Electron Beam Driven Plasma Accelerators & First FACET Results

EAAC 2013

Mark Hogan June 4, 2013

U.S. DEPARTMENT OF ENERGY

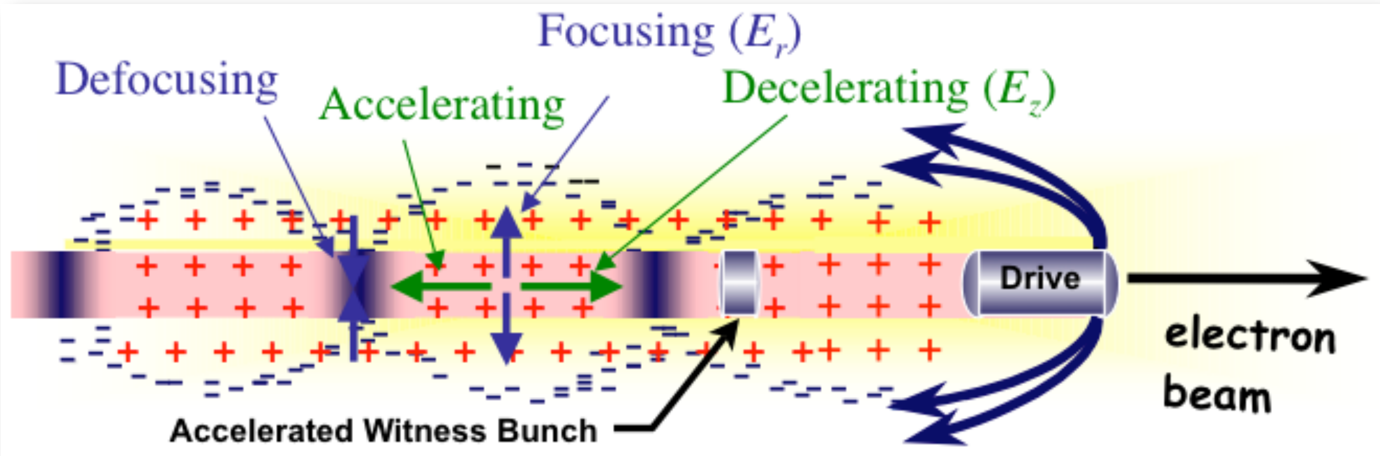
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

A Beam Driven Plasma Wakefield Accelerator

A very high frequency structure acting as an energy transformer

- Accelerating structure is created anew every shot
- High gradients need high density plasmas
  - ~10^{17} e^-/cm^3
  - >10GeV/m acceleration
  - >MT/m focusing



For wake excitation need a beam matched to plasma dimensions:

•Individual bunches, or a bunch train, 100's fs apart (or use SMI for long bunches)

•Individual bunches small in all three dimensions

- High bunch charge for blow-out with large wake amplitude & good transport

•Need long, uniform high-density plasmas

Several Facilities and Groups Are Ramping-up Efforts

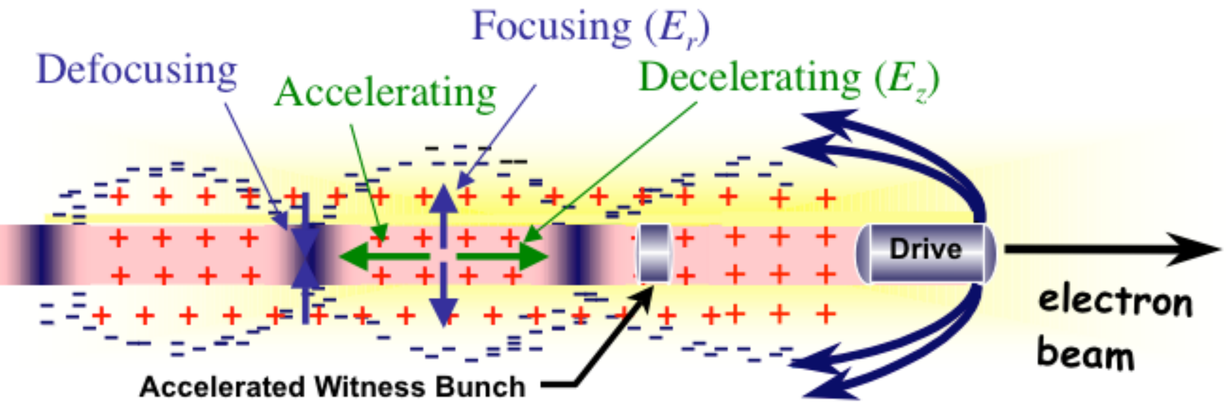
- BNL
  - Use masking technique to create bunch trains or tailored current profiles
  - Low peak current, beam density
    - Combine bunch trains with capillary and study resonant excitation
  - New round preparing to look at low charge mode for quasi-nonlinear regime
- SPARC
  - Pulse train (comb) onto photocathode
  - Control beam dynamics to recover time structure in electron bunch train
  - Will combine with plasma source for experiments in the next few years
- DESY 'Flash Forward'
  - Dedicated beamline to use FLASH-II beam for LWFA/PWFA hybrid experiments

FACET Has a Multi-year Program to Study PWFA

- Demonstrate a single-stage high-energy plasma accelerator for electrons
- Meter scale, high gradient, preserved emittance, low energy spread, and high efficiency
  - Commission beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)

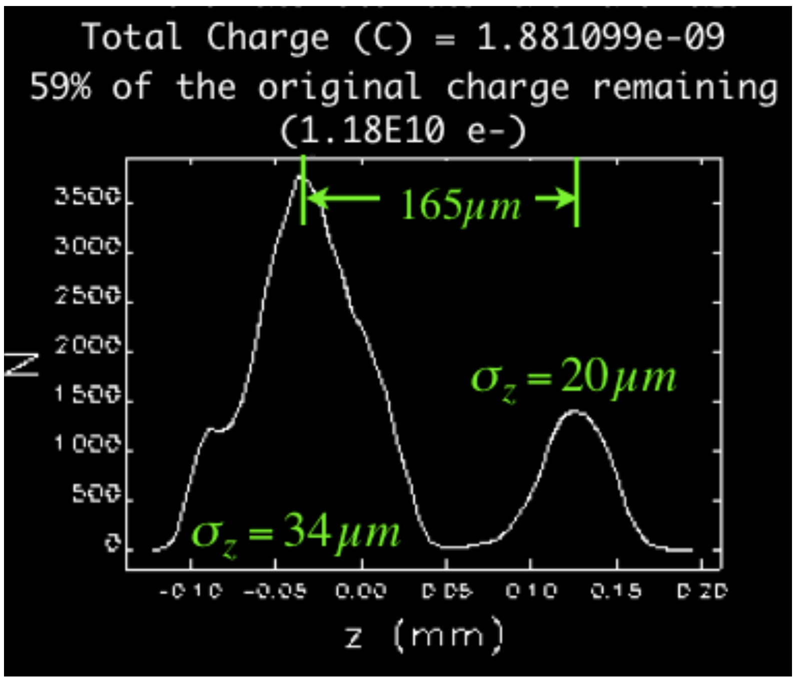
Primary Scientific Goal of FACET: Demonstrate a Single Stage Plasma Accelerator for Electrons

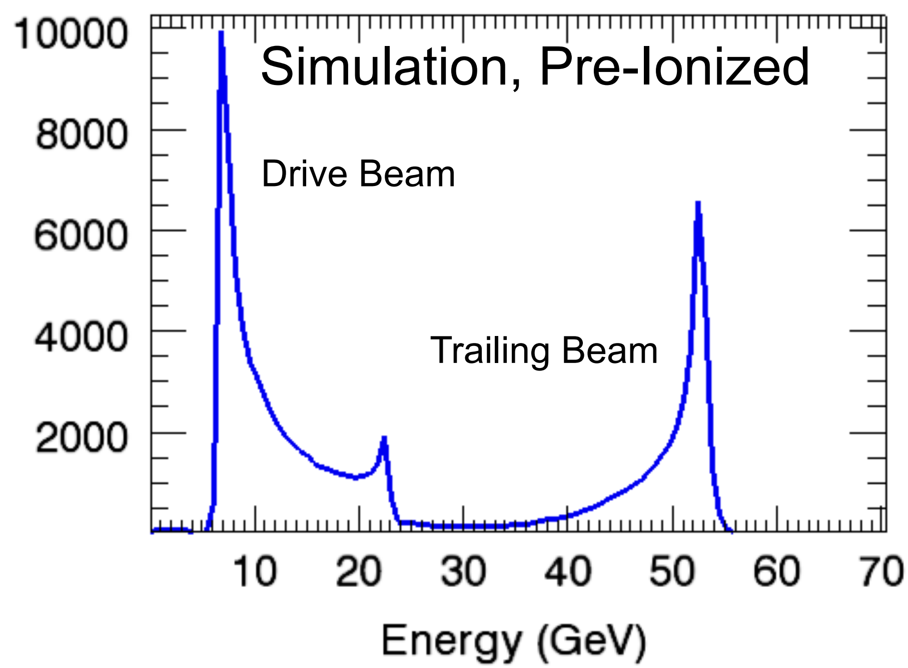
E200: Collaboration between SLAC/UCLA



After 143 cm of 5 x 10^16 plasma

- Energy Gain 30 GeV
- Energy Spread ~ 5%
- Energy Loss 17 GeV, Beam loading efficiency 64%

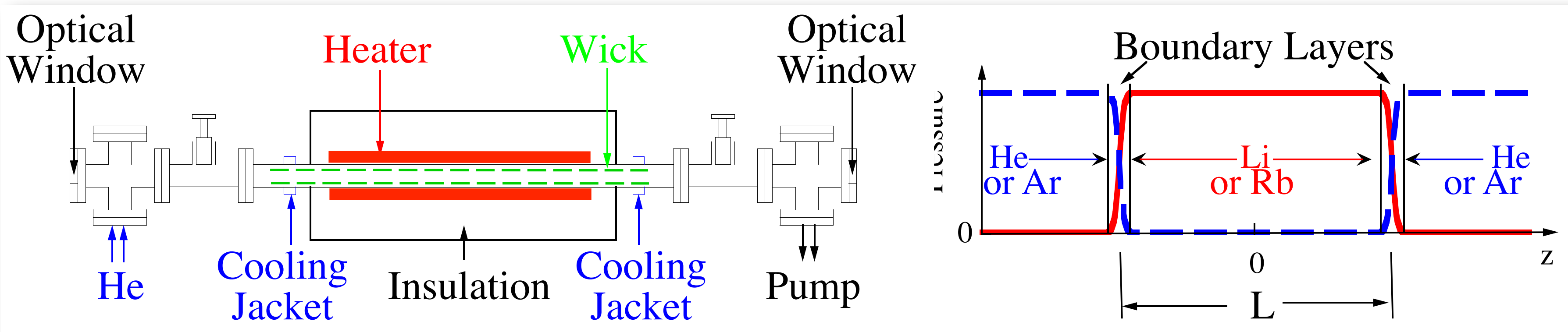




Singly ionized Rb plasma is created by the electric field of the beam. Betatron pinches further ionize Ar and Rb+

UCLA SLAC

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



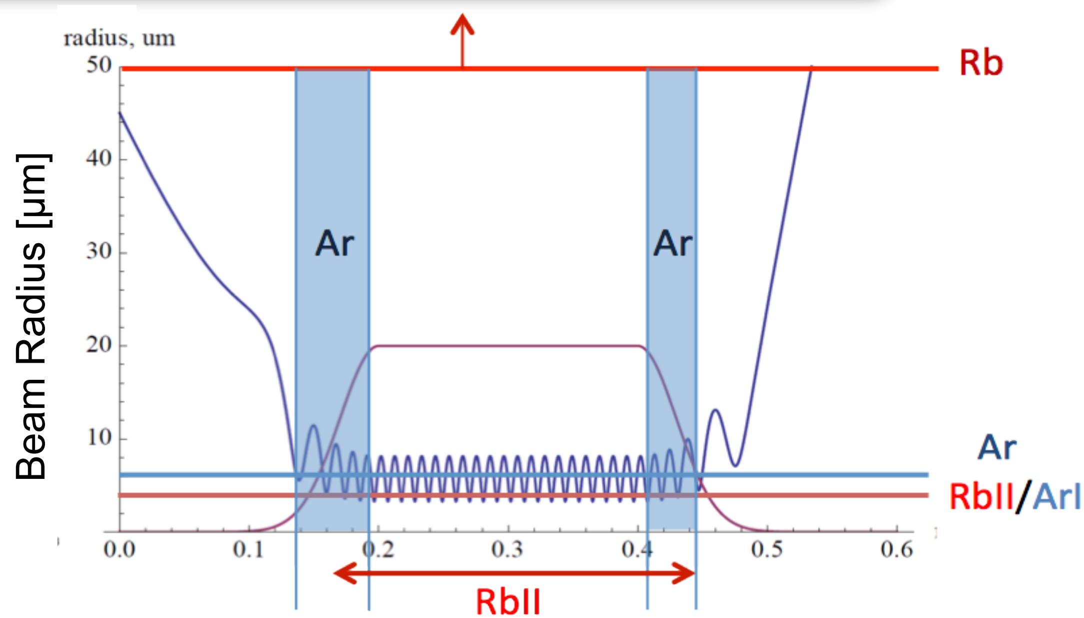
Peak Field For A Gaussian Bunch:

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

Ionization Rate for Li:

$$W_{Li}[s^{-1}] \approx \frac{3.60x10^{21}}{E^{2.18}[GV/m]} \exp\left(\frac{-85.5.}{E[GV/m]}\right)$$

See D. Bruhwiler et al, Physics of Plasmas 2003



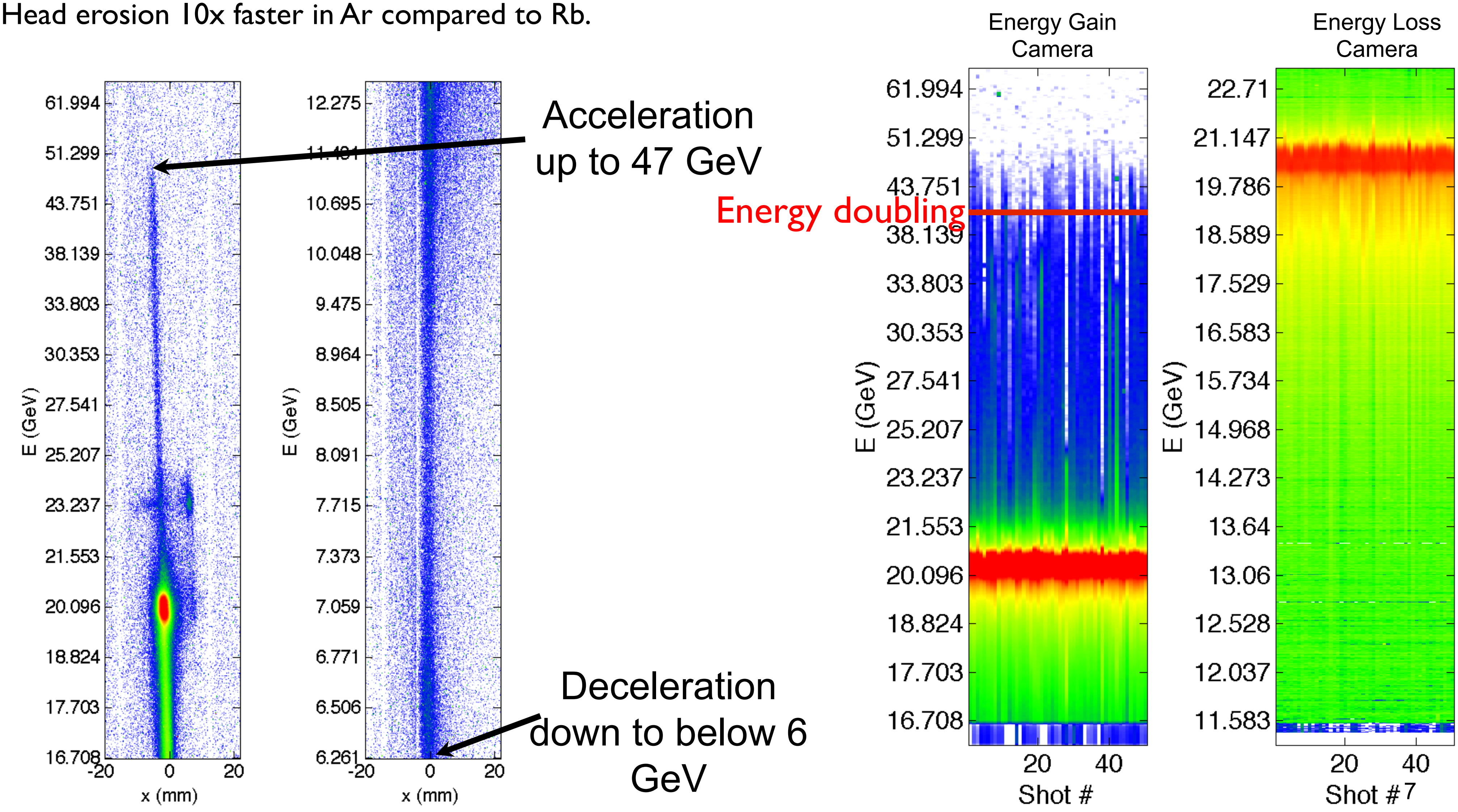
...but can suffer from Head Erosion

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

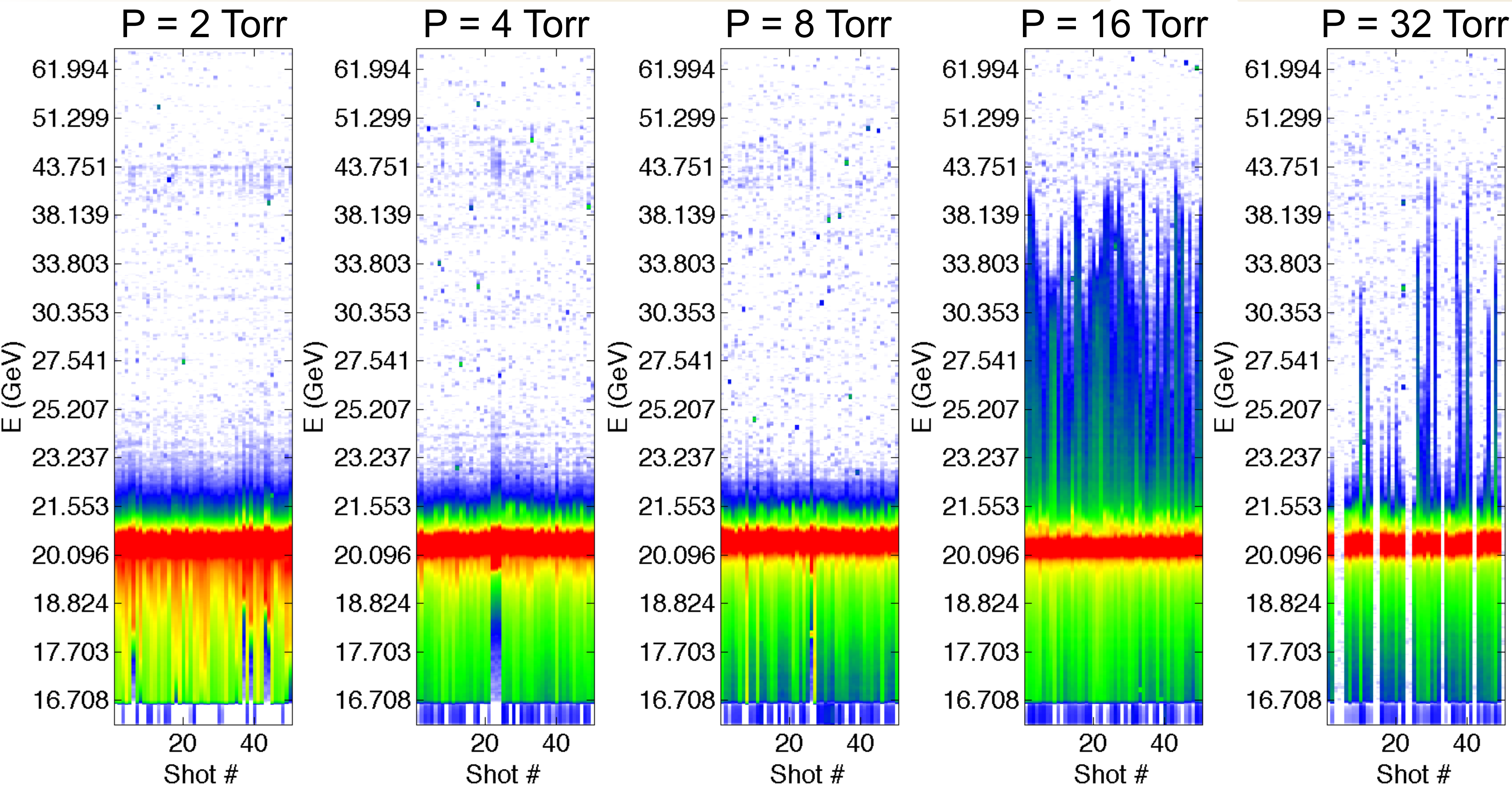
Study beam loading & Ionization injection from secondary ionization

Plasma acceleration in Argon

Impressive results in Argon gas at P ~ 20 Torr:
- The Facet electron beam was able to consistently field-ionize Ar (ionization potential = 15.8 eV).
- More than Energy Doubling in Ar! Acceleration from 20 GeV to ~47 GeV.
- Head erosion 10x faster in Ar compared to Rb.



Plasma acceleration in Argon



Many other studies revealed interesting behaviors:

- Waist dependance of beam-plasma interaction.
- Scan over beta functions.
- Use of various emittance spoiler foils.
- etc.

Beam-plasma interaction in Helium

Results in Helium gas:

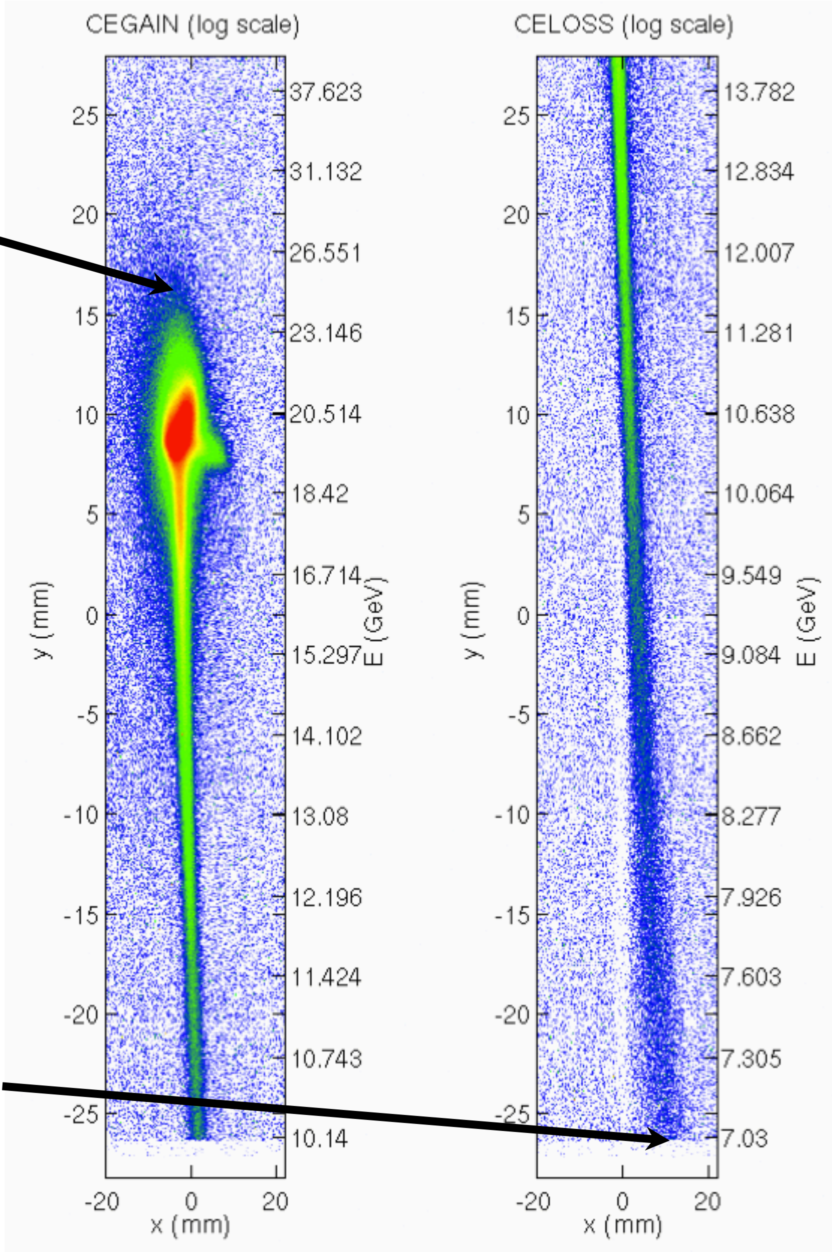
- The Facet electron beam was also able to consistently field-ionize He (ionization potential = 24.6 eV)!

- More than 90% of energy loss in He. Deceleration from 20.35 GeV to below 2.5 GeV.

- Head erosion 25x faster in He compared to Rb.

