FACET

Facility for Accelerator Science and Experimental Tests

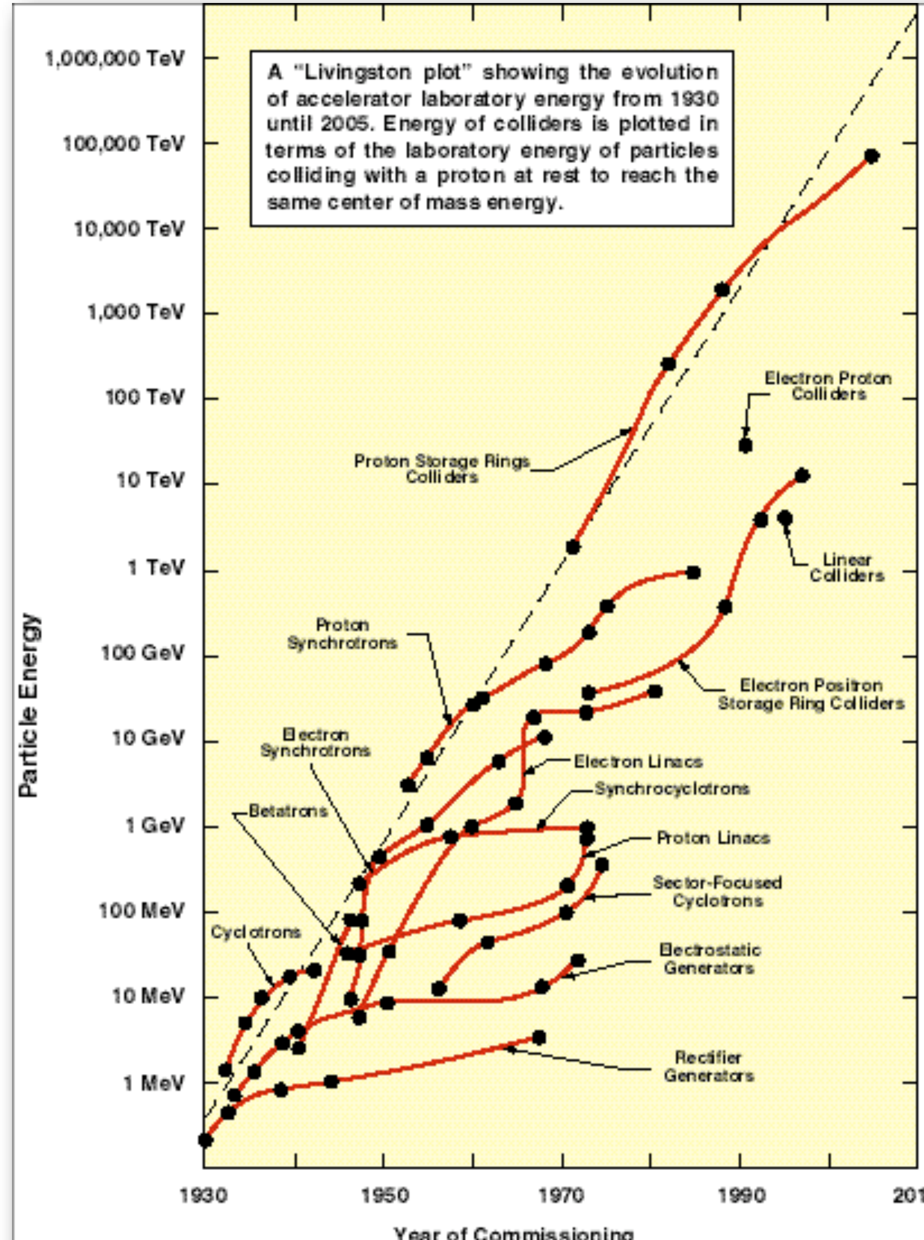
Mark Hogan

SLAC National Accelerator Laboratory

2010 Advanced Accelerator Concepts Workshop
Annapolis, MD
June 13-19, 2010

Accelerators and Particle Physics

- Particle physics addresses fundamental questions that are often answered at the energy frontier
- The Livingston curve shows the exponential growth in CM energy that has come from new accelerator physics & technology
- This growth has been followed by profound discoveries - CP violation in K's, two ν's, J, quarks, ψ, τ, gluons & QCD, W, Z, top quark..
- New applications, e.g. medicine, light sources (rings, linac based X-FELs)



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

2-017

Accelerators and Particle Physics

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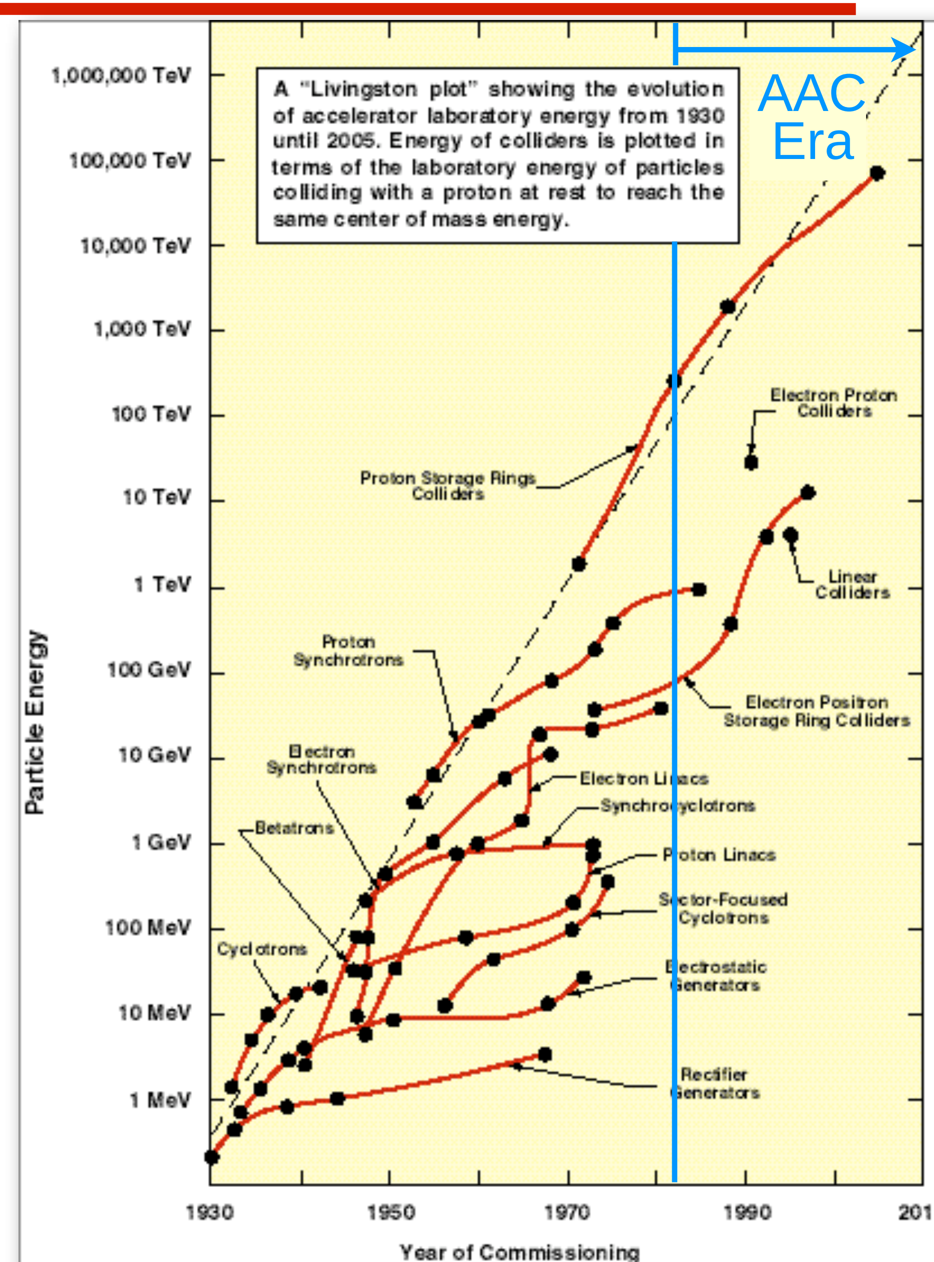
- New applications, e.g. medicine, light sources (rings, linac based X-FELs)
- DOE HEP Stewardship in AAC Era – looking for next generation of breakthroughs



The Evolution of Particle Accelerators & Colliders
by W. K. H. Panofsky

2-017

High Gradient Acceleration

- Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
- Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
- Many paths towards high gradient (e^-/e^+) acceleration
  - RF source driven microwave structures } ~100 MeV/m
  - Beam-driven microwave structures } ~100 MeV/m
  - Laser-driven dielectric structures } ~1 GeV/m
  - Beam-driven dielectric structures } ~1 GeV/m
  - Laser-driven plasmas } ~10 GeV/m
  - Beam-driven plasmas } ~10 GeV/m

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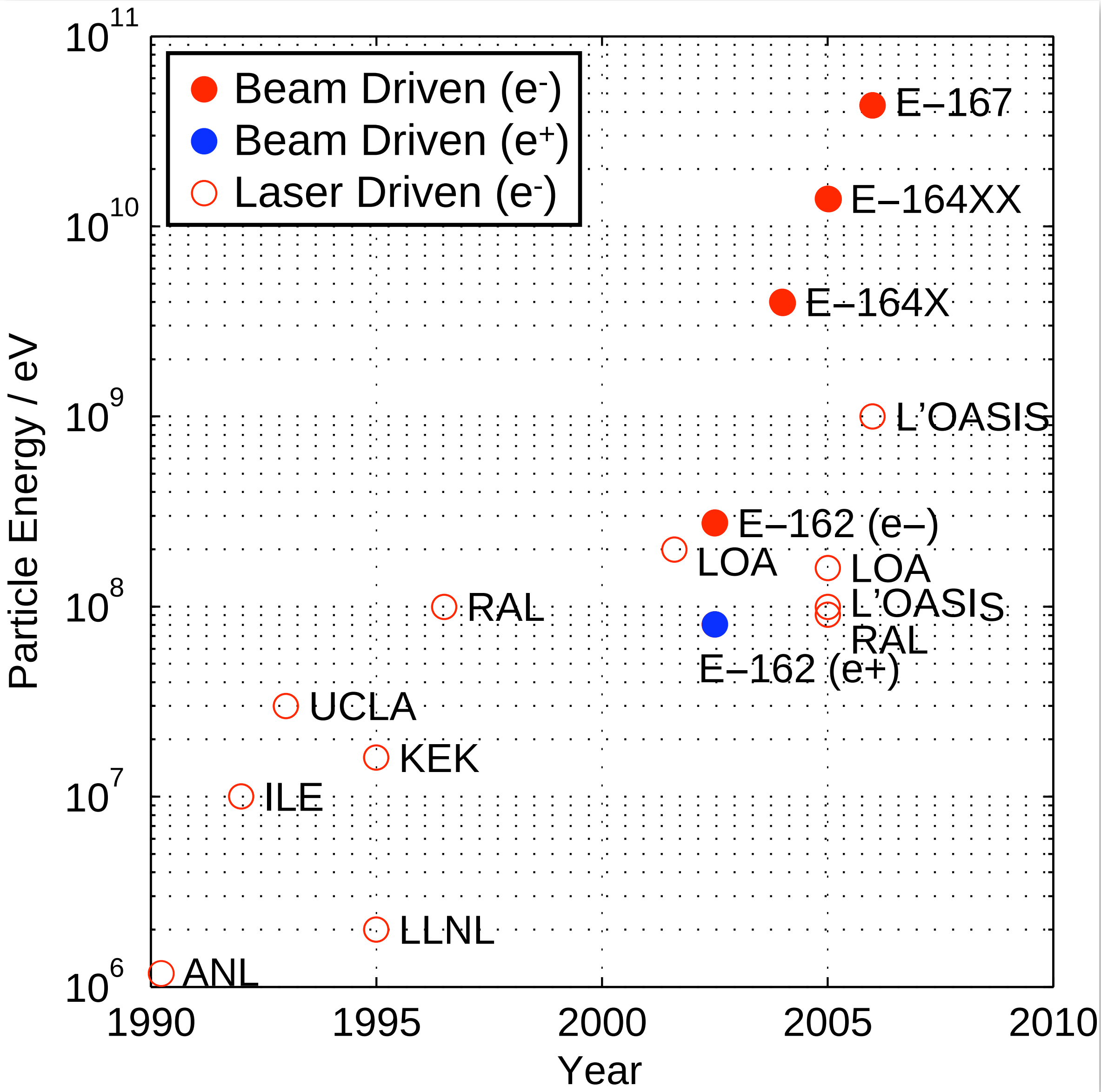
  - RF source driven microwave structures ← Tantawi
  - Beam-driven microwave structures
    - } ~100 MeV/m
  - Laser-driven dielectric structures ← Colby
  - Beam-driven dielectric structures ← Hogan
    - } ~1 GeV/m
  - Laser-driven plasmas ← Froula, Leemans, Sheng, Schroeder
  - Beam-driven plasmas ← Hogan, Muggli, Schroeder
    - } ~10 GeV/m

Plasma Livingston Plot



Laser Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length ~ cm's

Specialized Facilities:
- Multi-TW lasers
- Plasma Channels/Capillaries

Beam Driven Plasma Accelerators:

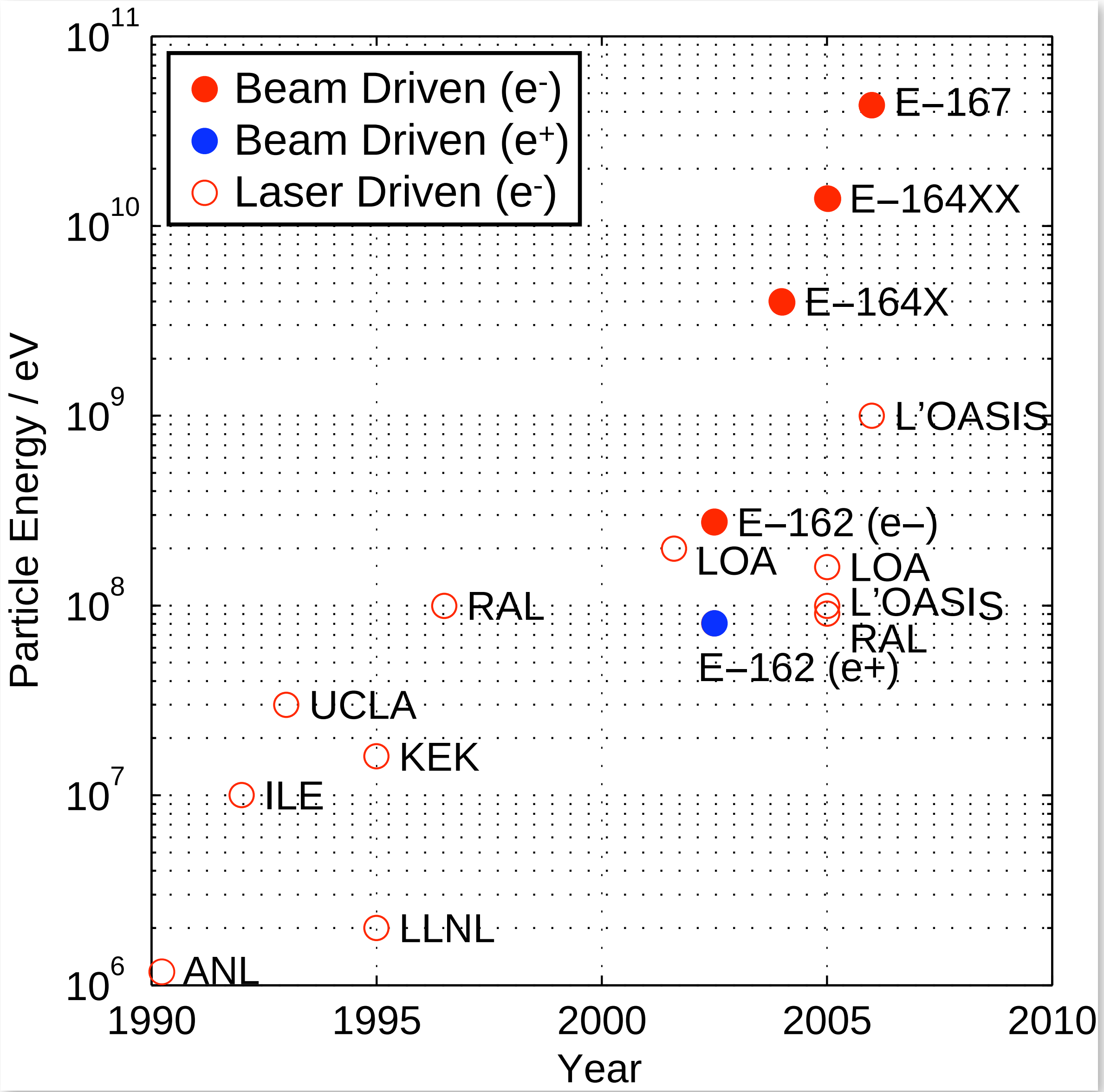
Large Gradients:
- Accelerating Gradients > 50 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length ~ meters

Unique SLAC Facilities:
- FFTB < 2006, FACET > 2011
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

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

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

Plasma Livingston Plot



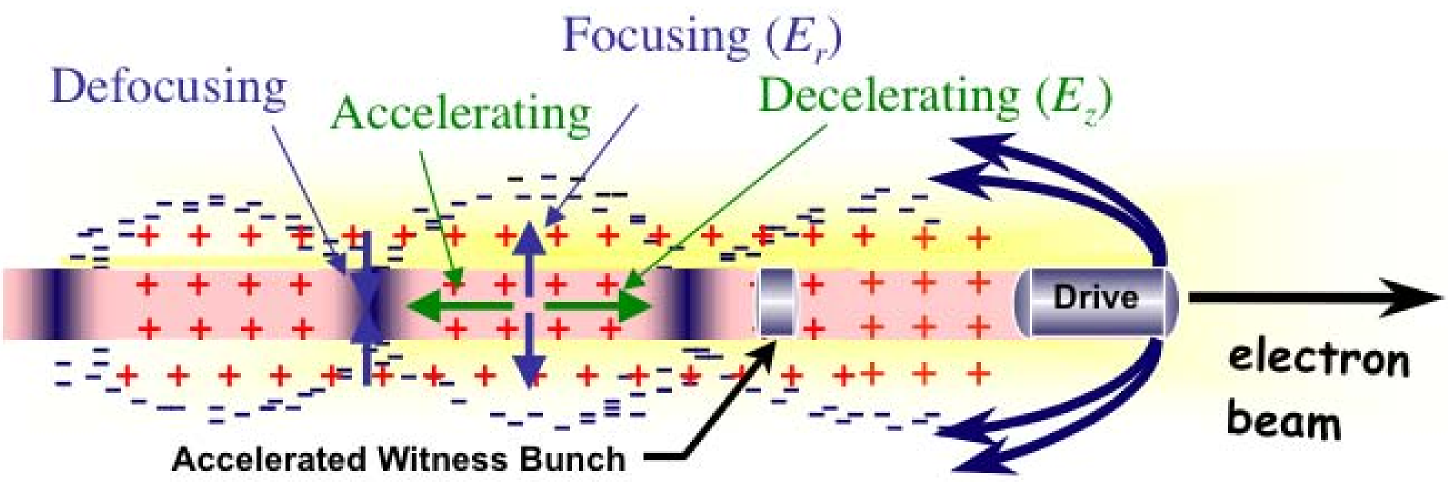
DOE HEP Office Of Science Issued CD-0 for Advanced Plasma Acceleration Facility February 2008

