Recent results from beam-driven plasma acceleration experiments at FACET

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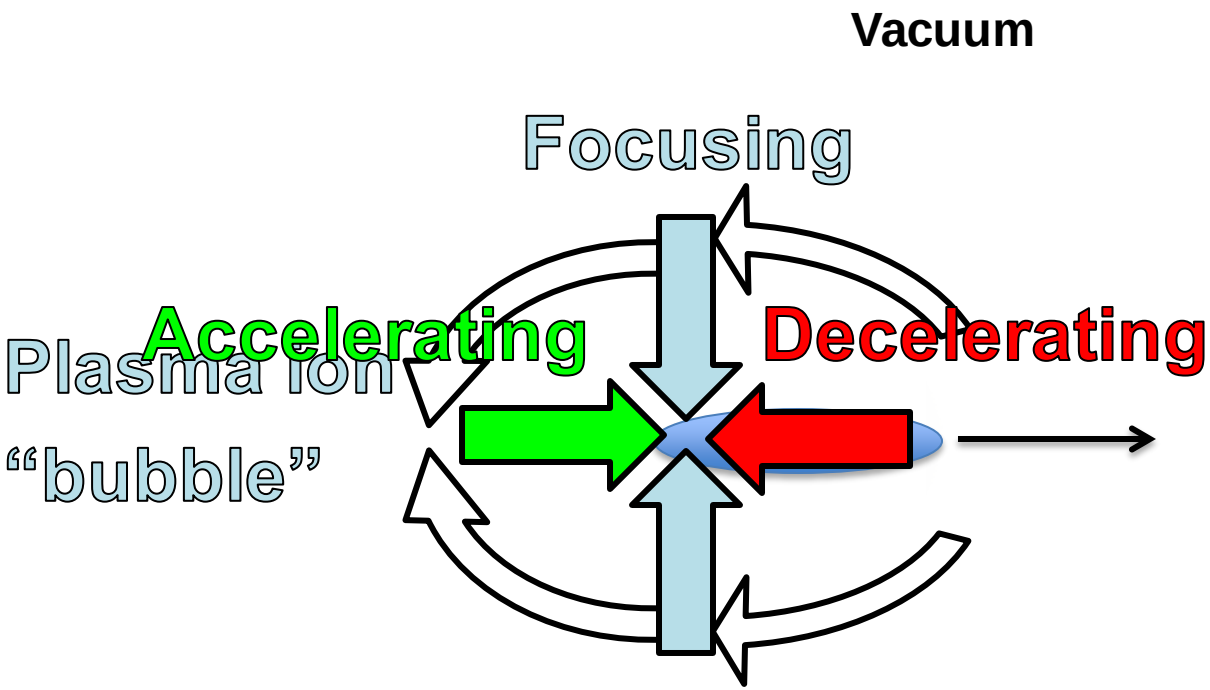
Outlook on Wake Field Acceleration: the Next Frontier, CERN, Switzerland
September 14, 2015

Plasma Wakefield Acceleration (PWFA)



[illegible] accelerating [illegible]

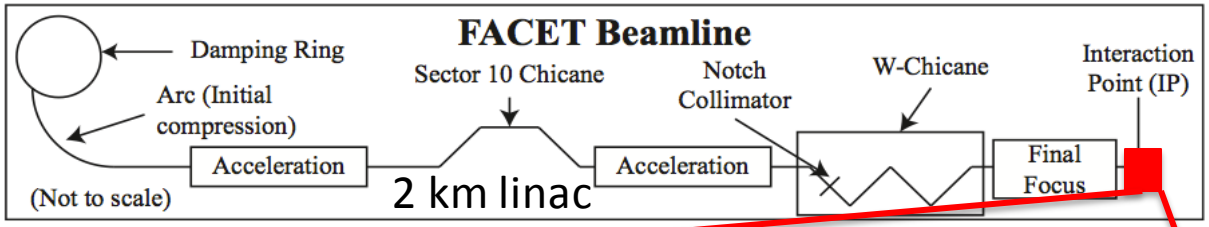
An electron [illegible] plasma.

FACET Milestones

The Facility for Advanced Accelerator Experimental Tests (FACET) at SLAC is executing a five year program that will help answer whether or not PWFA can be used as a technology in future accelerators:

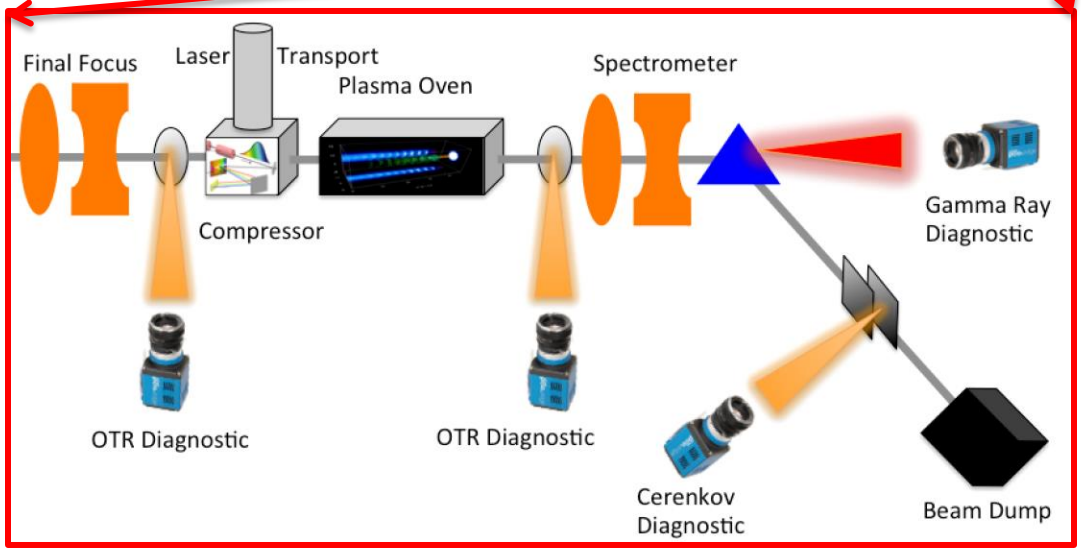
1. Meter scale plasmas ✓
1. High gradients ✓
1. Low energy spread ✓
1. High efficiency ✓
1. Multi GeV e^+ PWFA ✓
1. Emittance preservation

Experimental set-up at FACET

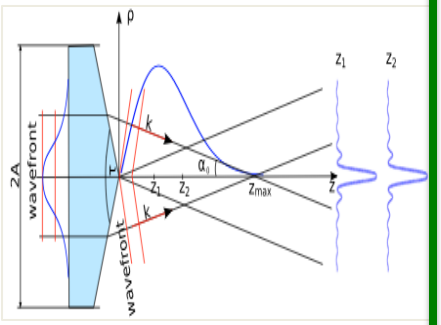


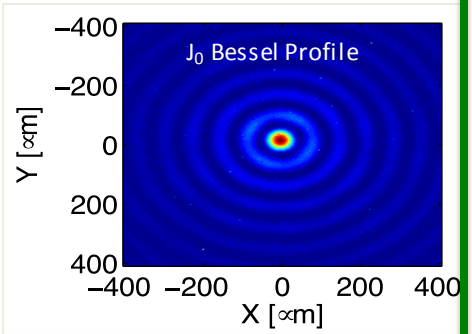
Electron, or Positron bunch

E = 20 GeV
Q = 3 nC
$\sigma_{z,min}$ = 20 um
$\sigma_{r,min}$ = 20 um
ε_n ~ 100 um



