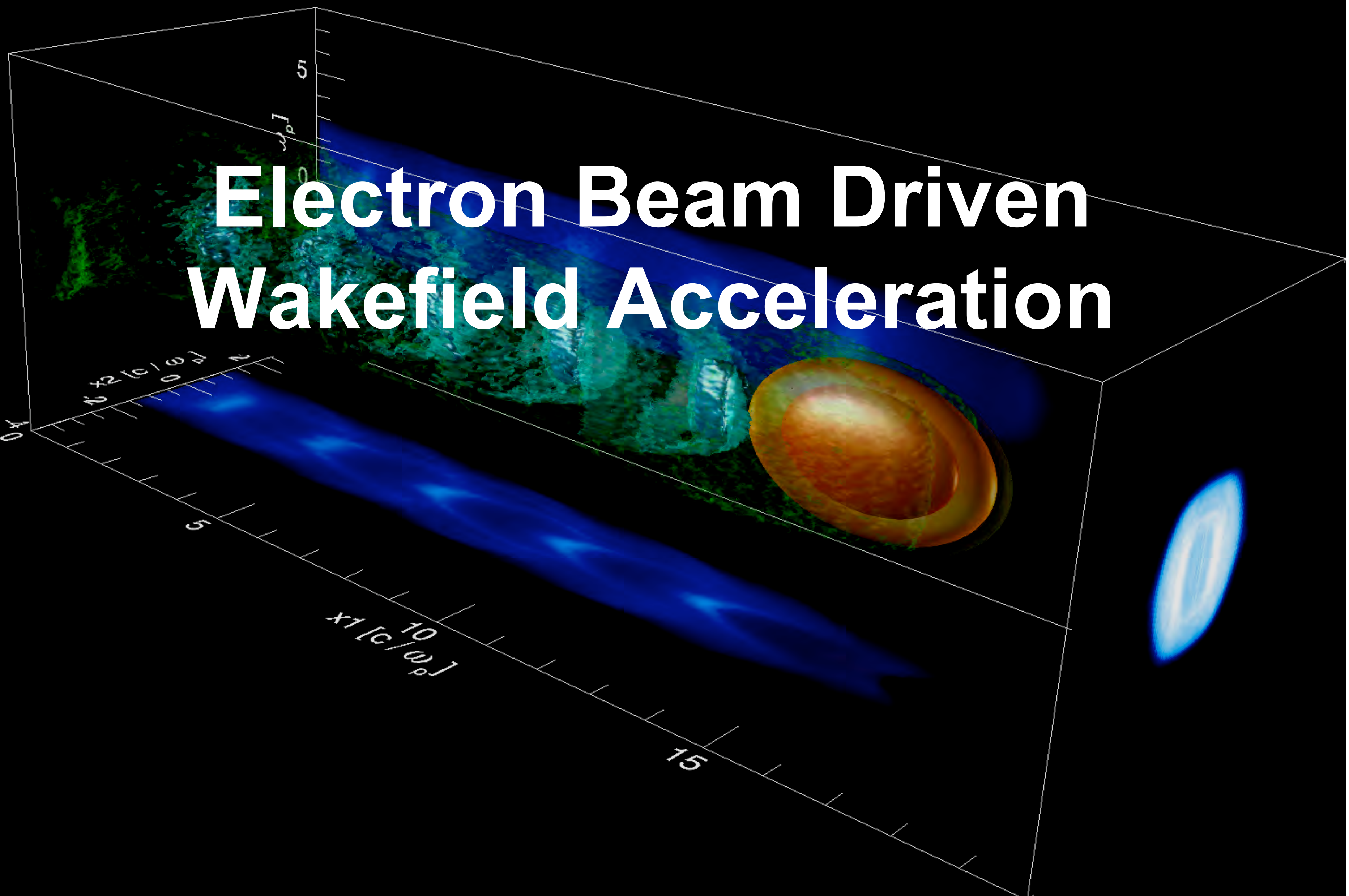
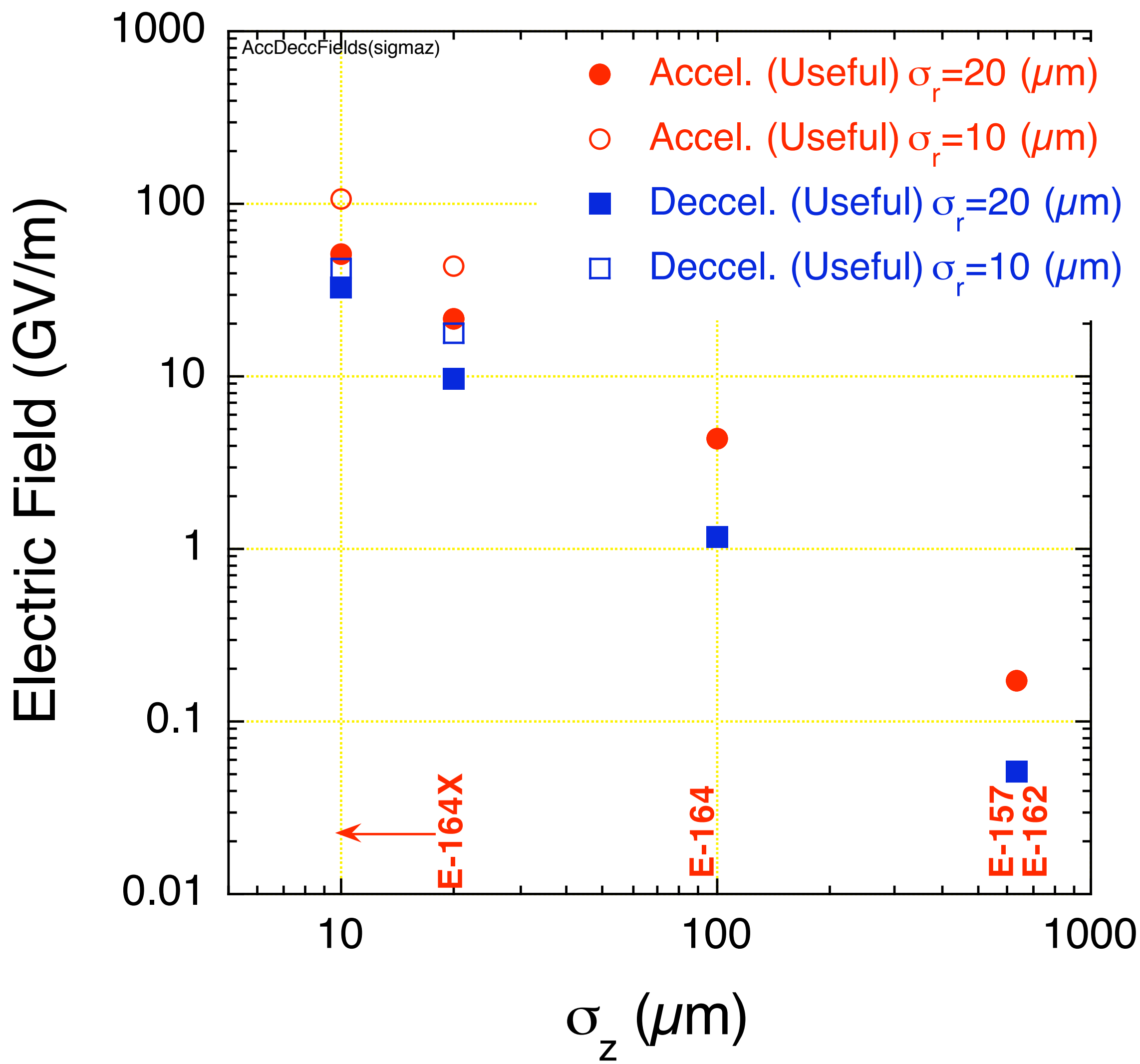
Electron Beam Driven Wakefield Acceleration



M.J. Hogan, ICFA Workshop on Physics and Application of High Brightness Beams - Erice, Sicily 2005

Wakefield Acccelerators Have Promising Potential

Electron Beam Driven Wakefield Accelerators Have the potential to deliver accelerating gradients many orders of magnitude larger than conventional metallic structures

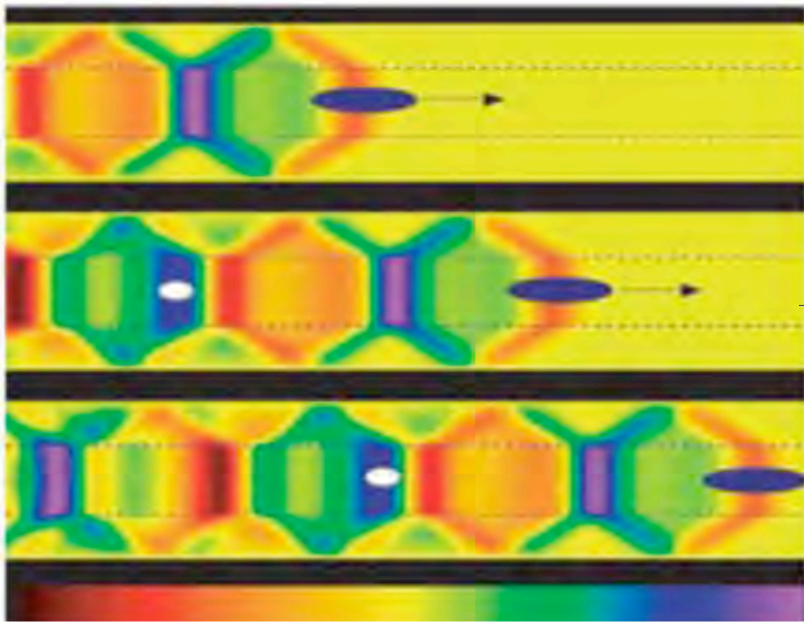


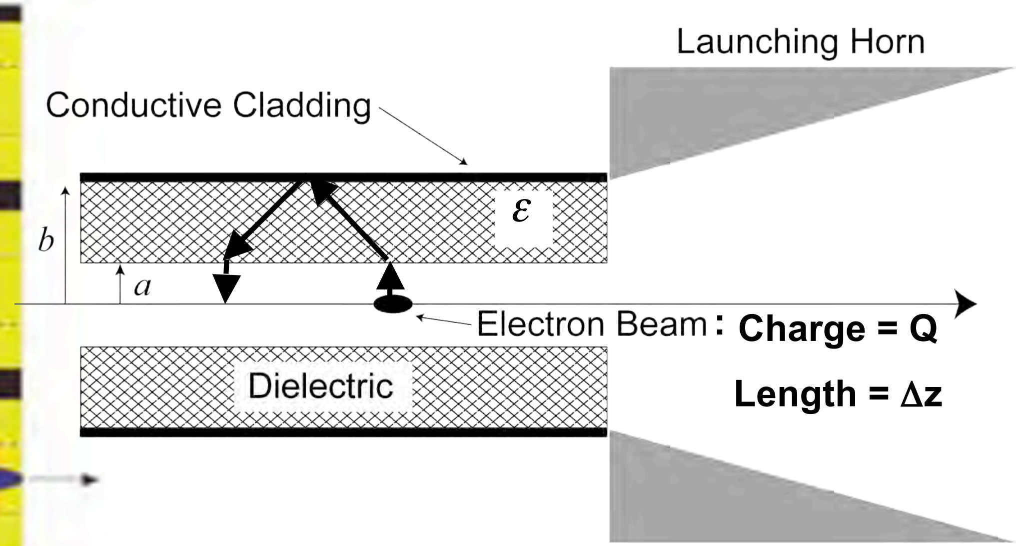
Many Issues Being Addressed by Experiments:

