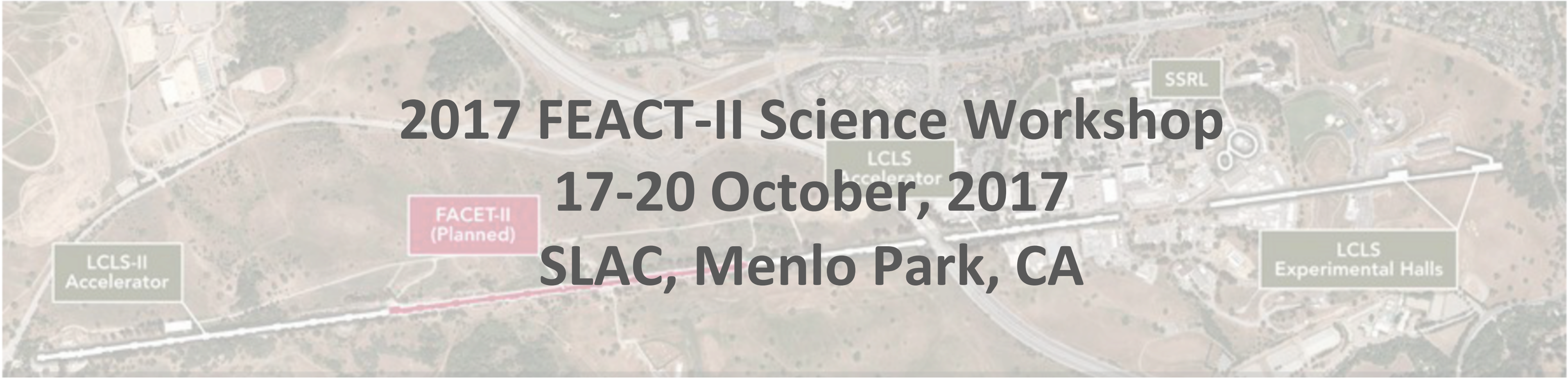

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SLAC, Menlo Park, CA

High quality beam generation in density downramp injection and its early applications

Xinlu Xu, Thamine Dalichaouch, Weiming An, Shiyu Zhou, Fei Li, Wei Lu, Mark Hogan, Chan Joshi and Warren Mori

UCLA/SLAC/THU
10/19/2017

Outline

- Introduction
- Physics behind density downramp injection
  - ➢ Injection process
  - ➢ How this injection process leads to low emittance?
    - \- Transverse deceleration process
  - ➢ How this leads to low energy spread?
    - low slice energy spread − break the longitudinal phase mixing
    - low projected energy spread - remove the initial energy chirp
  - ➢ Scaling law and X-FEL simulations
- Conclusions

Introduction

- High quality beam generation in plasma wakefield accelerators

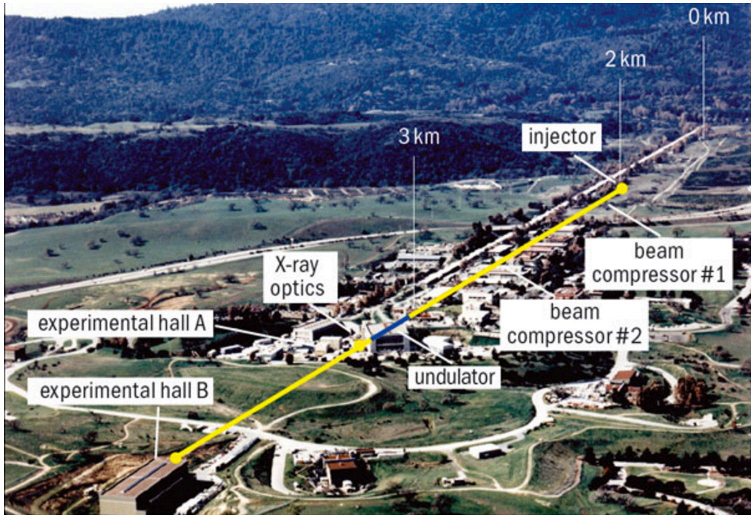
➢ emittance
➢ current
} 5D Brightness $B = \frac{2I}{\epsilon_{n,x}\epsilon_{n,y}}$

➢ energy spread (slice and projected)

X-FEL at LCLS[1]:

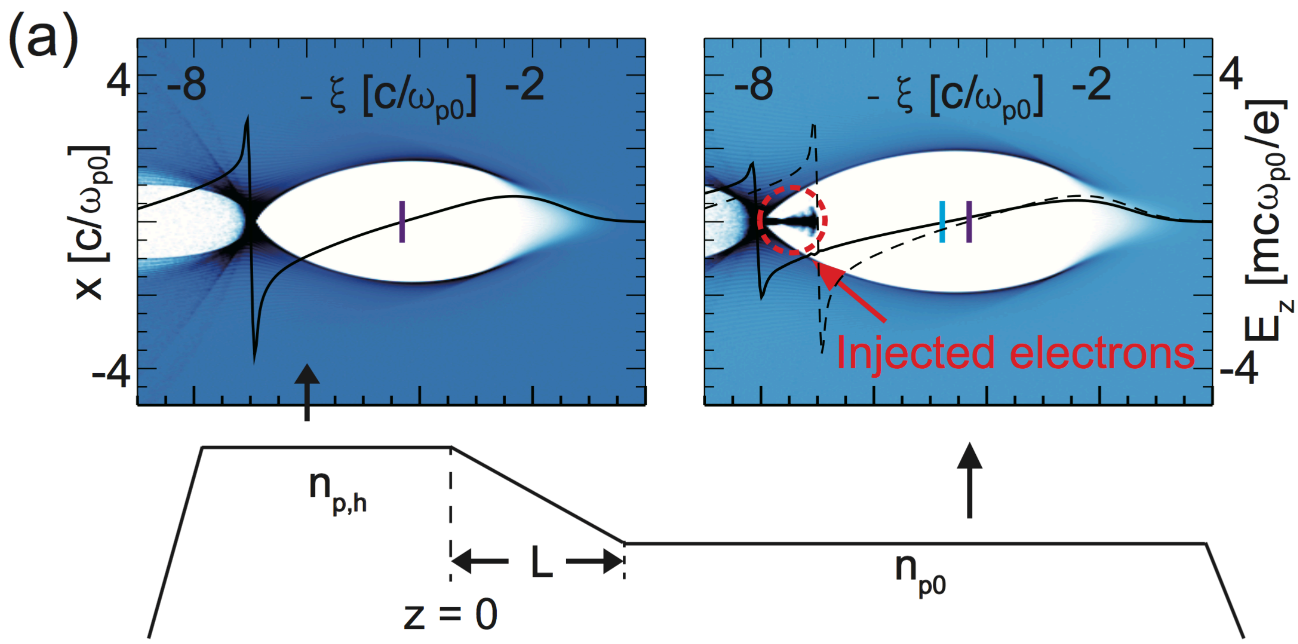
$$\sim 0.4 \times 10^{17} \mathrm{A/m^2/rad^2}$$

$$\sigma_\gamma/\gamma < \rho \sim 0.001$$



[1]P. Emma et al., Nature Photonics 4, 641-647 (2010).

Introduction – Downramp Injection



- S. Bulanov[2] et al. (1998), and H. Suk[3] et al. (2001) studied the injection process using **1D** analysis.

