# Plasma Wakefield Acceleration

## SLAC Summer Institute 2016 (SSI2016) – New Horizons on the Energy Frontier

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August 22, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

# Outline

- Motivation
- Electron Beam Driven Plasmas
- Laser Beam Driven Plasmas
- Positrons
- Proton Beam Driven Plasmas
- Roadmap to Colliders
- Summary

- For further information:
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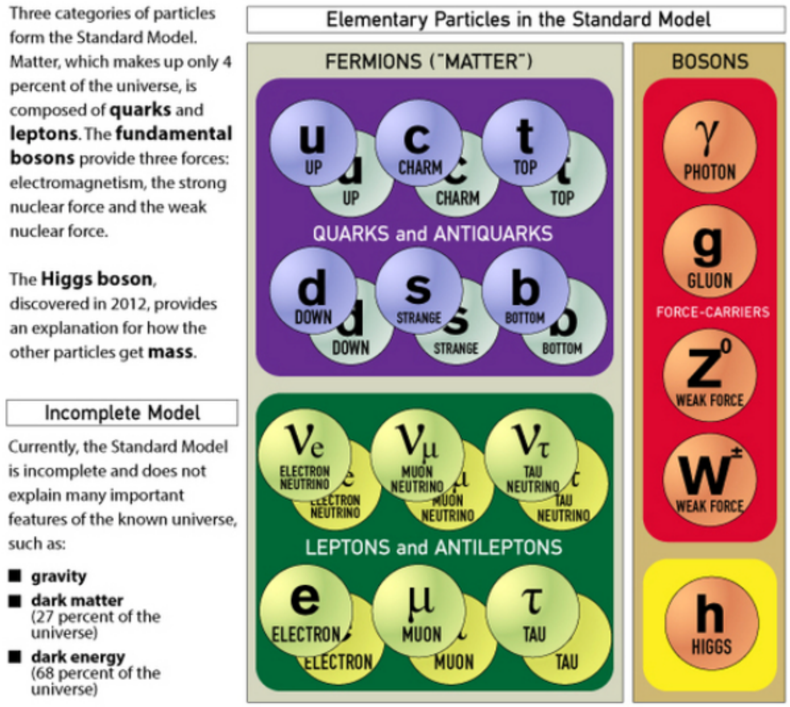
# Livingston Plot Illustrates the Moore’s Law for Accelerators

The Livingston curve shows the exponential growth in CM energy that has come from new accelerator physics & technology

Standard Model



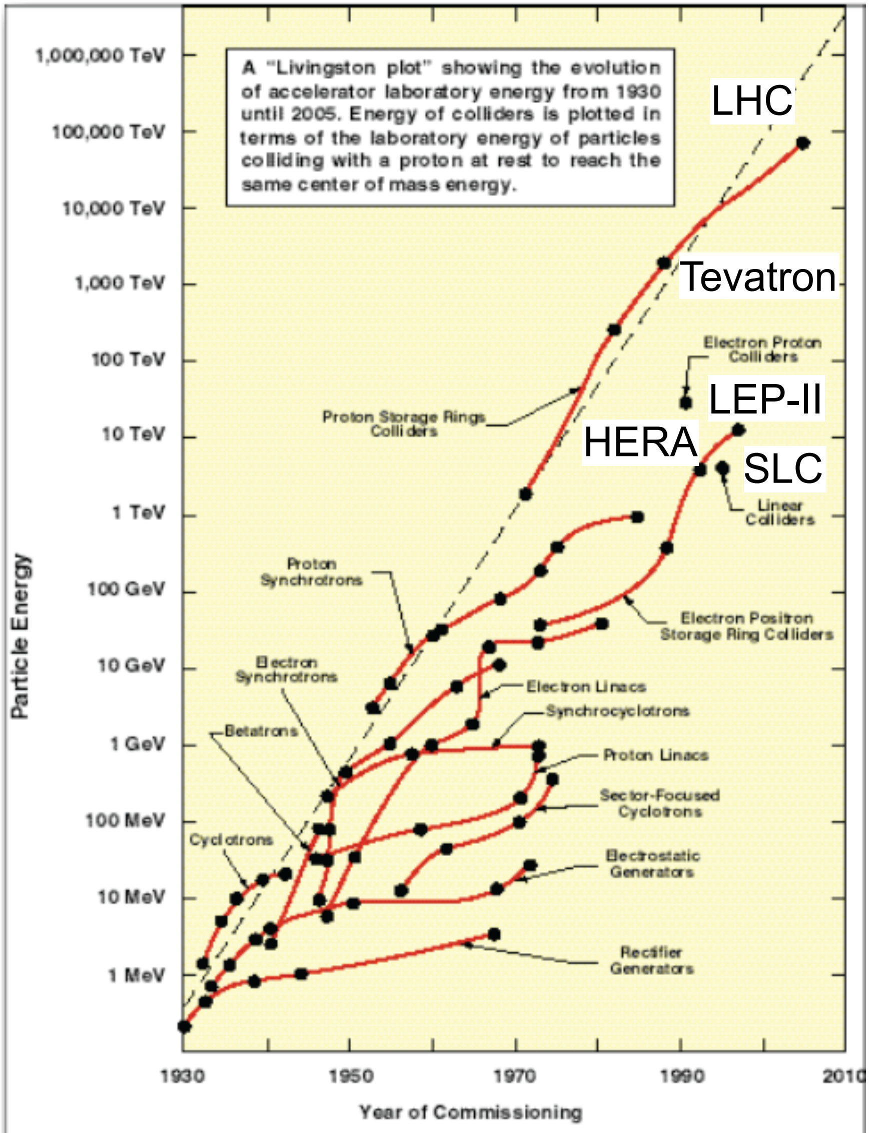
Three categories of particles form the Standard Model. Matter, which makes up only 4 percent of the universe, is composed of **quarks** and **leptons**. The **fundamental bosons** provide three forces: electromagnetism, the strong nuclear force and the weak nuclear force.

The **Higgs boson**, discovered in 2012, provides an explanation for how the other particles get **mass**.

Incomplete Model

Currently, the Standard Model is incomplete and does not explain many important features of the known universe, such as:

- **gravity**
- **dark matter** (27 percent of the universe)
- **dark energy** (68 percent of the universe)



A “Livingston plot” showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

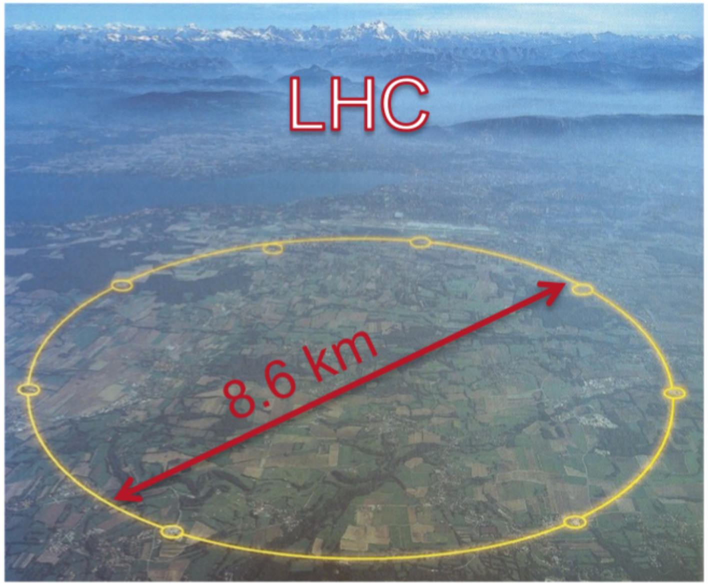
**The Evolution of Particle Accelerators & Colliders**
***by W. K. H. Panofsky***

2-017

# 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

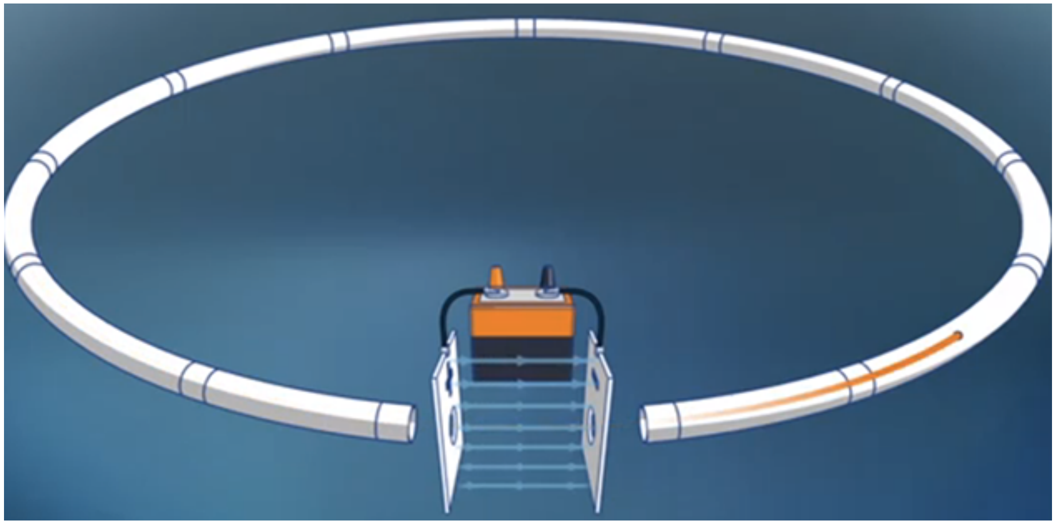
Time for a new acceleration technology!



# 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)

*So why don't we just make all accelerators circular?*

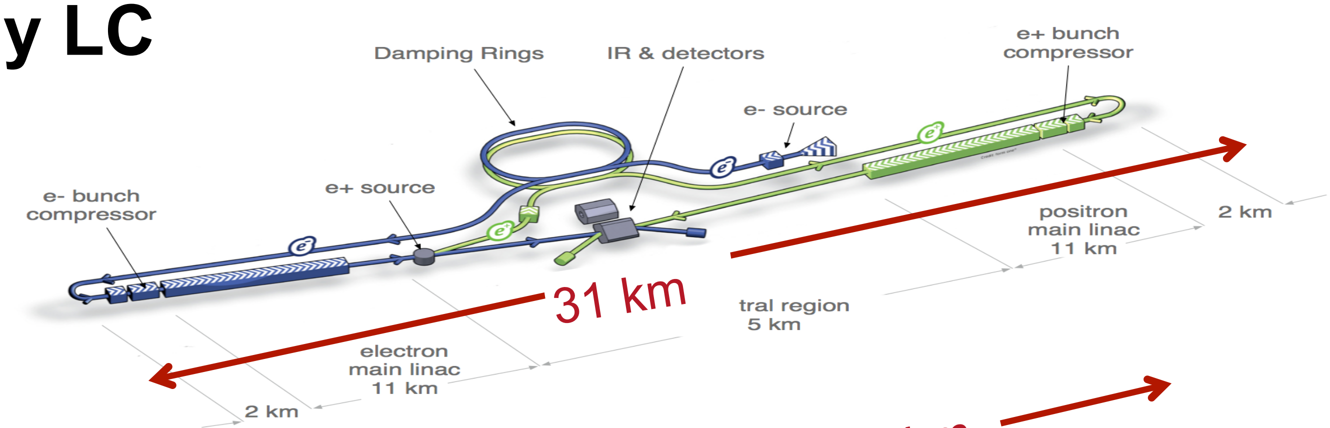


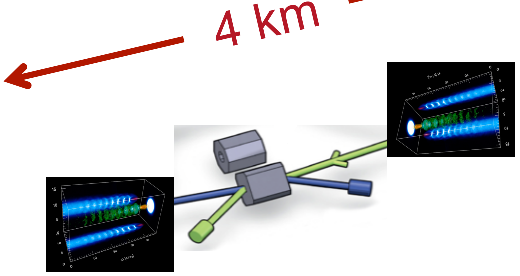
- A charged particle emits radiation when accelerated.
- **The good**: allows devices like synchrotron light sources and free electron lasers to work, and can be used to cool beams to make them brighter
- **The bad**: radiating can degrade the beam (especially coherent radiation)
- **The ugly**: power lost per revolution in a circular machine

scales as $P \sim \gamma^4 \sim E^4/m^4$ → **low-mass electrons radiate too much!**

# 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!

# Like Prof. Hansen on Stanford Campus Many Decades Before

~4 MeV ——— 60 years ——→ ~40 GeV

"We have accelerated electrons."

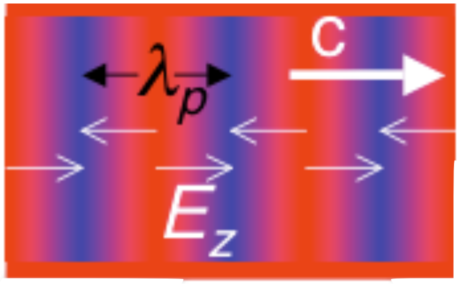
# Why Plasmas?

Relativistic plasma wave (electrostatic):

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

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

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

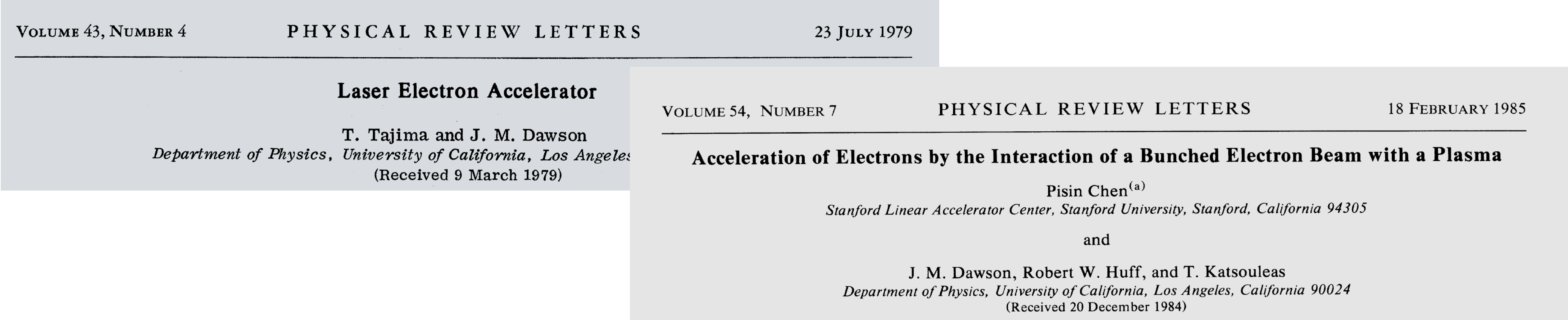


Large Collective Response!

*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 Electron Beam Driven Plasma Wakefield Accelerator



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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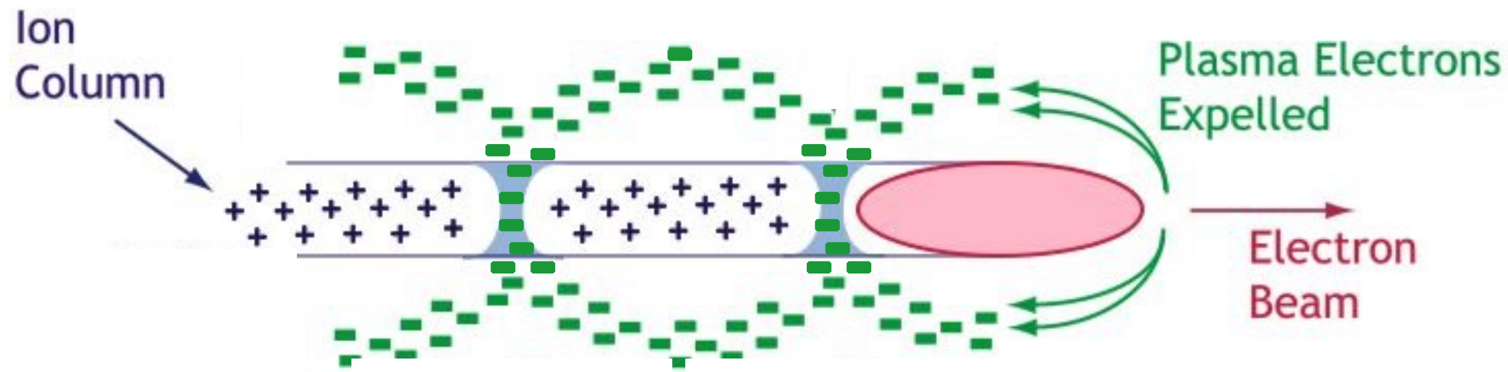
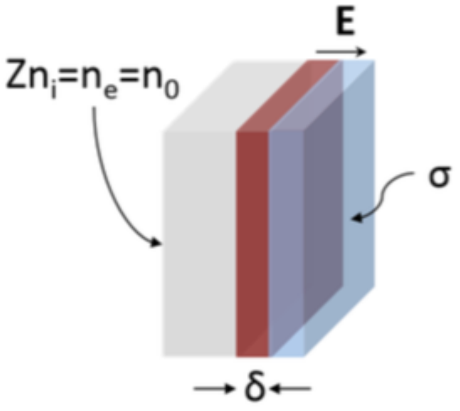


$$E_0 \sim 10\sqrt{\frac{n_0}{1\times 10^{16}[\mathrm{cm}^{-3}]}}[\mathrm{GeV/m}]$$

- Blow-out when $n_b >> n_p$
- Large accelerating gradients ~ GeV/m
- Strong ideal focusing ~ MT/m
- Relativistic driver, no de-phasing

