Design of a 5 GeV Laser Plasma Accelerating Module in the Quasi-linear Regime

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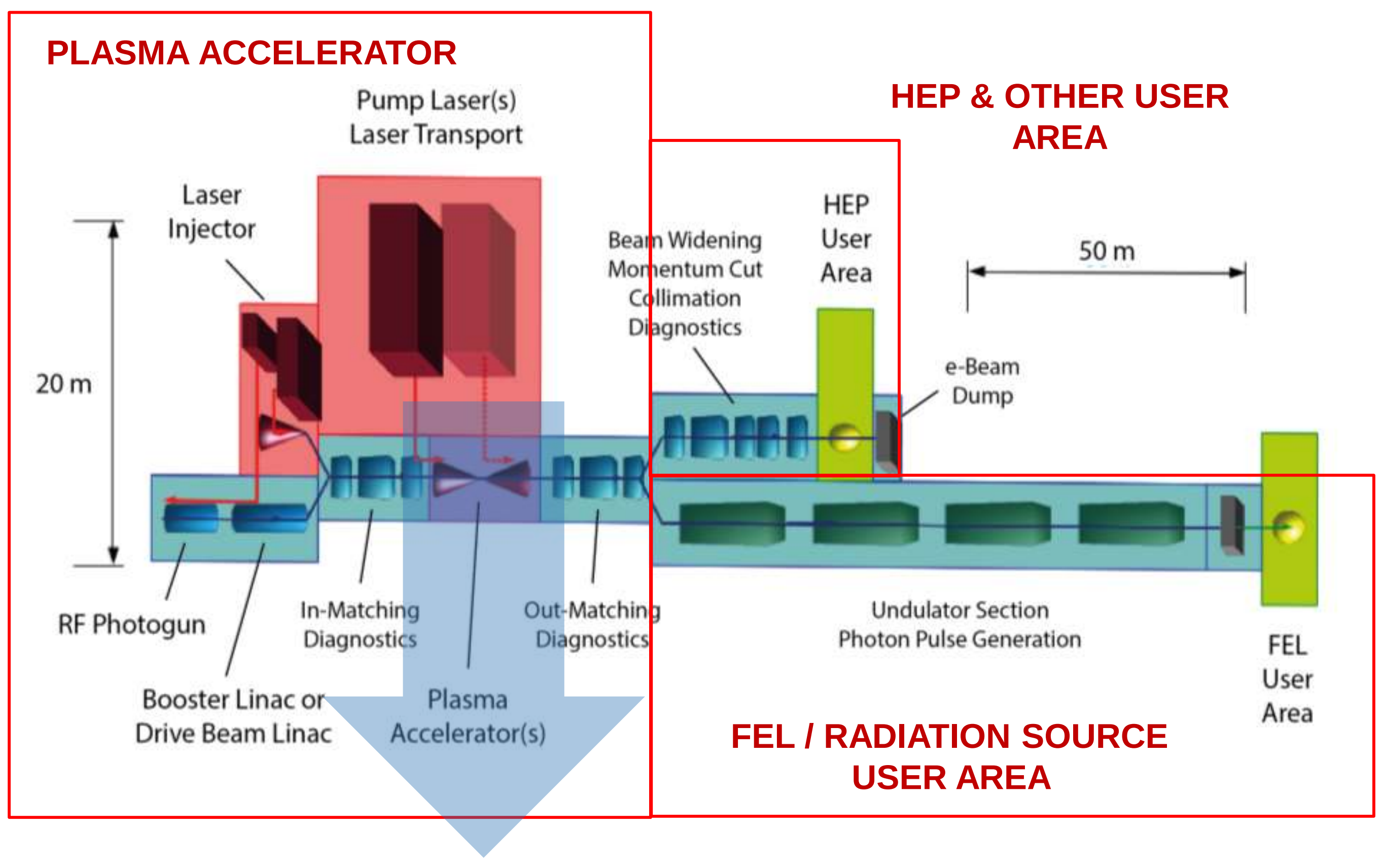
Abstract

A **30-cm** long plasma module has been designed for the **5 GeV** Laser Plasma Accelerator Stage (**LPAS**) of the **EuPRAXIA** project. The laser pulse (~**150 TW, ~15 J)** is quasi-matched into a plasma channel and the **bi-Gaussian** electron beam is externally injected into the wake field. The emittance is preserved throughout the acceleration. And a final **energy spread of <1%** is achieved. Several methods have been proposed to **reduce the slice energy spread** and are found to be effective. Simulations were conducted by the 3D PIC code **Warp** in the Lorentz boosted frame.

