What must the PWFA Collaboration do at FACET II

Overview of requirements for Plasma Sources based on experimental needs

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Outline of this talk

- First experiment aligned with the DOE-HEP's strategic plan
- Second Experiment aligned with early application
- What are the beam and plasma requirements, where are we, and what do we need to do to get there?
- Conclusions are independent of the type of plasma source.

1:Propose a major experiment that is consistent with DOE's one or more strategic goals

Proposal for an experiment at the FACET Science meeting at UCLA

- Deplete the drive beam of its energy
- 50% Energy extraction Efficiency
- 10 GeV energy gain for the trailing beam (TB)
- Minimize the energy spread of TB (<<1%)
- Demonstration of emittance preservation of TB
- (this is the first step towards eventually getting a collider quality beam)

- All at the same time

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2:Experiment aligned with early application

- General consensus at present is early application is generation of coherent light source.

- Need to produce electron bunches with brightness orders of magnitude larger than the brightest beams available today.

- What are the beam and plasma requirements?

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Experiment 1:Realizable because of Differences between FACET I and II beams

Parameter	FACET I	FACET II
Drive Beam	20 GeV	10 GeV
Norm. Emittance	20x100 um	< 3x7 um (without foil)
Pump Depletion	No	Yes
Trailing Beam		
Bunch Charge	>100 pC	> 100 pC
Energy Spread	<5%	<<1
Energy gain	max 8 GeV	10 GeV
Efficiency	30%	50%
Emittance Preservation	No	Yes?

We are going to optimize beam loading and demonstrate beam matching.

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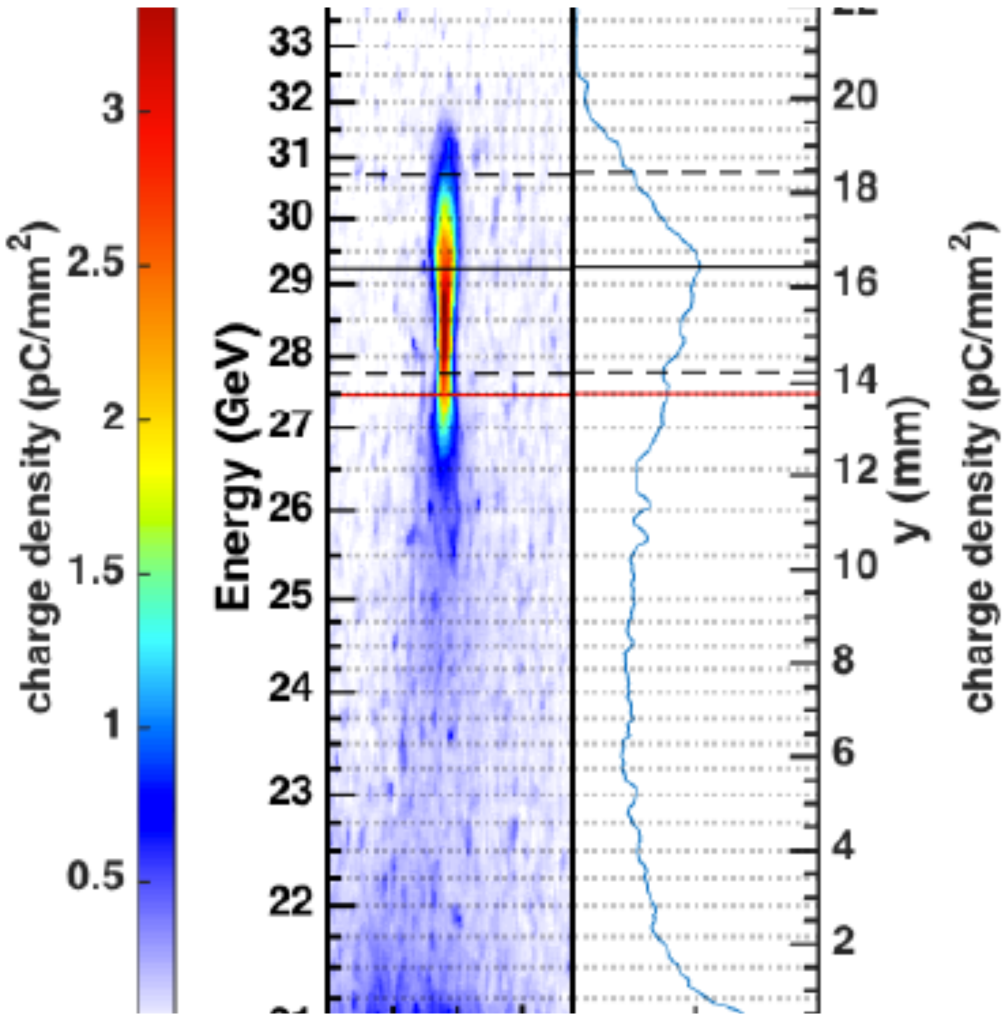
1 What have we already shown?

Acceleration of a witness bunch

- PWFA can accelerate a 100 pC bunch with~5% energy spread and 30% energy extraction efficiency with an energy gain of up to 9 GeV in 1.3 meters (7 GeV/m loaded)

- Ref. M. Litos et al PPCF 2015

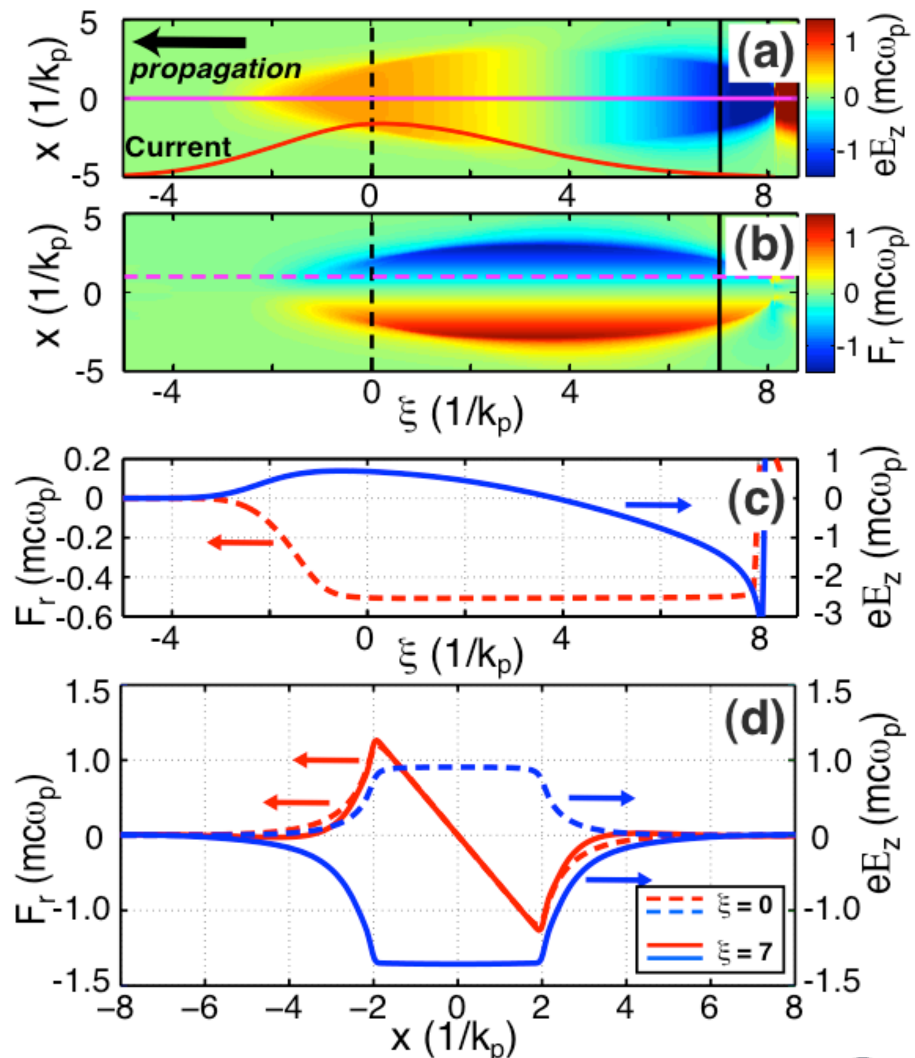


2 What have we already shown?

Panofsky-Wenzel Theorem for PWFA in blow-our regime

- PWFA cavity in the blow out regime has the field structure to accelerate particles at high gradient while preserving the emittance of the bunch

- Ref: C.E. Clayton et al Nature Communications 2016



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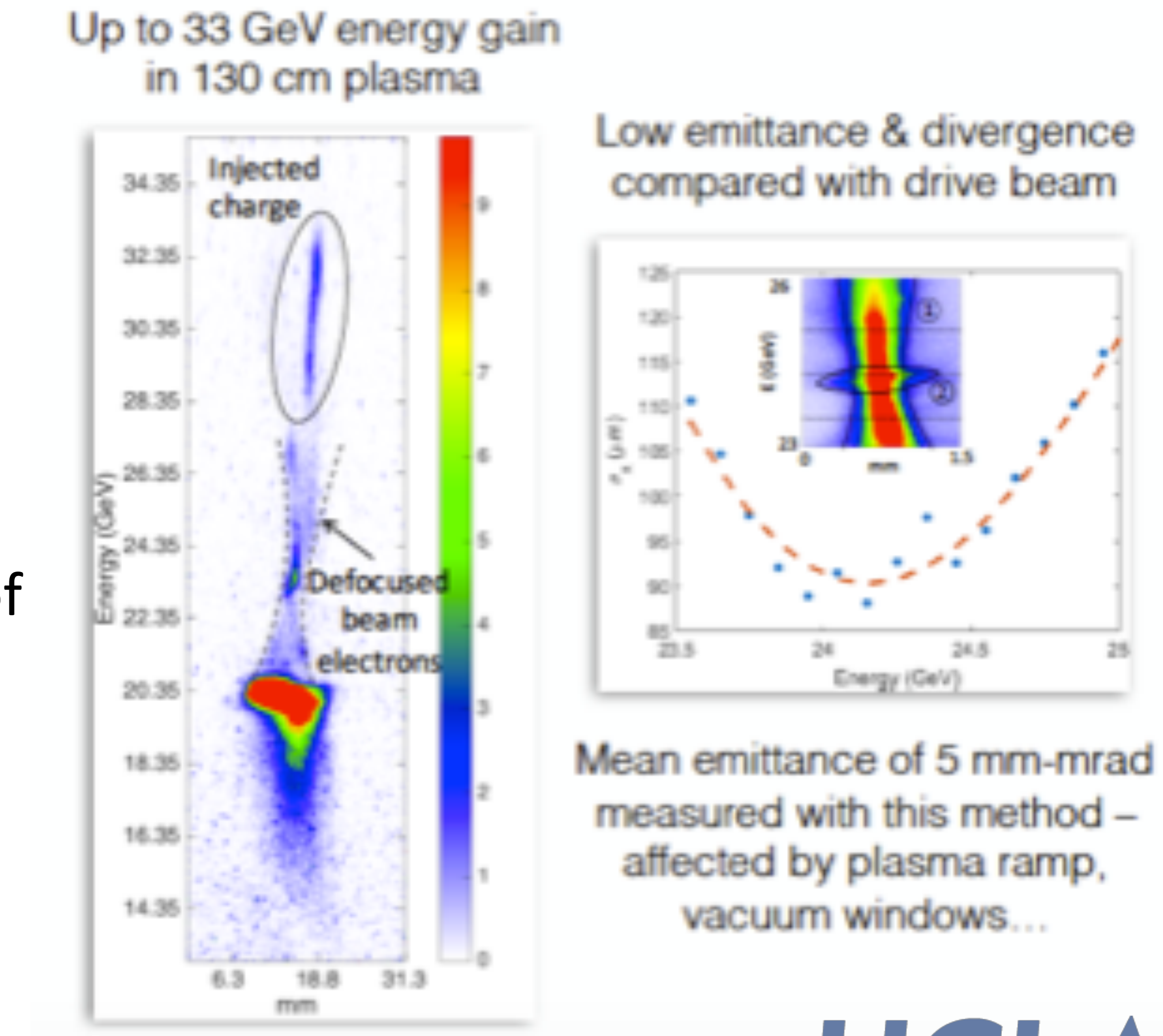
3 What have we already shown?

