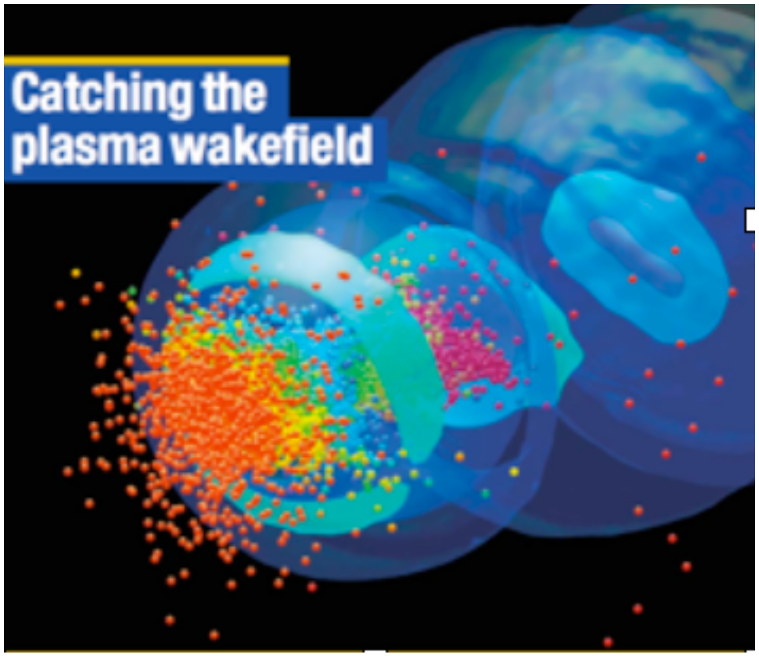

Deep Dive into Physics of E300

What will it take to make experiments
more like simulations?

Minimize centroid displacements and pre and post bunch tails

Chan Joshi

UCLA

On behalf of E300 collaboration

White, Hogan (SLAC), Fujii, Zhang, Zhao, Zan,Marsh, An (UCLA)

E300 Scientific Goals

OPEN ACCESS
IOP Publishing
Plasma Physics and Control
Plasma Phys. Control. Fusion **60** (2018) 034001 (14pp)
https://doi.org/10.1088/1361-65

Plasma wakefield acceleration experimen at FACET II

C Joshi[1], E Adli[2], W An[1], C E Clayton[1], S Corde[3], S Gessner[4], M J Hogan[5], M Litos[6], W Lu[7], K A Marsh[1], W B Mori[1], N Vafaei-Najafabadi[8], B O'shea[5], Xinlu Xu[1,5], G White[5] and V Yakimenko[5]

[1] University of California Los Angeles, Los Angeles, CA 90095, United States of America
[2] University of Oslo, NO-0316, Oslo, Norway
[3] LOA, ENSTA ParisTech, CNRS, Ecole Polytechnique, Université Paris-Saclay, F-91762 Palaiseau, France
[4] CERN, Geneva, Switzerland
[5] SLAC National Accelerator Laboratory, Menlo Park, CA 90309, United States of America
[6] University of Colorado Boulder, Boulder, CO 80309, United States of America
[7] Department of Engineering Physics, Tsinghua University, Beijing 10084, People's Republic of China
[8] Stonybrook University, Stony Brook, NY 11794, United States of America

E-mail: joshi@ee.ucla.edu

Plenary talk given at LPAW 2017, Jeju, Korea

UCLA

E300 Goals closely match the strategic goals of the DOE-HEP AA R&D Roadmap for PWFA

- Main Goals are as follows:

- 1) A net energy transfer efficiency of 40% from the drive to the trailing bunch-pump deplete the drive bunch
- 2)Minimize the energy growth of the trailing bunch- understand the factors that cause increase of energy spread
- 3) Minimize the emittance growth- understand the factors that cause emittance growth- beam mismatch, alignment error between the drive and trailing bunches
- 4)Conserve the charge of the trailing bunch

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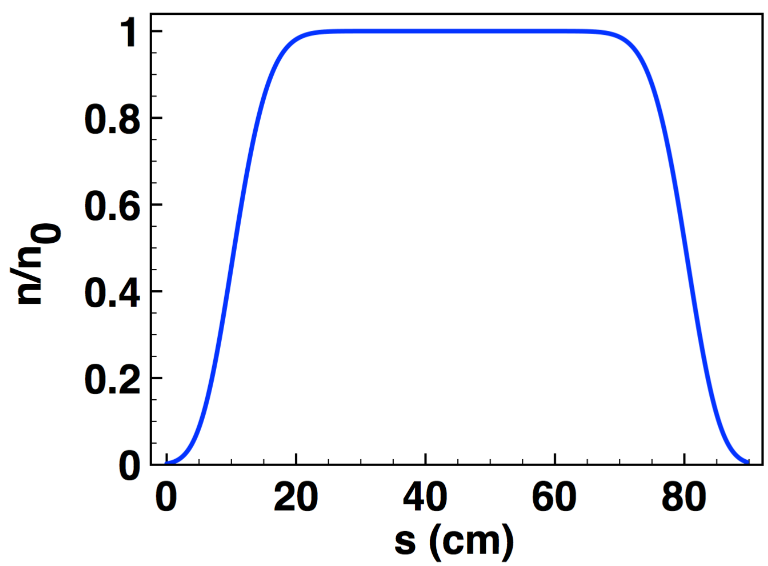
Near Ideal beam Matching and Loading leads to little emittance growth (Li plasma oven specified)

QuickPic Simulation with matching ramps but no He buffer

Drive Beam: E = 10 GeV, Ipeak=15 kA
β = 89.61 cm, α = 0.0653,
σ_r = 21.17 μm, σ_z = 12.77 μm ,
N =1.0 x 10^{10} (1.6 nC),
ε_N = 10 μm

Trailing Beam: E = 10 GeV, Ipeak=9 kA
β = 89.61 cm, α = 0.0653,
σ_r = 21.17 μm, σ_z = 6.38 μm ,
N =0.3 x 10^{10} (0.48 nC),
ε_N = 10 μm
Distance between two bunches: 150 μm
Plasma Density: 4.0 x 10^{16} cm^{-3} (with ramps)

Plasma Density Profile



Ref:: C. Joshi et al PPCF Jan 2018

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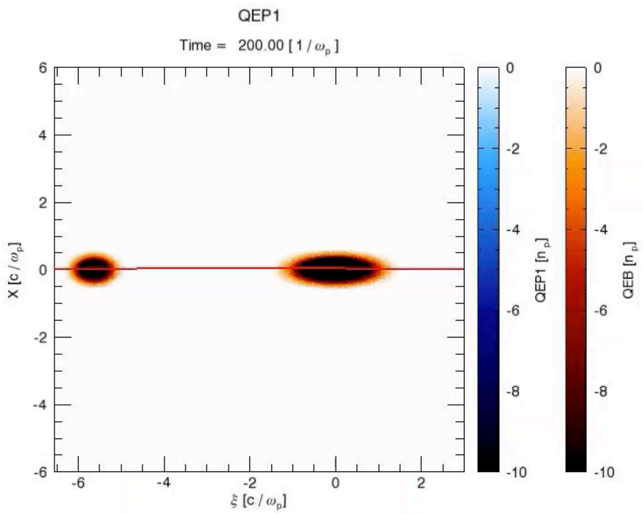
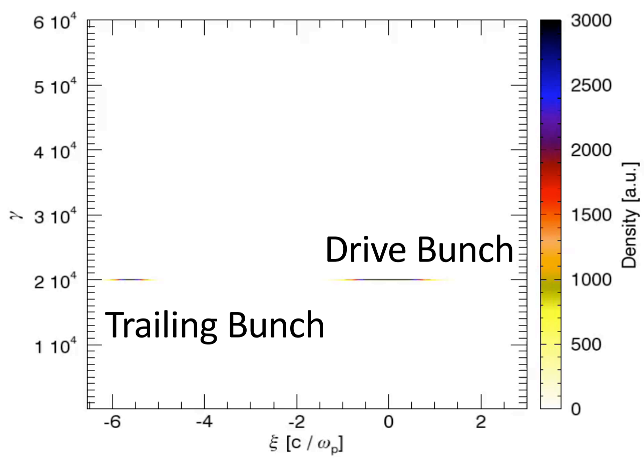
Beam and Plasma Density; Energy evolution and spot-size and emittance
Preformed plasma

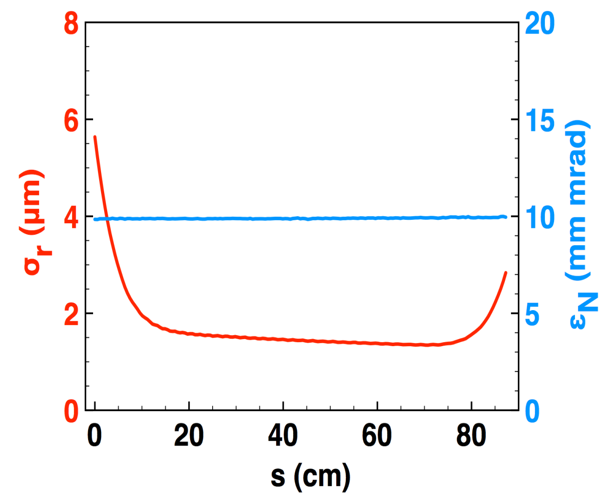
Plasma and beam density with on-axis Ez line out



Beam Energy



Projected beam spot size and emittance



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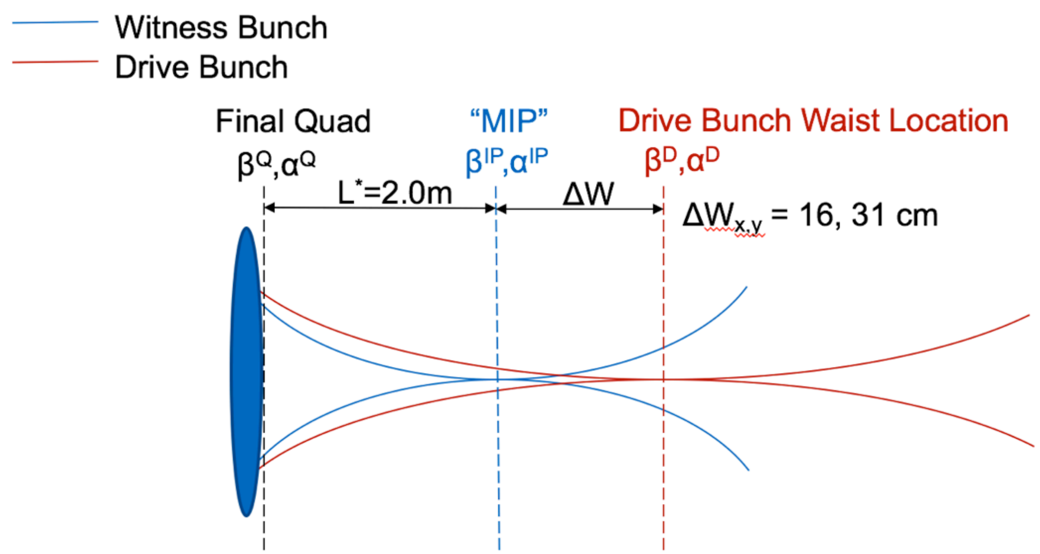
Final focus and IP as of June 2018

(for a 3um emittance we will likely ionize He in the ramps)



	α^Q [x,y]	β^Q [x,y]	α^{IP} [x,y]	β^{IP} [x,y]	α^D [x,y]	β^D [x,y]
Witness	40, 40	80, 80 m	0.0, 0.0	5.0, 5.0 cm	-3.1, -5.8	53, 185 cm
Drive	59, 12	127, 27 m	4.2, 1.6	70, 70 cm	0.0, 0.0	3.7, 19 cm

Figure 3.1: Final Focus at FACET II experimental area. Courtesy of Glenn White (SLAC).

E300 Beam Parameters (C. Joshi PPCF 2018)

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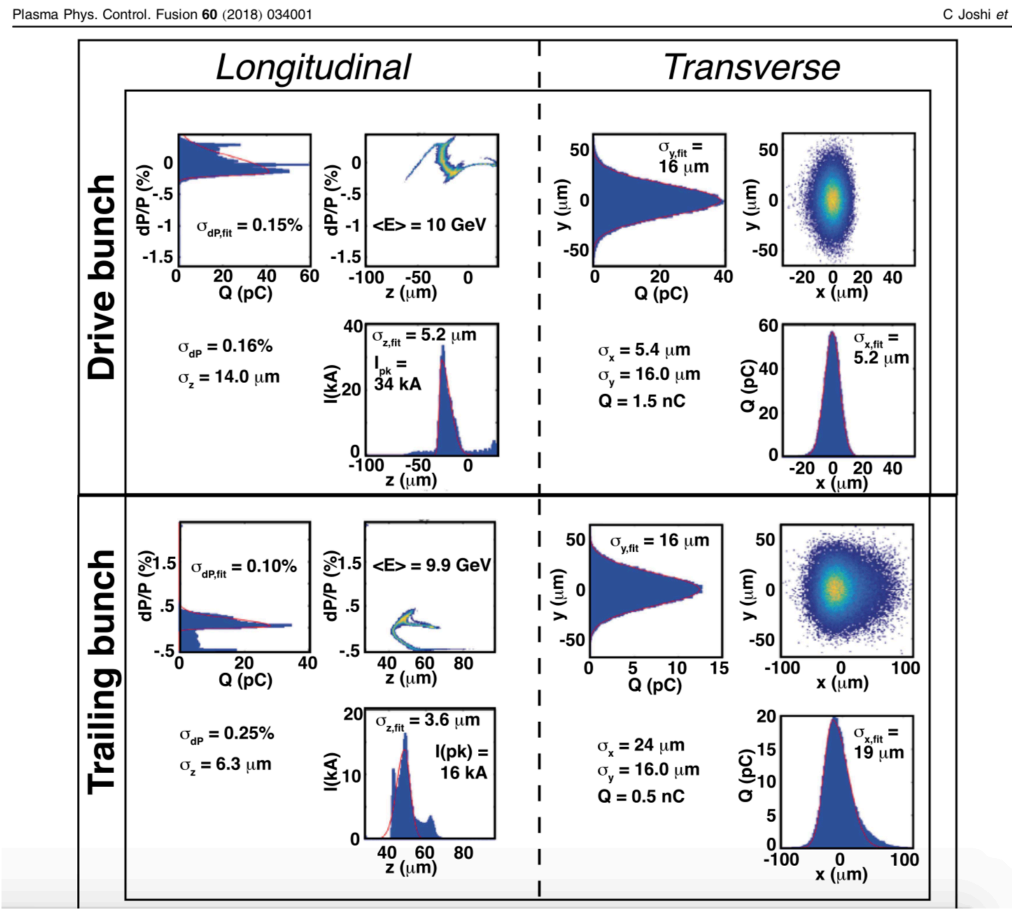