	Dielectric	Plasma
Material Issues	• Breakdown of the dielectric • Breakdown of the dielectric-conducting boundary surface ANL AWA UCLA/SLAC T-481	• Long, uniform high-density plasma sources can be difficult • Relativistic plasma-electrons, Ion motion BNL ATF PWFA UCLA/USC/SLAC E-164
Optimum Drive Beam	• High charge (100nC) • Short bunch lengths (~100fs) • Pulse trains with specific format ANL AWA	• Short bunch lengths (~100fs) • Pulse trains with specific format UCLA/USC/SLAC E-164 BNL ATF PWFA BNL ATF Stella-LWFA

Problems relating to the witness beam are still next generation (although near term) experiments

Dielectric Wakefield Accelerator (DWA)





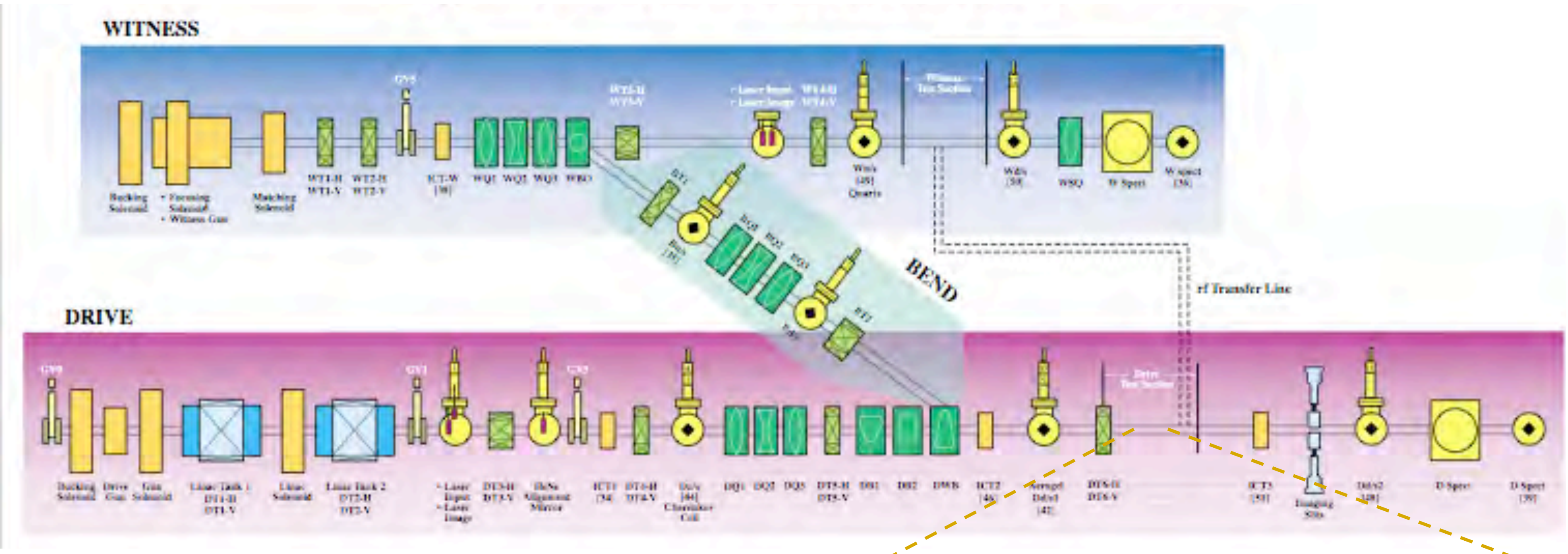
On Axis Accelerating Field & Dielectric Surface Field:

$$E_{z,vac} = \frac{4Q}{a\left[2\frac{\varepsilon}{\sqrt{\varepsilon - 1}}\Delta z + a\right]} \xrightarrow{\Delta z << a} E_{z,vac} = \frac{2Q}{a^2}$$

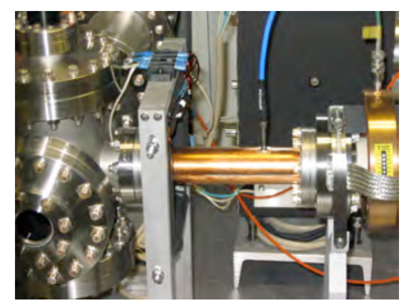
$$E_{r,surface} = \frac{1}{\epsilon_0}\frac{Q}{(2\pi)^{3/2} a\sigma_z + \frac{\sqrt{\varepsilon - 1}}{\varepsilon}\pi a^2}\left[\frac{\mathrm{V}}{\mathrm{m}}\right]$$

Want:
- High Charge
- Short Bunches
- Narrow Tubes

Argonne Wakefield Accelerator



15 GHz structure

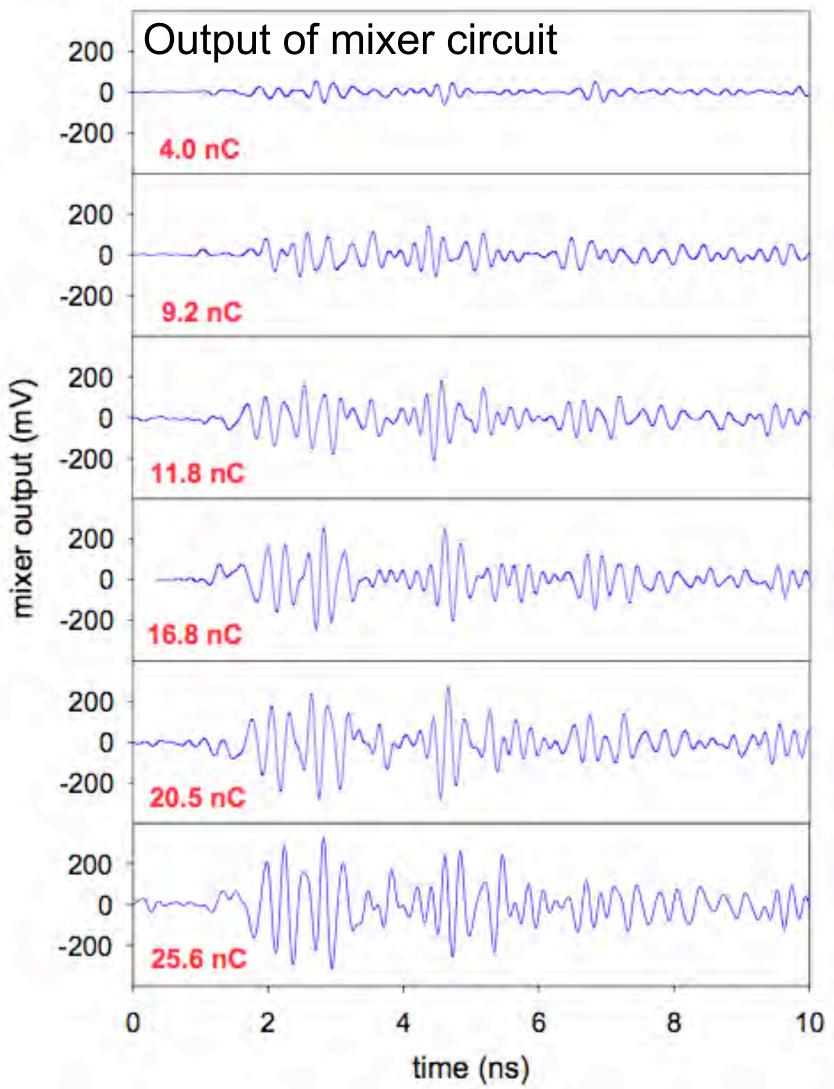


Parameters of recent experiment:

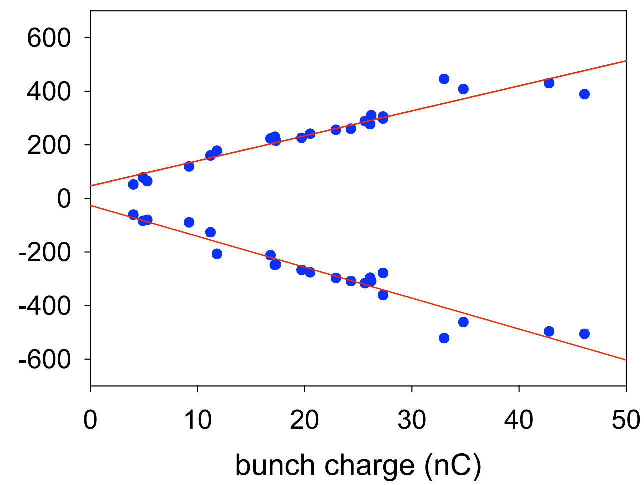
- Cylindrical ceramic tube (cordierite)
- Inner radius: 5 mm, Outer radius: 7.5 mm
- Dielectric constant: 5
- Length: 102 mm
- Standing-wave structure
- Field probe to sample the field (-60 dB)
- RF mixer, down convert from 15 GHz to 5 GHz, analyze with high bandwidth scope

Argonne Wakefield Accelerator

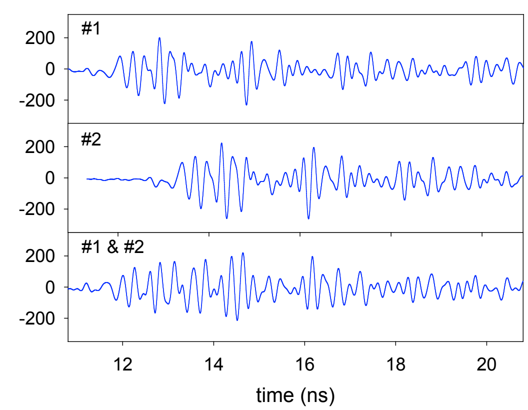
Recent 15 GHz Wakefield Measurements



~30 MV/m gradient.
No signs of breakdown!

