High Efficiency Acceleration of an Electron Beam in a Plasma Wakefield Accelerator

APS DPF Meeting – Ann Arbor, MI

Mike Litos, SLAC National Accelerator Laboratory

Aug. 7th, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

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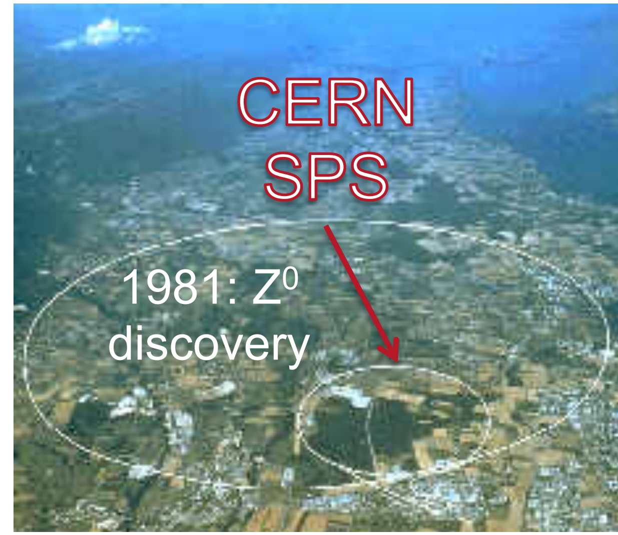
The Higgs has been found. Now what?

- Higgs Boson discovered by ATLAS & CMS at the LHC with m_H = 126 GeV/c^2
- Next machine: likely a lepton collider
  - lepton colliders → precision measurement
  - control over CM energy
  - lower backgrounds
  - historical example: Z^0
- Physics goals:
  - Clean observation of Higgs mass, width, spin, C and P numbers
  - Coupling to $W^{+/-}$, Z^0, leptons, and quarks
    - scale with mass
  - Self-coupling of Higgs field



Higgs Factories and Beyond…

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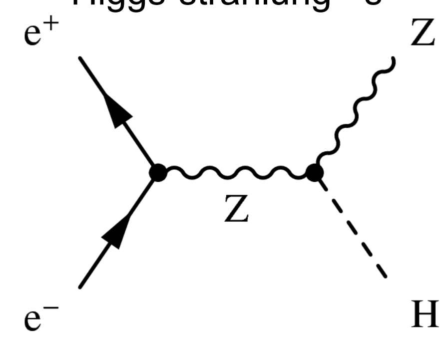
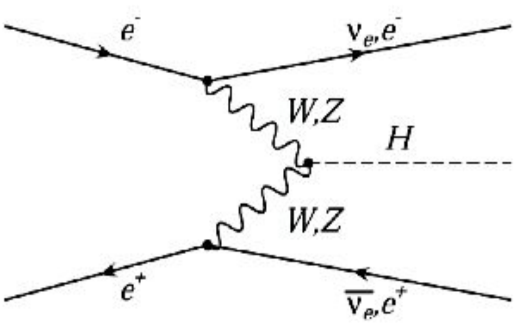
- Two general approaches:
  - Higgs Factory and that's it: ~250 GeV CM
    - $\gamma\,\gamma$ collider (Compton scatter off e^-)
    - $e^+ e^-$ collider ring (like LEP)
  - Higgs Factory upgradable to ≳TeV
    - $e^+ e^-$ linear collider
      - ILC (super conducting linac @ Japan[?])
      - CLIC (two-beam room temp. linac @ CERN)
      - Plasma Wakefield Accelerator
    - $\mu^+ \mu^-$ collider (@ Fermilab)
- Construction cost ~total length ~(accelerating gradient)$^{-1}$
- Operational cost ~power consumption
- **Need high gradient and high efficiency!**

Higgs Factory dominant production mechanism: Higgs-strahlung ~s^{-1}

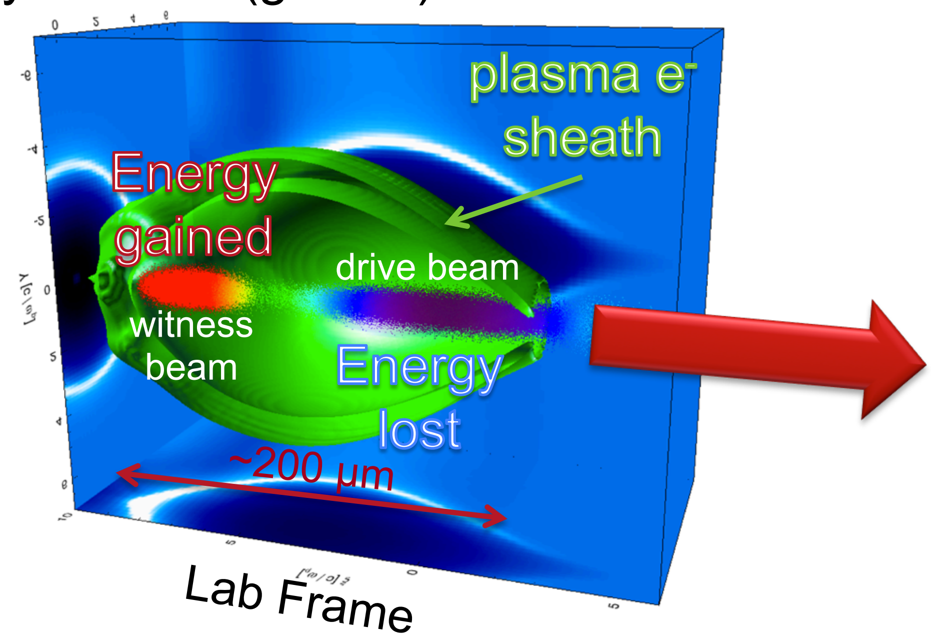


>TeV Energy dominant production mechanism: WW-fusion ~log(s/m_h^2) [also ZZ-fusion, and $e^+ e^- \rightarrow$ t tbar H]