[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);

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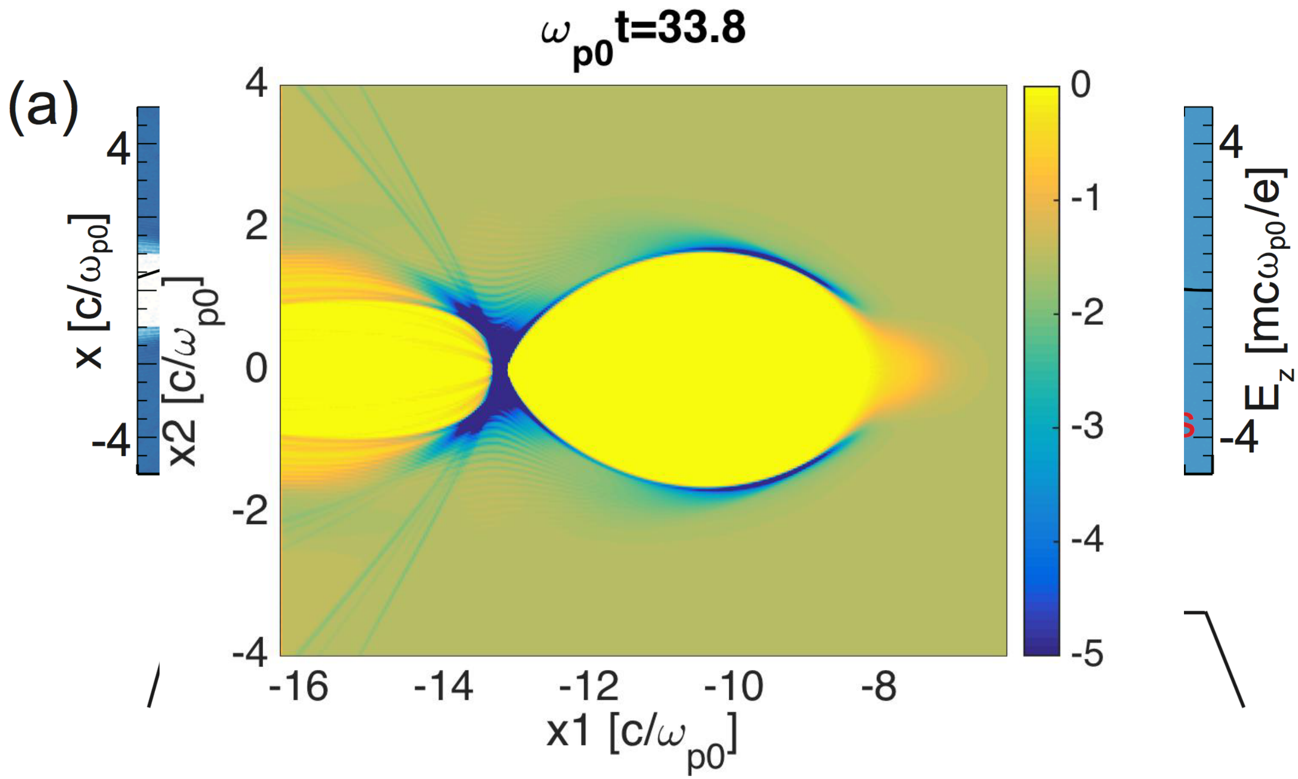

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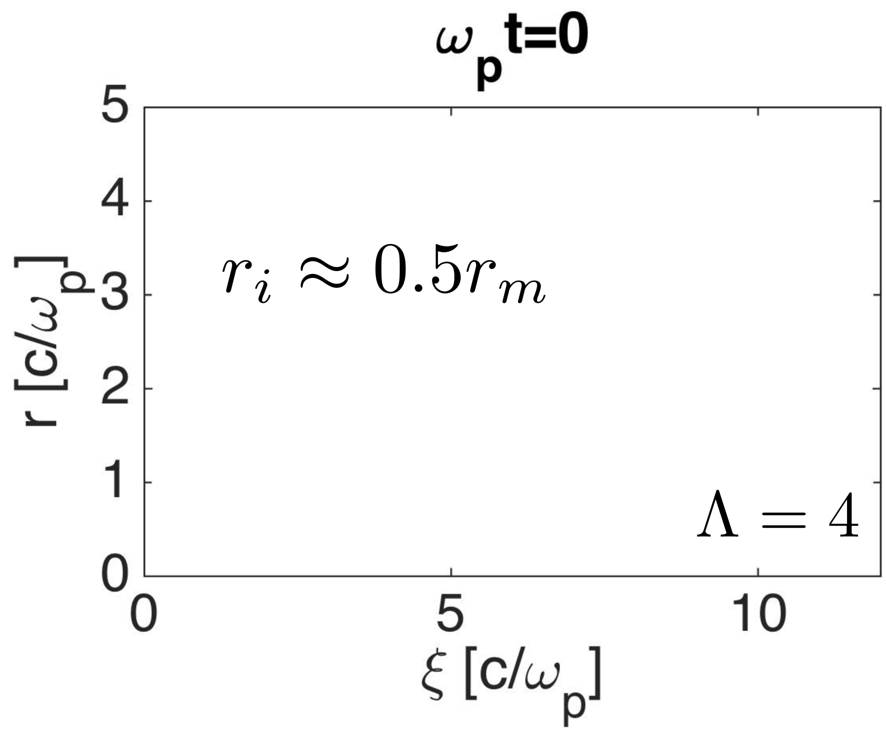
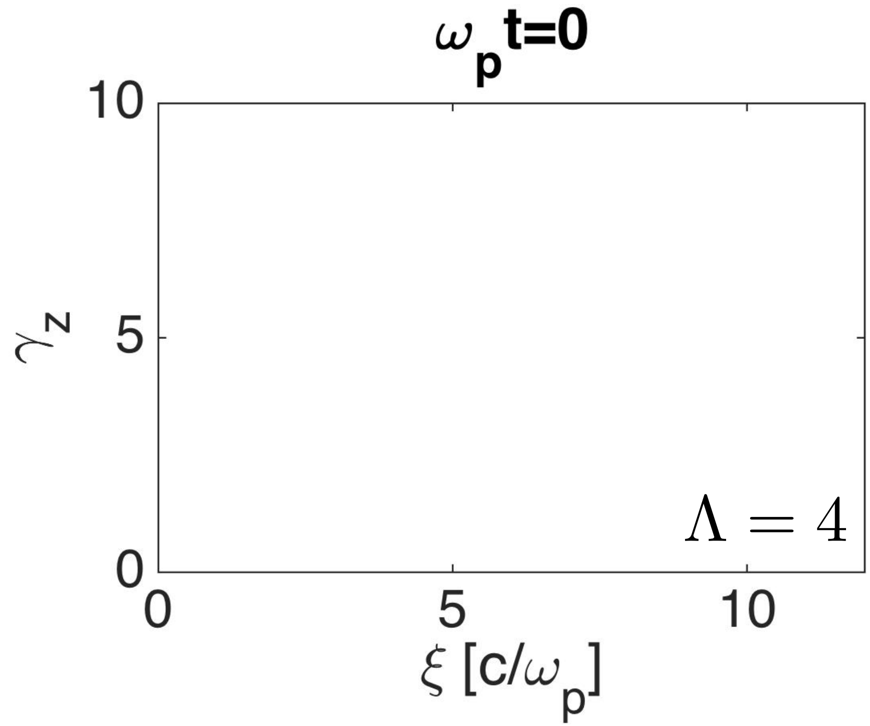
The particle velocity β_z

Injection Condition: $\beta_z \geq \beta_{ph}$





The particle velocity β_z

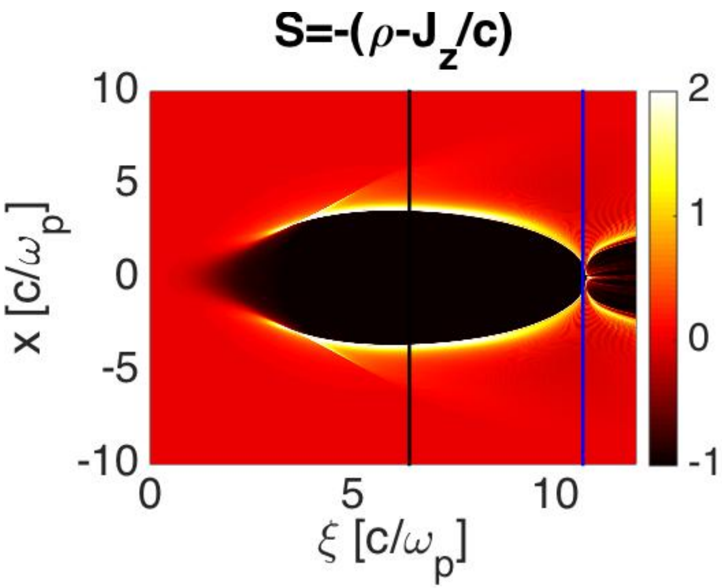
$$\beta_z = 1 - \frac{2(1+\psi)}{1 + p_\perp^2 + (1+\psi)^2}$$

