First results from the plasma wakefield acceleration transverse studies at FACET

Erik Adli (University of Oslo, Norway and SLAC)

For the FACET E200 collaboration :

M.J. Hogan, S. Corde, R.J. England, J. Frederico, S.J. Gessner, S. Li, Z. Wu, M.D. Litos (SLAC, Stanford, USA),

C. Joshi, W. An, C.E. Clayton, K.A. Marsh, W. Mori, N. Vafaei-Najafabadi

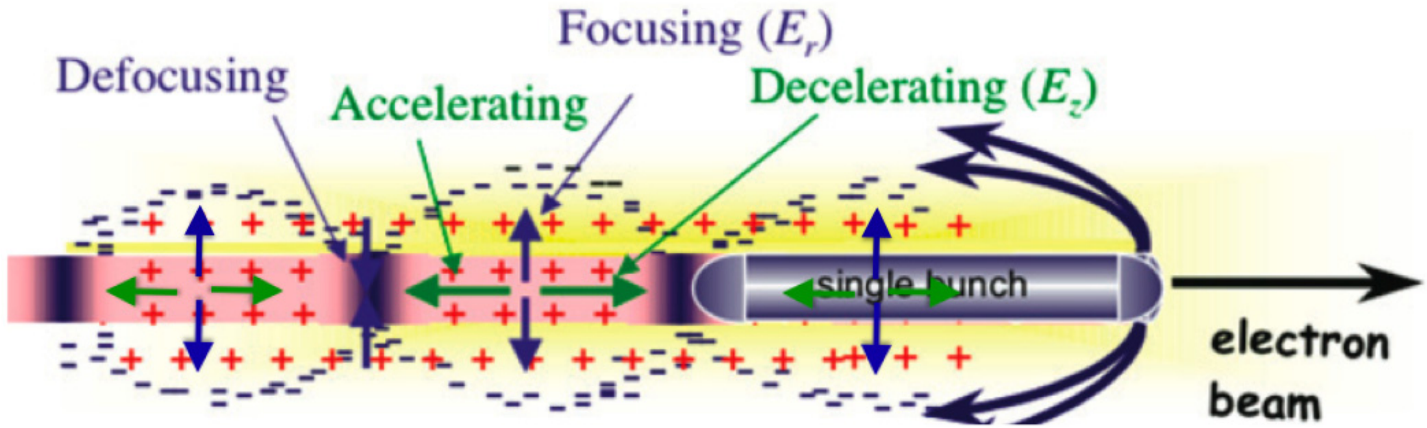
(UCLA, Los Angeles, USA), W. Lu (Tsinghua Univ. of Beijing, China and UCLA)

P. Muggli (MPP, Munich, Germany)

3rd International Particle Accelerator Conference IPAC'12

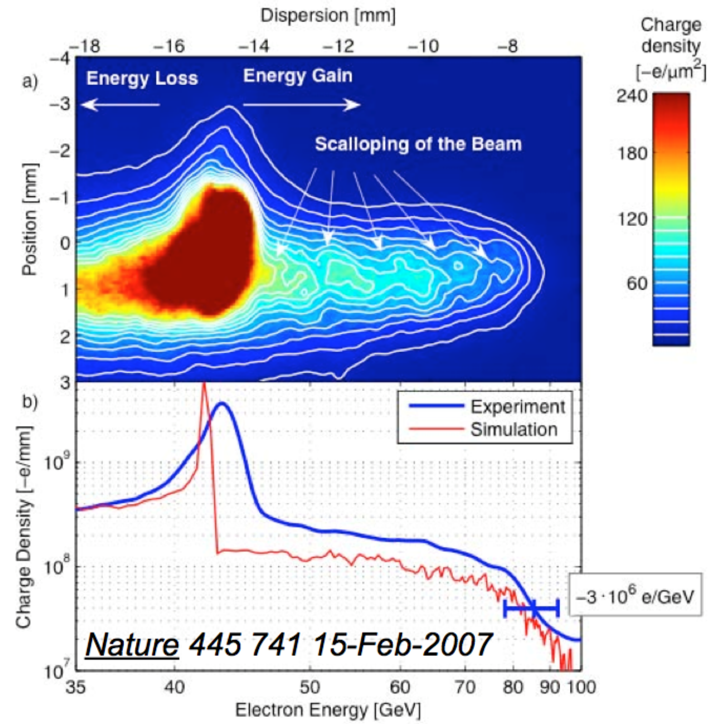
New Orleans, USA, May 21, 2012

Beam-driven plasma-wake field acceleration



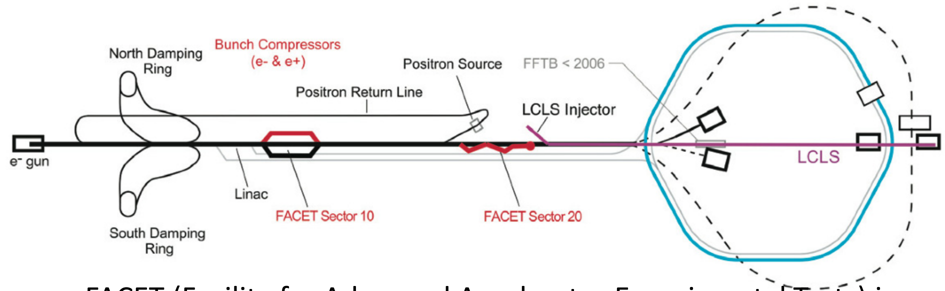
Principle of beam-driven plasma-wakefield acceleration (PWFA) :

- Plasma wave/wake excited by relativistic particle bunch
- Blow-out regime: complete blow out of plasma electrons; leaving "bubbles" with positive ions. Requires a beam density significantly higher than the plasma density
- Decelerating field at head of bubble extracts energy from bunch
- Accelerating fields will accelerate particles at the back of bubble
- Quadrupolar 1/r focusing fields (x and y) within the ion bubble
- Beam creates the ion bubble (accelerating cavity). Therefore beam-cavity alignment is not an issue in PWFA
- Typical: n_p~10^{17} /cm^3, λ_p~100 μm, G>MT/m, E>10 GV/m



