E-doubling with emittance preservation and pump depletion
Generation of Ultra-low Emittance Electrons
Testing a new concept for a novel positron source

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Outline of this talk

- First and second topics aligned with the DOE-HEP’s strategic plan.
- Third topic will strive to use the FACET II beam during the commissioning phase and beyond.
- What are the beam and plasma requirements, where are we, and what do we need to do to get there?

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

E-doubling with emittance preservation and pump depletion

- Deplete the drive beam of its energy
- 50% Energy drive (DB)-trailing bunch (TB)energy extraction efficiency
- 10 GeV energy gain for the TB
- Minimize the energy spread of TB
- 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: Generation of Ultra-low Emittance Electrons

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

- Localized ionization injection
- Downramp injection
- Colliding laser pulses inside a wake

3: A Novel Positron Source

- FACET II will initially have only electrons
- Sailboat chicane is in the future

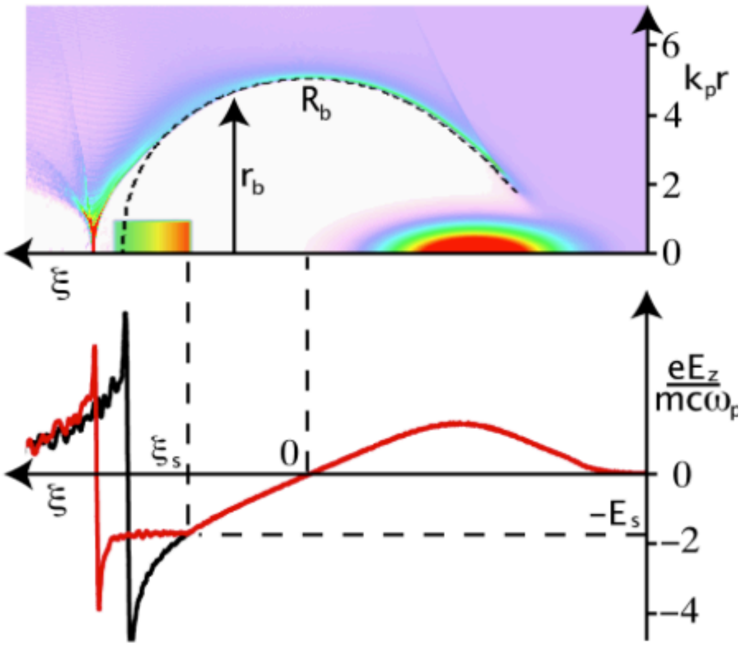
- Can we create a positron bunch and accelerate it on a wake produced by the electron beam?

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	50x200 um	< 3x7um (with diff. pumping)
Charge	<2 nC	<2 nC
Trailing Beam		
Bunch Charge	>100 pC	> 100 pC
Energy Spread	~5%	~ 1
Energy gain	max 8 GeV	10 GeV
Net Efficiency	30%	50%
Emittance Preservation	No	Yes?

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

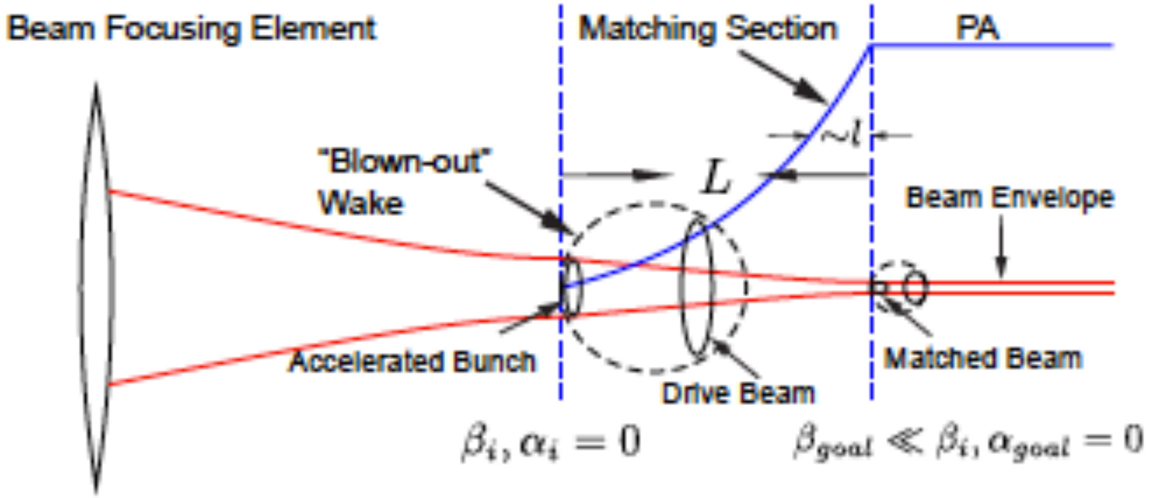
Two Key Concepts for high quality beams from plasma accelerators



Ref: M. Tzoufras et al PRL

Beam Loading

Energy Spread and Efficiency



Ref: X. Xu et al PRL 2015

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

Matching Section

Emittance Preservation

QuickPIC Simulation without ramps or ionization to optimize density, and D-T beam efficiency

Send a matched beam through preformed plasma

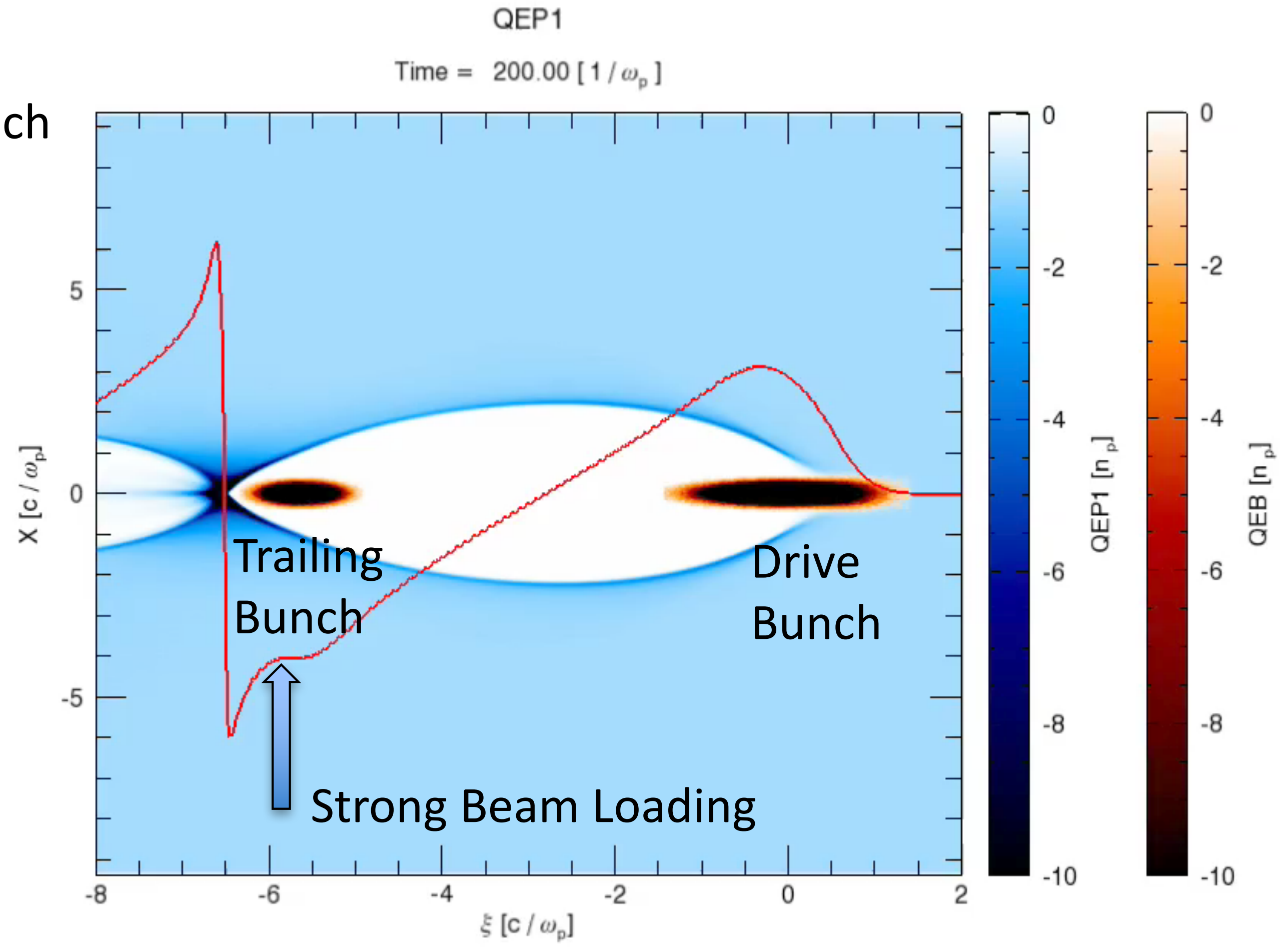
	Drive (Dr) Bu	Trailing (Tr) Bunch
γ(GeV)	10	10
I(kA)	15	7.5
ε_n (μm)	50	50
σ_z (μm)	14	8
σ_r (μm)	3.6	3.6

