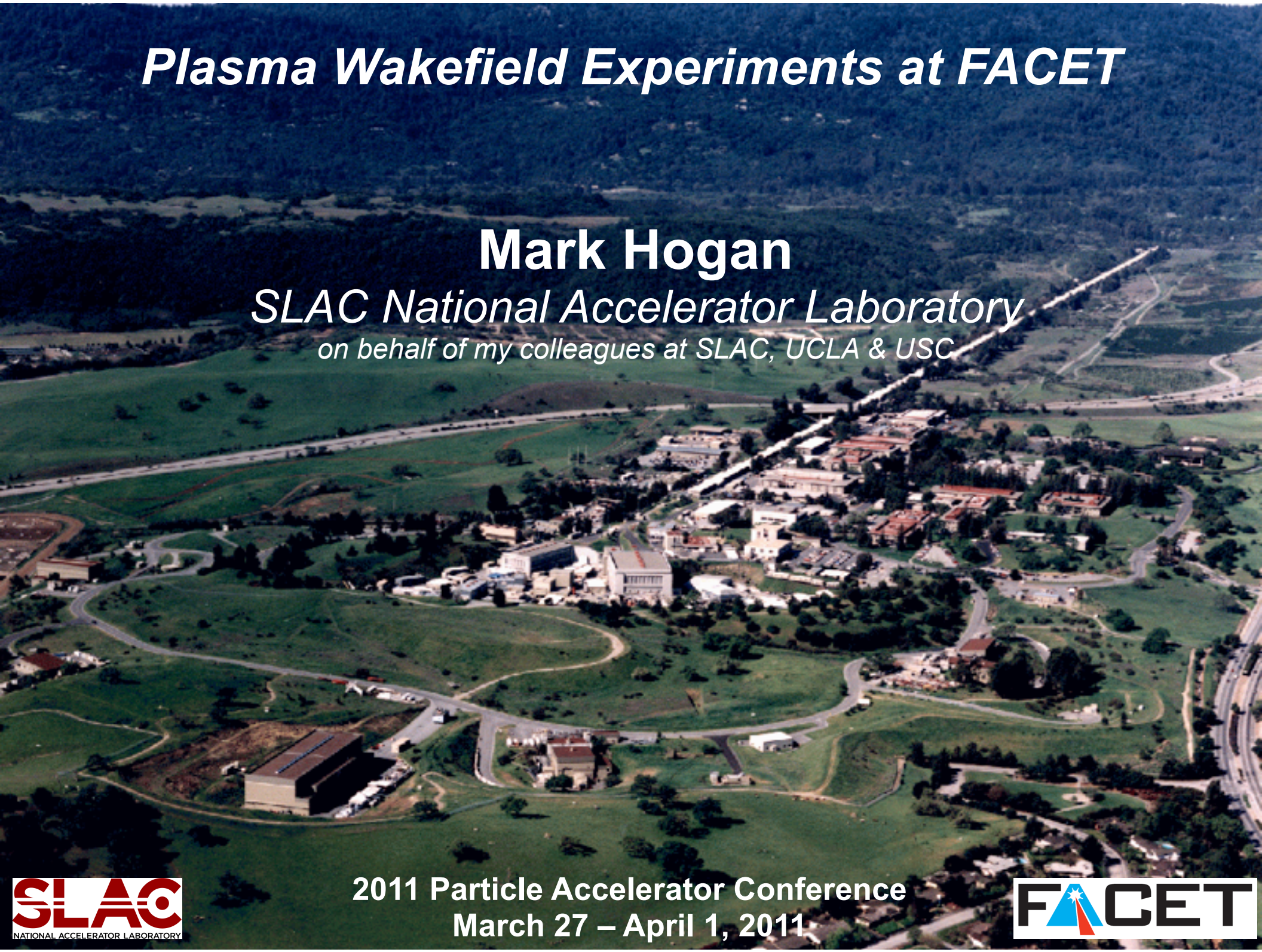
Plasma Wakefield Experiments at FACET



Mark Hogan

SLAC National Accelerator Laboratory

on behalf of my colleagues at SLAC, UCLA & USC

SLAC NATIONAL ACCELERATOR LABORATORY

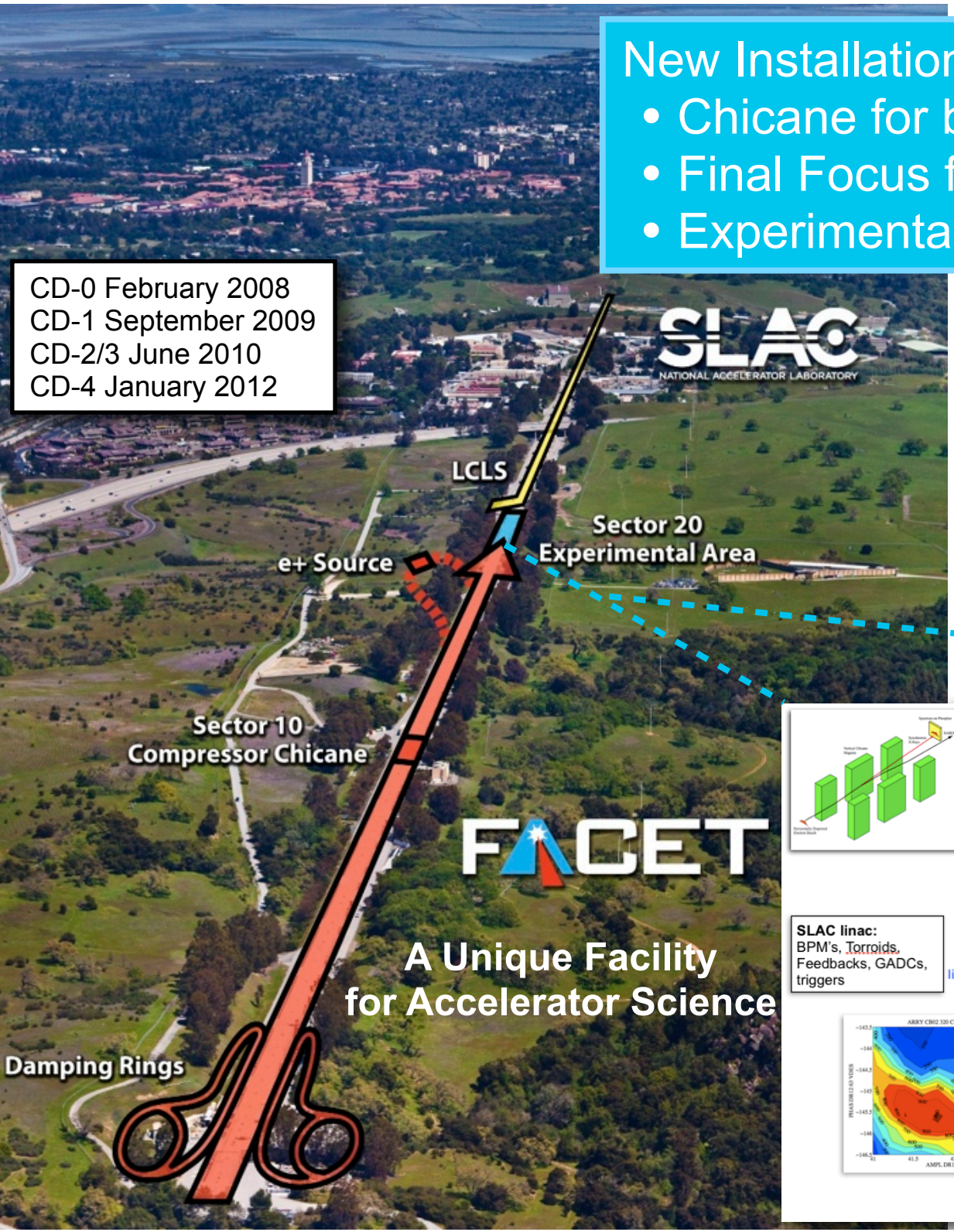
2011 Particle Accelerator Conference
March 27 – April 1, 2011

