Plasma beam dumps: an analytical model for passive and active schemes

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Collective deceleration: Toward a compact beam dump

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Collective deceleration: Toward a compact beam dump

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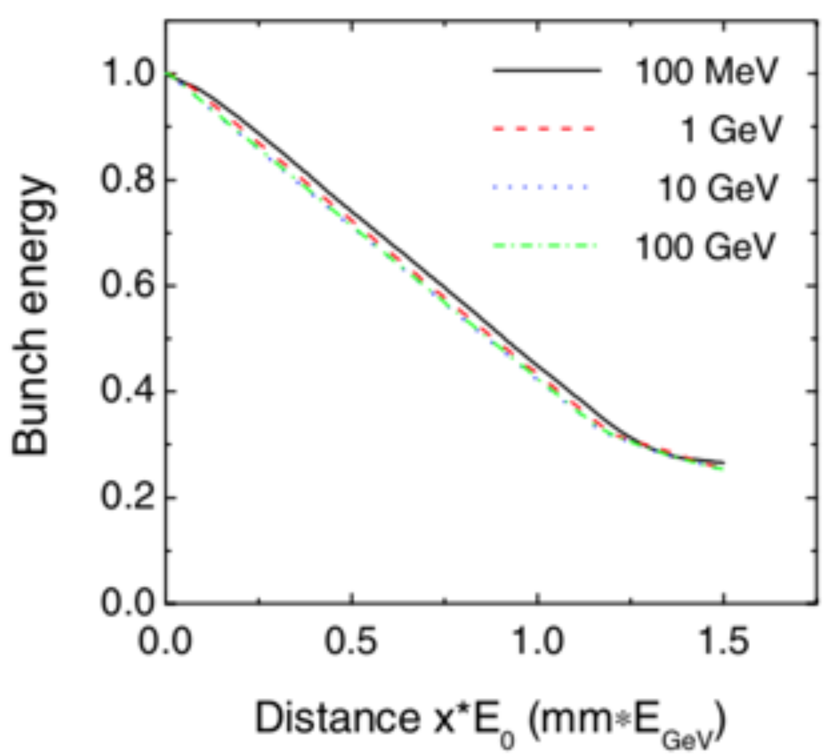
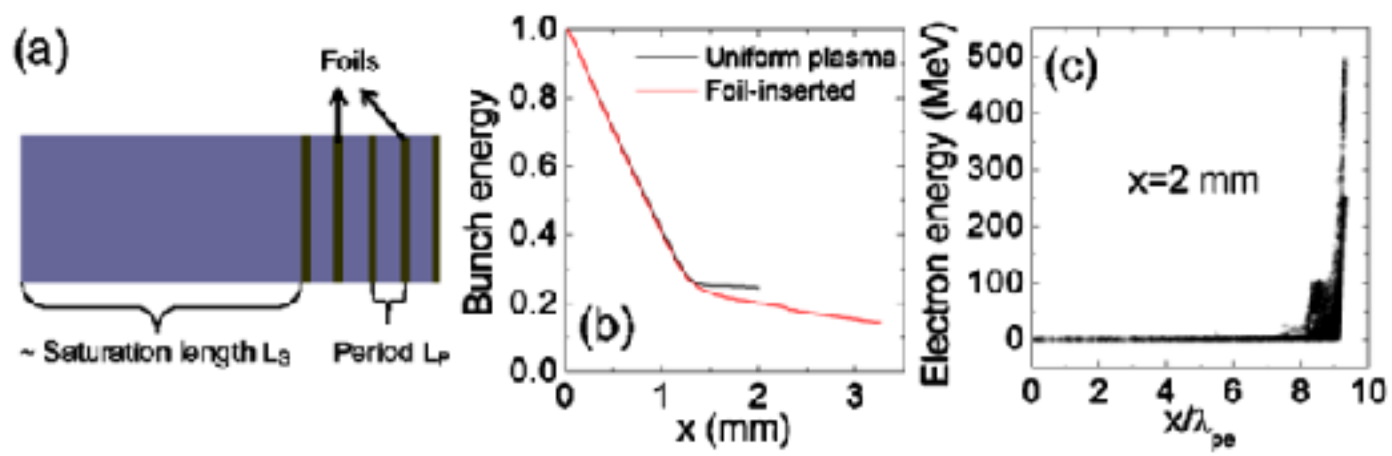
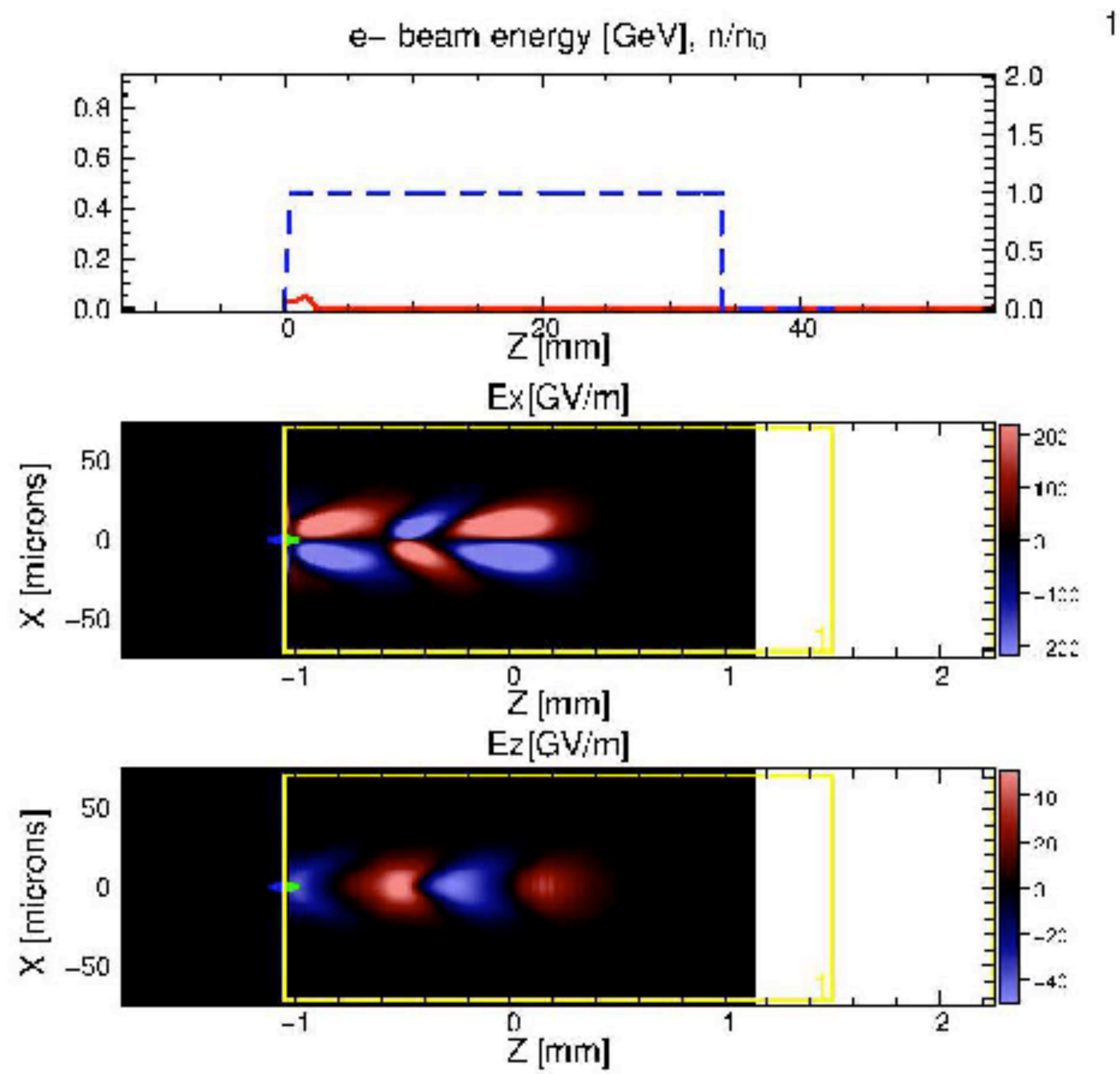