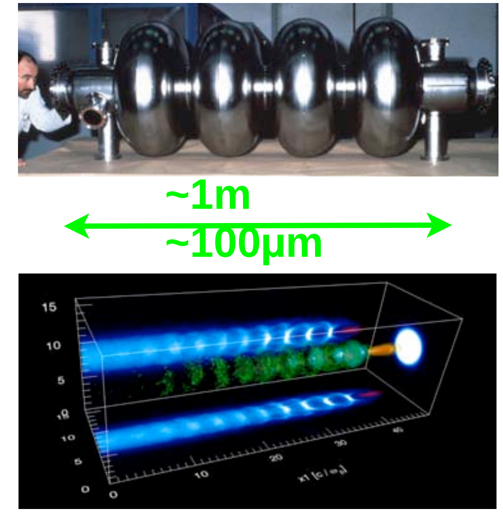
Answered by Two Facilities:
BELLA (LWFA)
FACET (PWFA)

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

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

The Beam Driven Plasma Wakefield Accelerator

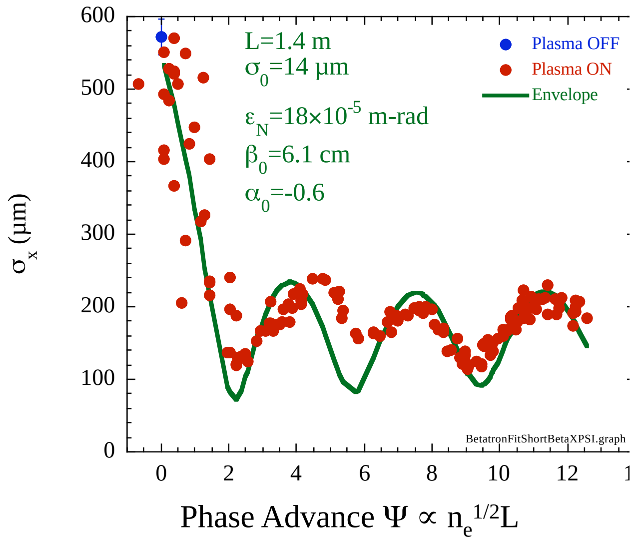




- Two-beam, co-linear, plasma-based accelerator
- Plasma wave/wake excited by relativistic particle bunch
- Deceleration, acceleration, focusing by plasma
- Accelerating field/gradient scales as $n_e^{1/2}$
- Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx 100$ µm, G>MT/m, E>10 GV/m
- High-gradient,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

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

Focusing & Matching e-

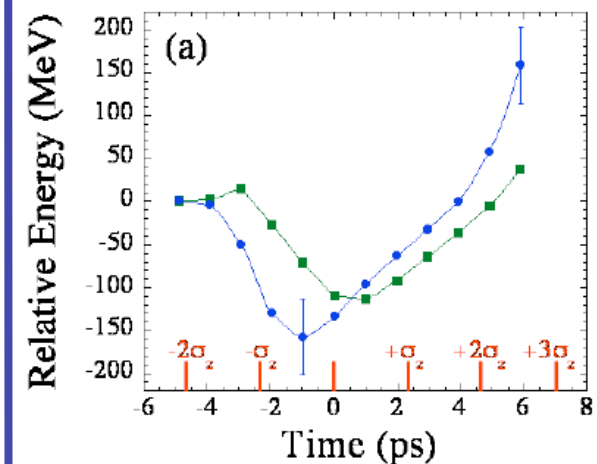


Phys. Rev. Lett. **93**, 014802 (2004)

X-ray Generation

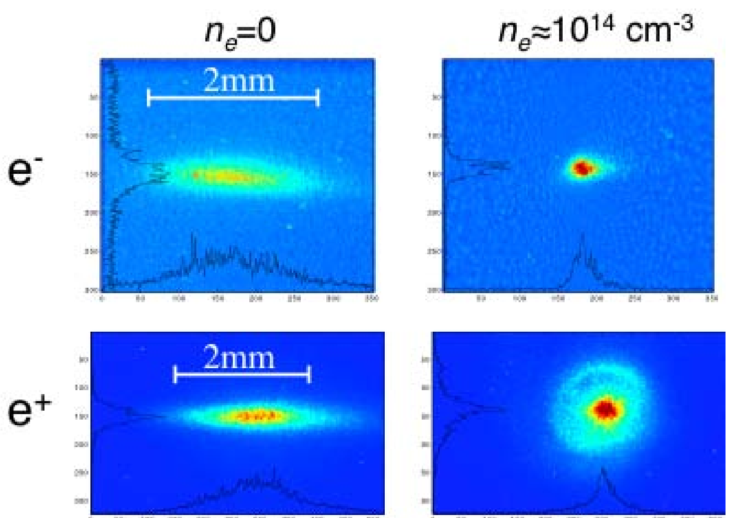
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e-



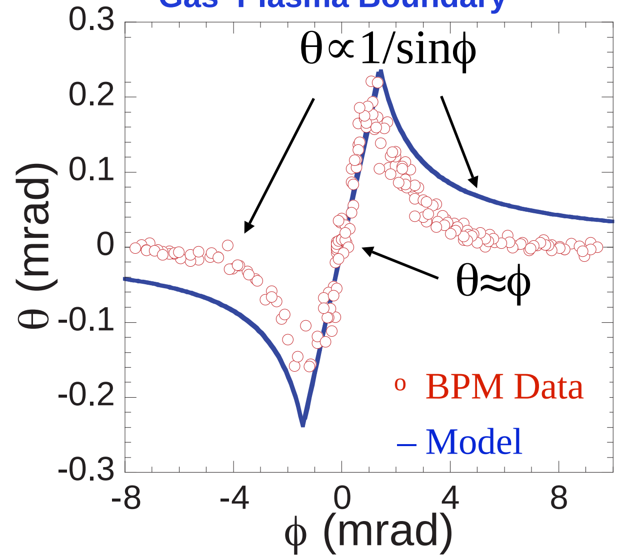
Phys. Rev. Lett. **93**, 014802 (2004)

Focusing & Halo Formation e+



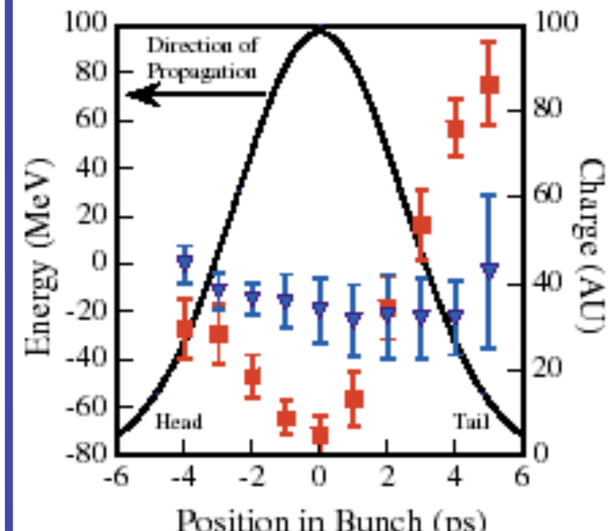
Phys. Rev. Lett. **101**, 055001 (2008)

Electron Beam Refraction at the Gas–Plasma Boundary



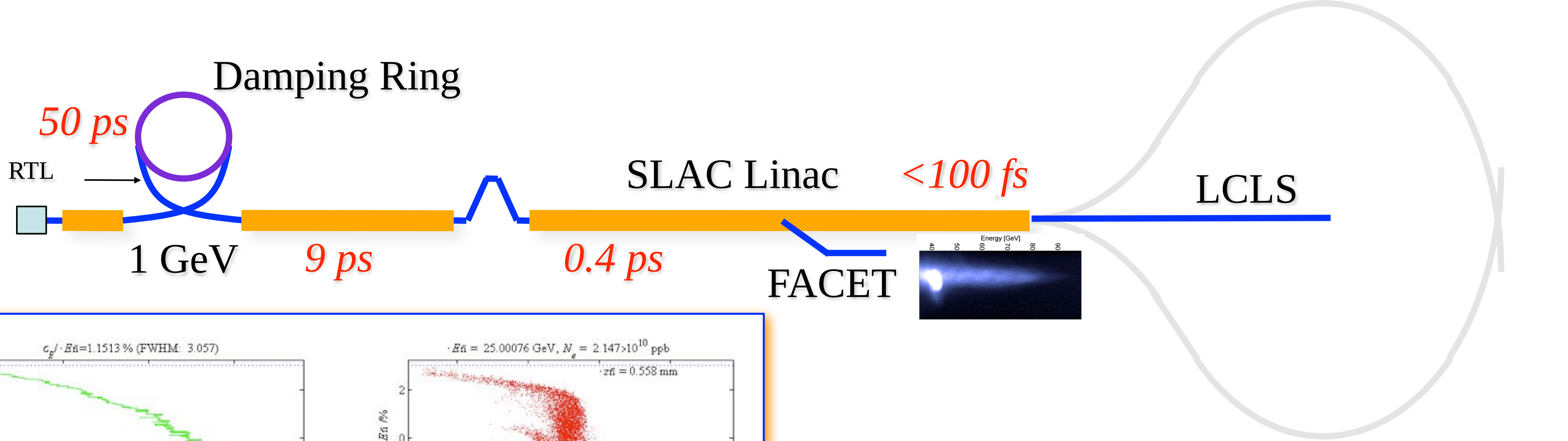
Nature **411**, 43 (3 May 2001)

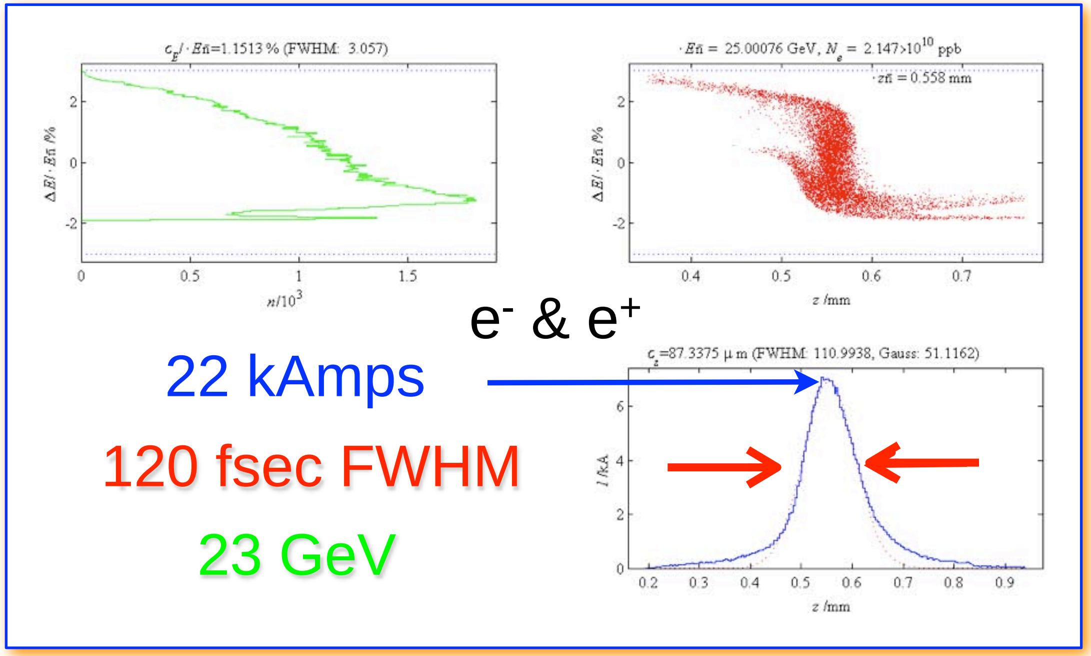
Wakefield Acceleration e+



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

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:

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

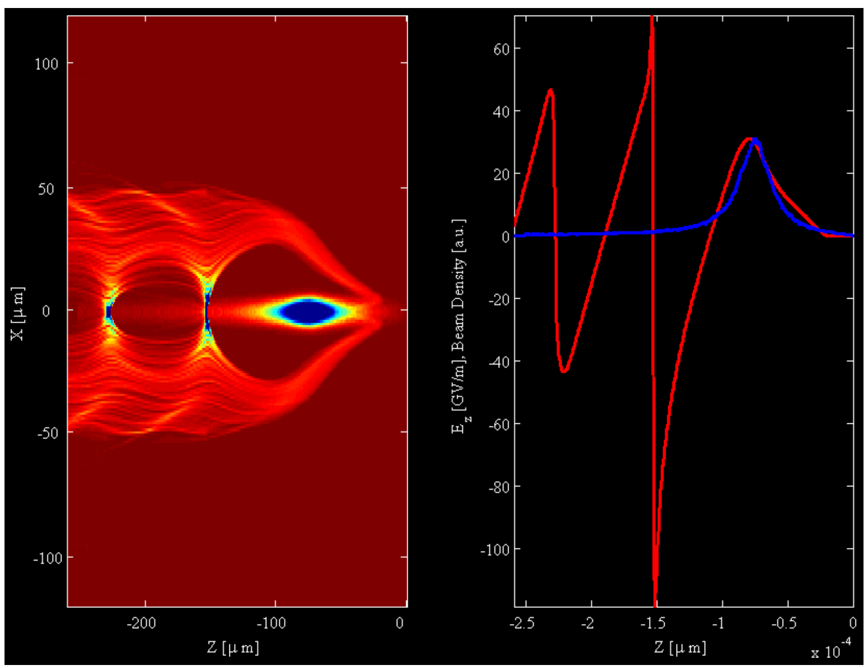
See D. Bruhwiler et al, Physics of Plasmas 2003

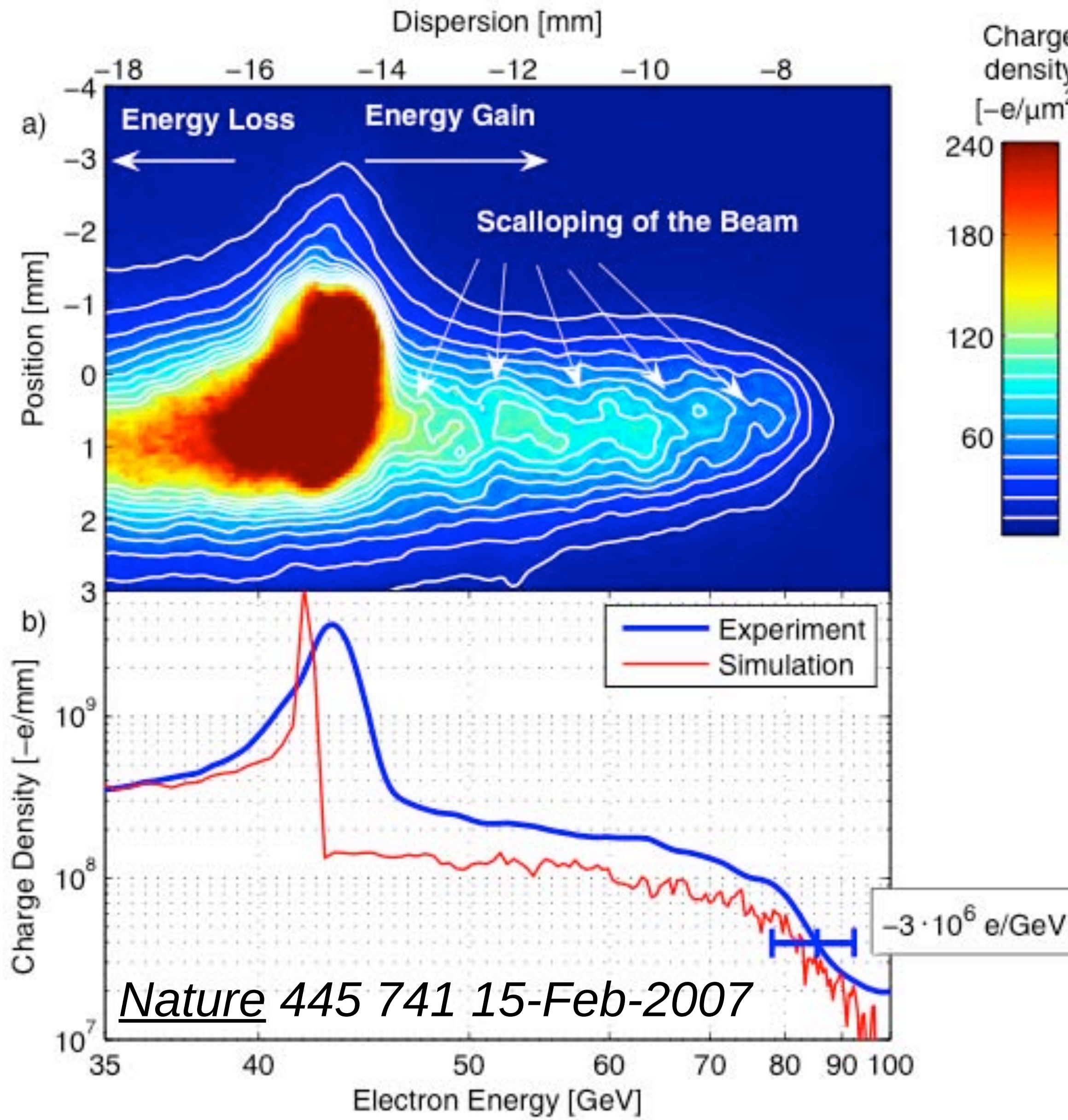
Space charge fields tunnel ionize the vapor!

