Ionization Injection- What We Have Learned and Next Steps

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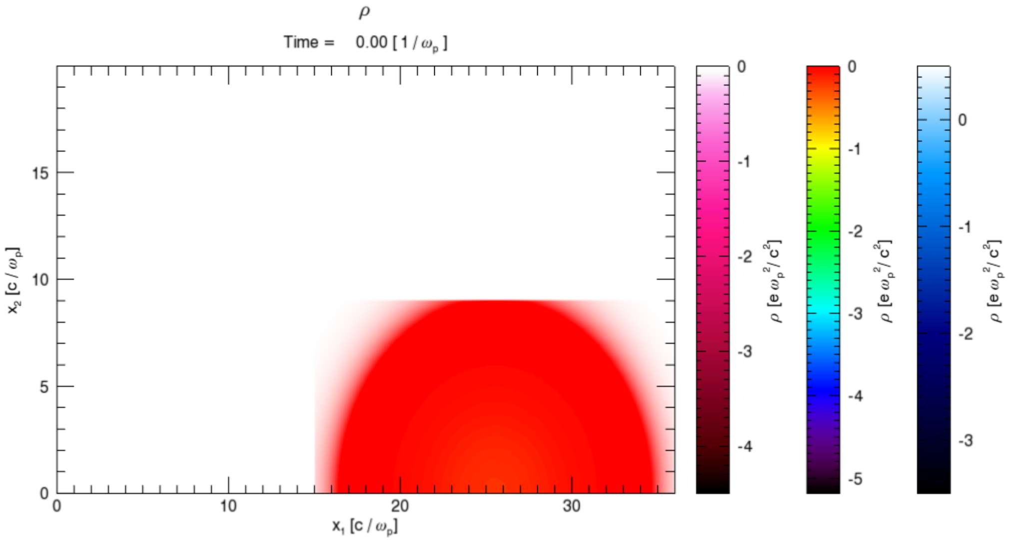
Stony Brook University



Synthesis

- Ionization injection can be detrimental or beneficial in a PWFA
- We encountered the detrimental effects of ionization injection in the form of heavy beam loading, occurring through distributed injection of charge (dark current) along a Rb plasma
- The beneficial effects of ionization injection appeared in the form of an injected beam with micron scale emittance from a drive beam of ~100 micron emittance in experiments with Li plasma. (emittance transformer)
- Simulations show a region of impurity confined to a single betatron cycle yields an electron bunch with micron scale emittance and ~3% energy spread
- FACET II’s high current beam provides exciting opportunities for the control of qualities of the injected beam

Outline

- Beam loading via distributed injection (Rb plasma)
- Generation of high energy beam with micron scale emittance (Li plasma)
- Localized injection of low emittance, low energy spread beam (Hydrogen plasma)
- FACET II Opportunities

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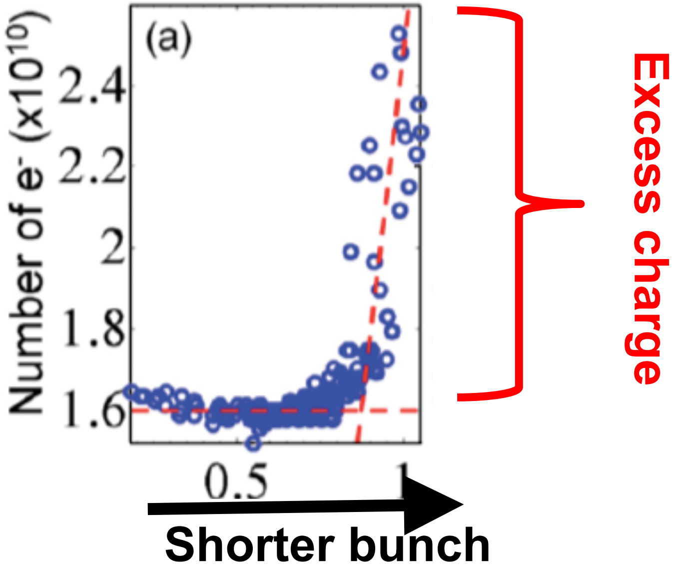
Early history of ionization-injection with SLAC Collaboration

FFTB E-167

◆Going to shorter bunch led to a large increase of “excess charge”

◆ => **trapped e-’s from the He buffer gas**.



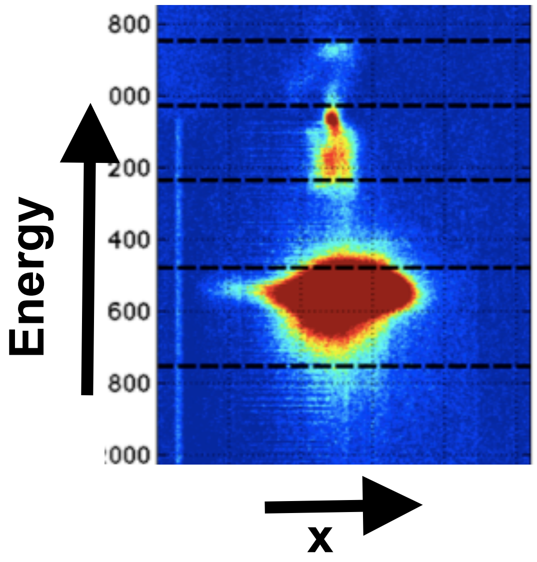
FACET E-200

◆Large amount of excess charge in Rb plasma

◆Early test using Ar impurity in He buffer.

◆**Hint of trapped charge.**

◆Abandoned due to Ar contaminating the Li oven

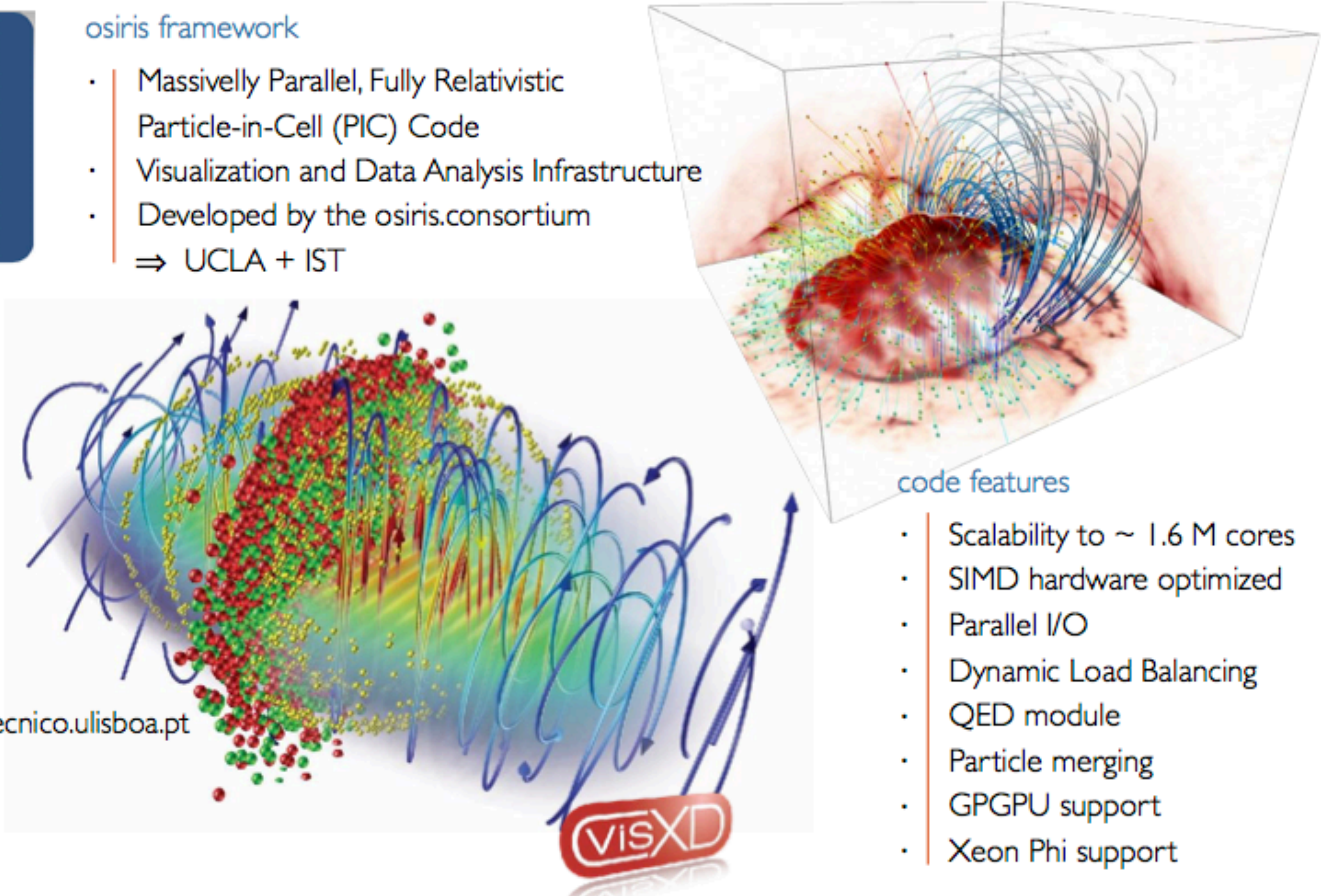


Oz, et al., Physical Review Letters, **98**, 084801 (2007)

Osiris 4.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

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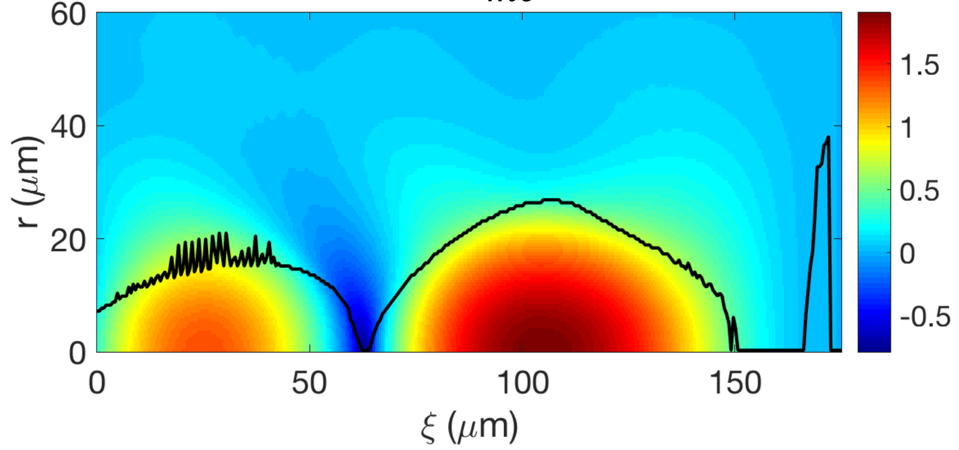
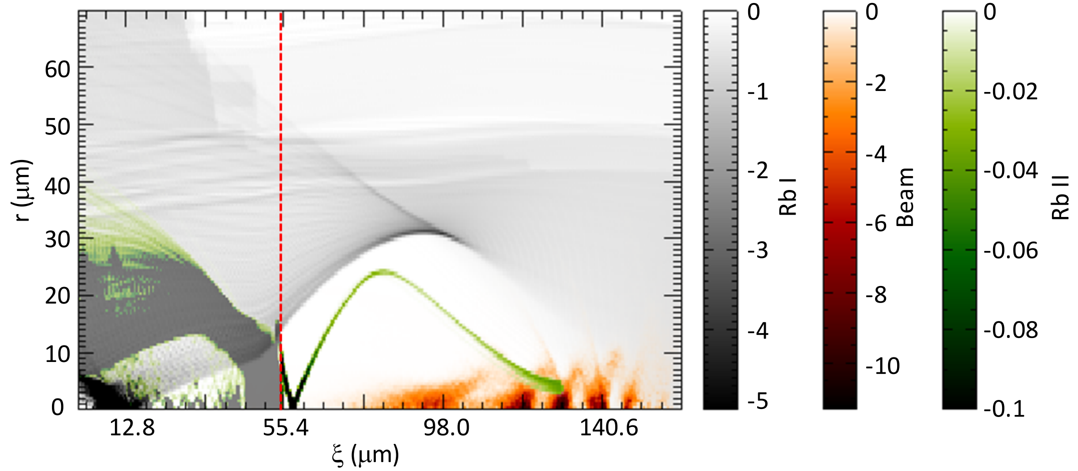
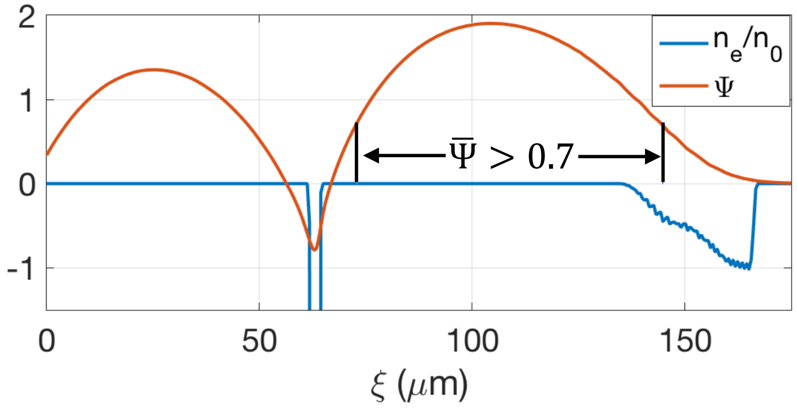
Physics of Ionization Injection of Unmatched Electron Beam

- Ionization Injection occurs when $\Delta\Psi < -1$
- In this case, if the electrons are ionized when $\Psi_i > 0.7$
- Beams get injected
- Accumulation of injected charge leads to beam loading