Plasma Wakefield Acceleration (PWFA): Efficient Energy Transformer

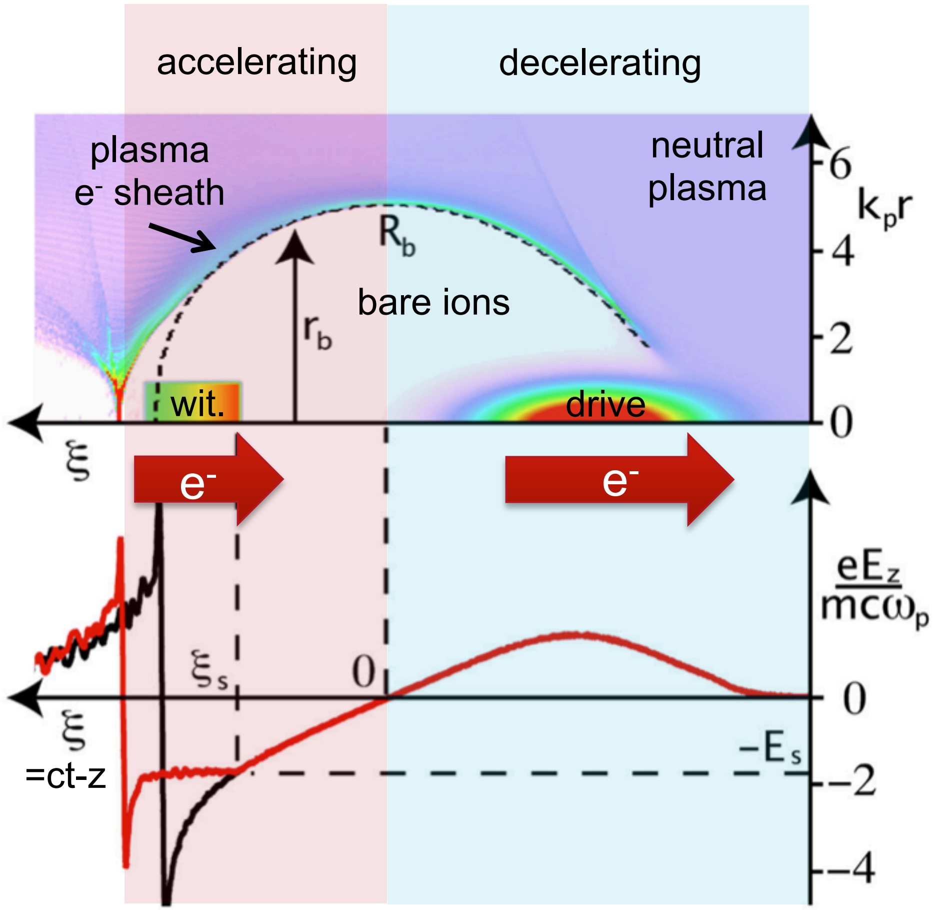
- Two e⁻ bunches enter, one e⁻ bunch leaves (with appreciable energy)
- "Energy transformer": higher current @ low E → lower current @ high E
- Simultaneously focuses (guides) and accelerates beam



- **High accelerating gradient: ~10 GeV/m**
- **High energy transfer efficiency: ~50% (drive → plasma → witness)**

Plasma Wakefield Acceleration Mechanism

- Plasma is already "broken down"; can sustain very high fields
- drive bunch repels plasma electrons outward
- massive ions remain in place; attracts plasma e^- back inward and focuses beam e^-
- current of plasma e^- sheath gives rise to accelerating "wake" field
- witness bunch rides inside the wake bubble near the rear
- properly shaped witness bunch can "flatten" field for minimized energy spread and maximized energy transfer efficiency



Tzoufras et al., PRL 101-145002 (2008)

PWFA Linear Collider Concept

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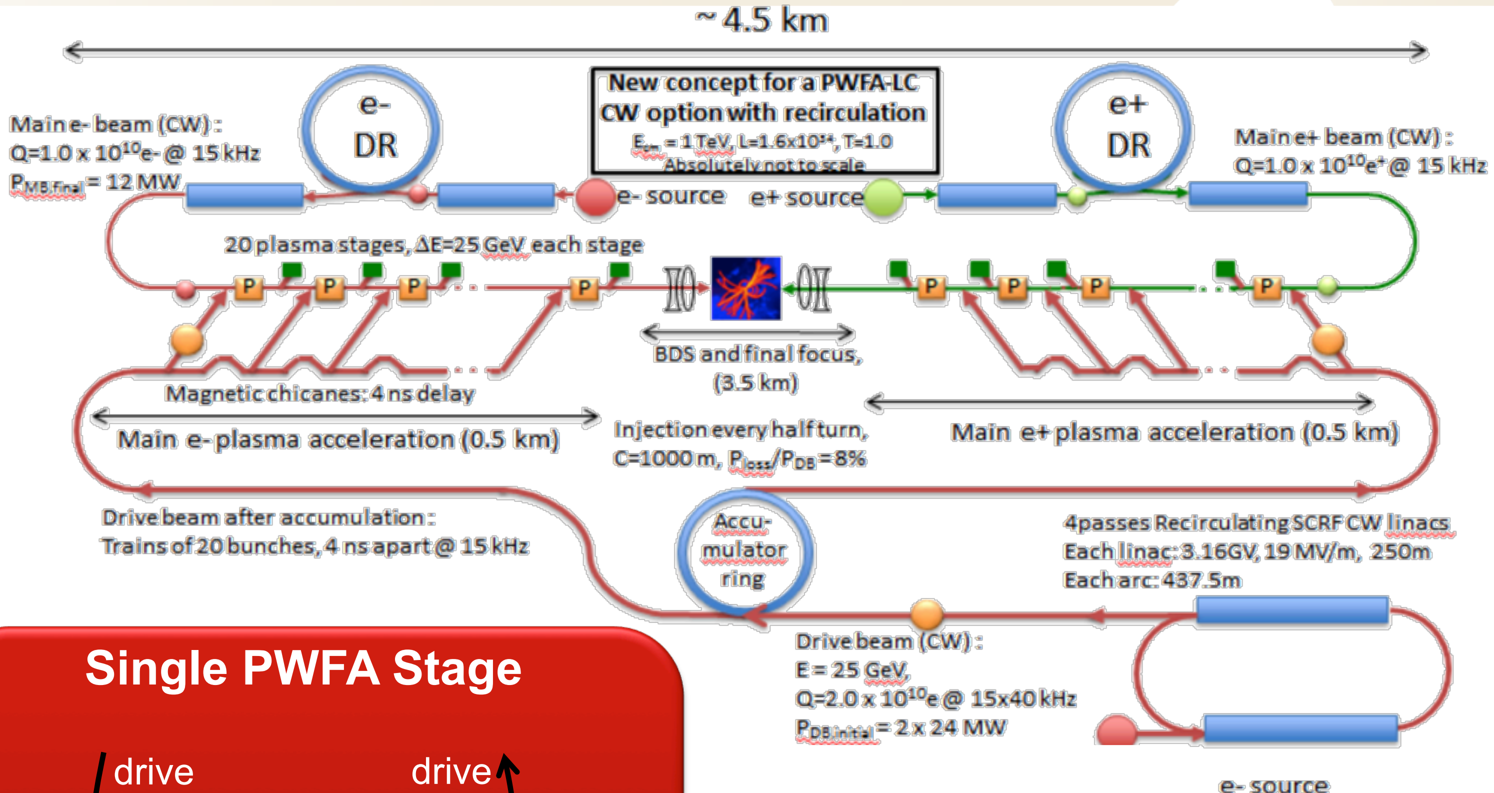

