Plasma Wakefield Acceleration of Leptons driven by Hadron Beams

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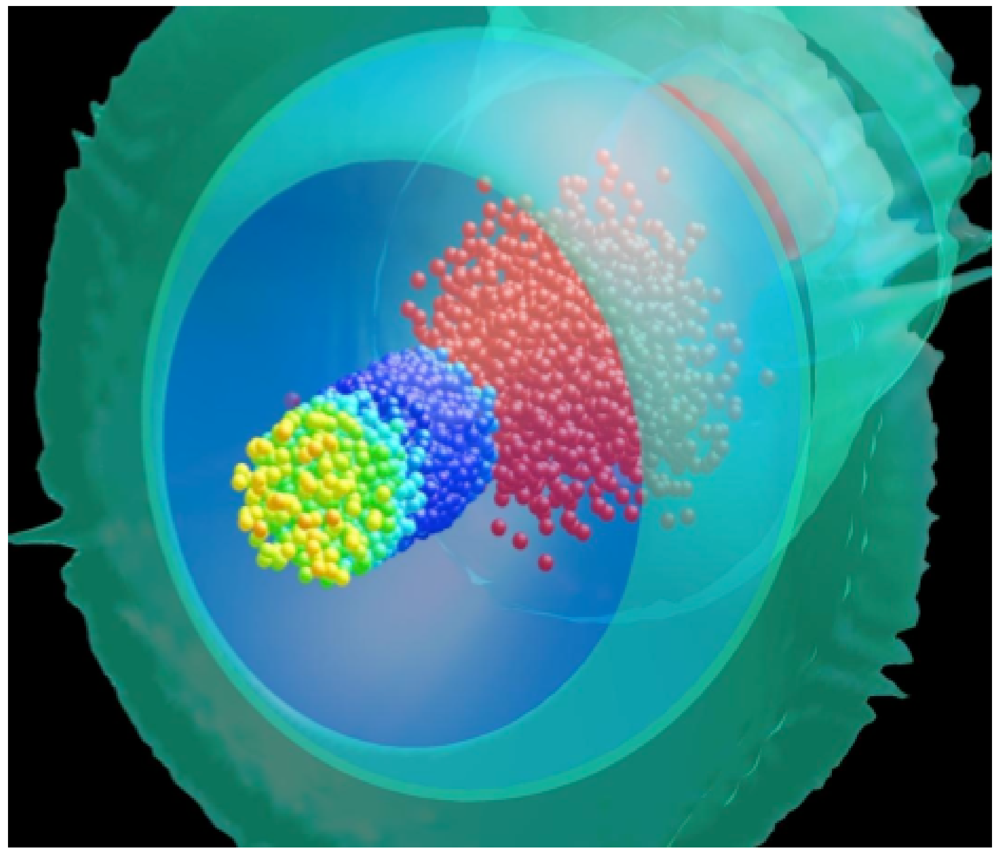
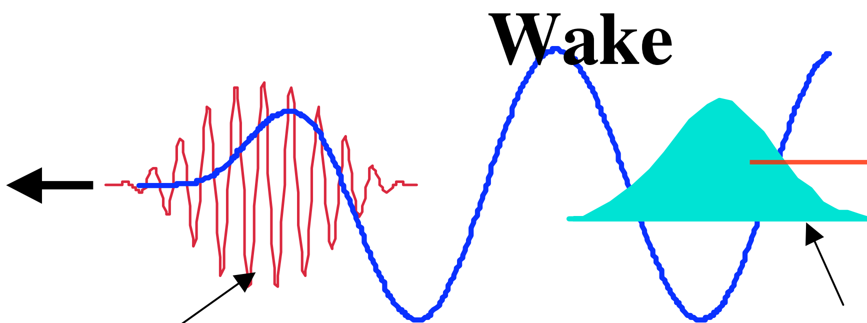


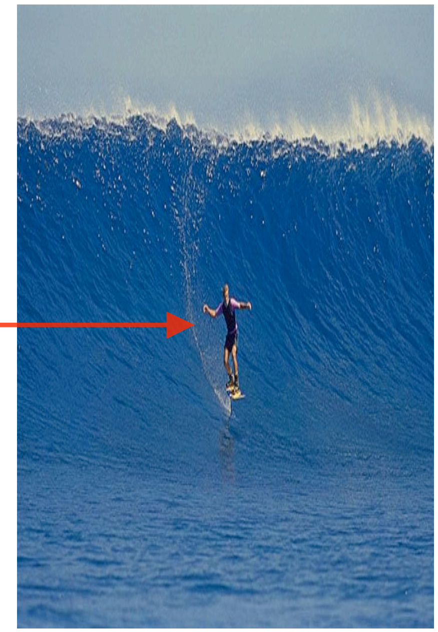
Jan. 13-14, 2010 Fermilab
Tevatron Accelerator Studies Workshop

