Latest Plasma Wakefield Acceleration Results from the FACET Project

NA-PAC 2013 – Pasadena, CA

Michael Litos - Oct. 3, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

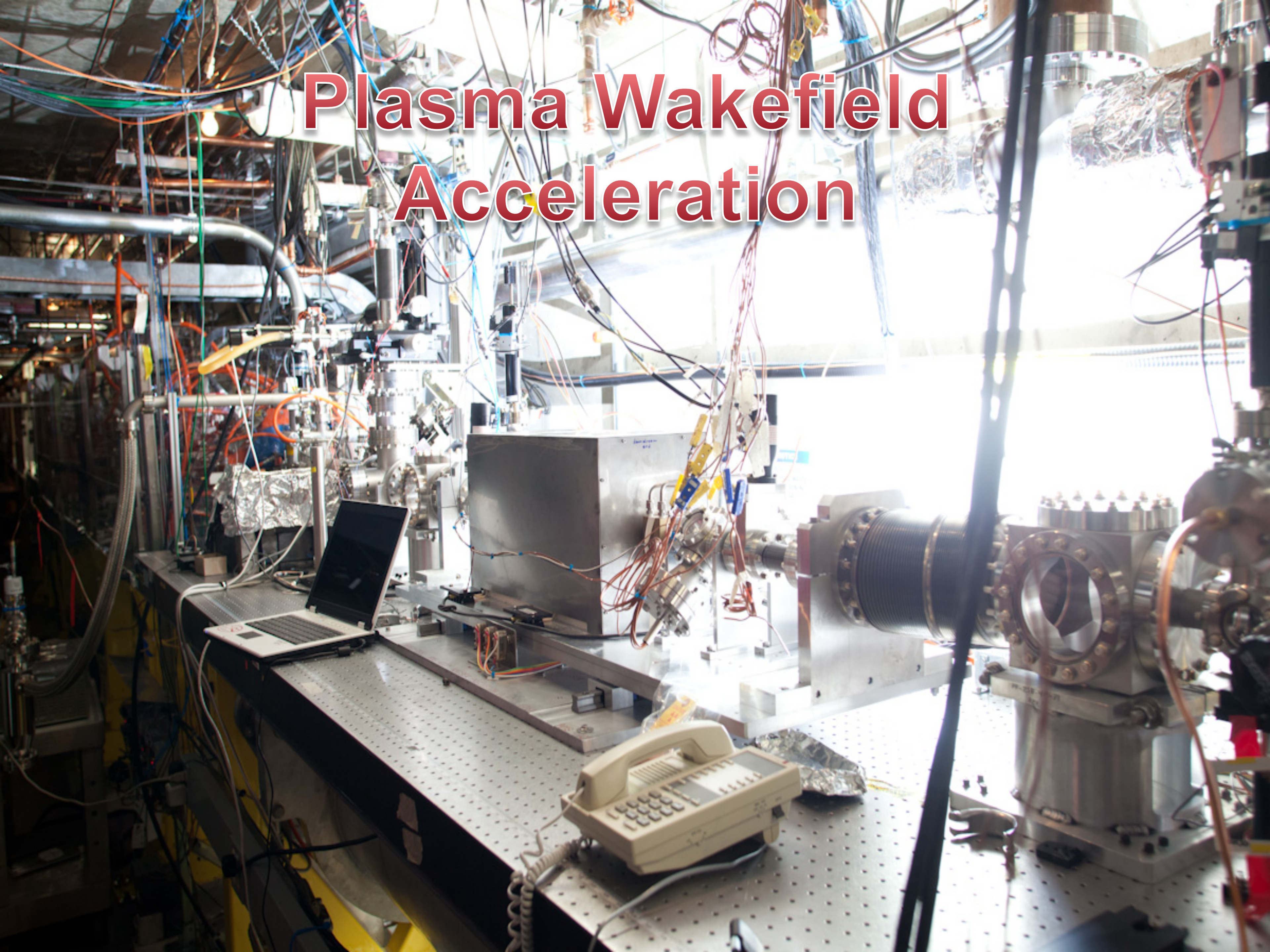
SLAC NATIONAL ACCELERATOR LABORATORY

E200 PWFA Collaboration at FACET

M. Litos, S. Corde, E. Adli, S. Li, S. Gessner, J. Frederico, G. White, A. S. Fisher, Z. Wu, D. Walz, R. J. England, C. I. Clarke, V. Yakimenko, M. J. Hogan, N. Vafaei-Najafabadi, K. A. Marsh, C. E. Clayton, W. An, W. Lu, W. B. Mori, C. Joshi, T. Katsouleas, A. Sahai, P. Muggli

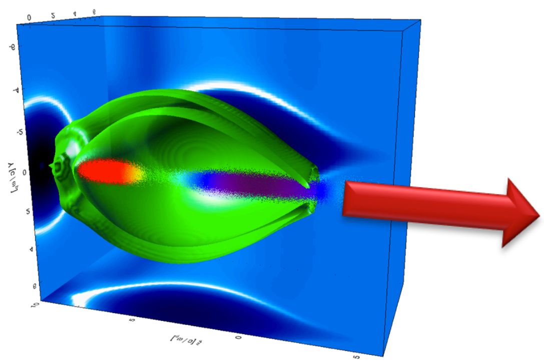
Work supported by DOE contracts DE-AC02-76SF00515, DE-AC02-7600515, DE-FG02-92-ER40727 and NSF contract PHY-0936266

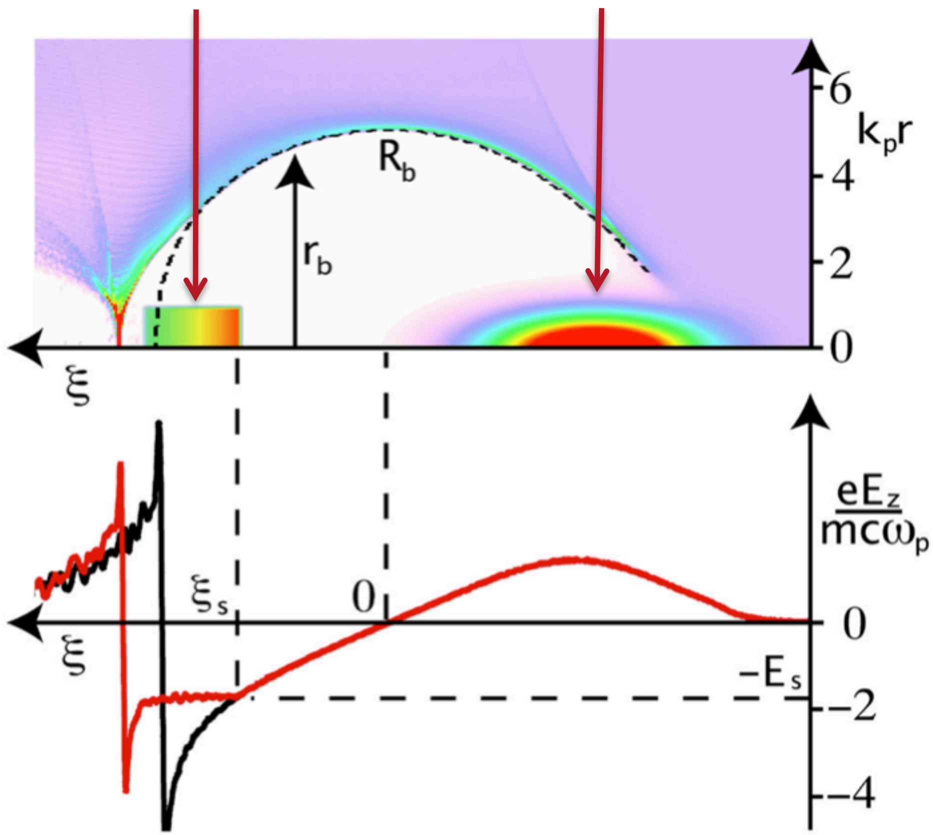
Plasma Wakefield Acceleration



Beam-Driven Plasma Wakefield Acceleration

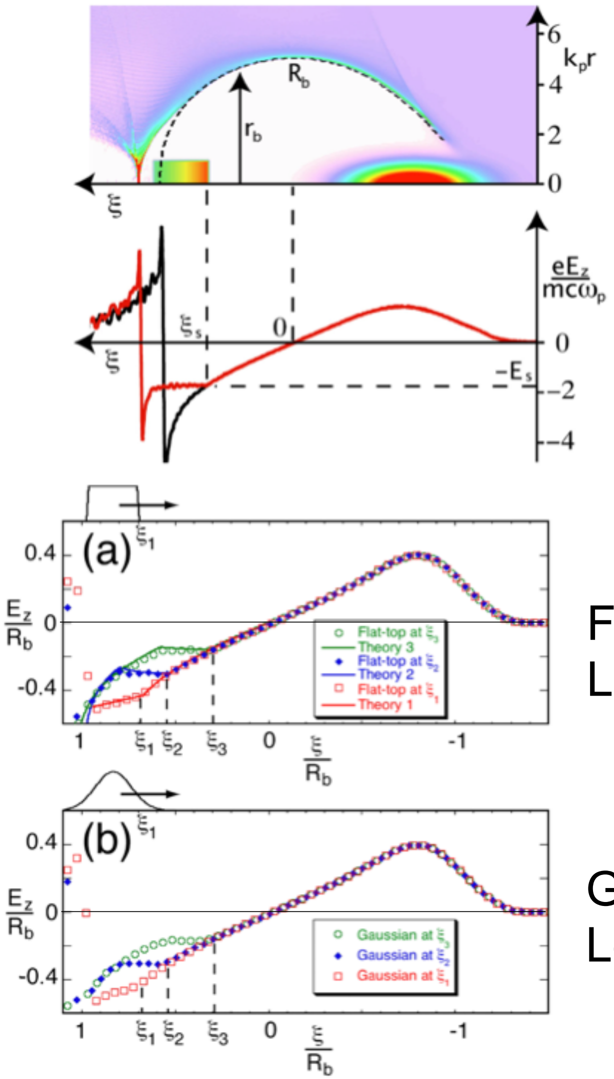
- Lead beam drives non-linear blowout in plasma
- Central region is depleted of electrons leaving ion column
- Longitudinal field depends only on ξ
- Focusing force is linear in radius
- Wakefields depends on plasma density and drive beam current
- Trailing beam is accelerated near back of bubble