Map of $\Psi = \frac{e}{mc^2}(\phi - v_\phi A_z)$

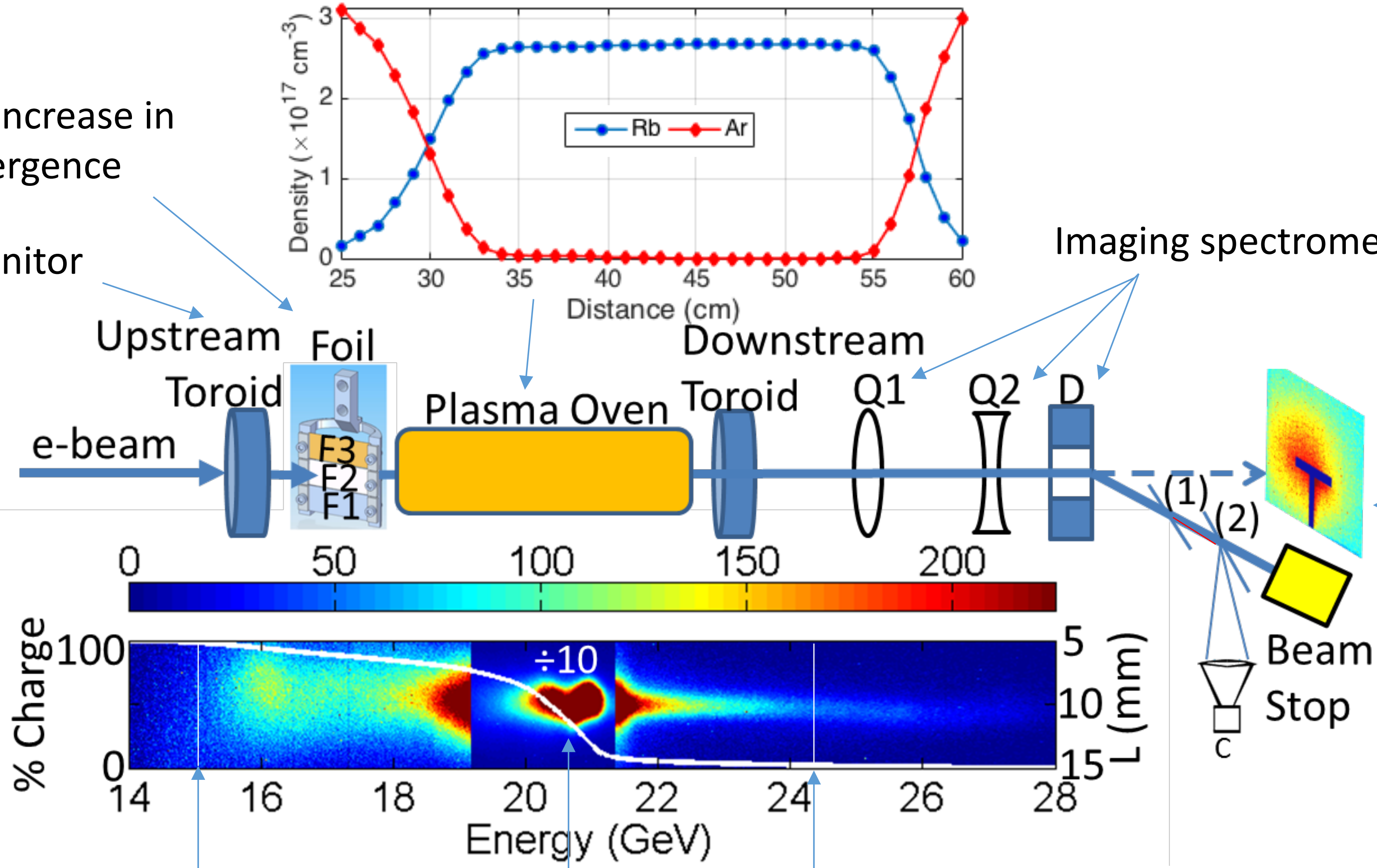






Oz, et al., Physical Review Letters, **98**, 084801 (2007)
Pak, et al. Physical Review Letters, **104**, 025003 (2010)

Experiment with Rubidium Plasma Source



Cause an increase in Beam divergence

Charge Monitor

Imaging spectrometer

Betatron X-rays

Energy Loss(ΔW^-)

Unaffected charge
~35% of initial charge

Energy gain (ΔW^+)

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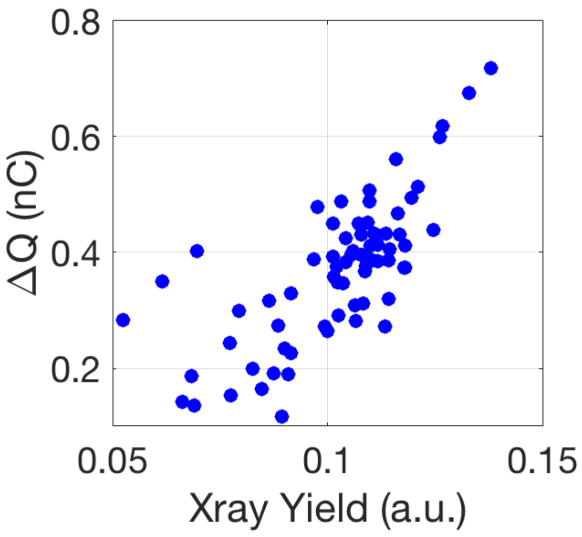
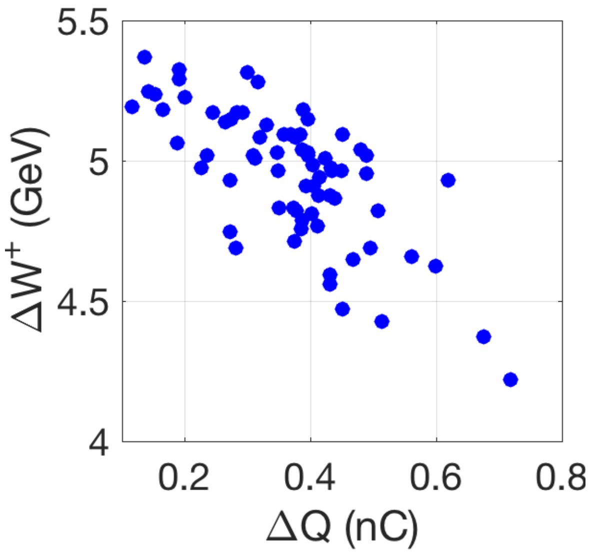
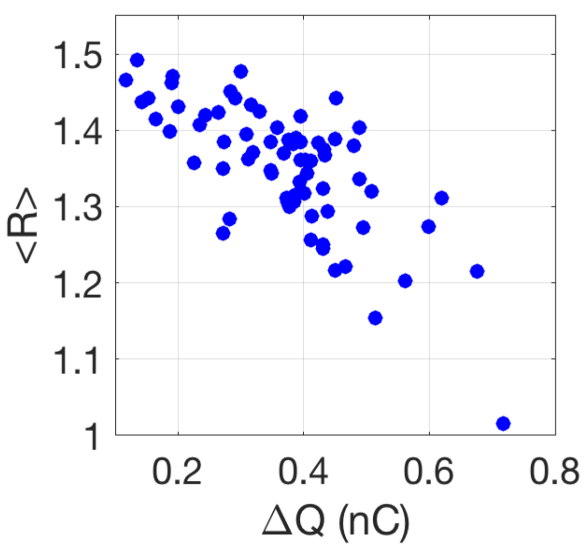
Experimental Evidence for Beam Loading



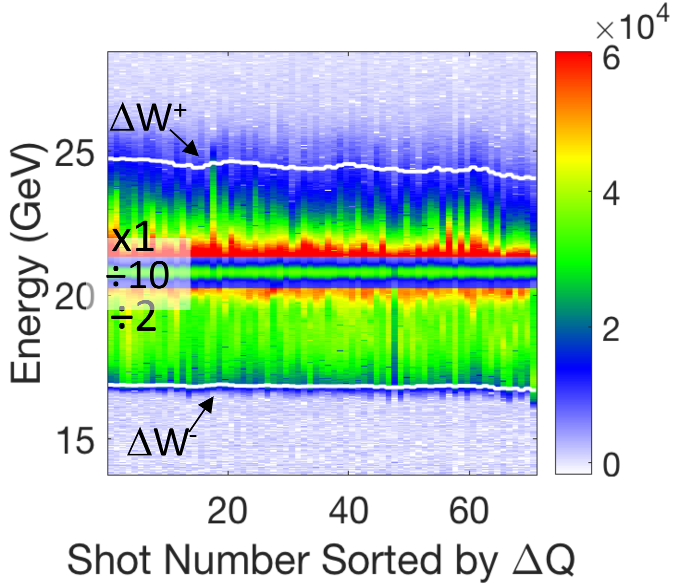
Correlation confirms understanding of transverse dynamics



Distributed injection strongly dampens energy gain



Results in 33% reduction in average transformer ratio



Reduction in transformer ratio visually observed

Simulations are consistent with the experimental conclusions

N. Vafaei-Najafabadi, et al., PRL, **112**, 25001 (2014)
N. Vafaei-Najafabadi, et al., PRAB, **19**, 101303 (2016)

Outline

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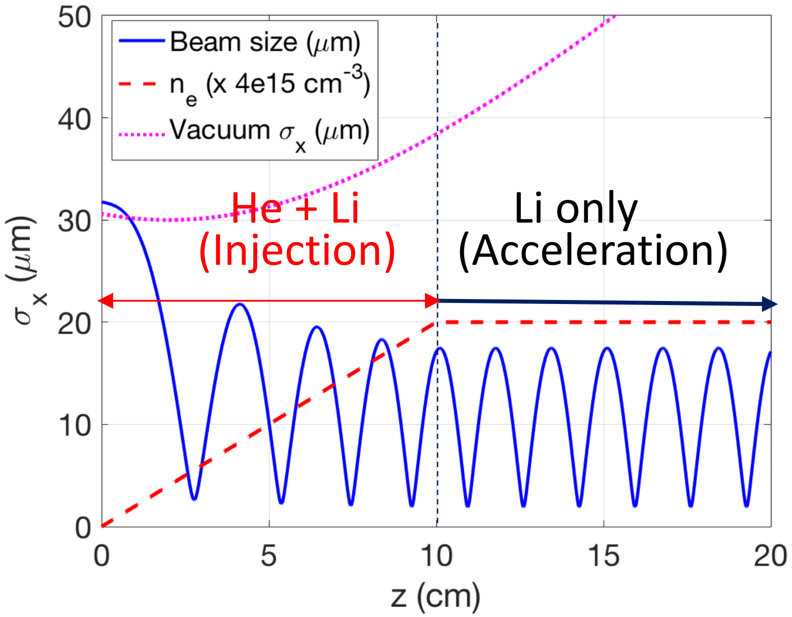
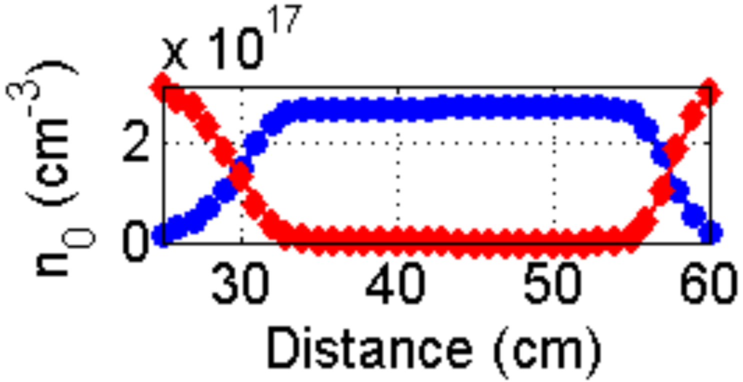
N. Vafaei-Najafabadi, et al., Plasma Physics and Controlled Fusion **58**, 034009 (2016)
N. Vafaei-Najafabadi, et al., PhD Thesis (2016)

Limiting Ionization Injection to Ramp



Element	IP (eV)	E_{th} (GV/m)	σ_r^* (μm)
RbI	4.17	3.0	103
Li I	5.39	4.7	65.6
Ar	15.8	30	10
Rb II/Ar II	~27.5	53	5.8
He	24.6	62.5	5.0
Li II	75.6	294	1.1