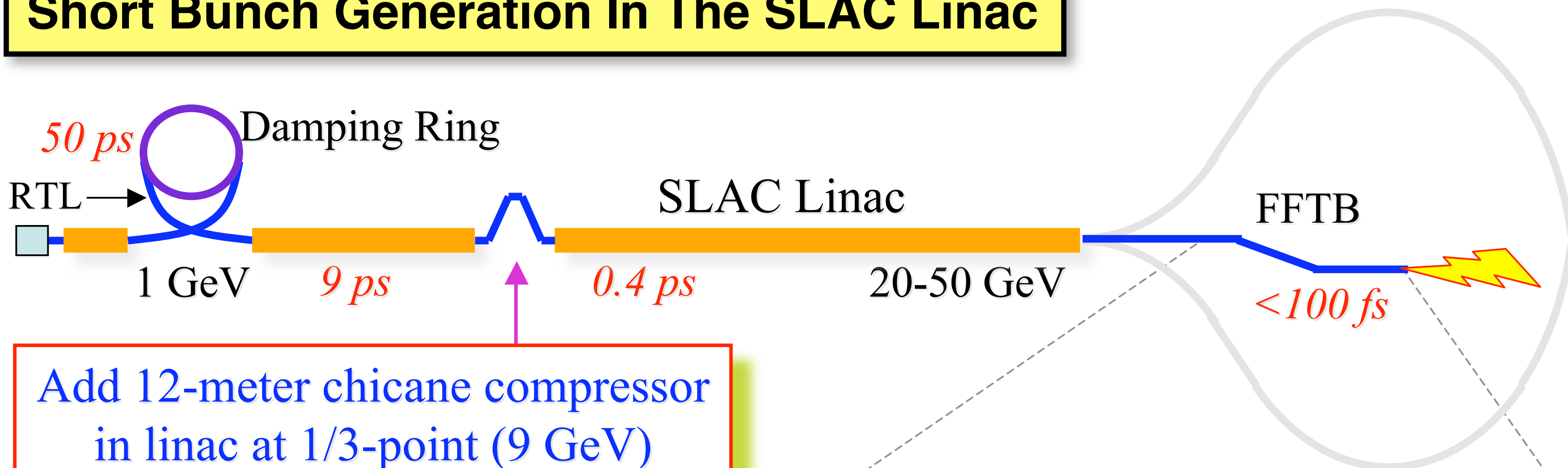


Excitation by single bunch and Two bunches separated by 1.5 ns:

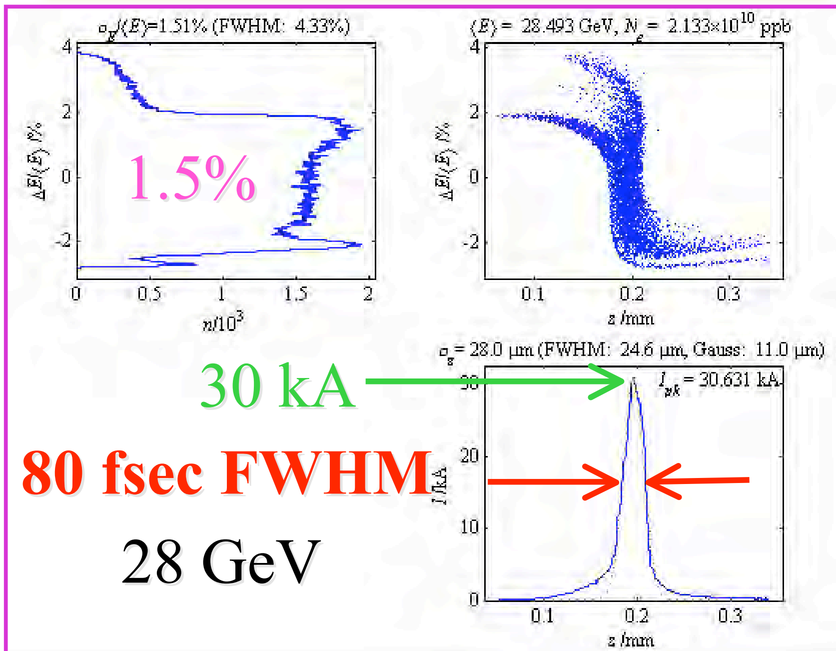


UCLA/SLAC Ultra-High Gradient DWA (T-481)

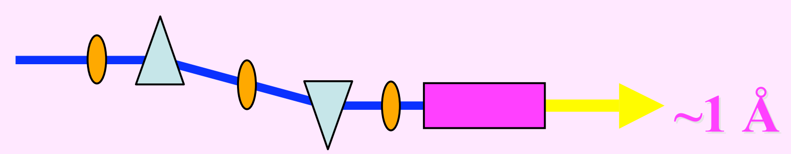
Short Bunch Generation In The SLAC Linac



Add 12-meter chicane compressor
in linac at 1/3-point (9 GeV)

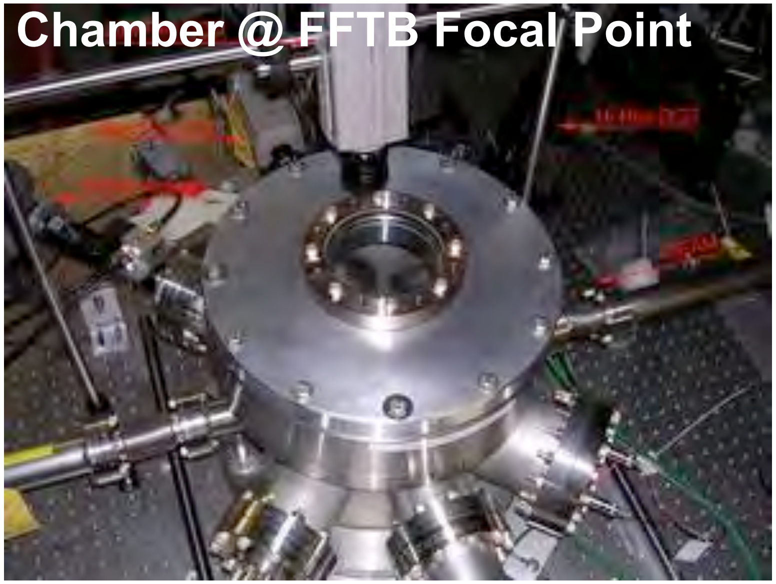


Existing bends compress to **<100 fsec**

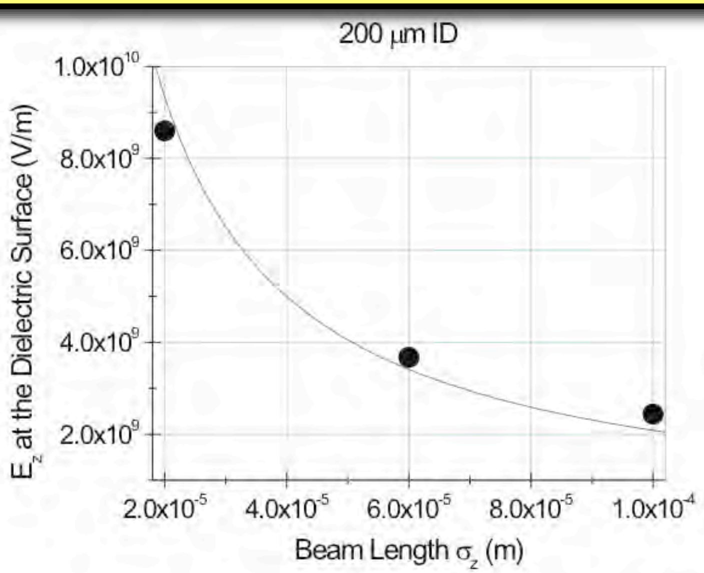


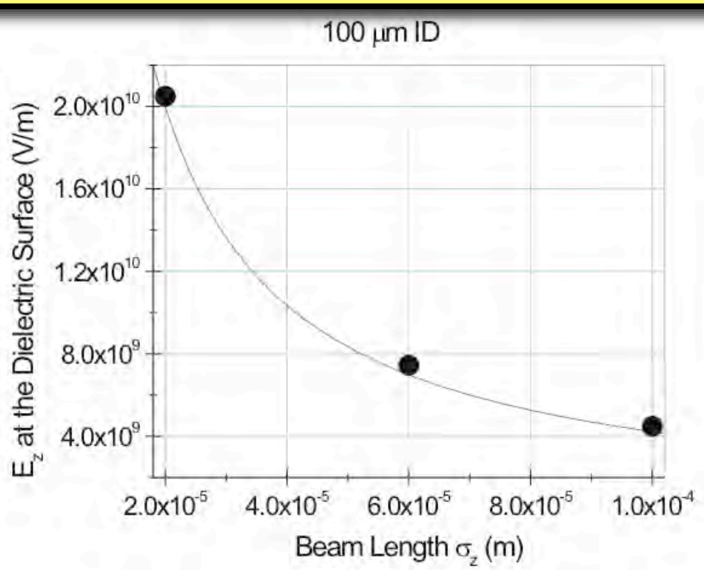
Adjust Bunch Length with
Linac Phase and FFTB R56

UCLA/SLAC Ultra-High Gradient DWA (T-481)



Study Breakdown As a Function of Bunch Length and Fiber Diameter



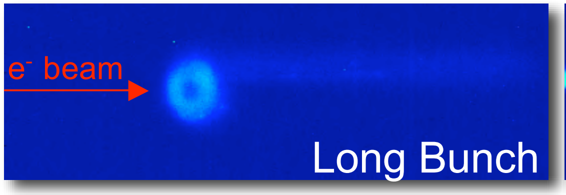


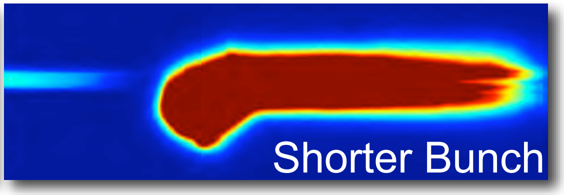
Phase One of the Experiment

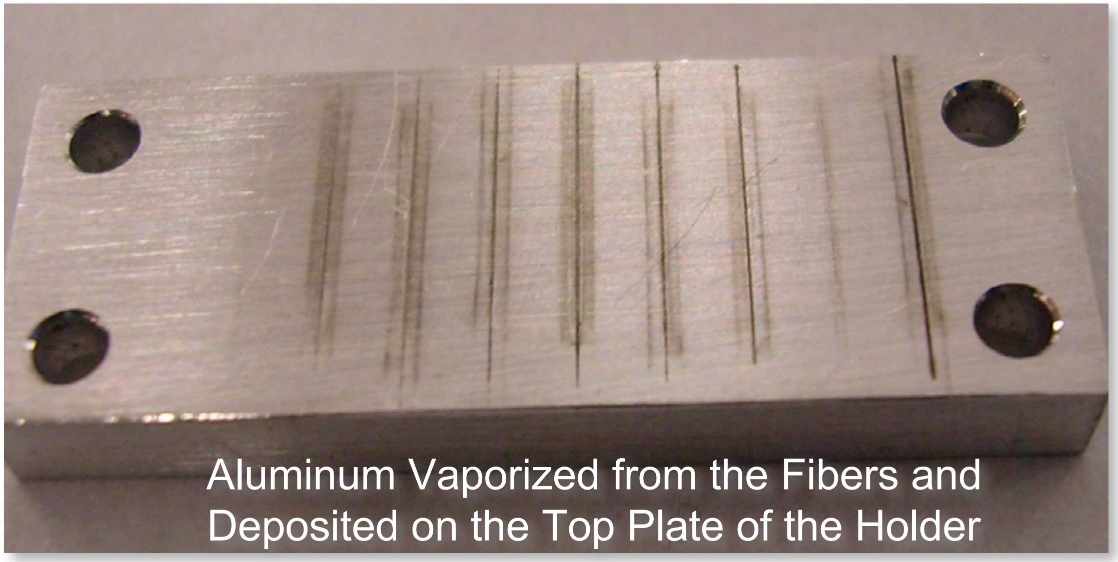
The first run of the experiment occurred in Aug 2005. The objective of the run was to examine breakdown thresholds. Direct Measurements of CCR will be attempted in the next run.