Drive Beam: E = 10.0 GeV,
N =1.0 x 10^{10} (1.6 nC),
β_x = 70.0 cm, $\alpha_{x,y}$ = 4.2, 1.6 β_y = 70.0 cm,
β^*_x = 3.8 cm, β^*_y =19 cm, σ_z = 5.2 μm,
$\sigma_{z,r.m.s.}$ = 14.0μm,
εNx = 3.4 μm, εNy = 3.0 μm
I_{peak}=34 KA

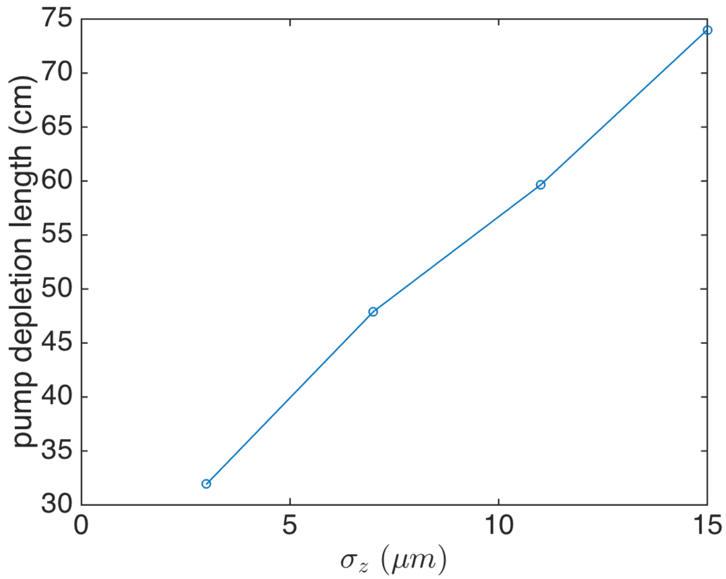
Trailing Beam: E = 9.9 GeV,
N =3.125 x 10^9 (0.5 nC),
β =5.0 cm, α = 0,
β* = 5.0 cm, s = 0 cm, σ_z = 3.6 μm ,
$\sigma_{z,r.m.s.}$ = 6.3 μm,
I_{peak}=16KA

εN = 3.15 μm
Bunch Separation: 150 μm

Charge asymmetry in x , beam tails were ignored

Pump depletion length

For all the σ_z tried the wake was generated over a distance limited by pump depletion and not by beam head erosion.



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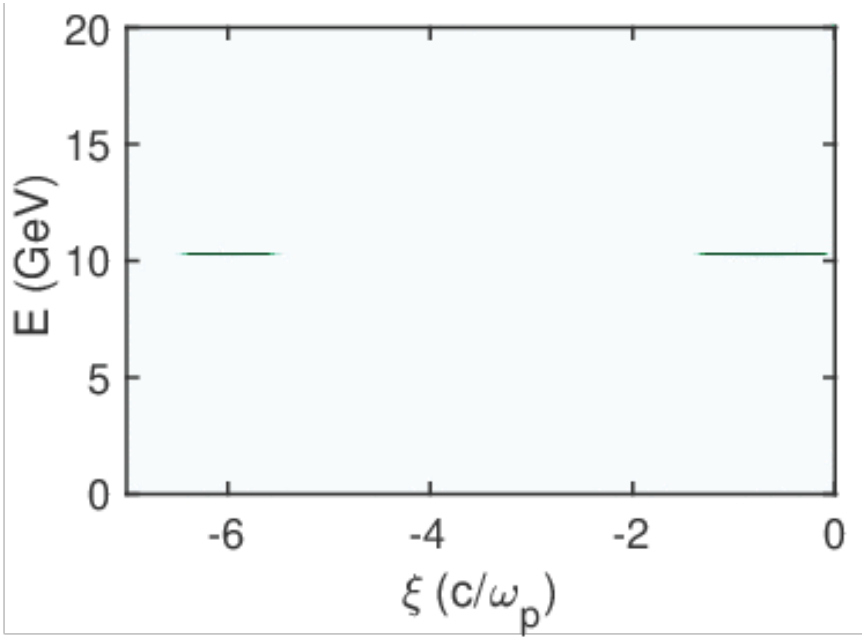
Pre-ionized vs. beam-ionized plasma (realistic ramps)

Energy gain:

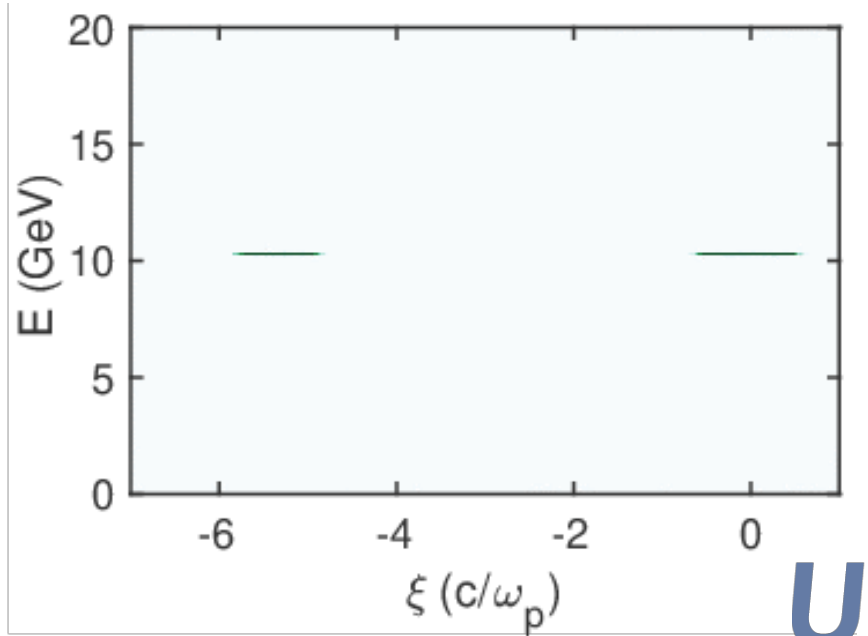
pre-ionized plasma

E_f=18 GeV, ΔE/E=0.9%



beam-ionized plasma

E_f=17 GeV, ΔE/E=1.0%



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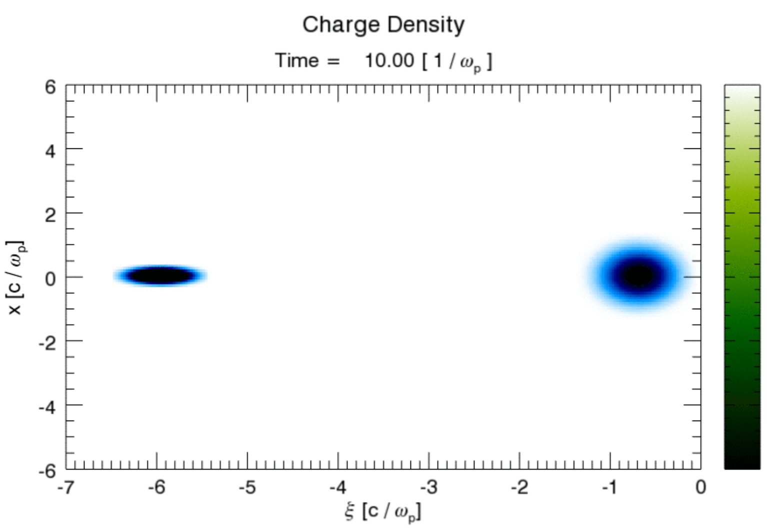
Pre-ionized vs. beam-ionized plasma (realistic ramps)

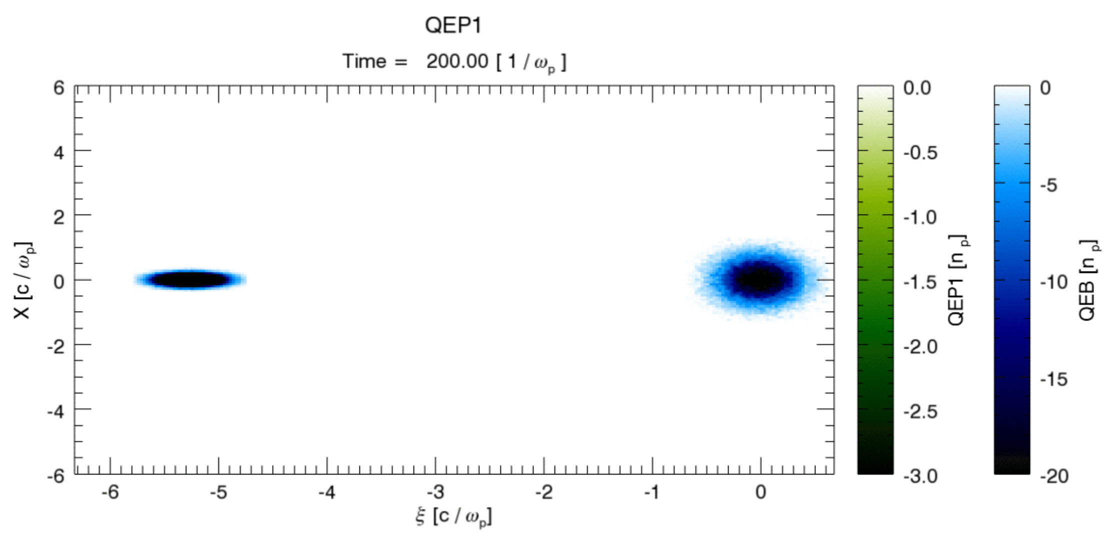
only trailing bunch is matched

Using Glen's parameters   C.Joshi et al PPCF 2018

pre-ionized plasma



beam-ionized plasma

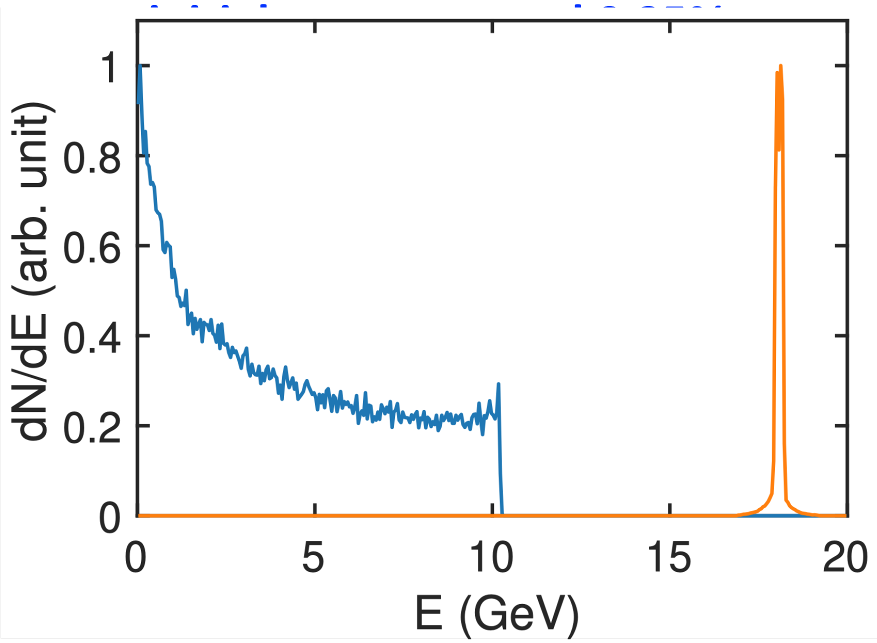


Pre-ionized vs. beam-ionized plasma (realistic ramps)

Final energy spectrum:

pre-ionized plasma

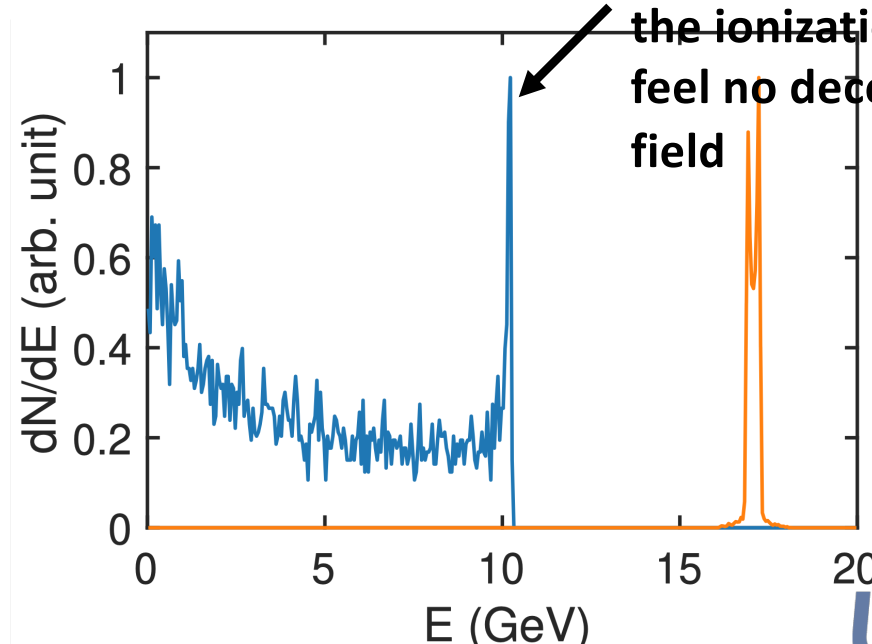
E_f=18 GeV, ΔE/E=0.9%



beam-ionized plasma

E_f=17 GeV, ΔE/E=1.0%

Electrons ahead of the ionization front feel no decelerating field

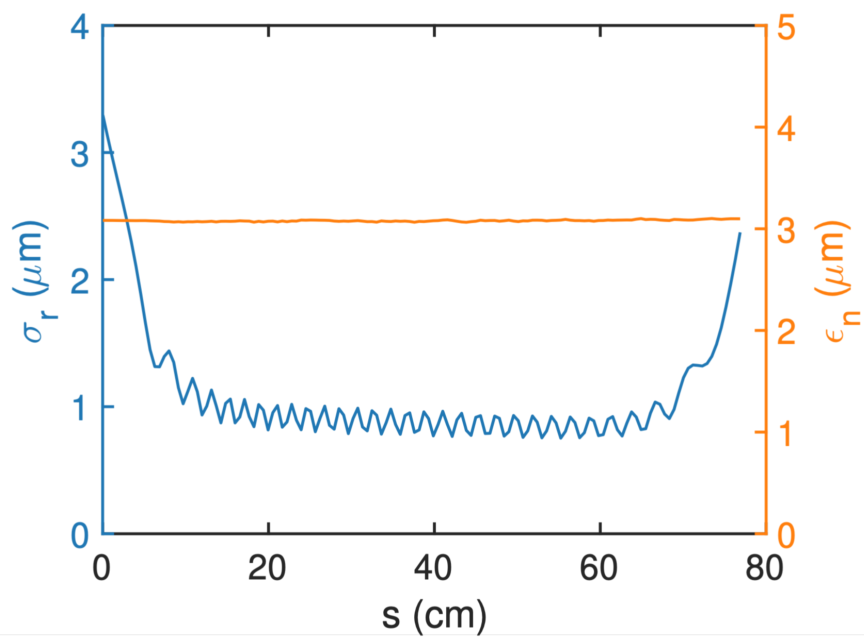


Pre-ionized vs. beam-ionized plasma (realistic ramps)

