First Measurements PWFA (E-200)

Goals:
Install hardware
Have an experiment running
Repeat energy gain with single/maximum compression e- bunch (FFTB)

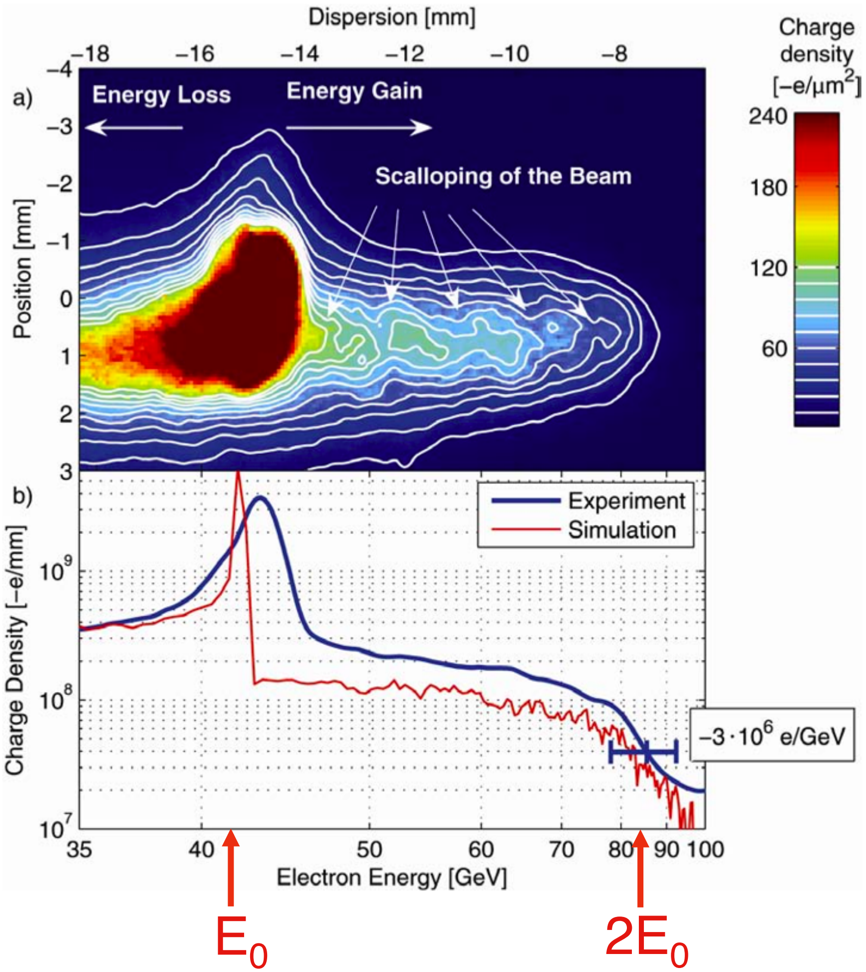
Future:
Drive-witness bunch in pre-ionized (laser) plasma

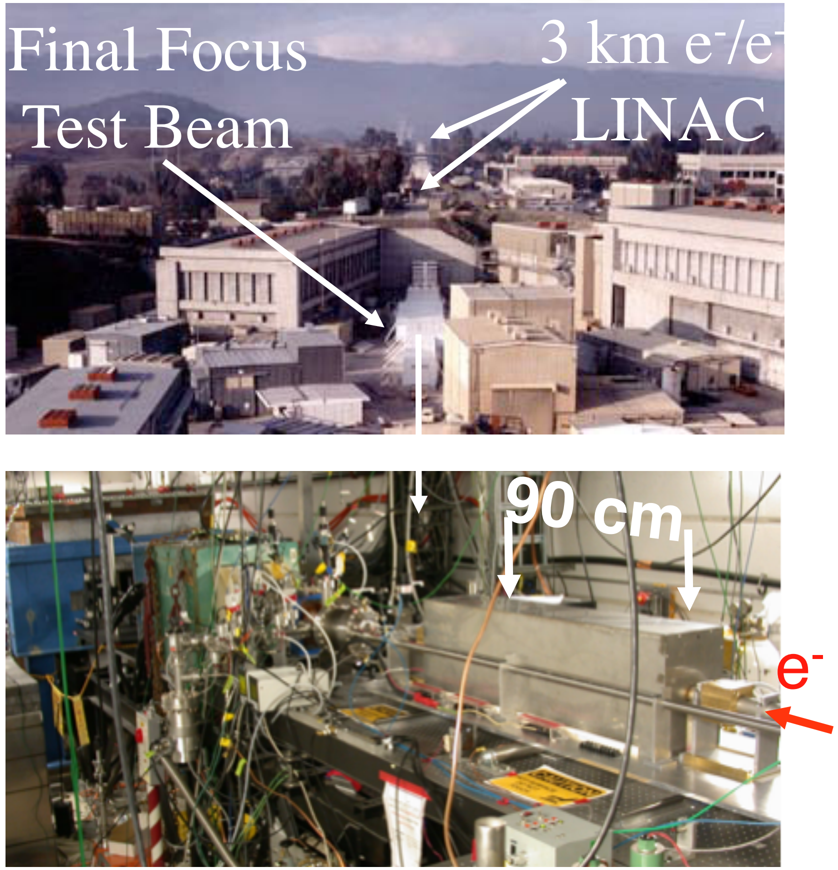
In the past:
Takes 2-3 weeks in “working” FFTB PWFA lab to get results.

e^- ENERGY DOUBLING

Blumenfeld, Nature 445, 2007

E_0=42 GeV, $\sigma_z \approx 25\ \mu m$

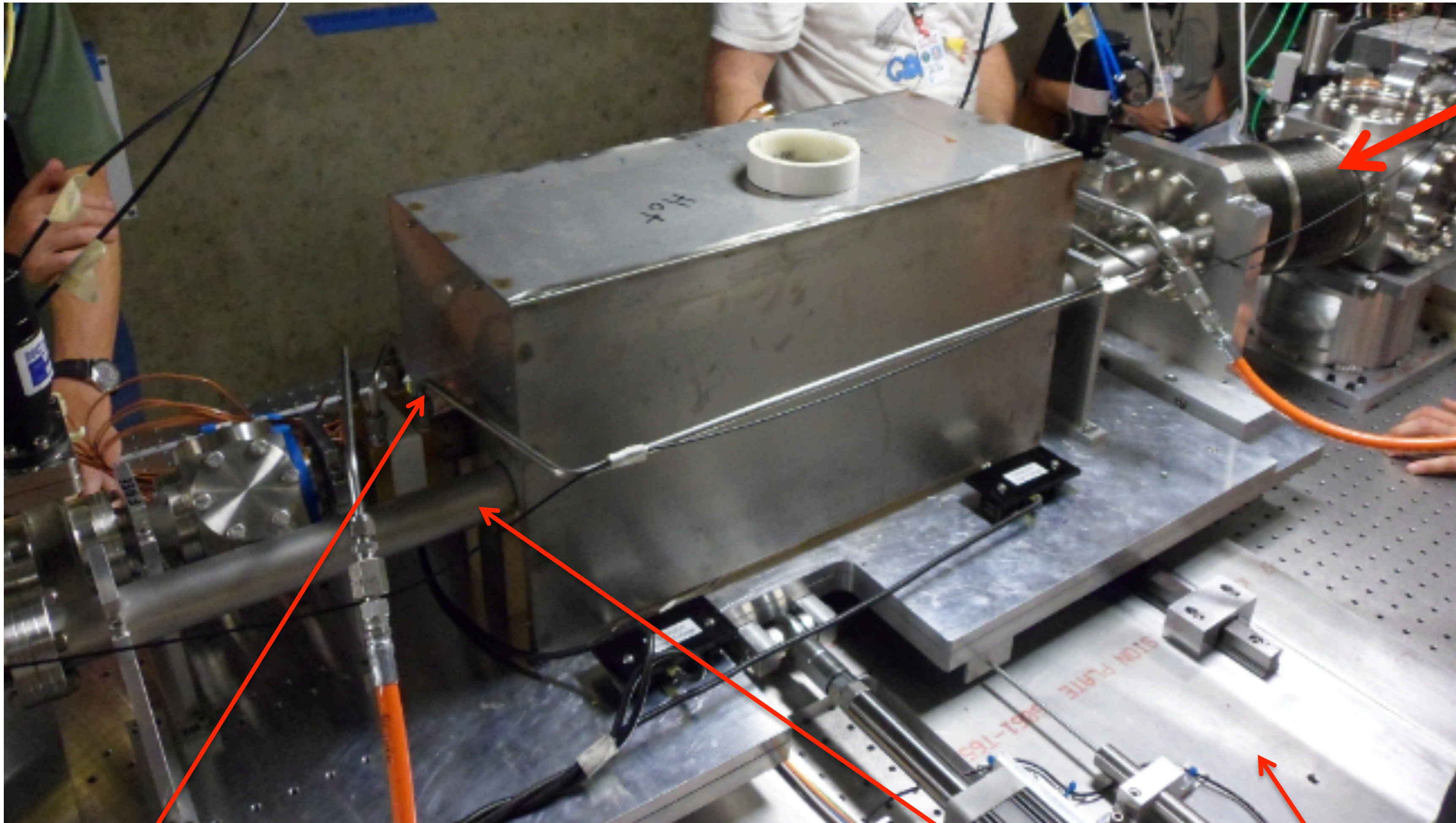




- Energy doubling of e^- over $L_p \approx 85$ cm, 2.7×10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