Plasma based Acceleration



- **Laser or beam**
- **Trailing beam**

$$c\tau \sim \lambda_p$$

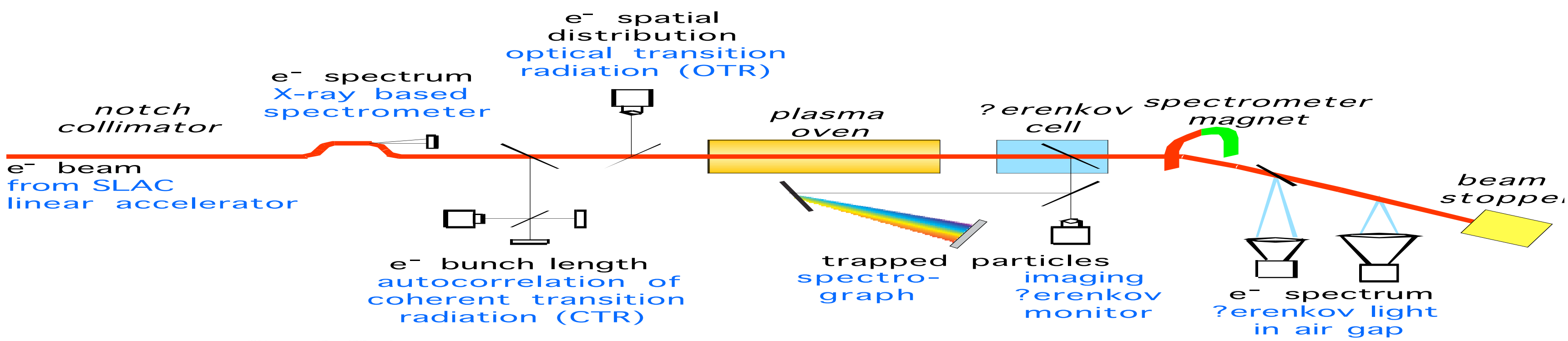


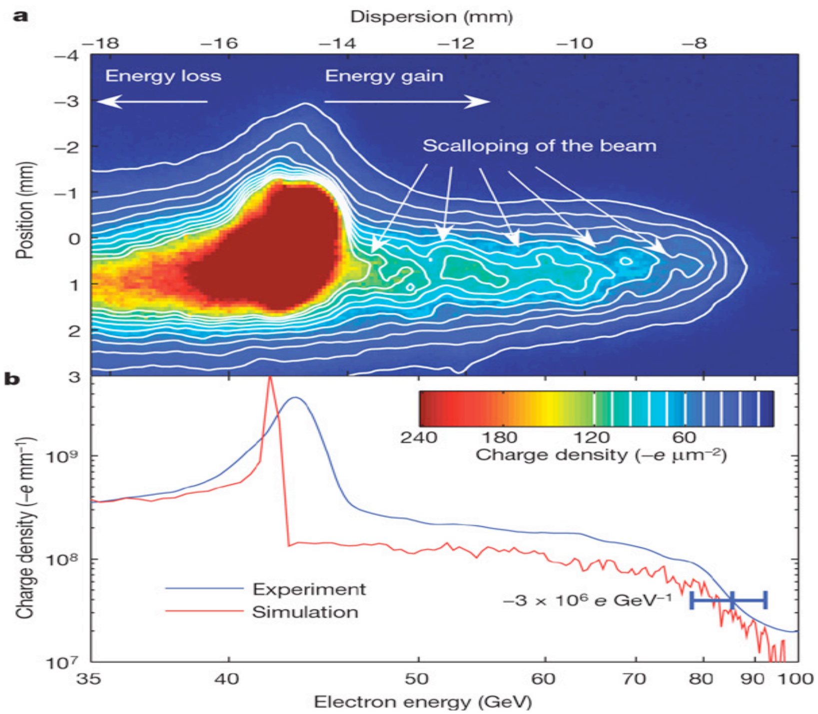
The key is the super high accelerating gradient!

$$E_{Acc} \approx \sqrt{n_p[cm^{-3}]}V/cm$$

T.Tajima and J.M. Dawson PRL (1979) **LWFA**
P.Chen, J.M. Dawson et.al. PRL (1983) **PWFA**

Energy doubling of 42GeV SLAC beam in Less than one meter!





Nature 445, 741-744, 2007

- **Most part of the 42GeV beam is nearly stopped in less than one meter**

- **The tail of the beam in the accelerating phase gains more than 42GeV energy**