Beam size and emittance evolution:

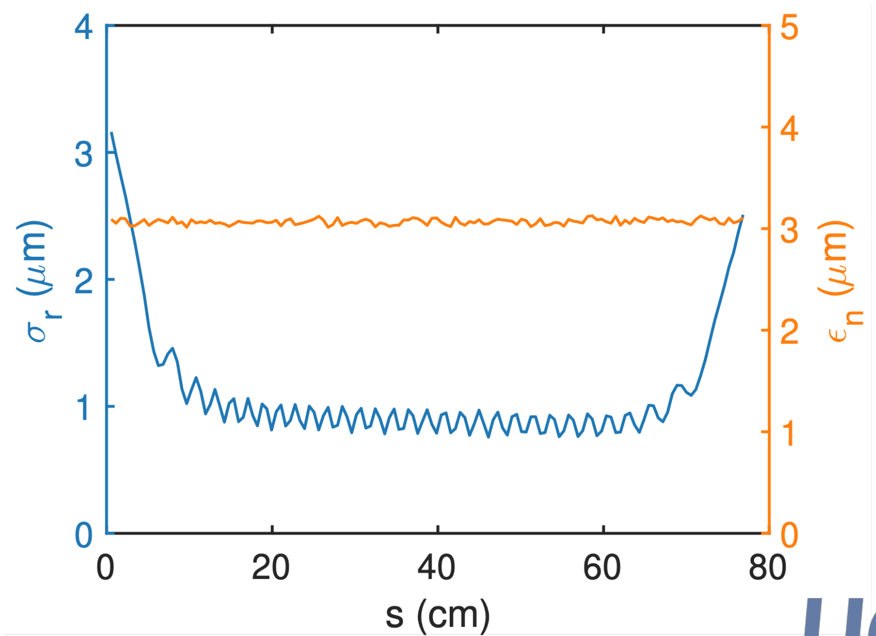
pre-ionized plasma

negligible emittance growth



beam-ionized plasma

negligible emittance growth



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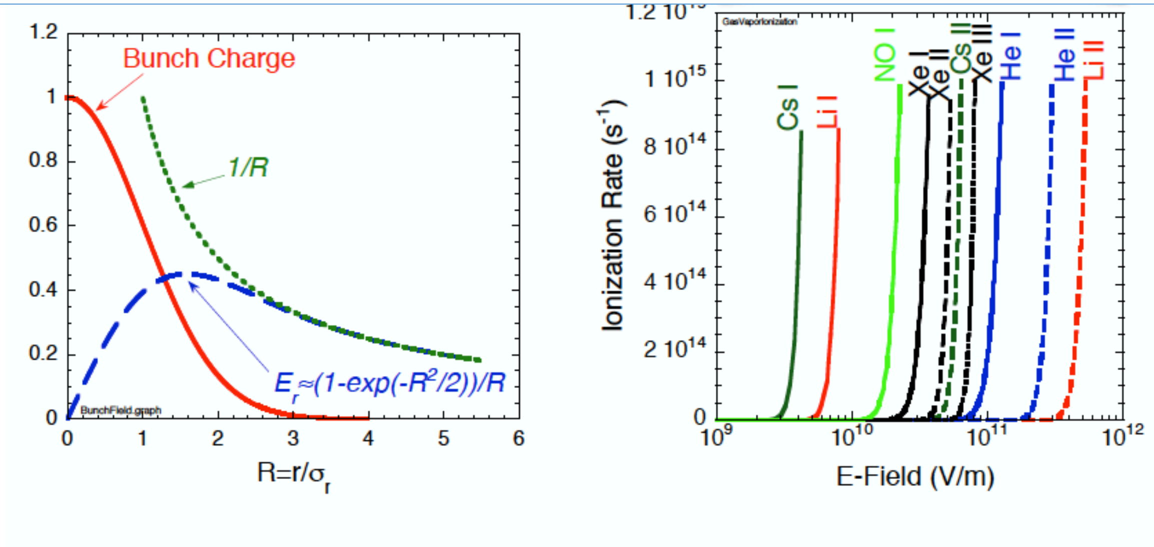
Ionization of He may beam load the wake/ alter density ramp: need to do full 3D OSIRIS simulations

- $E_r^{\max} = 10.4 \left[\frac{\mathrm{GV}}{\mathrm{m}}\right] \frac{N}{10^{10}} \frac{10}{\sigma_r[\mu\mathrm{m}]} \frac{50}{\sigma_z[\mu\mathrm{m}]}$, $(\sigma_r)^2_{\mathrm{matched}} = \varepsilon_n \, (c/\omega_p) \, (2/\gamma)^{1/2}$



90 GeV/m, 300 GeV/m to avoid full ionization of He and He^{1+} resp.

This is why the smallest emittance we can transport without measurable growth is ~20um, in Li plasma, Need some way of spoiling the emittance of the trailing bunch to 20 um.

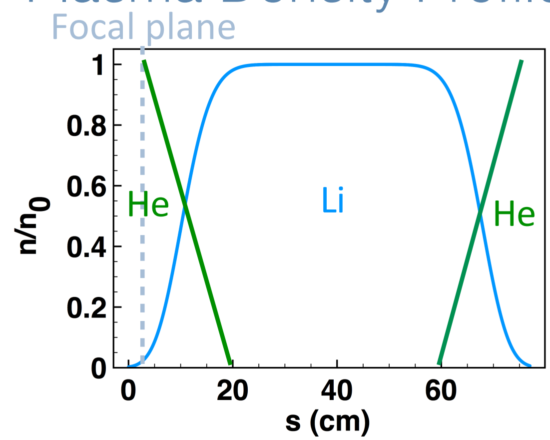
Two-Bunch PWFA with He ramps : OSIRIS

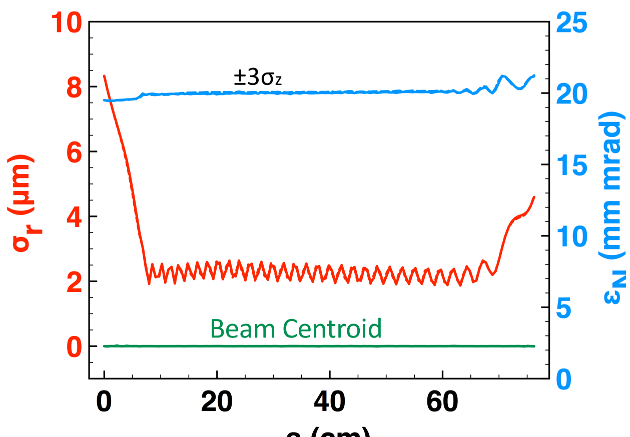
UCLA

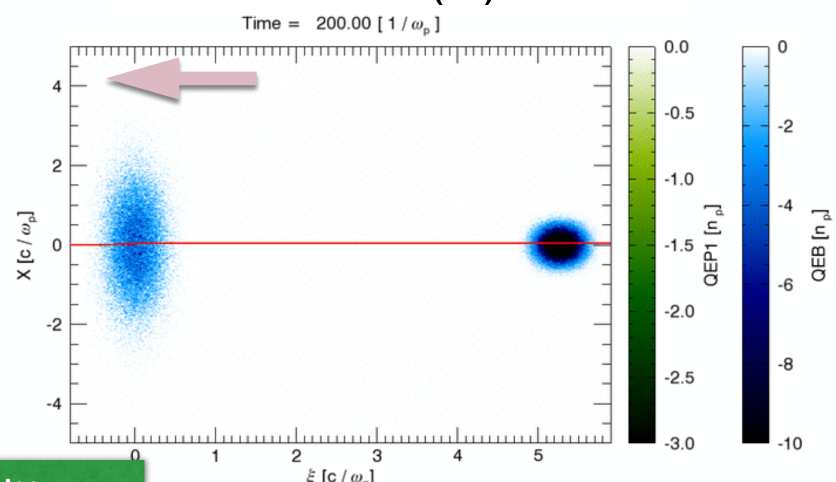
Drive Beam: E = 10 GeV, N =1.0 x 10^{10} (1.6 nC),
β_x = 0.9960 m, α_x =5.1291, β_y = 57.66 cm, α_y =1.4480,
β^*_x = 3.8 cm, β^*_y = 19 cm, σ_z = 6.4 µm ,
ε_{Nx} = 20.0 µm, ε_{Ny} = 20.0 µm

Trailing Beam: E = 10 GeV, N =3.125 x 10^9 (0.5 nC),
β =7.30 cm, α = 0.6784,
β^* = 5.0 cm, s = 3.39 cm, σ_z = 5.0 µm ,
ε_N = 20.0 µm
Distance between two bunches: 150 µm
Plasma Density: 3.5 x 10^{16} cm^{-3} (with ramps)

Plasma Density Profile





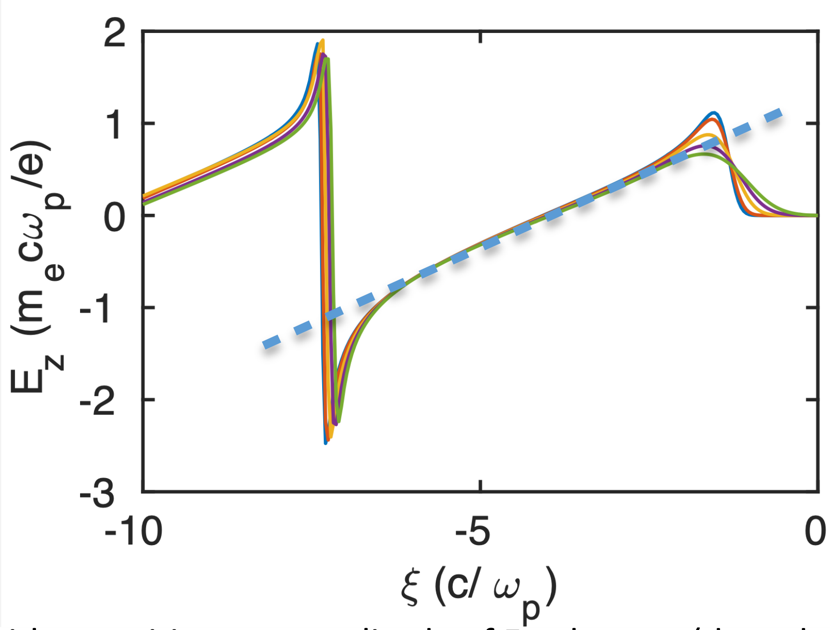


The projected beam spot size and emittance

What happens if drive beam pulsewidth or charge varies?

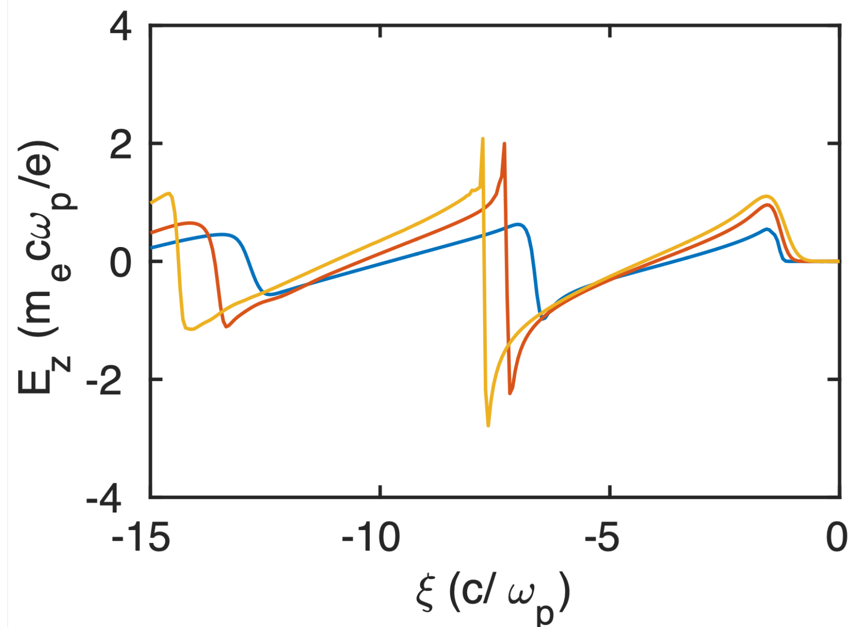
E_+/E_- for fixed charge

- **Q=1.2 nC, change σ_z [4, 5, 8, 11, 14] µm**



Neither position nor amplitude of E_z– changes (dotted straight line)
Beam loading will not be affected if position and current profile of
The trailing bunch remains the same.