Experimentally demonstrated at SLAC FFTB: 42 GeV energy gain in 85 cm of plasma

The E200 PWFA experiment at FACET

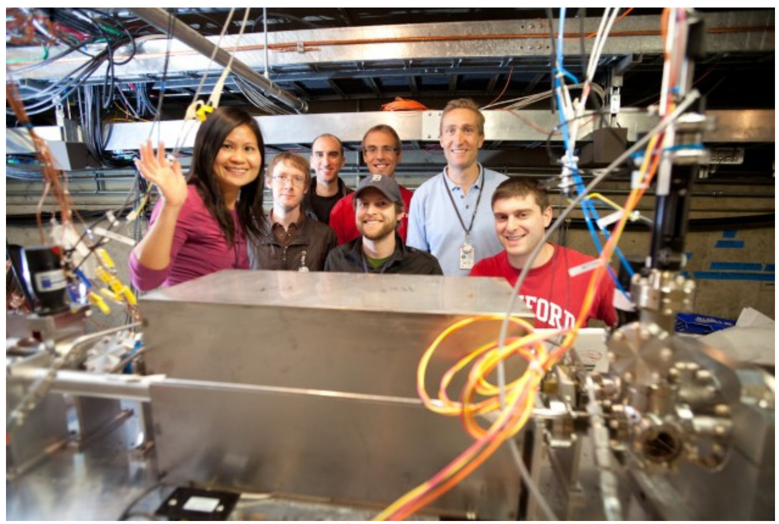


See FACET poster: C. Clarke, WEPP010

- FACET (Facility for Advanced Accelerator Experimental Tests) is a new User Facility at the SLAC National Accelerator Laboratory.
- High charge, highly compressed beams makes FACET **the ideal location for beam-driven PWFA.**
- The E200 experiment studies interaction of intense electron and positron beams with a dense plasma. In 2012 a Lithium heat-pipe oven without pre-ionization is installed, in 2013 a pre-ionizing laser will be available. The FACET beam must thus ionize the Lithium gas.
- The first User Run started in spring 2012 with 20 GeV, 3 nC electron beams.

FACET design parameters :

Energy	23 GeV
Charge	3 nC
Bunch Length σ_Z	20 μm
Spot Size σ_r	10 μm
Peak Current	22 kA
Species	e^- & e^+



The SLAC based-part of the E200 experiment team

E200 main study goals :

- Drive-witness bunch experiments (two-bunch acceleration)
- Plasma wake beam-loading
- Head-erosion
- High transformer ratios
- Betatron radiation
- **Transverse studies and instabilities**

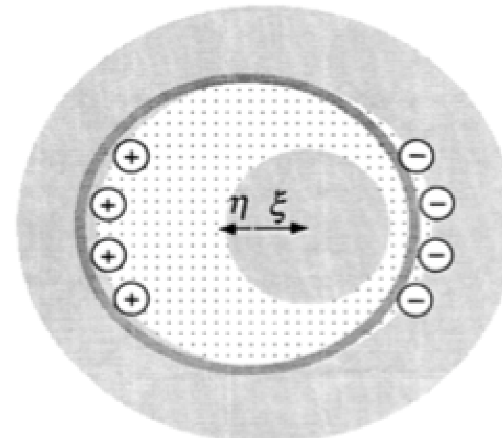
In this talk we focus on E200 transverse electron instability studies, in the single bunch blow-out regime.

The electron hose instability

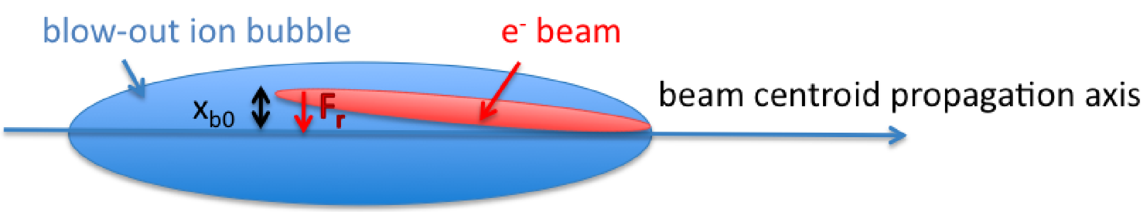
Basic hosing theory : coupled motion of an electron beam off center in a ion-channel and the surrounding plasma sheath electrons. Leads to **an instability growing along propagation in channel, s, and along bunch, ξ**. First estimates of growth factor, *Whittum et al. PRL 67, 991 (1991).* Asymptotic form :

$$x_b(s,\xi) = 0.34 x_{b0}(\xi) e^{A} \cos(k_\beta s - A/\sqrt{3} + \pi/4)/A^{3/2}$$

$$A(s,\xi) = 1.3[(k_\beta s)(\omega_0 \xi)^2]^{1/3}$$



From Whittum et al. [PRL 67, 991]

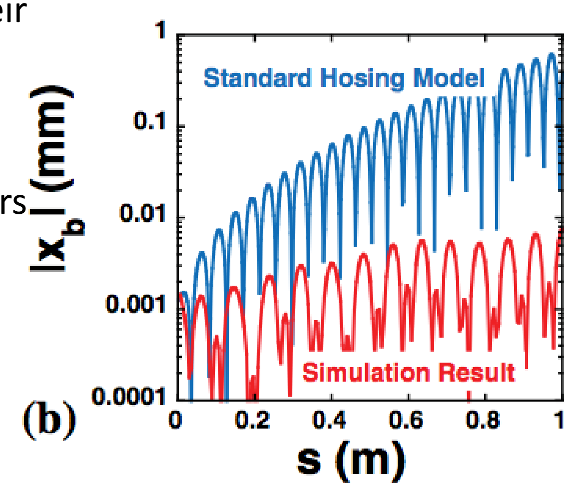


Unlike regular linac Beam-Break Up : cannot be mitigated by BNS-damping or their like (k_β, ω_0 given by plasma). Early estimates indicated a severe limitation for ion-channel beam propagation; blue curve.