Very weak acceleration

Very strong deceleration



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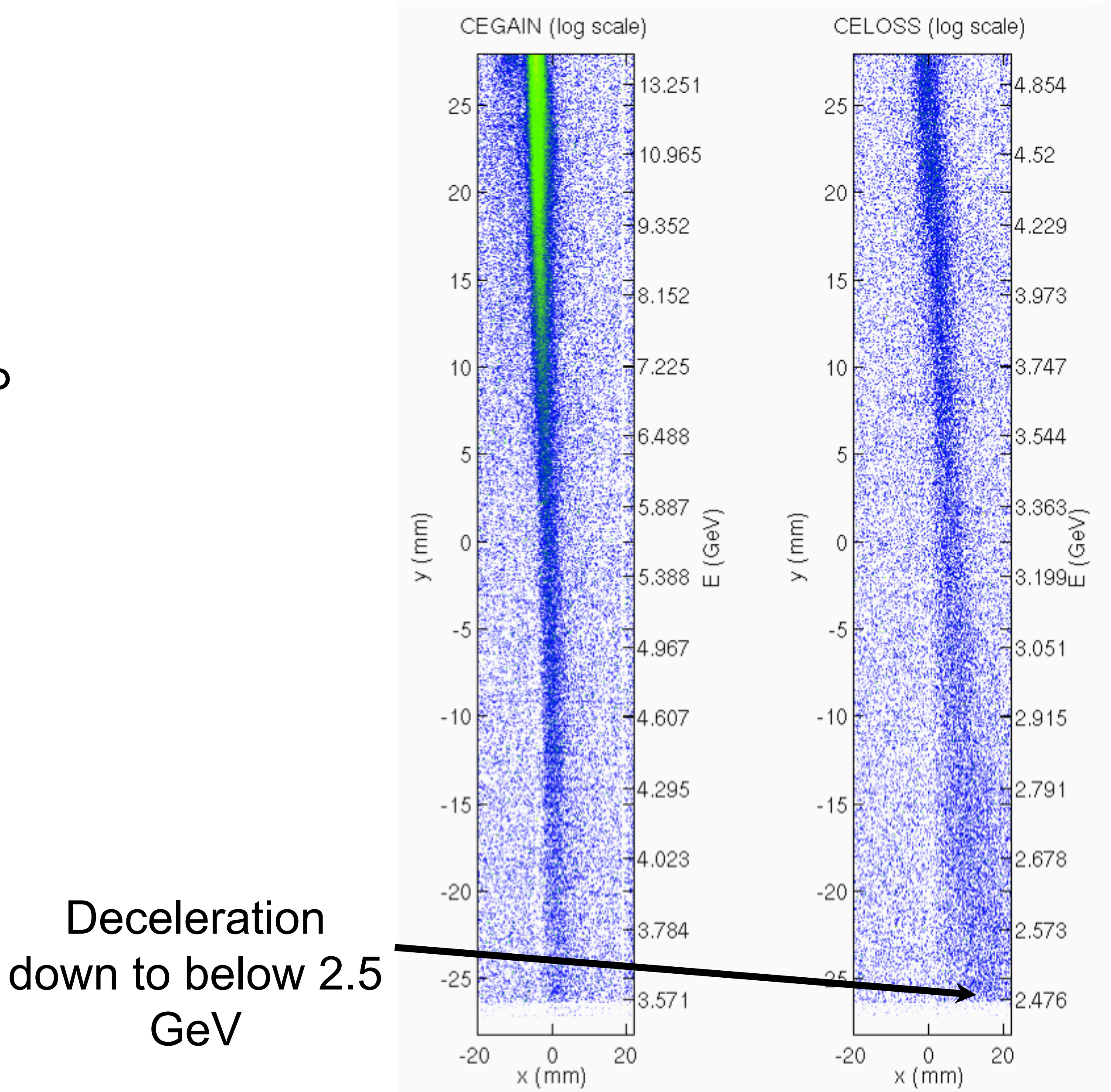


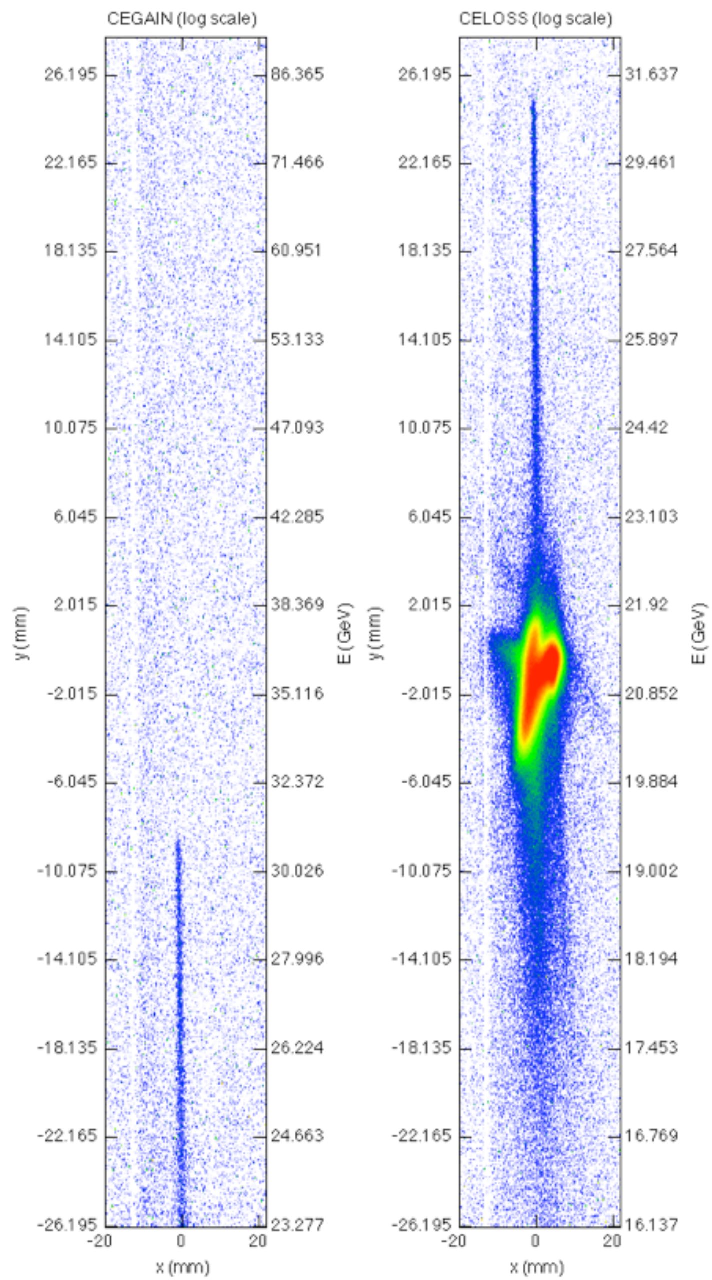
Energy gain suppression and recovery

UCLA SLAC

Ar 50%, He 50%P = 32 Torr

> 10 GeV energy gain

- No energy gain in pure He
- Energy gain recovered when partial pressure Ar back to 16 Torr

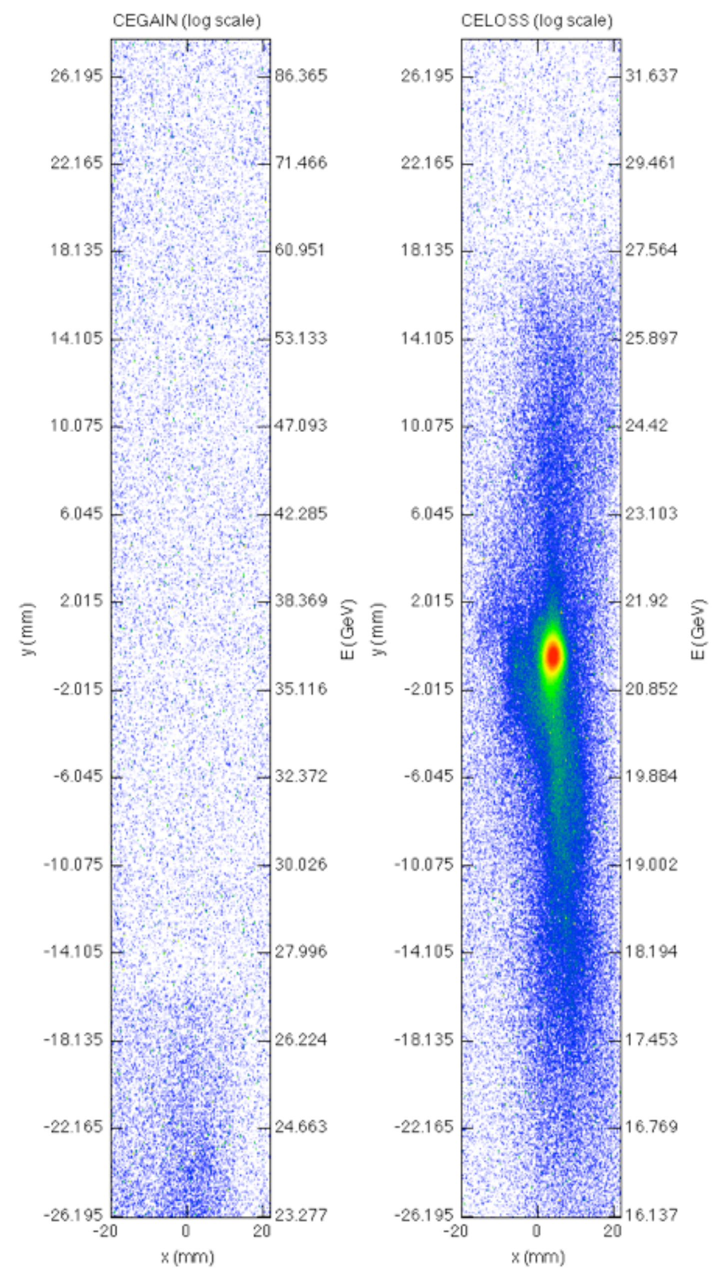


Energy gain suppression with multiple plasma densities

Li ovenP = 32 Torr

Energy gain strongly suppressed

- Peak beam density is very high!
- Ar/He ionization in addition to Li ionization
  - Multiple plasma species, densities give dephasing



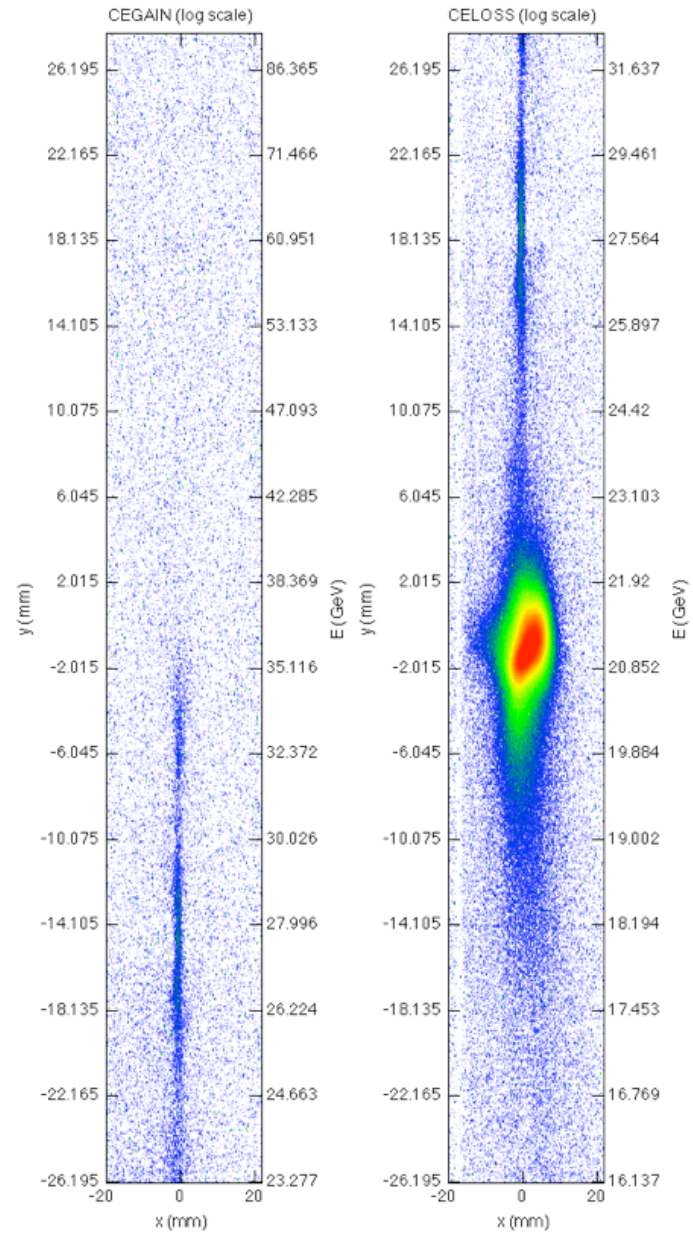
Energy gain recovered!