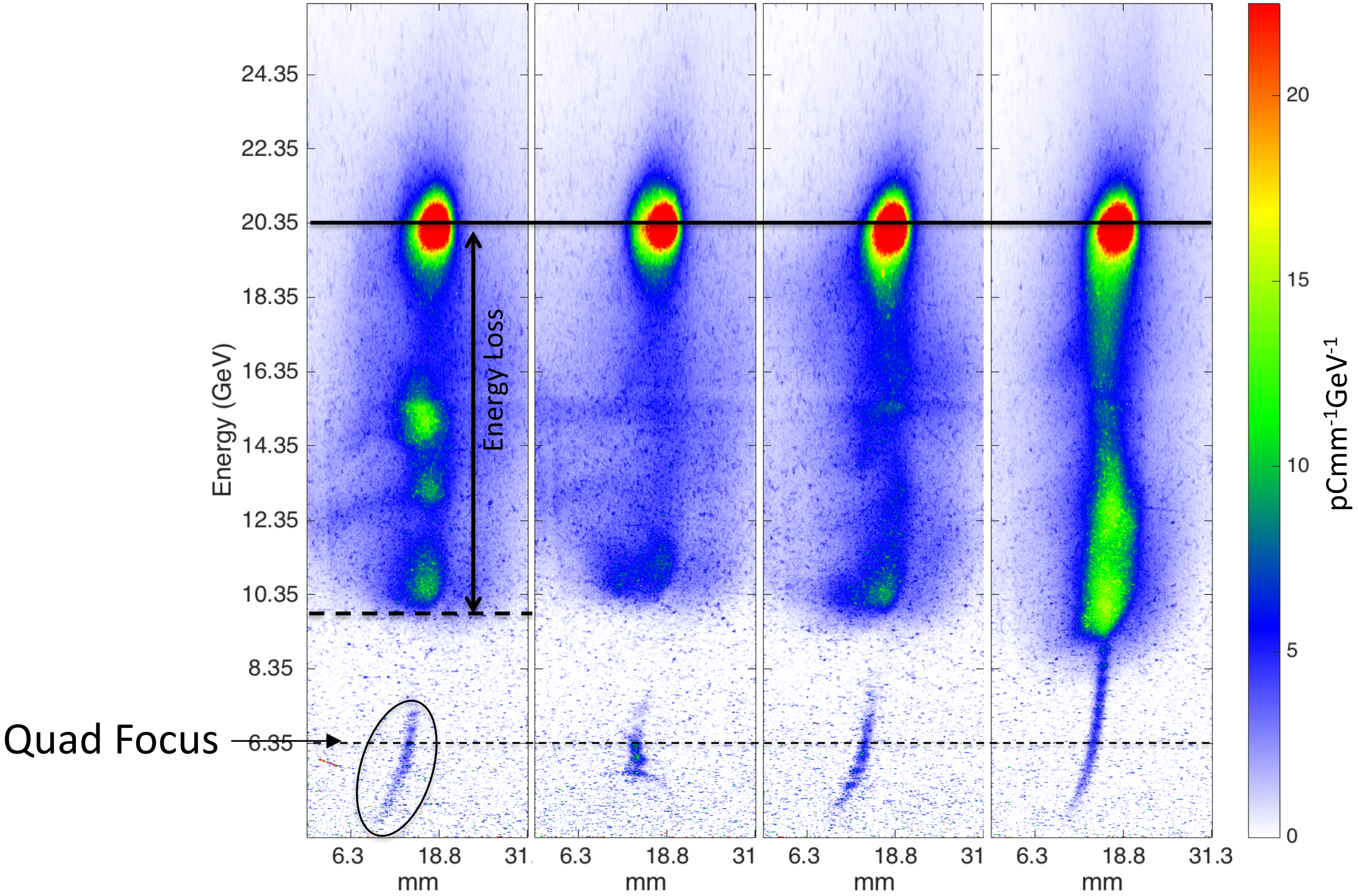
- Values obtained assuming 10% ionization, N=1.8x10^{10}, and σ_z=30 μm for the beam
  - σ_r^* is The spot size of the electron beam needed to ionize the elements



Secondary ionization is limited to helium

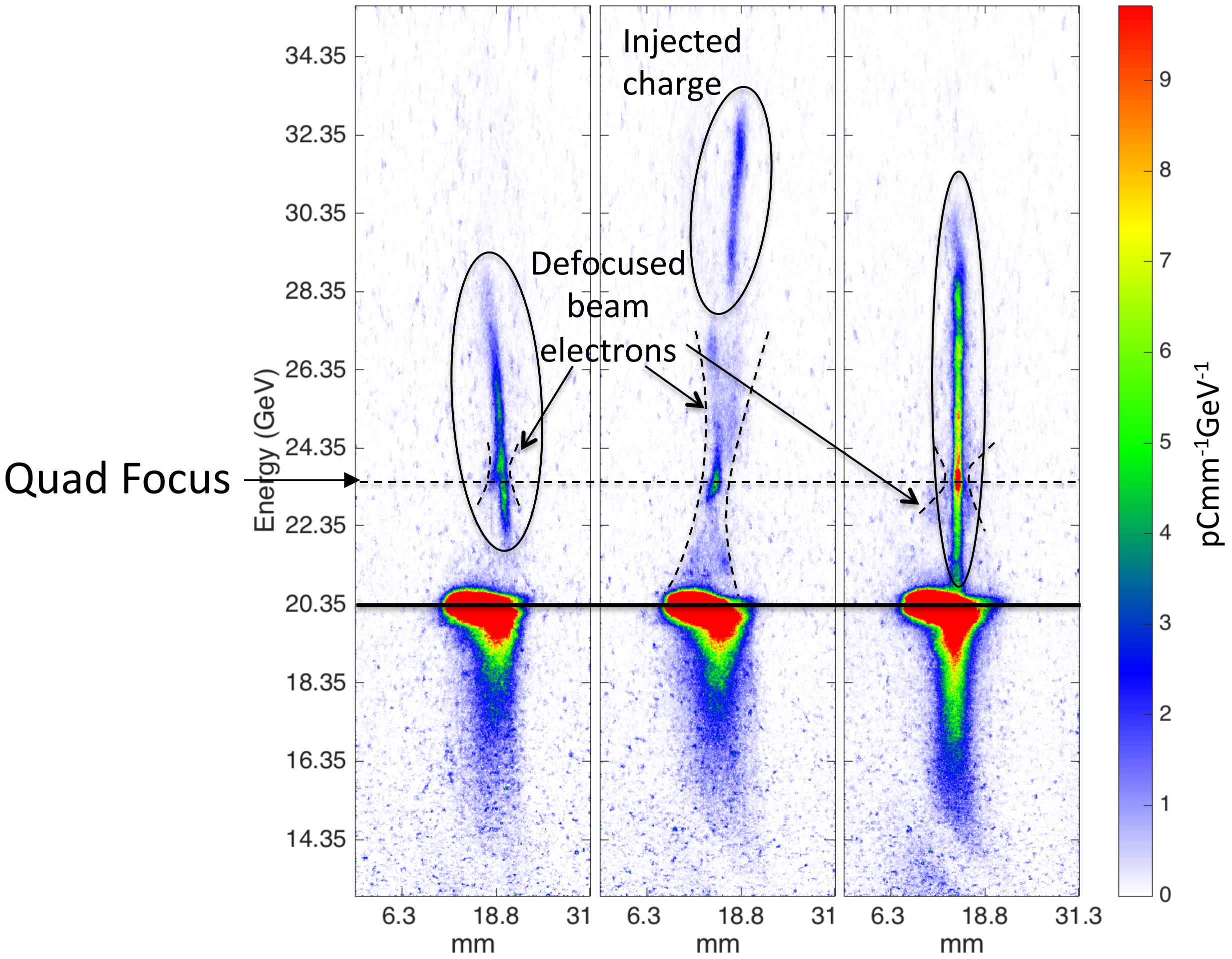
Ionization injection in a lithium oven is confined to the ramp

Experimental Results from the 30 cm Plasma



- Injected beam is observed as separate from the main beam
- Injected beam's divergence is ~4X smaller than the drive beam
- Injected beam is accelerated from 0 to 10 GeV

Experimental Results from 130 cm Plasma



- Energy gain continues to up to 33 GeV in 130 cm (25 GeV/m) plasma
- Low emittance beam verified to be injected charge due to their response to ionizing laser and transverse displacement (Erik Adli’s talk)

Evolution of Twiss Parameters

From Transfer Matrix to evolution of Twiss parameters

$$R = \begin{bmatrix} C & S \\ C' & S' \end{bmatrix} \longrightarrow \begin{bmatrix} \beta_f \\ \alpha_f \\ \gamma_f \end{bmatrix} = \begin{bmatrix} C^2 & -2CS & S^2 \\ -CC' & CS' + SC' & -SS' \\ C'^2 & -2C'S' & S'^2 \end{bmatrix} \begin{bmatrix} \beta_i \\ \alpha_i \\ \gamma_i \end{bmatrix}$$

Free Propagation in Space:

$$\begin{bmatrix} x_f \\ x'_f \end{bmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ x'_i \end{bmatrix} \longrightarrow \begin{bmatrix} \beta_f \\ \alpha_f \\ \gamma_f \end{bmatrix} = \begin{bmatrix} 1 & -2L & L^2 \\ 0 & 1 & -L \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \beta_i \\ \alpha_i \\ \gamma_i \end{bmatrix}$$

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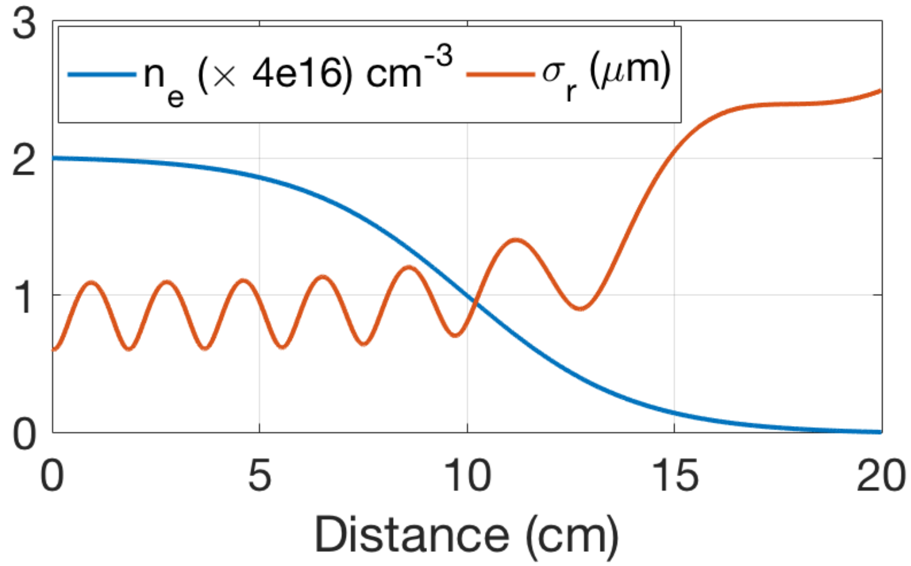
Ramp, Foils, Quads

Plasma Ramp: Continuous focusing element with

$$k = k_{beta} = \frac{\omega_p}{c\sqrt{2\gamma}}$$

$$R = \begin{bmatrix} \cos(k\ dz) & \frac{1}{\mathrm{k}}\sin(k\ dz) \\ -k\sin(k\ dz) & \cos(k\ dz) \end{bmatrix}$$



Be/Al foil: Multiple Scattering Angle $\Delta\theta$*

$$\epsilon_f = \sqrt{\epsilon_i(\epsilon_i + \beta_i\Delta\theta^2)}$$

$$\beta_f = \frac{\epsilon_i\beta_i}{\sqrt{\epsilon_i(\epsilon_i + \beta_i\Delta\theta^2)}}$$

$$\alpha_f = \frac{\epsilon_i\alpha_i}{\sqrt{\epsilon_i(\epsilon_i + \beta_i\Delta\theta^2)}} \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

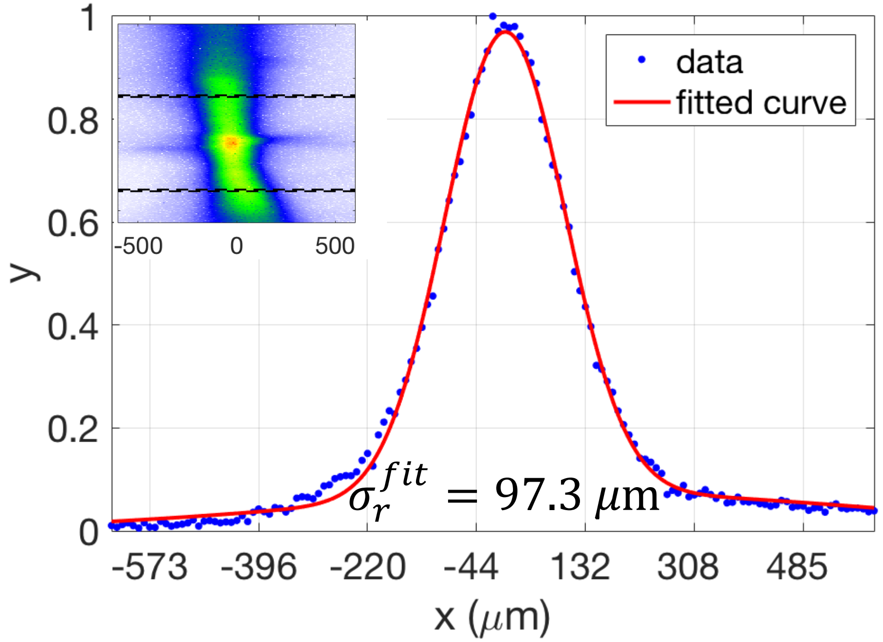
*$\Delta\theta$= 8.3 μrad for 75 μm Be window and 134 mrad for 5 mm Al

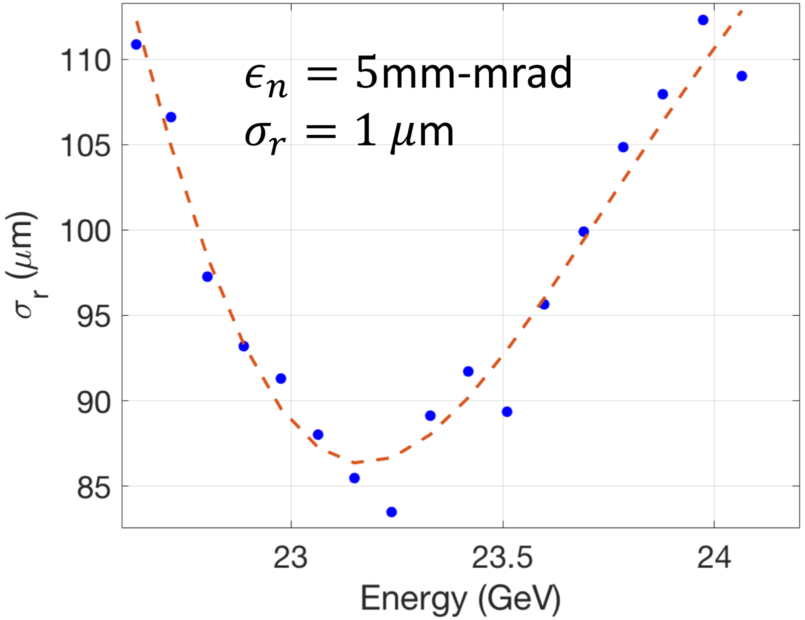
Quadrupole Focusing, $k = \frac{1}{\sqrt{Lf}}$

QS1 $$R = \begin{bmatrix} \cos(\sqrt{k}\ L) & \frac{1}{\sqrt{k}}\sin(\sqrt{k}\ L) \\ -\sqrt{k}\sin(\sqrt{k}\ L) & \cos(\sqrt{k}\ L) \end{bmatrix}$$