# Plasma Frequency



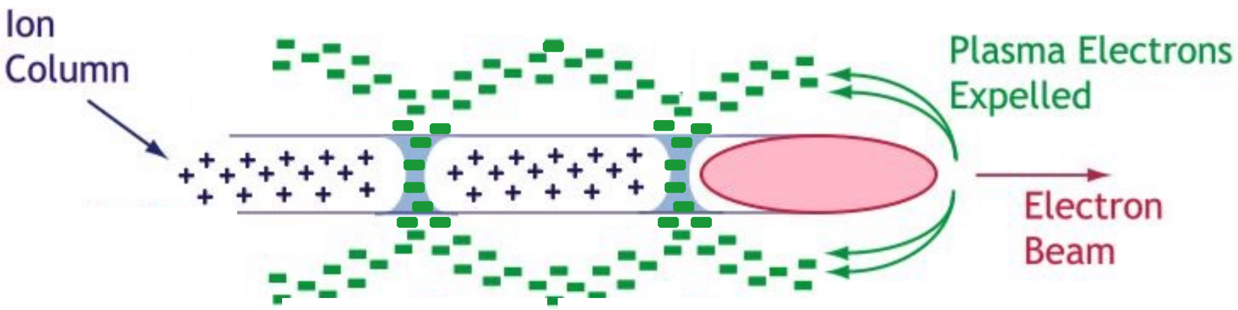
- Imagine an electron layer displaced in one dimension by length $\delta$
- Creates 'two capacitor plates' with surface charge density: $\sigma = en_e\delta$
- Electric field given by: $E = \frac{\sigma}{\varepsilon_0} = \frac{en_e\delta}{\varepsilon_0}$
- Creates a restoring force: $m_e\frac{dv}{dt} = -m_e\frac{d^2\delta}{dt^2} = -eE = \frac{e^2n_e\delta}{\varepsilon_0}$
- 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:

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

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

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

# Transverse Forces: Focusing in the Ion Column

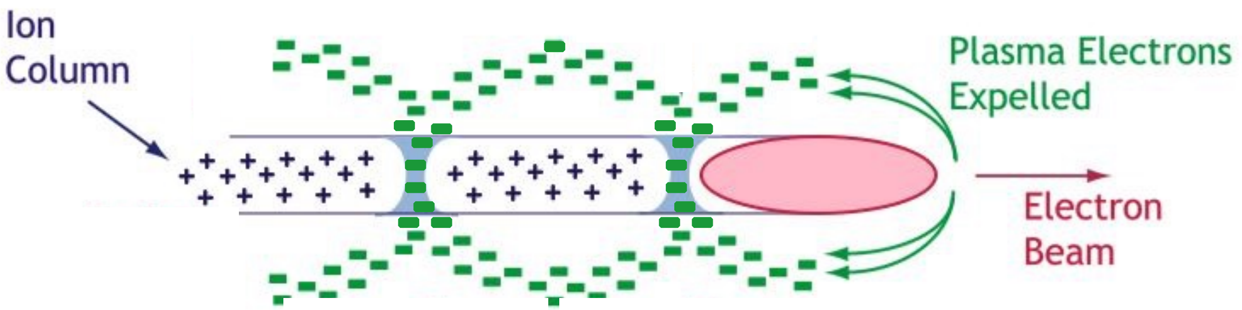


- Uniform ion density $n_i$ = initial plasma density $n_{e0}$
- Focusing is balance between radial E and v x B ~ $E_r$ - $cB_{phi}$
- Assume $n_b/n_p > 1$ and fully blown-out ion column
  - no plasma return currents within the beam (CFI)
  - In beam frame then no currents to drive $B_{phi}$
- Focusing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



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

- Motion of a single electron in the ion column:

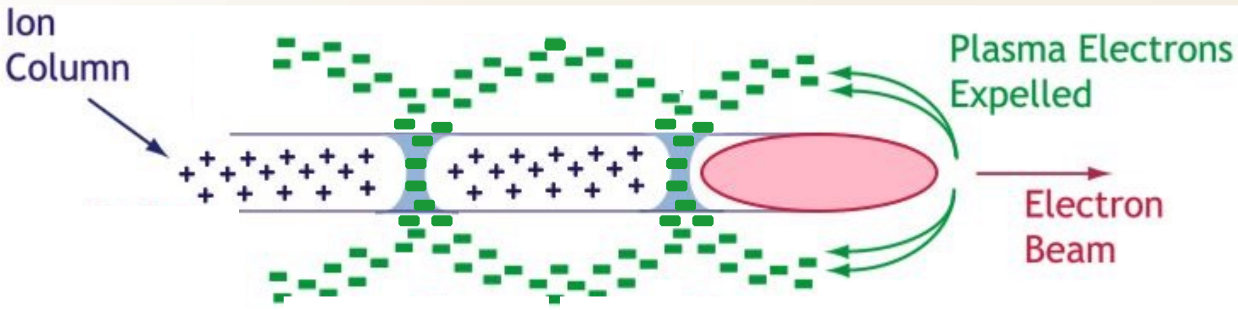
$$\gamma m\frac{dv_\perp}{dt} = F_\perp \quad \Rightarrow \quad \gamma mc^2\frac{d^2r}{dz^2} = e\frac{1}{2}\frac{en_{e0}}{\varepsilon_0}r \quad \Rightarrow \quad \frac{d^2r}{dz^2} = \frac{1}{2\gamma c^2}\frac{e^2n_{e0}}{m\varepsilon_0}r = \frac{\omega_{pe}^2}{2\gamma c^2}r = \frac{k_{pe}^2}{2\gamma}r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

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

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

- 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



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

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

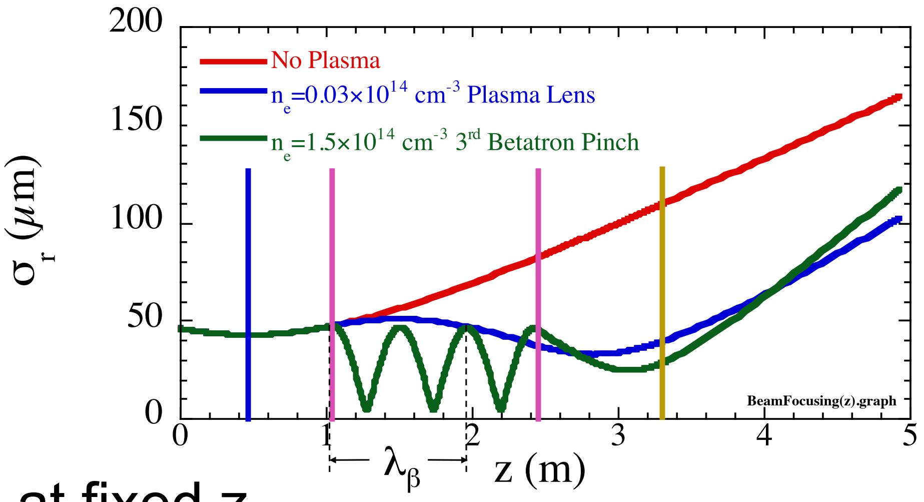
- There is a matched beta ($n_p$ dependent) – not a matched spot size ($e_n$ dependent), e.g. $n_p = 10^{17}$, $c/w_p$ = 17µm and Beta matched = 1mm (<<$L_p$!). For $e_n$ = 1µm, E = 1GeV get a matched sigma = 0.7µm

# Measured Plasma Focusing for Matched & Mismatched Beams

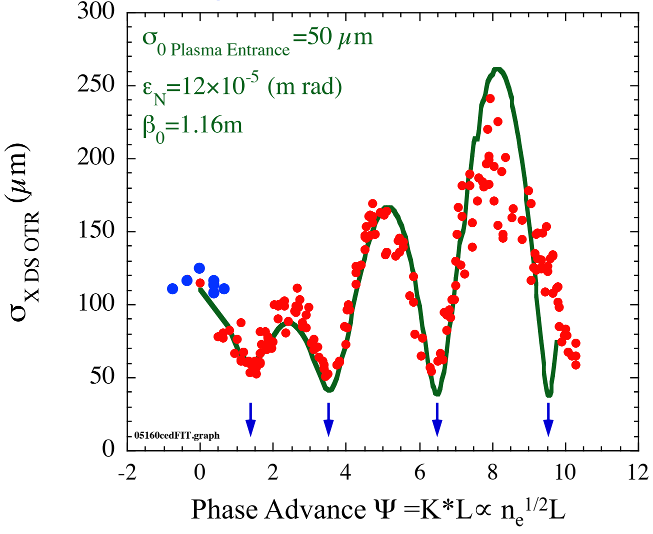
- Start with beam evolution in vacuum

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

- 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

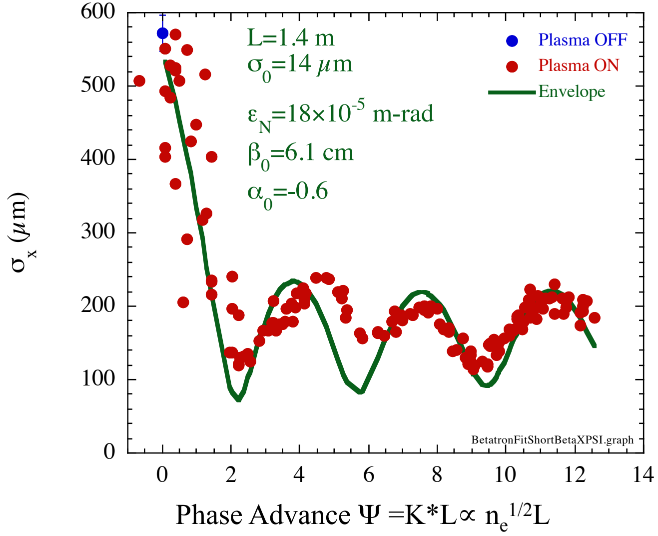


Large Beam Size (K>1/β0)



*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
- Enables high density beam propagation over long distances

# 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

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

Gauss's Law

Change variables

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

Equation for perturbed density

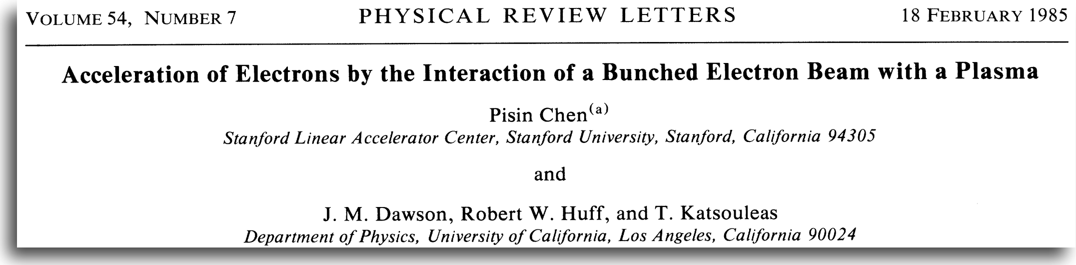
$$(\partial_\zeta^2 + k_p^2)\delta n = -k_p^2 n_b$$

Driving term for E

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

Simplify in narrow beam limit

$$k_p \sigma_r \ll 1$$



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Finally an equation for $E_z$ 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: $E_z \propto n_p^{1/2} \propto \dfrac{N}{\sigma_z^2}$

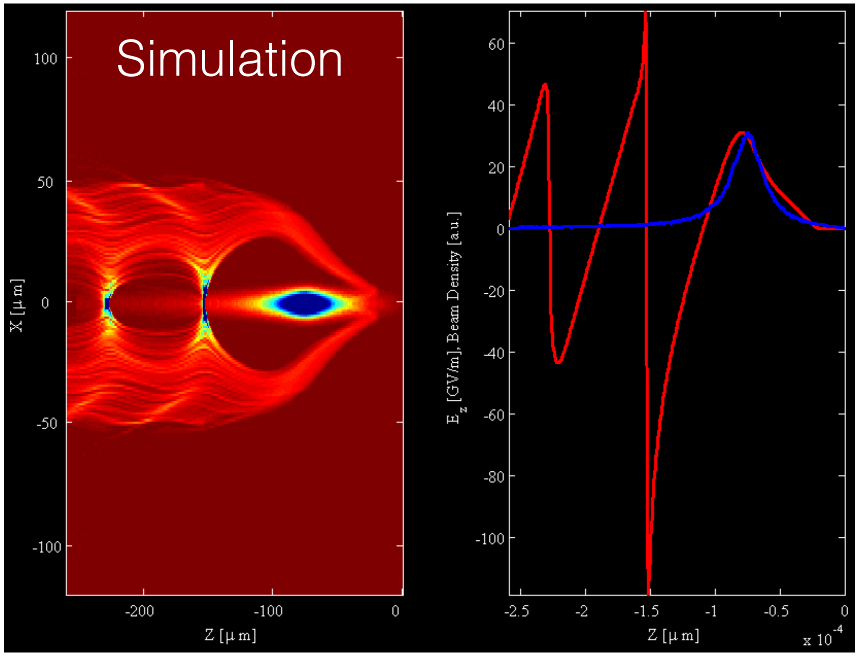
In practical terms

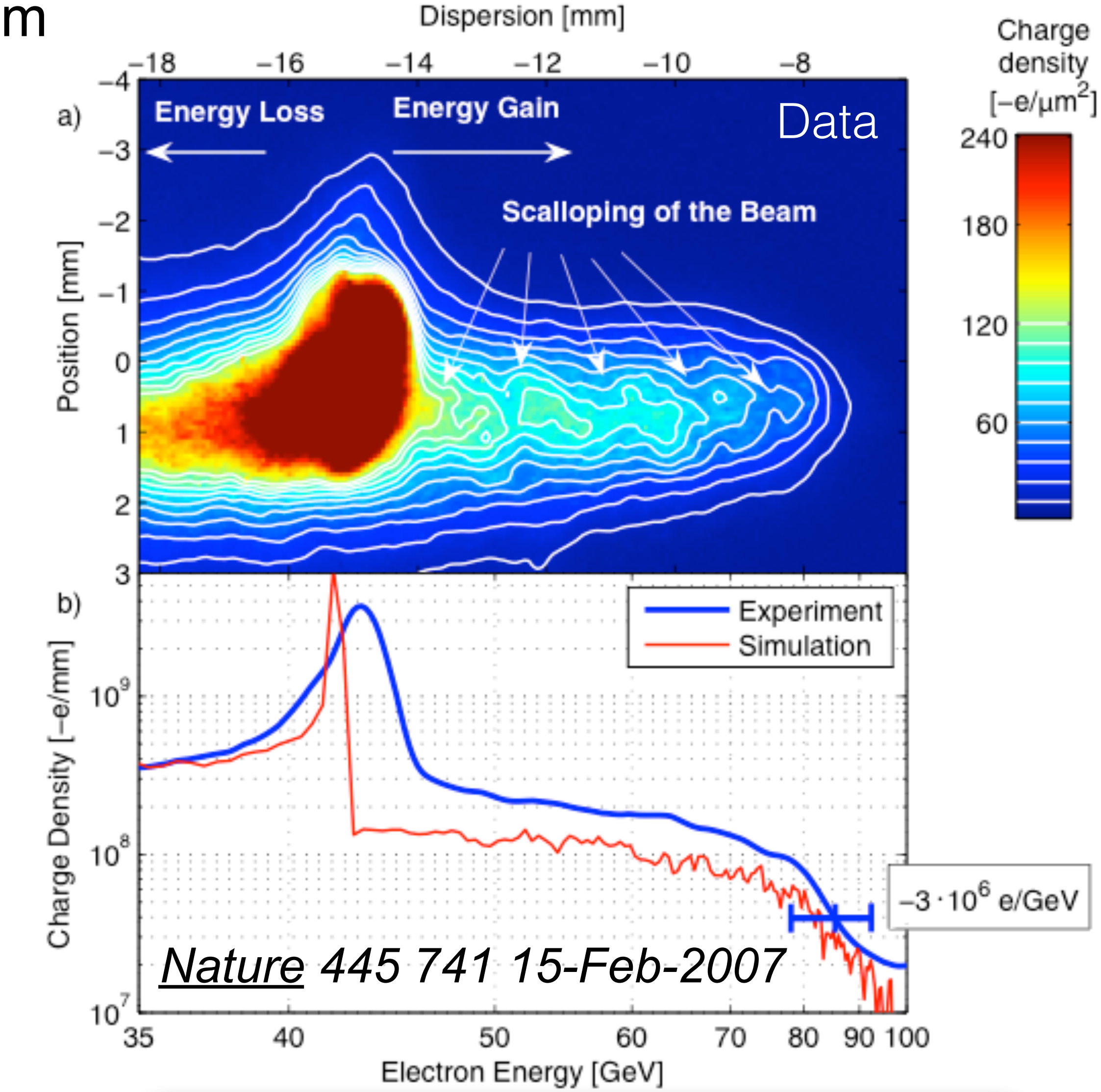
$$eE_z[MeV/m] \simeq 240 \times \left(\frac{N}{4 \times 10^{10}}\right)\left(\frac{0.6}{\sigma_z[mm]}\right)^2$$

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

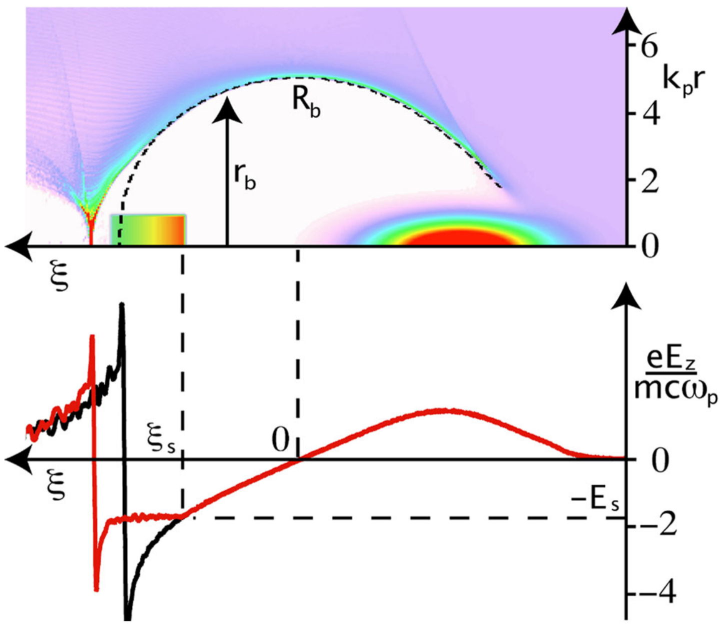
*Next Step: Particle acceleration to beam acceleration @ FACET*