We can measure emittance at 20+ GeV down to 5 um

- We have measured emittance of the ionization injected electrons as low as 5.5 um using an existing spectrometer with no special effort made to preserve the emittance of the beam



- Ref: N. Vafaei Najfabadi et al PhD thesis UCLA 2016

TBP

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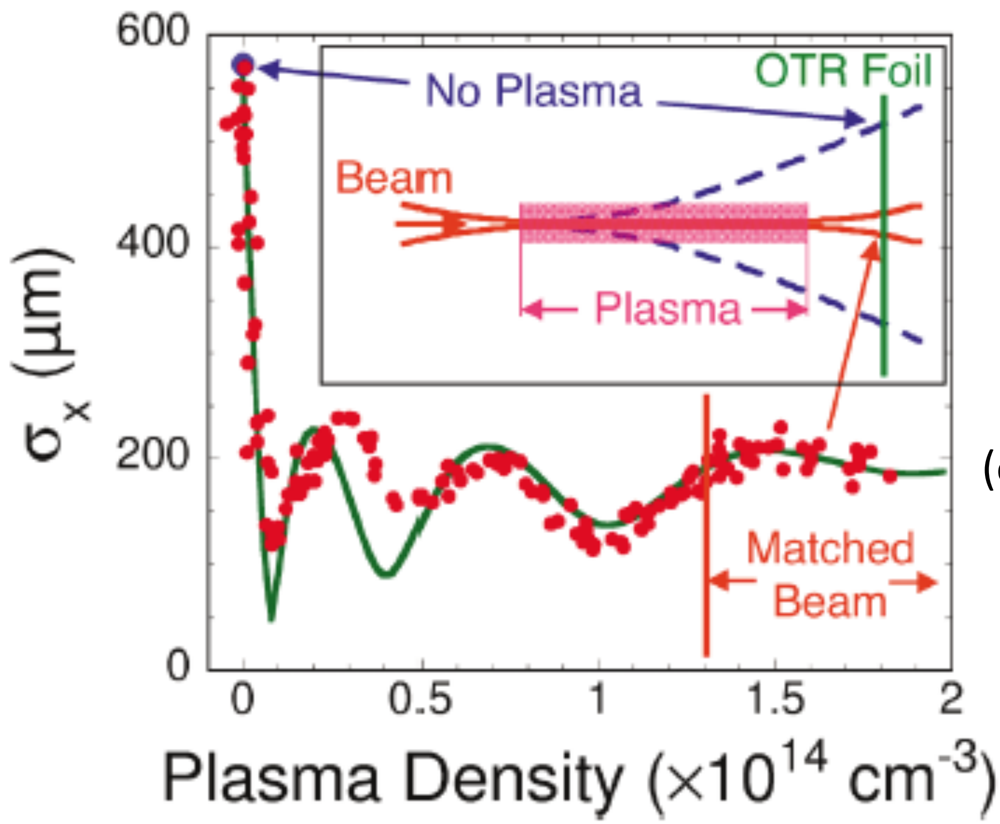
4 What have we already shown?

We have shown beam matching is possible using a Li source
Very low density but long plasmas can add a significant phase to the beam envelope



$(\sigma_{xm})^2 = \varepsilon_n\,(c/\omega_p)\,(2/\gamma)^{1/2}$

Ref; Muggli et al PRL 2004

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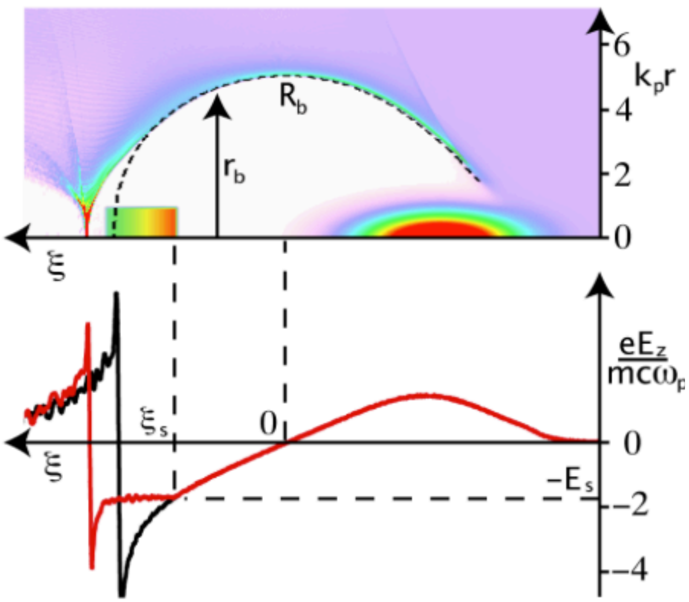
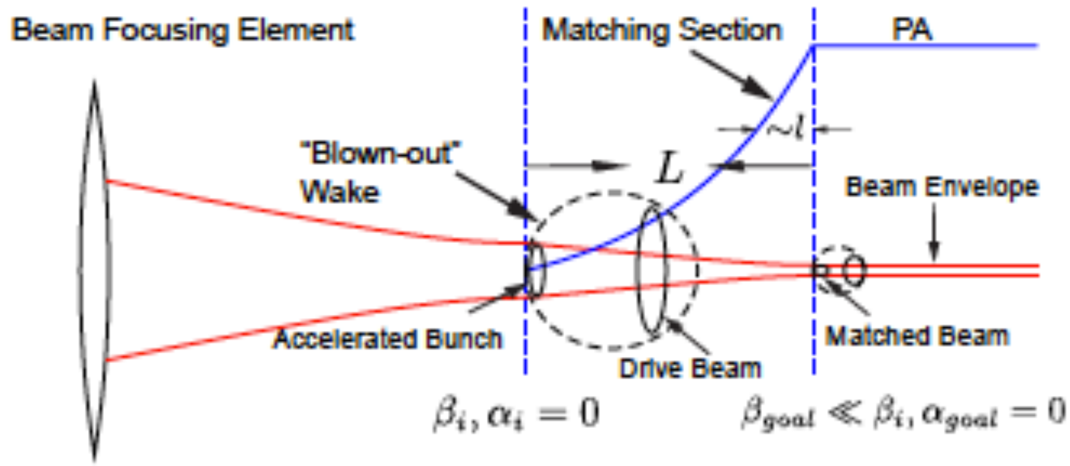
Two Key Concepts for high quality beams from plasma accelerators



Ref: M. Tzoufras et al PRL



Ref: X. Xu et al PRL 2015

Beam Loading

Energy Spread and Efficiency

Matching Section

Emittance Preservation

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QuickPIC Simulation without ramps or ionization to optimize density, and Dr-Tr beam efficiency

Send a matched beam through preformed plasma

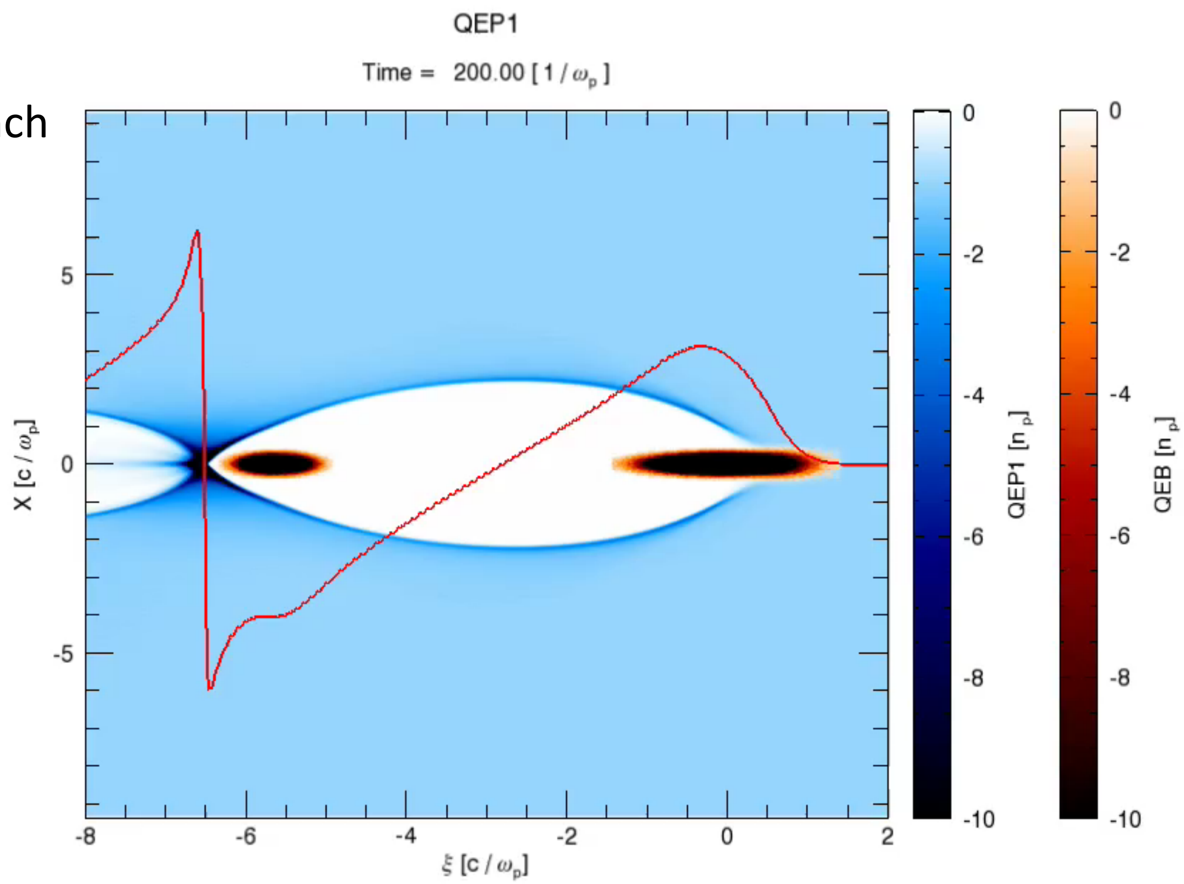
	Drive (Dr) Bu	Trailing (Tr) Bunch
γ(GeV)	10	10
I(kA)	15	7.5
ε_n (μm)	50	50
σ_z (μm)	14	8
σ_r (μm)	3.6	3.6