QS2 $$R = \begin{bmatrix} \cosh(\sqrt{k}\ L) & \frac{1}{\sqrt{k}}\sinh(\sqrt{k}\ L) \\ -\sqrt{k}\sinh(\sqrt{k}\ L) & \cosh(\sqrt{k}\ L) \end{bmatrix}$$

Emittance Measurement Method


Double Gaussian Fit


Experiment and Optimization Results

- Energy slices equivalent except for energy
- Elements affecting beam size measurement
  - Plasma down-ramp
  - 75 μm Be window
  - Two Quadrupole magnets (QS1,QS2)
  - 5 mm Al window
- ϵ_n, σ_r, α = (5.4 mm-mrad, 1.1 μm, -0.29) are results of optimization for this case
- Distance to Be window is used as a free parameter in optimization for sanity check

Properties of the Beam Injected in Li Oven

- Highlights:
    - Highest energy bunch from a plasma accelerator
    - Emittance on the order of mm-mrad
    - Energy spread on the order of 10%

- Downside
    - Little control over injection region

- Independent control of injection and acceleration region allows for optimization of parameters

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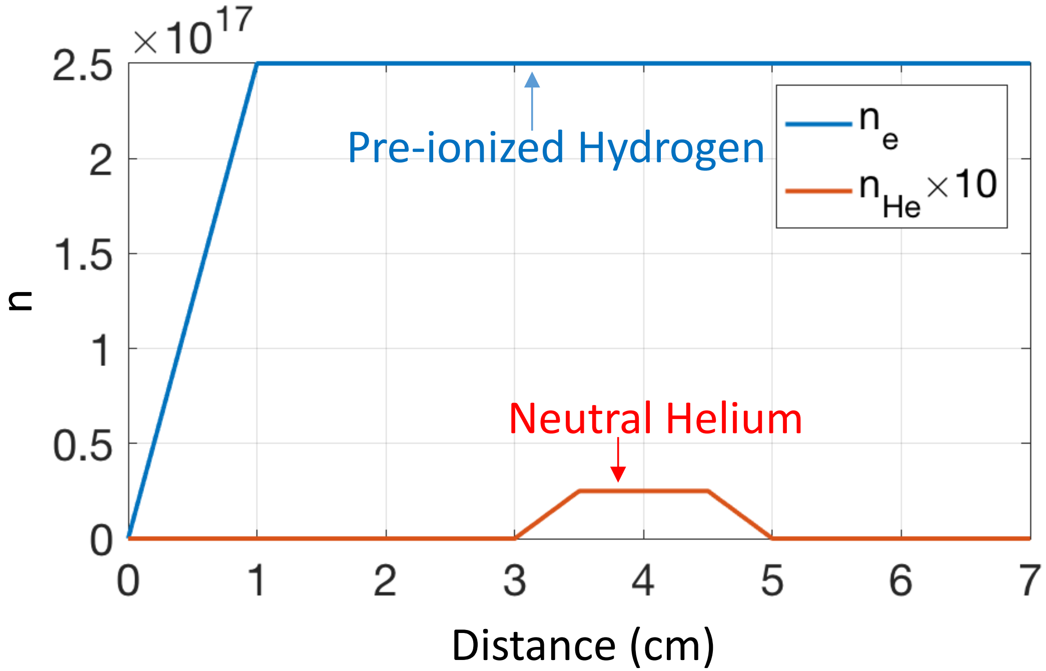
3D Simulation of Ionization Injection

- Beam:
  - $N=2\text{x}10^{10}$
  - Emittance = 120 mm-mrad
  - $\sigma_r=\sigma_z=30$ um

- H_2 plasma density: $2.5\text{x}10^{17}$ cm^{-3}
- Envelope oscillation wavelength ~ 1 cm
- The length of the jet set to twice oscillation wavelength
- He concentration: $2.5\text{x}10^{15}$ cm^{-3}
- Allowed for beam evolution over 3 cm before He region



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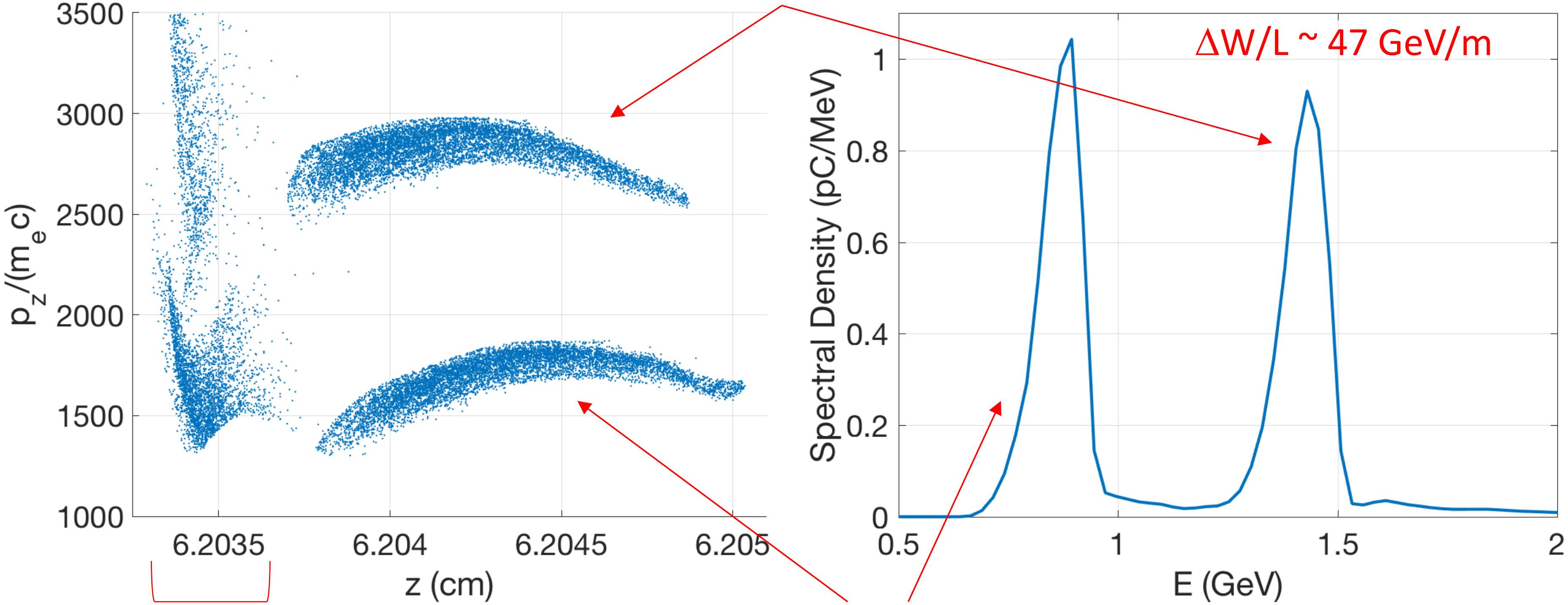
Helium Electron Properties after 6.2 cm



First Oscillation

ΔW/L ~ 47 GeV/m

Wide energy “dark current”

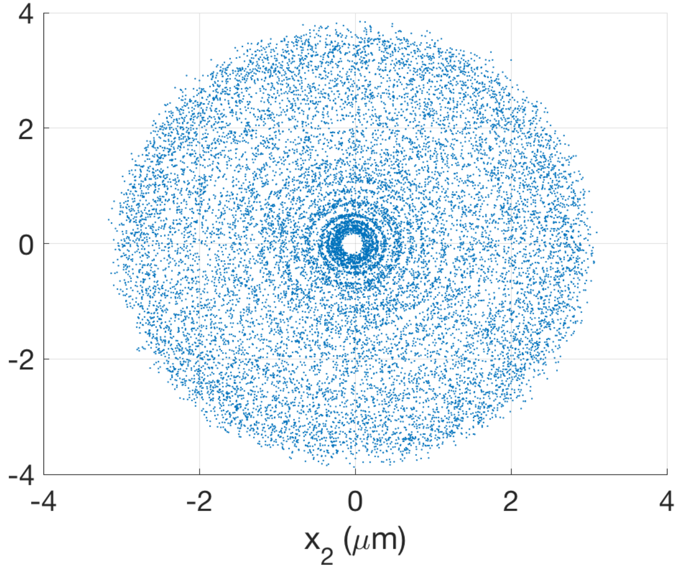
Second Oscillation

Total helium charge is 260 pC, most of it almost equally split between the electrons from the two betatron oscillation cycles

Peak current ~ 8 kA, FWHM ~ 8 μm

Phase Space and Emittance

High Energy Beam



x'^{rms}_2= 1.8 mrad

x_2^{rms}= 1.4 μm

$$\epsilon_g = \sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

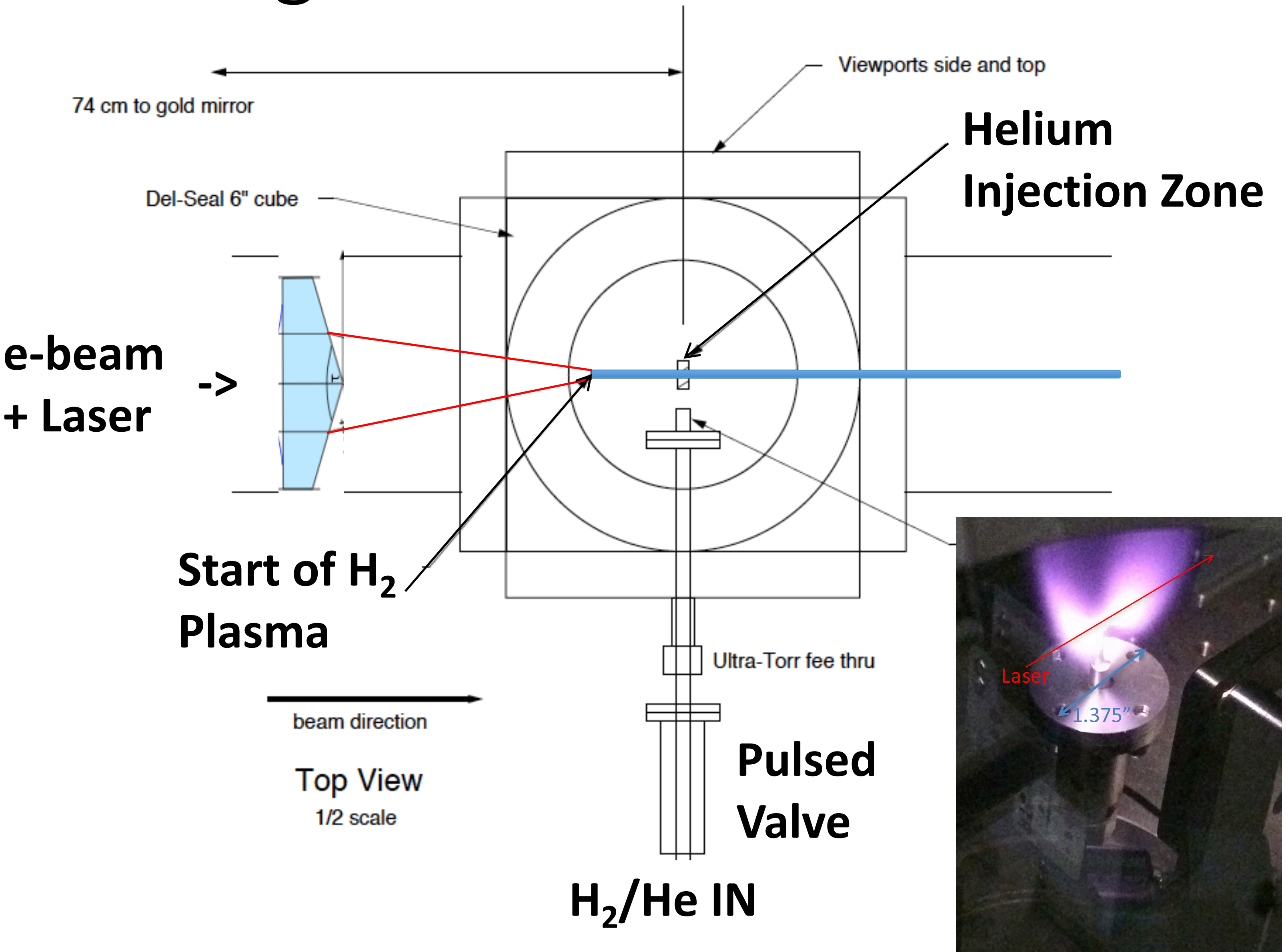
$$\epsilon_n = \gamma \epsilon_g$$

$$\gamma = < \sqrt{1 + \bar{p}^2} >$$

	ϵ_g (nm)	ϵ_n (mm-mrad)	γ
High γ	2.5	7.1	2802
Low γ	4.1	7.1	1690
Full beam	2.9	6.5	2278