Background

The EuPRAXIA Project:



Scope of this study: **LPAS** from ~ 150 MeV to 5 GeV, with good beam quality, e. g., low emittance and low energy spread, suitable for X-ray FELs

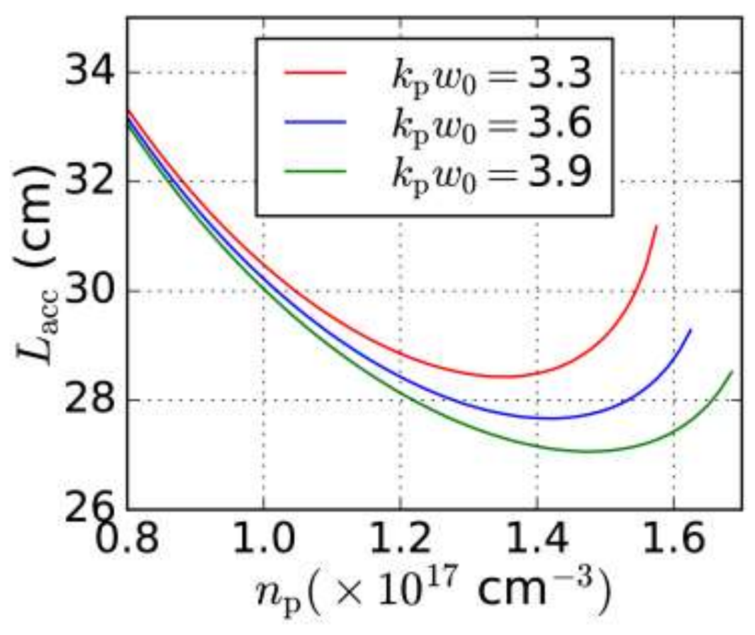
Scaling laws in quasi-linear regime

Energy gain:

$$\Delta\gamma_b = \frac{2}{\pi}\underbrace{k_p}_{\text{plasma wavenumber}} L_{dp} \frac{E_{z,\max}(0)}{\underbrace{E_0}_{\text{wave breaking field}}}\left[\left(1+\frac{\overbrace{L_{acc}}^{\text{plasma length}}}{\underbrace{L_{pd}}_{\text{power depletion length}}}\right)\sin\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right)+\frac{2}{\pi}\frac{\overbrace{L_{dp}}^{\text{dephasing length}}}{L_{pd}}\left(\cos\left(\frac{\pi}{2}\frac{L_{acc}}{L_{dp}}\right)-1\right)\right]$$

$E_{z,\max}(0) \simeq 0.76 a_0^2\, E_0/2\gamma_\perp$ is the amplitude of the acc. field (with resonant pulse length)