FACET

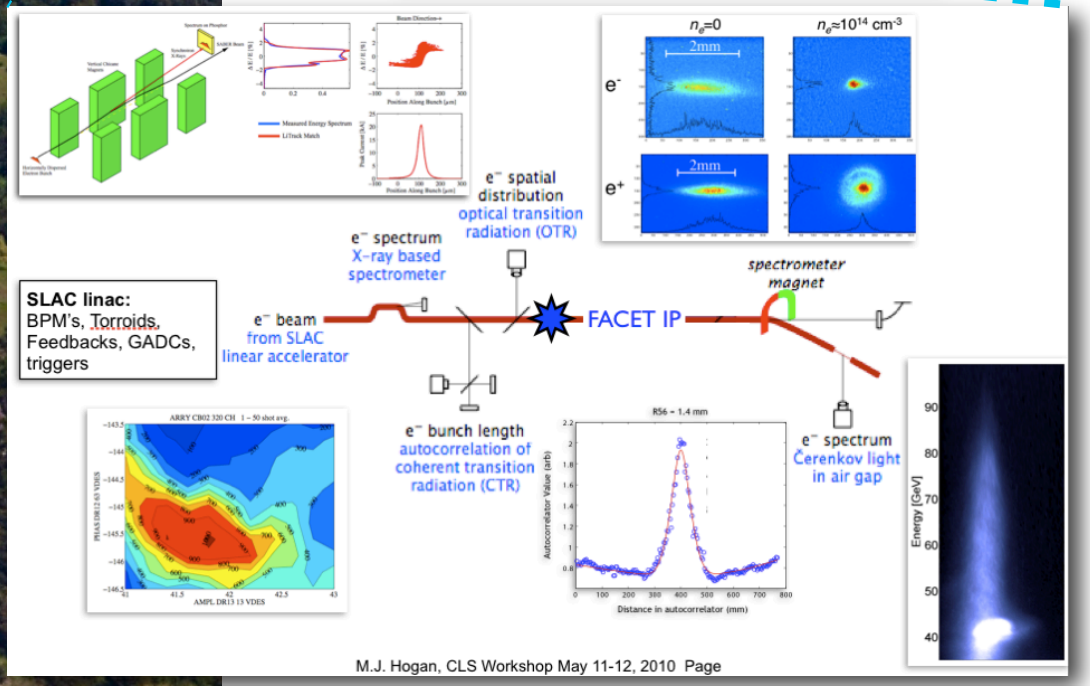
New Installation @ 2km point of SLAC linac:

- Chicane for bunch compression
- Final Focus for small spots at the IP
- Experimental Area (25m)

CD-0 February 2008
CD-1 September 2009
CD-2/3 June 2010
CD-4 January 2012



Beam Parameters	
Energy	23 GeV
Charge	3 nC
Sigma z	20 μm
Sigma r	10 μm
Peak Current	22 kAmps
Species	e^- & e^+

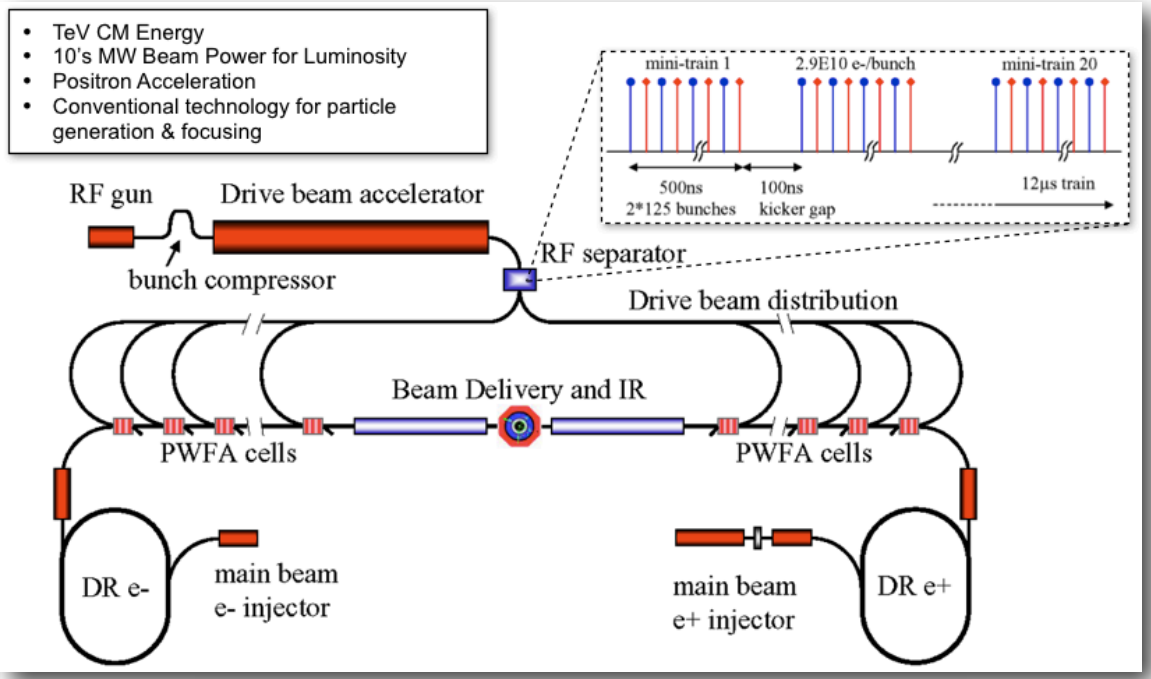


FACET Beamline Looking Upbeam

- User assisted commissioning this summer (2011)
  - Goal to get beam needed for science and commission accelerator configurations and experimental hardware
- FACET Project CD-4 early 2012
- First user runs in 2012: Four months total running/year for five years

A Self-consistent Design of a 1 TeV e^-e^+ Linear Collider Based on PWFA

- TeV collider design has multiple acceleration stages, each adding ~25 GeV/stage
- FACET PWFA program aims to demonstrate a single stage with needed Q, $\Delta E/E$, efficiency, emittance preservation
- Results will inform designs for future applications (HEP, Photon Science)



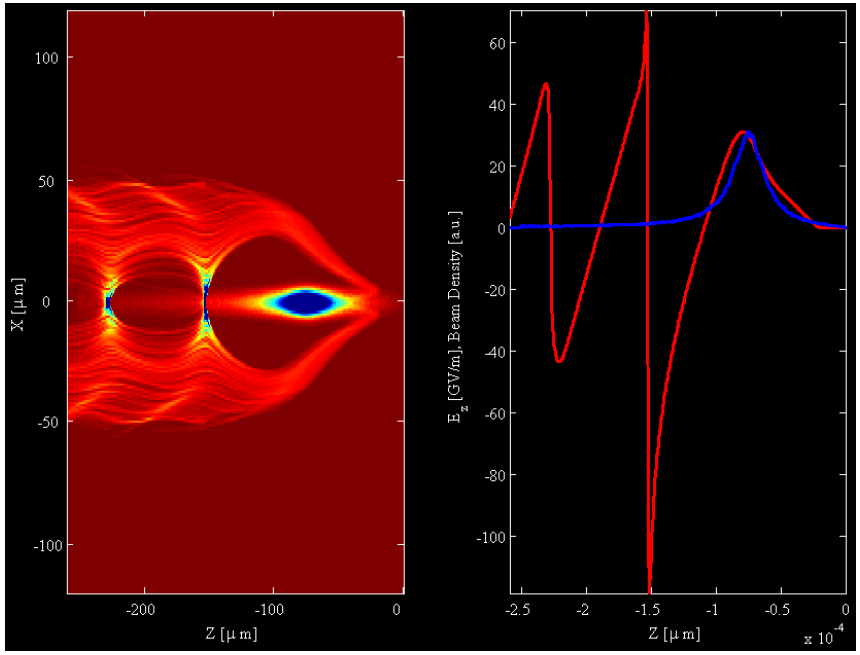
E_{cm} = 1 TeV, L = 10^{34} cm^2s^{-1}

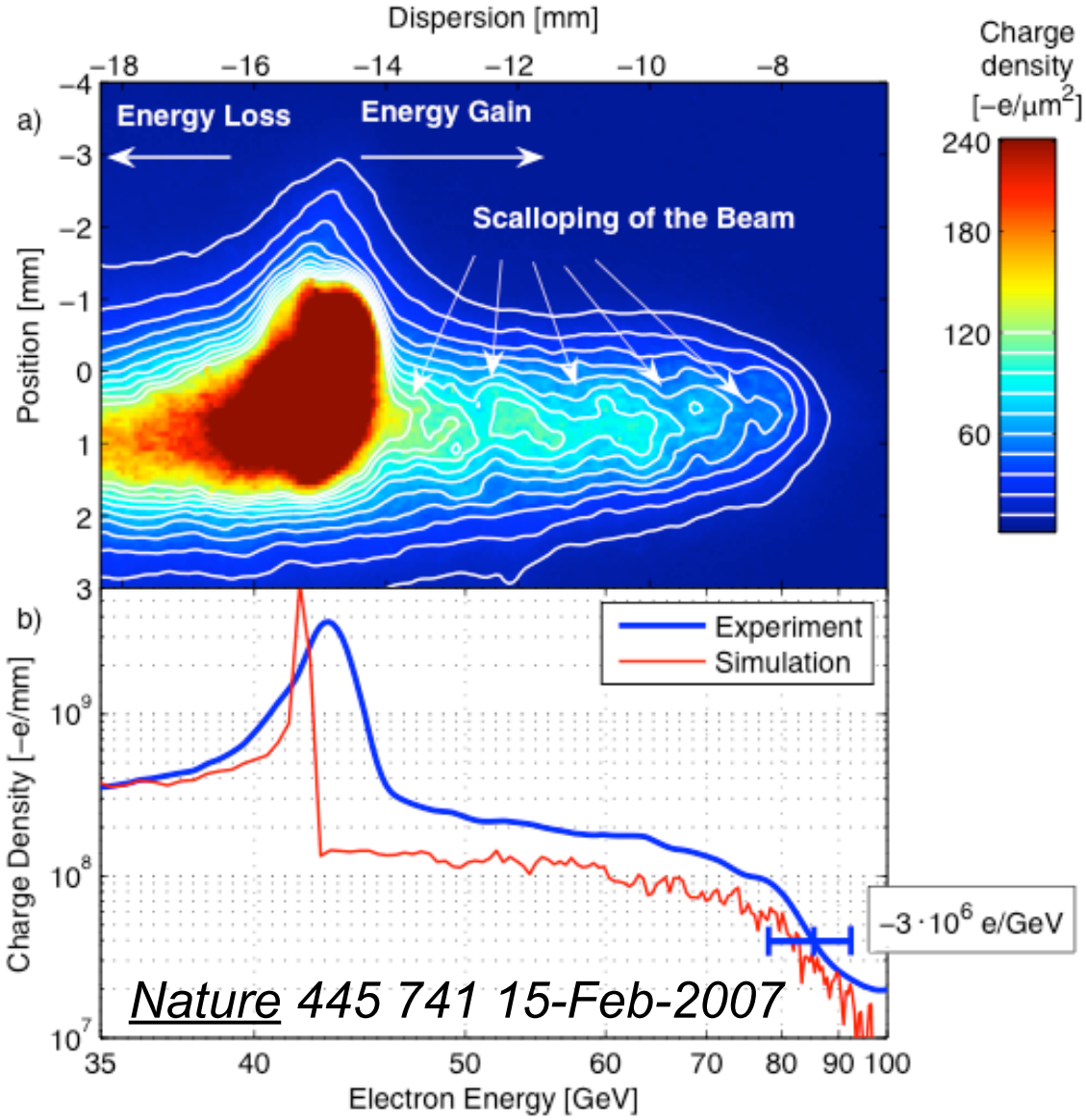
Luminosity	3.5×10^{34} $cm^{-2}s^{-1}$
Luminosity in 1% of energy	1.3×10^{34} $cm^{-2}s^{-1}$
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, $1\times10^{17}cm^{-3}$
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