Beams generated from betatron cycles are essentially identical

Injector Design



Helium Injection Zone

e-beam + Laser ->

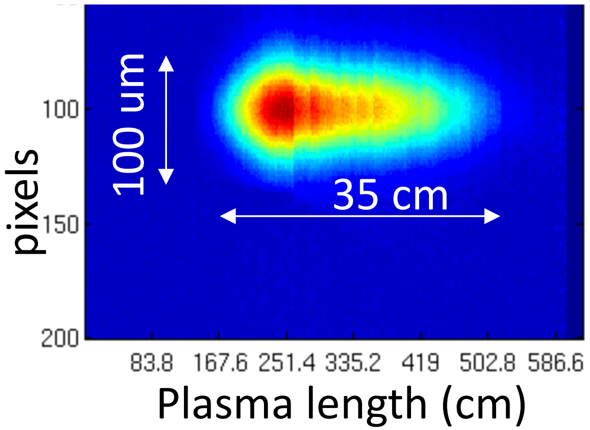
Start of H_2 Plasma

Pulsed Valve

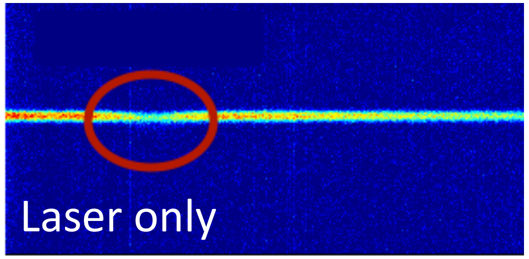
H_2/He IN

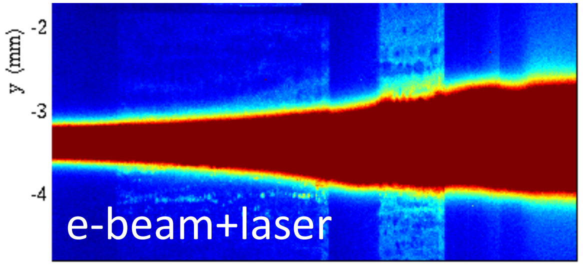
Hydrogen Plasma Experiment

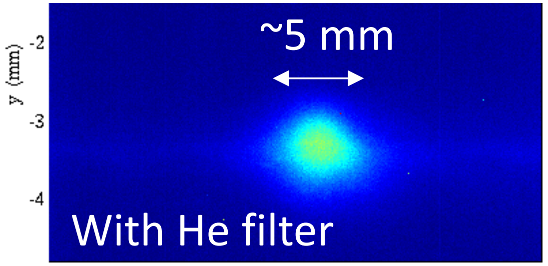
- ✓ Produced ~40 cm of preionized hydrogen plasma using the 10 TW laser and axilens optic



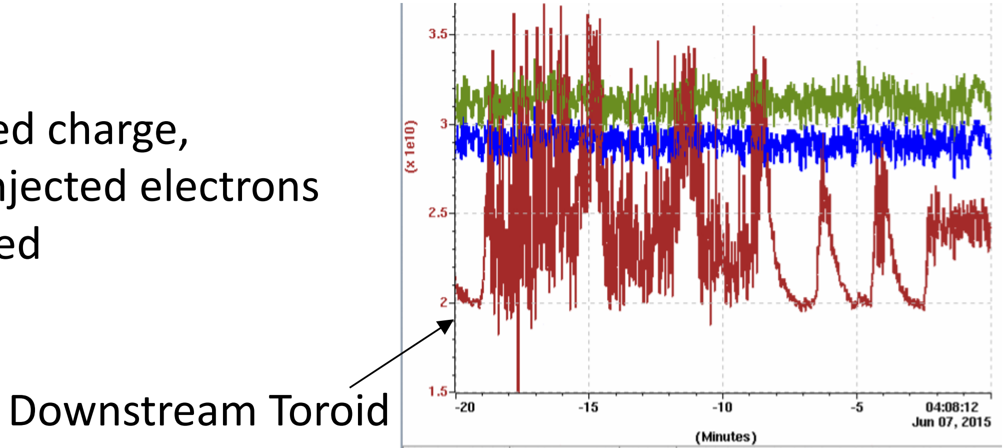
- ✓ Ionization of the helium impurity in the presence of the wakefield was observed using special line filter for helium

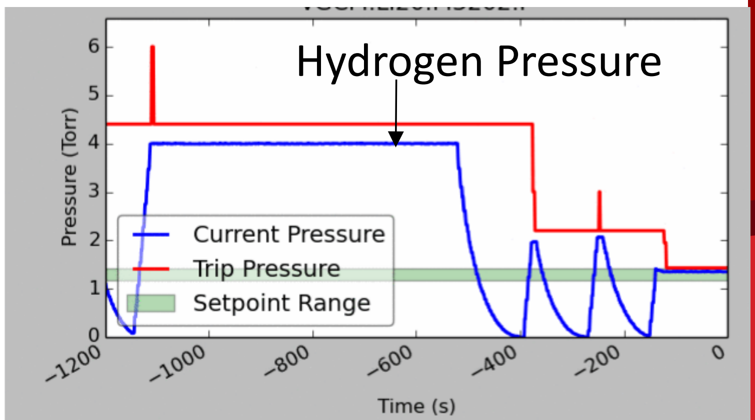






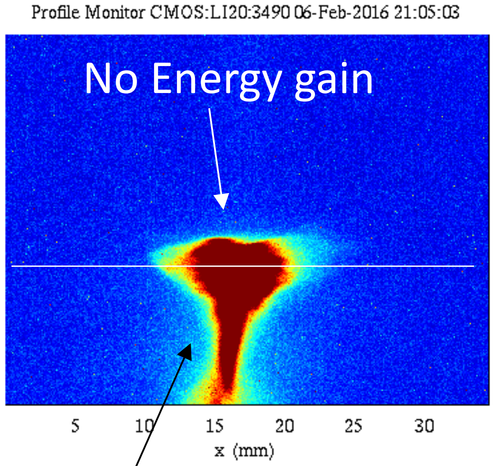
- ✓ Although we observed injected charge, correlation of dark current or injected electrons with helium jet was not observed





Why didn’t it work?

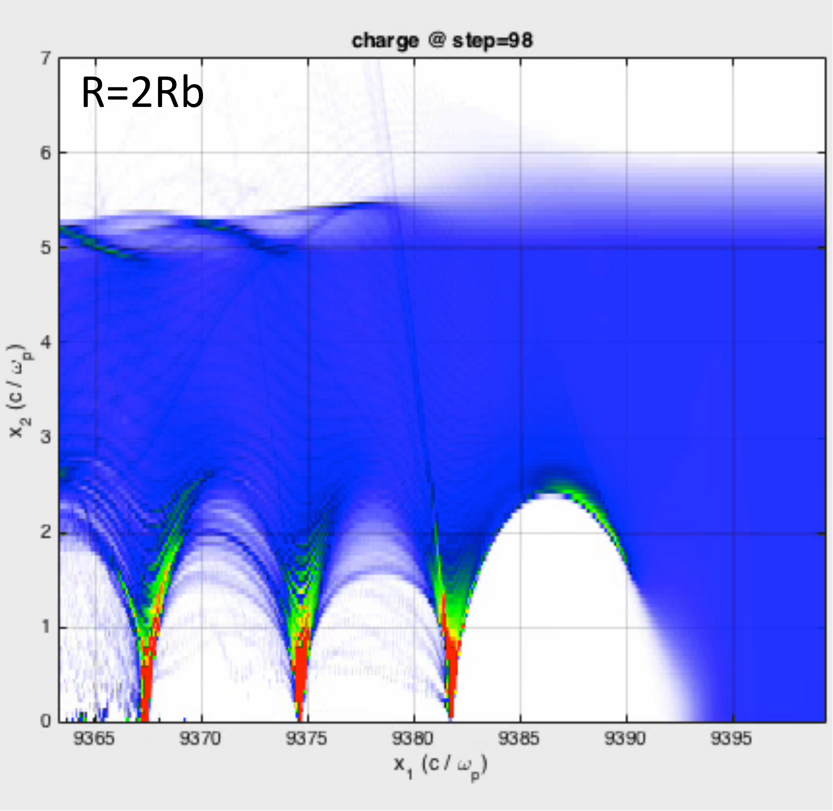
- Insufficient field for trapping due to weak electron-beam to plasma coupling (for instance, hydrogen plasma too narrow)
- Partially ionized H_2 beam loaded
- Gainless wake
- Beam did not have strong enough field to ionize helium
    - Possible if the region of plasma did not overlap with helium

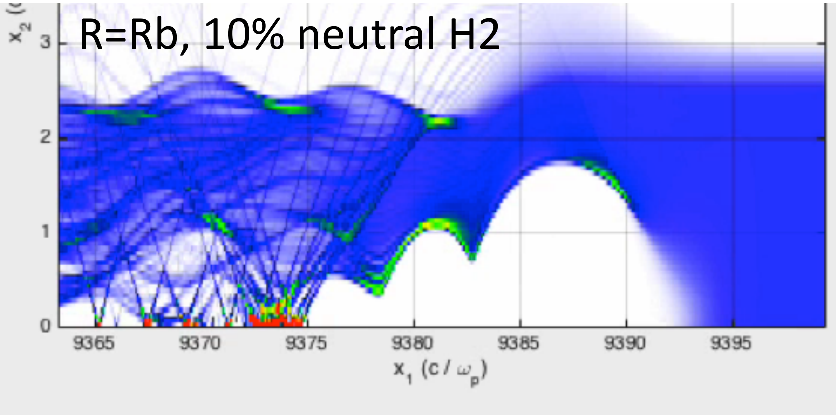


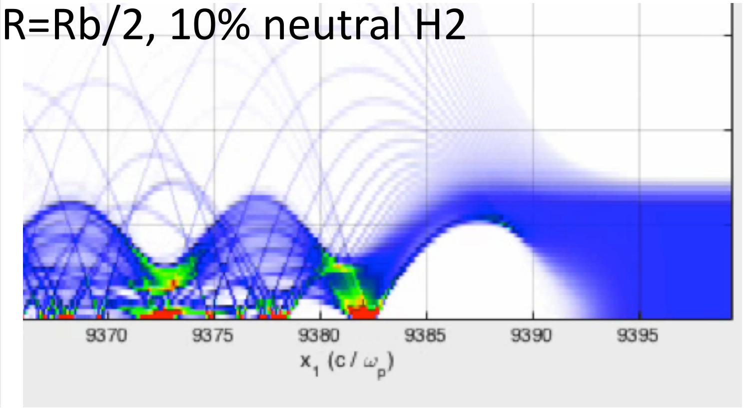
No Energy gain

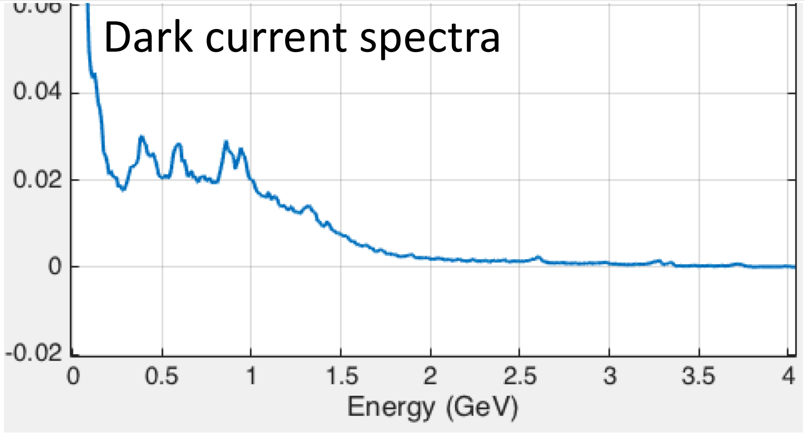
Energy loss > 5 GeV

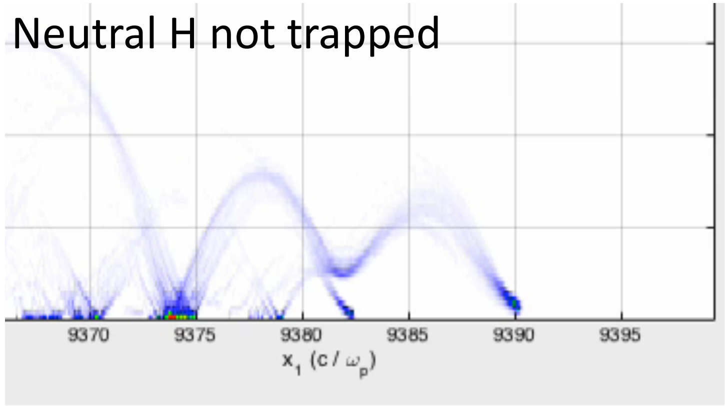
Narrowing of Plasma Column


R=2Rb


R=Rb, 10% neutral H2


R=Rb/2, 10% neutral H2


Dark current spectra


Neutral H not trapped

Peak field: 144 GeV/m

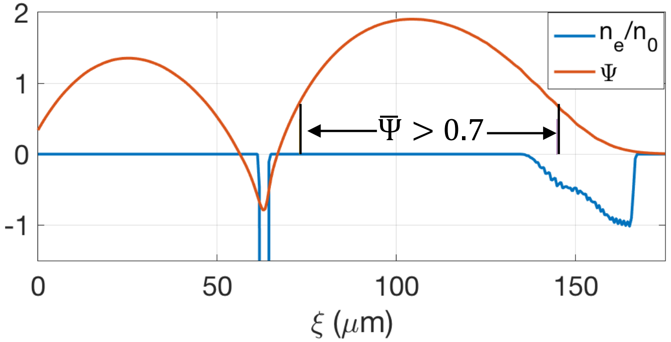
Peak field: 96(unloaded)->~ 25 (loaded) GeV/m

Peak field: ~25 GeV/m

Wake persists for small filaments, but there is a threshold where trapping no longer happens (in this case Rb/2<R<Rb)

FACET II

- Two important features of FACET II beam for this experiment:
  - High Peak Current
  - Small σ_z



- Consequences
  - Small injection zone enables very high current for injected beam
  - High peak current means ionization for (nearly) all longitudinal beam slices
  - This will result in an ultrashort, high current beam, but controlling the energy spread will be a primary challenge

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"Baseline Comparisons"

Experiment	σ_z	σ_r	ε_N	En	Q	β_T	Ib
e^- beam	30μm	30μm	120mm.mrad	20.35 GeV	3.2nC	30cm	13 kA