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

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

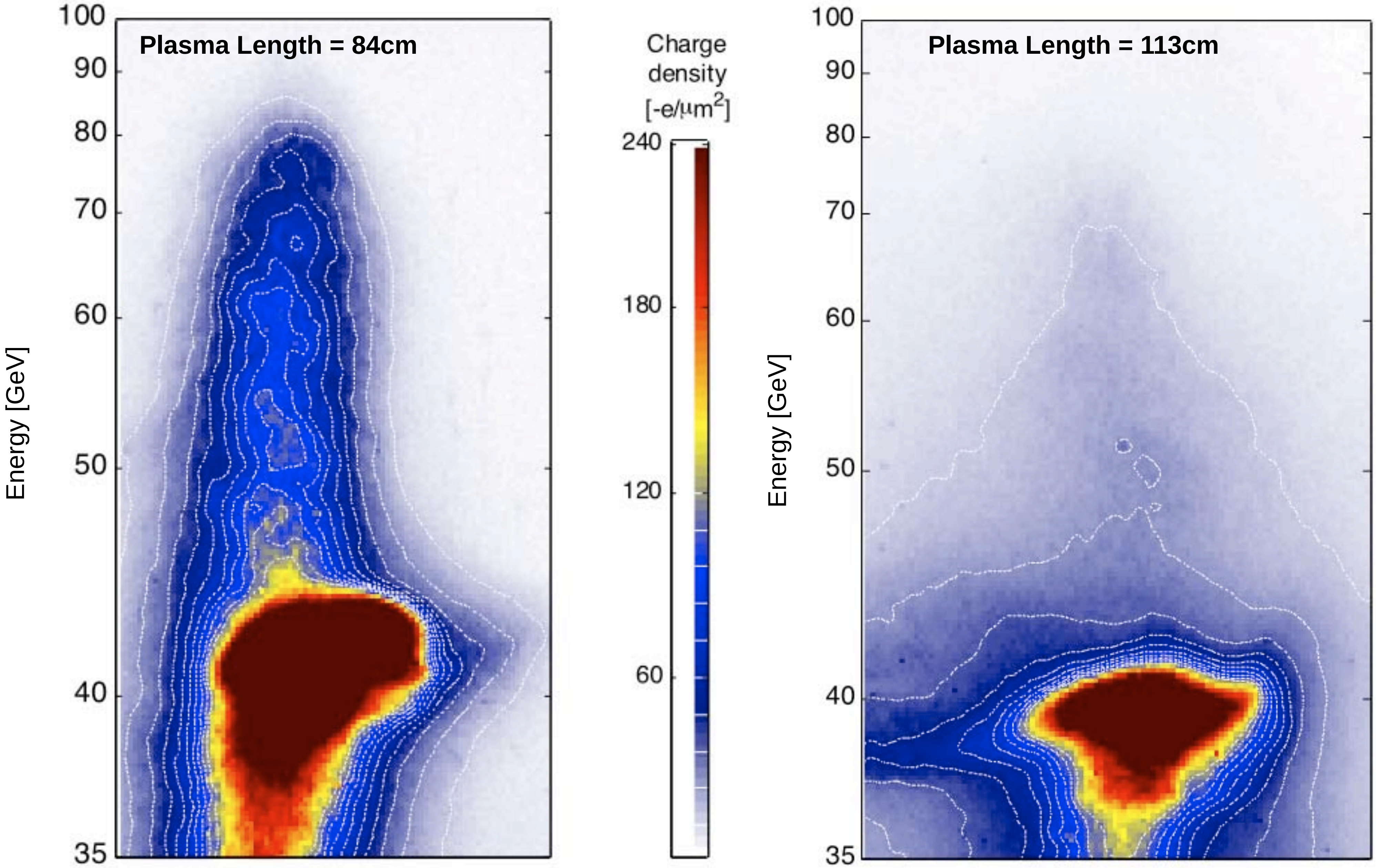
- Acceleration Gradients of ~50GeV/m (3,000 x SLAC)
  - Doubled energy of 45 GeV electrons in 1 meter plasma
- Single Bunch



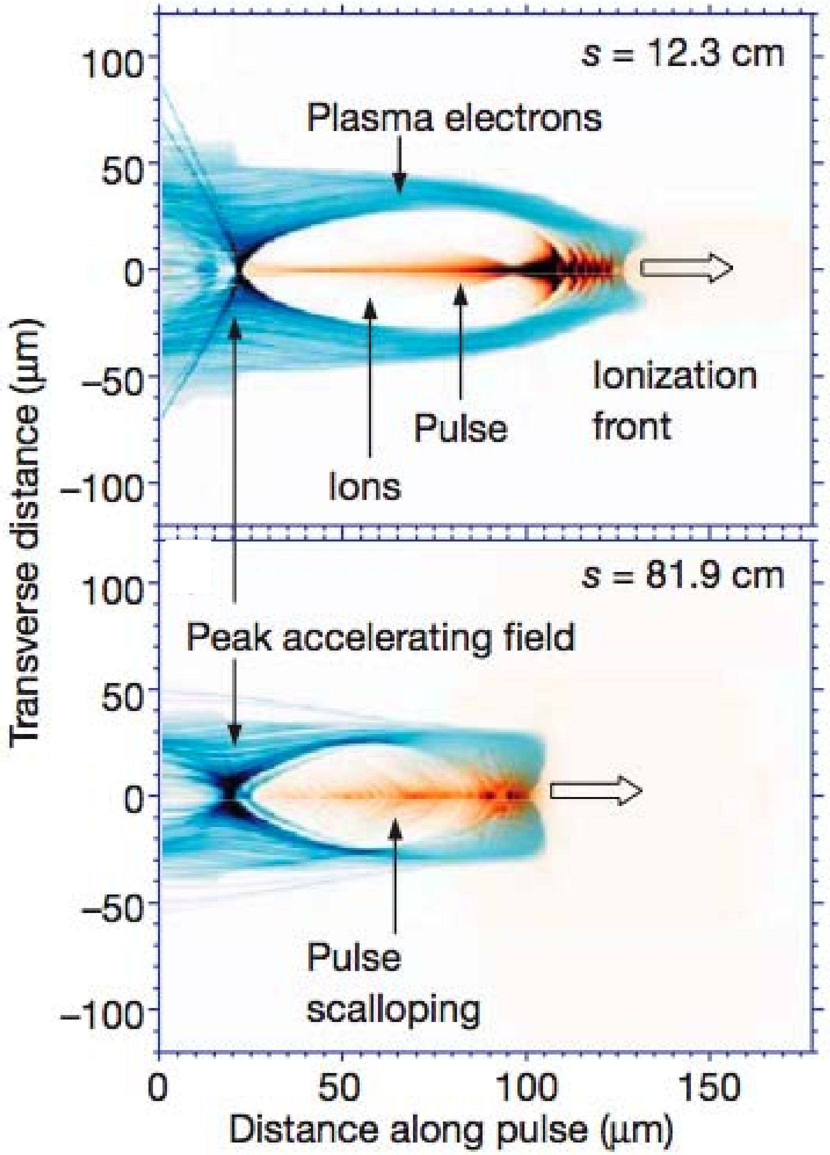


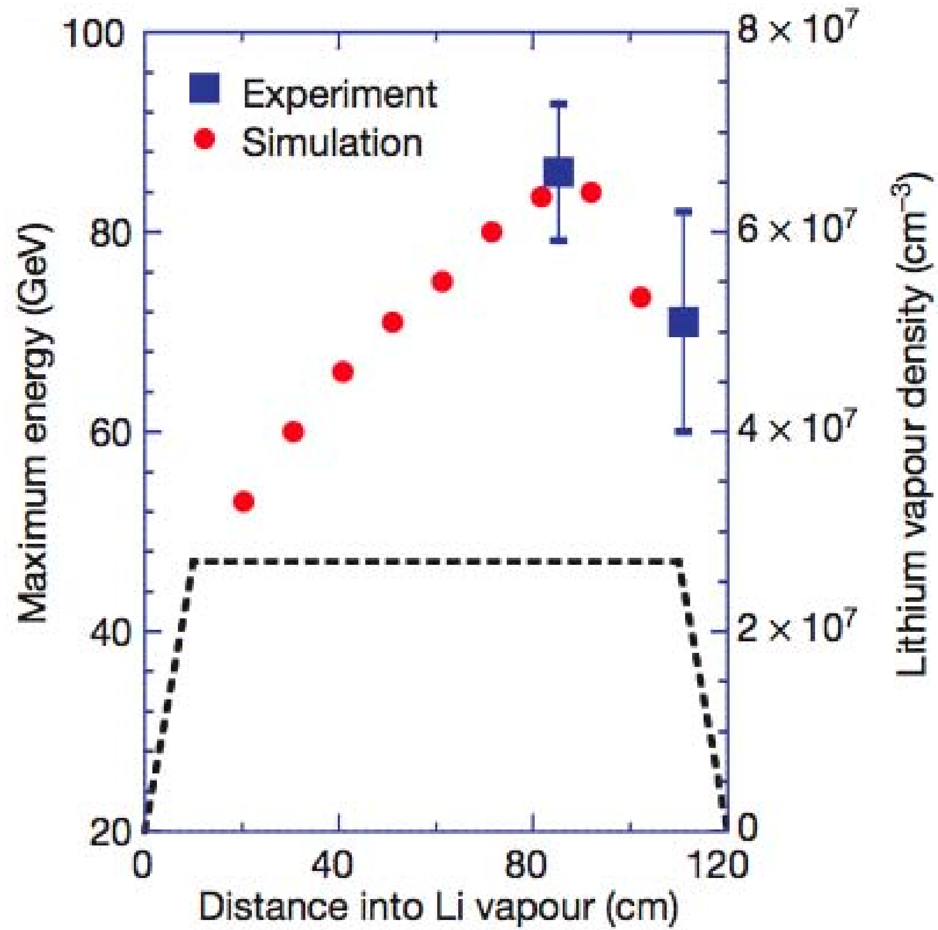
Nature 445 741 15-Feb-2007

Why Not Just Make the Plasma Longer?



Energy Gain Limited by Head Erosion





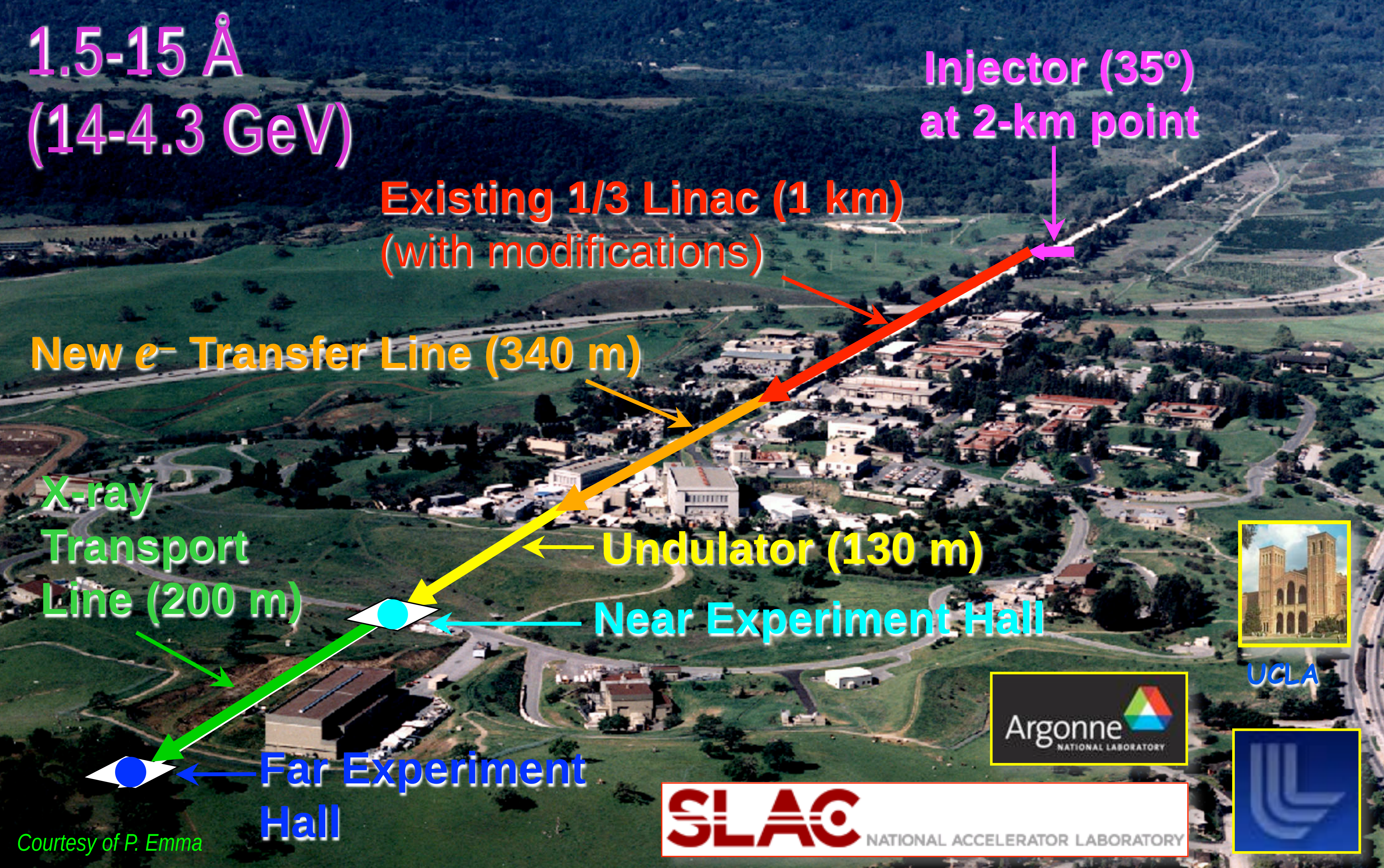
See I. Blumenfeld Stanford PhD Thesis 2009 and M. Zhou UCLA PhD Thesis 2008

$$V[\mu m/m] = (3.6617\cdot 10^4)\epsilon_i^{1.73}[eV]\frac{\epsilon_N[mm\cdot mRad]}{\gamma}\frac{1}{I^{3/2}[kA]}$$

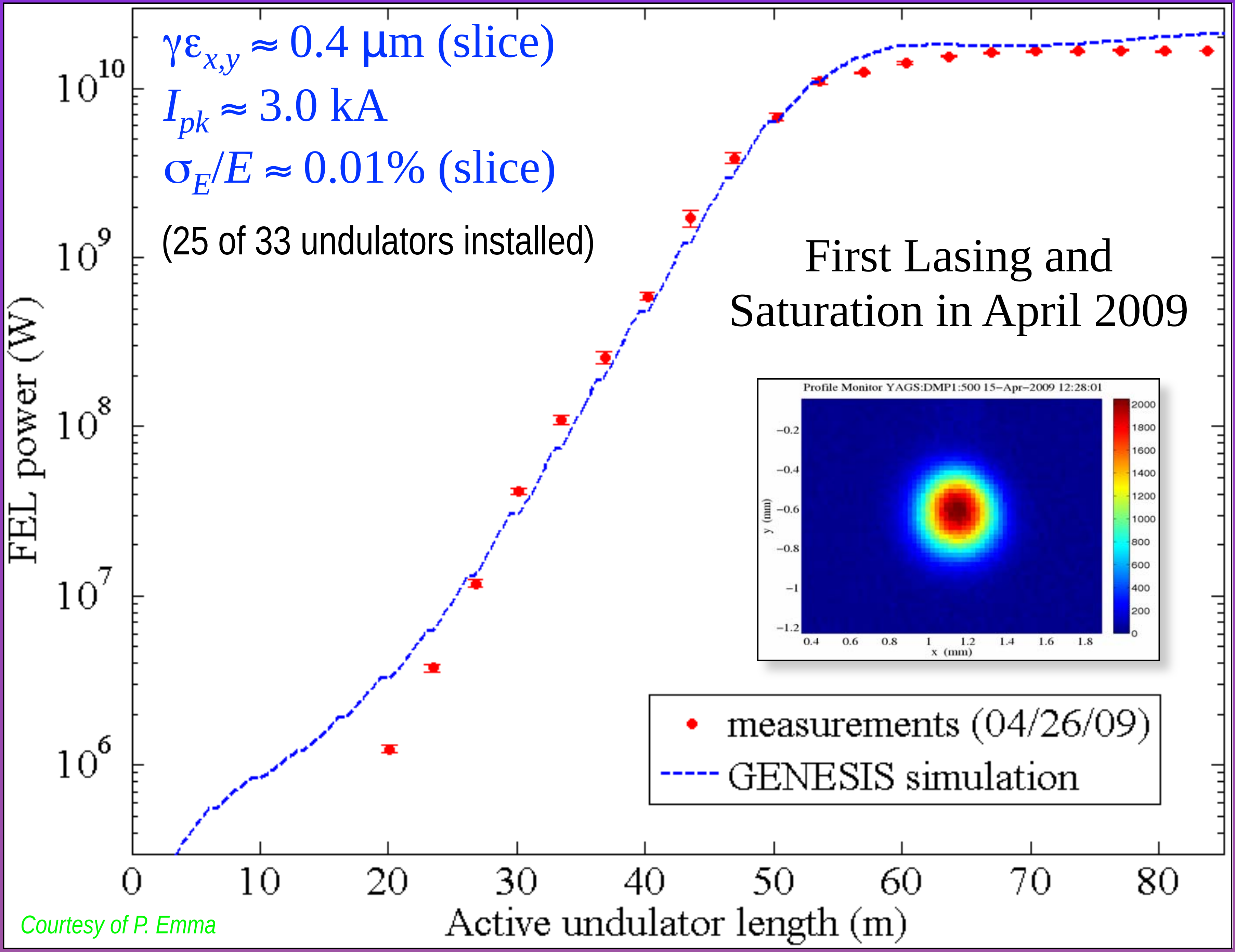
Previous work done at SLAC FFTB Facility

Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing 3-km linac

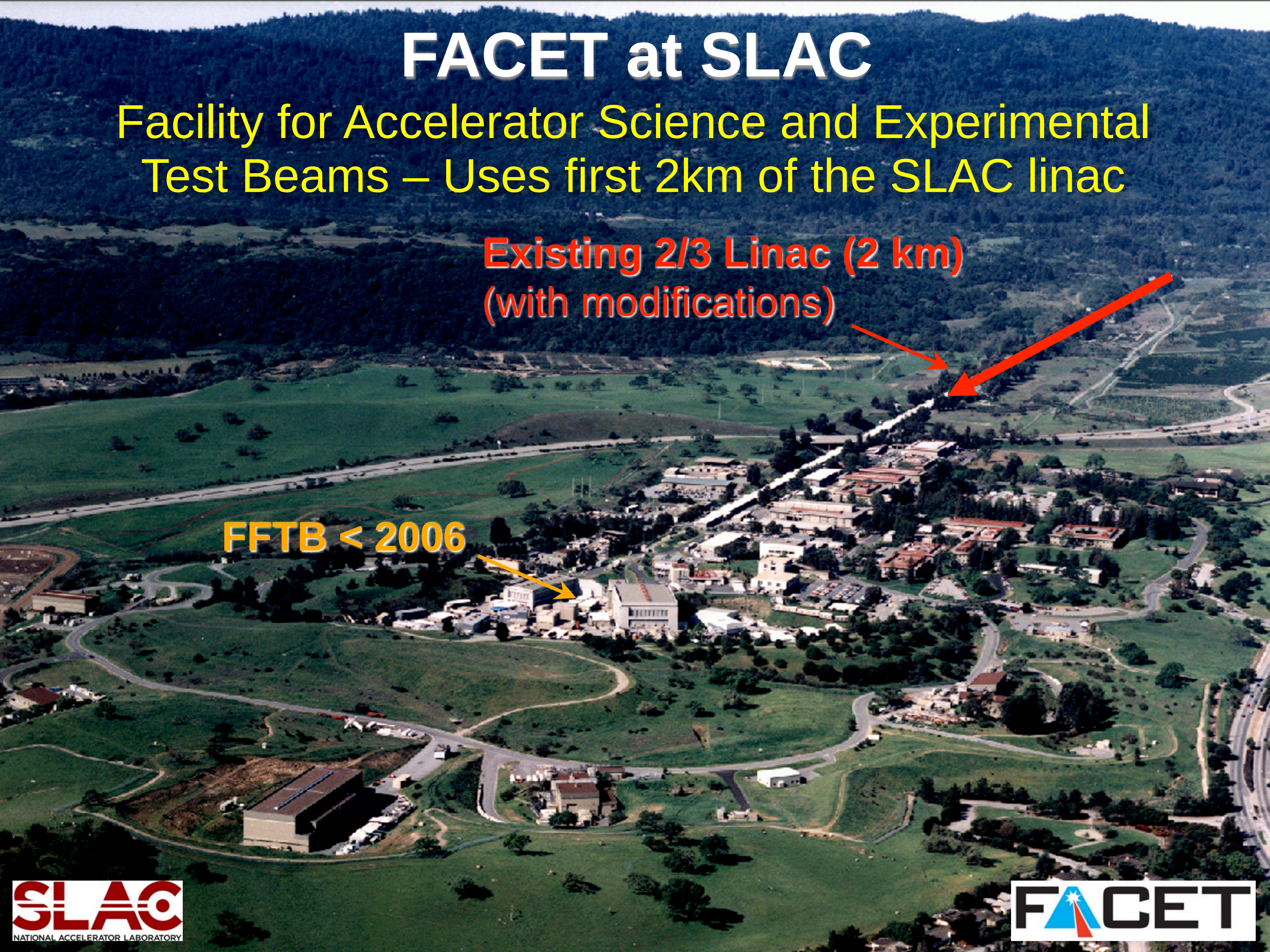


Undulator Gain Length Measurement at 1.5 Å: 3.3 m



FACET at SLAC

Facility for Accelerator Science and Experimental Test Beams – Uses first 2km of the SLAC linac

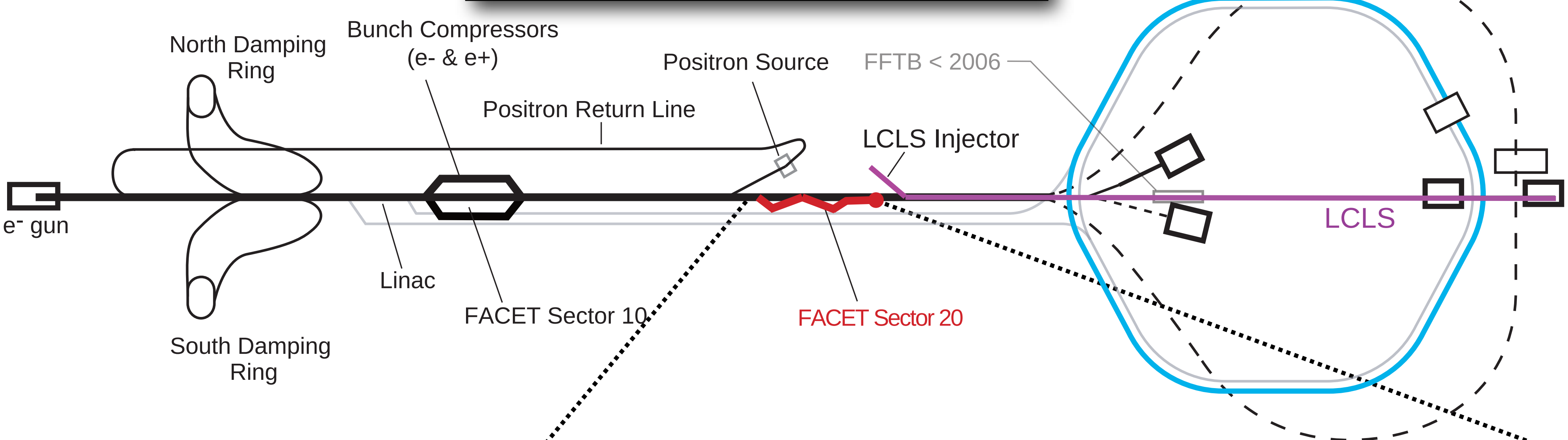


Beam Parameters Needed for Next Generation PWFA Experiments

- High gradients need high density plasmas
  - ~10^{17} e^-/cm^3 for >10GeV/m, >MT/m
    - Sets the plasma wavelength (106µm) & corresponding drive bunch length (24 µm)
    - Sets separation for two bunches
- Matched beams provide stable propagation through long plasmas with minimal synchrotron radiation loss
  - Sets matched beta function (~5mm) & transverse size
- Use field ionization for long, uniform, high density plasma production (requires large E_r, early in bunch)
- Good wake structure if ionize out to screening radius which corresponds to max ion channel radius (~50µm)
- Blow-out regime for beam transport & wake amplitude
  - These last three demand high charge in the bunch (>nC)

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

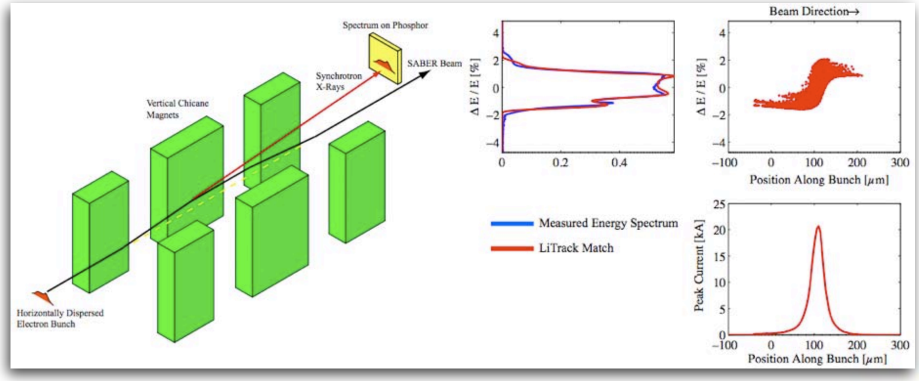
Delivered to 100m area with three distinct functions:

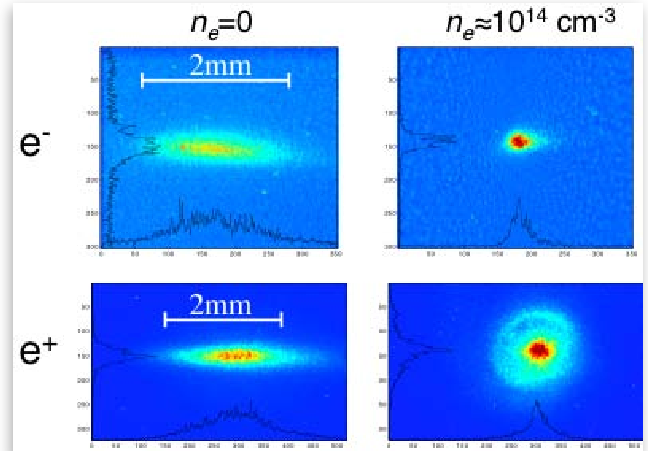
1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area(s)

Advantageous location:

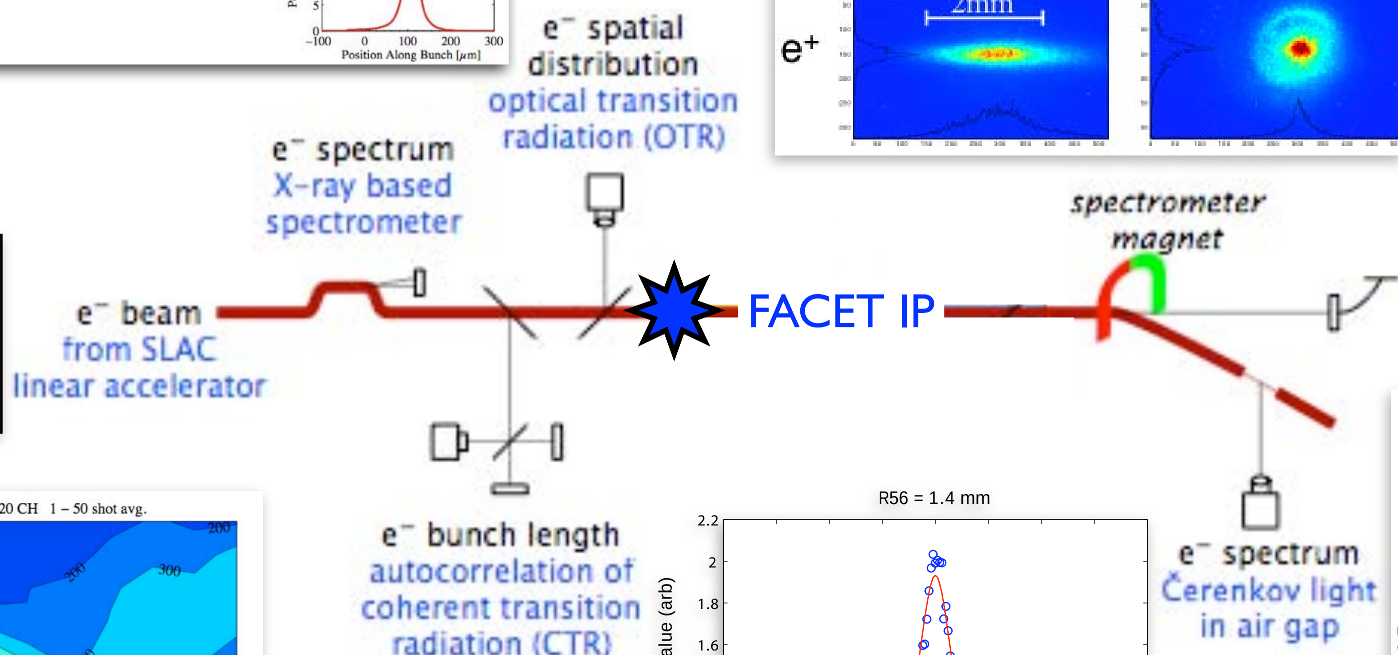
- Preserves e+ capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB

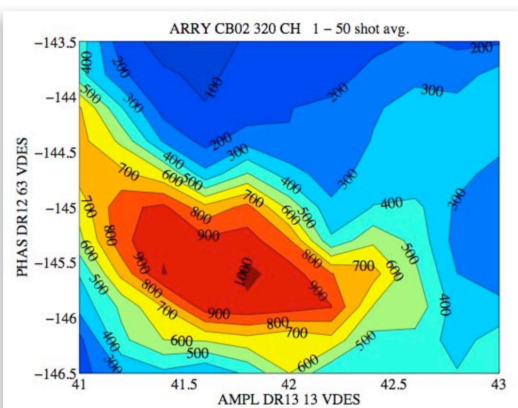
FACET Will Incorporate Many of the Single Shot Diagnostics Developed in the FFTB Plasma Program

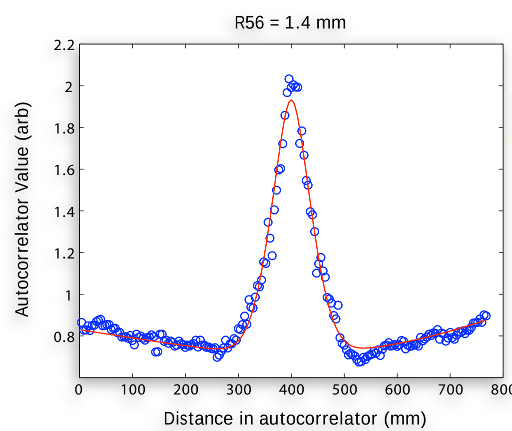


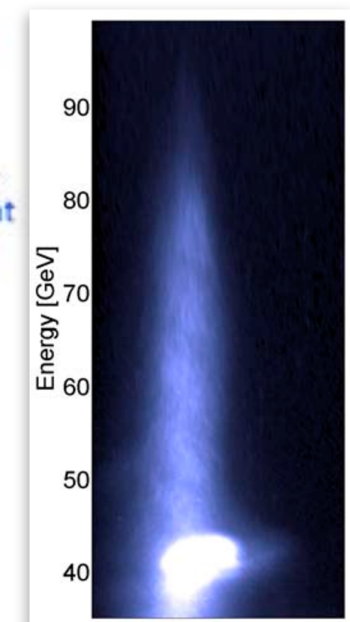


SLAC linac:
BPM's, Torroids, Feedbacks, GADCs, triggers







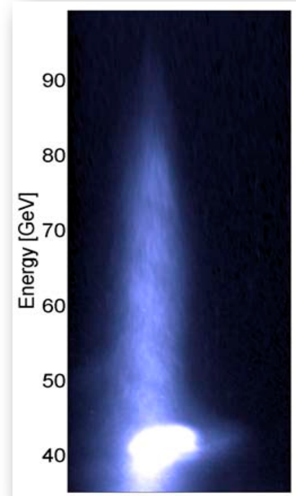


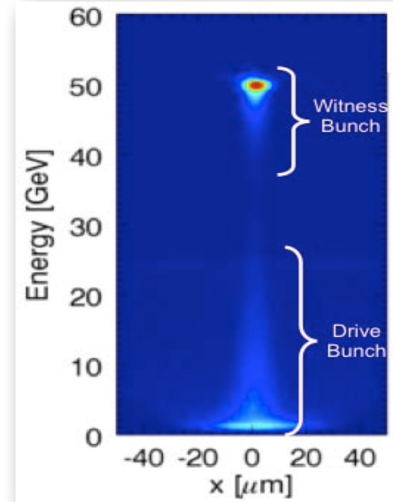
FACET is Getting Ready for First Experiments

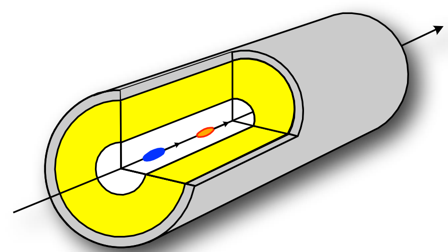
- FACET construction is expected to finish in Spring 2011 with accelerator and beam commissioning soon after.
- The experimental program will begin in the Summer of 2011
- First Users Workshop @ SLAC March 18-19, 2010
  - http://www-conf.slac.stanford.edu/facetusers/spring2010/
- 40 people, 9 institutions (Argonne, Brookhaven, Euclid Techlabs, Fermilab, SLAC, Stanford, UCLA, USC, UT Austin)
- 4 Working groups considered ideas for first experiments:
  - Plasma Wakefield Acceleration
  - Dielectric Wakefield Acceleration
  - Materials in Extreme Conditions
  - Crystals & Novel Sources of Radiation
- Beamtime allocated in an open, proposal driven process
- Proposals for beamtime in 2011 due July 2010

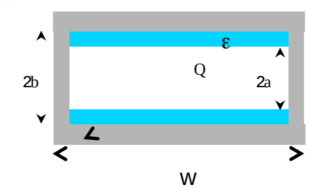
Many Opportunities Foreseen

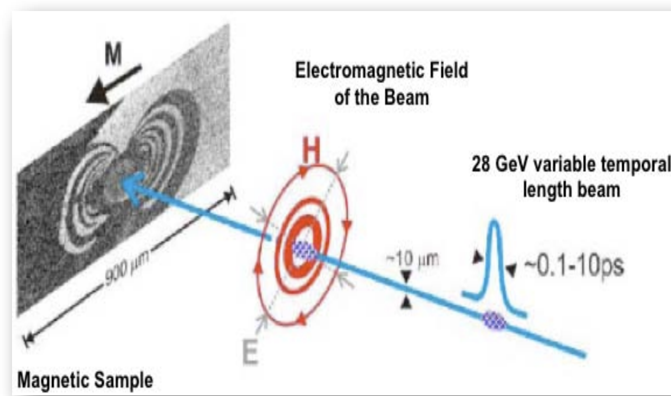
- PWFA: Extend 50 GeV/m particle acceleration to beam acceleration of electrons, compressed positrons.
- DWFA: Complete breakdown studies (Si, Diamond...), move to >GeV/m structures and accelerate particles, then beam
- Crystals: Study channeling, volume reflection, high-energy X/γ ray generation
- Materials in Extremes: Wide variety of possibilities using very-high, ultra-short duration beam fields or extracted THz