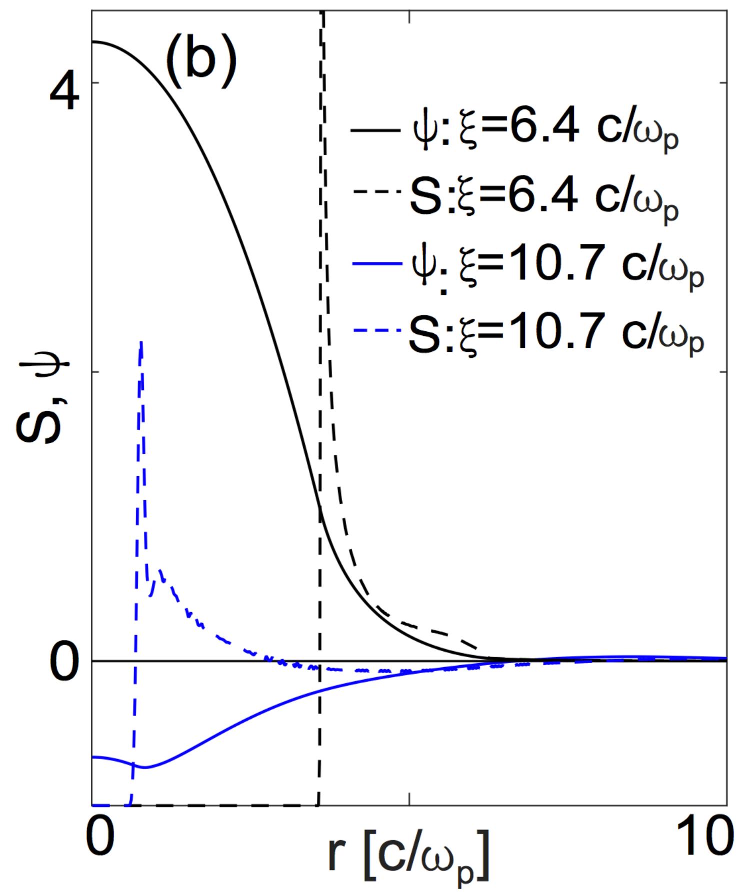
large $p_\perp$

or ψ is close to -1

The Possion-like Equation

$$\nabla_\perp^2 \psi = S \equiv -(\rho - J_z/c)$$





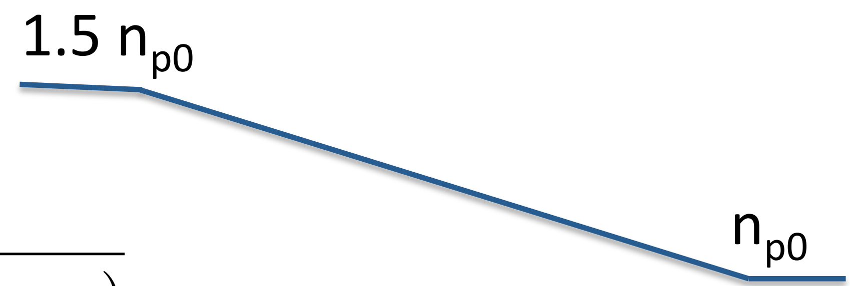
P. Mora and T. M. Antonsen Jr, Physics of Plasma 4, 217 (1997); W. Lu et al., PRL 96, 165002 (2006)

The phase velocity β_{ph}

- For a plasma wake

$$\phi(z,t) = \omega_p(z)(z/v_d - t)$$

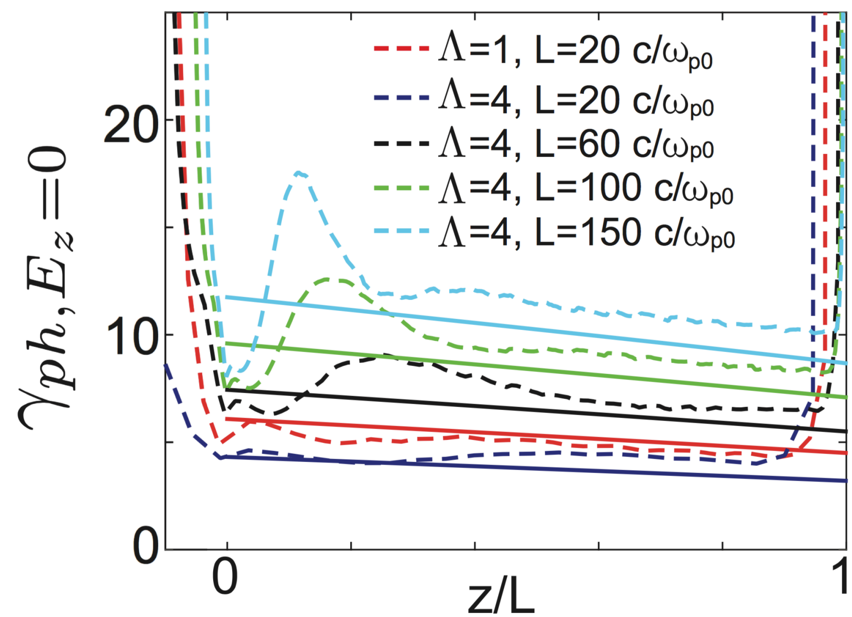
$$v_{ph}(z,t) = \frac{v_d}{1-(\mathrm{d}\omega_p/\mathrm{d}z)\omega_p^{-1}(v_d t - z)}$$



For the tail of the nonlinear wake[1],

$$v_{ph} \approx v_d\left(1 - 4\sqrt{\Lambda}\frac{\mathrm{d}\omega_p^{-1}}{\mathrm{d}z}\right)$$

$$\gamma_\phi \approx \left(8\sqrt{\Lambda}\frac{\mathrm{d}\omega_p^{-1}}{\mathrm{d}z}\right)^{-1/2}$$



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Transverse Deceleration

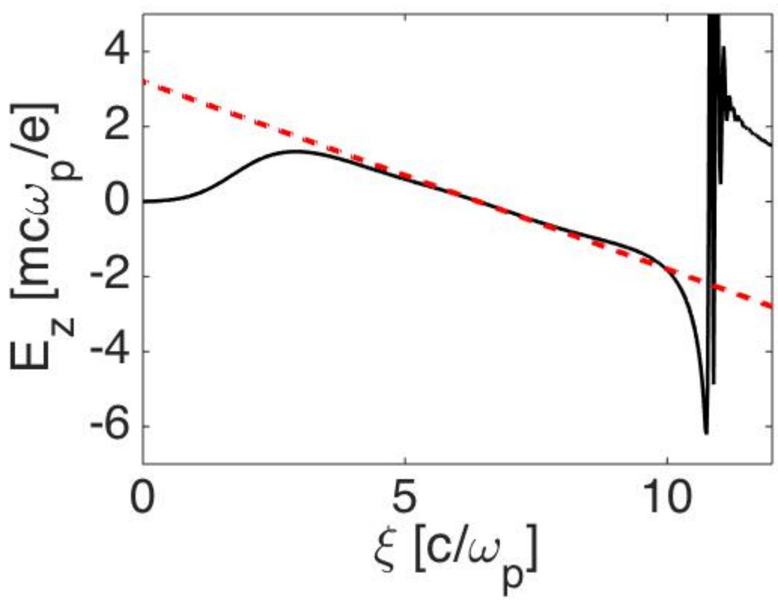
- The transverse force on the “sheath” plasma electrons

$$F_r = F_d + F_i + F_e$$

where $F_d = (1-\beta_z)\lambda(\xi)/r$ is from the driver --------- D

$F_i = -r/2$ is from the ion cavity --------- F

$F_e = -(r/2)(1-\beta_z)\mathrm{d}E_z/\mathrm{d}\xi$ is from the plasma electrons. -- D