Major Observations:

- A sharp increase in visible emission from the capillaries near the mid-range of beam current, probably indicating breakdown.
- Principle form of damage to the dielectric wake structures appear to be vaporization of the aluminum cladding. The fused silica appeared substantially intact.





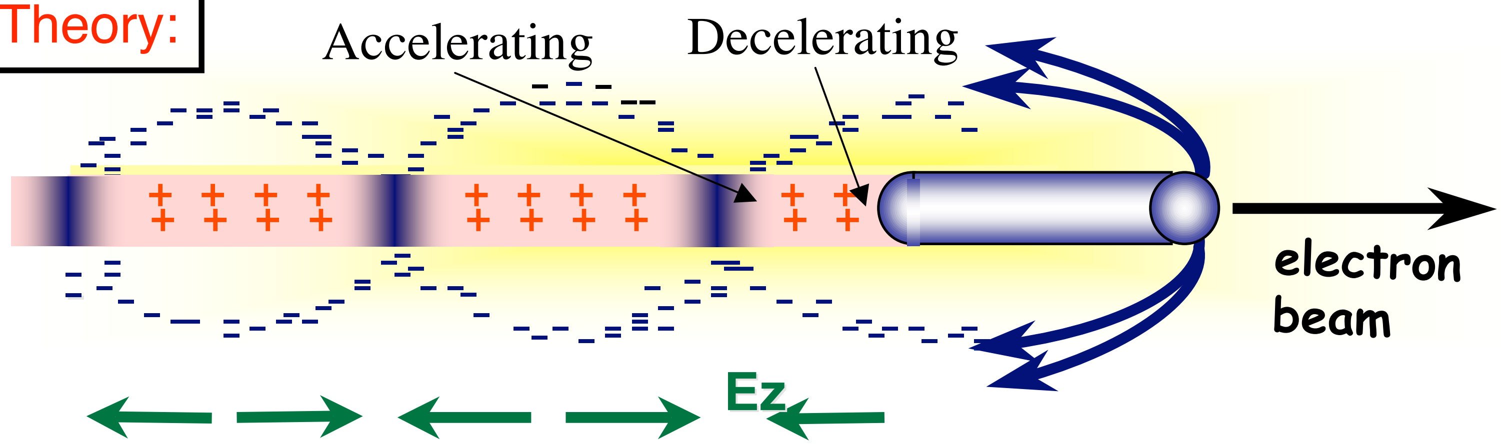


See Gil Travish Talk in WG4(?)

Plasma Wakefield Accelerator (PWFA)

- Space charge of drive beam displaces plasma electrons
- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)

Linear PWFA Theory:



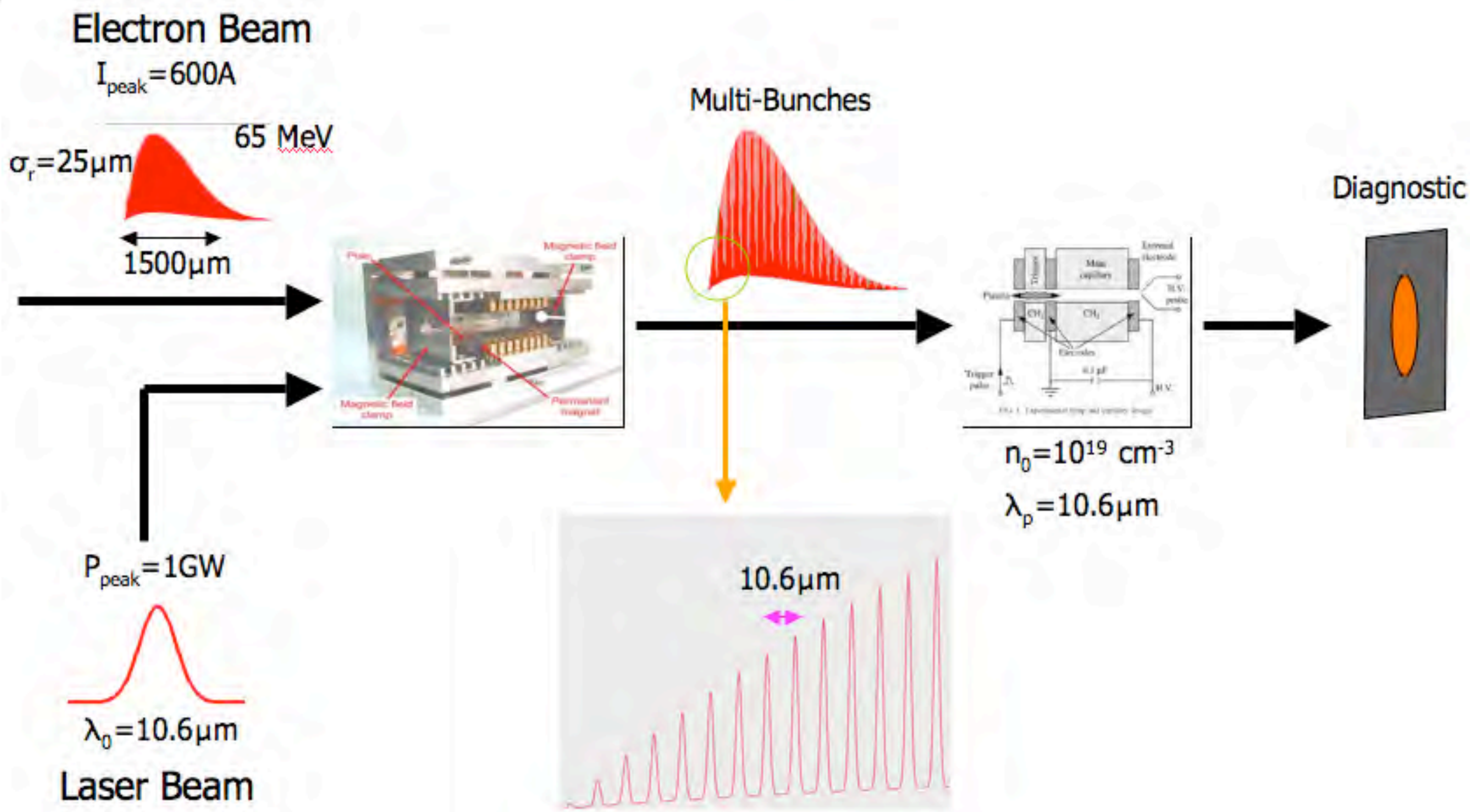
- $E_{z,linear} \propto \frac{N}{\sigma_z^2}$ ⇨ Short bunch!
- For $k_p\sigma_r << 1$ and $k_p\sigma_z \cong \sqrt{2}$ or $n_p \propto \frac{1}{\sigma_z^2}$

E_z: accelerating field
N: # e^-/bunch
σ_z: gaussian bunch length
k_p: plasma wave number
n_p: plasma density
n_b: beam density

- 2D/3D PIC Simulations have born out this dependence (snow plow etc…)

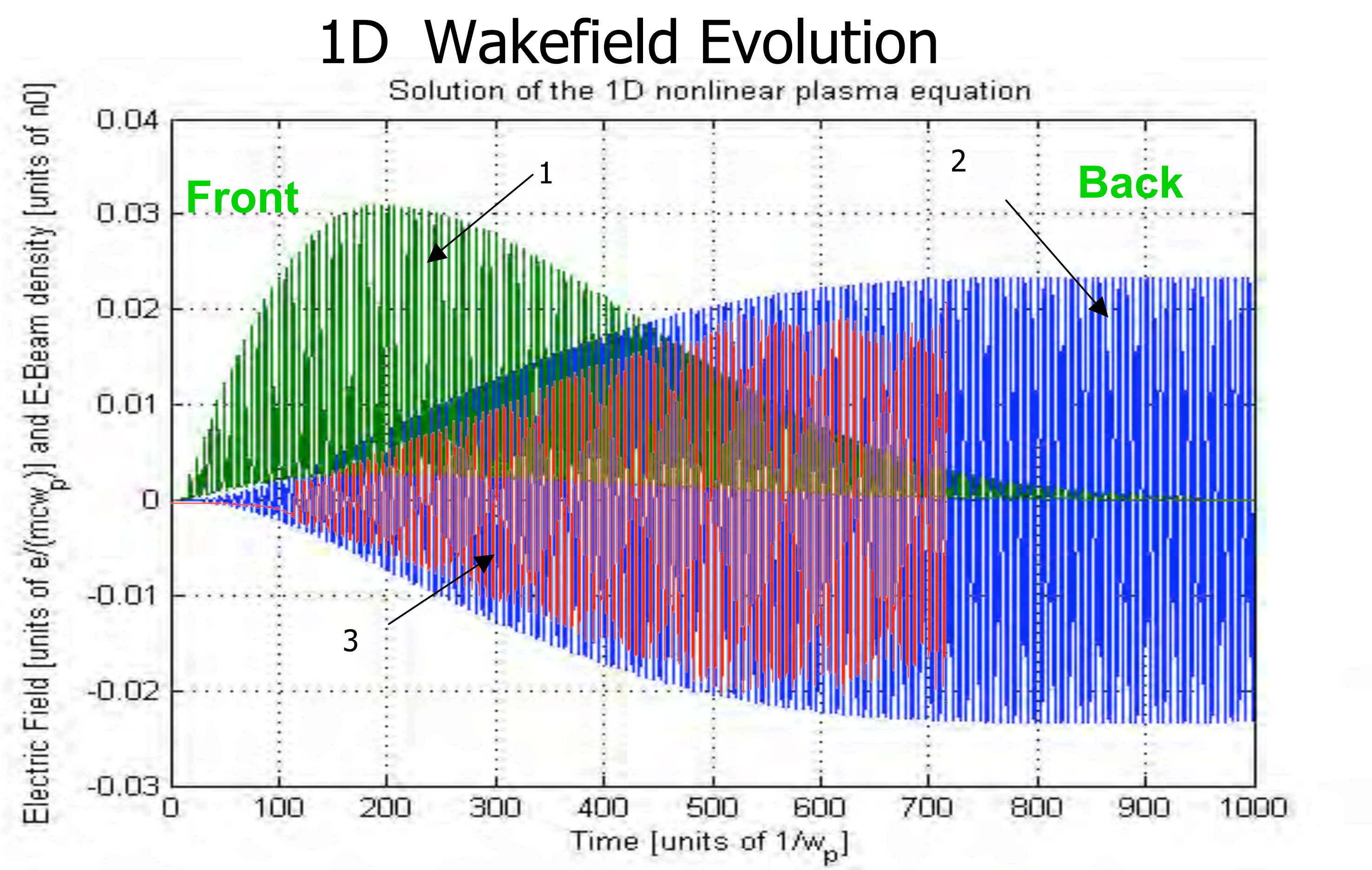
Multi-Bunch PWFA Experiment at Brookhaven ATF