$\Delta\xi$ (μm) 150

Plasma Density 4×10^{16} cm^{-3}

Preformed plasma

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



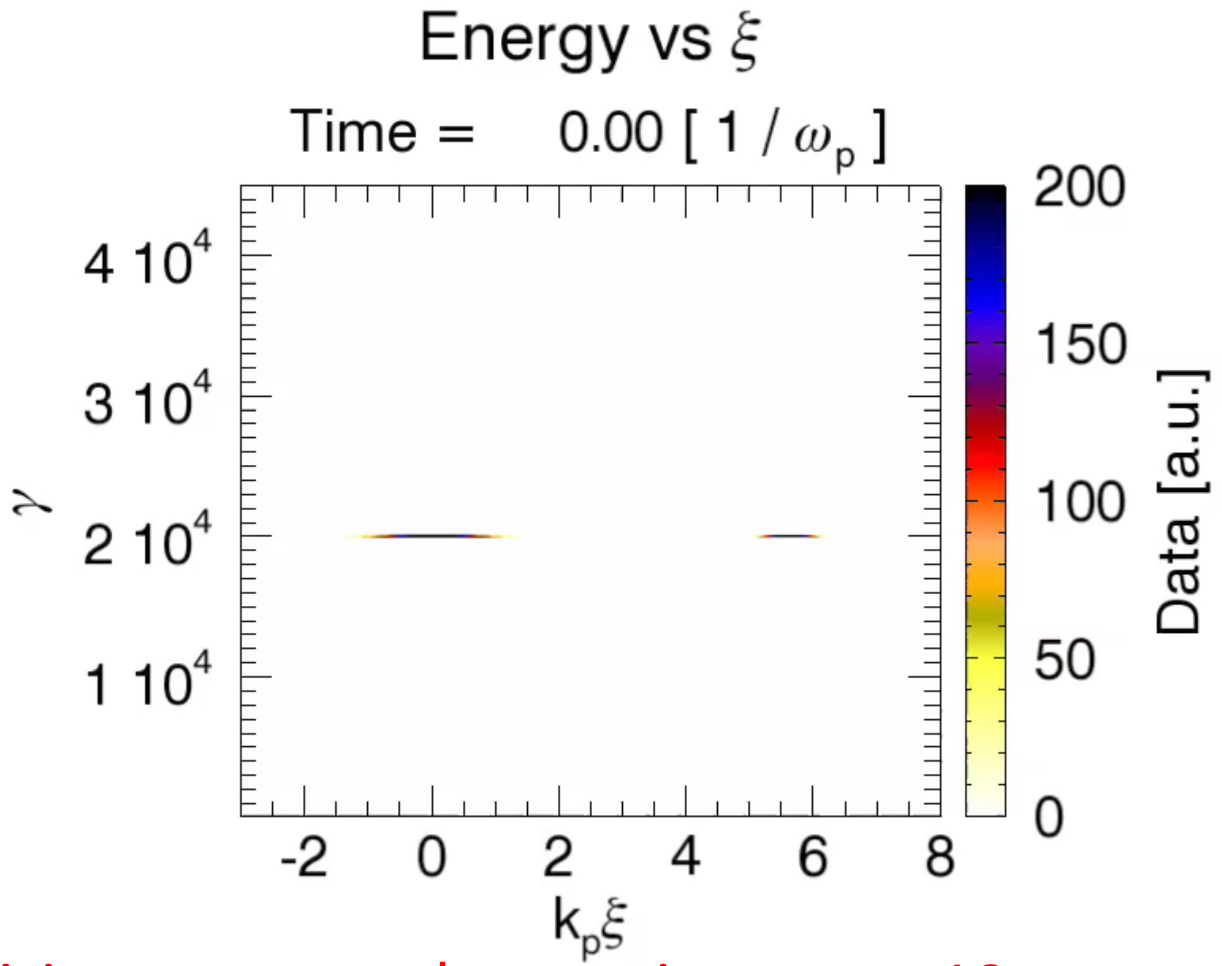
Trailing Bunch

Drive Bunch

Strong Beam Loading

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
Small energy spread



Looks extremely promising so now reduce emittance to 10um
and add ramps, ionization.
Ionization trapping may beam load the wake and reduce the TR

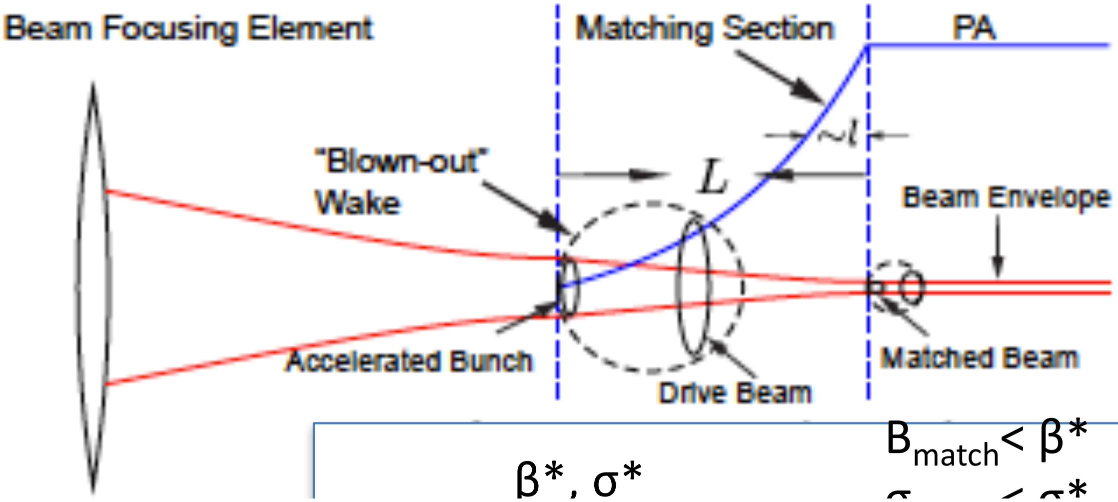
Numerical calculation of beam matching

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

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

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

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

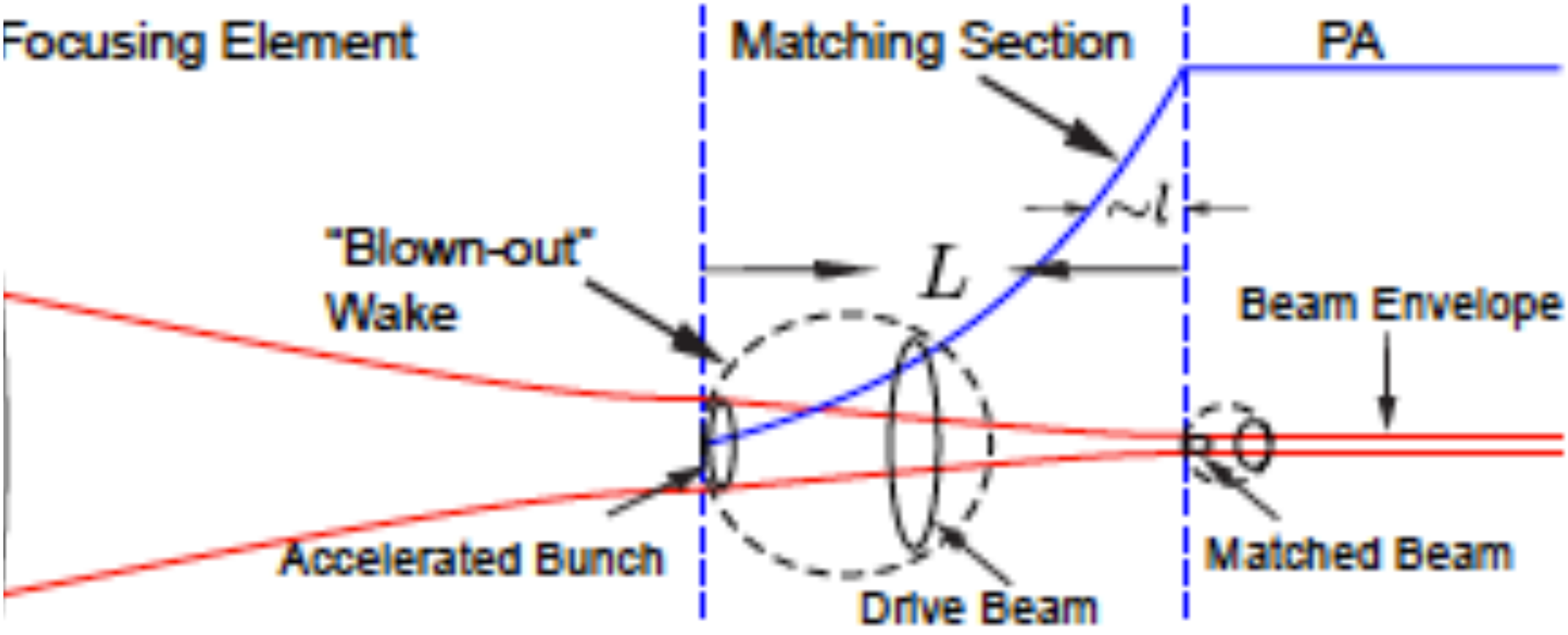


β^*, σ^*

$B_{match} < \beta^*$

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

Ref: Xinlu Xu PRL 2015



$(\sigma_{r,vac})^2 = (\sigma^*_{r,vac})^2 (1+ ((s-s^*_{vac})/ \beta^*_{vac})^2)$

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, 1.4 µm

10 GeV 20 GeV

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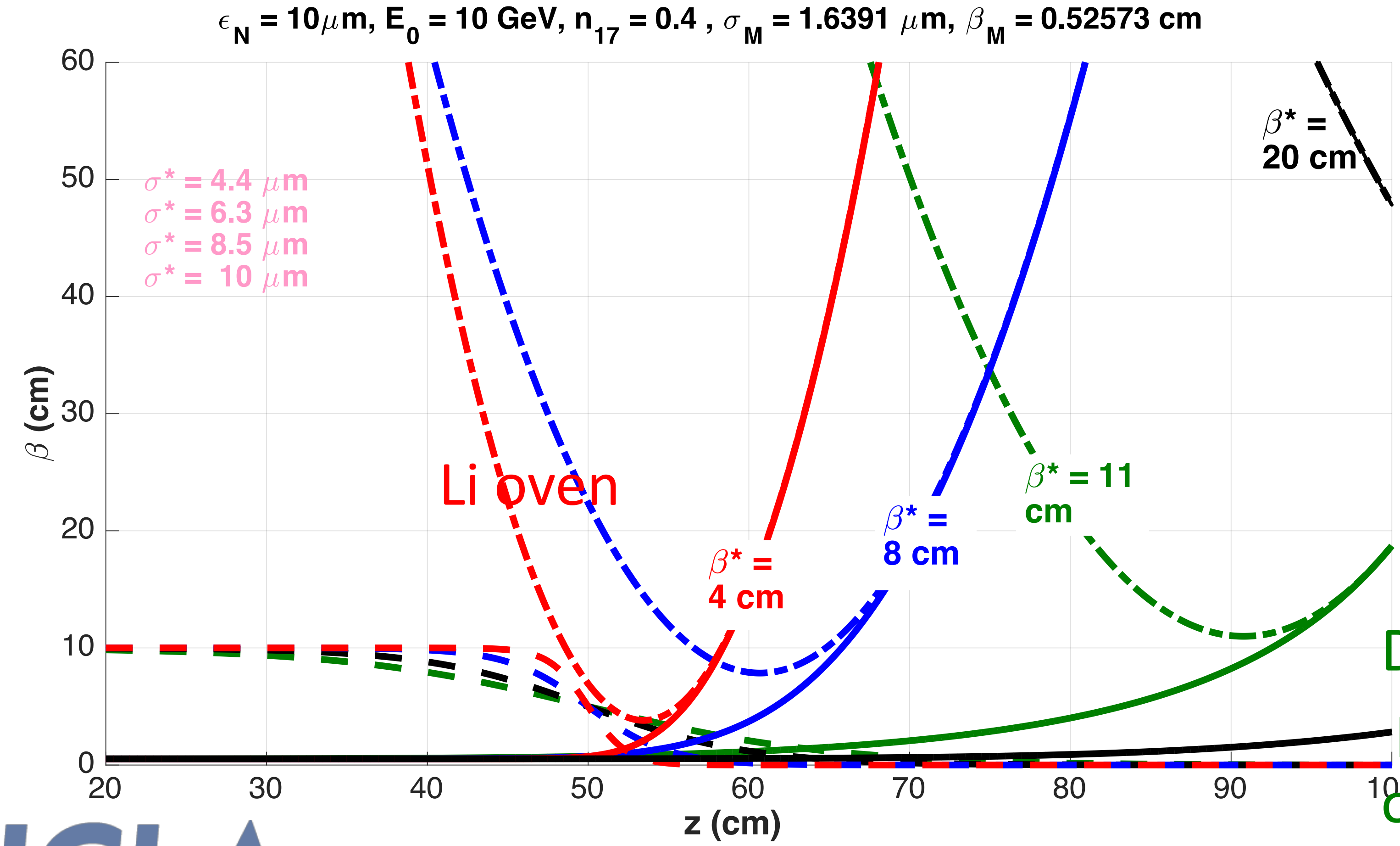
We can match to a variety of density profiles