Lithium vapor source/oven successfully installed

e-

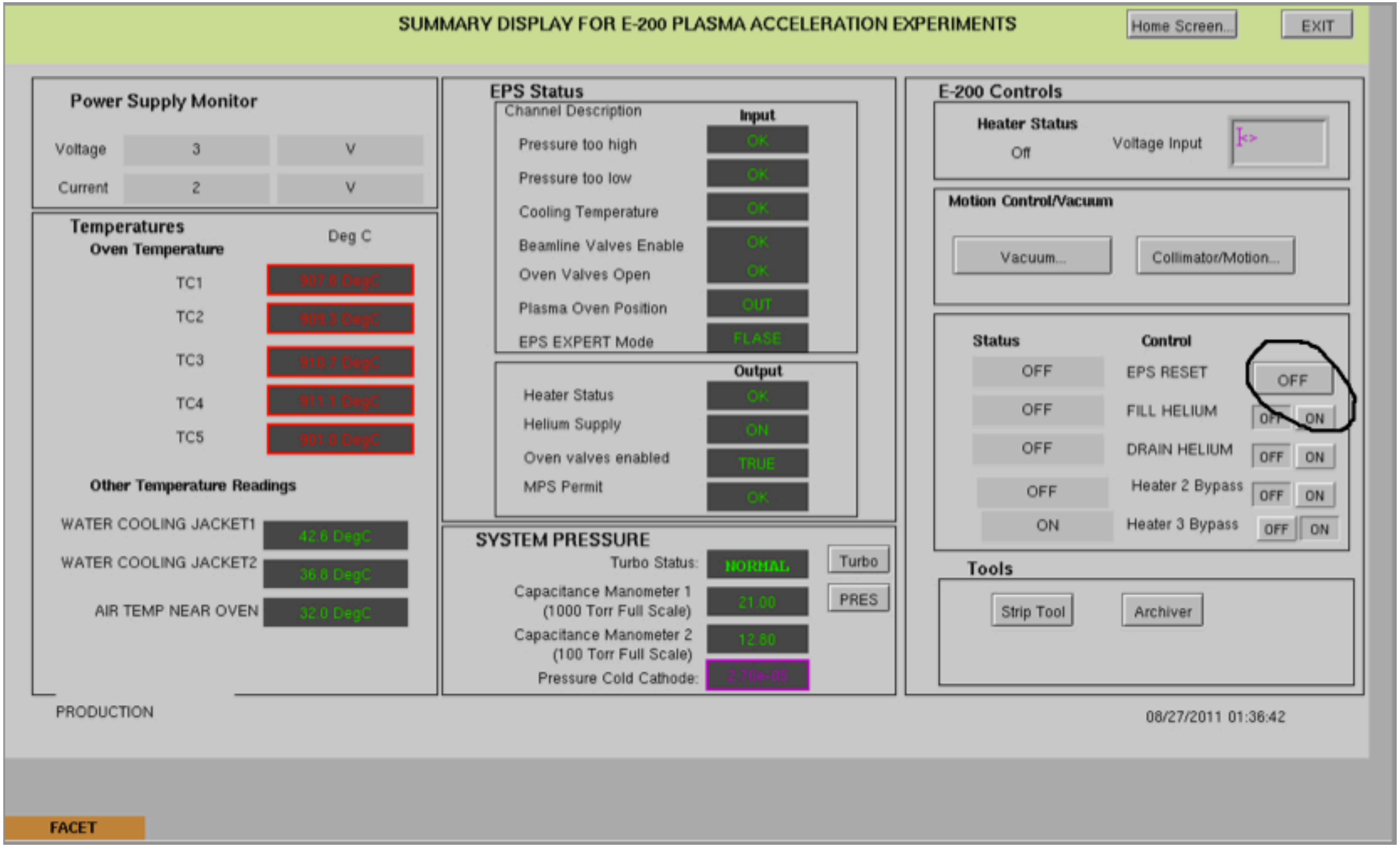


Lithium line @ ~1000C for n_e~10^{16}-10^{17}/cc
Plan: ionize vapor with short, small bunch

Bypass line, He @ room temp.
12-32Torr, no plasma

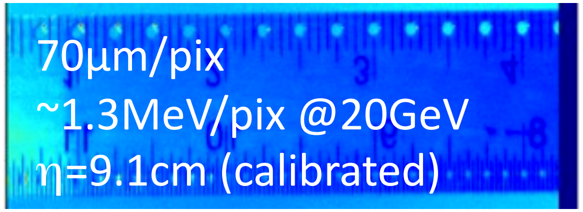
Oven mover

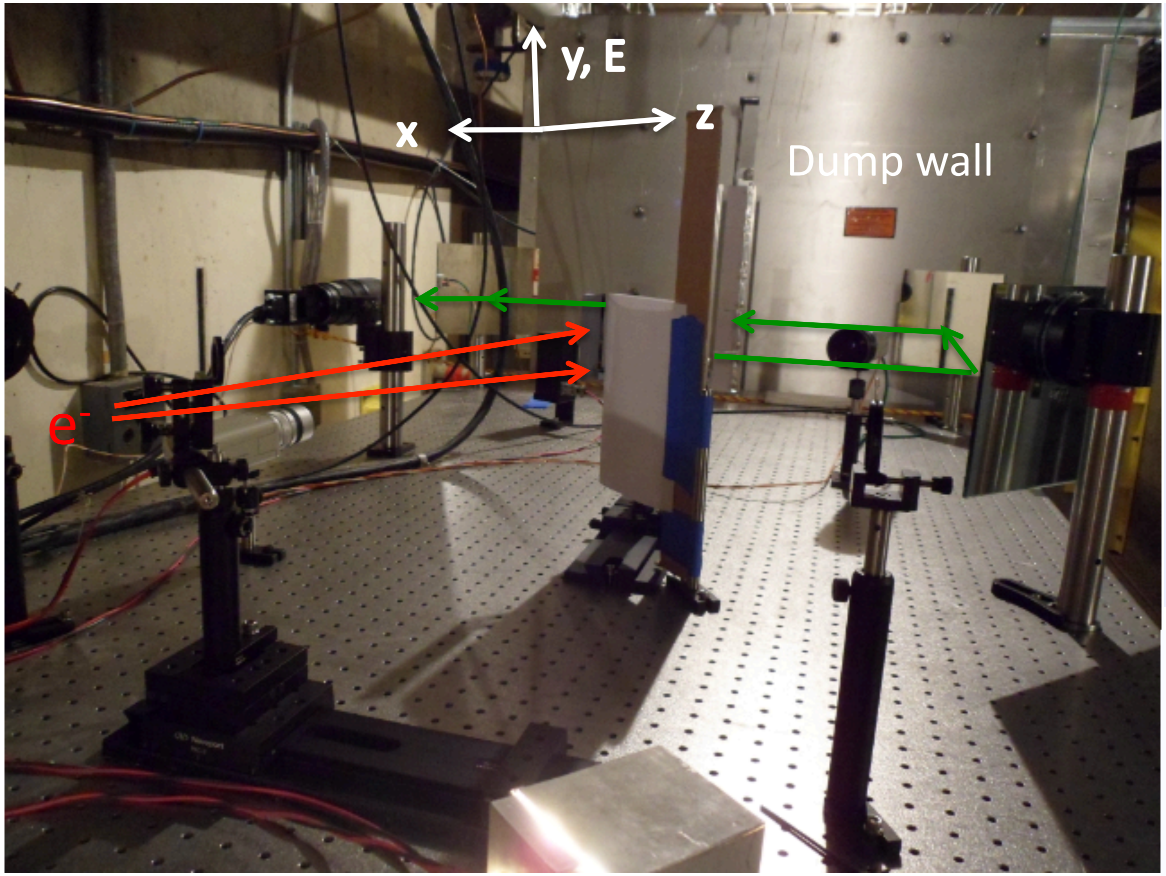
Successful remote operation, monitoring, MPS interaction, etc.