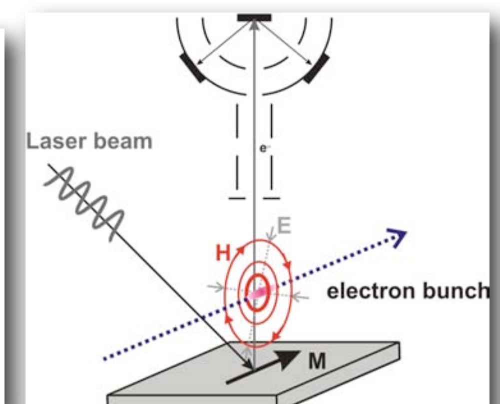












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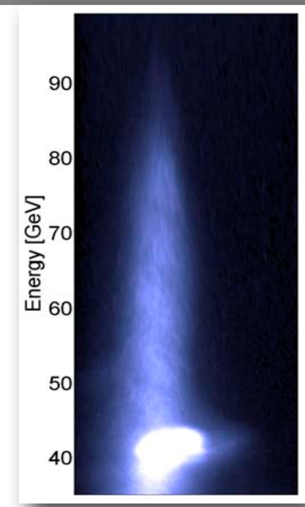
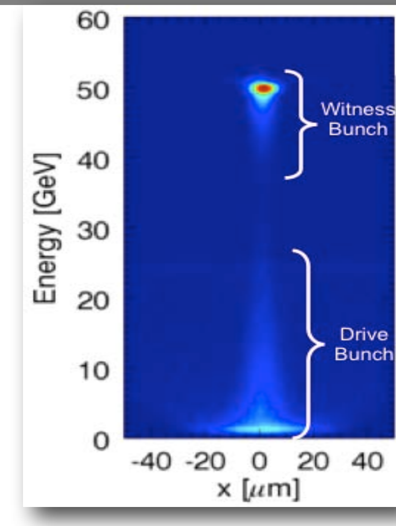
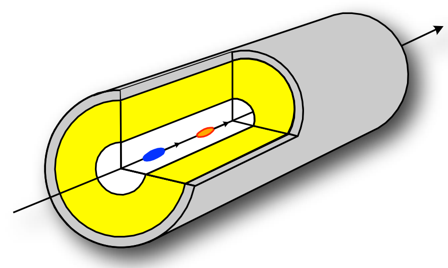
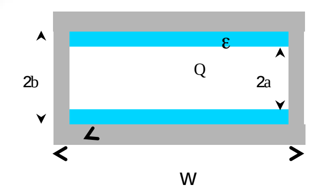
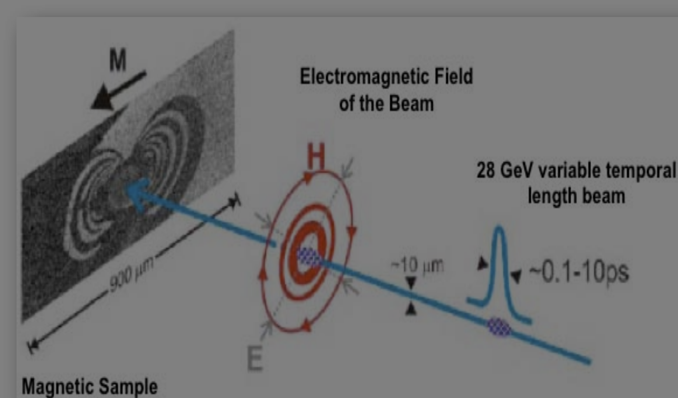
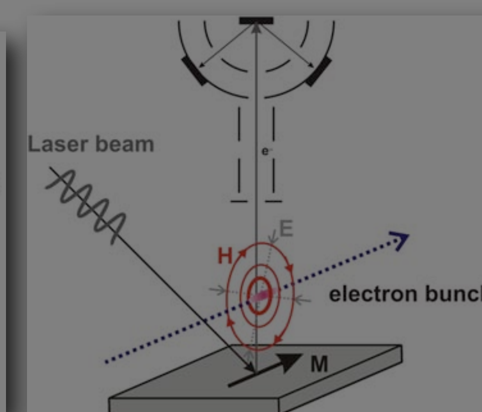










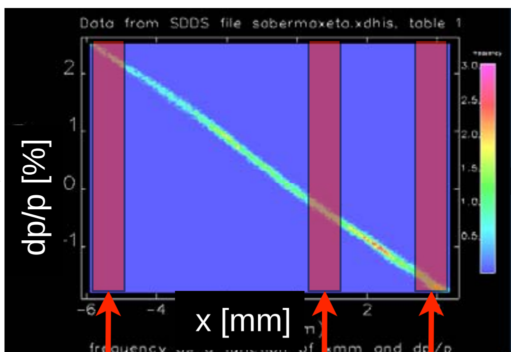


PWFA: Particle to Beam Acceleration

- Collimation system to craft drive/witness bunch from single bunch (similar to BNL ATF wire system)

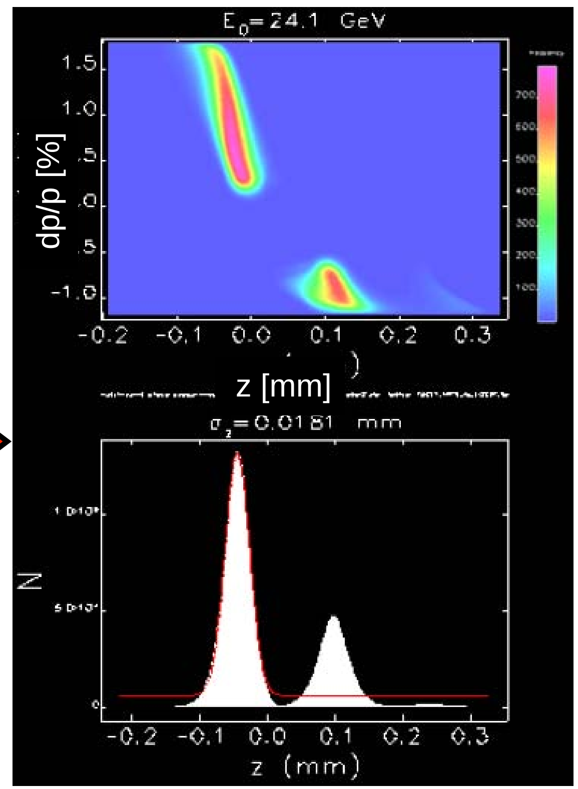
Disperse the beam in energy

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

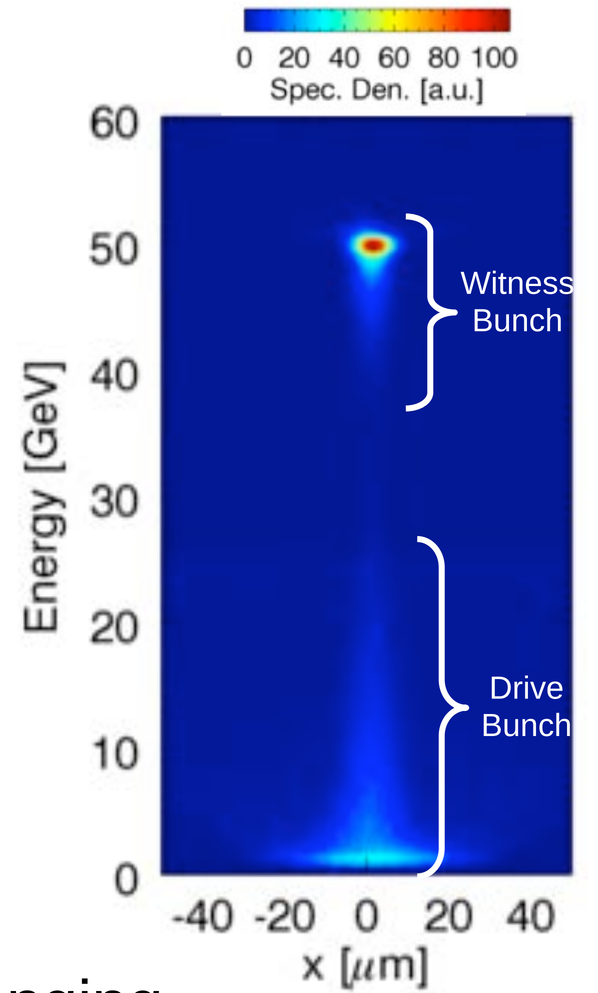


...selectively collimate

Adjust final compression



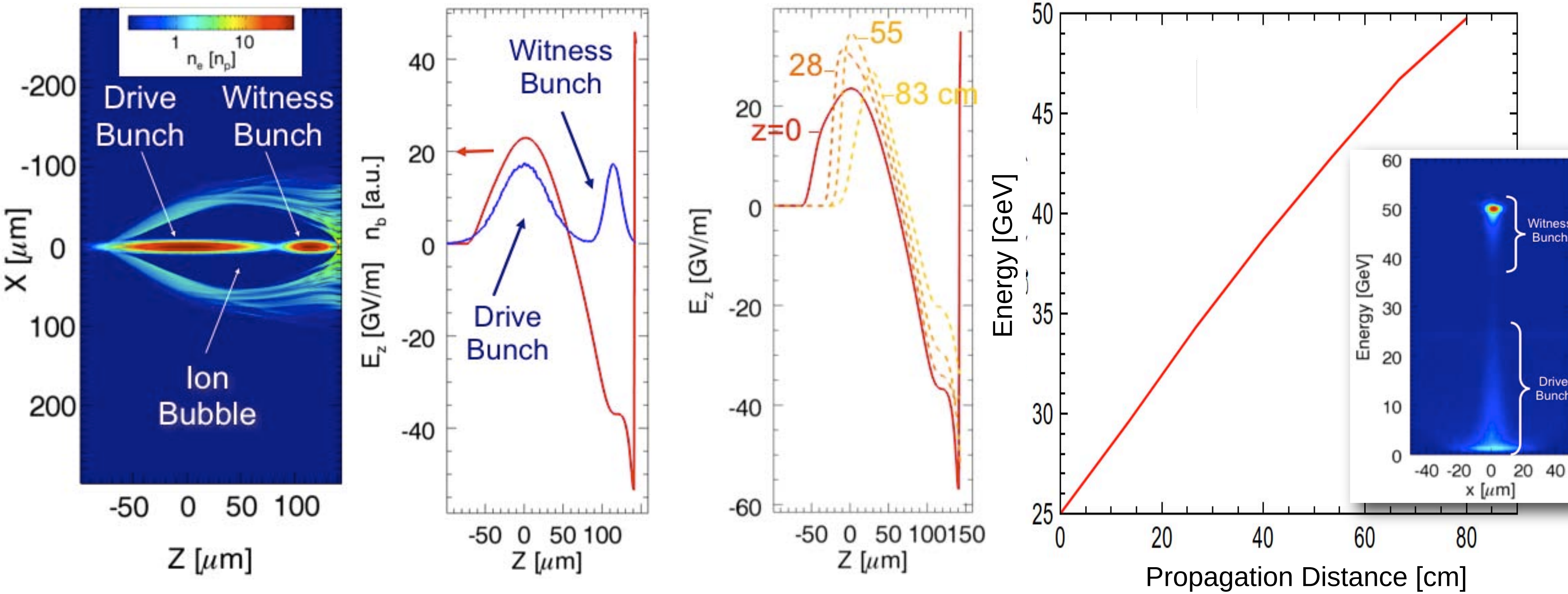
80cm Plasma



- Vary charge ratio, bunch lengths, spacing by changing collimators and linac phase, R56
- Study wake loading in the non-linear regime for the first time

Beam Loading & Wake Evolution

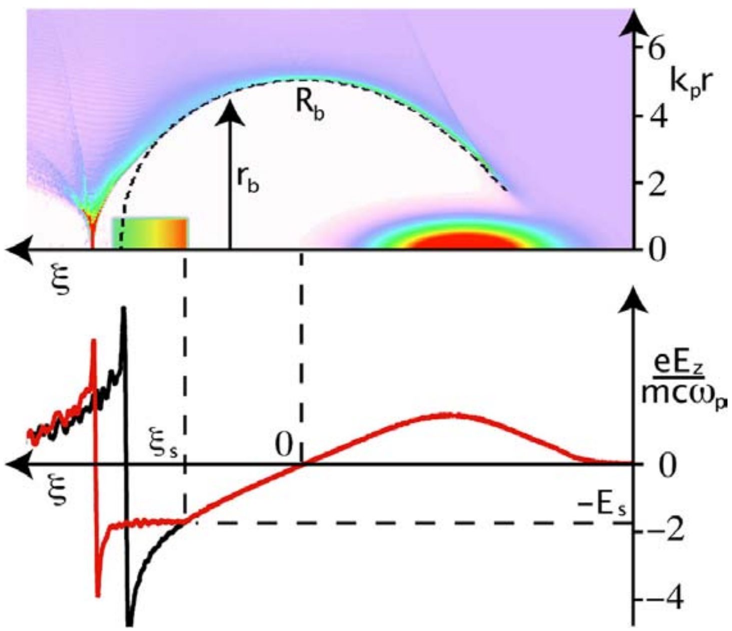
QuickPIC simulation, D: σ_z=30μm, N=3x10^{10}e$^-$, W: σ_z=10μm, N=1x10^{10}e$^-$, σ_{r0}=3μm, Δz=115μm, n_e=10^{17}cm^{-3}

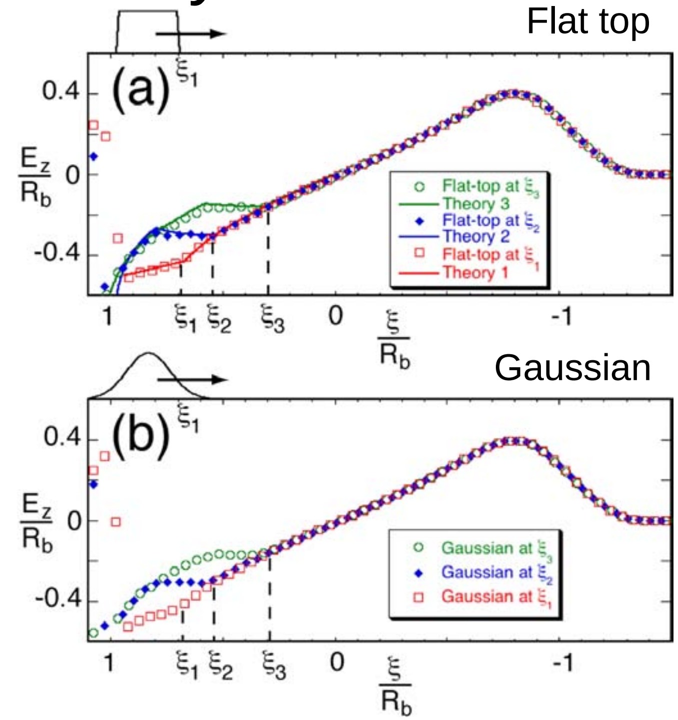


- Beam loading at 37GeV/m (z = 0)
- After 80cm plasma, gain 25GeV with 3% ΔE/E
- Wake evolution due to bunch head erosion, but no dephasing
- Wake evolution "bends" energy gain but preserves low ΔE/E
- Drive to witness Energy transfer efficiency ~ 30%

Beam Loading in Non-linear Wakes

- Theoretical framework, augmented by simulations

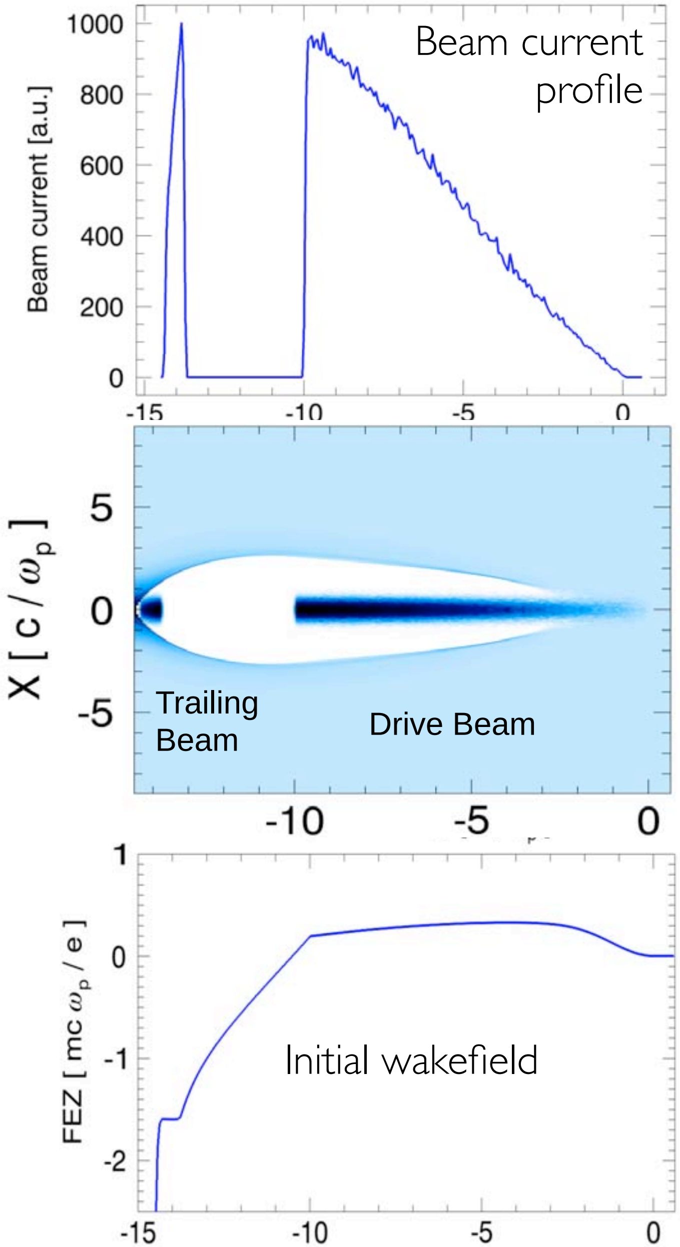




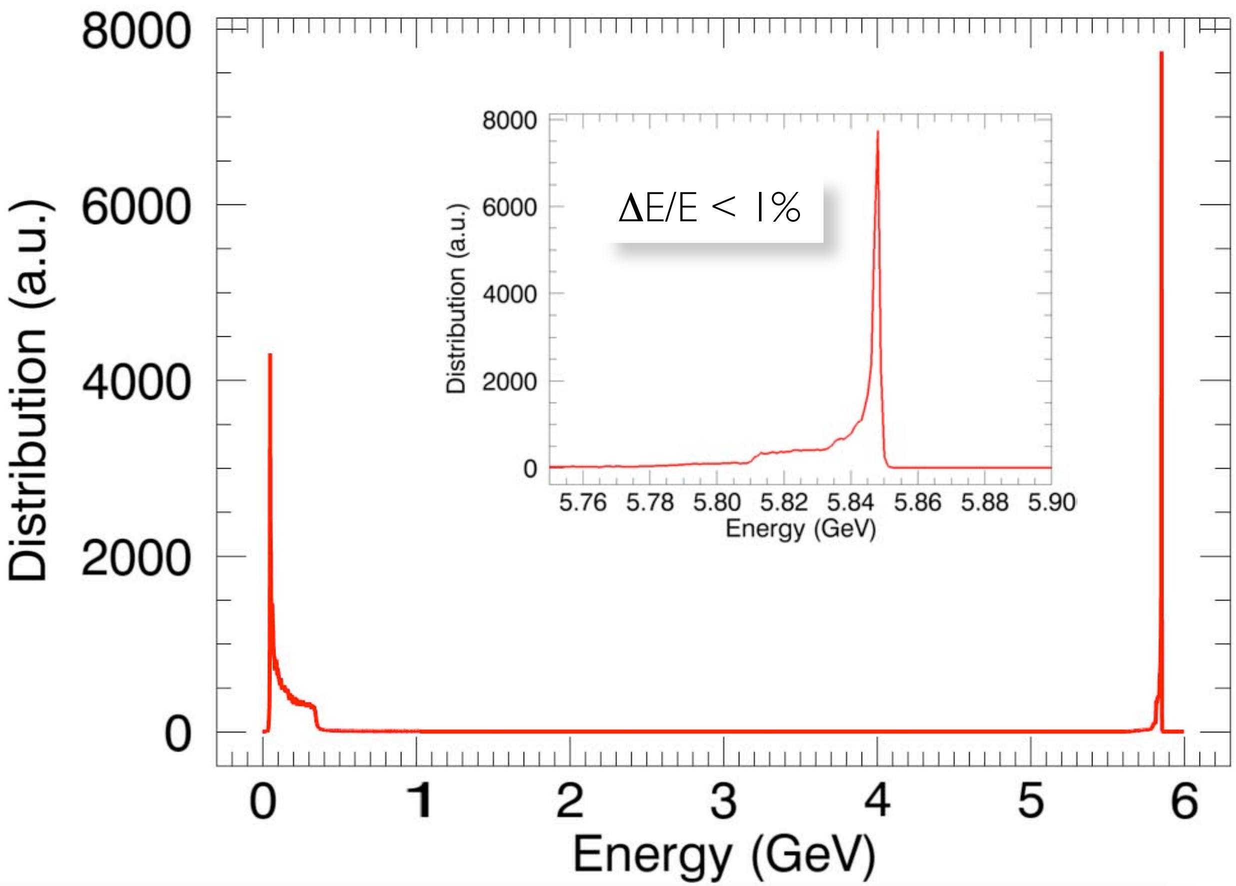
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards ΔE/E ~ 10^{-2} - 10^{-3}
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