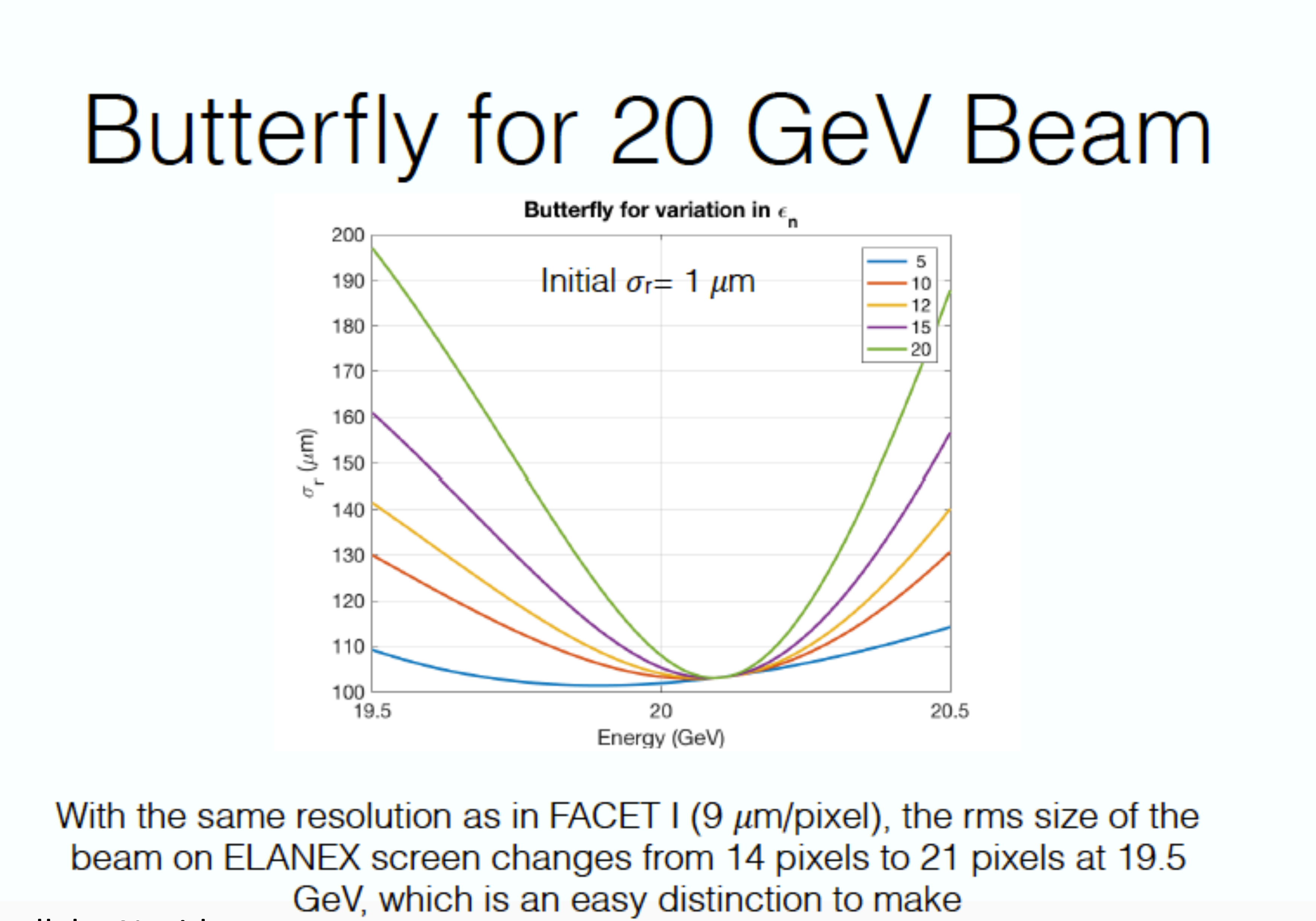
Summary: scale lengths L = {2.5, 5, 10,} cm
Key: dashed=n_e, solid=matched, dot-dash=vac.



Li oven

Differential pumped H2 cell
σ* ~ 10µm

We can measure 10s% changes in ε_m with existing setup (see Brendan and Nathan's talks)



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

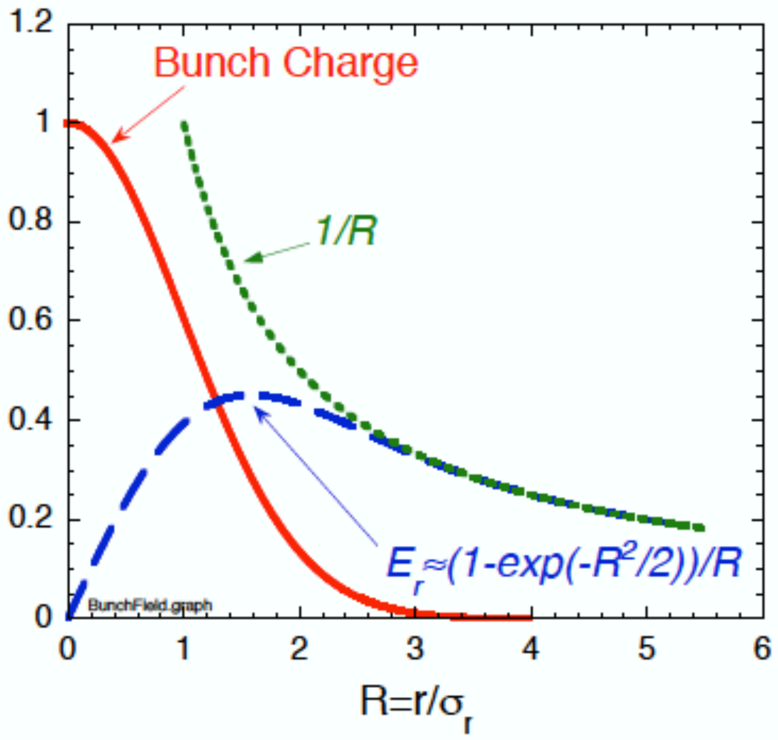
-Errors in the ramp density profile of the matching section from ideal.

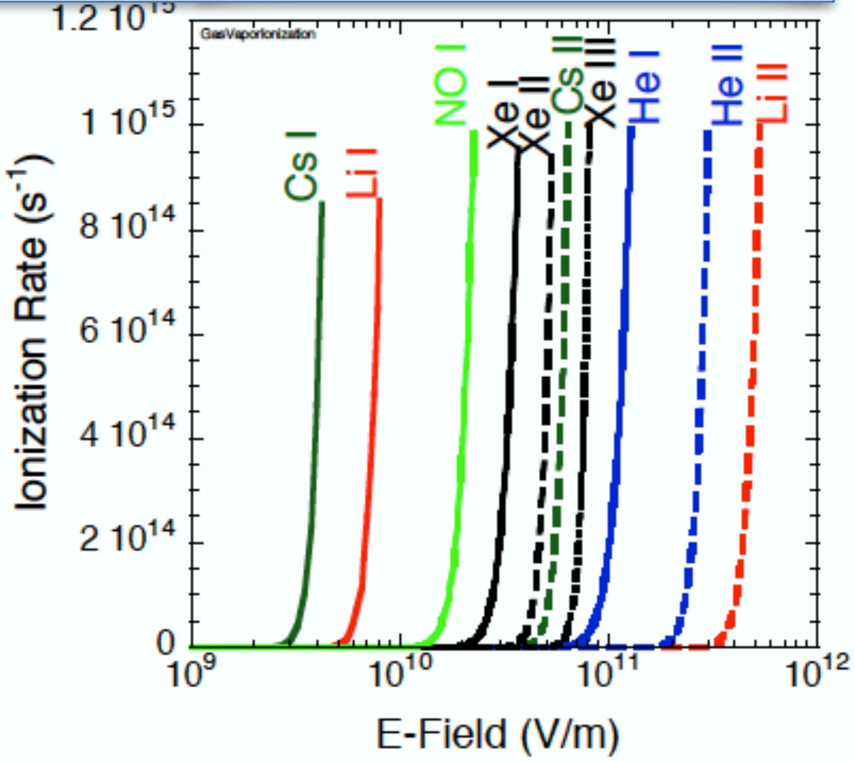
-The bunches have a finite energy spread, asymmetric emittance and complex phase space.

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

Ionization of He may beam load the wake

$$E_r^{\max} = 10.4 \left[\frac{\mathrm{GV}}{\mathrm{m}}\right]\frac{N}{10^{10}}\frac{10}{\sigma_r[\mu\mathrm{m}]}\frac{50}{\sigma_z[\mu\mathrm{m}]},$$