E_+/E_- for fixed current

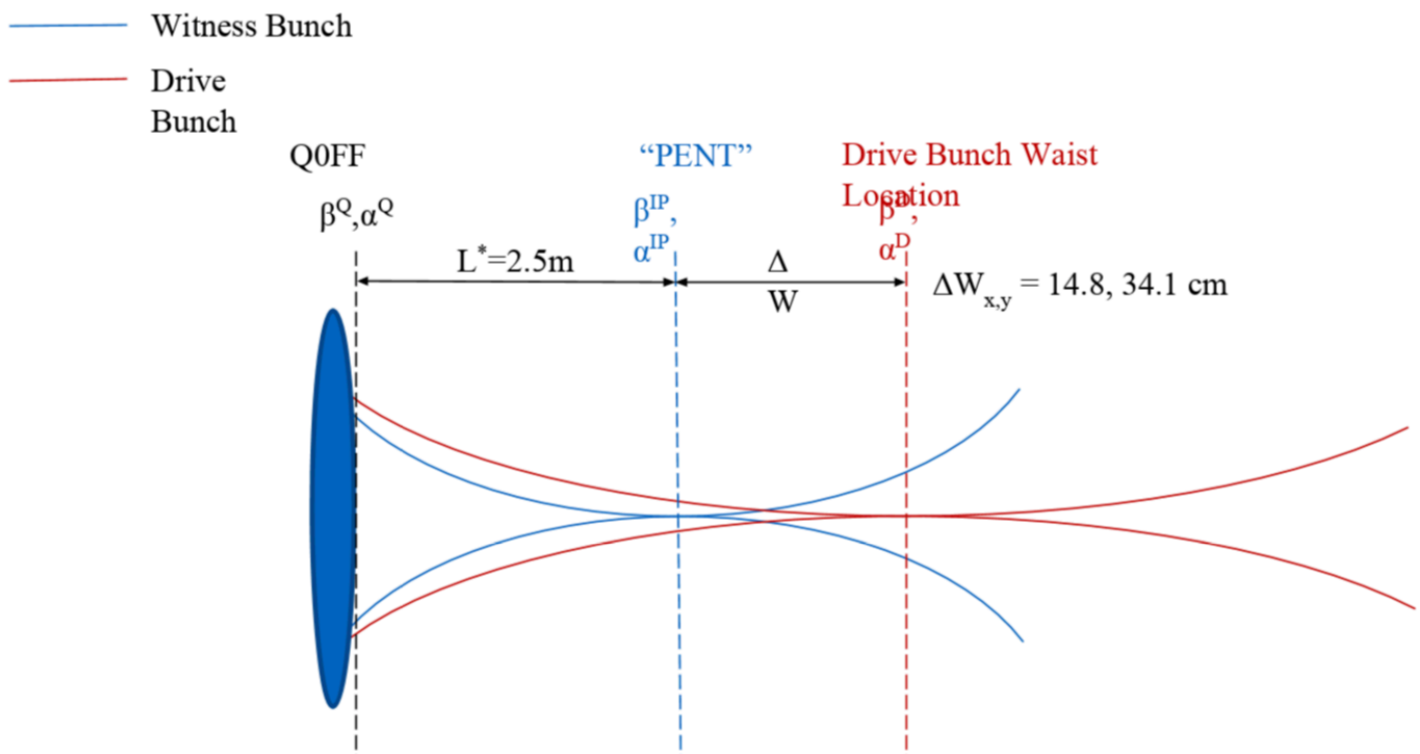


As long as the separation between bunches remains constant. Only efficiency will change.

IP Waist Locations for Drive and Witness Bunch

@ July meeting

SLAC



	α^Q [x,y]	β^Q [x,y]	α^{IP} [x,y]	β^{IP} [x,y]	α^D [x,y]	β^D [x,y]
Witness	54, 56	148, 148 m	0.1, 0.7	5.0, 7.0 cm	-2.9, -6.4	46, 203 cm
Drive	32, 19	91, 59 m	1.7, 2.2	33, 33 cm	0.0, 0.0	8.9, 16 cm

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July 2018

Beam @ Sector 20 IP (PENT) – 2 Bunch (Longitudinal)

Bunch separation still 150 um

Drive beam

I_{peak} = 68 KA

σ_z = 1.7 um(peak)

σ_z (rms) = 31 um

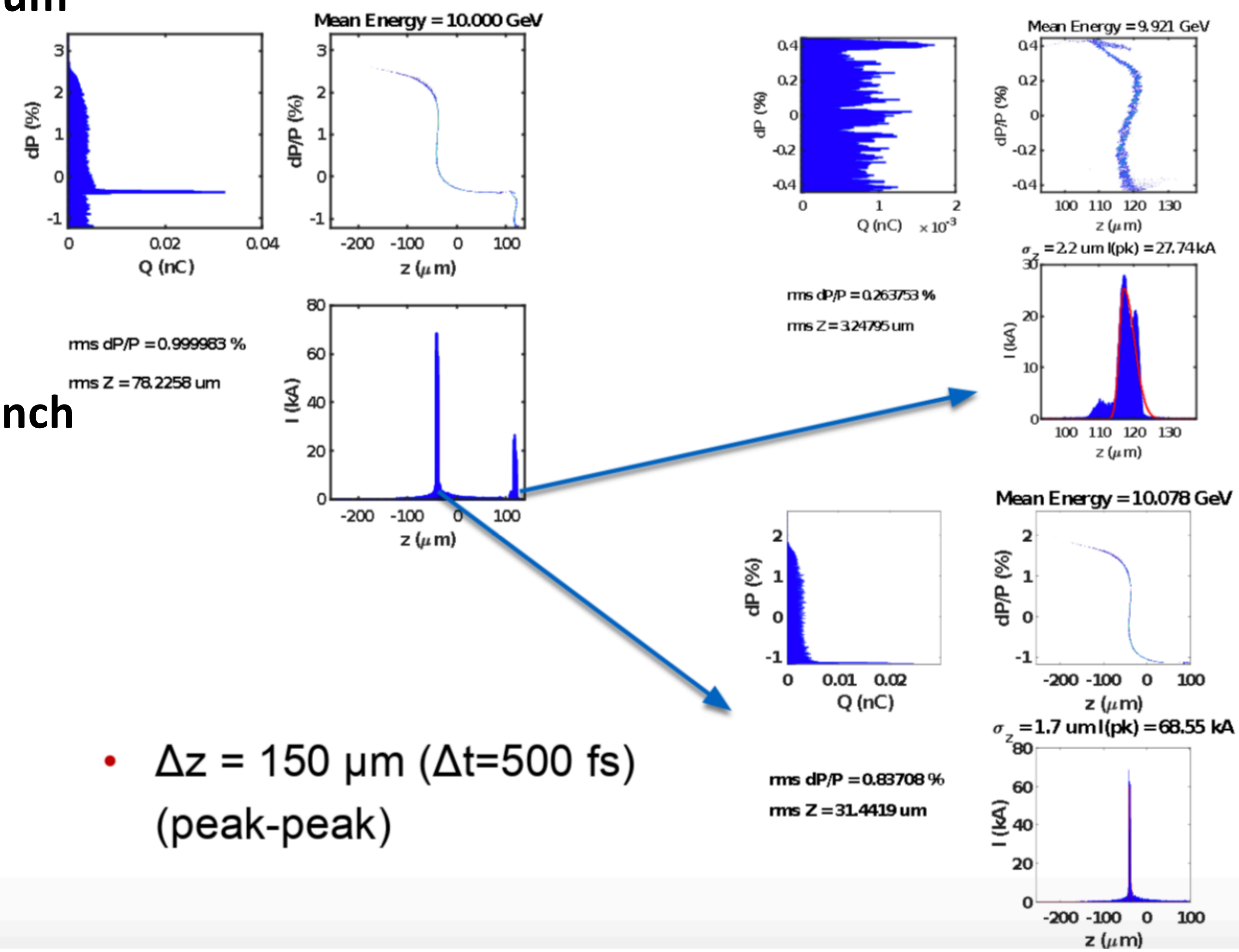
Drive bunch has a long tail that connects the drive bunch to the trailing bunch

Witness Beam

I_{peak} =27.7 KA

σ_z =2.2 um peak

σ_z(rms) = 3.24 um



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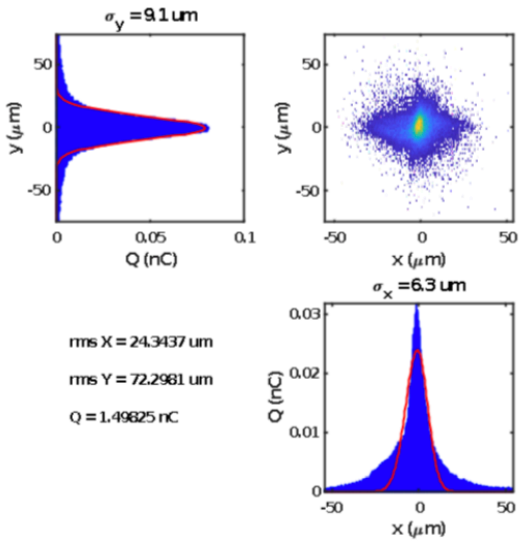
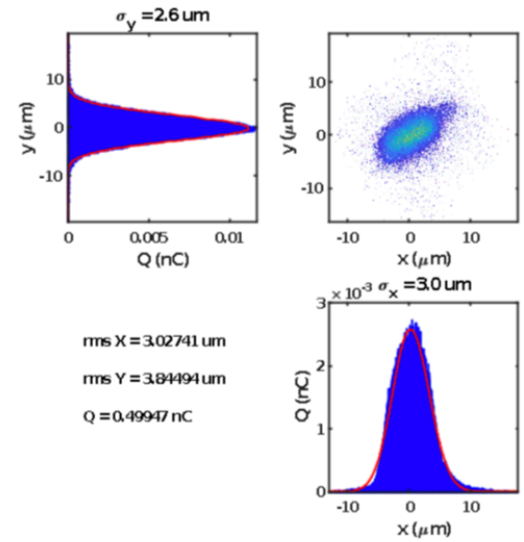
Beam @ Sector 20 IP (PENT) – 2 Bunch (Transverse)

Drive Bunch and Witness beam
Parameters were very different



Drive Bunch



Witness Bunch

- $\gamma\varepsilon_{x,y}$ = 35.0, 115 μm-rad
- $\gamma\varepsilon_{x,y}$ (90%) = 20.6, 37.1 μm-rad

- $\gamma\varepsilon_{x,y}$ = 3.7, 4.1 μm-rad
- $\gamma\varepsilon_{x,y}$ (90%) = 3.2, 2.6 μm-rad

Can we Load Electron 6D Phase Space into QuickPIC?

- When we use Gaussian fits to the data in QuickPIC we use 40 million particles and quiet-start.
- When theory group does hosing simulations to compare theory with simulations they use 1-10 B electrons.
- We find that when the drive and the trailing bunches are aligned there is no hosing and emittance can be preserved for the trailing bunch even with 40 M particles.
- If the bunches are misaligned hosing still happens. But this too may be overestimated.

- Initially 10^5 macroparticles – so each macroparticle represents 10^5 real particles.
- This leads to a tremendous noise source for hosing.
- We asked for 10 x more macroparticles. Outcome is not much better-hosing is a bit delayed but still occurs.

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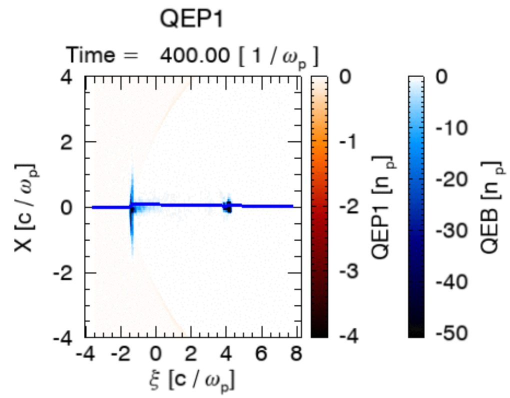
Instead of using Gaussian fits to beam phase space use the actual 6D phase space

Overview

Plasma density (Red), Beam density (Blue), Ez field (blue solid).



Used 10^5 particles for drive and trailing beam each

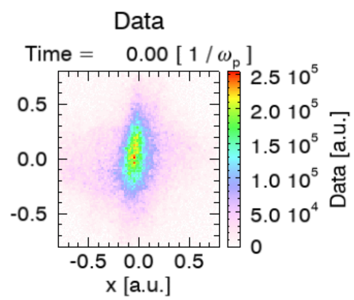
Preformed plasma w/ up-ramp : $n_0=3.5\times10^{16}$ cm^{-3} -> $c/\omega_p=28.4$ um.

Propagated for around 10,800*c/ωp ~ 30.6 cm

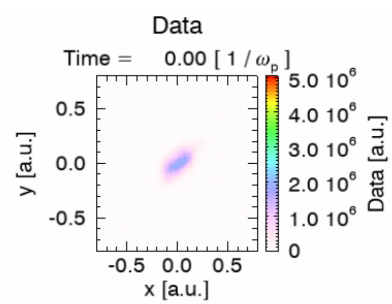
Box size 400x400x320 um, divided by 2^8

Transverse (X-Y) phase

Driver



Trailer



Observations :

1. Overloaded E_z leads to large energy spread. Bunch is too short
2. Macro particles might be insufficient as the beam data is noisy. (see later)
3. Extreme Hosing which almost certainly is exacerbated.