Goal: Resonantly drive a plasma wakefield using a train of microbunches ~1μm wide separated at 10.6μm



- 10.6μm IFEL Bunches the Electron Beam (STELLA)
- The Bunched Electron Beam Resonantly Drives a Plasma Wake in the $10^{19}cm^{-3}$ Capillary Discharge Plasma (not in blow-out regime)

Theory & Simulation

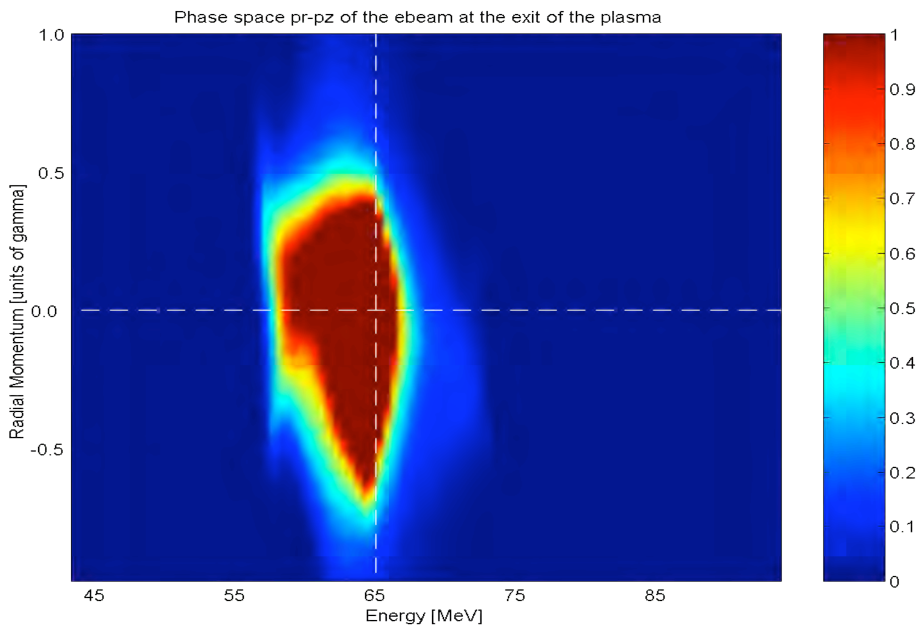


The electron beam density x100 (1), the theoretical wakefield (2) and the OSIRIS simulated wakefield (3) after 1mm of propagation in the plasma. Results for resonant plasma density (n_0=1.0*$10^{19}$$cm^{-1}$) for 10.6μm bunch spacing.

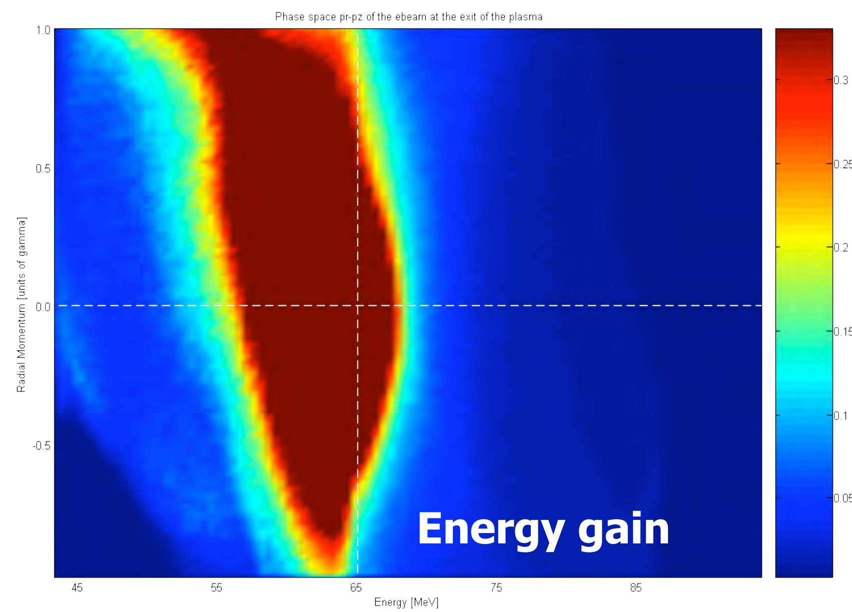
[0.01 $e/(mc\omega_p)$ = 30MV/cm]

PIC Simulations

After 1mm of plasma



After 3mm of plasma



- Expected Energy Gain is 21MeV Over 3mm of Plasma (70MeV/cm)
- Weak Focusing of the Electron Beam
- Characterizing the plasma density using Stark broadening and CO2 transmission
- Characterizing the electron bunching using CTR
- Ensure the plasma density resonance and observe the energy gain

Seeded Self-Modulated Laser Wakefield Acceleration (Seeded SM-LWFA)

- New hybrid plasma-based acceleration scheme combining both plasma wakefield acceleration (PWFA) and laser wakefield acceleration (LWFA) [1]
  - Use ultrashort (<<1 ps) seed *e*-beam pulse to generate wakefields in plasma
  - CO_2 laser pulse immediately follows and amplifies wakefields via SM-LWFA
  - Second *e*-beam pulse follows as witness and experiences energy exchange
- Experiment being performed at Brookhaven National Laboratory Accelerator Test Facility (ATF) using 0.5 - 1 TW CO_2 laser as part of STELLA-LW program
  - Use capillary discharge as plasma source (either polypropylene or gas-filled)
  - ATF has already demonstrated dual *e*-beam generation (i.e., seed & witness)
  - Can use chicane to compress seed to ~100 fs while not compressing witness
- Motivation: Provides means to use existing CO_2 laser beam and, at same time, may permit greater control of wakefield phase because wakefield does not start from noise as it typically does during SM-LWFA

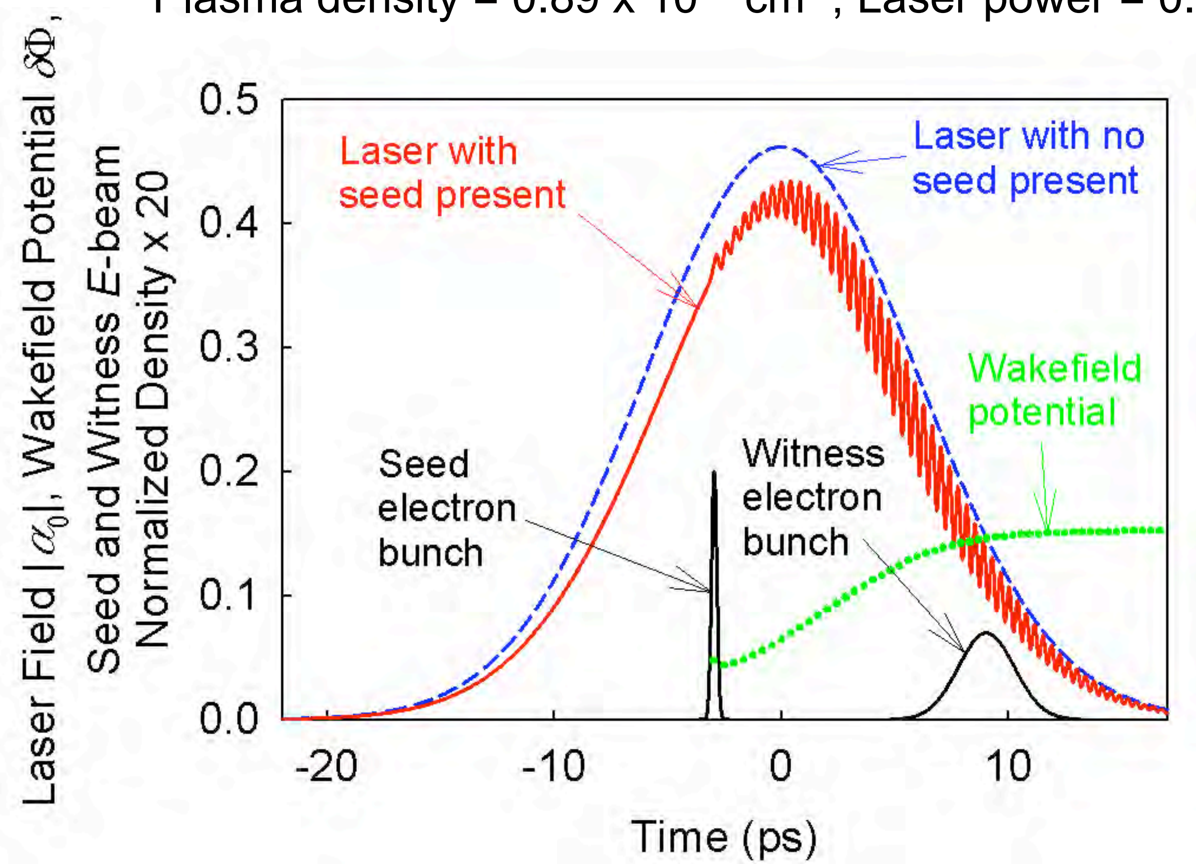
[1] W. D. Kimura, *et al.*, to be published in *Philosophical Transactions of the Royal Society*.