90 GeV/m, 300 GeV/m to avoid full ionization of He and He1+ resp.

Bur $E_{r,peak}$ ($\sigma^*_{matched}$= 1.6 μm and (σ_z= 15 μm)= 260 GeV/m

Ionization trapping and density ramp modification due to He ionization

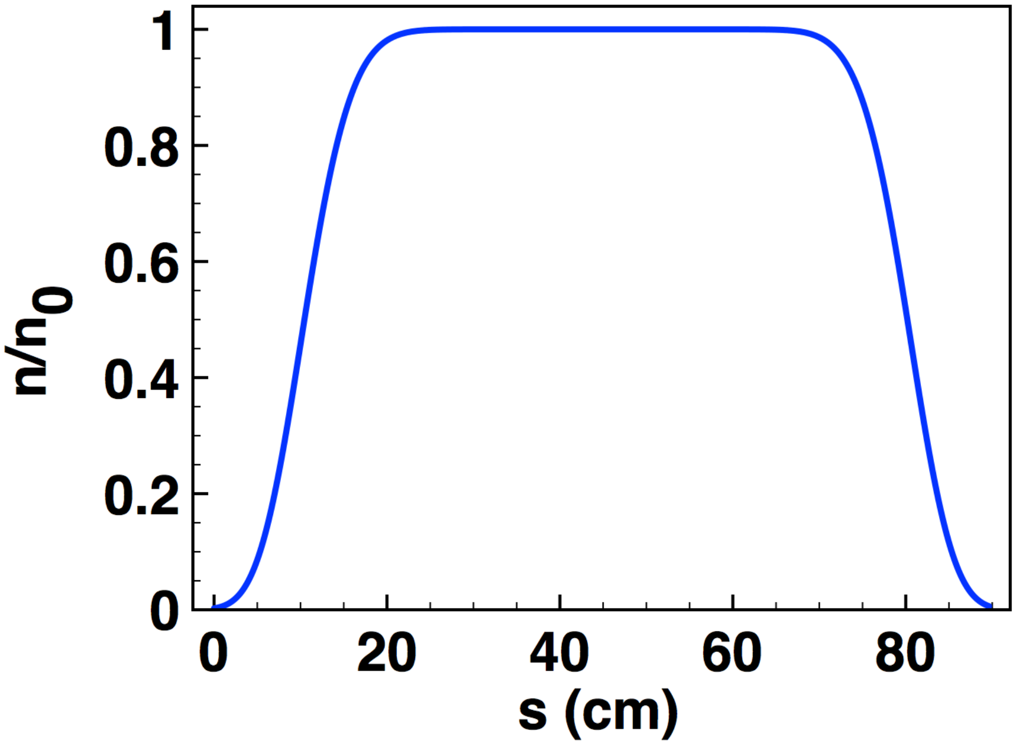
- He1+ ionized early on in the drive bunch and blown out
- He2+ ionized later but not trapped because beam loading by the trailing bunch reduced the pseudo-potential
- If we achieve the experimental parameters, He trapping does not occur
- The plasma ramp density profile does change and upsets the matching condition. May need to spoil the emittance of the drive beam such that the spot size is > 20 um to avoid He ionization.
- Ionization of He due to the trailing beam can increase the emittance by 20% .
- Hydrogen has no such problem.

Weiming An Private Communication

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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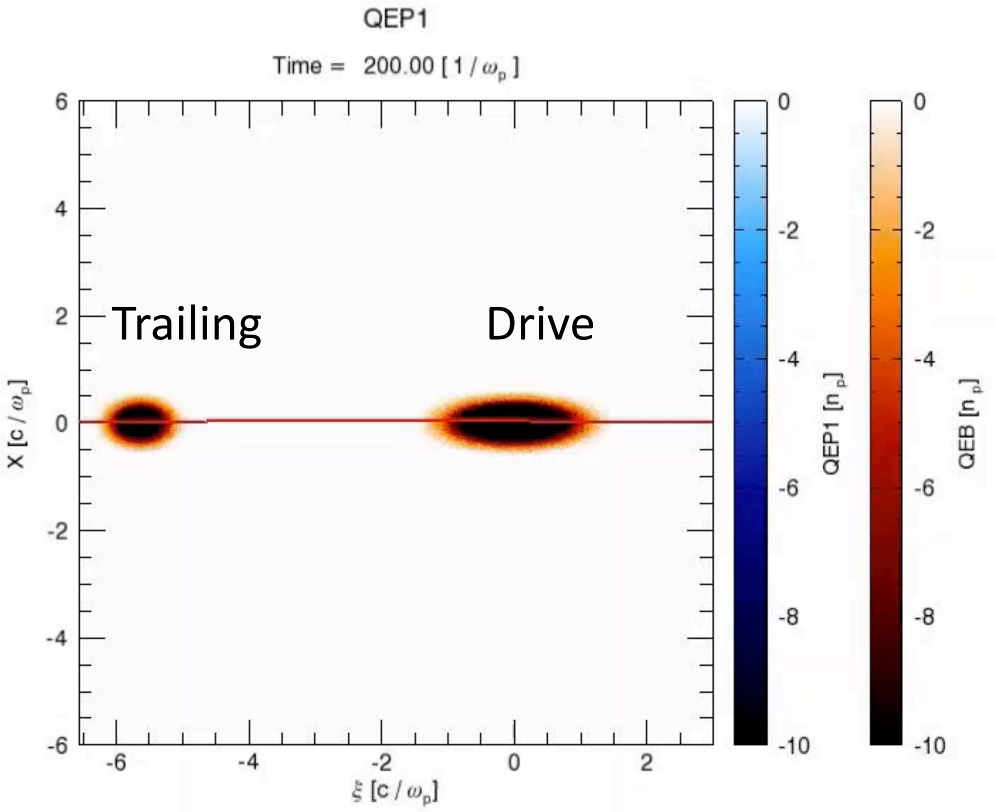
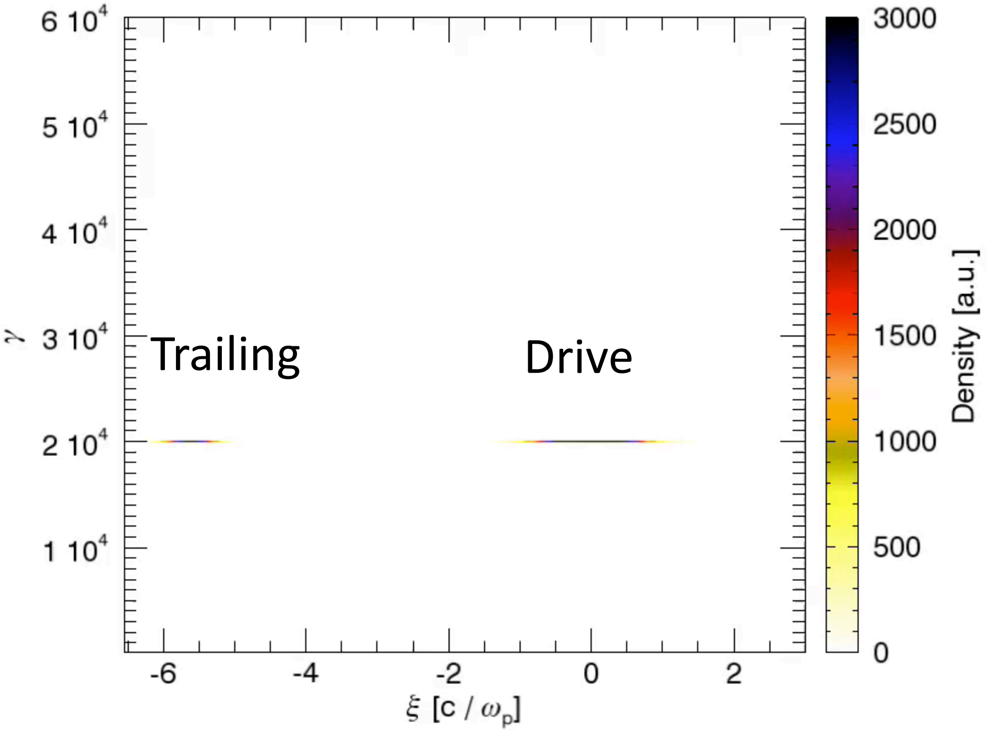
Beam and Plasma Density and Energy evolution

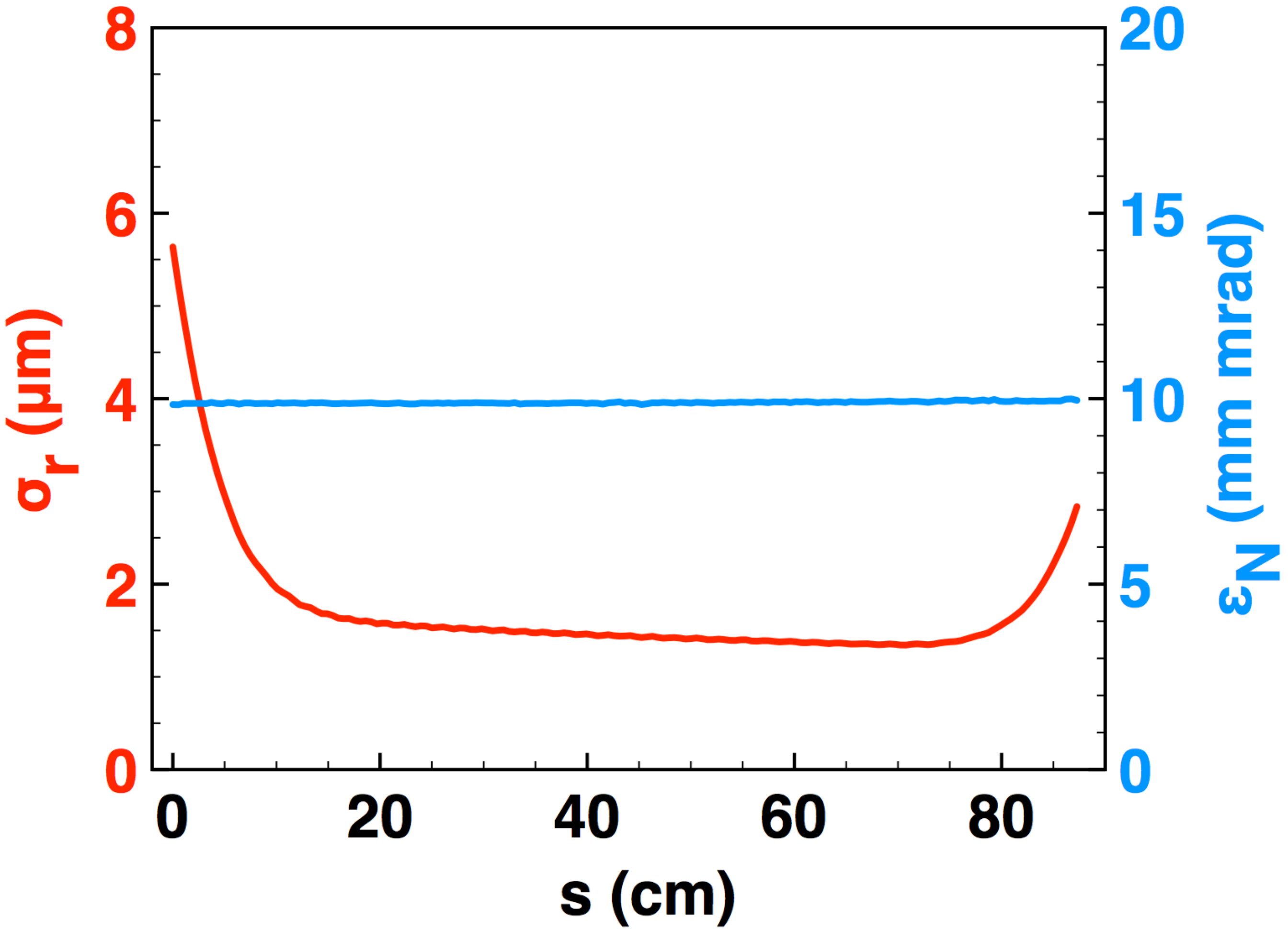
Plasma and beam density with on-axis Ez line out