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

Beam Loading



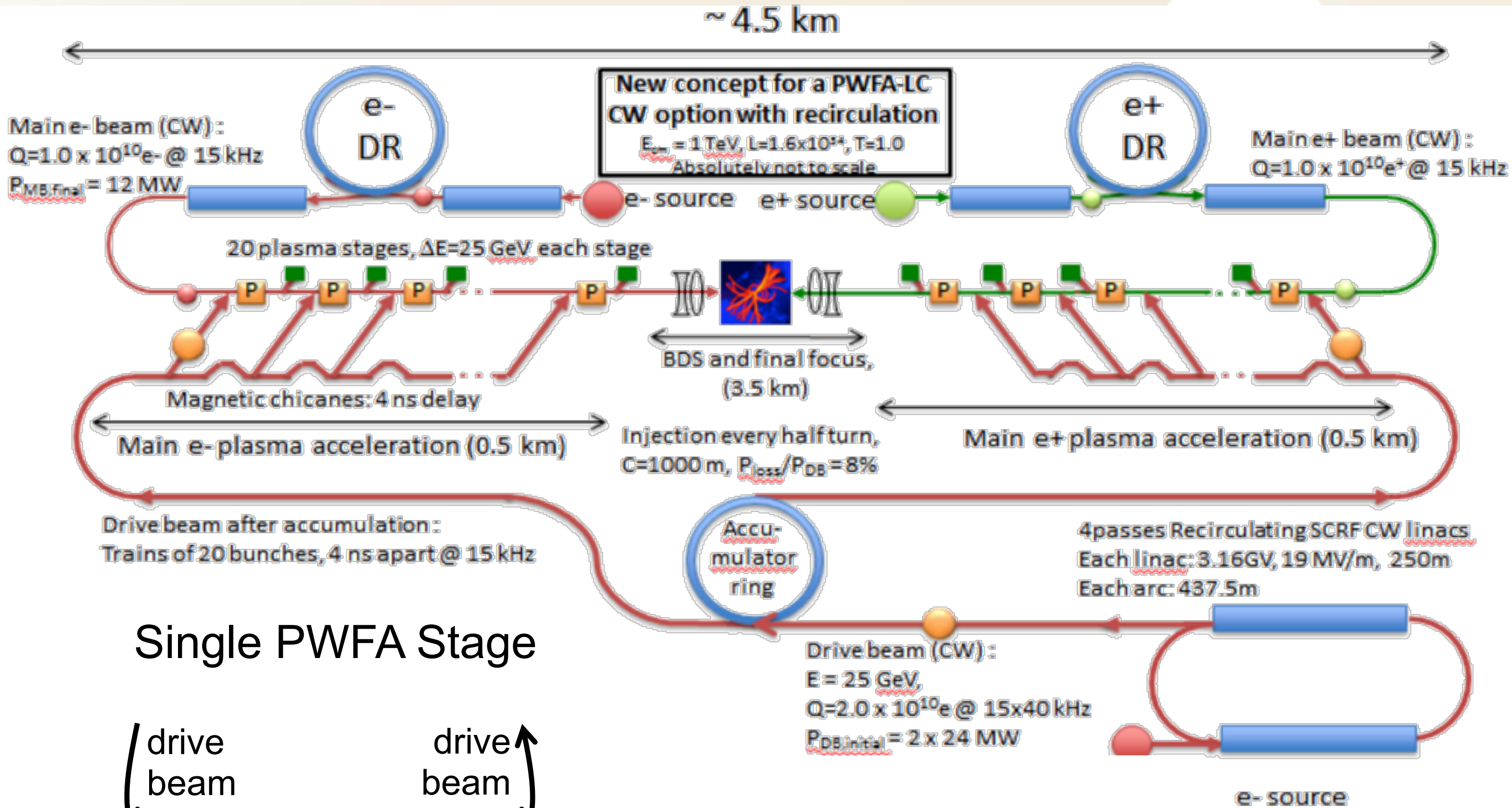
Flat-top Loading

Gaussian Loading

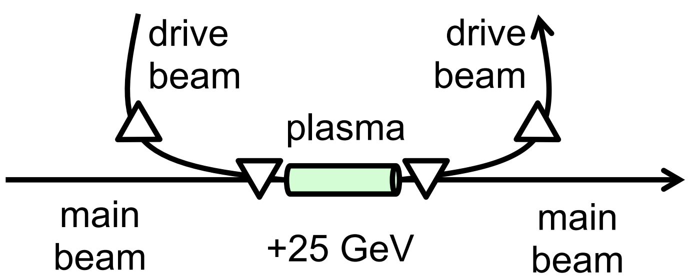
- For best wake flattening need trapezoidal current profile
- But Gaussian is not bad, either!
- Only somewhat sensitive to longitudinal position
- Peak field is linearly dependent on long. position: $E_z \sim \xi$
- Product of accelerated charge and accelerating field is constant: $Q\,E_z \propto R_b^4$

M. Tzoufras, W. Lu, et al., PRL 101-14 (2008)

PWFA Linear Collider Concept



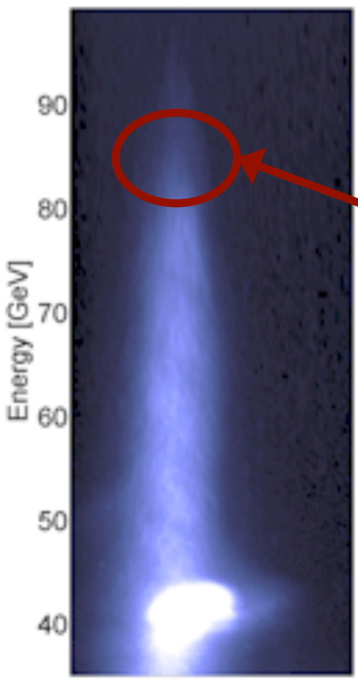
Single PWFA Stage



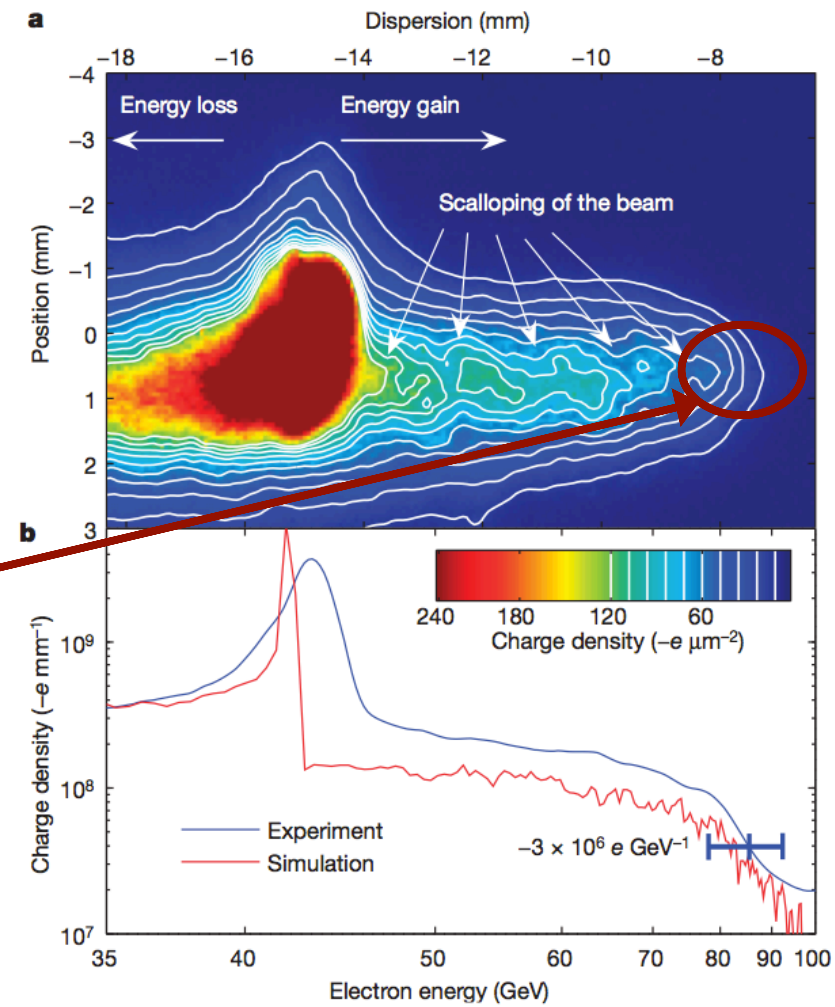
- 250 GeV – 3 TeV PWFA LC Concept
- 1 TeV design: 4.5 km, dominated by FF
- FACET general goal: demonstrate and study single PWFA stage

Particle Acceleration at FFTB

- Particles doubled in energy at SLAC's FFTB facility
- 42 GeV gained in 85 cm → 52 GV/m accelerating field



Energy Doubled



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

PWFA Stage Experimental Benchmarks

- ✓ High gradient fields
- ✓ Meter-scale propagation
- ❑ Acceleration of a beam
- ❑ Small energy spread
- ❑ Emittance preservation
- ❑ High efficiency

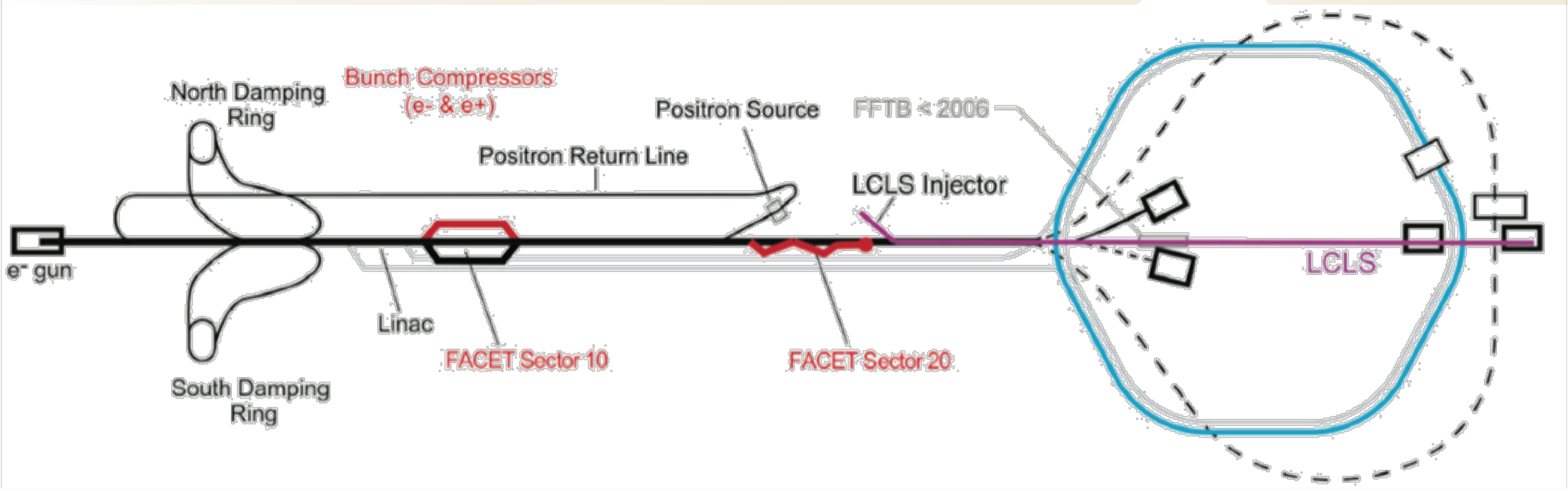
FACET Beamline and Diagnostics

FACET Beamline and Beam Parameters

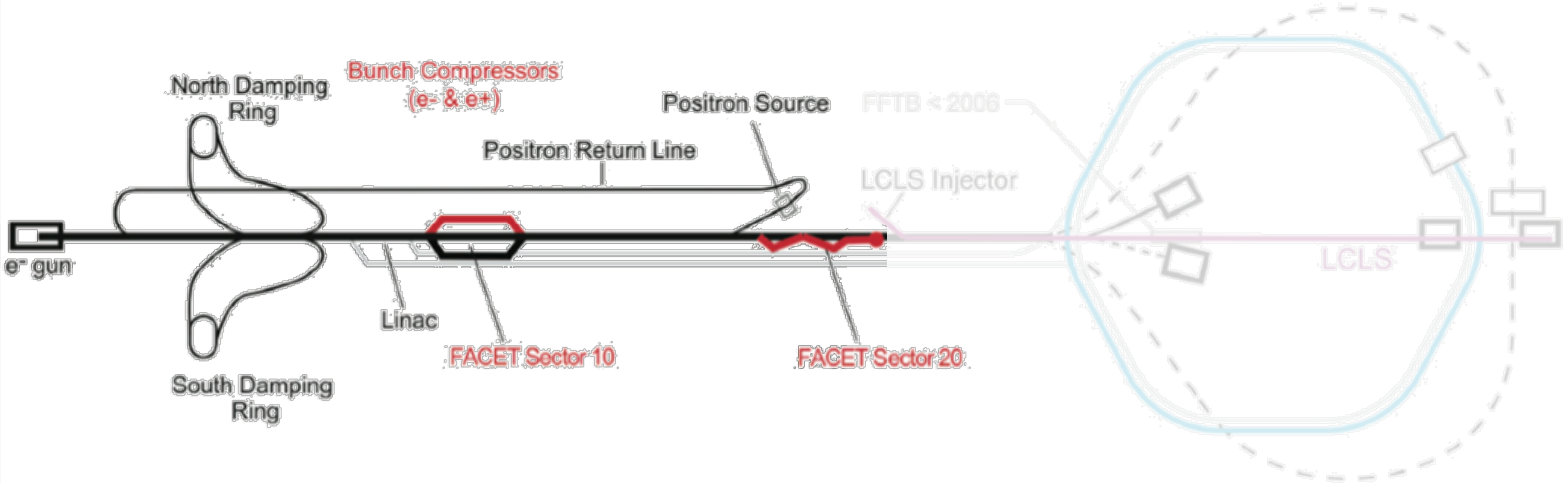
- Apr. – June 2013 run very successful for FACET beam
- Close to design value for all parameters
- Stable operation
- Good beam → Good science!