- **A gradient ~ 50 GeV/m is sustained over meter scale**

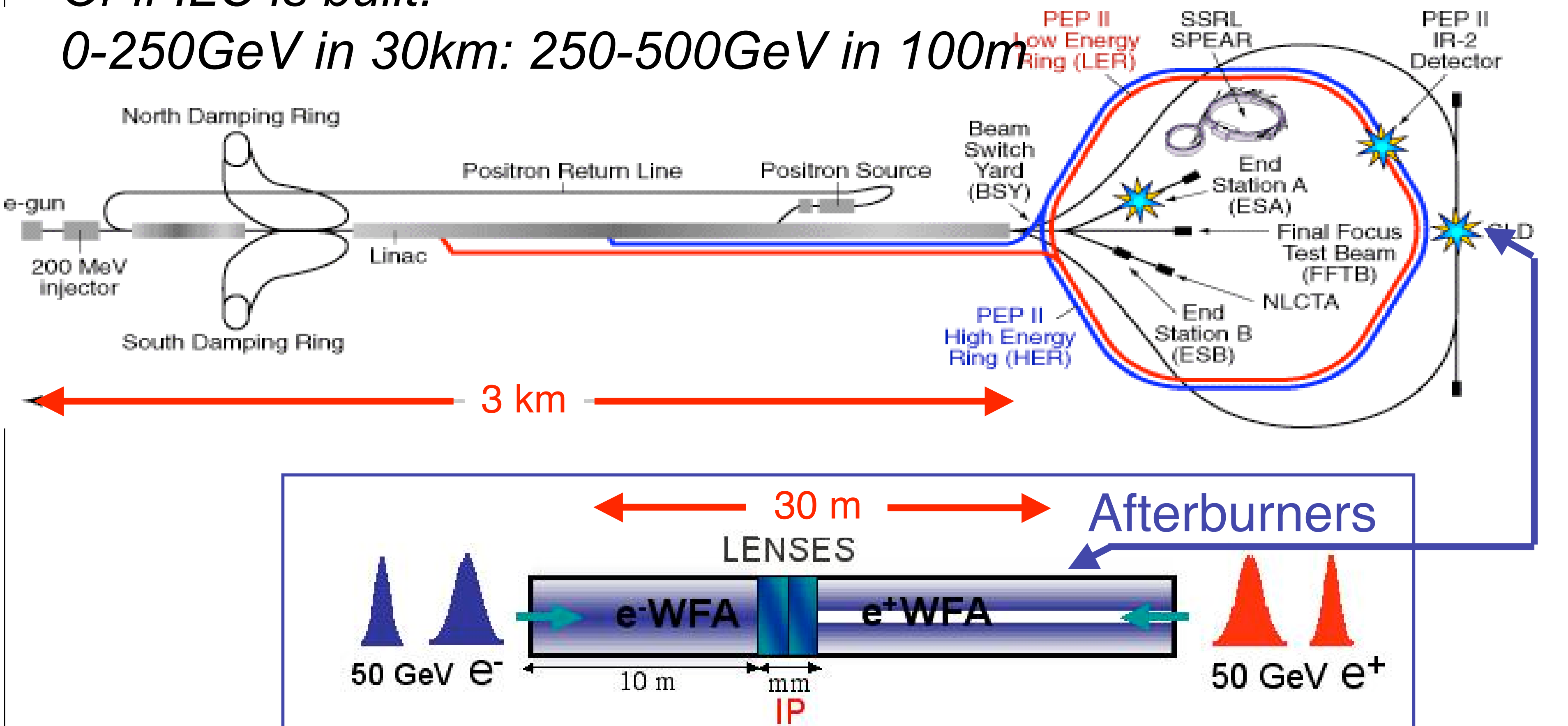
Plasma Afterburner (energy doubler)

Conceptually shown for SLAC parameters:

"0-50 GeV in 3 km: 50-100 GeV in 30 m"

Or if ILC is built:

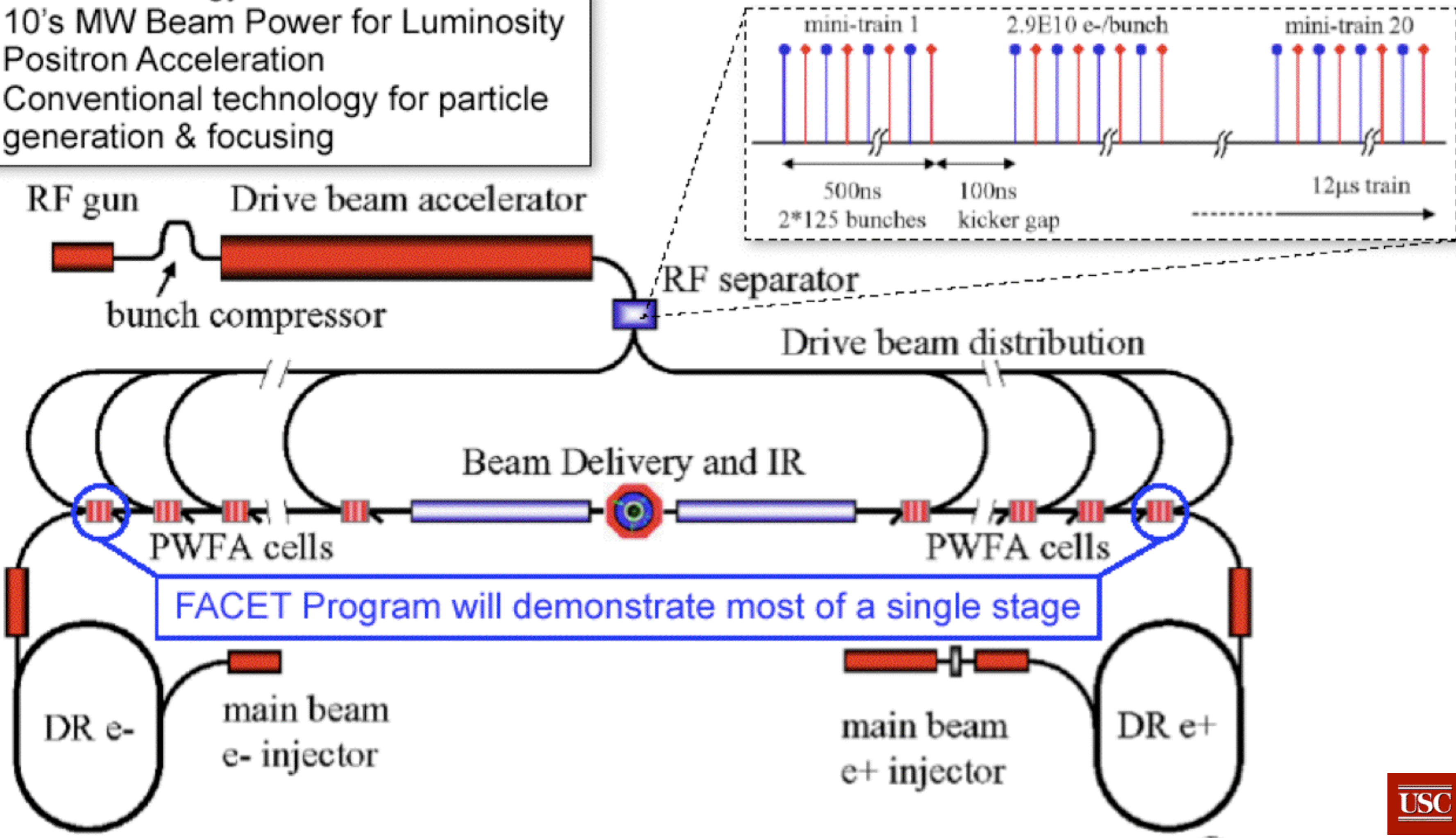
0-250GeV in 30km: 250-500GeV in 100m



S. Lee et al., Phys. Rev. STAB, 2001

Concept for a Plasma Wakefield Accelerator Based Linear Collider (Staging)

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



Proton Driven PWFA

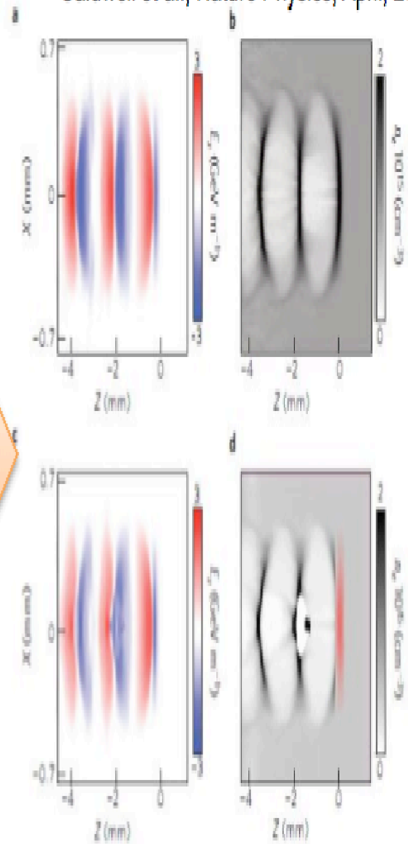
Proton parameters in LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

Caldwell et al., Nature Physics, April, 2009

Beam compressed to 100 μm



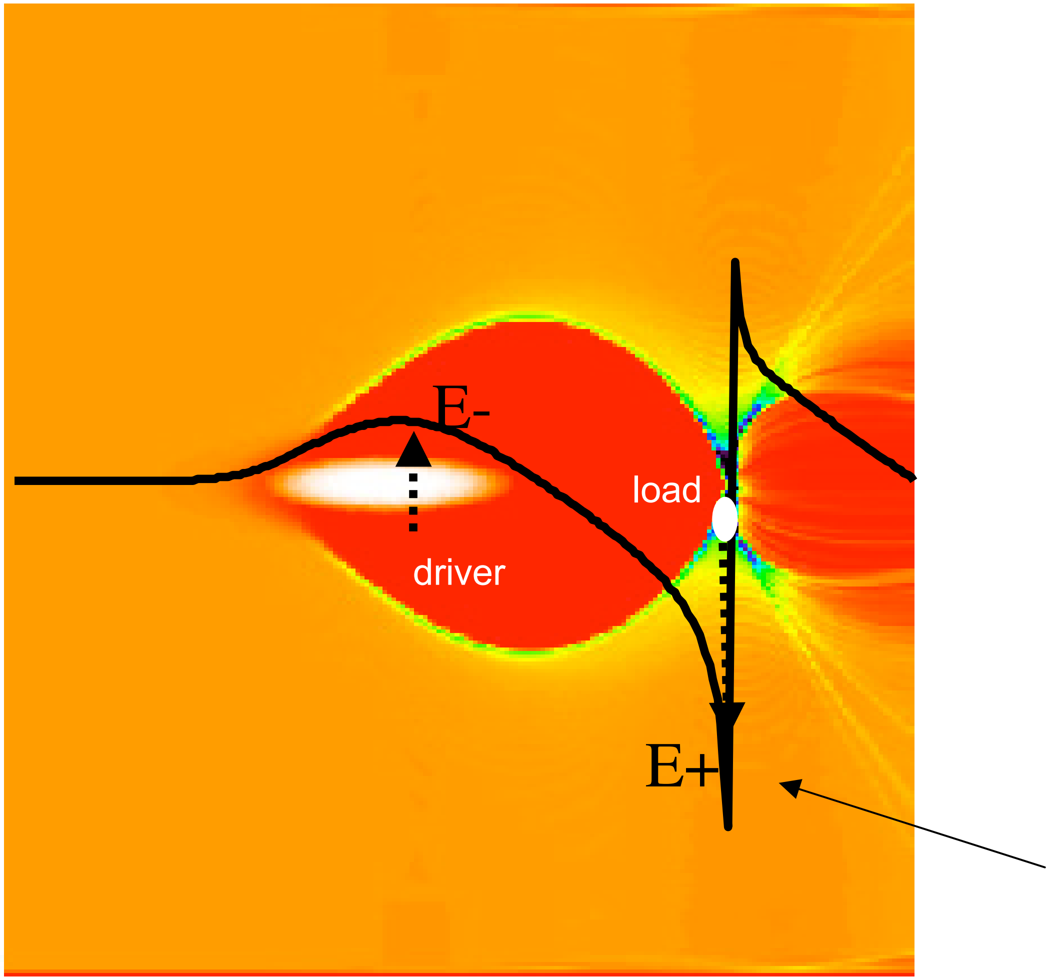
Similar to blow-out regime but also different in some aspects, e.g, focusing.