$a_0 = \sqrt{2}$, $\Delta E_b = 4.85$ GeV

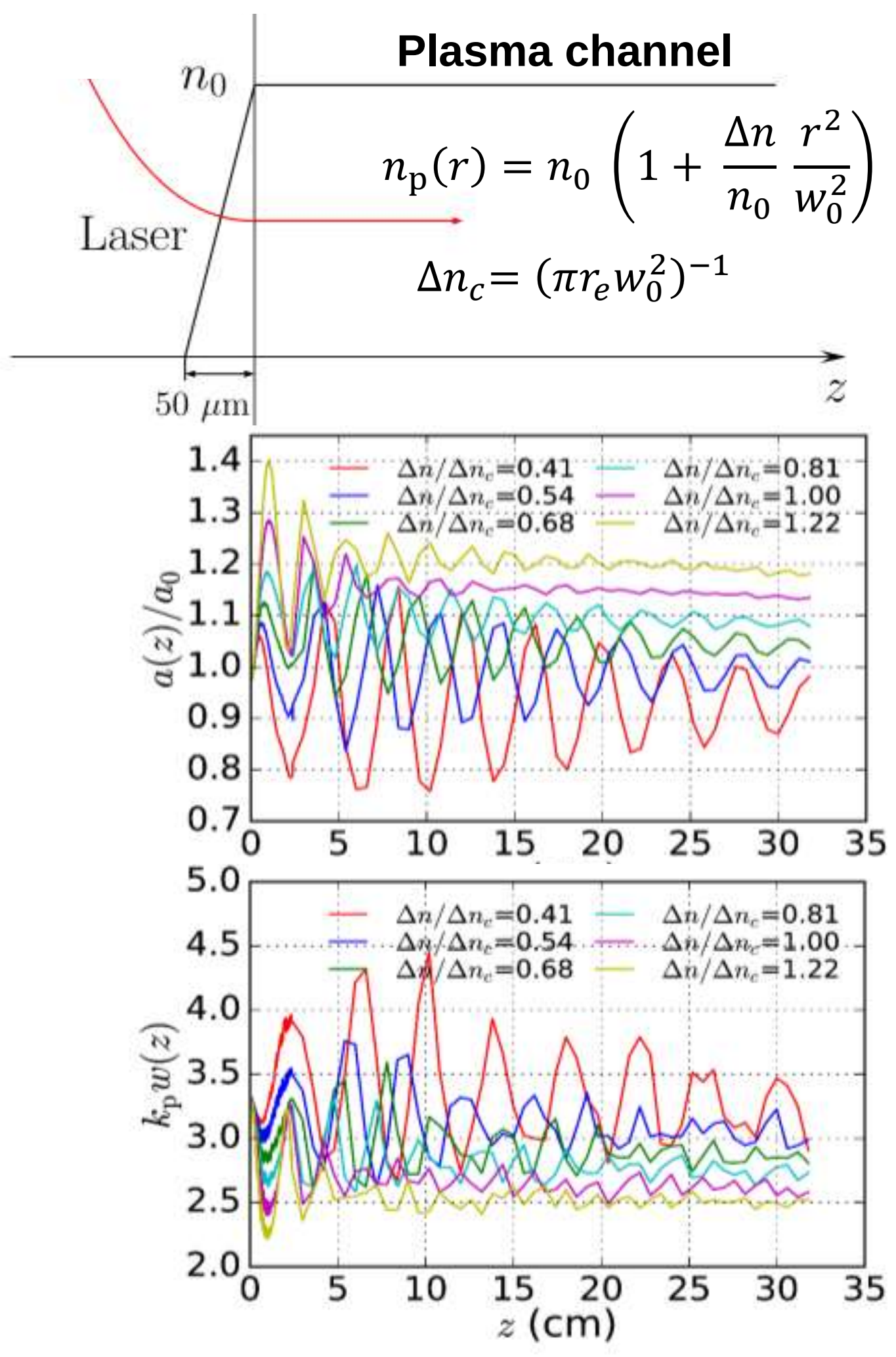


The optimal plasma density is around $n_p = 1.5 \times 10^{17}$ cm^{-3}

Laser		
strength a_0		$\sqrt{2}$
spot size $k_p w_0$		3.3
duration $k_p \sigma_z$		$\sqrt{2}$
peak power	[TW]	~ 150
energy	[J]	~ 15
Plasma		
density n_0	[10^{17} cm^{-3}]	1-2 (tbd)
channel depth $\Delta n/\Delta n_c$		<1 (tbd)
acc. length L_{acc}	[cm]	~ 30
Electron		
charge Q	[pC]	30
energy E_k	[MeV]	150
energy spread	[%]	0.5
beam size σ_x	[μm]	~1 (tbd)
emittance $\varepsilon_{n,x}$	[πmmmrad]	1.0
beam length σ_z	[μm]	1-3 (tbd)