See: M. Tzoufras et al, Phys. Plasmas ***16****, 056705 (2009); M. Tzoufras et al, Phys. Rev. Lett.* ***101****, 145002 (2008) and References therein*

Shaped Profile for Transformer Ratio ~ 5



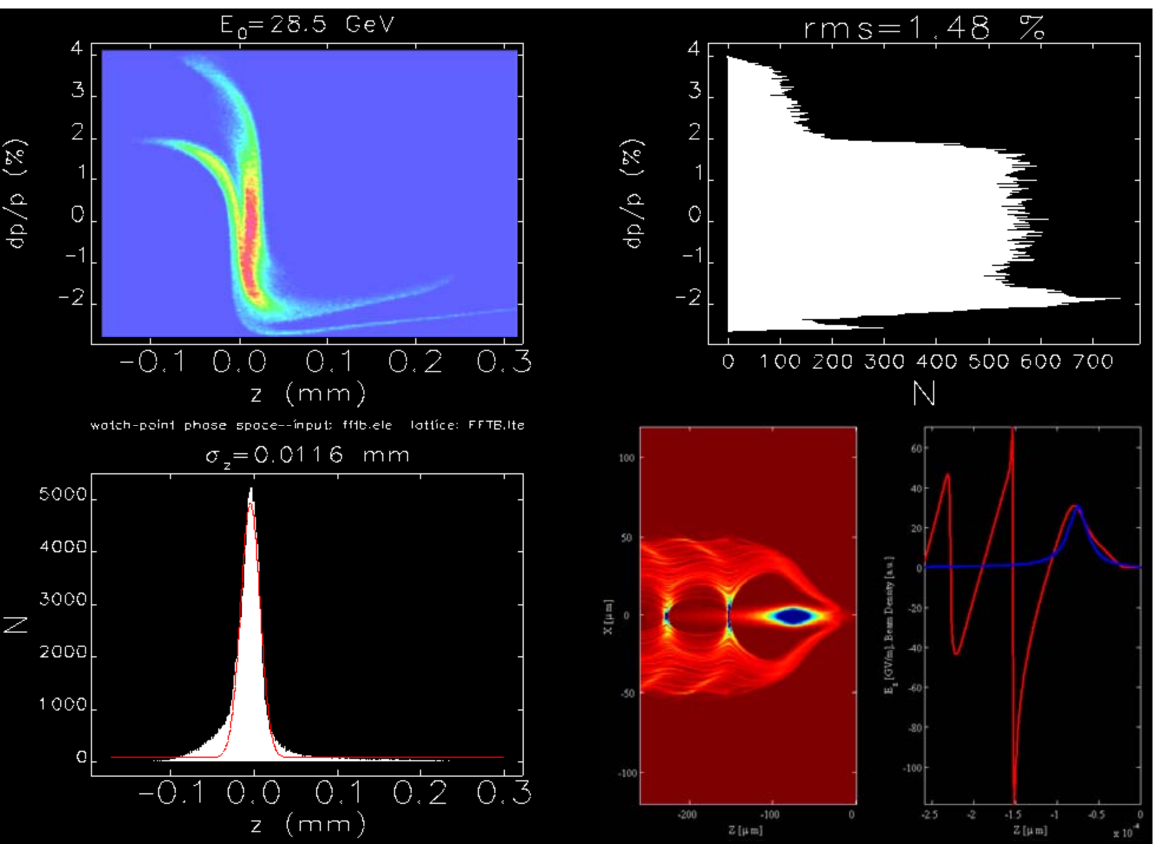
- Application to colliders & X-FELs
- Reduced energy spread
- Higher efficiency (beam power)
- Fewer stages



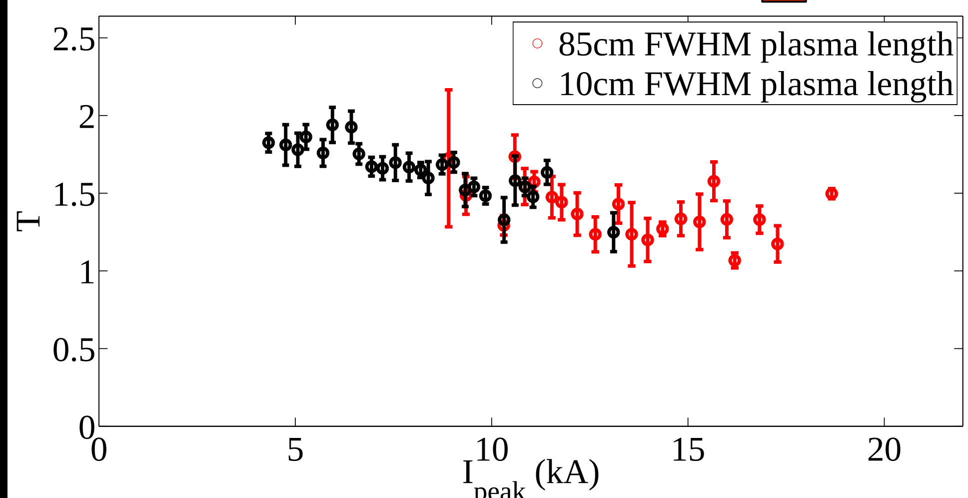
see W. Lu et al "High Transformer Ratio PWFA for Application on XFELs", PAC2009 Proceedings

Transformer Ratio Measured in FFTB

- FFTB measurements of unloaded transformer ratio with Gaussian bunches
  - Head erosion steepens current profile, lowers T in long plasma case
  - For same density, higher Ipk gives fewer particles at detection threshold, also lowering measured T

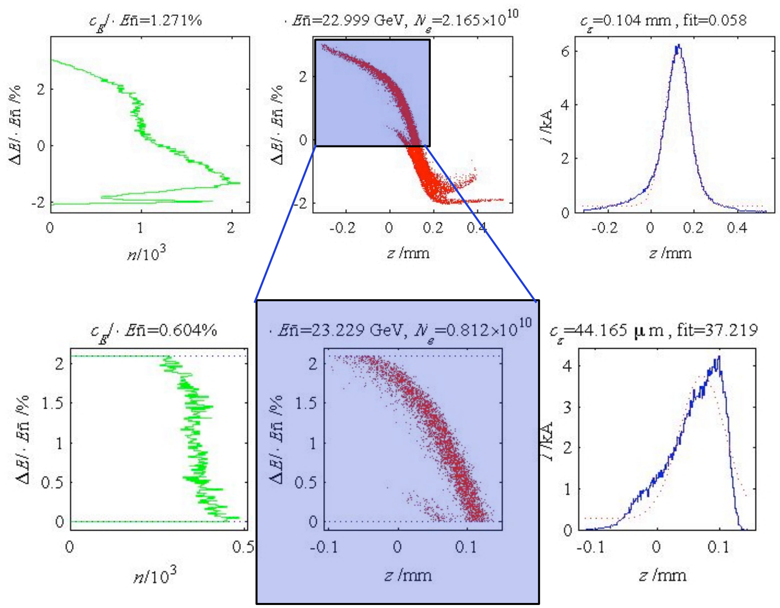


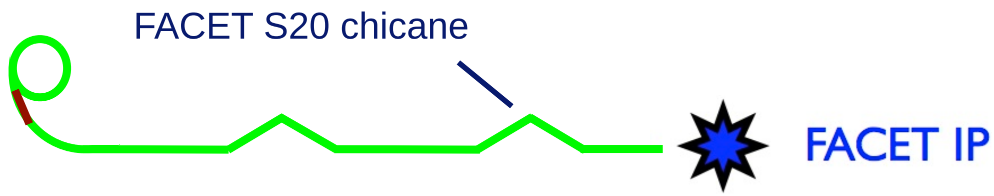
FACET
High T Experiments



I. Blumenfeld et al, submitted for publication

A First Step: High Transformer Ratio Driver

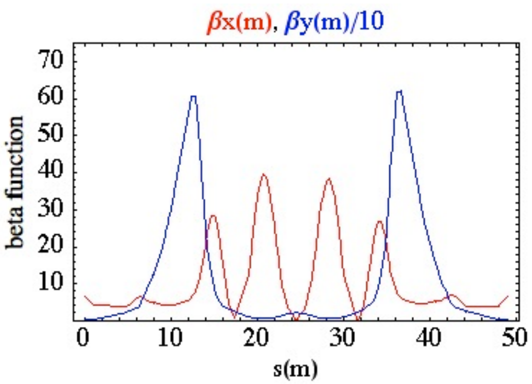


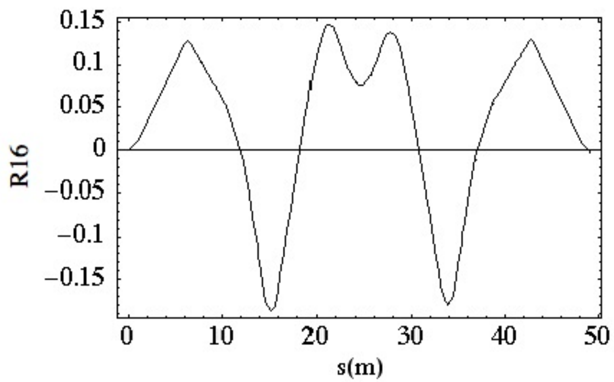


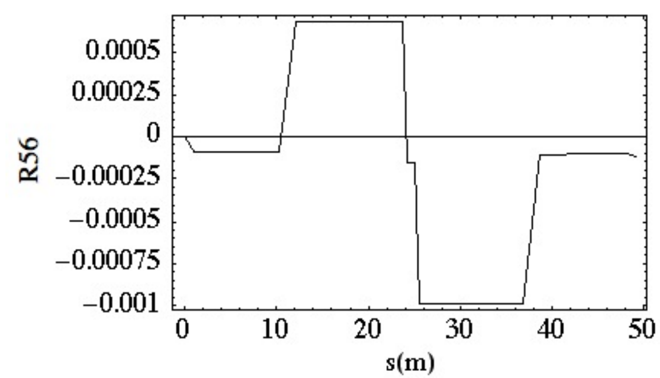
Due to upstream compression, need R56 = T566 = 0 in dogleg
Collimators (part of existing design) can remove low-E tail.

Ramped bunch has L = 200 μm ; Ipeak = 4 kA ; n_b/n_0 = 7
Transformer Ratio = 10 for plasma $n_0 = 3\text{x}10^{17}$ cm^{-3}

Isochronous 'dogleg' configuration: R56 = -0.1mm; T566 = -0.5mm; beta functions well-constrained





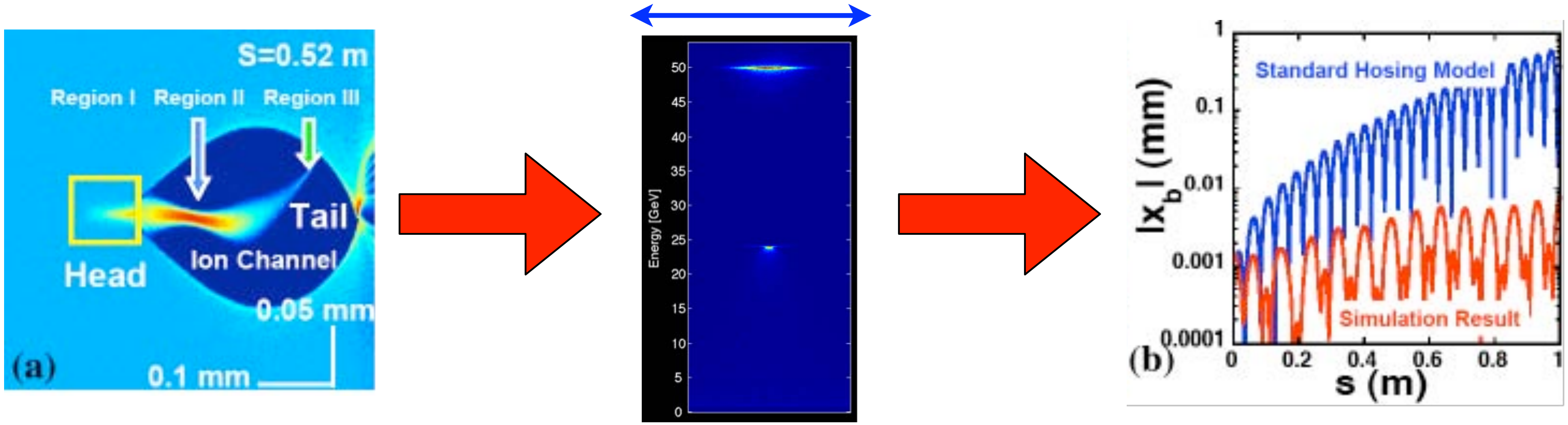


- Open questions: pre-ionized plasma, hosing, witness...

Presentation by J. England in WG4

FACET 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
- Synchrotron Radiation: High energy requires longer plasmas, multiple betatron periods. Large focusing forces, especially on mismatched beams, will lead to uncorrelated energy spread. $\frac{\sigma_E}{E} = \frac{1}{3}\epsilon_N r_e \gamma_{beam}^{3/2} k_p^2$
- Multiple Coulomb Scattering: Not significant for LC emittances until > 5TeV; effects are negligible for light source applications.
- CSR: Coherent synchrotron Radiation during pre/post plasma beam manipulation.

PWFA Questions Motivated by Application

- Challenge for HEP is access to the energy frontier with accelerators of finite footprint and cost with sufficient luminosity
  - High gradient, emittance preservation
- A challenge to photon science community is access to bright, coherent, short pulse x-rays for many more users (LCLS 50:1)
- Opportunity for plasma accelerators in X-FELs
  - Radiation wavelength
  - FEL Parameter
  - 1-D Gain Length
  - Gain bandwidth
  - ‘Radiation Emittance’
  - For good performance:
    - ☑ High energy for short wavelength
    - ☑ Short duration
    - ☑ Beam slice emittance ~ radiation emittance
    - ☐ Slice energy spread less than the bandwidth
    - ➡ Length scale of interest is the cooperation length

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + a_u{}^2 + \gamma^2\theta^2)$$

$$\rho = \left(\frac{a_u}{4\gamma}\sqrt{F_1(a_u)}\,\frac{\Omega_p}{\omega_u}\right)^{2/3}$$

$$L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

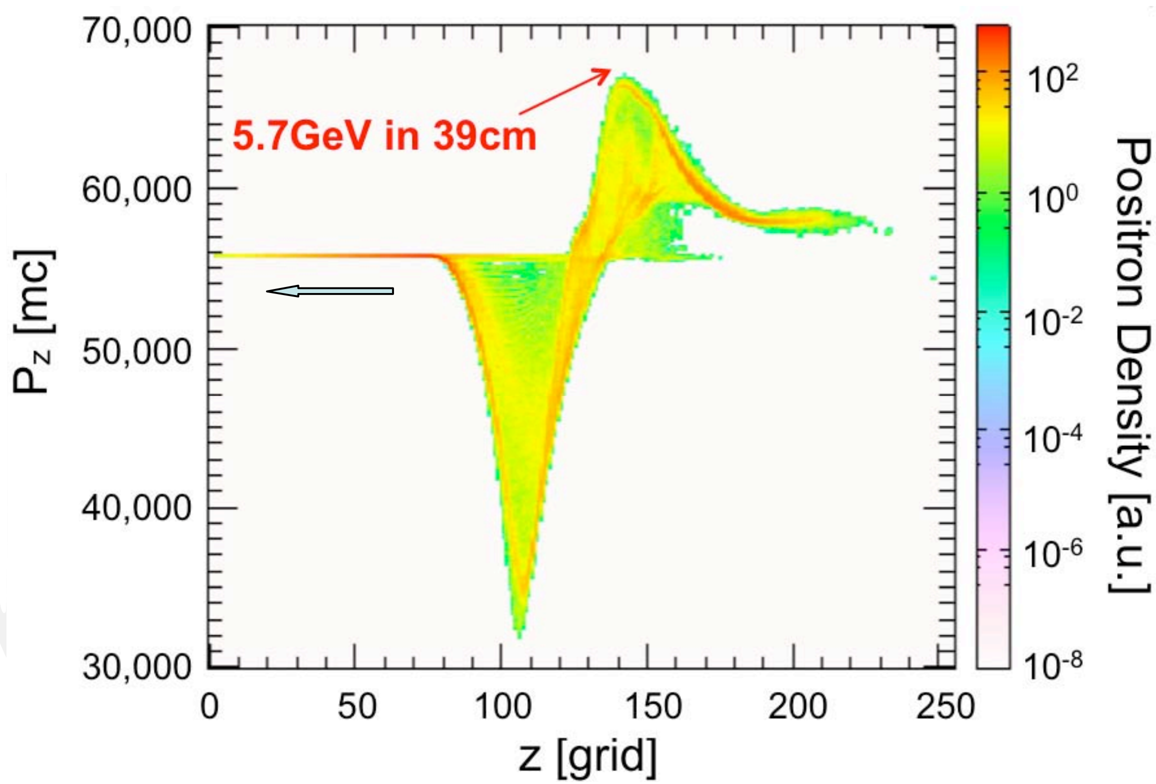
$$\frac{\Delta\omega}{\omega} = \frac{1}{N_u}$$