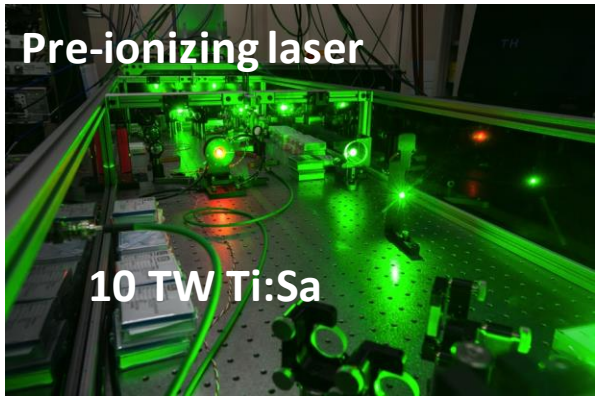
Laser axicon focusing





Plasma densities, n_0, 10^{16}-10^{17}cm^{-3}

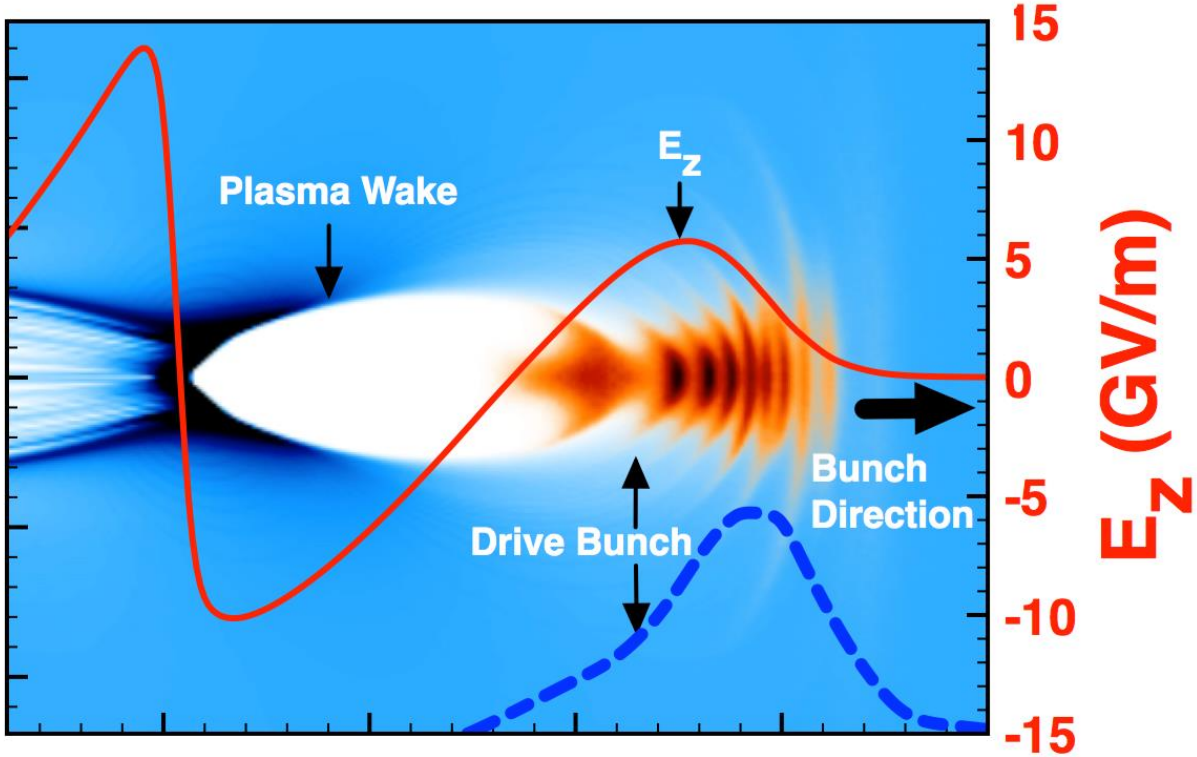
~ 1 m length



High gradients

Plasma Wakefield Acceleration: single bunch

QuickPIC (UCLA) simulation for FACET beam and plasma parameters.



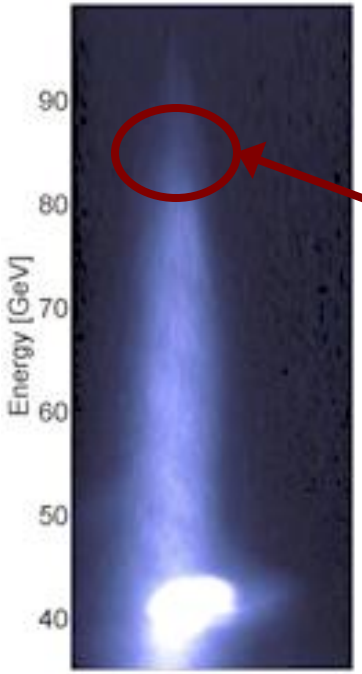
FACET experiments: study mostly the blow-out regime

Strong accelerating field when plasma electrons are pulled back by ions.

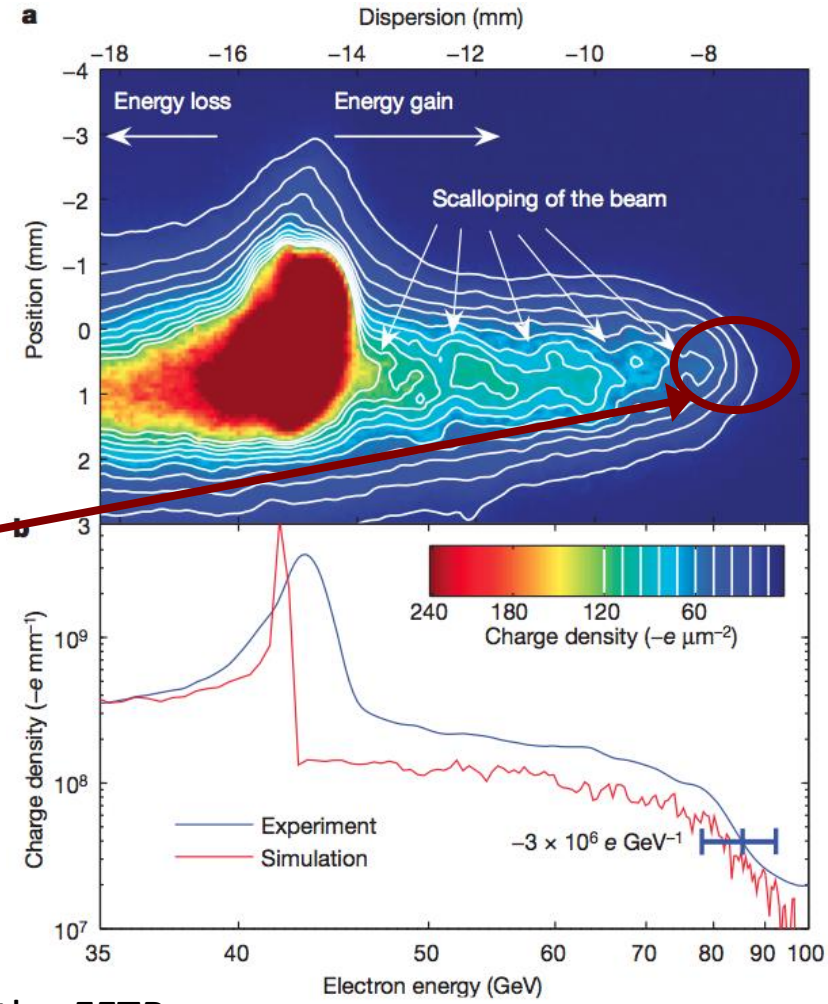
(Test) particles, beam tails, can sample all phases of the field.