Simulation parameters

Laser guiding

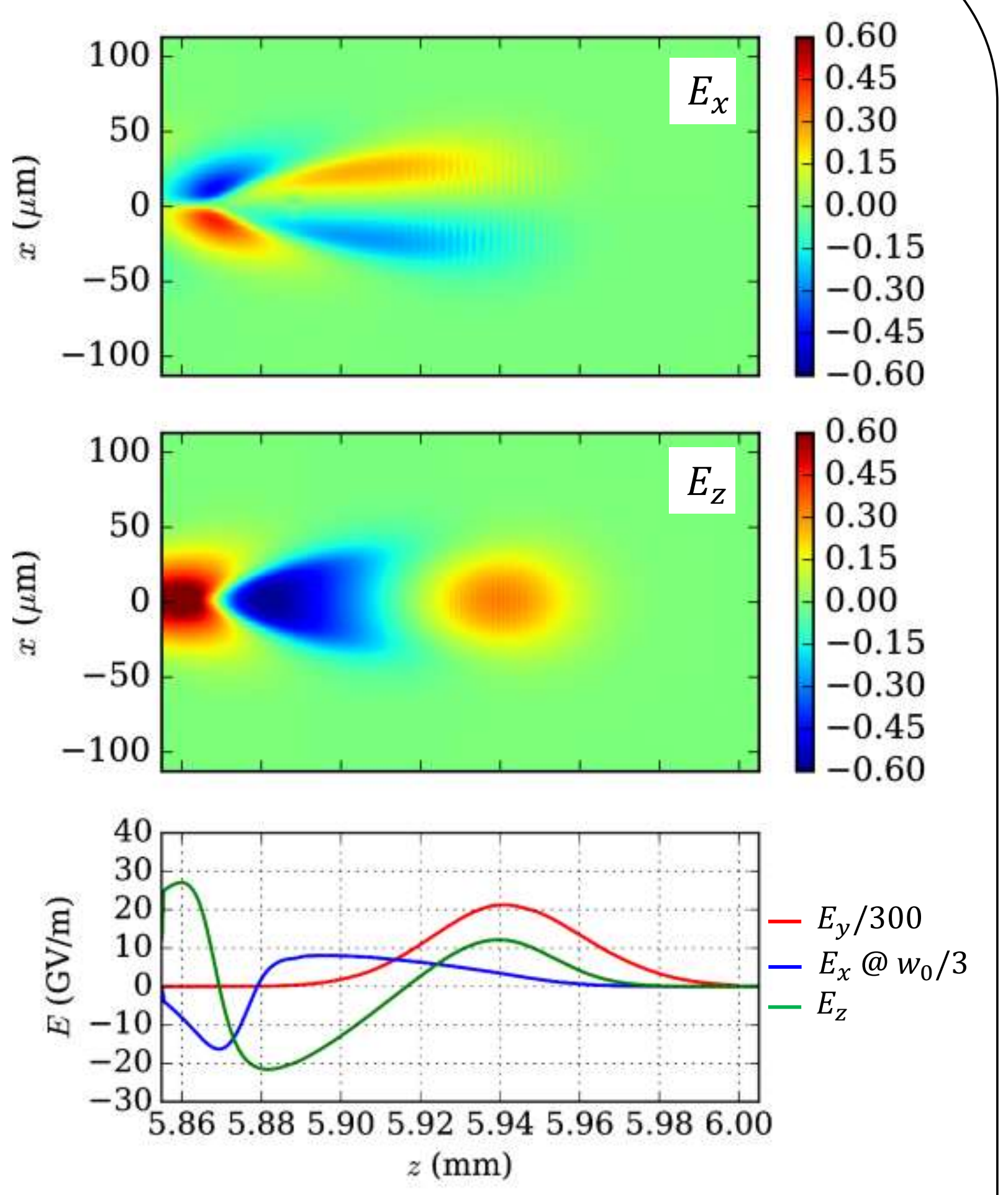


$$n_p(r) = n_0\left(1+\frac{\Delta n}{n_0}\frac{r^2}{w_0^2}\right)$$

$$\Delta n_c = (\pi r_e w_0^2)^{-1}$$

The laser pulse is quasi-matched with $\Delta n/\Delta n_c$~0.6

Plasma wake



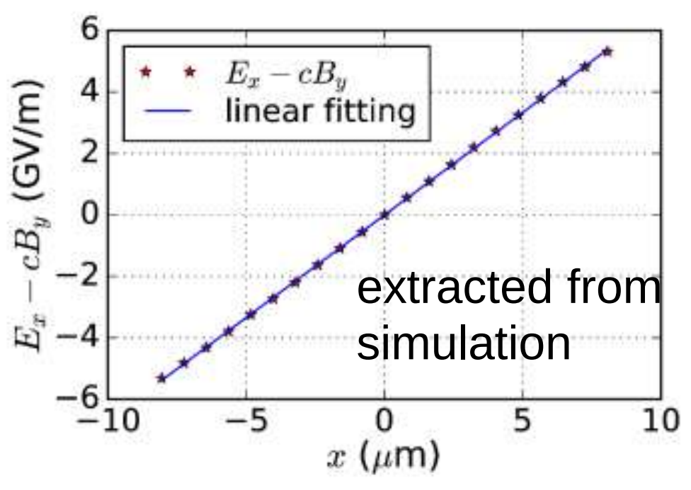
Density plots of E_x (top) and E_z (middle); amplitudes of the on-axis E_z (green line) and E_x (blue line); channel depth $\Delta n/\Delta n_c = 0.68$