Δξ (μm) 150

Plasma Density 4×10^{16} cm^{-3}

Preformed plasma

$(\sigma_r)^2_{matched} = \varepsilon_n\,(c/\omega_p)\,(2/\gamma)^{1/2}$



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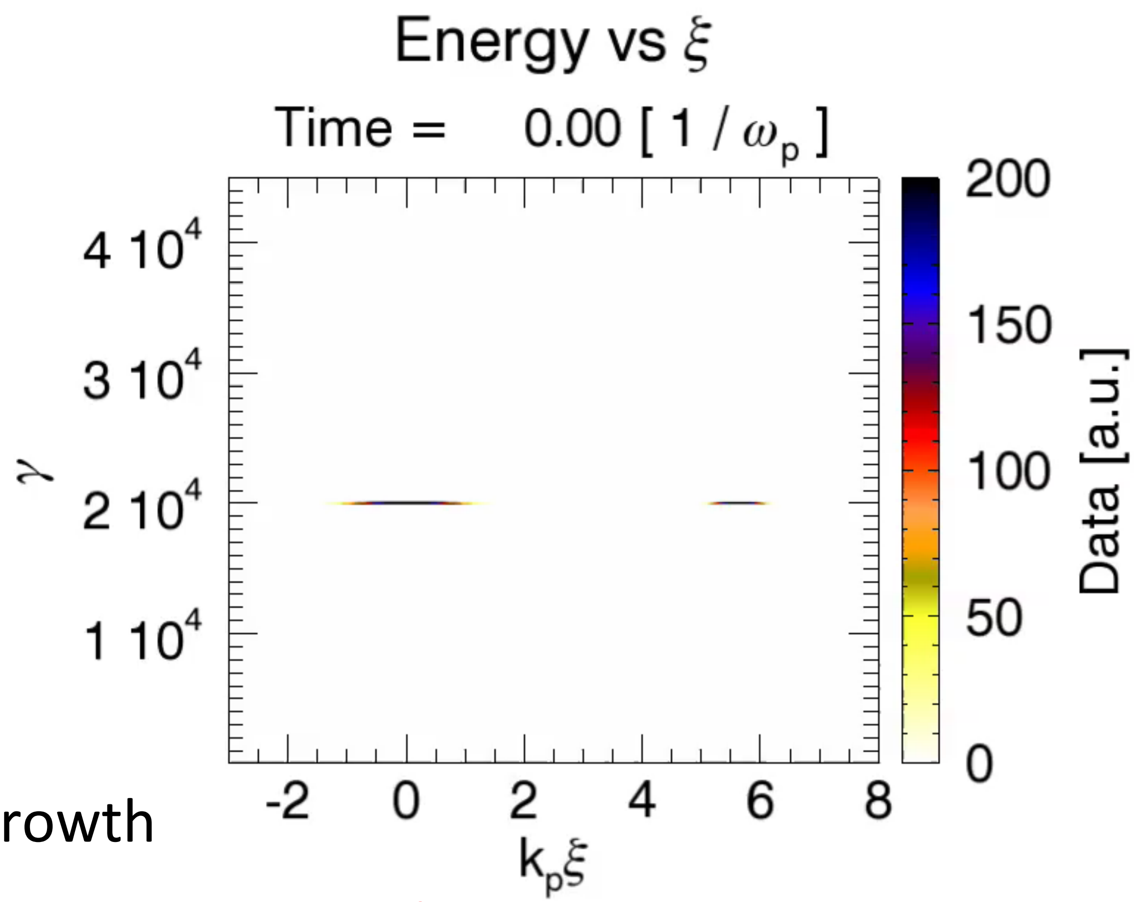
Energy Evolution of the two bunches

Energy Gain: >10 GeV
Energy spread 1%
Efficiency 50%
TR~ 1.2
Energy Loss >9 GeV
No envelope oscillations
No measurable hosing
Some energy spread so expect some emittance growth



Looks extremely promising so now reduce emittance to 10um and add ramps, ionization.

Ionization trapping may beam load the wake and reduce the TR

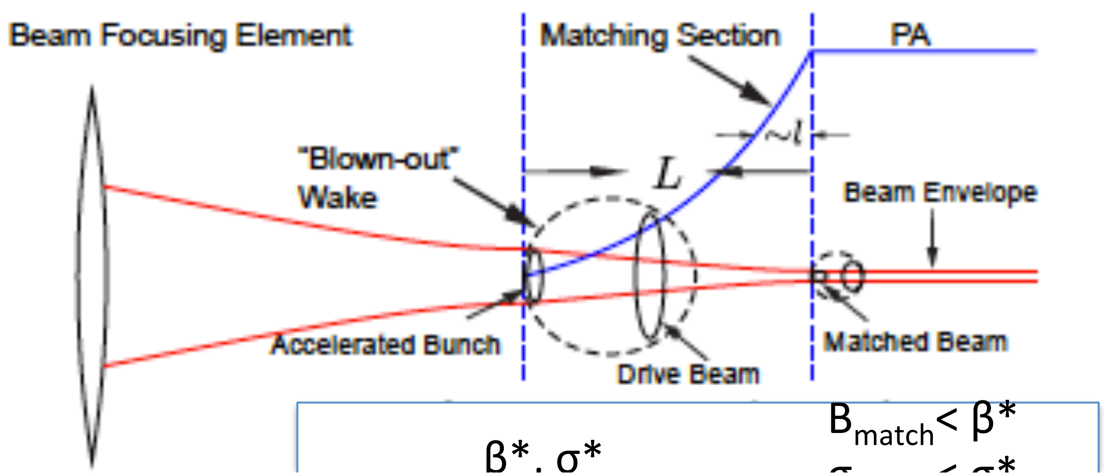
Numerical calculation of beam matching

follow the evolution of C-S parameters throughout the matching section starting from the matched beam in PA

$$M = \begin{pmatrix} \cos\sqrt{K}l & \frac{1}{\sqrt{K}}\sin\sqrt{K}l \\ -\sqrt{K}\sin\sqrt{K}l & \cos\sqrt{K}l \end{pmatrix} \quad (1)$$

where $K(z) = \frac{1}{2\gamma_b}\frac{\omega_p(z)^2}{c^2}$ and γ_b is the beam energy. The evolution of the C-S parameters of the beam in each segment is

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_f = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{pmatrix} \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_i \quad (2)$$



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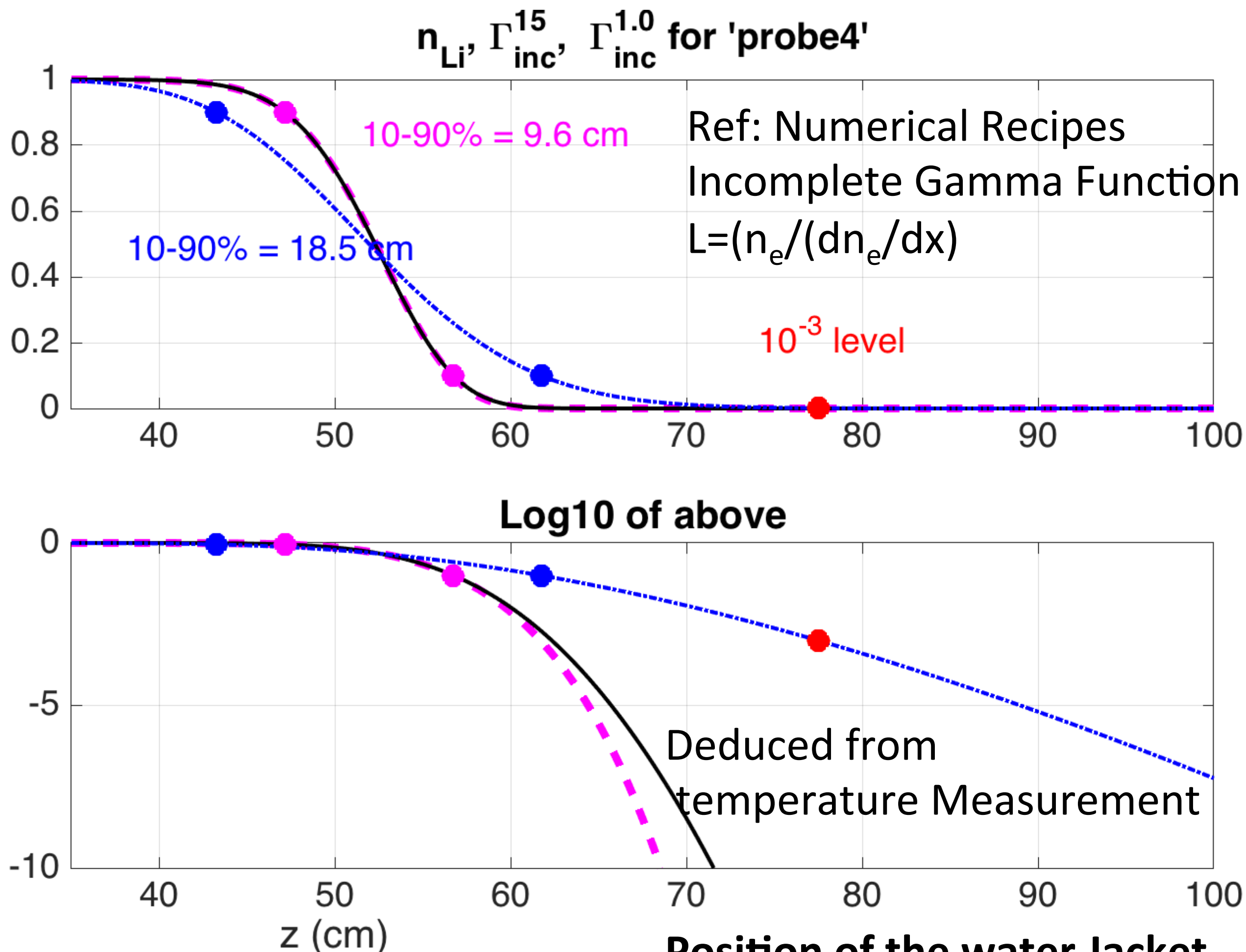
Density Profile of the Matching section