see A. Seryi et al., PAC09 Proceedings

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

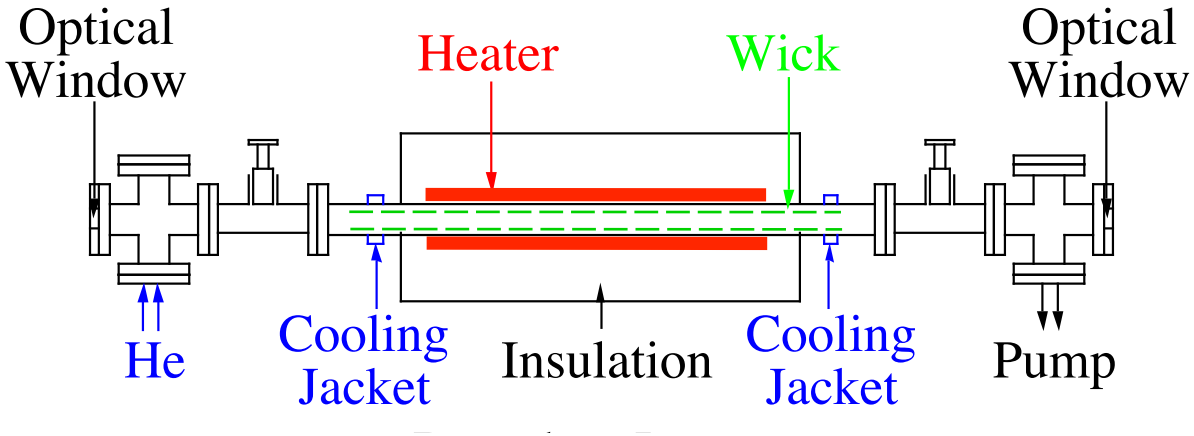


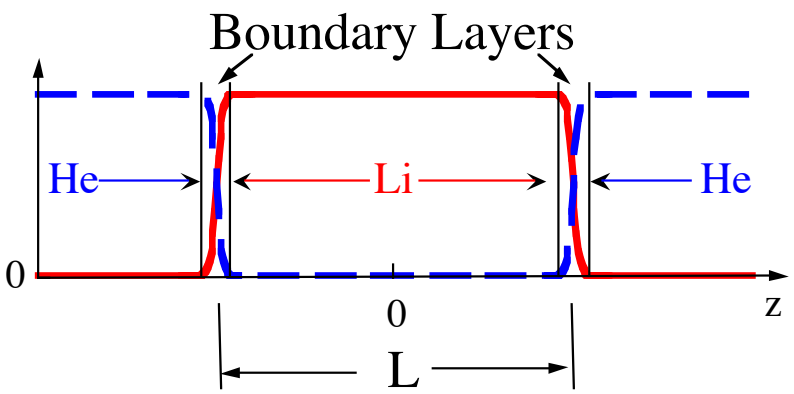


Next Step: Particle acceleration to beam acceleration @ FACET

Large Energy Gain Requires Meter Long, Uniform, High-density Plasma

- Plasma source starts with metal vapor in 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:

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

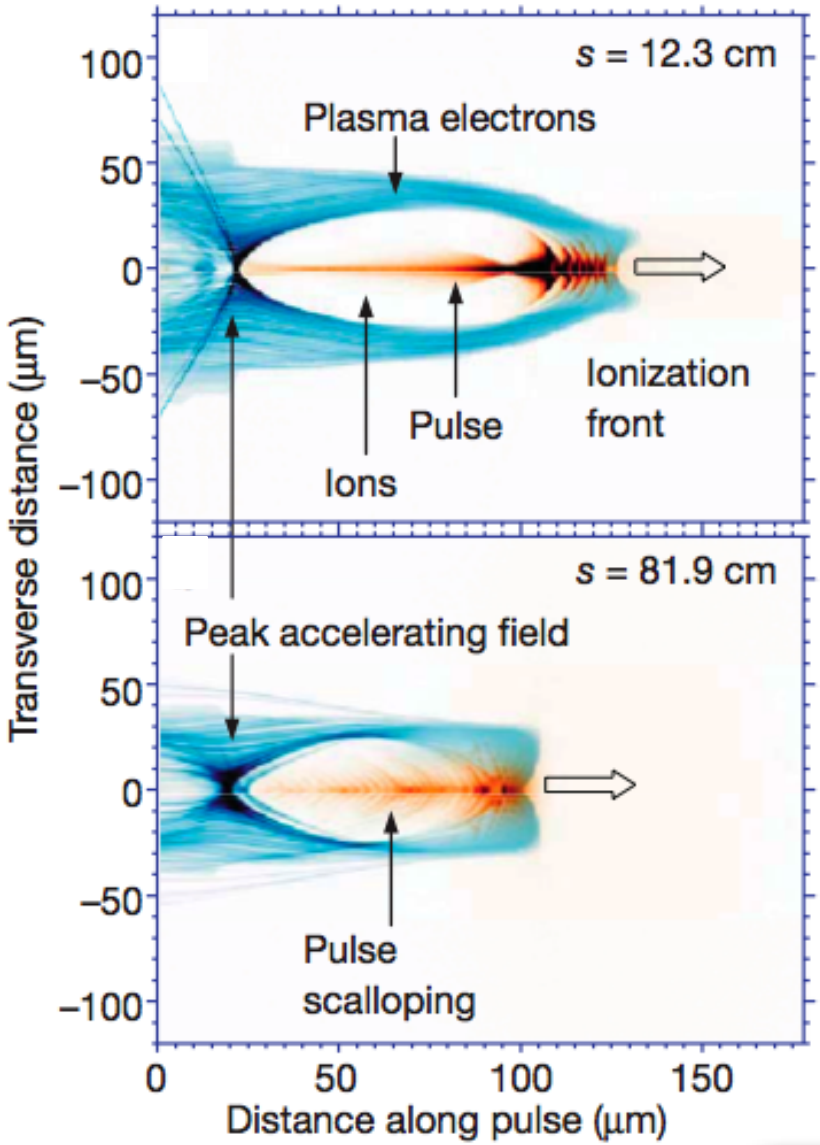
See D. Bruhwiler et al, Physics of Plasmas 2003

