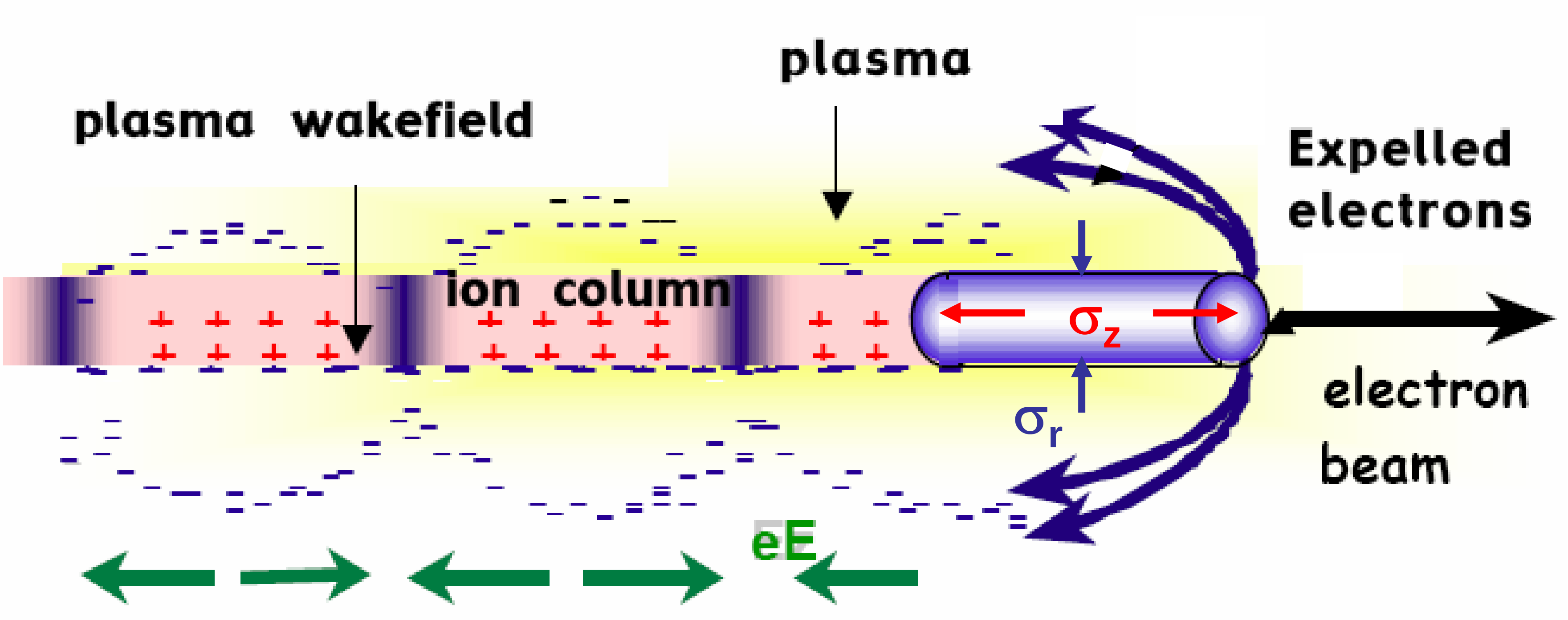
Workshop on
"Scientific Potential of High Repetition-Rate, Ultra-short Pulse ERL X-Ray Source"
Cornell University
June 14, 2006

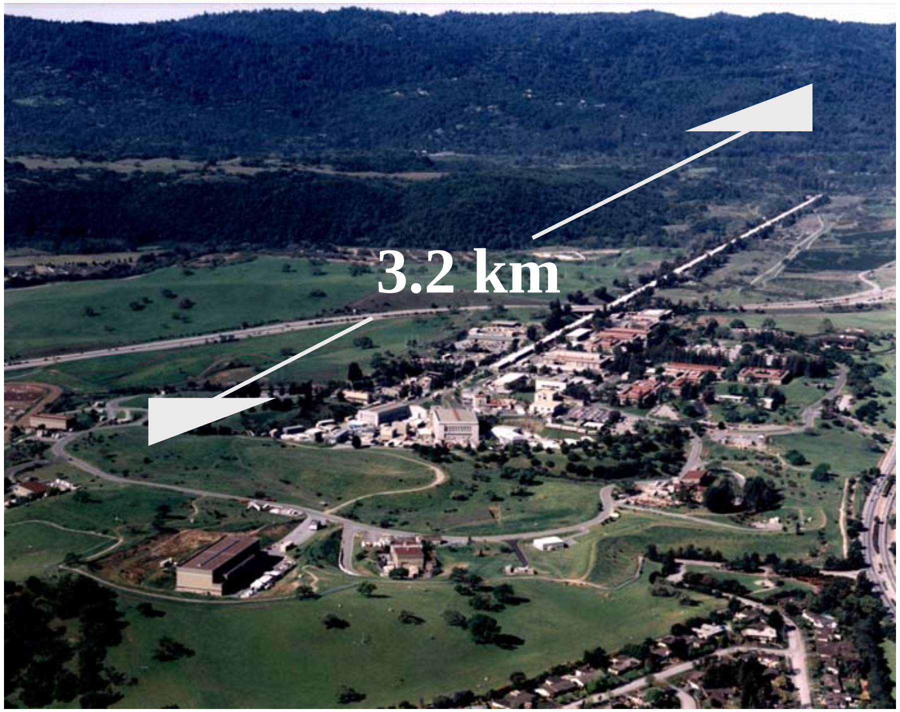
Plasma Wakefield Energy Doubler for Cornell's ERL

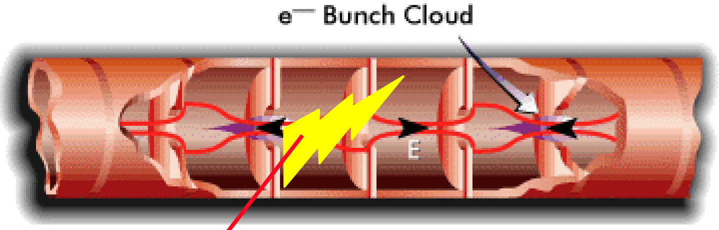
Mike Downer
Department of Physics
University of Texas at Austin



Goal: $\sigma_z \sim \lambda_p$ as short as possible; $\sigma_r << \sigma_z$

Conventional RF acceleration:
limited by material breakdown

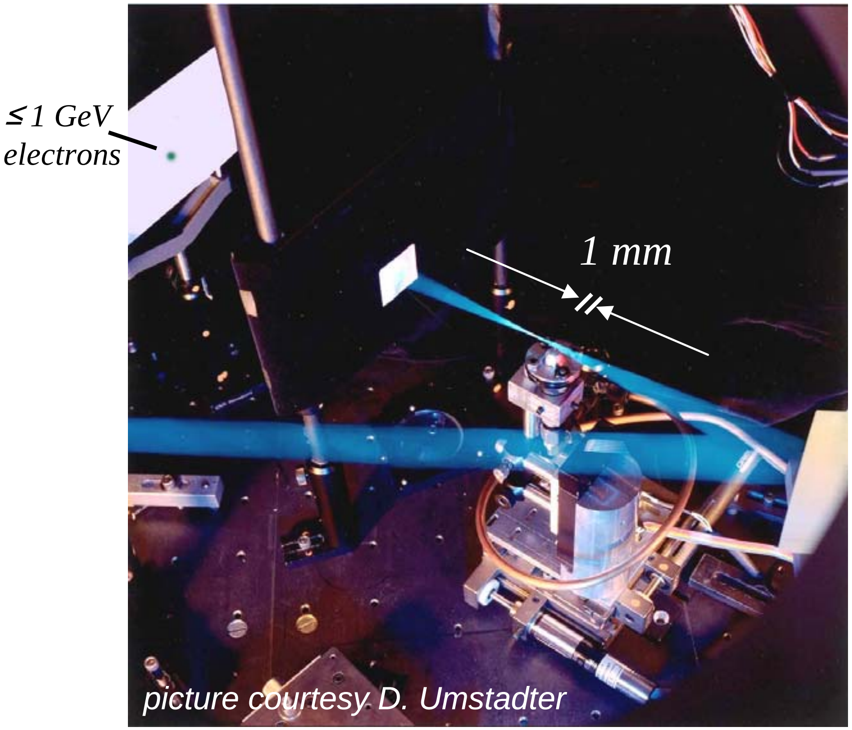




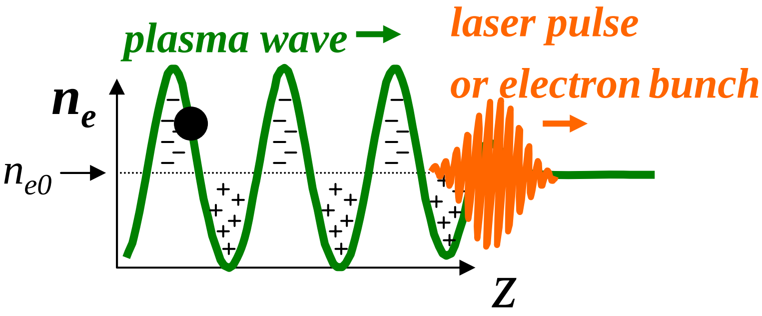
$E_{breakdown} \sim 10^7 V/m$

$30\ GeV \Rightarrow 3\ km$ (SLAC)