Asked for 10^6 particles to reduce numerical noise, longer bunch length

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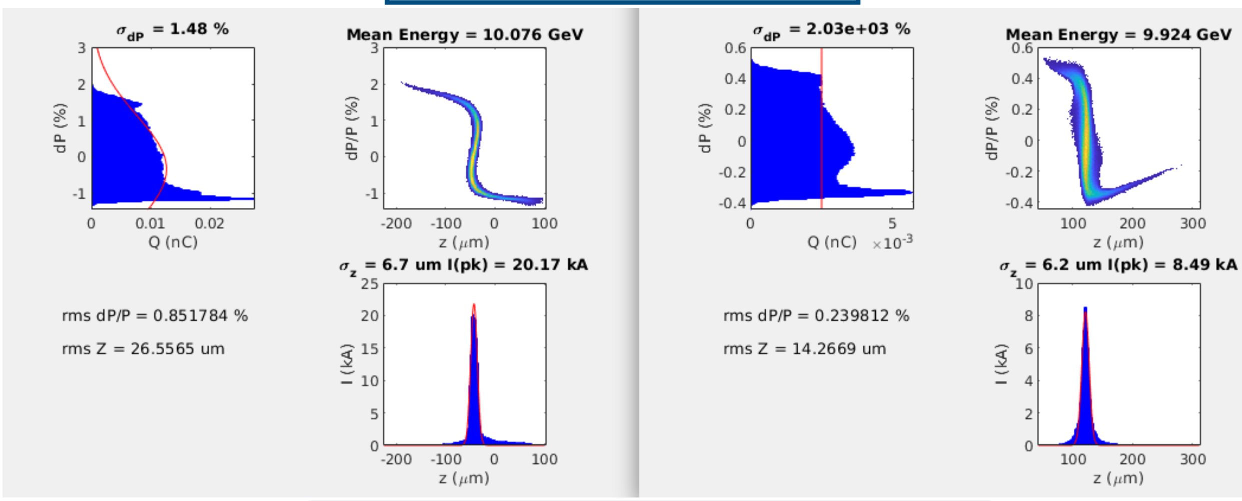
Distribution Ver. 3

Z and Pz provided by Glen

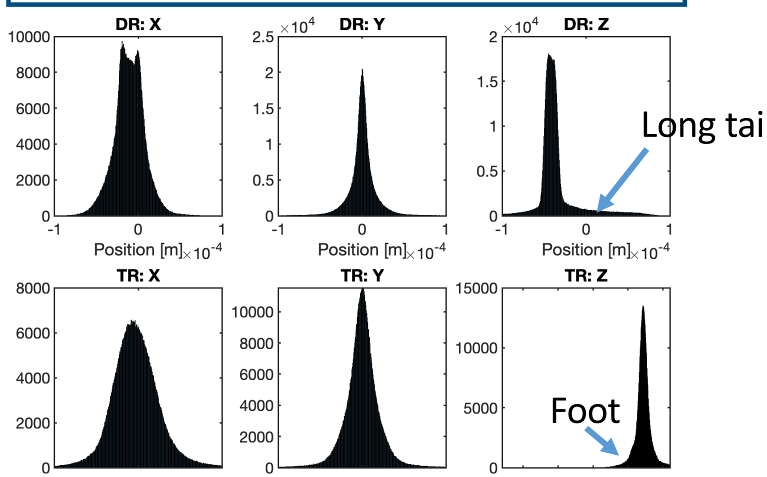


Driver has two peaks in x
Driver is off axis relative to Witness
Driver has 100 um long pre and post low current tails.

Spatial histogram regenerated (Hiroki)

Driver

Trailer



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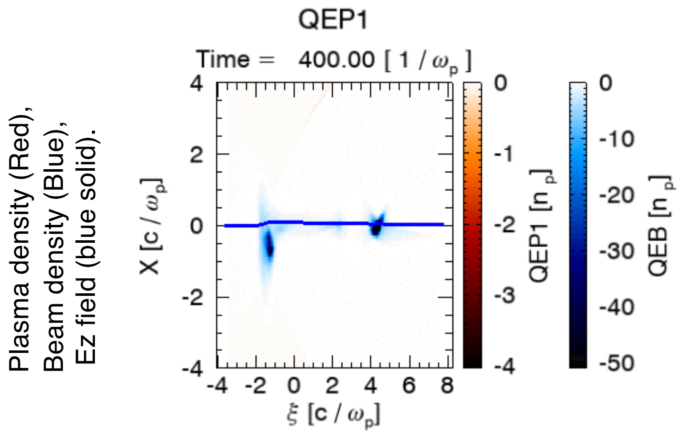
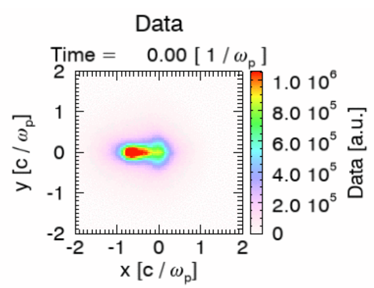
Overview

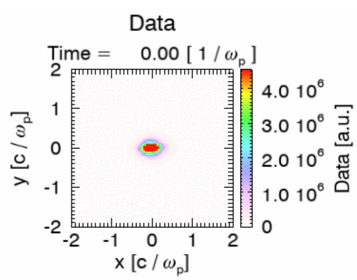


Transverse (X-Y) phase

Driver



Trailer



Used 10^6 particles for drive and trailing beam each
Preformed plasma w/ up-ramp :
$n_0=3.5\times10^{16}$ cm^{-3} -> $c/\omega_p=28.4$ um.
10-90 % ramp length: L=10 cm
Box size 400x400x320 um, divided by 2^8 grids respectively

Observations :

1. Ez flatter than before
2. Beam center off axis leads to hosing
3. Unbalanced Bi-modal distribution of the drive beam causes oscillations about the off-axis center

→Asked for singly peaked distribution, compare aligned results

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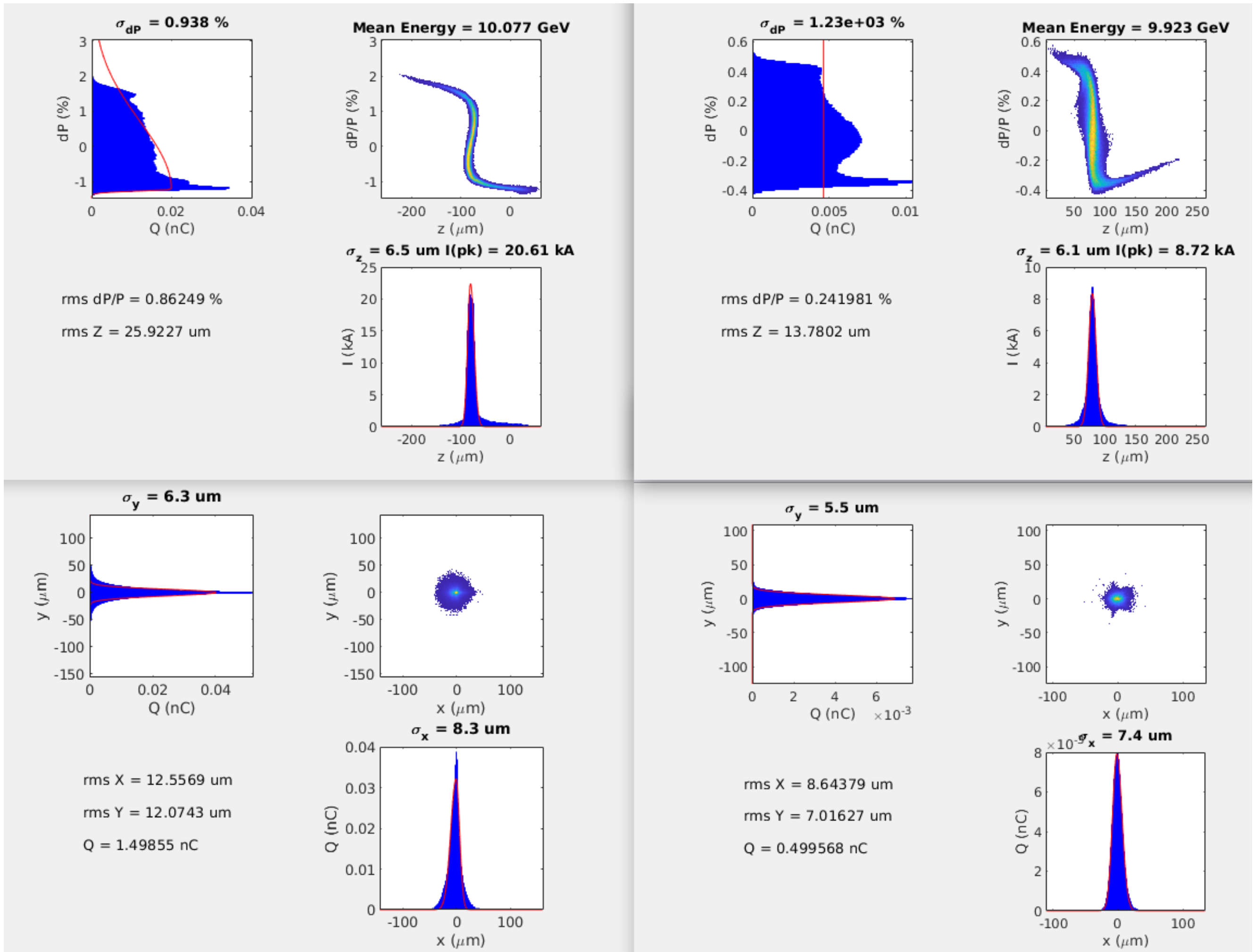
Distribution Ver. 4

spatial histogram provided by Glen



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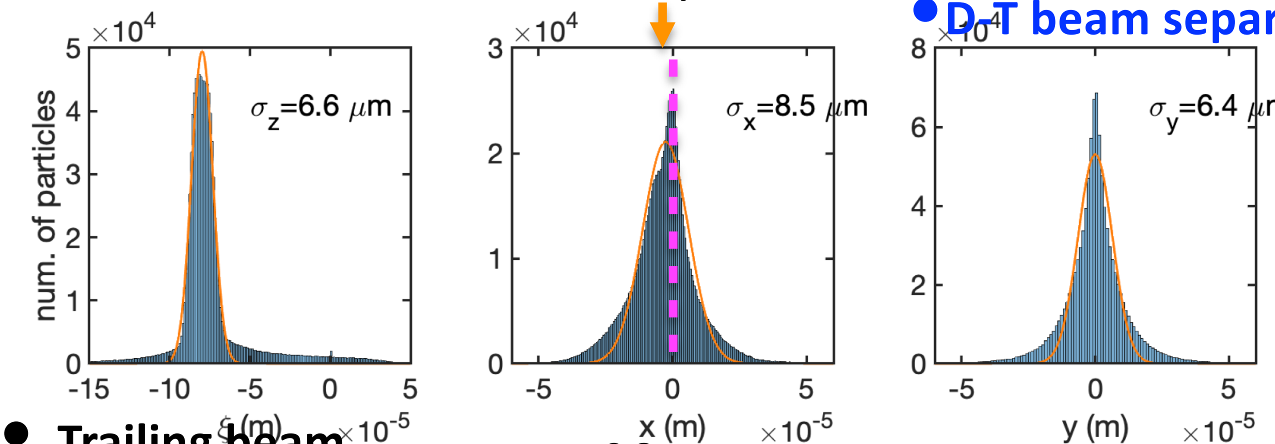
Glen's latest parameters (Oct 17th 2019)

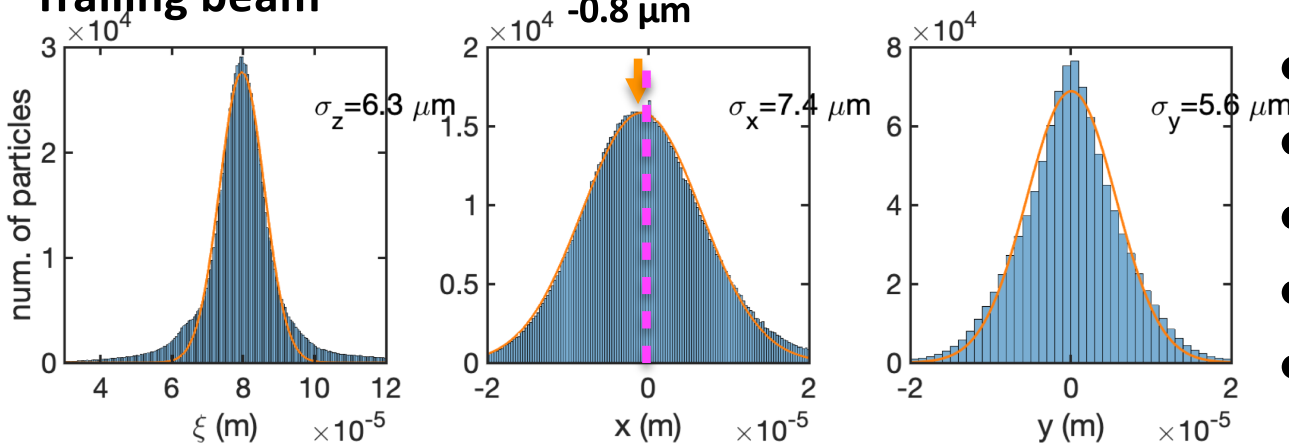
- **There is a ~2 μm misalignment in the x direction**
- **D-T beam separation: 160 μm (too large-low eff.)**

- **Drive beam**



- **ε_{nx}=20.4 μm, εny=41.7 μm**
- **ε_{nx}(90%)=11.4 μm**
- **ε_{ny}(90%)=9.9 μm**
- **Charge in the rms peak: 1.2 nC**
- **Peak current: 21.8 kA**

- **Trailing beam**



- **ε_{nx}=7.4 μm, εny=15.9 μm**
- **ε_{nx}(90%)=4.6 μm**
- **ε_{ny}(90%)=4.2 μm**
- **Charge in the rms peak: 0.43 nC**
- **Peak current: 8.2 kA**

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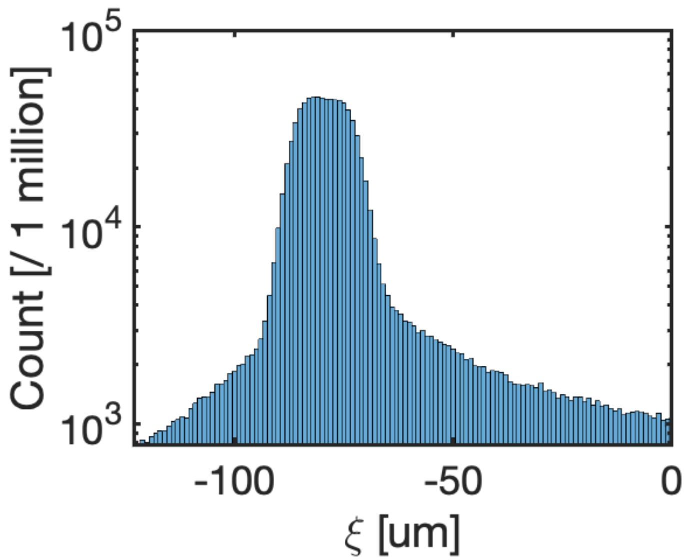
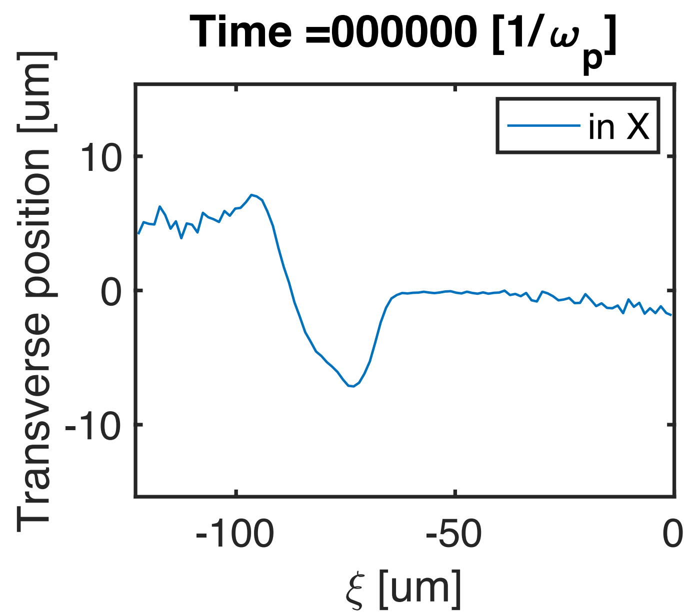
Particle distribution and slice Centroid displacement shows the source of noise for hosing





Is this centroid displacement real or due to insufficient no of particles in the distribution function?