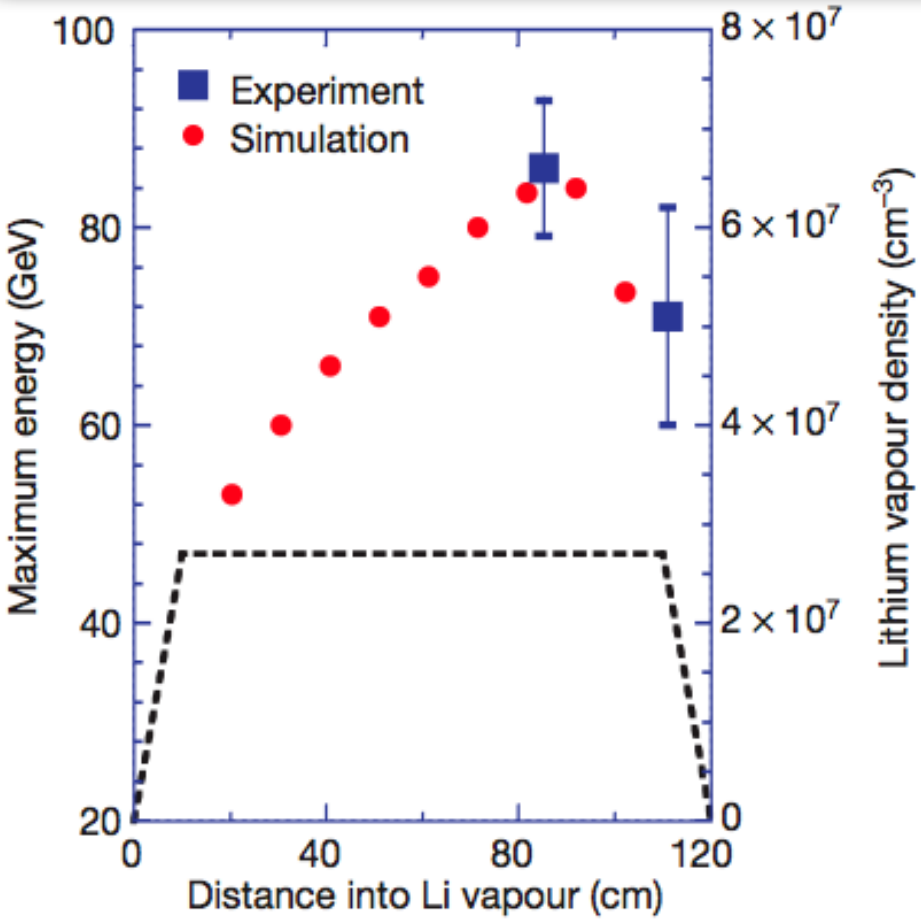
Space charge fields are high enough to field (tunnel) ionize - no laser!

- No timing or alignment issues
- Plasma recombination not an issue
- However, can't just turn it off!
- **Head erosion**

Single Stage Energy Gain Limited by Head Erosion

First experiments will parameterize head erosion vs. beam emittance, ionization potential





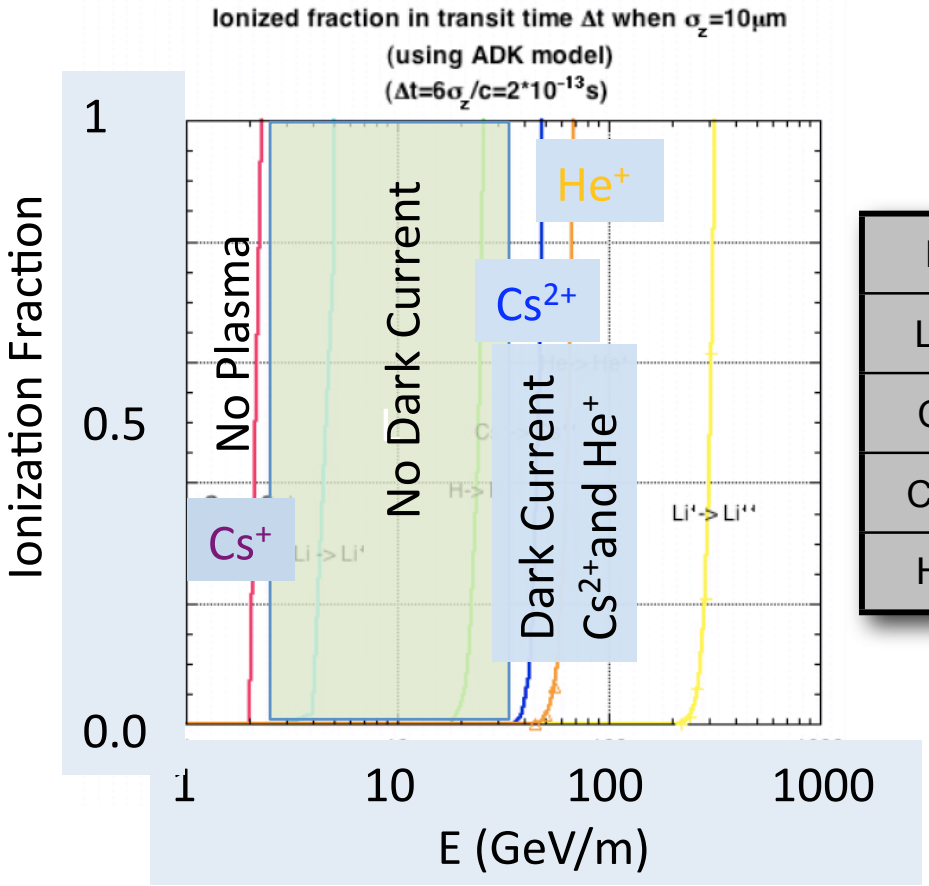
See I. Blumenfeld Stanford PhD Thesis 2009 and M. Zhou UCLA PhD Thesis 2008

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

Single Bunch Experiments Cs Plasma

- Parameterize head erosion for lower ionization potential (Cs vs. Li)
- Study onset of self-trapping (dark current)

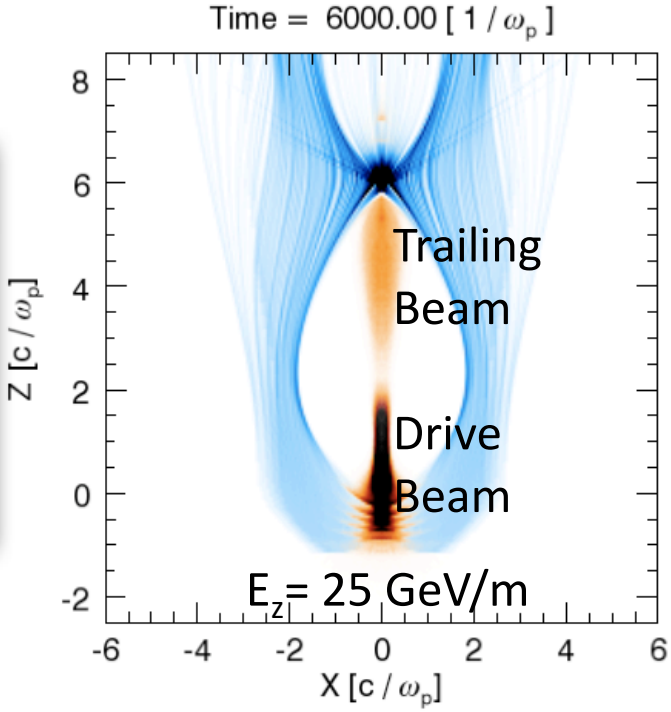
see K. Marsh TUOBN1



QuickPIC Simulations

Li	5.4eV
Li+	75.5eV
Cs	3.9eV
Cs+	25.1eV
He	24.5eV

Self-ionized Plasma in Li or Cs at s= 4.5 cm

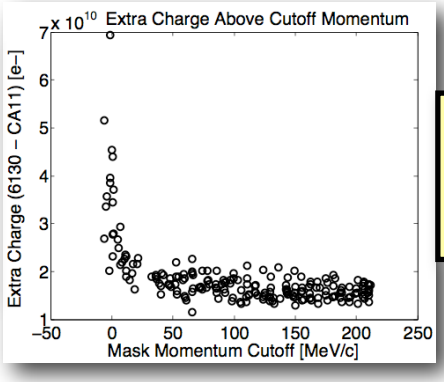


$E_{wake} > E_{beam}$ FACET (two Bunch)

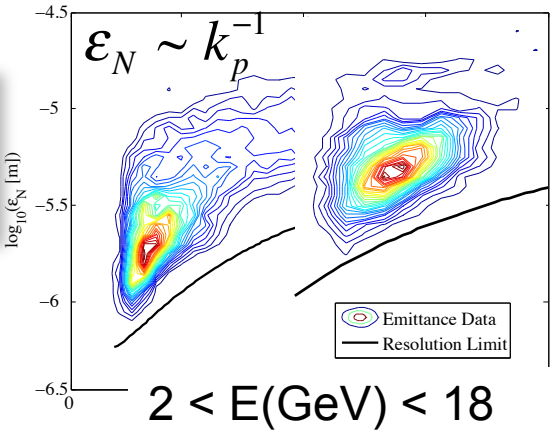
Plasma Density : 5 x10^{16} cm^{-3} Beam : $\sigma_{r1} = \sigma_{r2}$= 10 μm , σ_{z1} = 18 μm , σ_{z2} = 25 μm ,
N_1 = 6.7 x 10^9 , N_2 = 2.3 x 10^9 , $\varepsilon_x = \varepsilon_y$=100 mm·mad