Non-linear hosing theory developed later at UCLA, *Dodd et al. PRL 88, 125001 (2002) C. Huang et al. PRL 99, 2550012 (2007)*, found significant mitigating factors for the instability:

$$A(s,\xi) = 1.3[c_r c_\psi (k_\beta s)(\omega_0 \xi)^2]^{1/3}$$

The mitigating factors, c_r c_ψ are < 1 for the cases the channel radius varies along the beam ("non-adiabatic regime") and the contribution of the magnetic field originating from large electron plasma axial velocity becomes significant ("relativistic regime"); red curve. PWFA at FACET fulfills both criteria.



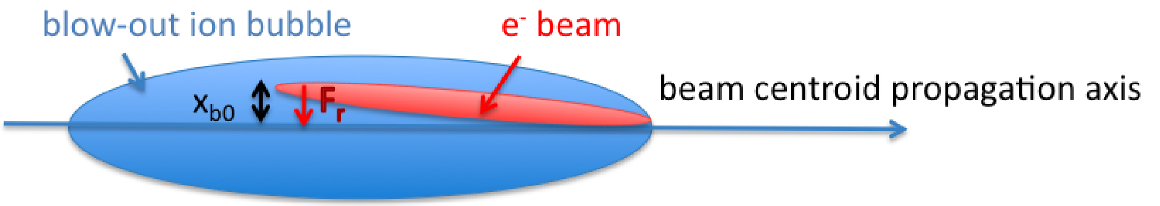
Hosing growth for FACET-like parameters. From Huang et al. 99, 2550012 (2007)

E200 transverse instability studies

Status of the PWFA electron hose instability work :

- Recent work shows hosing less severe than previously thought. Still, the electron hose instability will put tolerances for beam tilt angle, with possible implications for demanding applications like linear colliders and light sources
- Non-linear theory can give estimates for hosing growth for simple scenarios. Particle-in-cell simulations (PIC) of the coupled system beam-plasma covers more realistic scenarios
- However, the electron hose instability has never been benchmarked in a systematic way

The E200 collaboration seek to benchmark the electron hose instability experimentally.
Method : controlling the tilt angle of the beam entering the plasma, and observing the amplification of oscillations due to hosing

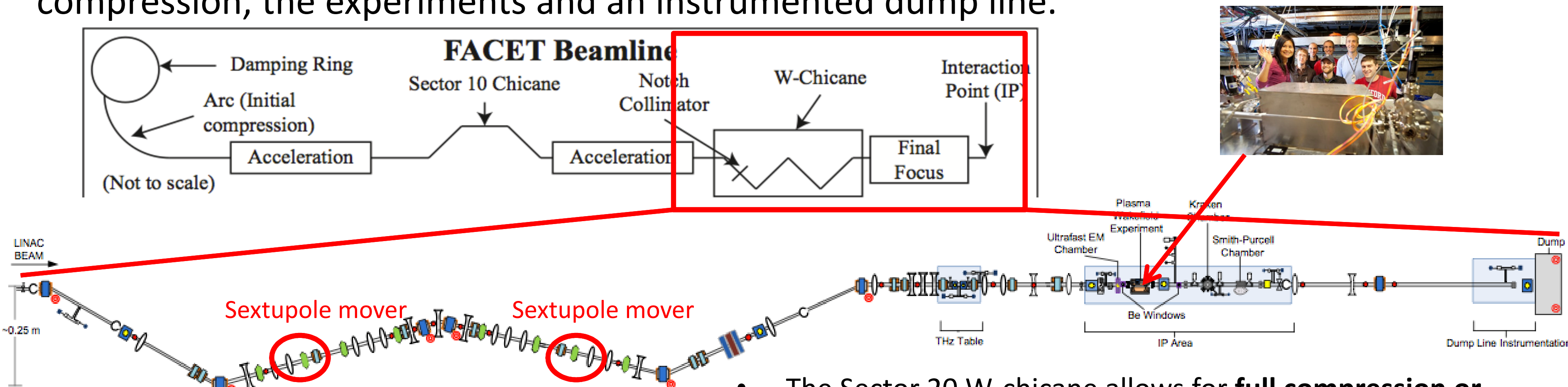


In the following slides we will cover :

- E200 experimental set-up
- Parameter choices and PIC simulation results
- Discussion of a transverse effect observed in simulations; to our knowledge not described by earlier PWFA theory
- Experimental status of the E200 experiment at FACET and the next steps

FACET experimental area

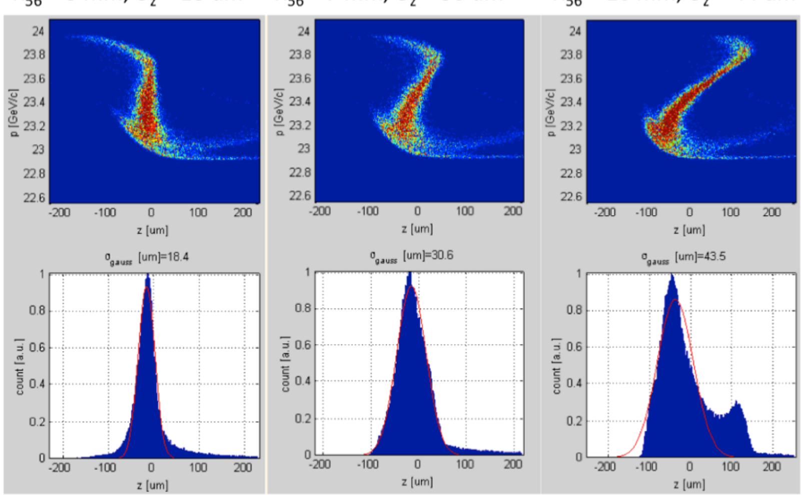
The FACET Sector 20 experimental area consists of a flexible W-chicane for longitudinal compression, the experiments and an instrumented dump line.



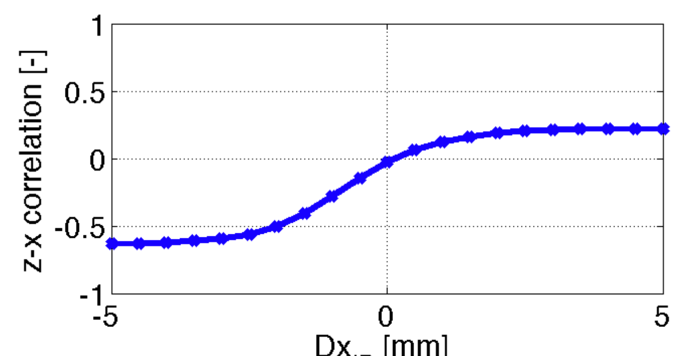
- The Sector 20 W-chicane allows for **full compression or over/under compression** at the plasma interaction point (IP).
- Two chicane sextupoles (in anti-phase) are mounted on 2D movers. Moving the two sextupoles anti-symmetrically horizontally changes the IP dispersion, D_x, with other parameters unchanged to 1st order. This allows for **dispersion control and bunch z-x correlation the IP**.

