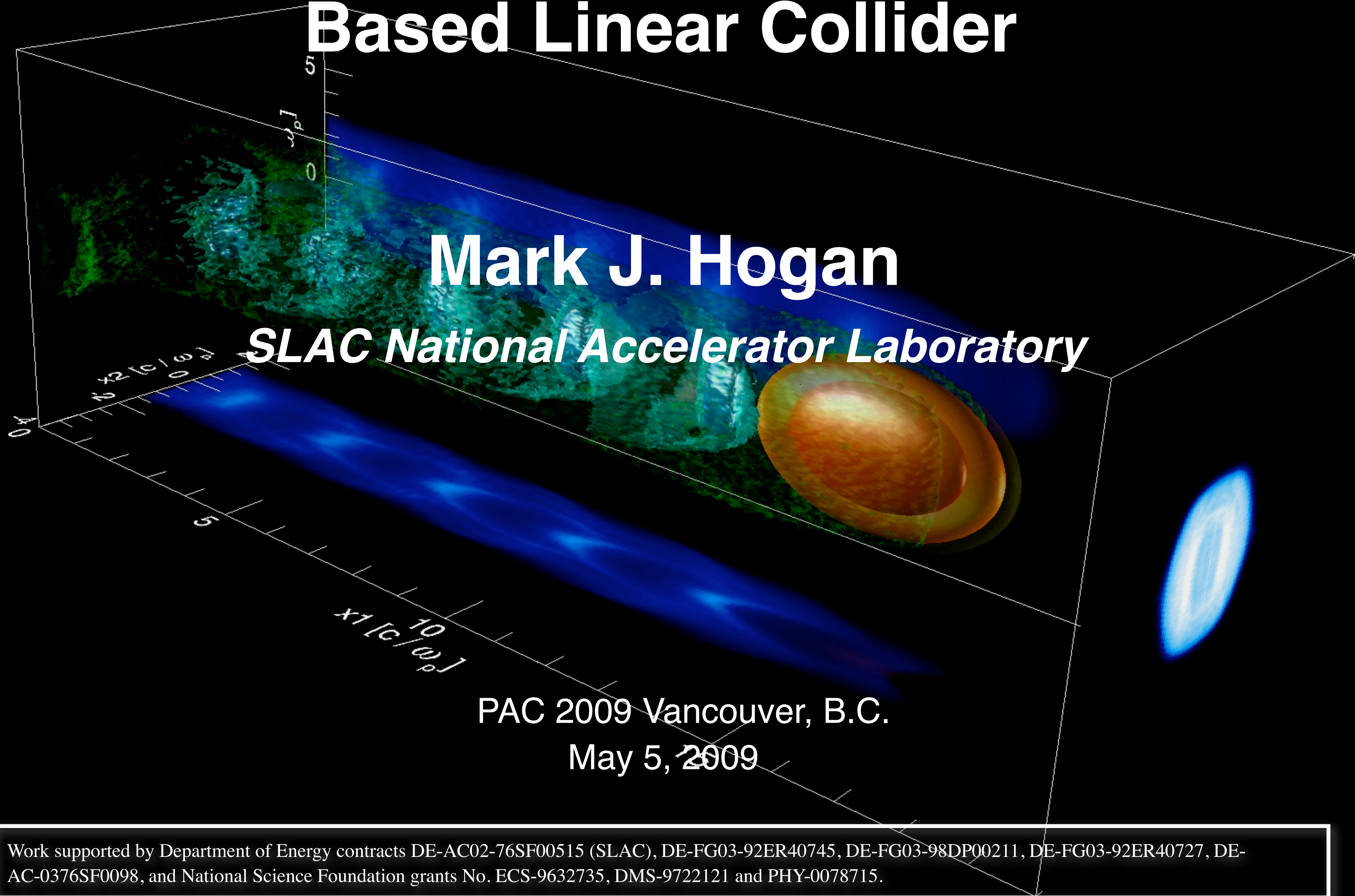
# Road to a Plasma Wakefield Accelerator Based Linear Collider




## Mark J. Hogan

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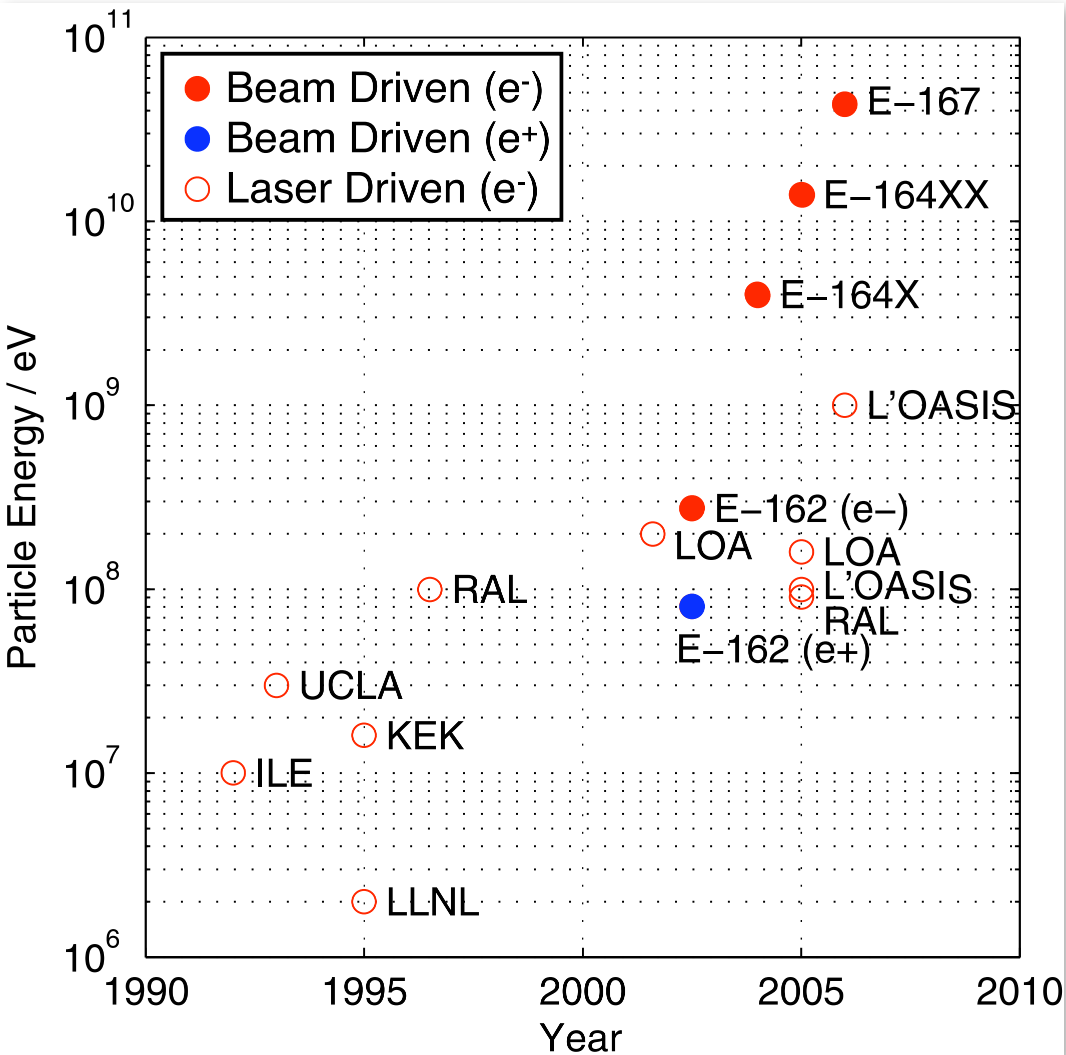
PAC 2009 Vancouver, B.C.
May 5, 2009

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC), DE-FG03-92ER40745, DE-FG03-98DP00211, DE-FG03-92ER40727, DE-AC-0376SF0098, and National Science Foundation grants No. ECS-9632735, DMS-9722121 and PHY-0078715.

# Plasma Acceleration has made tremendous progress in the last two decades




**DOE HEP Office Of Science Issued CD-0 for Advanced Plasma Acceleration Facility February 2008**

*T. Tajima and J. M. Dawson Phys. Rev. Lett. 43, 267 - 270 (1979)*

*P. Chen et al Phys. Rev. Lett. 54, 693 - 696 (1985)*

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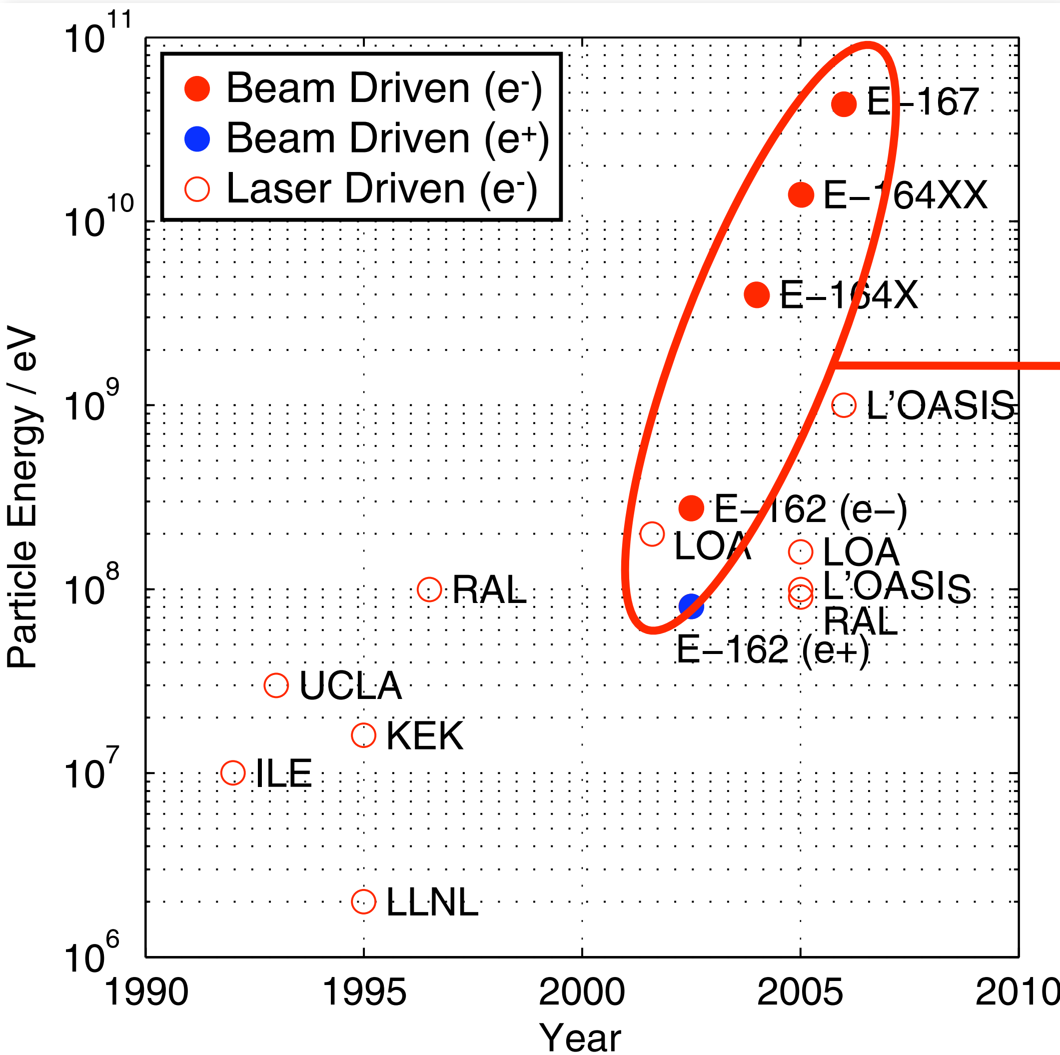


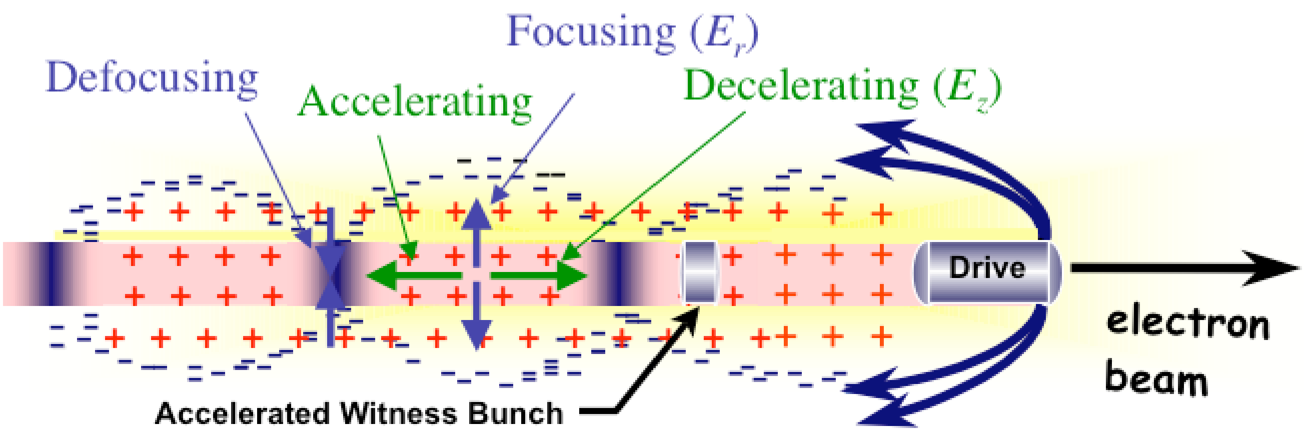

**DOE HEP Office Of Science Issued CD-0 for Advanced Plasma Acceleration Facility February 2008**

Tremendous progress in beam driven concepts entirely the result of the the capability of the SLAC linac to provide high energy, high peak current, low transverse emittance electron beams