Plasma Dark Current in E-167: Large Fields (Beam or Wake) Ionize He Buffer

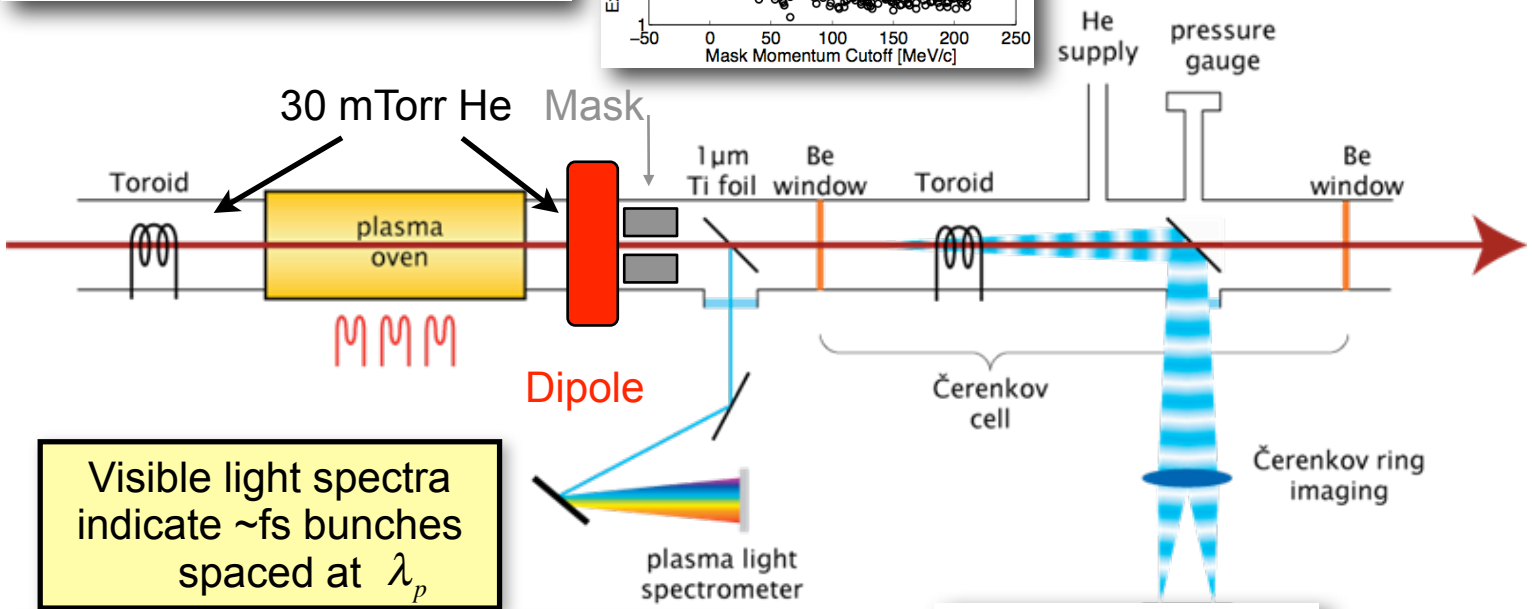
Electrons are trapped at He boundaries and accelerated out of the plasma



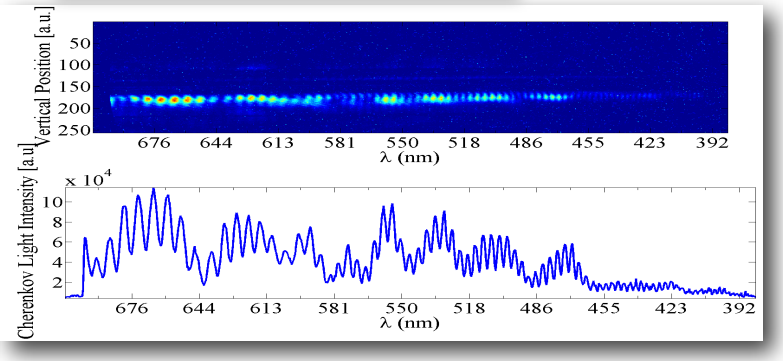
Two Main Features
- >4 times more charge
- >10^4 more light!

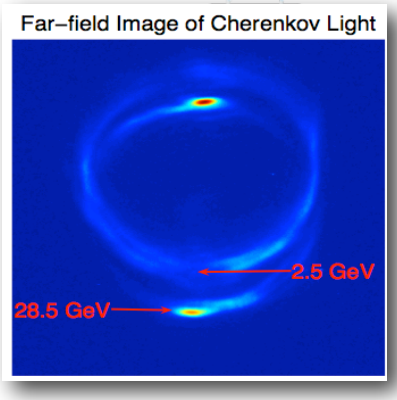


2 < E(GeV) < 18

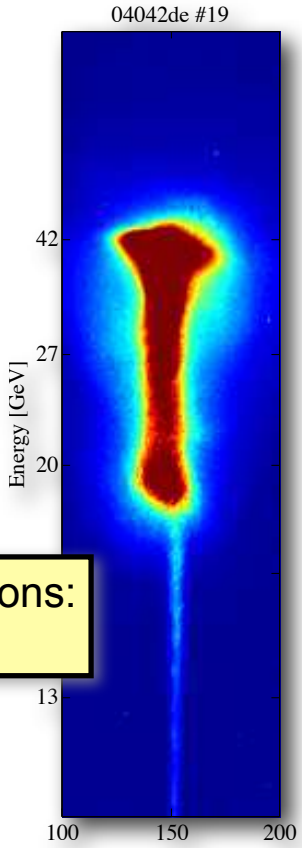


Visible light spectra indicate ~fs bunches spaced at λ_p

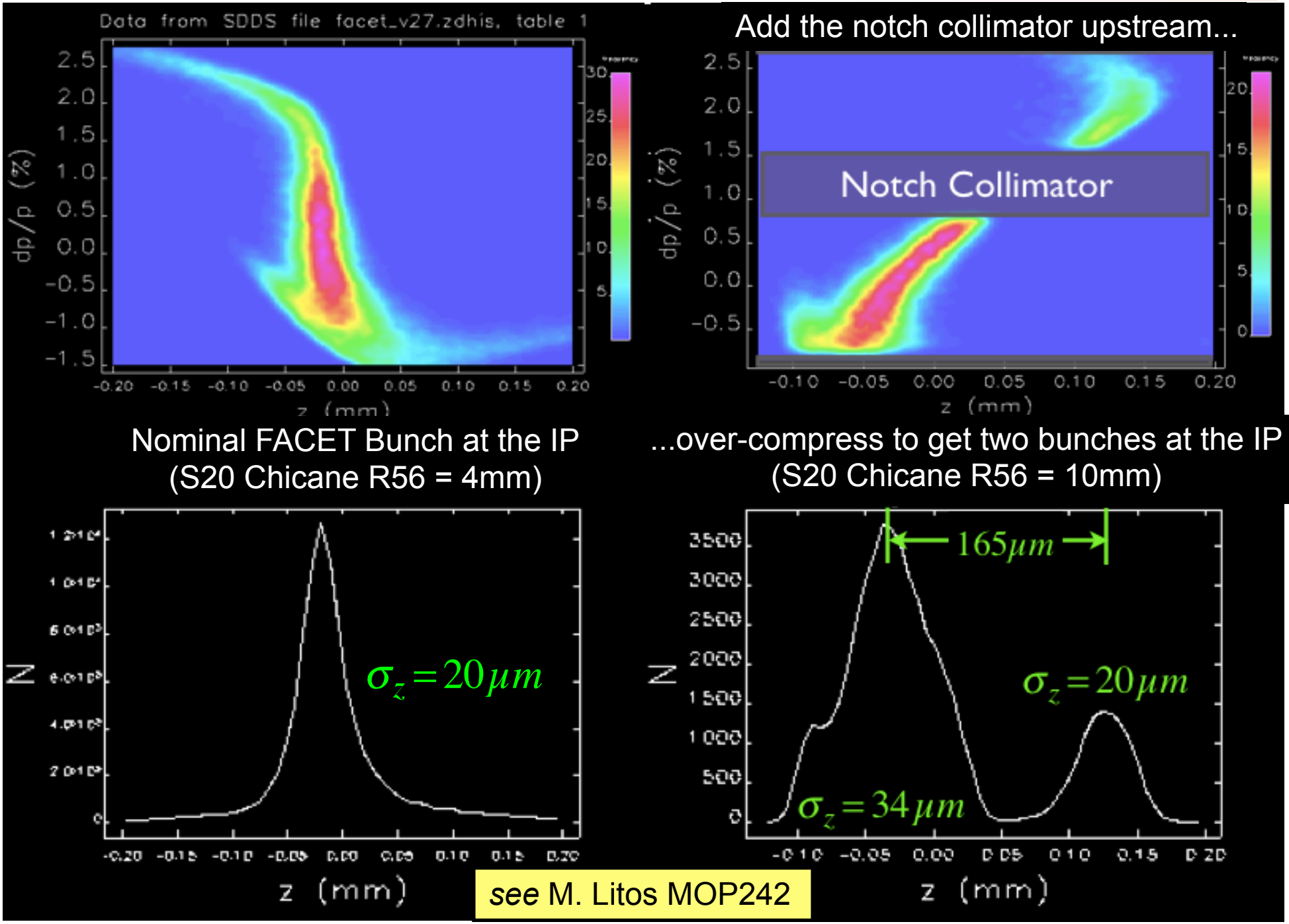




Two Energy Populations: MeV & GeV



Will Use Two Bunches to Study Beam Loading in the Non-linear Regime for the First Time