Plasma acceleration:
unlimited by material breakdown



picture courtesy D. Umstadter



$E_{accel} \sim 10^{11}\ V/m$

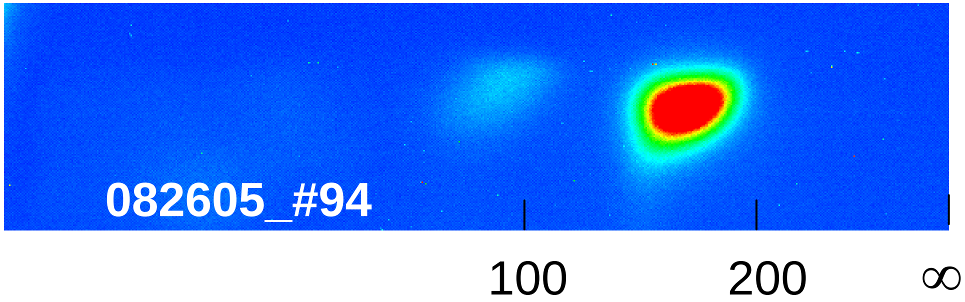
$30\ Gev \Rightarrow 0.3\ m$

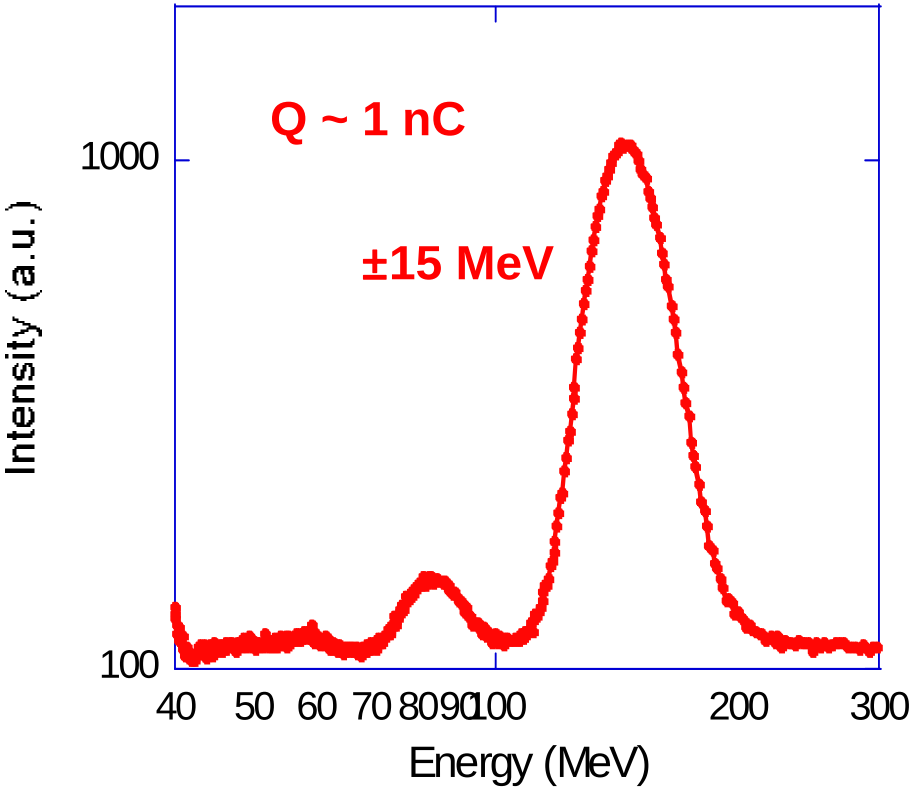
Quasi-monoenergetic (E_{max}=160 MeV*)...

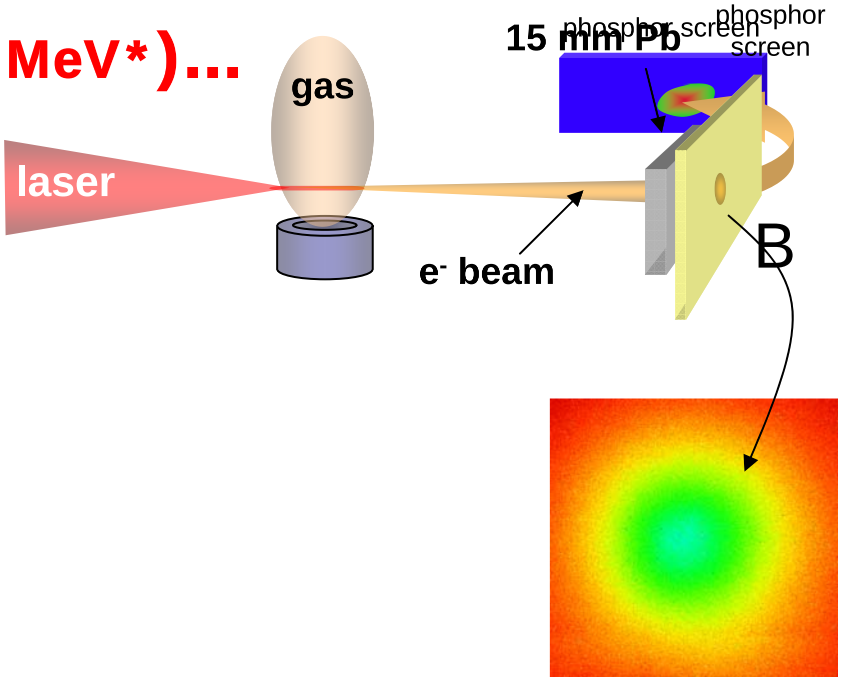
*Faure *et al.*, Mangles *et al, Nature* (2004)

recent results: E_{max} = 300 MeV (Michigan)