STELLA
Staged Electron Laser Acceleration

STI OPTRONICS

Model Results for Seeded SM-LWFA

- Assumes: Seed pulse length = 118 fs, focus size = 50 μm (1σ), 199 pC
  Witness pulse length = 1.23 ps, focus size = 20 μm (1σ)
  Plasma density = 0.89 x 10^{17} cm^{-3}; Laser power = 0.5 TW



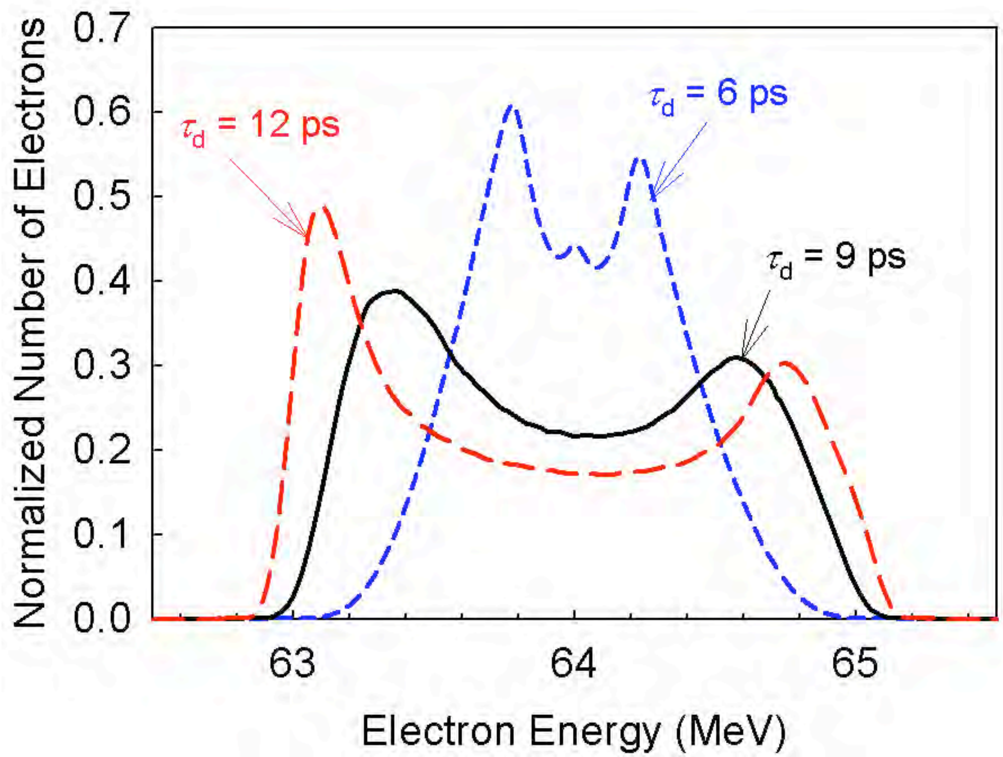
STELLA
Staged Electron Laser Acceleration

STI OPTRONICS

Energy Spectrum Prediction

- Assumes: Seed pulse length = 118 fs, focus size = 50 μm (1σ), 199 pC
  Witness pulse length = 1.23 ps, focus size = 20 μm (1σ)
  Plasma density = 0.89 x 10^{17} cm^{-3}; Laser power = 0.5 TW
  Plasma acceleration length = 2 mm; *e*-beam energy = 64 MeV

τ_d is delay time between seed and witness pulses

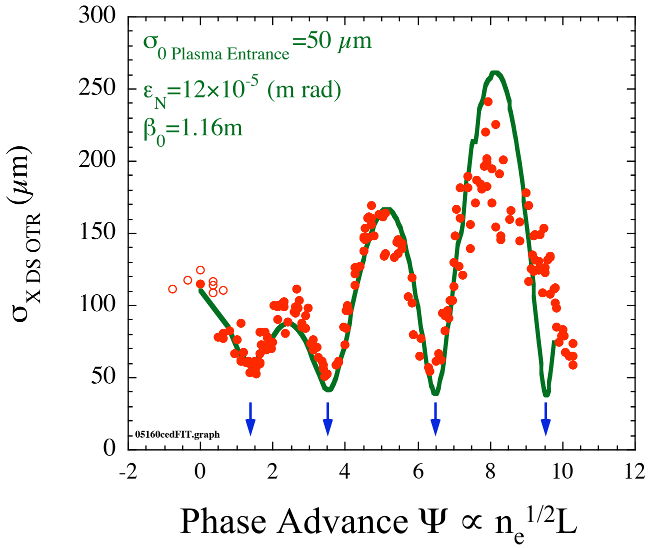


STELLA
Staged Electron Laser Acceleration

STI OPTRONICS

UCLA/USC/SLAC PWFA Experiments at the FFTB

Focusing e^-

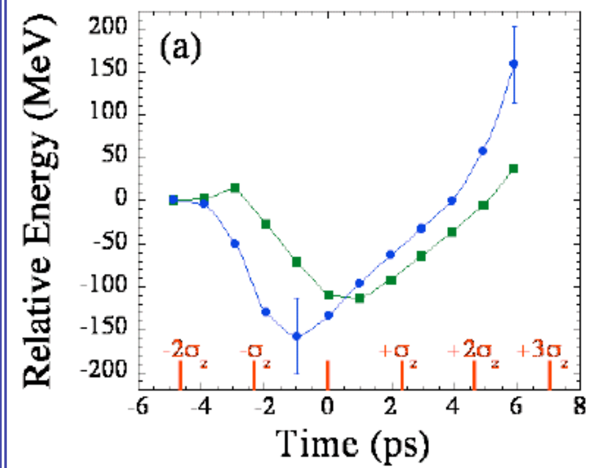


Phys. Rev. Lett. **88**, 154801 (2002)

X-ray Generation

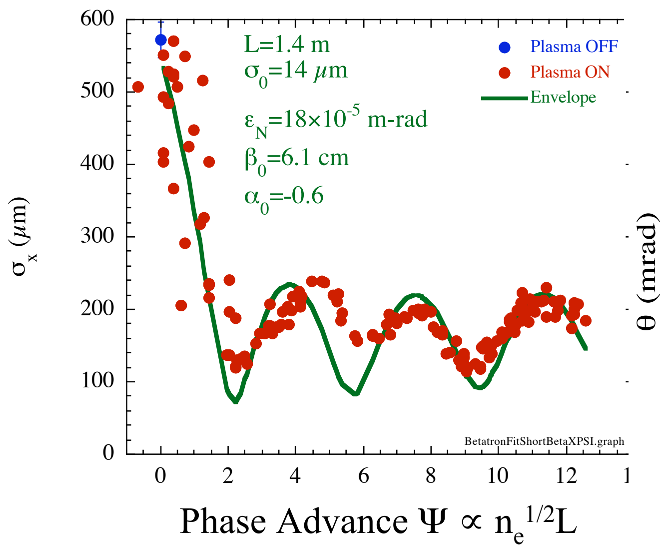
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e^-



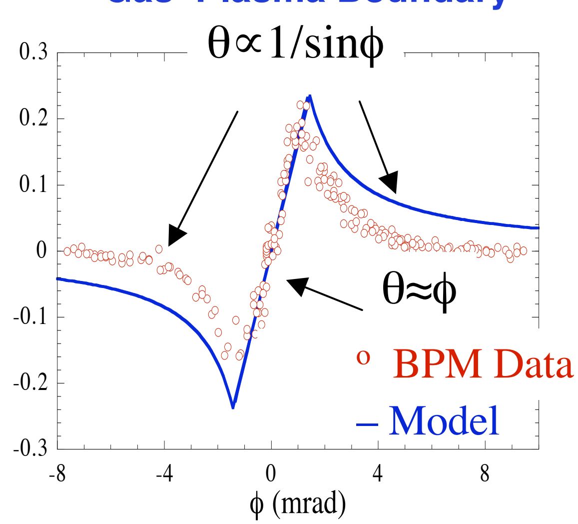
Phys. Rev. Lett. **93**, 014802 (2004)

Matching e^-



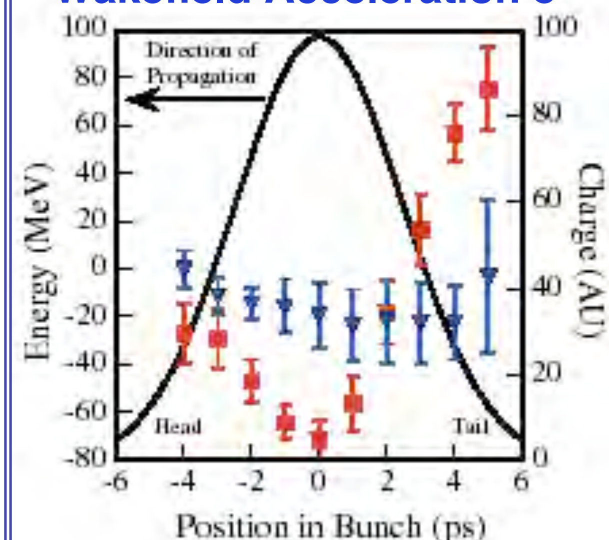
Phys. Rev. Lett. **93**, 014802 (2004)

Electron Beam Refraction at the Gas–Plasma Boundary



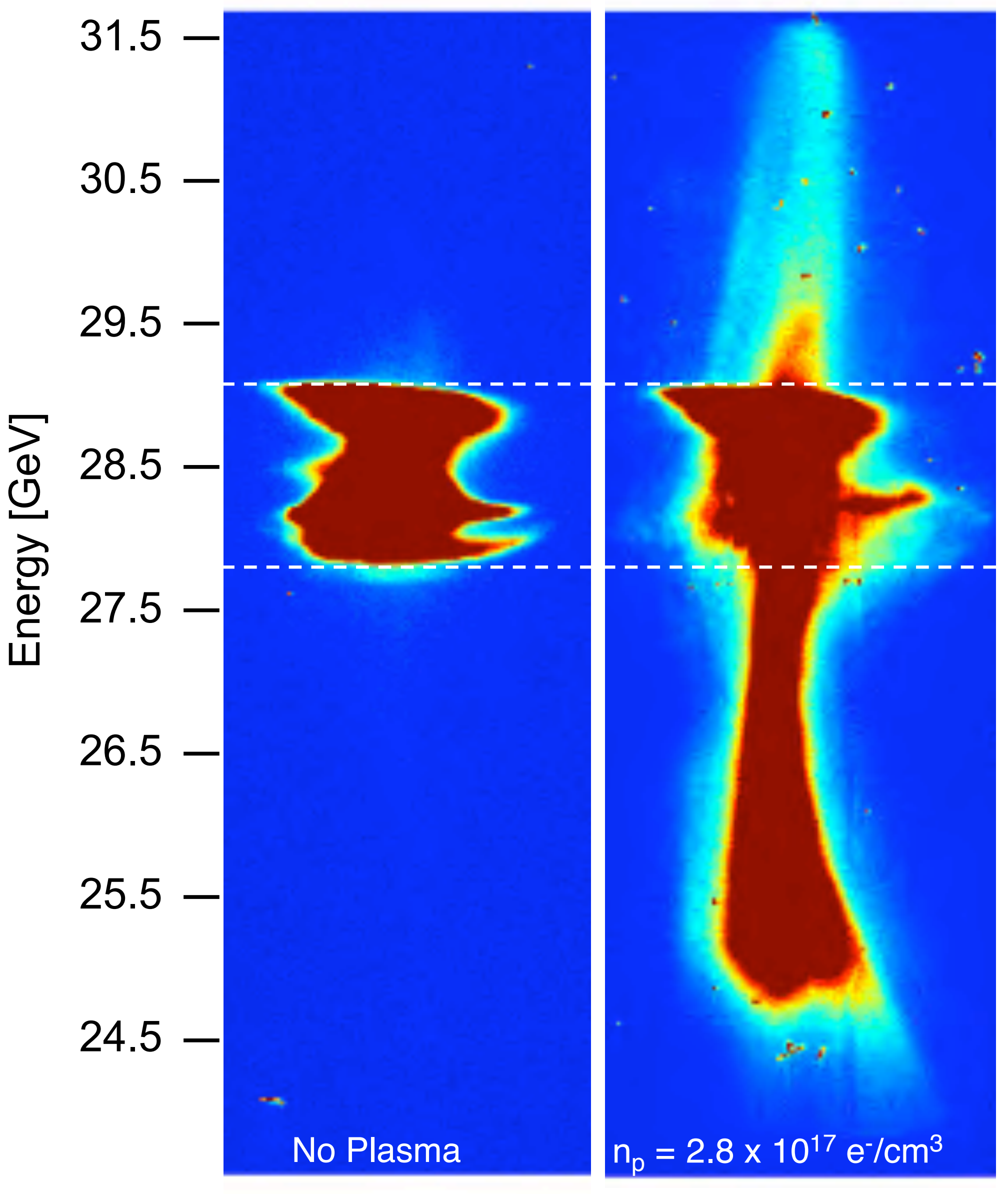
Nature **411**, 43 (3 May 2001)