Recap: Final Focus Test Beam Facility at SLAC

- 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



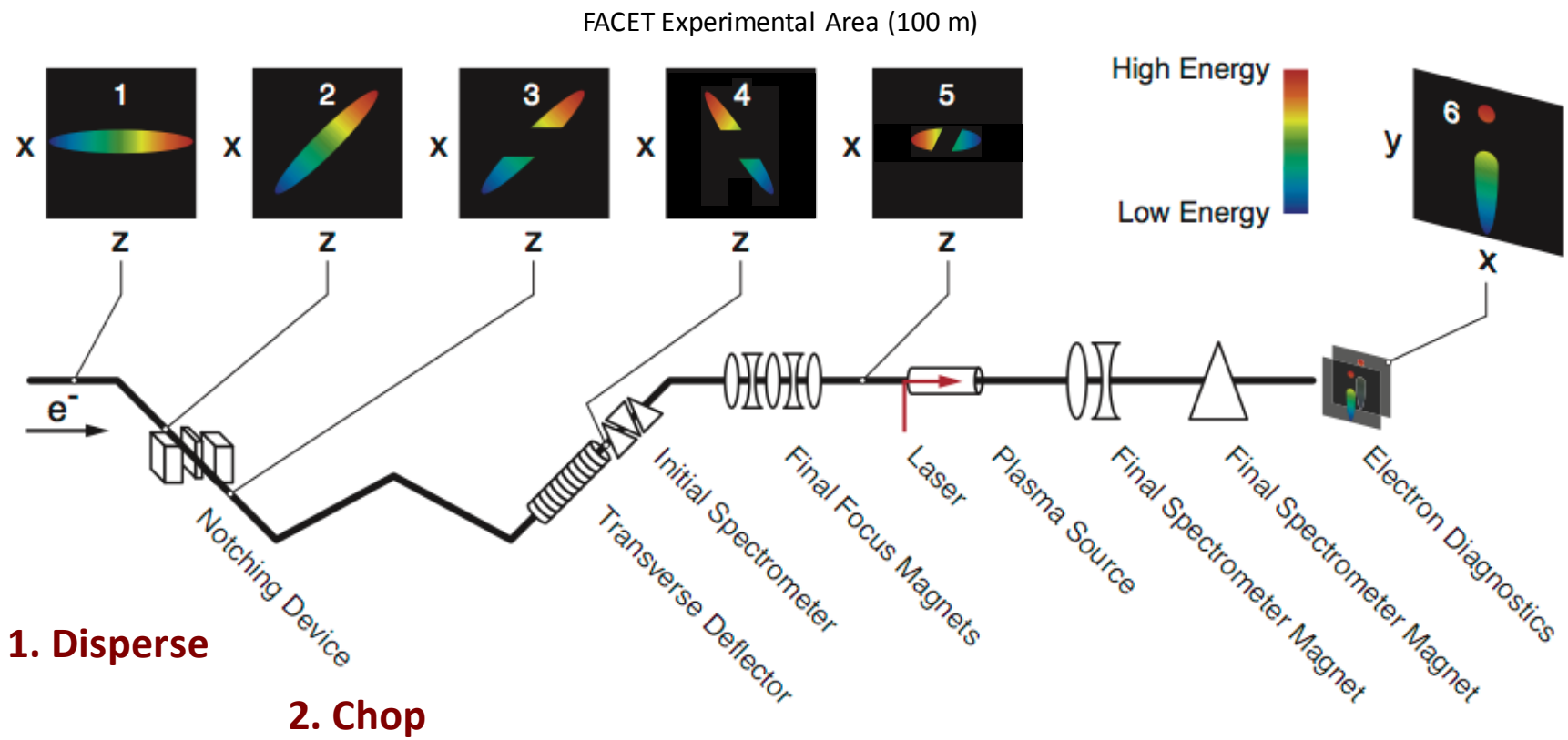
- Very high gradients in PWFA demonstrated at the FFTB
- Acceleration of little charge, sampling the wake fields

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

Two-beam acceleration experiments

Two-bunch generation

FACET generates single bunches. Must chop an ultrarelativistic bunch in two.



1. Disperse

2. Chop

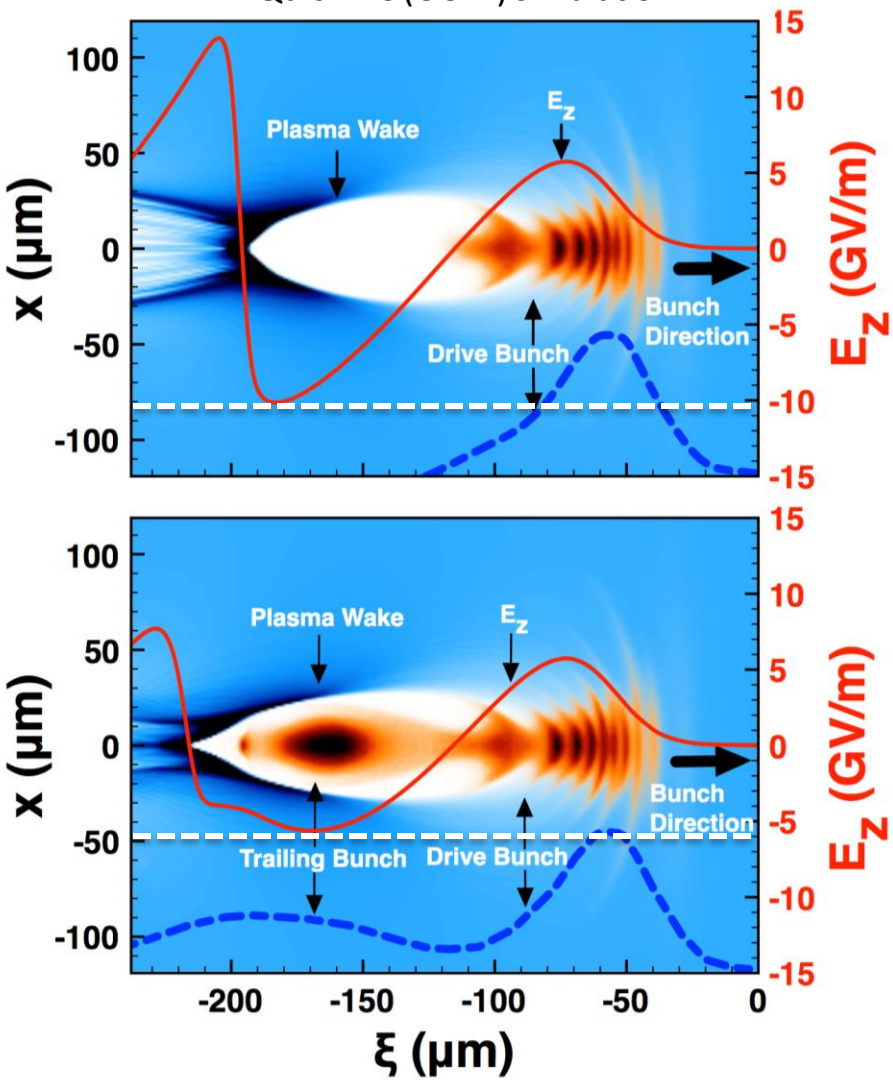
3. Compress

4. Accelerate

5. Diagnose

Low energy spread and high efficiency

QuickPIC (UCLA) simulation

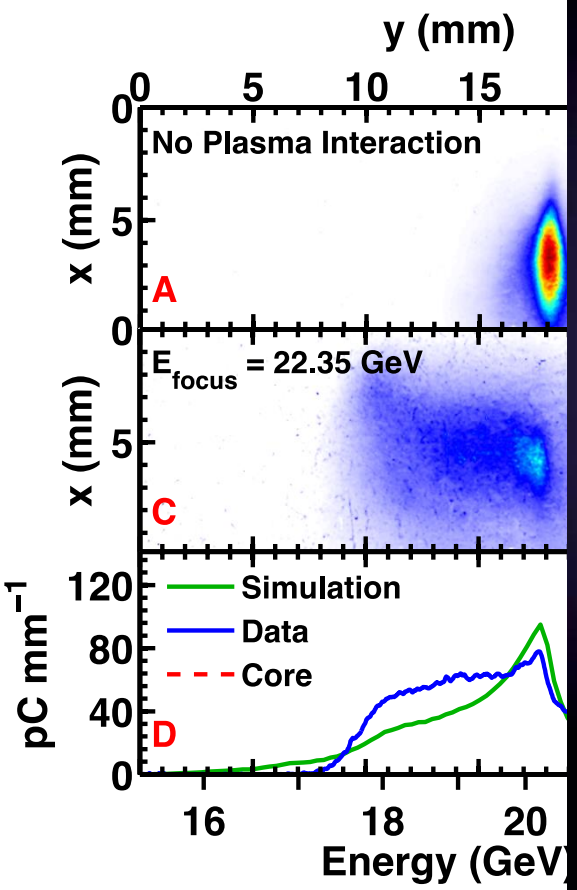


Efficiency :
energy gain by trailing bunch /
energy loss by drive bunch

Beam loading: The process we use to extract energy from the wake.