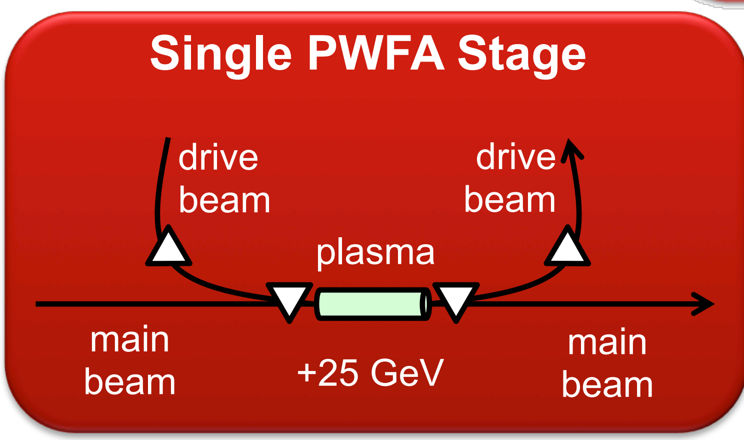

- **250 GeV – 3 TeV CM energy range**
- **1 TeV design: 4.5 km long (dominated by final focus)**

E. Adli, J. P. Delahaye, et al., arXiv:1308.1145v2

Colliders Compared by Length or Circumference

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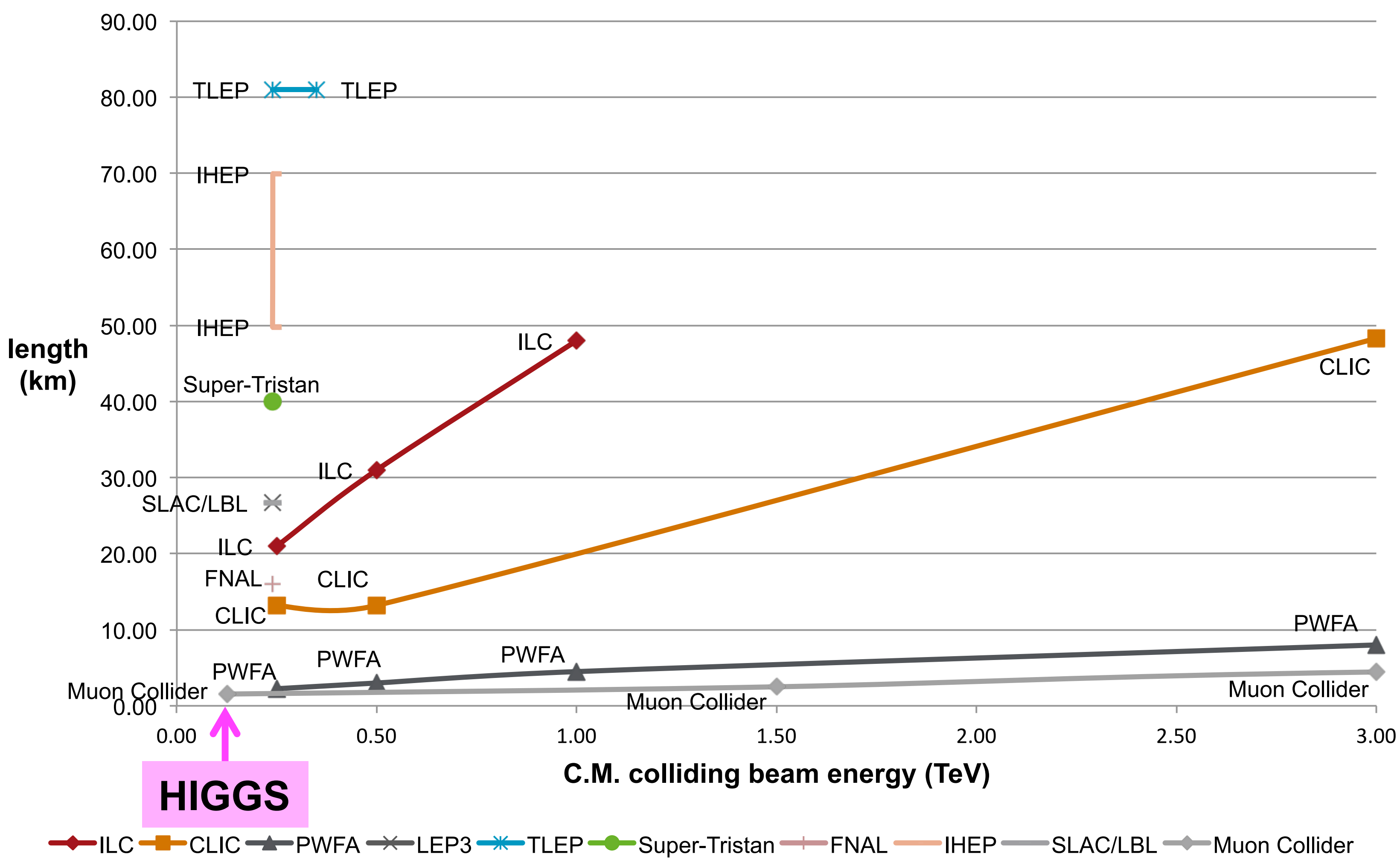
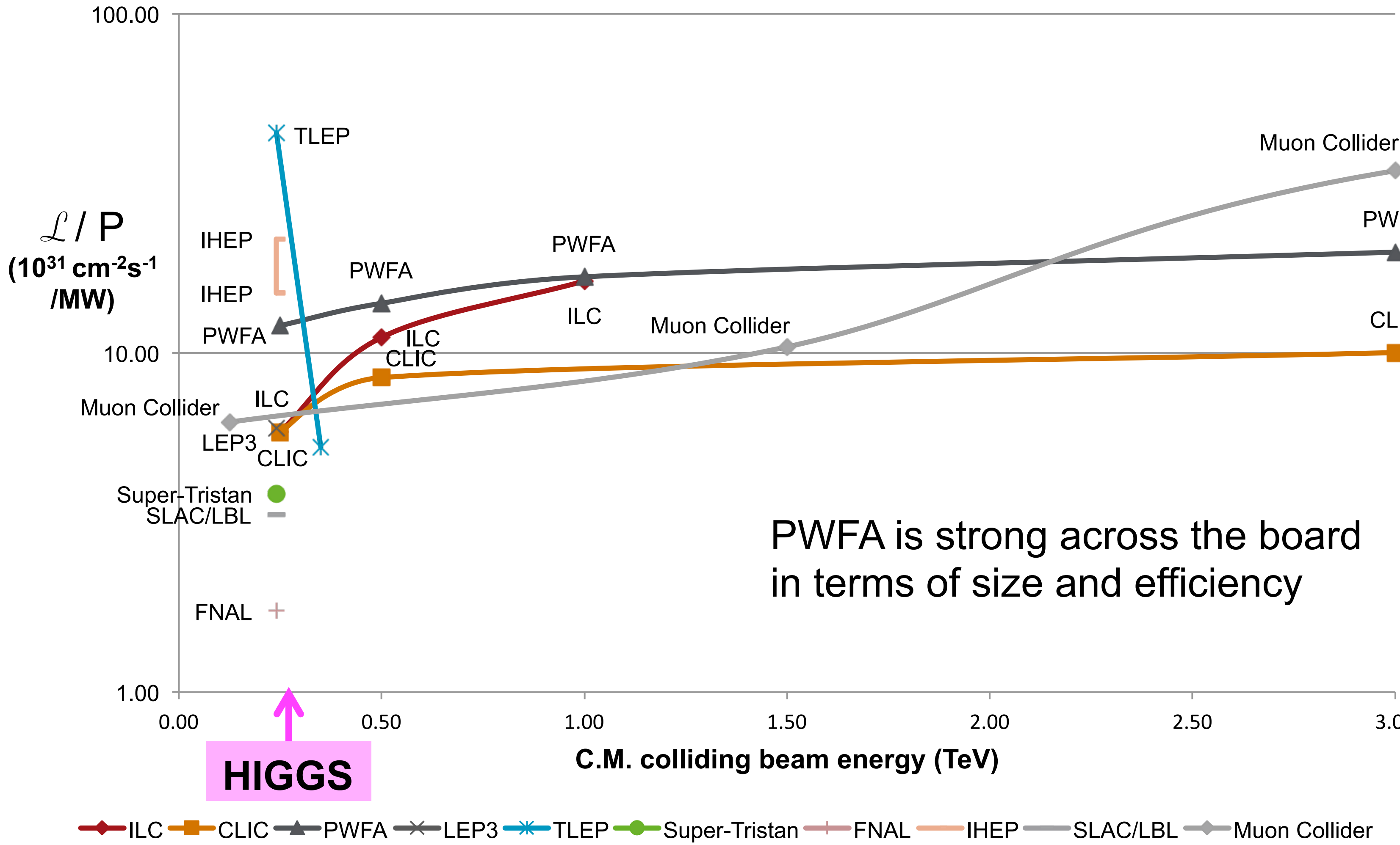