1 GeV (UC-Berkeley)







E > 70 MeV e^-

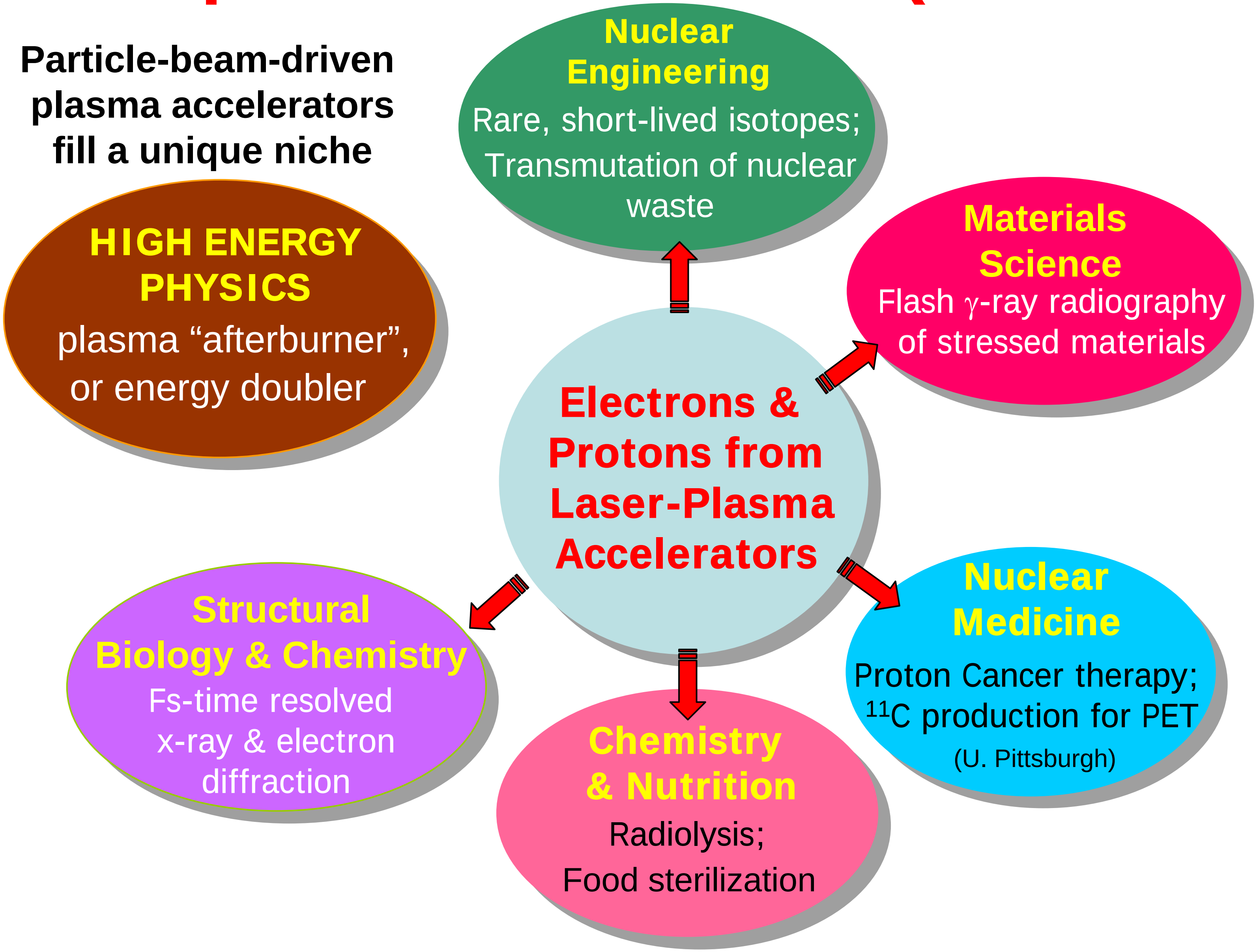
... & highly collimated ($\sigma_\perp$ = 0.1 π mm-mrad) beam can be produced

~10 fs bunch duration

convertible to 10 fs x-ray pulse

Emerging small-scale applications of LASER-plasma accelerators (0.1 - 1 GeV)

Particle-beam-driven plasma accelerators fill a unique niche



Electrons & Protons from Laser-Plasma Accelerators

HIGH ENERGY PHYSICS
plasma “afterburner”, or energy doubler

Nuclear Engineering
Rare, short-lived isotopes;
Transmutation of nuclear waste

Materials Science
Flash γ-ray radiography of stressed materials

Nuclear Medicine
Proton Cancer therapy;
^{11}C production for PET
(U. Pittsburgh)

Chemistry & Nutrition
Radiolysis;
Food sterilization

Structural Biology & Chemistry
Fs-time resolved x-ray & electron diffraction

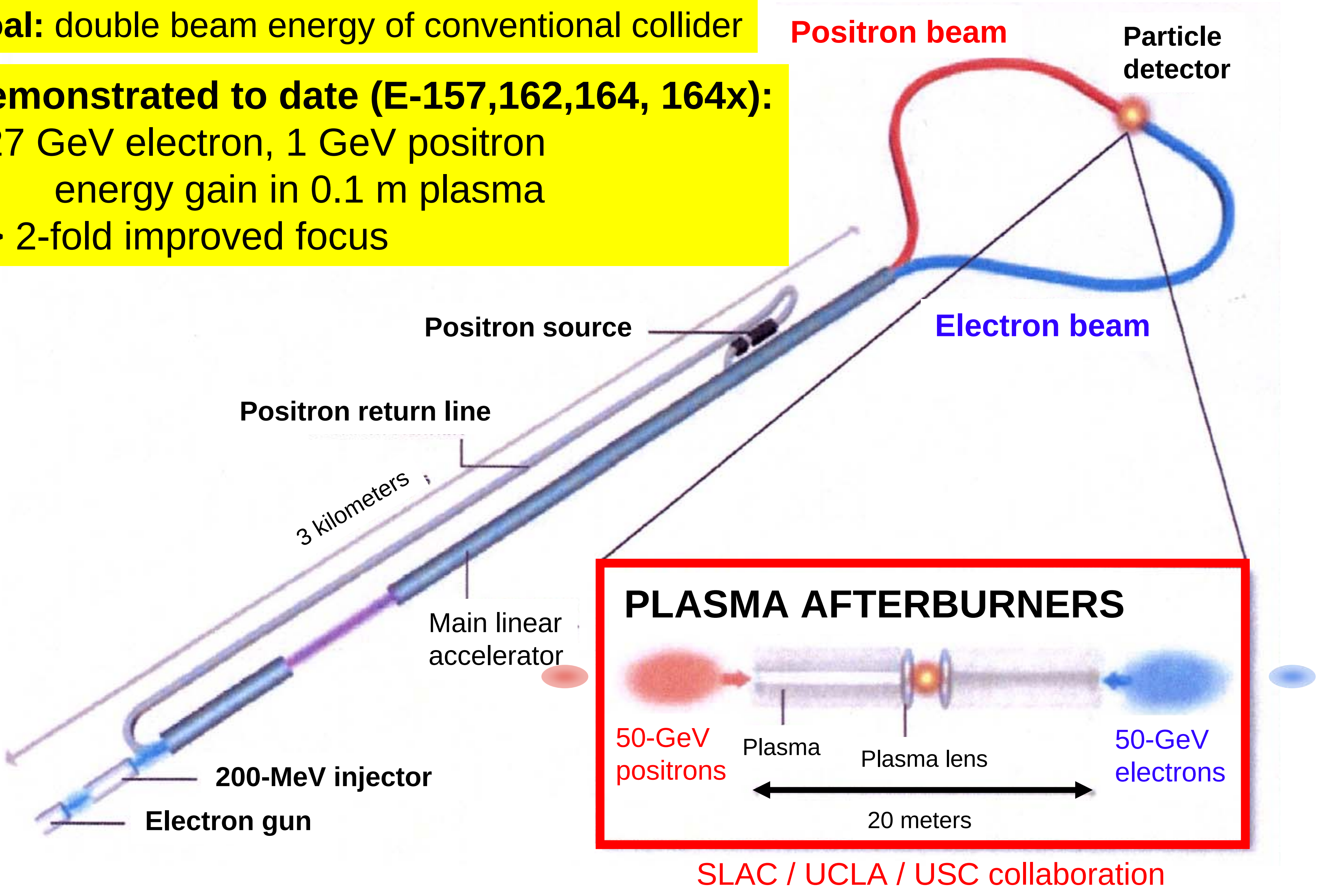
“Plasma Afterburner”: Booster for conventional accelerators

Chandrasekhar Joshi, *Scientific American* (Feb 2006)

Lee, Katsouleas *et al*., “Energy doubler for a linear collider,” *Phys. Rev. ST-AB* **5**, 011001 (2002)

Goal: double beam energy of conventional collider

Demonstrated to date (E-157,162,164, 164x):
- 27 GeV electron, 1 GeV positron energy gain in 0.1 m plasma
- > 2-fold improved focus