The presence of witness electrons "flattens" the E_z field.

FACET two-bunch results



2013

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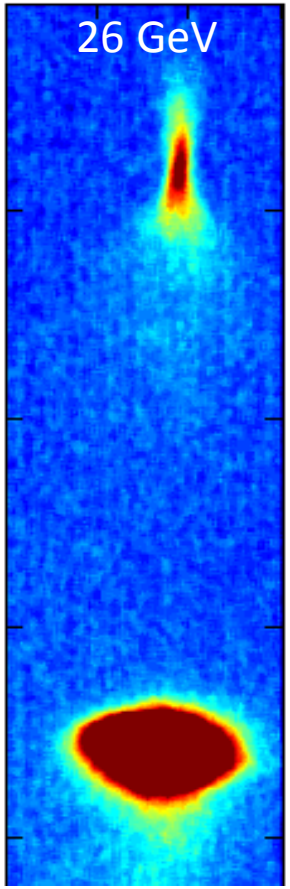
1.3 m plasma



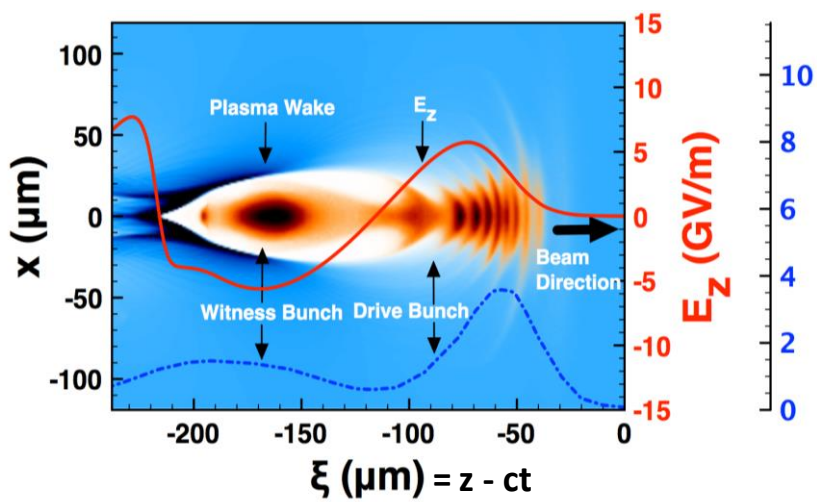
2014

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

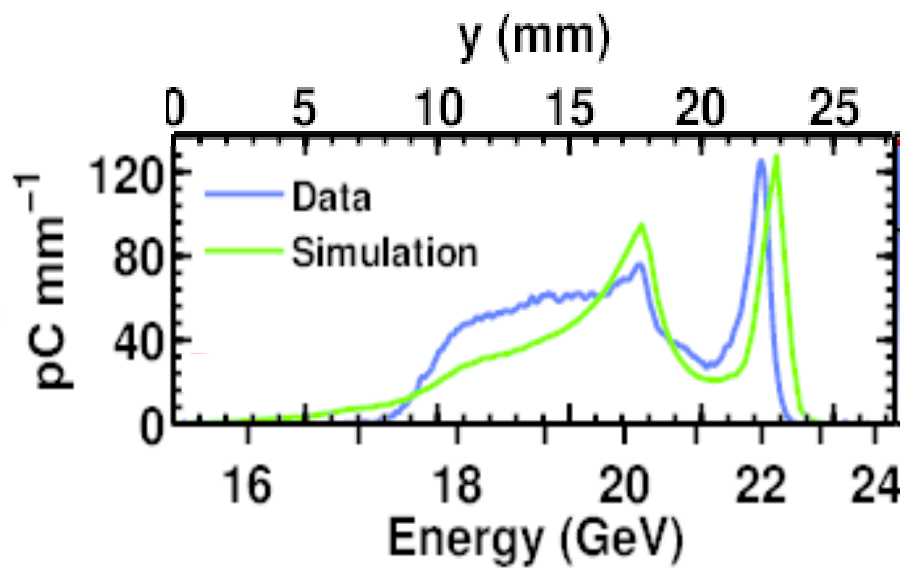
Comparison to Simulation

- Particle-In-Cell (PIC) simulation with QuickPIC (UCLA) for beam-plasma interaction + propagation through spectrometer optics
- 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, lost charge)
- Confirms that loading of the wake is key to low energy spread and efficient energy extraction