parameter	2013 value
E	20.35 GeV
Q	3.2 nC
σ_r	<30 µm
σ_z	<40 µm
species	e^-

SLAC Linac Layout



FACET Layout



FACET Sector 20 Layout

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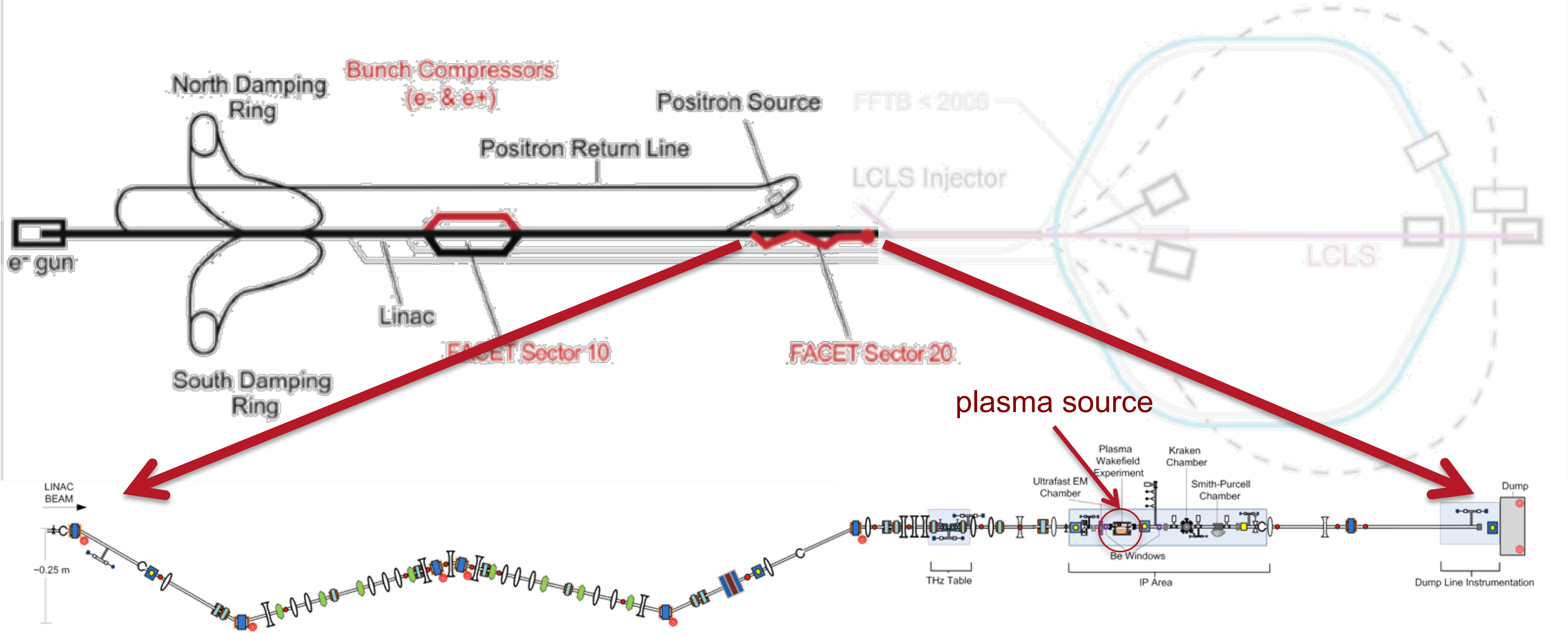
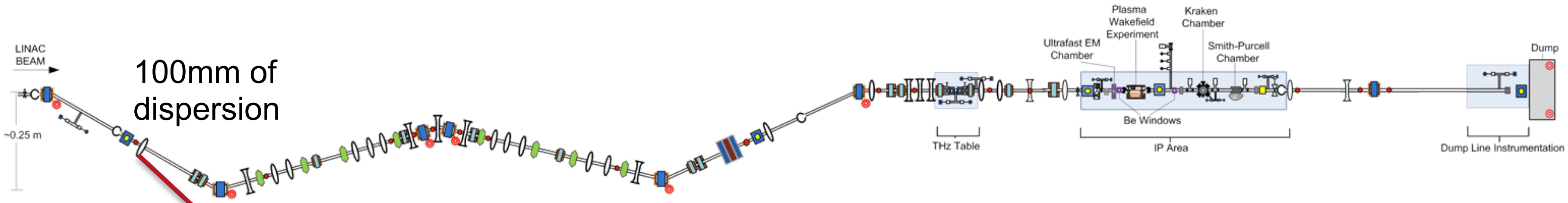


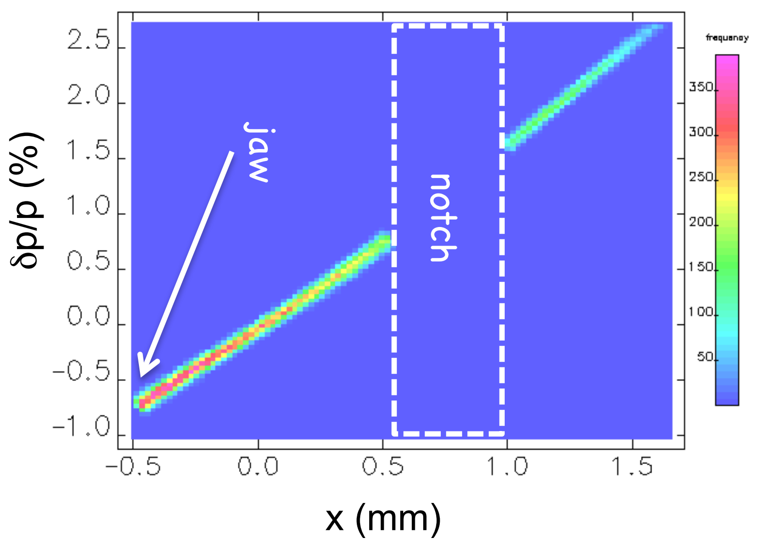
- Chicane for final compression
- Adjustable R_{56} : 0mm – 10mm
- Notch Collimator for two-bunch beam
- X-ray wiggler for beam spectrum before plasma

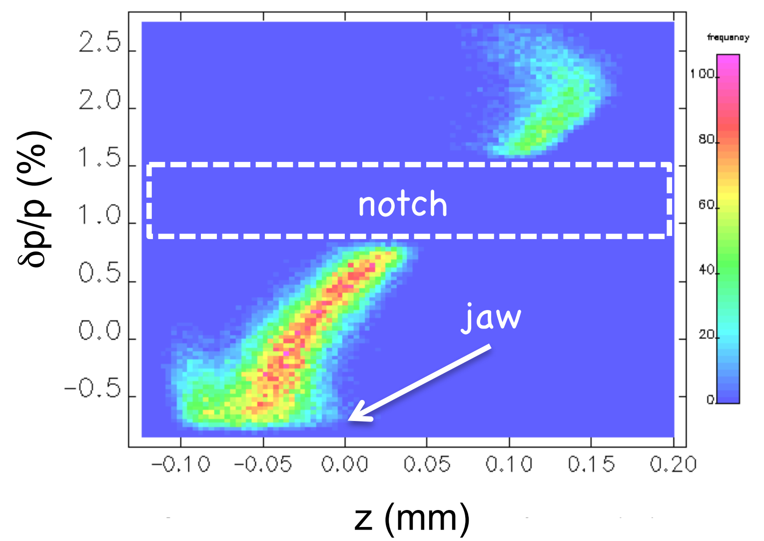
- X-band TCAV and CTR interferometer for longitudinal profile
- Many BPMs, OTRs, Wires, Toroids
- Lanex screens for betatron radiation
- Imaging spectrometer for final beam spectrum after plasma

Creating Two-Bunch Structure

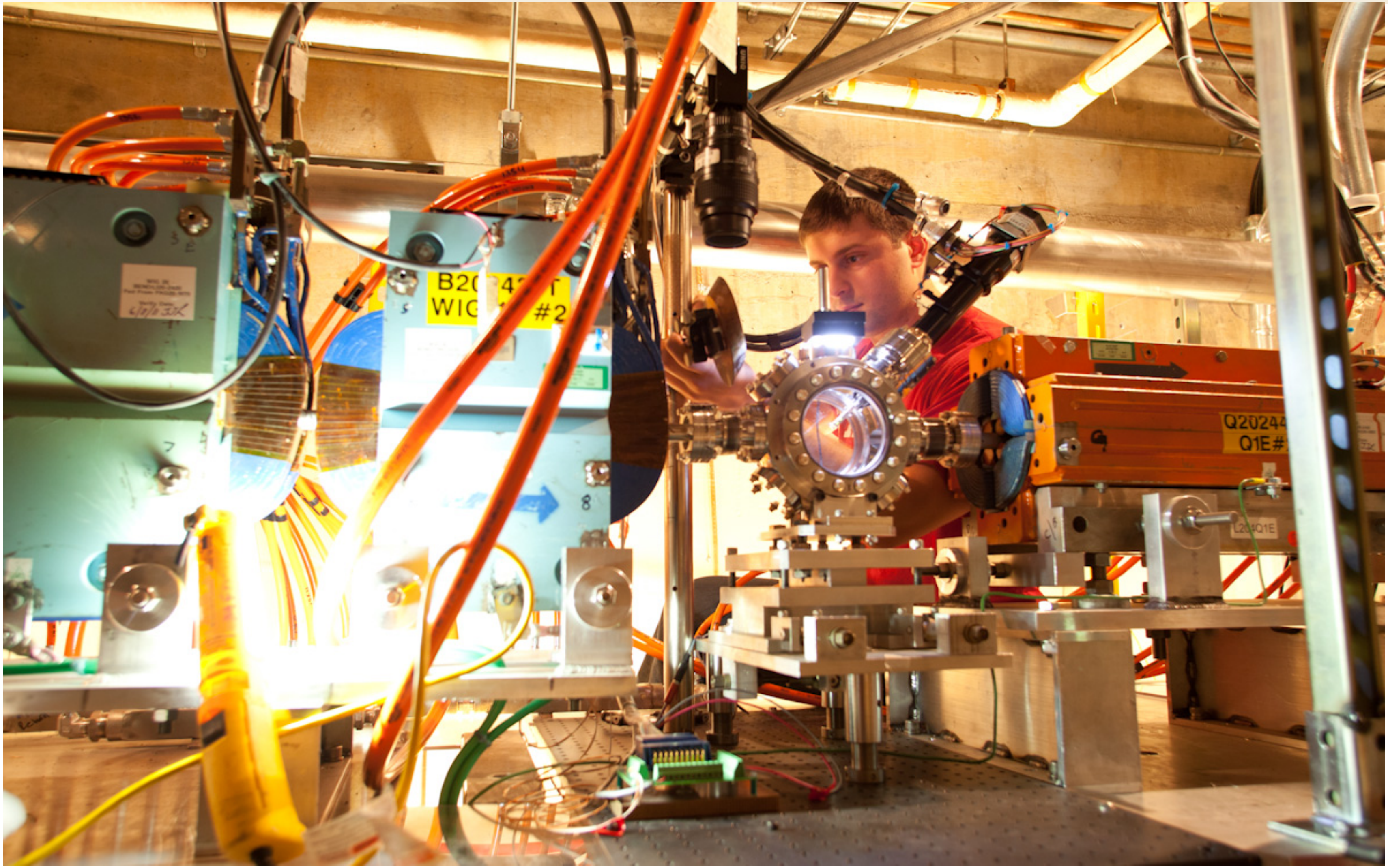


- Adjustable tantalum notch used to create two-bunch structure
- Jaw collimator removes low energy tail