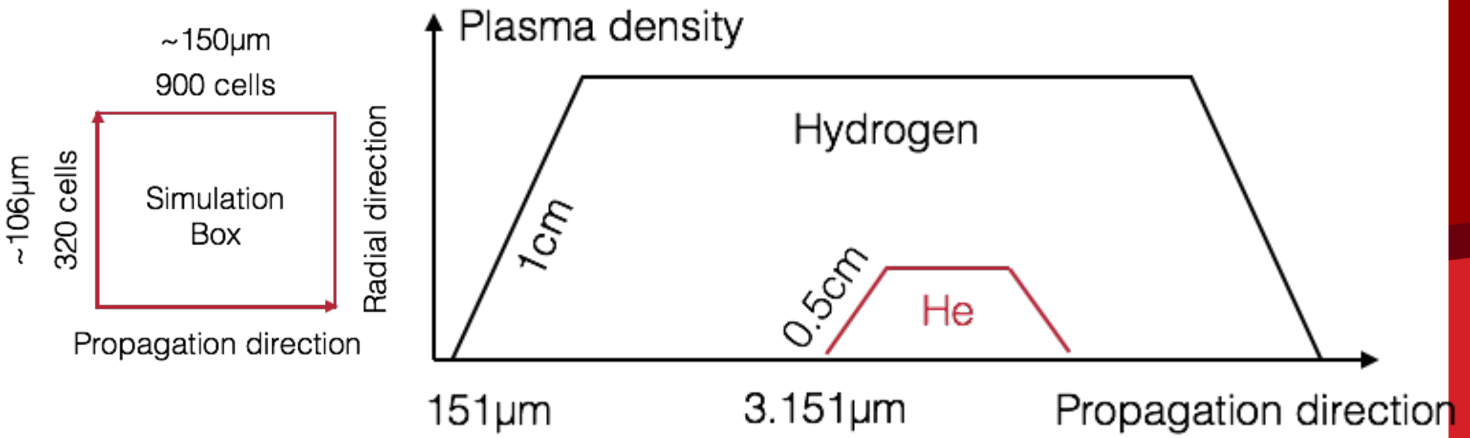
FACET I Beam

Experiment	σ_z	σ_r	ε_N	En	Q	β_T	Ib
e^- beam	10μm	10μm	10mm.mrad	10 GeV	2nC	20cm	23 kA

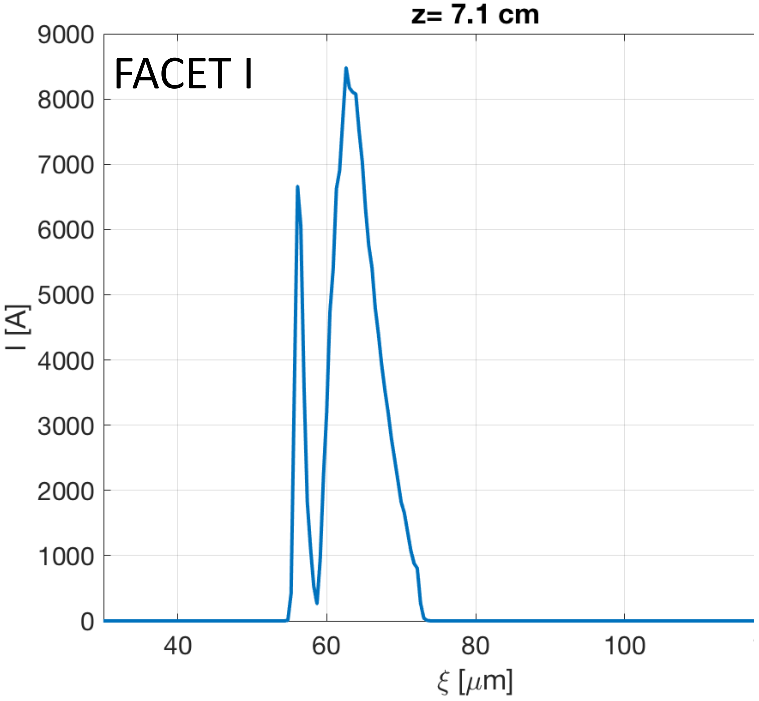
FACET II Beam

Experiment	σ_z	σ_r	ε_N	En	Q	β_T	Ib
e^- beam	**5μm**	10μm	10mm.mrad	10 GeV	**0.7nC**	20cm	**17 kA**

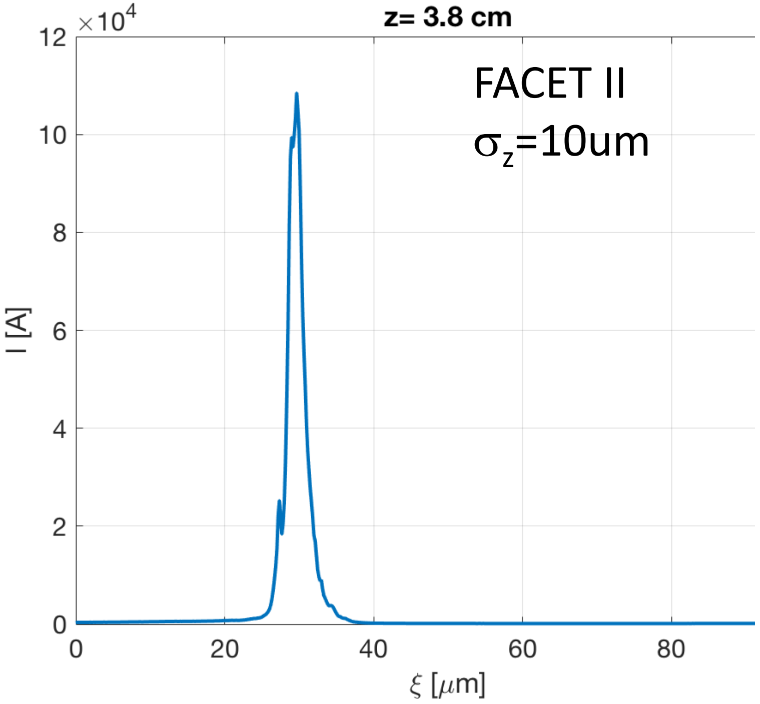
Experiment	n_{H2}	c/ω_{pH2}	n_{He}
Plasma	2.5×10^{17}cm^{-3}	10.6μm	2.5×10^{15}cm^{-3}



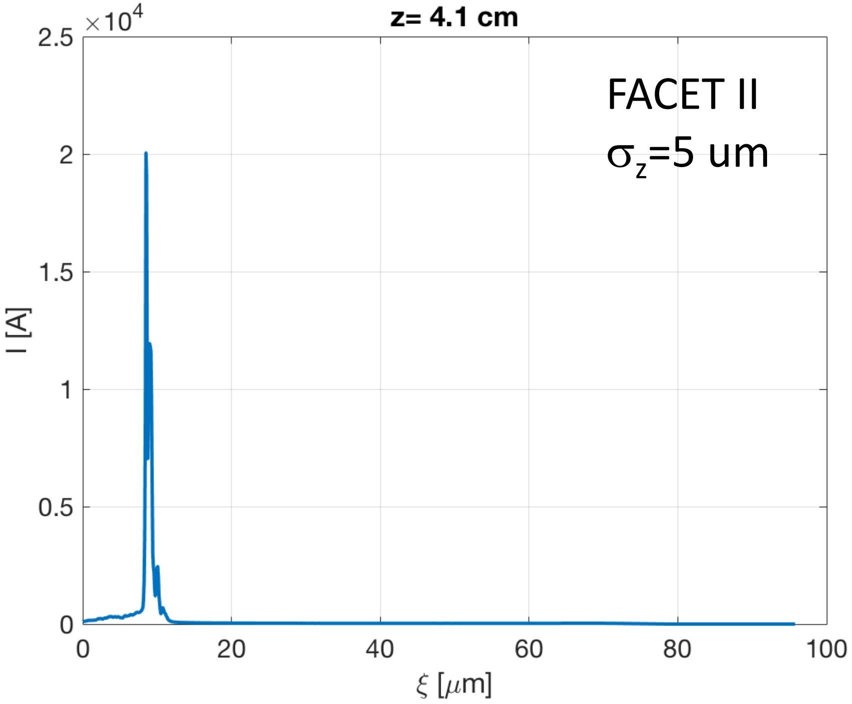
Injected Charge (preliminary)



FWHM =6.8μm (wide peak)
Total Q = 260 pC

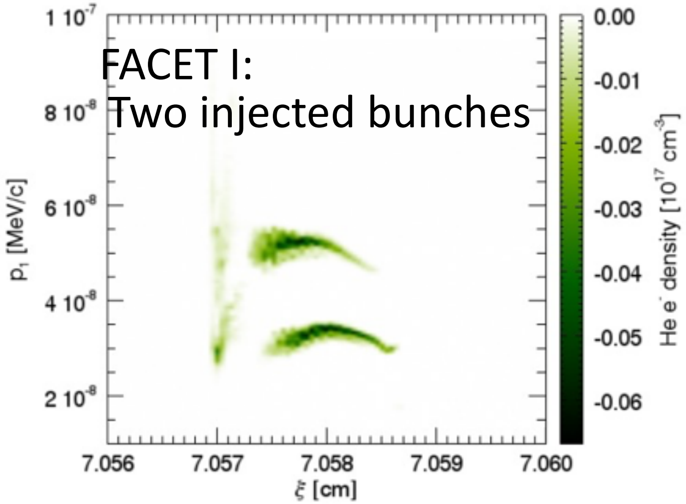


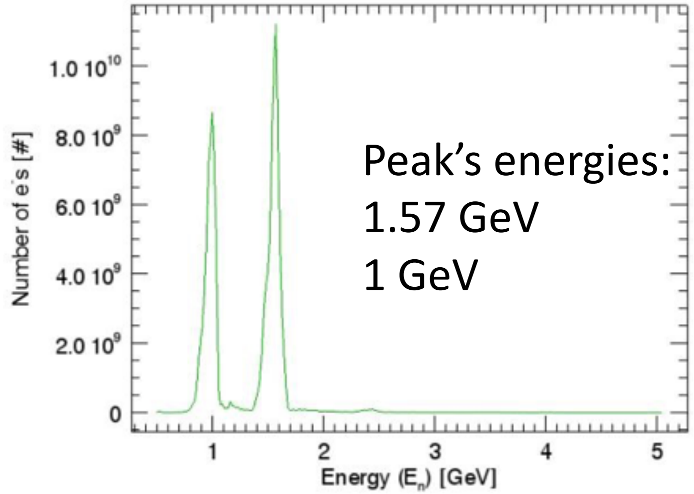
FWHM = 2.3 μm
Q>1nC (Heavily beamloaded on the helium plateau)

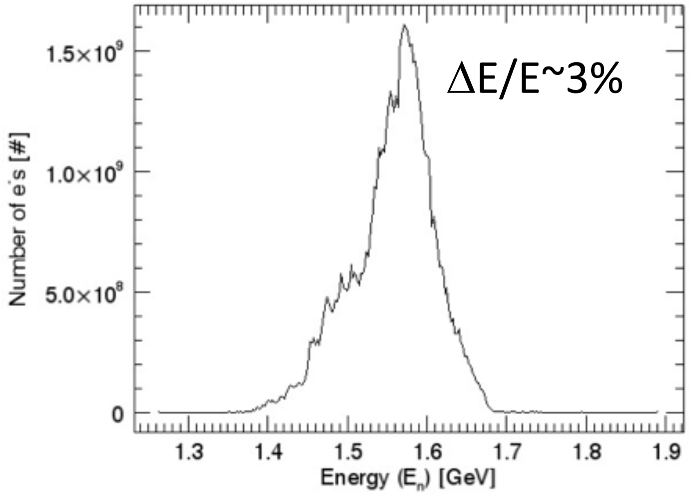


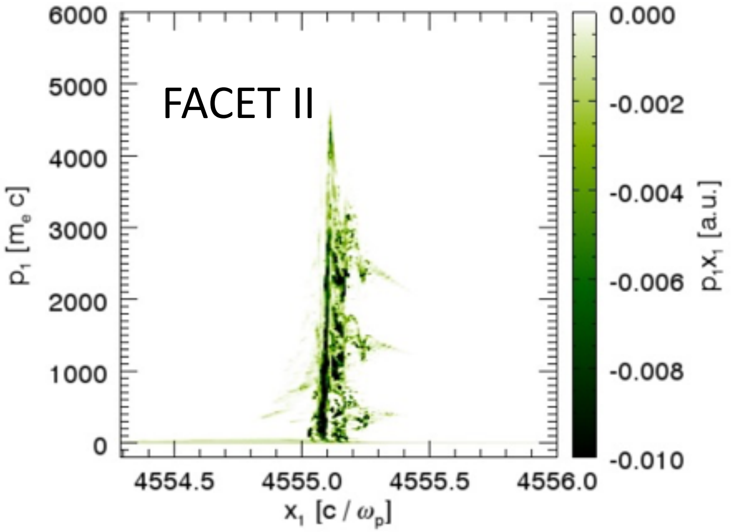
FWHM <0.5 μm
Q~ 70 pC

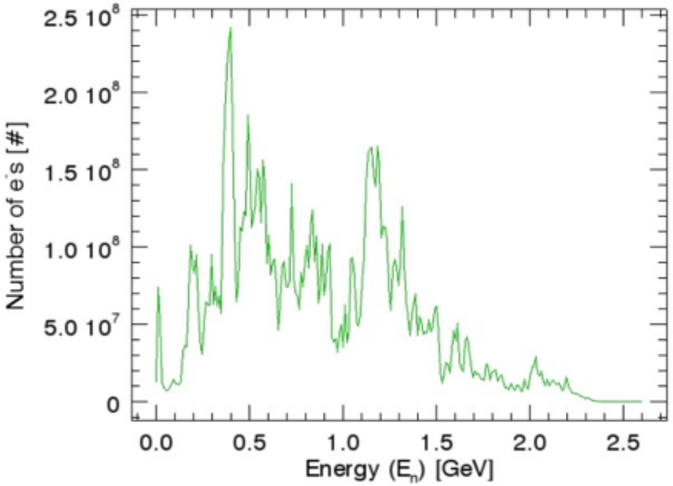
Phase space comparison (Preliminary)