Key features:

- **A positively charged TeV driver (proton)**
- **Low plasma density (<10^15cm-3)**
- **Low gradient and long structure (GeV/m, and 500-1000m)**
- **External guiding**

A 3D Nonlinear Regime (the Blowout Regime)

Electron Beam Driver

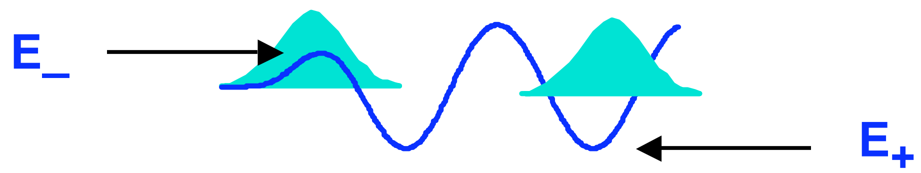


Rosenzweig et al., 1990, Lu et al., 2006

- Linear focusing for electrons
- Flat accelerating fields
- No dephasing
- No diffraction, but…
  - Head erosion
  - Hosing
- Transformer Ratio:

$$R \equiv \frac{\Delta\gamma_{load}}{\gamma_{driver}} \leq \frac{E_+ \cdot L}{E_- \cdot L} = \frac{E_+}{E_-}$$

Pump depletion and Transformer ratio



$$eE_{-}L_{pd} = \gamma_b Mc^2$$

$$L_{pd} = \gamma_b Mc^2 / eE_{-} = k_p^{-1}\gamma_b (\frac{M}{m}) / \varepsilon_{-}$$

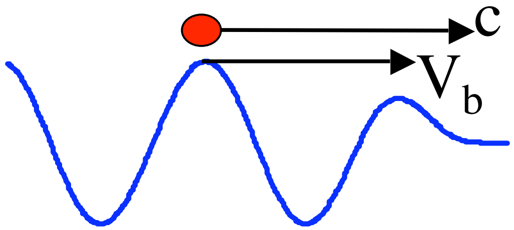
$$\Delta W = eE_{+}L_{pd}$$

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

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

Linear theory: For a symmetric bunch $\text{R} \leq 2$

Dephasing



$$L_{dph} = \frac{\lambda_p / 4}{1 - V_b / c} \approx \gamma_b^2 \lambda_p / 2$$

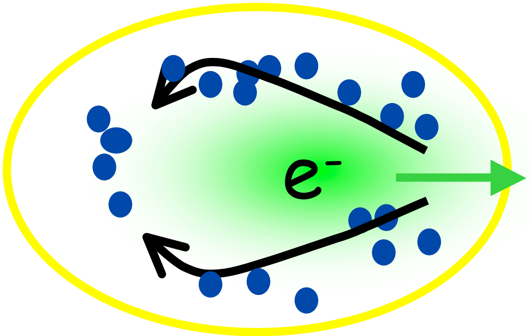
$$\frac{L_{dph}}{L_{pd}} = \pi \varepsilon_{-} \frac{m}{M} \gamma_b >> 1$$

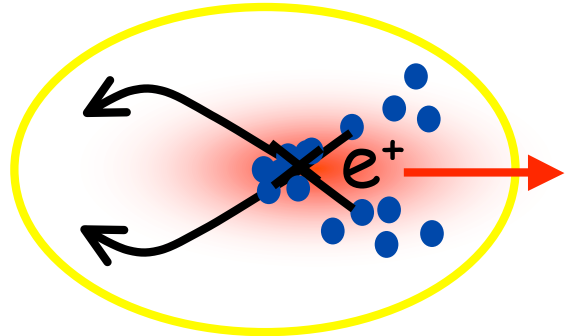
$$\Rightarrow \gamma_b > M / m$$

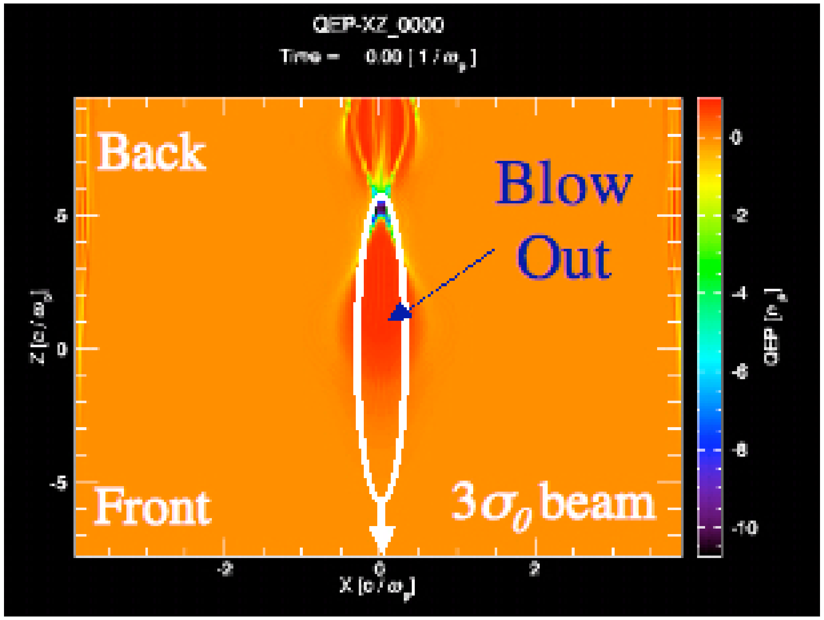
For example, for proton of energy around 1TeV, dephasing could be an issue