Linear Scale

Log Scale



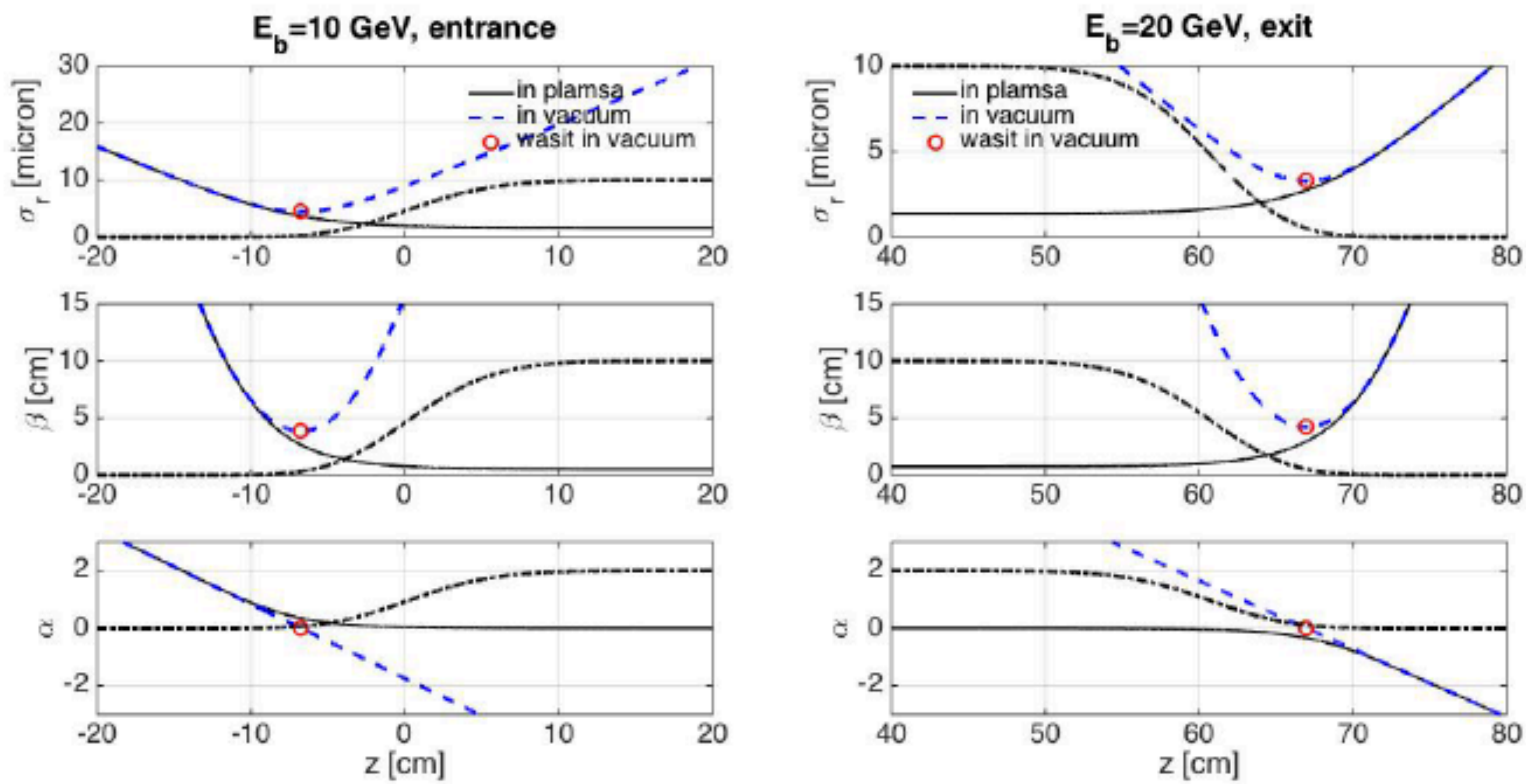
A Good starting point is deduced density from the measured temperature ramps
See Ken's talk

Beam Parameters Used

	Drive Bunch	Trailing Bunch
Energy(GeV)	10	10, 4, 0.3
Current(kA)	15	7.5, 2, 2
ε_n (μm)	10	10, 3, 1??
σ_z (μm)	15	8 , ??
Spacing (μm)	150	

- Plasma Density 4×10^{16} cm^{-3}
- 4 and 0.3 GeV bunch currents too low for beam loading but might be useful for demonstration of slice emittance preservation : needs more work

Example of beam matching



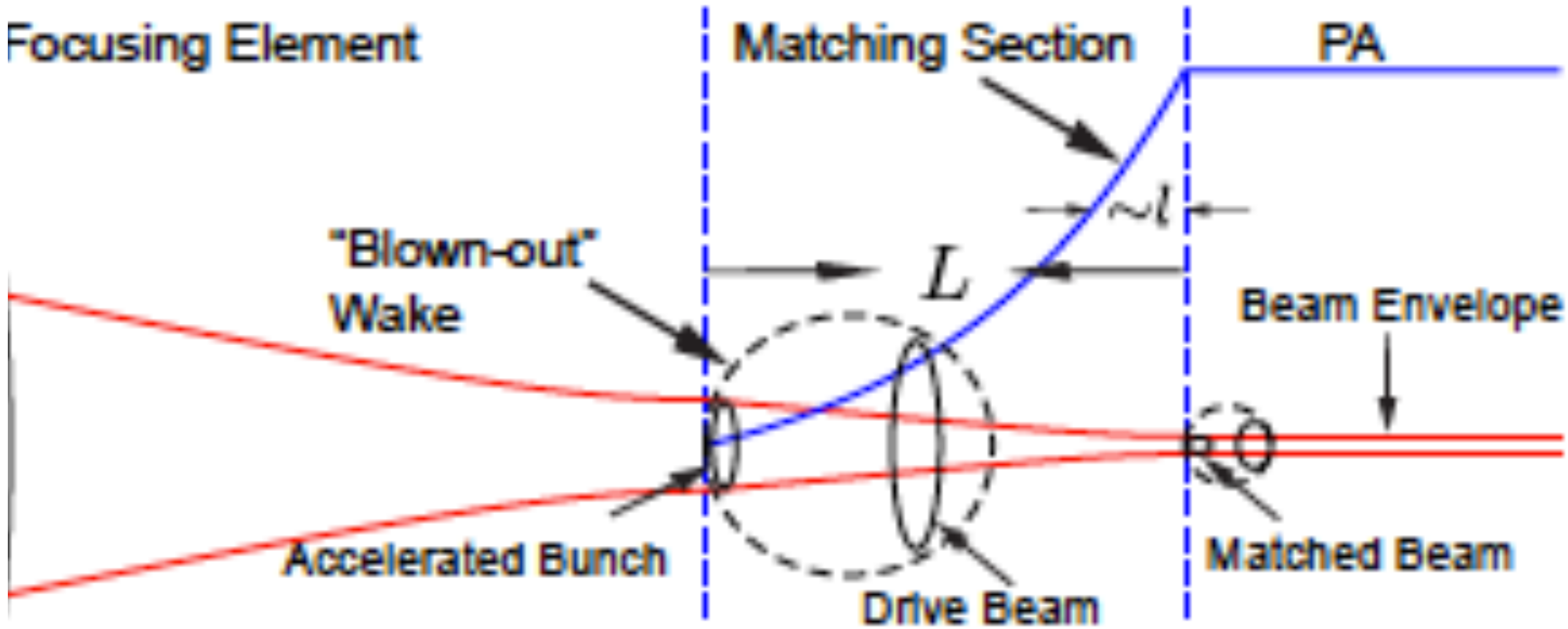
$$(\sigma_{rm})^2 = \varepsilon_n\,(c/\omega_p)\,(2/\gamma)^{1/2}$$

Figure 3: The evolution of the plasma density, β-function, α-function and the spot size of the witness beam in the plasma ramp. Left: at the entrance; right: at the exit. The input beam energy at the entrance is 10 GeV.

Ref: Xinlu Xu: private communication

A scenario for matching using an achievable density profile and 10 GeV Drive- Trailing beams, ε_n=10 μm

Ref: Xinlu Xu PRL 2015



β^*, σ^*	$B_{match} < \beta^*$ $\sigma_{match} < \sigma^*$

σ(z=2.2m, 7m)= 260 μm, 550μm

β^*= 3.9 cm, 4.2 cm
σ^*= 4.4 μm, 3.3 μm

10 GeV 20 GeV

β_{match}= 0.53 cm, 0.75 cm
σ_{match}= 1.6 μm, 0.75 μm

10 GeV 20 GeV

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Can we measure 10s% changes in ε_n?

Caveat: Not self consistent simulations

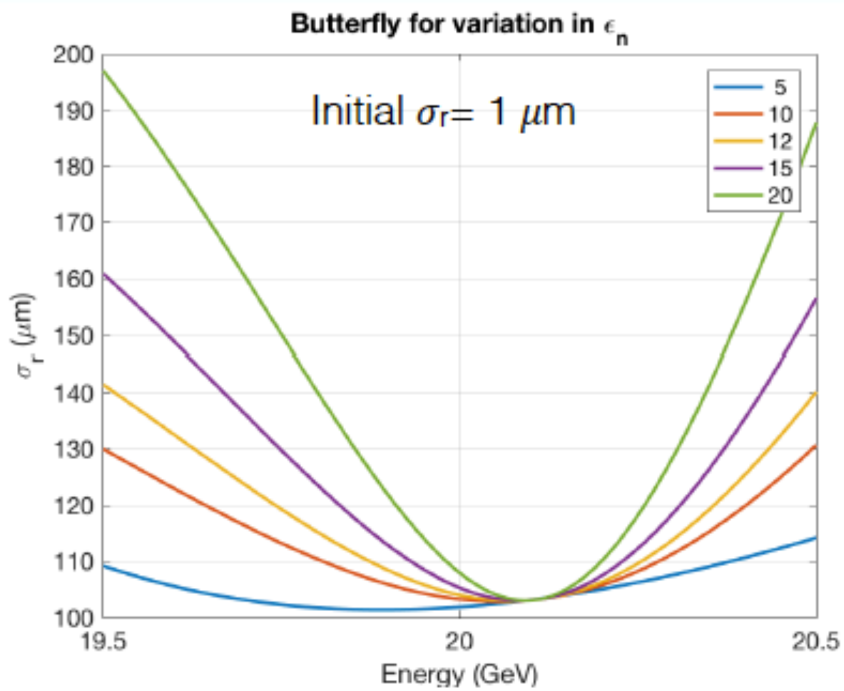
Assumptions Used

- Ramp: Same profile as the ramp of the 1.5 m lithium oven
- Magnet/foil location configuration: Same as the 1.5 m lithium oven
- Quad strengths: 258.03,-172.06.
  - Calculated for imaging at 20.35 GeV, image plane at ELANEX (z=2015.22), object plane at 12 cm upstream of the exit of the 1.5 m lithium oven (z=1997.85) — same config as last 1.5 m positron run
- Plasma density: assumed $5\text{x}10^{16}$ cm^{-3}.
- Energy for imaged electron beam: 20 GeV ± 1 GeV
- Butterfly Profile is plotted for different normalized emittance values for the initial beam 1 cm before the plasma ramp