Beam Energy



The projected beam spot size and emittance



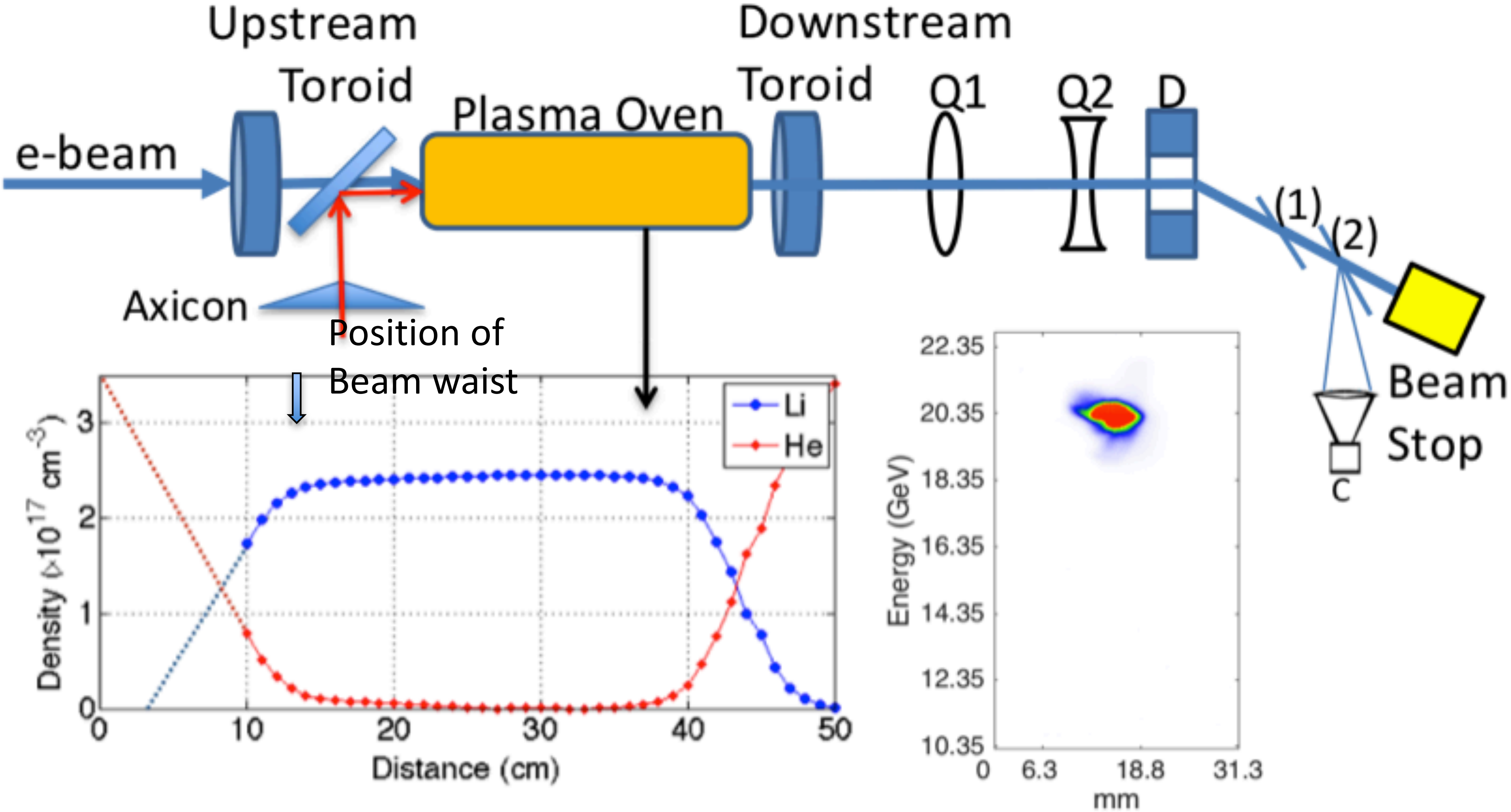
2: Generation of Ultra-low Emittance Electrons

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

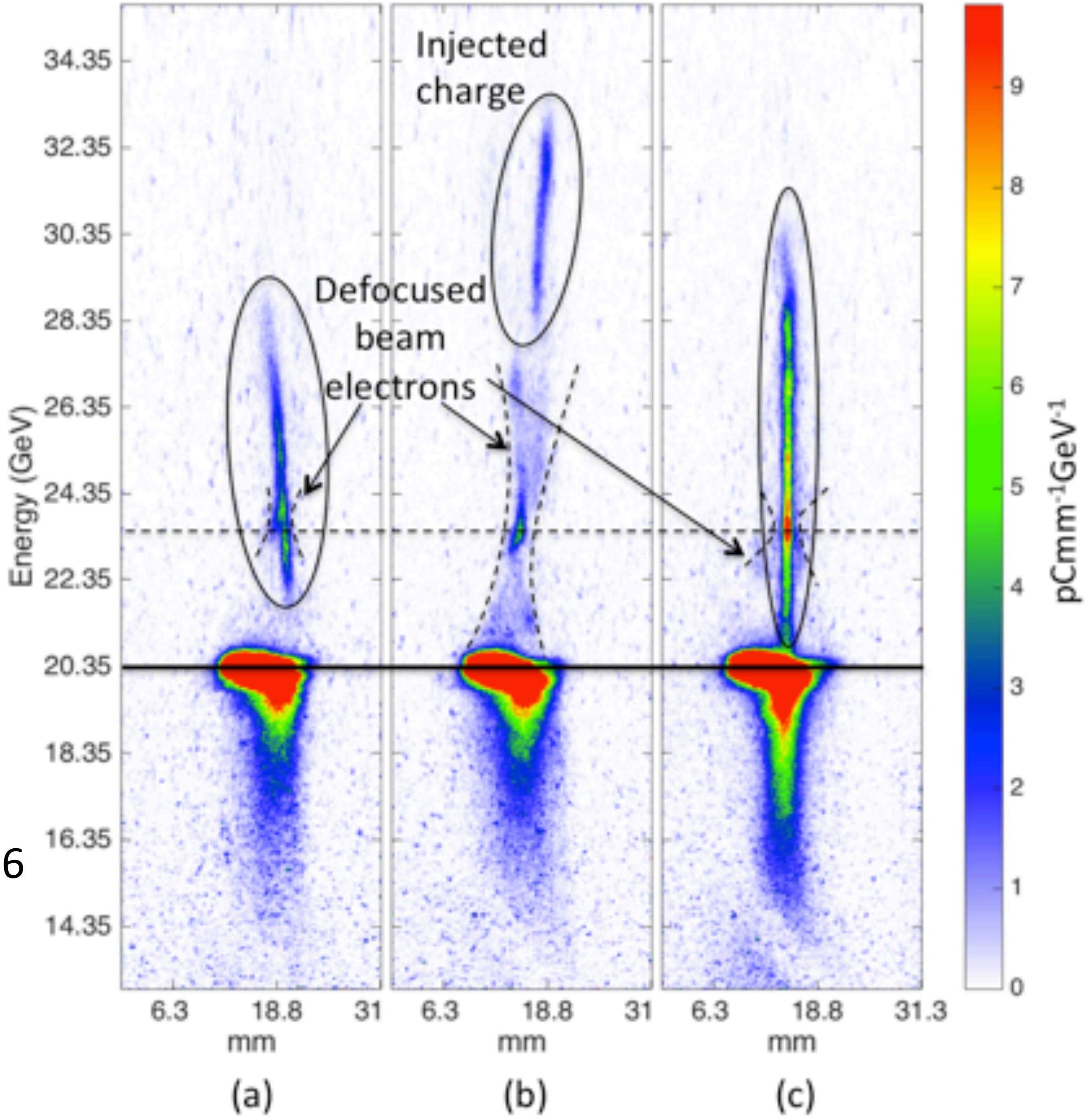
- Localized ionization injection
- Downramp injection
- Colliding laser pulses inside a wake

1) Localized Trapping of He Electrons in H wake

Ionization Injection of He Electrons in the Li plasma Wake

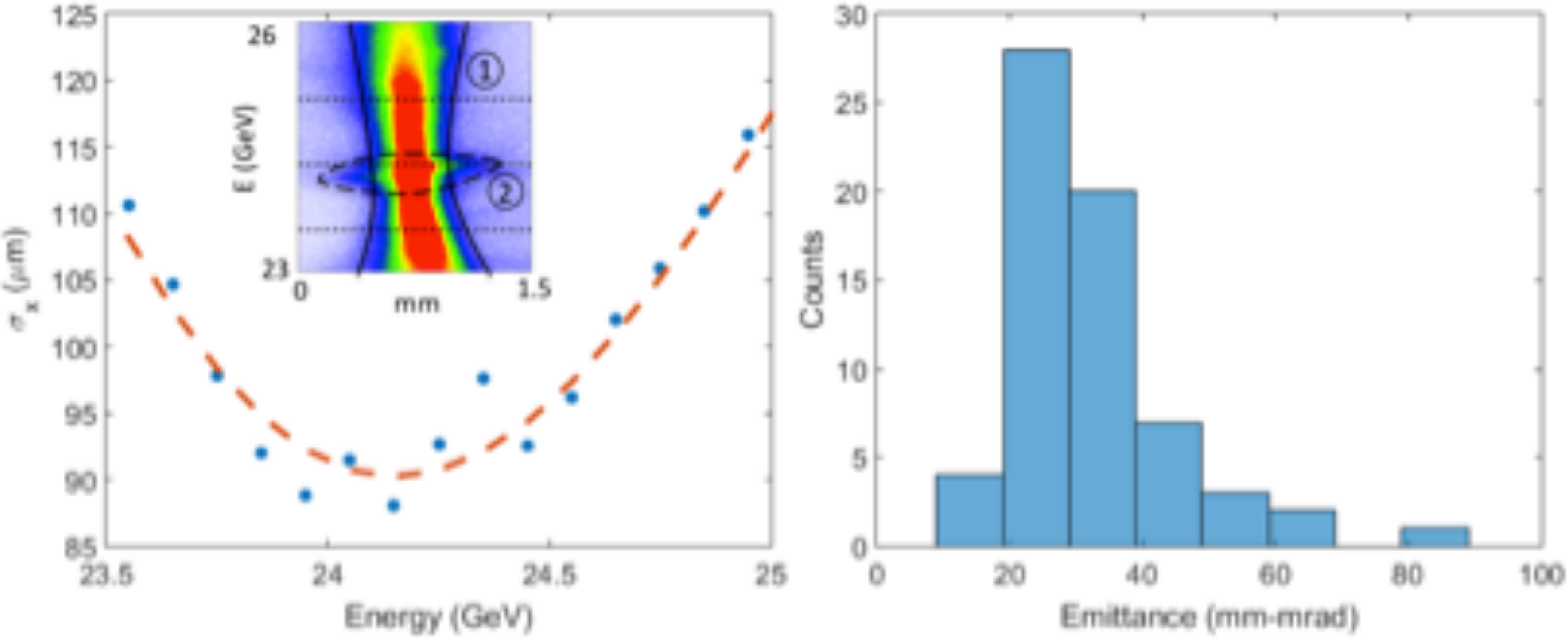


He Electrons were accelerated to > 30 GeV in 1 m



N. Vafaei et al PPCF 2016

Analysis of the beam size near the energy focus gives emittance



(a) (b)