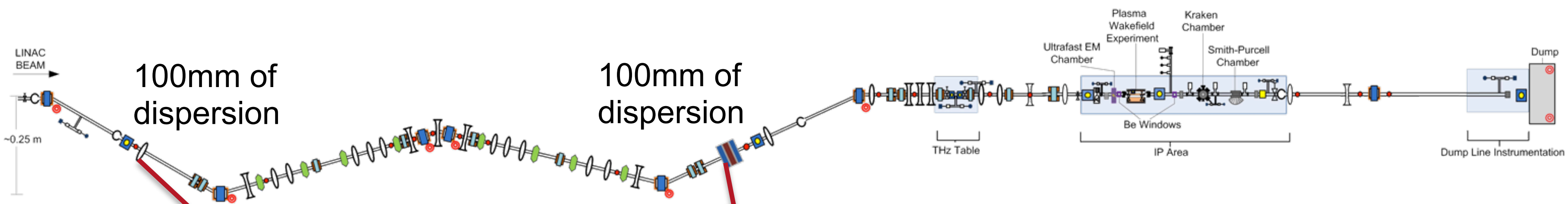




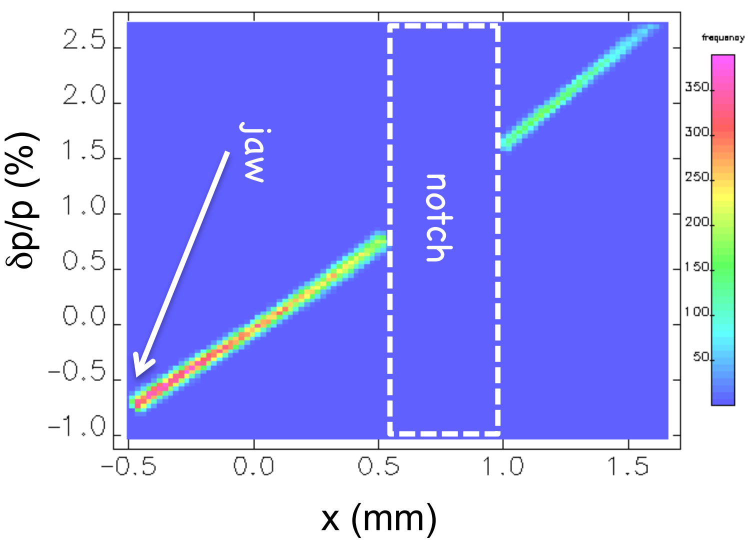
Wiggler Spectrometer

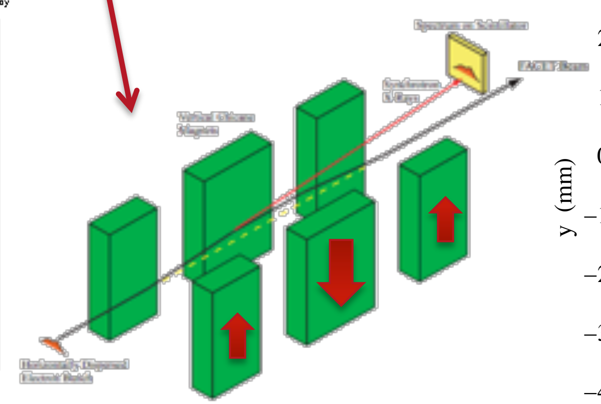


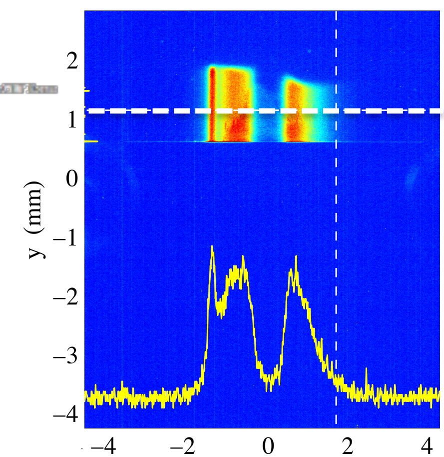
Pre-Plasma e-Beam Spectral Diagnostic



- Wiggler spectrometer at symmetric point in chicane from notch collimator
- Allows direct measurement of notching in x = energy of e-beam







x (mm) = δp/p (%)

XTCAV

Pre-Plasma Longitudinal Diagnostic

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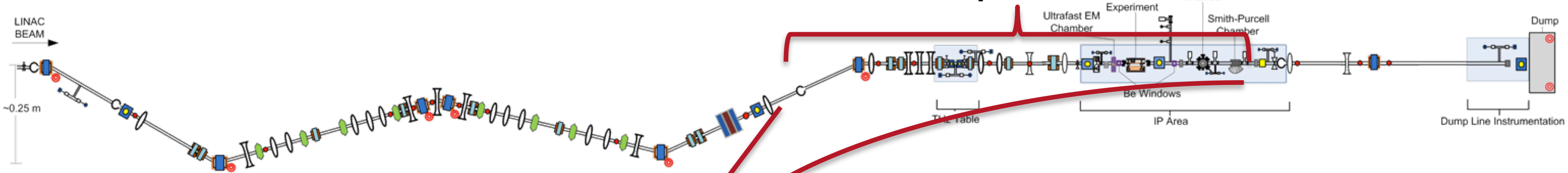
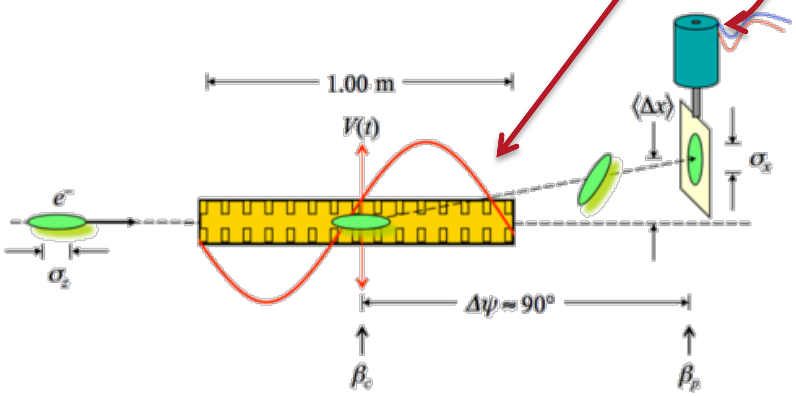
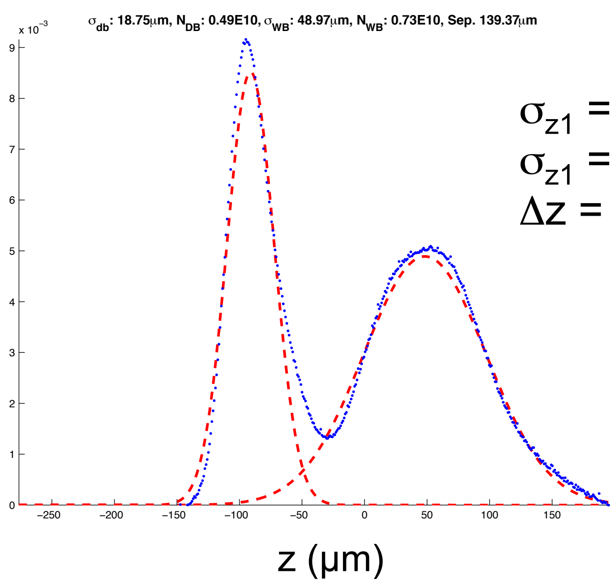
$\Delta\psi = \pi/2$



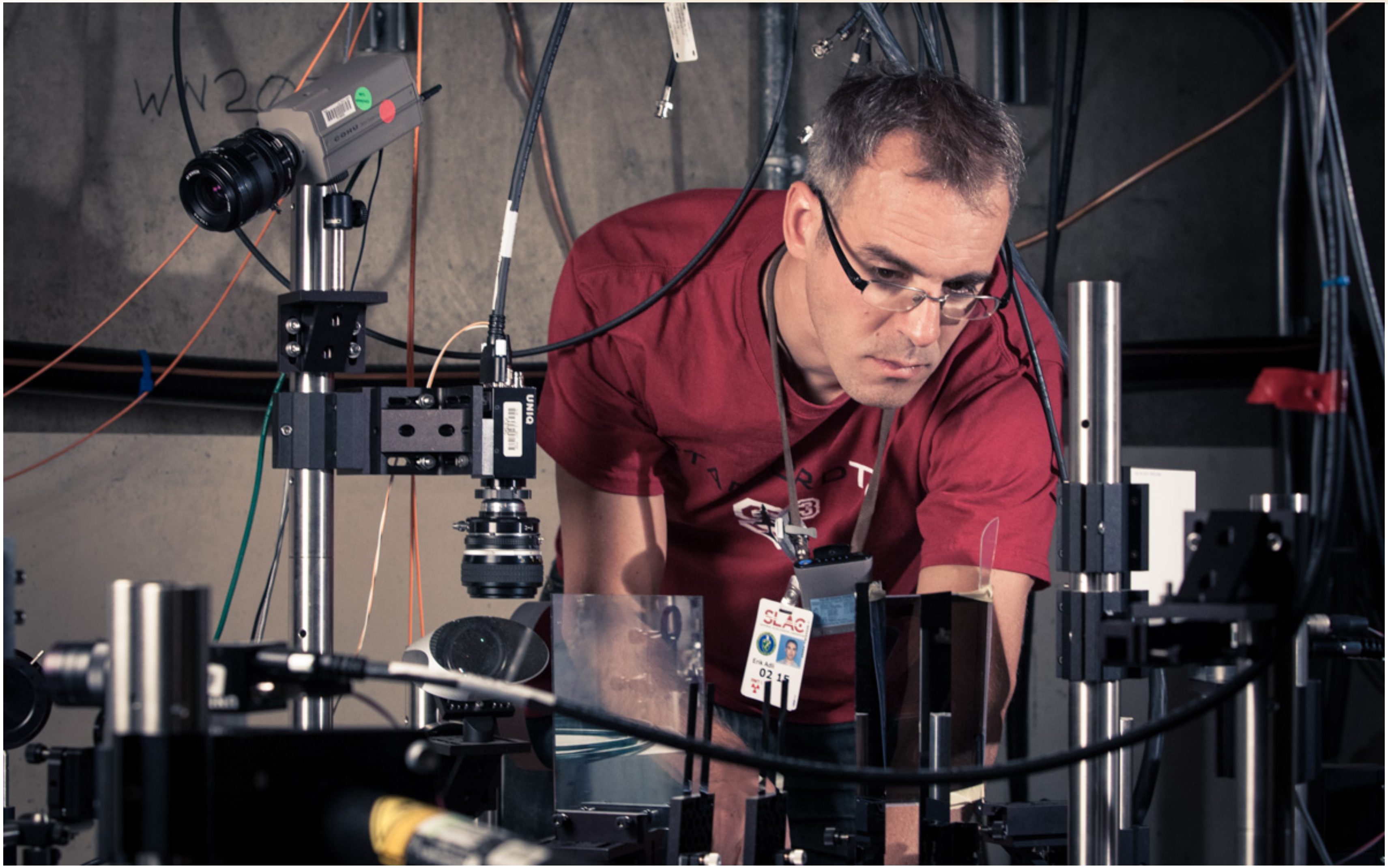
- X-band transverse deflecting cavity (XTCAV) streaks beam onto OTR screen
- Allows direct measurement of longitudinal charge profile of two-bunch beam