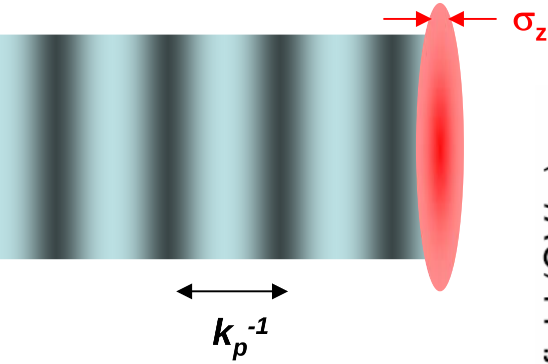
SLAC / UCLA / USC collaboration

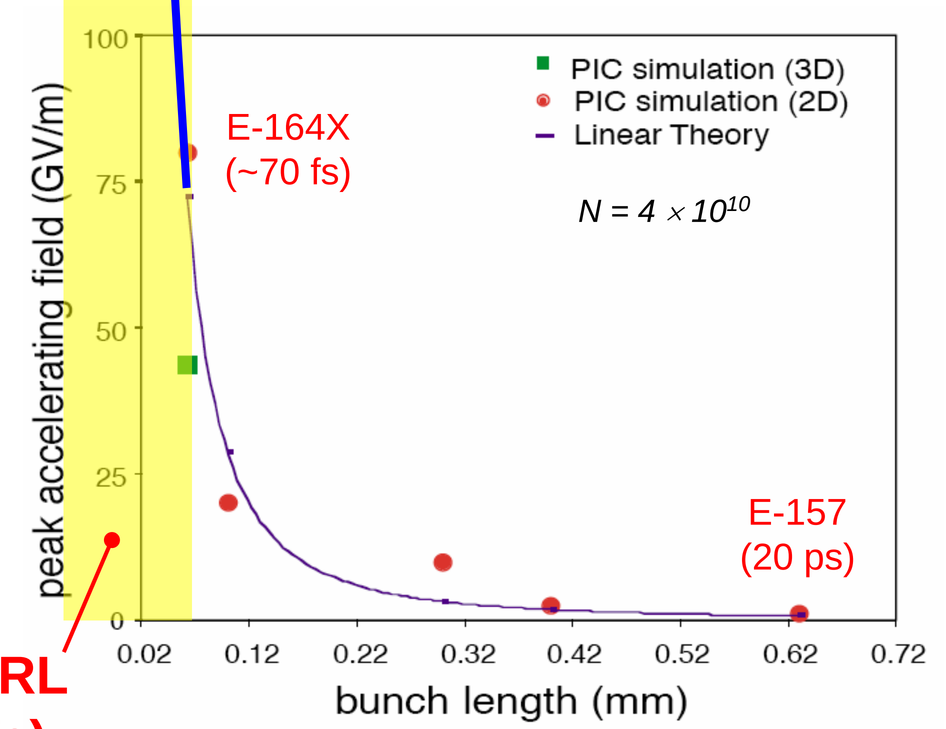
The largest accelerating gradients are realized in the densest plasmas, using the shortest drive bunches

Lee, Katsouleas *et al.*, Phys. Rev. ST-AB **5**, 011001 (2002)

For optimized $k_p\sigma_z \equiv \sqrt{2}$:

$$(eE)_{linear} = 240\frac{MeV}{m}\left(\frac{N}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z[mm]}\right)^2$$





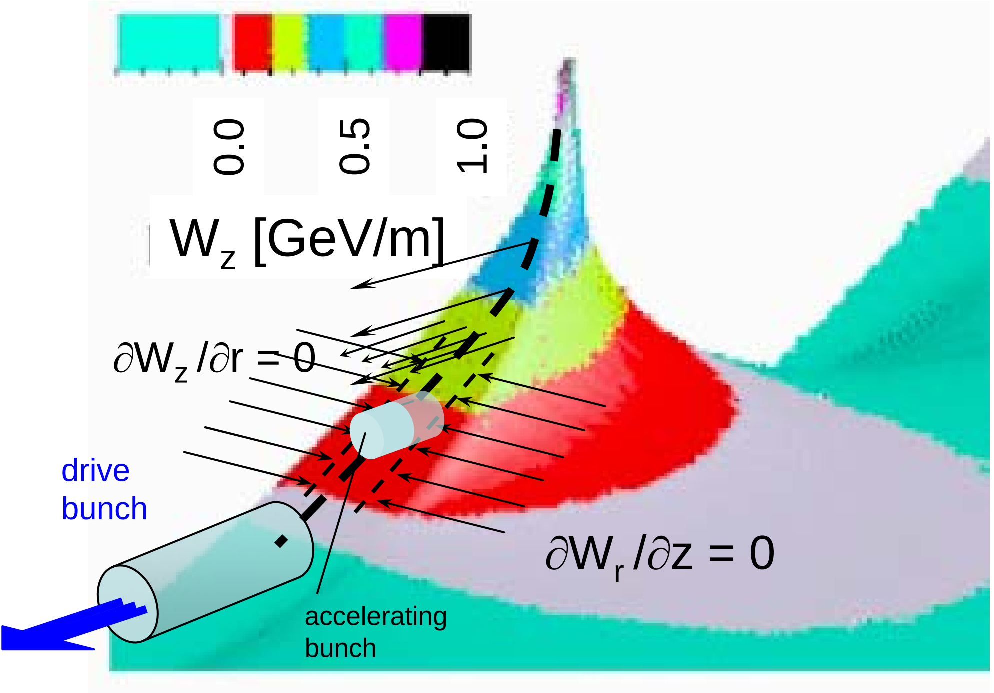
bunch length

Cornell ERL
(20 - 50 fs)

3D PIC simulations show the σ_z^{-2} dependence predicted by linear theory ($n_b < n_0$) persists into nonlinear regime ($n_b > n_0$)

For optimized bunch length $k_p\sigma_z = \sqrt{2}$, best PWFA is realized in the nonlinear “blowout” regime: $n_b >> n_0$ AND $k_p\sigma_r < 1$

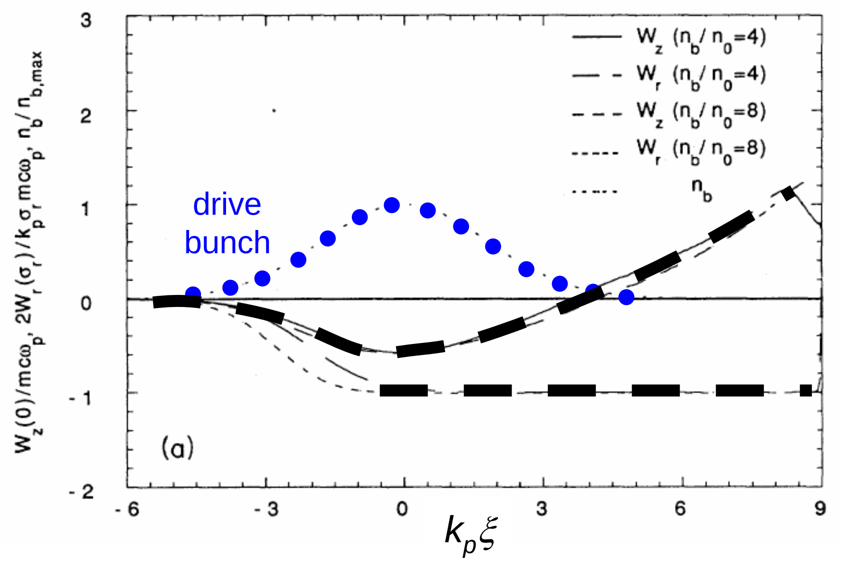
Rosenzweig *et al*., Phys. Rev. A **44**, R6189 (1991)
Hemker *et al*., Phys. Rev. ST-AB **3**, 061301 (2000)

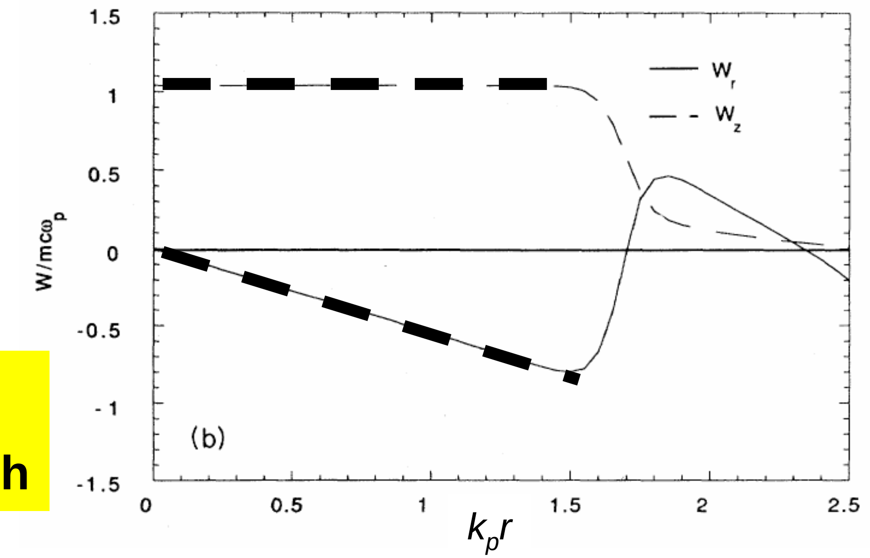


Desirable properties:

- **uniform accelerating field profile**
- **linear focusing force, independent of z**

⇒ drive pulse & trailing accelerating bunch propagate stably, w/ low emittance growth





Cornell ERL can pick up where SLAC left off

Expt.	τ_{bunch} [fs]	σ_z [μm]	σ_r [μm]	$n_{optimum}$ [10^{18} cm^{-3}]	E_z^{max} [GeV/cm]	L_{plasma} [cm]	ΔE [GeV]
SLAC E-157	2000	600	~50	0.00016	0.0024	100	0.24
SLAC E-164X	70	20	~20	0.14	0.5	3-30	1-15
Cornell Short-Pulse	50	15	< 5	0.25	1.0	1-5	1-5
Cornell Ultra-Short Pulse	20	6	< 2	1.56	5	~1	5

- E-157: long bunch, $\sigma_r/\sigma_z << 1$, low density, low gradient
- E-164X: short bunch, $\sigma_r/\sigma_z \approx 1$, medium density, high gradient
- Cornell: **ultrashort bunch**, $\sigma_r/\sigma_z << 1$, **high density, ultrahigh gradient**

THEORY SPARSE ⇒ EXPERIMENTS NEEDED

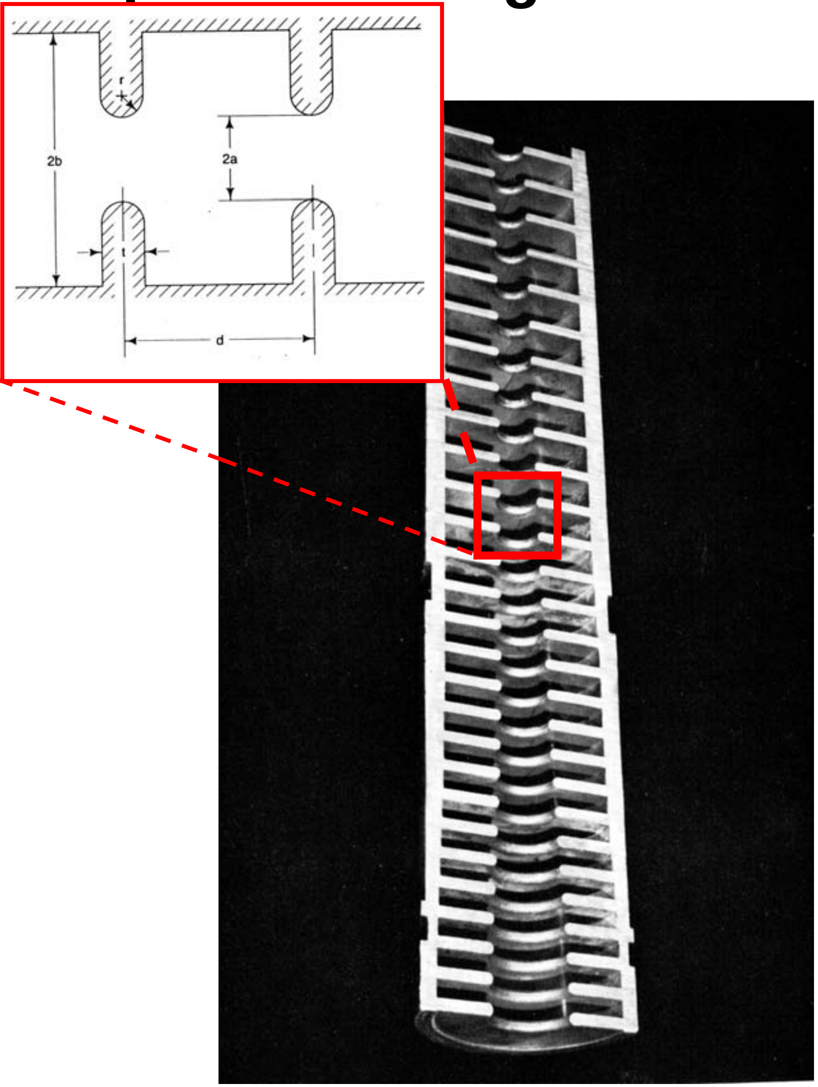
First Generation Experiment: to perfect plasma wakes, we must SEE them

- Generate wakefields in dense plasma (~ 10^{18} cm^{-3}) using ultrashort, low emittance ERL bunches

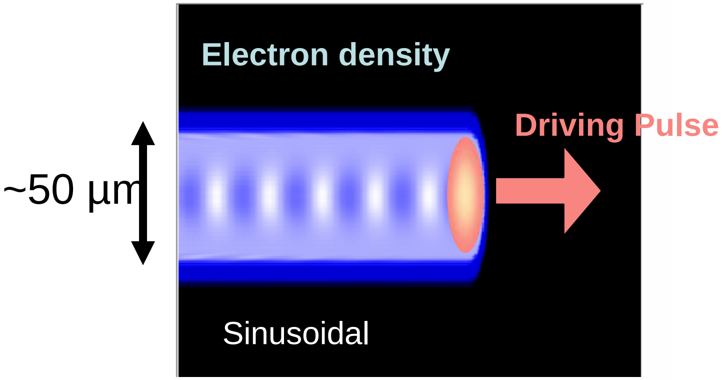
- Measure wake structure by Frequency Domain Holography, using ~ mJ probe laser pulses synchronized w/ photocathode laser

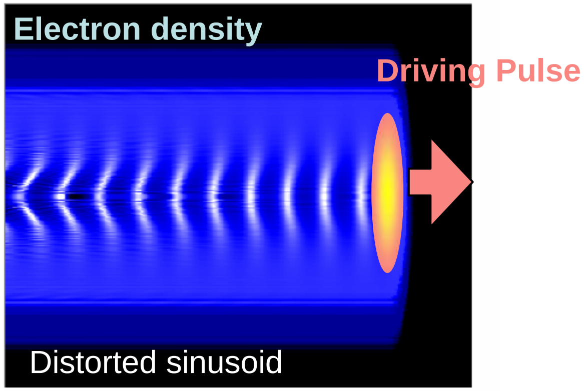
- Compare FDH measurements with (PIC) simulations

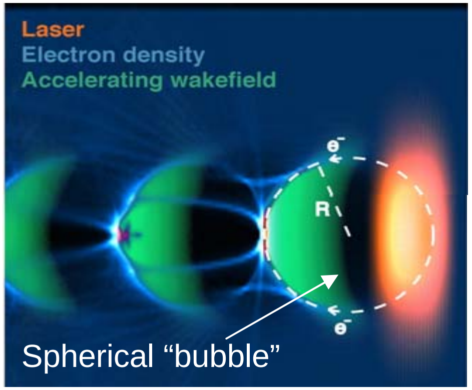
Copper RF accelerator cavities must be precision-engineered



Simulations show widely varying plasma wake structures...