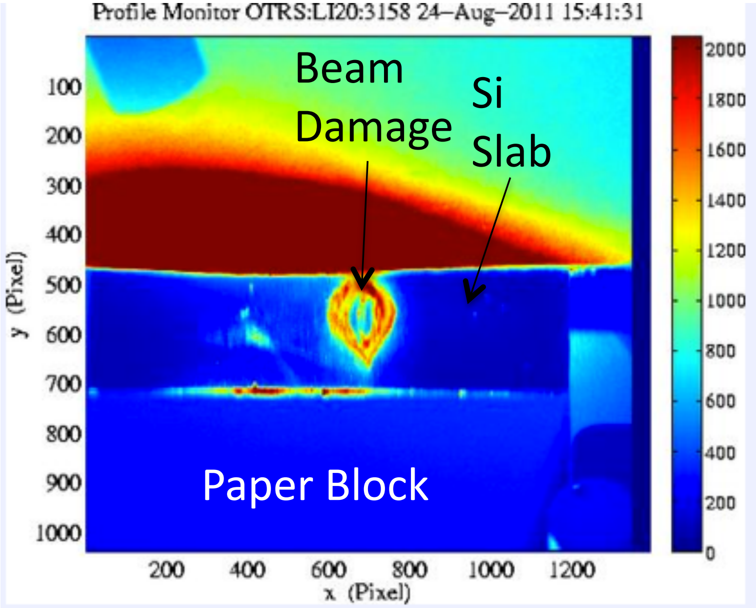


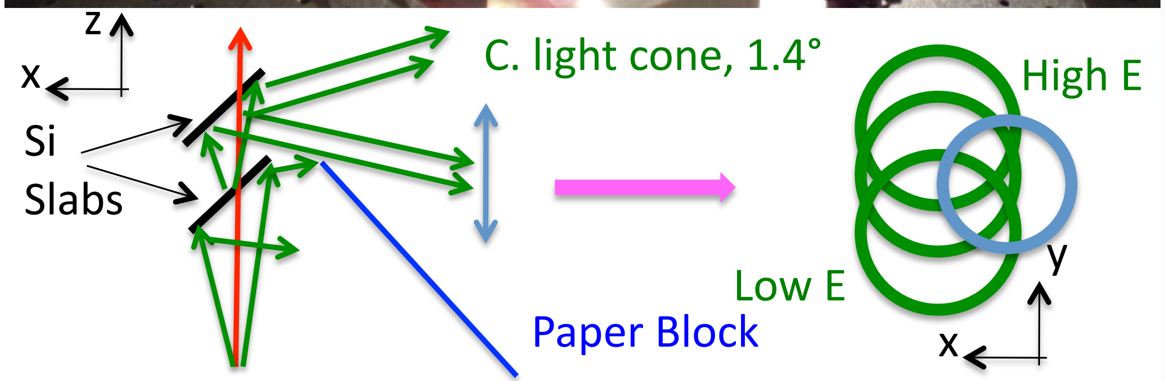
Cosmetic improvements needed

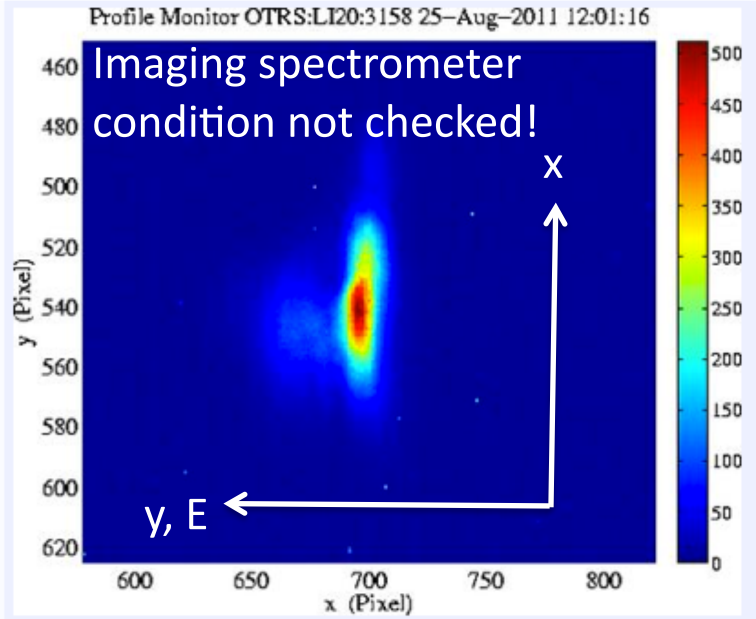
- Successful installation of Cherenkov light-based energy spectrometer with ±5GeV field of view
- C-light prompt, linear with N and high dynamic range



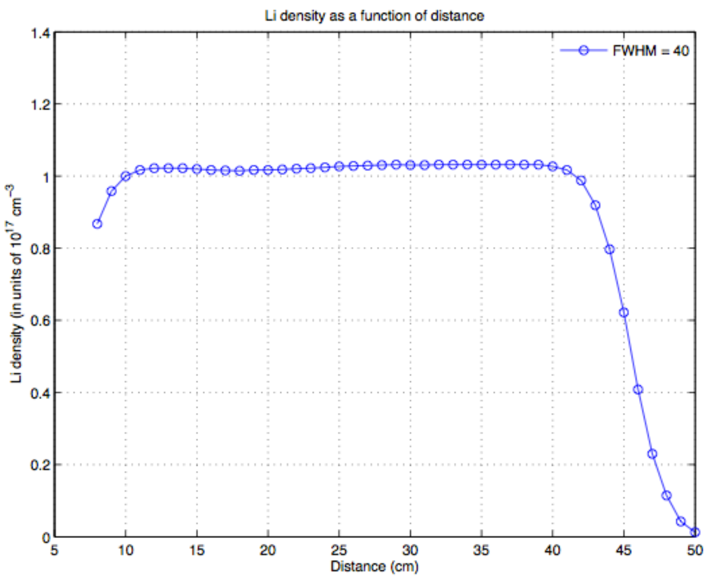








Chose longest profile with appropriate density of long bunch (~50µm)



Pressure = 12.61 torr
Power = 739 W
Voltage = 120 V
Current = 6.16 A
TC1 = 910.4
TC2 = 911.7
TC3 = 912.0
TC4 = 911.9
TC5 = 907