Wakefield Acceleration e^+



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

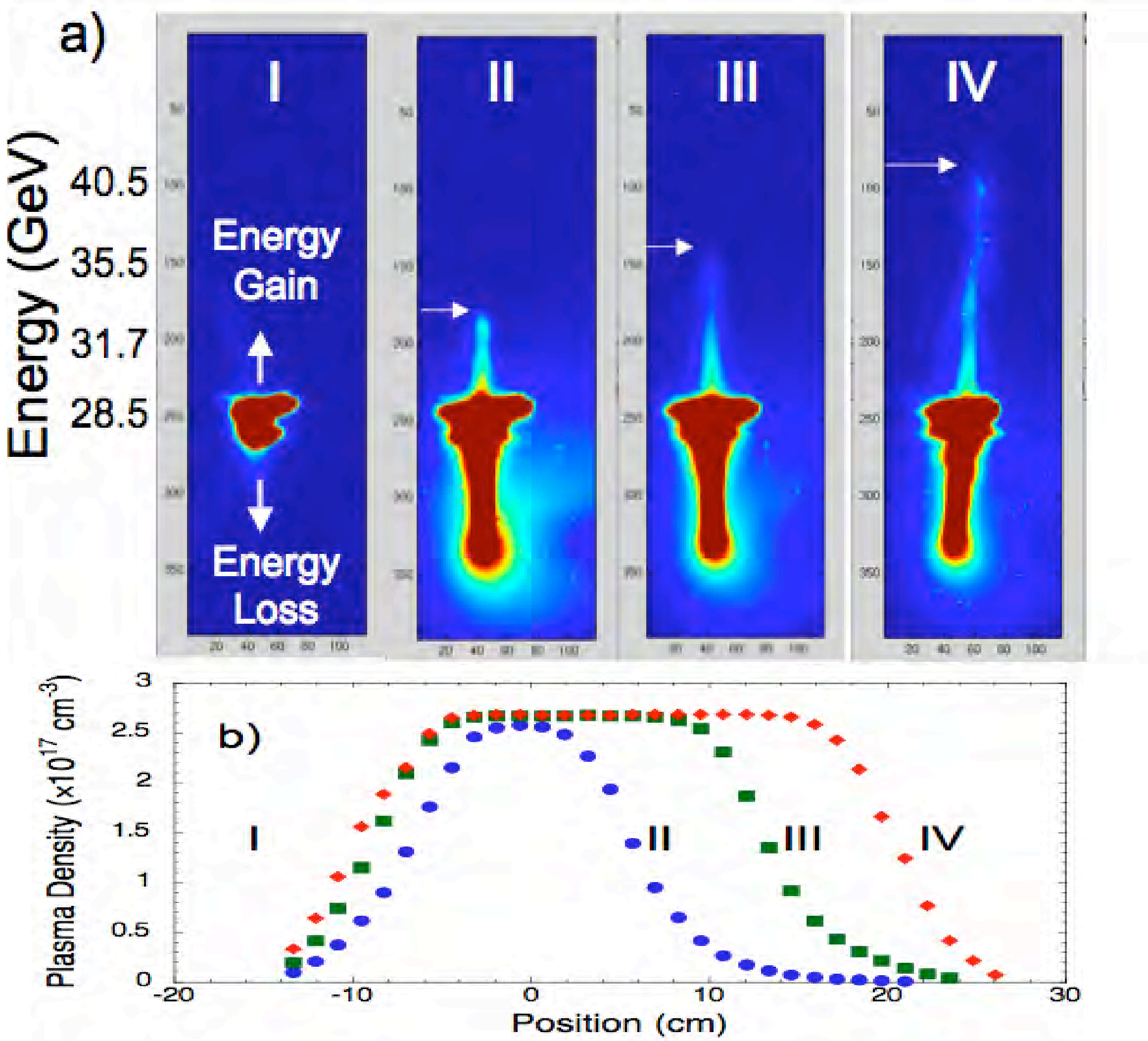
Accelerating Gradient > 27 GeV/m!
(Sustained Over 10cm)



- Large energy spread after the plasma is an artifact of doing single bunch experiments
- Future experiments will accelerate a second “witness” bunch
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmation of predicted dramatic increase in gradient with move to short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results

M.J. Hogan et al, Phys. Rev. Lett. 2005

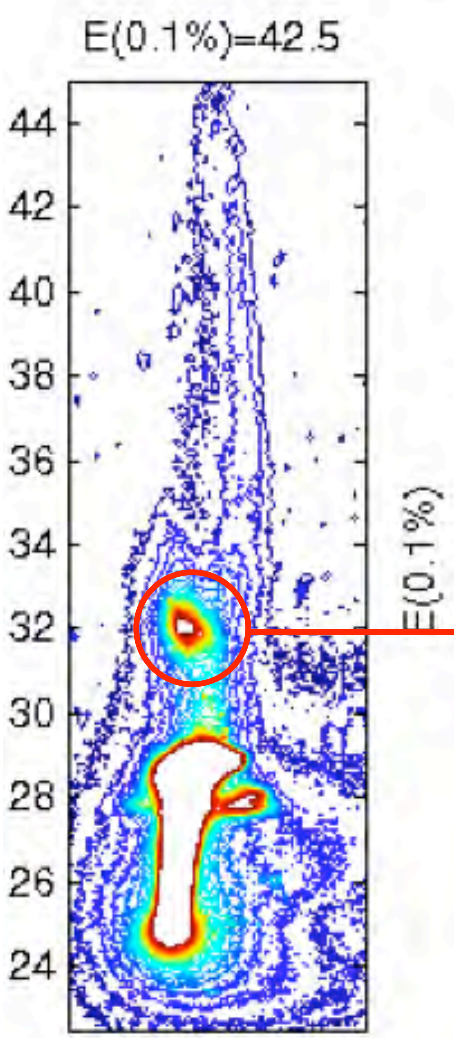
Energy Gain >10 GeV in 30cm Plasma



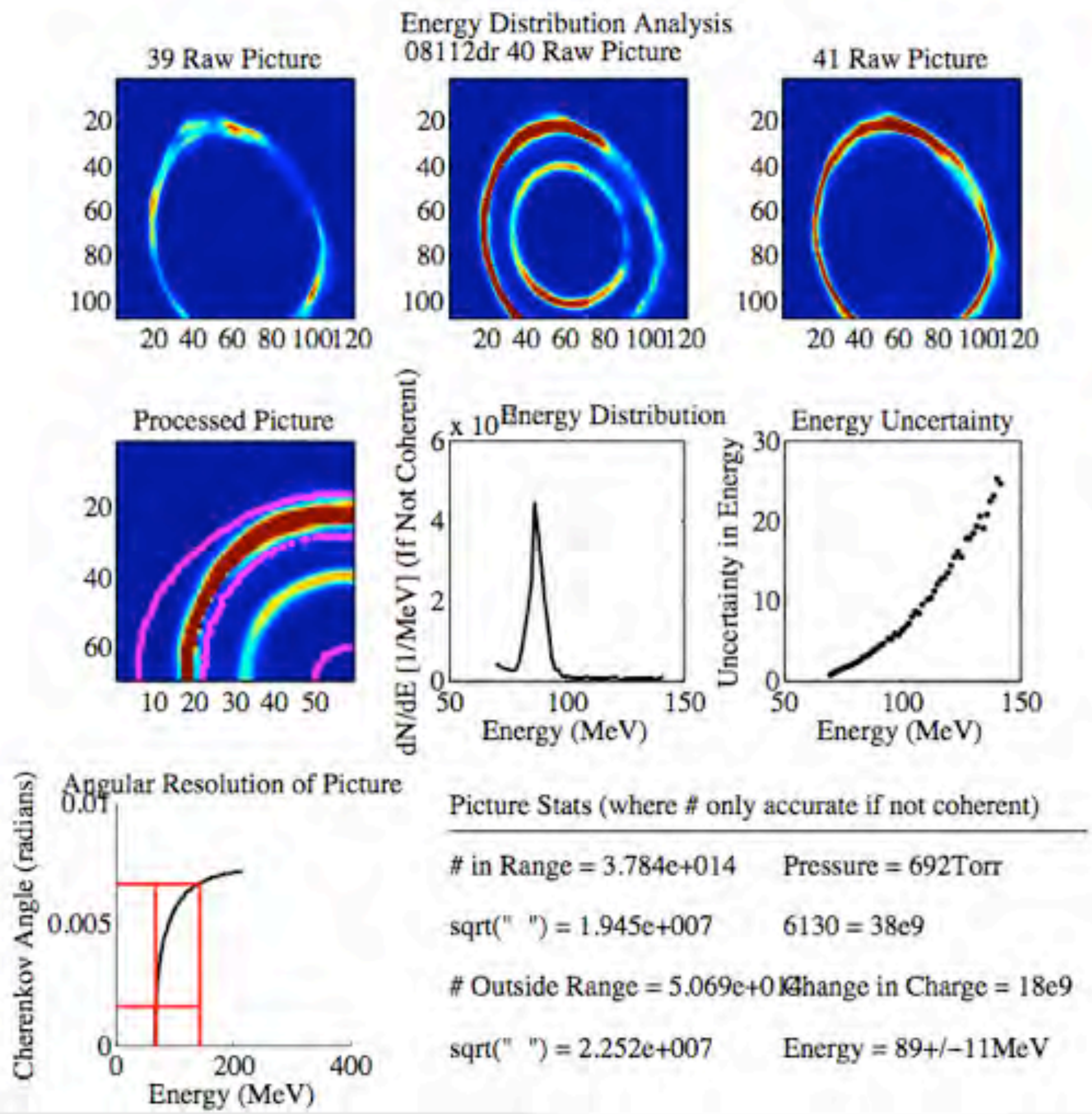
• Spectrometer Re-design Necessary to Transport Low Energy Electrons

Always New Things to Look at!