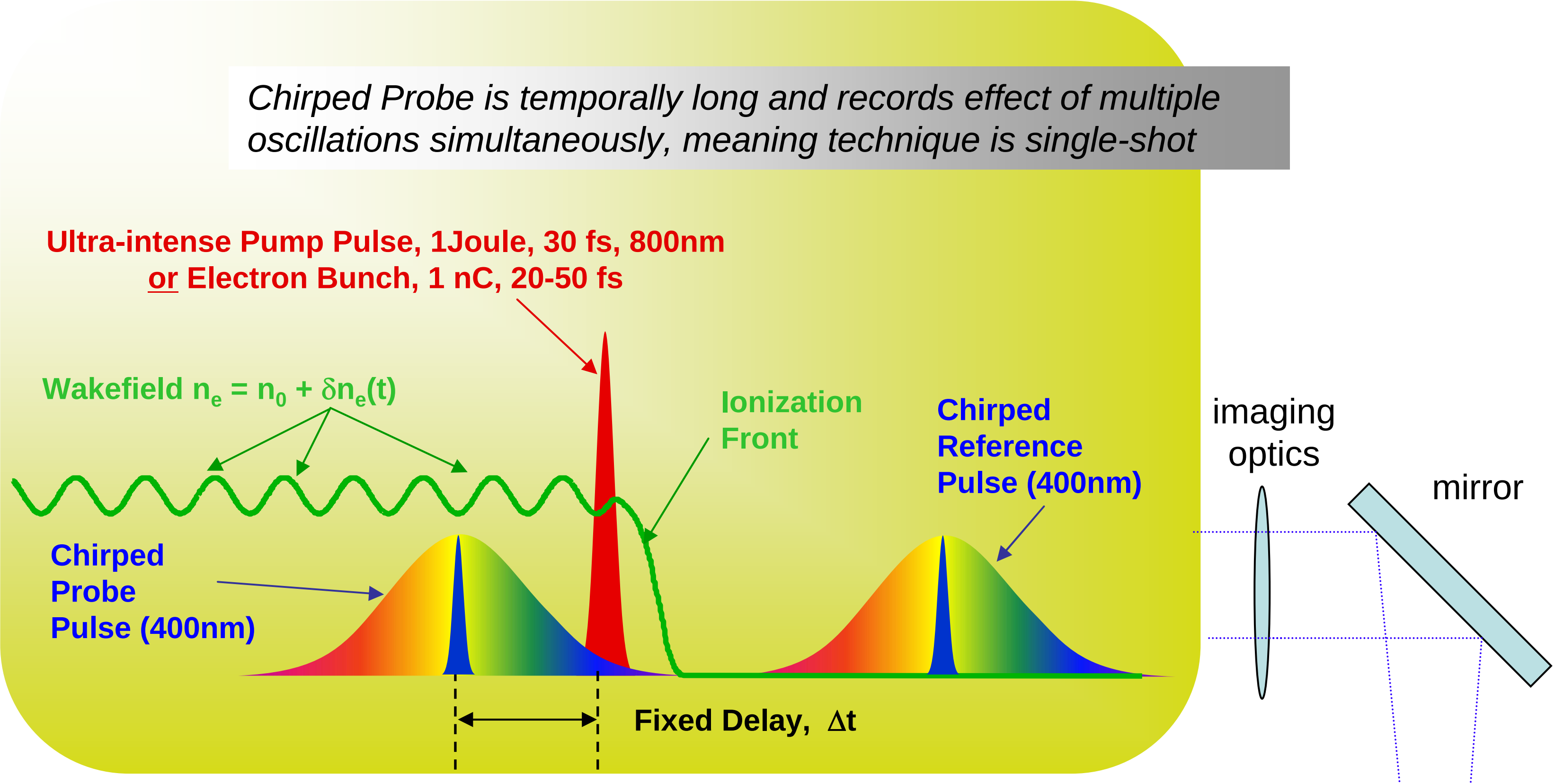




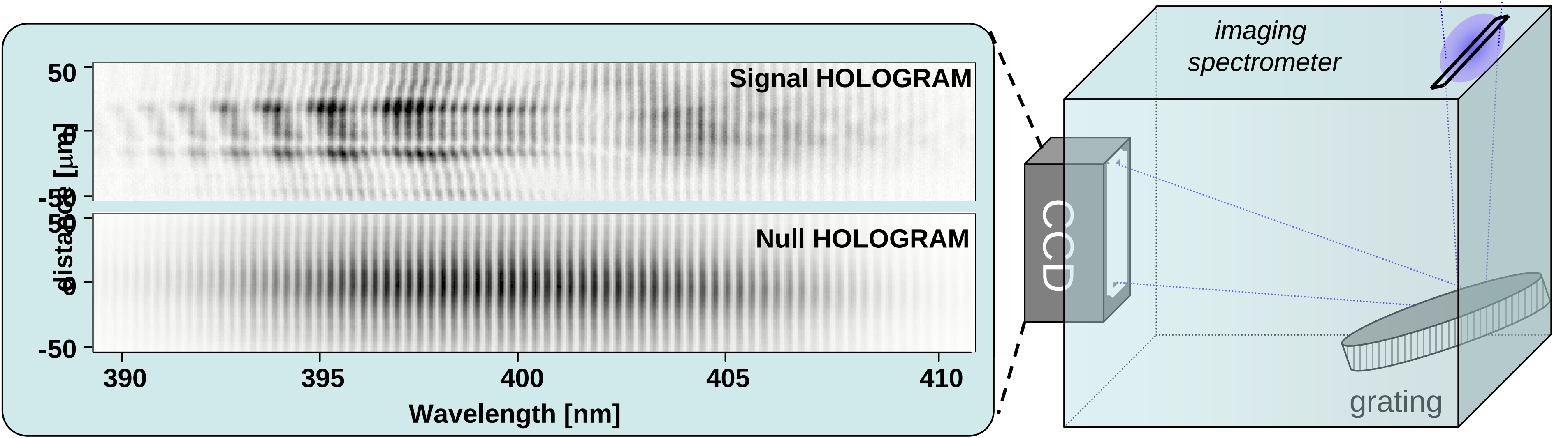
...AND we can’t even see them!

Single-Shot “Frequency Domain Holography”

Nicholas
Matlis
Ph.D.’06



Chirped Probe is temporally long and records effect of multiple oscillations simultaneously, meaning technique is single-shot



“Reading” the Hologram

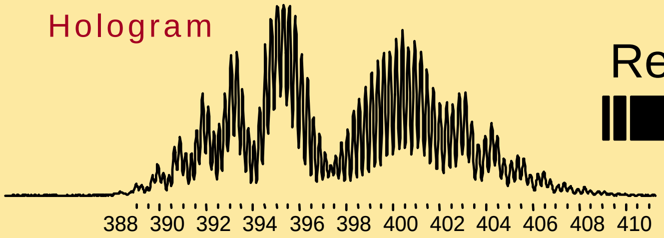
(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN

1. Reconstruct spectral E-field of probe pulse from holographic spectrum



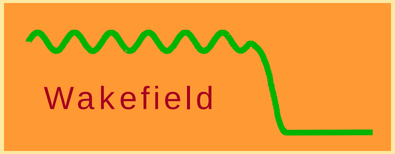
$$\xrightarrow{\text{Read}} E_{probe}(\omega) = |E(\omega)|\, e^{-i\phi(\omega)}$$

2. Fourier Transform to the time-domain to recover temporal phase

$$E_{probe}(\omega) \xrightarrow{\text{FFT}} E_{probe}(t) = |E(t)|\, e^{-i\delta\phi(t)}$$

3. Calculate electron density from extracted temporal phase

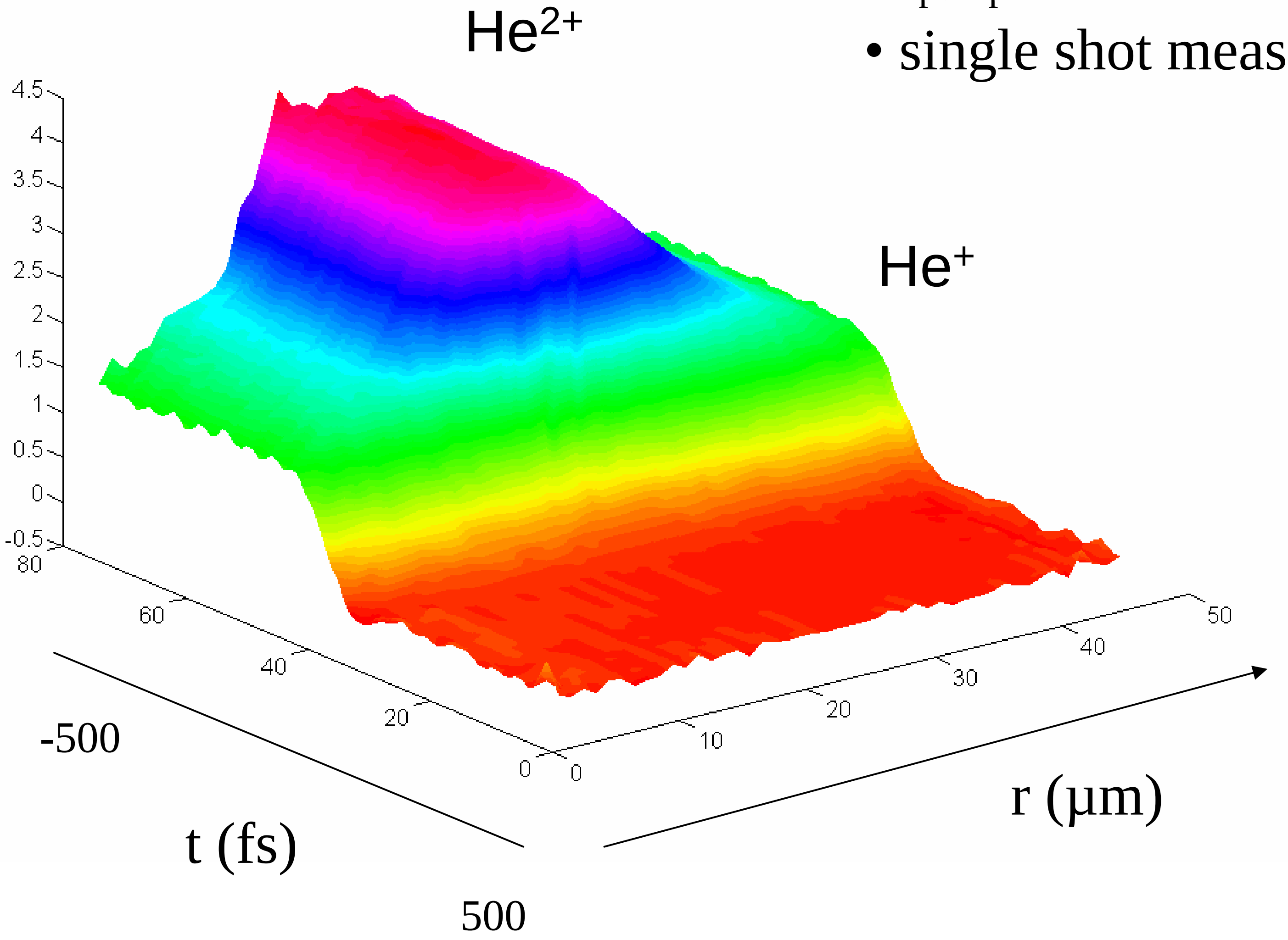
$$\delta\phi(t) \xrightarrow{\text{index}} \boxed{\delta n_e(t)}$$