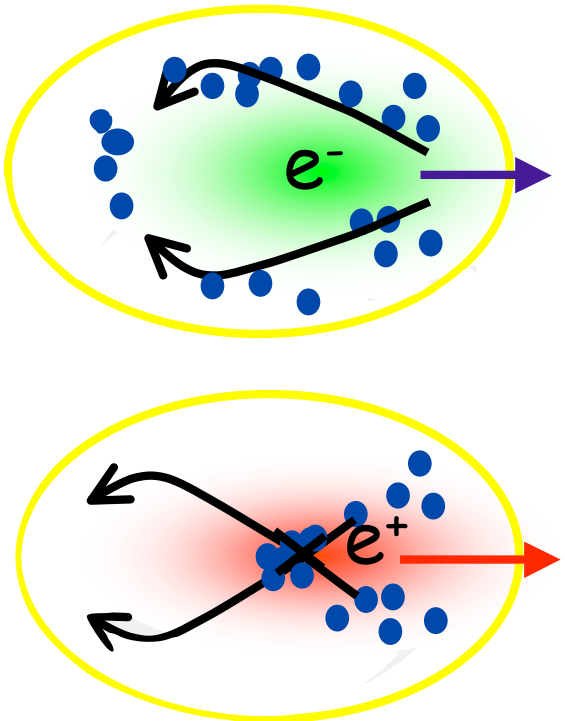
$$\sigma_c\sigma'_c = \frac{\lambda_r}{4\pi}$$

$$L_c = \frac{\lambda_r}{\lambda_u}L_G$$

FACET Will Allow PWFA with Compressed Positron Bunches for the First Time

QuickPIC simulation, σ_z=15μm, N=2x$10^{10}$$e^-$, σ_r=10μm, n_e=2x$10^{17}$$cm^{-3}$, E_0=28GeV

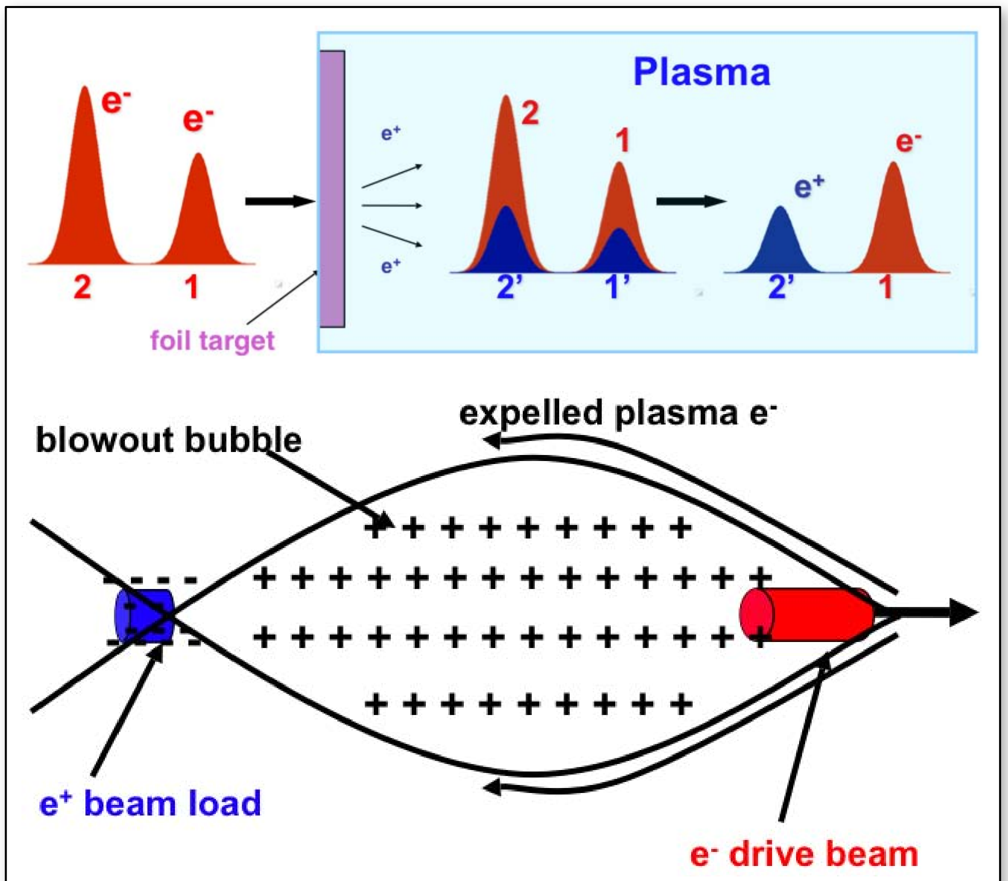


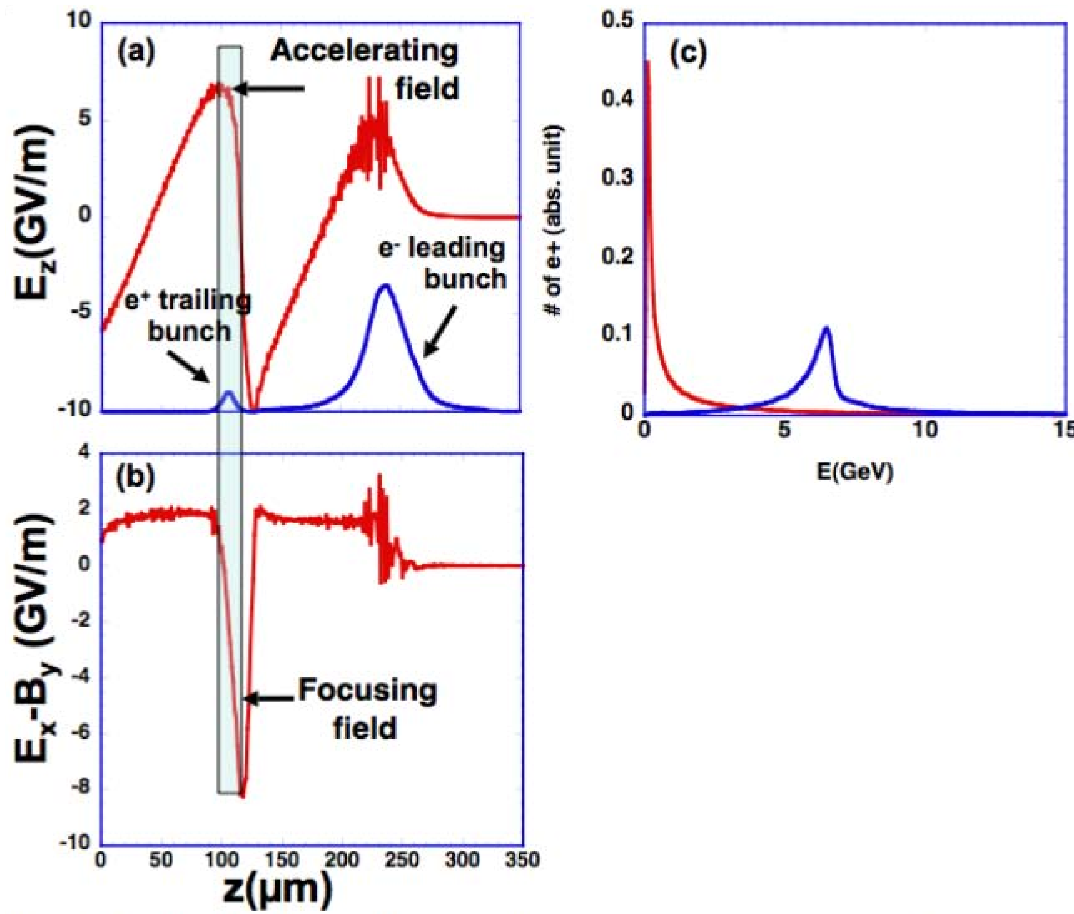


- Accelerating gradient ~ 15GeV/m
- Large energy spread
- Emittance growth (transverse, longitudinal field variations)
- Opportunity for new ideas, original solutions...
- Acceleration of e+ on e- driven wake?

Positron Acceleration in Electron Beam Driven Wakes

- Possible in the weakly non-linear regime
- Generating closely-spaced mixed-species bunches is simplified by creating the positrons in the plasma

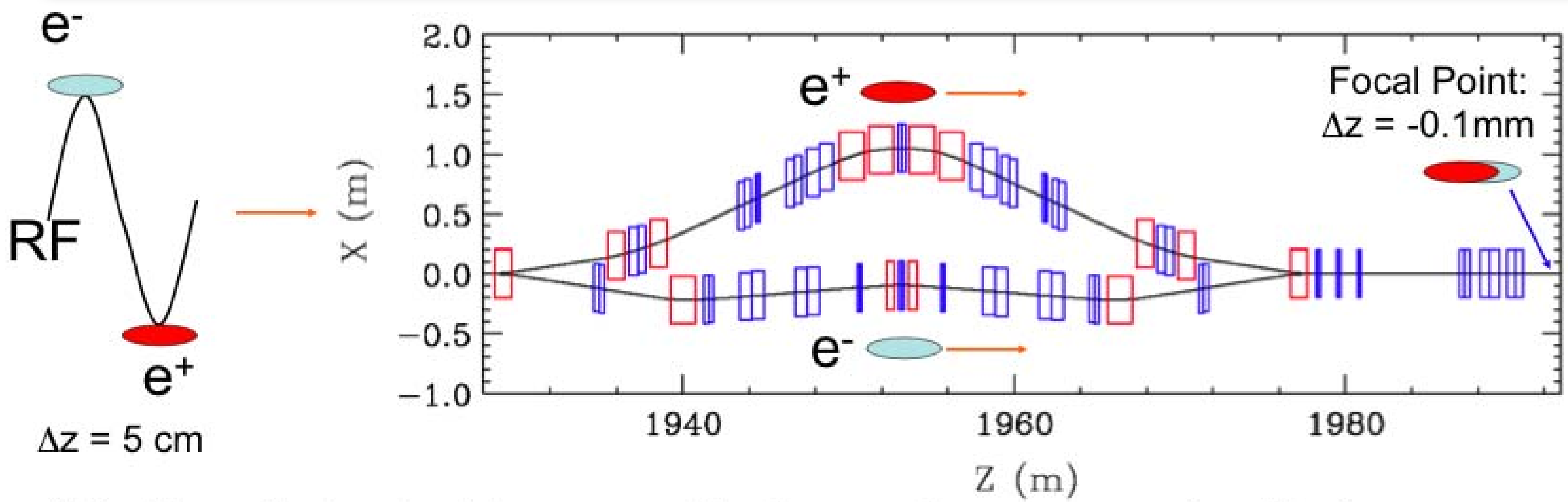




X. Wang et al. *Phys. Rev. Lett.* 101, 124801 (2008)

FACET Design is Forward Looking and Flexible, e.g. Sailboat Chicane Upgrade

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



Opens up many new avenues of research:

- Positron acceleration on electron driven wakes
- PD-PWFA
- Fast magnetic switching with delay between opposite field signs

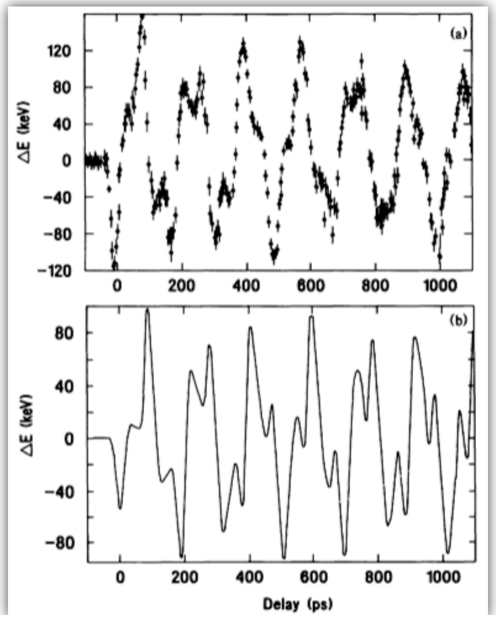
Dielectrics – The Other Wakefield Accelerator

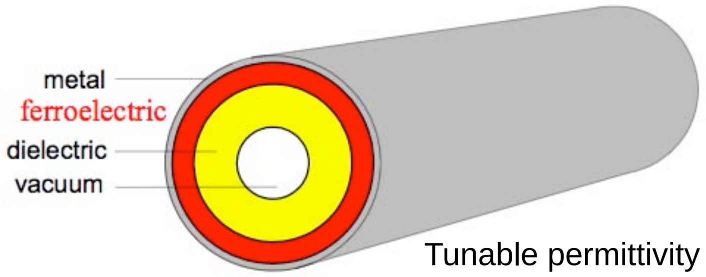
- Material limited breakdown (metal < dielectric < plasma)
- Nearly symmetric response for positrons

DWA Experimental History: Argonne / BNL experiments

- Proof-of-principle experiments
  (W. Gai, et al.)
  - ANL AATF
- Mode superposition
  (J. Power, et al. and S. Shchelkunov, et al.)
  - ANL AWA, BNL
- Transformer ratio improvement
  (J. Power, et al.)
  - Beam shaping
- Tunable permittivity structures
  - For external feeding
  (A. Kanareykin, et al.)

ΔE vs. witness delay



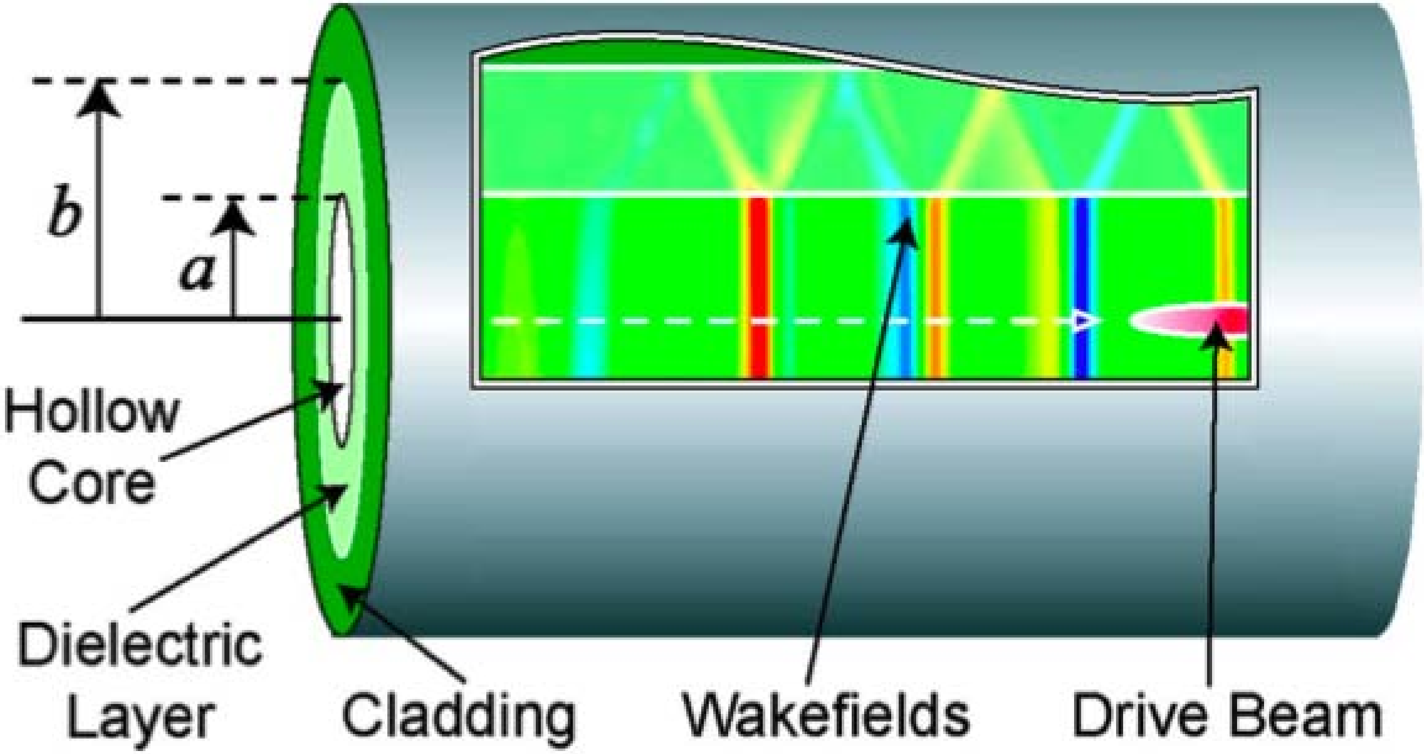


Tunable permittivity

Gradients ~100 MV/m, limited by available beam

FACET Beam is Well Suited for Studying DWA

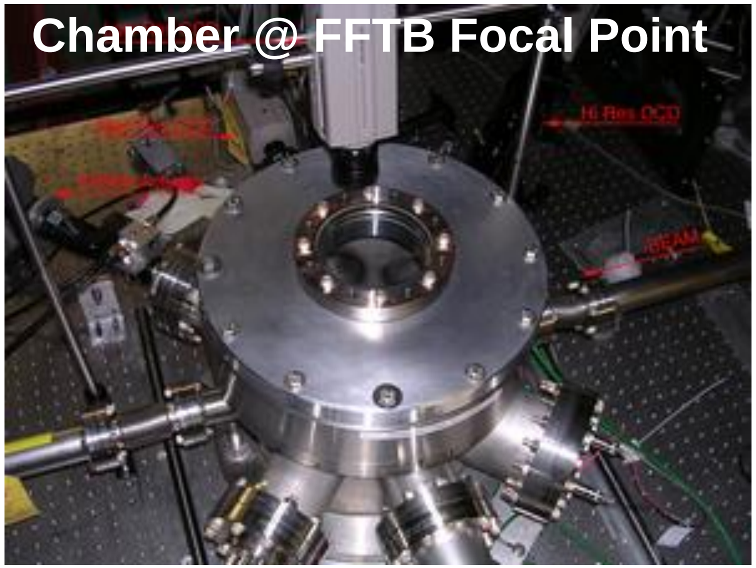
A "drive" beam excites wake-fields in the tube, while a subsequent witness beam (not shown) would be accelerated by the Ez component of the reflected wakefields (bands of color).



$$eE_{z,\mathrm{dec}} = eE_{r,\mathrm{surf}} \frac{\sqrt{\varepsilon - 1}}{\varepsilon} \cong -\frac{4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon - 1}}\varepsilon\sigma_z + a\right]}$$

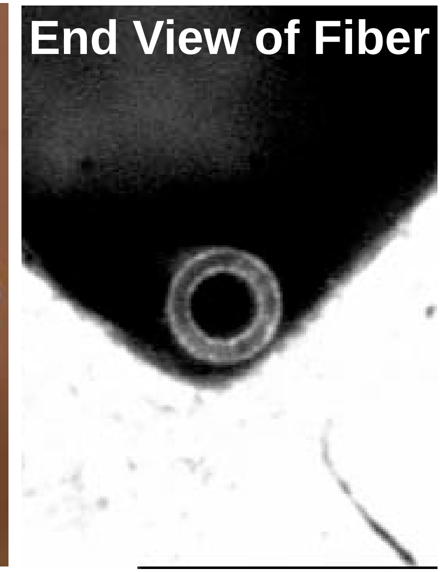
For large wakes want high charge, short bunches and narrow tubes,
e.g. 2E10 e-, σ_z=20μm, Si with 200μm ID get 85GV/m surface fields!