Li ovenP = 32 Torr

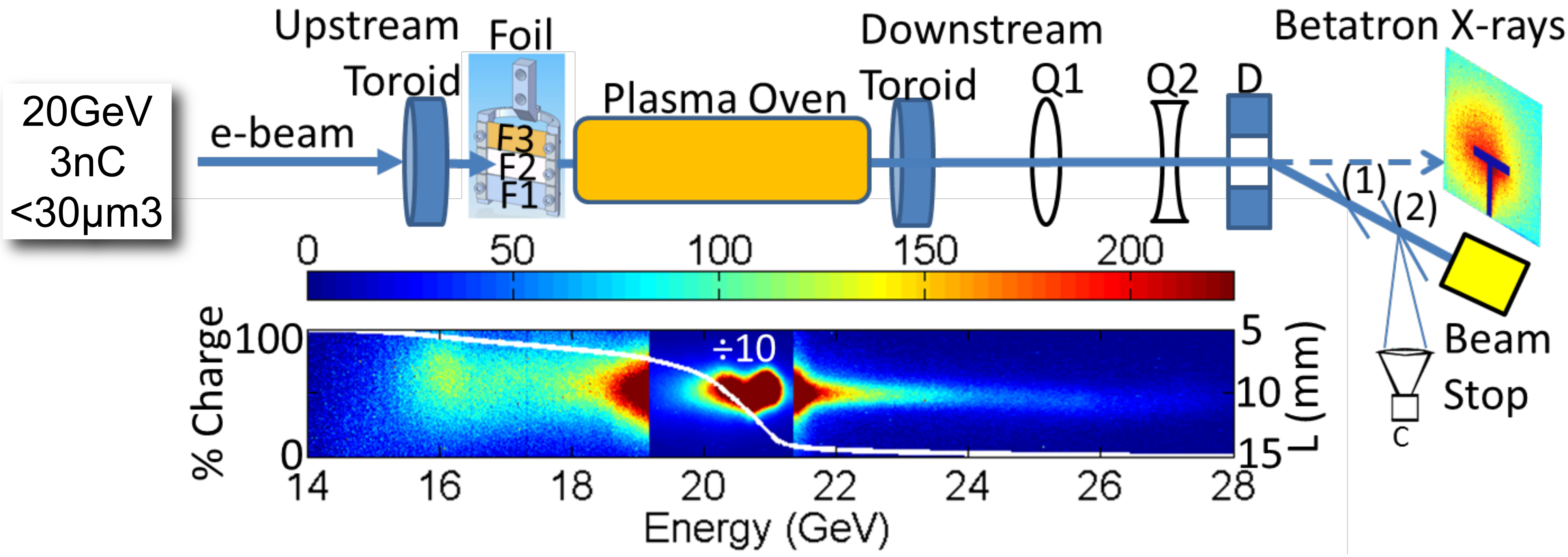
15 GeV energy gain

- Almost energy doubling

Ar/He ionization disabled (Emittance Spoiler Foil In) by limiting peak beam density



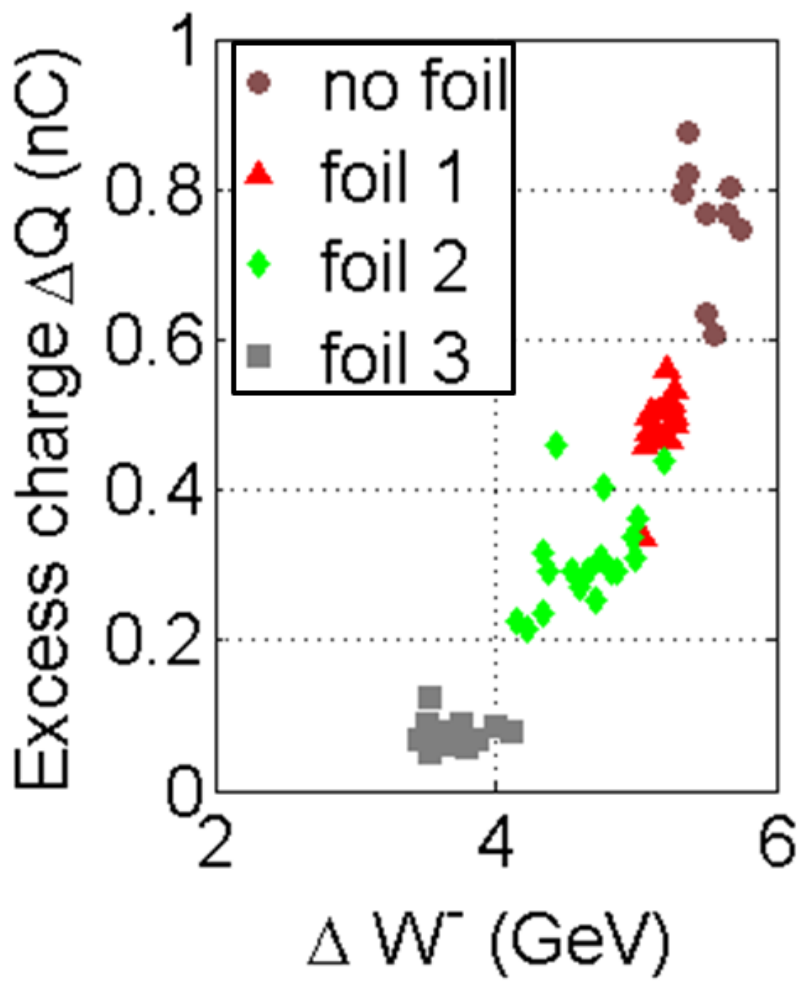
Experimental Set-up



- Secondary ionization depends on maximum beam density
- Foils of different thickness and composition used to increase the beam emittance and limit secondary ionization
- We measure how the distributed injection of this dark current loads the wake and reduces the transformer ratio T = E+/E-

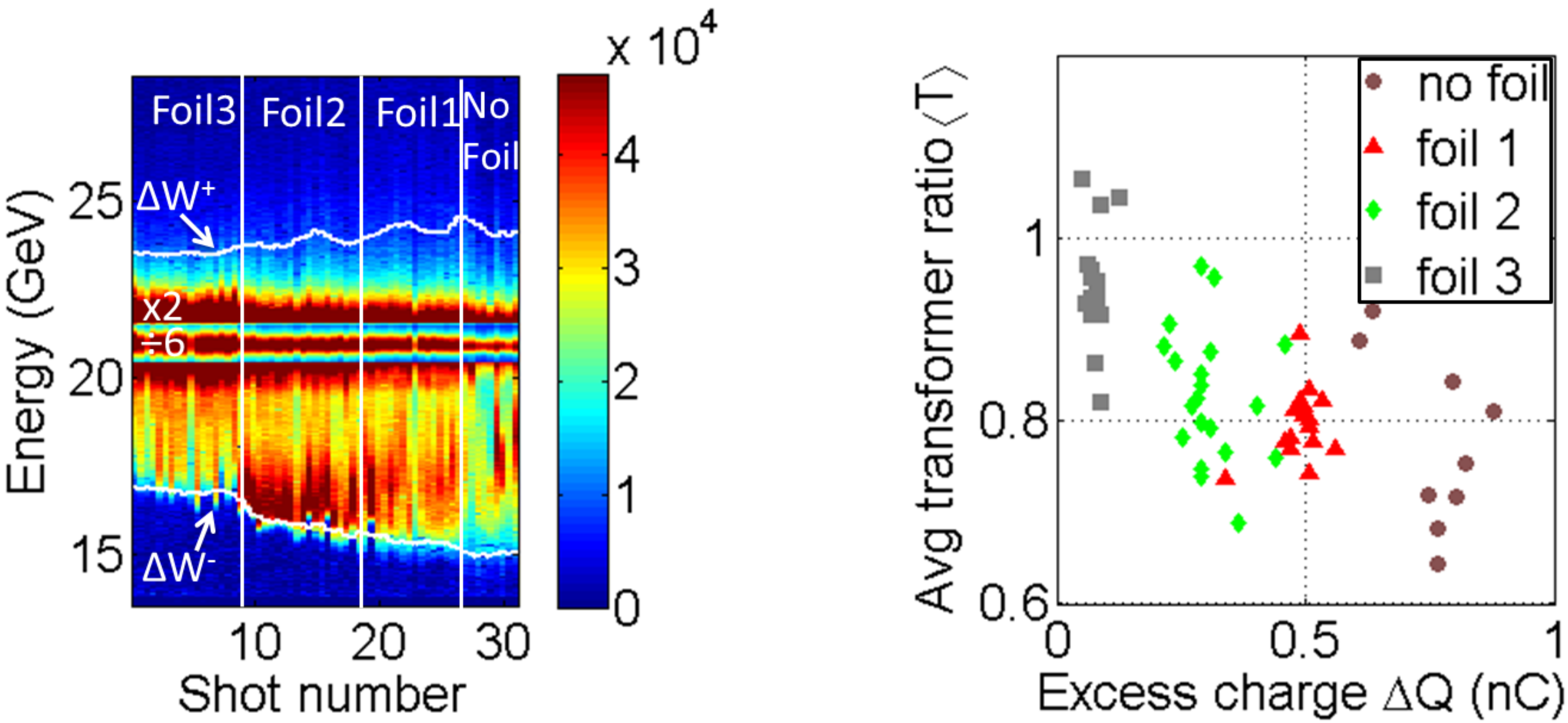
Emittance of the beam used to vary length of the wake (head erosion) and thereby vary energy loss

- As the length increases so does the number of envelope oscillations the beam makes.
- Each time the beam pinches down to a minimum it produces additional Rb 2+
- These new electrons (excess charge) are injected into the wake



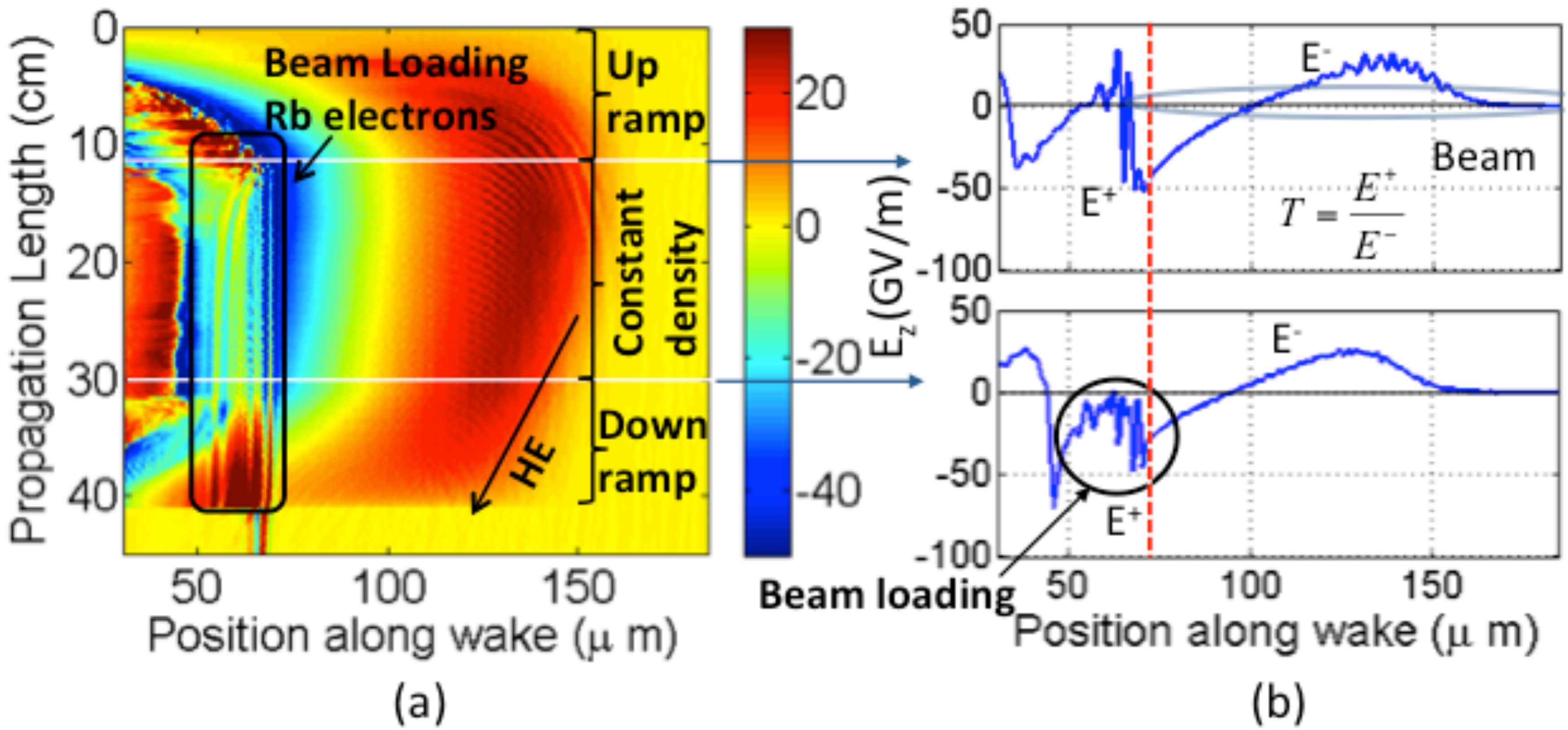
The Resulting Beam Loading reduces Transformer ratio