See talk by Navid

We can measure 10s % changes in ε_n with existing setup

Butterfly for 20 GeV Beam



With the same resolution as in FACET I (9 μm/pixel), the rms size of the beam on ELANEX screen changes from 14 pixels to 21 pixels at 19.5 GeV, which is an easy distinction to make

See talk by Navid

Sources of emittance growth

-Error in positioning the beam waist in the plasma matching section

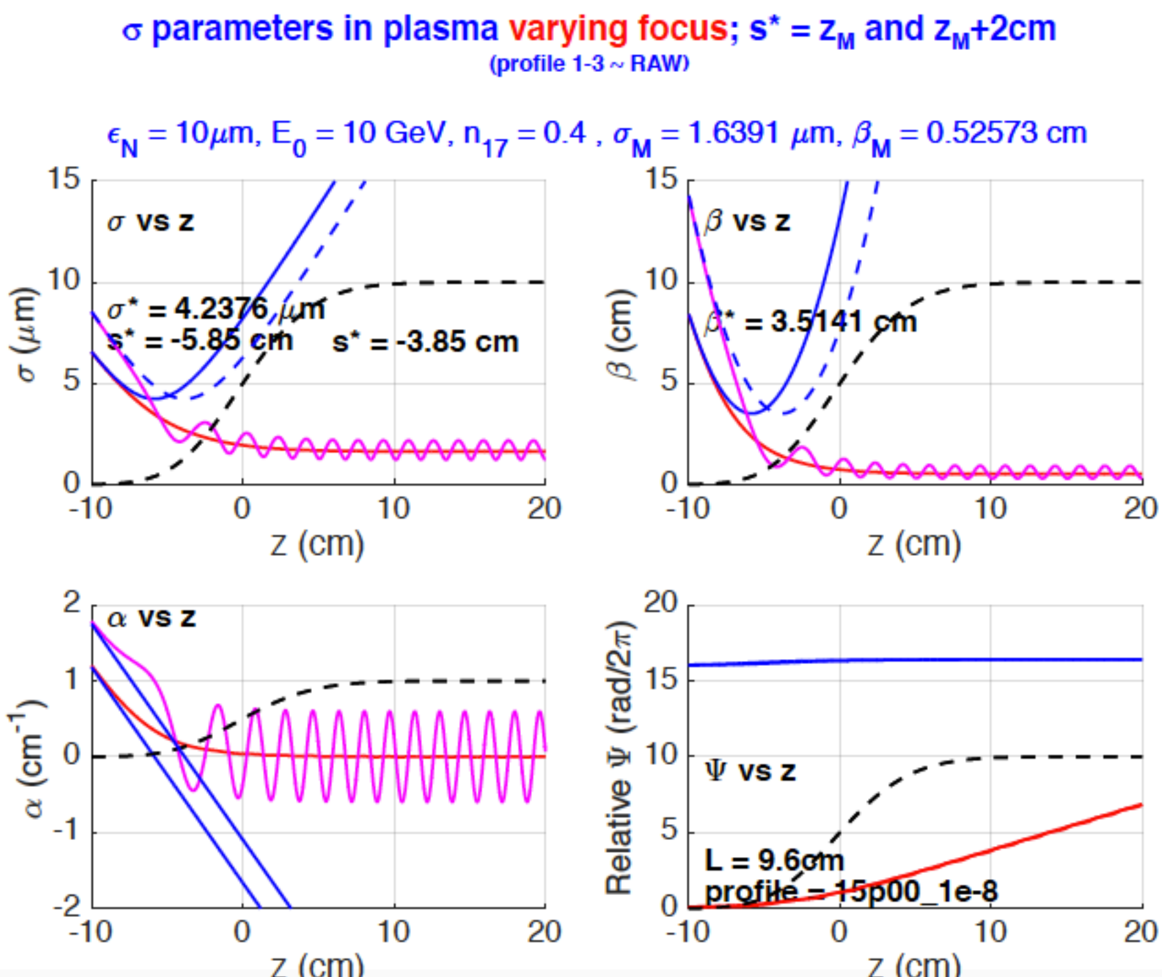
-Errors in the ramp density profile of the matching section from ideal.

-The bunches have a finite energy spread, asymmetric emittance and complex phase space.

Need to incorporate these into PIC codes. For now make estimates using C-S formulism for ideal beams but non-ideal matching.

Effect of Errors: 1 Position of vacuum beam waist

- As soon as the beam is not matched, it will undergo envelope oscillations and betatron yield will increase.



Ref: C. Clayton private communication

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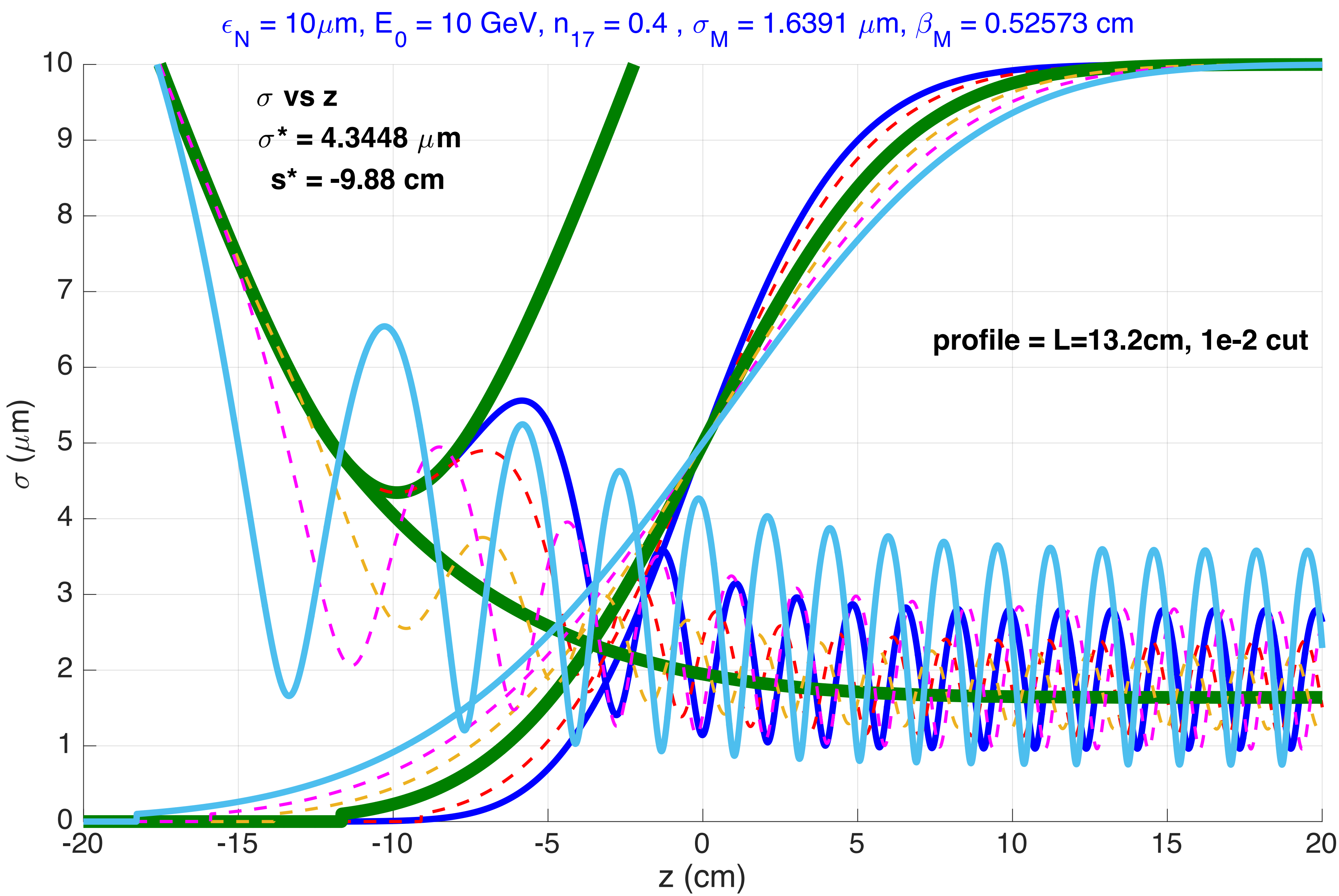
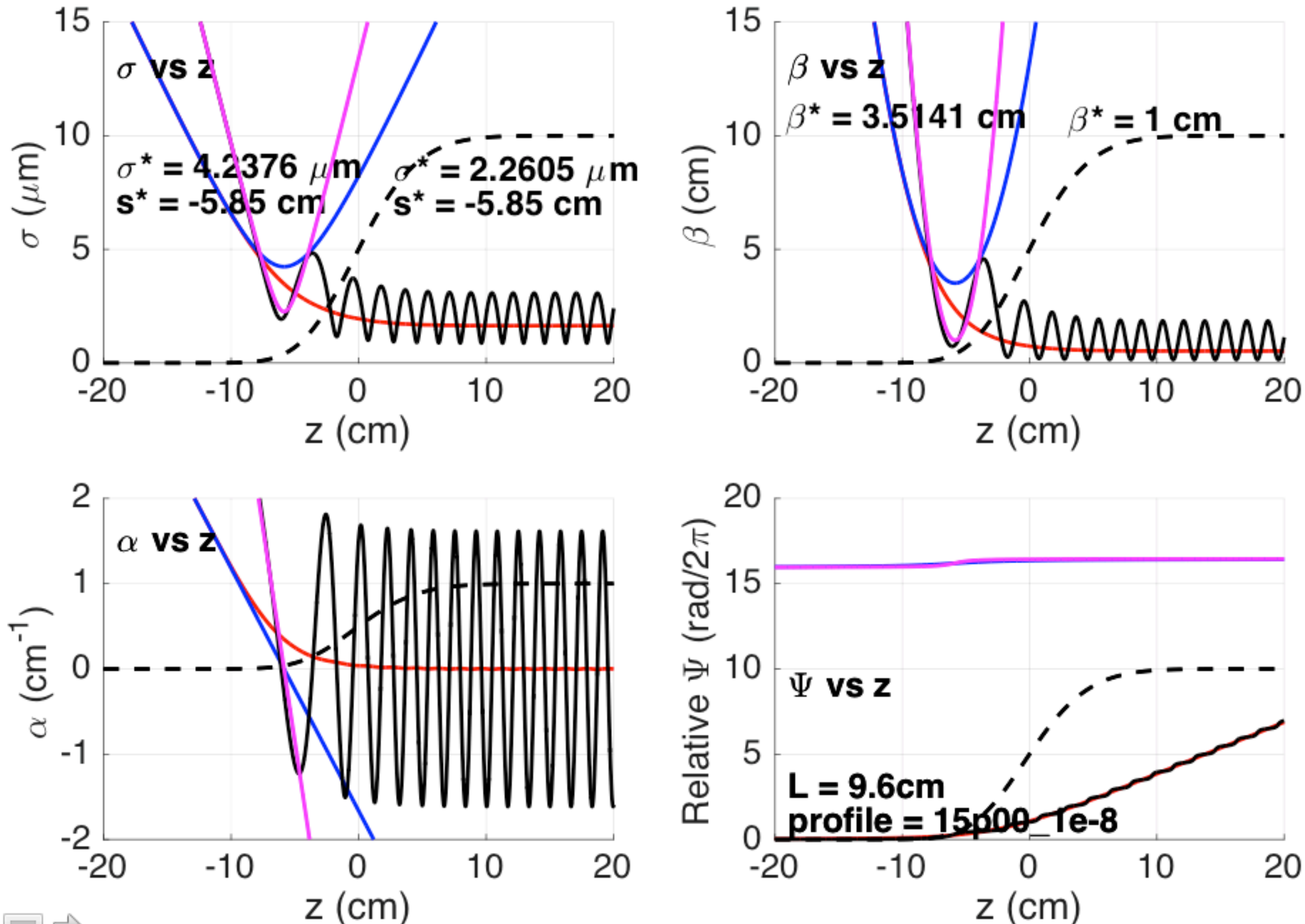
Visual summary of σ parameters in plasma varying scale length of ramp;



