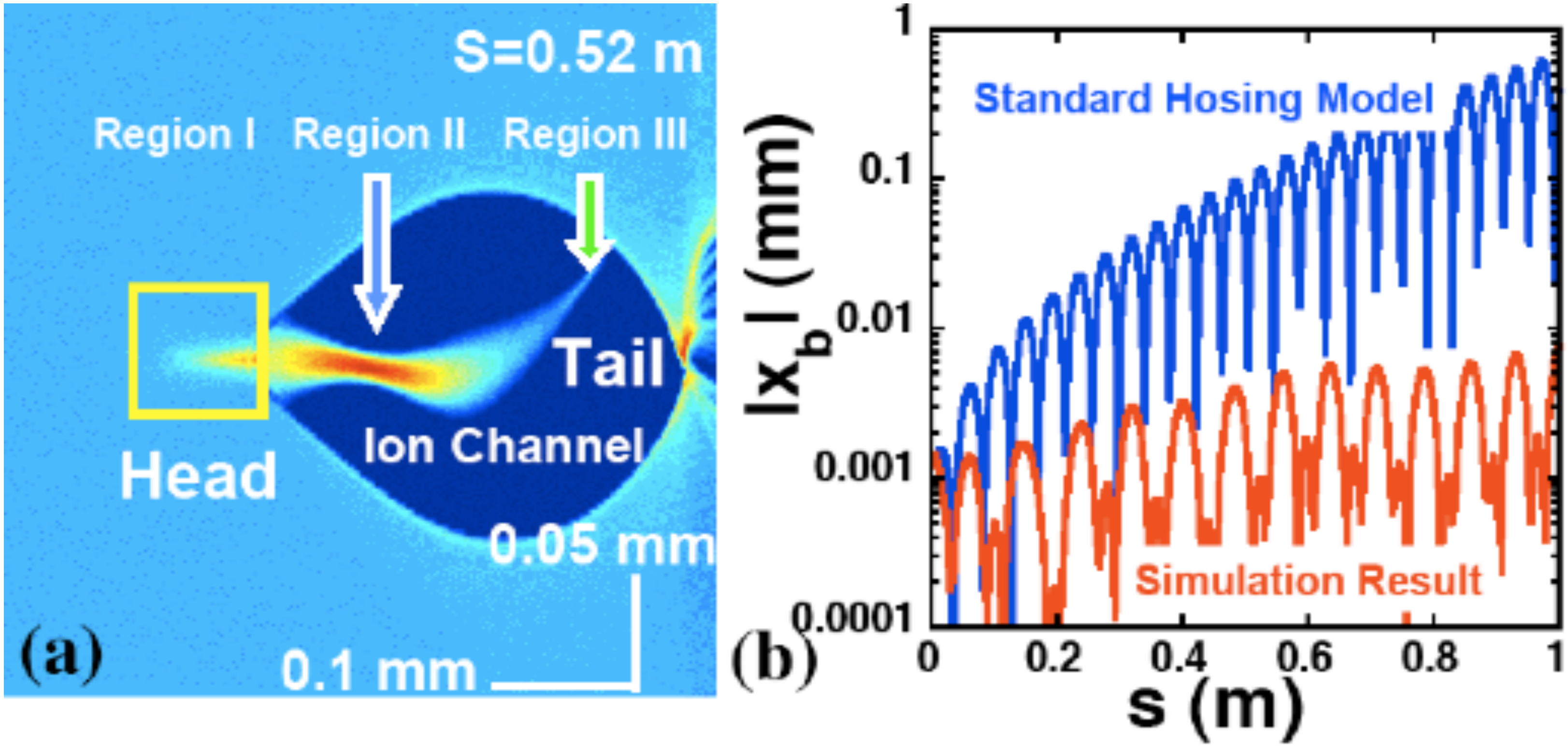
For a matched beam this can be rewritten as:

$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}}3.75x10^{-3}(\frac{\mathrm{E}}{250GeV})^{3/2}(\frac{n}{10^{16}})(\frac{\varepsilon_n}{10^{-6}m})$$

Hosing

Whittum et al. PRL 67 991 (1991)
and Huang et al. PRL 99 225001 (2007)