J.P. Delahaye (SLAC)
Snowmass 2013 Lepton Collider Workshop

Colliders Compared by Integrated Luminosity / Wall Plug Power



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PWFA Experimental Milestones

- ❑Demonstration of high-gradient acceleration
- ❑Demonstration of meter-scale propagation
- ❑Acceleration of a discrete beam of electrons
- ❑Demonstration of high energy transfer efficiency
- ❑Minimization of energy spread
- ❑Preservation of beam emittance

Final Focus Test Beam (FFTB) Facility at SLAC

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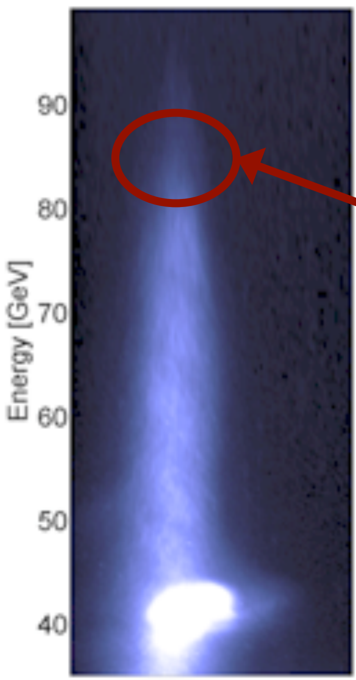
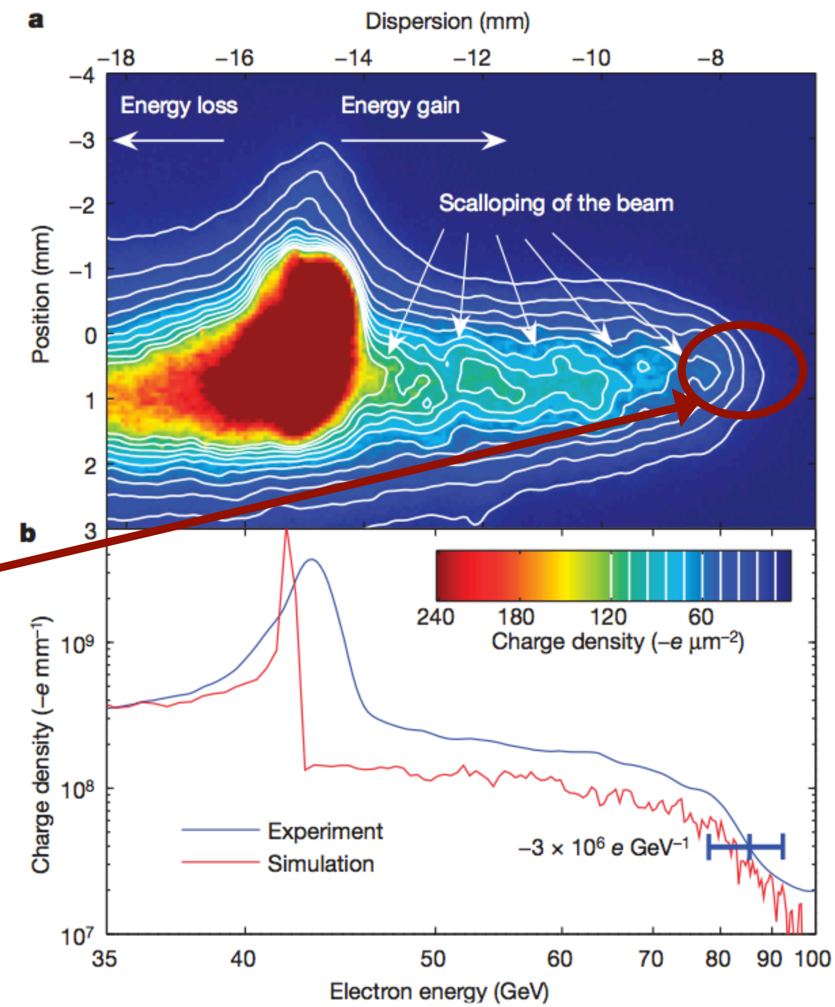
- Single beam experiment from 1990's to 2000's
- Particles in tail of 42 GeV beam were energy doubled in 85cm
- High gradient field: 52 GeV/m(!)