In most of the wake,

$$\frac{\mathrm{d}^2\psi_0}{\mathrm{d}\xi^2} = \frac{\mathrm{d}E_z}{\mathrm{d}\xi} = -\frac{1}{2}$$

At the very rear of the wake,

$$\left|\frac{\mathrm{d}^2\psi_0}{\mathrm{d}\xi^2}\right| \gg 1$$

W. Lu et al., PRL 96, 165002 (2006)

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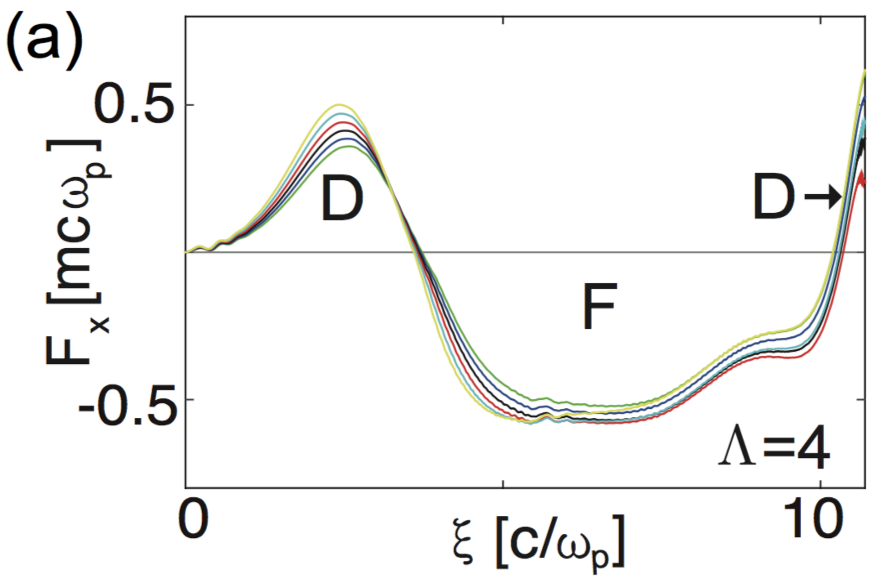
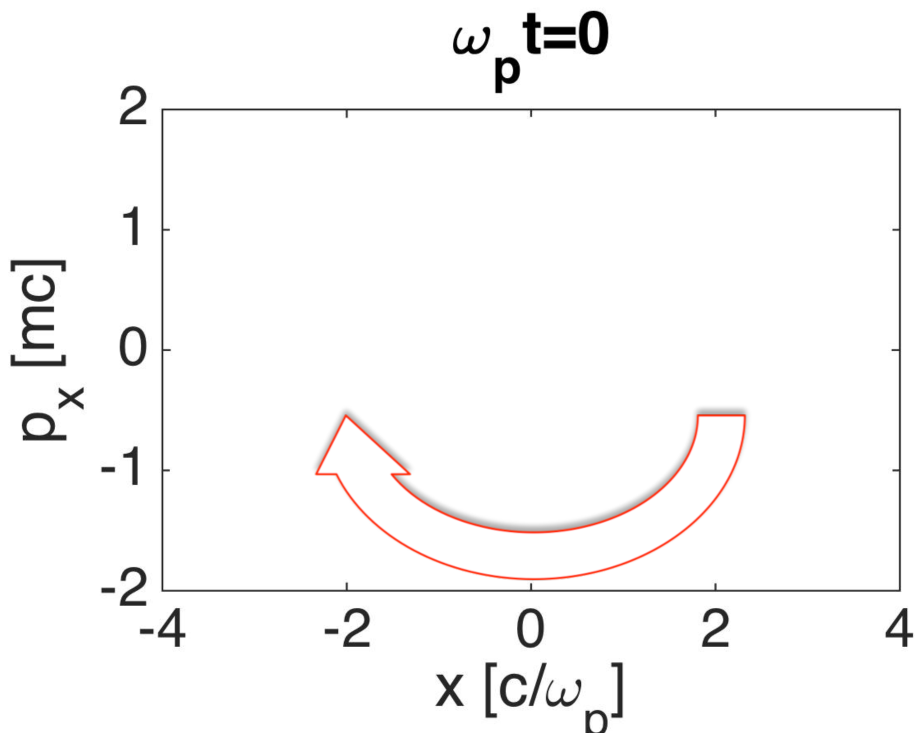
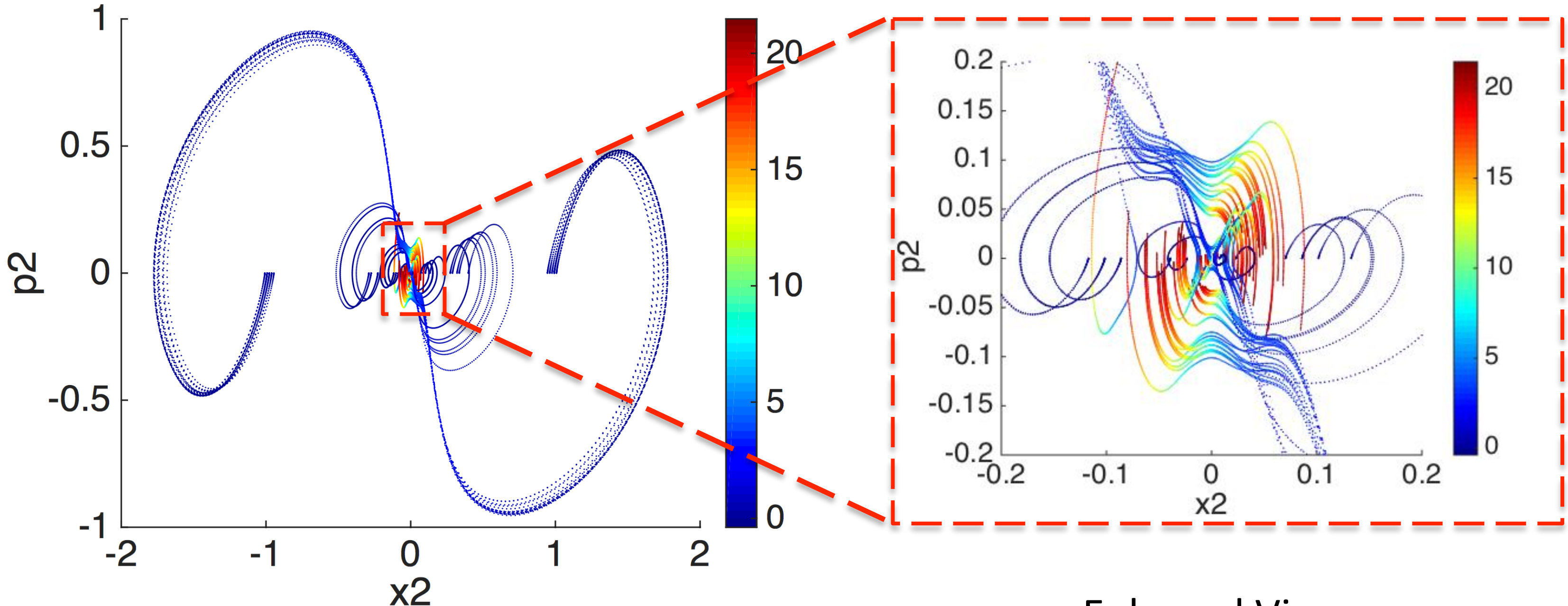