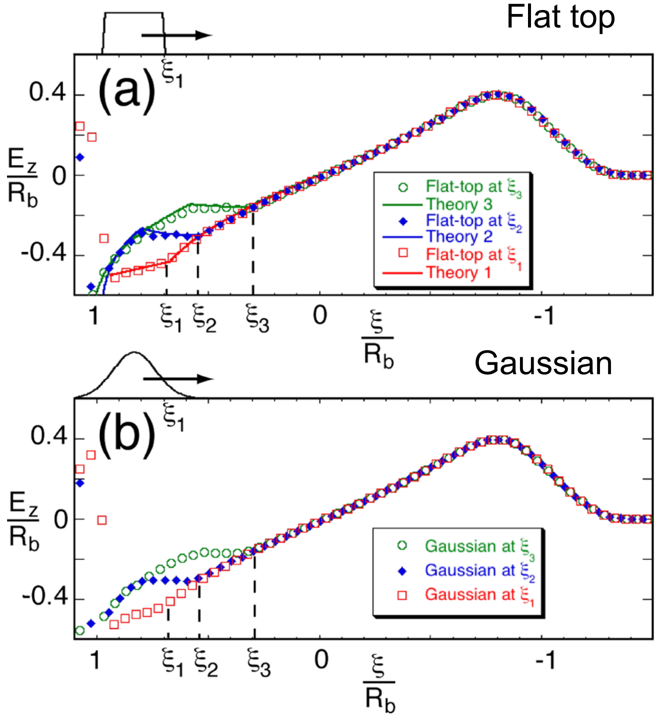
# Beam Loading in Non-linear Wakes

## 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:

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



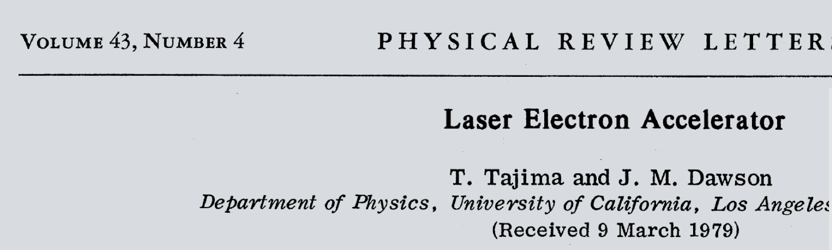


- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards $\Delta E/E \sim 10^{-2} - 10^{-3}$
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio ➡ Shaped Bunches

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

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

# Accelerating Particles to Accelerating Beams → FACET



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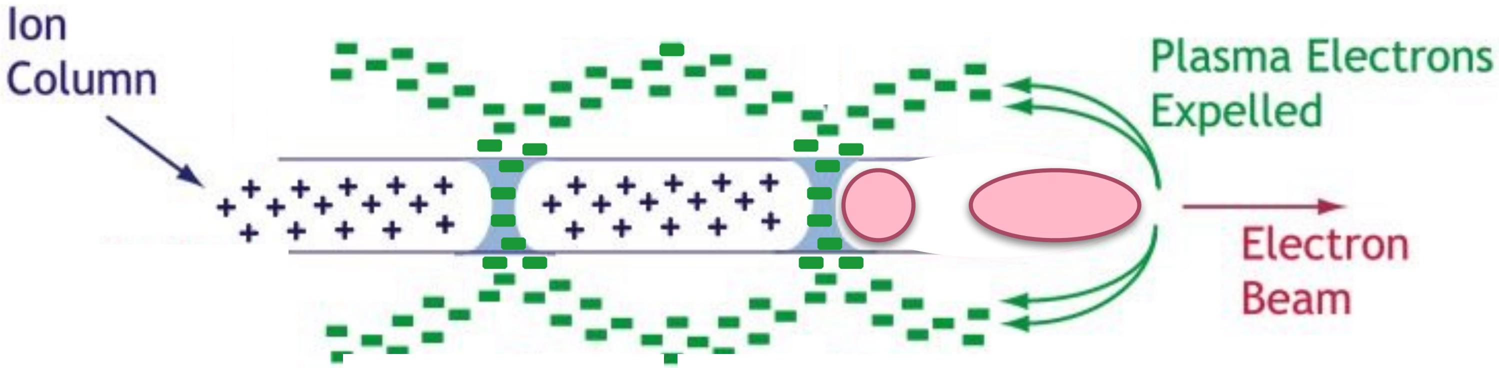


$$E_0 \sim 10\sqrt{\frac{n_0}{1 \times 10^{16}[\mathrm{cm}^{-3}]}}[\mathrm{GeV/m}]$$

- Two bunches externally injected
- Dimensions and spacing ~ $c/w_p$ ~ 20µm
- Blow-out when $n_b >> n_p$
- Plasma = highly efficient transformer

# FACET Project History


20GeV, 3nC, 20µm$^3$, e$^-$ & e$^+$

**Primary Goal:**

- Demonstrate a single-stage high-energy plasma accelerator for electrons

**Timeline:**

- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

**A National User Facility:**

- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

**Key PWFA Milestones:**

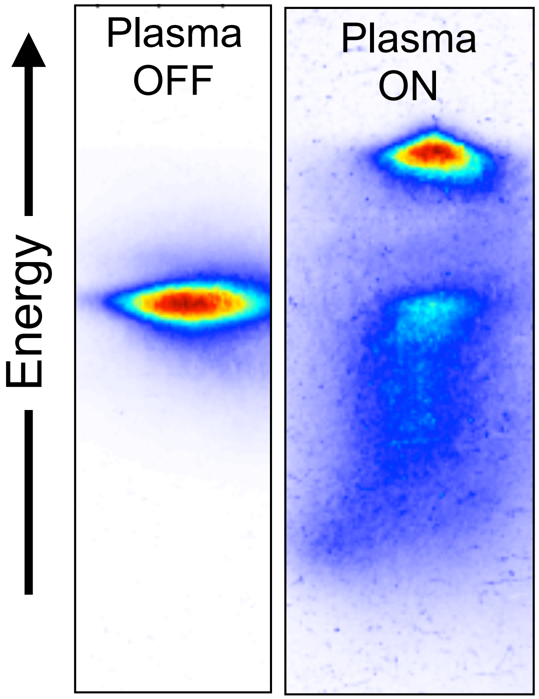
- ✓Mono-energetic e- acceleration
- ✓High efficiency e$^-$ acceleration (*Nature* **515**, Nov. 2014)
- ✓First high-gradient e$^+$ PWFA (*Nature* **524**, Aug. 2015)
- Demonstrate required emittance, energy spread (FY16)

The premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

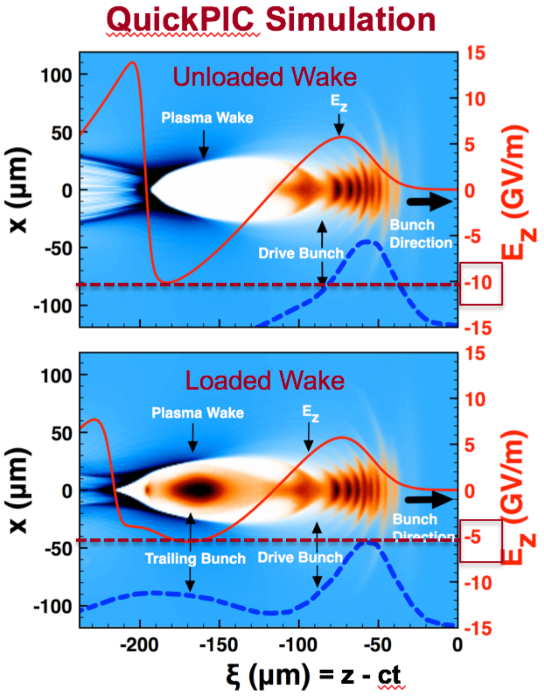
Litos et al., *Nature* November 2014

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

## Beam loading is key for:
## Narrow energy spread & high efficiency



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



nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

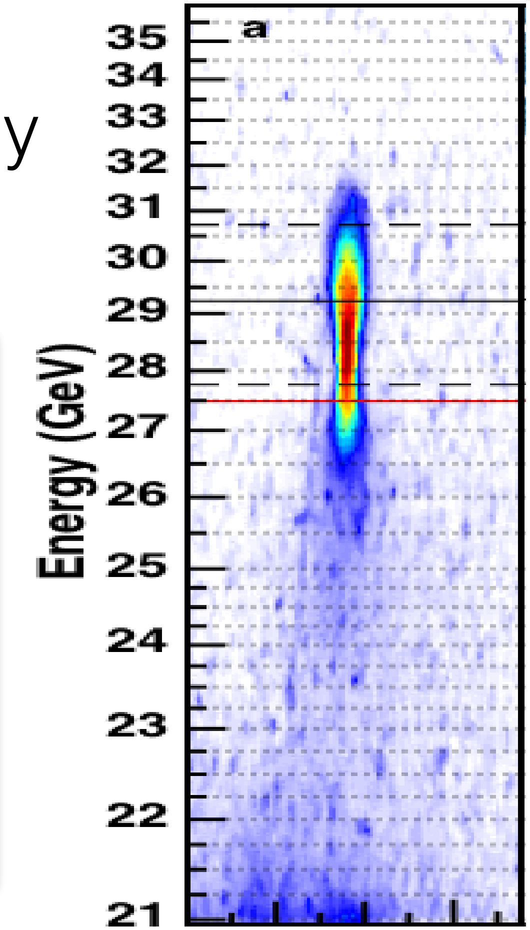
FULL SPEED AHEAD

*Plasma wakefield machines — the particle accelerators of the future?* PAGES 40 & 92

LIFE AFTER THE WALL

CASH, CONFLICT, CONSERVATION

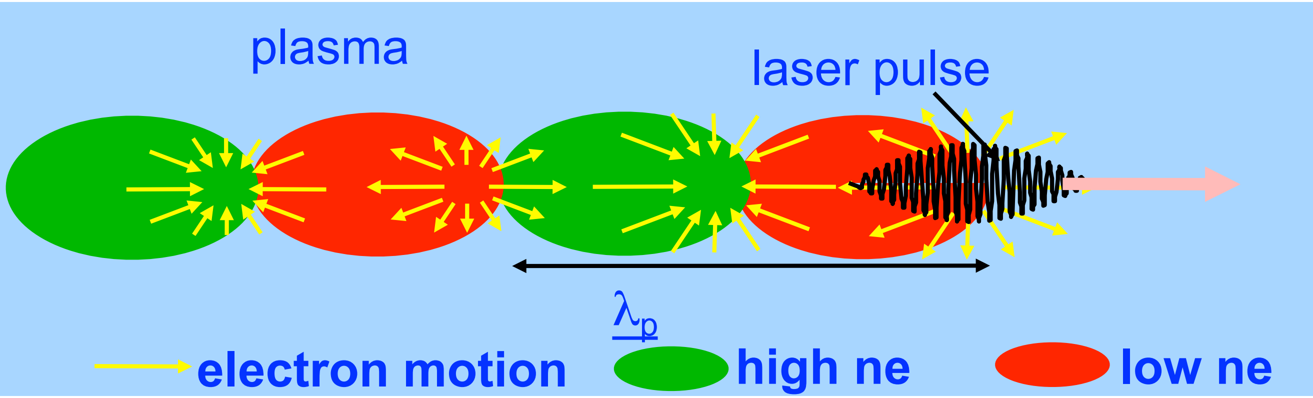
SHARE AND SHARE ALIKE



9 GeV
Energy Gain

Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

# 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 $\lambda_p$
  $L \sim \lambda_p \sim n^{-1/2} \sim 30\ \mu m$ (100 fs) for $n \sim 10^{18}$ cm$^{-3}$

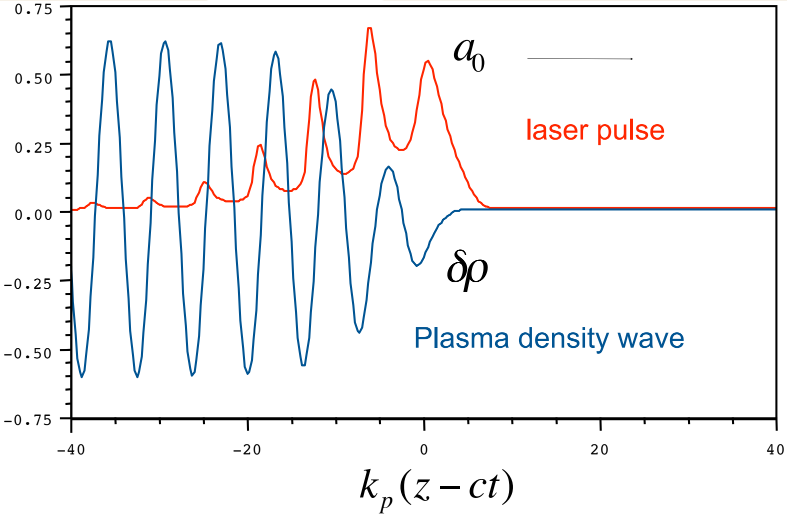
Tajima, Dawson (79); Gorbunov, Kirsanov (87); Sprangle, Esarey *et al*. (88), Esaray *et al*. Rev. Mod. Phys. 81, 1229 (2009)

# 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

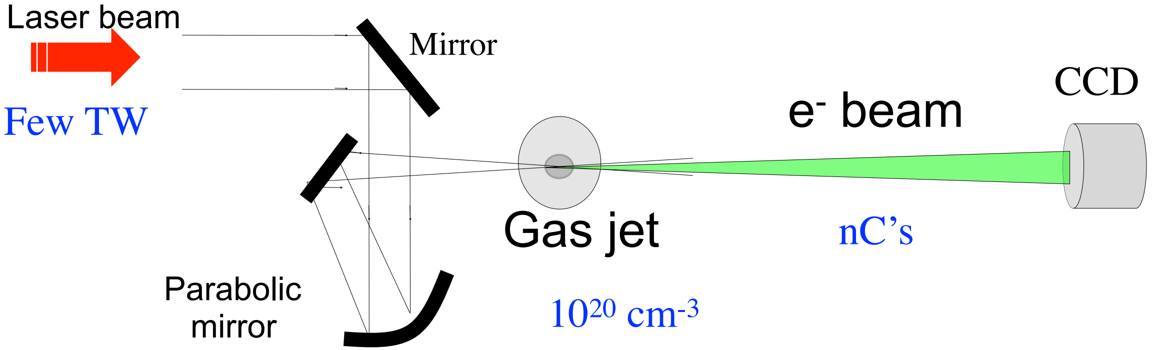
Sprangle *et al*. (92); Antonsen, Mora (92); Andreev *et al*. (92); Esarey *et al*. (94); Mori *et al*. (94)



SM-LWFA experiments routinely produce electrons with:

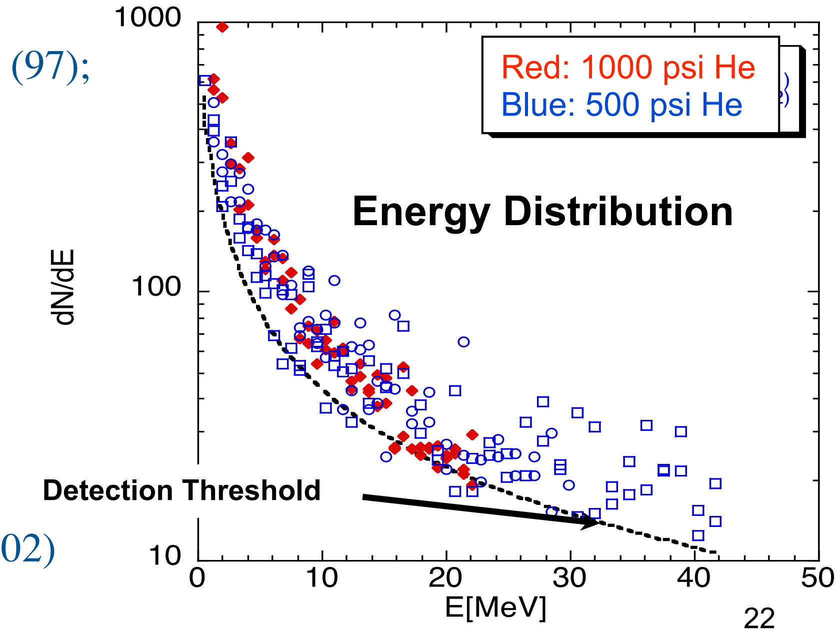
1-100 MeV (100% energy spread), multi-nC, ~100 fs, ~10 mrad divergence

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)



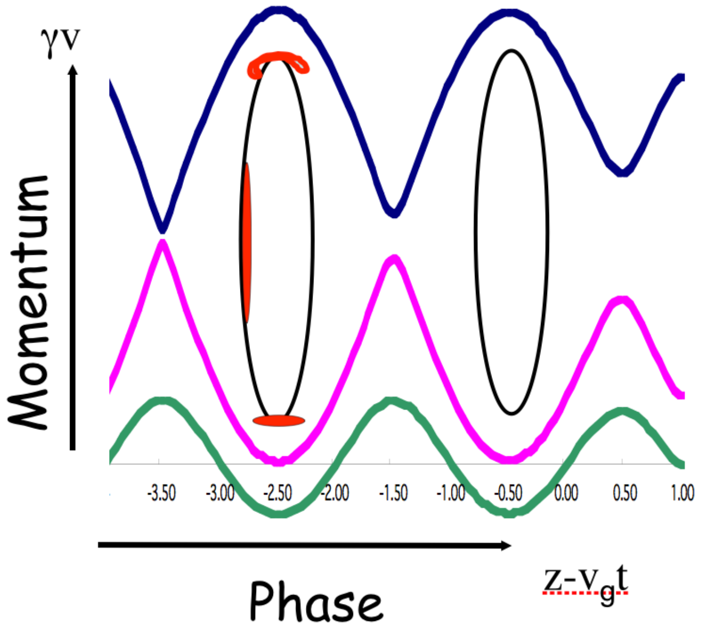
Courtesy of E. Esarey

Leemans *et al*. (02)