Energy Doubled



I. Blumenfeld et al., Nature 445 741 (2007)

PWFA Experimental Milestones

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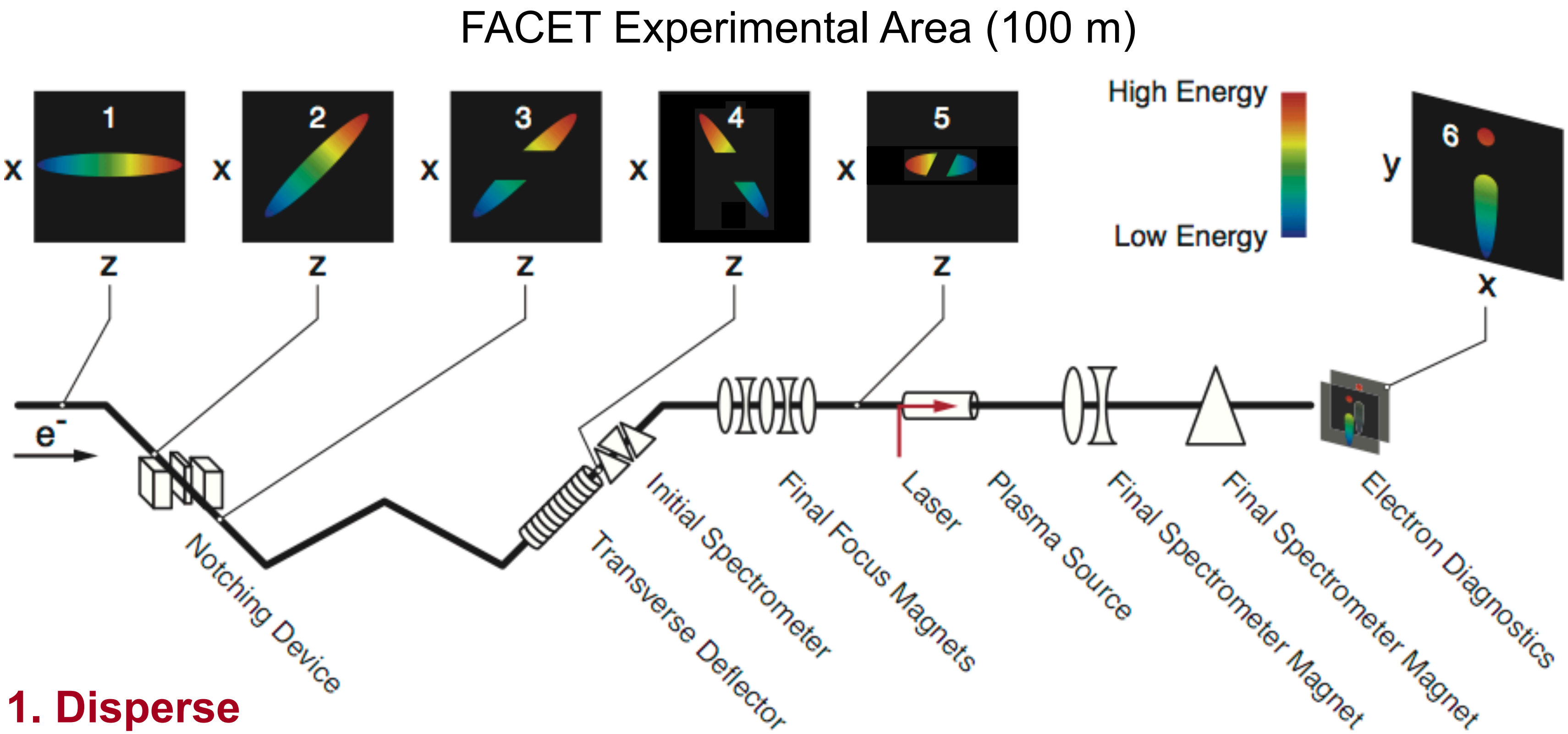
Facility for Advanced Accelerator Experimental Tests (FACET)

- Designed for PWFA
- E-200 PWFA Experiment lead by SLAC and UCLA
- 2km of SLAC linac provides compressed, 3 nC, 20 GeV electron or positron beam to experimental area
- Main beam is split into two bunches: one to drive wake, one to ride it
- Beam sent into Li vapor plasma source with density ~5x10^{16} cm^{-3}
- *Only source of such high energy density e^- and e^+ in the world!*