Transformer Ratio <T> = E+/E- = ΔW+/ΔW-



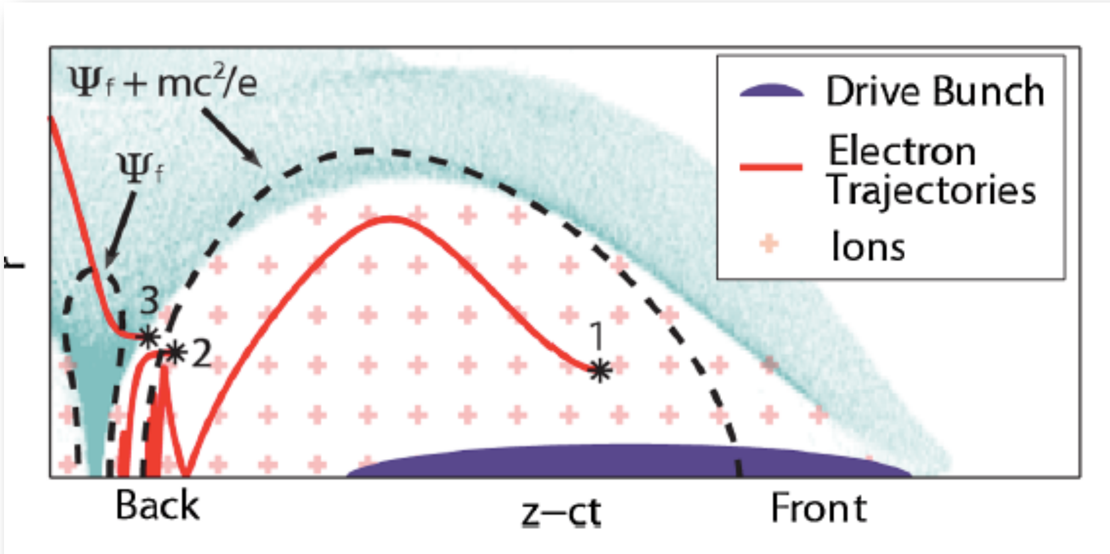
PIC Simulations Confirm that Beam Loading by Distributed Injection of Rb 2+ Electrons and Reduced T

- Peak Accelerating field decreases from 44 GeV/m to 35 GeV/m due to beam loading
- Transformer ratio decreases from 1 to 0.85

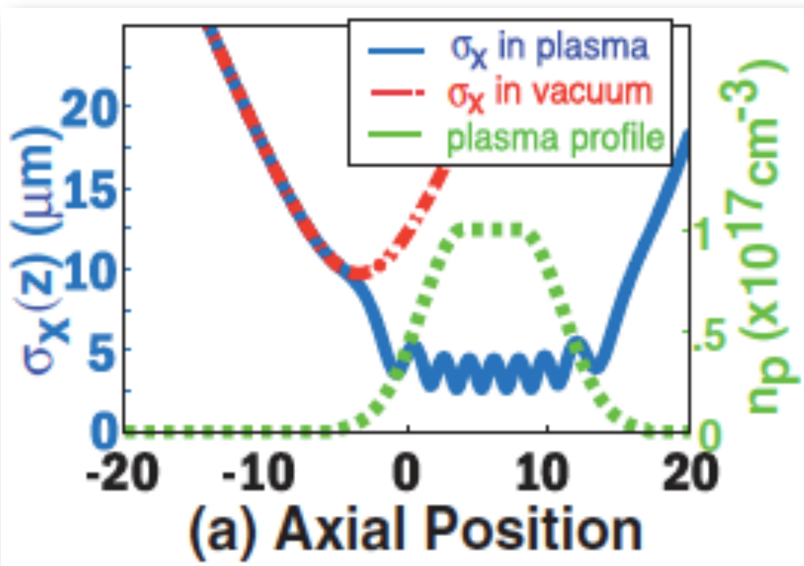


Can we use ionization injection in a controlled manner to get narrow energy spread beams?!

Concept for controlled ionization injection



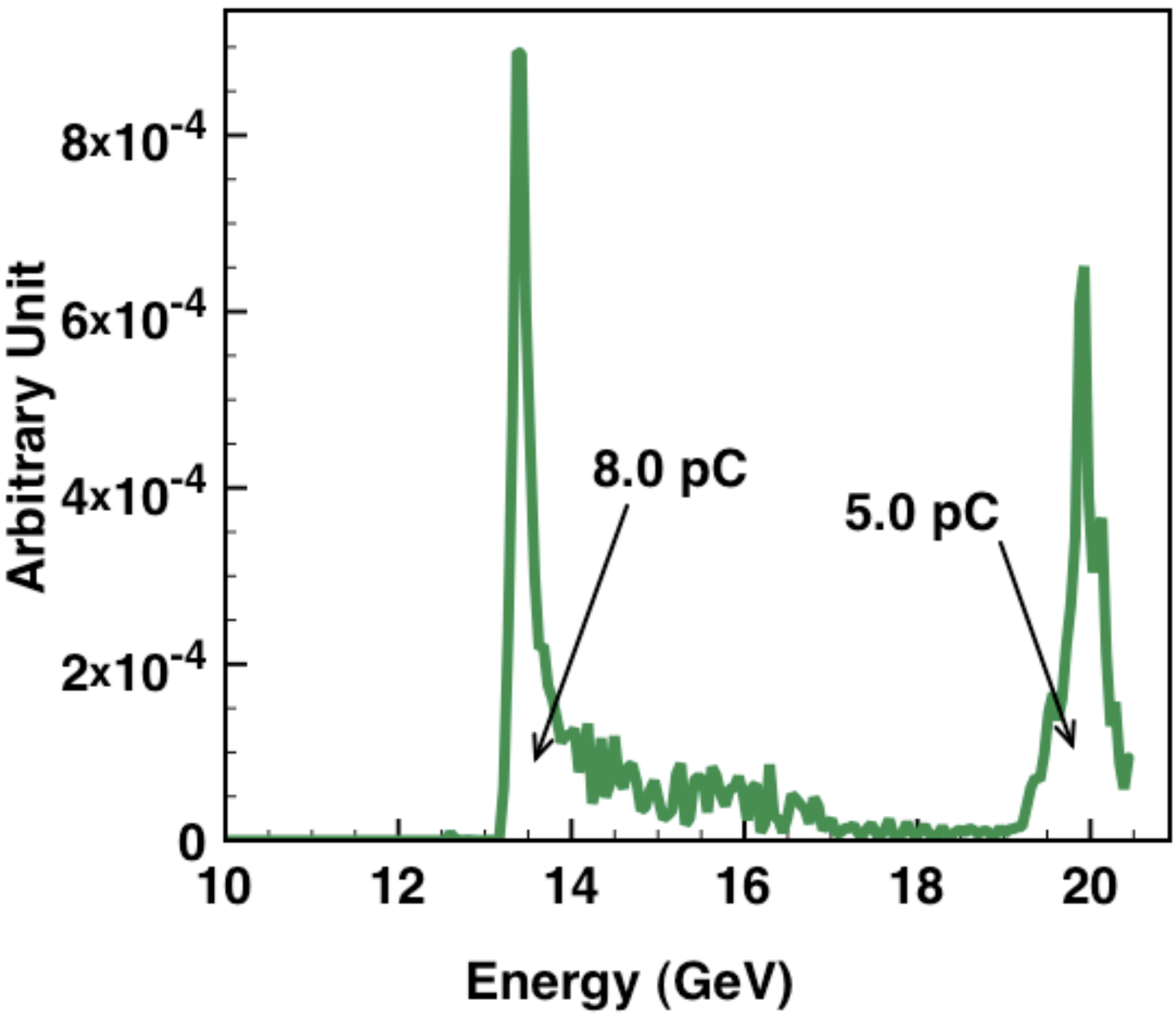
General concept of Ionization Injection into a PWFA



Use Li plasma (not Rb) to ensure no dark current (Li 2+ >70eV)

Use variable percentage He:Ar mix as buffer to control quantity of ionization-injection trapped charge

Simulations Show Monoenergetic Bunchlets with ~1% Energy spread



Mono-energietic bunchlets produced by ionization injection

energy

- Preliminary results are very encouraging!
- Preliminary analysis suggests mean charge of 30pC, dE/E few % and success rate of trapping about 80%
- Bunchlets often have transverse displacement as well
- Going forward we are working to improve control, stability and instrument resolution

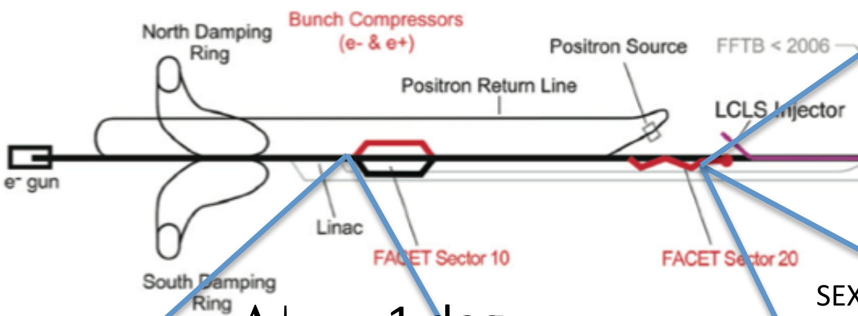
Mono-energietic bunchlets produced by ionization injection

Preliminary: two weeks old!

Hosing Studies

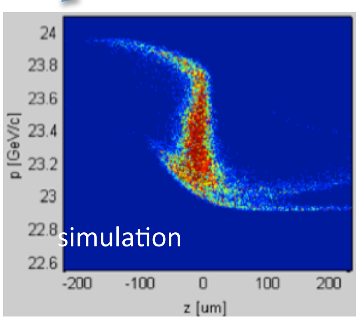
Goal: control and quantify hosing by inducing known z-x tilt on beam.
Current method: stretch beam in linac, add dispersion at IP with sextupole mover.
Main challenge: linac 6D phase-space not well know.

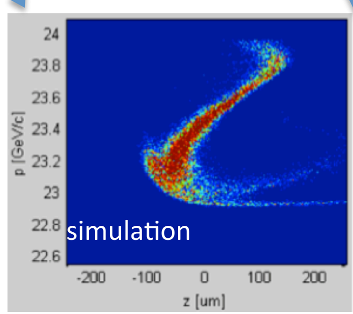
lasma parameters:
b vapour 1.1e17/cm³· 30
m FWHM
Ar buffer gas).



$\Delta\phi_{eq}$ = 1 deg

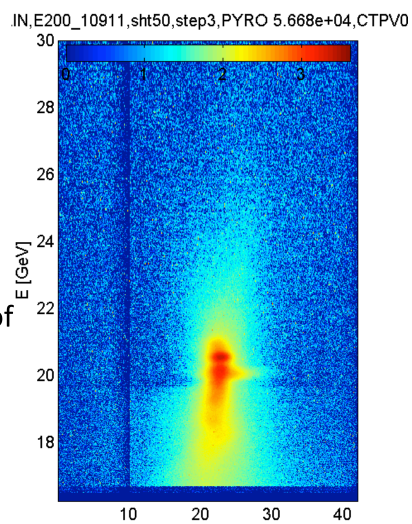
hase space simulations of
deal z-p profiles.

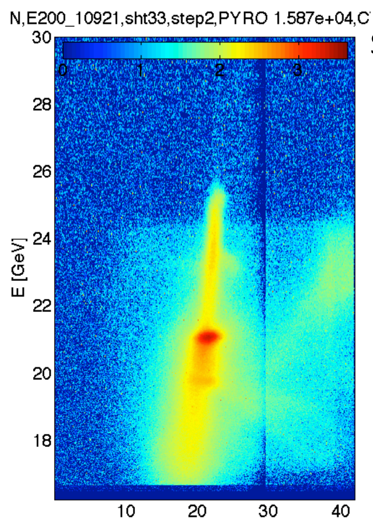




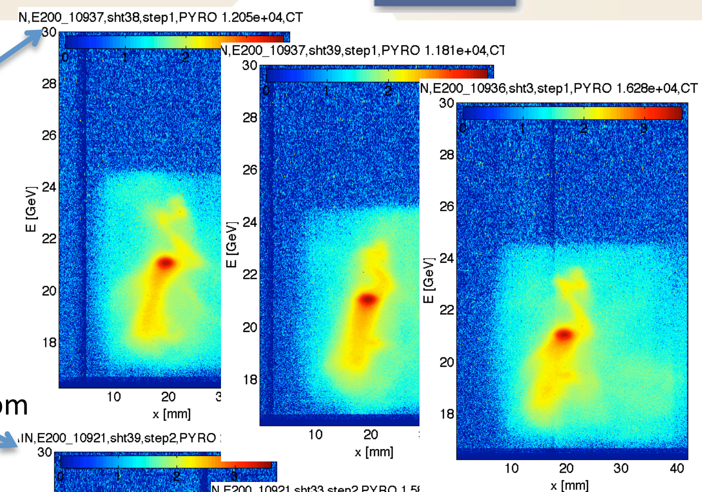
Hosing most easily
observable if tail part of
unch is in the accelerating
hase of the plasma bubble:

5 GeV acceleration by
changing the chirp phase
at entrance to S10
compressor by 1 deg
(beam enters acc. phase of
plasma).