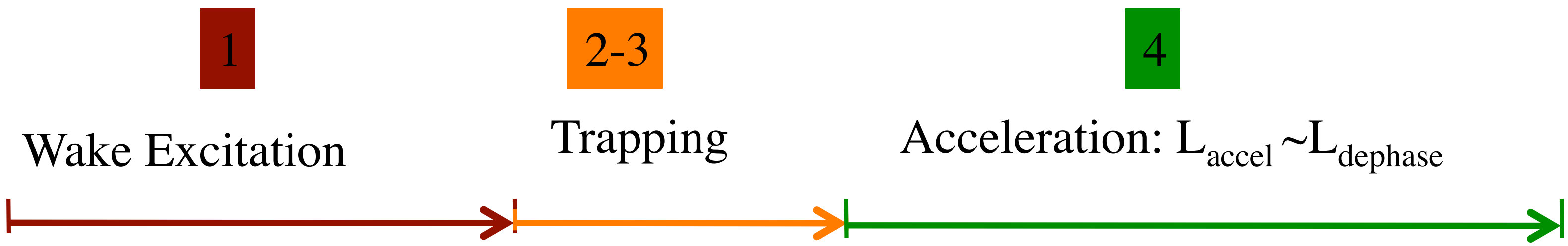


# LWFA: Production of a ‘Mono-energetic’ Beam

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


nature

Dream beam

The dawn of compact particle accelerators

Approach 1: Plasma channel

- LBNL/USA: Geddes et al.
  - Plasma Channel: 1-4x$10^{19}$ cm$^{-3}$
  - Laser: 8-9 TW, 8.5 $\mu$m, 55 fs
  - E-bunch: $2\times10^{9}$ (0.3 nC), 86 MeV, $\Delta E/E$=1-2%, 3 mrad

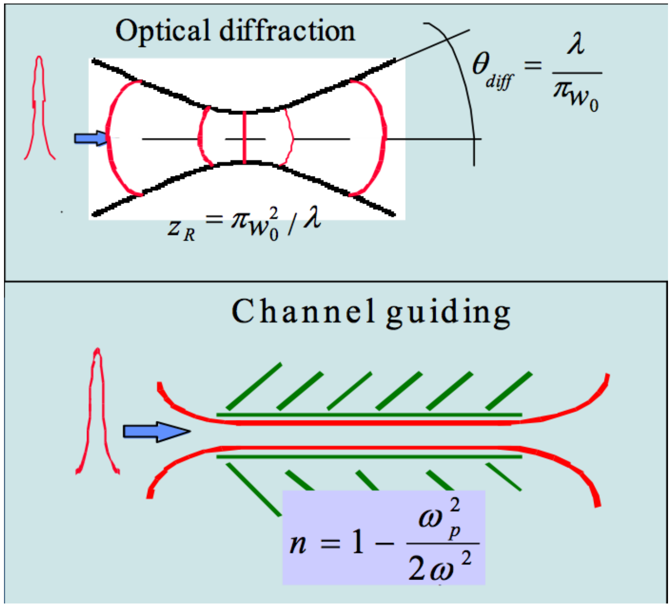
Approach 2: No channel, larger spot size

- RAL/IC/UK: Mangles et al.
  - No Channel: $2\times10^{19}$ cm$^{-3}$
  - Laser: 12 TW, 40 fs, 0.5 J, $2.5\times10^{18}$ W/cm$^{2}$, 25 $\mu$m
  - E-bunch: $1.4\times10^{8}$ (22 pC), 70 MeV, $\Delta E/E$=3%, 87 mrad
- LOA/France: Faure et al.
  - No Channel: 0.5-2x$10^{19}$ cm$^{-3}$
  - Laser: 30 TW, 30 fs, 1 J, 18 $\mu$m
  - E-bunch: $3\times10^{9}$ (0.5 nC), 170 MeV, $\Delta E/E$=24%,10 mrad

Channel allows higher e-energy with lower laser power

*Courtesy of E. Esarey*

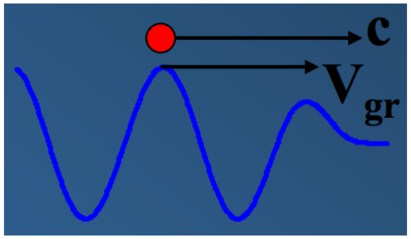
# Three Factors Limiting Energy Gain – Three D's of LWFA



- 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, $L_{dephase}$~ $L_{depletion}$

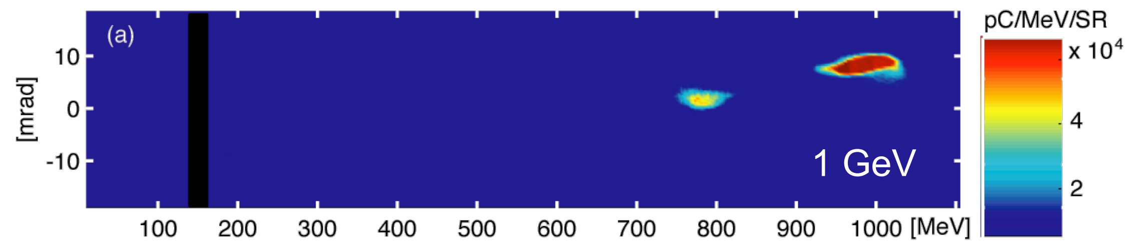
$$L_{deplete} \sim \frac{4L_{dephase}}{a_0^2}$$

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

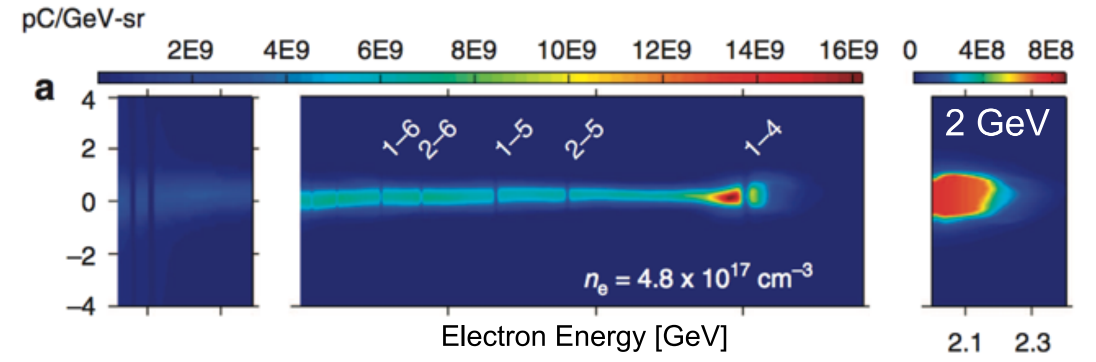
# Race for Maximum Energy Gain

## 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)

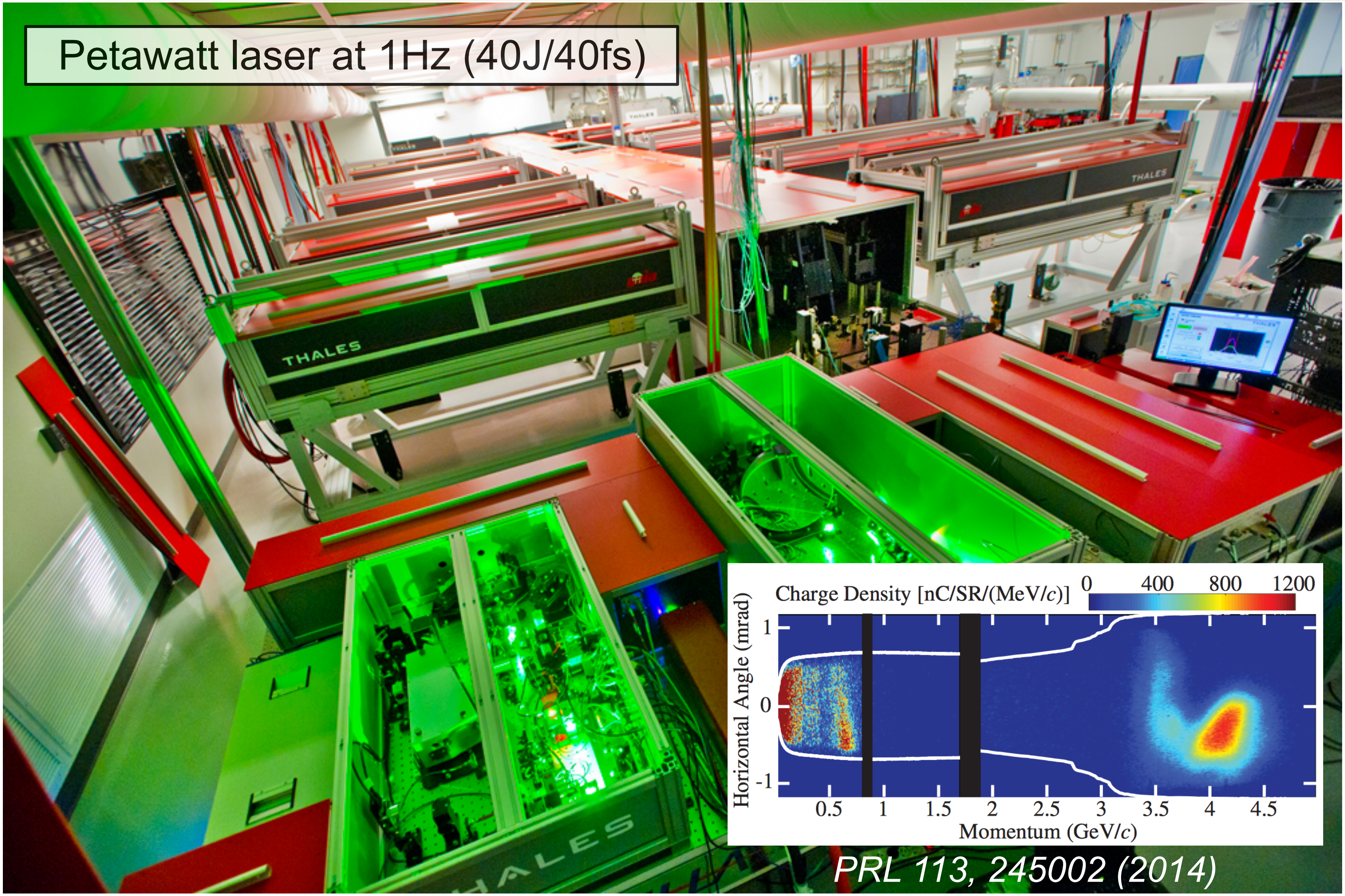


*Nat Commun.* ***4****:1988 doi: 10.1038/ncomms2988 (2013)*

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

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

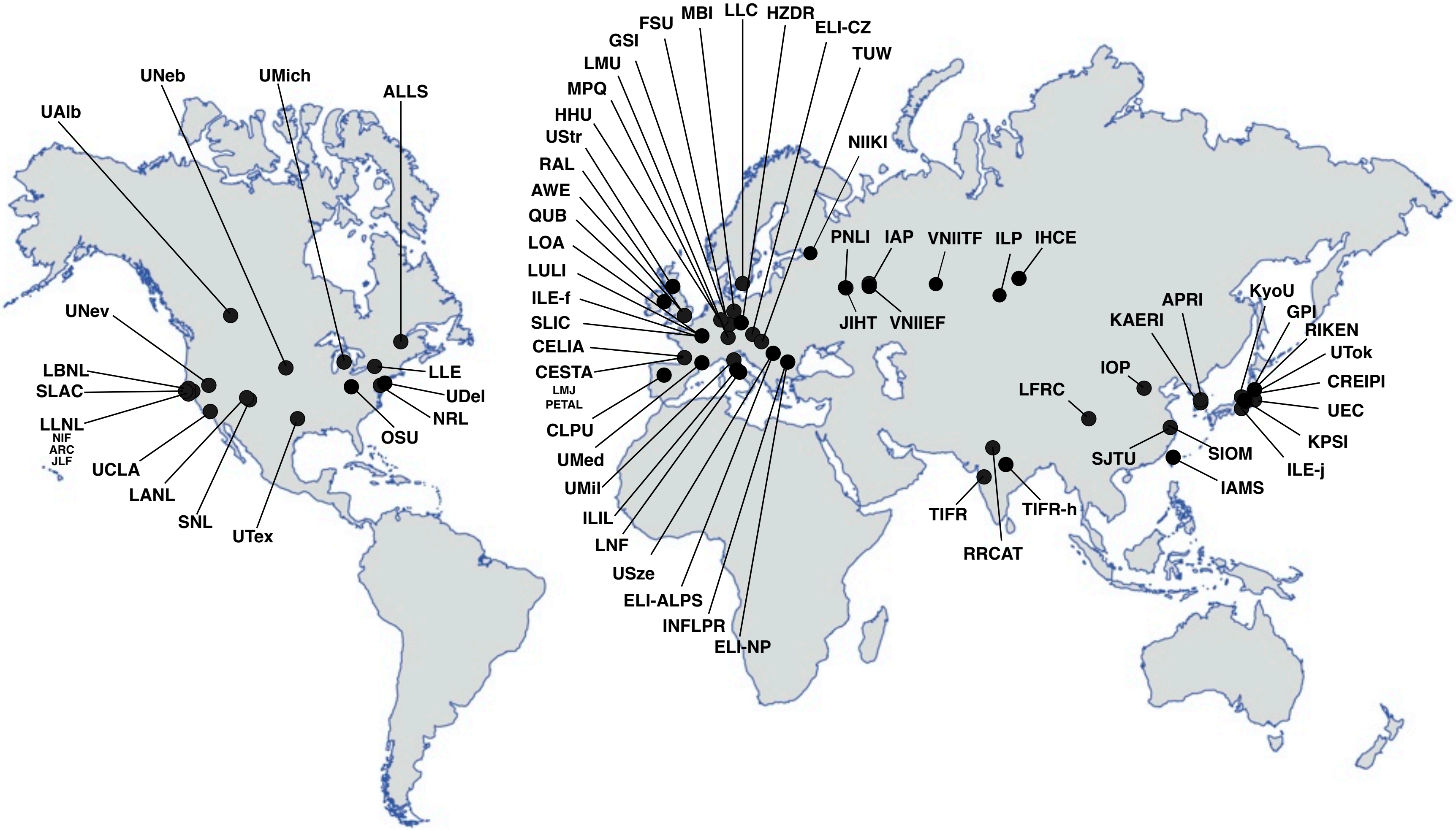
# BELLA Laser at Lawrence Berkeley Lab (LBNL)