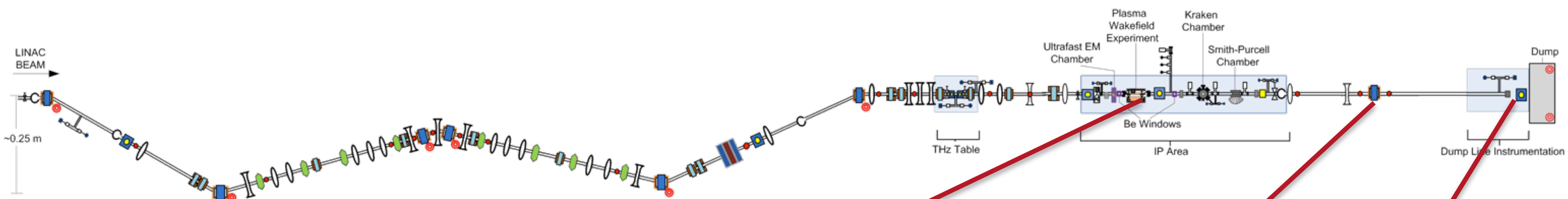


σ_{z1} = 20μm
σ_{z1} = 50μm
Δz = 125μm

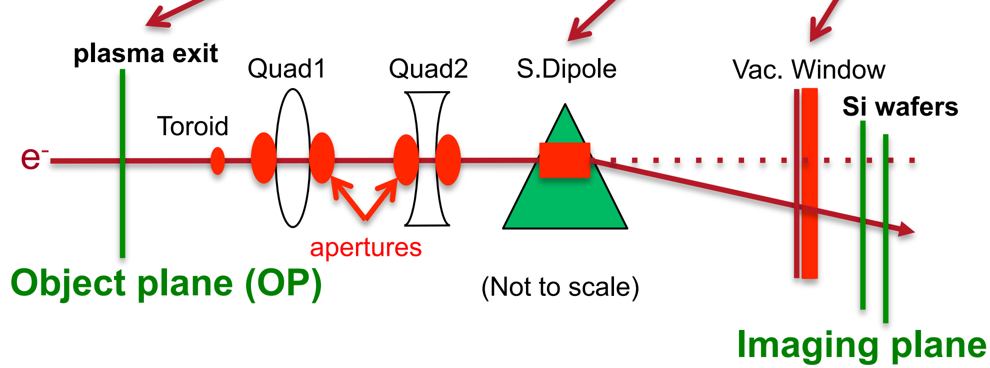
Cherenkov Monitor

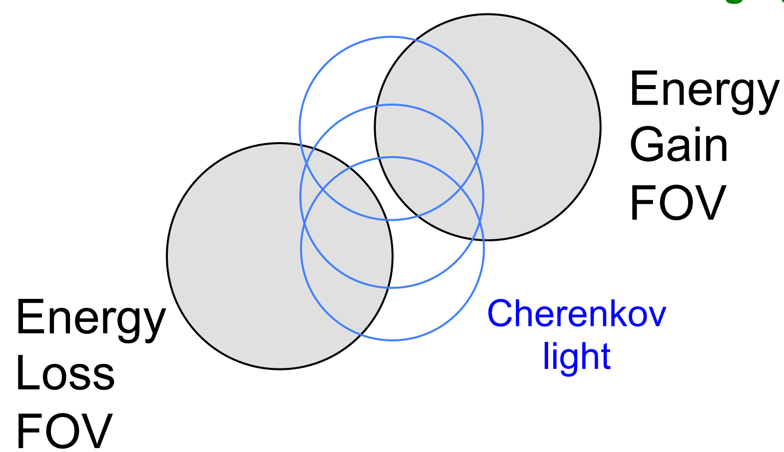


Imaging Final Beam Spectrum

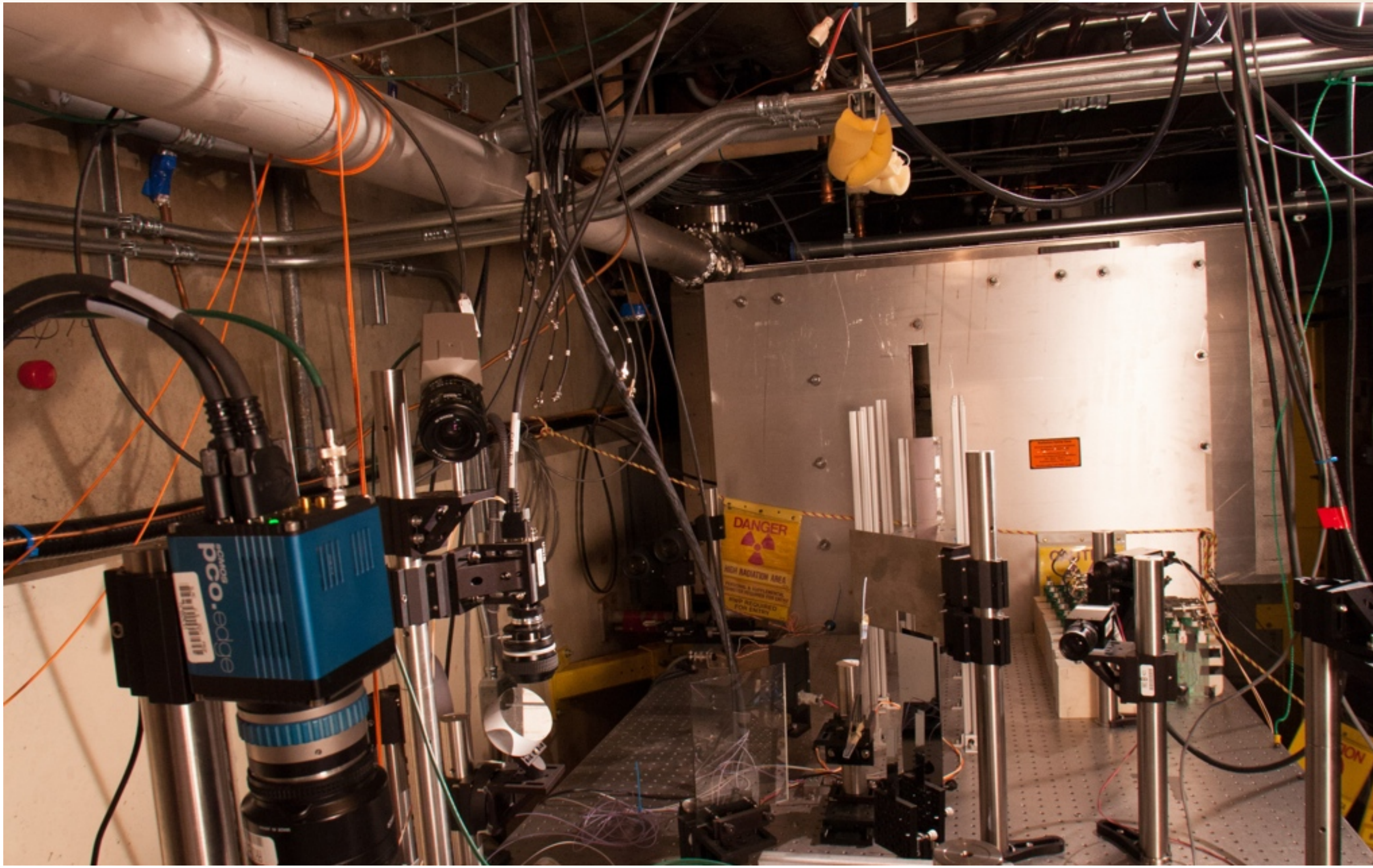


- Imaging spectrometer: 2 quad + spect. dipole
- Cherenkov light produced in air between Si wafers is imaged onto CCD cameras
- two cameras used with overlapping FOV:
  - energy gain camera
  - energy loss camera
- imaging condition set for particular energy (e.g. 20 GeV)
- apertures must be taken into account