W. Lu et al., PRL 96, 165002 (2006)

High brightness beam generation

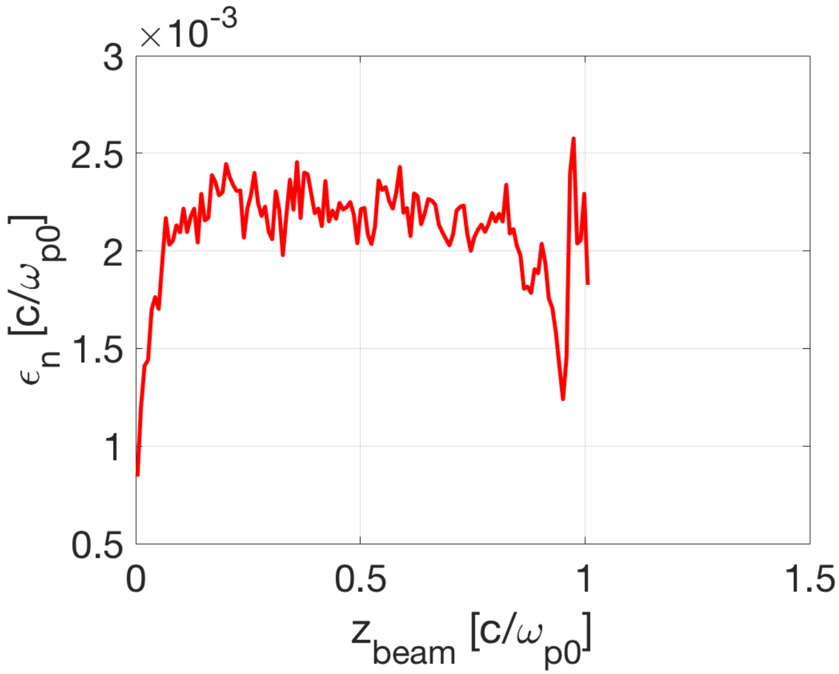
The trajectories of the injected electrons in downramp injection:

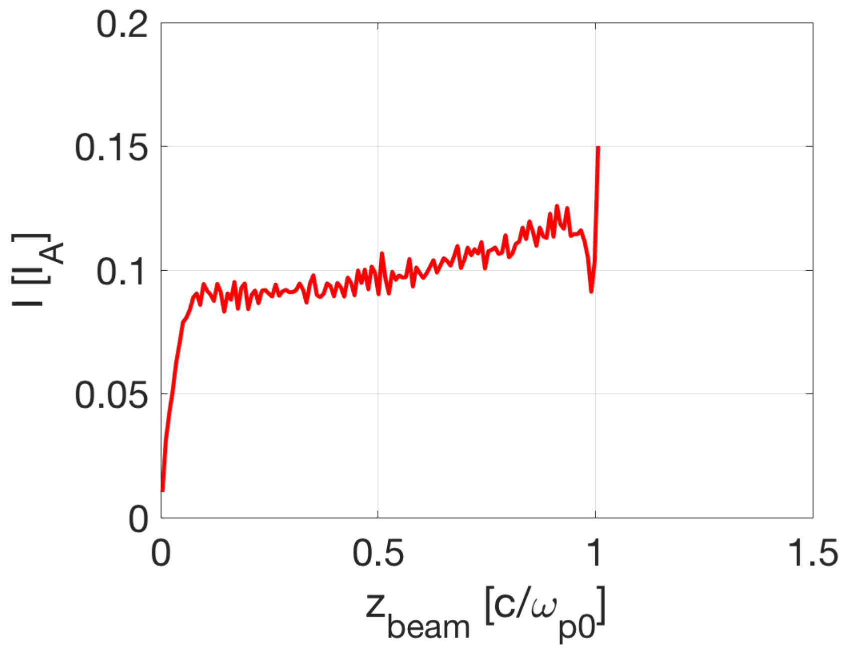


$\Lambda = 1, n_{p,h} = 1.5 n_{p0}, L = 20c/\omega_{p0}$

Enlarged View

High brightness beam generation





Λ=1, $n_{p,h}$=1.5 n_{p0}, L=20 c/ω_{p0}

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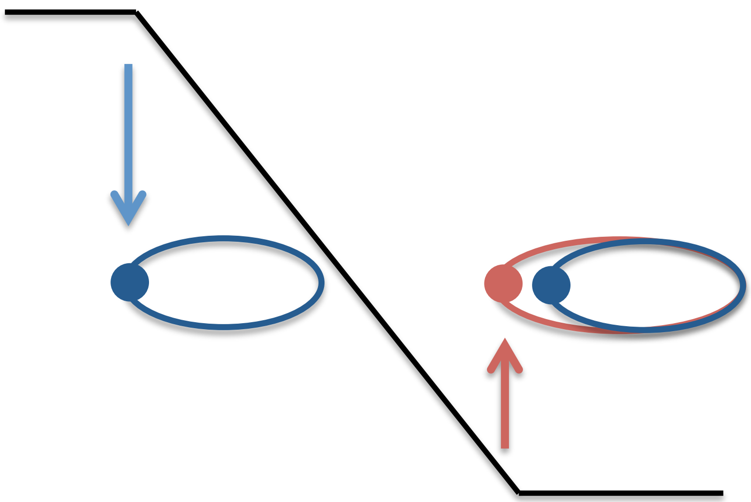
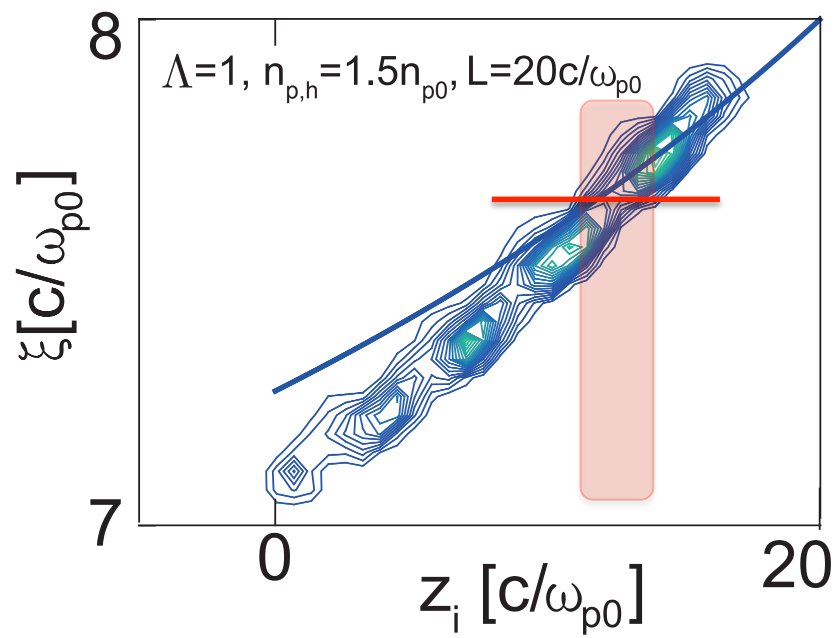
Low slice energy spread - Relations between z_i and ξ_f



$$\frac{d\xi}{dz_i} \approx \frac{d\lambda_{wake}}{dz_i} \approx 2\frac{dr_m}{dz_i}$$