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

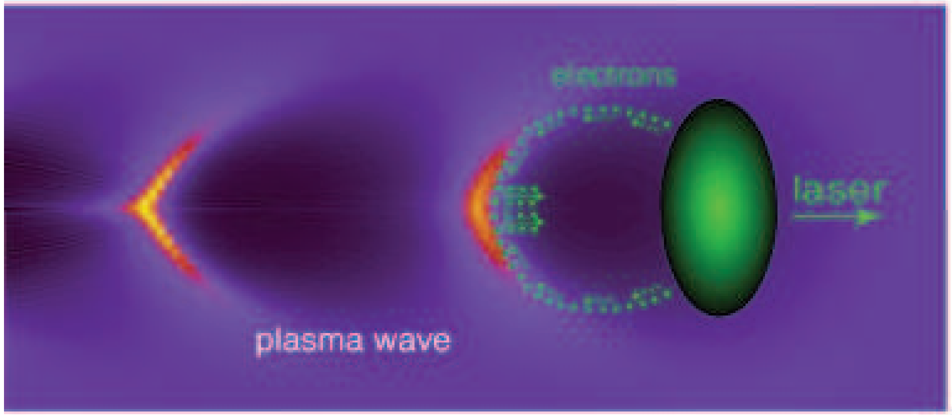
*PRL 113, 245002 (2014)*

# 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

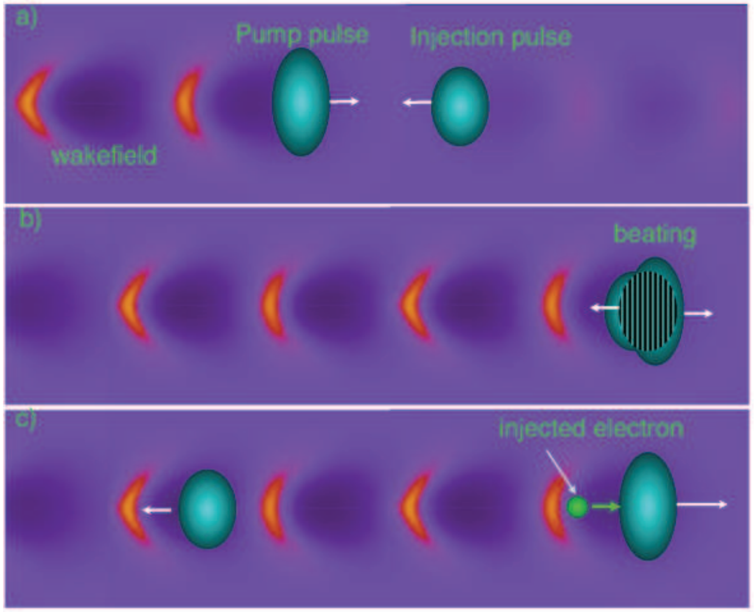


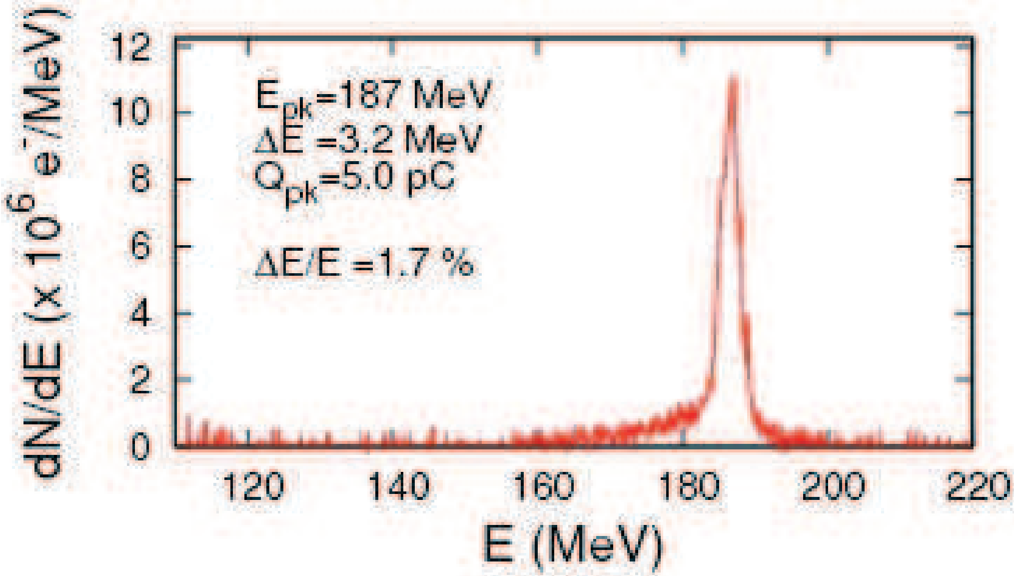
## Standard Injection

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

## Colliding Pulse Injection

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



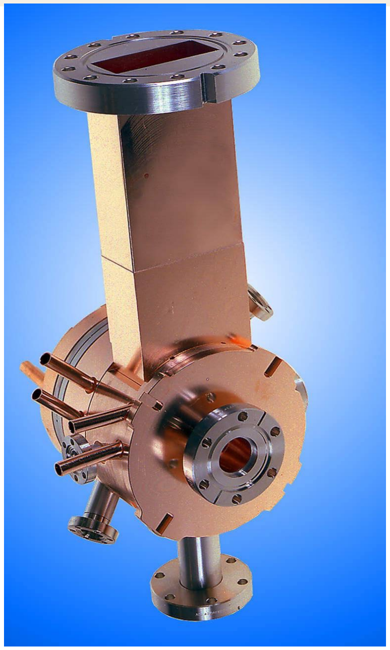


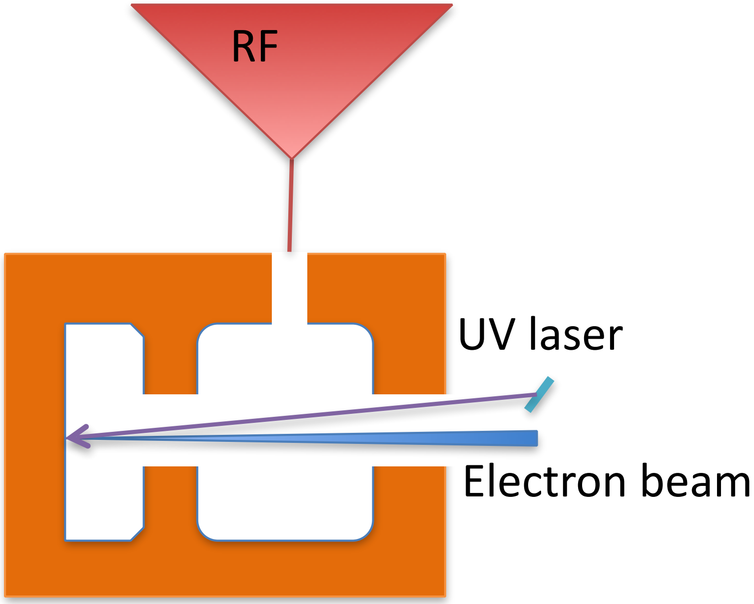
See: Esarey et al, PhysRevLett.79.2682 and Victor Malka (2010). Laser Plasma Accelerators: towards High Quality Electron Beam, Laser Pulse Phenomena and Applications, Dr. F. J. Duarte (Ed.), ISBN: 978-953-307-405-4 and References within

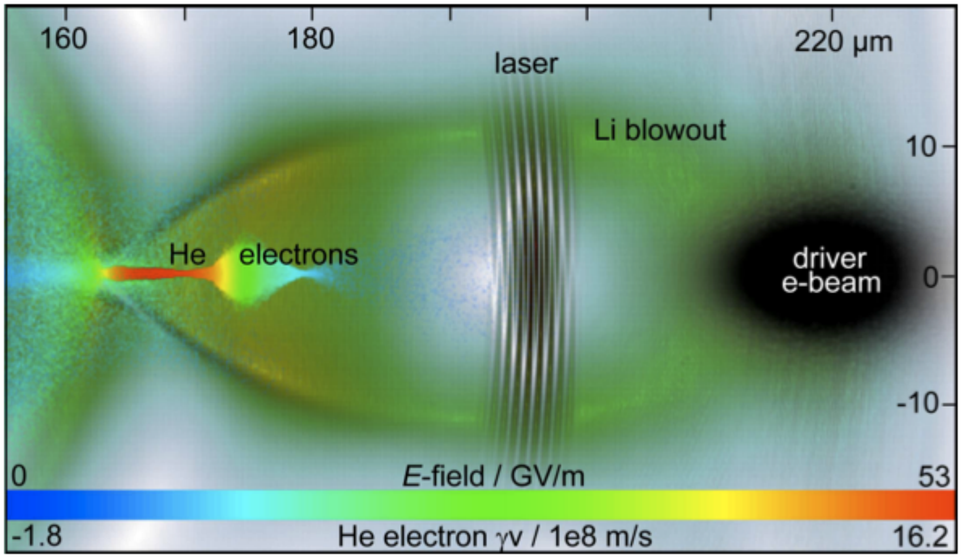
# Development of High-Brightness Electron Sources

## LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)



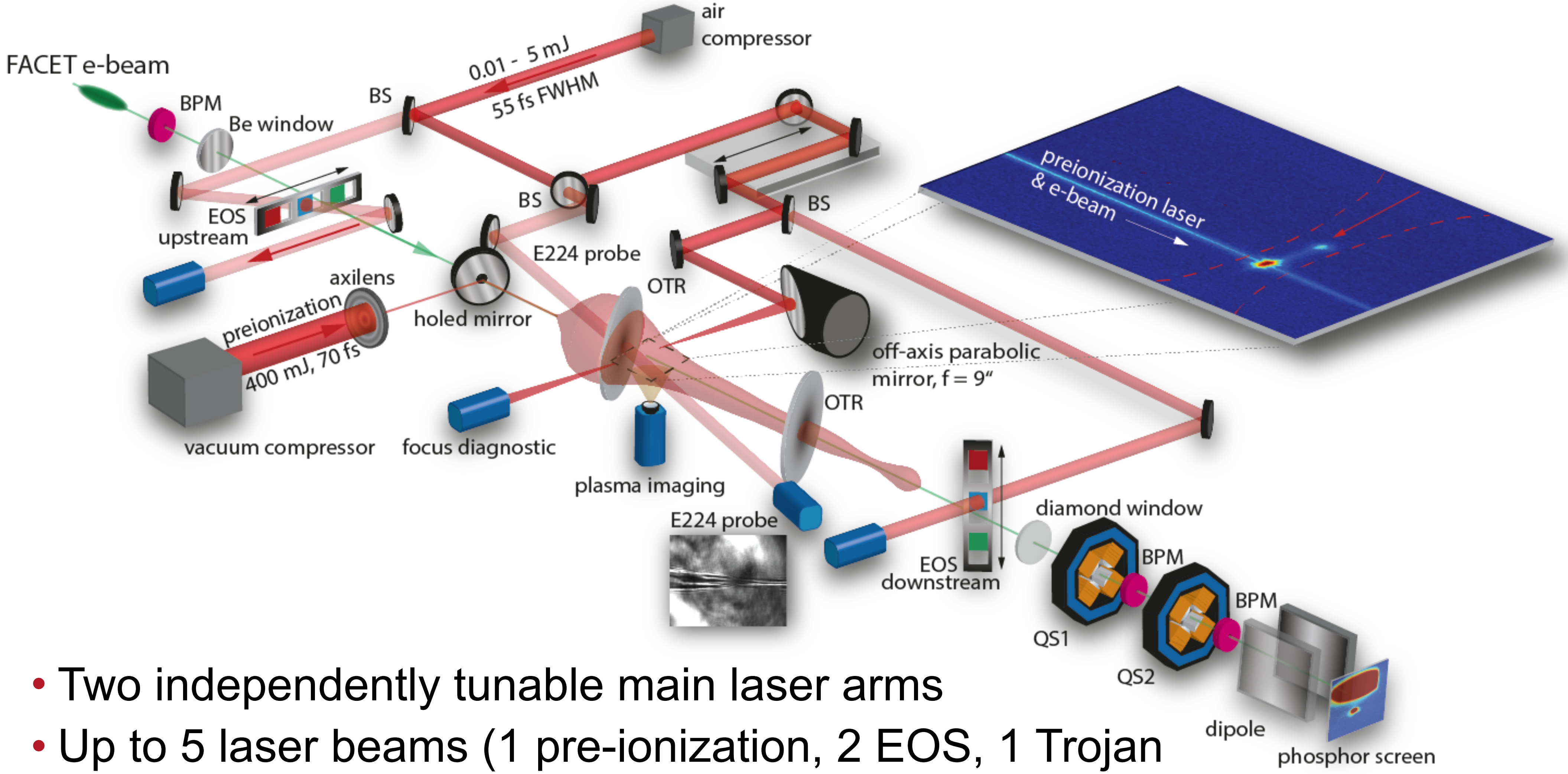




## Plasma Photoinjectors

- 100 GeV/m
- fs beams, µm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

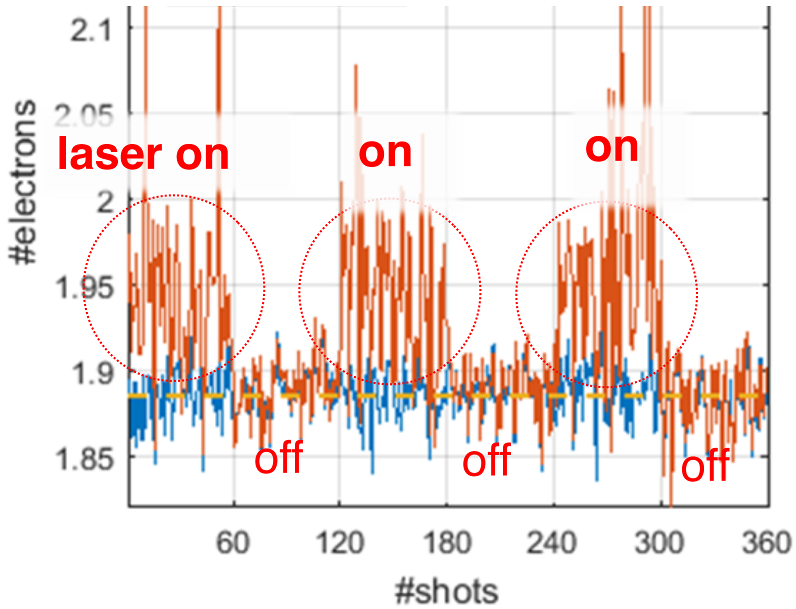
# 2015/2016: Full Trojan Horse setup

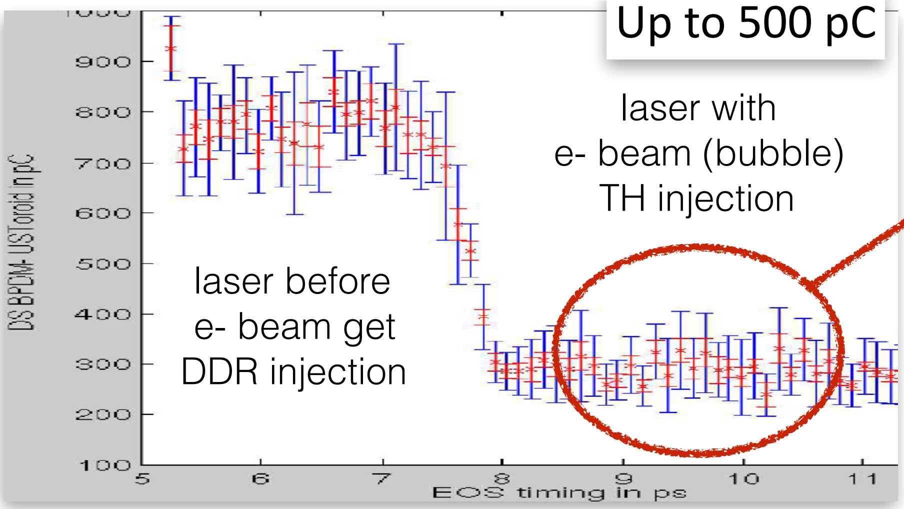


- Two independently tunable main laser arms
- Up to 5 laser beams (1 pre-ionization, 2 EOS, 1 Trojan photocathode, 1 probing) synchronized with the electron beam driver

# Experimental Data from Trojan Horse Injection Experiment

## Laser Triggered Charge



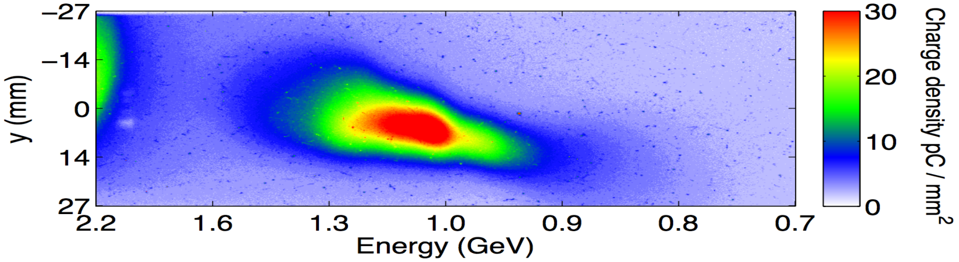


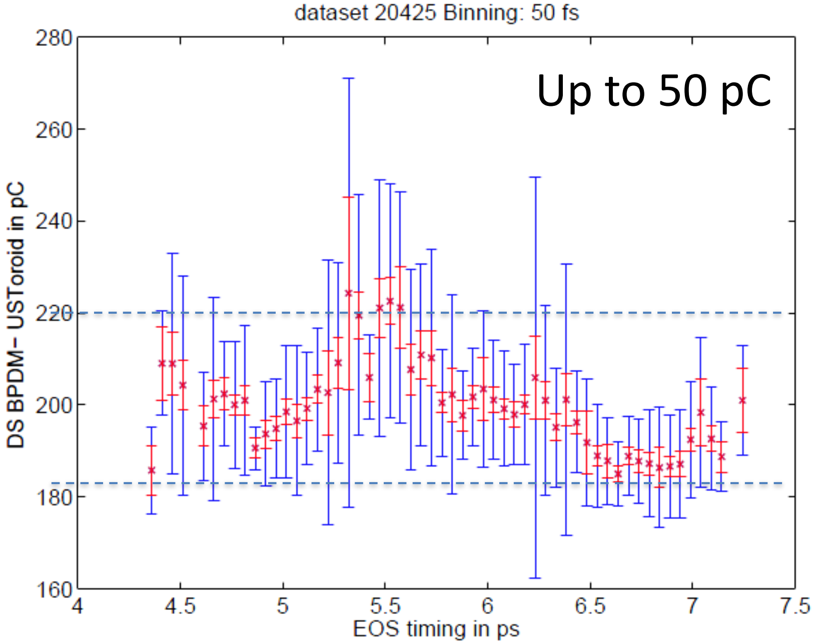
Up to 500 pC

laser with
e- beam (bubble)
TH injection

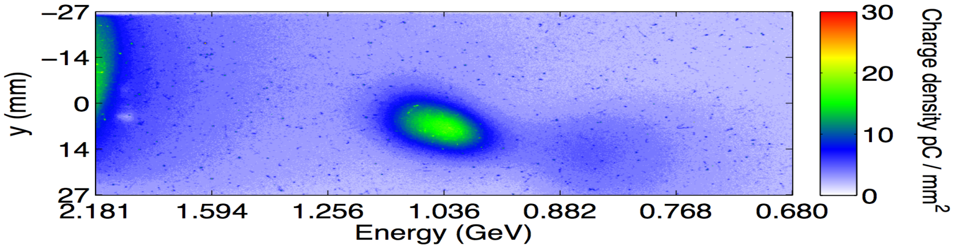
laser before
e- beam get
DDR injection

## Up to 4 GeV measured



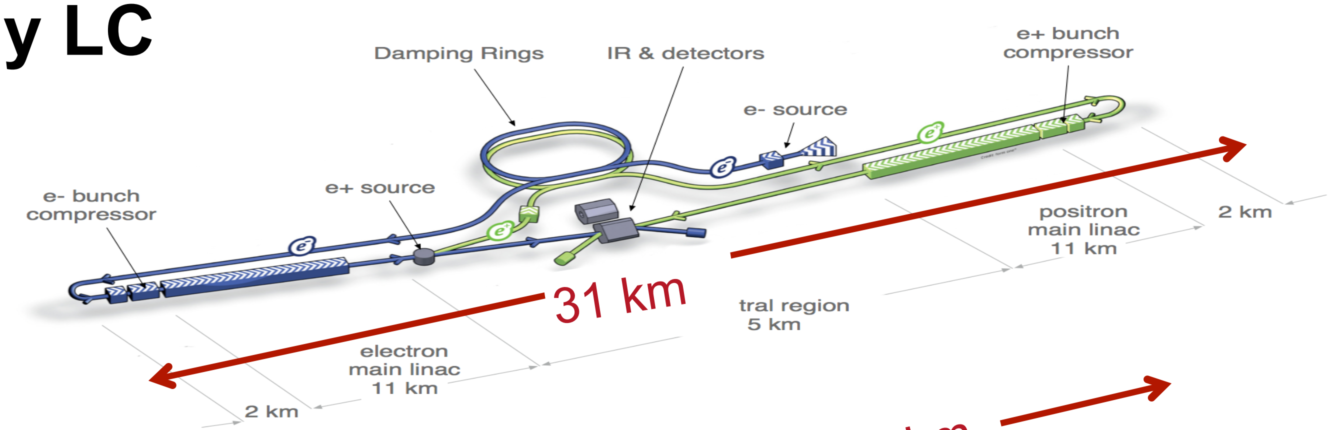


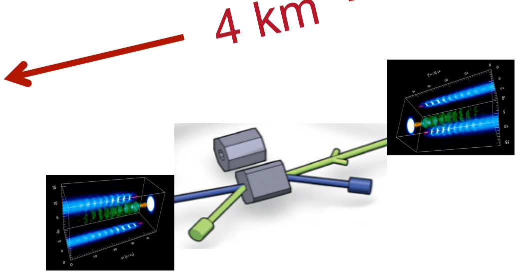
Up to 50 pC



# 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:**

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

- High-efficiency

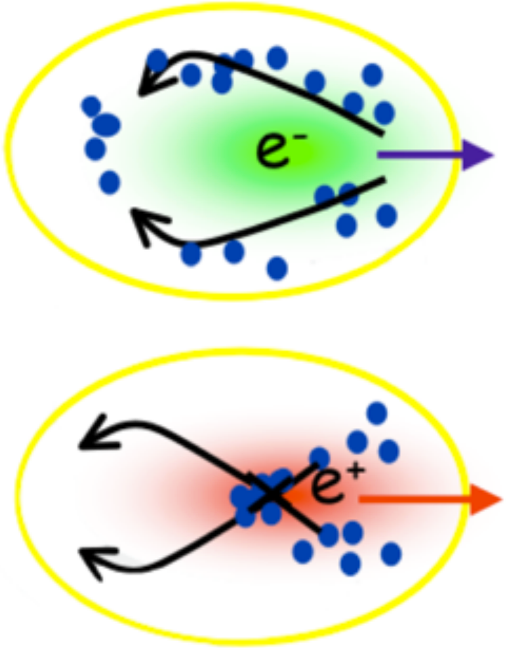
…and must do it for positrons too!