Two-Bunch Beam Generation



1. Disperse

2. Chop

3. Compress

4. Accelerate

5. Diagnose

Plasma Source: Laser + Metal Vapor

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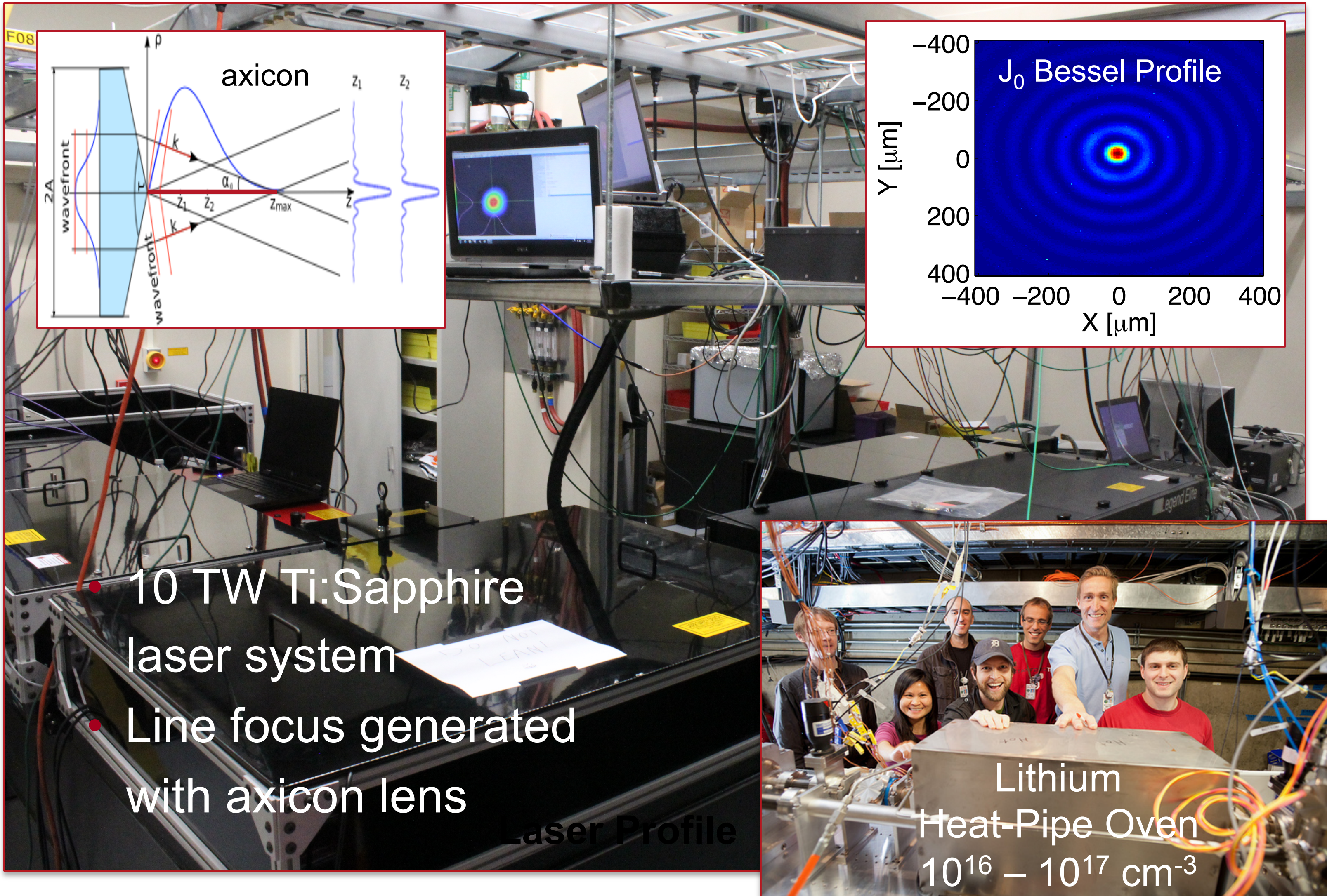
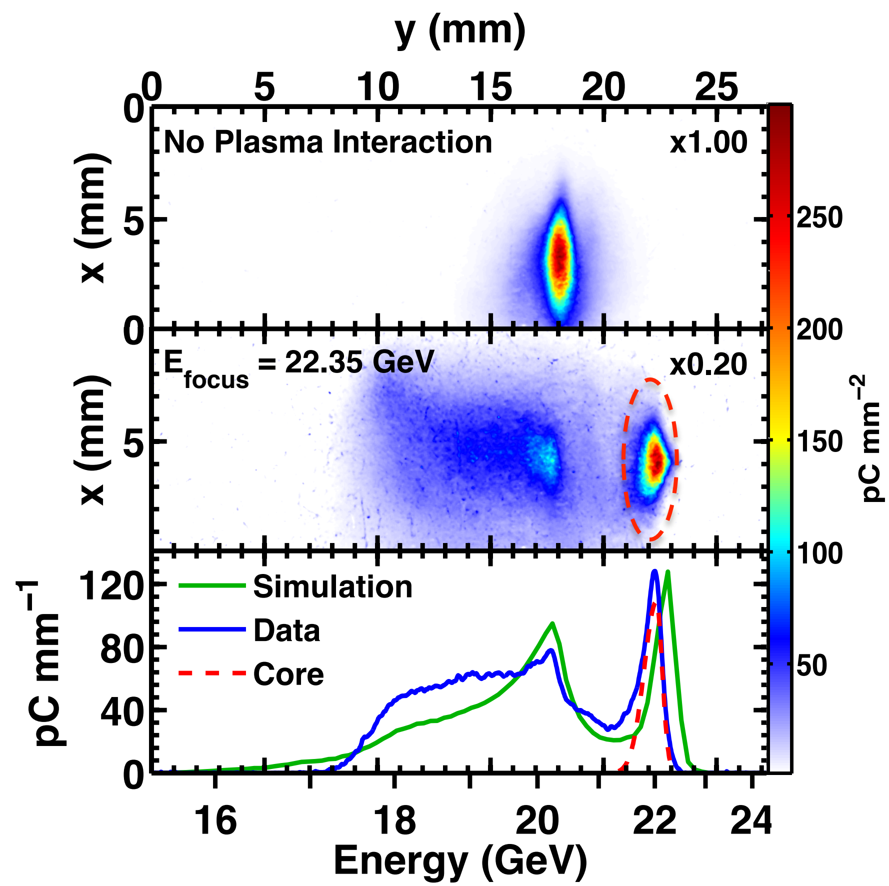


- 10 TW Ti:Sapphire laser system
- Line focus generated with axicon lens

E-200: First Demonstration

- 70 pC accelerated in 30 cm pre-ionized Li vapor plasma
- Mean energy gain: 1.7 GeV
- Mean energy spread ~2%
- Gradient of ~5 GeV/m
- Mean wake-to-bunch energy transfer efficiency 18%

Spectrally dispersed final beam



M. Litos, APS DPF Meeting, Aug. 7, 2015

E-200: First Demonstration

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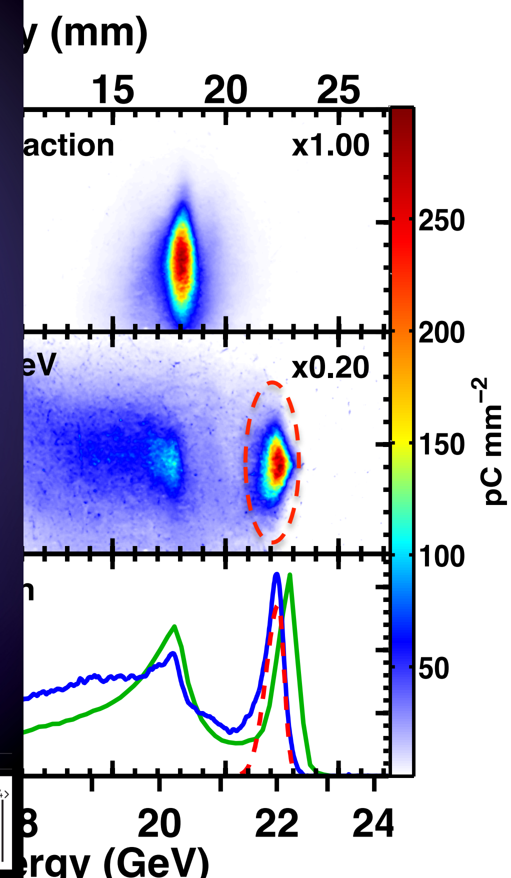
spersed final beam