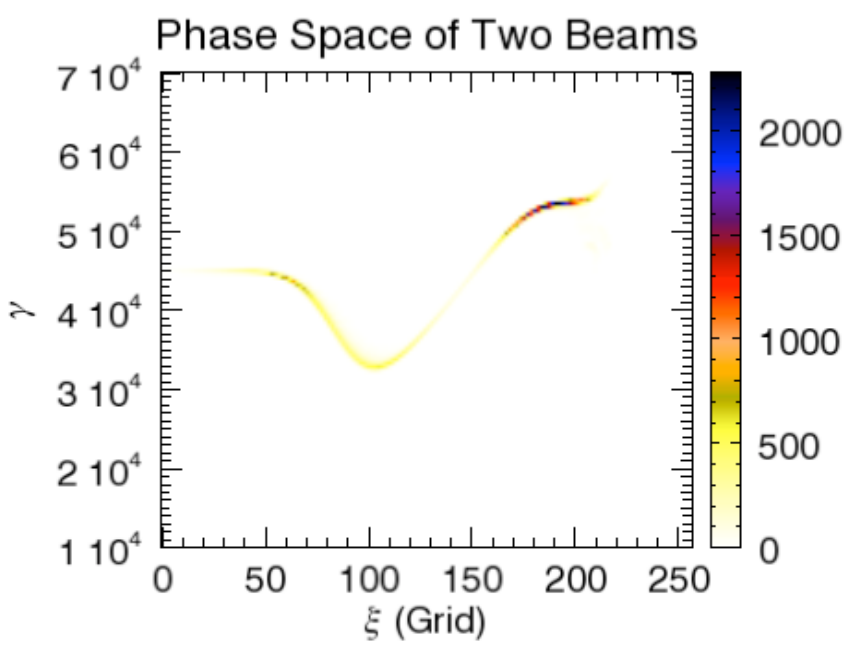


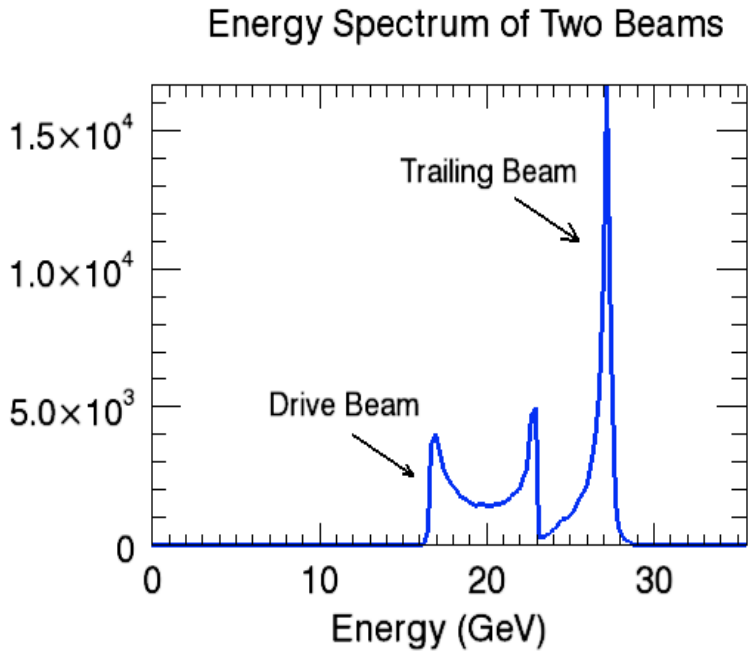
see M. Litos MOP242

Two-bunches in Field-Ionized Cs Plasma

- After 88.5 cm of 3.7 x 10^{16} plasma
  - Energy Gain 5 GeV
  - Energy Spread ~ 3%
  - Variable with plasma density, beam emittance, ionization potential

see W. An MOP016





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

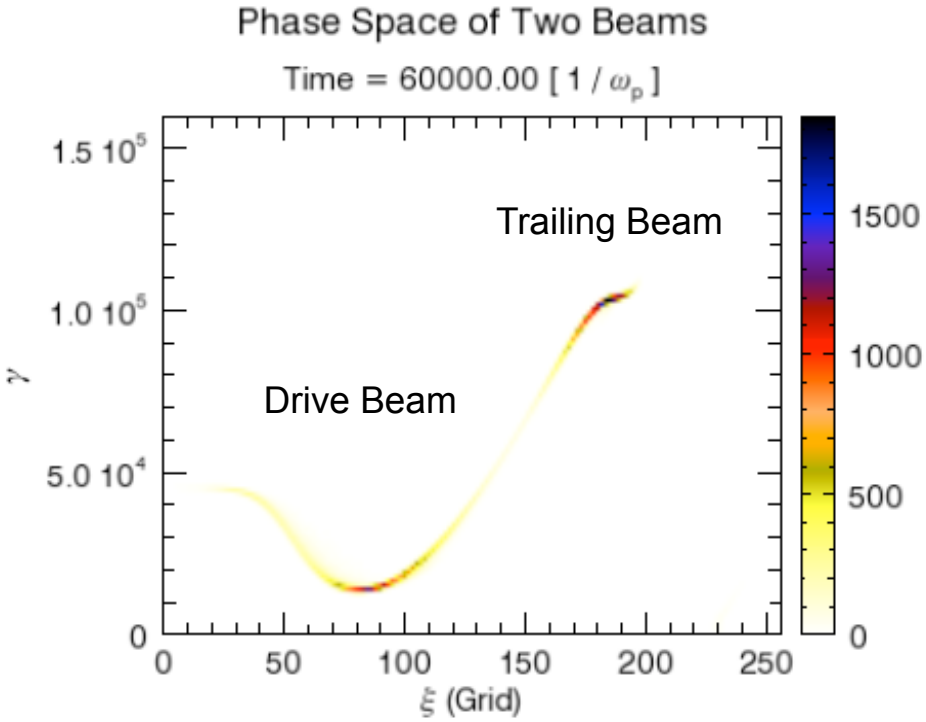
Drive Beam : σ_r = 10 μm , σ_z = 34.1 μm , N_1 = 9.57 x 10^9, ε = 100 mm·mrad
Trailing Beam: σ_r = 10 μm , σ_z = 19.3 μm , N_2 = 4.33 x 10^9 , ε = 100 mm·mrad
Distance between two beams : 130 μm Plasma Density : 3.7 x 10^{16} cm^{-3}

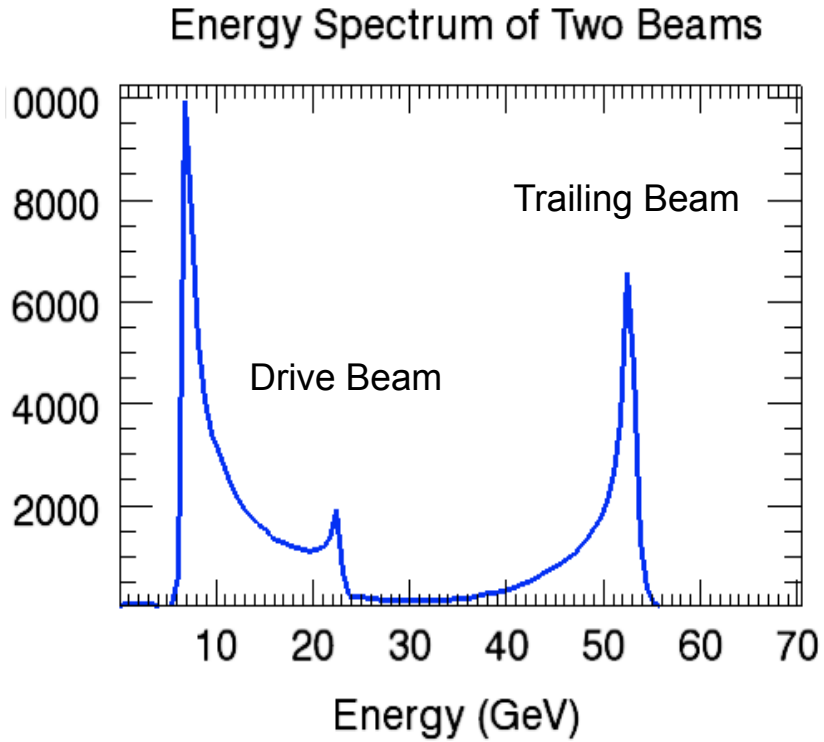
see J. Frederico WEP042

Two-bunches in Pre-formed Cs Plasma

- After 143 cm of plasma
  - Energy Gain 30 GeV
  - Energy Spread ~ 5%
  - Energy Loss 17 GeV, Beam loading efficiency 64%