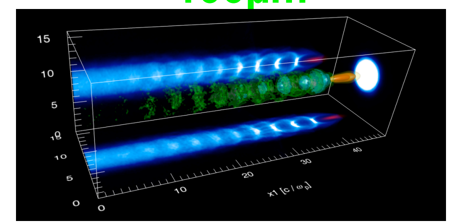
*T. Tajima and J. M. Dawson Phys. Rev. Lett. 43, 267 - 270 (1979)*

*P. Chen et al Phys. Rev. Lett. 54, 693 - 696 (1985)*

# The Beam Driven Plasma Wakefield Accelerator



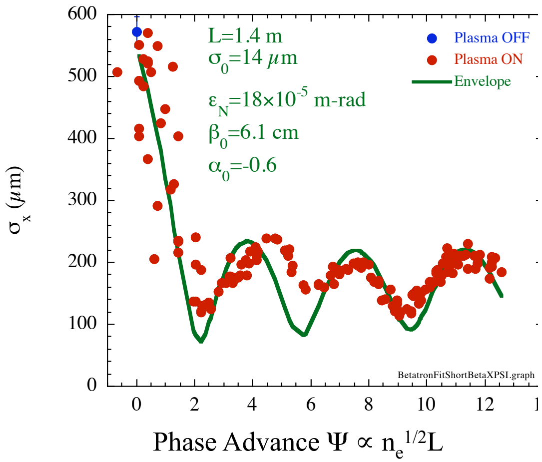




* Two-beam, co-linear, plasma-based accelerator
* Plasma wave/wake excited by relativistic particle bunch
* Deceleration, acceleration, focusing by plasma
* Accelerating field/gradient scales as $n_e^{1/2}$
* Typical: $n_e \approx 10^{17}$ cm$^{-3}$, $\lambda_p \approx 100$ µm, G>MT/m, E>10 GV/m
* High-gradient, high-efficiency energy transformer

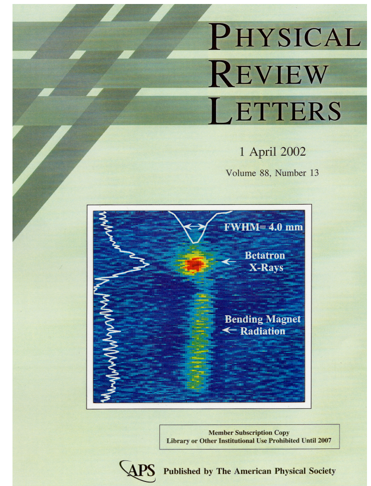
# SLAC/UCLA/USC Experiments @ FFTB
# Studied all aspects of beam-plasma interaction

### Focusing & Matching e⁻



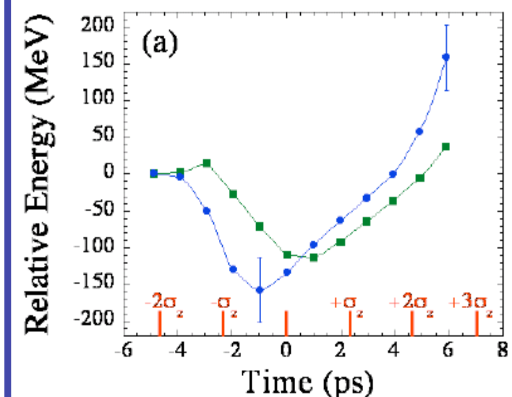

*Phys. Rev. Lett.* **93**, 014802 (2004)

### X-ray Generation



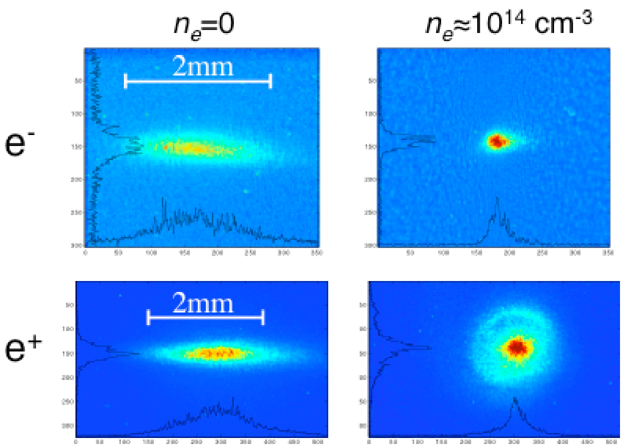

*Phys. Rev. Lett.* **88**, 135004 (2002)

### Wakefield Acceleration e⁻



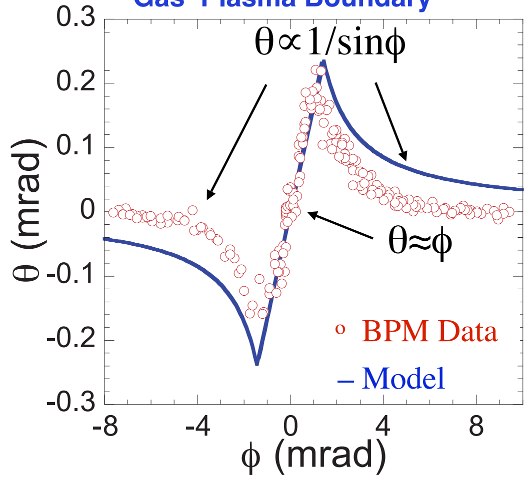

*Phys. Rev. Lett.* **93**, 014802 (2004)

### Focusing & Halo Formation e⁺



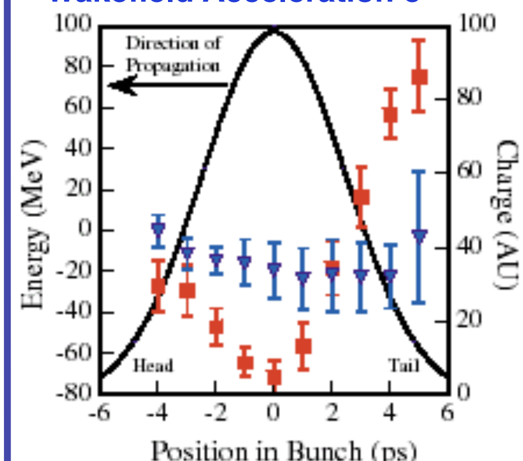

*Phys. Rev. Lett.* **101**, 055001 (2008)

### Electron Beam Refraction at the Gas–Plasma Boundary




*Nature* **411**, 43 (3 May 2001)

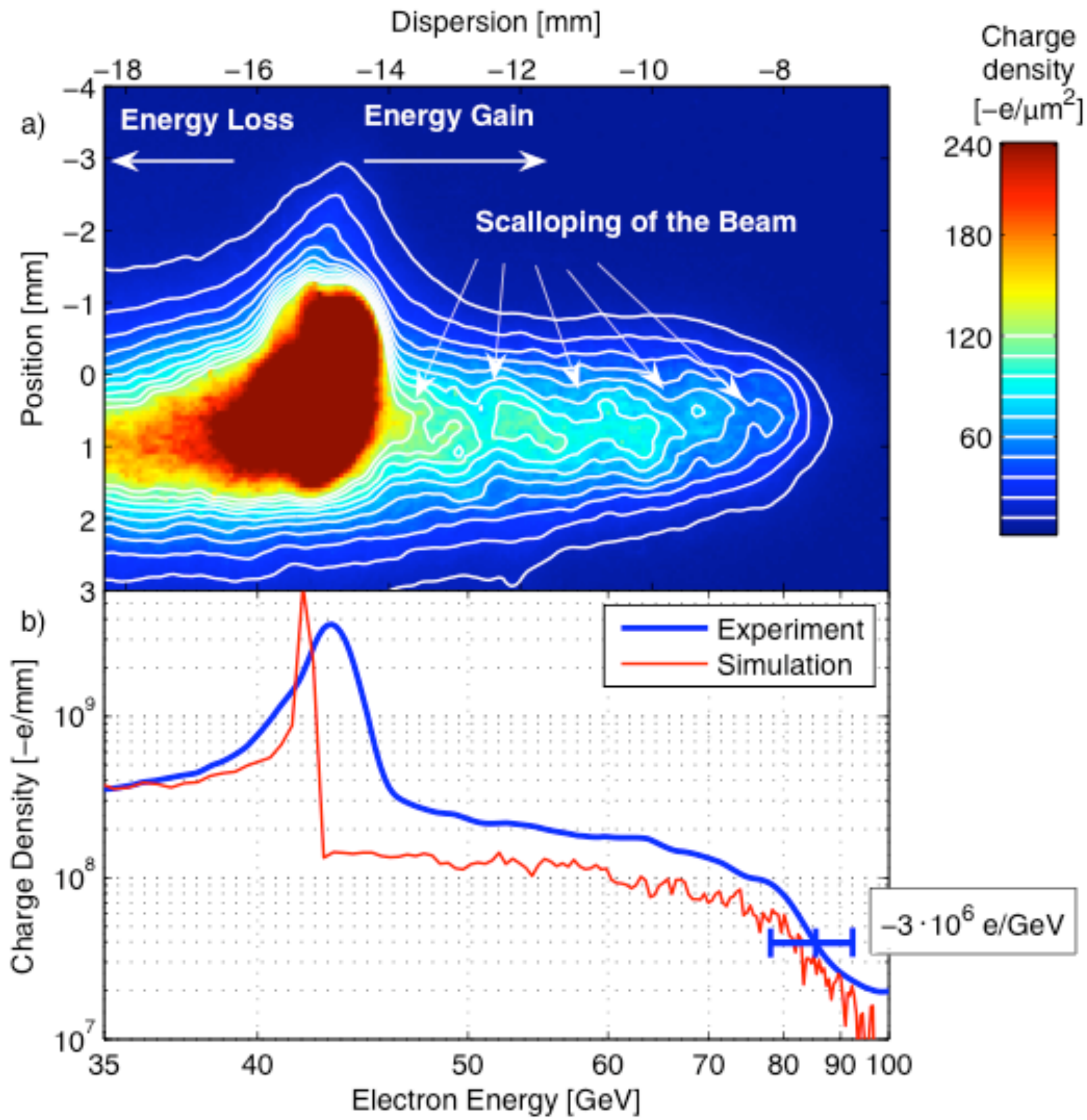
### Wakefield Acceleration e⁺




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

# E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB (April 2006)

* Acceleration gradients of ~50 GV/m (3000 x SLAC)
  – Doubled energy of 45 GeV beam in 1 meter plasma
  – Record Energy Gain
  – Highest energy electrons ever produced at SLAC
  – Significant advance in demonstrating the potential of plasma accelerators



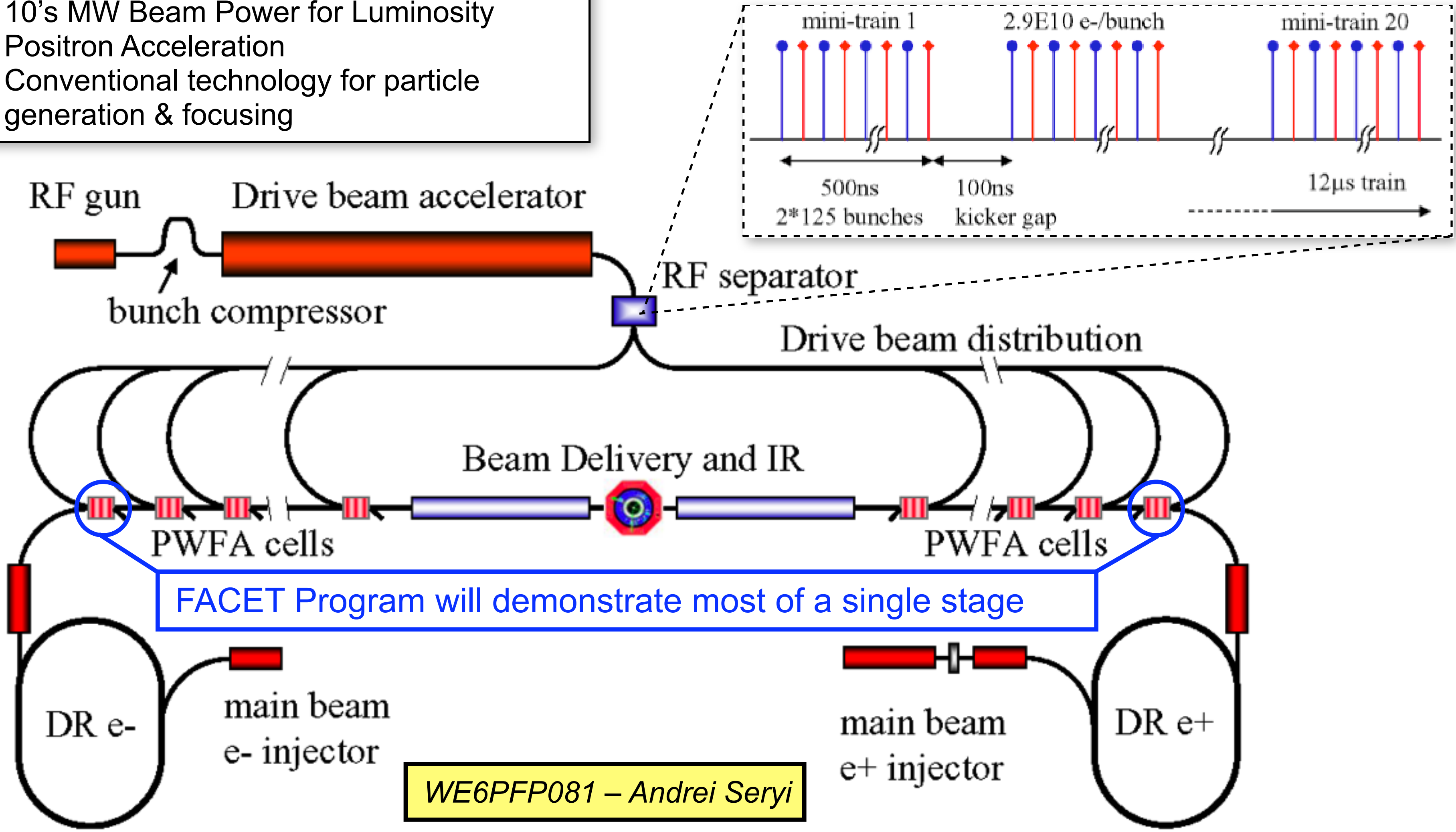

_Nature_ *445 741 15-Feb-2007*

# Approach to PWFA-LC concept

* Many ideas for plasma wakefield-based linear colliders
  - "Afterburner" double energy of a conventional rf linear collider just before the IP
  - Multi-stage afterburner
  - Proton driver (for $e^-$)
* Our present concept for a PWFA-LC:
  - Benefits from three decades of extensive R&D performed for conventional RF linear colliders
  - Possible to generate drive power extremely efficiently
  - Optimized to take advantage of the salient PWFA feature (gradient)
  - Reasonable set of R&D milestones that could be realized over the next ten years