FACET I:
Two injected bunches


Peak's energies:
1.57 GeV
1 GeV


$\Delta E/E$~3%


FACET II



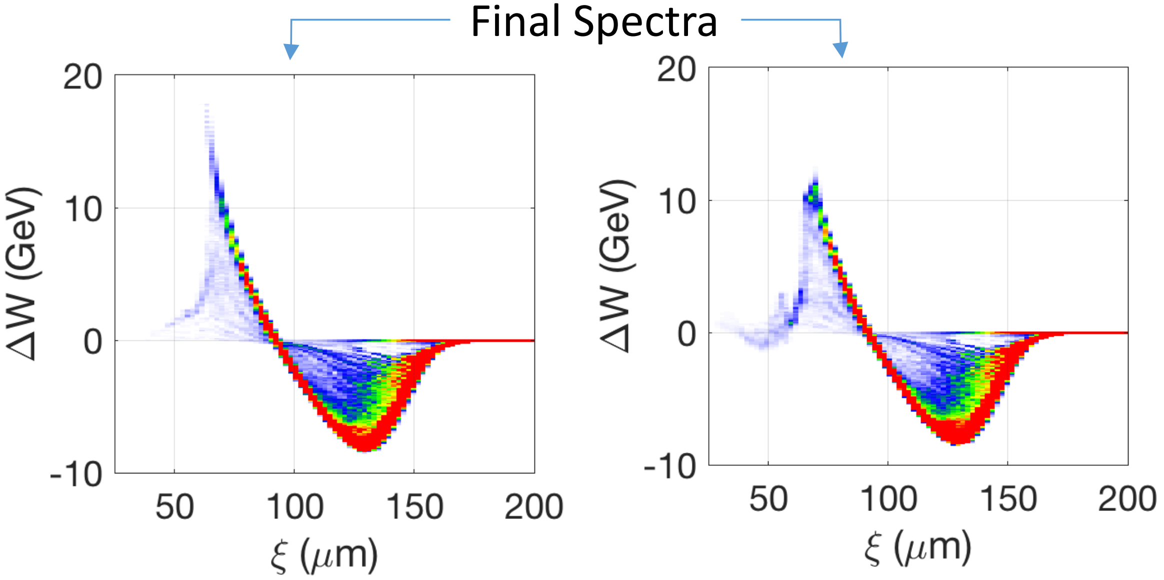
Continuous injection of beam results in high energy spread

Conclusions

- Ionization injection can be detrimental or beneficial in a PWFA
- We encountered the detrimental effects of ionization injection in the form of heavy beam loading, occurring through distributed injection of charge (dark current) along a Rb plasma
- The beneficial effects of ionization injection appeared in the form of an injected beam with micron scale emittance from a drive beam of ~100 micron emittance in experiments with Li plasma. (emittance transformer)
- Simulations show a region of impurity confined to a single betatron cycle is enough to act as injection zone to yield an electron bunch with micron scale emittance and ~3% energy spread
- FACET II's high current beam provides exciting opportunities for the control of qualities of the injected beam

The End

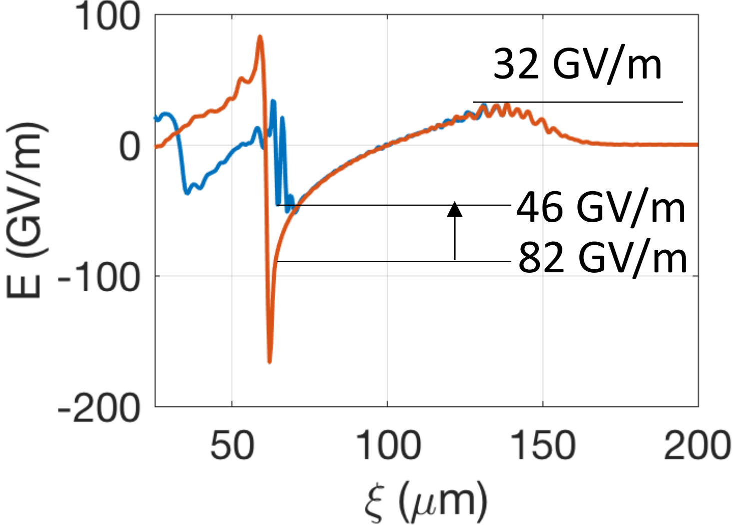
Rb II Beam Loading of The Wake in Simulation


Final Spectra

Without secondary Injection

With secondary Injection

- Energy Loss = 8 GeV
- Unloaded Energy gain = 17.5 GeV
- Loaded Energy gain = 12 GeV
- Beam loading reduced R from 2.2 to 1.5

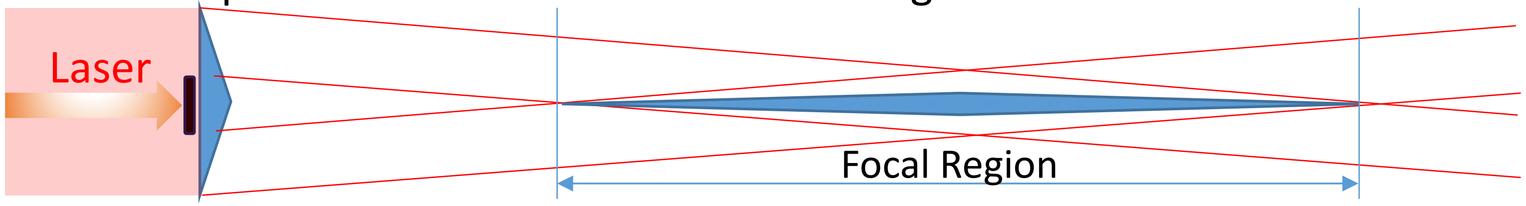

Longitudinal Fields

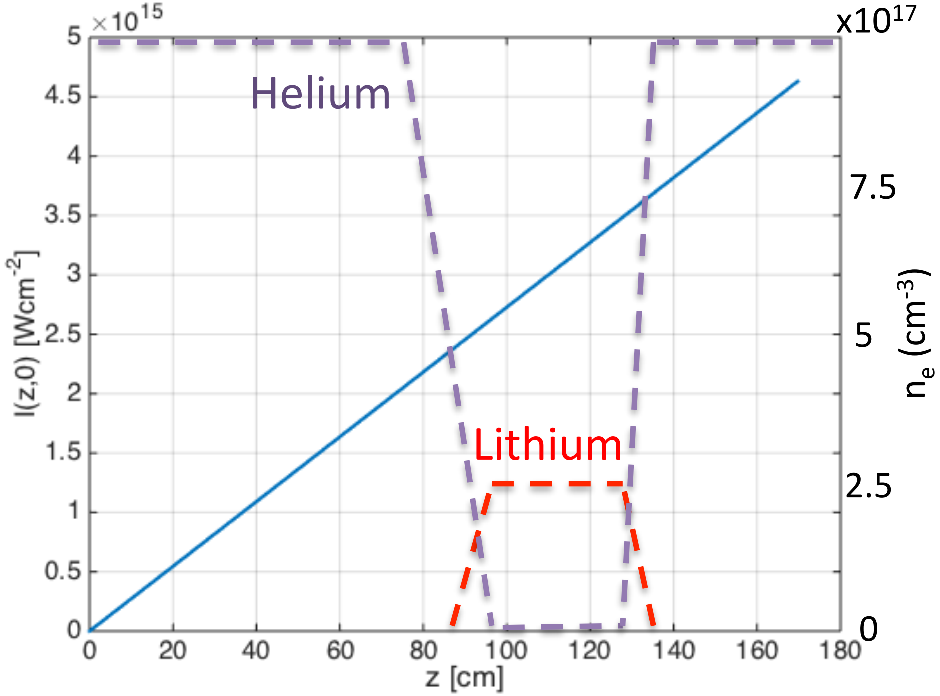
Both Simulations

- Unloaded Transformer Ratio: 2.7
- Loaded Transformer Raio: 1.6
- Beam loading reduced energy gain from 82 GV/m to 46 GV/m