see W. An MOP016



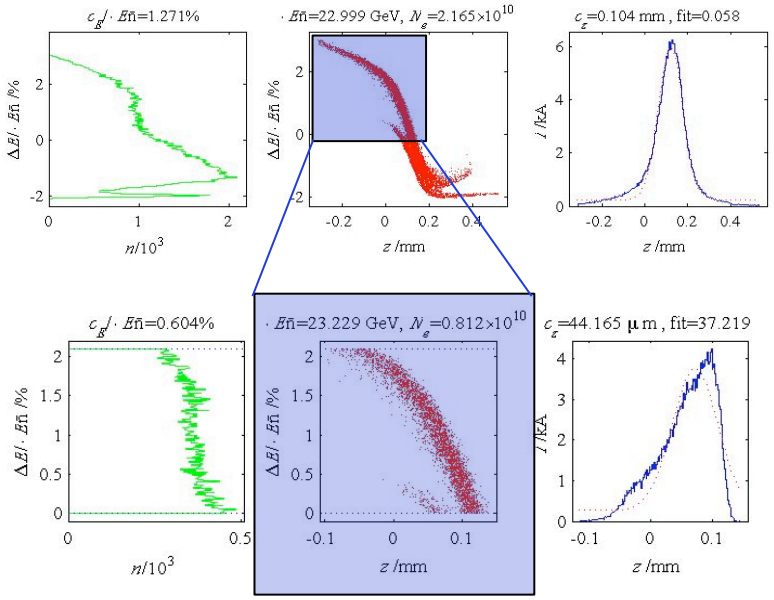


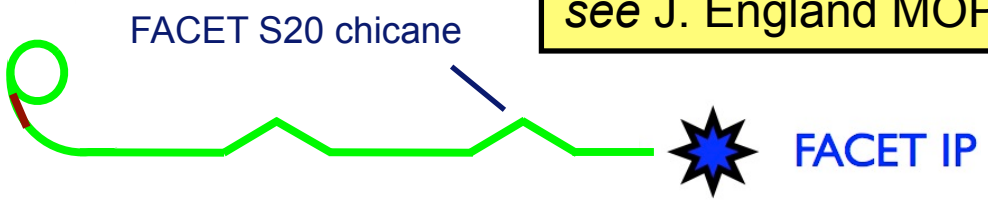
Drive Beam : σ_r = 10 μm , σ_z = 34.1 μm , N_1 = 9.57 x 10^9, ε = 100 mm·mrad

Trailing Beam: σ_r = 10 μm , σ_z = 19.3 μm , N_2 = 4.33 x 10^9 , ε = 100 mm·mrad

Distance between two beams : 130 μm Plasma Density : 5.0 x 10^{16} cm^{-3}

Use High Transformer Ratio to Maximize Efficiency and Energy Gain per Stage





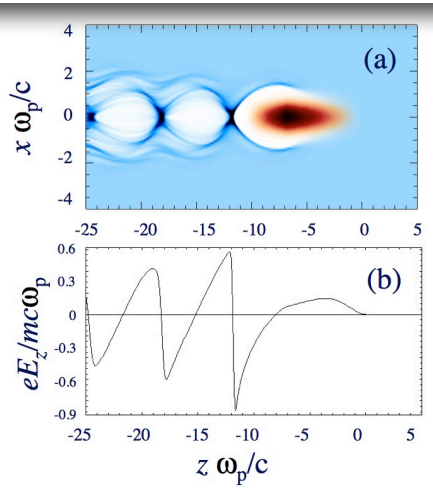
see J. England MOP088

Due to upstream compression, need R56 = T566 = 0 in dogleg
Collimators (part of existing design) can remove low-E tail.

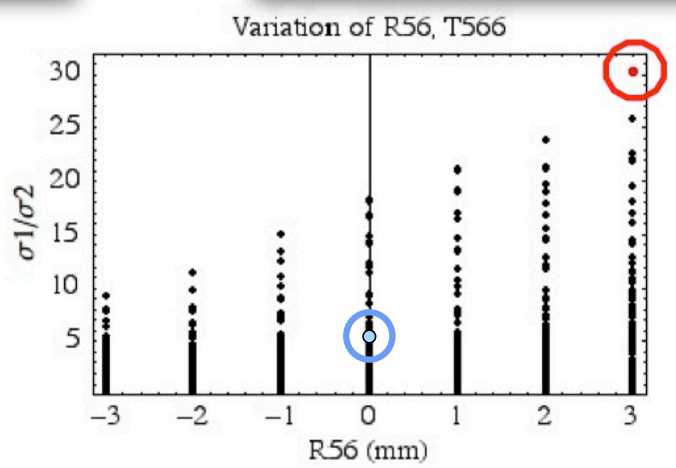
Ramped bunch has L = 200 μm ; Ipeak = 4 kA ; n_b/n_0 = 7
Transformer Ratio = 10 for plasma n_0 = 3x10^{17} cm^{-3}

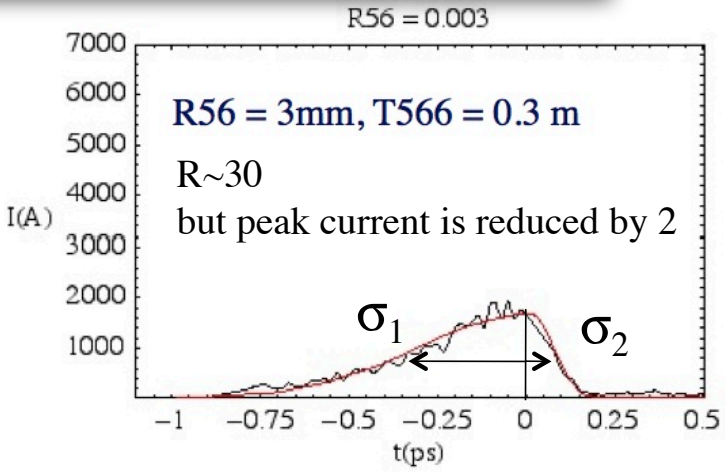
see W. Lu MOP103

QuickPIC gives unloaded T=6



Beamline & collimator optimization ongoing

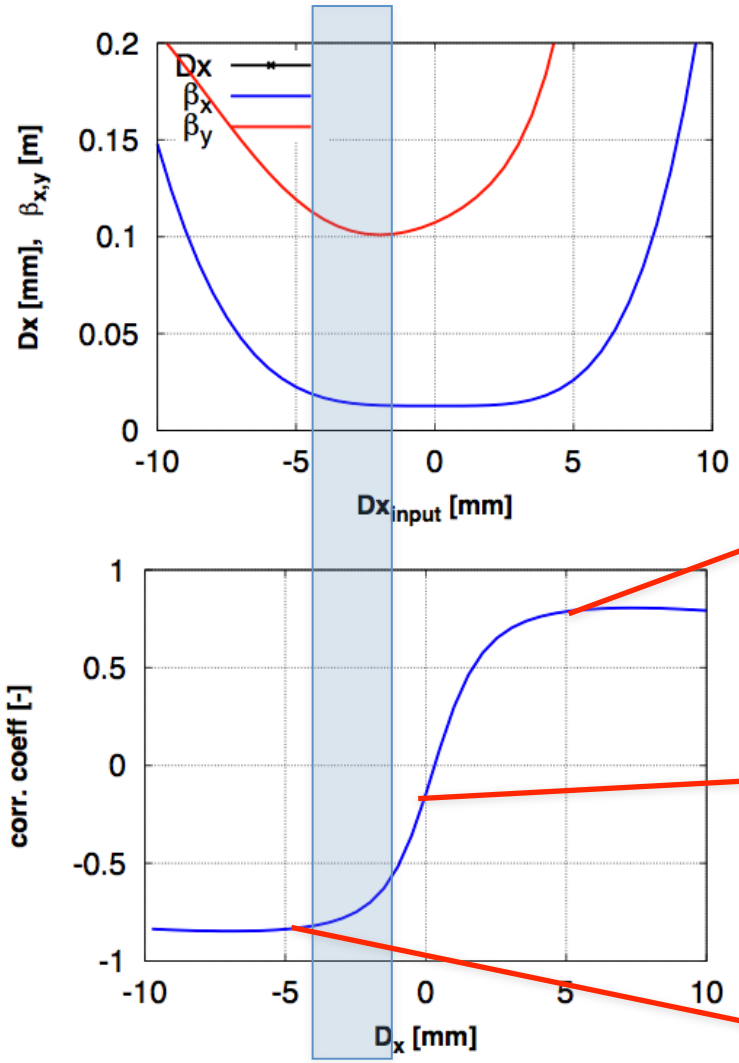




- Open questions: pre-ionized plasma, witness bunch, hosing...

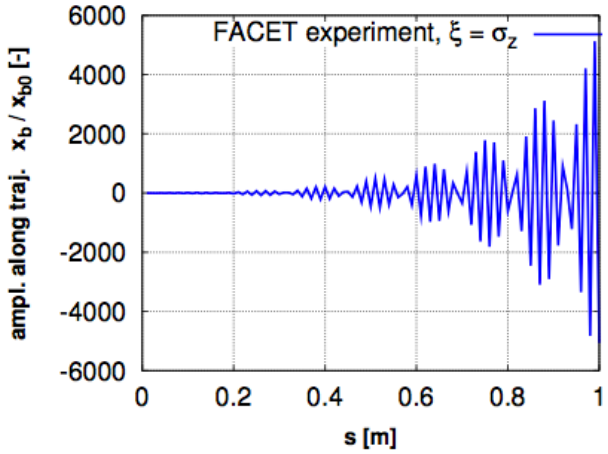
Investigating the Hosing Instability at FACET

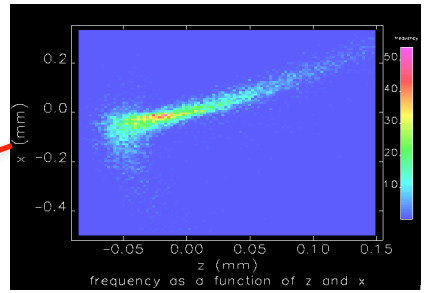
Using dispersion knobs to induce z-x correlation.