FACET Sector 20 chicane settings

R_{56} = 5 mm, σ_z = 18 um R_{56} = 7 mm, σ_z = 30 um R_{56} = 10 mm, σ_z = 44 um



z-p phase-space (top) and charge distribution (bottom) at the plasma IP

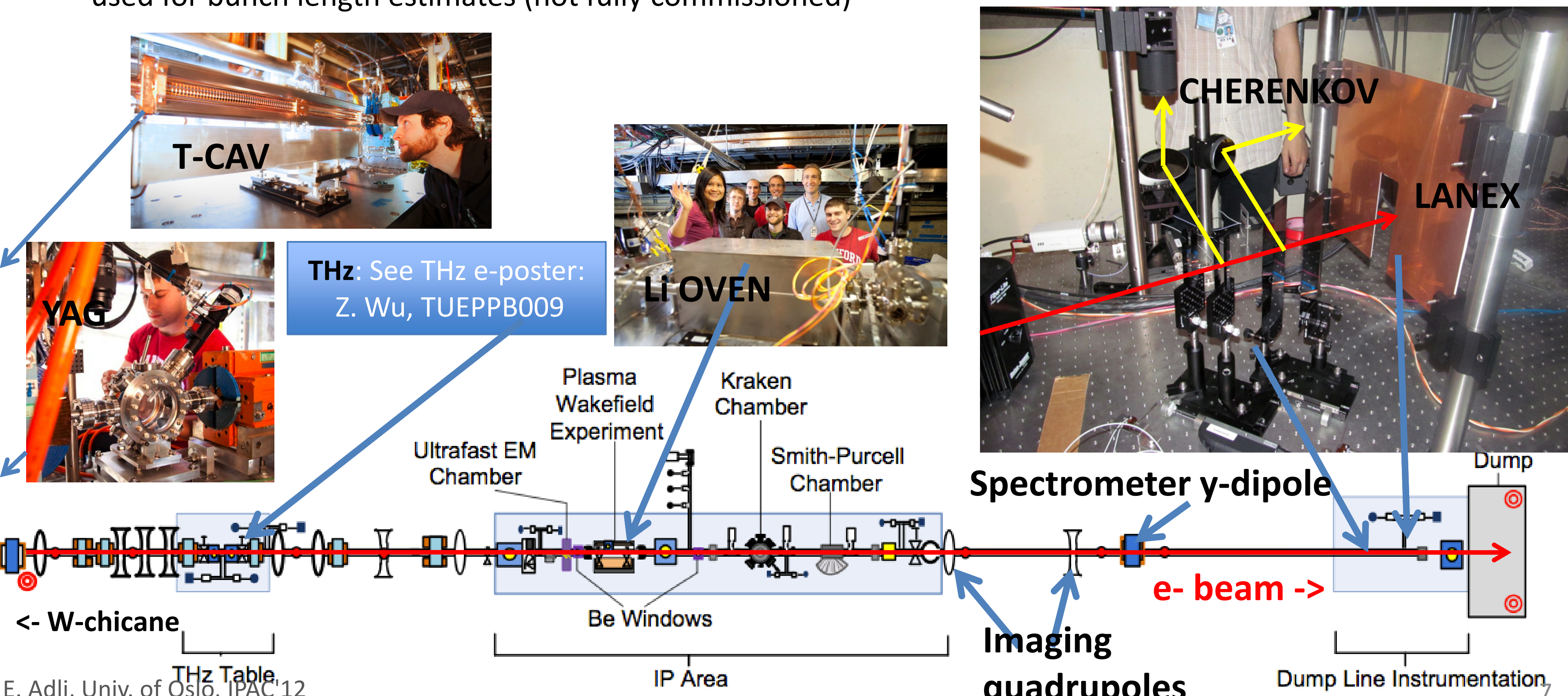


z-x versus D_x for R_{56} = 10 mm

E200 experimental set-up

The E200 experimental set-up downstream of the W-chicane includes :

- a Lithium oven; potentially to be exchanged by a Rubidium oven.
- a YAG crystal x-ray spectrometer to measure the initial beam energy spread
- a lanex screen to observe betatron radiation
- a Cherenkov light based vertical spectrometer with imaging magnetic quadrupoles
- OTRs upstream and downstream of the oven to take out pulse to pulse jitter
- a THz radiation generation table (non-intrusive) and a transverse deflecting cavity (intrusive) will be used for bunch length estimates (not fully commissioned)