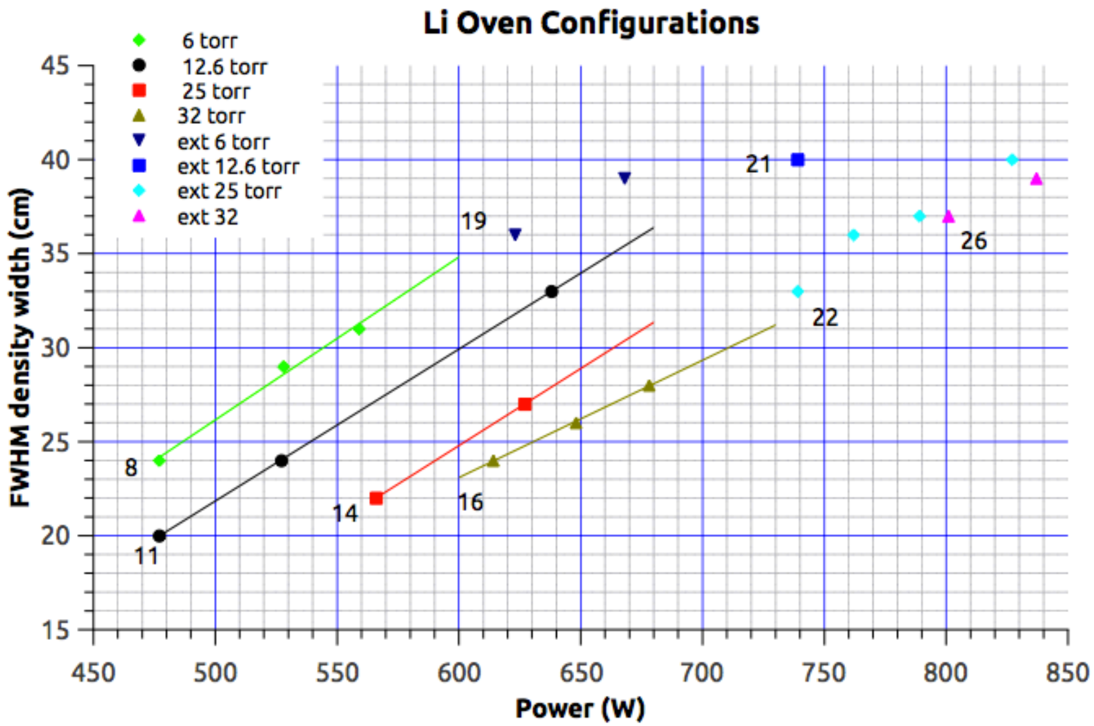
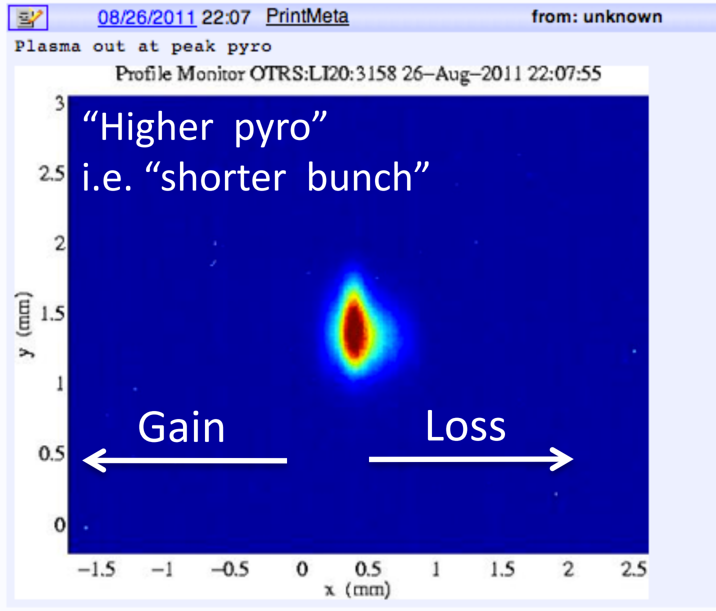


Figure 1:

Note: number of profiles available for various plasma densities and lengths (K.A. Marsh, UCLA): 0.5, 1, 1.9, 2.5x10^{17}cm^{-3}.

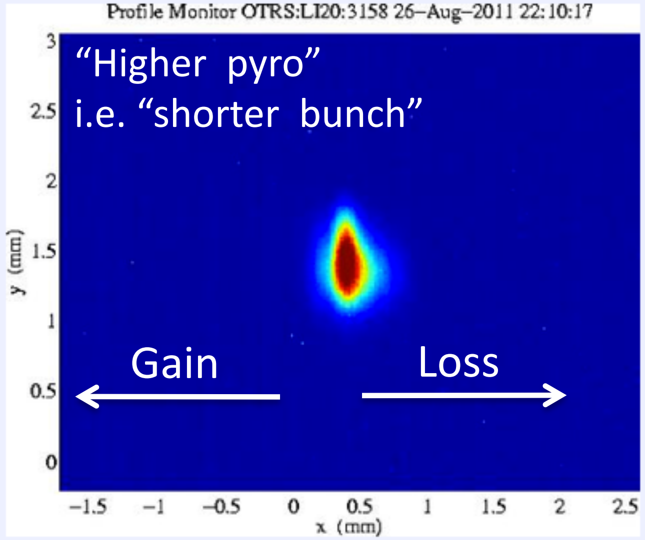


“Oven OUT”, “Plasma OFF” no plasma possible

Incoming energy spectrum

08/26/2011 22:10 E-200 Experimenters -22 degS BNS

Energy spectrometer at the dump, plasma in at pyro peak



“Oven IN” possibly “Plasma ON” if ionization occurred

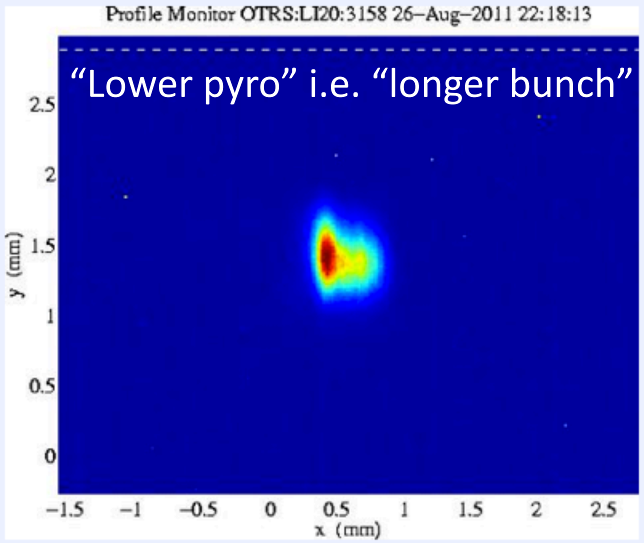
08/26/2011 22:18 PrintMeta from: unknown

Is that energy loss to the wakefield or just a tail (that happens to be in the energy loss direction)????

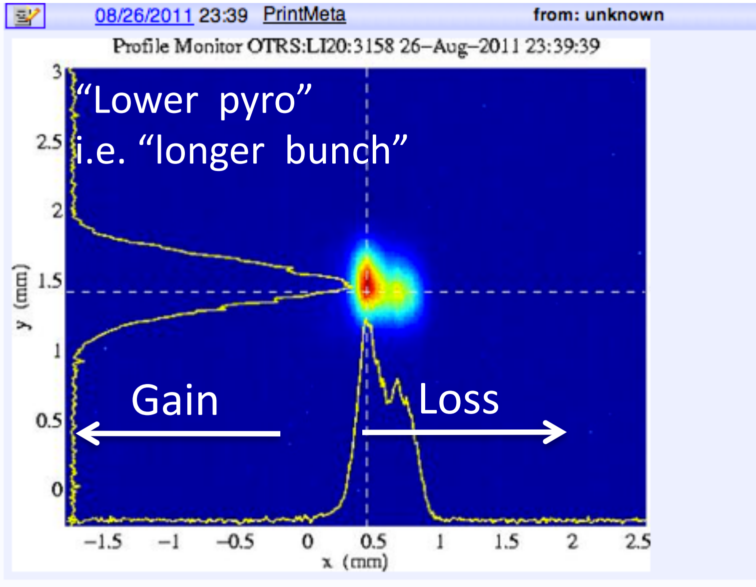
(Secret answer:

http://physics-elog.slac.stanford.edu/facetelog/show.jsp?dir=/2011/34/26.08&pos=2011-08-26T23:39:51

)



Energy loss or tail?



"Oven OUT", "Plasma OFF" no plasma possible

Secret answer: "It's a boy"

"Energy gain without plasma!", it's a tail!

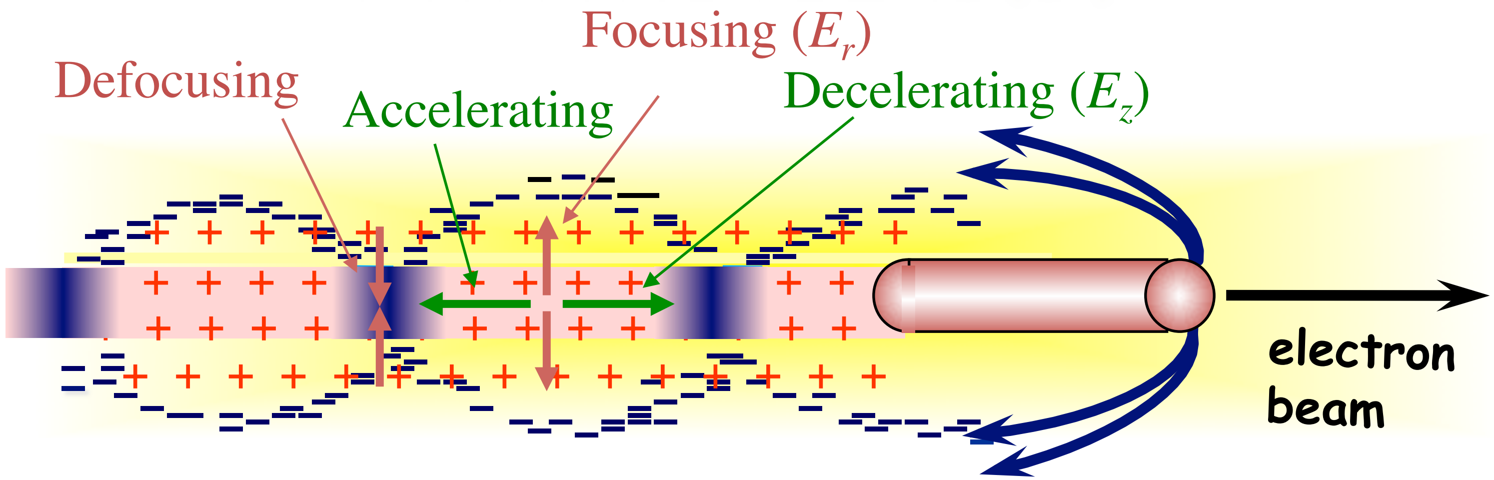
Scans of linac phase to vary compression, beam waist location, all to increase bunch e-field led to not beam-plasma interaction.

