Advanced Laser/Plasma Accelerators and Applications

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Motivation
- Beam Driven Plasmas
- Laser Driven Plasmas
- Towards first applications
- Summary

- For further information:
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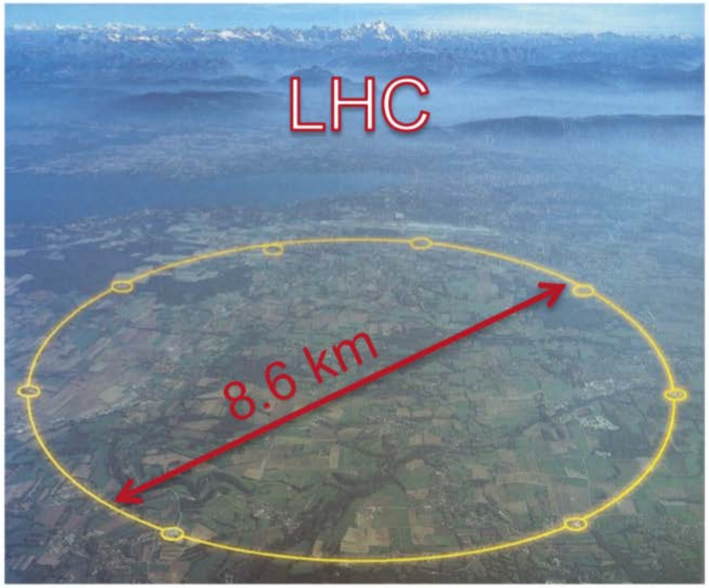
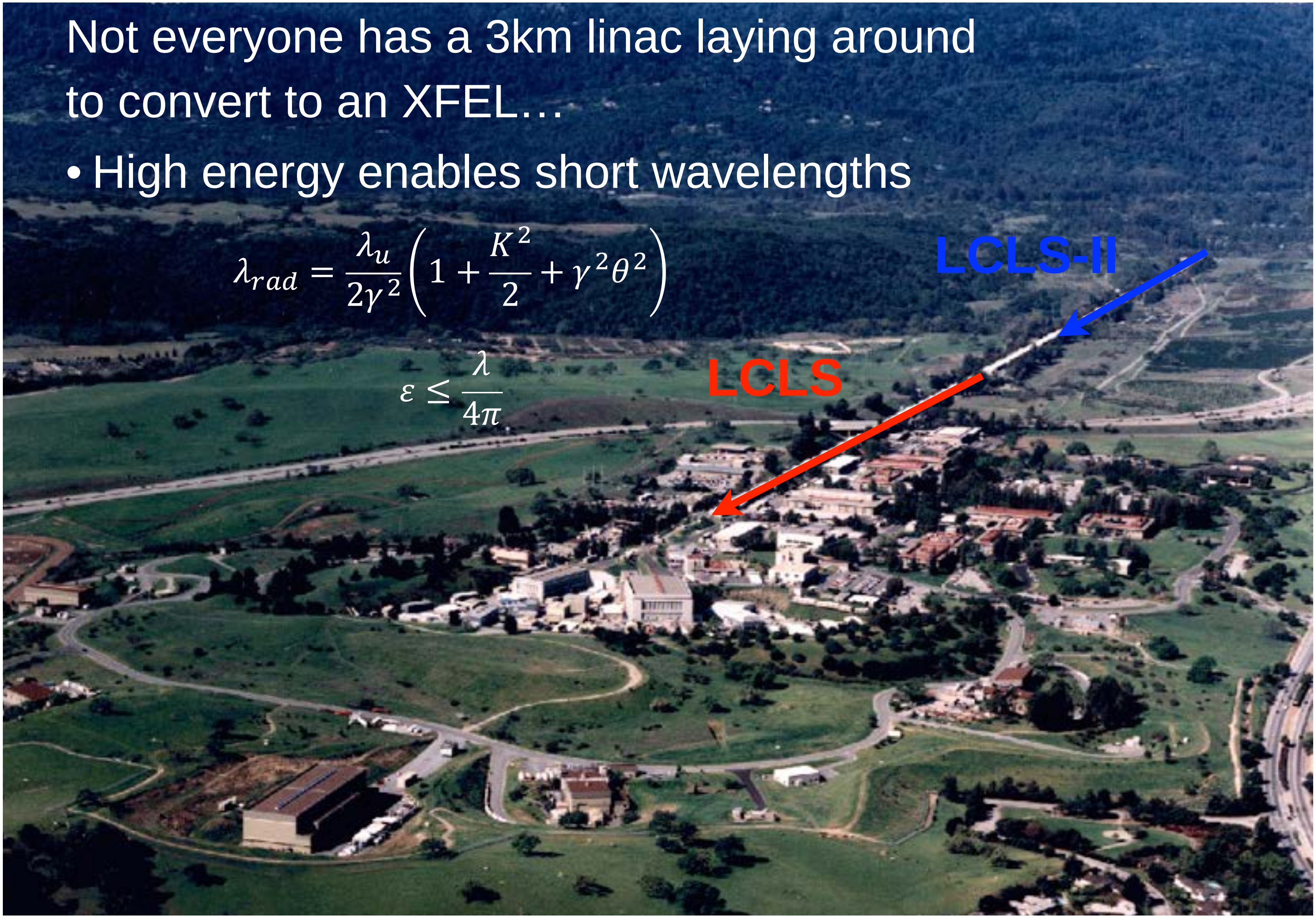
The Higgs has been found. Now what?

- Higgs Boson discovered at the LHC
- Next big machine: linear e^-e^+ collider
- SLC only linear collider so far:
  - 3 km long; 2 x 50 GeV beams
- Next collider needs higher energy beams (250GeV - 1.5TeV)
- ILC design: 30km long
- CLIC design: 50km long
- Limited by breakdown of metallic structures and/or cryo-technology
  - Accelerating gradient < 100MeV/m
- **Time for a new acceleration technology!**



Important for Photon Science too!



Not everyone has a 3km linac laying around to convert to an XFEL…

- High energy enables short wavelengths

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$\varepsilon \le \frac{\lambda}{4\pi}$$

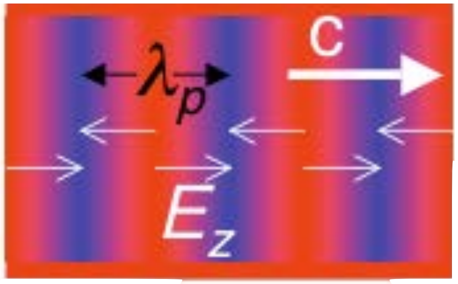
Why Plasmas?

Relativistic plasma wave (electrostatic):

$$\vec{\nabla}\cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}$$

$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

$n_e=10^{14}$ cm^{-3}

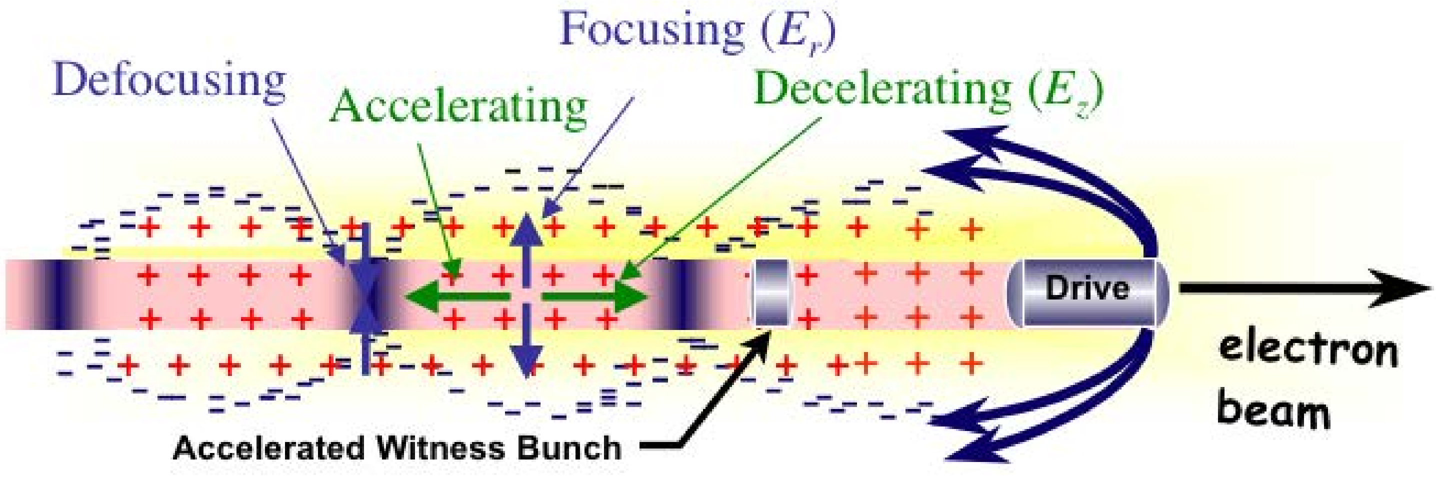


Large
Collective Response!

Compare: SLAC linac ~ 20MeV/m

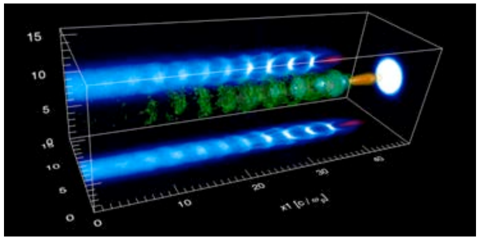
- Plasmas can sustain very large E_z field, acceleration
- Plasmas are already ionized (partially), difficult to break down
- High energy, high gradient acceleration!
- Plasma wave can be driven by:
  - ➡ Intense laser pulse (LWFA)
  - ➡ Short particle bunch (PWFA)

The Beam Driven Plasma Wakefield Accelerator



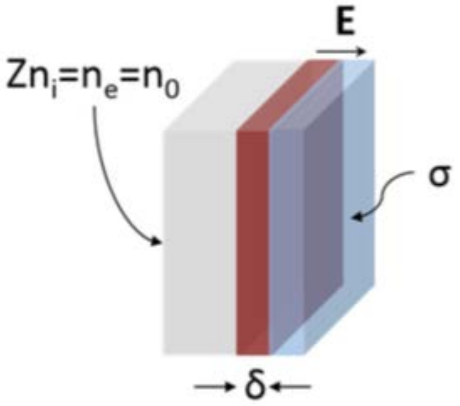
~1m

~100µm



- 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 $n_b/n_p \gg 1$

Plasma Frequency



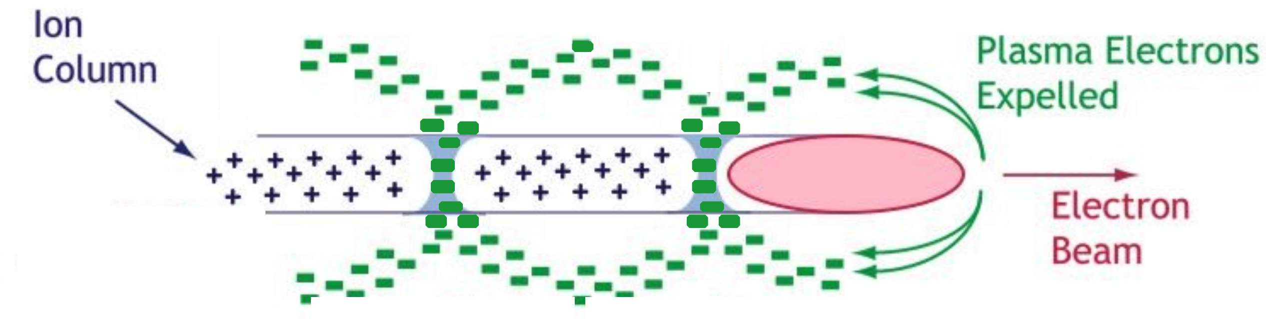
- Imagine an electron layer displaced in one dimension by length δ
- Creates 'two capacitor plates' with surface charge density: $\sigma = e n_e \delta$
- Electric field given by: $E = \frac{\sigma}{\varepsilon_0} = \frac{e n_e \delta}{\varepsilon_0}$
- Creates a restoring force: $m_e \frac{dv}{dt} = -m_e \frac{d^2\delta}{dt^2} = -eE = \frac{e^2 n_e \delta}{\varepsilon_0}$
- May be re-written as harmonic oscillator equation: $\frac{d^2\delta}{dt^2} + \omega_p^2 \delta = 0$
- With a characteristic electron plasma frequency and wavelength:

$$\omega_p[s^{-1}] \equiv \left(\frac{e^2 n_e}{\varepsilon_0 m_e}\right)^{1/2} \cong 6\times10^4 \sqrt{n_e[cc]}$$

$$\lambda_p \sim 100\mu m \cdot \left(n_p[cc]/10^{17}\right)^{-1/2}$$

More rigorous derivation in, e.g. F.F. Chen "Introduction to plasma physics and controlled fusion"

Transverse Forces: Focusing in the Ion Column

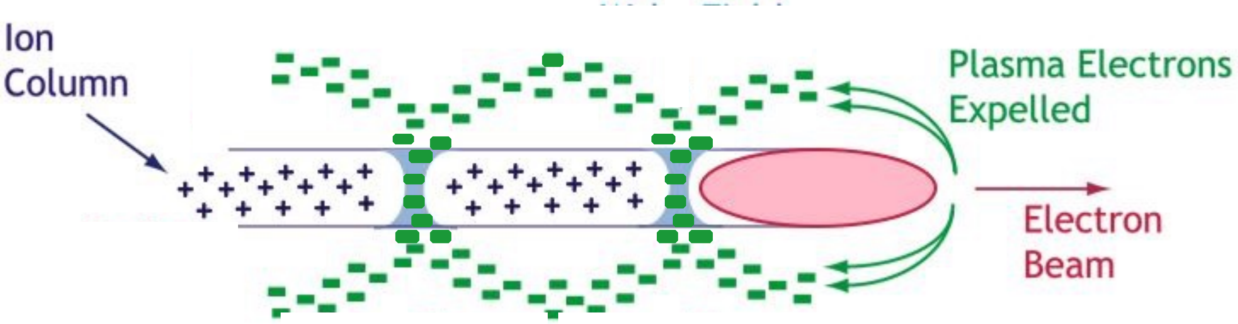


- Uniform ion density n_i = initial plasma density n_{e0}
- Focusing is balance between radial E and v x B ~ $E_r - cB_{phi}$
- Assume $n_b/n_p > 1$ and fully blown-out ion column
  - no plasma return currents within the beam (CFI)
  - In beam frame then no currents to drive B_{phi}
- Focusing then simply obtained from Gauss law for an infinite cylinder (approximation)

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \quad \Rightarrow \quad 2\pi r dz E_r = \frac{\pi r^2 e n_i}{\varepsilon_0} \quad \Rightarrow \quad E_r = \frac{1}{2}\frac{e n_{e0}}{\varepsilon_0} r$$

  - linear in r (ideal lens, no geometric aberration)
  - May preserve incoming emittance

Propagation in the Ion Column – Single Electron



$$E_r = \frac{1}{2}\frac{e n_{e0}}{\varepsilon_0} r$$

- Motion of a single electron in the ion column:

$$\gamma m \frac{dv_\perp}{dt} = F_\perp \quad \Rightarrow \quad \gamma m c^2 \frac{d^2 r}{dz^2} = e\frac{1}{2}\frac{e n_{e0}}{\varepsilon_0} r \quad \Rightarrow \quad \frac{d^2 r}{dz^2} = \frac{1}{2\gamma c^2}\frac{e^2 n_{e0}}{m\varepsilon_0} r = \frac{\omega_{pe}^2}{2\gamma c^2} r = \frac{k_{pe}^2}{2\gamma} r = k_\beta^2 r$$

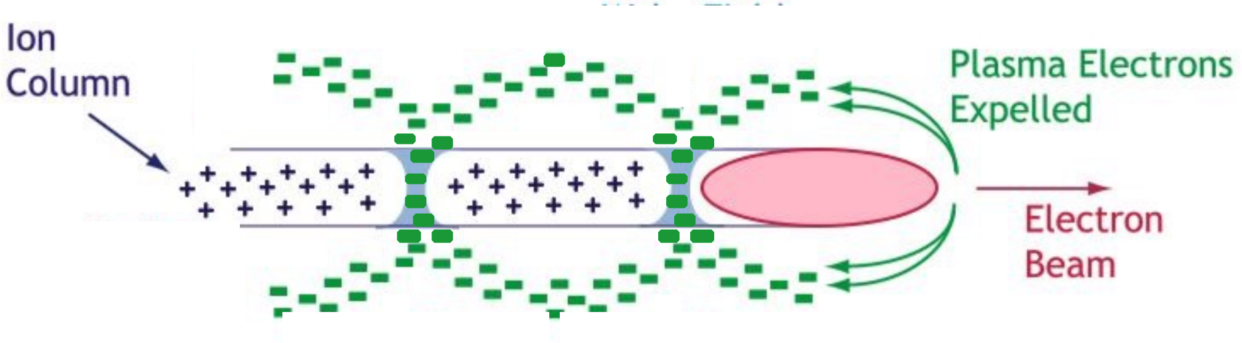
- Harmonic motion as long as no energy gain or loss:

$$\frac{d^2 r}{dz^2} = k_\beta^2 r \quad \Rightarrow \quad r(z) = r_0 e^{i k_\beta z}$$

- Relativistic electrons though, so will get synchrotron (betatron) radiation

- Particles oscillate at: $k_\beta^2 = \frac{k_p^2}{2\gamma}$ or $\omega_\beta = \omega_{pe}/\sqrt{2\gamma} << \omega_{pe}$

Propagation in the Ion Column for a Beam of Electrons



$$E_r = \frac{1}{2}\frac{e n_{e0}}{\varepsilon_0} r$$

- Beam evolution described by the envelope equation:

$$\frac{d^2\sigma}{dz^2} + K\sigma = \frac{\varepsilon^2}{\sigma^3} \quad \text{with} \quad K = \frac{k_p^2}{2\gamma} = k_\beta^2$$

- No evolution of spot size (sigma) when have matched condition:

$$\frac{d^2\sigma}{dz^2} = 0 \Rightarrow K = \frac{\varepsilon^2}{\sigma^4} = \frac{1}{\beta^2} \quad \text{or} \quad \beta_{matched} = \frac{\sqrt{2\gamma}}{k_p} = \sqrt{2\gamma}\,\frac{c}{\omega_p}$$

recalling $\sigma^2 = \beta\varepsilon$

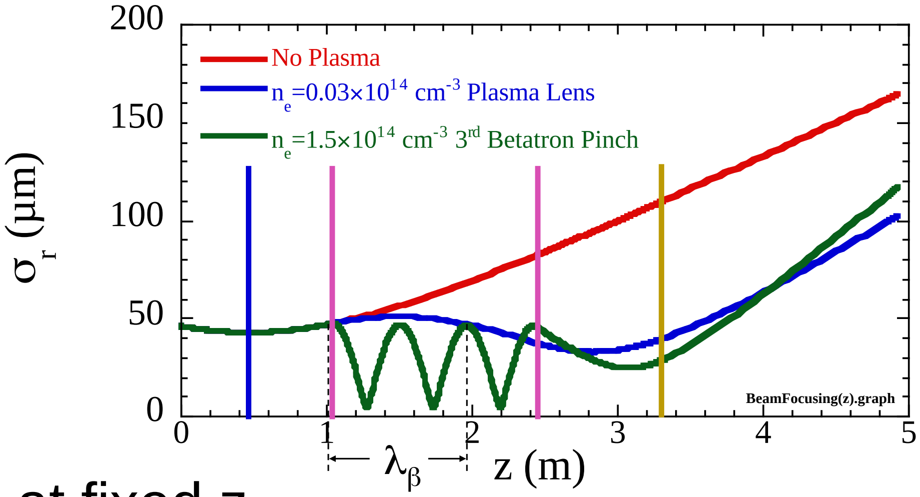
- There is a matched beta (n_p dependent) – not a matched spot size (e_n dependent), e.g. $n_p = 10^{17}$, c/w_p = 17µm and Beta matched = 1mm (<<L_p!). For e_n = 1µm, E = 1GeV get a matched sigma = 0.7µm