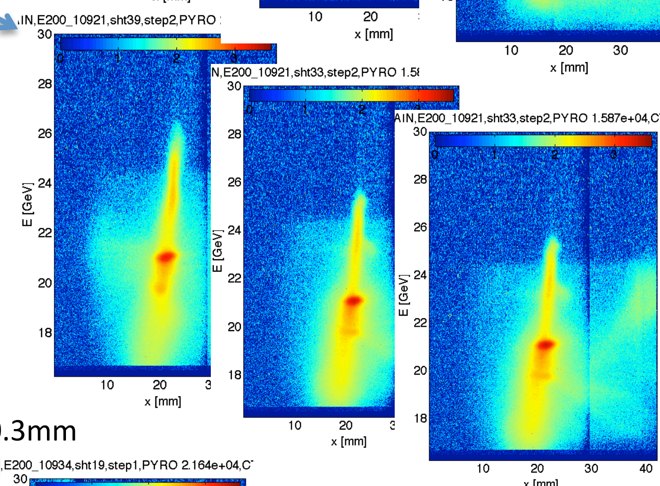




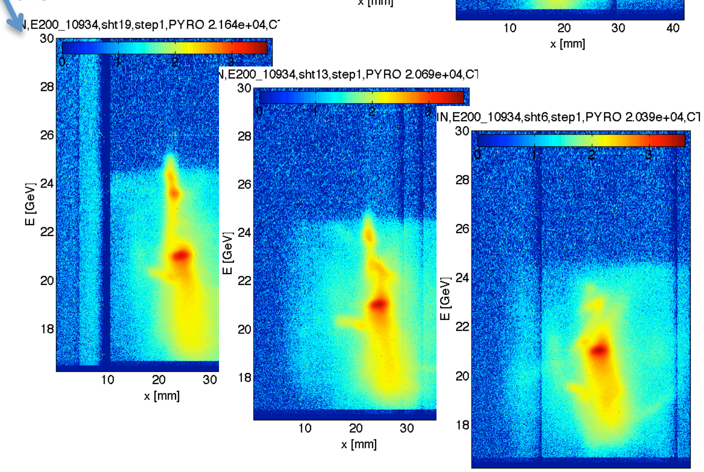
SEXT-2ER X: -0.2 mm



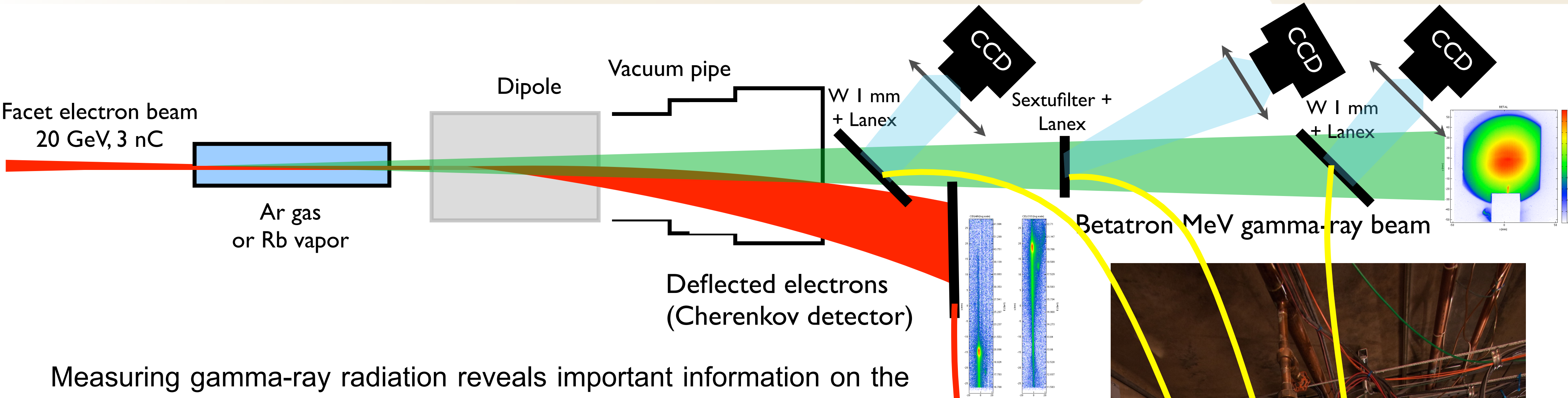
SEXT-2ER X: nom

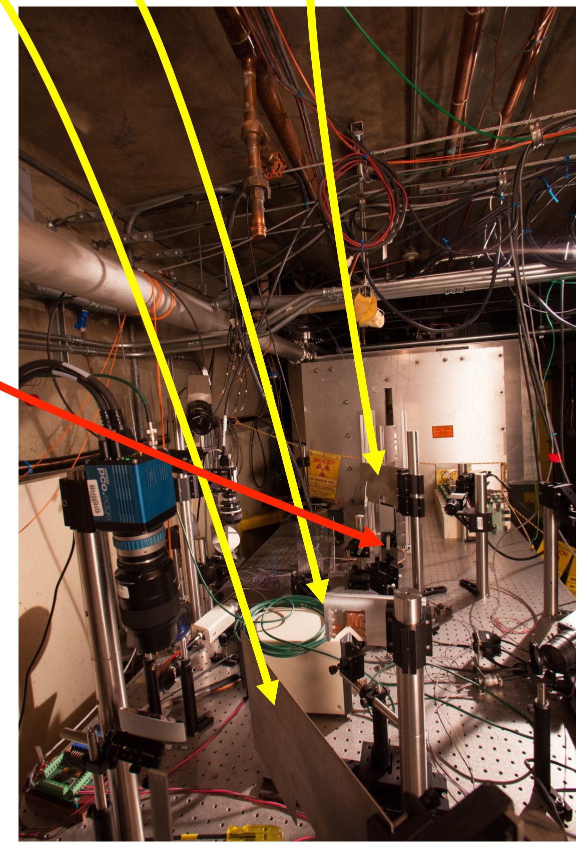


SEXT-2ER X: +0.3mm



Betatron gamma-rays

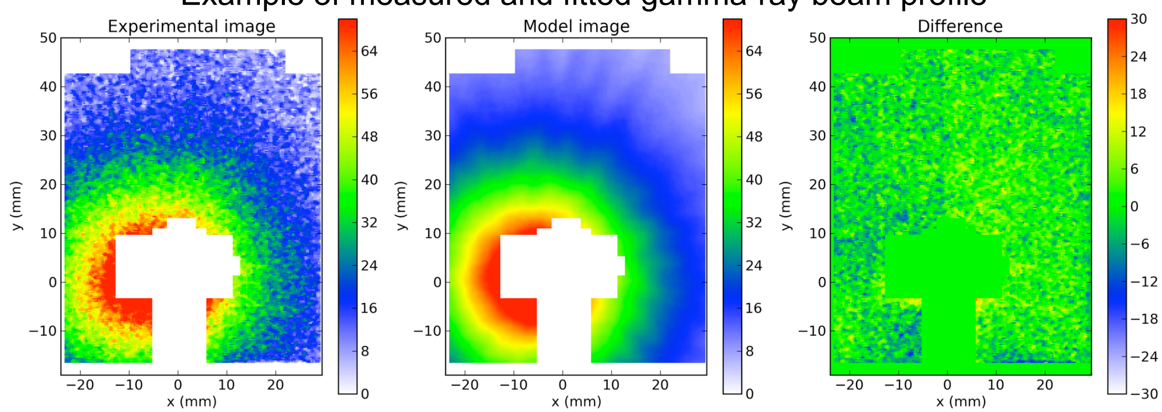




Measuring gamma-ray radiation reveals important information on the beam dynamics in the plasma.

---> Assessing the matching of the beam in the plasma cavity and the potential emittance growth in the plasma.

Example of measured and fitted gamma-ray beam profile



---> Best fit for a 10 um beam size and 150 mm.mrad normalized emittance (BMAG = 2.6).

The Future: This Month

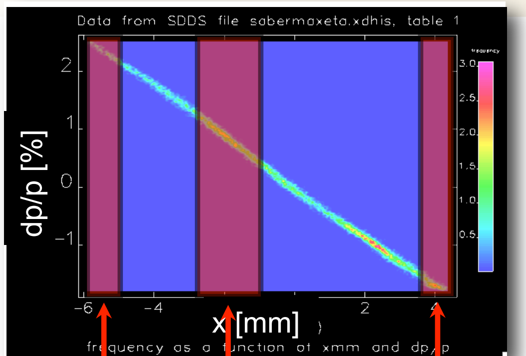
Already a very successful run in 2013!

- Improved performance of SLAC linac and resulting high beam density has opened new avenues for beam-plasma interaction
  - Lower ionization potential vapors better for head-erosion but un-controlled dark current can load the wake and limit the transformer ratio
  - Simple Ar gas cell for beam-ionized plasma source gives good performance for single bunch experiments
    - High plasma density, fields ~ 100GeV/m
    - Adiabatic taper, low divergence exit
  - Investigating controlled ionization injection for low dE/E witness bunch

The remainder of the run will focus on:

- Creating an independent drive/witness bunch from the linac
- Injecting them into a pre-formed laser ionized Li plasma