Probable reason: bunch SC field too low to ionize (~6GV/m), bunch long and/or too large.

Best parameters: ?? σ_x=60µm, σ_y=45µm, σ_z=60µm ??

Note: spectrometer imaging not verified!

PWFA NUMBERS (e^-)



- Linear theory ($n_b << n_e$) scaling: $$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{\left(\sigma_z/0.6mm\right)^2} \approx N/\sigma_z^2$$

  $$@\ k_{pe}\sigma_z \approx \sqrt{2}\ \ (with\ k_{pe}\sigma_r << 1)$$

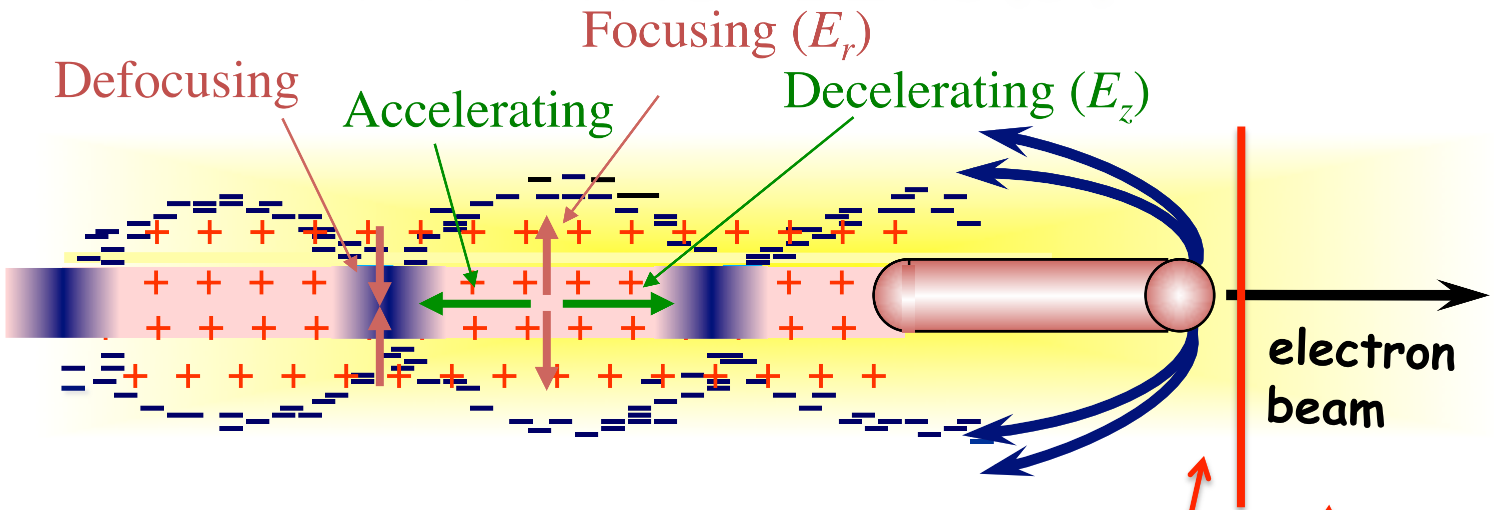
- Focusing strength: $$\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3})$$ ($n_b > n_e$)

- $N=2\times10^{10}$: $\sigma_z=600\ \mu m$, $n_e=2\times10^{14}\ cm^{-3}$, $E_{acc}\sim 100$ MV/m, $B_\theta/r=6$ kT/m
  $\sigma_z=$ 20 μm, $n_e=2\times10^{17}\ cm^{-3}$, $E_{acc}\sim$ 10 GV/m, $B_\theta/r=6$ MT/m

- Frequency: 100GHz to >1THz, "structure" size 1mm to 100μm

- Conventional accelerators: MHz-GHz, $E_{acc}<150$ MV/m, $B_\theta/r<2$ kT/m

PWFA NUMBERS (e^-)



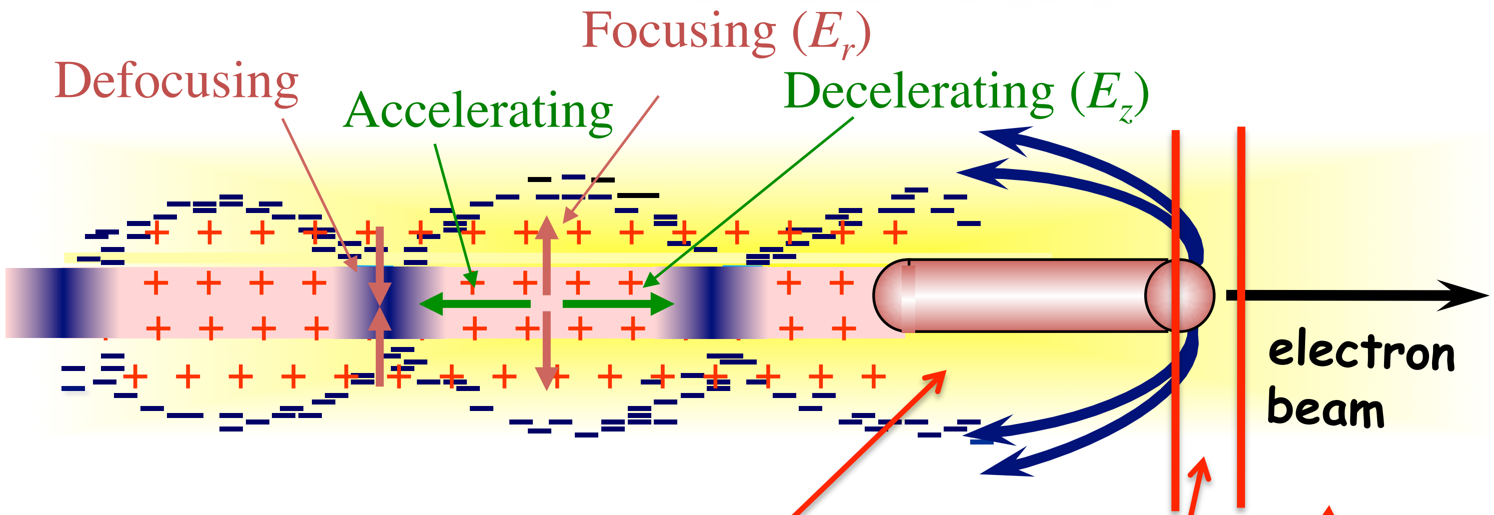
Ionized Li vapor (plasma)

The bunch can drive the wakefield

Neutral Li vapor

The bunch expands according to its β

PWFA NUMBERS (e⁻)