Holographic snapshot of an ionization front

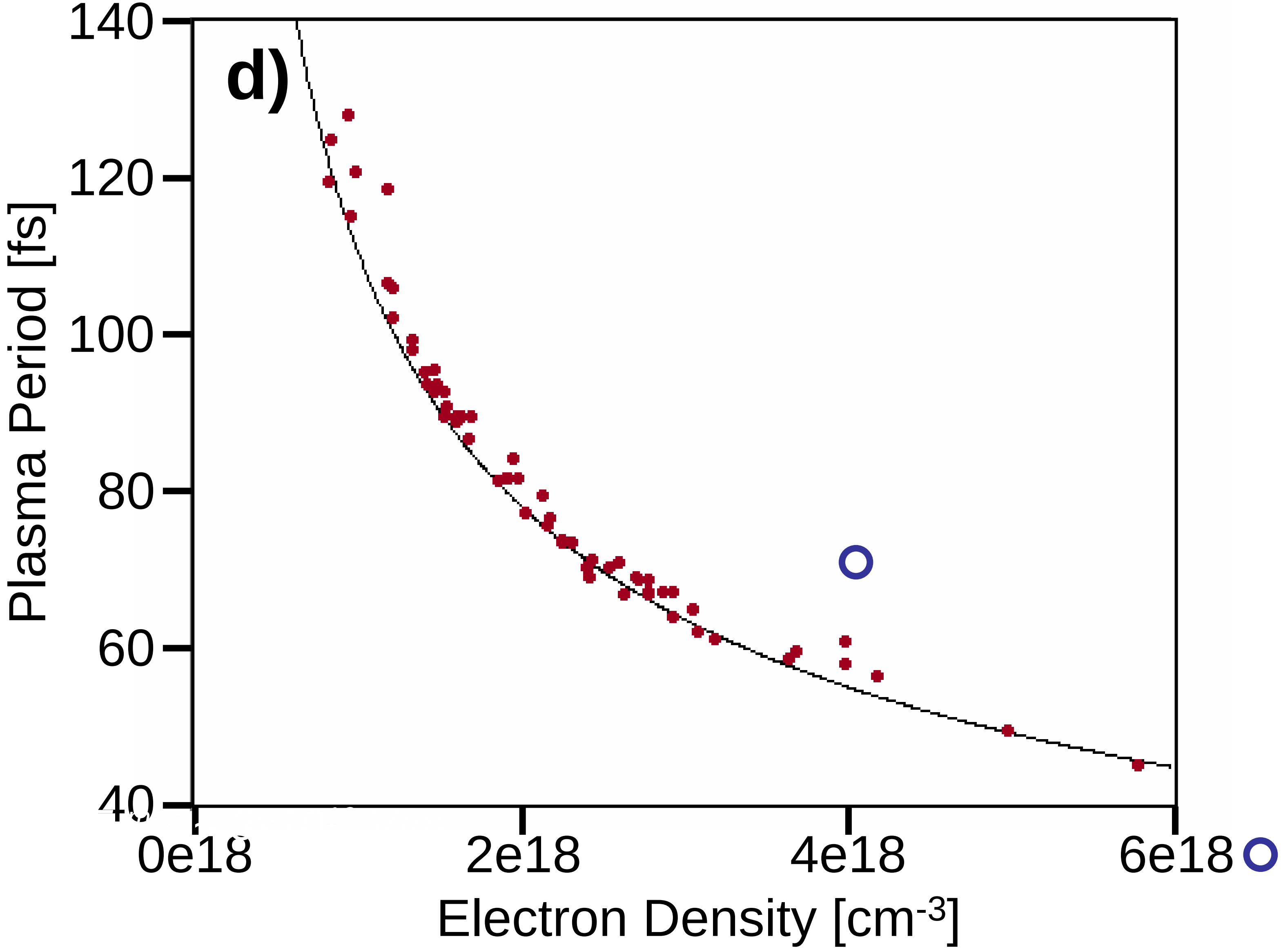
LeBlanc, Matlis, MD, *Optics Letters* **25**, 764 (2000)

- $I_{pump} = 10^{16}$ W/cm^2
- single shot measurement



Holographic snapshots of laser wakefields

$P \sim 10$ TW, $I \sim 10^{18}$ W/cm^2



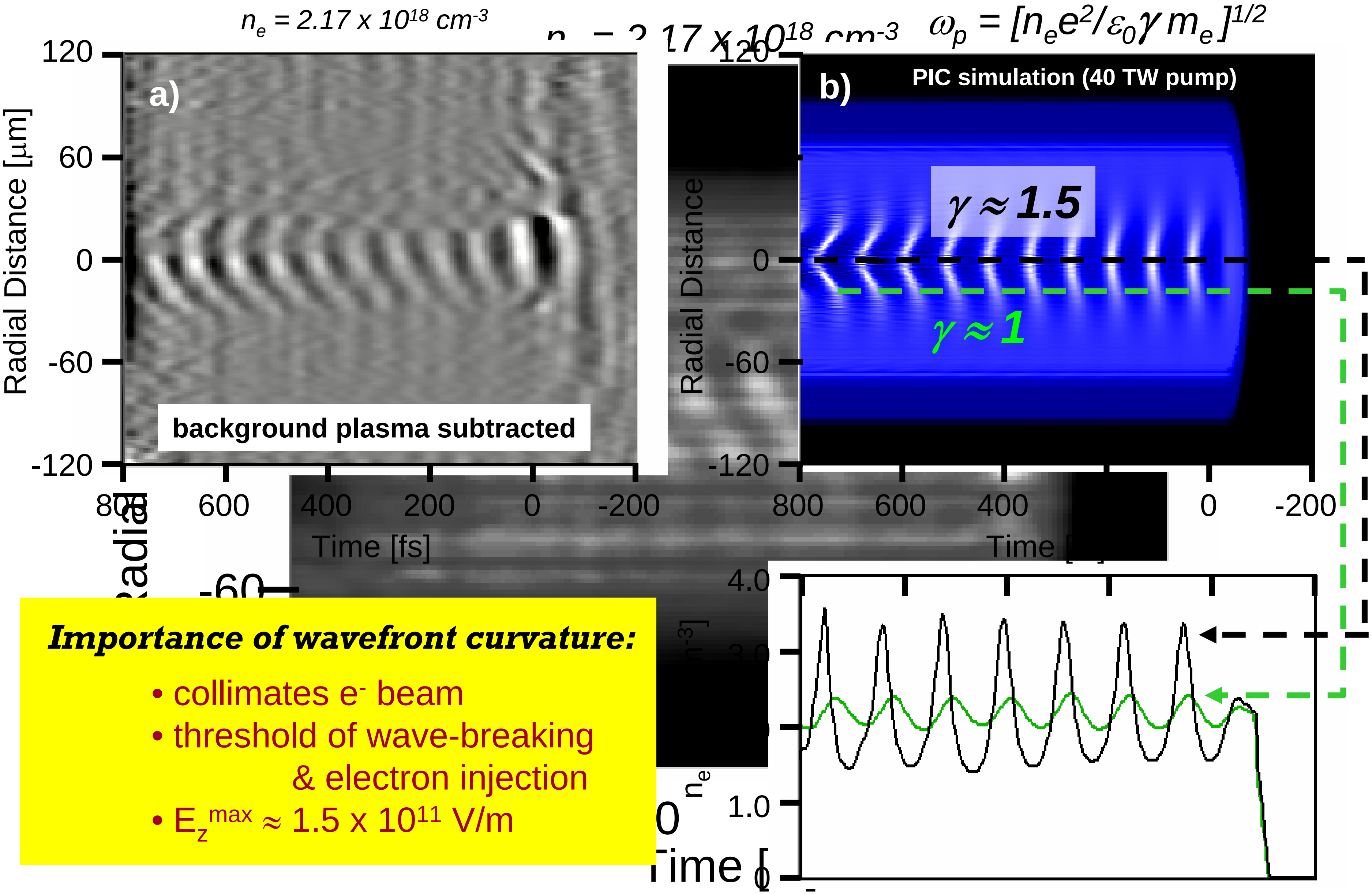
N. H. Matlis et al., submitted to Nature Physics (2006)