Effect of Errors 3: Departure from Ideal β*

σ parameters in plasma beta* = 3.51 cm (matched) and 1.0 cm (2.5 cm shorter) **(profile 1-3 ~ RAW)**

ϵ_N = 10μm, E_0 = 10 GeV, n_{17} = 0.4 , σ_M = 1.6391 μm, β_M = 0.52573 cm



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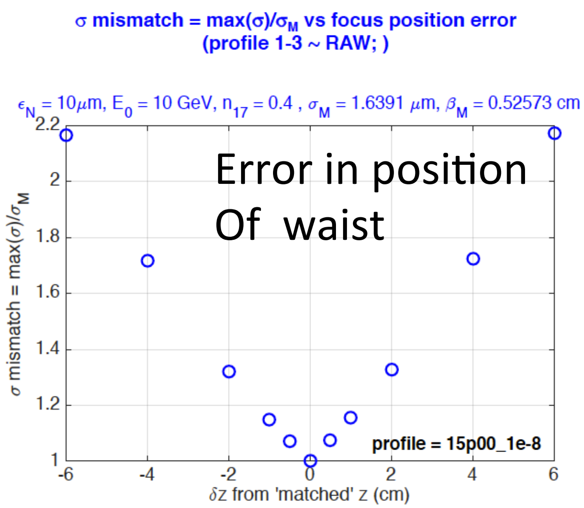
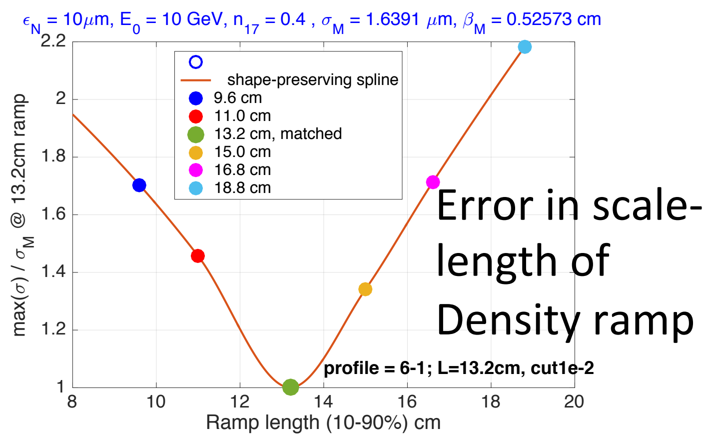
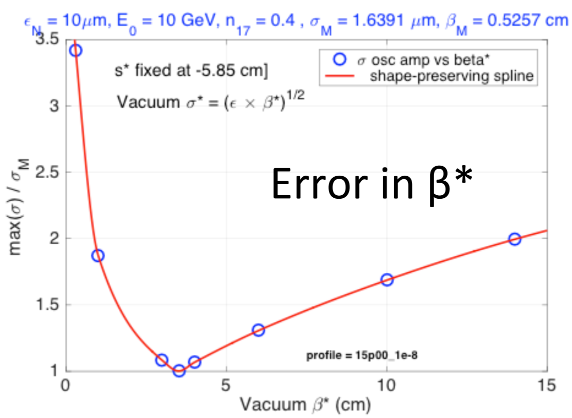
Departure from non optimal matching conditions The spot size becomes larger in the plasma and oscillates at betatron wavelength







Errors in waist position and β* will lead to
An increase in growth of projected emittance
Need to do more careful PIC simulations to
Estimate.
The optimum ramp profile must not be disturbed
By the beams, for instance by further ionization.

Ref: C. Clayton, Private communication

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Entrance and Exit C-S Parameters for 0.3 GeV, 4 GeV and 10 GeV Witness Bunches

Table 1: Parameters of the witness beam

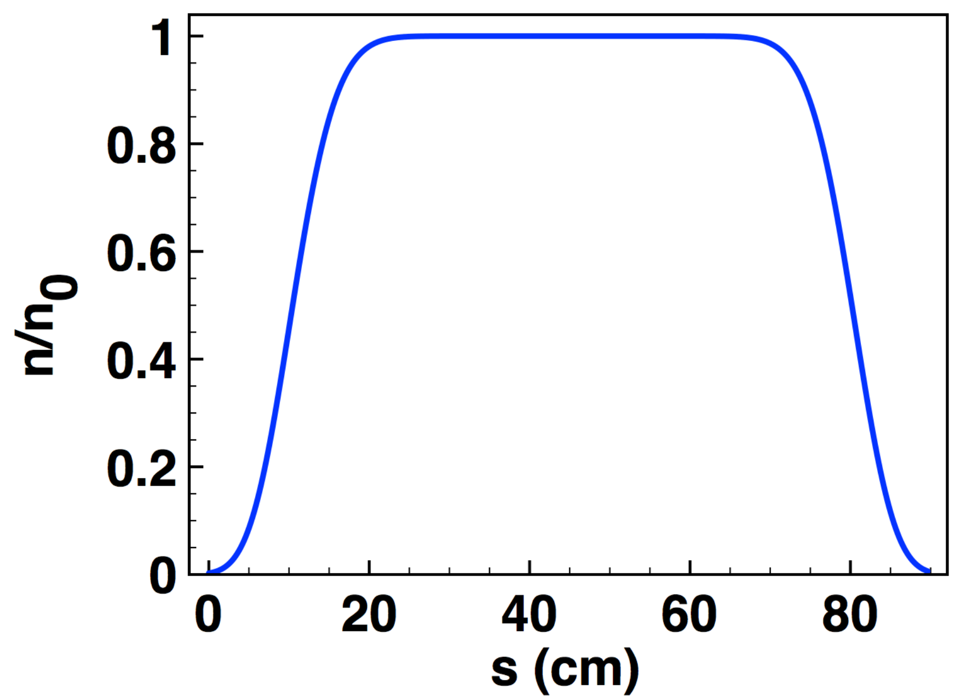
	Entrance	Entrance	Entrance	Exit	Exit	Exit
E_b [GeV]	0.3	4	10	10.3	14	20
ϵ_n [μm]	10	10	10	10	10	10
β_{match} [cm]	0.09	0.33	0.53	0.53	0.62	0.75
α_{match}	0	0	0	0	0	0
β^* [cm]	2.7	3.5	3.9	3.9	4.0	4.2
$\sigma_{r,match}$ [μm]	3.9	2.1	1.6	0.53	0.62	0.75
σ_r^* [μm]	21.5	6.7	4.4	4.4	3.8	3.3
z_{waist} [cm]	-10.1	-7.7	-6.8	67.7	67.4	67

Assumption: The drive bunch is the same in all cases and produces a wake in the blowout regime throughout the matching region

QuickPic Simulation with matching ramps

Drive Beam: E = 10 GeV, I_{peak}=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, I_{peak}=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: Weimng An and Xinlu Xu: Private Communication

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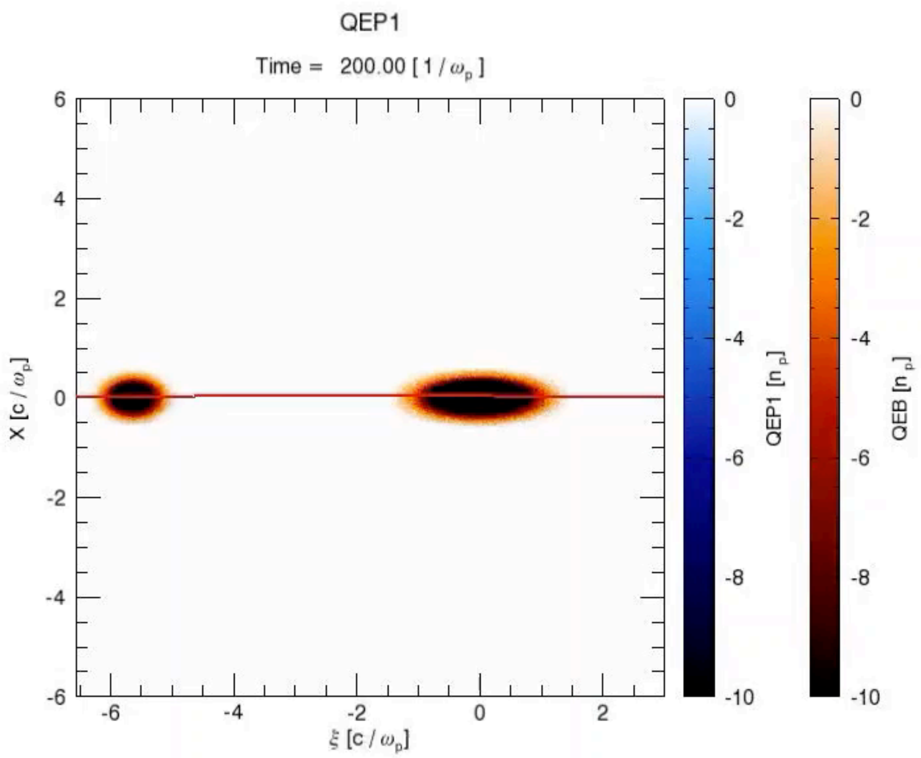
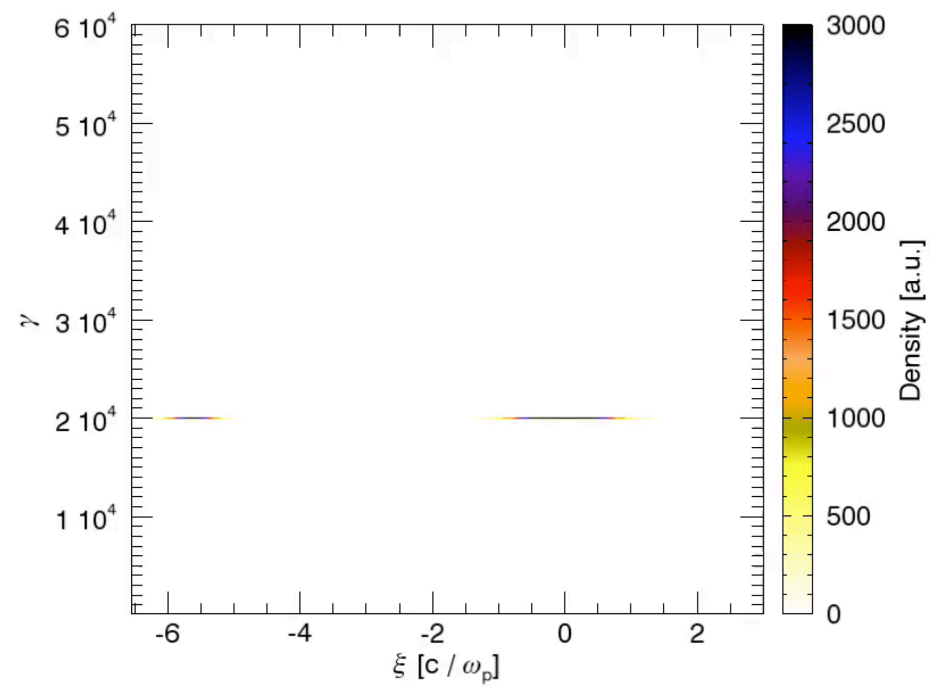
Beam and Plasma Density and Energy evolution