# A Concept for a Plasma Wakefield Accelerator Based Linear Collider

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




*WE6PFP081 – Andrei Seryi*

# Key features of PWFA-LC concept

* Electron drive beam for both electrons and positrons
* High current low gradient efficient 25GeV drive linac
  – Similar to linac of CERN CTF3, demonstrated performance
* Multiple plasma cells

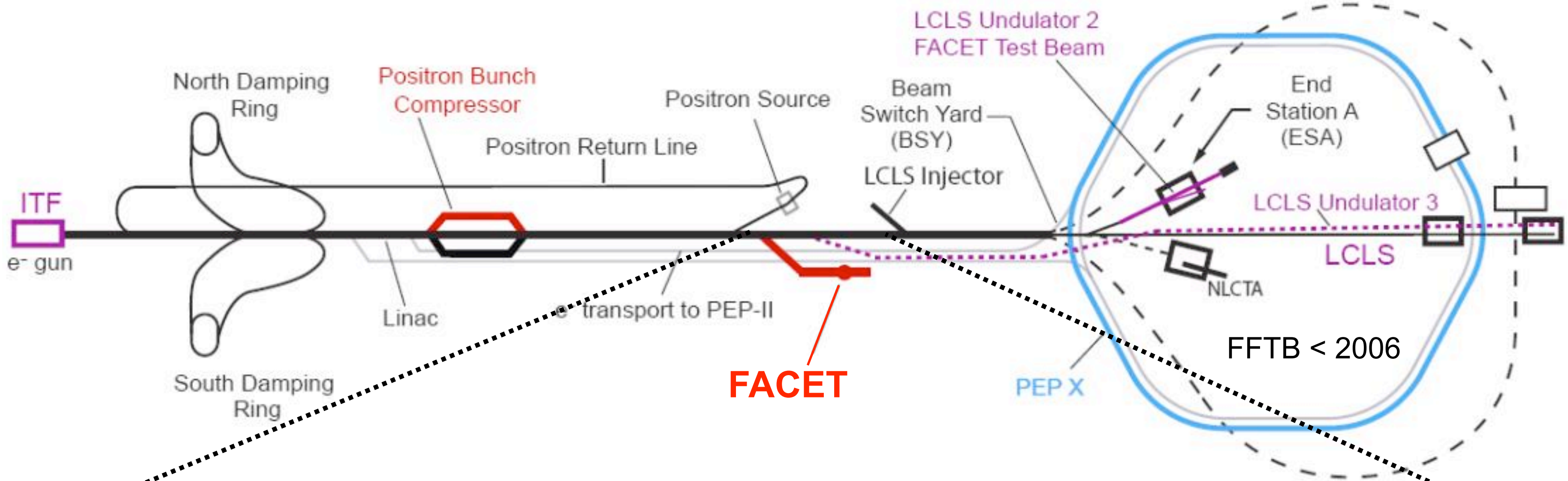
  *WE6PFP079 – Shilun Pei*

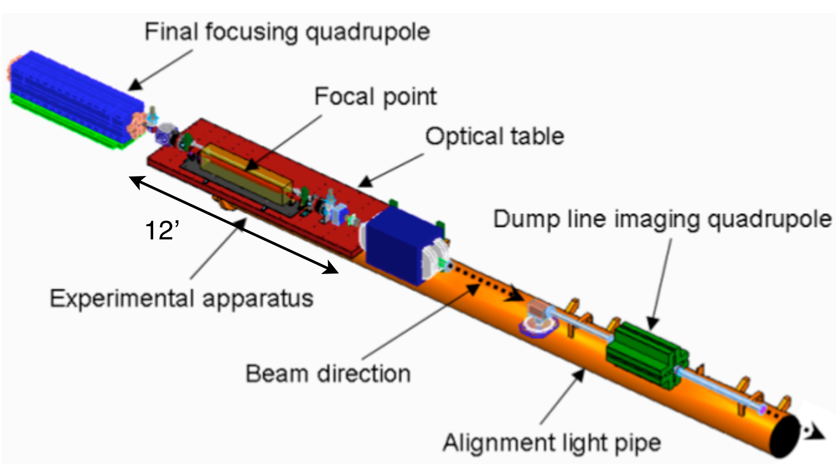
  – 20 cells, meter long, 25GeV/cell, 35% energy transfer efficiency
* Main / drive bunches

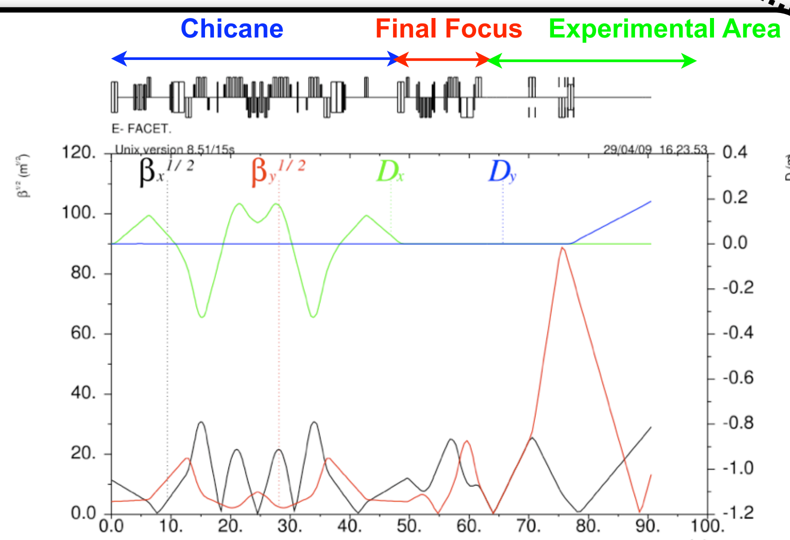
  *WE6RFP097 – Chengkun Huang*

  – 2.9E10 / 1E10
* PWFA-LC concept will continue to evolve with further study and simulation
  – Bunch charge; Non-gaussian bunch profiles; Flat vs round beams; SC vs NC pulse format; ...
* Need a new facility to investigate and iterate these ideas through experiments

# FACET A new facility to provide high-energy, high peak current $e^-$ & $e^+$ beams for PWFA experiments



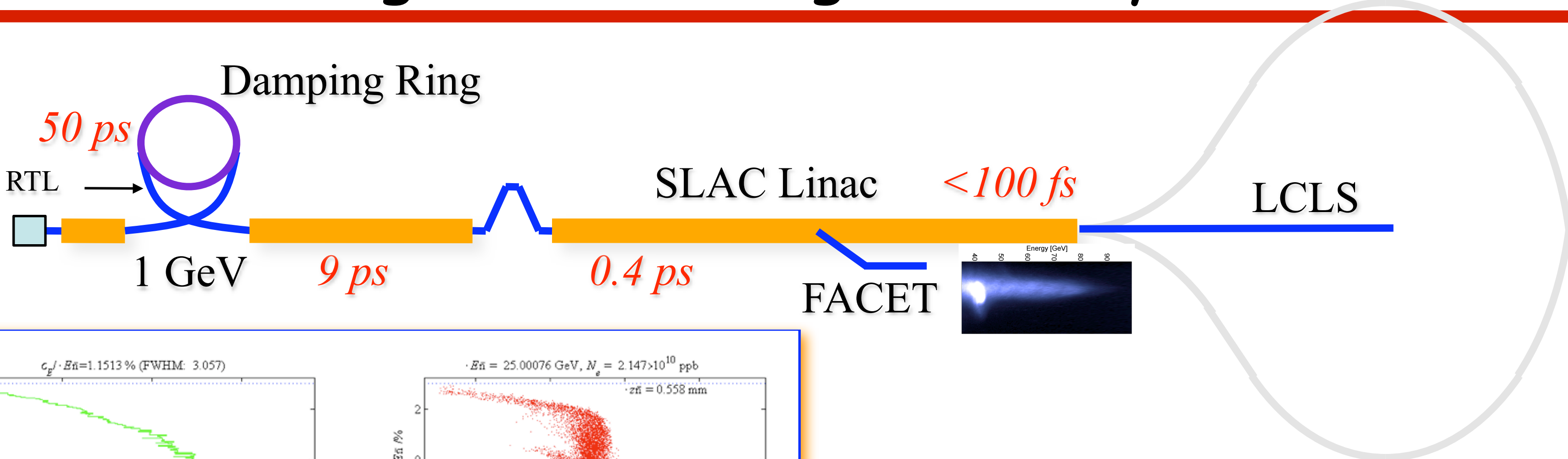



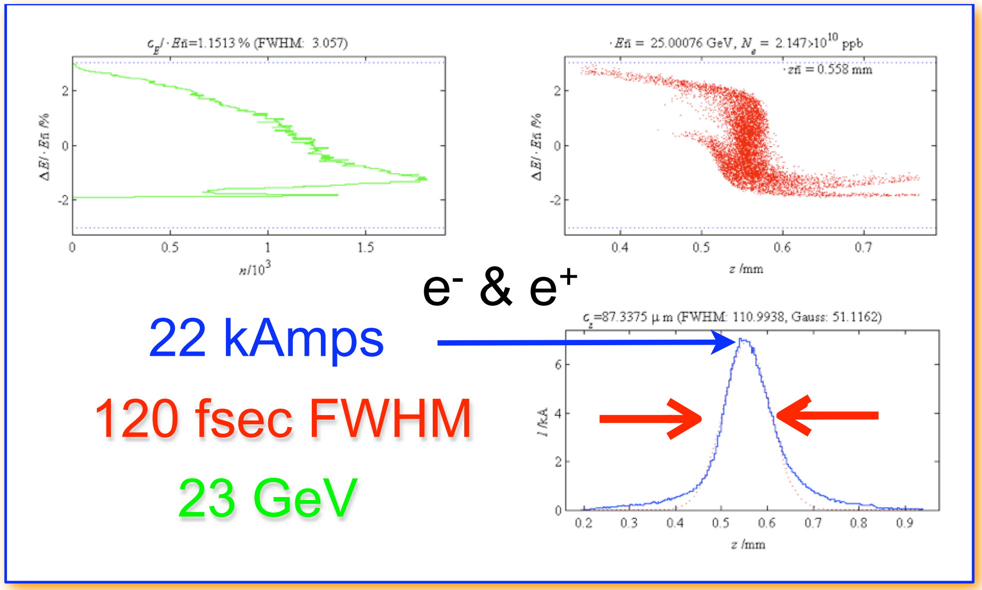



# Primary Issues for any Plasma-based LC

* Need to understand acceleration of electrons & positrons
* Luminosity drives many issues:
  – High beam power (20 MW) → efficient ac-to-beam conversion
  – Well defined cms energy → small energy spread
  – Small IP spot sizes → small energy spread and small $\Delta\varepsilon$
* These translate into requirements on the plasma acceleration
  – High beam loading of e+ and e- (for efficiency)
  – Acceleration with small energy spread
  – Preservation of small transverse emittances – maybe flat beams
  – Bunch repetition rates of 10's of kHz
* Multiple stages allow better beam control and use of drive-beam
  – possible to demonstrate single stage before full system test