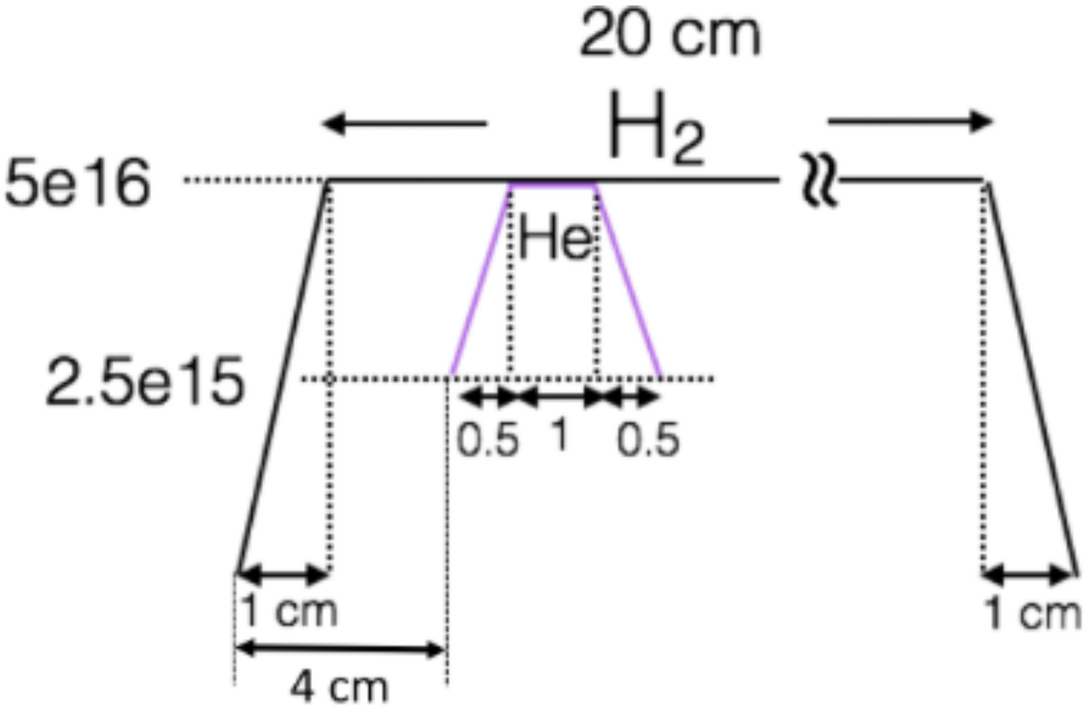
Reanalysis of this data shows emittance as small as 5um.
We need to be able to measure emittance down to 1 um or even less.

Talk here by Brendan O’Shea: here later this morning

Localized Trapping of He Electrons in H wake

Goal: To get narrower energy spread and smaller emittance

by restricting the ionization volume to one betatron pinch (see Navid's talk).



Tried this experiment on FACET,

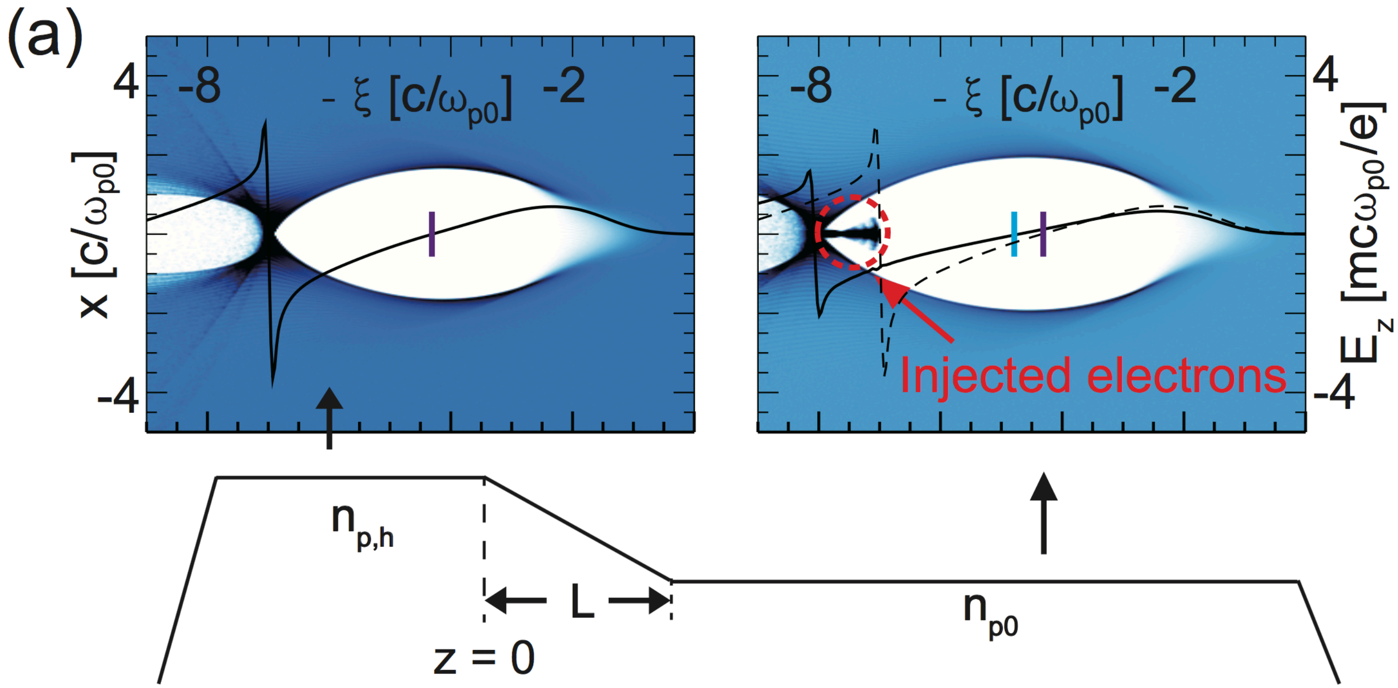
Beam quality too erratic to produce stable H plasmas