The wakefield is fully developed

Ionized Li vapor (plasma)
The bunch can drive the wakefield

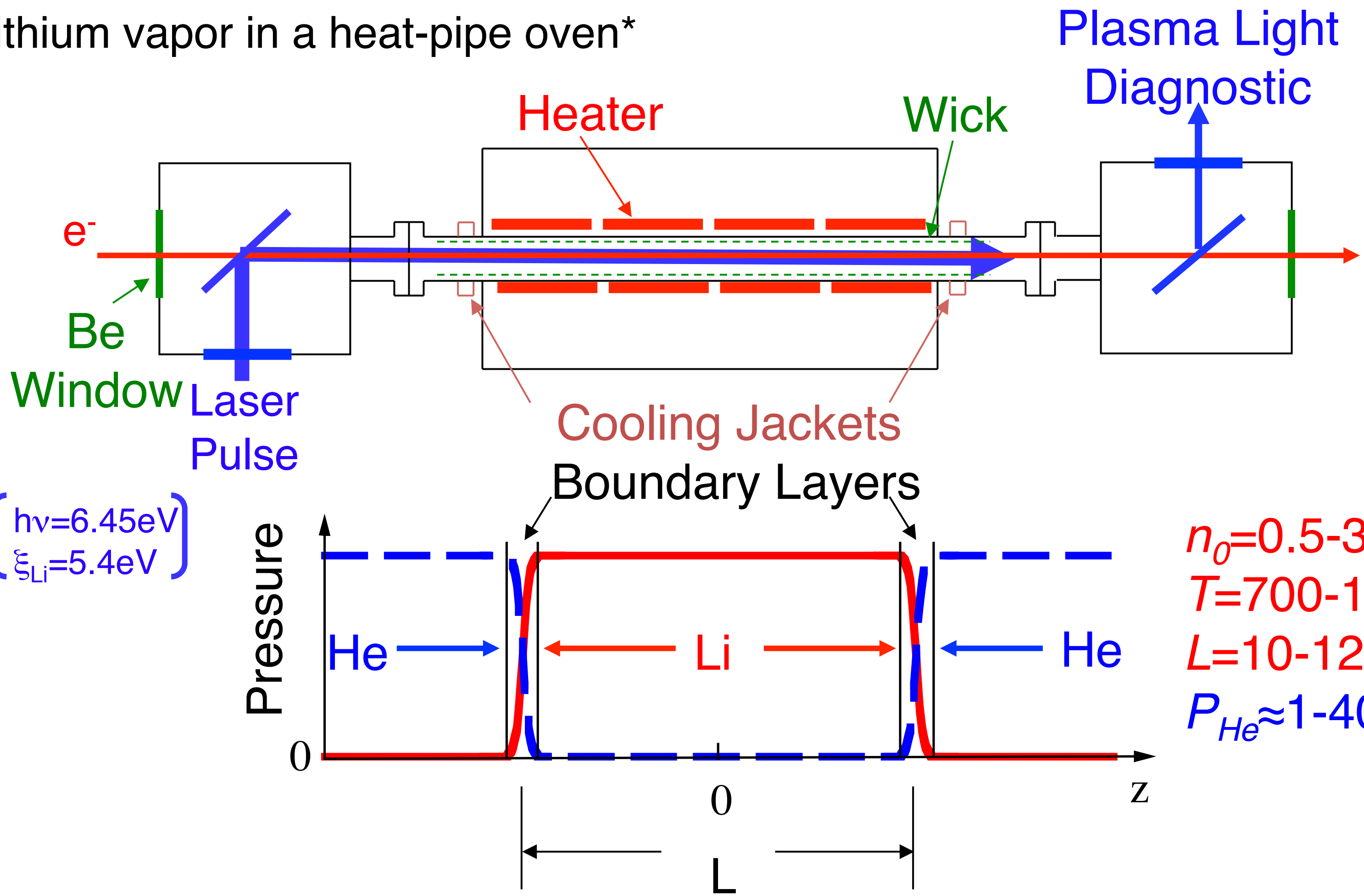
Neutral Li vapor
The bunch expands according to its β

It takes some time for the sequence ionization – wakefield excitation to develop, leading to bunch head erosion

PLASMA SOURCE

P. Muggli *et al.*, IEEE Trans. on Plasma Sci. 27, 791 (1999).

- Lithium vapor in a heat-pipe oven*



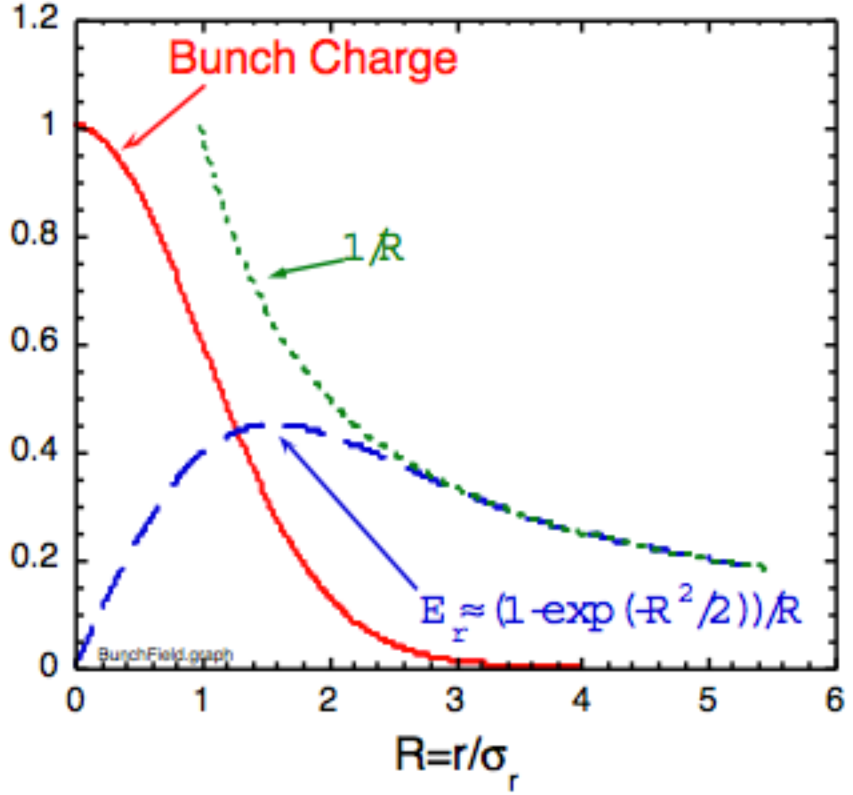
n_0=0.5-3.5×10^{17} cm^{-3}
T=700-1050°C
L=10-120 cm
P_{He}≈1-40 T

- Laser, photo-ionized for “small” n_eL
- Field-ionized by the bunch field for “large” n_eL

* C. Vidal, J. Appl. Phys. (1960)

Space charge field of ultra-relativistic Gaussian bunch:

$$E(r,z) = \frac{1}{(2\pi)^{3/2}} \frac{e}{\varepsilon_0} \frac{N}{\sigma_r \sigma_z} \frac{\left(1 - e^{-r^2/2\sigma_r^2}\right)}{r/\sigma_r} e^{-z^2/2\sigma_z^2}$$



$$E_{r,\max}[GV/m] \approx 5.2 \times 10^{-19} \frac{N}{\sigma_r \sigma_z}$$ @r~1.6σ_r

The accelerator size is c/ω_p and ionization must be over $r>c/\omega_p$

Need enough field from N and σ_z to ionized over $r>c/\omega_p$

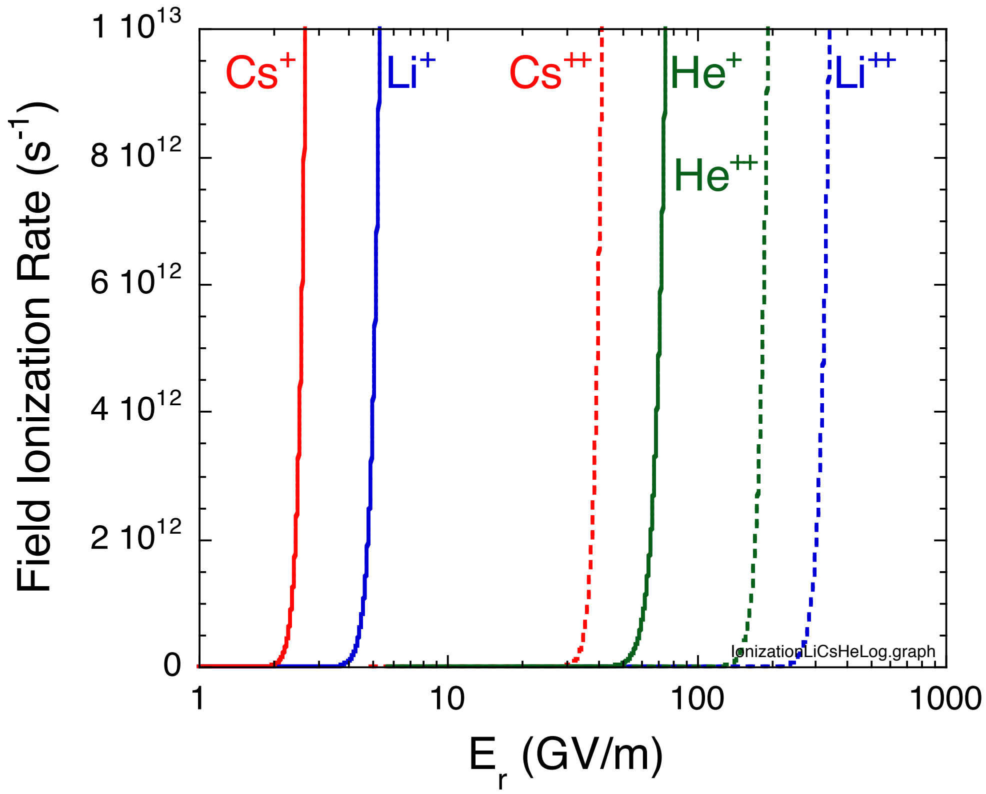
ADK field ionization rate for atomic state *n*, with ionization potential ϕ_i and in field *E*:

$$\omega_i = 4\omega_0 \left(\frac{\phi_i}{\phi_H}\right)^{5/2} \frac{E_a}{E} e^{\left[-\frac{2}{3}\left(\frac{\phi_i}{\phi_H}\right)^{3/2}\frac{E_a}{E}\right]}$$