Measured Plasma Focusing for Matched & Mismatched Beams

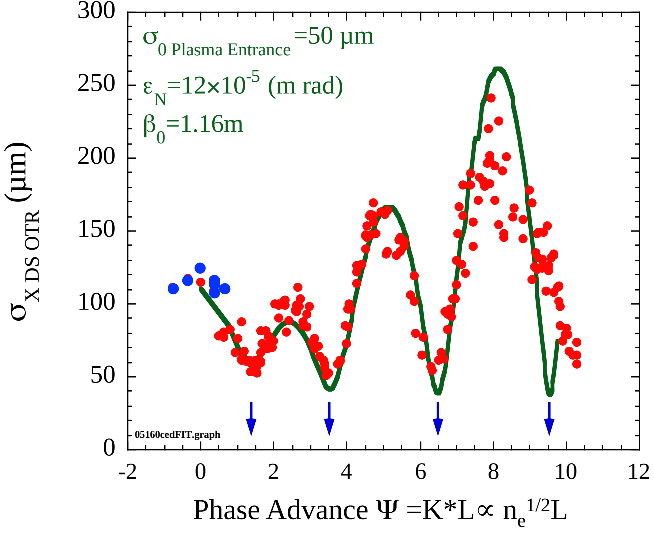
- Start with beam evolution in vacuum

$$\sigma_r(z) = \sigma_{r0}\left(1+\frac{\varepsilon^2 z^2}{\sigma_0^4}\right)^{1/2} = \sigma_{r0}\left(1+\frac{\varepsilon^2}{\beta_0^2}\right)^{1/2}$$

- Increase the density/focusing
  - Can’t always measure in plasma
  - Look on profile monitor downstream
  - Sigma(z) at fixed np same as sigma(np) at fixed z

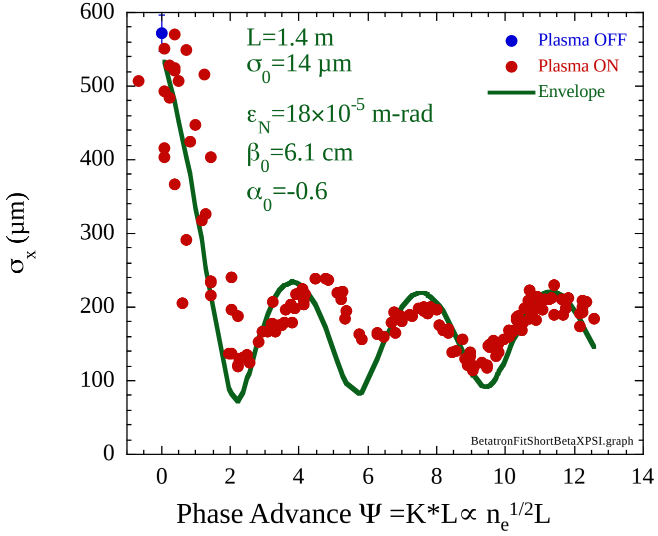


Large Beam Size (K>1/β₀)



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

Small Beam Size (K≤1/β₀)



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

- Focusing orders of magnitude larger than beamline quadrupoles
- Well described by simple model
- Multiple foci within the plasma

Accelerating Fields

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{e\mathbf{E}}{m}$$ Momentum/Force equation

$$\frac{\partial}{\partial t}\left[\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{v}\right] = 0$$ Continuity equation

$$\nabla \cdot \mathbf{E} = -4\pi e(\delta n + n_b)$$ Poisson equation

Change variables

$\zeta = z - ct$ and substituting k_p^2 for ω_p^2/c^2

Equation for perturbed density

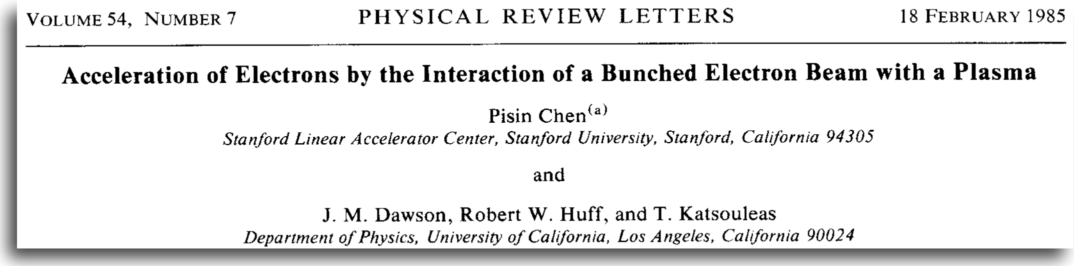
$$(\partial_\zeta^2 + k_p^2)\delta n = -k_p^2 n_b$$

Driving term for E

$$\left(\nabla_\perp^2 - k_p^2\right)\mathbf{E_z} \quad = \quad -4\pi e \nabla \delta n$$

Simplify in narrow beam limit

$$k_p \sigma_r \ll 1$$



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024

Finally an equation for Ez behind the beam

$$E_z = \frac{8\pi e N}{\sigma_z^2} u e^{-u} \qquad \text{with} \qquad u = k_p^2 \sigma_z^2/2$$

Maximized when bunch length matched to n_p

$$k_p \sigma_z = \sqrt{2}$$

With notable scaling: $E_z \propto n_p^{1/2} \propto \dfrac{N}{\sigma_z^2}$

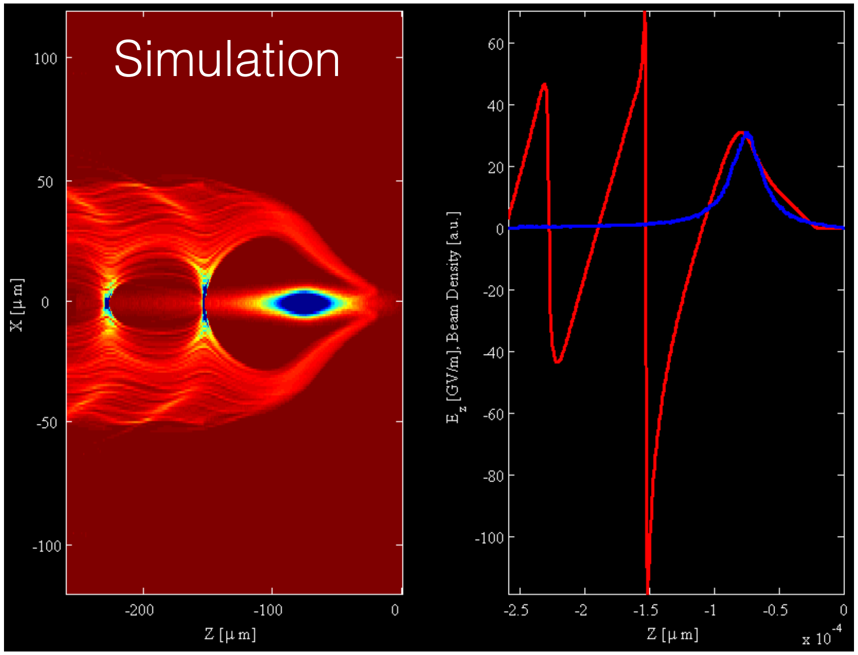
In practical terms

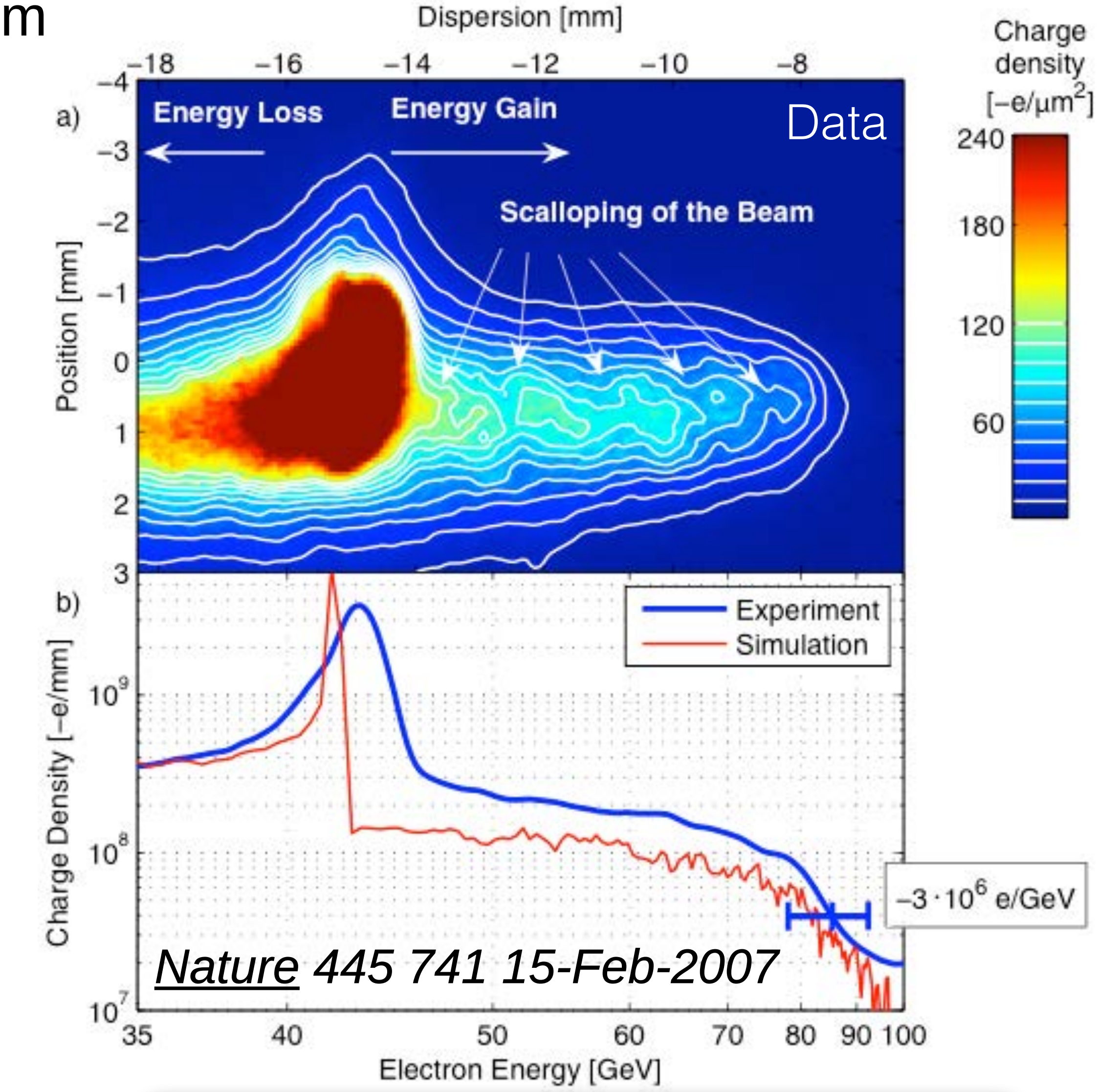
$$eE_z[MeV/m] \simeq 240 \times \left(\frac{N}{4 \times 10^{10}}\right)\left(\frac{0.6}{\sigma_z[mm]}\right)^2$$

e.g. 2E10, 30μm gives 50GeV/m!

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

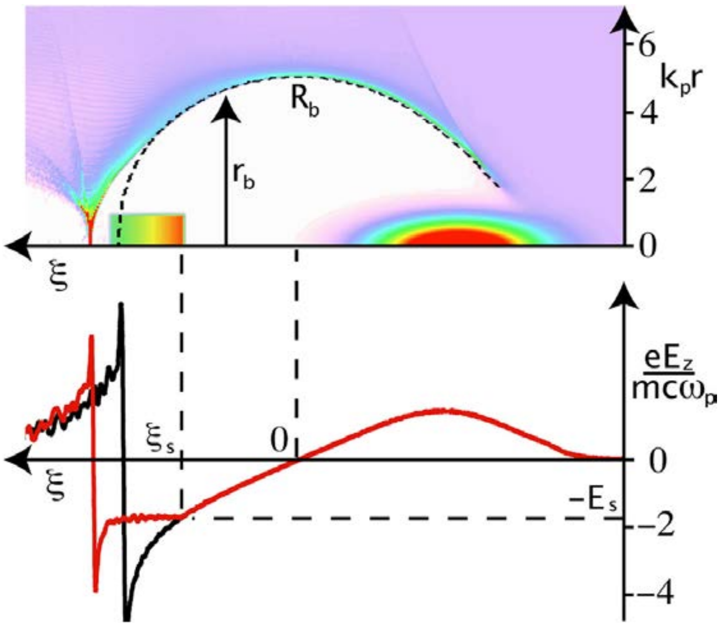
Next Step: Particle acceleration to beam acceleration @ FACET

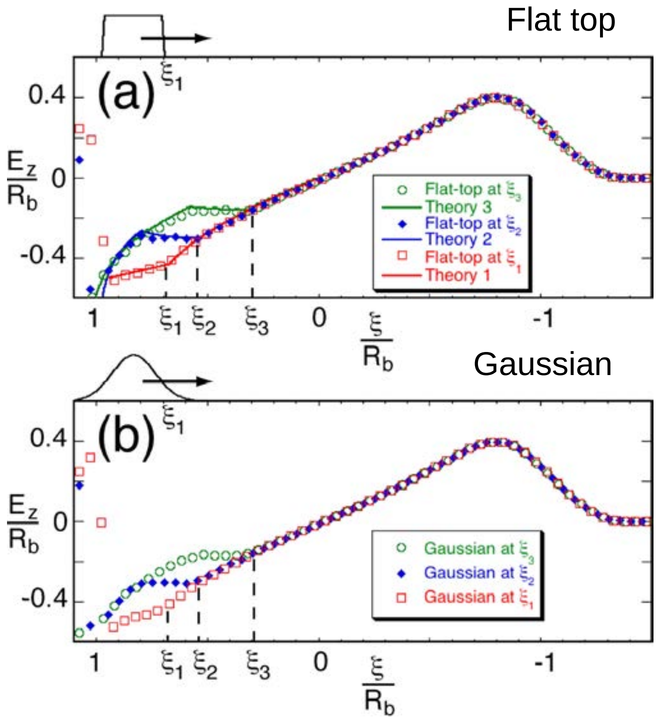
Beam Loading in Non-linear Wakes

Theoretical framework, augmented by simulations

Quasi-static approximation, co-moving frame at v=c, by symmetry find E_{phi}, B_z, $B_r = 0$ and:

$$E_z = -\frac{1}{c\epsilon_0}\int_r^\infty dr\, j_r$$



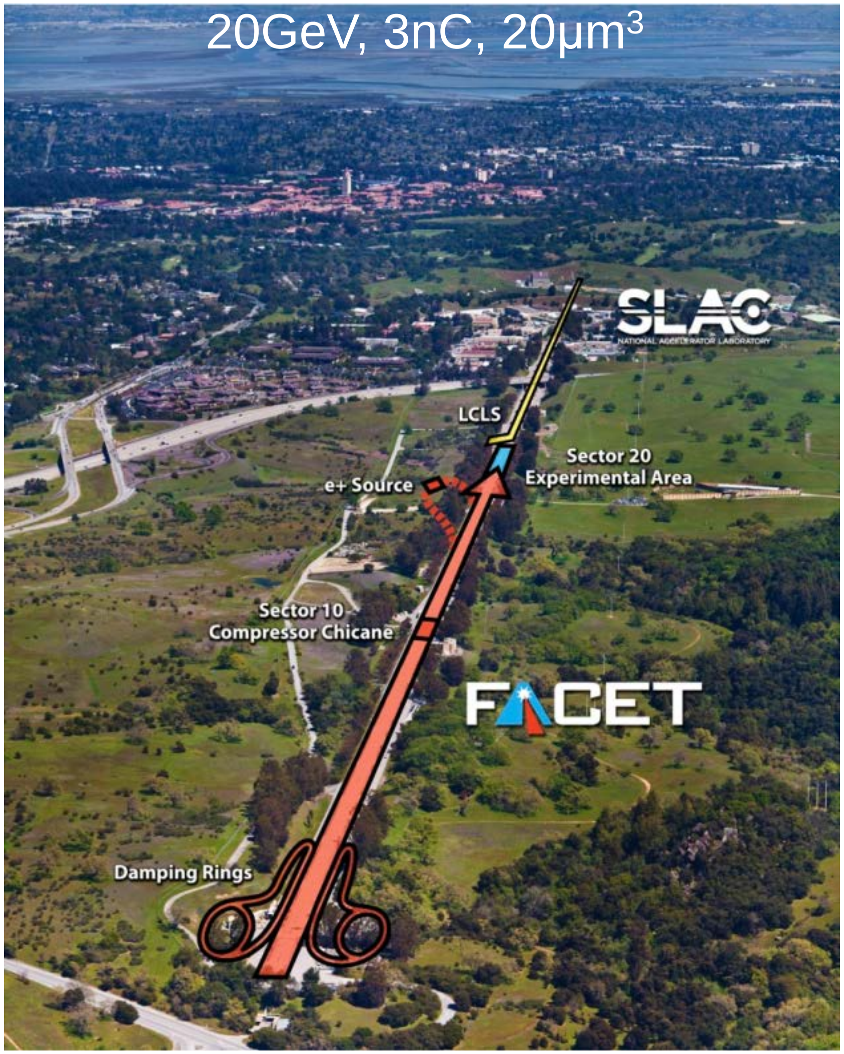


- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards $\Delta E/E \sim 10^{-2} - 10^{-3}$
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

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

FACET Has a Multi-year Program to Study PWFA



Primary Goal: Demonstrate a single-stage high-energy plasma accelerator for electrons.