PIC Simulation

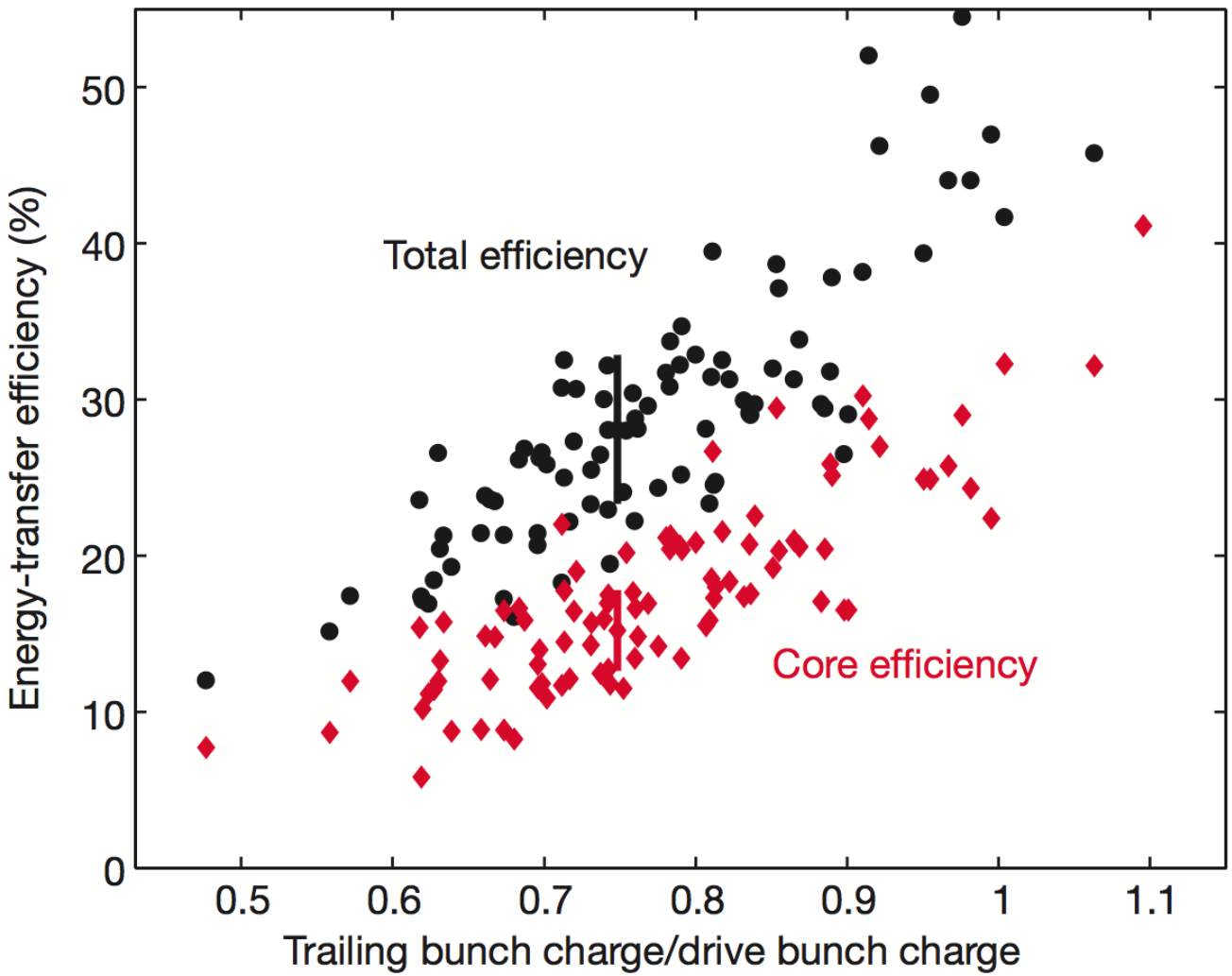


Final Dispersed Beam Profile



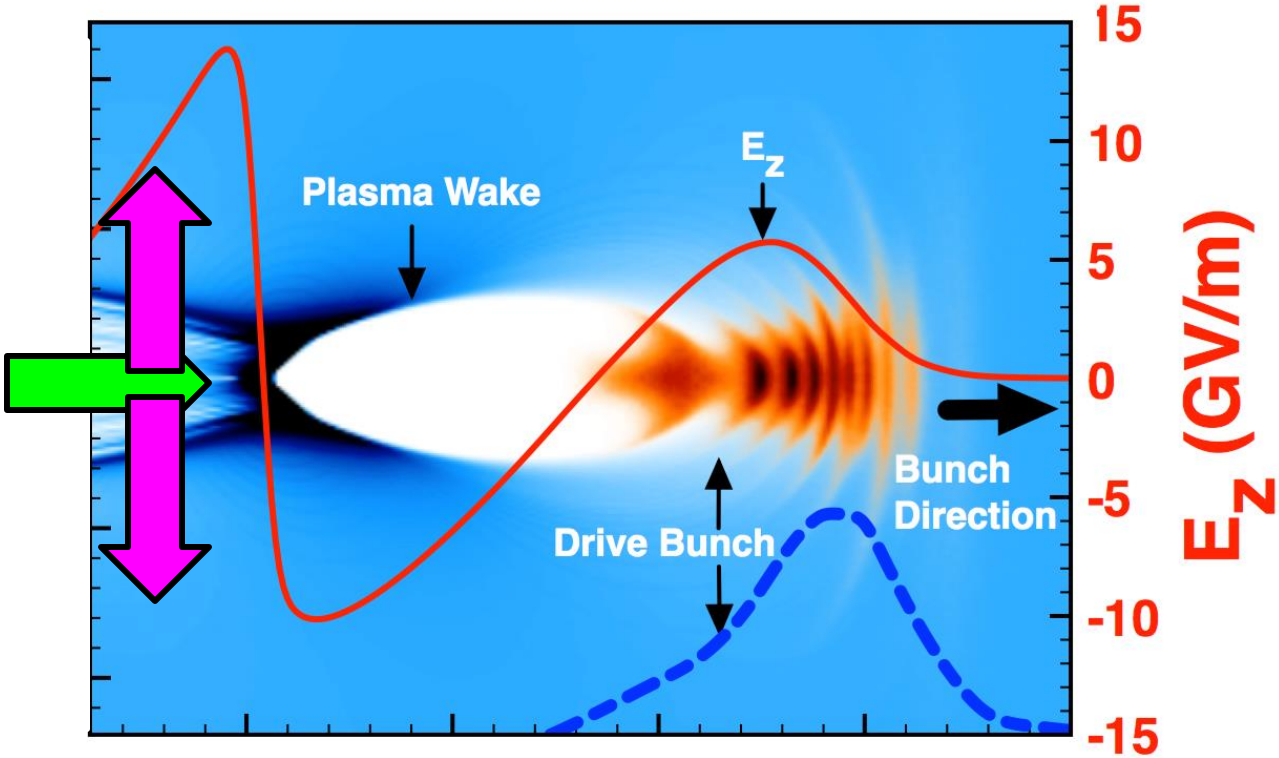
Correlation : efficiency with wake loading

Efficiency : energy gain by trailing bunch / energy loss by drive bunch



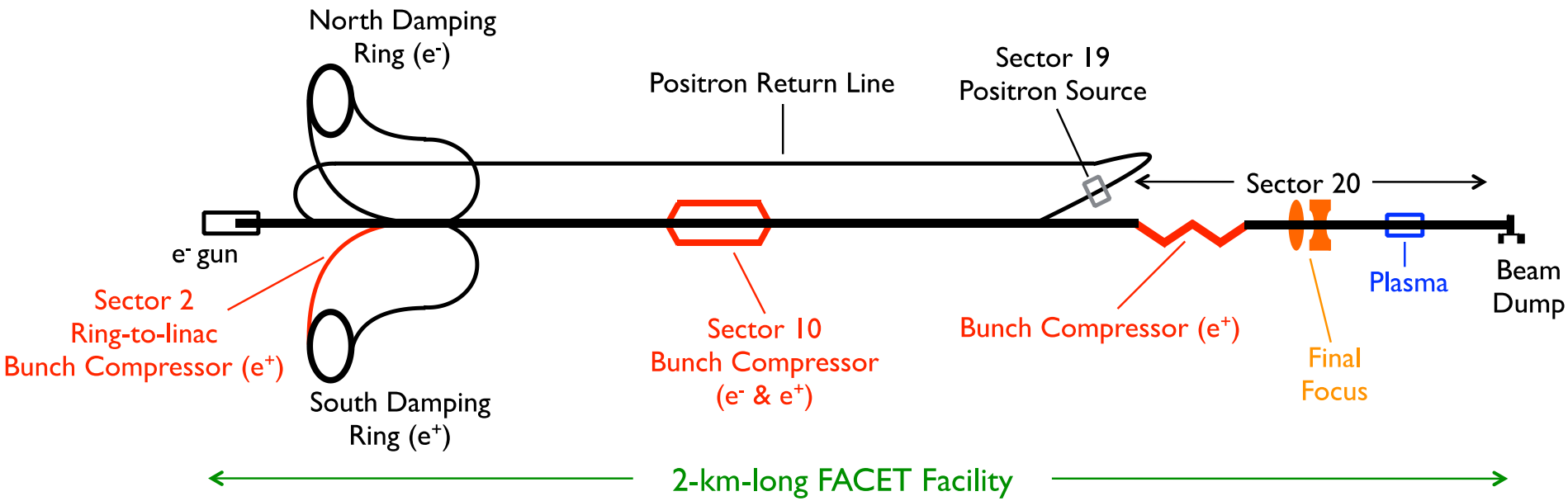
Positron acceleration in a plasma

Positron acceleration



But the field is defocusing in this region.