$\omega_0 = 2\varepsilon_0 a_0 h/e^2 \approx 2.5\times10^{-17}$ s

$E_a = e^2/(4\pi\varepsilon_0 a_0^2) \approx 5.1$ GV/m

$\phi_H = 13.6$ eV



=> Need bunch field >6GV/m to ionize Li to Li^+ over a time scale ~10^{-13}s or 100fs

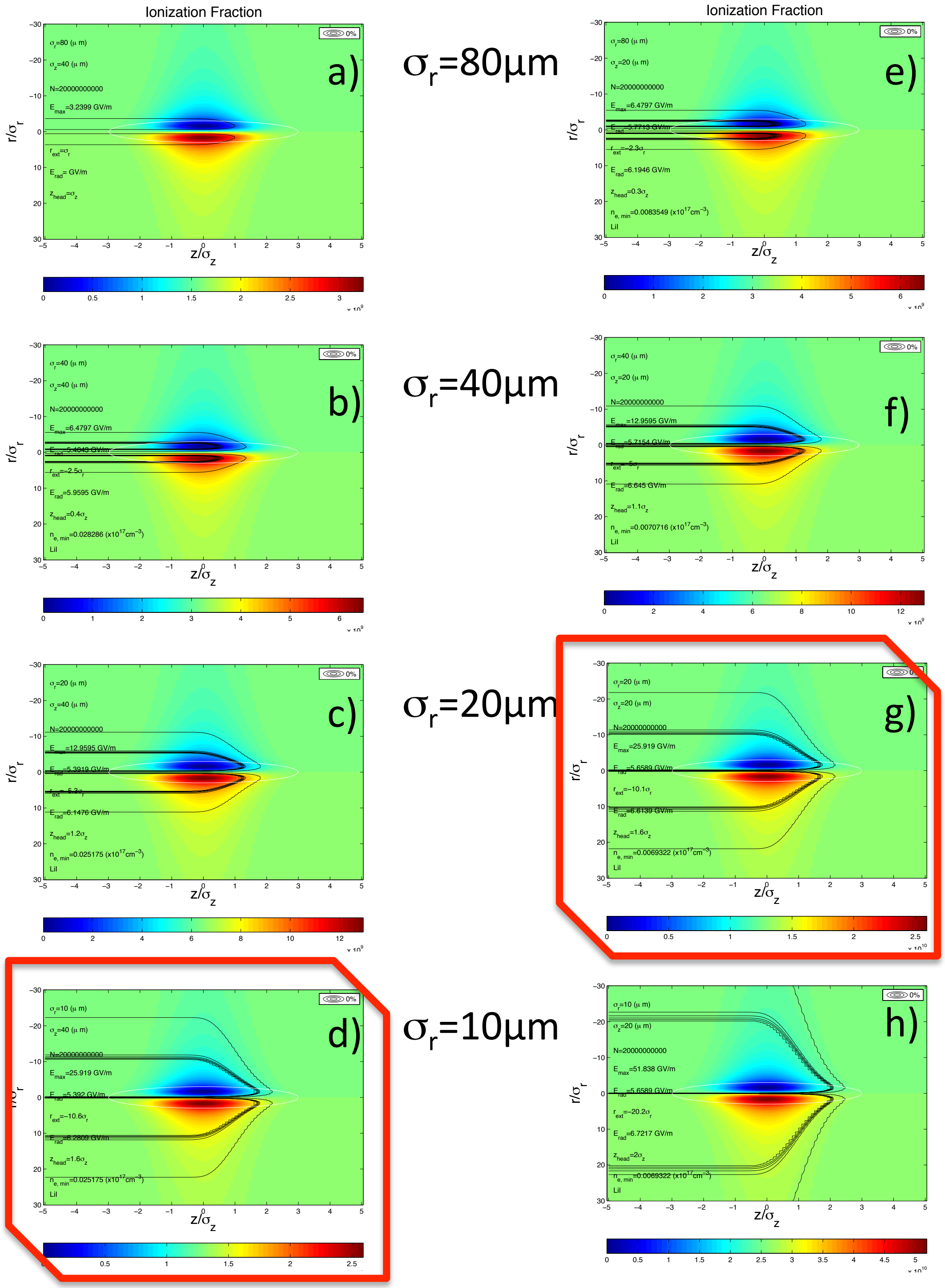
=> With N=2×10^{10}, $\sigma_r\sigma_z$<~1700μm^2

In addition, the ionization radius must be >c/ω_{pe}, the radius of the accelerator "cavity"

Integrate the ionization rate along z (i.e, along the bunch at various radii for Li (ϕ_i=5.45eV):

LHS: σ_z=40μm

LHS: σ_z=20μm



“Rough rule-of-thumb”

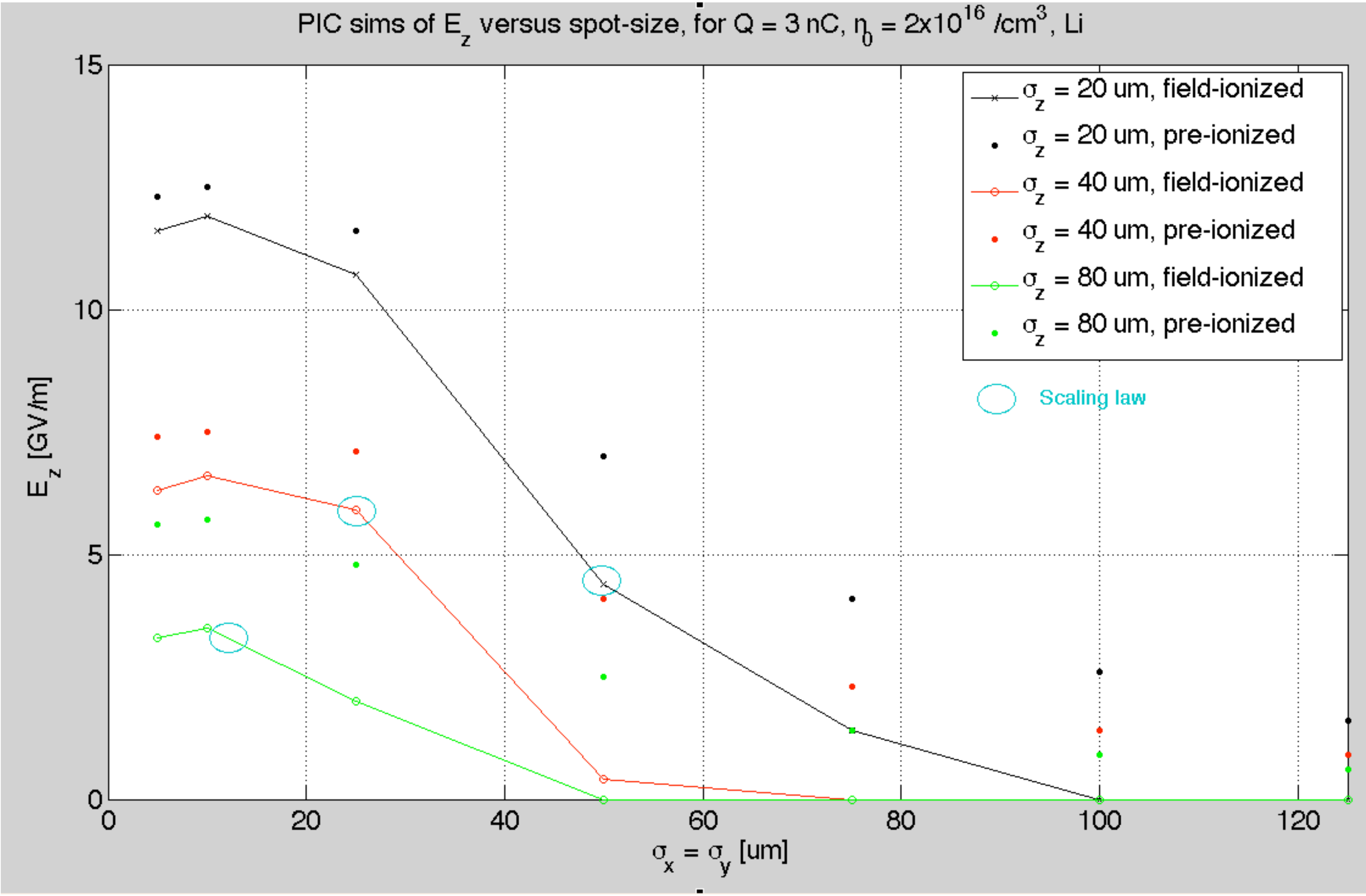
Rough criterion for good ionization (I put this in logbook) :