- Meter scale ✓
- High gradient ✓
- Preserved emittance
- Low energy spread ✓
- High efficiency ✓

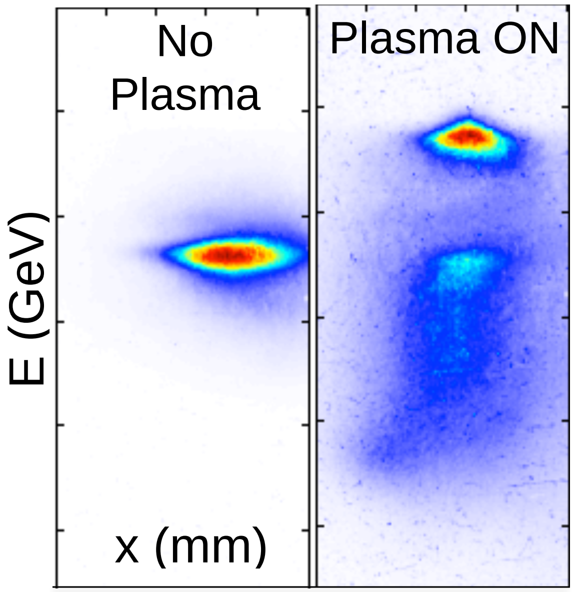
Timeline:

- CD–0 2008 ✓
- Commissioning (2012) ✓
- Drive & witness e^- bunch (2012-2013) ✓
- Optimization of e^- acceleration (2013-2015)
- First high-gradient e^+ PWFA (2014-2016)

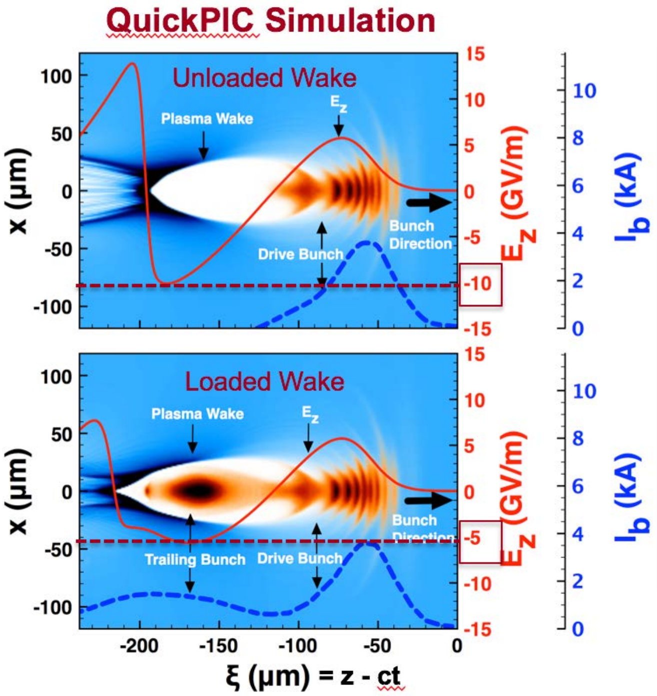
FACET user program is based on high-energy high-brightness beams and their interaction with plasmas and lasers

High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

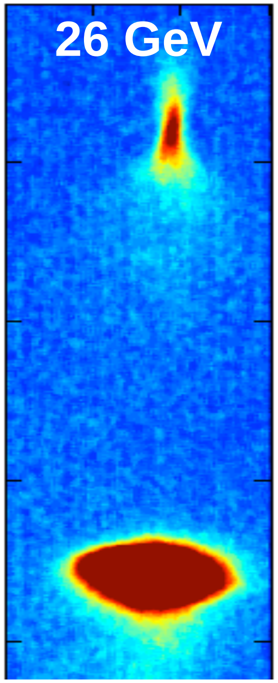
- Inject two beams into the plasma
  - One drives the wake, one samples the wake
- Beam loading is key for:
  - Narrow energy spread & high efficiency



2 GeV Energy Gain
~2% dE/E
~30% efficiency

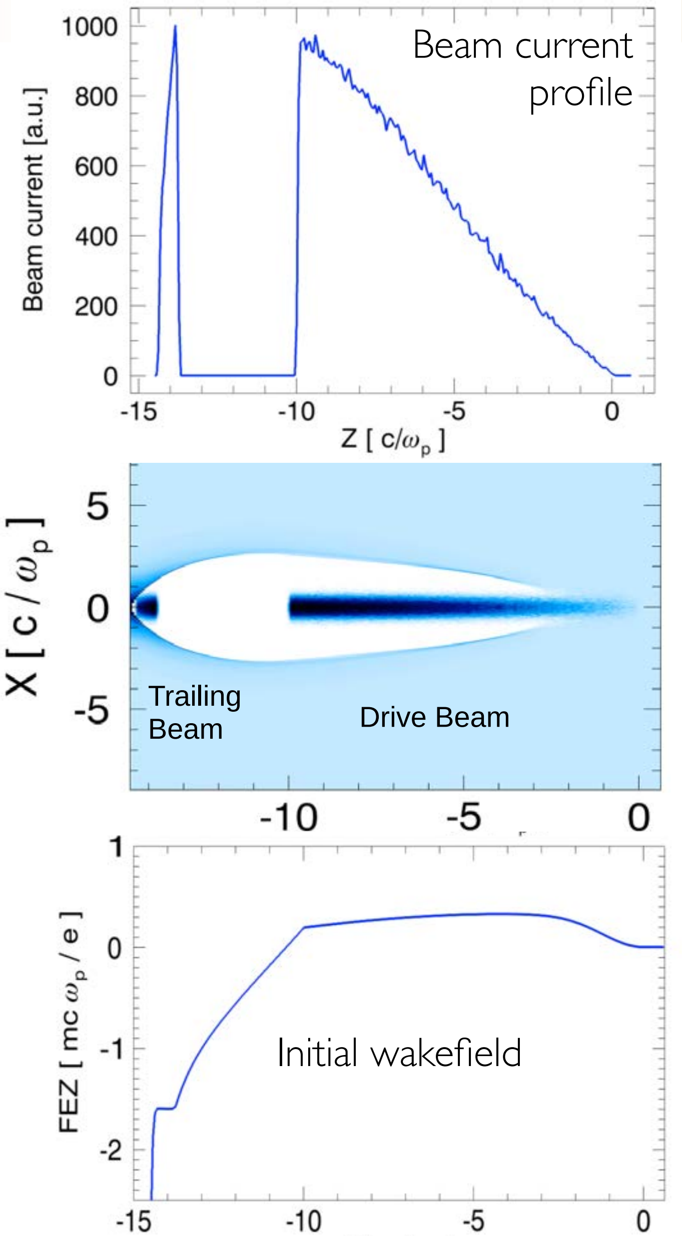


Nature ***515****, 92-95*
(November 2014)

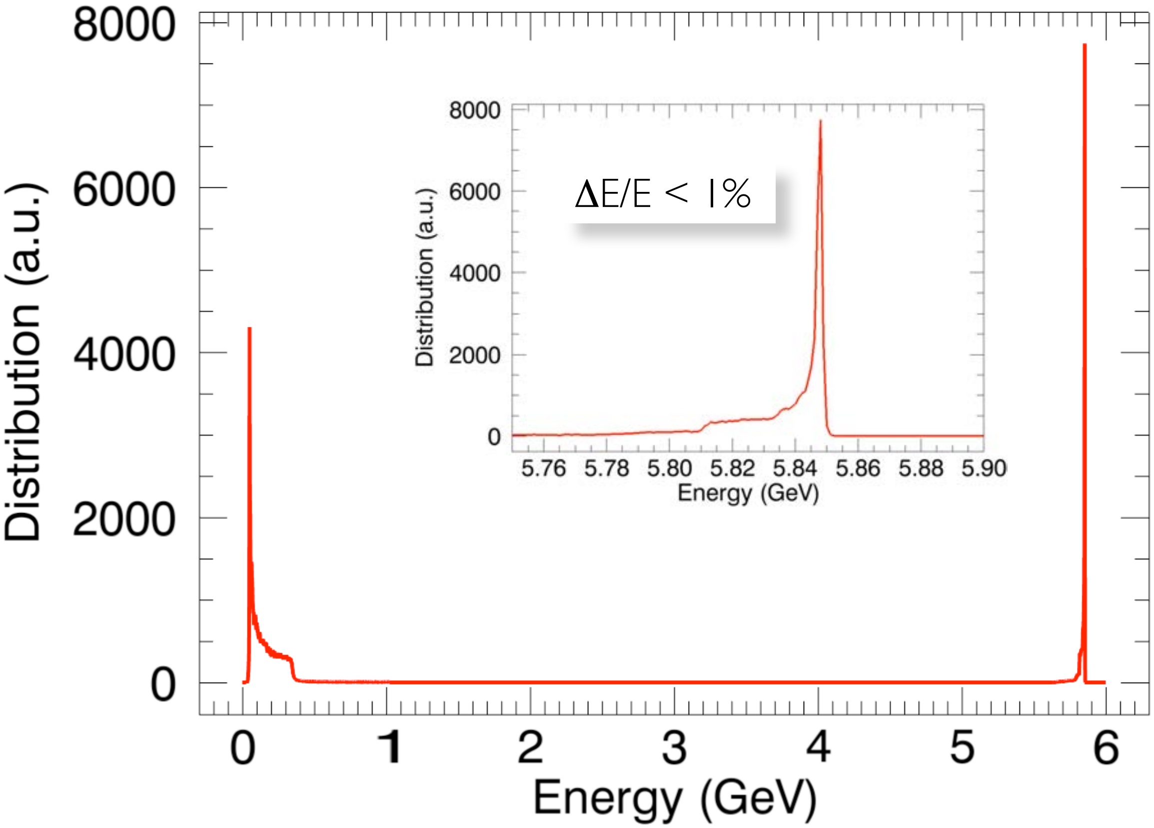


Single shot
6 GeV
Energy Gain

Looking Ahead: Shaped Profile for Transformer Ratio ~ 5

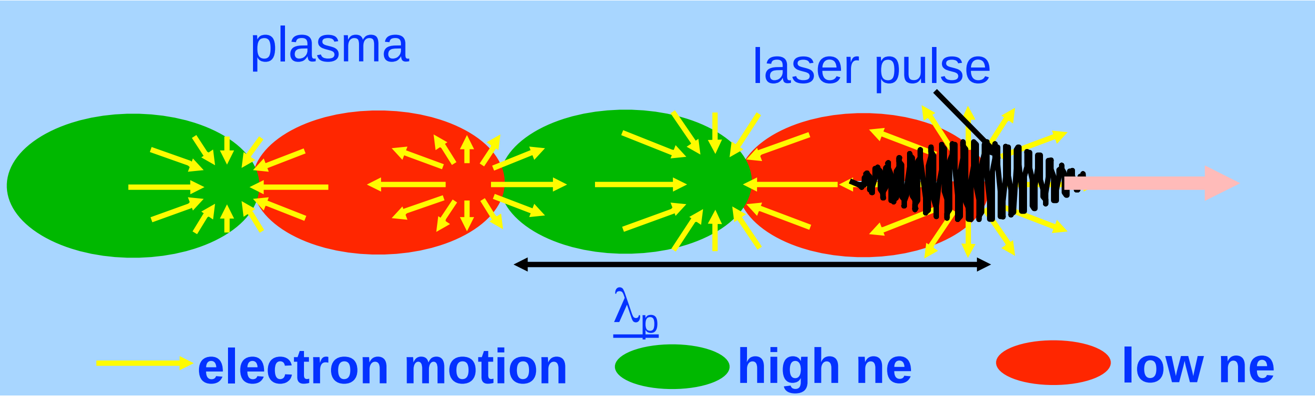


- Application to colliders & X-FELs
- Reduced energy spread
- Higher efficiency (beam power)
- Fewer stages



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

Laser Driven Excitation of Plasma Waves: Laser Wakefield Accelerator (LWFA)



- Standard regime (LWFA)
  - Pulse duration matches plasma period
  - Radiation pressure of intense laser pulse excites plasma wave (wakefield)

$$E = E_0 \sin(\omega t) \qquad \frac{dv}{dt} \simeq \frac{-eE_0}{m_e}\sin(\omega t) \qquad \Rightarrow v = \frac{-eE_0}{m_e\omega}\cos(\omega t)$$

$$a_0 \equiv \frac{v}{c} = \frac{-eE_0}{m_e \omega c} \qquad a_0 = 0.85\times10^{-9}\lambda[\mu m](I_0[W/cm^2])^{1/2}$$

e.g. $a_0 \sim 1$ for 1μm, 10^{18}W/cm^2

- Excitation possible with longer laser pulses too
  - SMI/Raman Forward Scattering
  - Beat wave
  - Scaling same as for beam drivers →

- Electric field of plasma wave (n = density):
  $E \sim n^{1/2} \sim 100$ GV/m for $n \sim 10^{18}$ cm^{-3}
- Laser Pulse length ~ plasma wavelength λ_p
  $L \sim \lambda_p \sim n^{-1/2} \sim 30$ μm (100 fs) for $n \sim 10^{18}$ cm^{-3}

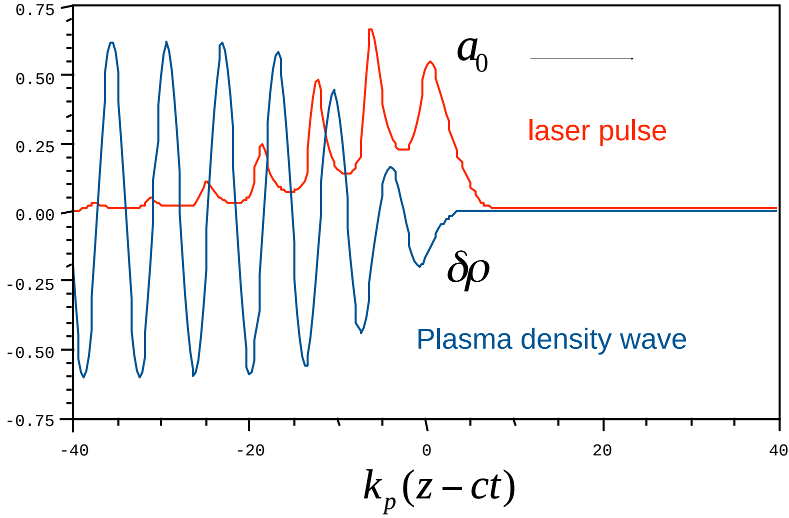
Tajima, Dawson (79); Gorbunov, Kirsanov (87); Sprangle, Esarey *et al.* (88), Esaray *et al.* Rev. Mod. Phys. 81, 1229 (2009)

State-of-the-Art Prior to 2004:
Self-Modulated Laser Wakefield Accelerator (SM-LWFA)

Self-modulated regime:

- Laser pulse duration > plasma period
- Laser power > critical power for self-guiding
- High-phase velocity plasma waves by
  - Raman forward scattering
  - Self-modulation instability

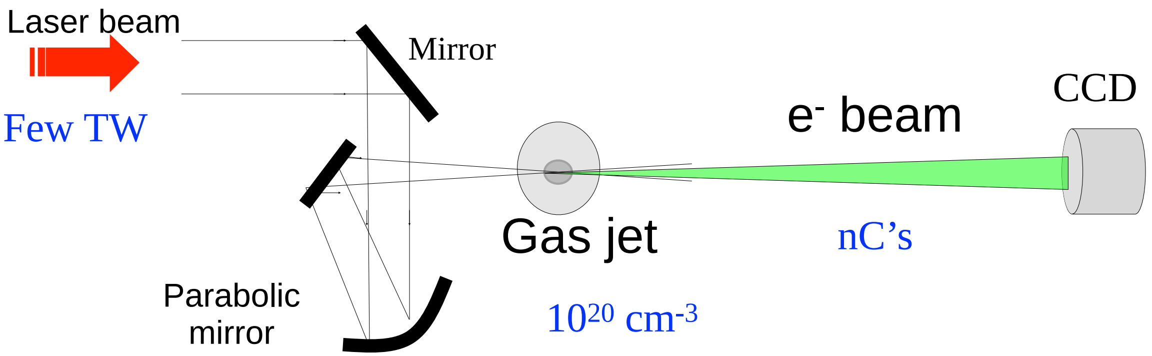
Sprangle *et al.* (92); Antonsen, Mora (92); Andreev *et al.* (92); Esarey *et al.* (94); Mori *et al.* (94)



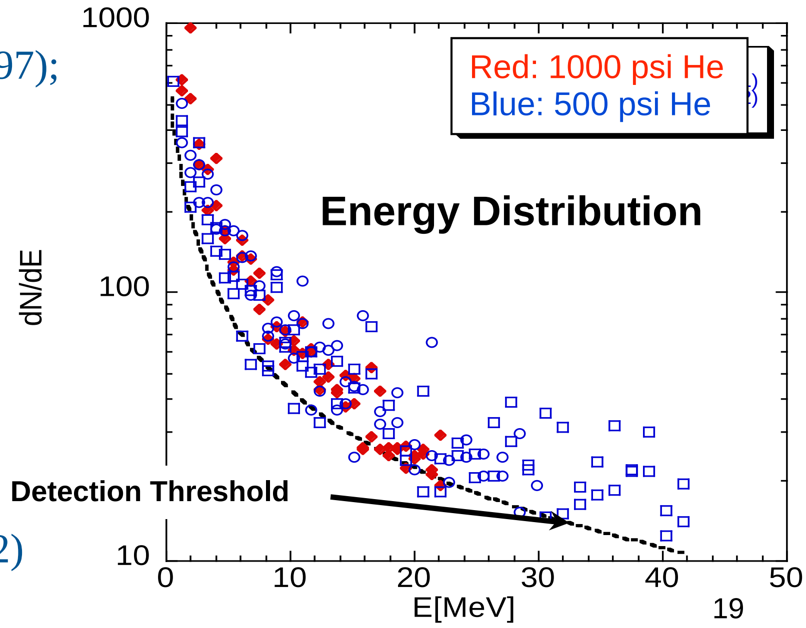
SM-LWFA experiments routinely produce electrons with:

1-100 MeV (100% energy spread), multi-nC, ~100 fs, ~10 mrad divergence

Modena *et al.* (95); Nakajima *et al.* (95); Umstadter *et al.* (96); Ting *et al.* (97); Gahn *et al.* (99); Leemans *et al.* (01); Malka *et al.* (01)

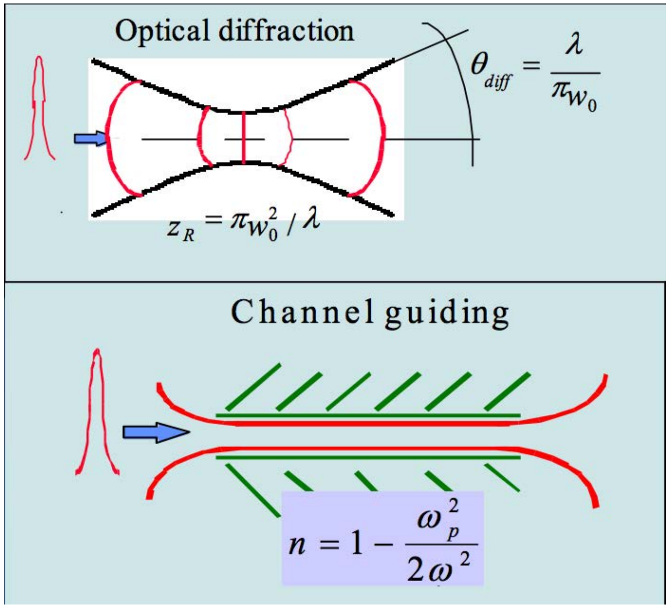


Leemans *et al.* (02)



Courtesy of E. Esarey

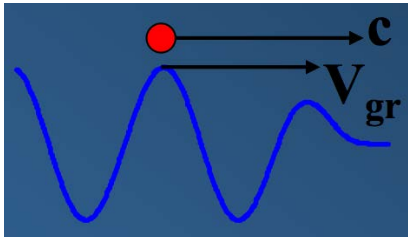
Three Factors Limiting Energy Gain – Three D's of LWFA



- Diffraction
  - Order ~mm for 1μm laser with 17μm waist
  - May be overcome with channel guiding or relativistic self-focusing

$$Z_R = \frac{\pi\omega_0^2}{\lambda}$$

- Dephasing:



$$L_{dephase} = \frac{\lambda_p}{2(1-\beta_p)} \approx \frac{\lambda_p^3}{\lambda^2} \propto n_p^{-3/2}$$

e.g. 10^{18}/cc, 1μm = 3cm

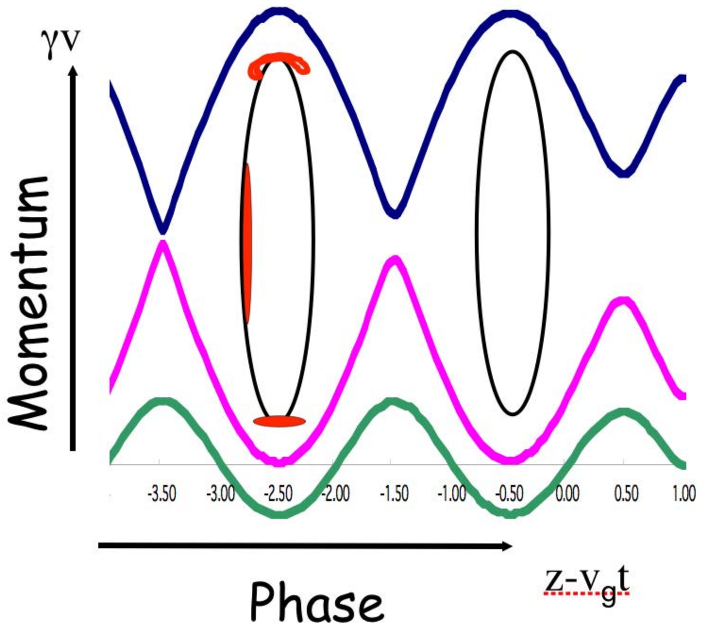
- Depletion
  - For small intensities (a_0<1) >> $L_{dephase}$
  - For relativistic intensities a_0>1, $L_{dephase}$~ $L_{depletion}$

$$L_{deplete} \sim \frac{4L_{dephase}}{a_0^2}$$

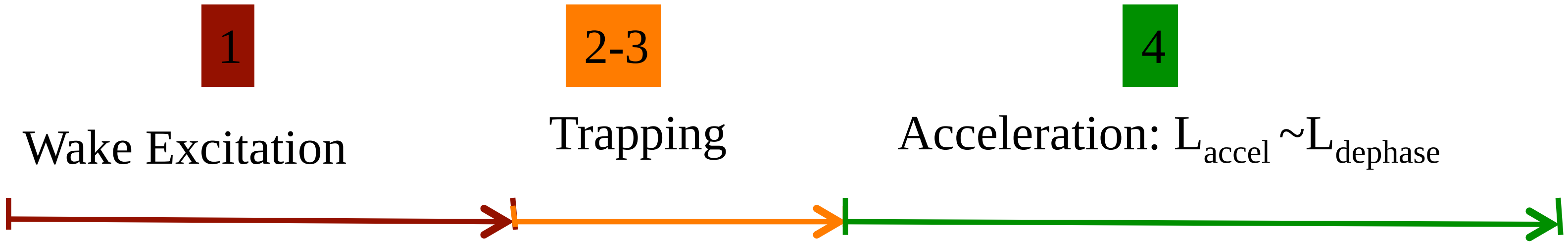
E. Esarey et al. Reviews of Modern Physics ***81*** *1229 (2009)*