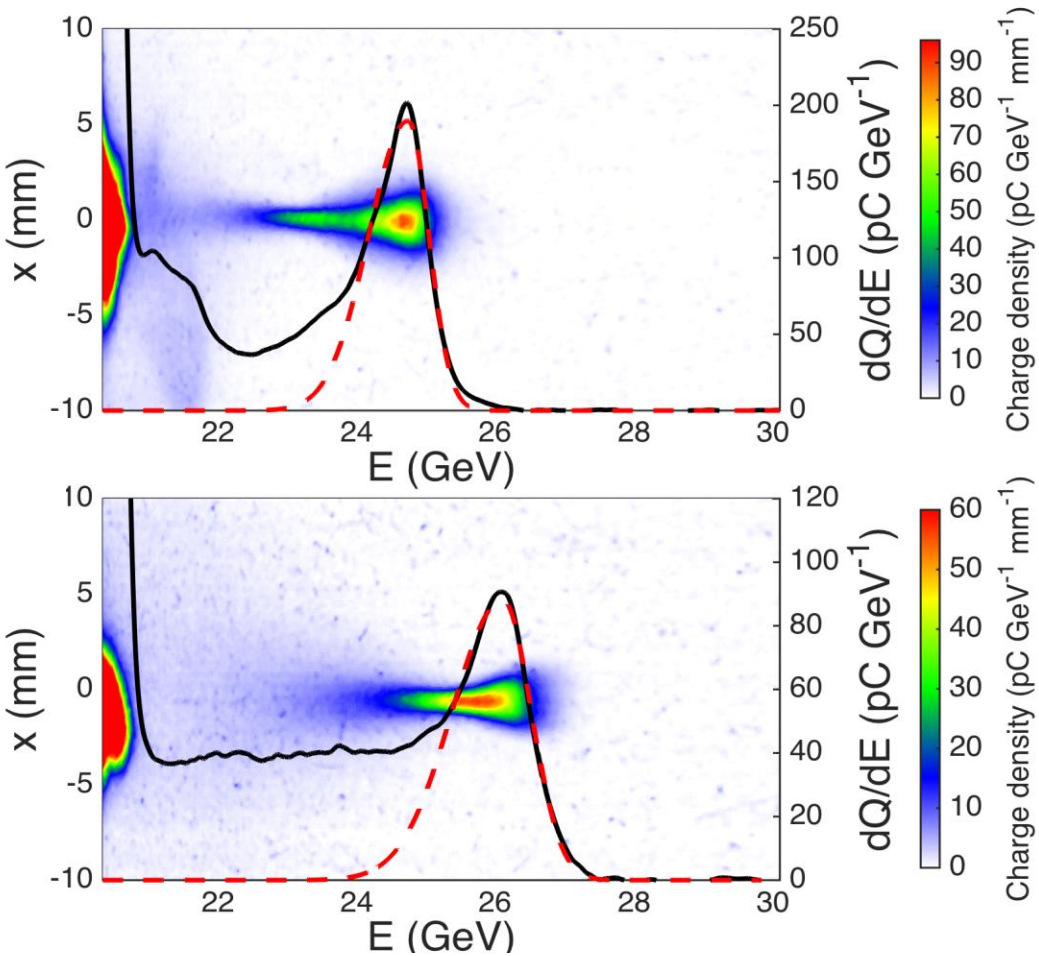
Positron production at FACET



- Positrons originate from the electromagnetic shower produced when a 20.35 GeV electron beam passes through a thick tungsten alloy target.
- Separate bunch compressor in Sector 10 to compress the positron bunch.
- Experimental area (sector 20) magnet polarity inversion (e- *or* e+)
- Unique capability : short (~20 um) and intense (~10 kA) positron beams.

Positron results at FACET

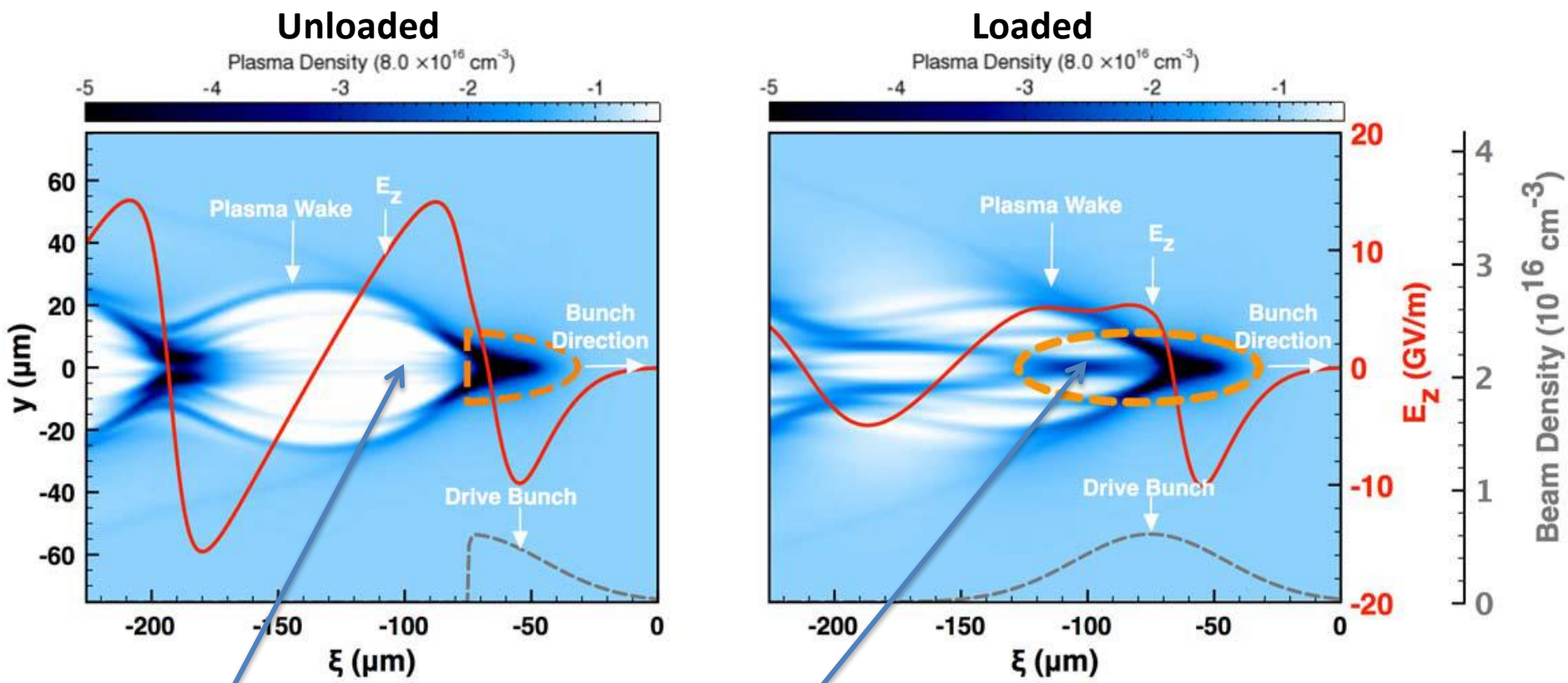
- **Sent single high charge, high density e^+ bunch into high density plasma for the first time : an unexpected result!**
- **We observed a spectrally-distinct positron beamlet gain 5 GeV of energy.**
- **The beamlet has low energy spread (few %)**
- **Of interest for "afterburner" applications**