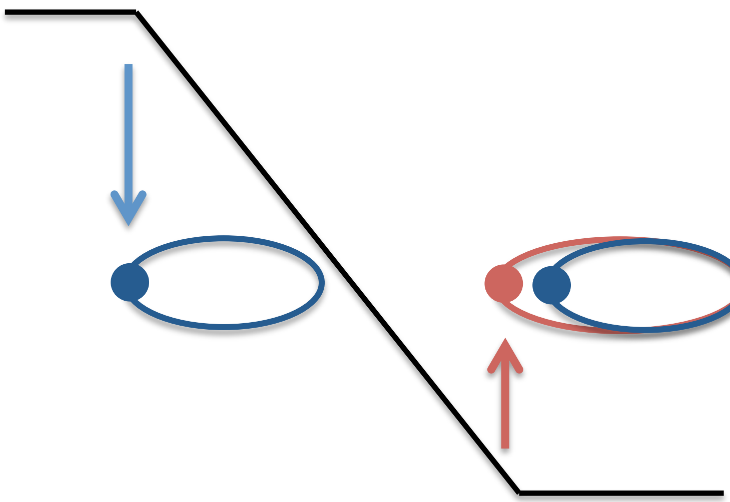


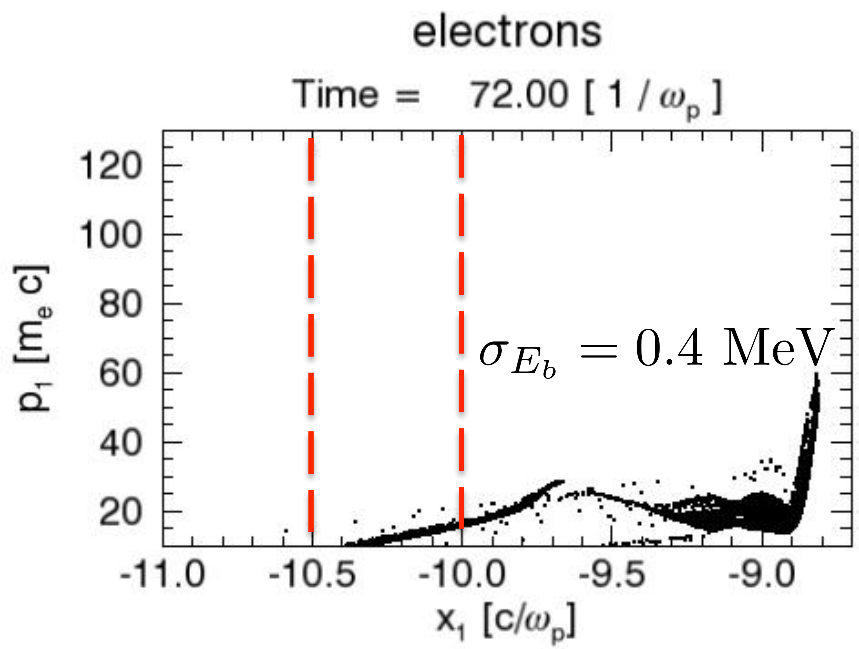
Longitudinal phase mixing[1] is broken!

Slice energy spread ~ O(0.1) MeV!

[1]X. L. Xu, et al., PRL 112, 035003 (2014).

Low projected energy spread – play with the chirp

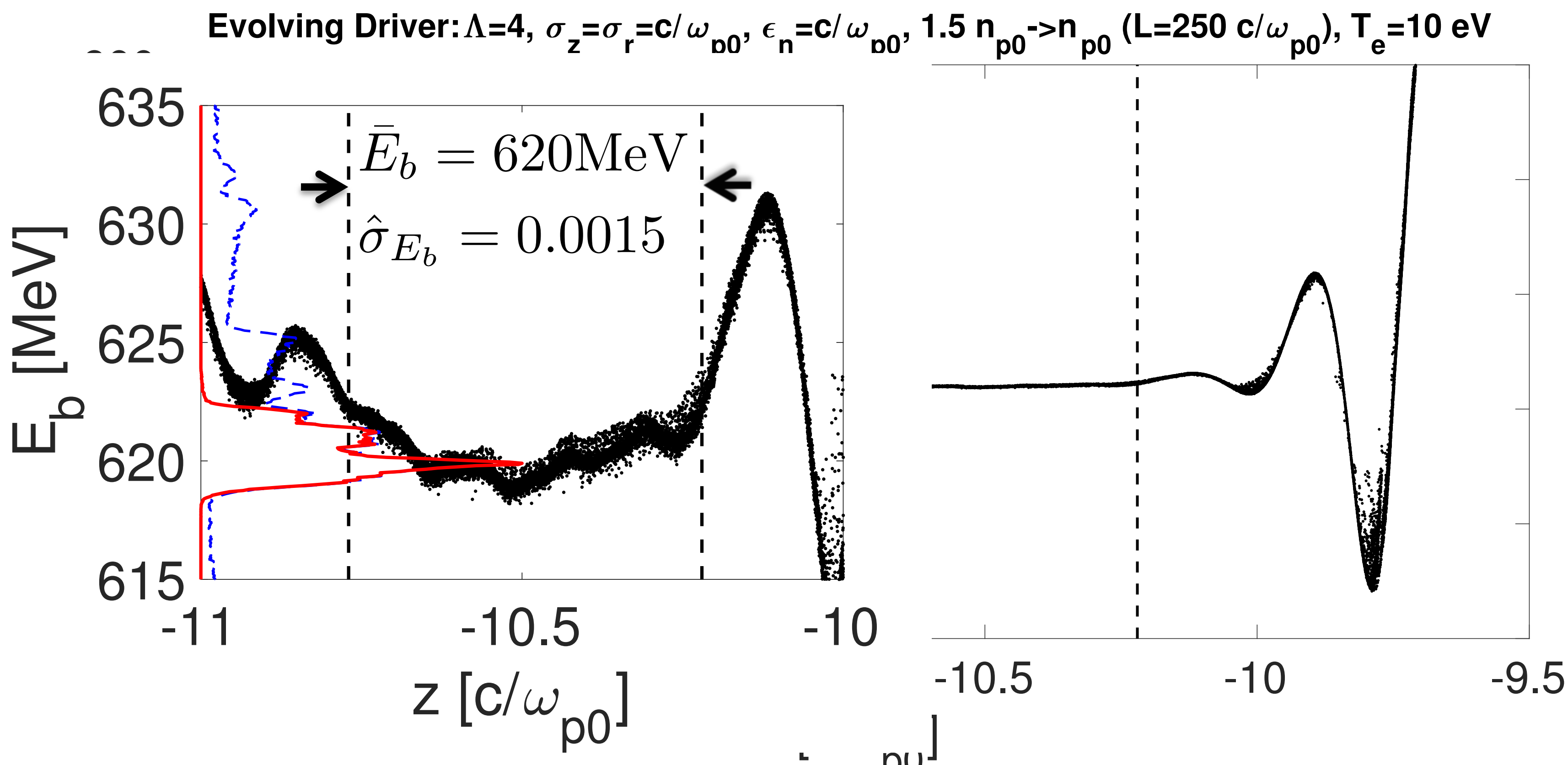




Initial energy chirp $\Delta\gamma_i = -\kappa\Delta\xi_i$ can be removed when $L_{acc} = 2\kappa$ and $\gamma_o = \gamma_i + \kappa\xi_i$ at this optimized distance.

Low projected energy spread – play with the chirp

$$\gamma_o = \gamma_i + \kappa \xi_i$$



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Scaling law

	I	ε_n, τ and σ_r	B	σ_E/E	n	Q
e^- Beams	n_{p0}^{0}	$n_{p0}^{-0.5}$	n_{p0}^{1}	n_{p0}^{0}	n_{p0}^{1}	$n_{p0}^{-0.5}$

	Ramp Length[1]	Acceleration Distance[2]
Plasma	$\propto n_{p0}^{-0.5}$	$\propto n_{p0}^{-0.5}$

Take 1.5 n_{p0} → n_{p0} (L=250 c/ω_{p0}) as an example:

	n_{p0} [cm^{-3}]	I [kA]	ε_n [nm]	τ [fs]	σ_r [um]	B [$A/m^2/rad^2$]	E [MeV]	σ_E/E	Q [pC]
Injected beam	10^{18}	14	80	10	0.2	4e18	620	1.5e-3	140
	10^{20}	14	8	1	0.02	4e20	620	1.5e-3	14