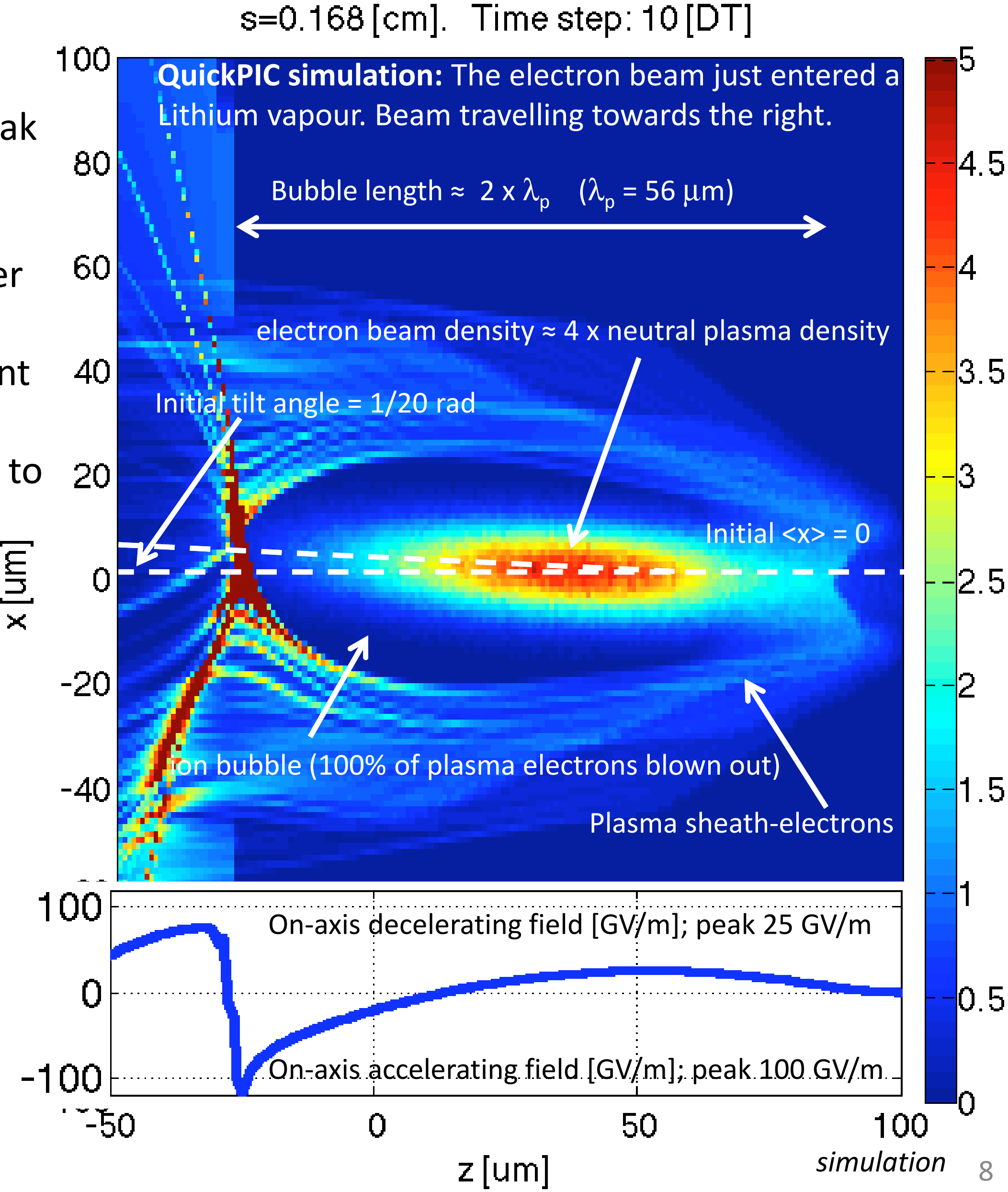
Choice of beam and plasma parameters

Multiple constraints :

- Beam space-charge field must be intense enough to field-ionize the plasma (large peak current I_{peak})
- Bunch must sample both decelerating and accelerating wake (bunch length same order of the ion-bubble length)
- Bunch can not be fully compressed; we want over-compression for tilted beam
- To reach blow-out regime we need a beam to plasma ratio $n_b / n_0 > 1$

Suggested transverse studies working point :

- E = 20 GeV
- Chicane R_{56} = 7 mm; σ_z = 30 um
- beam spot sizes and emittances: as small as possible (maximize ionization and minimize head-erosion)
- For the simulation studies, based on FACET beam commissioning preliminary targets, we use σ_r = 20 um, $\varepsilon_{N,\{x,y\}}$ = {550, 55} um
- This results in I_{peak}= 13 kA and $n_b / n_0 \sim 4$