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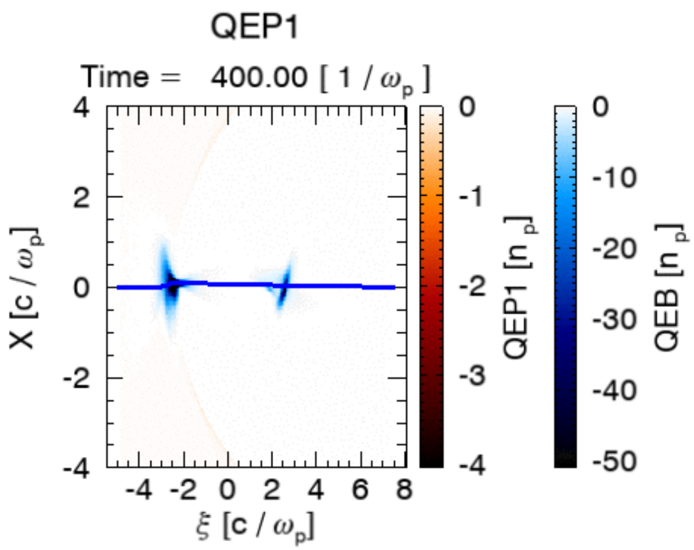
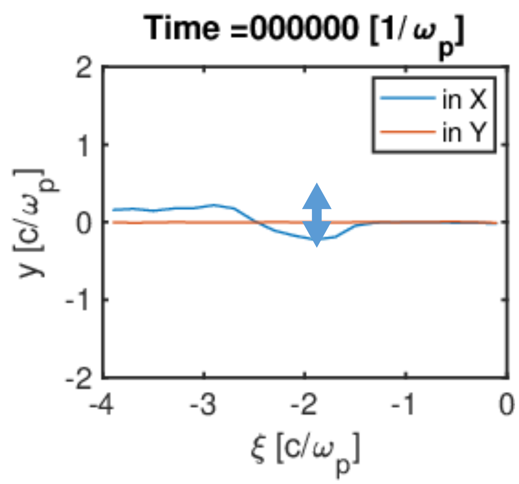
Beam propagation for artificially centered case

X-Z Slice



Drive beam centroid motion in X and Y



Nearly 10 um shift in centroid

Note : Each centroid calculated by more than 5,000 particles

Hosing of the trailing beam is driven not only by the misalignment of two bunches
The drive beam has a 100 um long tail and trailing bunch has a 20 um foot.
How about truncating the drive beam?

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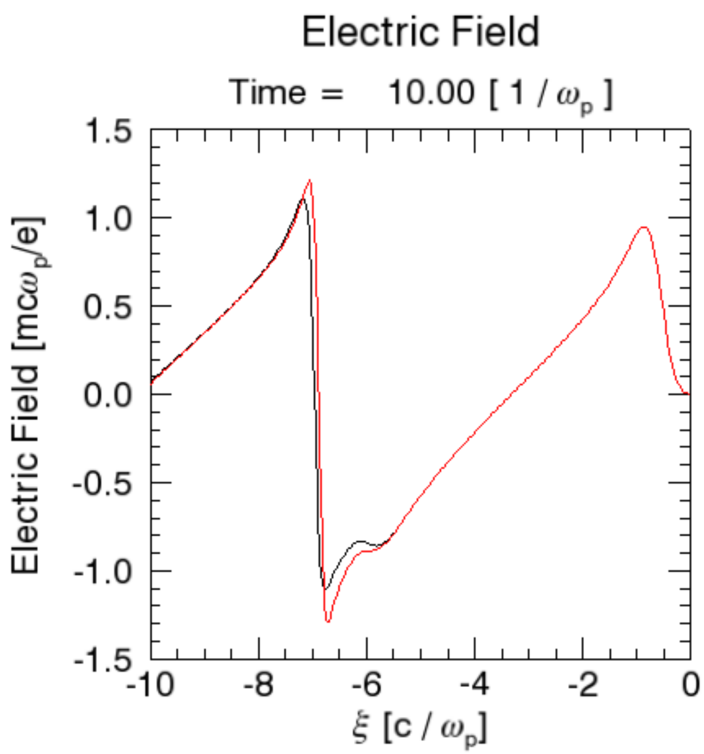
Are all these deleterious effects real?

We go back to using Gaussian fits to beams

Optimize beam loading by reducing the peak current of the trailing beam: use gaussian fits

- **Adjust the charge in the trailing beam to optimize beam loading**
- **Use uniform pre-ionized plasma, one-step quickpic simulation**



- **Black line: I=8.2 kA, Q=0.43 nC, Λ≈3**
- **Red line: I=6.8 kA, Q=0.36 nC, Λ≈2.5**

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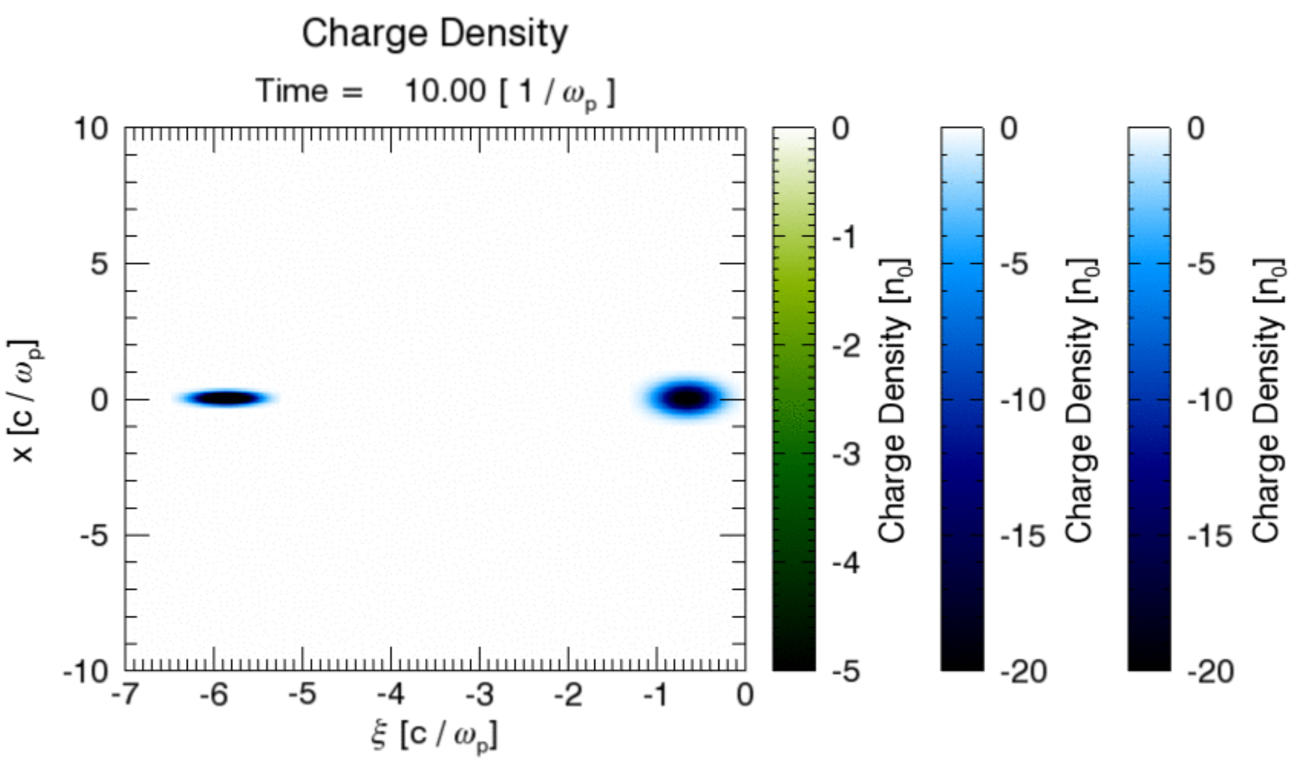
Aligned Gaussian beams; Quiet start in QuickPIC

- **Fit the 6D phase space data with Gaussian beams**
- **Align the drive and trailing beams, tails are cut off**

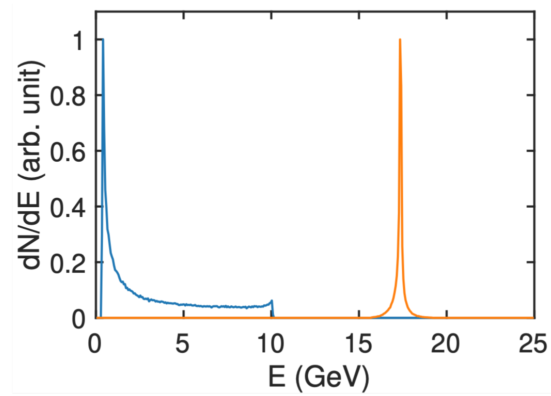


Final energy spectrum

Energy gain 7.3 GeV

ΔE/E~1.8% (rms)

ΔE/E~0.7% (FWHM)



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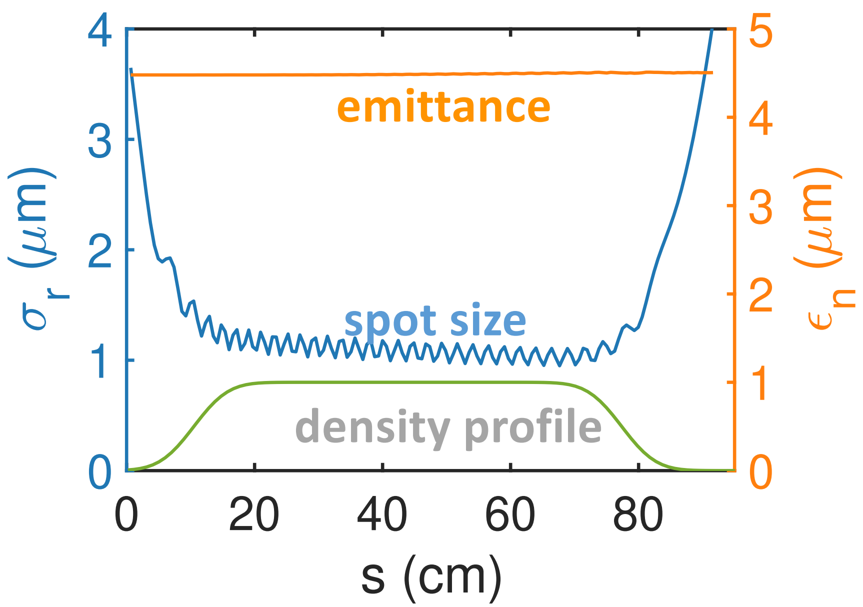
Simulation using Gaussian beams (fit to Glen's data V4)

- **Drive beam: σ_z=6.6 μm, σ_x=8.5 μm, σ_y=6.4 μm, Q=1.2 nC, I=22 kA**
- **Tailing beam: σ_z=6.3 μm, σ_x=7.4 μm, σ_y=5.6 μm, Q=0.36 nC, I=6.8 kA (to optimize beam loading)**



- **Emittance preserved**
- **Trailing beam matched**
- **Negligible spot size oscillation**

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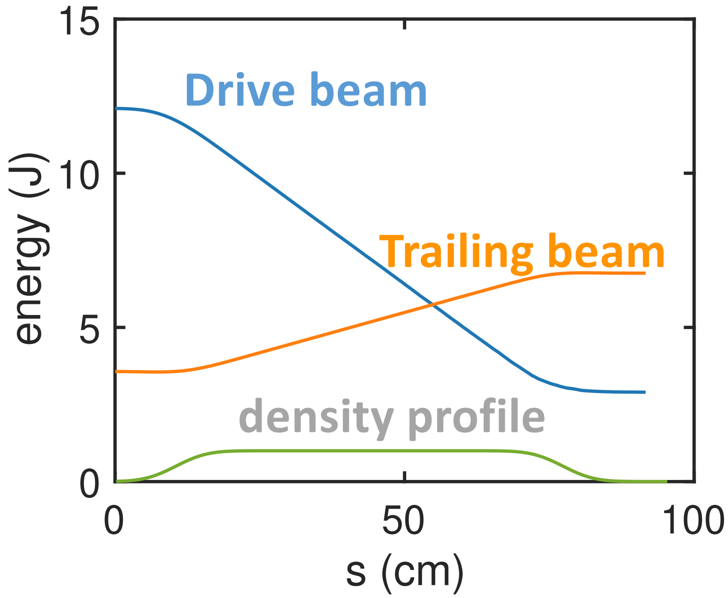
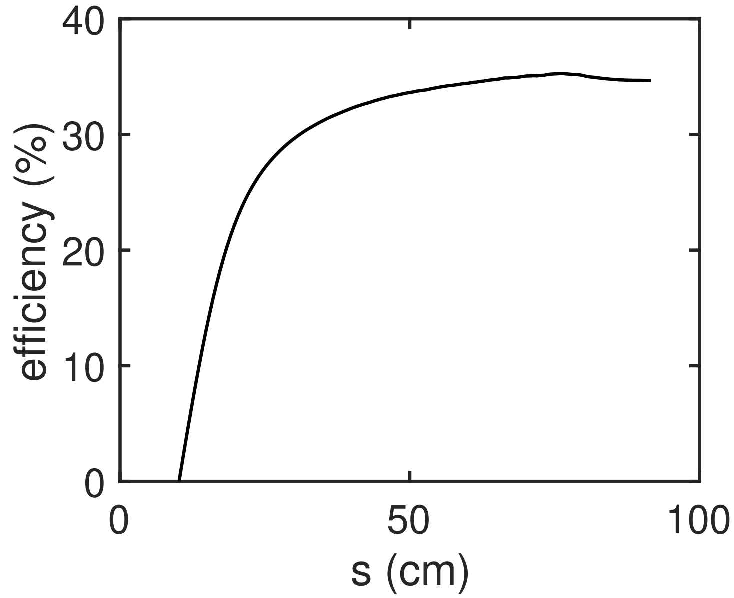
Energy Transfer and efficiency