Plasma and beam density
with on-axis Ez line out



Beam Energy



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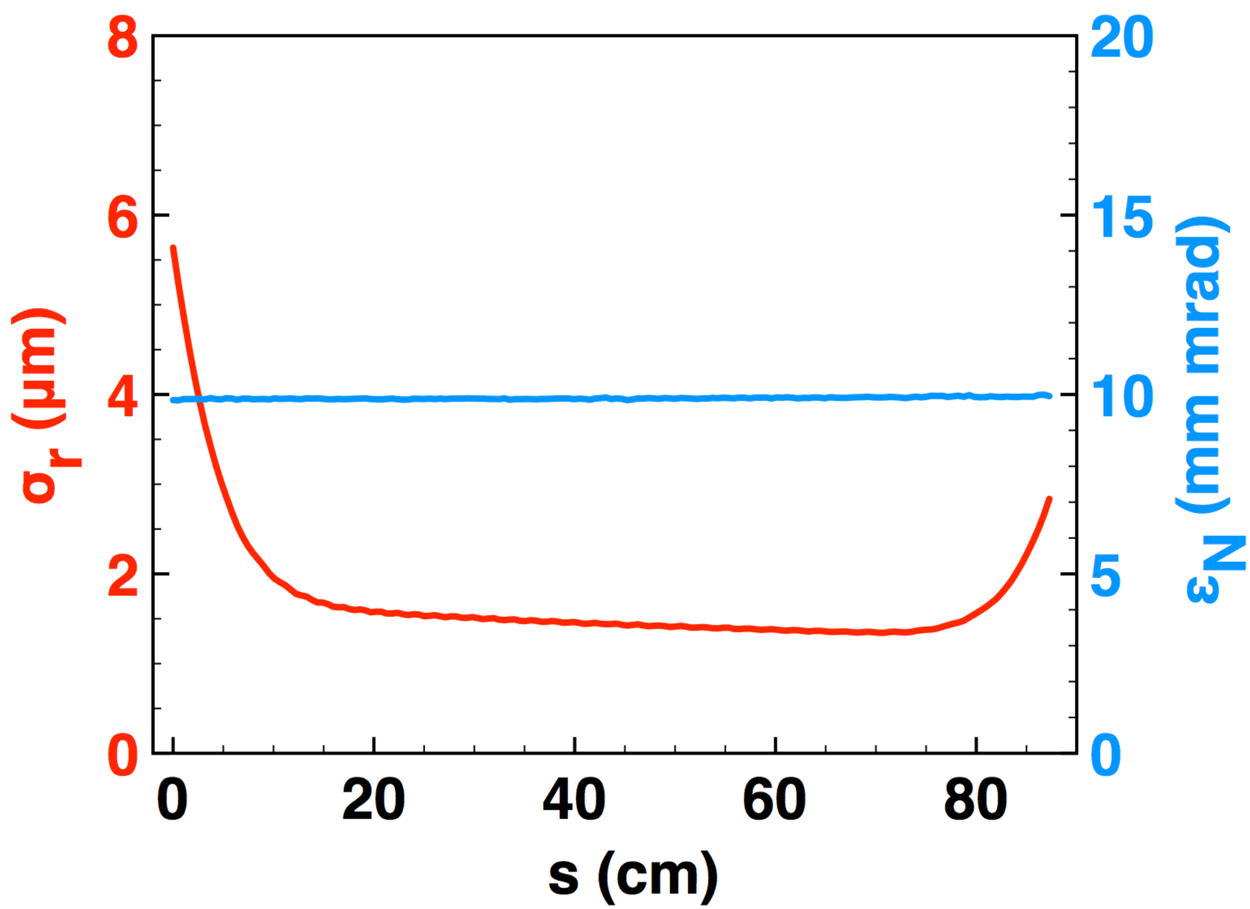
The projected beam spot size and emittance



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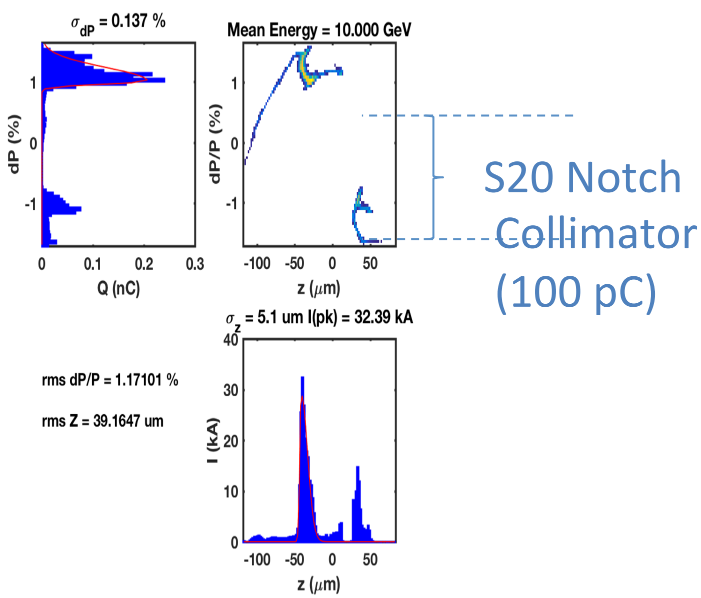
Beam Parameters from Particle Tracking @ E200 IP

Ref: Glen SLAC



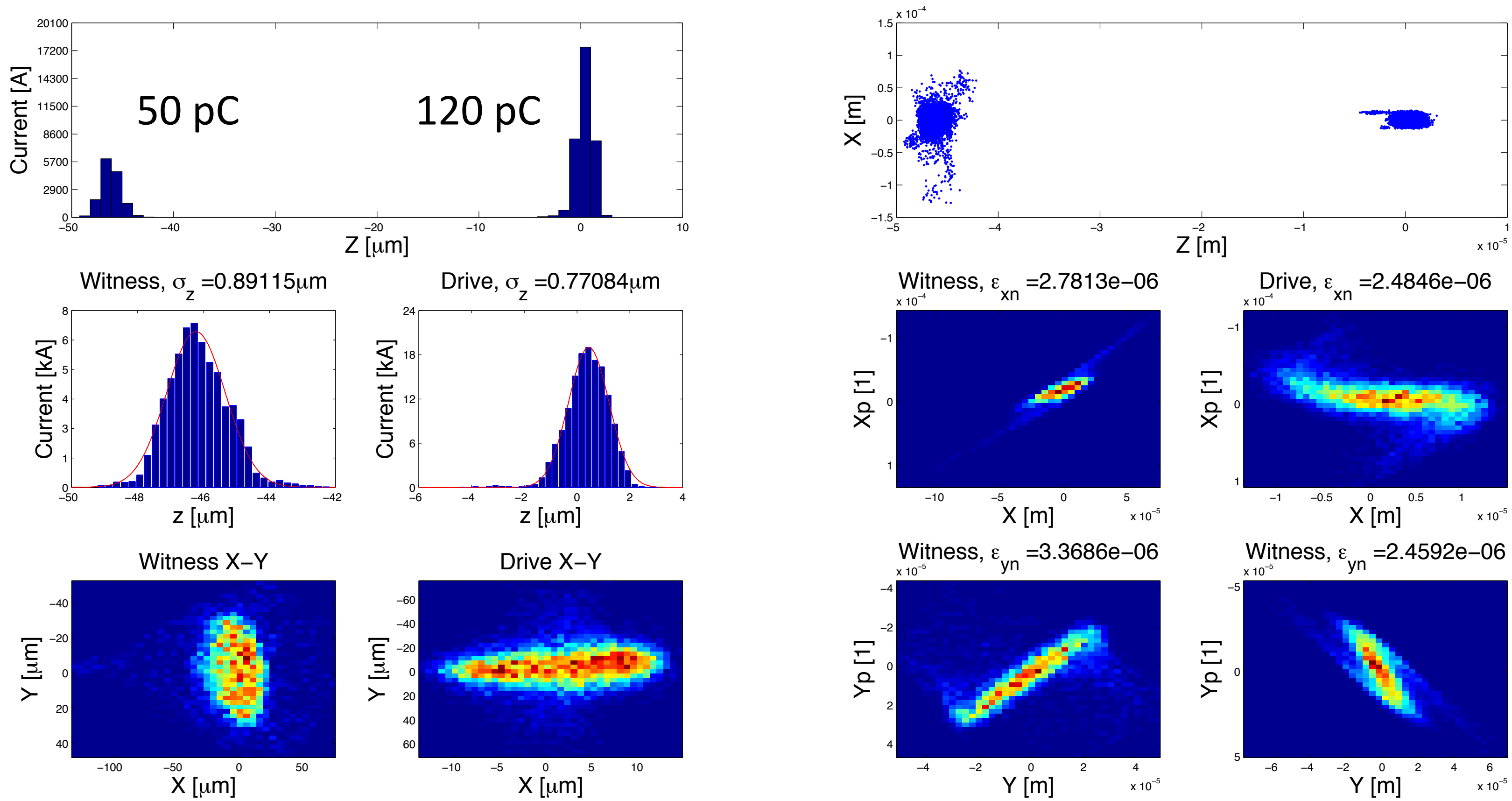
Parameter @ IP	No COLL		S20 Notch COLL	
	Drive	Witness	Drive	Witness
Q / nC	1.6	0.5	1.5	0.5
δ_E / E (% rms)	0.24	0.24	0.16	0.25
I_{pk} / kA	32	16	34	16
$\gamma\varepsilon_y$ / μm-rad	3.4	3.2	3.3	3.2
$\gamma\varepsilon_x$ / μm-rad	6.4	7.8	5.6	7.8
$\gamma\varepsilon_x$ / μm-rad (90%)	5.7	6.1	5.1	6.1