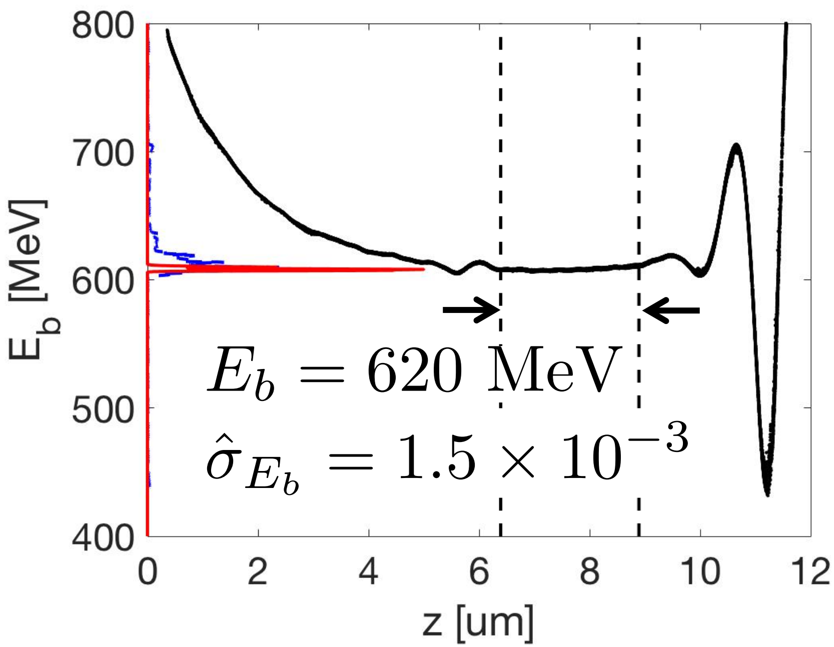
	n_{p0} [cm-3]	Density change [cm^{-3}]	L_{ramp} [mm]	L_{acc} [mm]
Plasma	10^{18}	0.5e18	1.33	3.3
	10^{20}	0.5e20	0.133	0.33

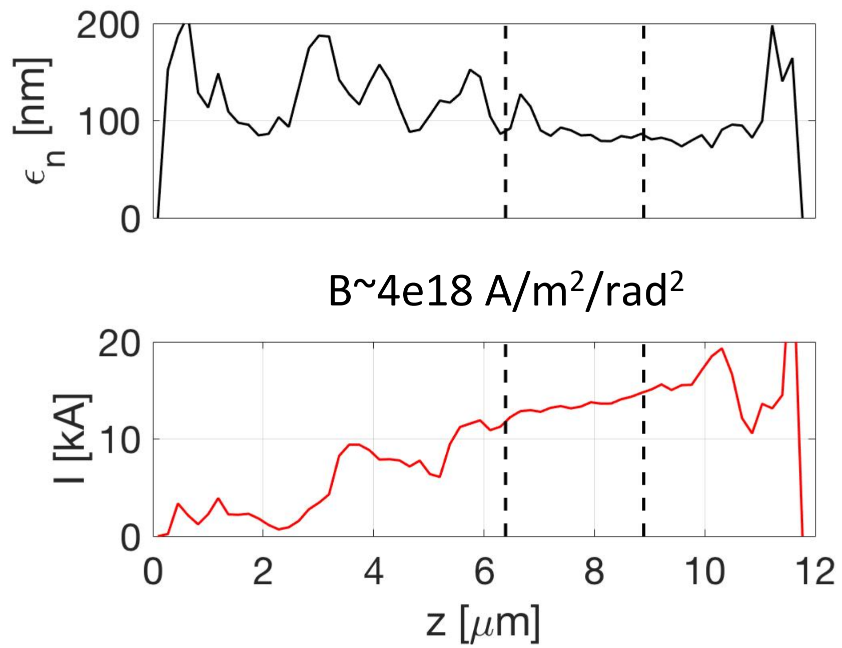
[1]For fixed density change; [2]To remove the energy chirp.

Injector for an X-FEL

	I [kA]	σ_r [um]	σ_z [um]	ε_n [um]	Q [nC]	E_b [GeV]
Driver beam	34 (Λ=4)	5.3	5.3	5.3	1.5	10

	$n_{p,h}$ [cm^{-3}]	n_{p0} [cm^{-3}]	L_{ramp} [mm]	L_{acc} [mm]	Initial T [eV]
Plasma	1.5e18	1e18	1.33 (250 c/ω_{p0})	3.3	10





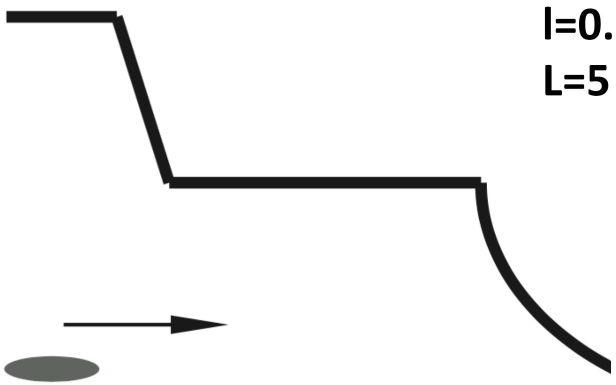
X-FELs Driven by Plasma Accelerators

High quality beam generation

Matching

Plasma Matching + Quadrupoles

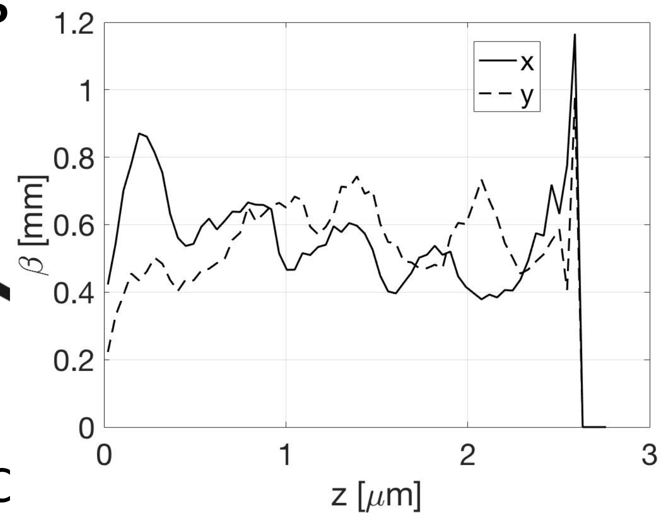
Radiator

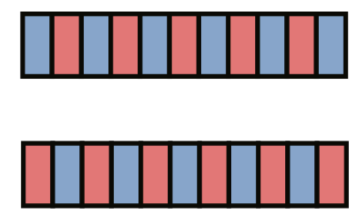


I=0.30mm

L=5

4 quads, ~300 T/m





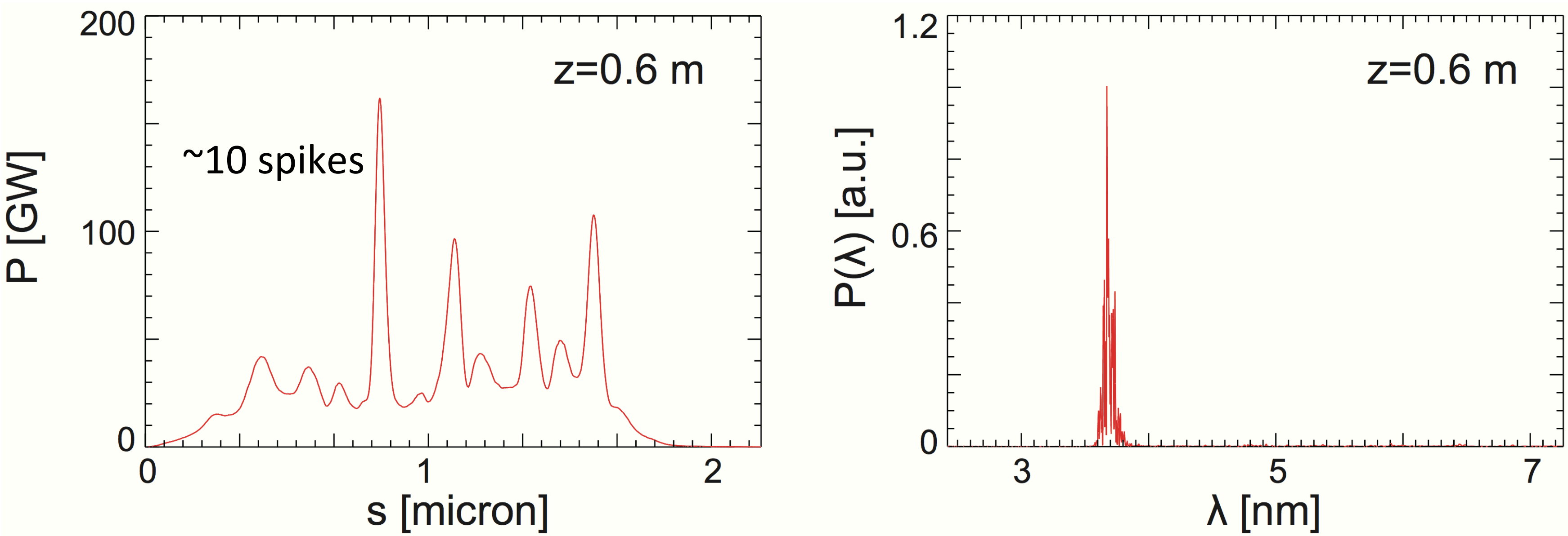
Codes: OSIRIS (+ QuickPIC

Genesis 1.3

FEL radiation – soft X-ray

- Undulator: λ_u=0.5 cm, K=1[1] → λ_r=3.6 nm

Genesis 1.3 Simulation Results[1]:



[1]S. Reiche, Nucl, Instrum. Methods Phys. Res., Sect. A 429, 243 (1999).