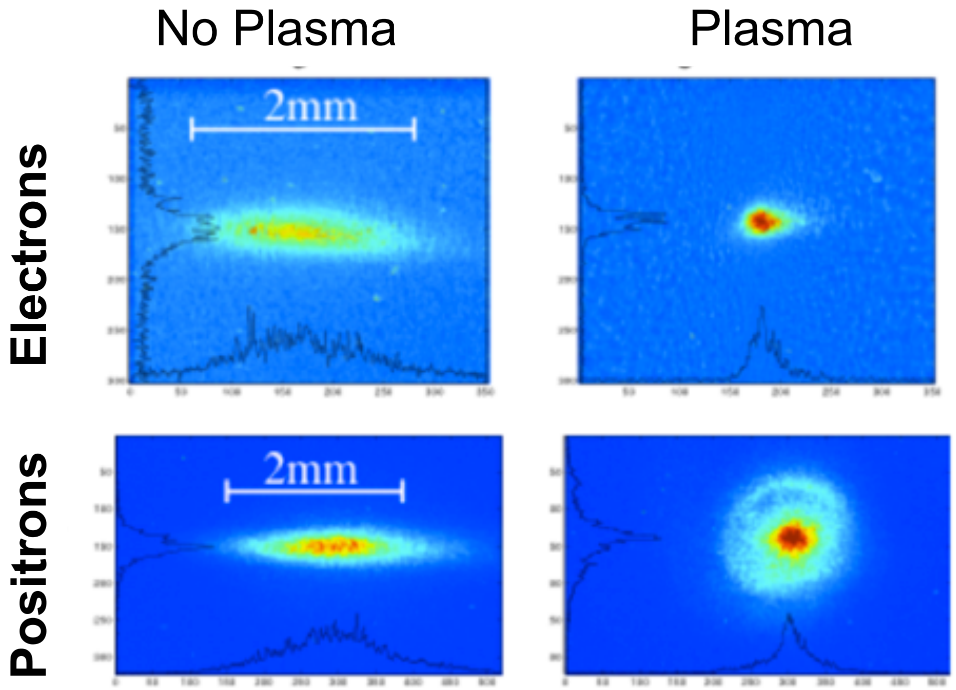
# Extending to Positrons is Not Trivial

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

**“Blow-out”**

**“Suck-in”**





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

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

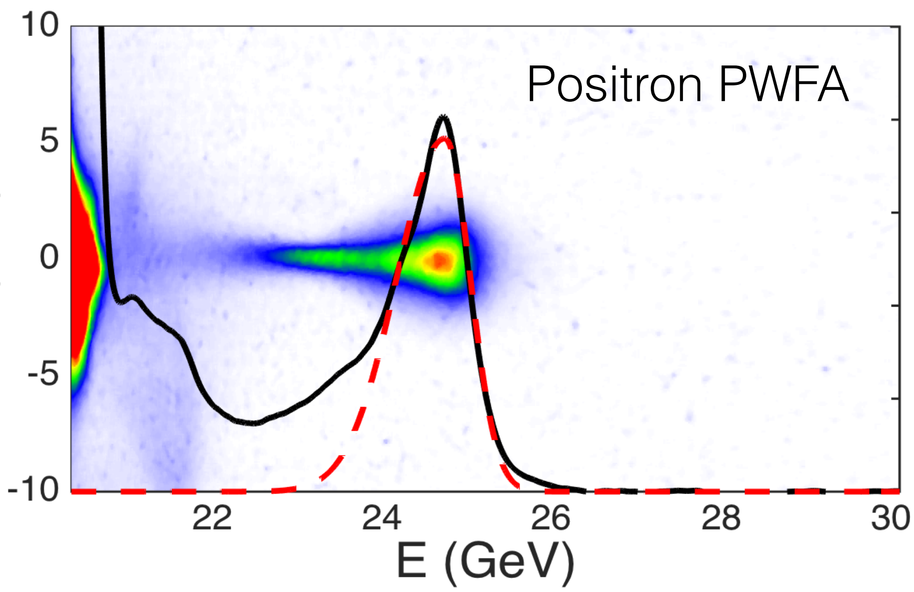
The nonlinear blowout regime will not work for positron PWFA

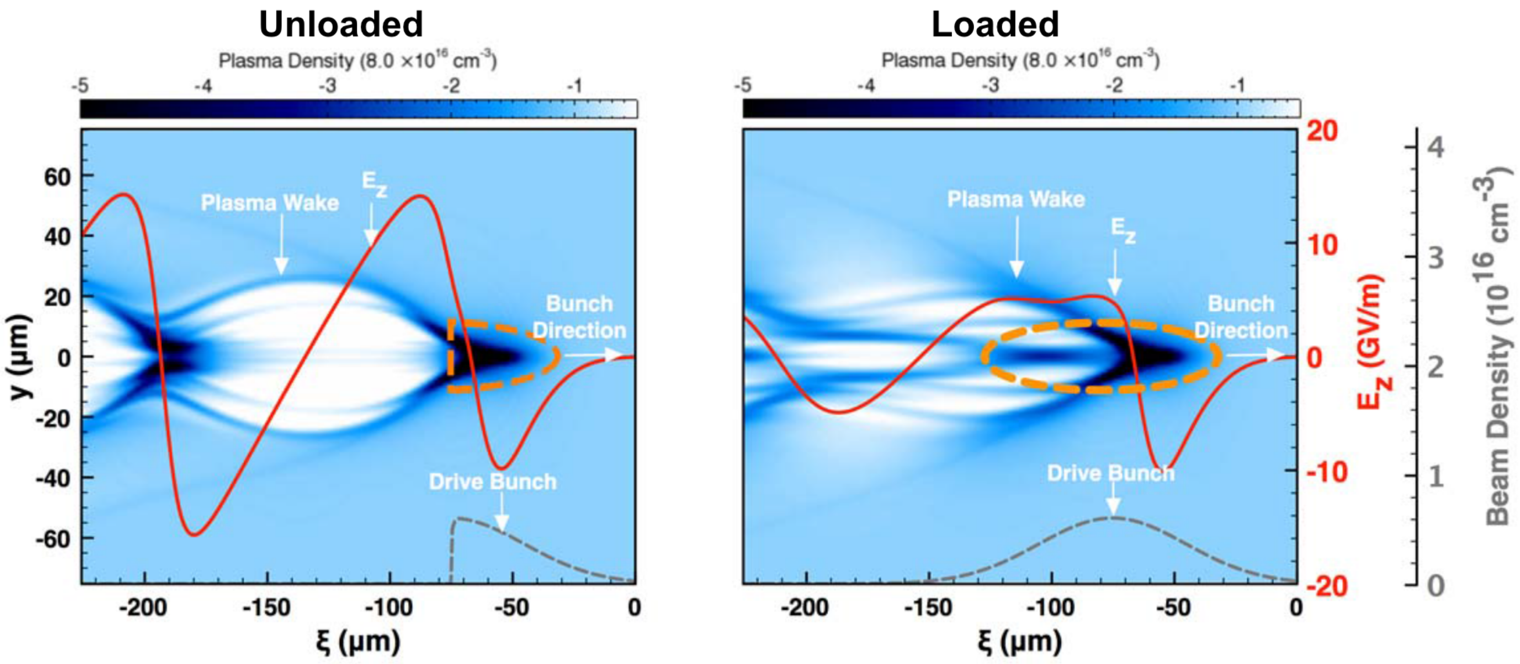
Corde et al., *Nature* August 2015

# Multi-GeV Acceleration of Positrons

Injecting a single high-intensity positron bunch produced a very surprising result!

- Energy gain 4 GeV in 1.3 meters
- 1.8% energy spread
- Low beam divergence
- No halo

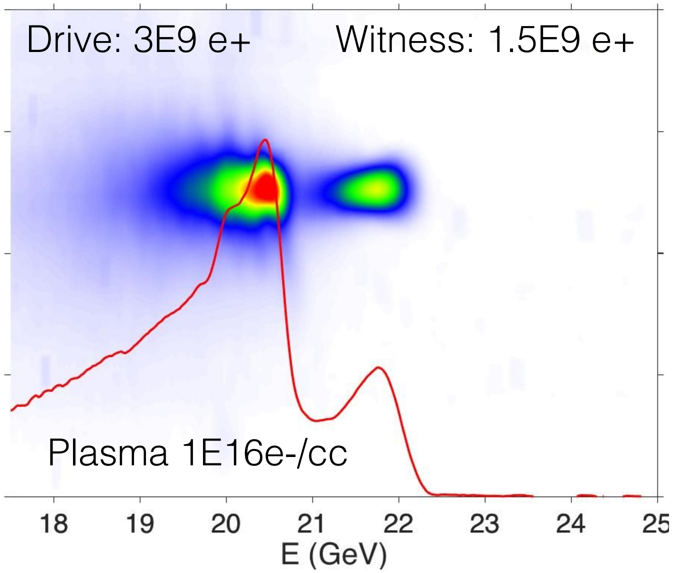


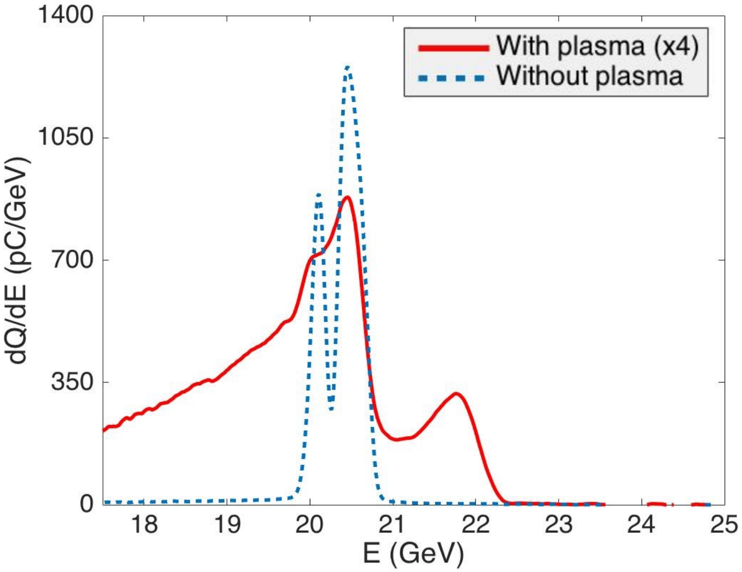


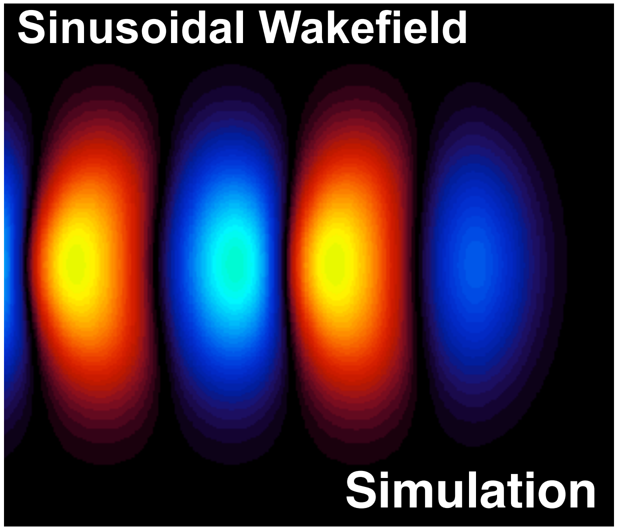
New PWFA regime warrants further exploration and development towards plasma afterburner applications

# Positron Acceleration with Low Density Drive-Witness Pair

- Reduced individual bunch charge then varied the incoming beam emittance:
  - Clear correlations in Emax, accelerated charge, transmitted charge, divergence
  - In agreement with **transition to a more linear regime**
- Of interest to both the PWFA and LWFA for linear collider applications
- Greater than 1 GeV energy gain of witness beam in 1.3 m-long plasma

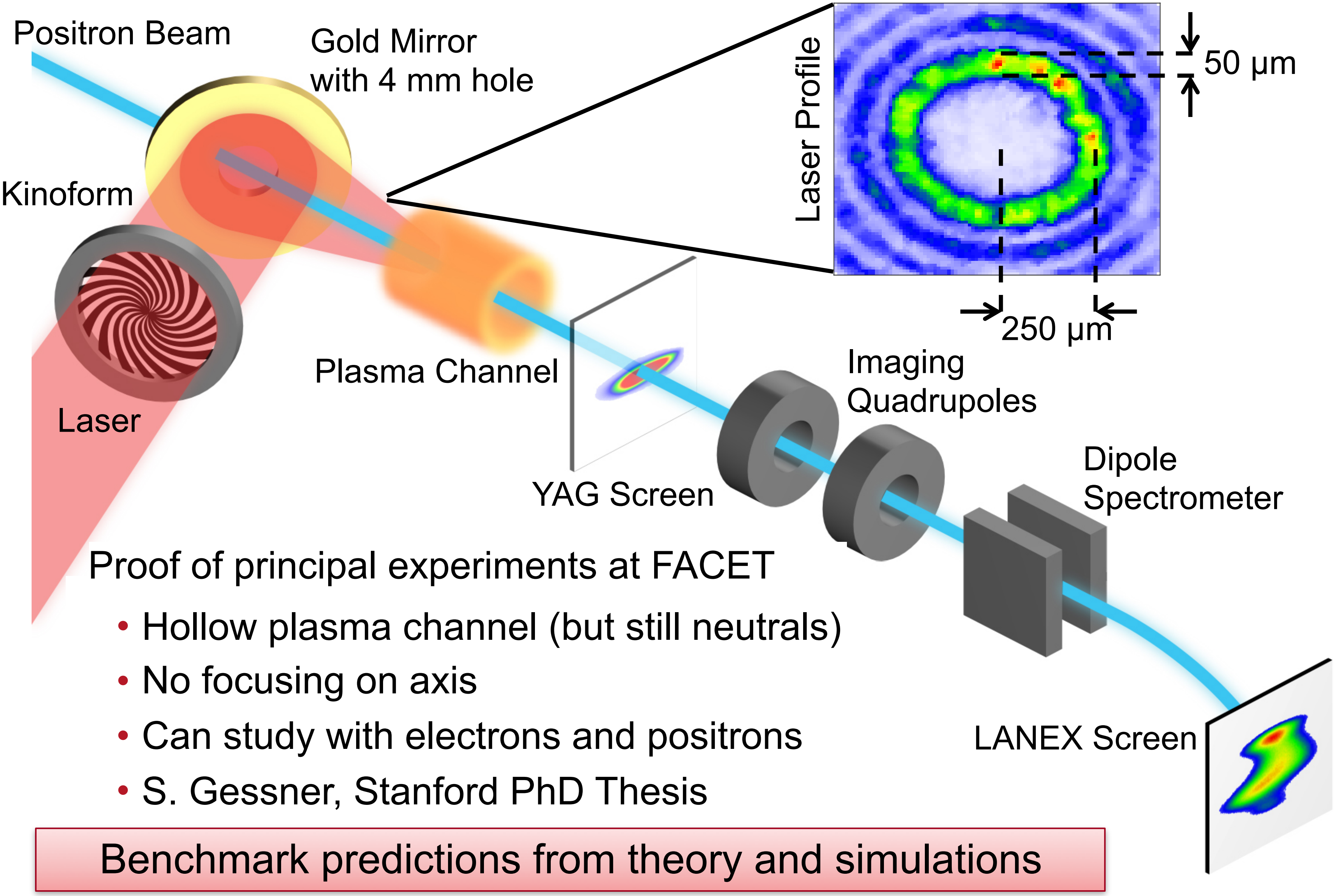






This technique can be used to accelerate a positron witness beam in the wake of an electron beam or a laser beam

# Hollow Channel Plasma Wakefield Acceleration – Engineer the Plasma Source to Control the Fields



Proof of principal experiments at FACET

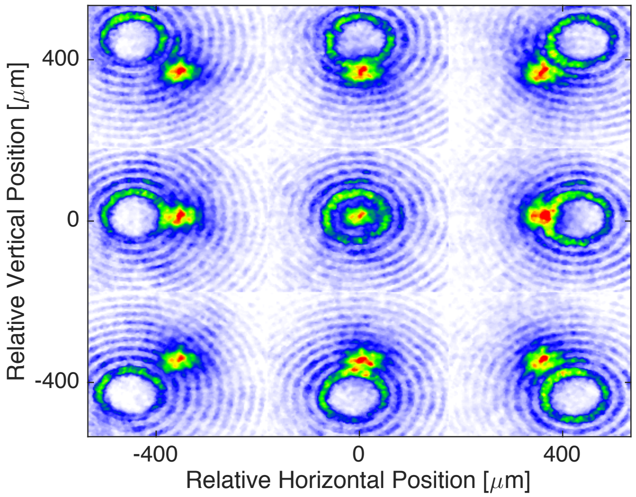
- Hollow plasma channel (but still neutrals)
- No focusing on axis
- Can study with electrons and positrons
- S. Gessner, Stanford PhD Thesis