Optimization of emittance

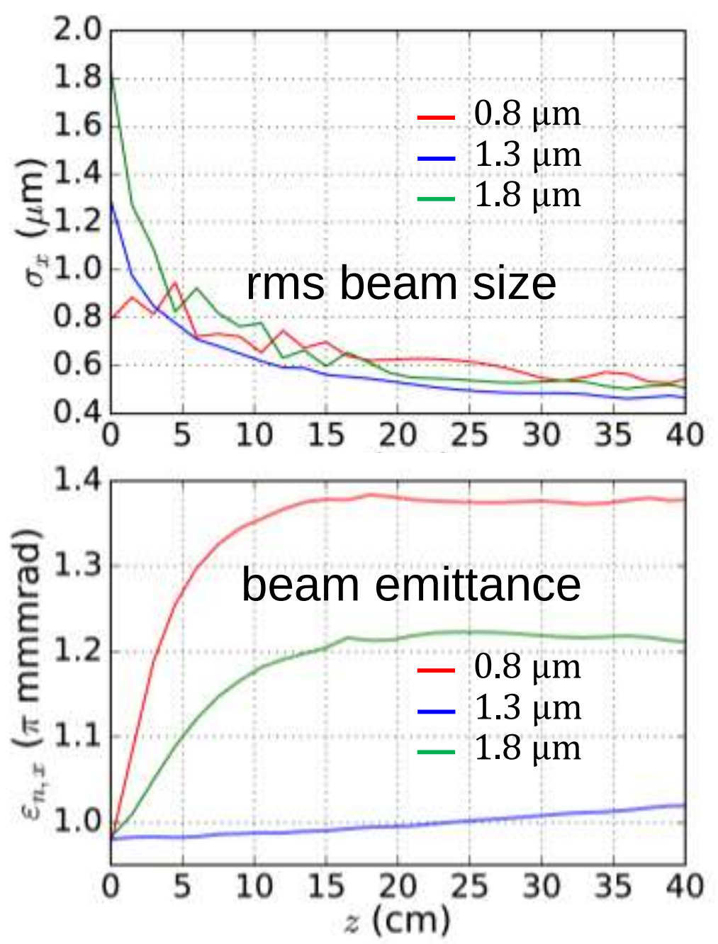
Tranverse matching:

$$\sigma_x^2 = \beta_m \frac{\varepsilon_n}{\gamma_b}$$

$$\frac{1}{\beta_m^2} = \frac{e}{\gamma_b m_0 c^2}\frac{\partial(E_r - cB_\theta)}{\partial r}$$