LWFA: Production of a ‘Monoenergetic’ Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
   - Requires high density
     - Large fields and slow v_{ph}
3. Termination of trapping (e.g., beam loading)
4. Acceleration
   - If > dephasing length: large energy spread
   - If ≈ dephasing length: monoenergetic



Dephasing distance: $$L_{dph} \approx \left(\lambda_p^3 / \lambda^2\right) \propto n_e^{-3/2}$$



1

Wake Excitation

2-3

Trapping

4

Acceleration: $L_{accel} \sim L_{dephase}$

Courtesy of E. Esarey

Breakthrough Results: High Quality Bunches

30 Sep 2004 issue of *nature*:

Three groups report production of high quality e-bunches

Approach 1: Plasma channel

- LBNL/USA: Geddes et al.
  - Plasma Channel: 1-4x10^{19} cm^{-3}
  - Laser: 8-9 TW, 8.5 μm, 55 fs
  - E-bunch: 2×10^{9} (0.3 nC), 86 MeV, $\Delta E/E$=1-2%, 3 mrad

Approach 2: No channel, larger spot size

- RAL/IC/UK: Mangles et al.
  - No Channel: 2×10^{19} cm^{-3}
  - Laser: 12 TW, 40 fs, 0.5 J, 2.5×10^{18} W/cm^{2}, 25 μm
  - E-bunch: 1.4×10^{8} (22 pC), 70 MeV, $\Delta E/E$=3%, 87 mrad
- LOA/France: Faure et al.
  - No Channel: 0.5-2x10^{19} cm^{-3}
  - Laser: 30 TW, 30 fs, 1 J, 18 μm
  - E-bunch: 3×10^{9} (0.5 nC), 170 MeV, $\Delta E/E$=24%,10 mrad

Channel allows higher e-energy with lower laser power

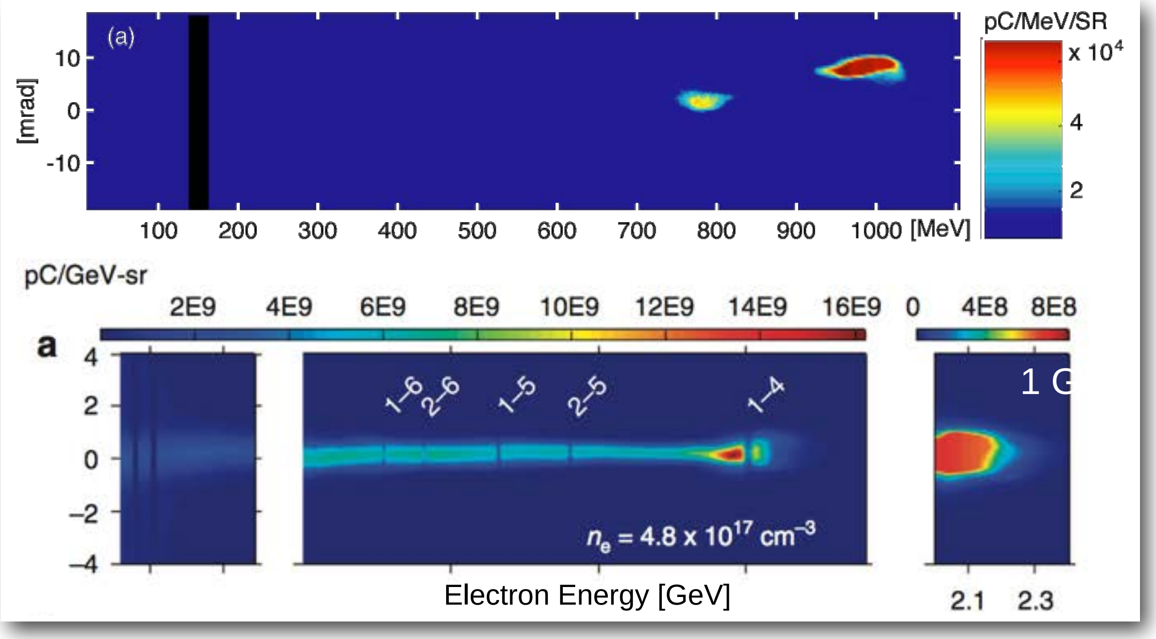
Courtesy of E. Esarey

Race for Maximum Energy Gain

Laser Driven Plasmas:

- 50 GeV/m fields, stable over cm’s
- High quality <μm emittance beams created and accelerated in the plasma

Nature Physics **2**, 696 - 699 (2006)

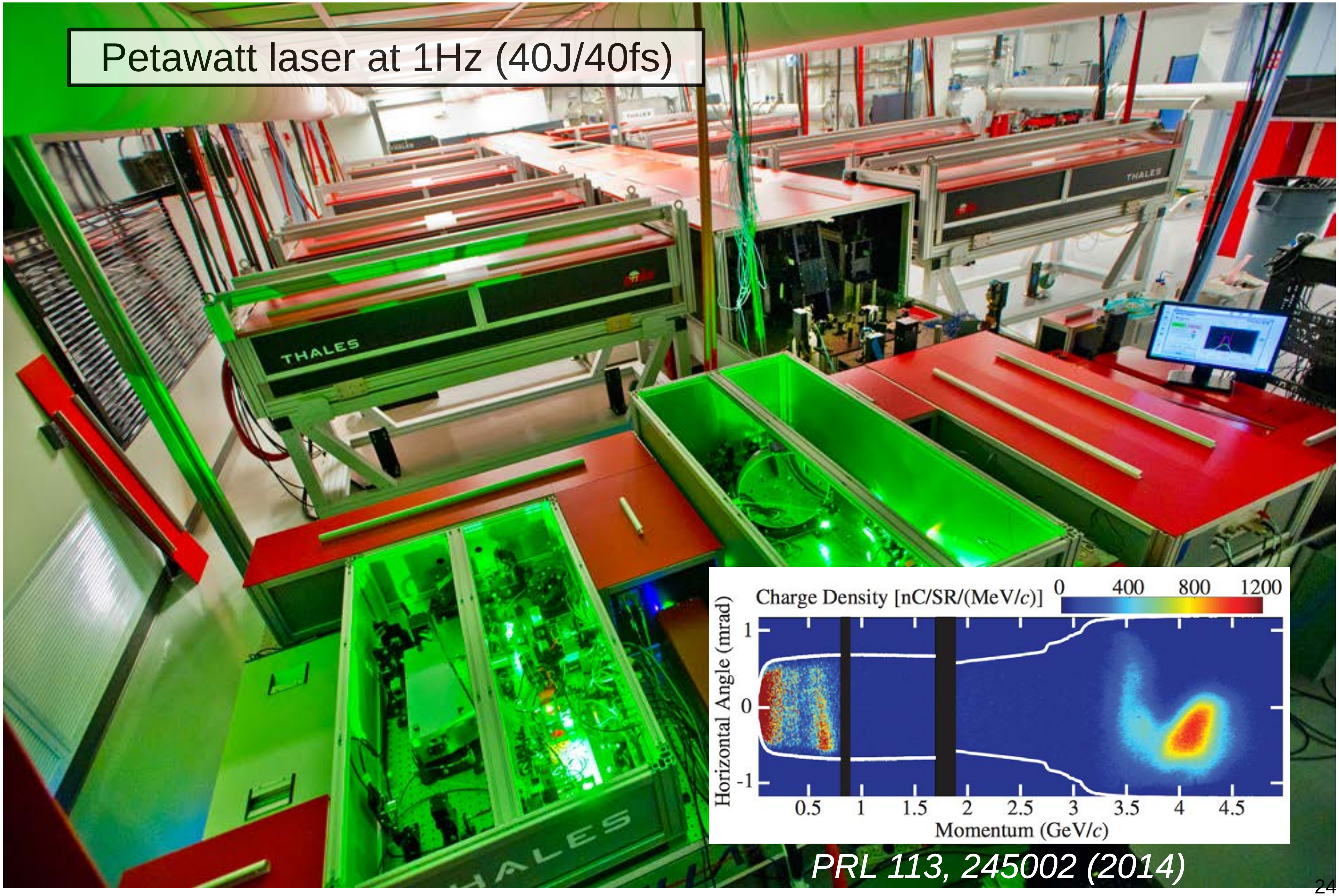


Nat Commun. ***4****:1988 doi: 10.1038/ncomms2988 (2013)*

How to balance or overcome the three D’s of LWFA:

- Diffraction (guiding), De-phasing (lower denisty, tailored plasma profiles), Depletion (more laser energy)

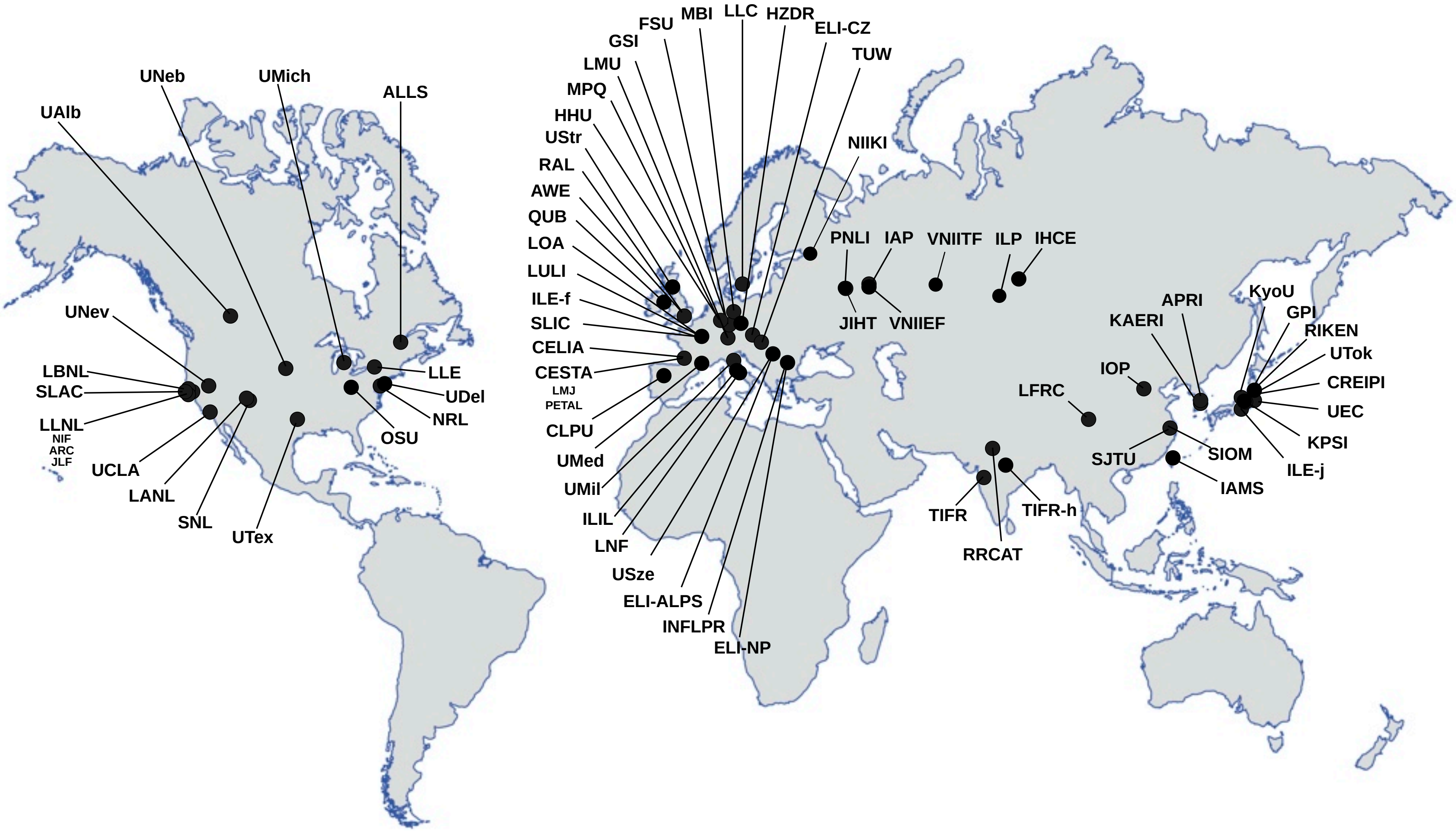
BELLA Laser at Lawrence Berkeley Lab (LBNL)


Petawatt laser at 1Hz (40J/40fs)

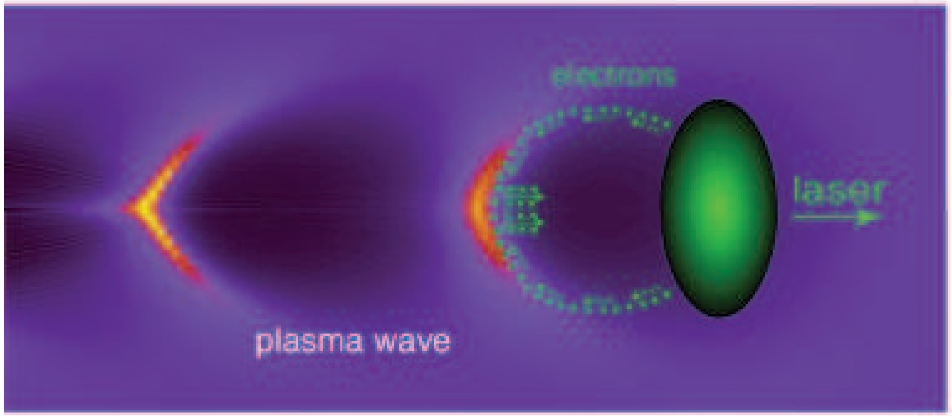
PRL 113, 245002 (2014)

2010 ICUIL World Map of Ultrahigh Intensity Lasers

Many groups looking into ways to improve not just peak energy, but also stability, beam quality



Controlled Injection for Better Beam Quality & Stability

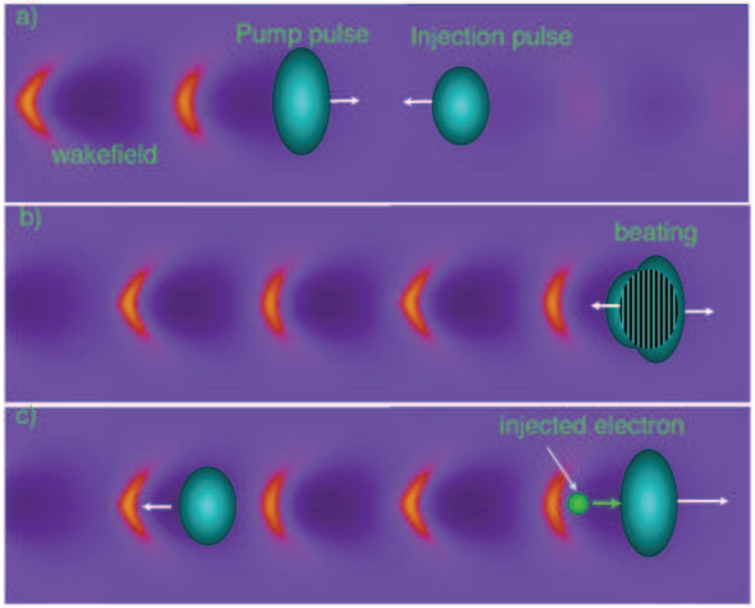


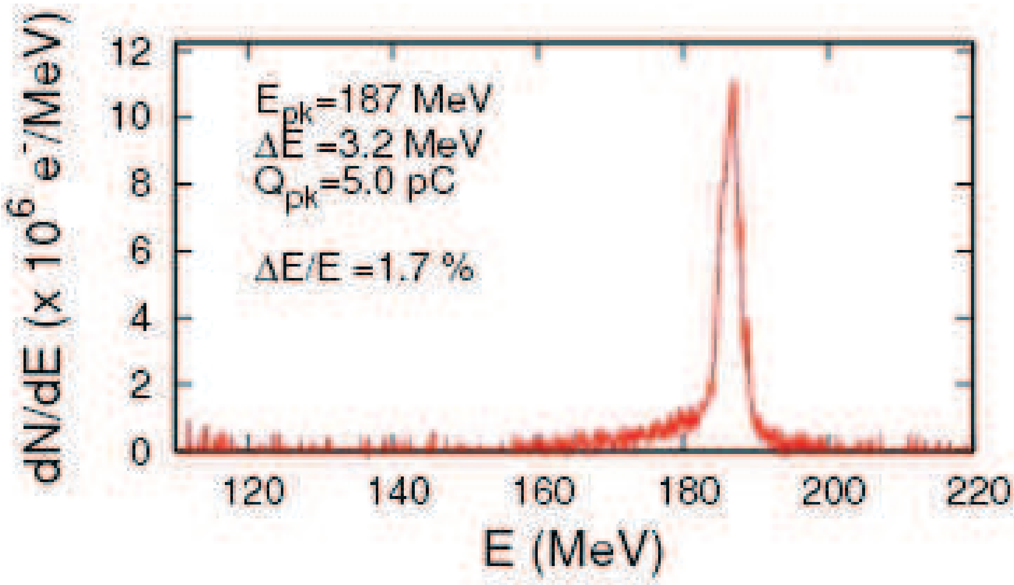
Standard Injection

- Electrons circulate around the cavitated region before being trapped and accelerated at the back of the laser pulse

Colliding Pulse Injection

- Beatwave of two laser counter propagating laser pulses
- Controls injection process/location for higher quality/stability

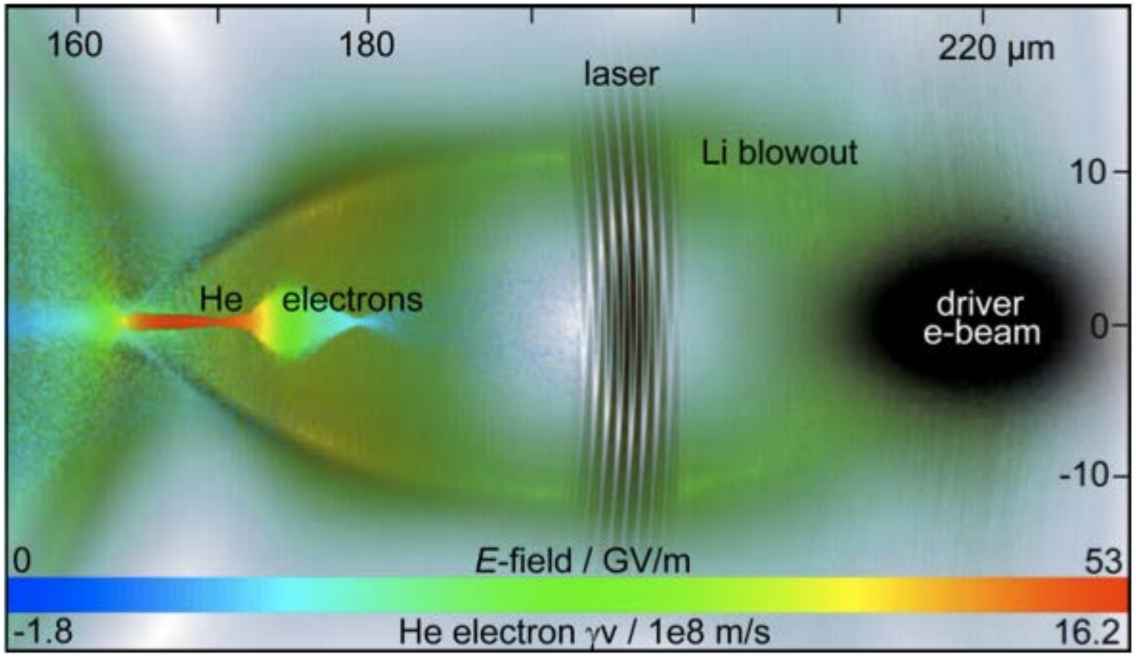




See: Esarey et al, PhysRevLett.79.2682 and Victor Malka (2010). Laser Plasma Accelerators: towards High Quality Electron Beam, Laser Pulse Phenomena and Applications, Dr. F. J. Duarte (Ed.), ISBN: 978-953-307-405-4 and References within

Underdense Plasma Photocathode a.k.a. the 'Trojan Horse Technique'

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Photoinjector + 100GeV/m fields in the plasma = Ultra-high brightness beams
  - Unprecedented emittance (down to 10^{-8} m rad)
  - Sub-μm spot size
  - fs pulses
- Two gas species with relatively high & low ionization potential
- Electron beam forms plasma in LIT gas and drives strong wakefield (bubble)
- Injection laser (short pulse, tight focus, fs synchronization) releases HIT electrons in the bubble

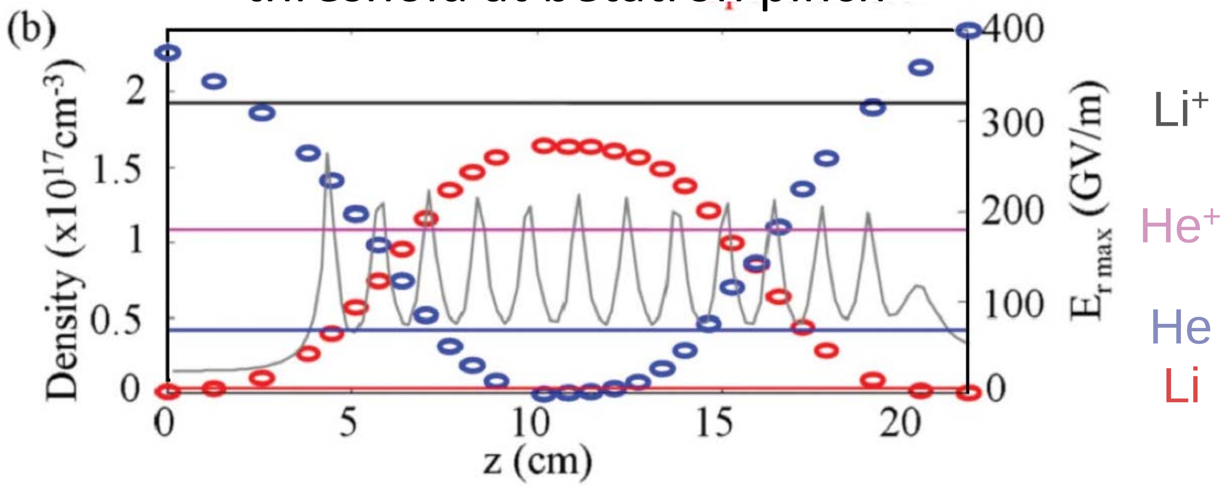


B. Hidding *et al.* Phys. Rev. Lett. 108, 035001 (2012)

Experiment in progress at FACET - stay tuned!