Optics functions and z-x correlation as function of induced dispersion.

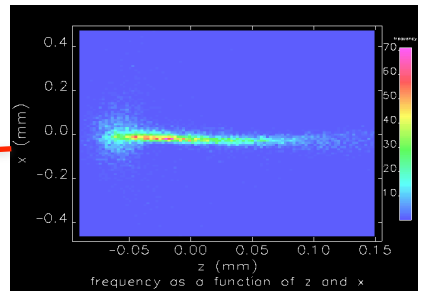
FACET : new parameter regime. (A ~ x2 higher than E167). Potential large and observable amplification of transverse tilt :



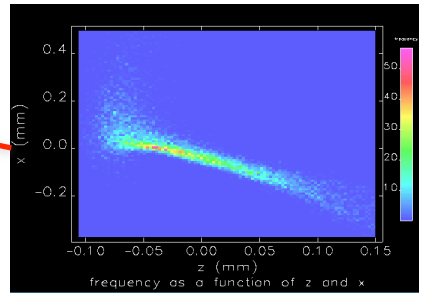


D=5 mm, corr = 0.79
x_{b0} ~ 50 μm

see Y. Nosochkov MOP090



D=0 mm, corr = -0.14
x_{b0} ~ 0 μm

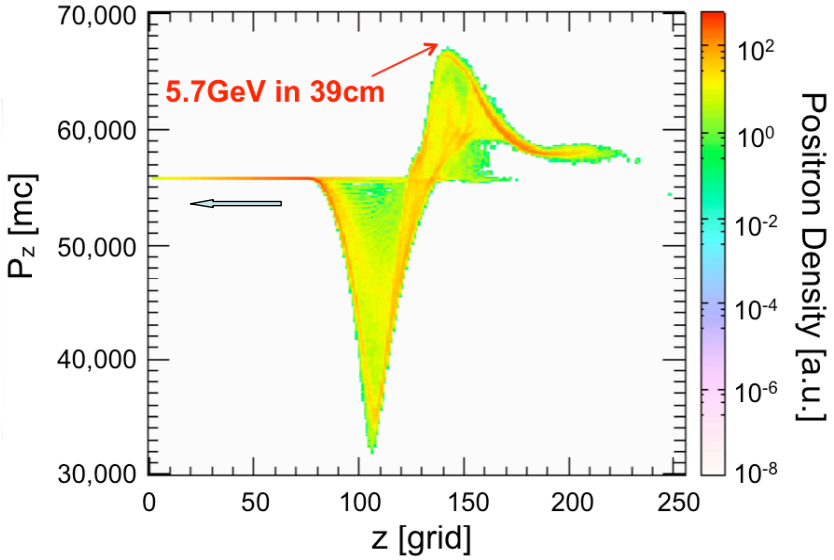


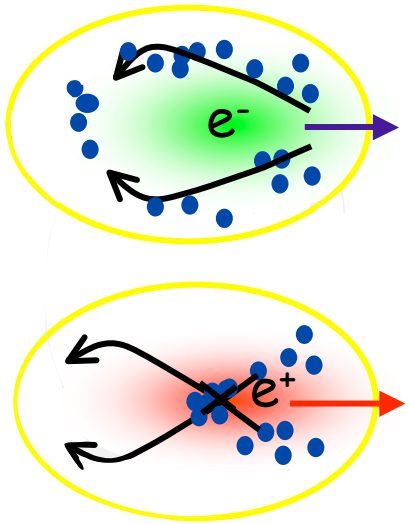
D = -5 mm, corr = -0.84
x_{b0} ~ -50 μm

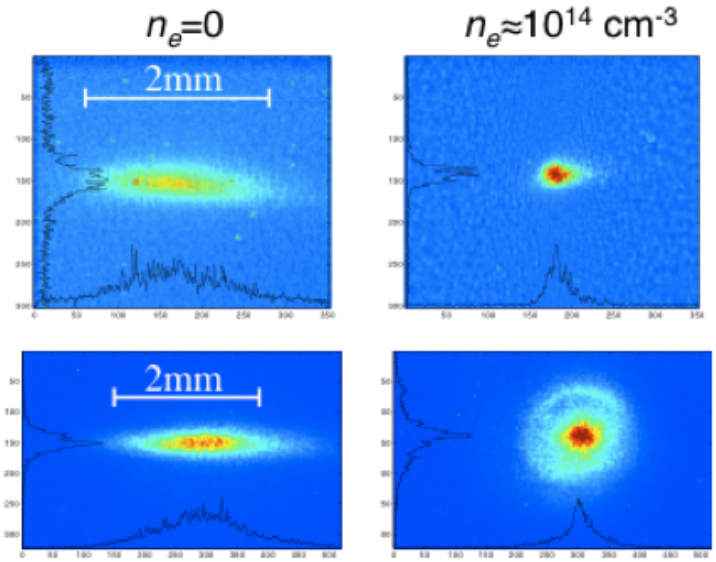
z-x plots (Gaussian input beam)

FACET Will Allow PWFA with Compressed Positron Bunches for the First Time

QuickPIC simulation, σ_z=15μm, N=2x10^{10}e$^-$, σ_r=10μm, n_e=2x10^{17}cm^{-3}, E_0=28GeV





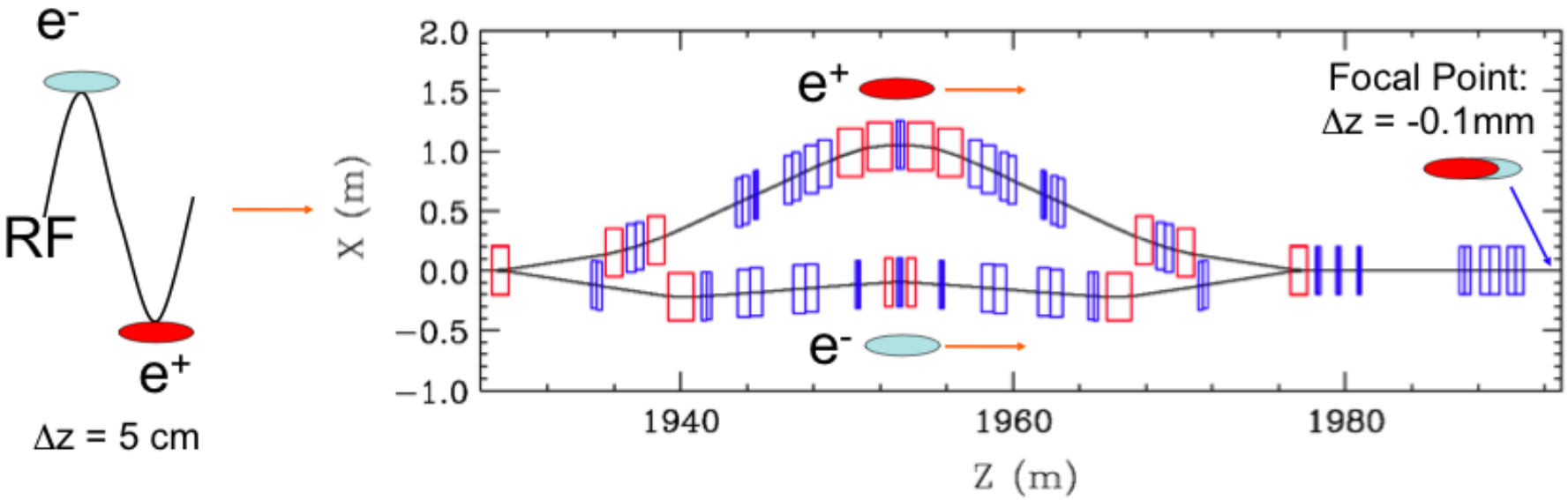


Phys. Rev. Lett. ***101***, *055001 (2008)*

- Accelerating gradient ~ 15GeV/m
- Large energy spread
- Emittance growth (transverse, longitudinal field variations)
- Opportunity for new ideas, original solutions...
- Acceleration of e+ on e- driven wake?

FACET Design is Forward Looking and Flexible, e.g. Sailboat Chicane Upgrade

- Extract e^- & e^+ from damping rings on same linac pulse
- Accelerate bunches to sector 20 while 5.25 cm apart
- Use 'Sailboat Chicane' to put them within 100μm at entrance to plasma



Opens up many new avenues of research:

- Positron acceleration on electron driven wakes
- Platform for evaluating proton driven PWFA concept

see S. Pinkerton MOP106

Summary

- FACET will provide high energy density electron and positron beams unique in the world (23GeV, 3nC, >20kA, <10μm) primarily to study plasma wakefield acceleration
- Beam parameters are well suited for next generation PWFA experiments:
  - Beam loading in non-linear regime
  - High transformer ratio with shaped bunches
  - Positron acceleration (w/ electron or positron drivers)
- User assisted commissioning this summer (2011)
- CD-4 end of 2011 with first official user run early 2012
- FACET expected to operate 4 months/year for 5 years
- FACET PWFA program will demonstrate key components of single plasma cells for PWFA driven X-FELs and linear colliders
- *Questions?* Drop by the FACET Satellite Meeting T 6-8PM