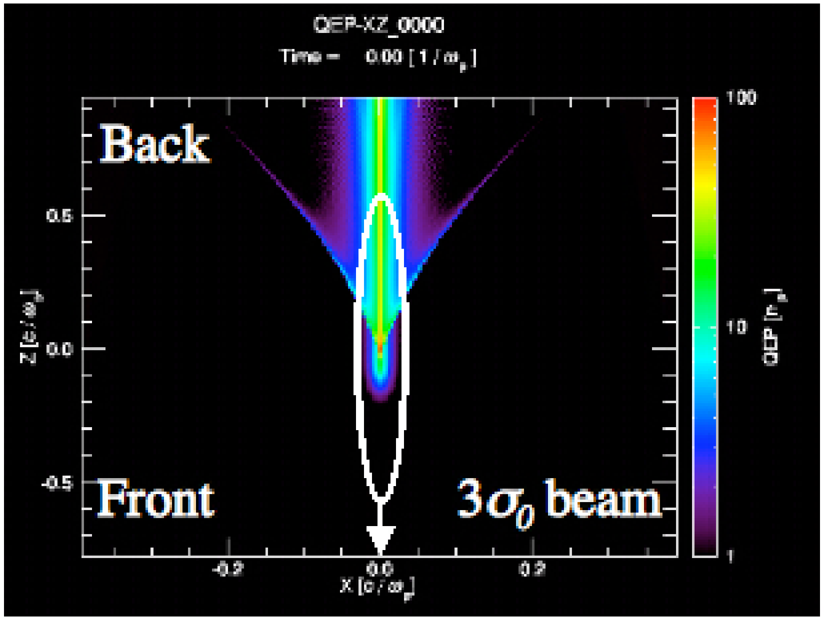
Not a problem for high energy lepton drivers, but could be significant for hadron drivers

Differences between negatively and positively charged drivers









- "Uniform" focusing force (r,z)

- Non-uniform focusing force (r,z)
- Smaller accelerating force

Ref. S. Lee et al., Phys. Rev. E (2000); M. Zhou, PhD Thesis (2008)

Advantages and Challenges of Using Hadron drivers

Major Advantages:

- TeV class drivers (LHC/Tevatron) are available!

Major Challenge:

- Compressing anti-proton/proton bunch to sub-ps level

Special physics issues for hadron driven PWFA:

- Energy spread induced driver spreading
- Beam head erosion due to diffraction
- Dephasing due to lower gamma_b drivers

Anti-Proton is Better!

Wakes produced by anti-proton is just like wakes produced by electrons, it is in general better than wakes produced by positively charged beams!

Anti-Proton driver (sigma_z~ 40um, N~10^11/bunch, sigma_r~10um, normalized emittance~10um):

1. Higher plasma density (n_p~10^16cm-3)

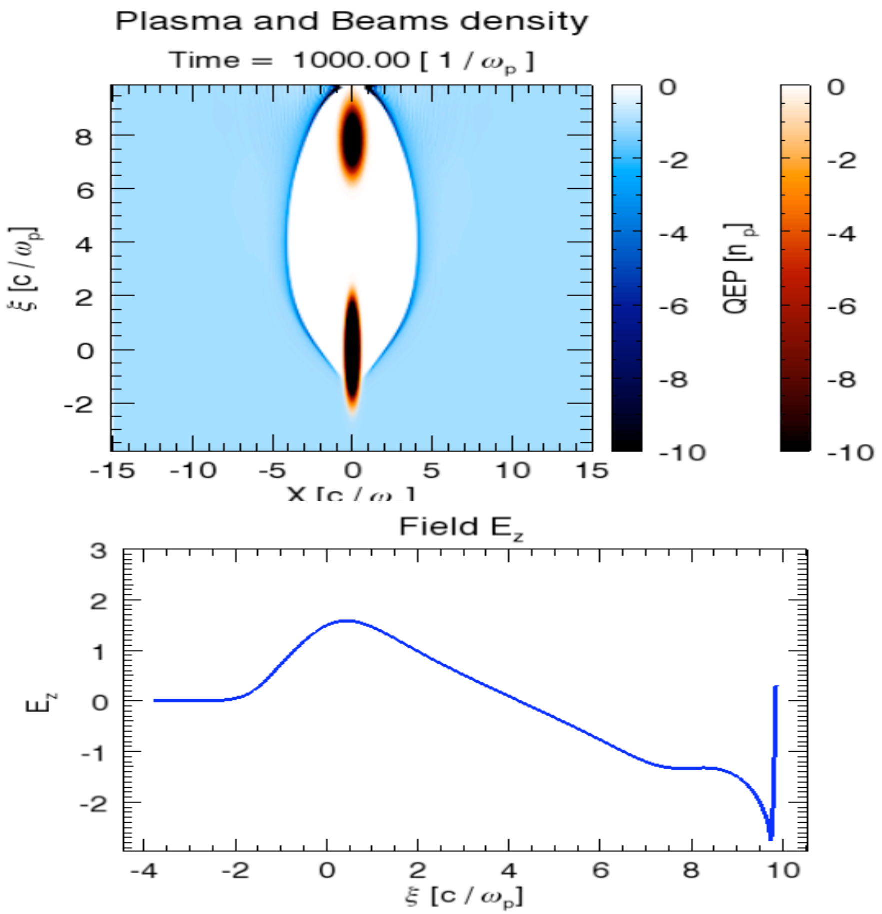
2. Shorter plasma source (~50-100m) due to larger gradient (10-20GeV/m)