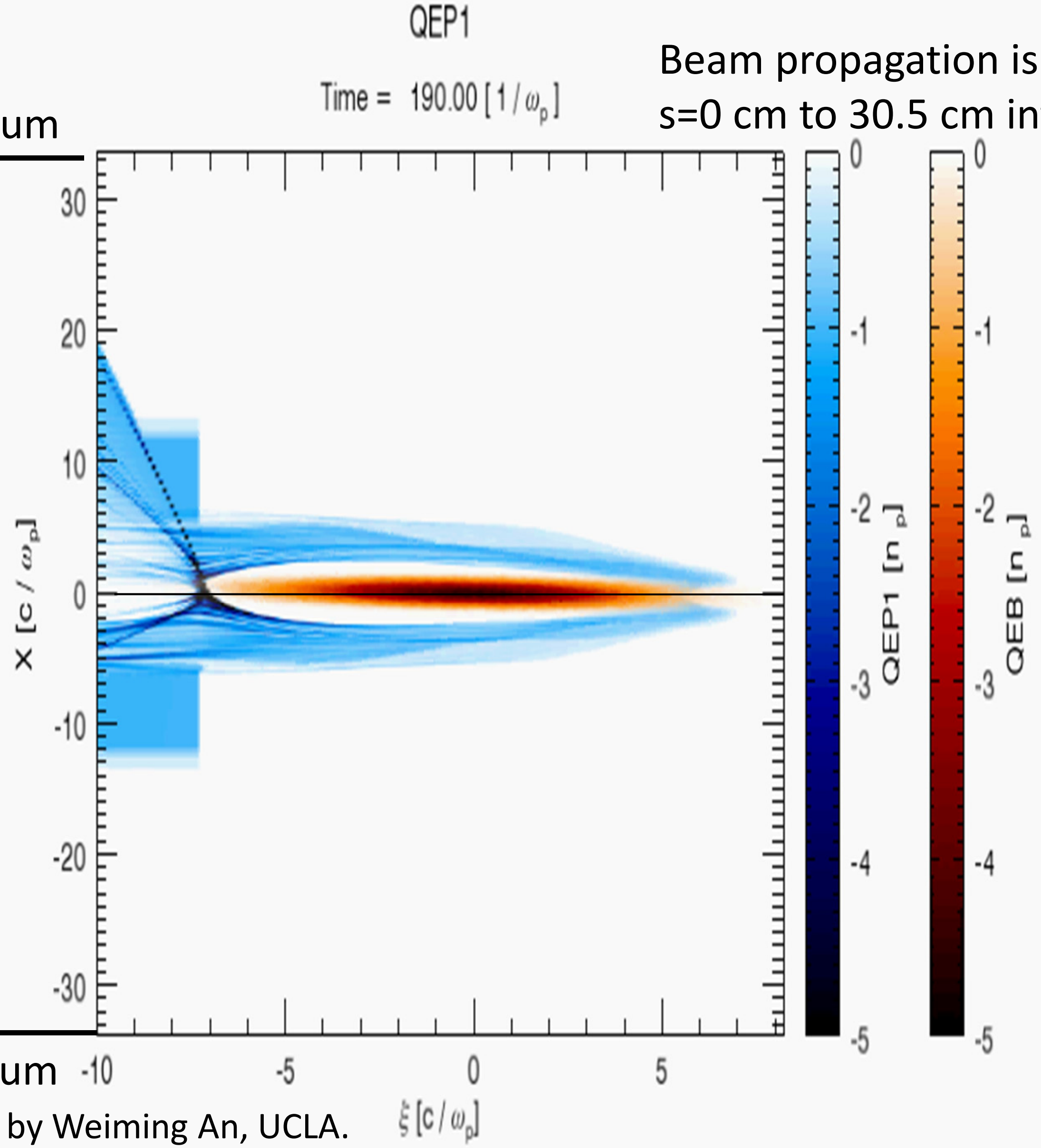


simulation

QuickPIC simulation: FACET bunch in field-ionized Li plasma

Beam propagation is from
s=0 cm to 30.5 cm into the plasma

x = +100 um



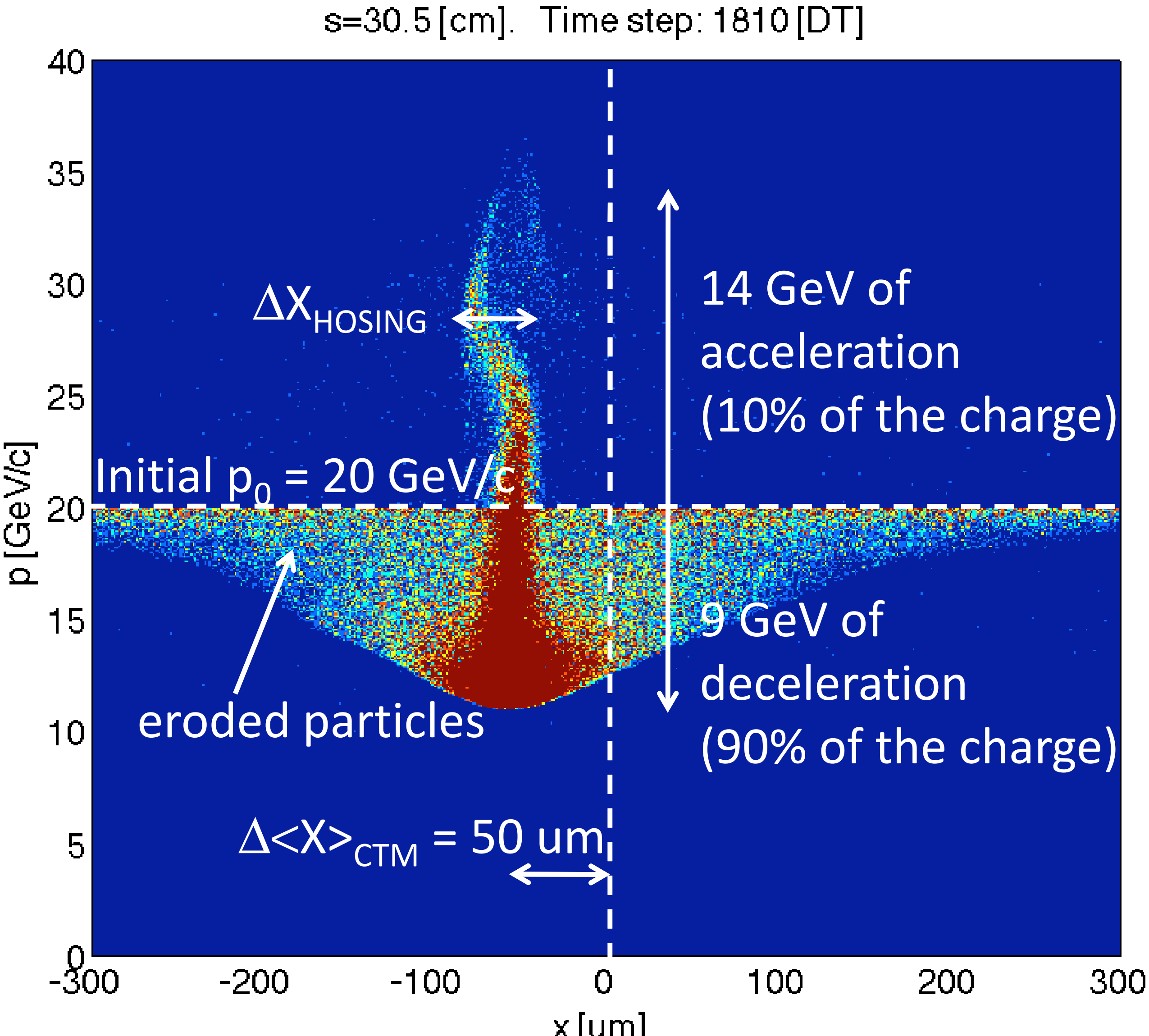
x = -100 um

e- beam travelling towards the right, through a Li vapour, ionizing the Li and blowing out the plasma electrons.

Beam is matched to plasma in the horizontal plan. Not matched and breathing in the vertical plane. (Assumed a factor 10 higher vertical than horizontal beta function at FACET IP).