The drive beam does not pump deplete

- **Energy gain (Trailing beam) and loss (drive beam)**

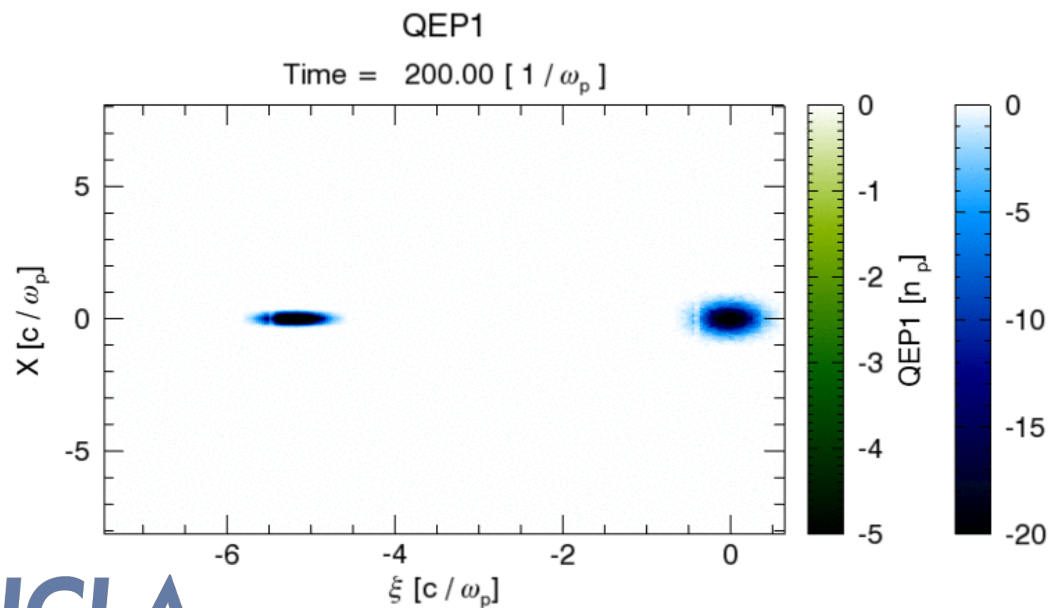


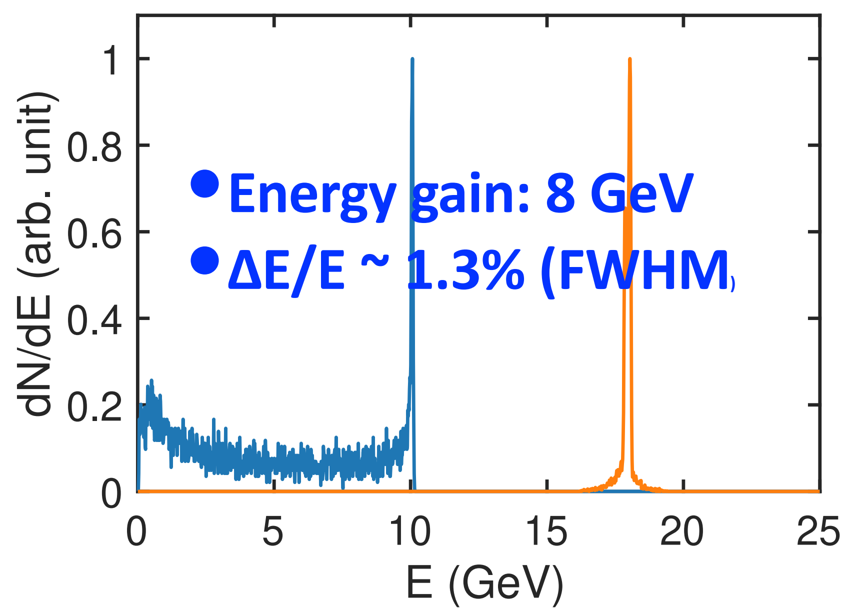
- **Efficiency (energy gain/energy loss)**
- **~35%**



Simulation of plasma formed by the beam using Gaussian beams (fit to Glen's data); Plasma profile optimized (3e16, length extended by 10 cm compared to profile shown in PPCF 2018 paper)

- **Drive beam: σ_z=6.6 μm, σ_x=8.5 μm, σ_y=6.4 μm, Q=1.2 nC, I=22 kA**
- **Tailing beam: σ_z=6.3 μm, σ_x=7.4 μm, σ_y=5.6 μm, Q=0.36 nC, I=6.8 kA (to optimize beam loading)**





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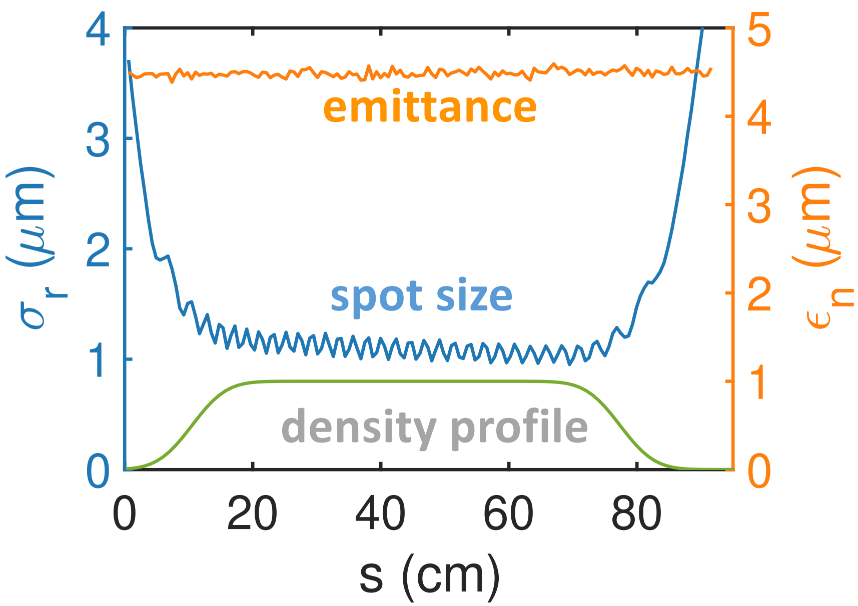
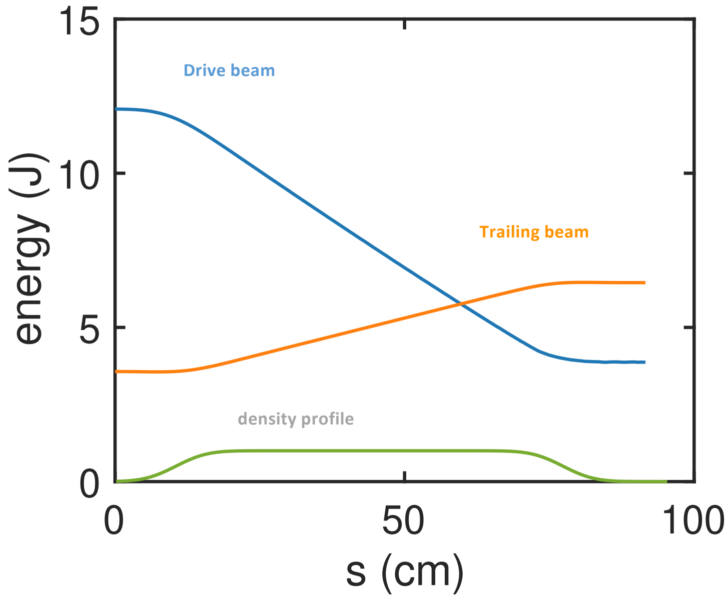
Same simulation, emittance evolution



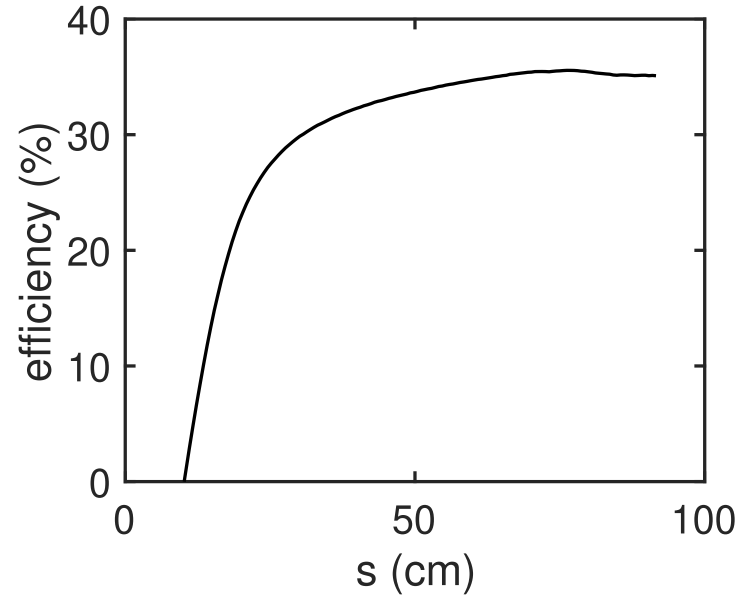
- **Emittance preserved**
- **Trailing beam matched**
- **Negligible spot size oscillation**

Same simulation, efficiency is the same of ~35%

- **Energy gain (Trailing beam) and loss (drive beam)**



- **Efficiency (energy gain/energy loss)**
- **~35%**



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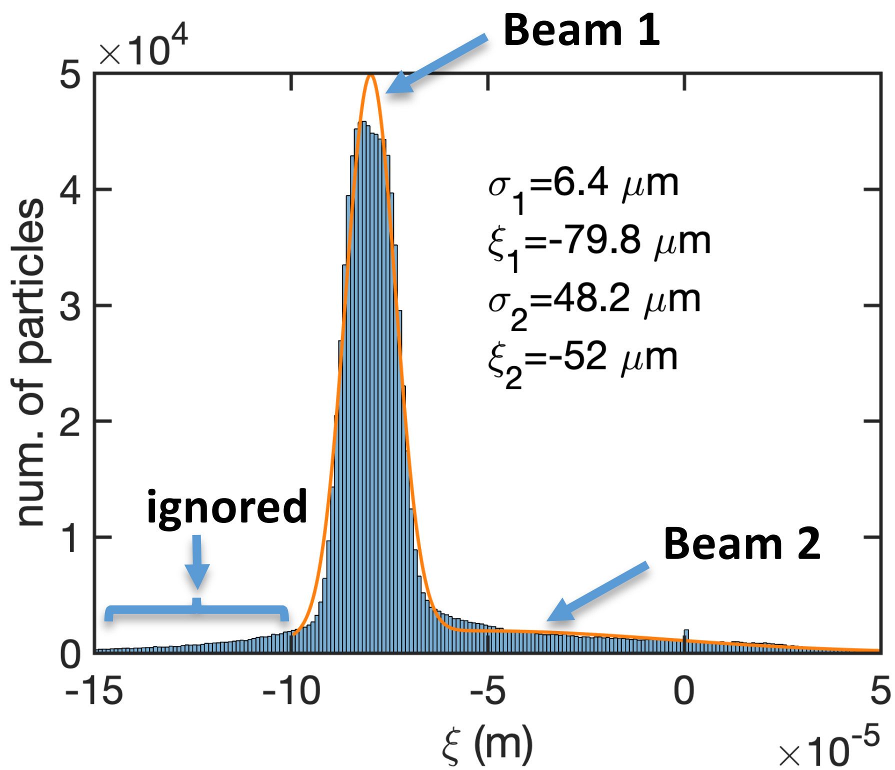
Simulation including the low-current tail of the drive beam

- **Fit the drive beam using a bi-Gaussian distribution**



- **Beam 1: σ_z=6.4 μm, Q=1.15 nC, I=21.5 kA**
- **Beam 2: σ_z=48 μm, Q=0.35 nC, I=0.87 kA**

- **We ignore the foot or the prepulse because the foot will expand away since the beam current will be below the Li ionization threshold of 6KA.**
- **In a preionized plasma the misalignment of the foot and tail cannot be ignored.**