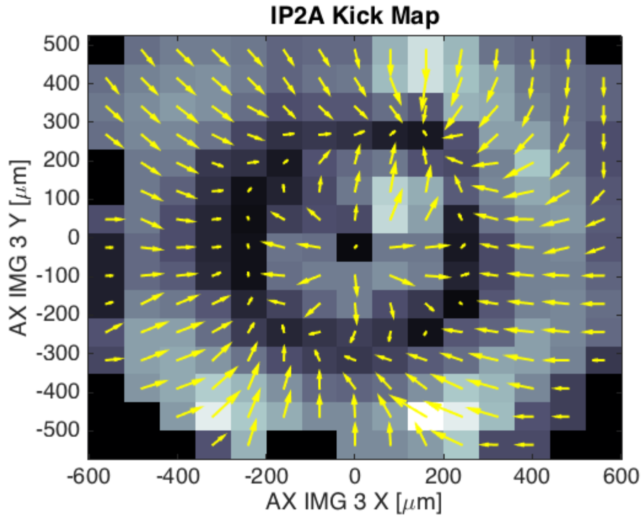
**Benchmark predictions from theory and simulations**

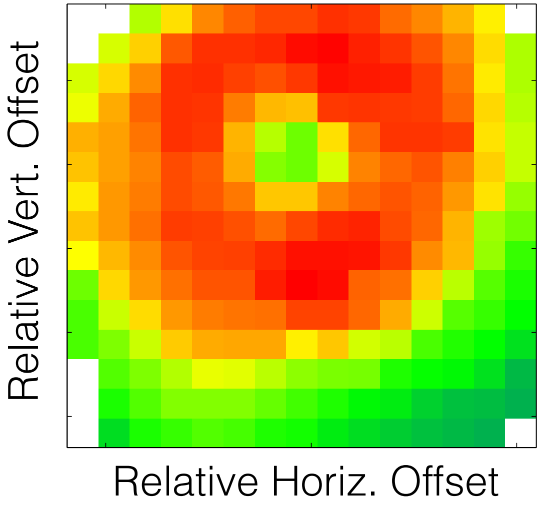
Gessner et al., *Nature Communications* June 2016

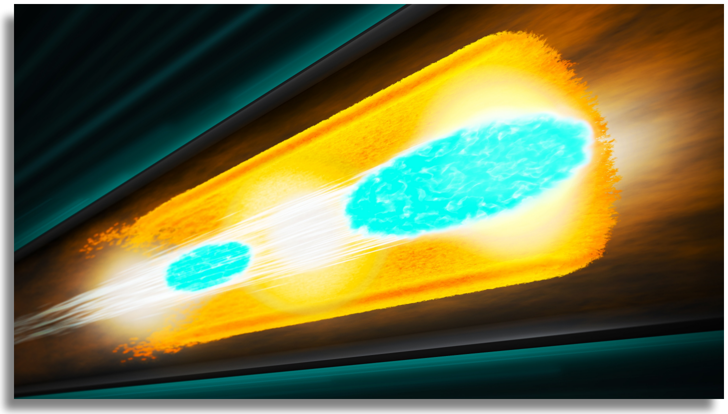
# Demonstration of Acceleration in Hollow Channel Plasmas

## Raster Scan of Beam-Channel Alignment
## Focusing Forces Minimized in Channel Center

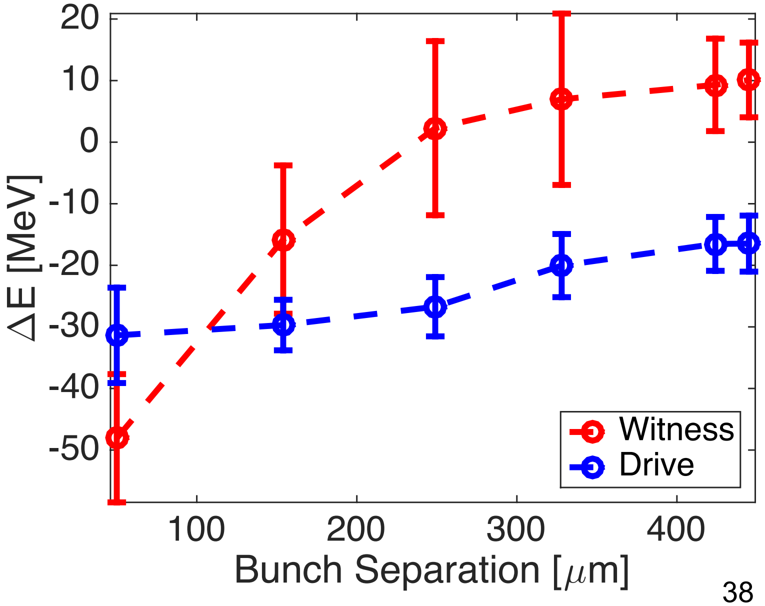








Change bunch spacing to map the longitudinal wakefield



# Paths to a Linear Collider

| | Advantages | Challenges | Open Questions |
|---|---|---|---|
| **Non-Linear Acceleration** | Extremely large gradients.<br>Simple experimental setup. | No known solution using an electron drive beam. | What are the optimal beam and plasma parameters for an afterburner application? |
| **Quasi-Linear Acceleration** | Very large gradients.<br>Works with a driving electron beam. | Scaling the plasma and drive beam parameters for an LC-quality witness bunch looks challenging. | Can the emittance of the witness beam preserved? |
| **Hollow Channel Acceleration** | Emittance preservation by precise alignment.<br>Works with a driving electron beam. | Modest accelerating gradients. | Can we increase the wake amplitude while maintaining the quality of the witness bunch? |

These are critical questions on the path to a plasma-based Linear Collider

# AWAKE Collaboration Will Study Proton Driven PWFA

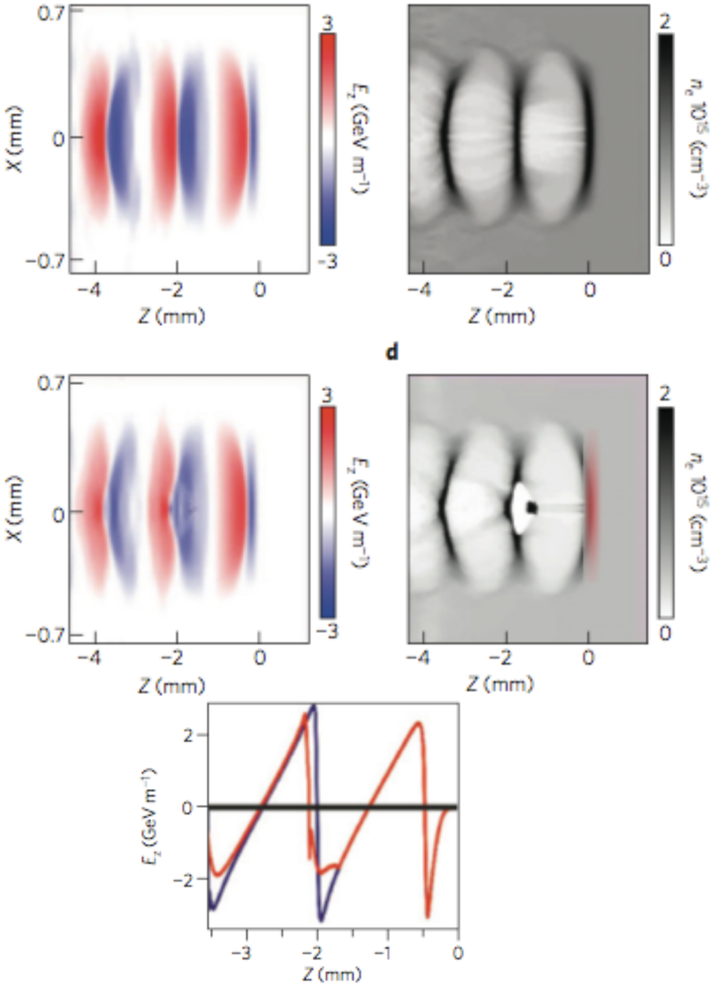
nature physics

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]

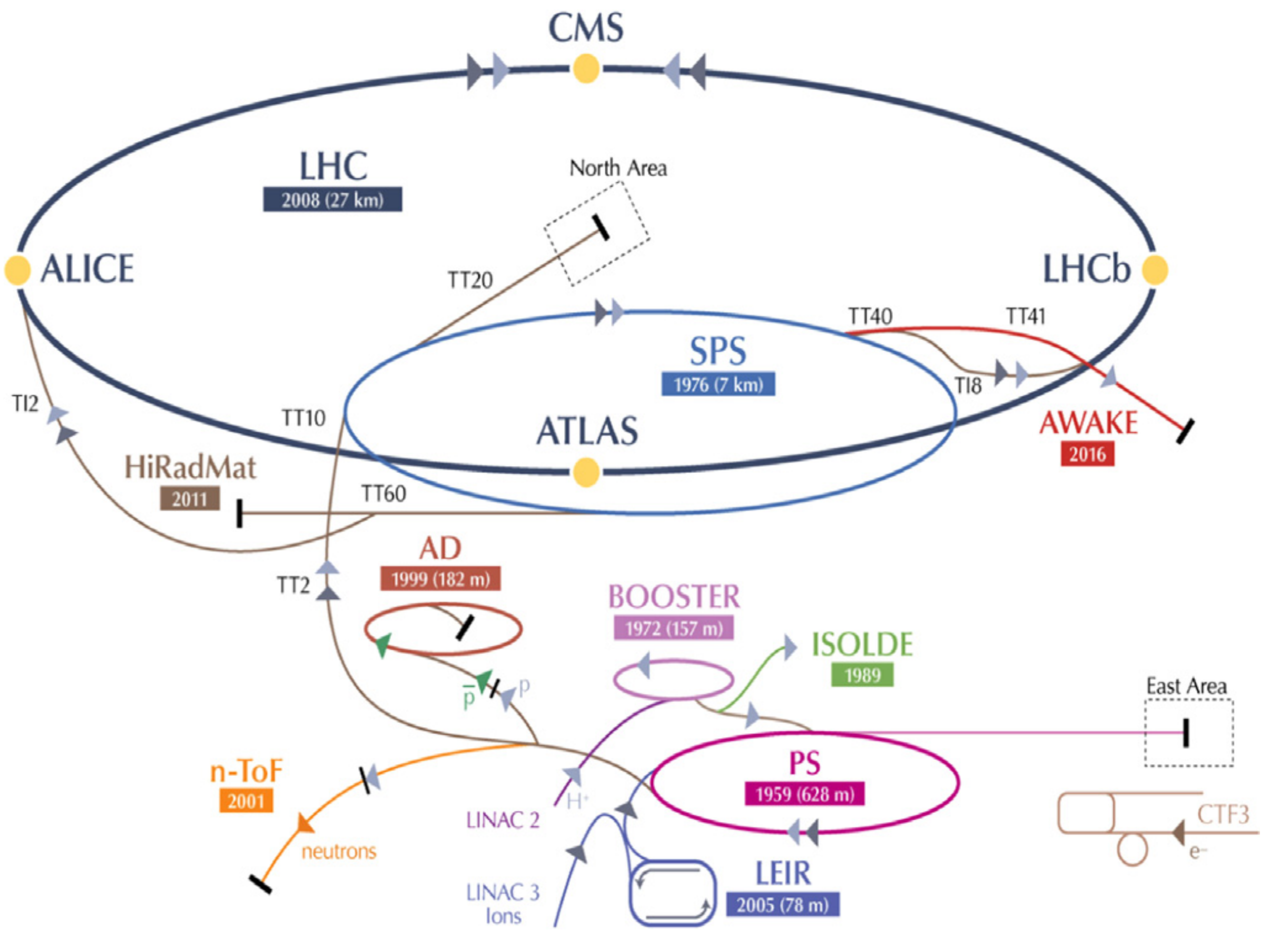


Idea to Harness the Large Stored Energy in Proton Bunches to make High Energy Electrons

## Goals of the AWAKE Collaboration:

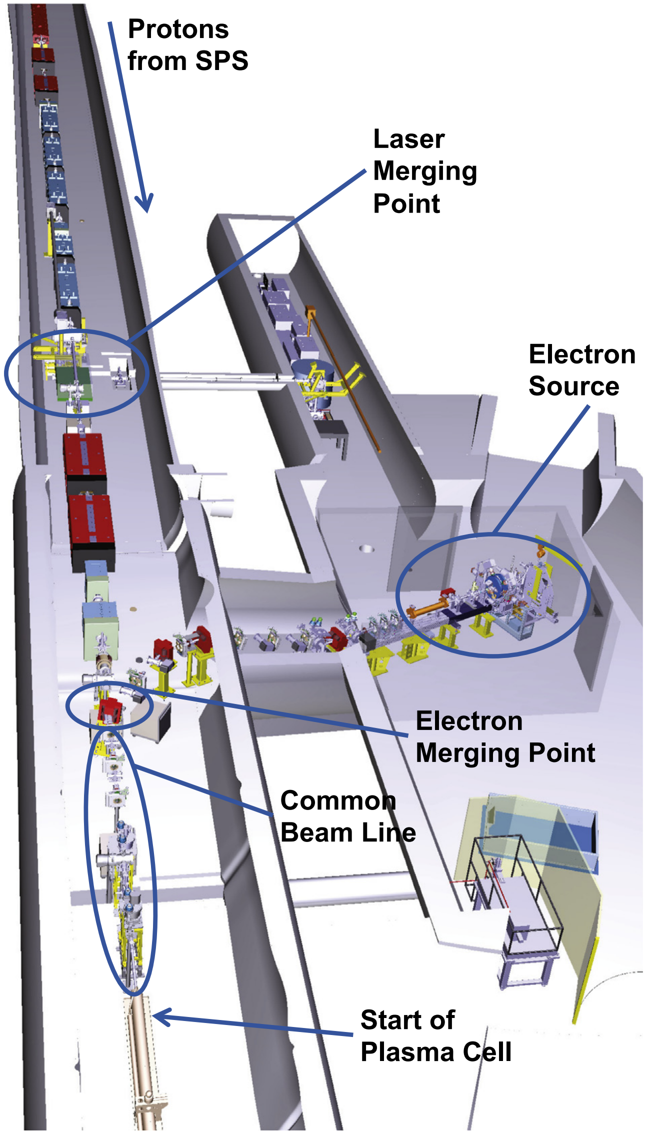
- ☐ >500 GeV e- in single long plasma cell (400m)!
- ☐ Requires short proton bunches (100µm vs 10 cm)
- ☐ Study physics of self-modulation of long p bunches
- ☐ Probe wakefields with externally injected e-
- ☐ Study injection dynamics for multi-GeV e-
- ☐ Develop long, scalable and uniform plasma cells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

# The AWAKE Experiment at CERN



CERN Accelerator Complex

## AWAKE Experimental Area

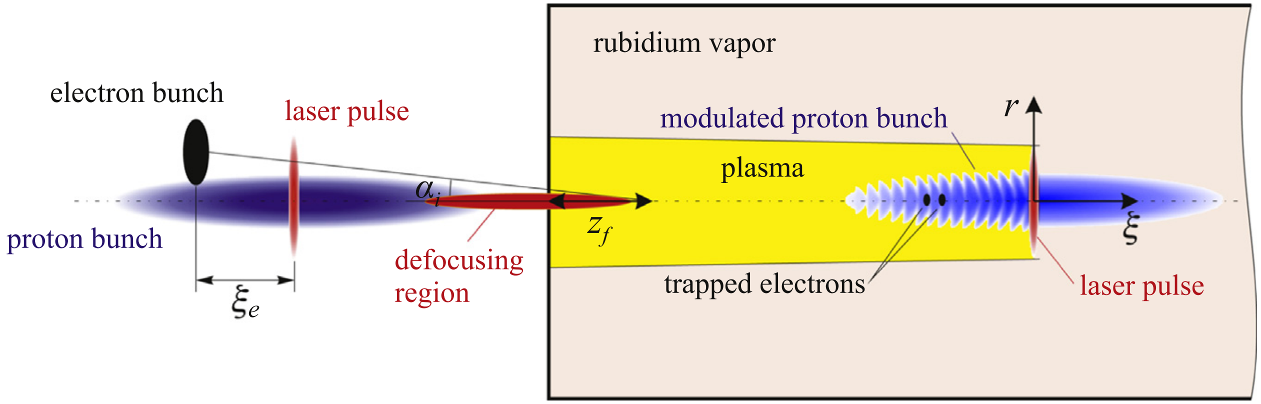


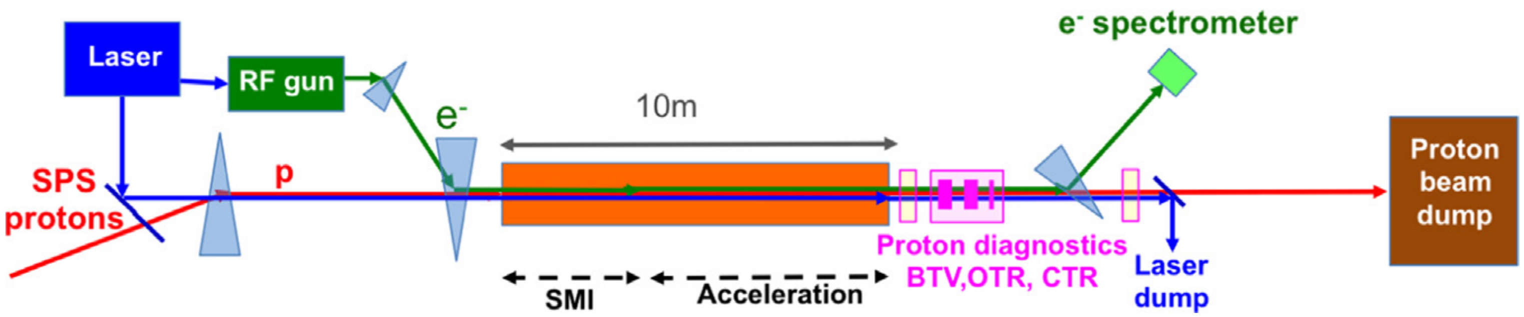
E. Gschwendtner et al. *N.I.M. A* 829 (2016)

# The AWAKE Experiment at CERN

Run1:

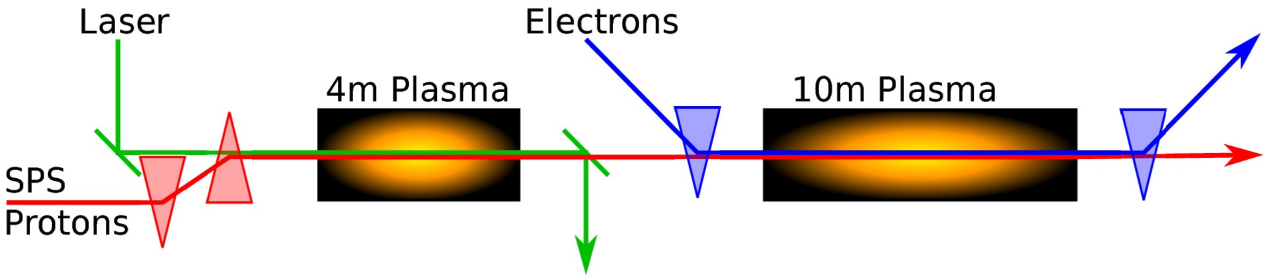
- 2016: SMI of long proton bunches in plasma
- 2017-2018: Externally injected long electron bunches





Run2 (after long LHC shutdown):

- Short e- bunches in wake of pre-modulated p bunch

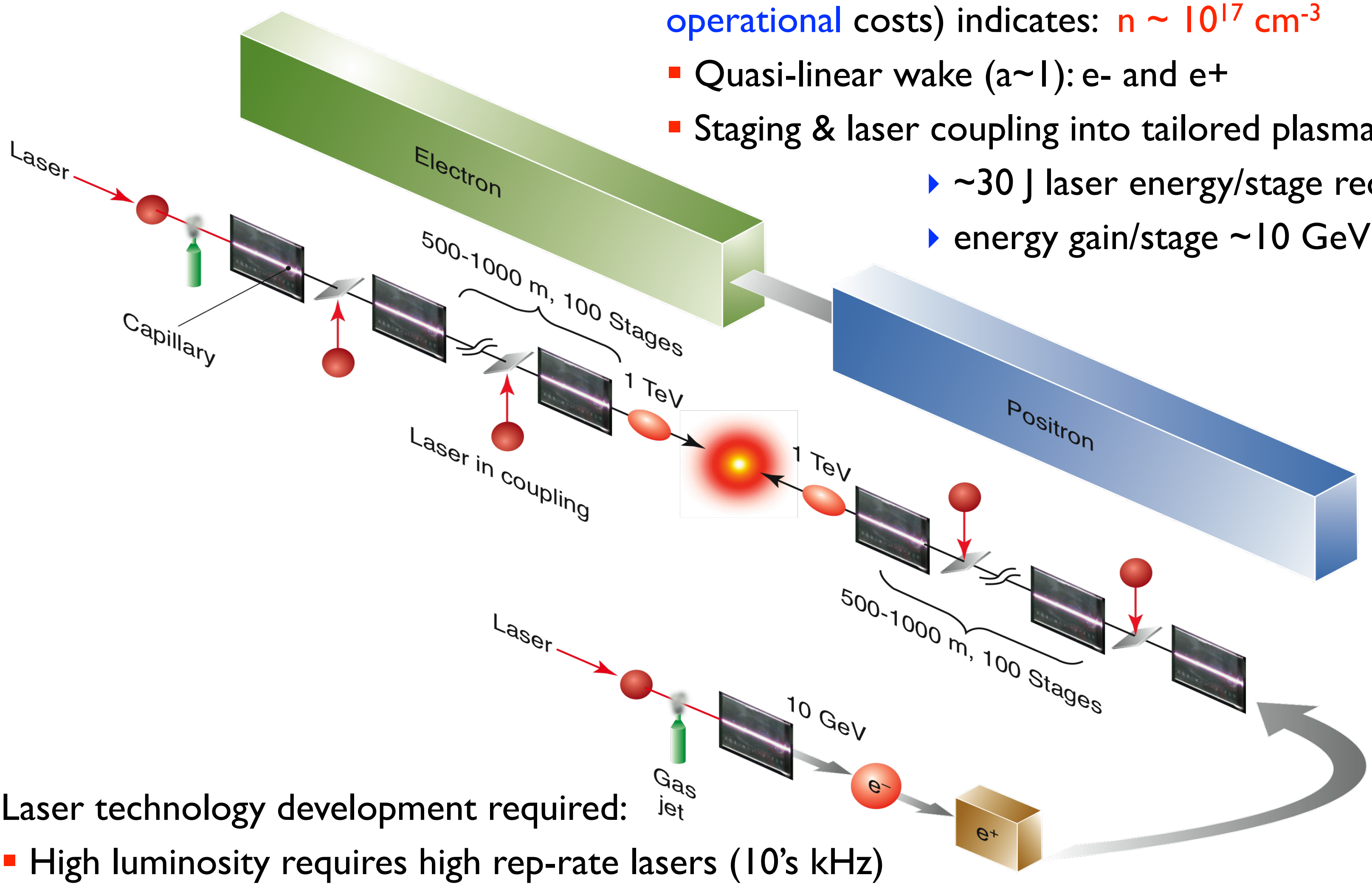


*Proposed setup for AWAKE Run 2.*

# Laser-plasma Accelerator Based Collider Concept

Leemans & Esarey, Physics Today (2009)

- Plasma density scalings (minimize construction and operational costs) indicates: n ~ $10^{17}$ $\mathrm{cm}^{-3}$
- 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

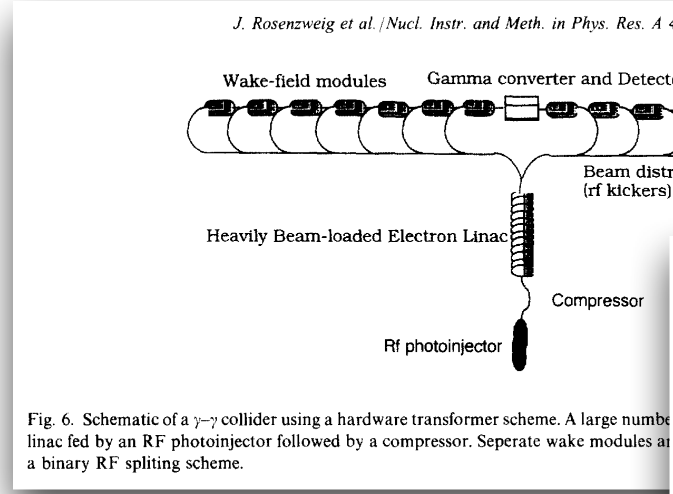


Laser technology development required:

- 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 %)

# PWFA Research Roadmap:
# Goal is to Get To A TeV Scale Collider for High Energy Physics

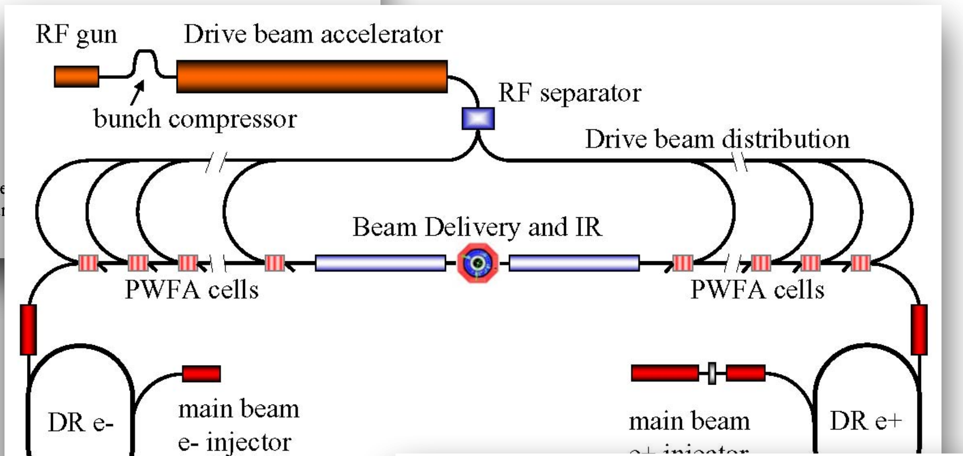
Rosenzweig *et al* (1998)



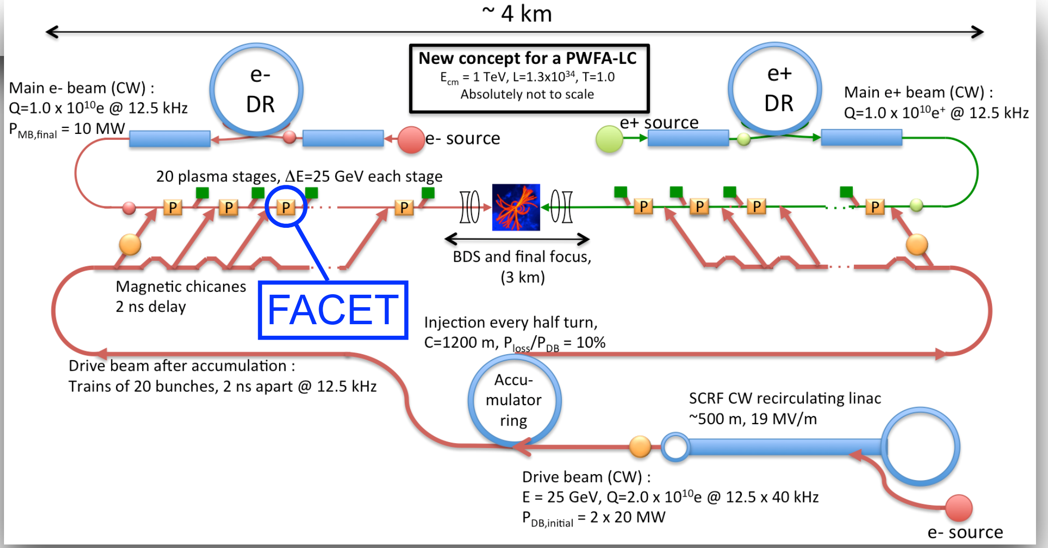
J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543 539

Fig. 6. Schematic of a $\gamma$–$\gamma$ collider using a hardware transformer scheme. A large numbe
linac fed by an RF photoinjector followed by a compressor. Seperate wake modules ar
a binary RF spliting scheme.

Seryi *et al* (2008)

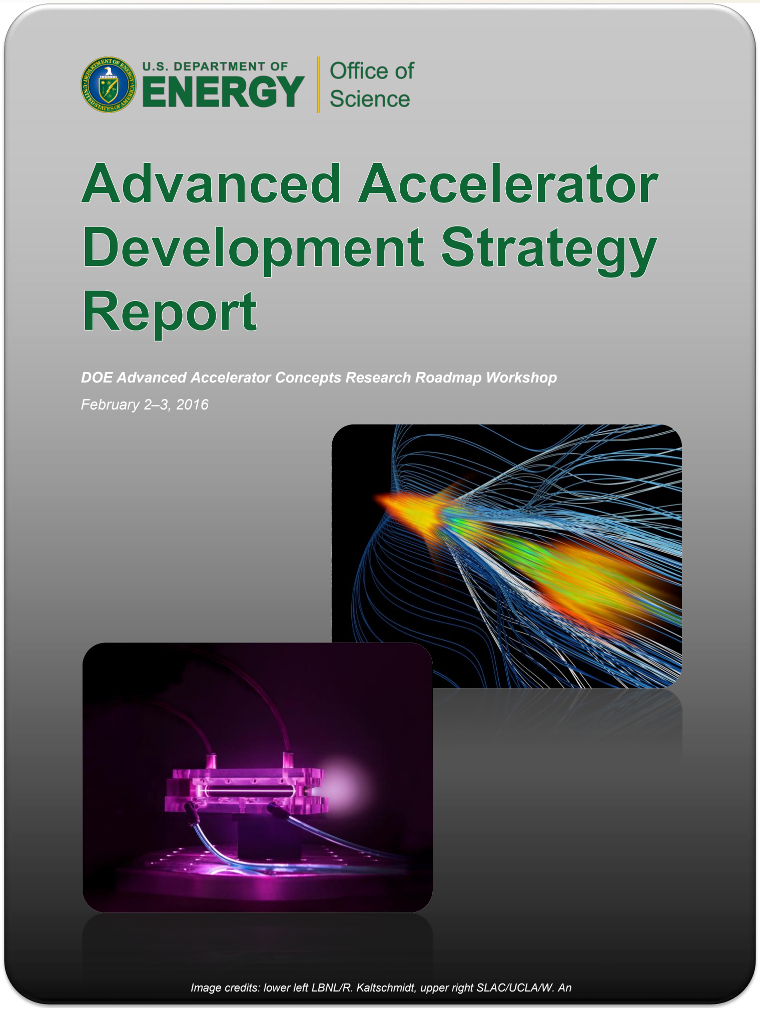


Adli *et al* (2013)



PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. efficiency, positrons

# A Roadmap for Future Colliders Based on Advanced Accelerators Contains Key Elements for Experiments and Motivates New Facilities



U.S. DEPARTMENT OF ENERGY | Office of Science

**Advanced Accelerator Development Strategy Report**

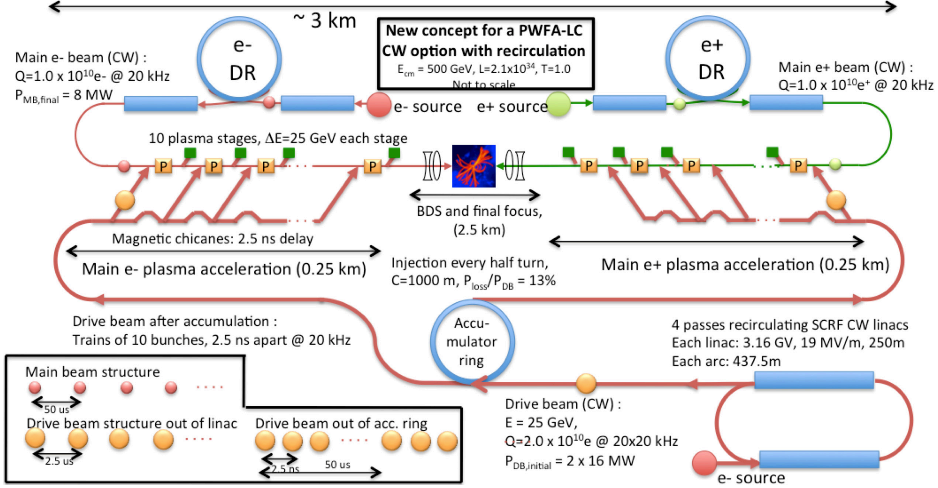
*DOE Advanced Accelerator Concepts Research Roadmap Workshop*

*February 2–3, 2016*

*Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An*

http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

## A Conceptual PWFA-LC



E. Adli et al., ArXiv 1308.1145

J. P. Delahaye et al., Proceedings of IPAC2014

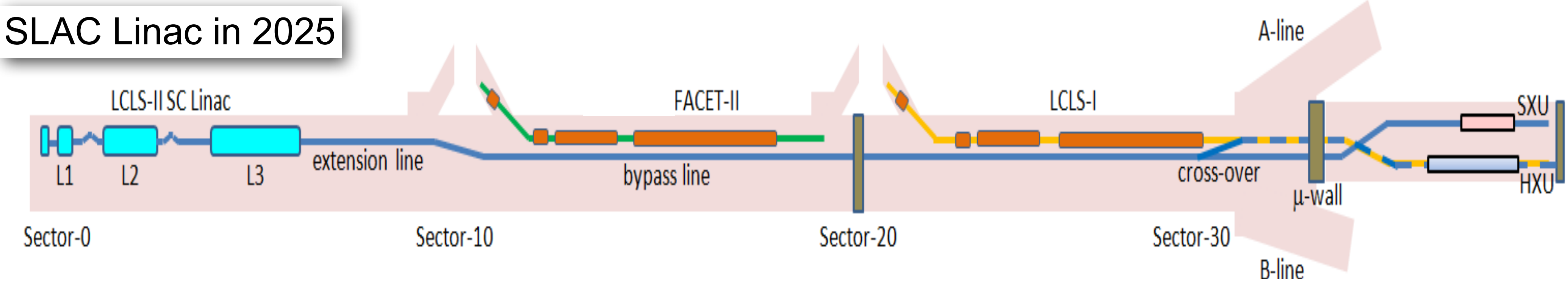
Key elements for the next decade:

- Beam quality – focus on emittance preservation at progressively smaller values
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

# Planning for FACET-II as a Community Resource

- FACET stopped running in April 2016 to begin LCLS-II construction
- Over the next few years FACET-II will add new capabilities:
  - LCLS style photoinjector with state of the art electron beam
  - Flexibility e.g. low-charge mode or 'two color' operation for two-bunch PWFA
  - Nominal **e$^-$** parameters: 10GeV, 2nC, 15kA, 30Hz (**2019**) → Beam quality
  - Nominal **e$^+$** parameters: 10GeV, 1nC, 6kA, 5Hz (**2021**) → Positron Acceleration
  - External injection → Staging studies, ultra-bright sources
- Continue to plan experimental program with **Science Workshops** (October 2015, 2016…)

SLAC Linac in 2025



FACET-II has been designed to address many of the R&D challenges of the Beam Driven Roadmap

# Planning for FACET-II as a Community Resource

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**Are you a PhD or Postdoc & looking for a challenge?**

**We are hiring!**

FACET-II has been designed to address many of the R&D challenges of the Beam Driven Roadmap

# National and International Context

ELI Beamlines:

- Extreme Light Infrastructure, 10PW

EuroNNAC, DESY:

- Fully funded horizon 2020 proposal Eupraxia "European Plasma Research Accelerator with eXcellence In Applications"

CERN

- AWAKE Proton Driven Plasma

DESY

- The FLASHForward Project

INFN

- SPARC_LAB

BNL

- ATF & ATF-II

Research and Discovery Phase

- Worldwide Efforts at Universities and Smaller Labs – Breadth of expertise, genesis of new ideas, student recruitment and conceptual development

# Summary

- 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!***

# Summary

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“People who say it cannot be done should not interrupt those who are doing it” – George Bernard Shaw

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