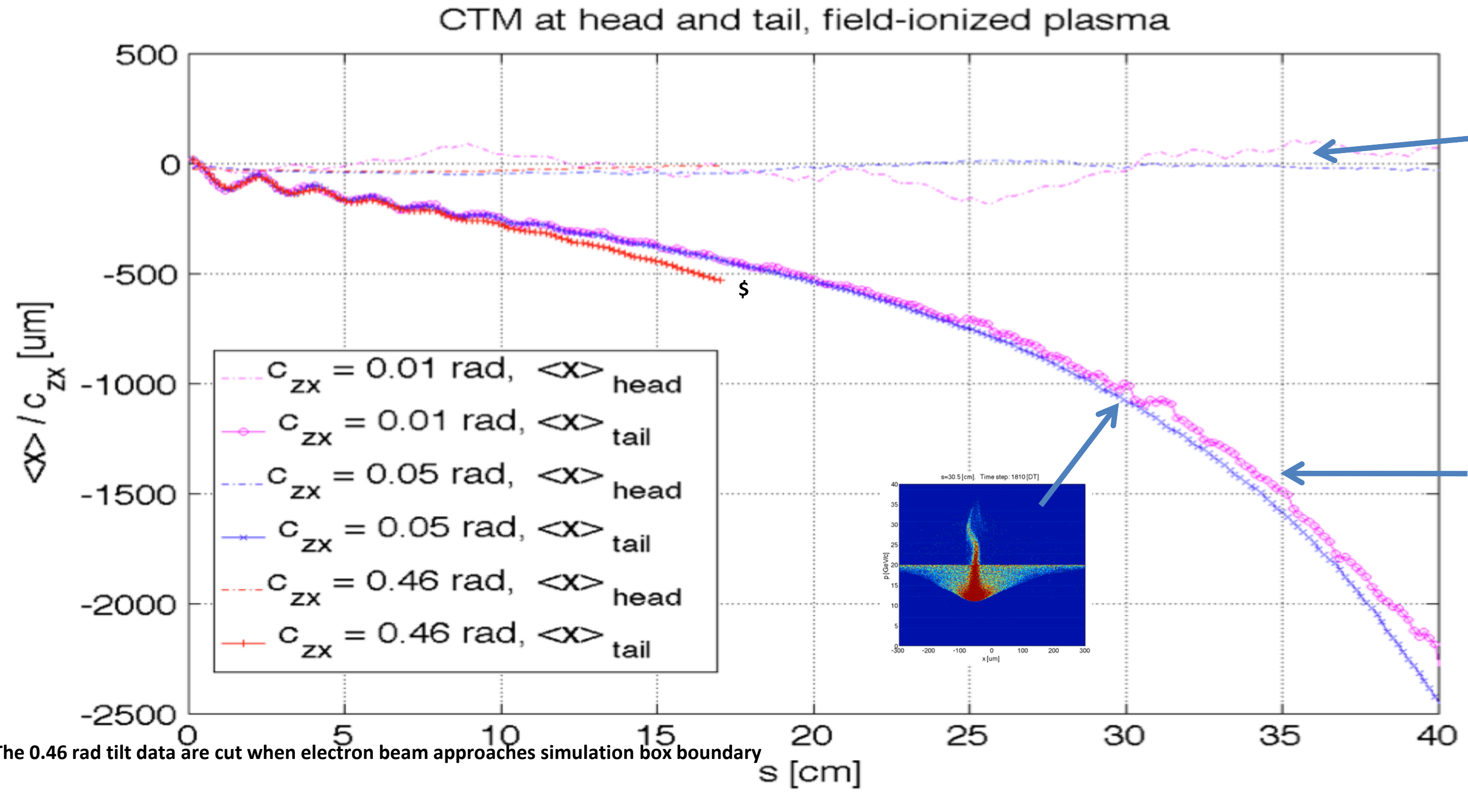
Movie generated by Weiming An, UCLA.
All QuickPIC simulations are performed on the Hoffman2 Cluster at UCLA.

x-p phase-space of electron bunch after 30 cm propagation



The simulated x-p phase-space just after the plasma exit (30 cm flat top).
The x-p phase-space will be imaged at the Cherenkov spectrometer. *simulation*

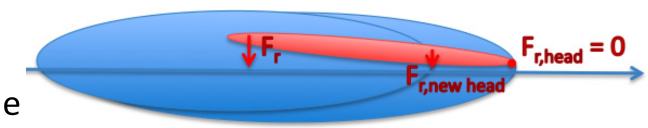
Observation of a coherent transverse motion (CTM)



$ The 0.46 rad tilt data are cut when electron beam approaches simulation box boundary

- **This coherent transverse motion is to our knowledge not described by earlier PWFA theory.** We have performed tests to rule out whether motion is a simulation artifact.
- The CTM is reproduced by the momentum-conserving 3D PIC code Osiris.
- The CTM seems to be proportional to the tilt angle.
- The magnitude depends strongly on the beam parameters like emittance and charge profile; for low emittance beams we observe small or no CTM
- The CTM is not present in a two-bunch scenario with an offset witness bunch
- We still work on a complete physical understanding of the CTM; we believe the motion might be linked to the fact that while the head of the beam erodes, the new head of the beam picks up a transverse momentum from betatron motion.