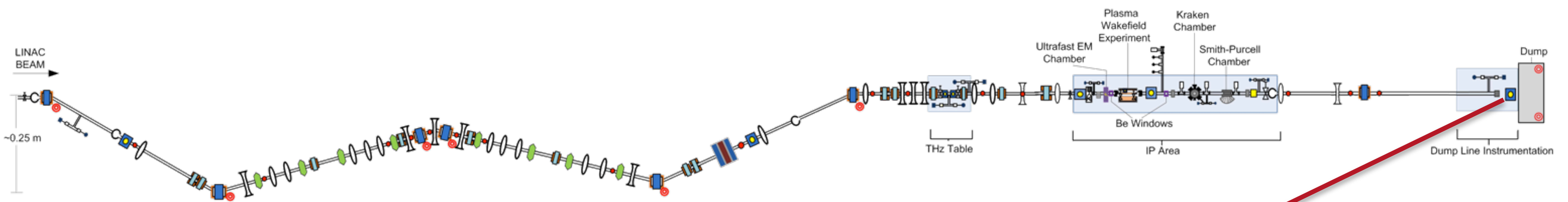




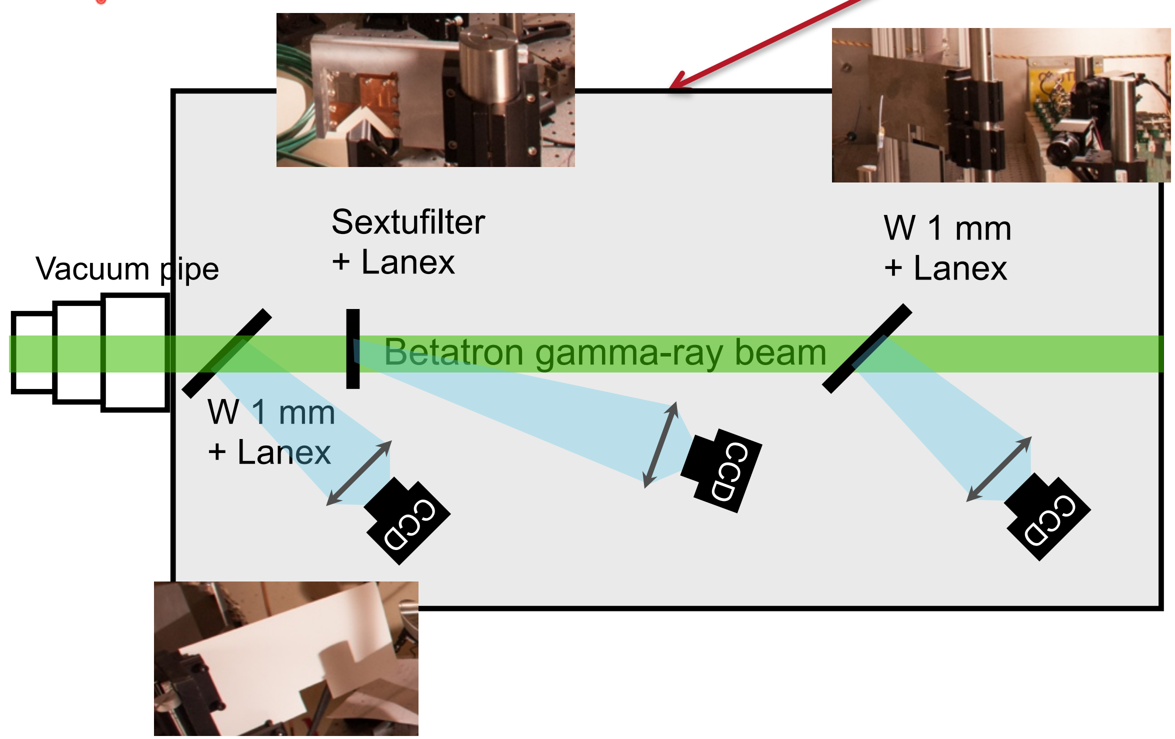
Betatron Radiation Monitor



Gamma-Ray Divergence and Spectrum

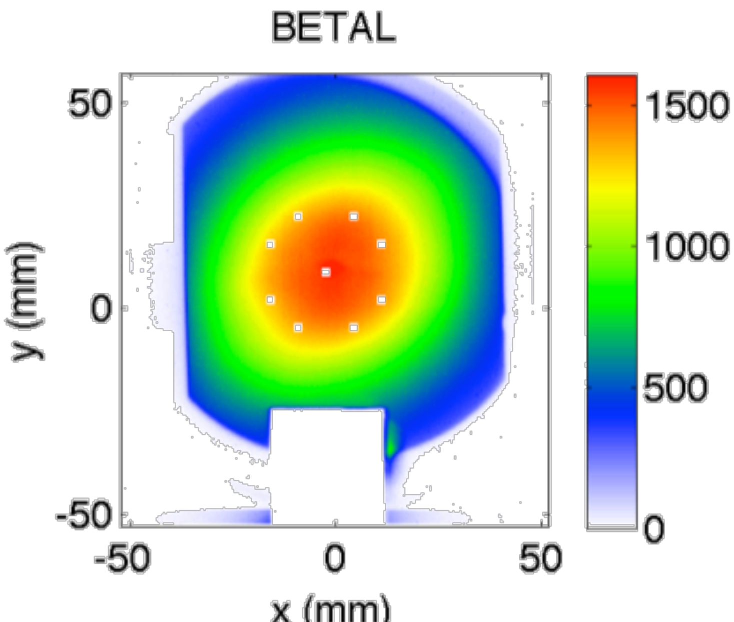


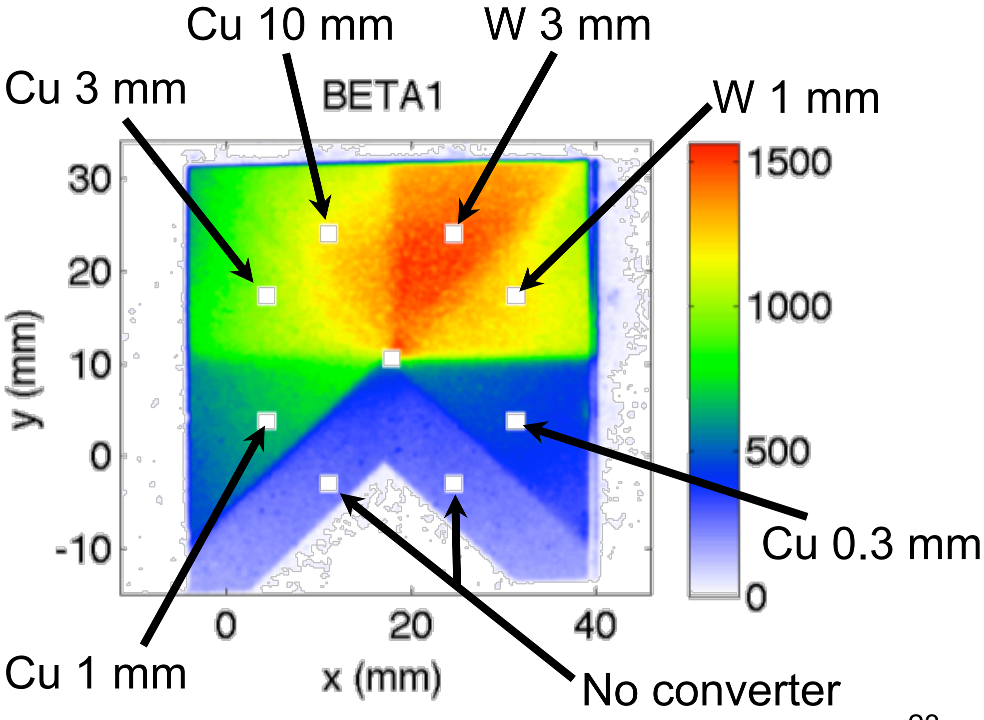
- Transverse focusing forces in plasma cause beam particles to undergo betatron oscillations about axis
- Field strength ~ MT/m
- Gamma-rays emitted with synchrotron-like spectrum
- Critical energy ~ 10 MeV
- Divergence ~ mrad
- 10^{10} – 10^{11} photons per shot
- .1 – 1 J of energy per shot



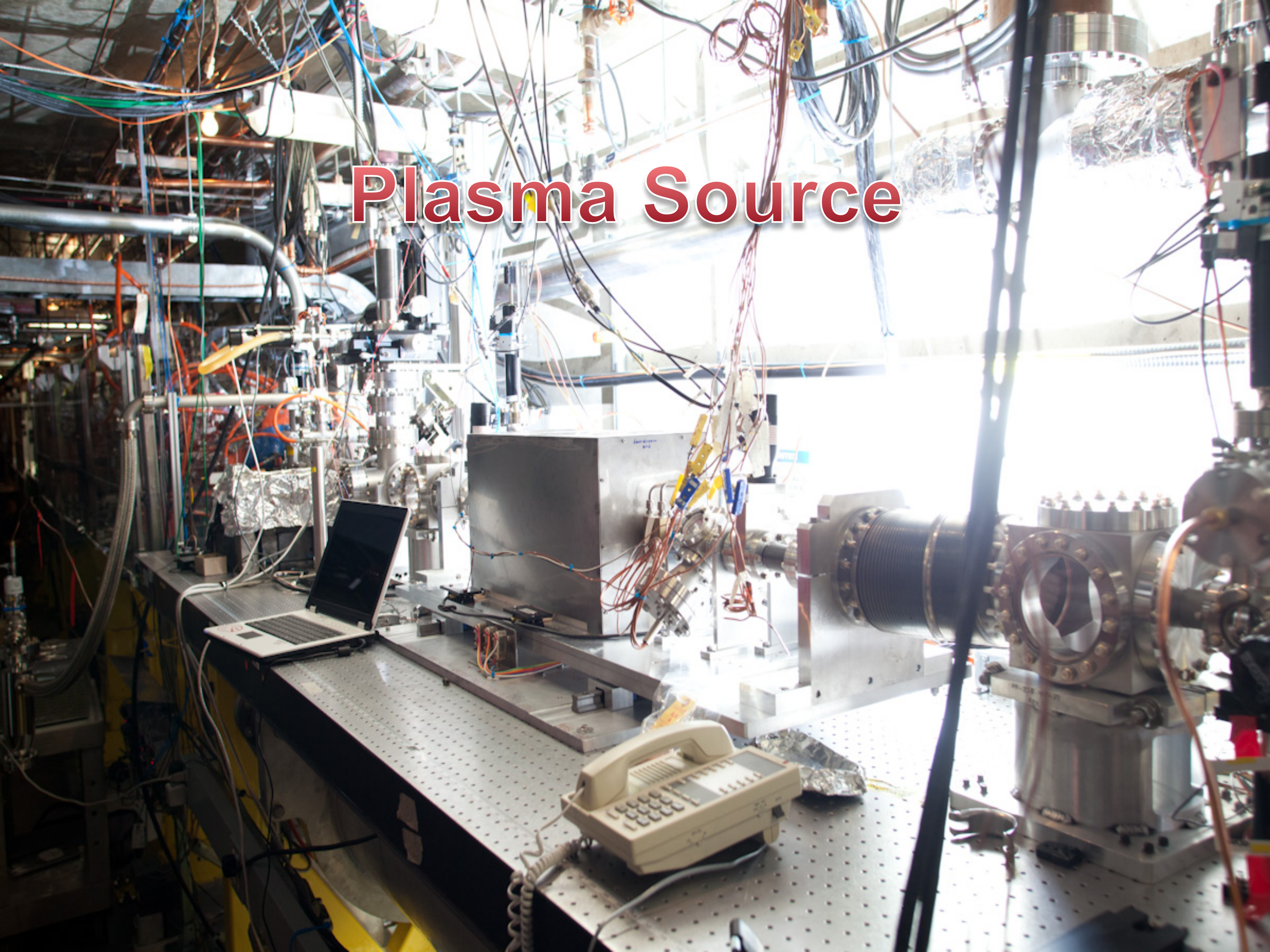
Gamma-Ray Sextufilter

- Assortment of materials and thicknesses to sample the spectrum
- Normalized to no-filter Lanex screen
- Data matched to EGS4 sims to find critical energy



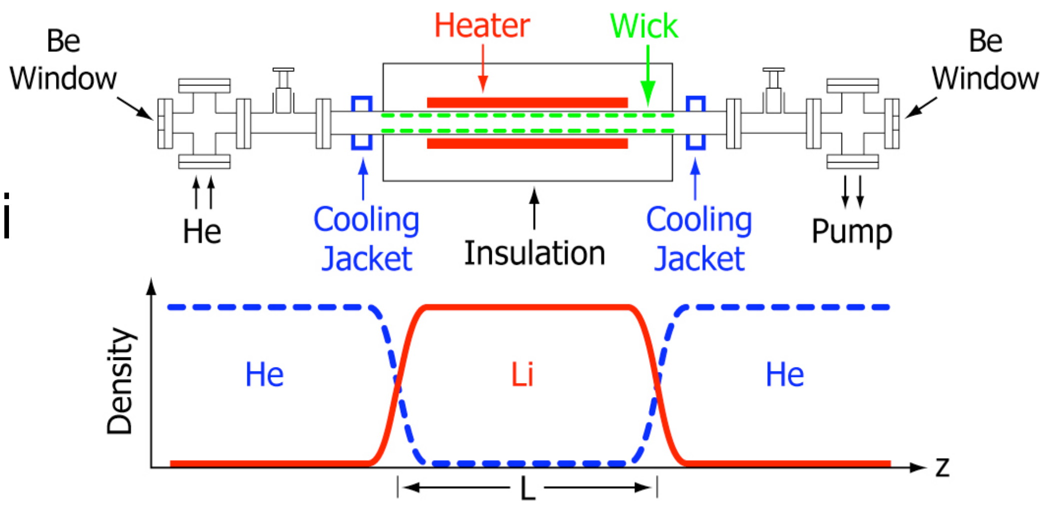


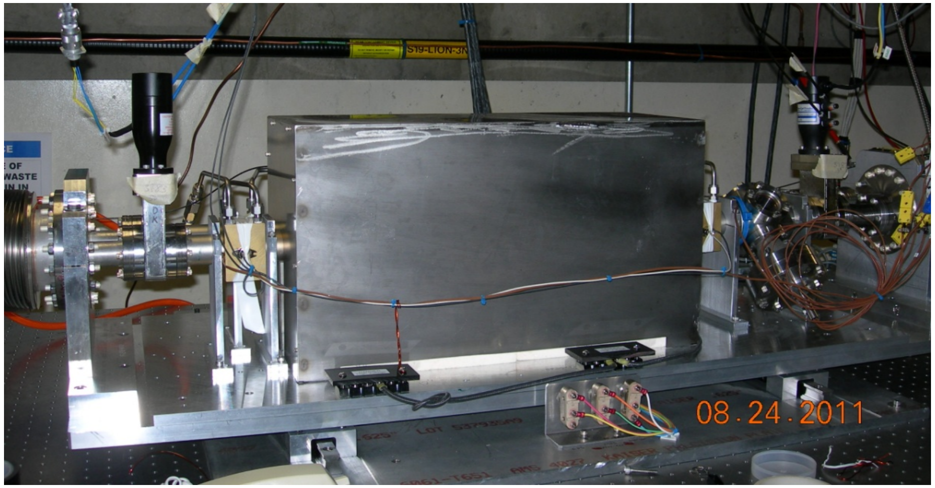
Plasma Source



Plasma Source

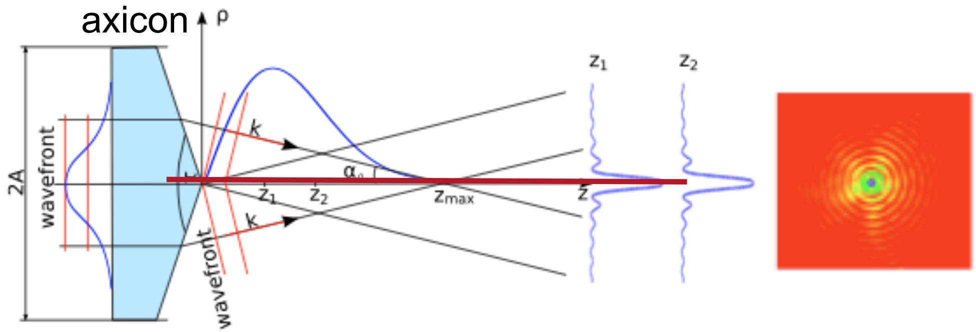
- Need long, uniform, high density plasma
- Heat pipe oven creates Li vapor contained by room temp. noble gas buffer
- Nominal density: $5 \times 10^{16}\ \mathrm{cm}^{-3} \rightarrow \lambda_p = 150\mu\mathrm{m}$
- For 2-bunch beam, field ionized plasma unfeasible
- Need to pre-ionize