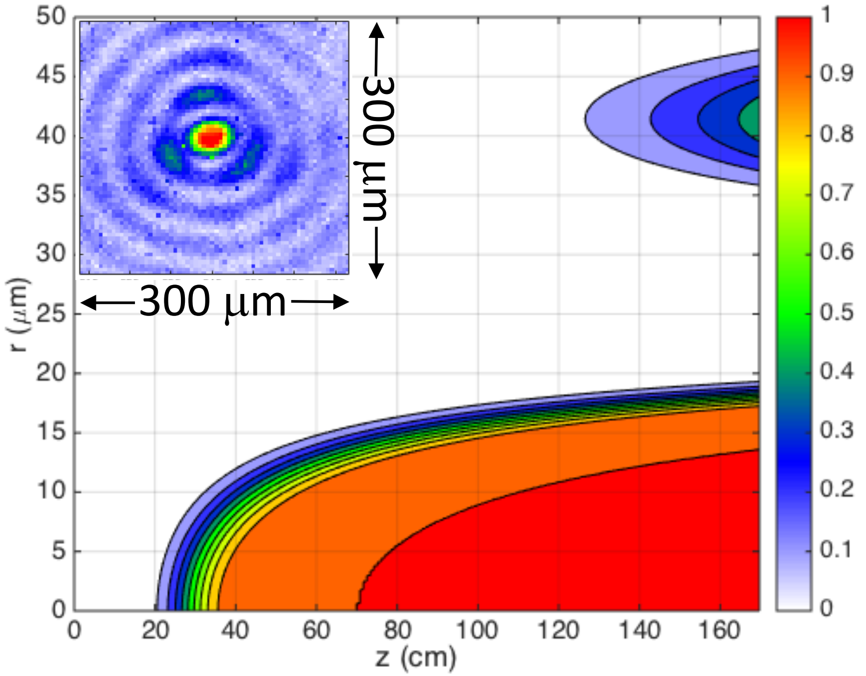
Ionization of Helium

Axicon optic is used to ionize a controlled region





- Threshold for ionization of neutral helium is about 2×10^{15} Wcm^{-2}

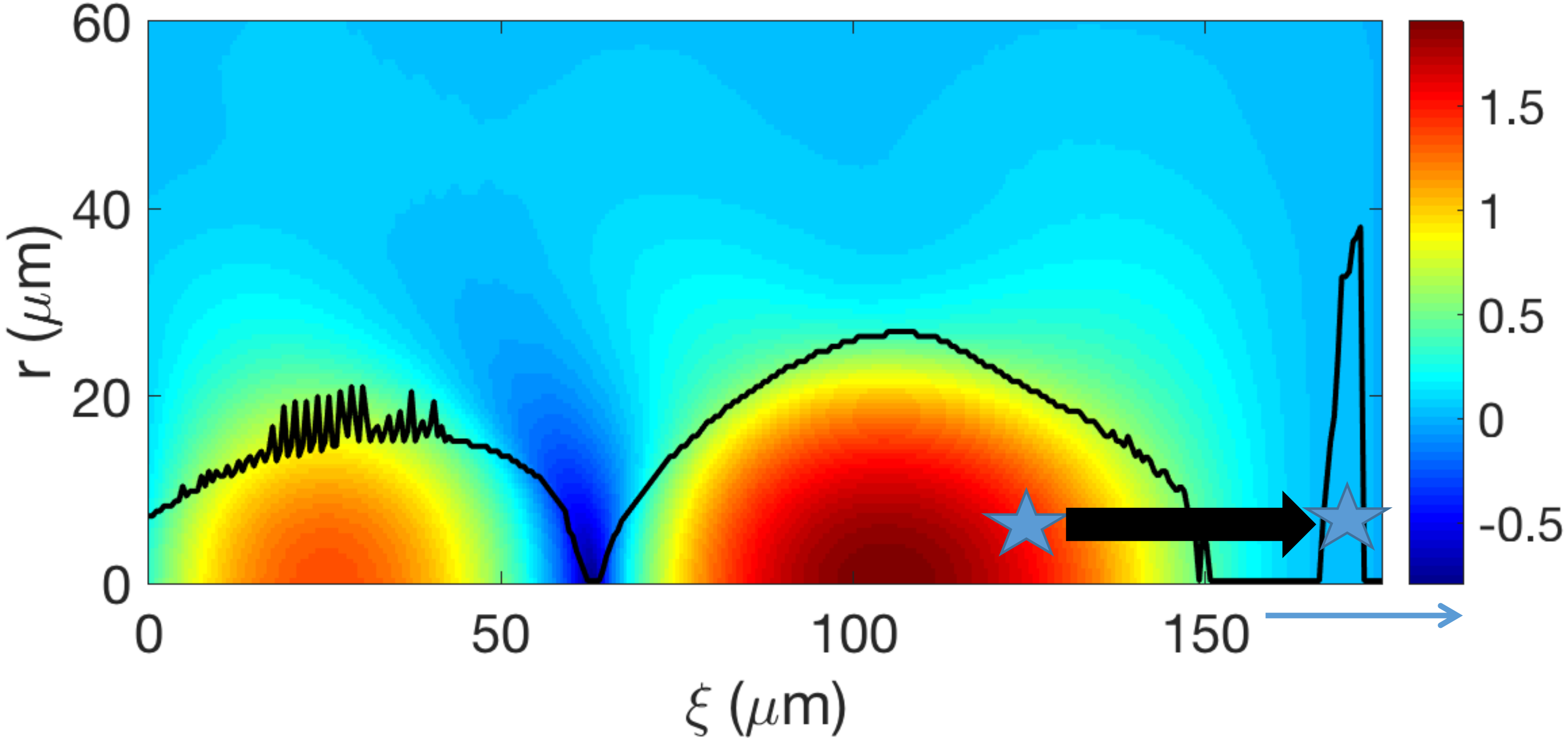


- Laser will ionize helium in the Li ramp

Stony Brook University

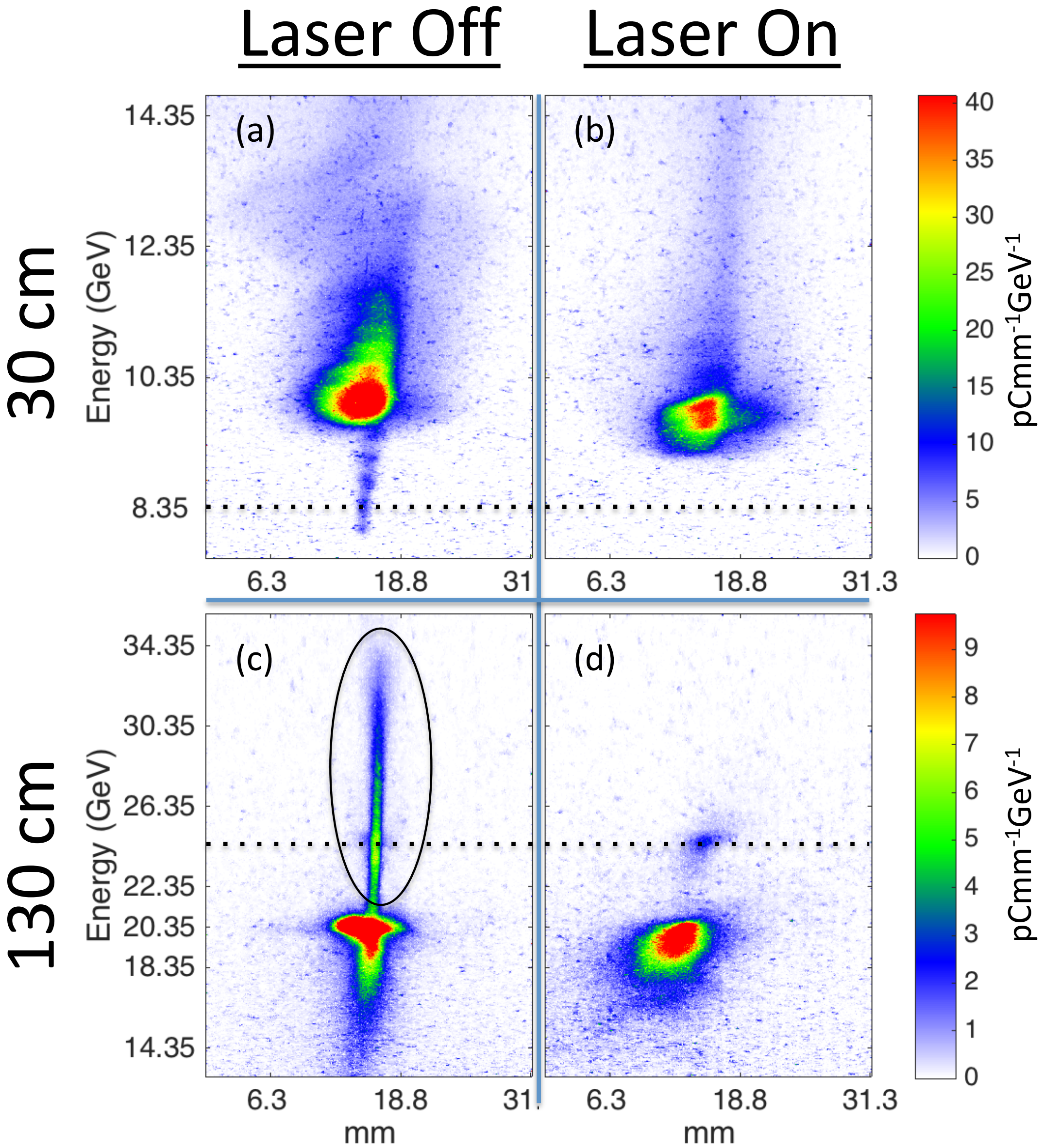
UCLA

Effect of Ionizing Laser



Laser ionized helium electrons outside the bubble where $\Delta\Psi < -1$ is not satisfied

Laser Ionization in Experiments and Length Scaling



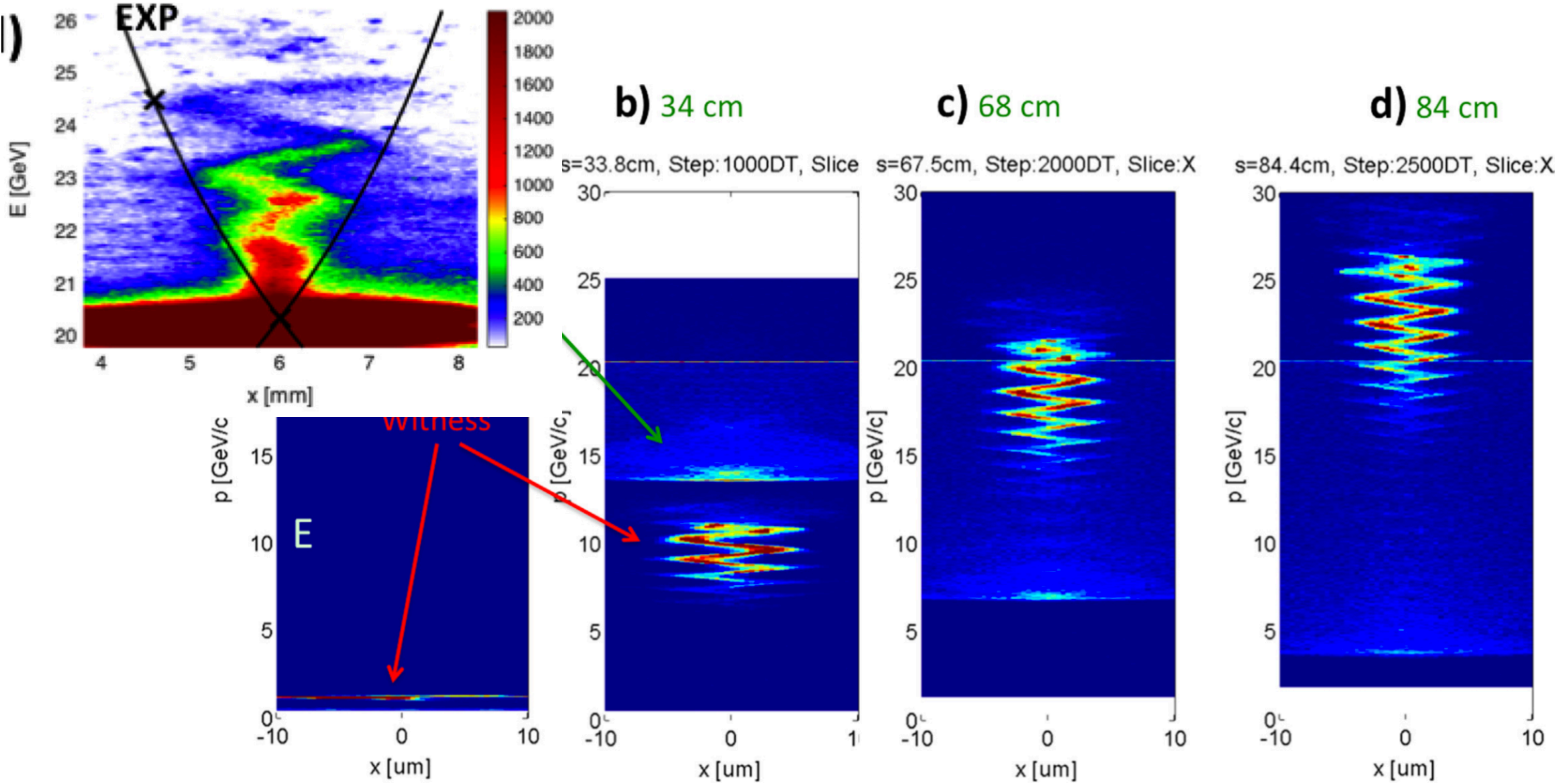
30 cm plasma:

- Injected beam observed for beam ionized case
- Peak energy gain ~ 10 GeV
- Injected charge disappears when helium is preionized by laser

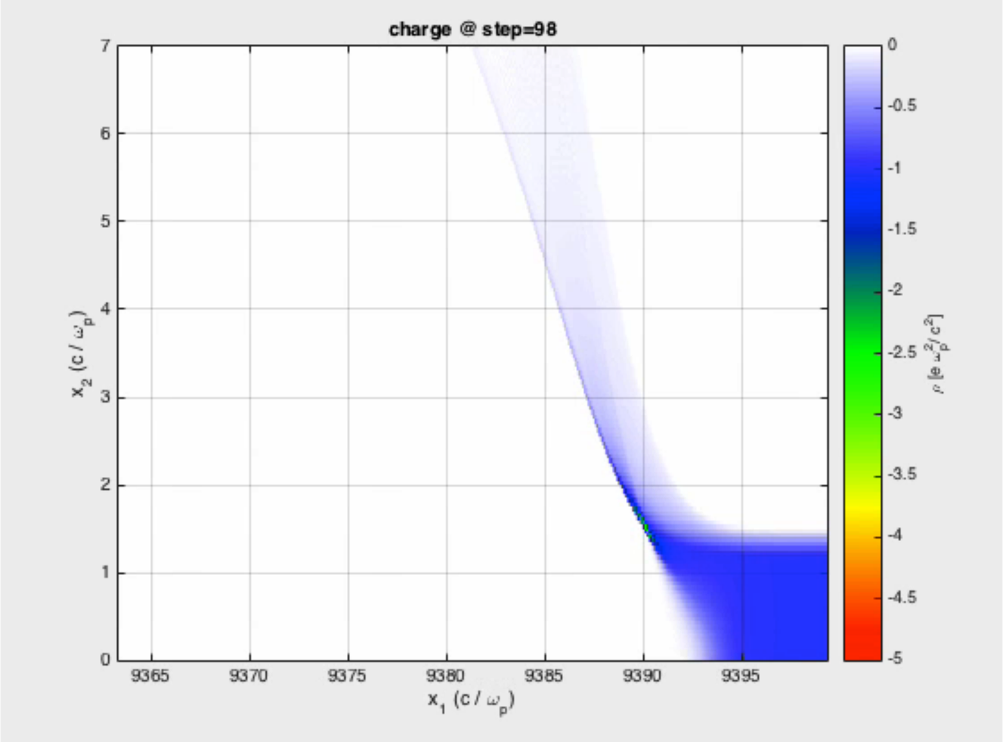
130 cm plasma:

- Injected beam observed for beam ionized case
- Peak energy gain ~ 34 GeV
- Injected charge disappears when helium is preionized by laser

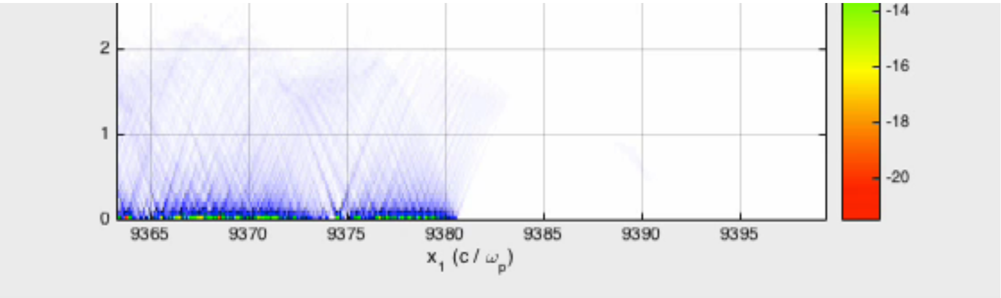
Effect of Transverse Displacement

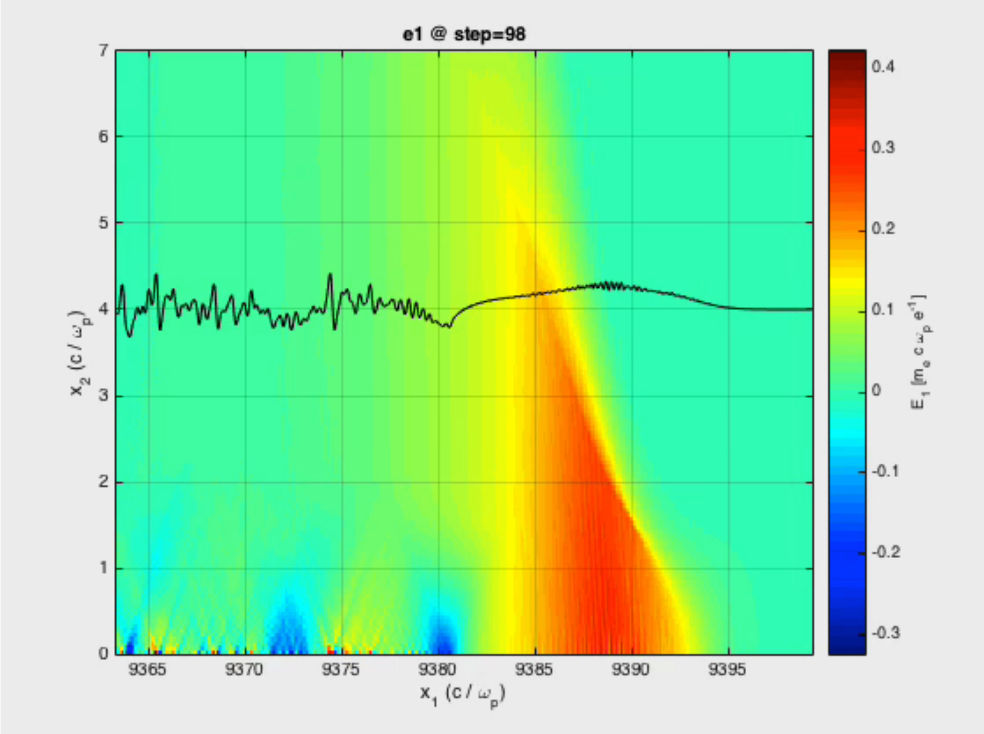


Gainless Wake, $\sigma_r = \sigma_{r0}/2 = 15\ \mu m$



Neutral H2 ionized, but not trapped





Peak decelerating field ~ 24 GeV/m
Peak accelerating field: ~ 4 GeV/m
Peak transverse field occurs at r<0.5 c/wp

Injected Beam Observed in H_2