Hosing for an intense beam



Parameters: $n_0 = 2.0 \times 10^{16} cm^{-3}$ $L = 2.5m$

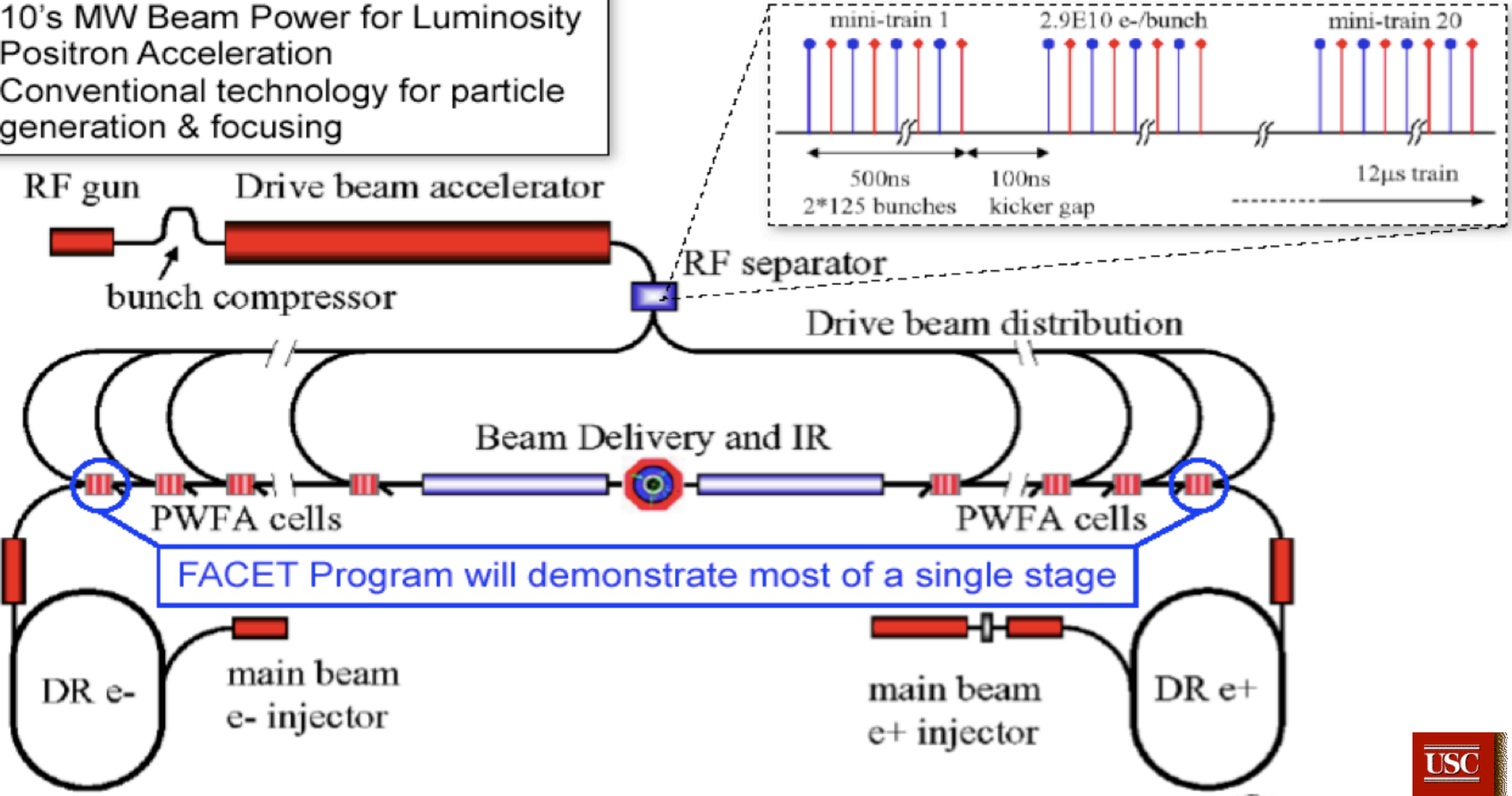
$n_b / n_0 = 25.9$ $tilt = 0.011$

$I_{peak} = 7.7$ kA

A concept for a Plasma Wakefield Accelerator based linear collider

A. Seryi et al. PAC Proceedings 2009

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



FACET Program will demonstrate most of a single stage