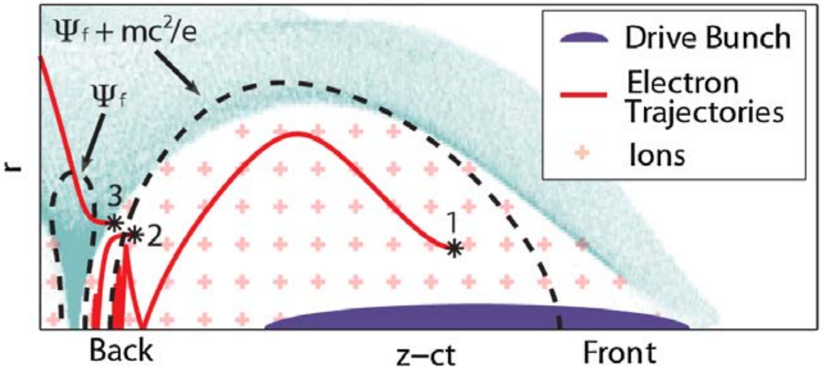
Ionization-Induced Electron Trapping in Ultra-relativistic Plasma Wakes

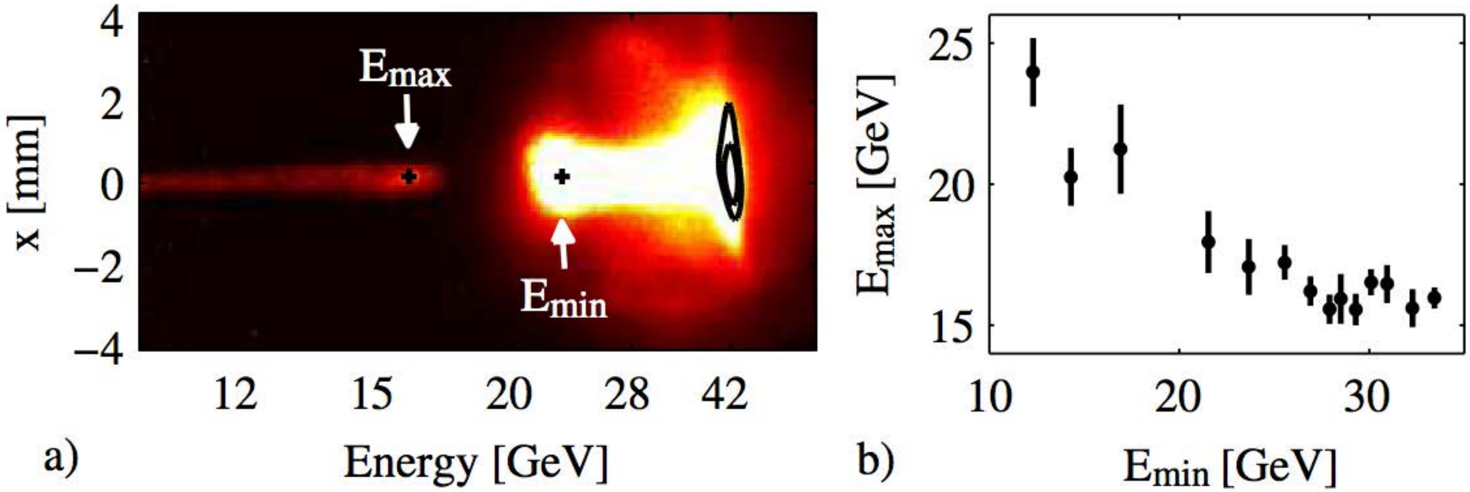
Beam fields exceed ionization threshold at betatron pinch



Phys. Rev. Lett. ***98****, 084801 (2007)*

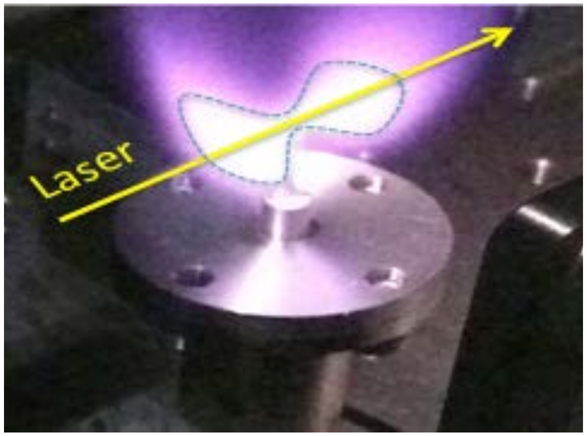
Electrons ionized within wakefield can get trapped and accelerated





Phys. Rev. ST – Accel. and Beams ***12****, 051302 (2009)*

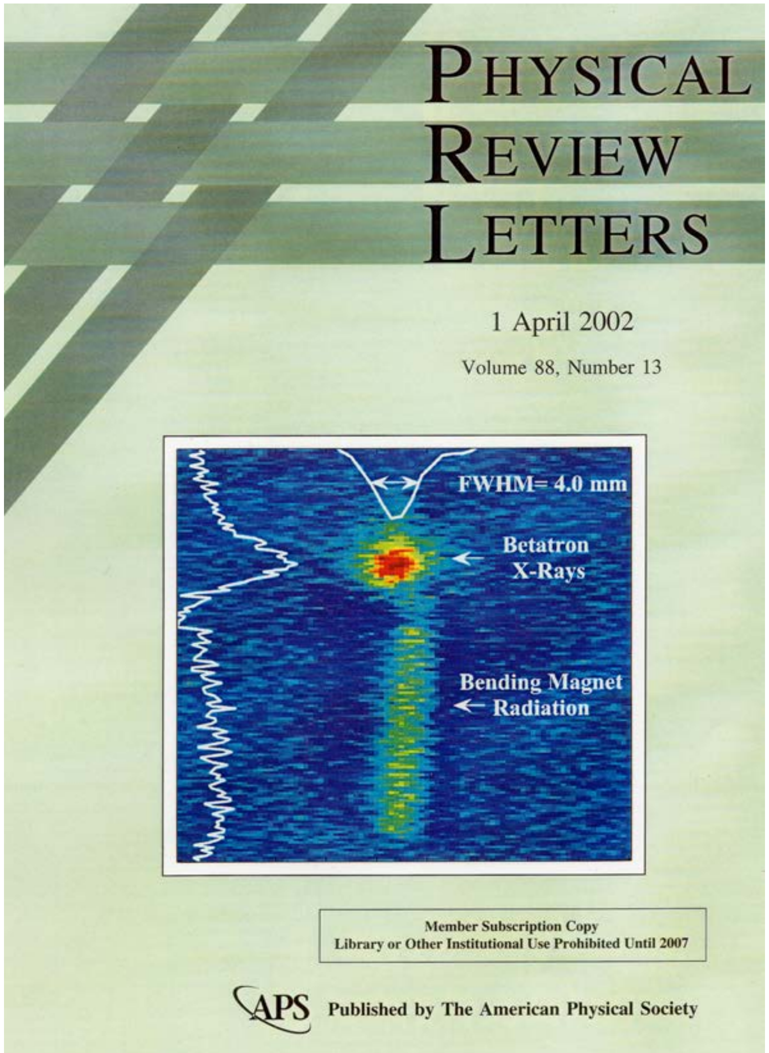
FACET Experiment 2015



A Capillary creates localized helium region

With lasers: A. Pak et al., PRL 104, 025003 (2010), C. McGuffey et al., PRL 104, 025004 (2010)

X-Ray Emission & Positron Production by X-Rays Emitted by Betatron Motion In A Plasma Wiggler


PHYSICAL
REVIEW
LETTERS

1 April 2002

Volume 88, Number 13

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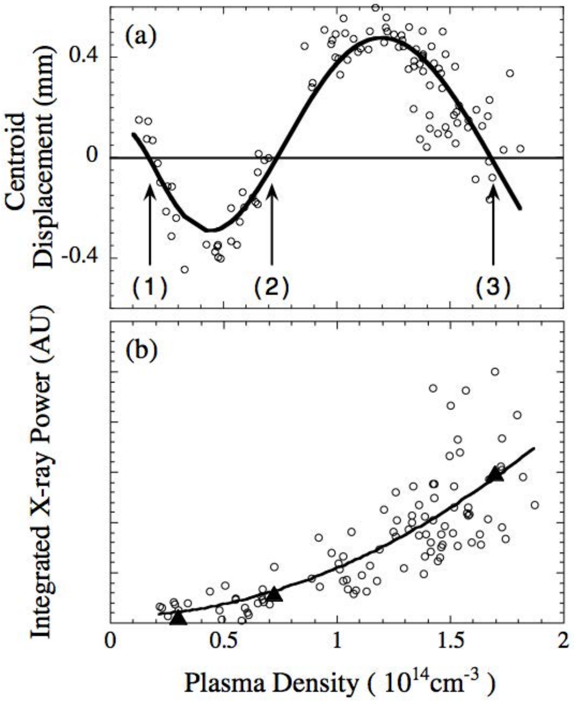
APS Published by The American Physical Society



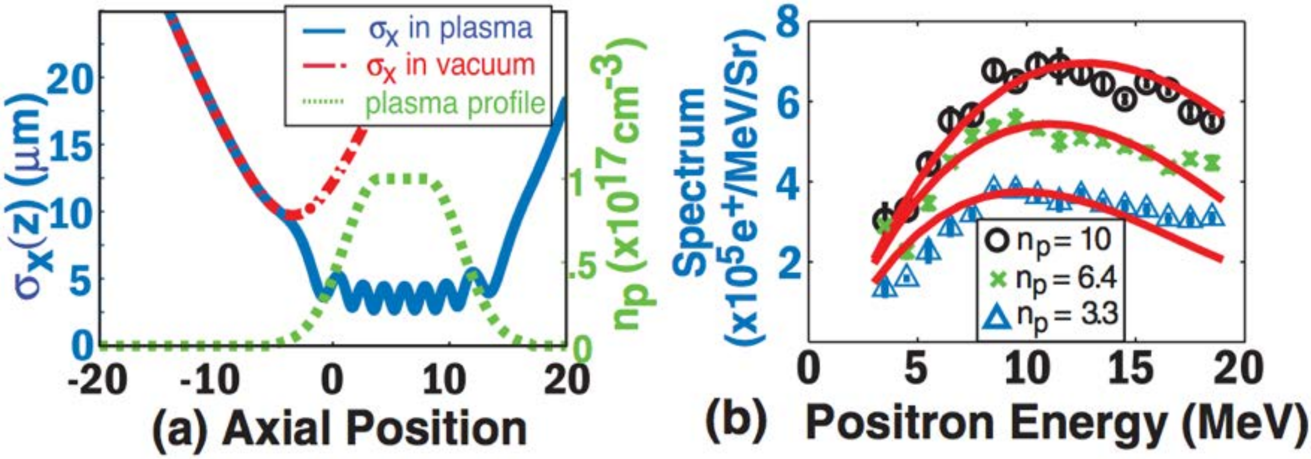
$$\lambda_\beta \simeq (2\gamma)^{1/2}\lambda_p$$

$$a_\beta = \gamma k_\beta r_\beta$$

$$a_\beta \approx 0.13\sqrt{\gamma\, n[10^{18}\mathrm{cm}^{-3}]}\, r_\beta[\mu\mathrm{m}]$$

$$\hbar\omega_c[\mathrm{keV}] \approx 10^{-5}\gamma^2 n[10^{18}\mathrm{cm}^{-3}]\, r_\beta[\mu\mathrm{m}]$$

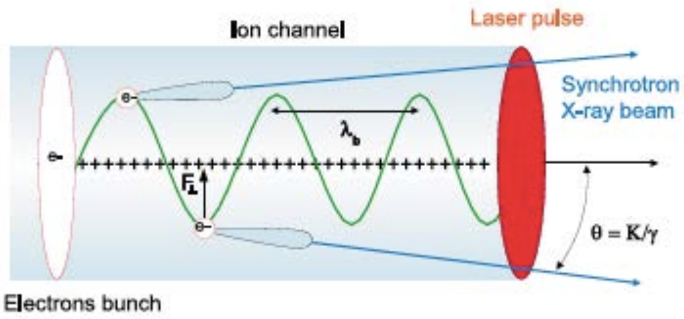
e.g. 5GeV, 10^{17}/cc, 10μm
MeV critical energy!

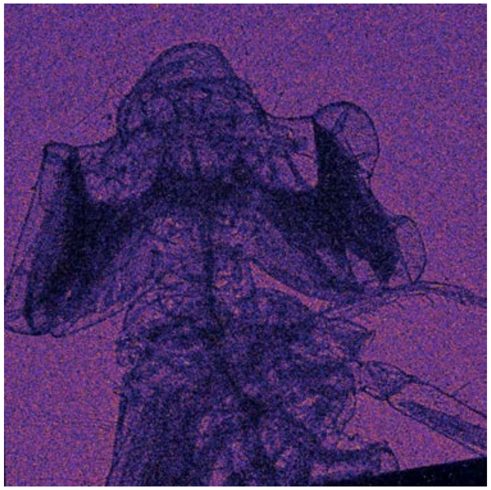


Physical Review Letters ***97***, *175003 (2006)*

Betatron Radiation & Search for First Applications

Femtosecond bursts of x-rays from electron acceleration (up to 800 MeV) can be used for phase contrast imaging





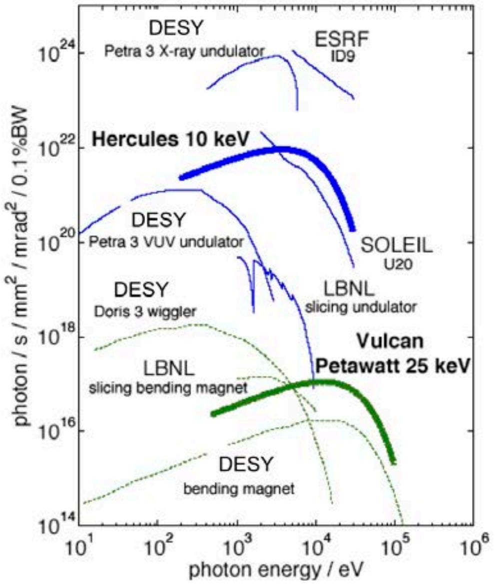
at Michigan:

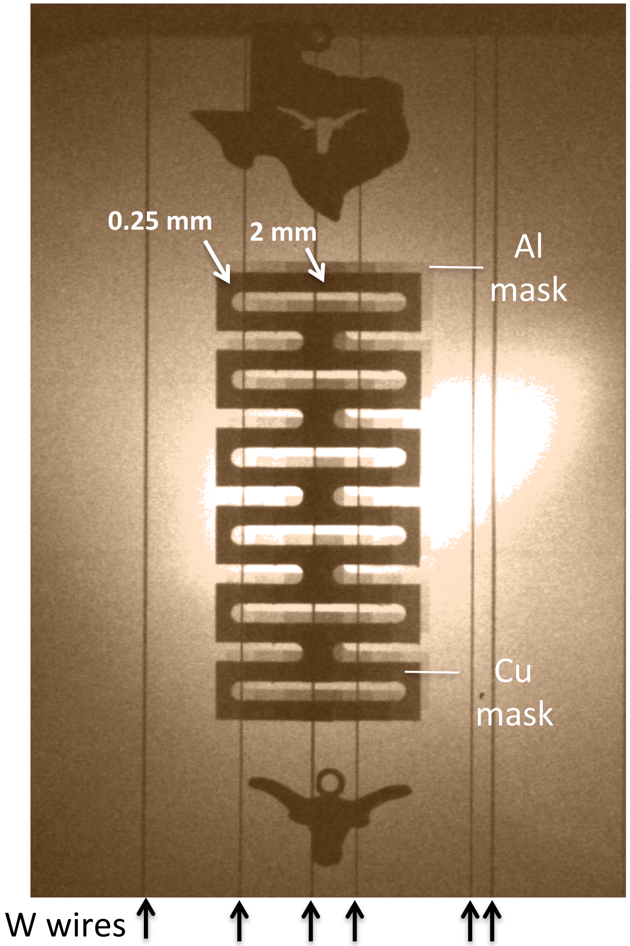
Hercules 100 TW,
S. Kneip, et. al., APL (2011)
. Kneip et al.,, Nature Physics (2010)

Petawatt, kJ laser
S. Kneip, et. al., PRL (2008)

...and elsewhere:

Rousse, *PRL* **93**, 135005 (2004)
Kneip *et al*., *Nature Phys*. **6**, 980 (2010)
Cipiccia *et al*., *Nature Phys*. **7**, 867 (2011)





Also Undulator Radiation, ICS...