Ionization of He was seen but not reproducible to scan spectrometer focus

Ref: Navid Vafaei Najafabadi PhD thesis UCLA

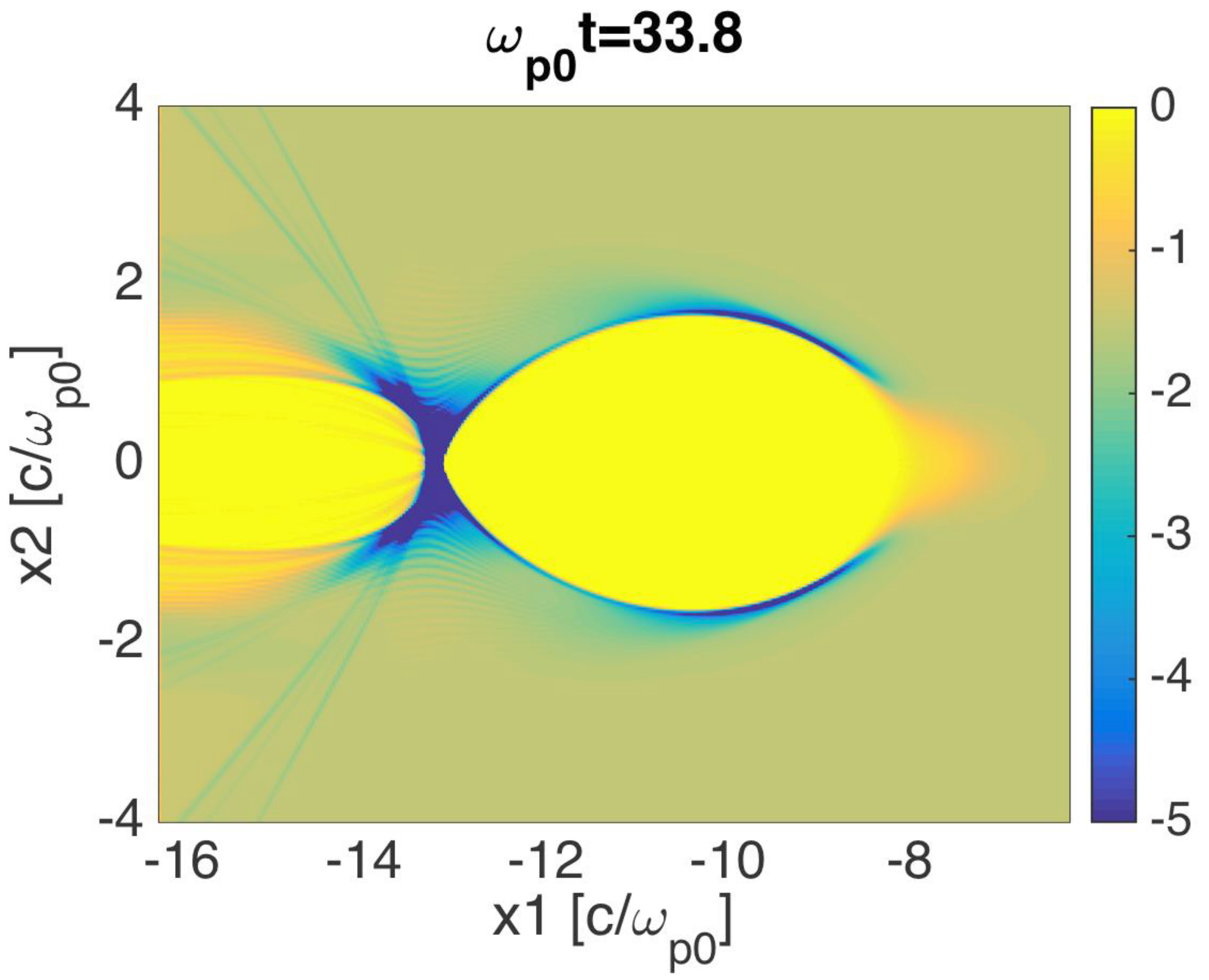
2)Downramp Injection

Talk on Thursday by Xinlu Xu

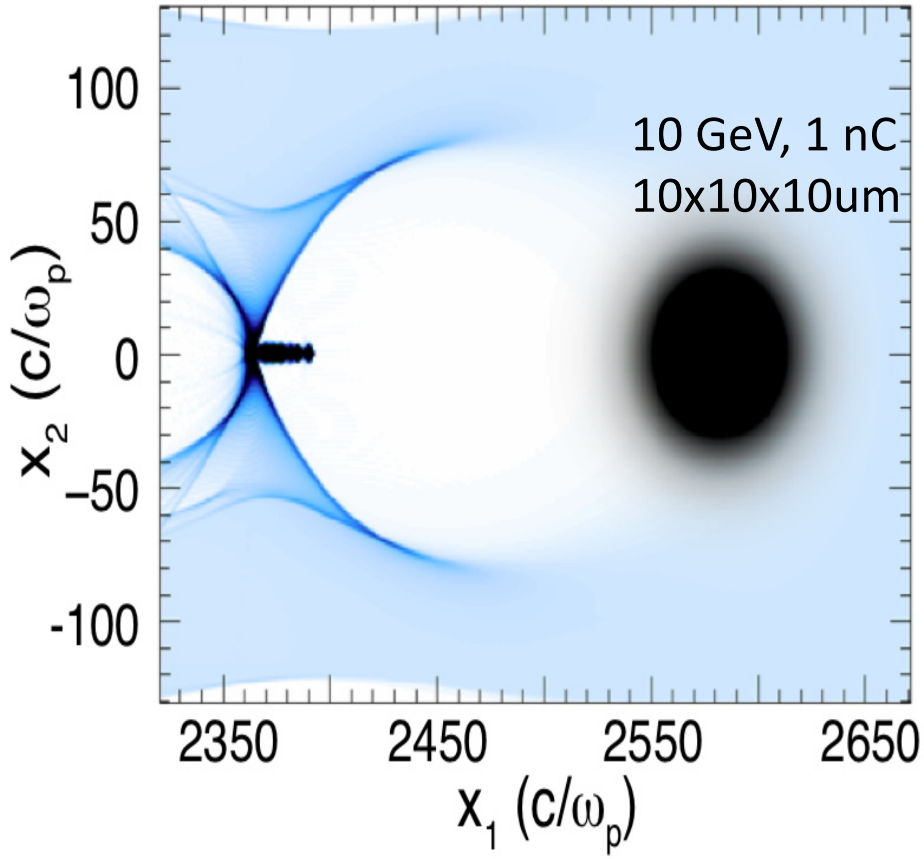


[1]T. Katsouleas, Phys. Rev. A 33, 2056 (1986); [2]S. Bulanov, et al., Phys. Rev. E 58, R5257 (1998); [3]H. Suk, et al., Phys. Rev. Lett. 86, 1011 (2001);

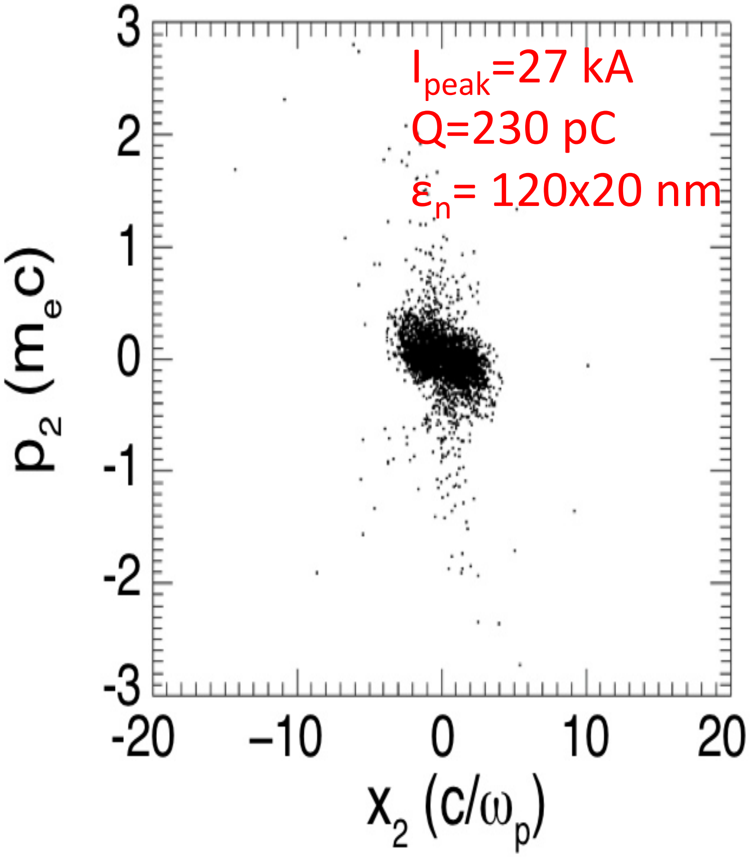
Downramp Injection; 3D PIC



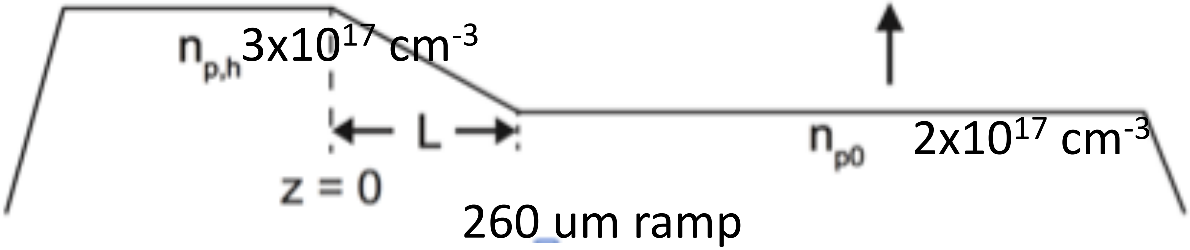
Results of 3D PIC simulations of Downramp Trapping



10 GeV, 1 nC
10x10x10um



I_{peak}=27 kA
Q=230 pC
ε_n= 120x20 nm



3×10^{17} cm^{-3}

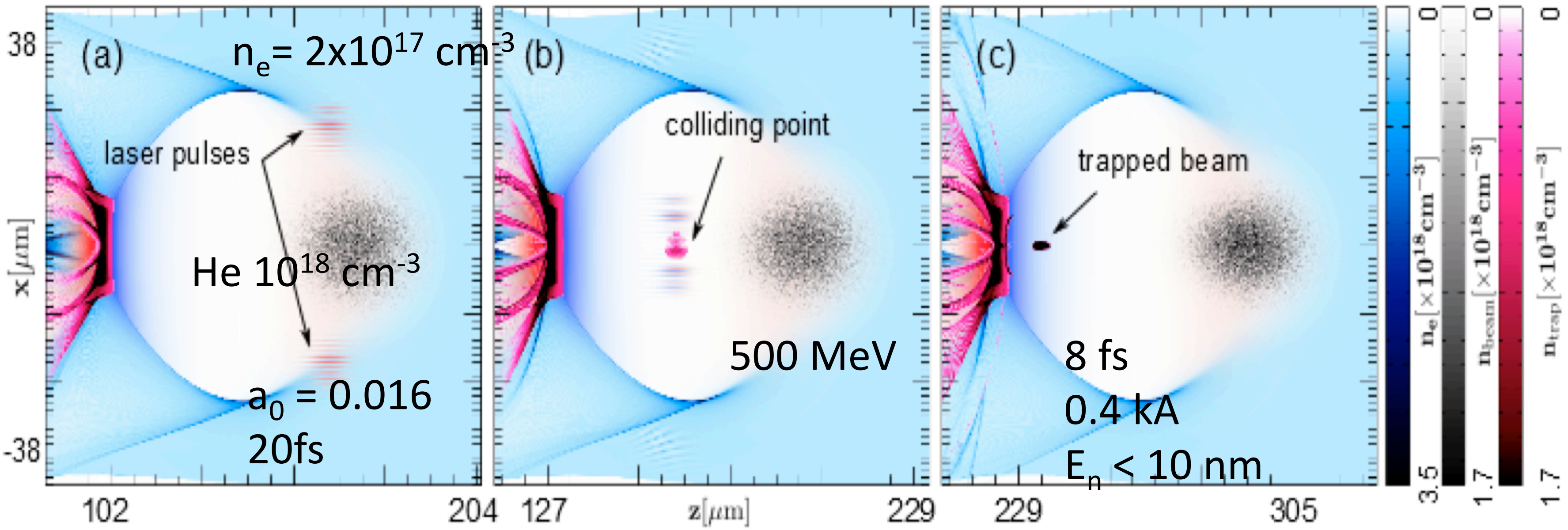
2×10^{17} cm^{-3}

260 um ramp

FACET II Design Report, From; F. Li and W. Lu; Also talk by Xinlu Xu here

3 Transverse Colliding Laser Pulses

F.Li et al PRL 2013



$n_e = 2\text{x}10^{17}\ \mathrm{cm}^{-3}$

He $10^{18}\ \mathrm{cm}^{-3}$

$a_0 = 0.016$
20fs

500 MeV

8 fs
0.4 kA
$E_n < 10$ nm

Variation of the ionization injection scheme
Two extremely tightly focussed , ultrashort laser pulse minimize the volume of ionization
The peak intensity at the peak of the interference pattern just exceeds ionization threshold
Electrons injected into the wake with small residual momentum in the longitudinal direction
Transverse emitance of the electrons is expected to be sub 100nm.

3 Positron Acceleration on an Electron Bunch-produced Wake: Poor man's sailboat chicane

Positron bunches will not be available at FACET II for some time

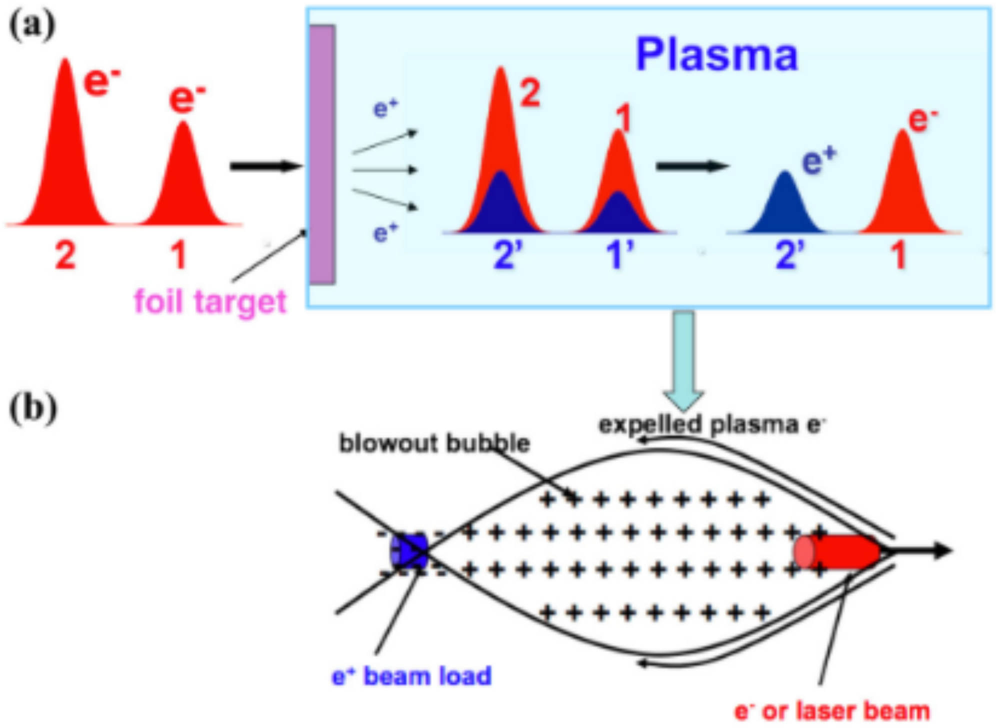
Can we produce a positron test beam (10 pC), 10-100 MeV for injection into electron Beam-driven wakes?