Narrow Energy Spread

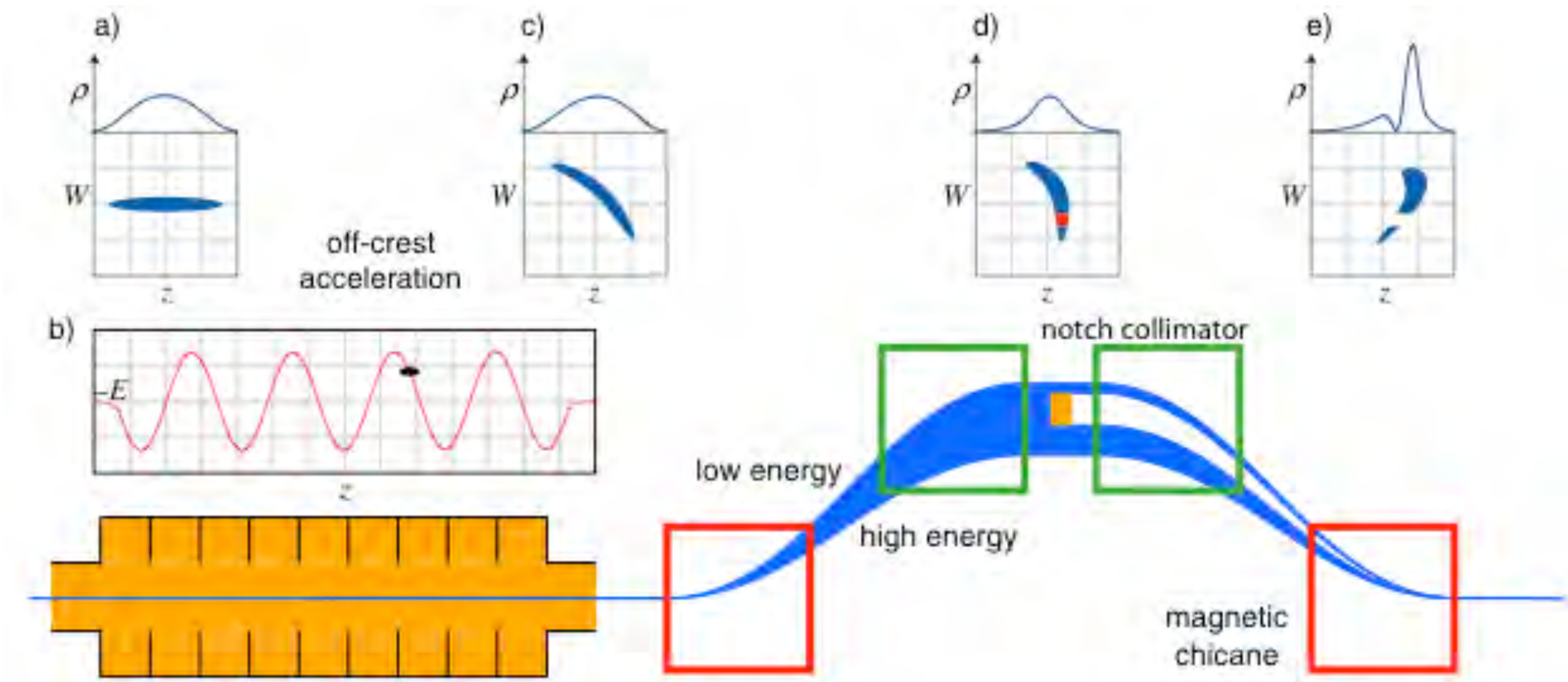


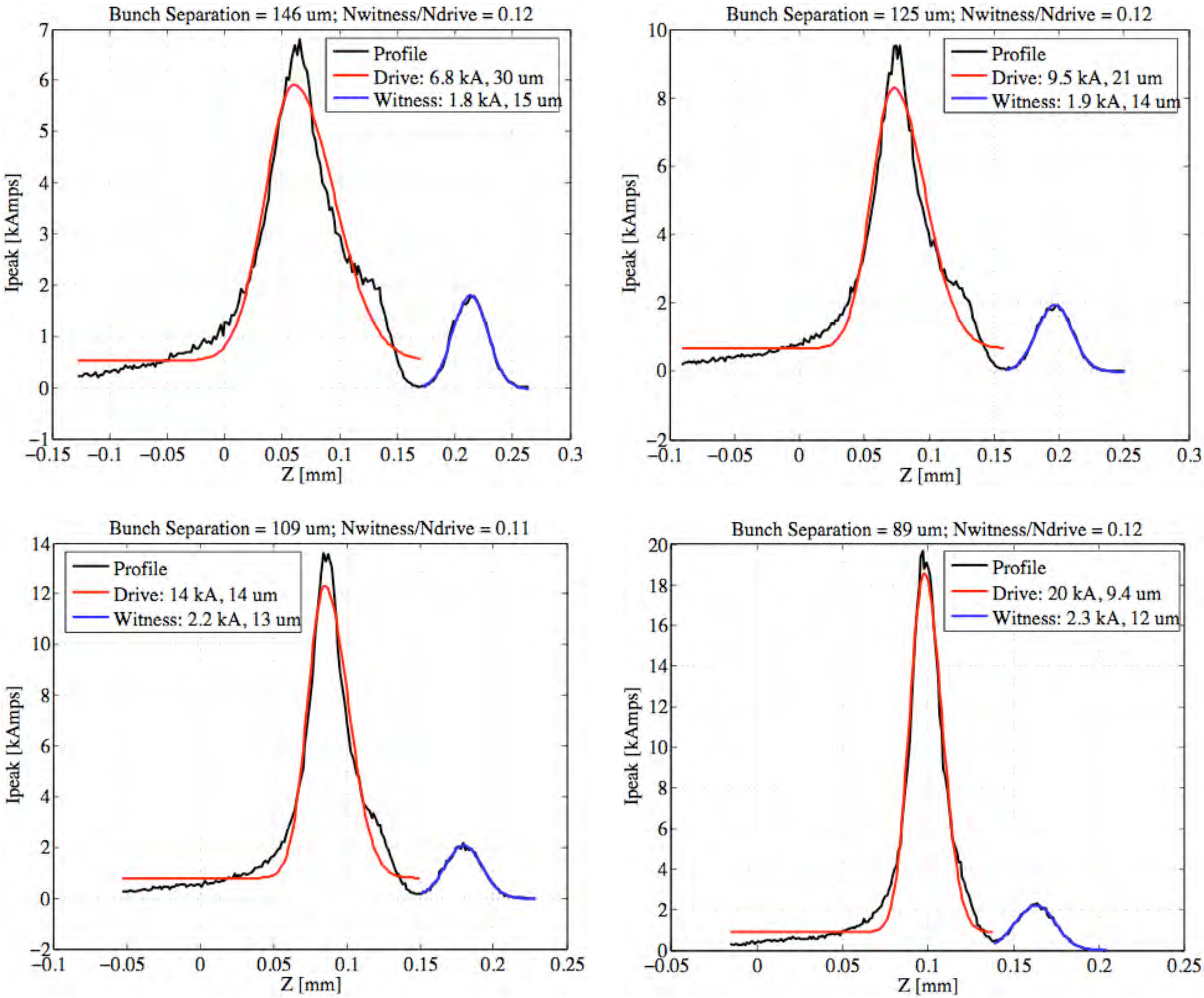
Trapped Particles



Future Experiments (~ 6 months)

- Redesign Spectrometer for Larger Energy Acceptance
- Try to Double Energy of Some Electrons in 1 Meter Plasma
- Two bunches via notch collimator in FFTB:




Bunch Separation = 146 um; Nwitness/Ndrive = 0.12
Profile
Drive: 6.8 kA, 30 um
Witness: 1.8 kA, 15 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 125 um; Nwitness/Ndrive = 0.12
Profile
Drive: 9.5 kA, 21 um
Witness: 1.9 kA, 14 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 109 um; Nwitness/Ndrive = 0.11
Profile
Drive: 14 kA, 14 um
Witness: 2.2 kA, 13 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 89 um; Nwitness/Ndrive = 0.12
Profile
Drive: 20 kA, 9.4 um
Witness: 2.3 kA, 12 um
Ipeak [kAmps]
Z [mm]

Conclusions:

- Exciting Time for Beam Driven Wakefield Experiments
- Dielectric Wakefield Accelerators show promise with good dielectric tolerance to large surface fields
- Plasma Wakefield Accelerators have demonstrated very large gradients and multi-GeV energy gain
- Much more work to be done:
  - Accelerate a second bunch (not just particles) with narrow energy spread and good emittance
  - Positrons???
- Care needs to be taken when extrapolating to future scenarios and experiments designed accordingly

Argonne Wakefield Accelerator Group

W. Gai, M. Conde, C. Jing, R. Konecny, W. Liu, J. Power, H. Wang, Z. Yusof

UCLA/SLAC Ultra-High Gradient Cerenkov Wakefield Accelerator Experiment

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UCLA Dept. of Physics and Astronomy
M. Hogan, R. Ischebeck, N. Kirby, R. Siemann, D. Walz
Stanford Linear Accelerator Center
P. Muggli – University of Southern California
A. Scott – UCSB Dept. of Physics R. Yoder - Manhattan College

Multibunch Plasma Wakefield Acceleration Experiment at ATF

Efthymios Kallos, Tom Katsouleas, Patric Muggli (USC, Los Angeles, California),
Ilan Ben-Zvi, Igor Pogorelsky, Vitaly Yakimenko, Igor Pavlishin, Karl Kusche,
Marcus Babzien, Daniil Stolyarov, (BNL, Upton, Long Island, New York),
Feng Zhou (Physics and Astronomy Department, UCLA, Los Angeles, CA 90095) and
Wayne D. Kimura (STI Optronics, Inc., Bellevue, Washington).

Seeded Self-Modulated Laser Wakefield Acceleration (Seeded SM-LWFA)

W. D. Kimura, N. E. Andreev, M. Babzien, I. Ben-Zvi, D. B. Cline, C. E. Dilley, S. C. Gottschalk,1 S. M. Hooker,6 K. P. Kusche,2 S. V. Kuznetsov,4 I. V. Pavlishin,2 I. V. Pogorelsky,2 A. A. Pogosova,4 L. C. Steinhauer,7 A. Ting,8 V. Yakimenko,2 A. Zigler,5 and F. Zhou3 1 STI Optronics, Inc., Bellevue, WA 98004-1495, USA 2 Brookhaven National Laboratory, Upton, NY 11973 USA 3 University of California at Los Angeles, Los Angeles, CA 90095 USA 4 Institute for High Energy Densities, Russian Academy of Sciences, Moscow 125412, Russia 5 Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel 6 University of Oxford, Oxford, OX1 3PU, United Kingdom 7 University of Washington, Redmond Plasma Physics Laboratory, Redmond, WA 98052 USA 8 Naval Research Laboratory, Washington, DC 20375, USA

Beam-Driven Plasma Wakefield Experiments at SLAC

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