Laser Driven Soft X-ray Undulator Source

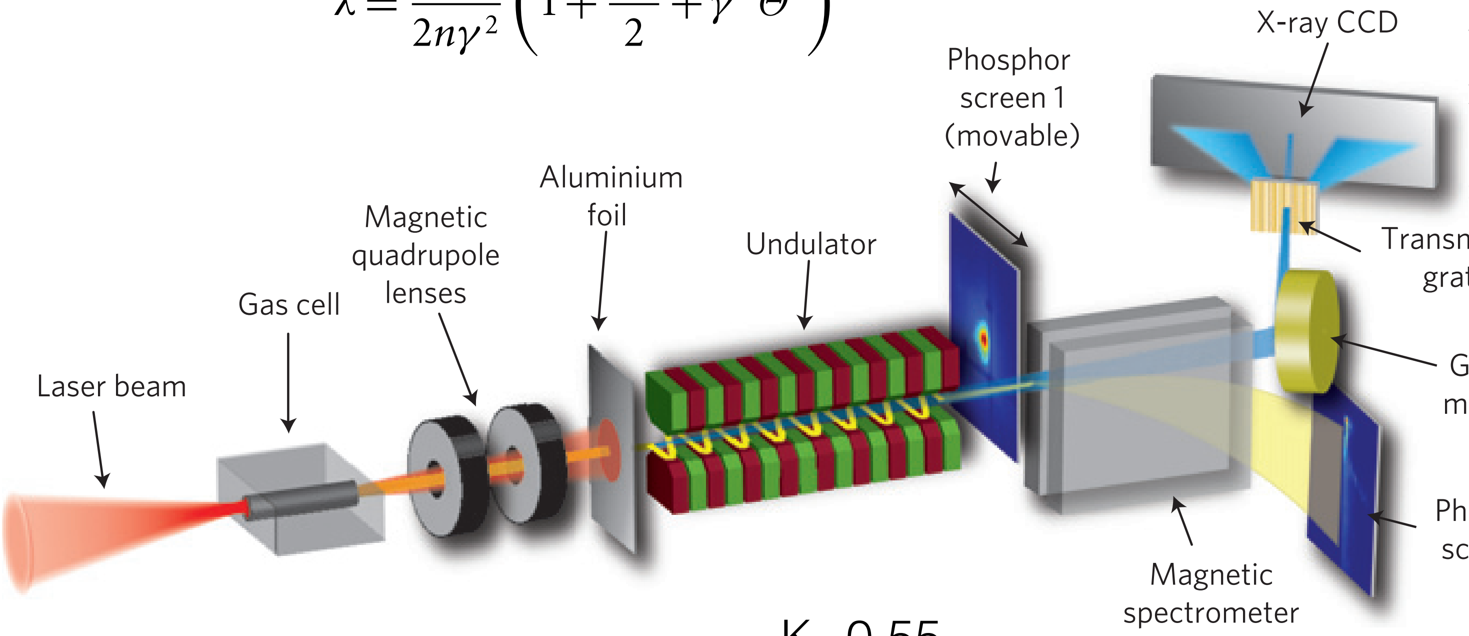
LETTERS M. Fuchs *et al.*

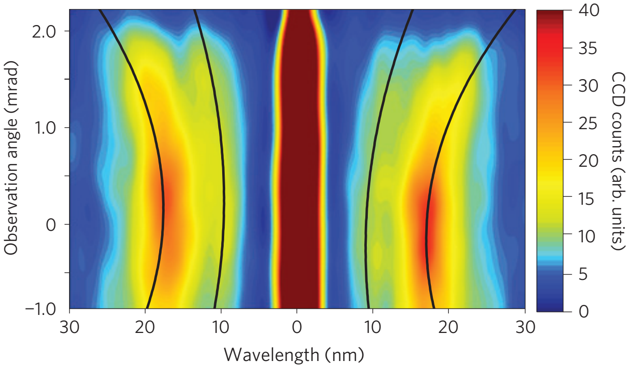
PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1404

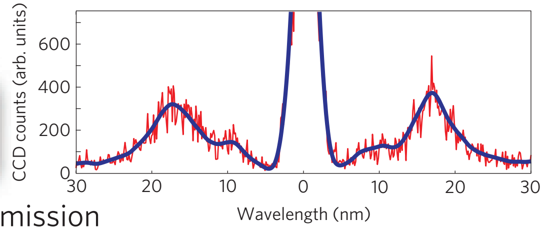
nature physics

Measure first and second harmonic

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\Theta^2\right)$$



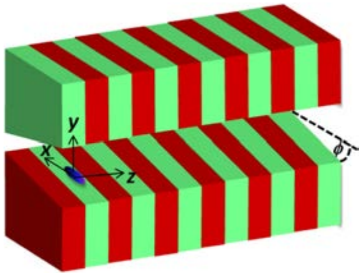




$n_p = 8\times10^{18}$ 10pC, 210MeV K=0.55 λ_u=5mm

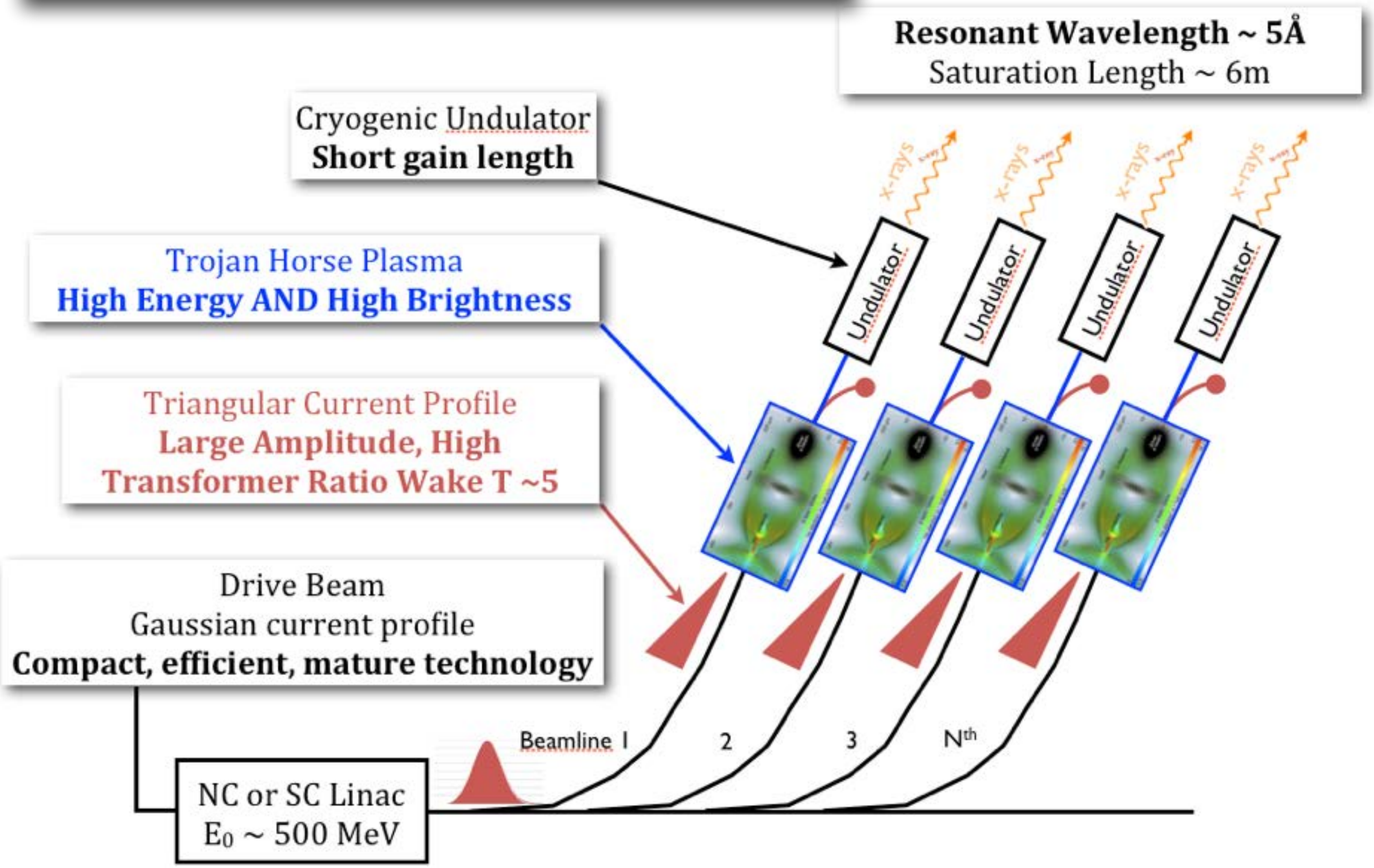
Z. Huang *et* al.
PRL 109, 204801 (2012)

FELs may require novel configurations such as TGU



Imagine a New Generation of Light Sources

Plasma Based FEL Concept



Resonant Wavelength ~ 5Å
Saturation Length ~ 6m

Cryogenic Undulator
Short gain length

Trojan Horse Plasma
High Energy AND High Brightness

Triangular Current Profile
Large Amplitude, High Transformer Ratio Wake T ~5

Drive Beam
Gaussian current profile
Compact, efficient, mature technology

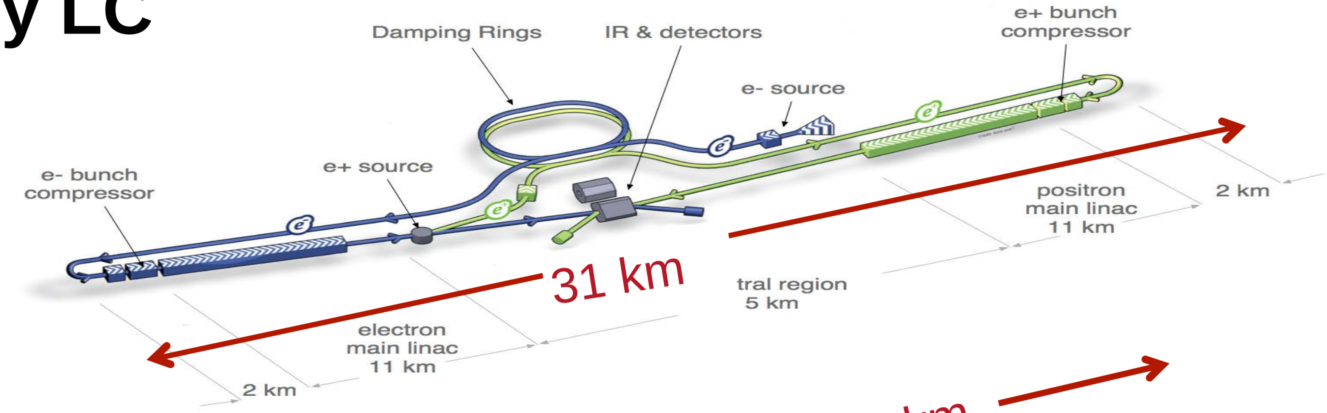
NC or SC Linac
E_0 ~ 500 MeV

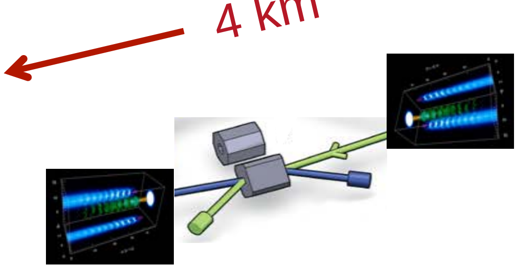
Drive Beam	
Charge	3nC
Energy	500 MeV
Rep Rate	1MHz
Bunch length	210μm, ramped
Peak Current	8.5kA
Normalized Emittance	2.25 mm-mrad
Trojan Horse (plasma)	
Plasma Density	10^{17} e^-/cc
Plasma Length	20 cm
Transformer Ratio	5
Trojan Horse (beam)	
Charge	3 pC
Energy	2.5 GeV
Energy Spread	2×10^{-4}
Normalized Emittance	3×10^{-8} m-rad
Peak Current	300A
Bunch length	12 fs
Brightness	7×10^{17} A/m^{2}rad^2
Undulator Parameters	
Period	9 mm
K	2
Number of periods (N)	660
Radiation Parameters	
Wavelength	5.4 Å
Single pulse energy	50 μJ
Number of Photons	$>10^{11}$
Peak Power	1.6 GW

Leverage high rep-rate beam drivers with plasma as source of high-brightness high-energy electrons

The Scale for a TeV Linear Collider

Today’s technology LC – a 31km tunnel:





Plasma Wakefield Technology LC:

- GeV/m accelerating gradient

The Luminosity Challenge:

- High-efficiency

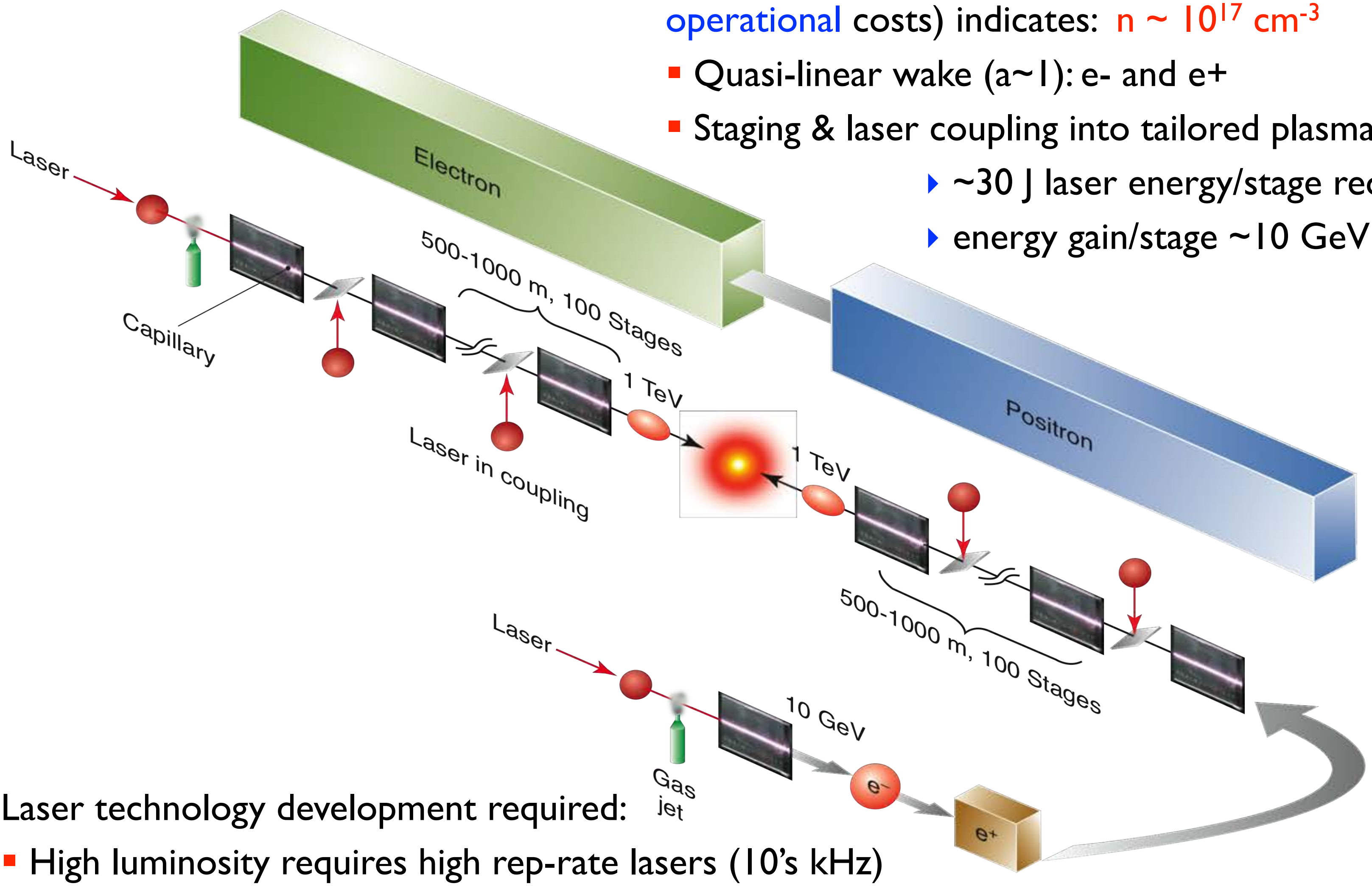
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

…and must do it for positrons too!

Laser-plasma Accelerator Based Collider Concept

Leemans & Esarey, Physics Today (2009)

- Plasma density scalings (minimize construction and operational costs) indicates: n ~ 10^{17} cm^{-3}
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into tailored plasma channels:
  - ~30 J laser energy/stage required
  - energy gain/stage ~10 GeV in ~1m

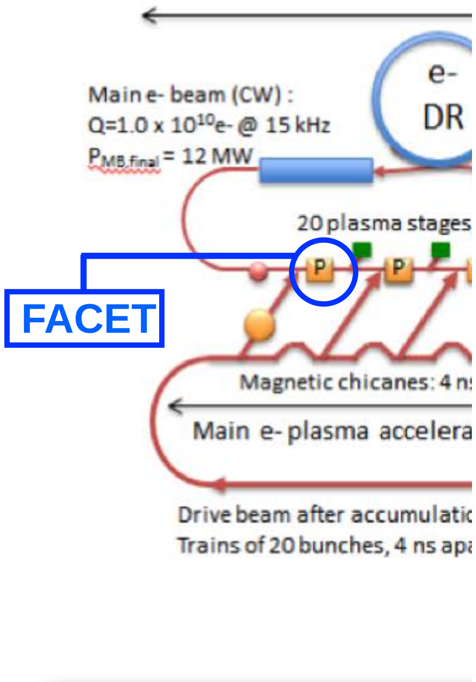


Laser technology development required:

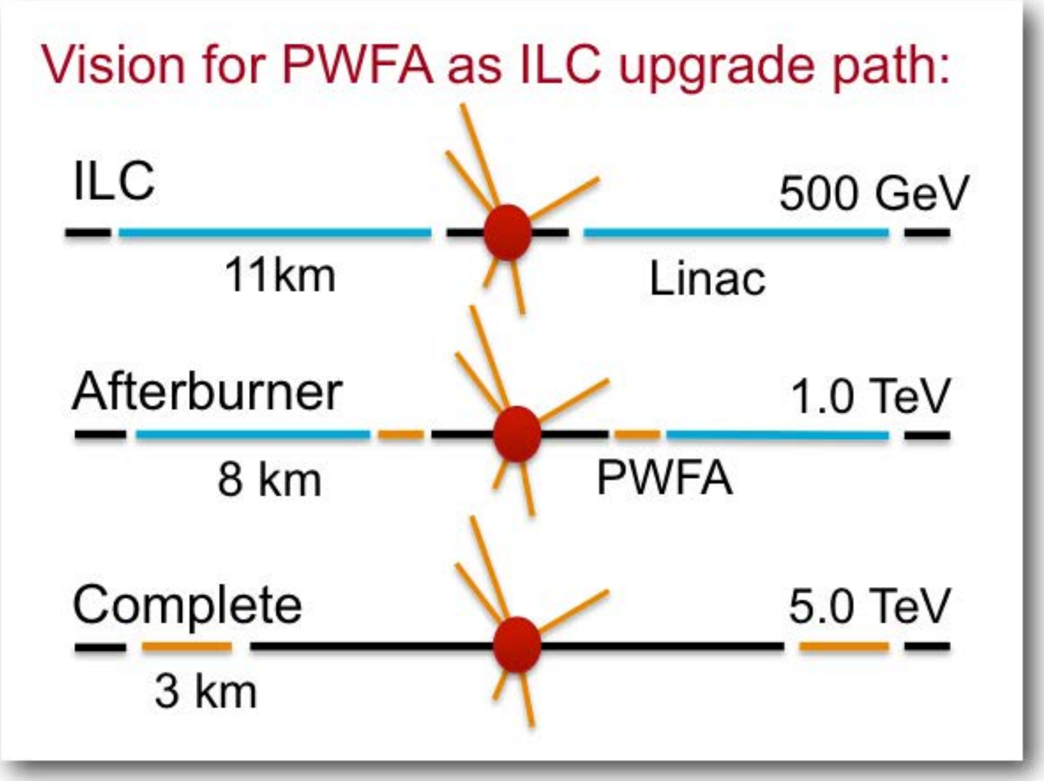
- High luminosity requires high rep-rate lasers (10's kHz)
- Requires development of high average power lasers (100's kW)
- High laser efficiency (~tens of %)

FACET in the Middle of the 2^{nd} Phase of PWFA

- SLAC FFTB demonstrated electron acceleration with 50GeV/m for 85cm
- FACET addresses issues of a single stage
- FACET-II staging, high-brightness beams



A conceptual PWF



E_{cm} = 1 TeV
L = 10^{34} $cm^2 s^{-1}$
$\text{Efficiency}_{\text{wall plug}}$ ~ 11%