Use a Notch Collimator to Create Drive-Witness Bunches



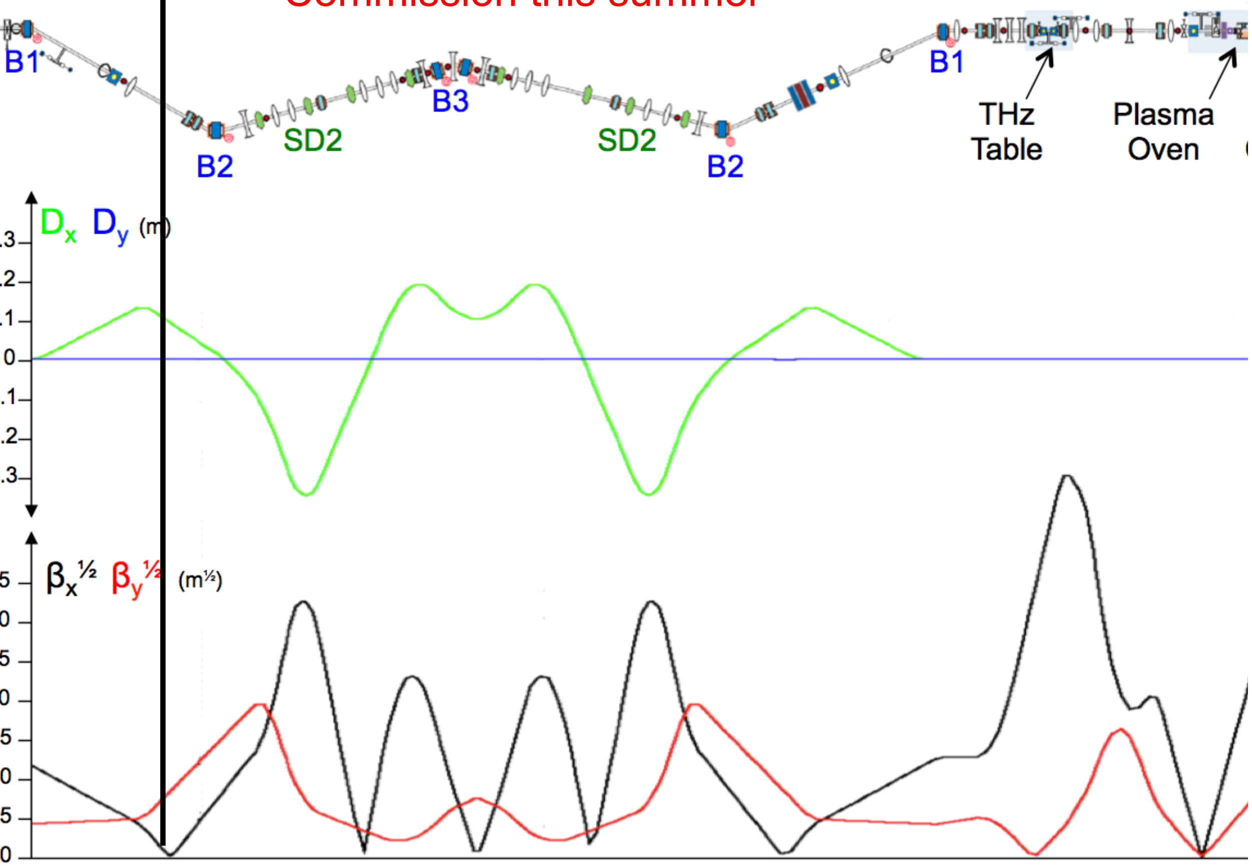
R56 = 10mm

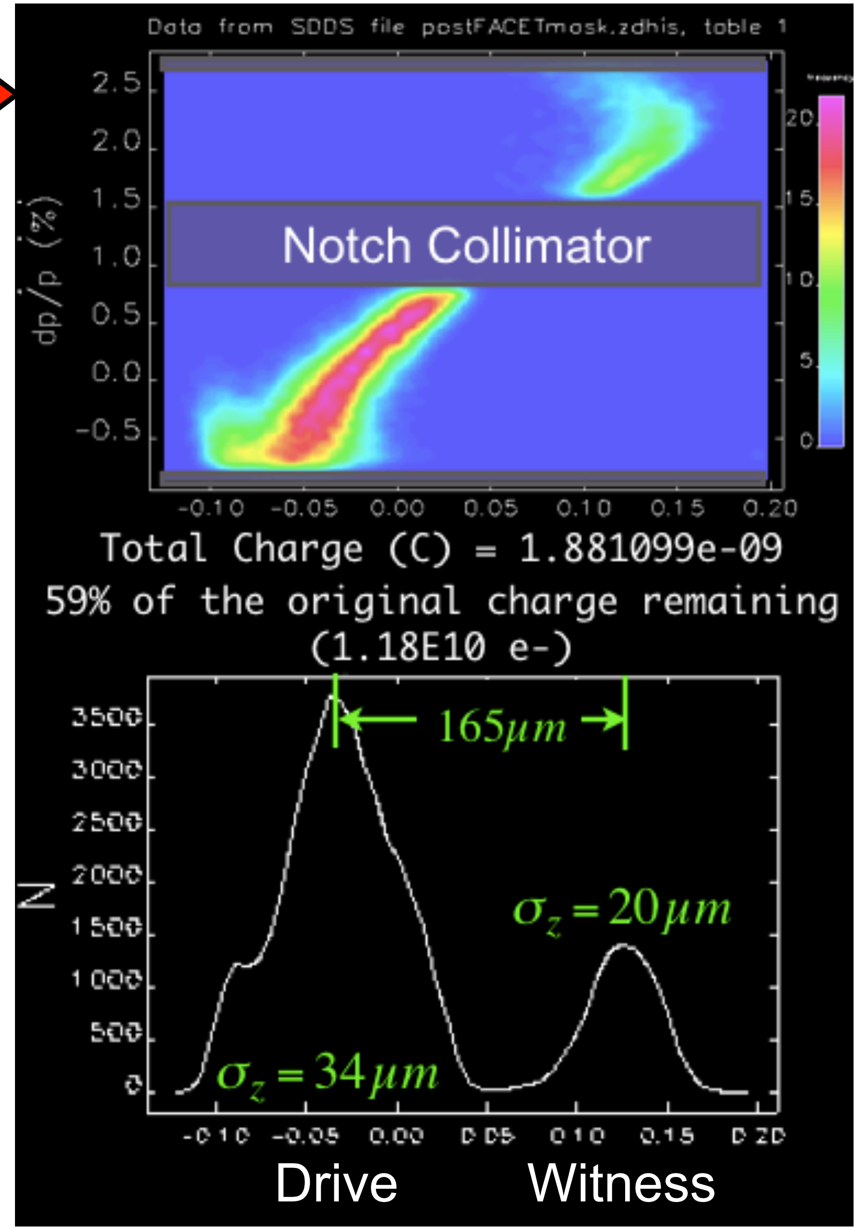
$x \propto \Delta E/E \propto t$

'Over-compressed'

...selectively collimate

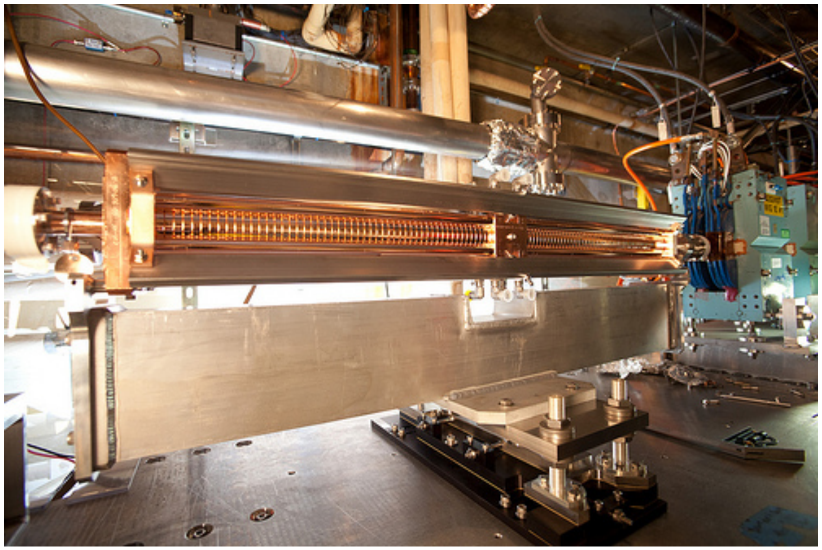
Commission this summer

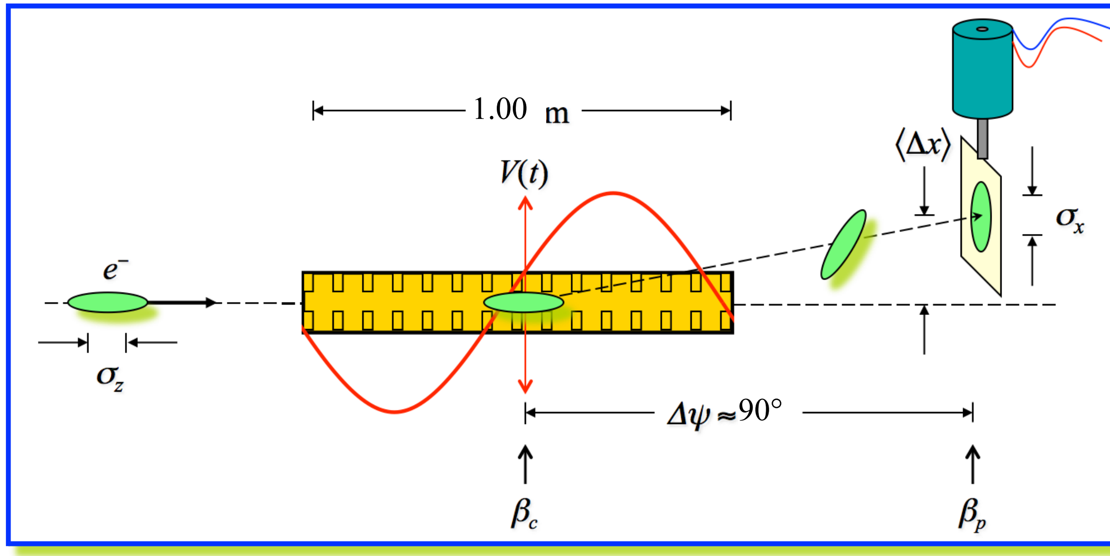


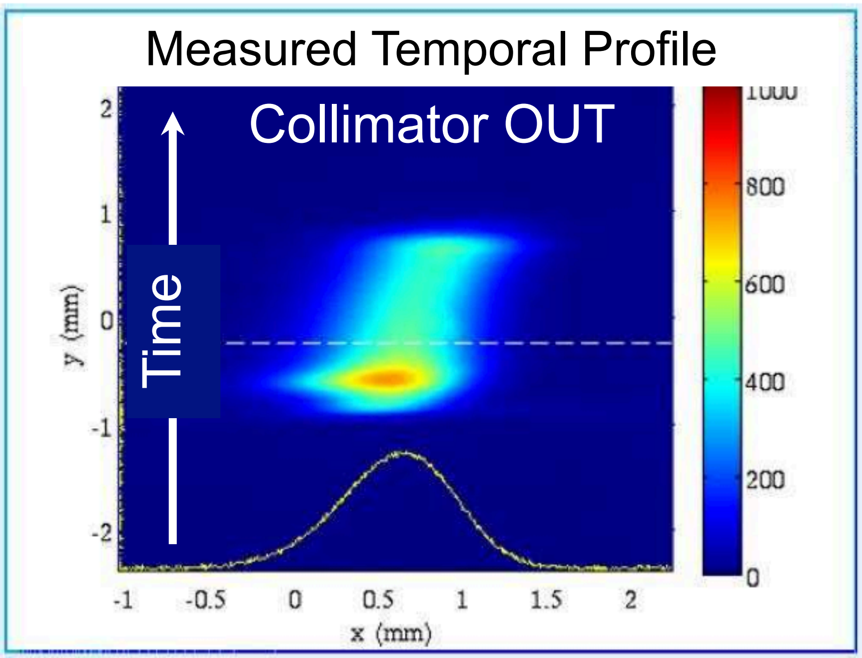


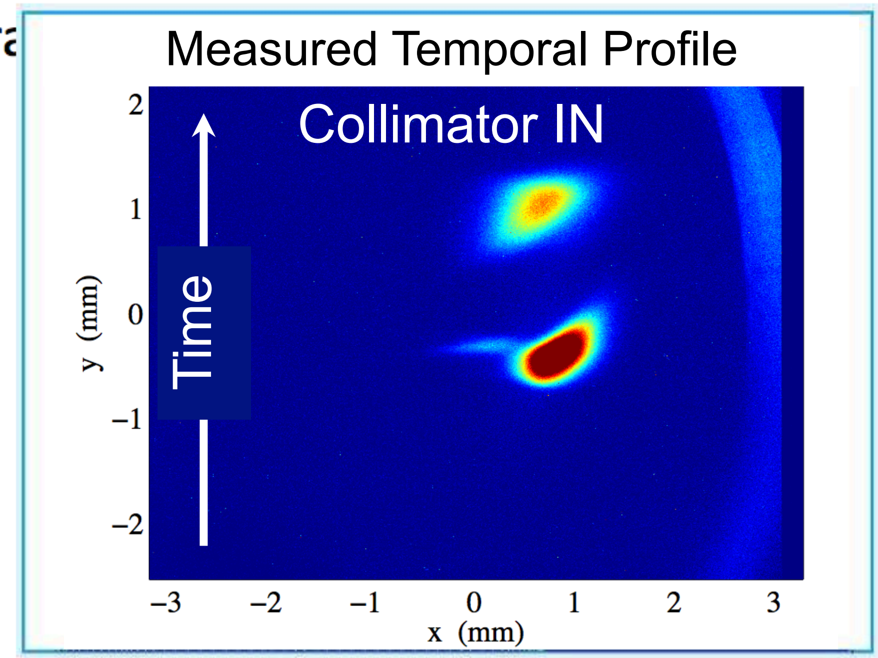
Now operating the tools to make and measure beams for the two bunch PWFA experiments