Conclusions

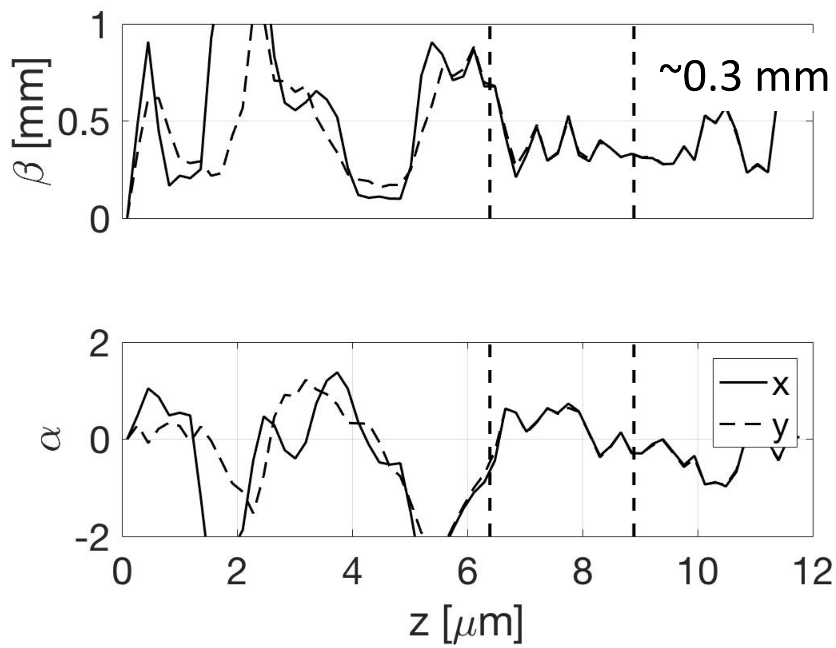
- We studied the injection dynamics in downramp injection in the 3D blowout regime and found high quality (high current, low emittance, low slice and projected energy spread) electron beams can be generated with suitable parameters.
- By combing the plasma matching section and quadrupoles, this high quality beam can be transported to the undulator to drive a X-FEL.

- Thanks!

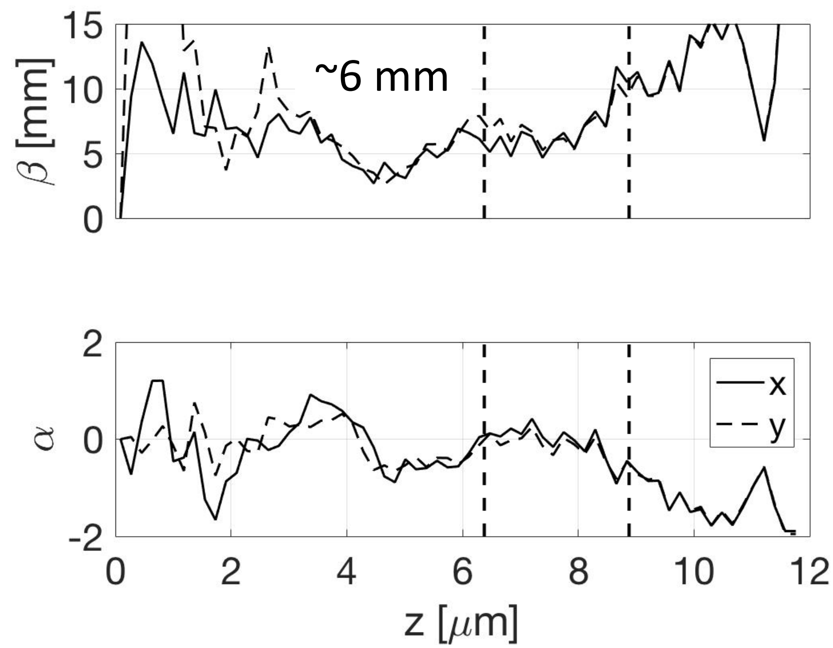
Plasma Matching Section

- Characteristic l=0.30 mm, Total L=5.7 mm

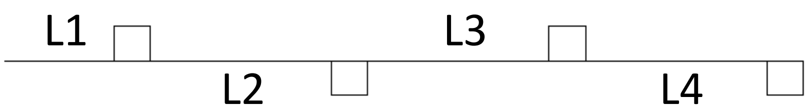
Before Matching section

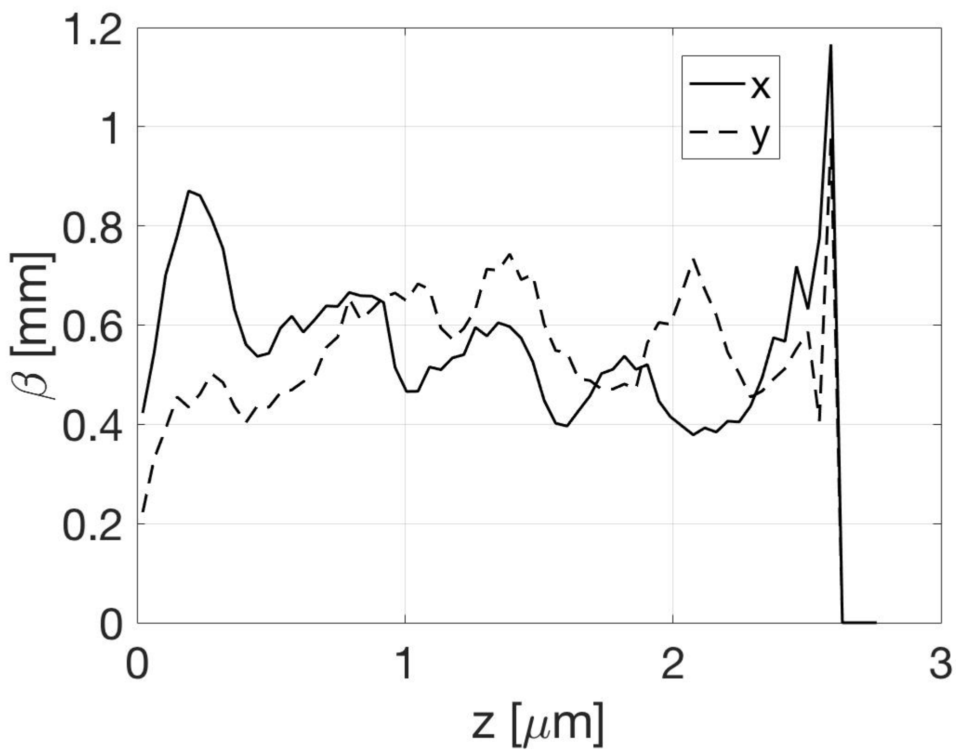


After Matching section



Magnetic transport lines





Parameters	Value
L1 [m]	0.3
L2 [m]	0.9
L3 [m]	0.9
L4 [m]	0.9
K1 [m^{-2}]	28.1
K2 [m^{-2}]	-16.3
K3 [m^{-2}]	16.4
K4 [m^{-2}]	134.9*
Width [m]	0.1

*corresponding to 270 T/m