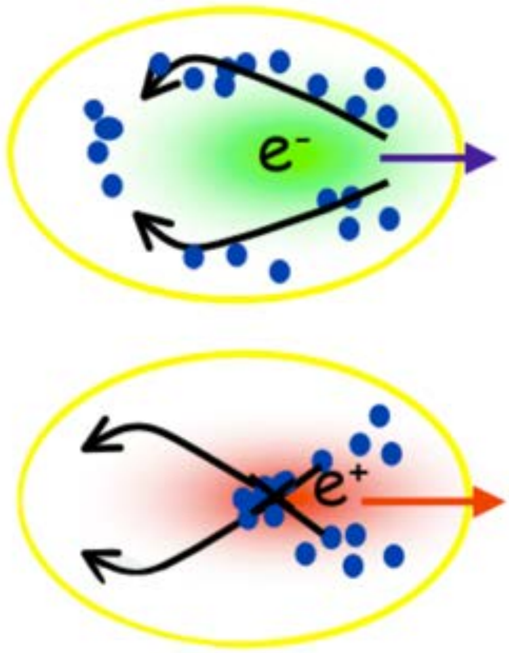
SLAC-PUB-15426
http://arxiv.org/abs/1308.1145
E. Adli *et al*, IPAC14

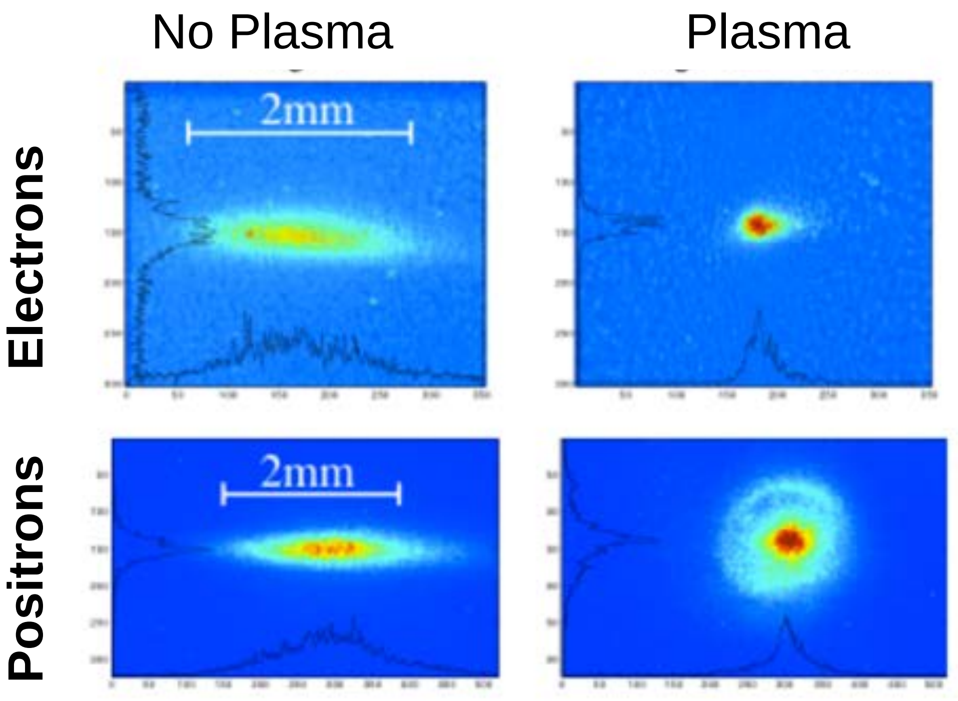
FACET-II program will optimize positron acceleration and investigate issues of staging multiple plasma cells for very high energy

Extending to Positrons is Not Trivial

“Blow-out”

“Suck-in”





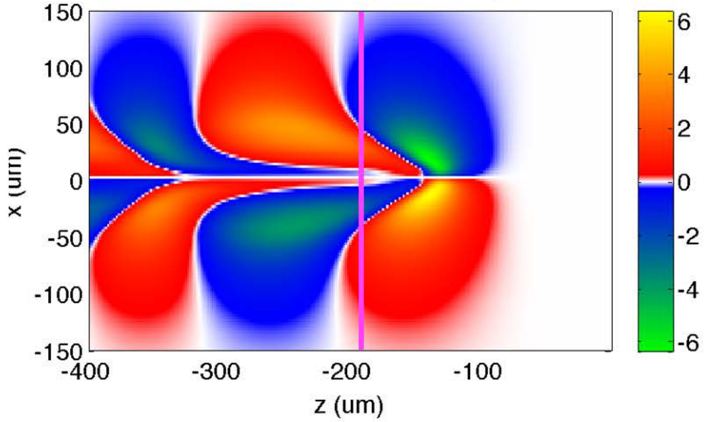
Phys. Rev. Lett. **90**, 205002 (2003)

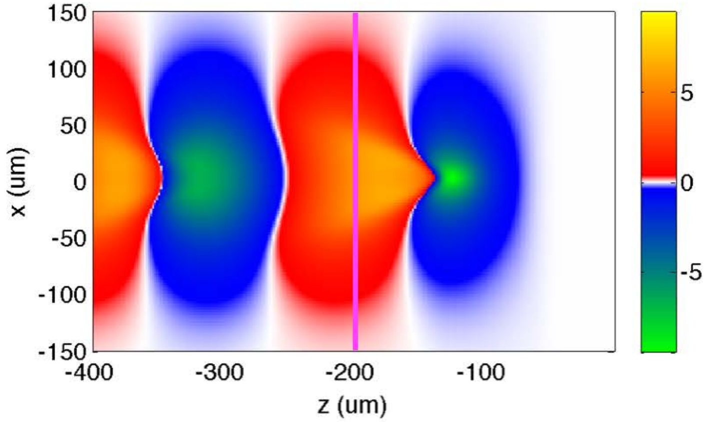
Phys. Rev. Lett. **101**, 055001 (2008)

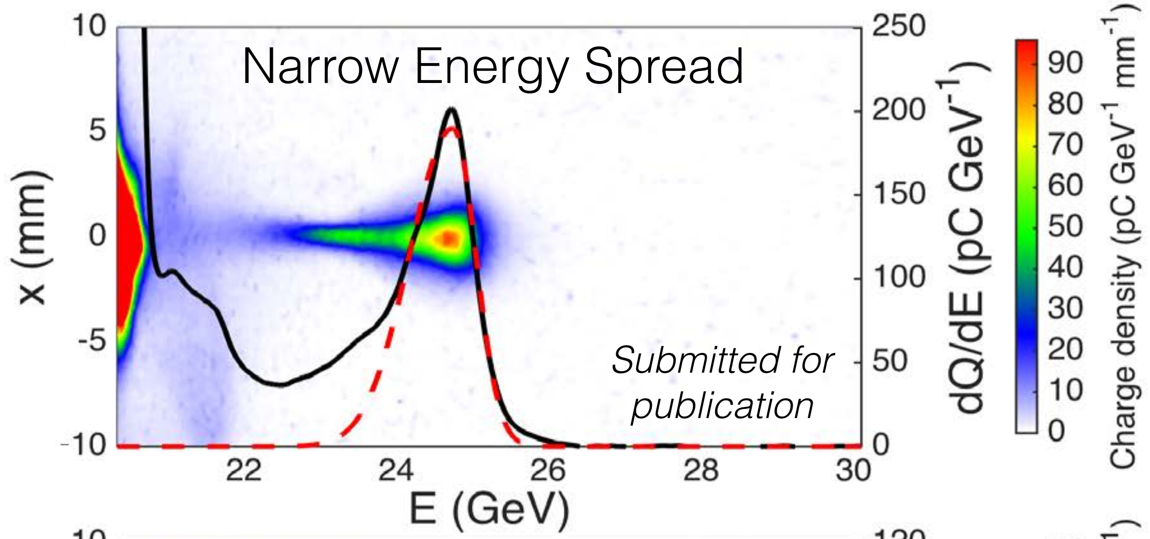
Experiments at SLAC FFTB in 2003 showed that the positron beam was distorted after passing through a low density plasma.

Multi-GeV Acceleration of Positrons

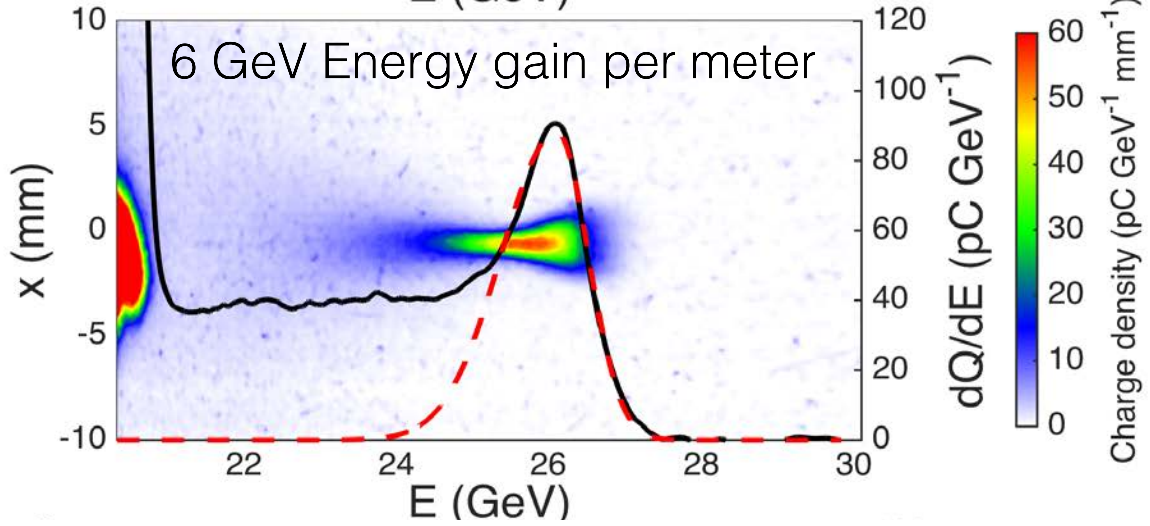
New regime: focusing and accelerating region for positrons in the wake of a positron beam


Transverse Field (GeV/m) @ 105cm


Accelerating Field (GeV/m) @ 105cm

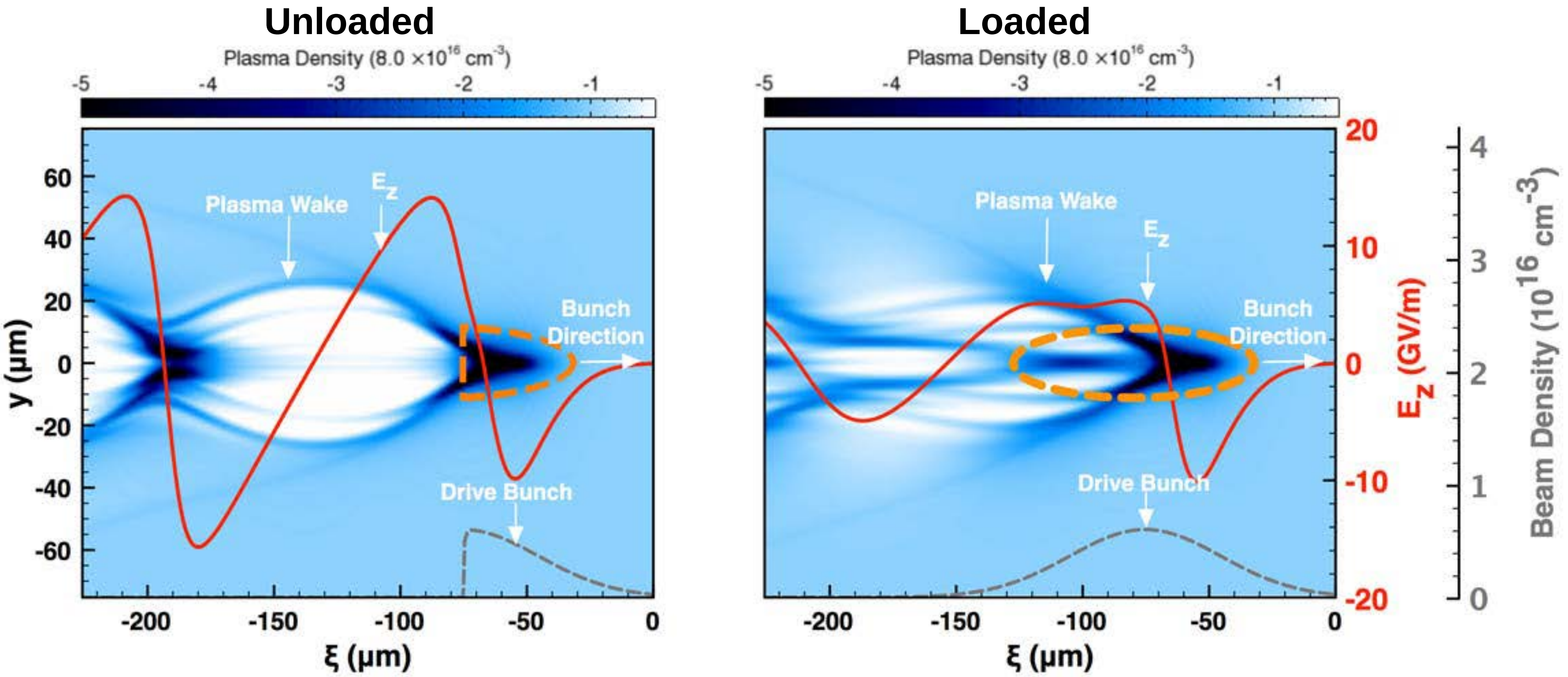

Narrow Energy Spread

Submitted for publication


6 GeV Energy gain per meter

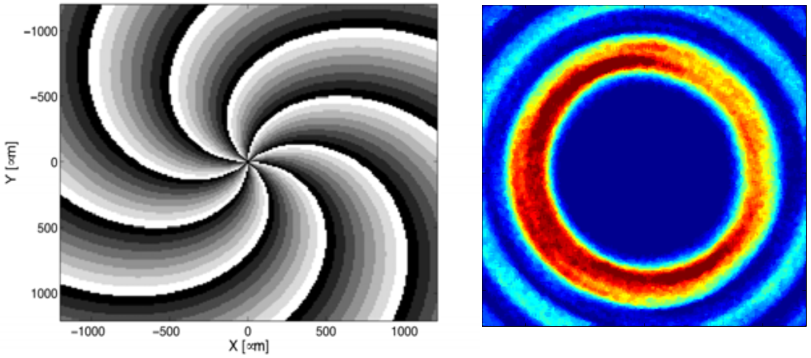
This study is important for plasma afterburner as an energy doubler

Understanding the Result: Longitudinal and Transverse Beam Loading



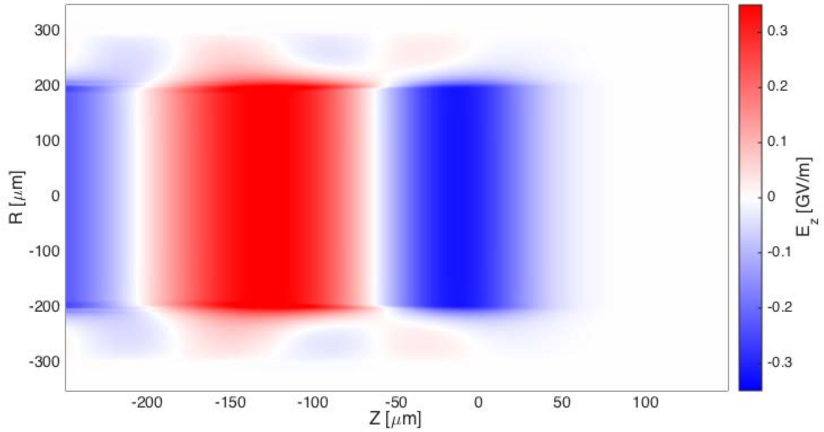
Some plasma electrons remain on axis and both guide the positron beam and flatten the accelerating fields!

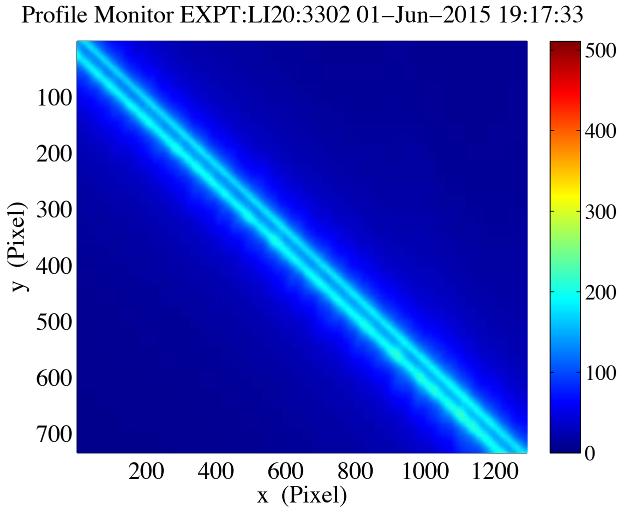
E225: Hollow Channel Plasma Wakefield Acceleration

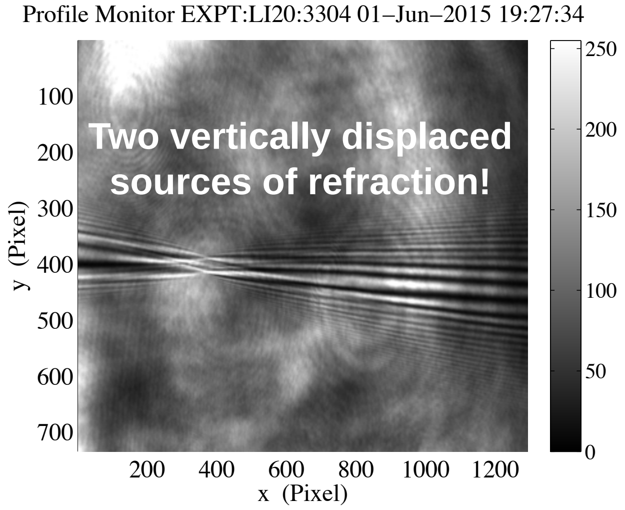


We use a spiral phase grating to create hollow laser beams

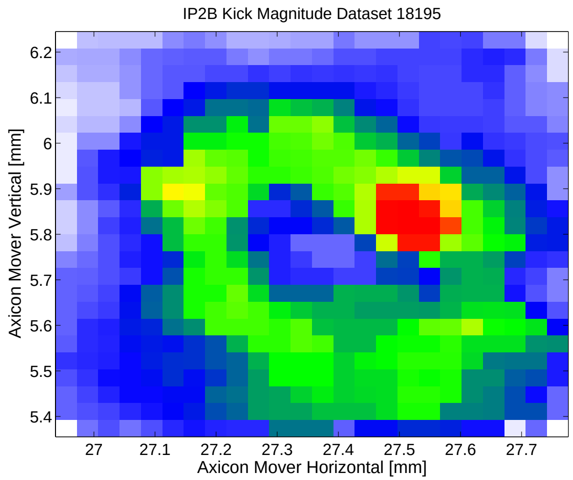
Accelerating Fields with No Focussing Forces







Two vertically displaced sources of refraction!