$$\sigma_z[\mu m]\sigma_r[\mu m] \lesssim \frac{1}{2}\frac{11.5Q[pC]}{\varepsilon_i^{1.73}[eV]}$$

So for $Q = 3$ nC, Li ($\varepsilon_{i,Li} = 5.39$ eV),

$$\sigma_z[\mu m]\sigma_r[\mu m] \lesssim 1,000$$

Erik Adli



Notes :

- Absolute field depends on plasma density; more interesting is the difference between pre-ionized and field-ionized plasma
- Even with full ionization, the field might not be sustained for a long time due to erosion.

Erik Adli

Bunch head erosion requires low emittance and high energy (erosion length ~$(\gamma\varepsilon)^{-1}$)

IOP Institute of Physics DEUTSCHE PHYSIKALISCHE GESELLSCHAFT

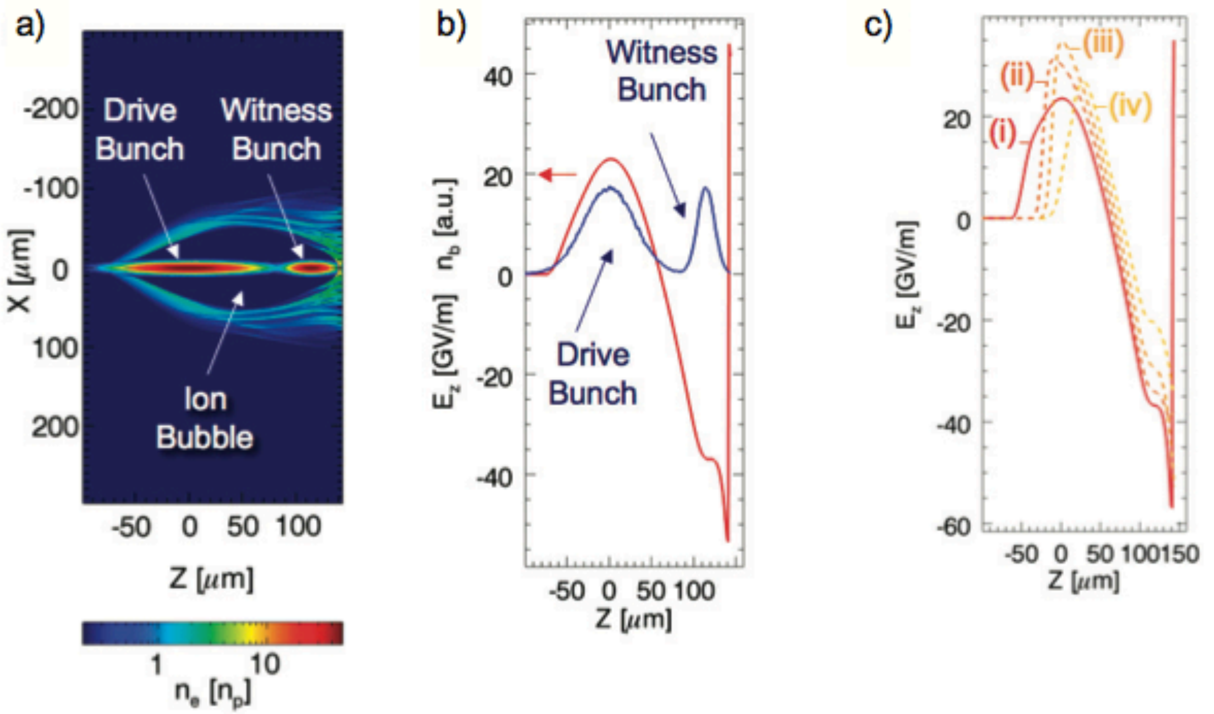
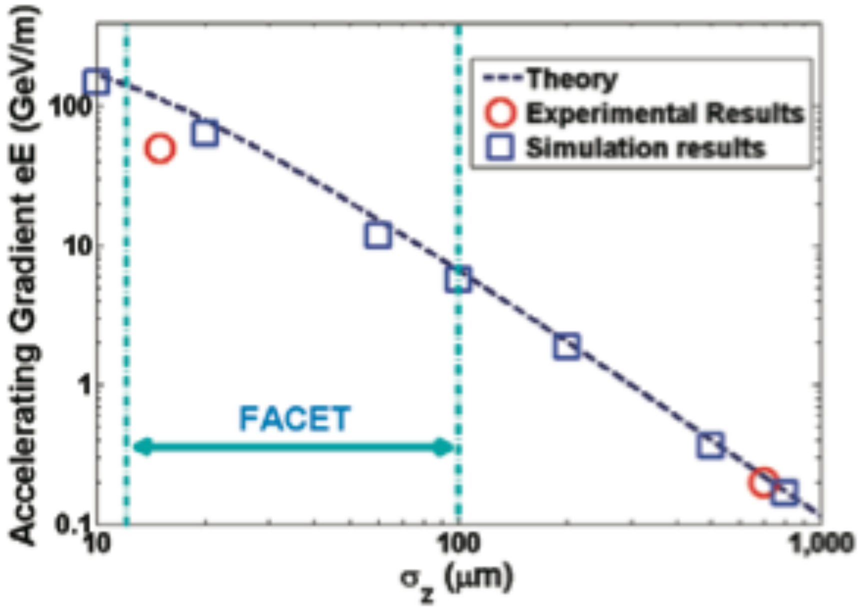


Figure 7. QuickPIC simulation results showing a PWFA utilizing a drive/witness bunch configuration produced using a mask in the dispersion plane. Panel (a) shows the plasma and beam densities at the entrance of the plasma. Panel (b) shows the positions of the two bunches relative to the longitudinal wakefield on the axis. Panel (c) shows the evolution of the wakefield at (i) $z = 0$, (ii) 28, (iii) 55 and (iv) 83 cm.

Hogan et al., New Journal of Physics 12 (2010) 055030
Simulations, W. AN, UCLA

Head erosion limits the acceleration distance and the energy gain.

Wakefield amplitude scales as $N\backslash\sigma_r 2 \sim Nn_e$ for $k_p\sigma_r \sim \surd 2$



Hogan et al., New Journal of Physics 12 (2010) 055030
Simulations, W. AN, UCLA

Summary:

- Installation of E-200 equipment went smoothly:
  - Lithium oven with various lengths and densities available
  - Cherenkov light-based single bunch energy spectrometer
- Attempted PWFA experiment with available bunch parameters
- Observations showed no effect probably because the bunch was too long and/or wide to ionize Li
- To run meaningful experiments need:
  - Bunch parameters (N, σ_r, σ_z) sufficient to ionize Li (or Cs, …) ~$N/\sigma_r\sigma_z$
  - Bunch parameters (N, σ_r, σ_z) sufficient to drive large amplitude wakefields ~N/σ_z^2
  - Low emittance and high energy bunch to minimize head erosion ~$(\gamma\varepsilon)^{-1}$
  - Alignment and calibration of diagnostics (USOTR, DSOTR, x-spectrometer, c-spectro), i.e., extended run (days, weeks)
  - Well defined beam orbit and stable beam (1+9Hz excellent!)
  - Ability to change bunch parameters (length, waist location, etc.)
  - Controlled accesses
- New operation with multiple simultaneous experiments may require more robust equipment (cameras/detectors mounts, etc.)

Thank you to all who contributed!
See you soon!