3. Higher tolerance on energy spread of the driver (<50%)

4. Dephasing issue is less severe

5. External guiding may not be needed

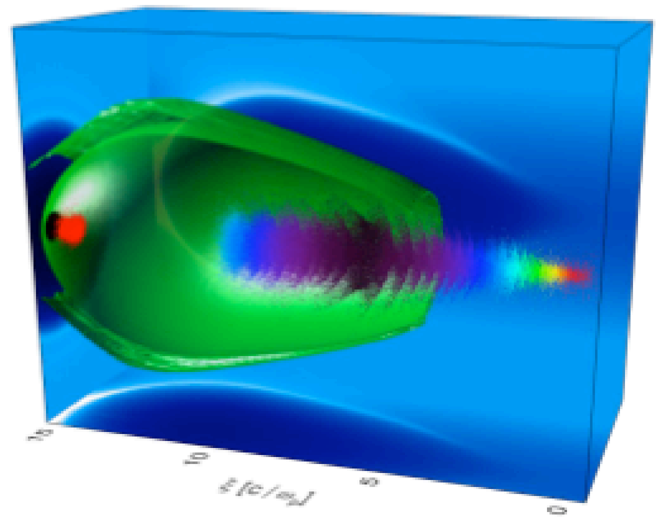
An example:

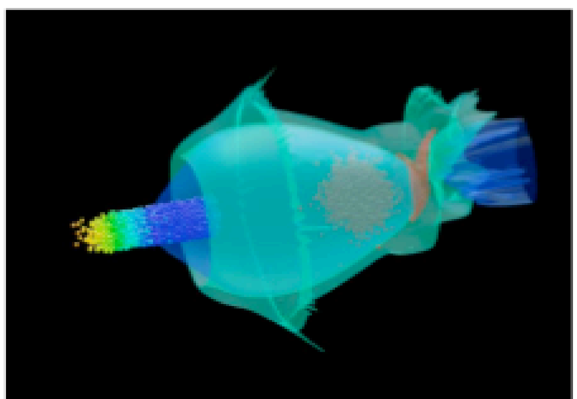


Modeling tools: Quasi-static QuickPIC

QuickPIC

- Massivelly Parallel, 3D Quasi-static particle-in-cell code
- Ponderomotive guiding center for laser driver
- 100-1000+ savings with high fidelity
- Field ionization and radiation reaction included
- Simplified version used for e-cloud modeling
- Developed by the UCLA+UMaryland+IST





New Features

- Particle tracking
- Parallel scaling to 1,000+ processors
- Enhanced Pipelining algorithm enabling scaling to 16,000+ processors and unprecedented simulation resolution down to nm