Verified we can create and align the hollow channel to the positron beam

AWAKE Collaboration Will Study Proton Driven PWFA

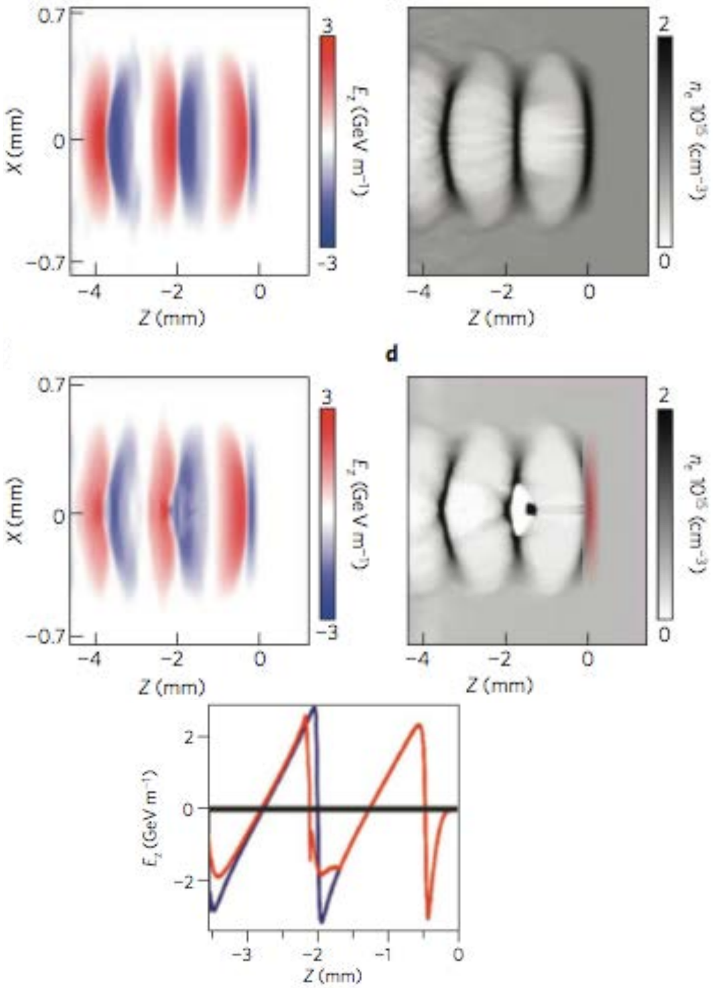
nature physics

ARTICLES

PUBLISHED ONLINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI:10.1038/NPHYS1248

Proton-driven plasma-wakefield acceleration

Allen Caldwell[1]★, Konstantin Lotov[2,3], Alexander Pukhov[4] and Frank Simon[1,5]



Idea to Harness the Large Stored Energy in Proton Bunches to make High Energy Electrons

Goals of the AWAKE Collaboration:

- ☐ >500 GeV e- in single long plasma cell (400m)!
- ☐ Requires short proton bunches (100µm vs 10 cm)
- ☐ Study physics of self-modulation of long p bunches
- ☐ Probe wakefields with externally injected e-
- ☐ Study injection dynamics for multi-GeV e-
- ☐ Develop long, scalable and uniform plasma cells
- ☐ Develop schemes for production and acceleration of short p bunches

Conclusions

- There is tremendous optimism and tremendous progress in plasma acceleration around the world
- There is a healthy mix of competition and collaboration
- Need larger projects AND smaller R&D – “can’t connect the dots looking forward”
- Plenty of room for new ideas (positrons, ultra-dense beams, kHz rep rates...)
- Need a bridge application on the way to HEP, likely photon science, maybe plasma based XFEL
- Stability, reliability won’t get you the cover of Nature but they are crucial to a user facility so likely developed close to one
- Combine compelling scientific questions, University-Lab collaborations, and state of the art facilities and experienced experimentalists, powerful scientific apparatus and rapid scientific progress follow naturally from these three

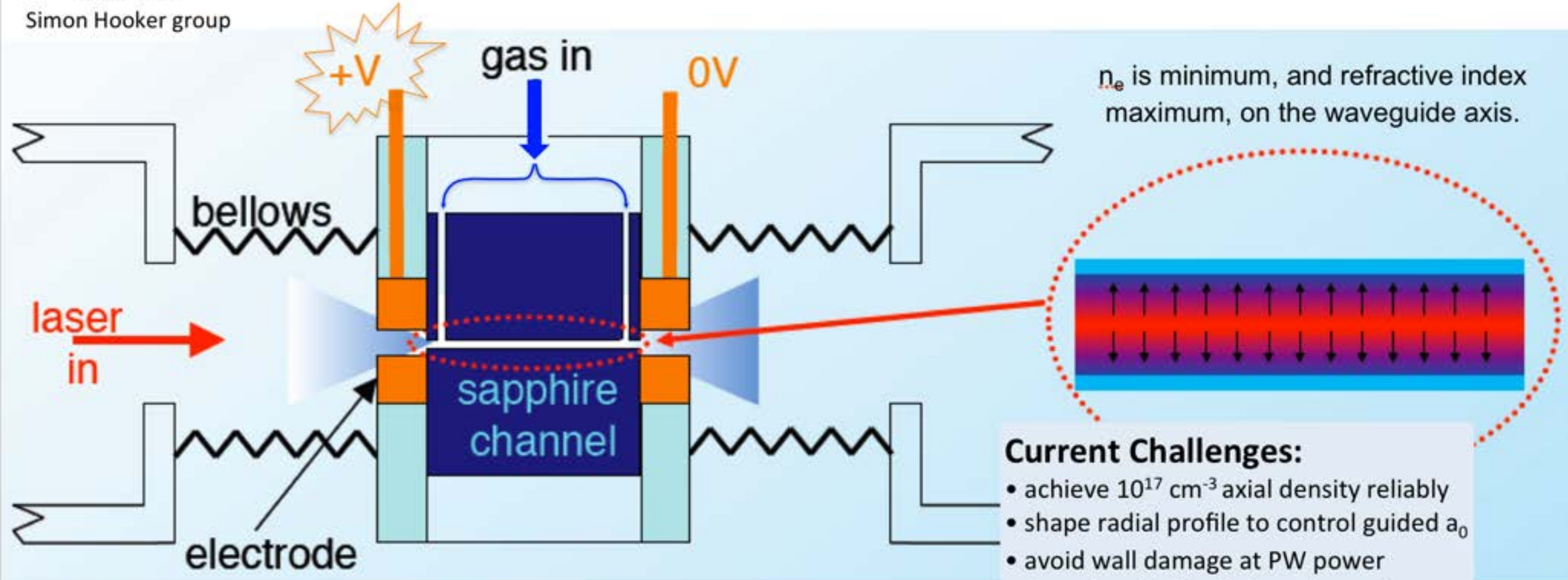
Thank you to all my colleagues who contributed material for this talk!

Plasma Source Development: Jets to Capillaries

Oxford U.
Simon Hooker group

Gas-filled capillary discharge waveguides extend acceleration length over gas jets

Spence, *Phys. Rev. E* **63**, 015401 (2001): Butler, *Phys. Rev. Lett.* **89**, 185003 (2002)

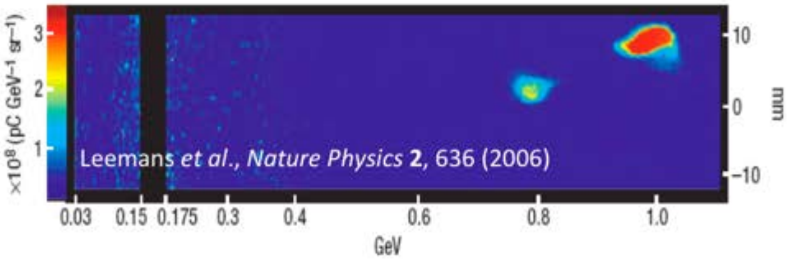


n_e is minimum, and refractive index maximum, on the waveguide axis.

Current Challenges:
- achieve 10^{17} cm^{-3} axial density reliably
- shape radial profile to control guided a_0
- avoid wall damage at PW power
- taper longitudinally to enhance L_d

- Capillary diameter = 100 - 400 μm
- Gas injected near each end of channel
- $n_e \sim 10^{18} - 10^{19}$ cm^{-3}
- Gas ionized by pulsed discharge
  - Peak current 200 - 500 A
  - Rise-time 50 - 100 ns

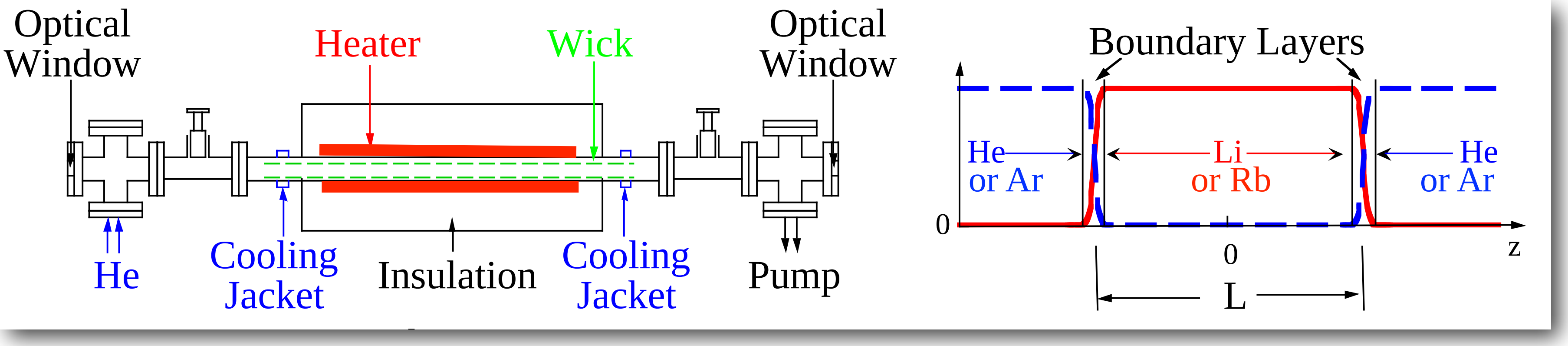
Essential to optimizing 30 TW LPA!



Leemans *et al.*, *Nature Physics* **2**, 636 (2006)

Beam Experiments Using Meter Scale Plasmas: Alkali Metal Vapor, Hydrogen Cells…

Plasma source starts with a heat pipe oven: Scalable, $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm



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

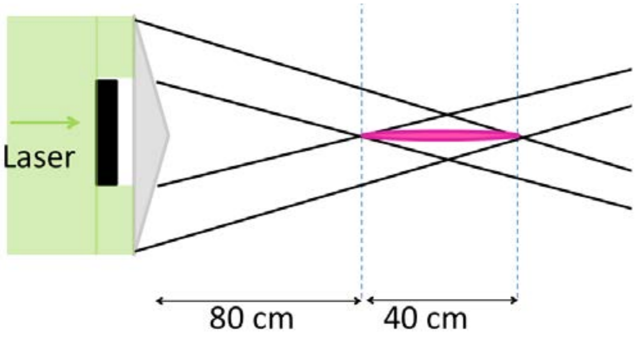
...but can suffer from Head Erosion

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

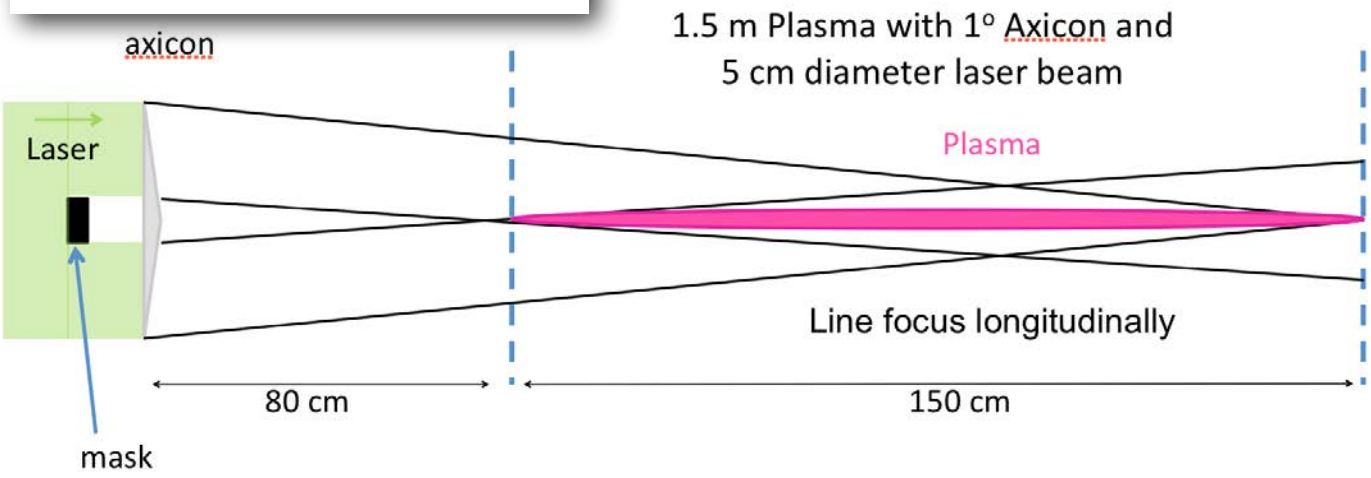
Low ionization potential alkali vapors can be ionized by the beam or a laser

Use a Laser to Turn Lithium Vapor into a Plasma – Axicon Geometry Determines the Plasma Length

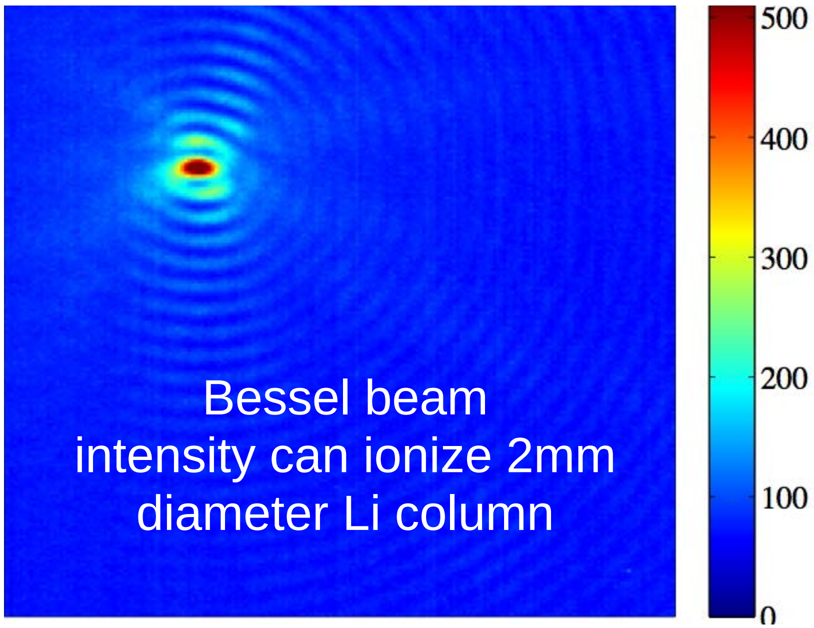
July ’13 ~250mJ:



November 2014 ~500mJ:

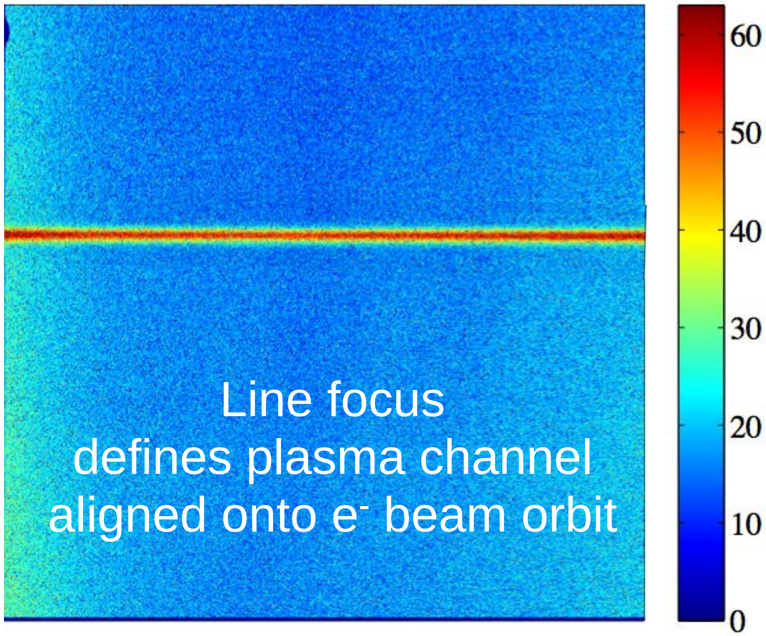


Measured Transverse Profile



Bessel beam
intensity can ionize 2mm
diameter Li column

Side View of Plasma Column



Line focus
defines plasma channel
aligned onto e^- beam orbit

Use Laser Infrastructure to Directly Image Wakefields

- Plasma has many roles: laser waveguide, electron source, accelerator...
- Structure is dynamic and evolving – would like to ‘see’ this in the lab

“Frequency Domain Holography”
Images Wakefields in a Single-Shot

N. Matlis *et al.*, “Snapshots of laser wakefields,”
Nature Physics **2**, 749 (2006)

Wakefield snapshots see laser-plasma
acceleration physics in unprecedented detail

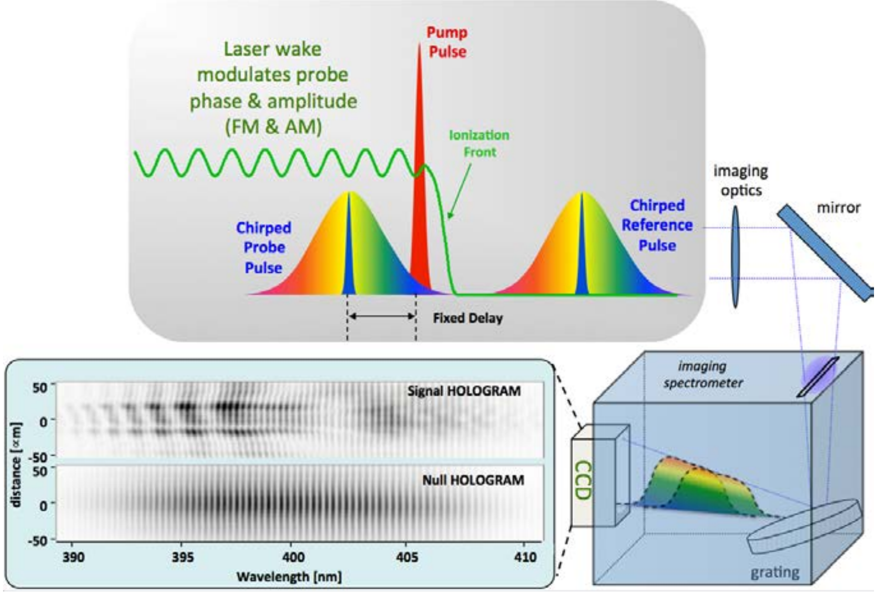
P. Dong *et al.*, “Holographic Visualization of Laser Wakefields,”
New Journal of Physics **12**, 045016 (2010).

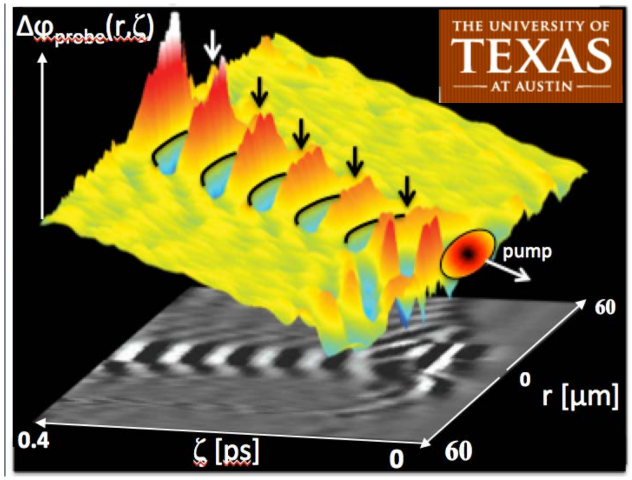
Frequency-Domain “Streak Camera” Records
EVOLUTION of Plasma Bubble in ONE shot

Z. Li *et al.*, *Opt. Lett*. 35, 4087 (2010)
Research Highlight, *Nature Photonics* **5**, 68 (2011)

Frequency-domain tomography (FDT) records
multiple phase streaks in one shot…

Z. Li *et al.*, *Nature Commun*. (2014)





Confirm details of wake structure:

- Relativistic wave front curvature
- Peaks grow, narrow & break behind pump

Beams vs Lasers

Physics:

- Wakes and beam loading are similar
  - Minor differences in transverse profiles
- Driver propagation and coupling efficiency:
  - Beams more easily propagate over meter scales (no channel needed)

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

  - Beams have higher coupling efficiency to wake (~2x)
  - Lasers can distort due to de-phasing, dispersion, photon deceleration, but to the plasma a 25GeV and 2GeV beam are nearly identical

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

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

- 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
  - Lasers need considerable development and \$/Watt costs are guess

Why aren't electrons accelerated in circular machines?

- High energy (multi-GeV) electron beams have many applications in HEP (SLC, PEP-II) and Photon Science (LCLS)
- A charged particle emits radiation when accelerated.
  - For the classical case, Larmor's formula applies:

$$P \propto \frac{2Ke^2}{3c^7}\left[\frac{E^4}{m^4}\frac{1}{r^2}\right]$$

- The good: allows devices like synchrotron light sources and free electron lasers to work, and can be used to cool beams to make them brighter
- The bad: radiating can degrade the beam (especially coherent radiation)
- The ugly: power lost per revolution in a circular machine scales as $P \sim \gamma^4 \sim E^4/m^4$ → low-mass electrons radiate too much!