X-band TCAV installed in Sector 20

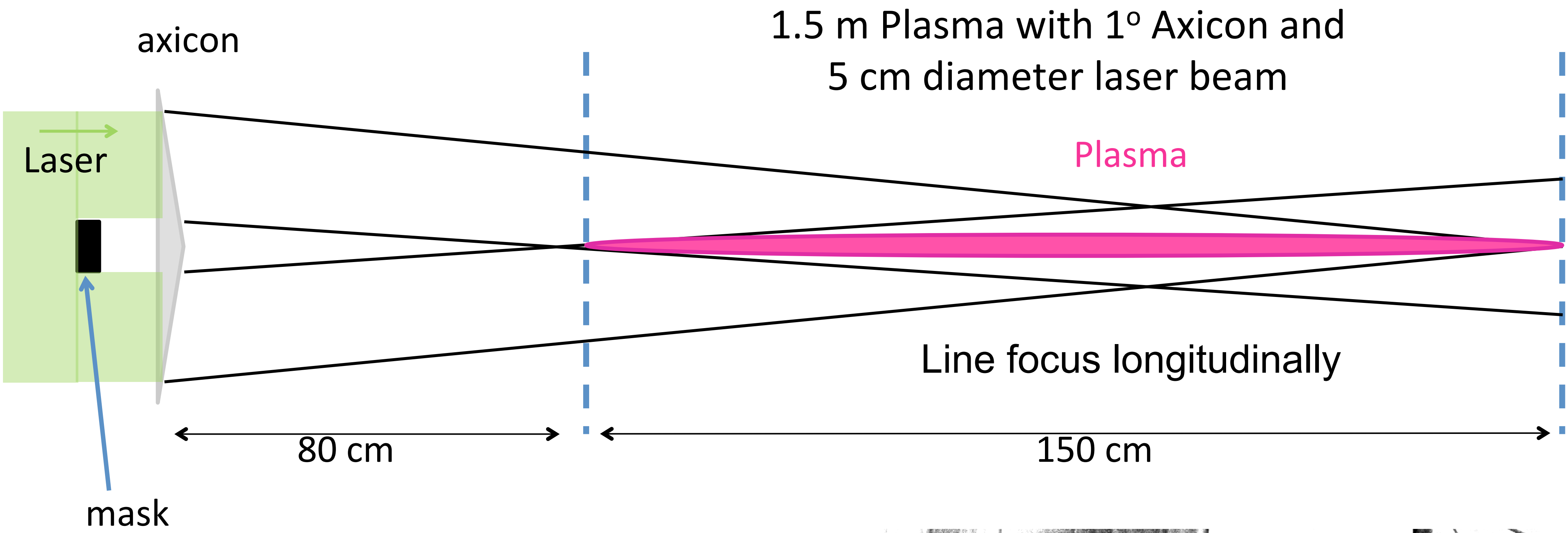




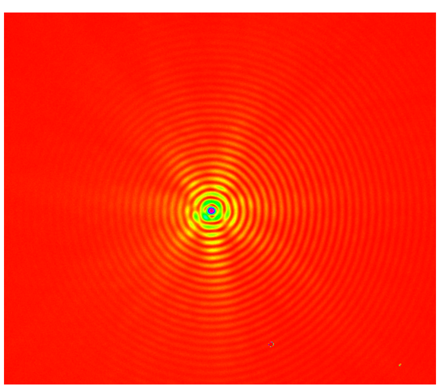


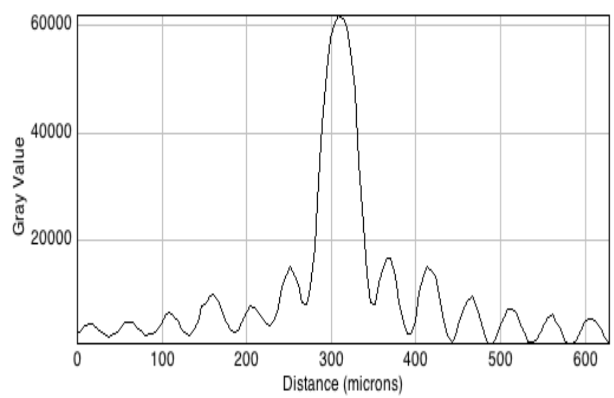


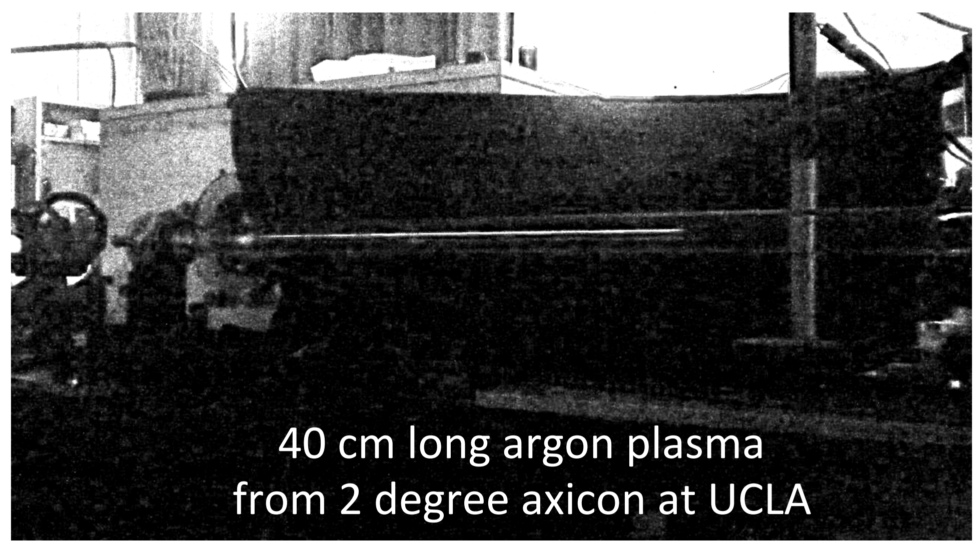
Use a Laser to Turn Lithium Vapor into a Plasma – Axicon Geometry Determines the Plasma Length



Bessel beam radial profile



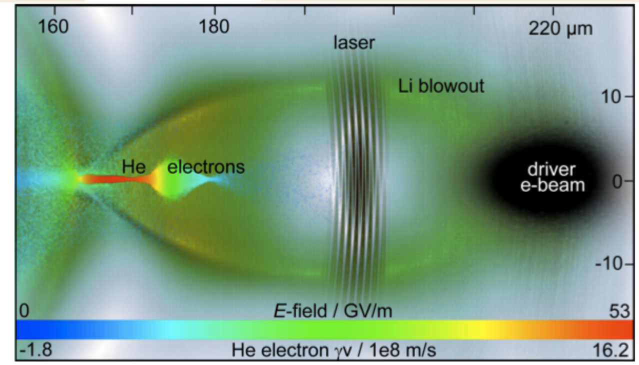


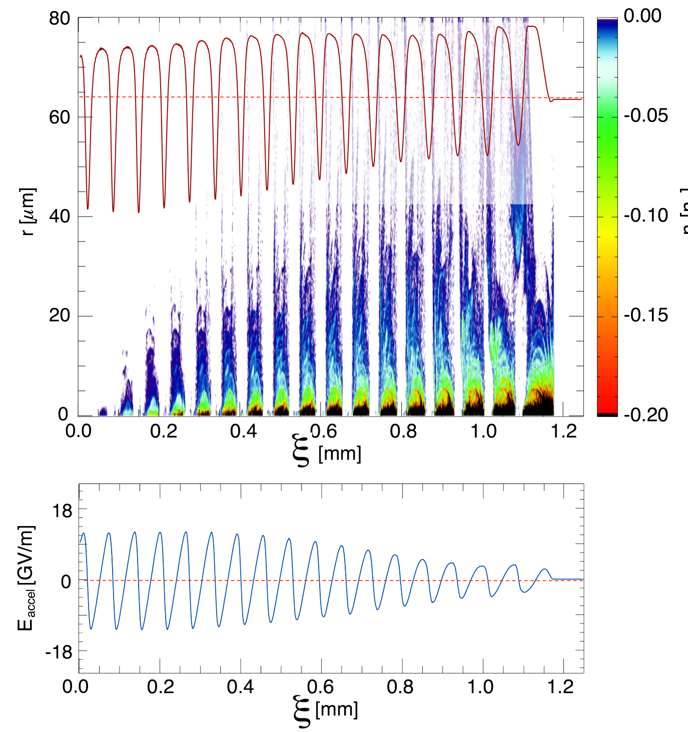


40 cm long argon plasma
from 2 degree axicon at UCLA

The Future: The next Few Years
Expanding Plasma Collaborations and Directions

- Trojan Horse Plasma Wakefield Acceleration
  - (UCLA/SLAC/Tech-X/MPI/HHU)
- Study of the Self-Modulation of Long Lepton Bunches in Dense Plasmas and its Application to Advanced Acceleration Techniques
  - (IST/MPI/SLAC)
- Investigation of Hot Plasmas and Fourier Domain Holography of Plasma Wakes
  - (Duke/SLAC/U.T. Austin/UCLA)
- Helmholtz VI for Plasma Acceleration
- Others too, but not with plasma





Facility upgrades like the laser are enabling additional programs that will accelerate progress and increase FACET science output

The Future: **July 25-26, 2013**
Program Advisory Committee to review new proposal

SLAC

SLAC NATIONAL ACCELERATOR LABORATORY

DOE | Stanford | SLAC | SSRL | LCLS | AD | PPA | Photon Science | PULSE | SIMES

FACET
An Office of Science User Facility

ACCELERATOR DIRECTORATE

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- SAREC 4th Meeting (July 2013)
- Users Meeting
- Agenda
- Registration (no fees)
- Participants
- Information for Proposers & Experimenters
- SLAC Test Facilities Information & Contacts
- Accommodation & Local Travel
- Travel & Directions
- Visa Information
- Wireless Internet Access
- SAREC OCT12 Meeting Photos

U.S. DEPARTMENT OF ENERGY
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SLAC Accelerator Research Experimental Program Committee (SAREC)

4th. SAREC REVIEW MEETING - July 25th-26th, 2013
Cypress Conference Room (B40/147) - View Map
SLAC National Accelerator Laboratory

Charge to committee:

The Accelerator Research Division (ARD) at the SLAC National Accelerator Laboratory manages a strong R&D program in Accelerator Science and Technology. As part of this program, the

TIMELINE
- Call for Proposals - May 21st
- Proposals Due - June 17th
- Comments from SLAC - June 28th
- Comments from SAREC - July 12th
- Proposal changes due - July 19th
- Review - July 25th

REVIEW INFORMATION
- Proposal Template

SAREC REVIEW SITES
- July-2013 Proposals & Agenda
- Oct-2012 Proposals & Agenda
- Jan-2012 Proposals & Agenda
- Jan-2011 Proposals & Agenda

You are invited!

The Future: Beyond FACET...FACET-II

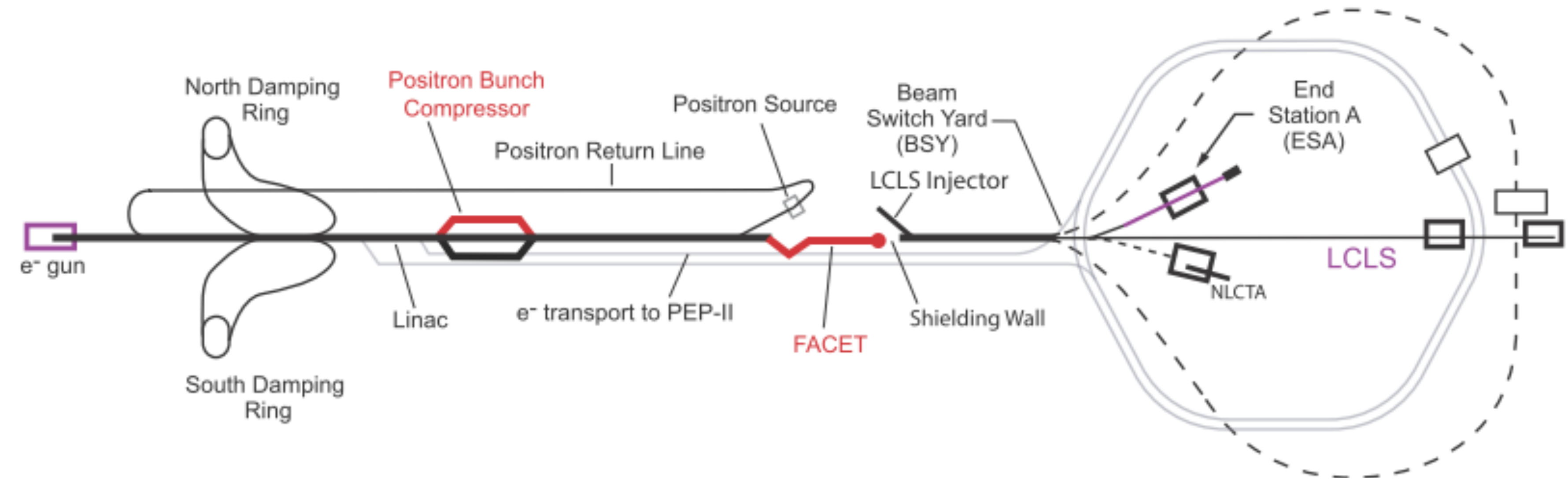
In 2016 SLAC will start begin the second phase of the x-ray laser program and start constructing LCLS-II

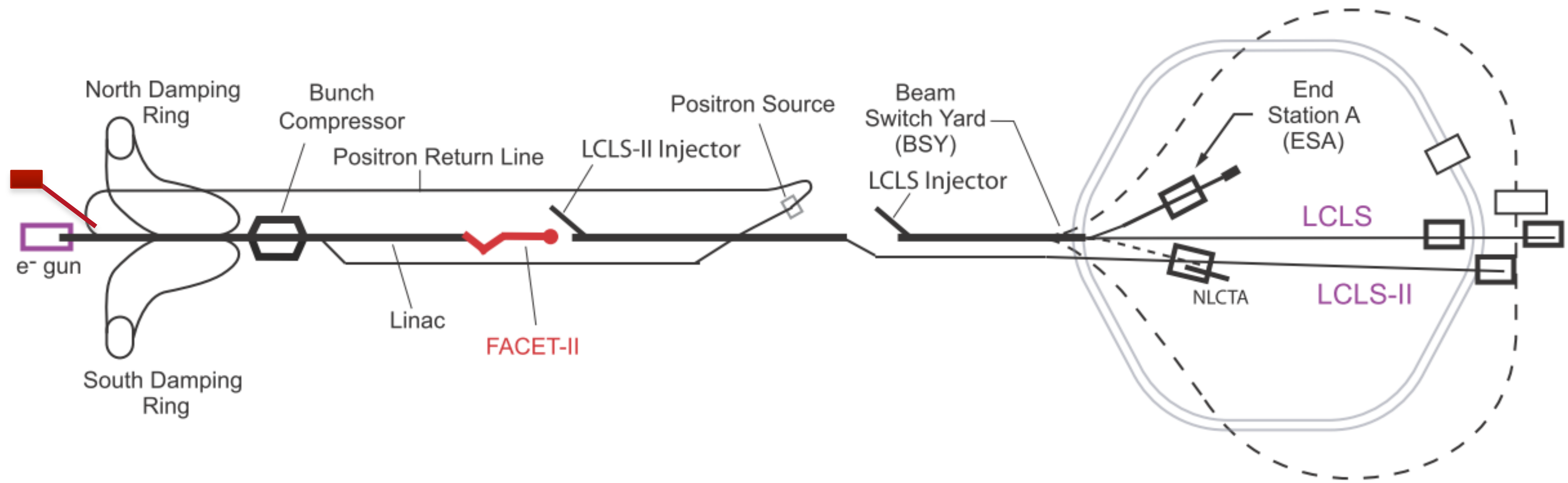
- Impact to the middle kilometer of the SLAC linac will halt FACET operations

Working with DOE to develop ideas for FACET-II

- Want to minimize interruption to existing programs
- Want to build off success of FACET and expand capabilities
- Science case developed and submitted in February
- We look forward to hearing your ideas at this workshop!

FACET II





In early 2016, LCLS-II, will begin commissioning using part of the tunnel occupied by FACET

Three main themes at FACET II

- High gradient acceleration techniques that will reduce the cost of both a future high-energy collider and linac-based light sources

- High brightness beam techniques that improve the generation, preservation, and application of such beams

- Novel radiation techniques (spanning terahertz to gamma-rays) that can be generated by FACET's high brightness beams

Summary

It is a very exciting time for beam driven plasma accelerators!

- Optimistic we will see demonstration of high-gradient meter scale plasma stage within the next year with good beam quality and efficiency
- Coming years will build on this with injection and higher brightness beams paving the way for the first applications

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