For $\varepsilon_{n,x} = 1\mu$m, the matched size is 1.3 μm



The optimal beam size is $\sigma_x = 1.3\ \mu m$, agreeing well with theories

Optimization of energy spread

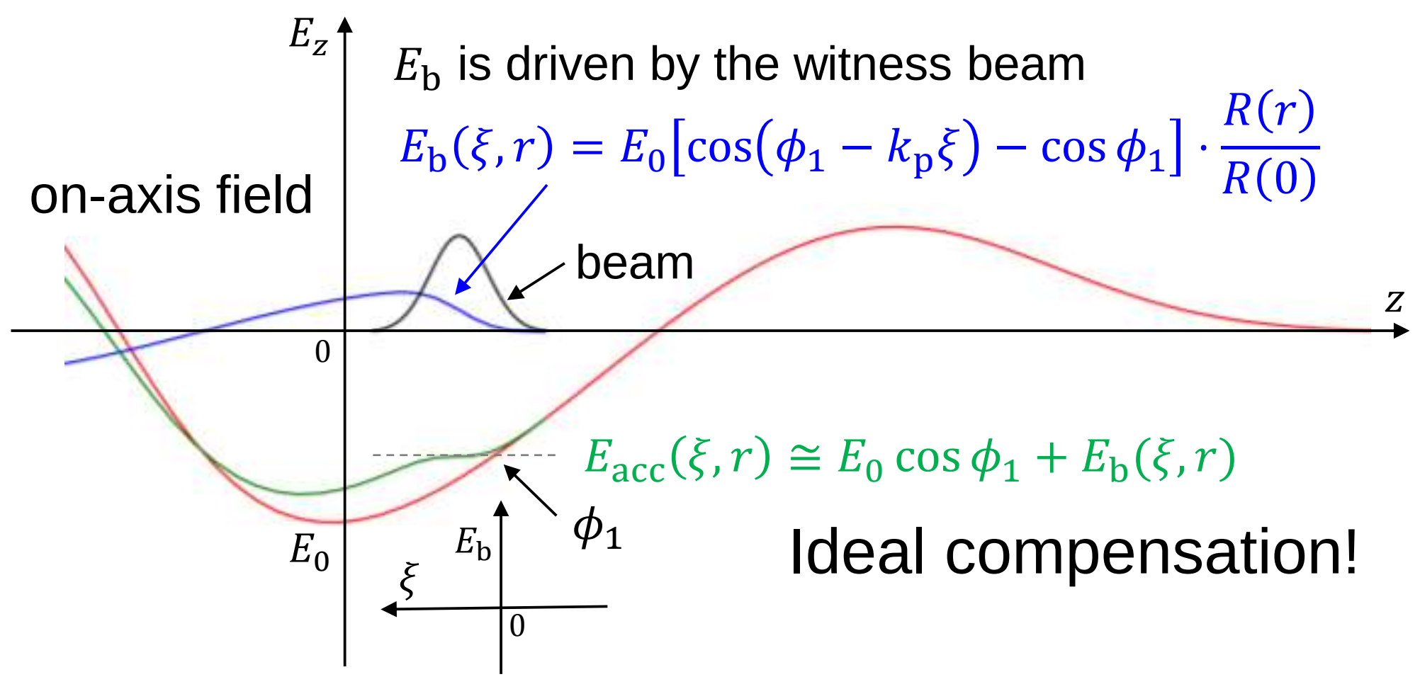
Sources of energy spread:

Longitudinally → **phase dependence** of the acc. field due to bunch length
can be compensated by the **beam loading effect**

Transversely → **radial dependence** of the long. field driven by the laser
negligible when the laser spot size is much larger than the beam size
→ **radial dependence** ($R(r)$) of the long. field driven by the beam
induces slice energy spread that cannot be ignored

Beam loading effect:

$$\boxed{R(r) = \frac{k_p^2}{2\pi}\int_0^{2\pi} d\theta \int_0^{\infty} r' dr' \rho_\perp(r') K_0(|\vec{r} - \vec{r}'|)}$$



E_b is driven by the witness beam

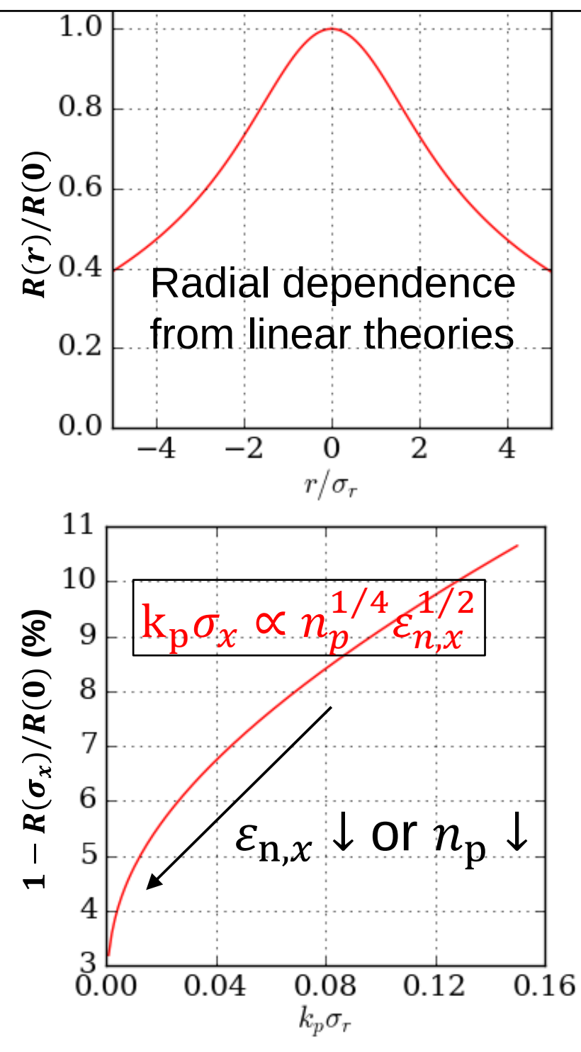
$$E_b(\xi, r) = E_0[\cos(\phi_1 - k_p\xi) - \cos\phi_1]\cdot\frac{R(r)}{R(0)}$$