# Short Bunches Bring Large Gradients and Long, Uniform High-Density Plasmas




**Peak Field For A Gaussian Bunch:**

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

**Ionization Rate for Li:**

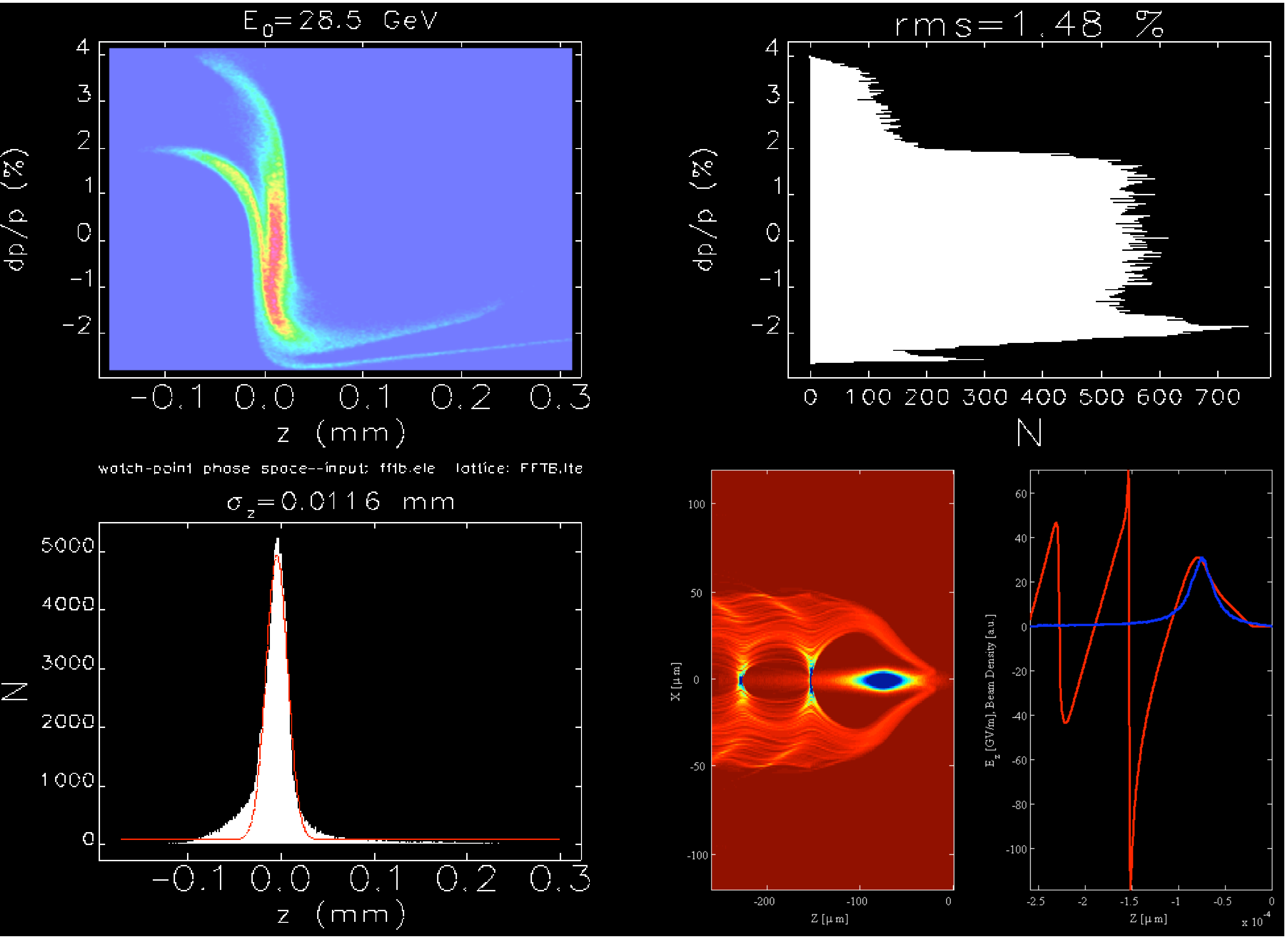
$$W_{Li}\left[s^{-1}\right] \approx \frac{3.60x10^{21}}{E^{2.18}\left[GV/m\right]} \exp\left(\frac{-85.5.}{E\left[GV/m\right]}\right)$$

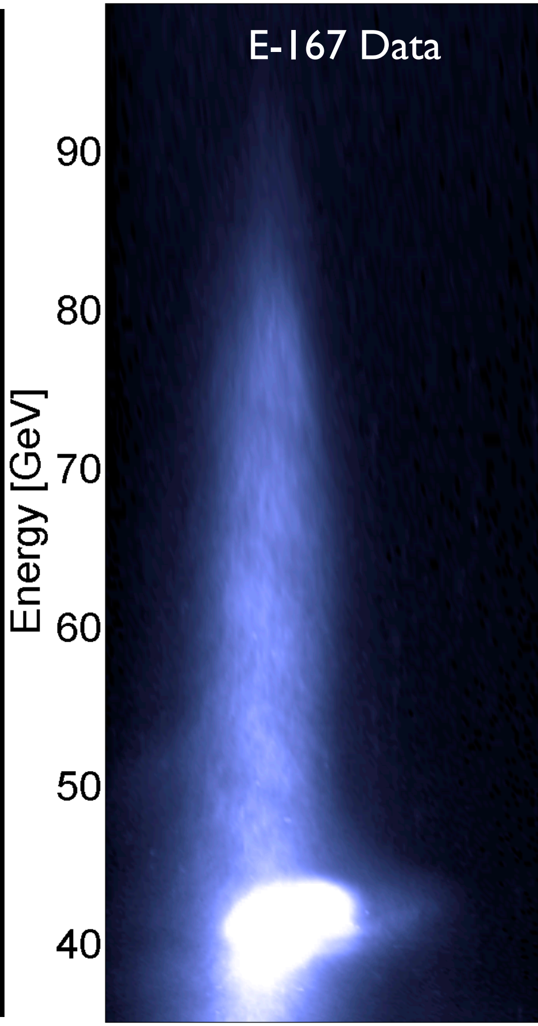
*See D. Bruhwiler et al, Physics of Plasmas 2003*

**Space charge fields tunnel ionize the vapor!**

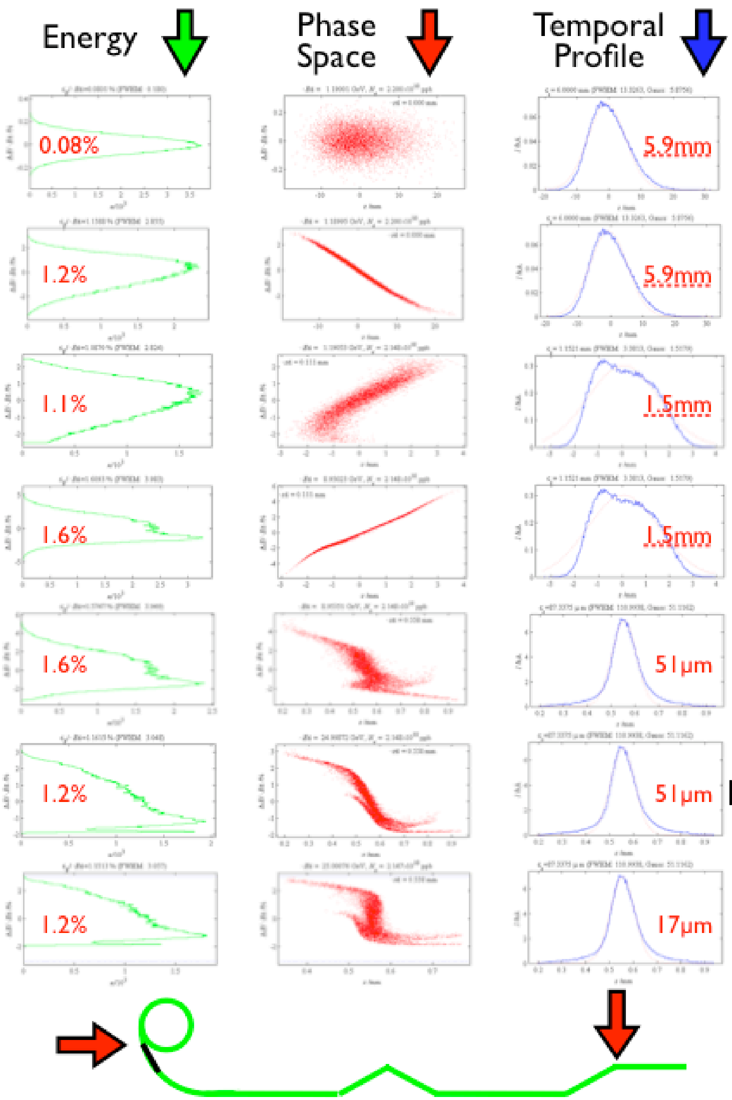
- No timing or alignment issues
- Long high-density plasmas now possible