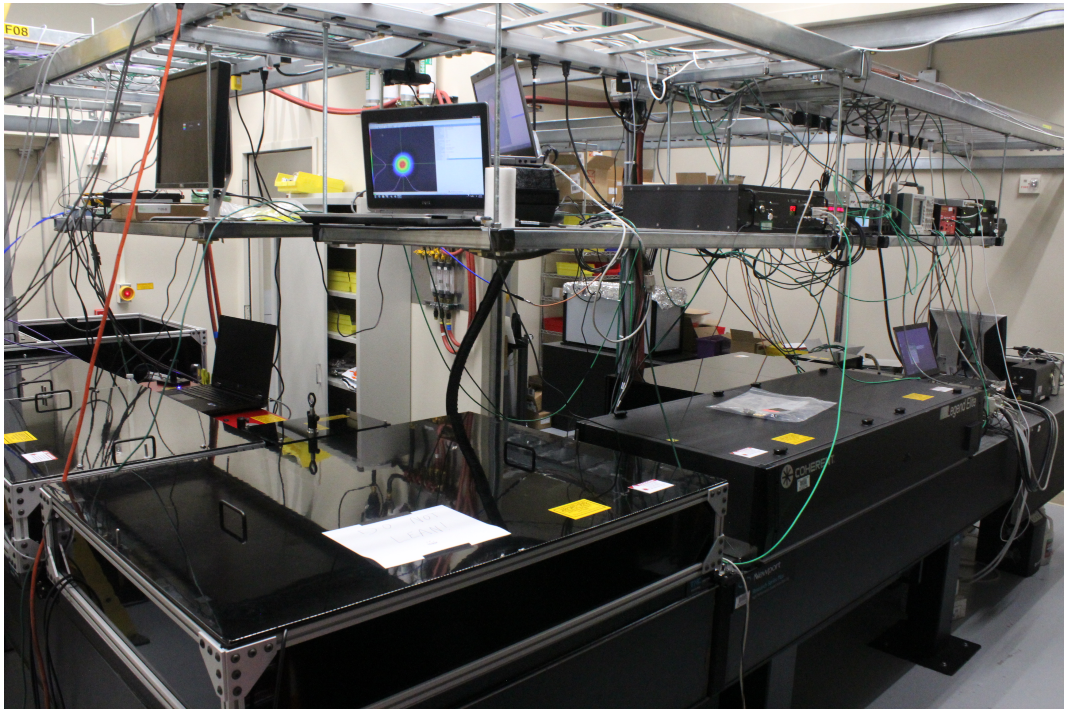




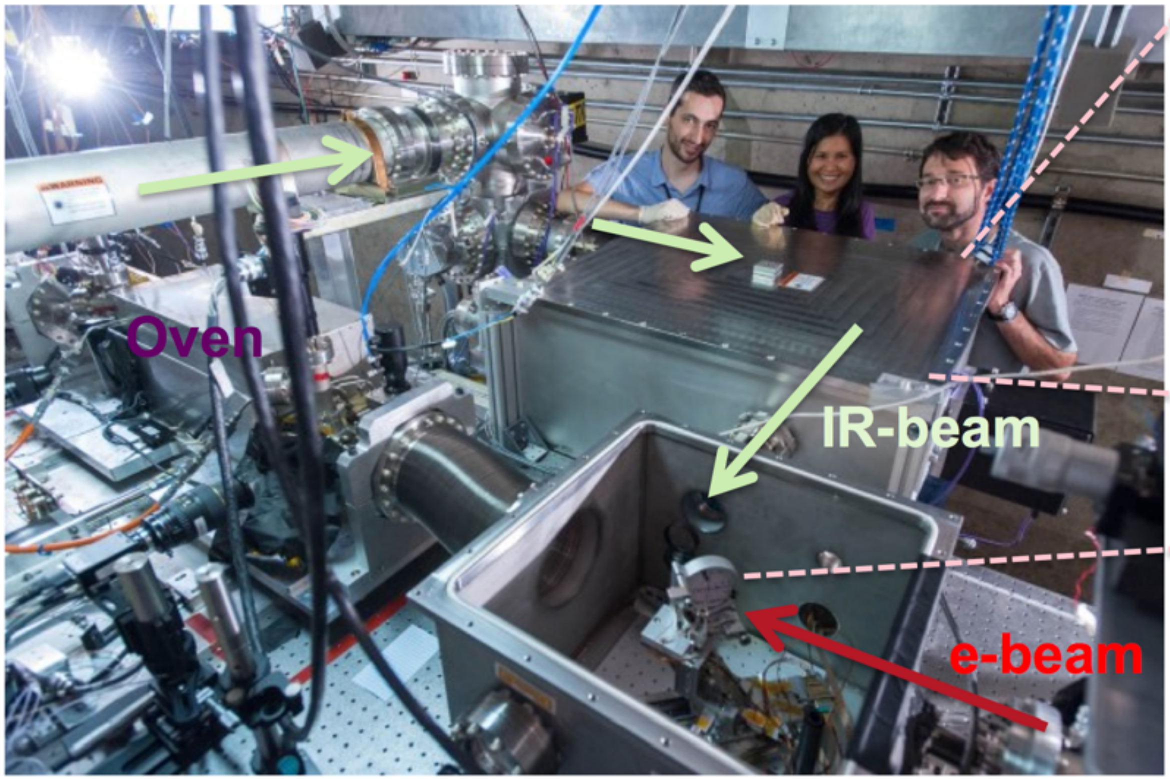
Pre-Formed Plasma Source

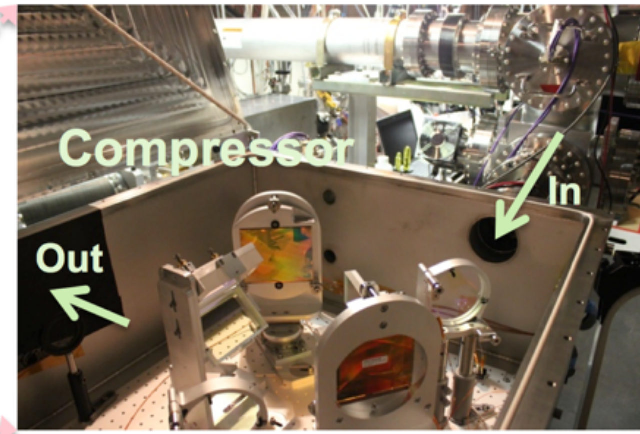
- New 10 TW Ti:Sapphire laser system commissioned and used during 2013 run
- Project start-to-finish: <7 months(!)
- Line focus generated with axicon lens
- O(10^{14} W/cm^2) intensity on axis – 4×10^{12} W/cm^2 needed to ionize Li
- ~36cm plasma formed in Li oven