T-481: SLAC/UCLA/USC Collaboration Focused on Damage Threshold of Fused Silica

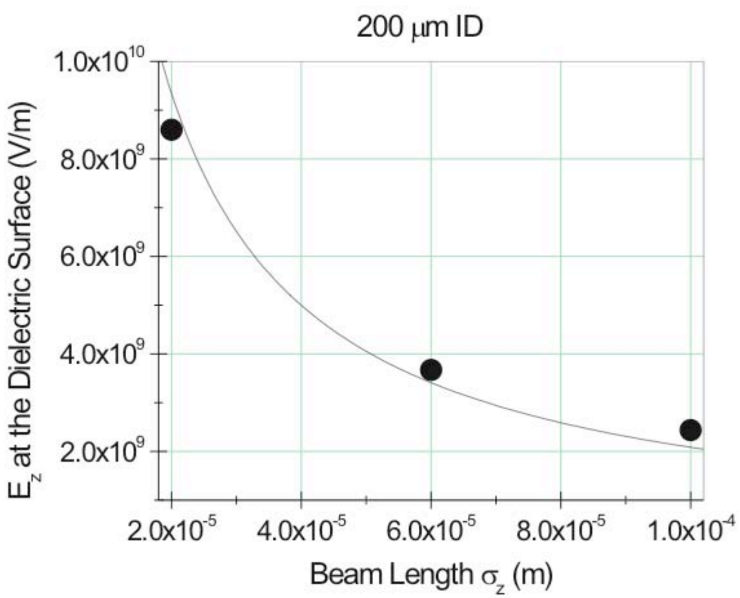


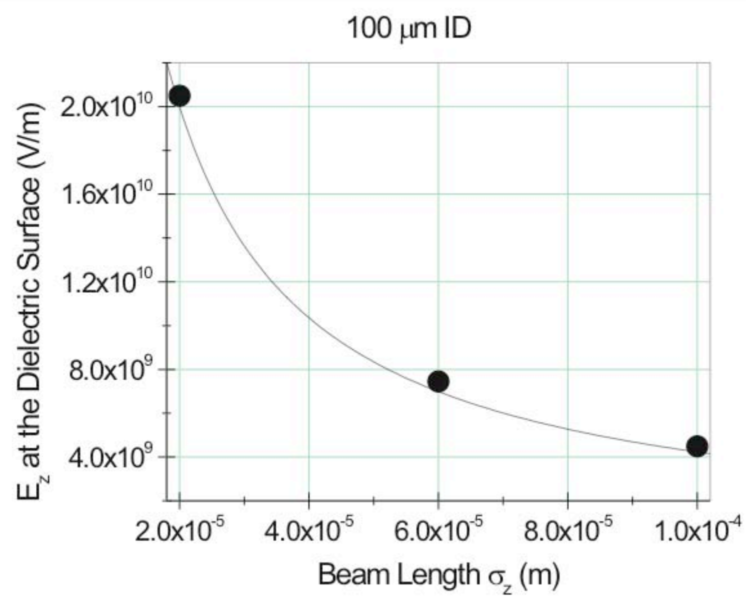
Chamber @ FFTB Focal Point


Dielectric Tube Holder


End View of Fiber

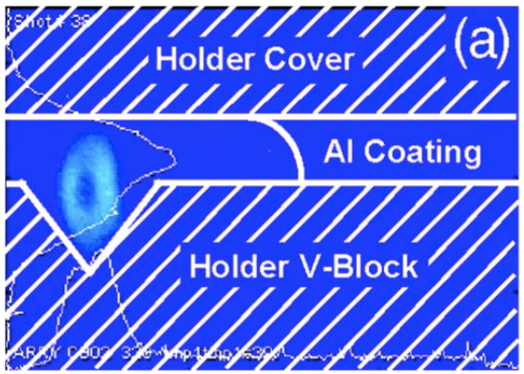
Study Breakdown As a Function of Bunch Length and Fiber Diameter

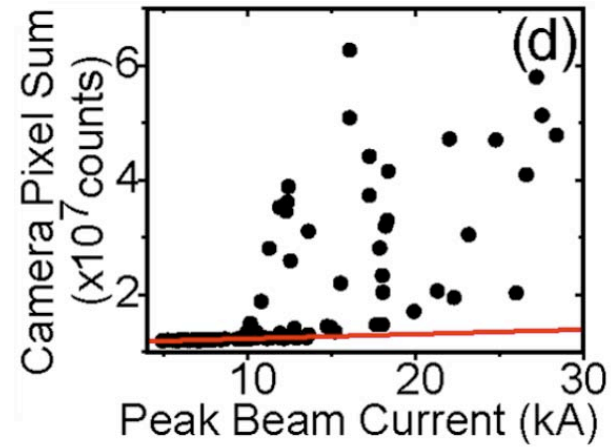




Initial Measurements Indicate High Damage Threshold, but also Yield Surprises

- Breakdown in capillary when Ipeak > 10 kAmps
- Corresponding breakdown threshold:
  - ~14 GV/m on the dielectric surface and ~6 GV/m on axis



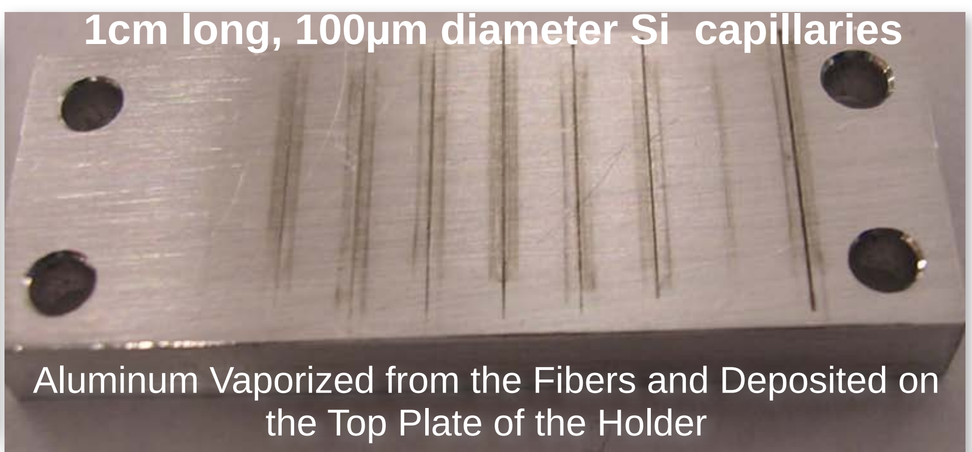


M.C. Thompson et al Phys. Rev. Lett. ***100****, 21480 (2008)*

- Aluminum cladding vaporized! Fused silica substantially intact.

Next steps for beam driven DWA:

- Requires specialized facilities (FACET early 2011)
- Replace metallic outer layer with dielectric
- Compare CVD-diamond fibers with Si
- Increase tube length ~meter and measure change to beam energy spectrum



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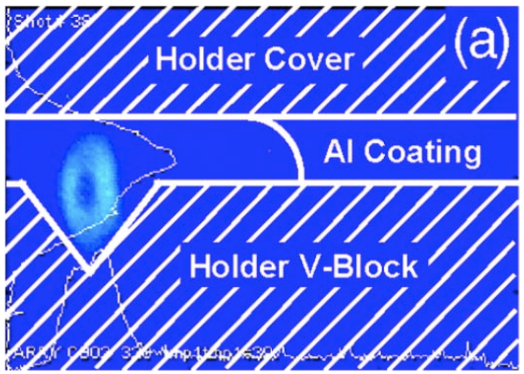

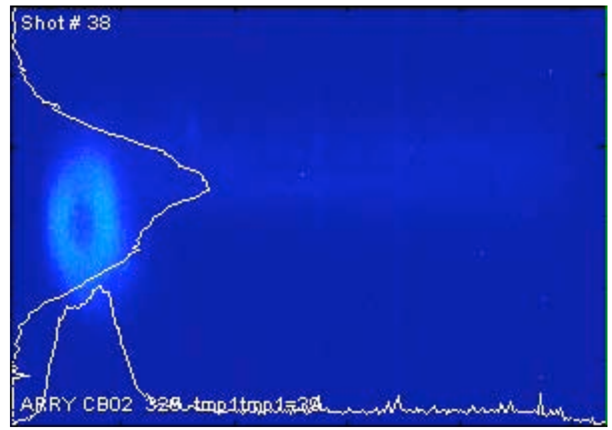

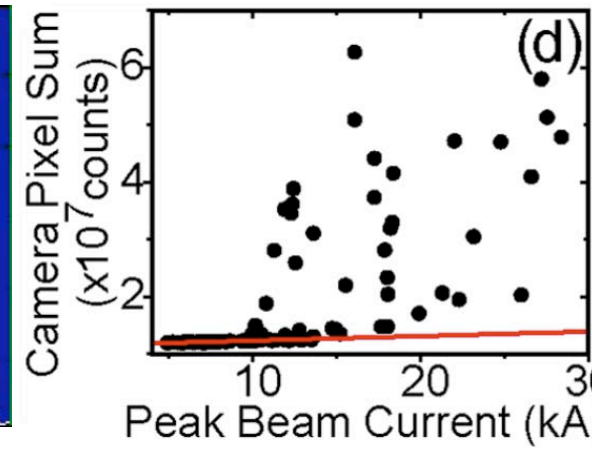

M.C. Thompson et al Phys. Rev. Lett. ***100****, 21480 (2008)*

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- Increase tube length ~meter and measure change to beam energy spectrum

1cm long, 100μm diameter Si capillaries

Aluminum Vaporized from the Fibers and Deposited on the Top Plate of the Holder

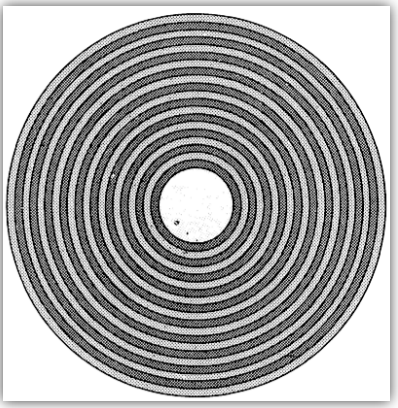
DWA: High-gradient Acceleration

T-481 group (SLAC/UCLA/USC) has formed a collaboration to continue this research at FACET

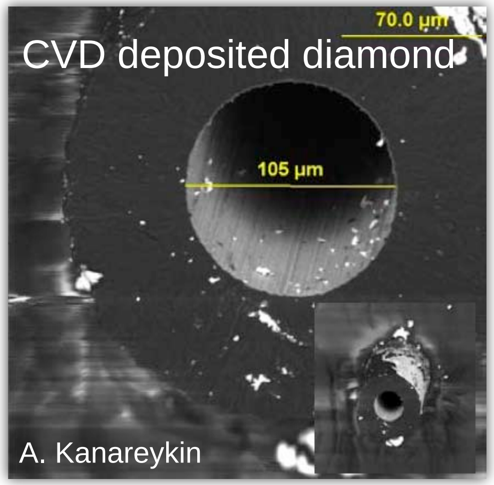
First Steps:

- Complete the breakdown studies (dielectrics into plasmas!)
  - Explore parameter space (fiber diameter(s), bunch length)
  - Alternate cladding
  - Alternate dielectric (e.g. CVD diamond from Euclid Tech Labs)

σ_z	≥ 20 µm
σ_r	< 10 µm
E	23 GeV
Q	3 nC



Bragg fiber

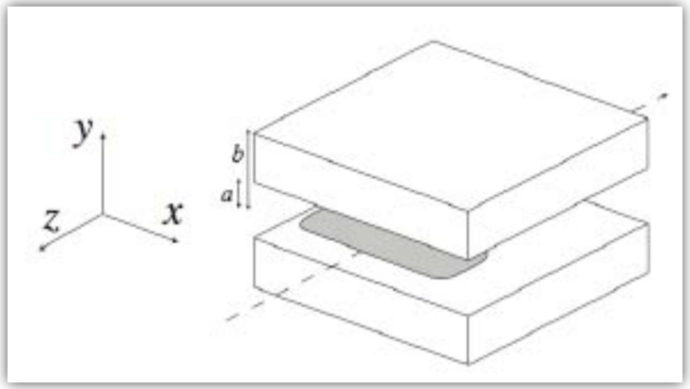


- Coherent Cerenkov measurement
  - Total energy gives information on the fields
  - Harmonic content sensitive to bunch length

Alternate structure geometries
Connect to laser driven dielectric structures

❑ Slab Structures

- Suppresses transverse wakes *
- ...at the expense of lower long wakes
- >600MeV/m test cases

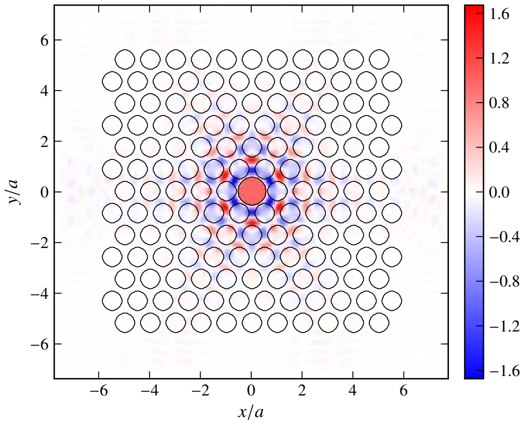


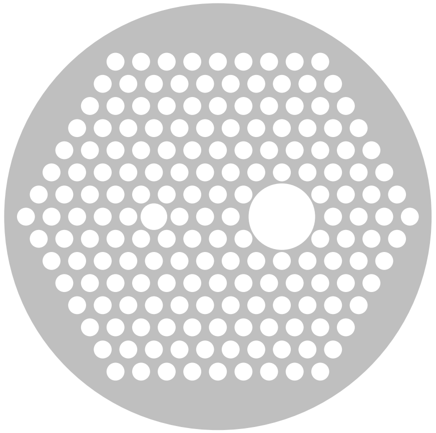
Energy	σ_x	σ_z	σ_y	$2a$	$2b$	Q	ε
25 GeV	500 um	20 um	10 um	125 um	1100 um	3 nC	5.5

*A. Tremaine, J. Rosenzweig, P. Schoessow Phys. Rev. E 56, 7204 (1997)

❑ Photonic Bandgap Structures (PBG)

- Confine a synchronous mode in all-dielectric structure — no metal breakdown
- Confines only in narrow range of frequencies — HOMs automatically damped
- Explore transformer ratio enhancement by “tunneling” through PBG lattice from low-impedance to high-impedance guide

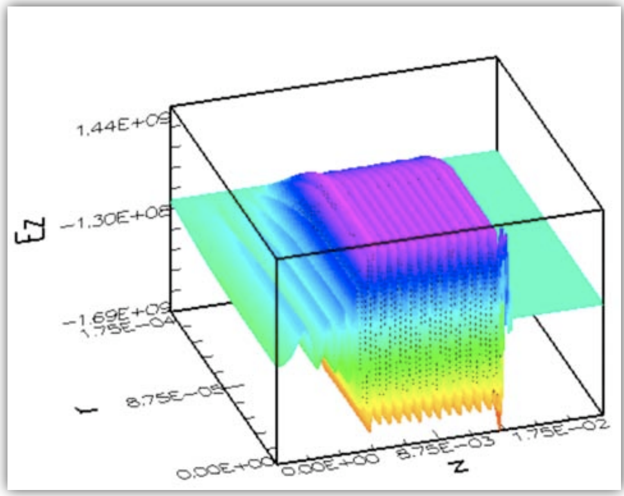


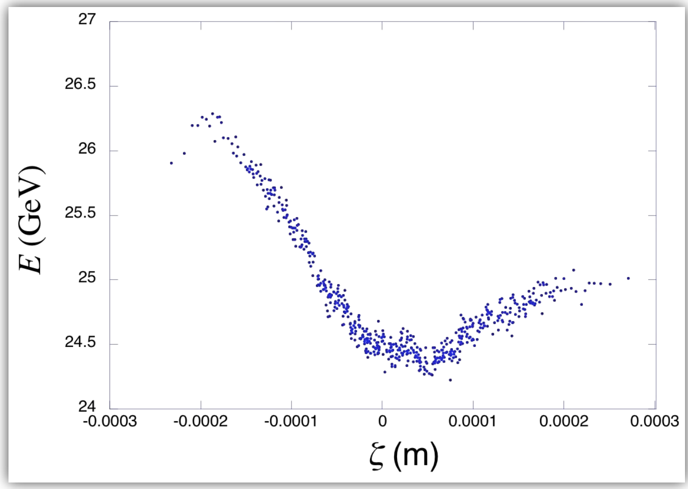


DWA: High-gradient Acceleration

Next Steps:

- Observe Acceleration!
  - Longer tube lengths (10-30cm)
  - Scale beam parameters to stay below breakdown threshold
  - “Moderate Gradients” ~ a few GeV/m
- Scale to 1-meter Long Structures
  - Alignment, transverse wakes, BBU...
  - Combination of scaled beam parameters and external focussing
- Alternate Species – Positrons
  - Polarity of electric field pulls electrons out of material
  - Breakdown could be enhanced
  - Unique opportunity SLAC (FACET)





Momentum distribution after 33 cm (OOPIC)

Summary

- FACET will provide high energy density electron and positron beams unique in the world (23GeV, 3nC, >20kA, <10μm) for experiments in many fields
- Beam parameters are well suited for next generation PWFA experiments but also flexible and adaptive to a wide range of users
- Successful first users workshop March 2010, already envision many experiments
- Many open questions in wakefield acceleration – look forward to good discussions in WG 4, hopefully new ideas, new experiments and new users
- Open for first round of proposals due July 15, 2010
- FACET construction is expected to finish in Spring 2011 with accelerator and beam commissioning soon after.
- The experimental program will begin in the Summer of 2011
- We are hiring! Looking for a staff scientist & postdocs

http://facet.slac.stanford.edu/