# Single FFTB Bunch Sampled All Phases of the Wake Resulting in ~ 200% Energy Spread



# Generate Two Bunches by Selectively Collimating During Bunch Compression Process

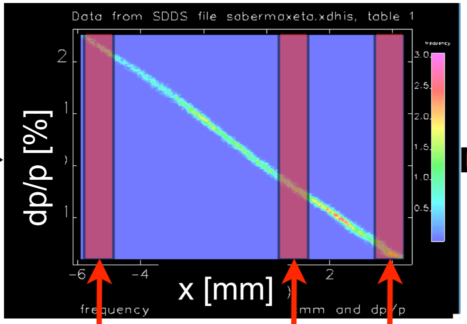



**Exploit Position-Time Correlation on e- bunch to create separate drive and witness bunch**

*FR5RFP022 – Patric Muggli*

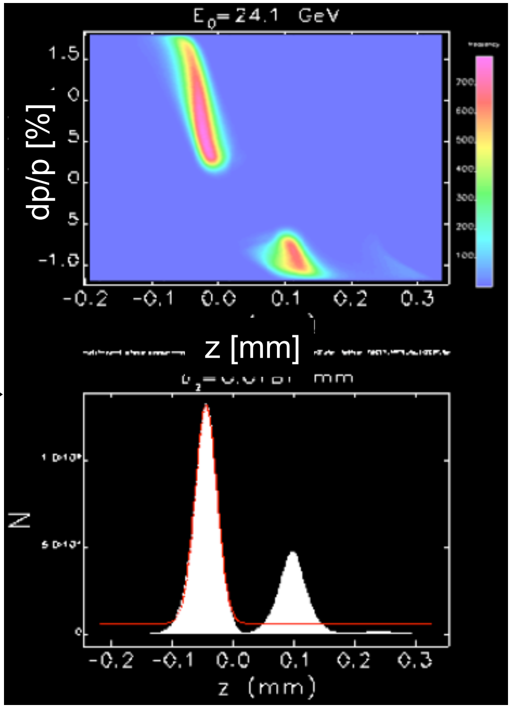
Disperse the beam in energy

$$x \propto \Delta E/E \propto t$$




...selectively collimate

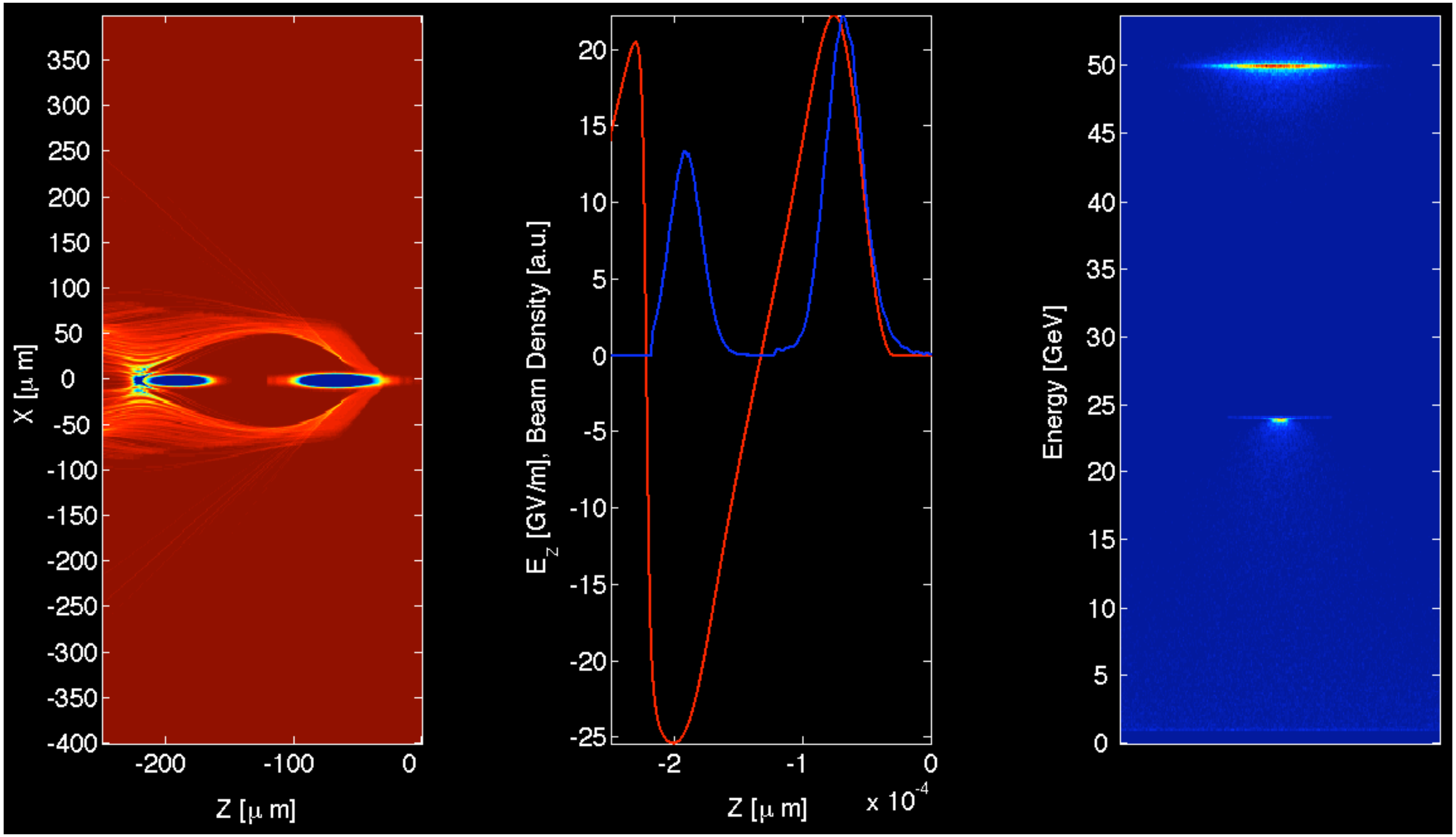
Adjust final compression



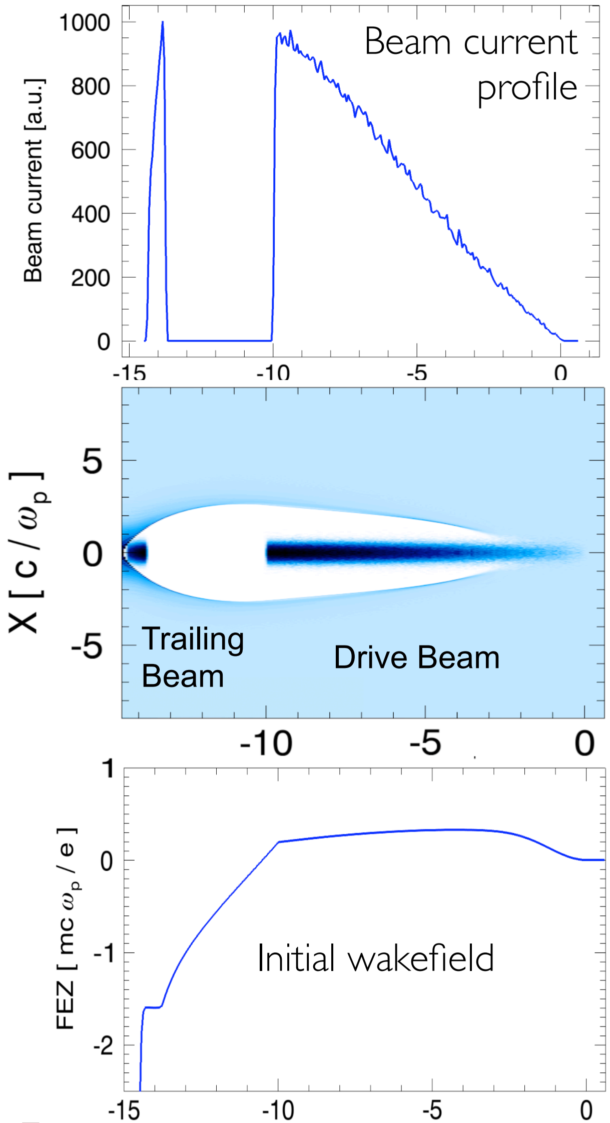
# FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

WE6RFP097 – Chengkun Huang

* Double Energy of a 25GeV Beam in ~1m
* Drive beam to witness beam efficiency of ~30% with small dE/E



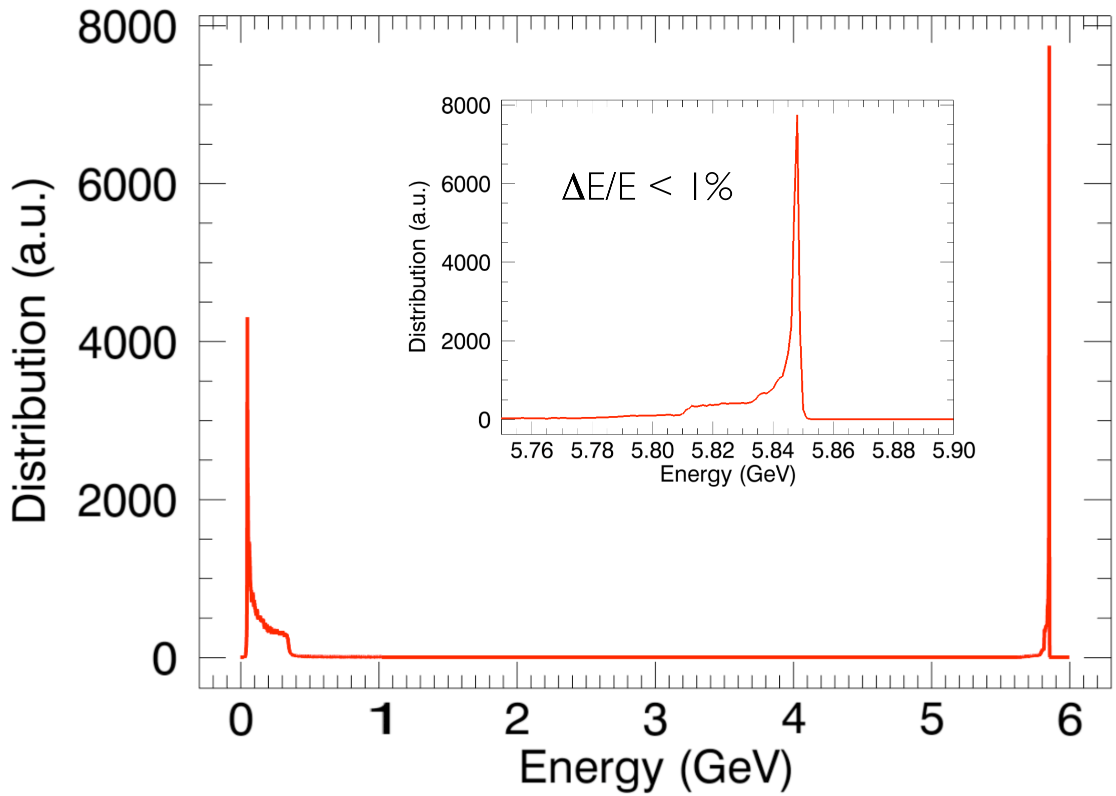
# Simulation of PWFA with Transformer Ratio~5




**Higher efficiencies possible with non-gaussian bunch profiles**

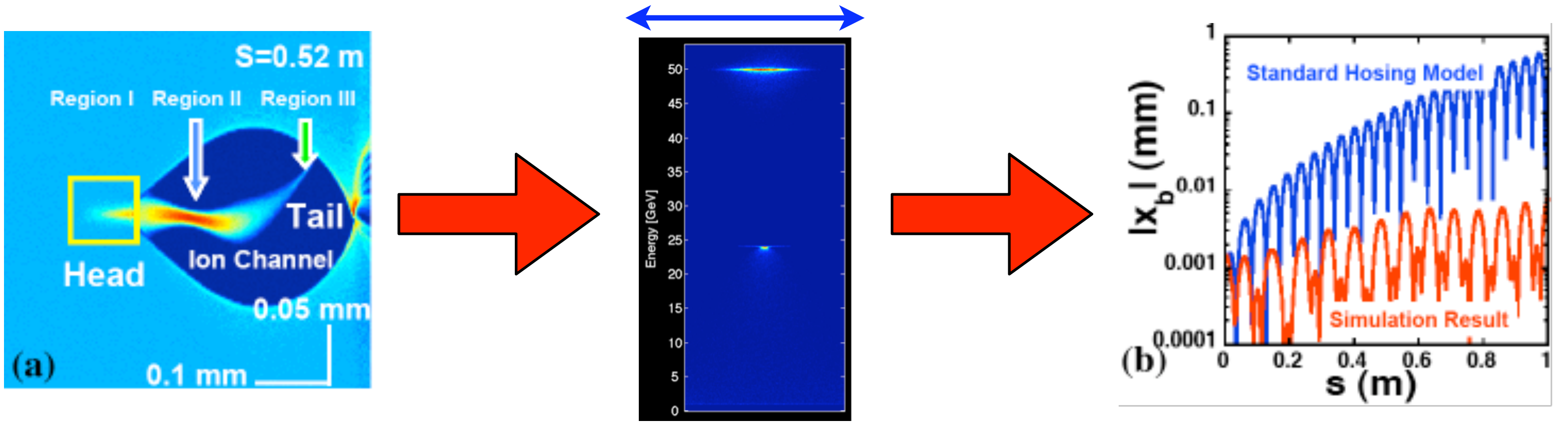
*TH3GBI02 – Joel England*

*WE6RFP098 – Wei Lu*



# FACET program will investigate emittance growth from several sources

* **Hosing**. Experimental signature is exponentially growing transverse displacement of accelerated bunch. Will excite through deliberate r vs. z correlation on drive bunch.



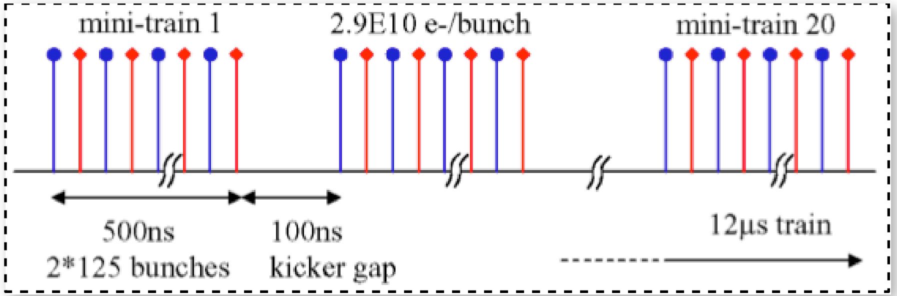

* **Ion motion**. Potentially an issue when $n_b/n_p \sim m_i/m_e$. Partially mitigated by using large emittance drive beam. FACET will attempt to quantify this for the first time by lowering the plasma density and measuring the emittance vs the ratio $n_b/n_p$.

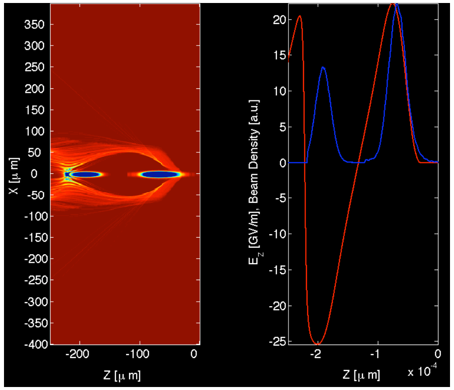
| | Normalized Emittance [mm-mrad] | Sigma z [μm] | $n_p$ | $n_b/n_p$ |
|---|---|---|---|---|
| FFTB < 2005 | >120 (x & y) | 700 | $10^{14}$ | ~10 |
| FFTB > 2005 | 50 x 10 | >12 | $10^{17}$ | ~10 |
| FACET | 30 or 50 x 10* | >18 | $10^{14}$ - $10^{17}$ | $<10^4$ |
| PWFA-LC | D = 100, M = 2 x 0.05 | D = 30, W= 10 | $10^{17}$ | 100, $10^4$ |

*Smaller emittance possible with upgrades

# Plasma Stability & Cooling (1Hz to 1MHz)

* Hollow plasma channels were mentioned as one area for plasma source development
* Warm conducting PWFA-LC concept maximizes efficiency with ~ns bunch spacing

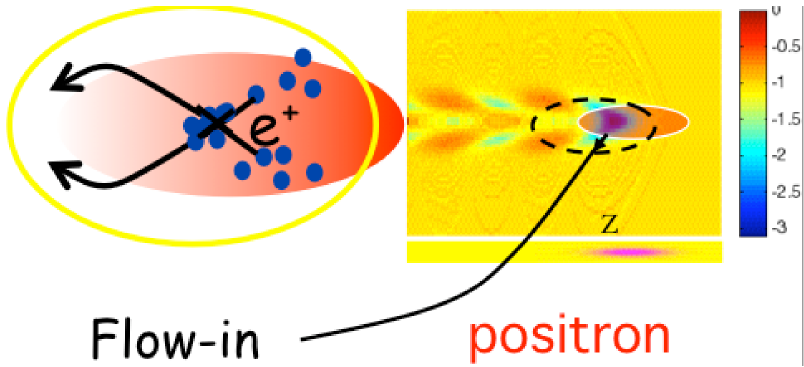



* Plasma stability/reproducibility on ns time scales over several hundred shots has yet to be studied in plasma accelerators
* Proof of principle experiment possible by extracting several damping ring bunches at integer*5.6ns spacing
  – Energy spectrum vs shot number will indicate effective density

# High Gradient Plasma Acceleration of Positrons

* e+/plasma interaction much less studied than e-/plasma
* Focusing force on e+ bunches is nonlinear

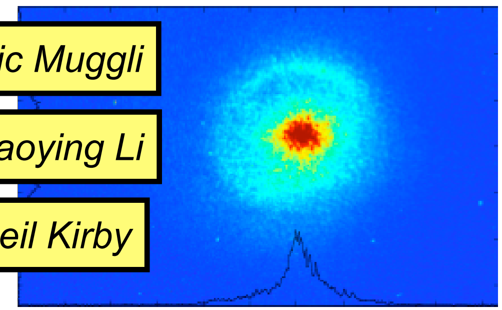



* Emittance growth for single e⁺ bunch in uniform plasma
* Possible remedies include hollow plasma channel, linear wake