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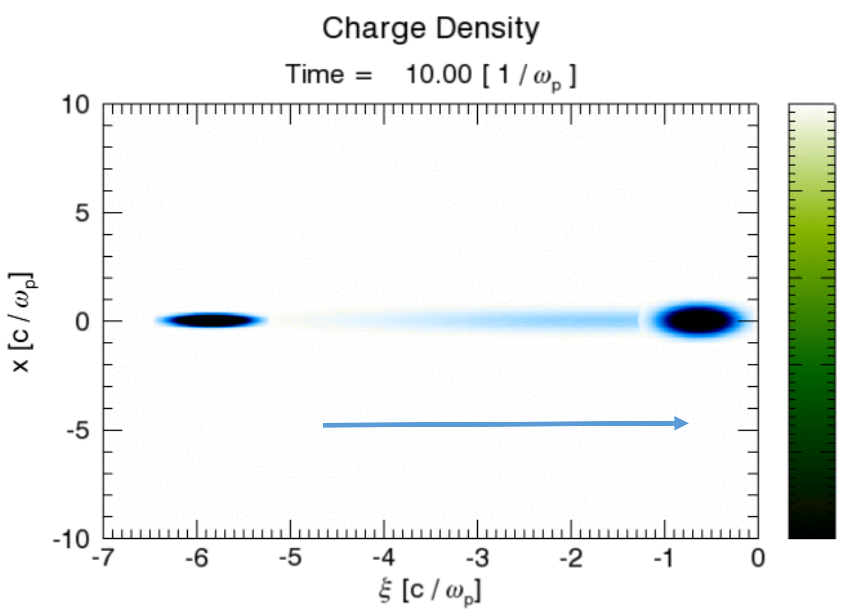
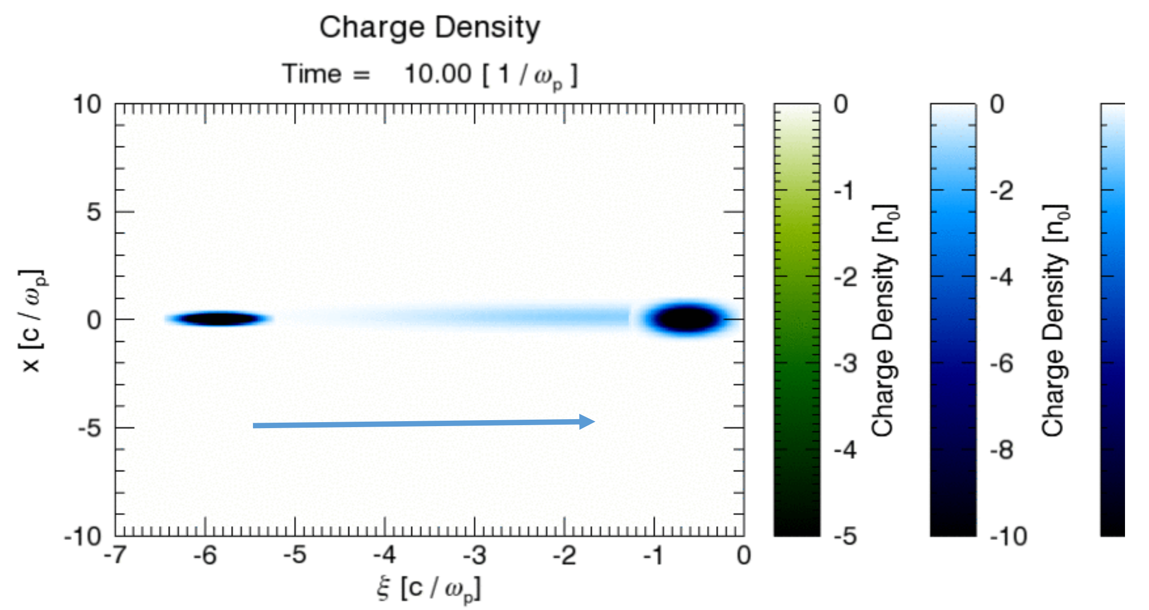
Simulation including the low-current tail of the drive beam

- **All three beams aligned**



- **Drive beam and trailing beam aligned**
- **Tail of the drive beam off centered by 3 µm**



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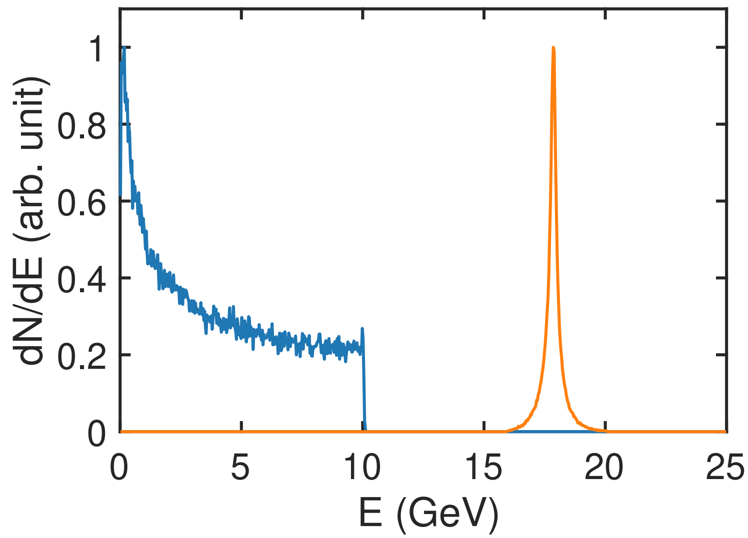
Simulation including the low-current tail of the drive beam

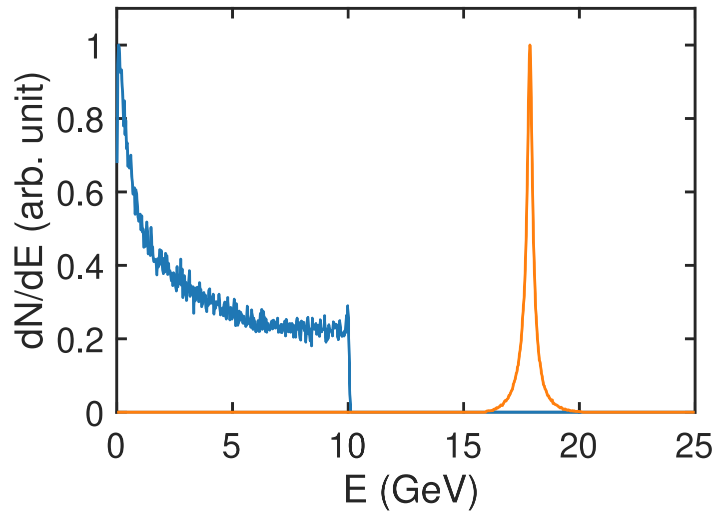
- In these particular simulations, the hosing instability did not affect the energy spectrum

- All three beams aligned



- Energy spectrum
- Energy gain: 7.9 GeV
- ΔE/E=1.8% (FWHM)

- Drive beam and trailing beam aligned
- Tail of the drive beam off centered by 3 µm



- Energy spectrum
- Energy gain: 7.9 GeV
- ΔE/E=1.6% (FWHM)

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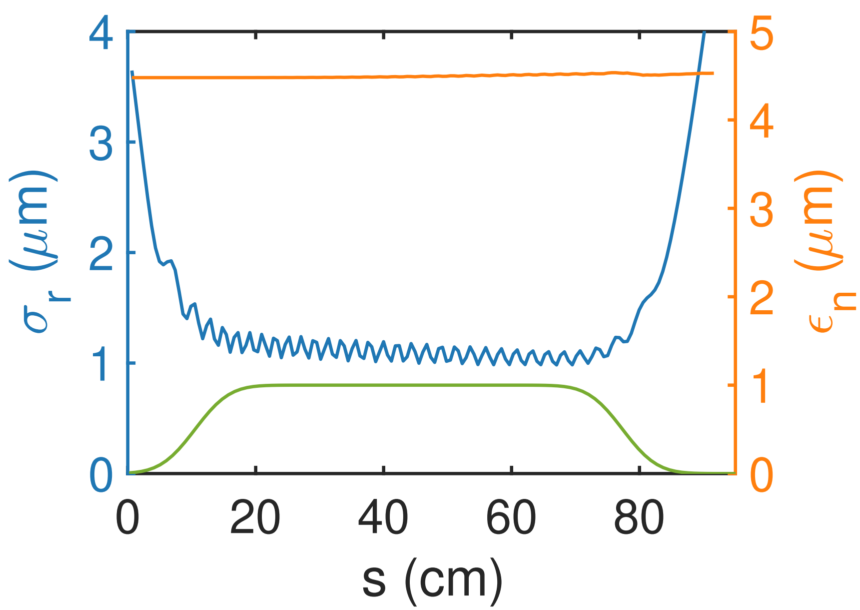
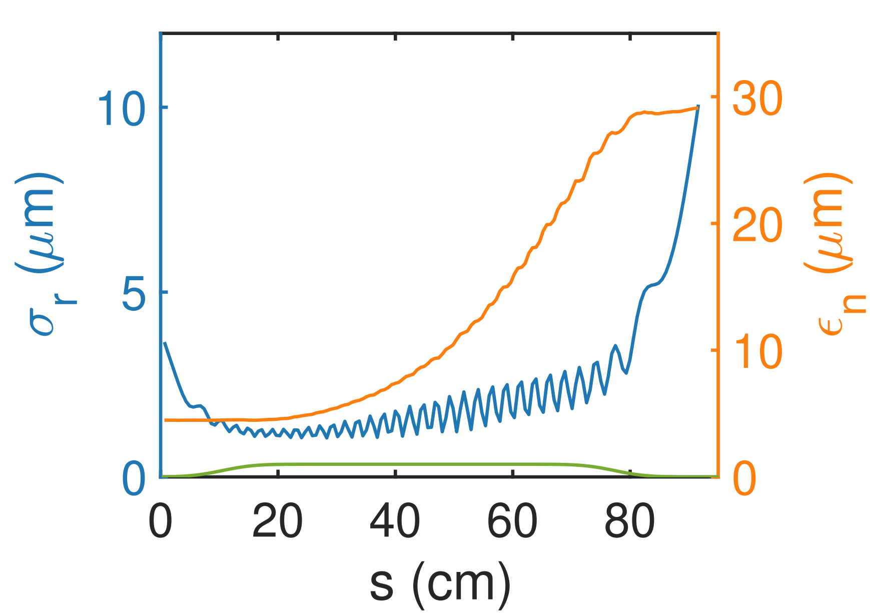
Simulation including the low-current tail of the drive beam

- **All three beams aligned**



- **Emittance preserved**

- **Drive beam and trailing beam aligned**
- **Tail of the drive beam off centered by 3 μm**



- **Emittance increased by almost an order of magnitude**

Lithium Oven – Can we use Laser Preionization?

Work done by M. Litos ' group.

Advantage: Get rid of He. Might be able to reduce the trailing beam emittance to 4 um.

Laser Parameters

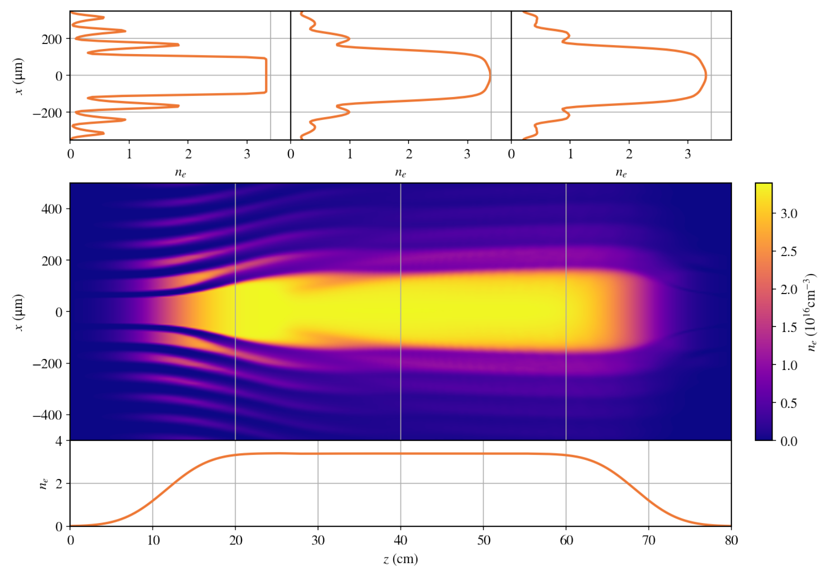
Laser energy:	20mJ
Pulse duration:	70fs
Wavelength:	796nm
Beam width:	40mm FWHM
Beam profile:	Super Gaussian

Laser refraction simulation

Split step Fourier based code.
Energy loss due to ionization.
No dispersion, no self-focusing.

Beam Energy:

Energy to ionize:	2.84mJ
Plasma heating energy:	~2mJ
Energy after optics:	7.28mJ
Optics efficiency:	80%
Energy before optics:	9.1mJ
Lost to aberrations:	2.5mJ
Lost to aperture:	6.5mJ
Required energy:	18.1mJ



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Takeaways from latest simulations

- 1) It is essential to have drive and trailing bunch centroids aligned
- 2) The long tail after the core of the drive bunch is probably deleterious if it is not aligned with the drive bunch peak
- 3)Although QuickPIC simulations use 40 M macroparticles, hosing can occur without Quiet Start. This means that importing of 6D phase space with only 1M macroparticles will always be noisy and prone to hosing
- 4)Optimum beam loading will need some control over trailing bunch charge

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Implications for E300

- 1) Pump Depletion
- This requires only the drive beam
- Need to know the charge and bunch length on each shot.
- Can we hope to measure 6um bunches with EO diagnostic?

- 2) Energy Doubling with High Efficiency, charge throughput and narrow energy spread
- Need to know bunch separation, bunch lengths, energy loss and gain screens, need submicron accuracy alignment between the two bunches.

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Implications for E300

- 3) Emittance Preservation
- These simulations did not take into account ionization of He. Previous work has shown that if the bunches have emittance of 20 um or greater He ionization is negligible and we can preserve it.
- Bunch alignment
- No long tail following the drive bunch or before the trailing bunch
- Deliver the stated beam focusing performance . Achieve matching by moving the IP a few cm
- Ability to measure the butterfly image of the accelerated bunch that may have 1% energy spread.

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How does one measure progress?

Assume that FACET II will deliver the drive and trailing bunch charge, current and bunch spacing as advertised.

1) Pump depletion of the drive bunch (year1)
2) Energy doubling of the trailing bunch (year1)
3) Minimize energy spread of the trailing bunch (year 2)
4) Investigate the factors that cause emittance growth (year 2)
5) Learn to match the 10-20 um trailing bunch to the PA (year 2-3)
6) Do an integrated (1,2,3,and 5) experiment (year 3)
7) Optimizing the charge throughput (year 3)

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Time Request (flexible)

Yr 1   4, 2 week runs every 3 months assuming year round operation of the facility.

EOS and TCAV correlated with YAG screen working to a high degree of confidence.

In subsequent years 3, 3 week runs depending on scheduling.

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Conclusions

Assuming we are successful in matching the witness bunch to and from the plasma

- 1 We can pump deplete drive beam in flat plasma region only 50-60 cm long with a density of 3.5-4x10^{16} cm^{-3}
- 2 We can get an energy gain of 7-8 GeV for the trailing bunch with no loss of particles in $\pm 2\sigma_z$
- Energy spread is <1% for particles contained within$\pm\sigma_z$
- Energy extraction efficiency ~30% (need to increase it to 40%)
- Emittance preservation at 20 um level even with He buffer gas.
- More simulations work needs to be done before we can be confident that we are getting

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