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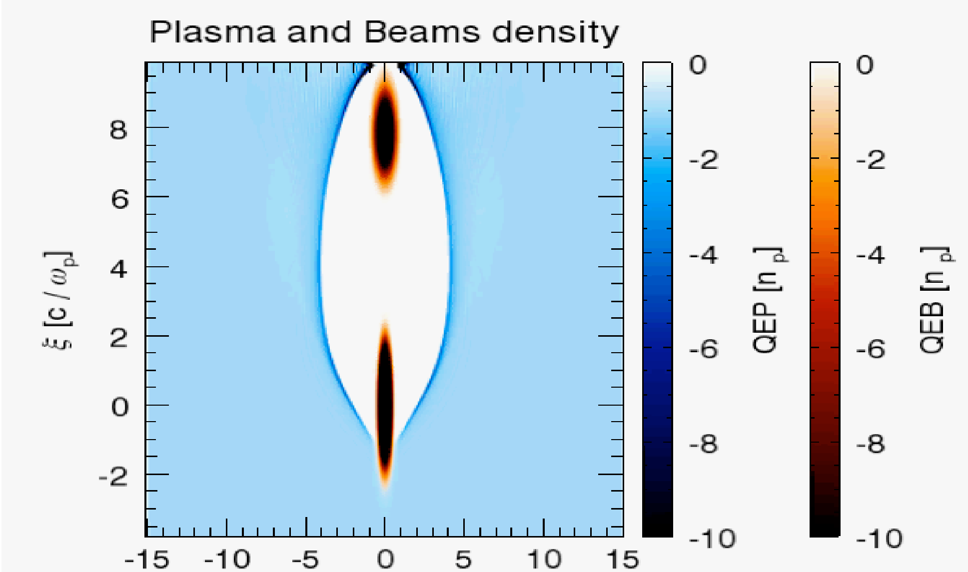
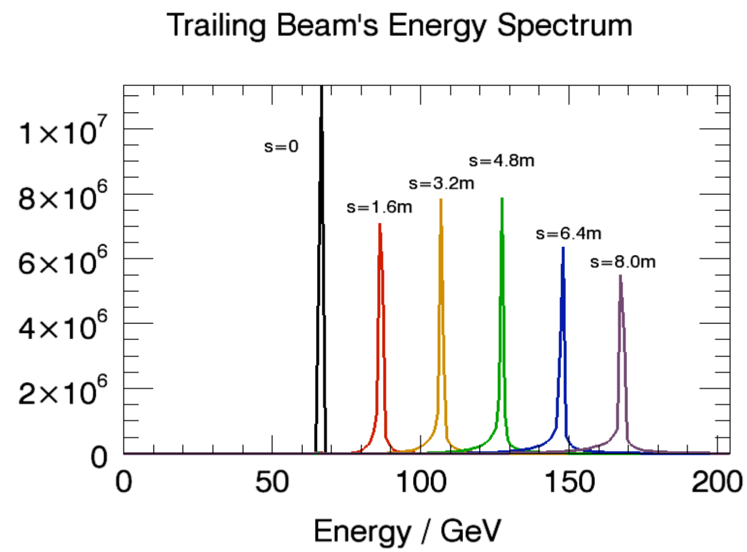
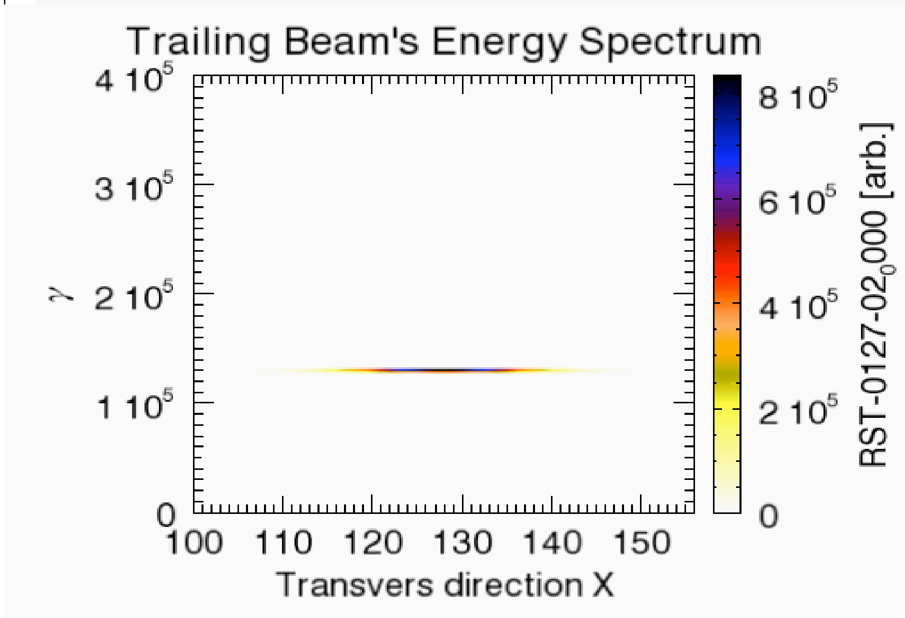
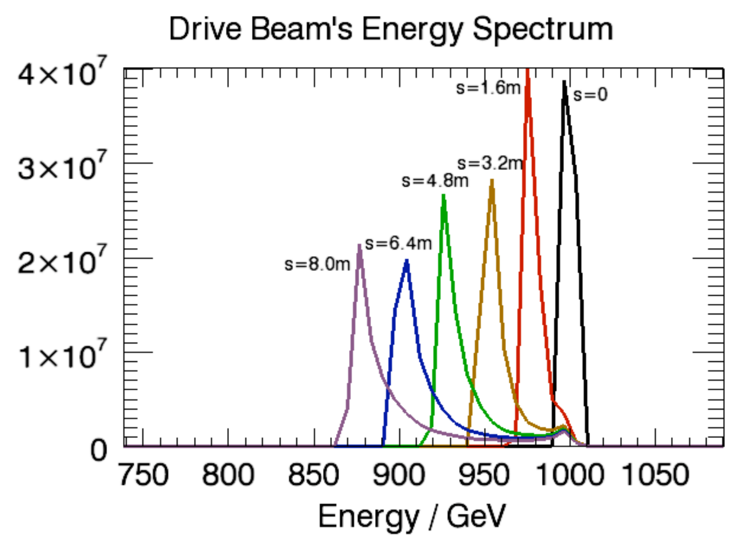
http://exodus.physics.ucla.edu/
http://cfp.ist.utl.pt/golp/epp

Preliminary Simulation result









Summary

- Hadron (Proton/Anti-Proton) driven PWFA is an interesting approach for achieving single stage TeV high quality electron acceleration: driver exists minus the pulse compression.
- Compared to lepton drivers, additional issues need to be considered: dephasing, pulse broadening, and head erosion due to diffraction.
- Full scale modeling is essential for evaluating the full potential of this idea and QuickPIC is an ideal tool.
- Anti-proton drivers would be better than proton drivers.

Discussions

- **What kind of beam density modulation can be obtained at Tevatron?**
- **Is it possible and how challenging to compress the ns long beam down to ps range?**
- **Is it possible to demonstrate GeV level energy modulation by using a meter long plasma?**