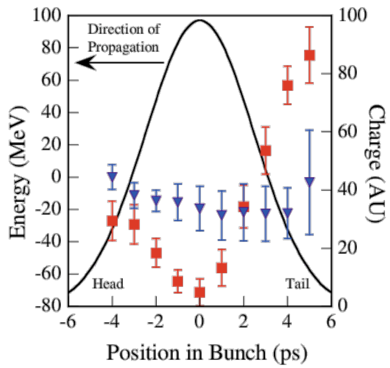
*TH3GBI04 – Patric Muggli*

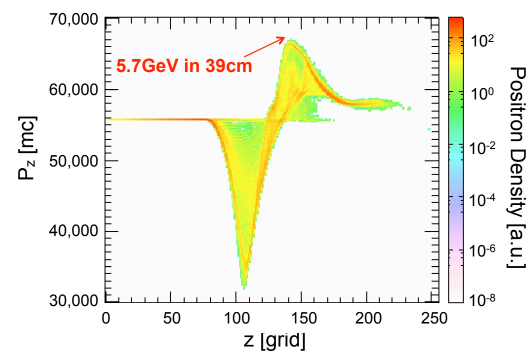
*FR5RFP025 – Xiaoying Li*

*FR5RFP017 – Neil Kirby*

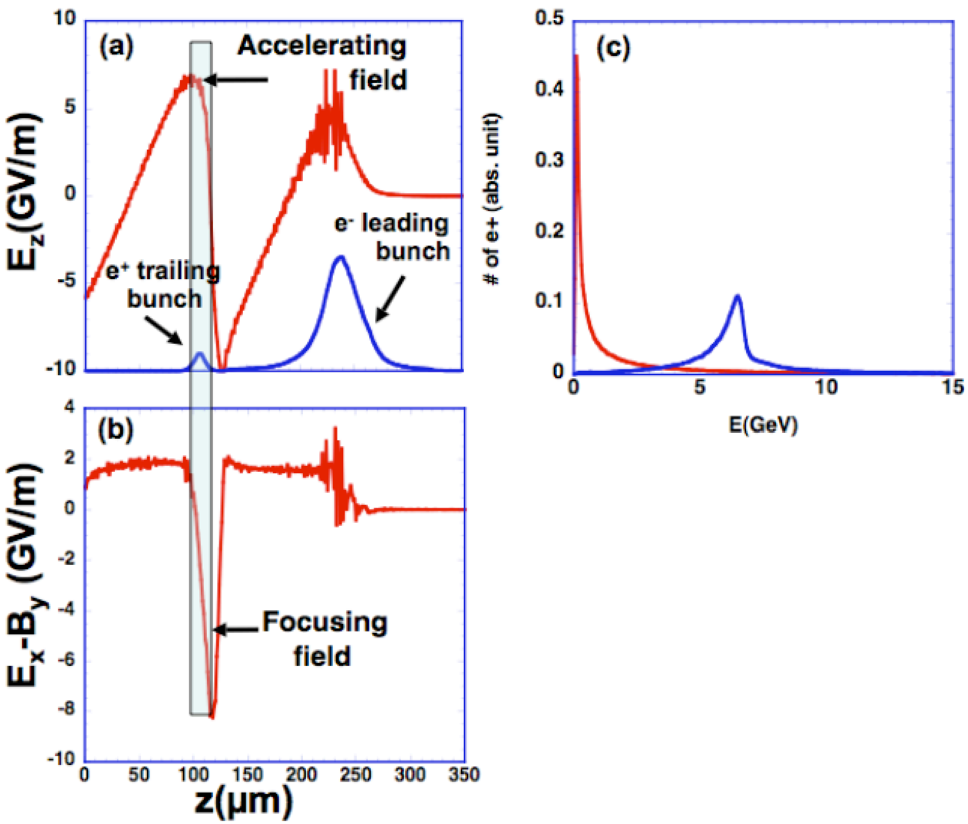


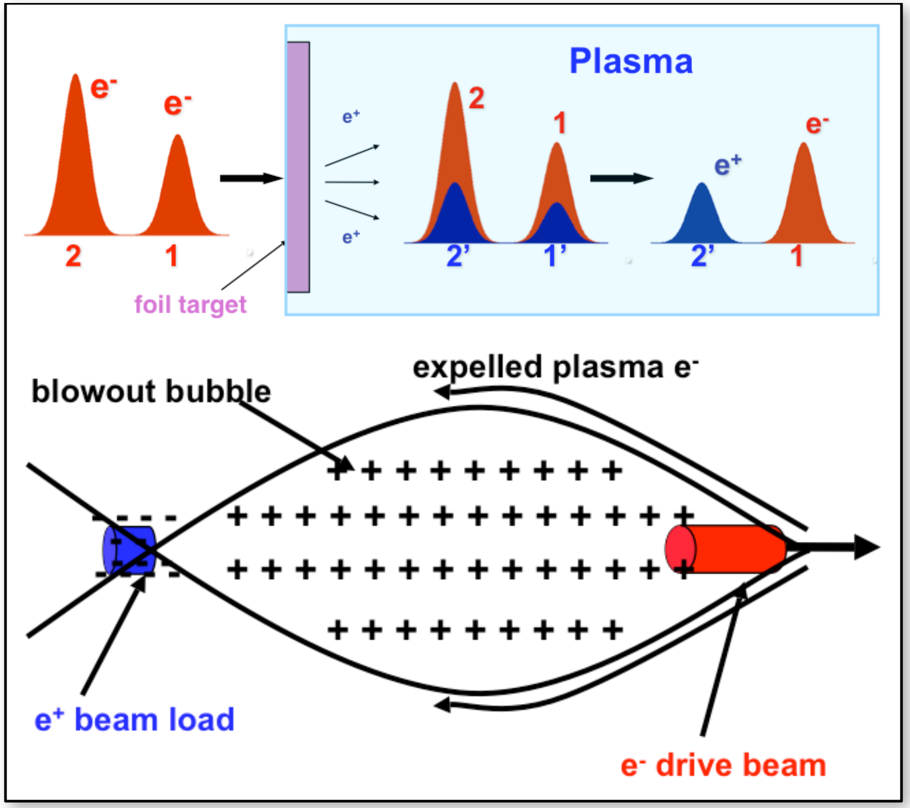
* e⁺ can be accelerated with in e⁺ driven plasma wakes, but accelerating force is also nonlinear



# Positron Acceleration in Electron Beam Driven Wakes is possible in the weakly non-linear regime



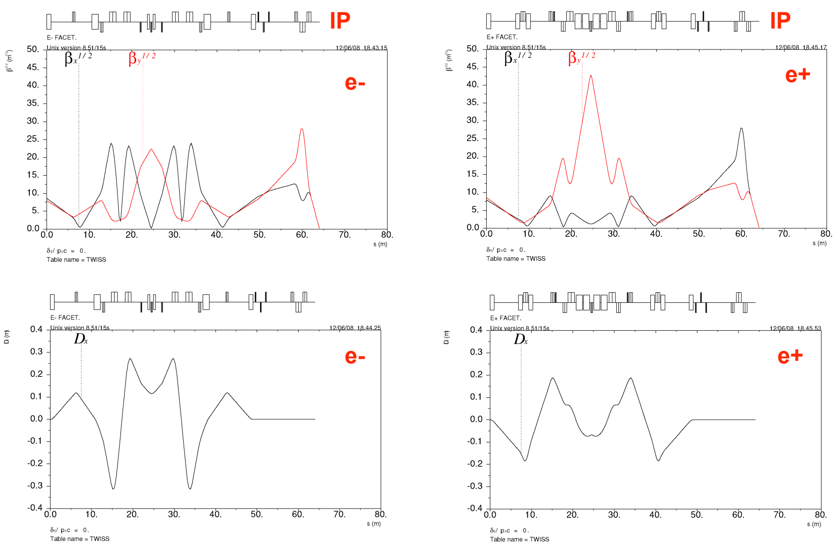

Generating closely-spaced mixed-species bunches is simplified by creating the positrons in the plasma

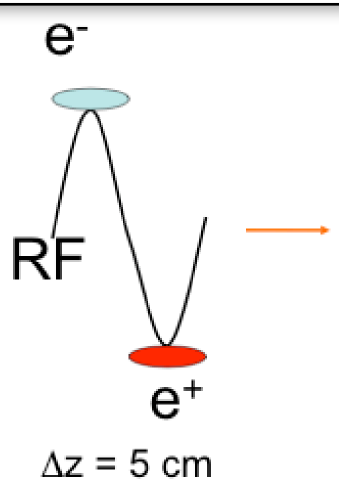
X. Wang et al. *Phys. Rev. Lett.* 101, 124801 (2008)

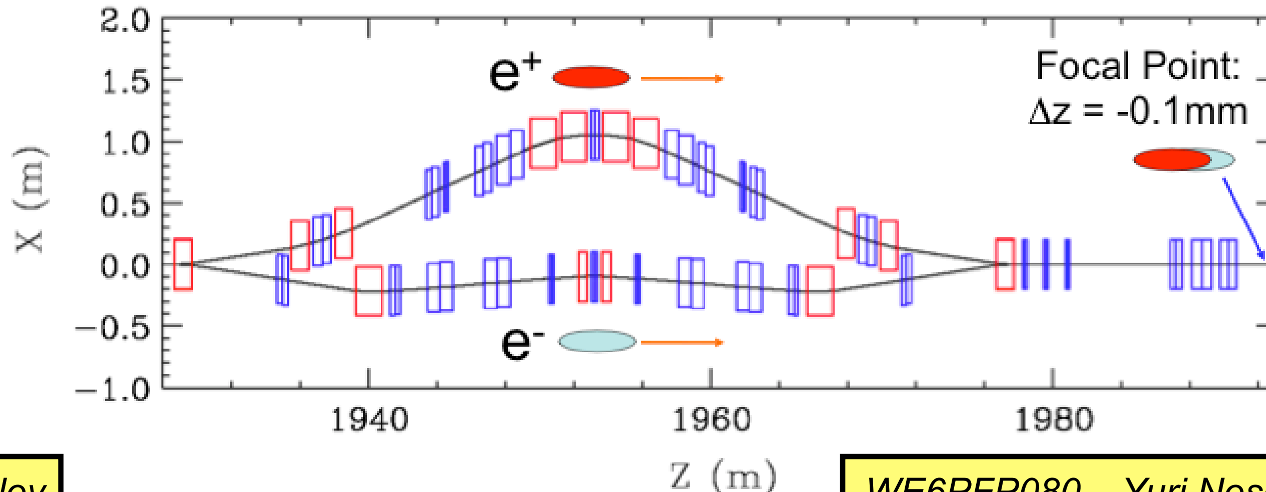
# Sailboat Chicane Upgrade will enable full exploration of plasma acceleration of $e^+$ in $e^-$ wakes

- Extract e- & e+ from damping rings on same linac pulse
- Accelerate bunches to sector 20 5cm apart
- Use 'Sailboat Chicane' to put them within 100$\mu$m at entrance to plasma
- Large beam loading of $e^-$ wakes with high charge $e^+$ beams

**Beta functions and dispersion in chicanes and FF**



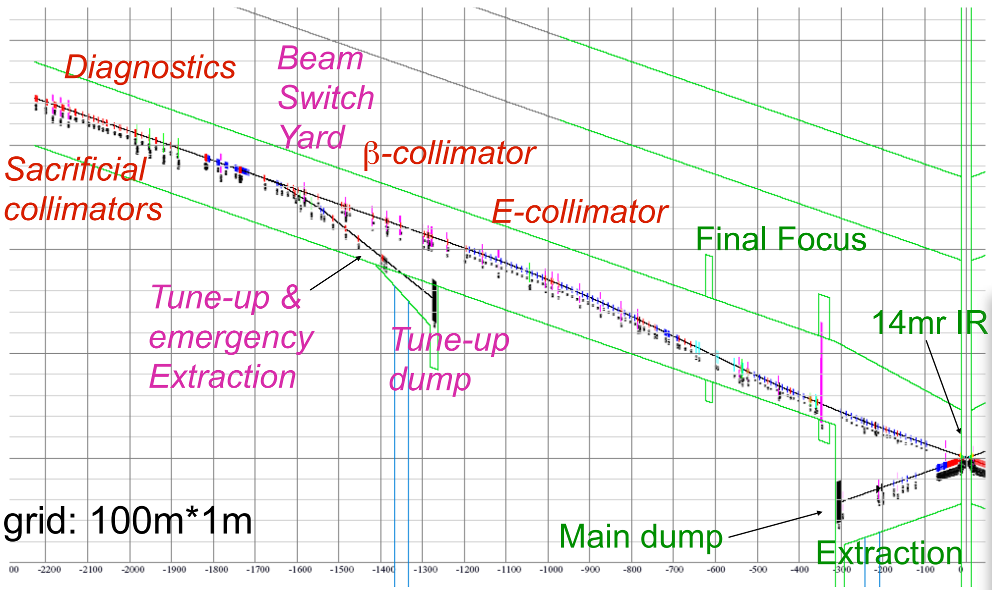




FR5RFP084 – Steve Molloy

WE6PFP080 – Yuri Nosochkov

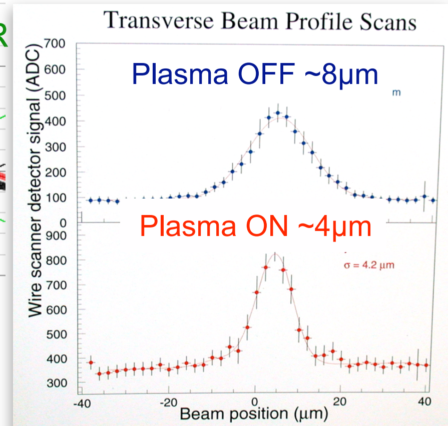
# Opportunities Beyond Acceleration e.g. Beam Delivery & Plasma Lens

ILC Beam Delivery for 1TeV CM

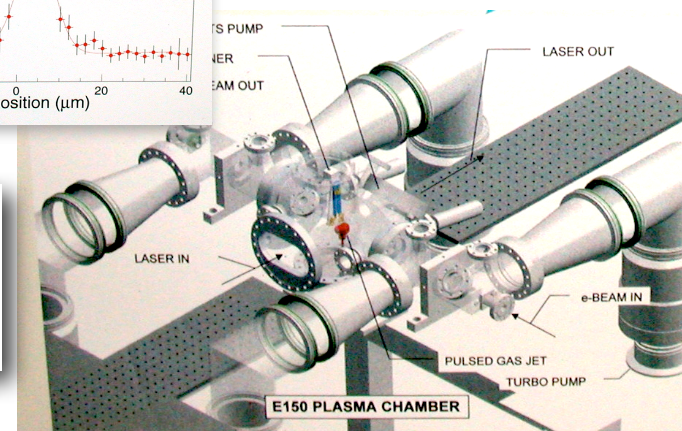



**Early low-energy demonstration experiments in early to mid-nineties with electrons: FNAL (1990), JAPAN (1991), UCLA (1994)…**