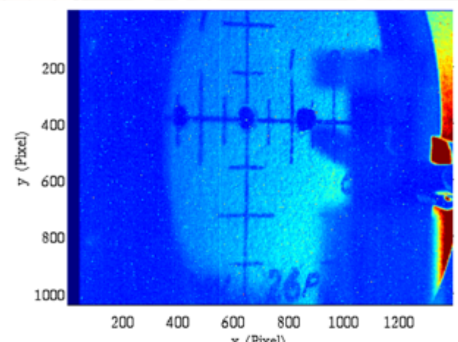




Laser Delivery to Plasma Source

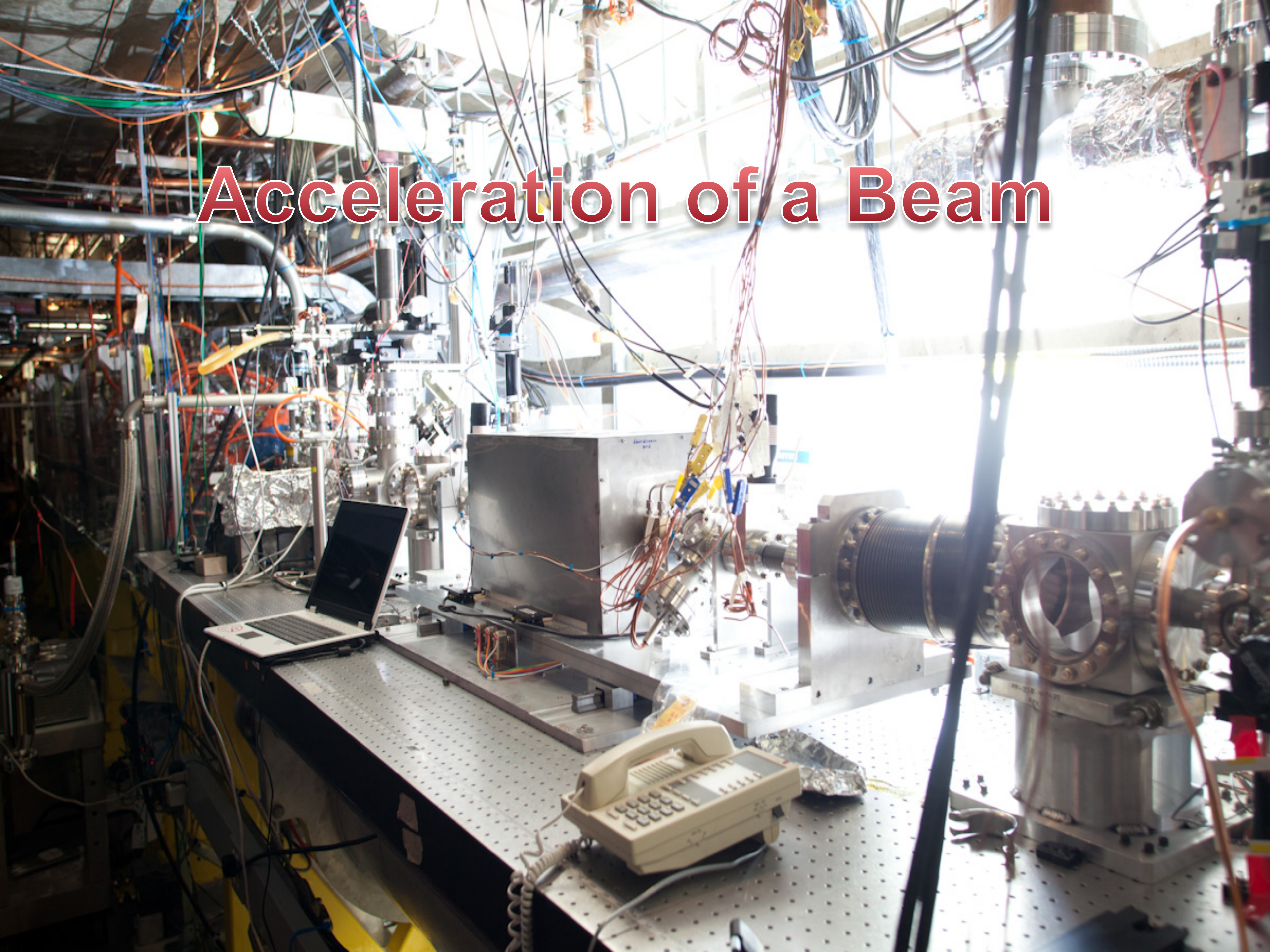






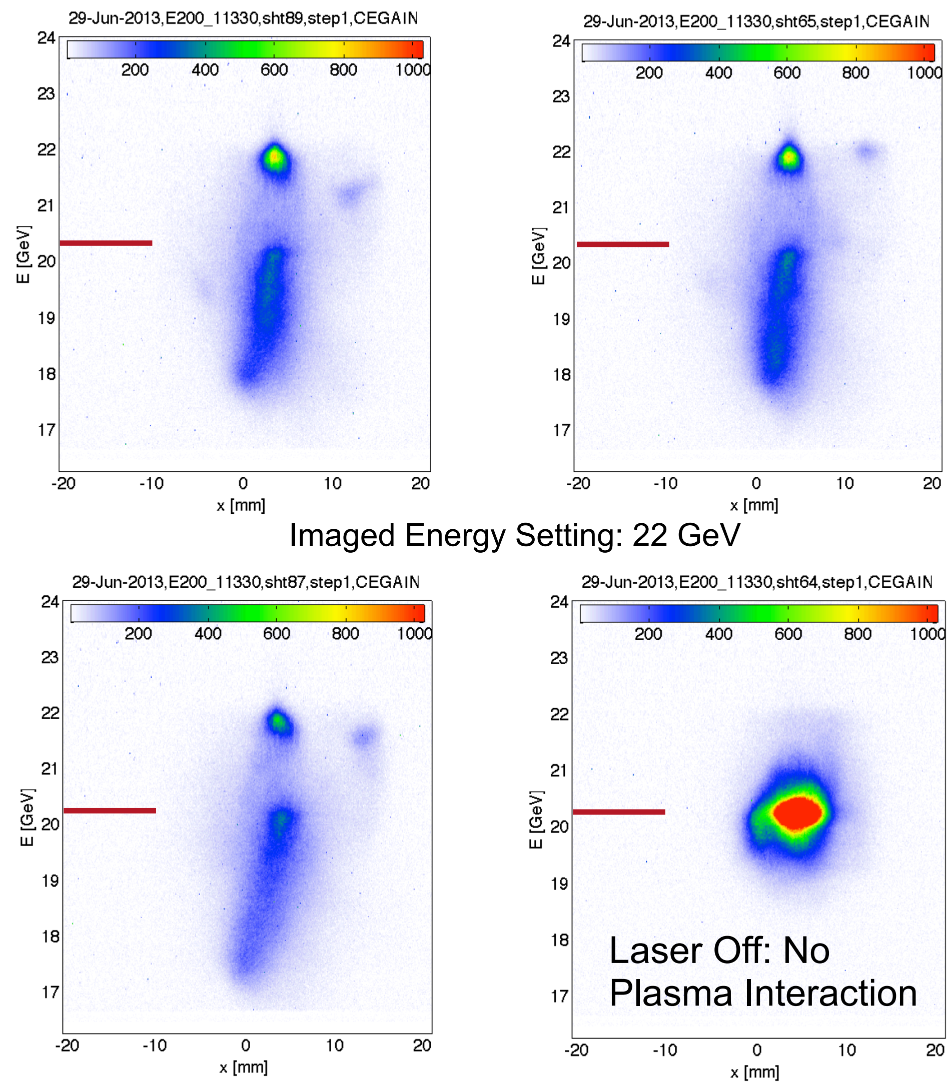
Gold mirror: 6 mm diameter hole

Acceleration of a Beam



Experimental Results

- Final energy of witness bunch: 22 GeV
- ΔE = 2 GeV in 36 cm
- Gradient of ~5 GeV/m
- ≲300 pC accelerated
- Energy spread ~1%
- **First experimental demonstration of acceleration of high energy and high charge witness bunch in a beam-driven plasma wake**

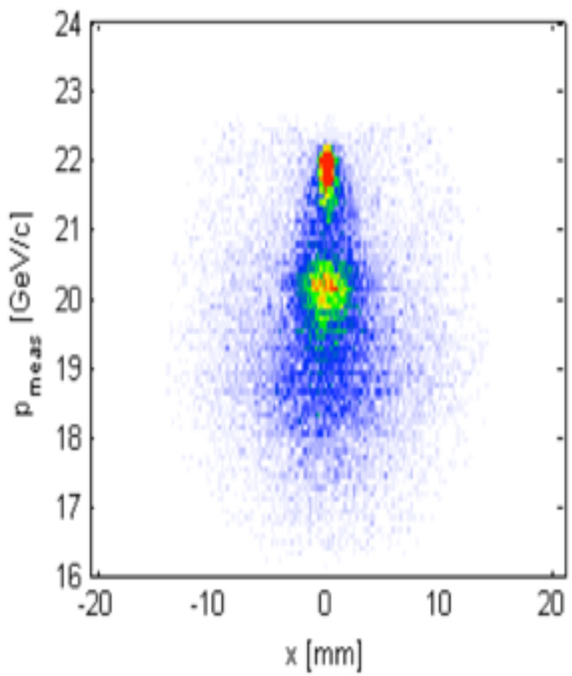


Simulation of Results Using QuickPIC

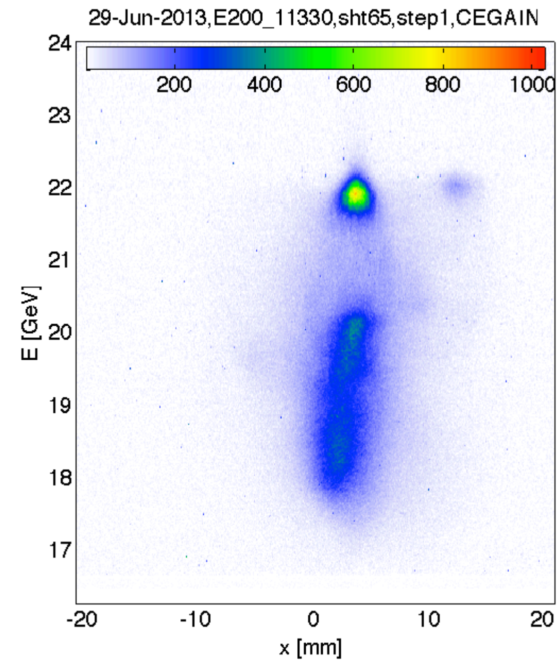
SLAC

- QuickPIC used to simulate PWFA interaction
- Plasma conditions:
  - 5×10^{16} cm^{-3}
  - pre-ionized
  - ramped profile
  - FWHM: 36cm
- Beam conditions:
  - $\beta^* = 10cm \times 100cm$
  - $\sigma = 30\mu m \times 30\mu m$
  - waist within β^* of matching location
  - $\Delta z = 134\mu m$
  - $Q_{drive} = 640$ pC
  - $Q_{witness} = 310$ pC
- Results:
  - final E = 22 GeV
  - average gradient 5.5 GeV/m
  - some charge lost, cut by wake

Simulation



Data

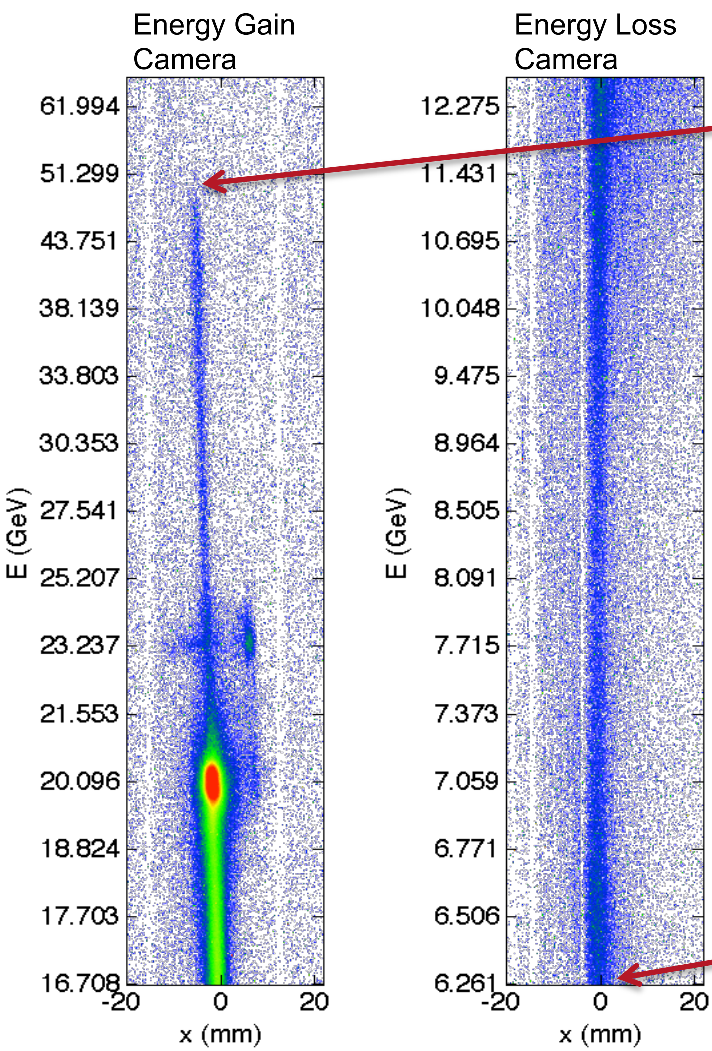


PWFA Stage Experimental Benchmarks

- ✓ High gradient fields
- ✓ Meter-scale propagation
- ✓ Acceleration of a beam
- ❑ Small energy spread
- ❑ Emittance preservation
- ❑ High efficiency


PWFA in a Noble Gas

High Energy Gain in Field-Ionized Argon Gas



Acceleration up to 47 GeV

150 GV/m over 18cm!

Deceleration to below 6 GeV

- ADK: critical E-field must be >6.5 times higher in Ar than Li
- FACET is making some very good beams!
- Process begins with partial ionization
- Focusing in low density plasma allows beam to ionize more gas
- Betatron gamma-rays indicate beam was focused to down 2-3 μm
- Ar pressure for data presented: 20 Torr → density: 7×10^{17} cm^{-3}
- Energy doubling of beam observed: max energy = 47 GeV
- Lots of participating charge, lots of deceleration: min energy < 6 GeV

Future Outlook and Summary

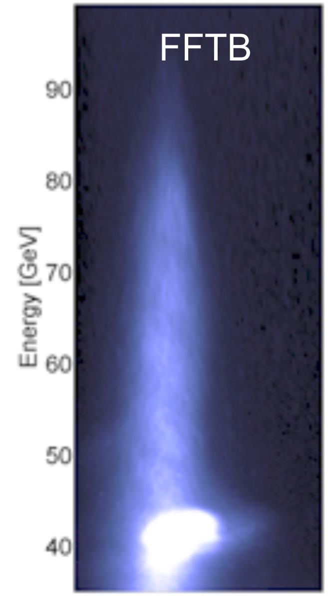
(Near) Future Outlook

- Next run begins Nov. 2014, will continue for ~6 months
- Higher net gain with longer plasma source → up to 1.5m
  - laser upgrade: higher power, cleaner bessel beam
  - longer oven
- Improved diagnostics
  - better resolution of final e-beam spectrum
  - better dynamic range of final e-beam spectrum
- Emittance measurement
  - removal of vacuum window that spoils emittance
  - phosphor screen with 1:1 imaging camera
  - betatron radiation divergence and spectral measurements
- Beam loading studies
  - systematic scans of $Q_{witness}$ and n_p

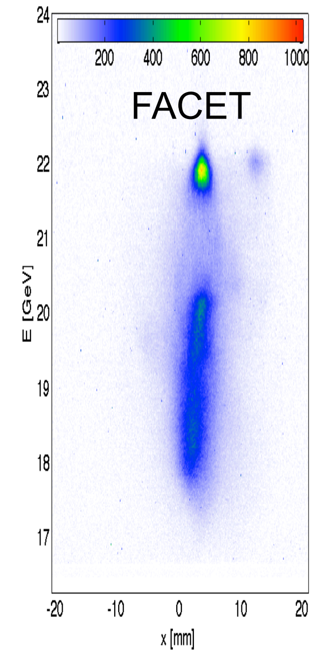
Summary

- **FACET has demonstrated beam-driven PWFA of a high-energy, high charge witness beam for the first time ever**
- 20 GeV, 3.2 nC bunch dispersed and chopped into two bunches
- Plasma source pre-ionized using new 10 TW laser system
- Up to 300 pC accelerated by 2 GeV
- 5 GV/m achieved over 36cm
- Good agreement with simulations
- Energy doubling in self-ionized Ar
- Future experiments will have higher net energy gain, improved diagnostics, and more systematic studies of PWFA physics

From this…



To this…



“particle acceleration” →
“beam acceleration”

Thank you!