$$E_{acc}(\xi, r) \cong E_0\cos\phi_1 + E_b(\xi, r)$$

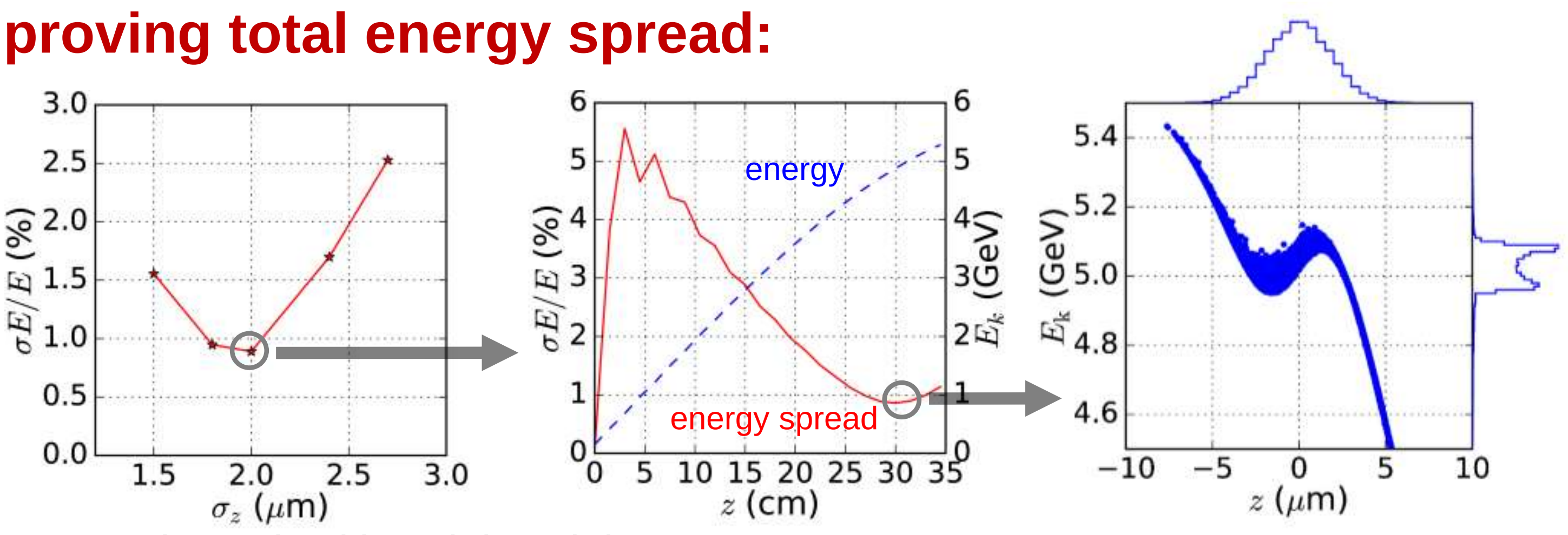
Ideal compensation!

For a slice at $z = \xi$:

$$\frac{\Delta E_s(\xi,r)}{E_s} = \frac{E_{acc}(\xi,r) - E_{acc}(\xi,0)}{E_{acc}(\xi,0)} = \frac{\cos(\phi_1 - k_p\xi) - \cos\phi_1}{\cos\phi_1}\cdot\left[1 - \frac{R(r)}{R(0)}\right]$$

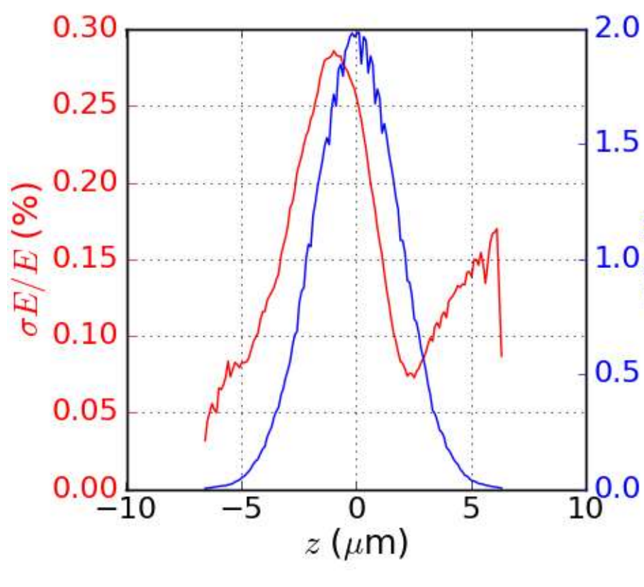


Improving total energy spread:



The optimal bunch length is $\sigma_z = 2.0\ \mu m$

Improving slice energy spread:

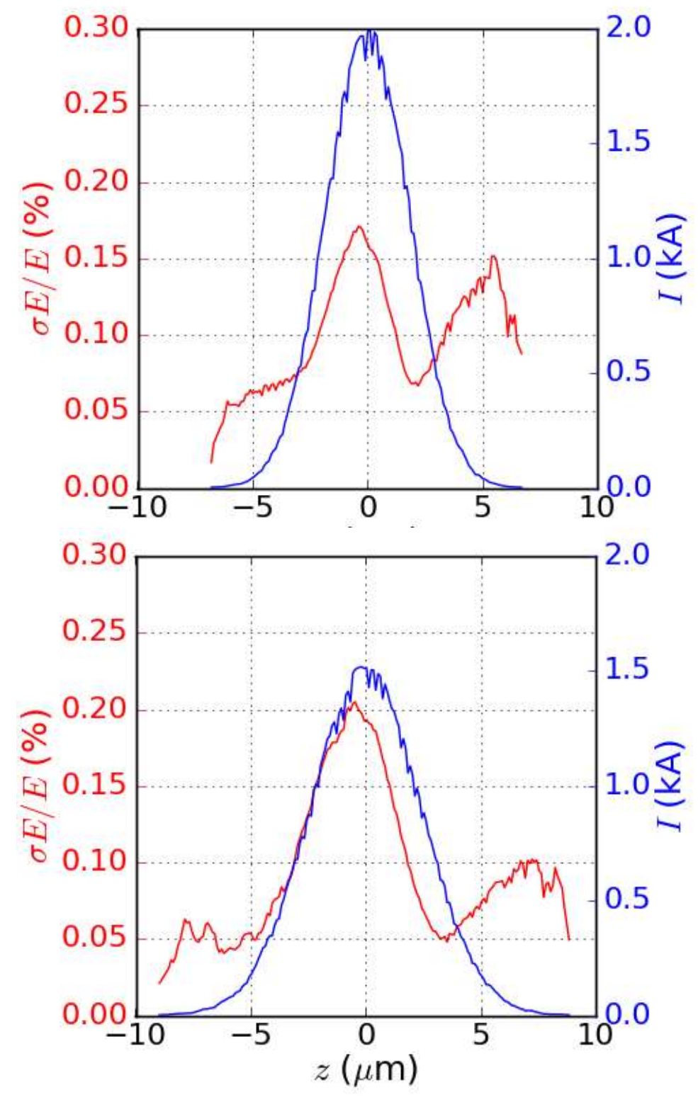


$\boxed{\varepsilon_{n,x} = 1.0 \to 0.5\mu\text{m}}$

$1 - \frac{R(r)}{R(0)}$ ↓

$\boxed{n_p = 1.5 \to 1.0 \times 10^{17}\ \text{cm}^{-3}}$

$\phi_1 \to 0\ \&\&\ 1 - \frac{R(r)}{R(0)}$ ↓



Conclusion

By optimizing the beam size and length, low emittance and low energy spread (<1%) electron beam can be obtained from laser plasma accelerators. The slice energy spread might be furthermore reduced by choosing a lower plasma density, approaching the requirement (<0.1%) of downstream X-ray free electron lasers.

References: [1] P. A. Walker, *et al.*, *Journal of Physics: Conf. Series*, **2017**, 874, 012029; [2] B. A. Shadwick, *et al.*, *Physics of Plasmas*, **2009**, 16; [3] C. B. Schroeder, *et al.*, *Phys. Rev. ST Accel. Beams*, **2010**, 13, 101301 ; [4] E. Esarey *et al.*, *Rev. Mod. Phys.*, **2009**, 81, 1229; [5] T. Katsouleas *et al.*, *Part. Accel*, **1987**, 22: 81-99; [6] Vay, J.-L, *et al.*, *Physics of Plasmas*, **2011**, 18; [7] M. Tzoufras, *et al.*, *Phys. Rev. Lett.*, **2008**, 101, 145002