**In 2001, E-150 Demonstrated plasma lensing of 28.5GeV electron *and* positron beams**




Demagnification of 2
High Energy Beam with µm level spots

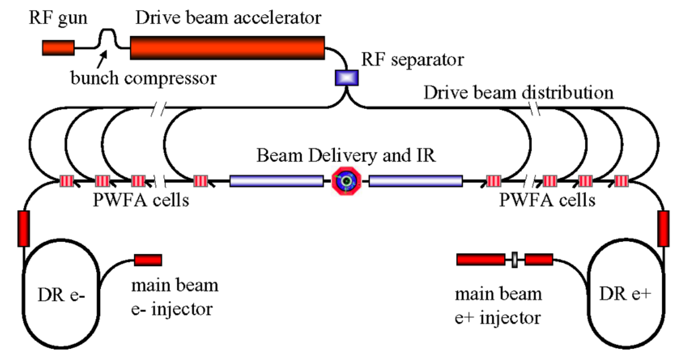



Plasma Potential:

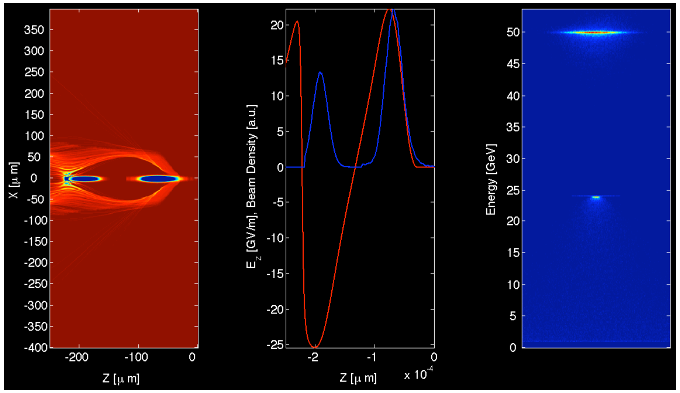
- > MT/m focusing to reduce the 600m final focus
- PWFA-LC design could re-distribute other functions

# Summary

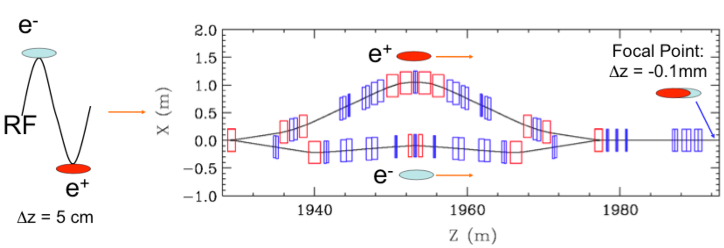
* Presented you a concept for PWFA-LC
  – Optimal use of Plasma Acceleration features
  – Experience of 30+ years of LC R&D to produce efficient design
  – Flexible concept, to allow changes resulting from FACET R&D




* FACET designed to address major issues of a PWFA -LC stage and lead to the next step
  – Accelerate a discrete bunch (not just particles)
    • With narrow dp/p, preserved emittance
  – Identify optimum method for e+ acceleration (e+ or e- driven wakes)




* Successful completion of FACET
  – Define all parameters of PWFA-LC
  – Next would be a pre-construction demo of the final configuration




* Experiments resume in early 2011!

# Present collaborators

| | |
|---|---|
| B. Allen | USC |
| W. An | UCLA |
| K. Bane | SLAC |
| L. Bentson | SLAC |
| I. Blumenfeld | SLAC |
| C.E. Clayton | UCLA |
| S. DeBarger | SLAC |
| F.-J. Decker | SLAC |
| R. Erickson | SLAC |
| R. Gholizadeh | USC |
| M.J. Hogan | SLAC |
| C. Huang | UCLA |
| R.H. Iverson | SLAC |
| C. Joshi | UCLA |
| T. Katsouleas | Duke University |
| N. Kirby | SLAC |
| N. Li | SLAC |
| W. Lu | UCLA |
| D.B. MacFarlane | SLAC |
| K.A. Marsh | UCLA |
| W.B. Mori | UCLA |
| P. Muggli | USC |
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| S. Pei | SLAC |
| T.O. Raubenheimer | SLAC |
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| A. Seryi | SLAC |
| R.H. Siemann | SLAC |
| P. Tenenbaum | SLAC |
| J. Vollaire | SLAC |
| D. Walz | SLAC |
| X. Wang | USC |
| W. Wittmer | SLAC |

# PWFA Experimental timeline for FACET Program

(from FACET proposal with construction start beginning FY09)

| Experimental Tasks and Milestones | FY09 | FY10 | FY11 | FY12 | FY13 | FY14 | FY15 | FY16 |
|---|---|---|---|---|---|---|---|---|
| Accelerate e- bunch with sufficient charge | | FACET | FACET | | | | | |
| Accelerate e- bunch achieving low energy spread | | | FACET | FACET | | | | |
| Accelerate e- bunch with high efficiency | | | FACET | FACET | | | | |
| ***Demonstration of electron acceleration: high $\eta$, low $\Delta E$*** | | | | | ★ | | | |
| Emittance preservation of e- bunch | | | FACET | FACET | FACET | | | |
| ***Demonstration of a single stage of an electron PWFA-LC*** | | | | | | ★ | | |
| Acceleration of e+ bunch by e+ drive | | | FACET | FACET | FACET | | | |
| Initial test of e+ acceleration in e- wakes | | | | FACET | FACET | | | |
| Emittance preservation of e+ bunch | | | | FACET | FACET | | FACET | |
| *Upgrade Sector-20 chicane* | | | | | ● | | | |
| Accelerate e+ by e- drive; charge, low dE/E | | | | | | FACET | FACET | |
| Accelerate e+ by e-, high efficiency, low emittance | | | | | | FACET | FACET | |
| ***Selection of optimum positron acceleration mechanism for a PWFA-LC*** | | | | | | | | ★ |
| *Upgrade injector with rf gun* | | | | ● | | | | |
| Plasma cell with jet and power removal | Study | Study | Eng. | Eng. | FACET | FACET | FACET | |
| ***Design plasma cell with needed stability and cooling*** | | | | | | | | ★ |

*...Proceeding in parallel with PWFA-LC design, simulation and engineering*

# Beams vs Lasers

* Physics:
  - Wakes and beam loading are similar for laser and beam driven plasmas
  - Driver propagation and coupling efficiency differ:
    - Lasers distort due to de-phasing, dispersion, photon deceleration, but to the plasma a 25GeV and 2GeV beam are nearly identical

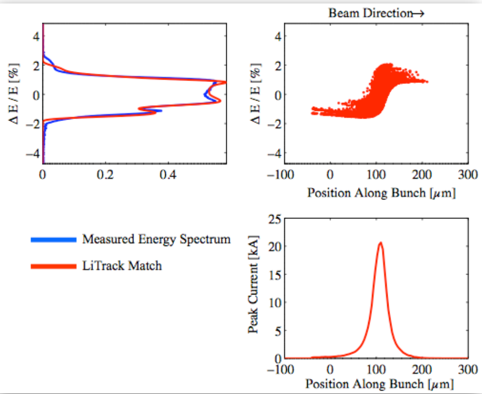
      → Beams have higher coupling efficiency to wake (~2x)
    - Beams easily propagate over meter scales (no channel needed)

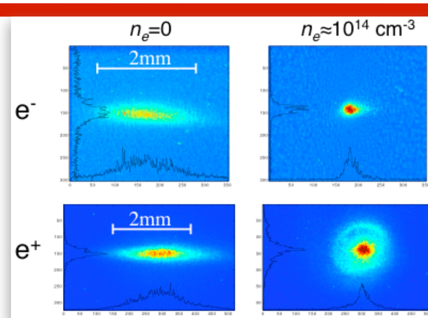
$$L_R \sim \pi\sigma^2/\lambda \sim \pi\sigma^2/1\mu \text{ vs } \beta^* \sim \pi\sigma^2/\varepsilon_y \sim \gamma\pi\sigma^2/1\mu$$

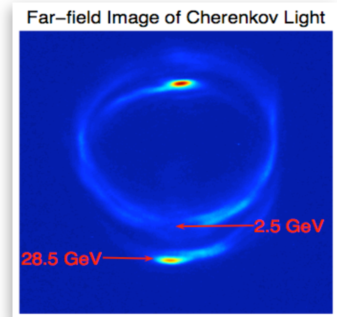
* Economics:
  - Lasers can more easily reach the peak power requirements to access large amplitude plasma wakes
    - \$100K for a $T^3$ laser vs >\$5M for even a 50MeV beam facility
  - However, need peak power AND average power (unlike DLA)
  - Average power costs sets the timescale for HEP applications
    - \$$10^4$/Watt for lasers currently x 200MW ~ \$2T driver. Much research on developing high power lasers but...
    - \$10/Watt for CLIC-type RF x 100MW ~ \$1B driver

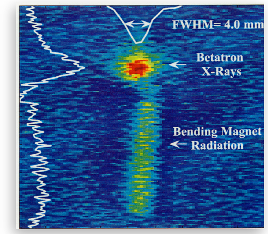
$$L = \frac{P_{beam}}{4\pi E_{beam}} \frac{N}{\sigma_x \sigma_y} H_D$$

# Extensive FFTB Program Developed Required Techniques & Apparatus for FACET Plasma Program



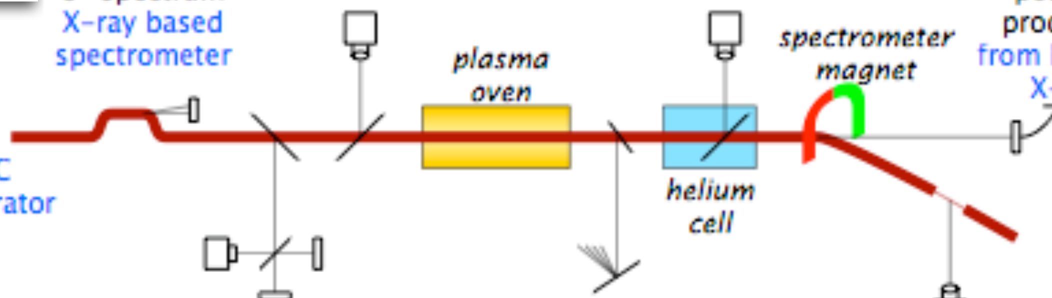

e⁻ spatial distribution
optical transition radiation (OTR)

trapped particles
imaging Čerenkov monitor

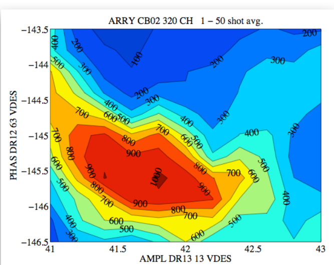
e⁻ spectrum
X-ray based spectrometer

positron production
from betatron X-rays

SLAC linac:
BPM's, Torroids,
Feedbacks,
GADCs, triggers



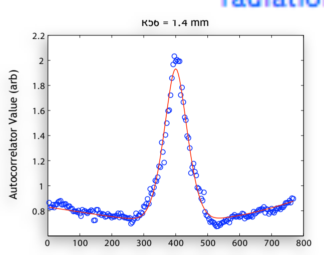

e⁻ beam
from SLAC linear accelerator

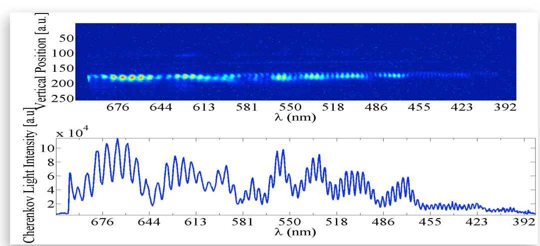


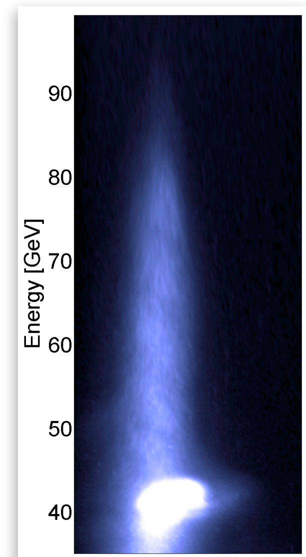

e⁻ bunch length
autocorrelation of coherent transition radiation (CTR)

plasma light spectrum
grid spectrometer

e⁻ spectrum
Čerenkov light in air gap



# Linear Collider requirements

* For e+ e- linear collider, luminosity is given by

$$L = f_{rep} N^2/(4\pi\sigma_x\sigma_y)$$

major dependence is

$$L \sim \delta_B^{1/2} P_{beam} / \varepsilon_{ny}^{1/2}$$

* The achievable emittance $\varepsilon_{ny}$ is limited, thus
* beam power $P_{beam}$ determines the luminosity

* TeV collider call for $P_{beam}$ ~10 MW of continuous power, small emittances and nanometer beams at IP

# Hollow Channel Plasmas may offer better accelerating wakes and reduce emittance growth

* Potential for larger accelerating fields and less aberrated focusing
* Synergy with DWA which may work equally well with e- & e+
* Challenge for plasma source development in field ionized regime
* Potential to engage new users/collaborators:

STI OPTRONICS

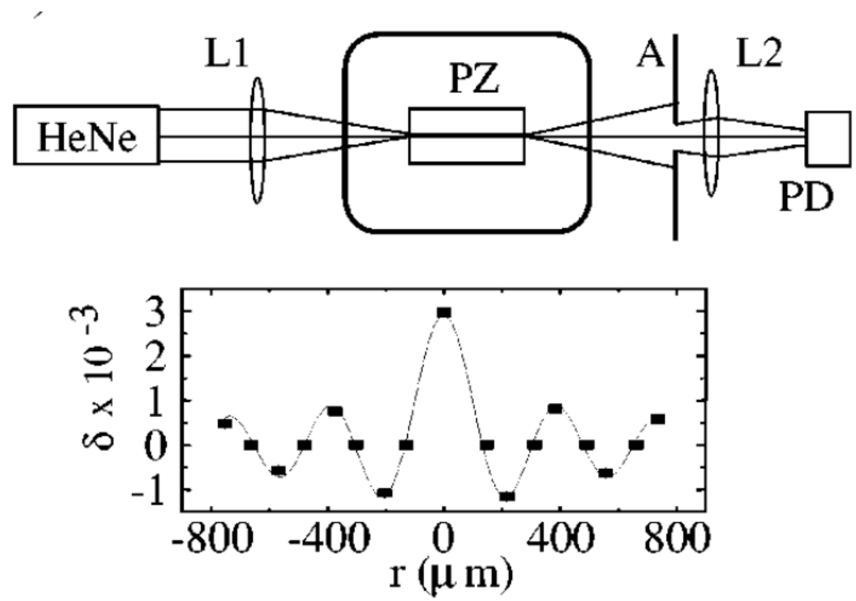
**HOLLOW PLASMA CHANNELS FOR POSITRON PLASMA WAKEFIELD ACCELERATION**

STI Optronics, Inc.
2755 Northup Way
Bellevue, Washington 98004-1495

Principal Investigator: Dr. Wayne D. Kimura

**Guiding characteristics of an acoustic standing wave in a piezoelectric tube**

C. M. Fauser, E. W. Gaul, S. P. Le Blanc, and M. C. Downer[a]
*University of Texas at Austin, Department of Physics, Austin, Texas 78712*




Appl. Phys. Lett., Vol. 73, No. 20, 16 November 1998

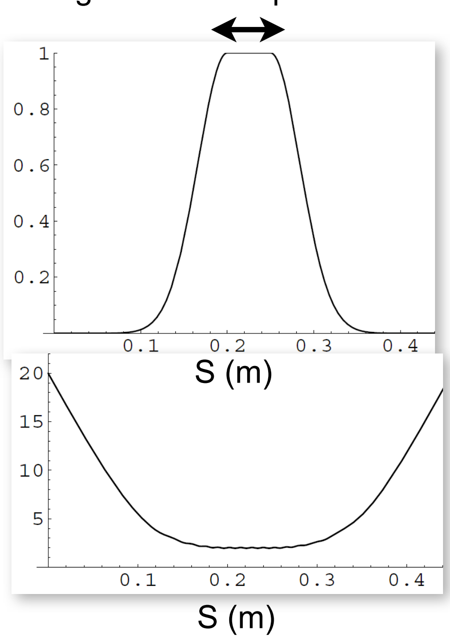
# Matching to plasma cells

- Matching into axial focusing plasma channel is important for emittance preservation
  - matched beta:
    $\beta_0$=23mm (E/500GeV *1E17/n)$^{1/2}$
- Profile of plasma density: adiabatic matching, easier optical system
  - good control/knowledge of plasma density profile required
  - Eases beta-matching by an order of magnitude
- The above describes e- in blowout regime, situation with e+ needs to be studied

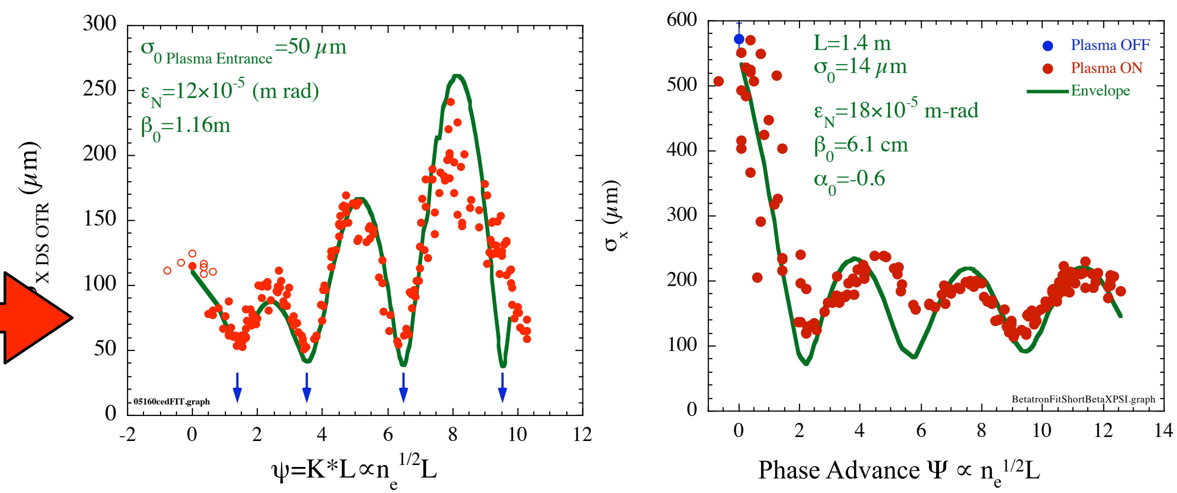
Adjust plasma length with oven power

Plasma density profile /$n_0$

$\sigma_R$ (μm)



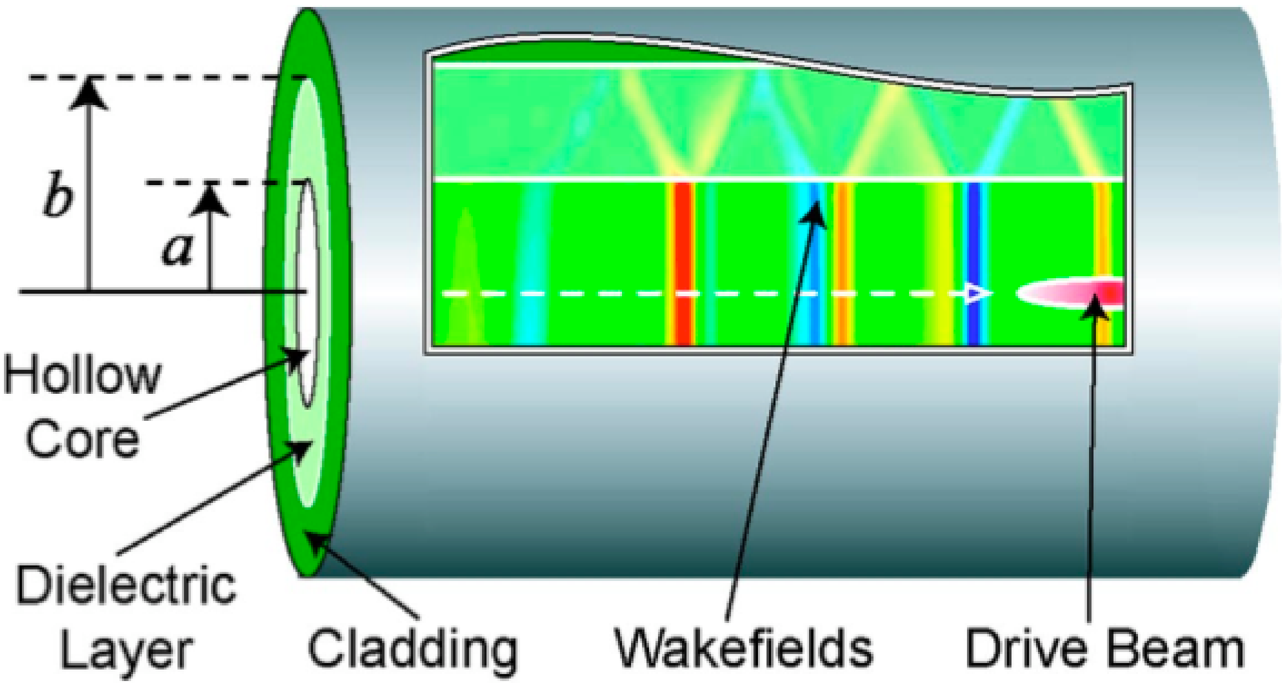

Emittance measurement through strong focusing from plasma channel...




... or conventional quad scan in dumpline

# DWA: Dielectric Wakefield Accelerator

A "drive" beam excites wake-fields in the tube, while a subsequent witness beam (not shown) would be accelerated by the Ez component of the reflected wakefields (bands of color).

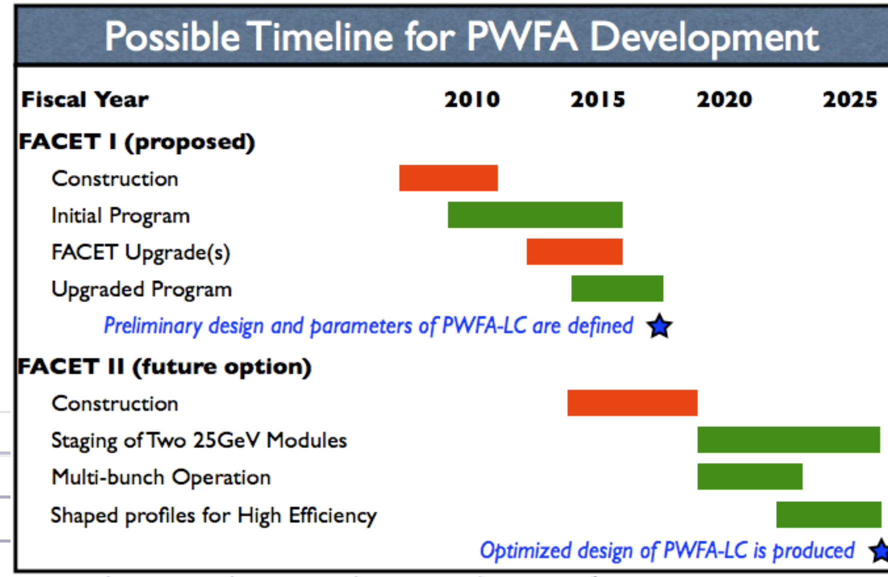



$$eE_{z,\mathrm{dec}} = eE_{r,\mathrm{surf}} \frac{\sqrt{\varepsilon - 1}}{\varepsilon}$$

$$\cong - \frac{4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon - 1}}\varepsilon\sigma_z + a\right]}$$

For large wakes want high charge, short bunches and narrow tubes → **FACET**

# Plasma accelerator research at FACET is in the context of a broader, longer term effort




| Concurrent Design and Engineering Tasks and Milestones | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Multi-bunch PWFA acceleration | Study | Study | Study | | | | | |
| Initial tolerance studies | Study | Study | Study | | | | | |
| Colinearity of main and drive beams | | Study | Study | | | | | |
| Timing offset of main and drive beams | | Study | Study | | | | | |
| Drive beam generation, affordable power | | Study | Study | | | | | |
| Drive beam utilization | | Study | Study | | | | | |
| Combiner recombiner, reasonable footprint | | Study | Study | | | | | |
| Shaping the drive bunches for high efficiency | | | Study | Study | | | | |
| Main beam injector, compressor & DR | | | Study | Study | | | | |
| Final focusing, large energy acceptance | | | | Study | Study | | | |
| Cleaning or collimation of the accelerated beam | | | | | Study | Study | | |
| Evaluate physics reach of PWFA-LC options | | | | | Study | Study | Study | |
| Detailed design of PWFA-LC subsystems | | | | | | Study | Study | Study |

# Additional Applications of Plasma Wakefield Acceleration

* PWFA acts as a transformer and uses existing technology
  - High charge, low energy bunch → low charge, high energy bunch
  - Transformer ratios of x2 predicted for gaussian bunches; high with shaped bunches
  - RF acceleration & notch collimation technology exist
* Increase energy reach of existing linacs, e.g. linac based radiation sources
* Simplify construction of new linacs
  - Many applications need low charge bunches: Storage ring injectors, SASE FELs, Medical linacs
  - RF linacs naturally accelerate high charge bunches
  - Use PWFA for much more compact system
* Linear Colliders or other high energy linacs
  - Dedicated drive beam → inexpensive generation of high power beams
  - PWFA → Cost effective access to very high energies

# Consistent High-Level Parameters for PWFA-LC

| | |
|---|---|
| Luminosity | $3.5\times10^{34}$ $cm^{-2}s^{-1}$ |
| Luminosity in 1% of energy | $1.3\times10^{34}$ $cm^{-2}s^{-1}$ |
| Main beam: bunch population, bunches per train, rate | $1\times10^{10}$, 125, 100 Hz |
| Total power of two main beams | 20 MW |
| Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$ | 2, 0.05 mm-mrad |
| Main beam sizes at Interaction Point, x, y, z | 140 nm, 3.2 nm, 10 μm |
| Plasma accelerating gradient, plasma cell length, and density | 25 GV/m, 1 m, $1\times10^{17}cm^{-3}$ |
| Power transfer efficiency drive beam=>plasma =>main beam | 35% |
| Drive beam: energy, peak current and active pulse length | 25 GeV, 2.3 A, 10 μs |
| Average power of the drive beam | 58 MW |
| Efficiency: Wall plug=>RF=>drive beam | 50% × 90% = 45% |
| Overall efficiency and wall plug power for acceleration | 15.7%, 127 MW |
| Site power estimate (with 40MW for other subsystems) | 170 MW |

# Plasma Acceleration Program and Challenges

* Accelerator physics: produce drive/witness bunches
  – For $n_p \sim 10^{17}$ cm$^{-3}$, need two bunches within 100μm!
* High Gradient Acceleration of witness bunch in ~ 1 m-long plasma
* Narrow energy spread & preserved emittance of the accelerated witness bunch

  particle acceleration ⟶ beam acceleration
* Beam loading of plasma wake, energy transfer efficiency
* Positrons in PWFA
* Plasma Stability and Tolerances
* Further developments in simulation tools