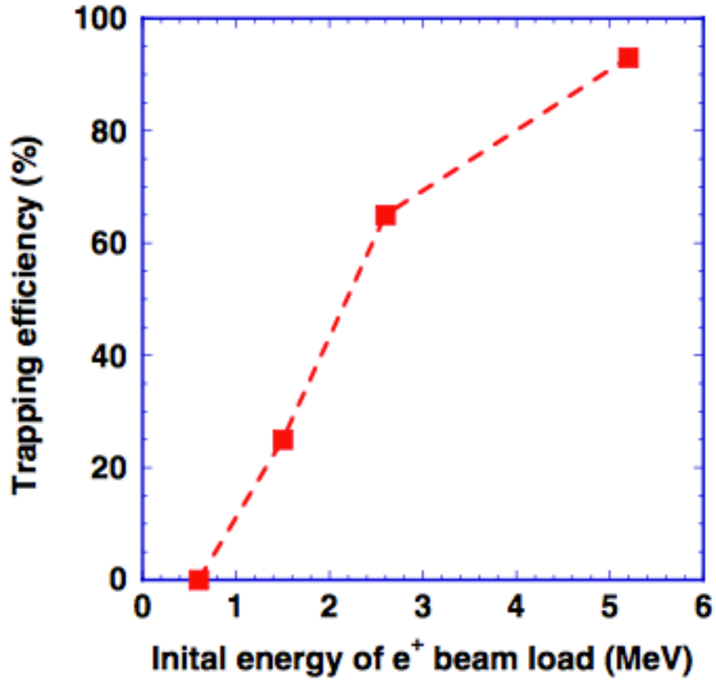
Can we test both linear and nonlinear regime of PWFA for positron acceleration?

Can we do this during the commissioning phase of FACET II

Answer: We can!!

In Situ Generation of Positrons and Acceleration in an Electron Beam Driven PWFA





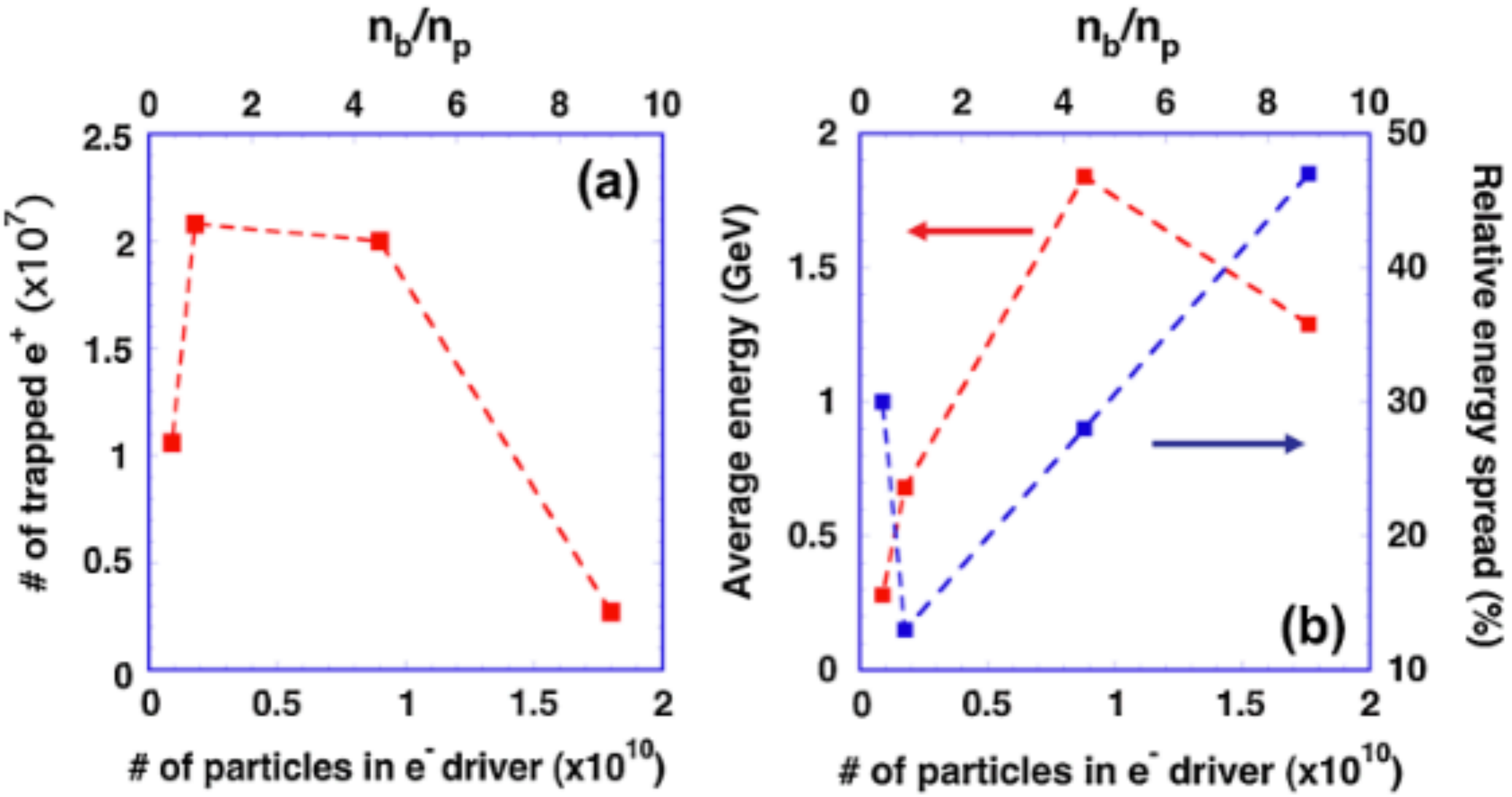
Double electron bunch format is incident on a high Z foil target (Ta)

Produces positrons from real and virtual photons with identical temporal structure but different energies and emittances.

The resultant electron and positron bunches enter the plasma where the excess electrons in the drive pulse excite either a linear or a nonlinear wake

With appropriate plasma density e- in the second bunch are blown out, e+ are accelerated.

For FACET II Conditions Possible to get a few pC, GeV class e⁺ beam



The drive bunch need not be ultra-low emittance
Perfect for the commissioning phase
Could use Rb oven with a Ta insert for e+ generation followed by acceleration

Ref: X. Wang et al P.R.L. 2008, PRSTAB 2009

Conclusions

- FACET II will enable an exciting PWFA program

- Pump depletion
- 10 GeV energy gain per stage
- Emittance preservation and mechanisms that degrade the emittance
- Ultra bright beam generation
- In situ positron generation and acceleration
- Extremely rich discovery science yet to be done in PWFA

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

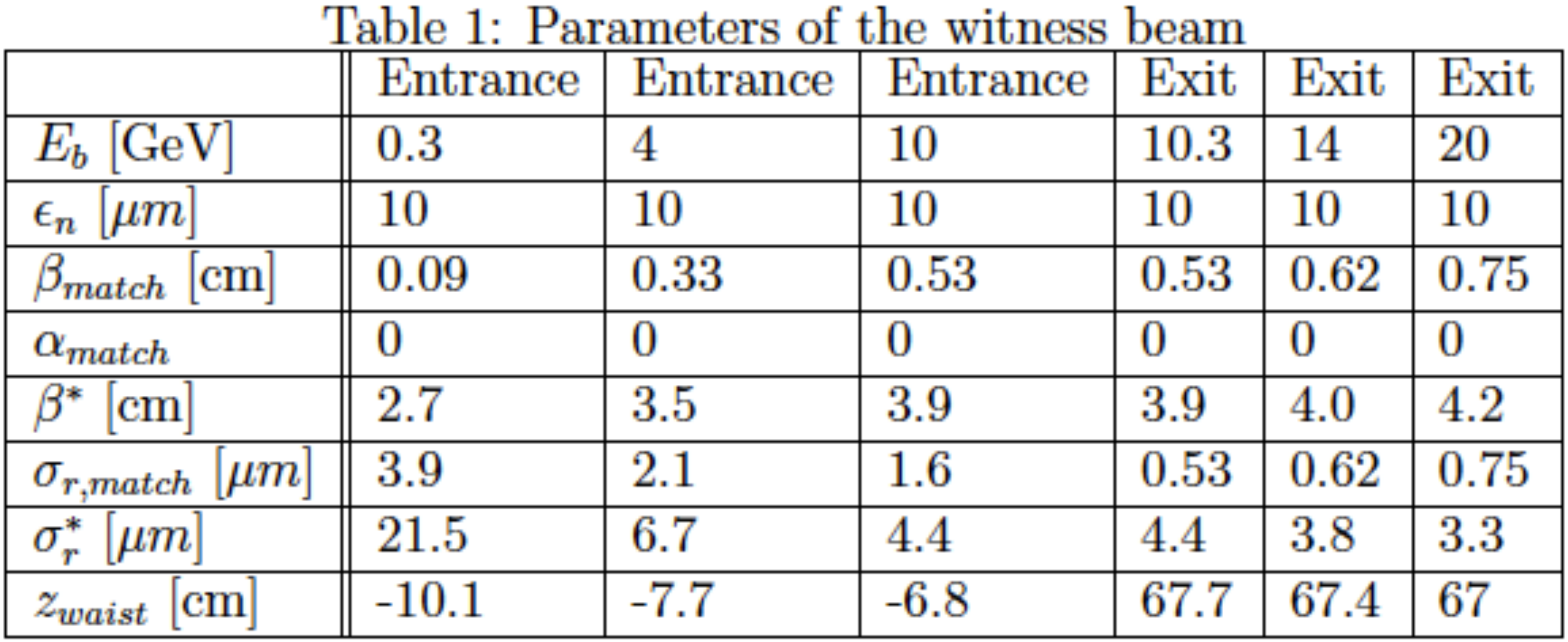


Table 1: Parameters of the witness beam

	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