CTM:
Will be benchmarked experimentally at FACET

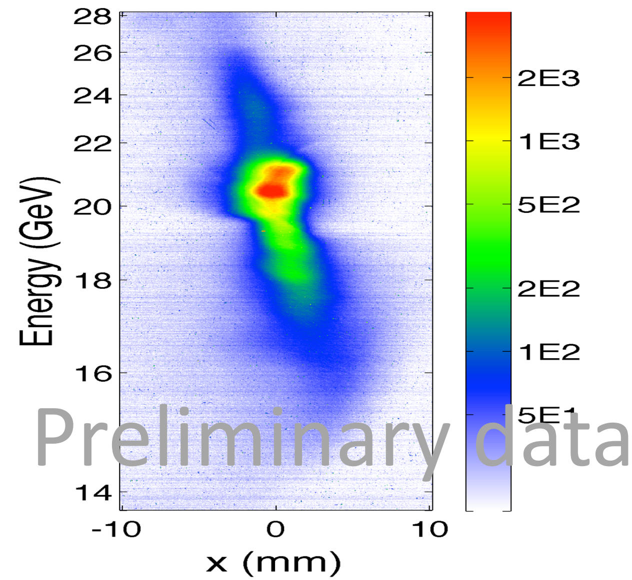


simulation

Experimental status

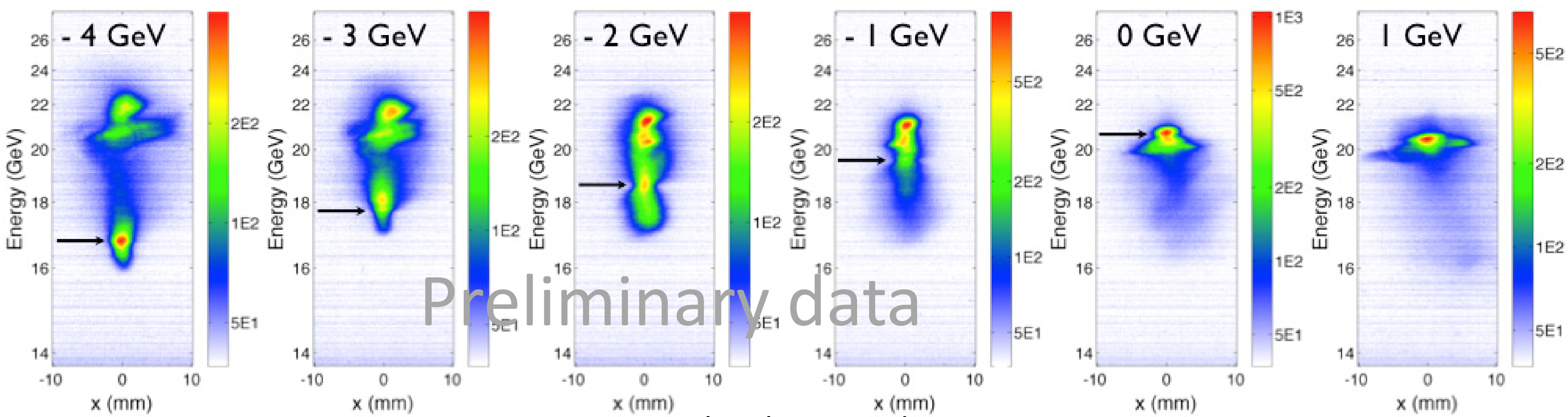
E200 first experimental run started Apr 27, 2012

Some preliminary first results from May 2012 are presented here.



Left: fraction of electron bunch is decelerated by up to 4 GeV. Small fraction accelerated by up to 5 GeV, corresponding to a gradient > 10 GV/m. The Li column FWHM was 24 cm. The FACET beam conditions for this plot corresponds to the best we have had so far; not always reproducible. The tilt may be linked to a tilt at the diagnostics present during the first run week.

By varying the imaging energy of the imaging quads we can focus onto the different energy particles. This confirms that the tails observed are actually declaration and acceleration :

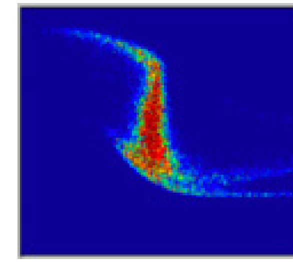


Plots by S. Corde

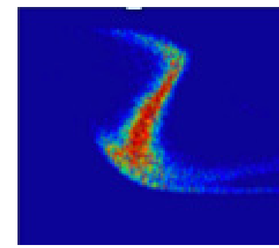
experimental data

Steps towards completing the transverse studies

Experimental conditions are not yet at the stage where we can benchmark hosing nor CTM, however, steady improvement is expected during the FACET experimental run.



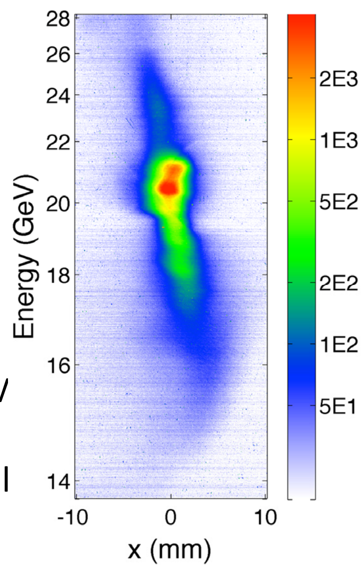
Current z-p correlation



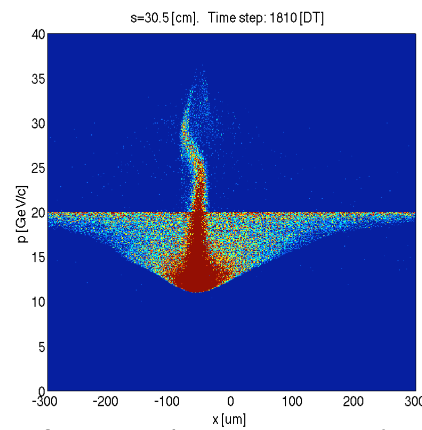
Desired z-p correlation

The following steps must be completed towards transverse study experiments :

1) FACET beam currently optimized for short bunch length (peak compression to ensure ionization and blow-out). To vary the z-x tilt using dispersion knobs, an over-compressed beam is needed (z-p correlation) with small (< 20 um) spot sizes.
2) The FACET dispersion need to be controlled to a better level; at the time of the first E200 experiments significant dispersion were leaking out of the IP.
3) Better levels of ionization and smaller emittances (less head-erosion) is needed to benchmark the PIC simulations results with experiment.
4) Pre-ionized plasma will relax some experimental parameters; will be available in 2013.



Experiment: a few GeV deceleration and acceleration for a small fraction of the charge



Simulation: about 12 GeV deceleration and 14 GeV acceleration, for a significant percent of the charge.

See FACET machine talk: G. Yocky, MOOAB02 (next talk!)

See also FACET posters: J. Frederico, TUPPC051 A. Latina, TUPPR029

Conclusions

- Theory and PIC simulations give predictions for PWFA electron hosing which we seek to benchmark against experiments in FACET
- PIC simulations show a coherent transverse motion in PWFA for tilted beams. Needs to be fully understood. Will be benchmarked against experiments in FACET
- The E200 experiment at FACET is up and running with its hardware mostly commissioned
- We have observed first ionization, deceleration and acceleration of > 10 GV/m, within a single electron bunch
- To perform transverse studies : need an over-compressed bunch; better dispersion control and better ionization and emittances

Acknowledgements

- We acknowledge gratefully the strong support of the FACET machine team and the always helpful omnipresent FACET User Manager Christine Clarke
- We have greatly appreciated stimulating discussions with Alex Chao and Jean-Pierre Delahaye
- All QuickPIC simulations are performed on the Hoffman2 Cluster at UCLA