M. Litos, et al., Nature **515** 92-15 (2014)

High Wake-to-Bunch Energy Transfer Efficiency

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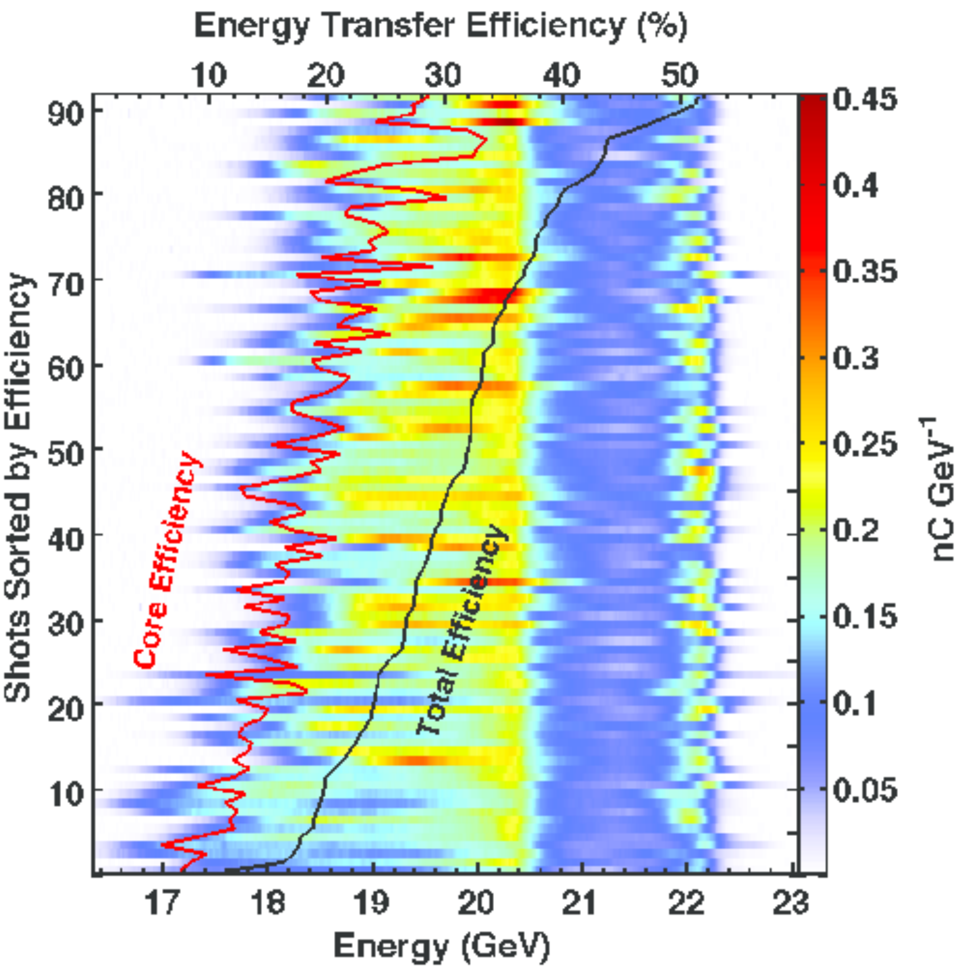

- Energy loss of drive bunch = energy put into wake
- Energy transfer efficiency from wake to trailing bunch: energy gain by trailing bunch / energy loss by drive bunch
- Mean wake-to-bunch energy transfer efficiency of 18% core, 31% total
- Max efficiency of 30% core, 50% total
- Approaching collider design

Comparison to Simulation

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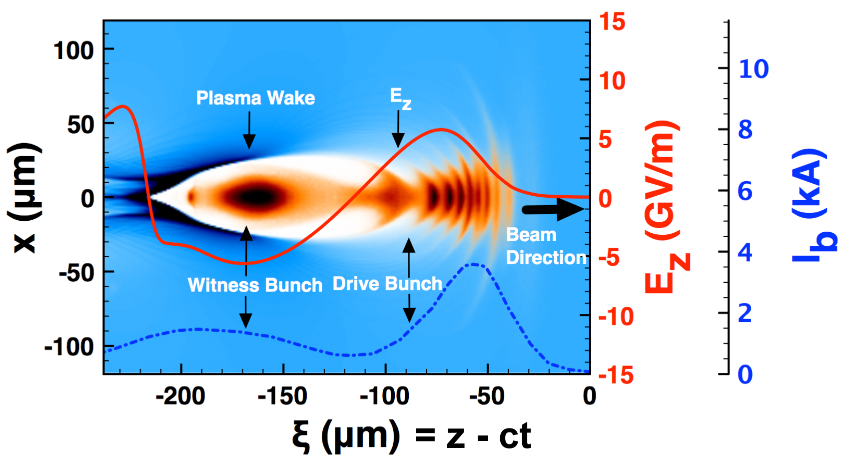
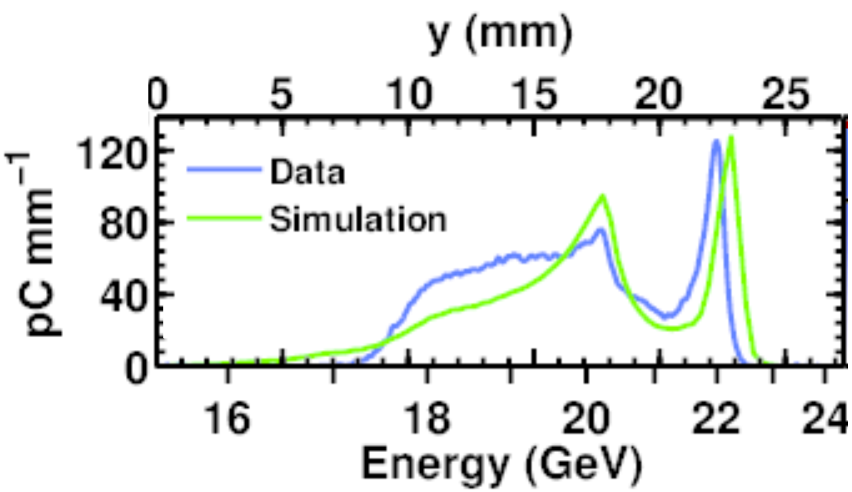
- Particle-In-Cell (PIC) simulation with QuickPIC (UCLA) for beam-plasma interaction
- PIC output then propagated through simulated beamline
- Shows very good qualitative agreement with observed final spectrum
- Gives insight into beam-plasma coupling: trailing bunch was too long and wide to fully couple into plasma wake
- Shows loading of wake → key to efficient energy extraction

PIC Simulation



Final Dispersed Beam Profile



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E-200: Multi-GeV Positron PWFA