Linac RF Phase Settings

- L1 $\phi = -18.0^0$
- L2 $\phi = -38.0^0$
- Δt @ IP = 250 fs
- BC11 & BC14 unchanged

$$I_{peak} = Q/(2\pi)^{1/2}\,\sigma_z/c$$

Experiment 2: Extreme Bunches a la Brendan/Glen



Q_d 120 pC, Q_w 50 pC , ε_n ~ 3 μm , σ_z ~ 1μm, spacing variable

Extreme Bunches a la Brendan

- Good news and Bad news

- First the bad news
- The charge in the witness too low to beam load the wake, need 2:1 ratio of beam currents for beam loading

- Now the Good News: we can use just the drive beam to do the following
- Can operate at high density $2x10^{20}$ cm^{-3}
- No dephasing and TeV/m gradients
- Ionization injection and downramp injection possible
- May be possible to generate collider quality ultra-bright beams.
- May be the easiest route to a first application-generation of coherent x-ray radiation
- We are developing plasma sources for such beams

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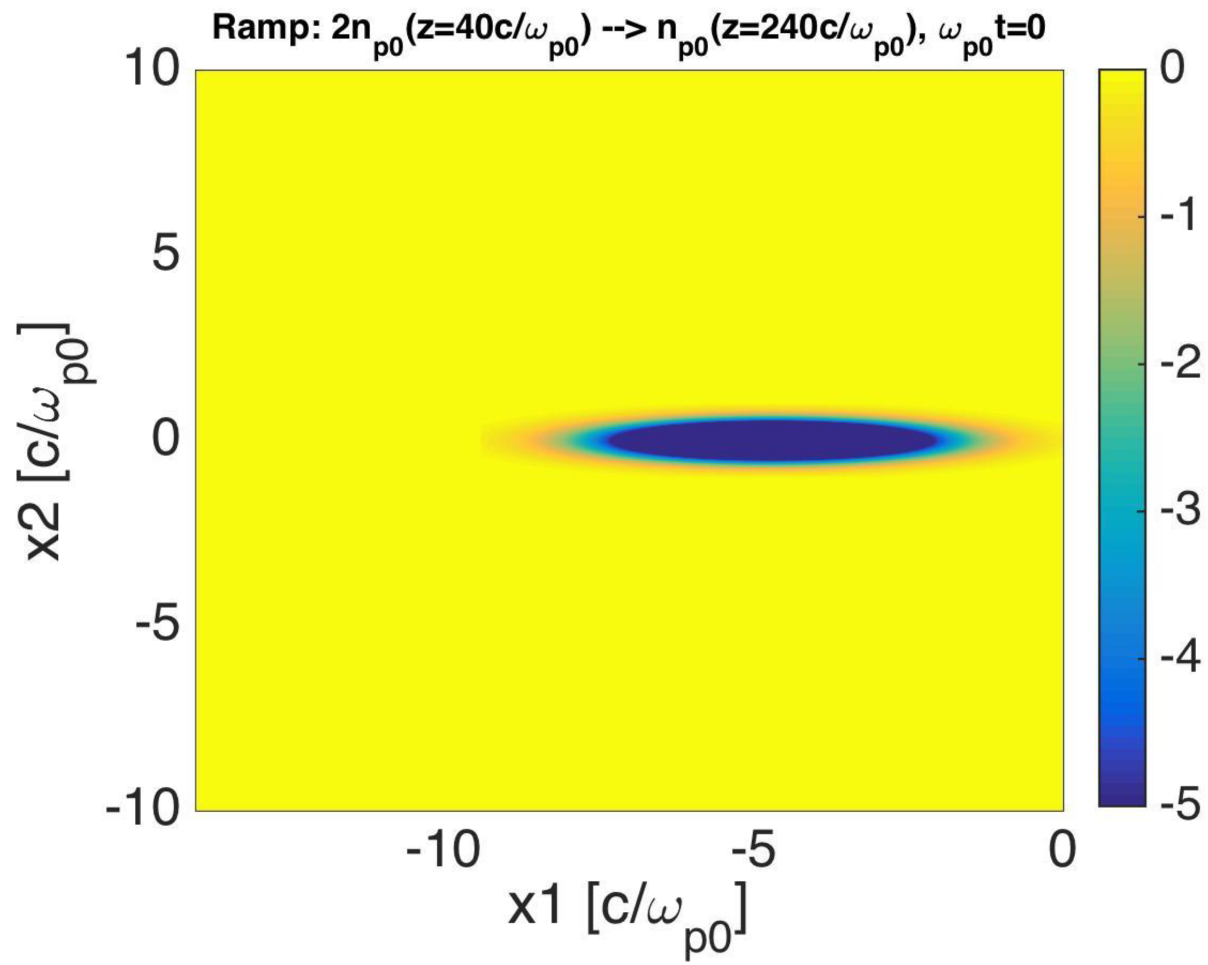
Preliminary Downramp injection Example



Ref: Xinlu Xu Private Communications, submitted

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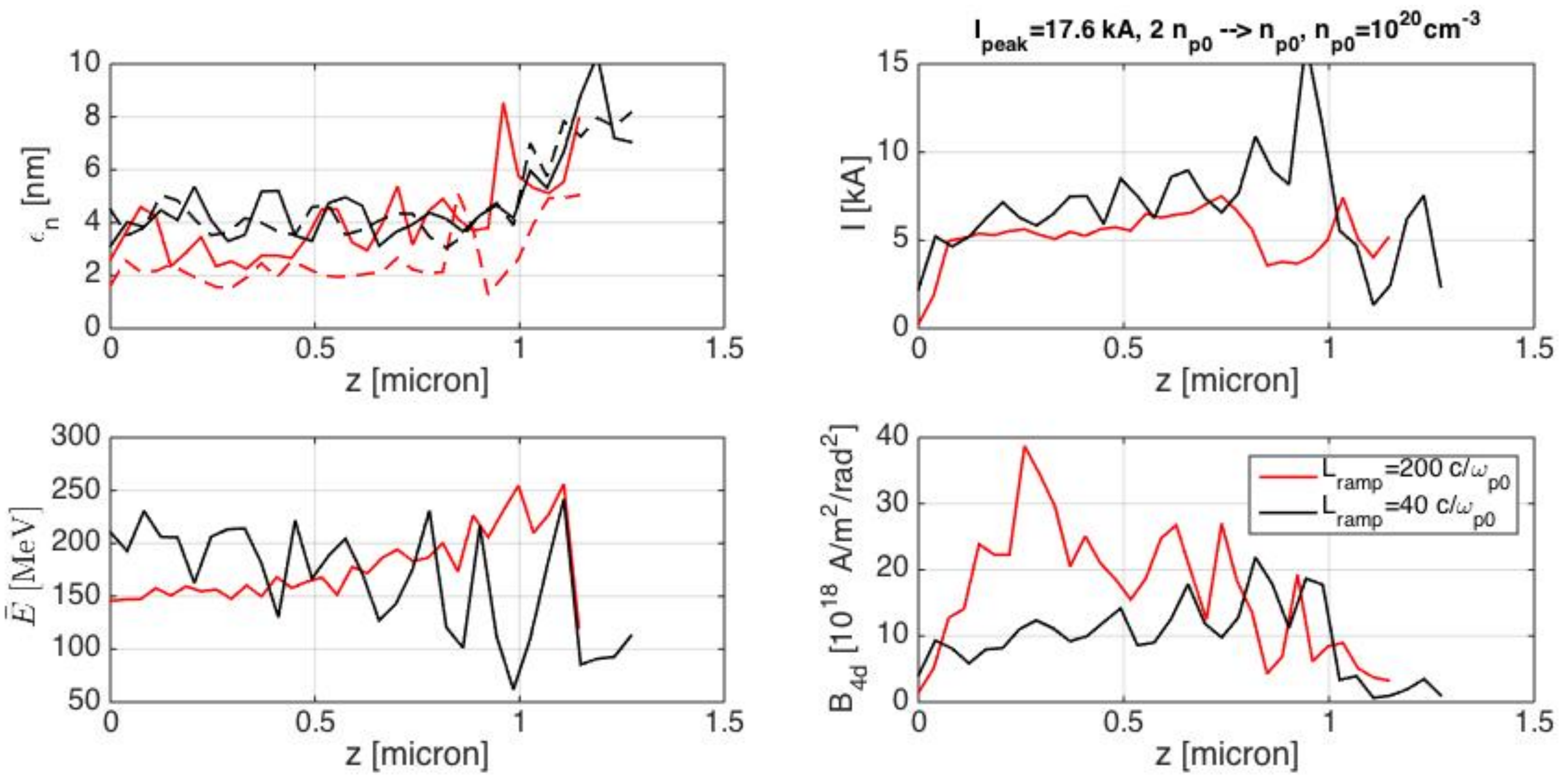
Generation of ultra-low emittance beams in downramp injection



See talk by Ken

Conclusions 1

- We must and can do a very high profile experiment on FACET II in the first 3 years

- Demonstrate full pump depletion, energy doubling, little or no increase of energy spread and emittance and 50% beam-to-beam energy transfer efficiency.

Lots of careful work needed to make a plasma source with suitable ramps, and FACET must deliver the beams and ability to accurately focus them.

With Li oven source, modification of ramps due to

Ionization and energy spread arising from non-optimal beam loading are the biggest dangers.

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Conclusions 2

- Extreme beams open up new discovery opportunities

No dephasing until pump depletion

Ionization injection and downramp trapping to explore if ultra-low emittance beams can be generated.

This might be an easier route towards a first application.

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Conclusions 3

- More work is needed to explore 0.3 and 4 GeV injectors.
- 1-2 KA peak current seems too low to beam load the wake.
- Can these bunches be compressed more to increase the beam current to 7-8 KA?
- If yes then, we can explore emittance preservation down to 3 um but injection more difficult.

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