S. Corde *et al.*, Nature **524**, 442 (2015)

Plasma Wakefield Acceleration: Positrons

Understanding the results: longitudinal and transverse beam loading



Defocusing for positrons

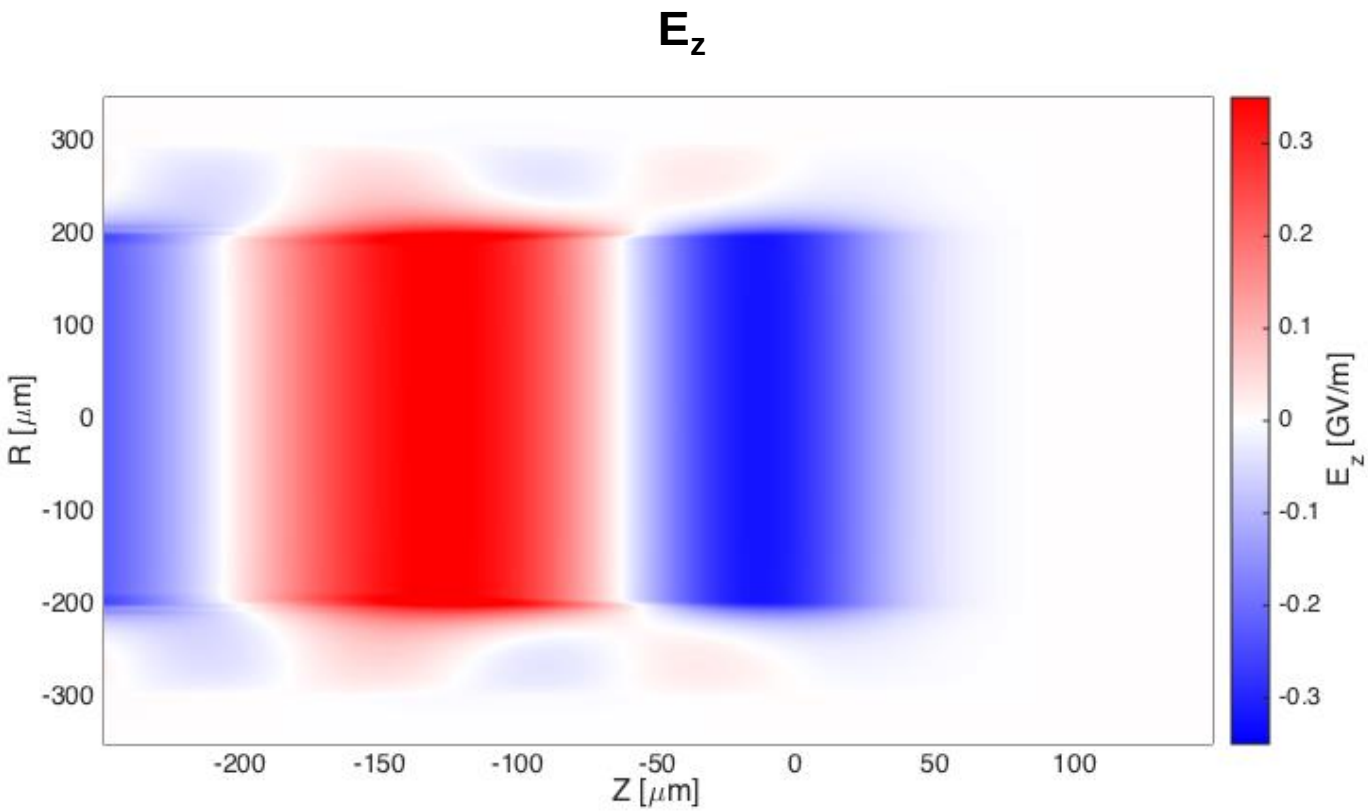
Focusing for positrons

Transverse beam loading is an important effect for positron driven wakes

S. Corde *et al.*, Nature **524**, 442 (2015)

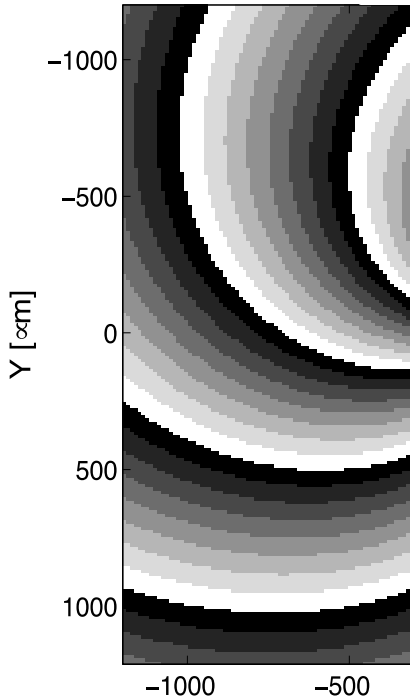
Formation of hollow plasma channels

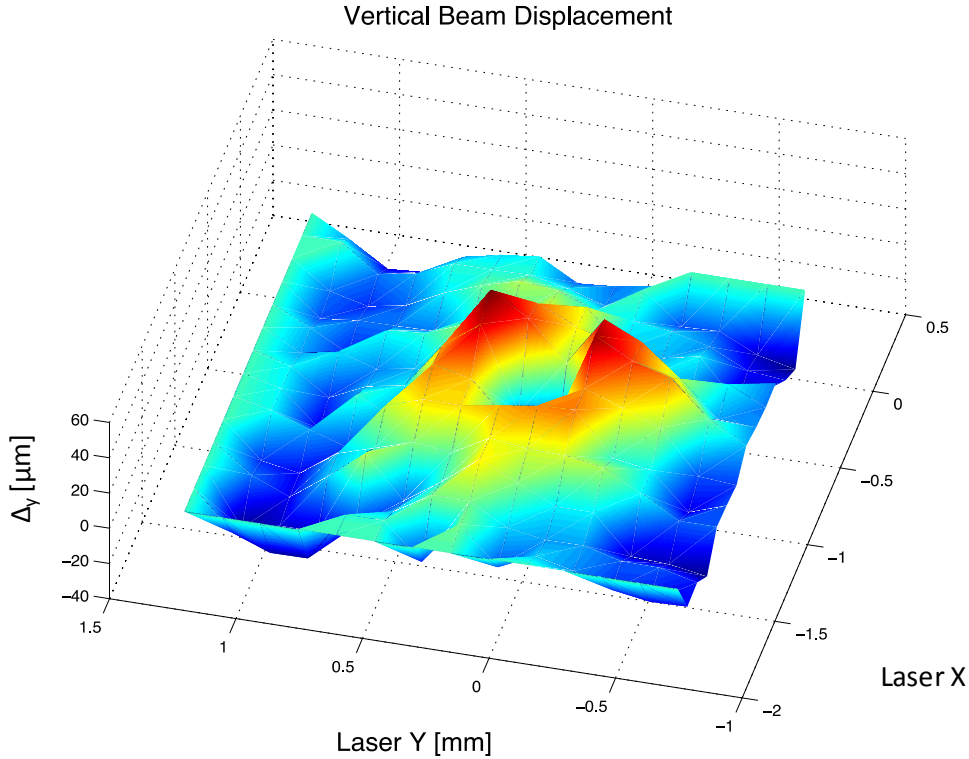
Plasma Wakefield Acceleration: Hollow Channels

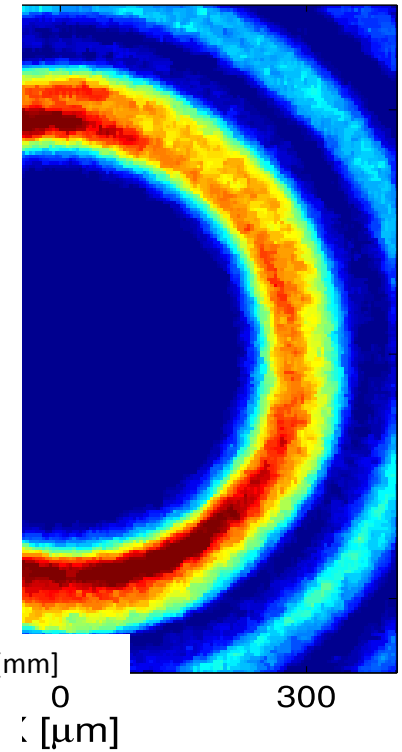


Hollow channels provide large accelerating fields *without* focusing fields.

Plasma Wakefield Acceleration: Hollow Channels







We've observed the effect of the hollow channel on a positron beam.

We use a spiral phase grating to create hollow laser beams.

The laser ionizes an annulus of plasma.

Conclusions

- Progress at FACET has been rapid:
  - Meter-long plasma source with high gradients
  - High-efficiency, low energy spread two-bunch acceleration
  - Multi-GeV positron acceleration in a new self-loaded wakefield regime
  - Hollow Channel PWFA
- Unexpected positron results mean that there is a lot more to study

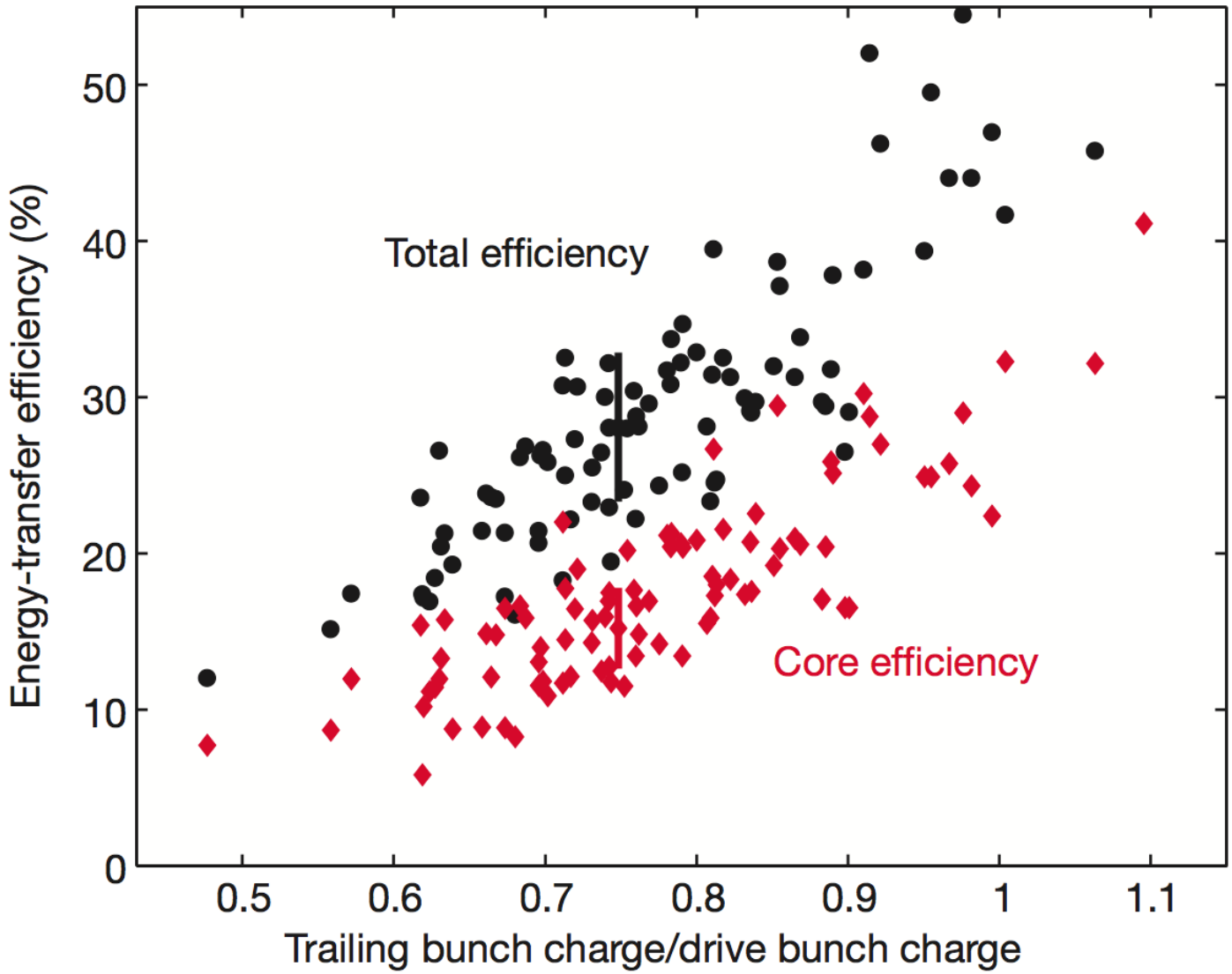
There is more positron beam time planned for FACET.