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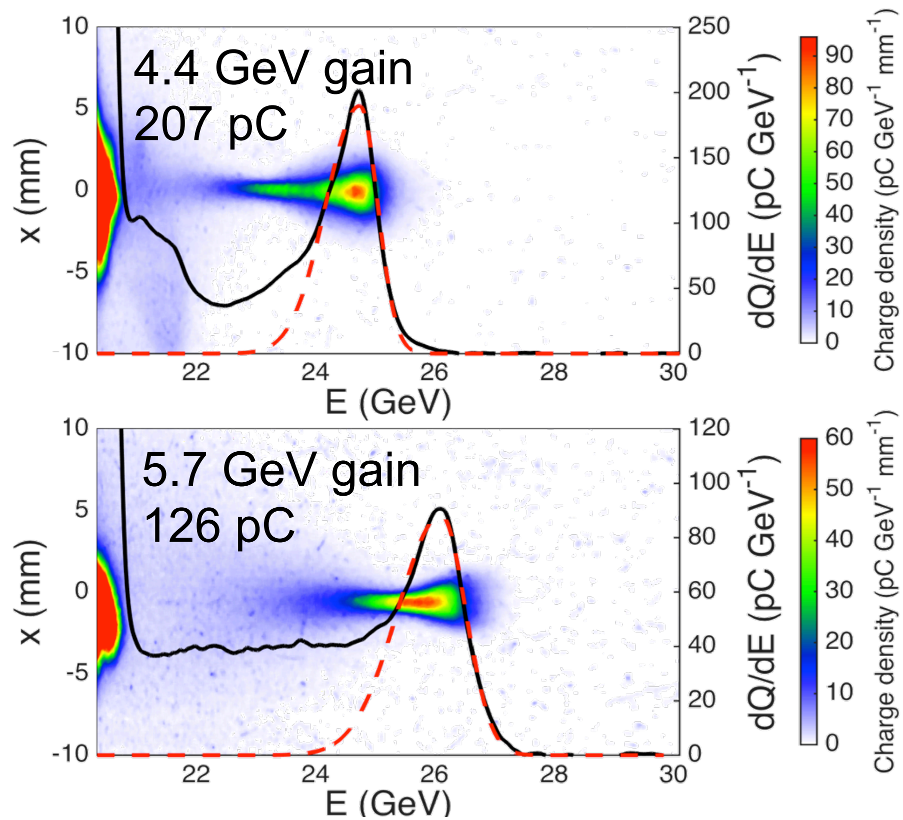
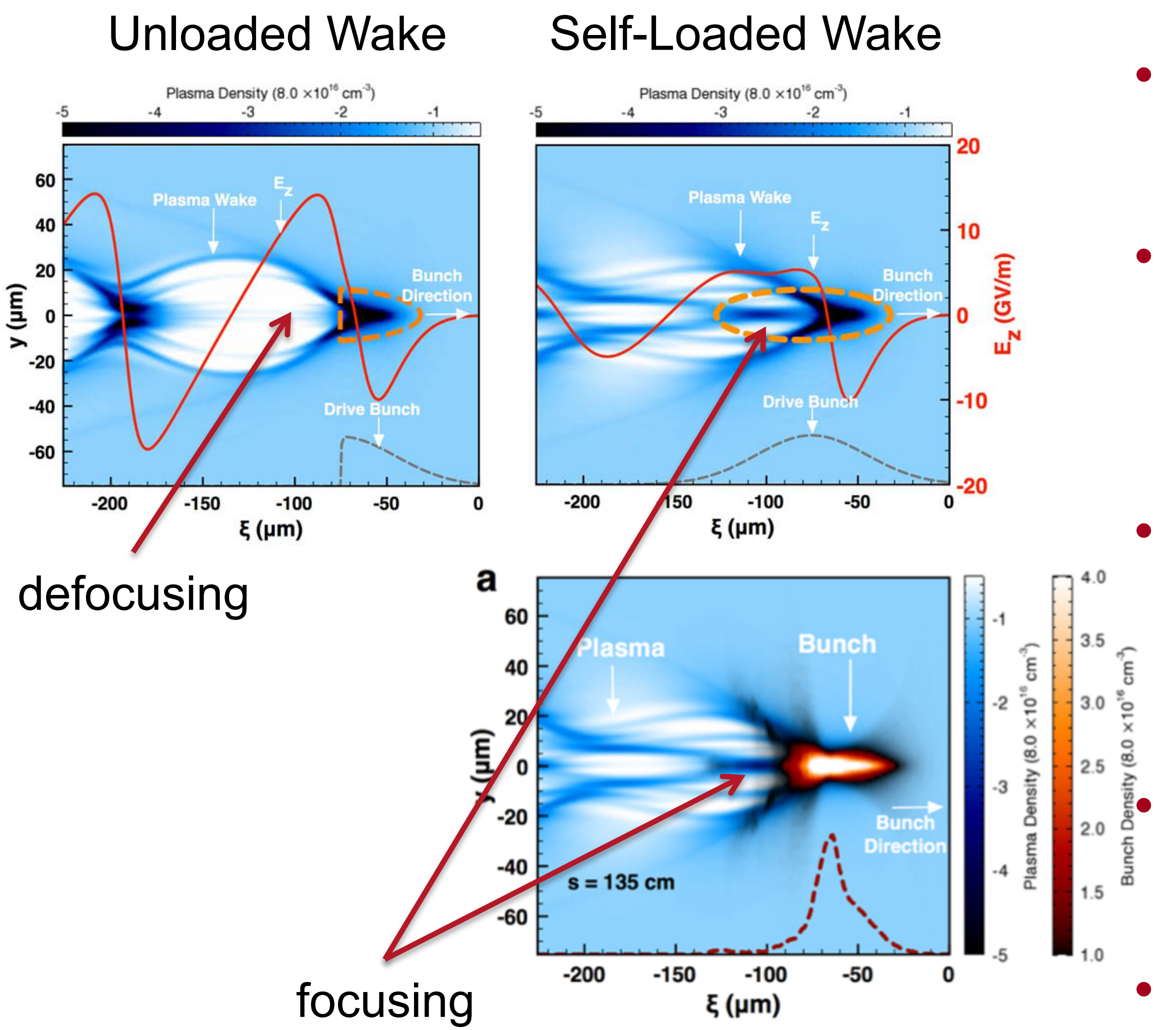
- Sent high charge, high density e^+ beam into high density plasma for first time ever → Surprise result!
- Observed features:
  - High energy gain
  - Small energy spread
  - Low divergence
  - High charge
- **Experimental discovery of positron PWFA in self-loaded, non-linear plasma wake!**



$n_p = 8\times10^{16}$ cm^{-3}
L_p = 1.3 m

Understanding the Result: Longitudinal and Transverse Beam Loading



- After first results, barrage of simulations at UCLA
- Helped understand physical mechanism of e^+ self-loading PWFA
- Channelling of plasma electrons is key to focusing and loading
- Suggests afterburner application
- *Accepted for publication*

What Lies Ahead

- FACET (2011-2016)
  - Optimize two-bunch e^- PWFA
  - Optimize e^+ PWFA
  - High-brightness witness bunch injection schemes
  - PWFA of e^- and e^+ with hollow channel plasma
- FACET-II (2018-20XX)
  - Witness beam emittance preservation
  - Witness beam energy spread minimization
  - Staging studies
  - Positrons in electron driven wakes
  - Lots more…
- Target Applications
  - Near future: Light sources (XFEL)
  - Far future: ILC after burner
  - Farther future: PWFA linear collider!

Summary

- The next big particle physics machine will be a lepton collider
- PWFA linear collider fits the bill
  - PWFA: compact and efficient energy transformer
  - scalable from Higgs Factory to >TeV
- SLAC has achieved important milestones:
  - high gradient and meter scale propagation at FFTB
  - discrete bunch acceleration and high efficiency at FACET
- New regime of e^+ PWFA discovered at FACET
  - potential after-burner application
- Experiments continue at FACET and soon FACET-II toward applications from light sources to colliders

The FACET E-200 PWFA Collaboration

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Thank you!
FACET L120
FACET LINAC