Strong wakes have curved wavefronts

P ~30 TW, I ~ 3 x 10^{18} W/cm^2

$n_e = 2.17 \times 10^{18}$ cm^{-3}

$\omega_p = [n_e e^2/\varepsilon_0 \gamma m_e]^{1/2}$



Importance of wavefront curvature:

- collimates e$^-$ beam
- threshold of wave-breaking & electron injection
- $E_z^{max} \approx 1.5 \times 10^{11}$ V/m

Plasma wake physics to observe by FDH

- PWF microstructure vs. drive parameters (σ_z/σ_r, N) in the *high density blowout regime*, where theory is sparse and simulations problematic.
- Effect of beam loading & drive bunch depletion on wake structure
- Onset of wave breaking & electron injection from background plasma
- Onset of hosing instability

⋮

PWF-accelerated beam properties to measure

- energy
- energy spread
- transverse emittance
- bunch charge
- bunch length

Characterize x-rays emitted by...

- Re-injection into ERL undulators
- Betatron oscillations in ion column [*e.g.* 10^7 photons @ 6.4 keV in .01° cone][1]
- Thomson scatter by counter-propagating intense laser pulse [10^8 photons@ 1keV][2]

[1] SLAC E-157

[2] T Phuoc, PRL **90**, 075002 (2003), laser wakefield

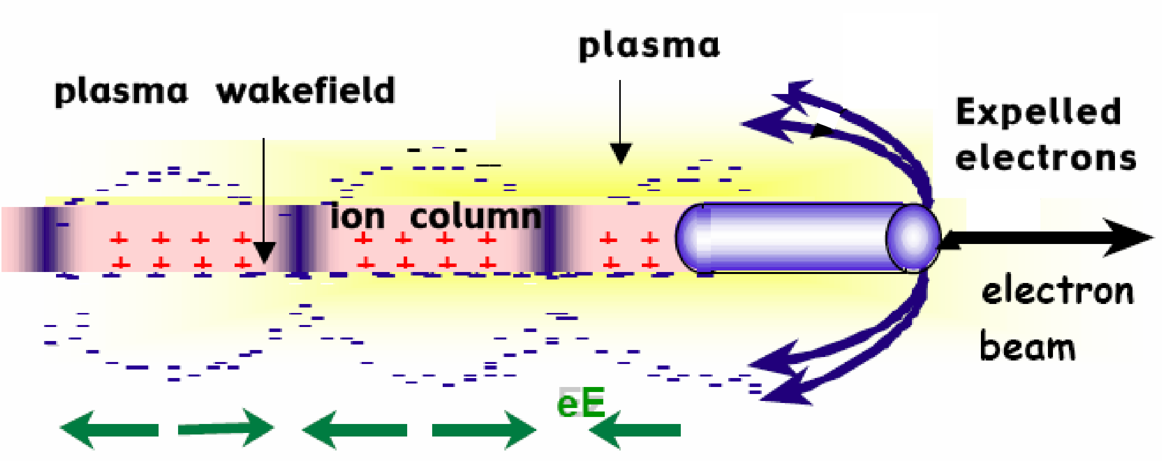
Summary

- Plasma wakefield boosters can potentially add flexibility to the Cornell ERL at low cost

  - optional increased energy
  - auxiliary ultrashort hard x-ray source

- R&D using visualization methods such as Frequency Domain Holography, is needed to perfect them

- They may also provide low-cost upgrades for HEP accelerators



The Cornell ERL is well qualified for 2nd generation plasma afterburner accelerator experiments

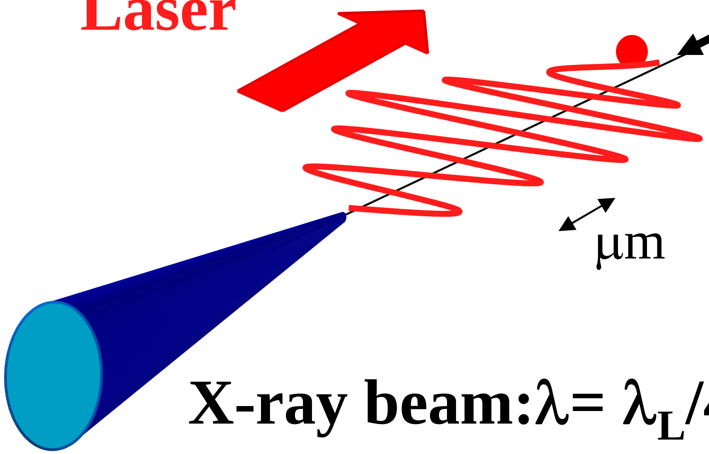
- **basic physics**
- **accelerator development**

Characteristic	SLAC E-164X	**Cornell ERL**	Importance
τ_{bunch}	~70 fs	20-50 fs	resonantly drive WF in dense ($n_e > 10^{17}$ cm^{-3}) plasma ⇒ high accelerating gradient ($E_z > 100$ GeV/m)
transverse emittance	60 ×15 mm-mrad	5 mm-mrad	tight focus $\sigma_r < \lambda_p \sim 10$ µm "blowout" regime: • stable propagation • low emittance growth • optimum E_z
bunch charge	~ 5 nC	~ 1 nC	$n_{bunch} > n_e$
repetition rate	10 Hz	~ MHz	• high S/N in physics experiments • high average current from plasma WF accelerator

Counter-propagating Thomson scatter:

tunable, fs X-ray pulses on a table-top

Banerjee *et al.*, Phys. Plasmas (2002)
Ta Phuoc *et al.*, PRL **90**, 075002 (2003)

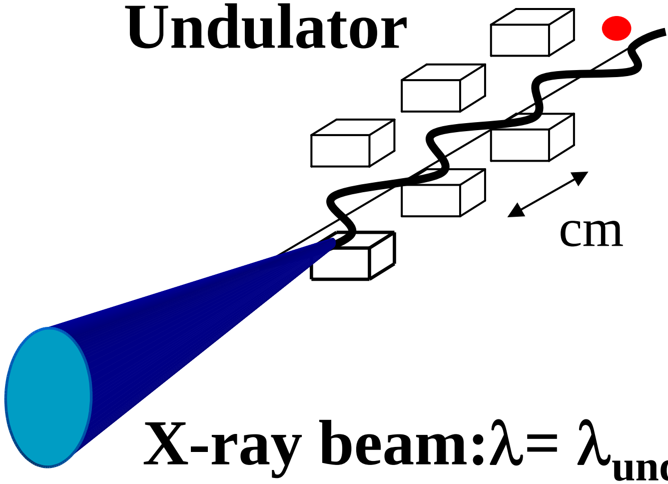


Counter-propagating Laser

LWFA
e$^-$ beam
(~tens MeV)

μm

X-ray beam:$\lambda = \lambda_L/4\gamma^2$



Undulator

synchrotron
e$^-$ beam
(GeV)

cm

X-ray beam:$\lambda = \lambda_{und}/2\gamma^2$