What Lies Ahead

- FACET (up to April 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 (2018/19 and onwards)
  - Witness beam emittance preservation
  - Witness beam energy spread minimization
  - Staging studies
  - Positrons in electron driven wakes
  - Lots more…

Backup

Energy-transfer efficiency dependence on wake loading

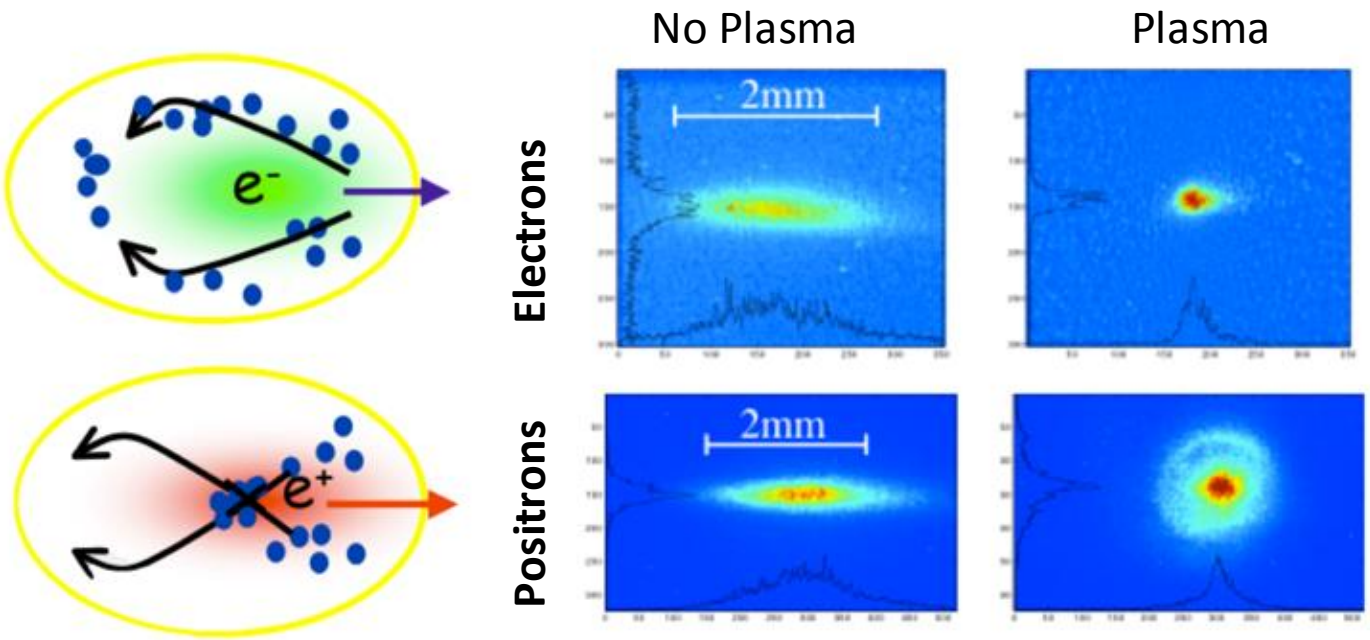


Previous experimental results

Previous results with positrons (long bunches, low density plasmas):

"Blow-out"

"Suck-in"



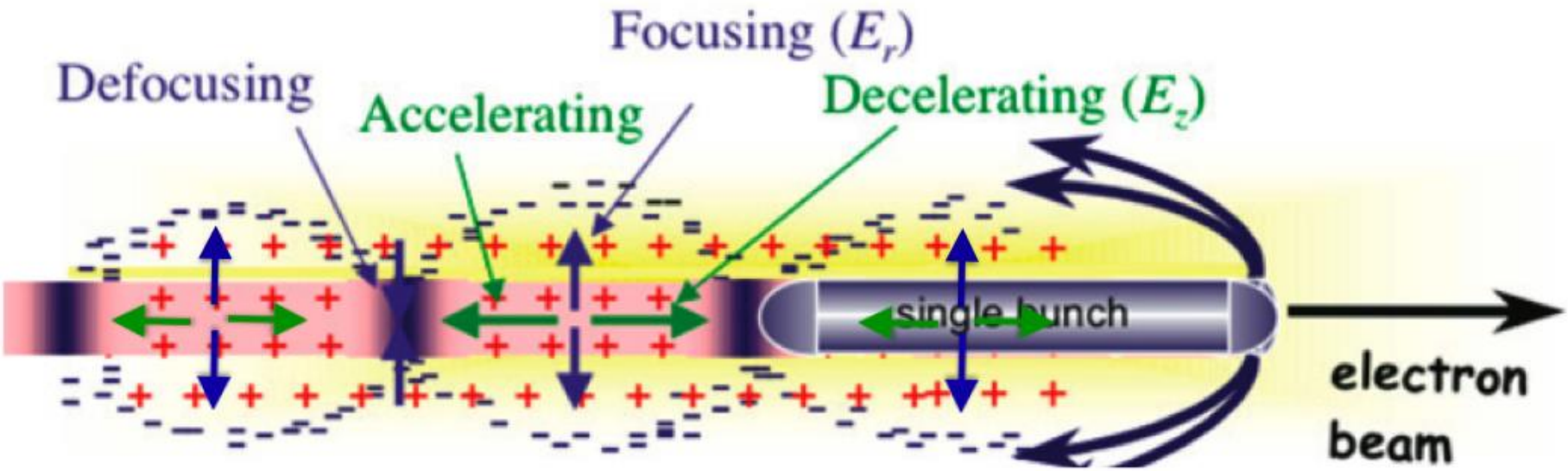
Phys. Rev. Lett. **90**, 205002 (2003)

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

The plasma confines and channels the electron beam as it passes through the plasma.

Experiments at SLAC FFTB in 2003 showed that a long positron beam was distorted after passing through a low density plasma (halo formation).

Plasma Wakefield Acceleration (PWFA)



Plasma wave excited by relativistic particle bunch. Wave velocity is speed of light

If driver is strong enough (nb > n0): plasma electrons are blown out : Blow-out regime

Decelerating field at head of bubble extracts energy from bunch

Accelerating fields at the back of bubble

Quadrupolar 1/r focusing fields (x and y) within the ion bubble