Transportable quasi-monoenergetic femtosecond photon source from LPA-based Thomson scattering

- Single-stage accel.-decel. scheme:



S. G. Rykovanov, *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* 47 (2014).

J.-L. Vay *et al.*, *Proceedings of NPNSNP* (2015).

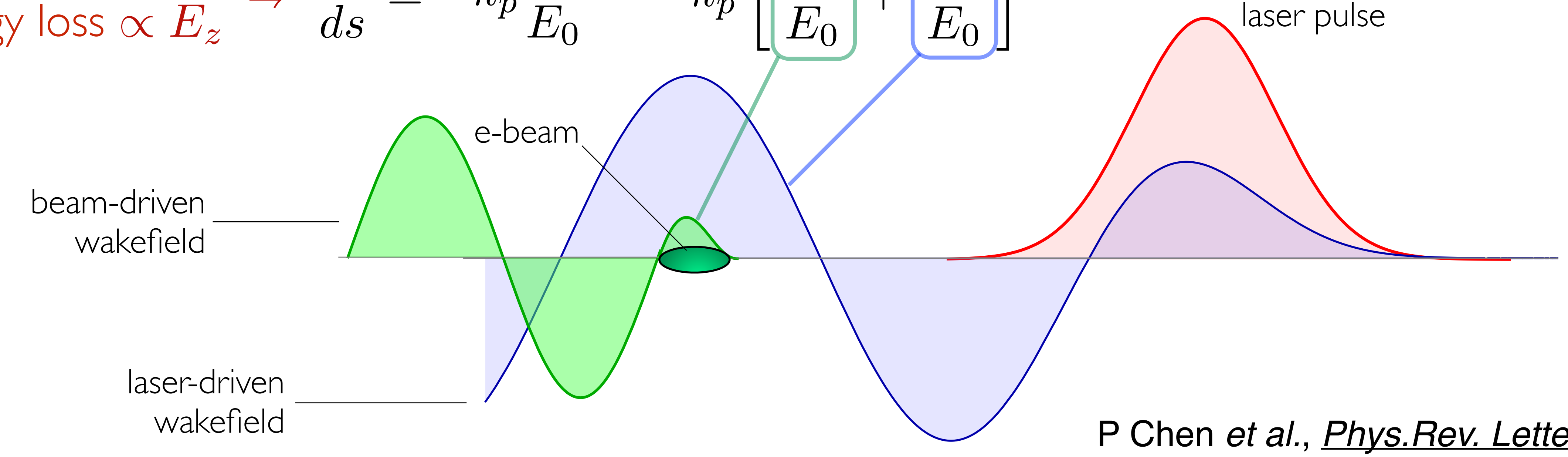
Courtesy: J.-L. Vay

Passive and active (laser-driven) beam dump

- High-energy e-beam propagating in a plasma ($v_b \simeq c$):

beam-driven wakefield laser-driven wakefield

1st. order: beam energy loss $\propto E_z$ $\Rightarrow$ $\dfrac{d\gamma}{ds} \simeq -k_p \dfrac{E_z}{E_0} = -k_p \left[\boxed{\dfrac{E_{zb}}{E_0}} + \boxed{\dfrac{E_{z\ell}}{E_0}} \right]$



$s \equiv c\,t\ ,\ k_p = \omega_p/c = (4\pi n_0 e^2/m_e)^{1/2}/c$

$E_0 \equiv m_e c\,\omega_p/e\ ,\ E_z/E_0 \ll 1$

P Chen *et al.*, Phys.Rev. Letters, (1985)

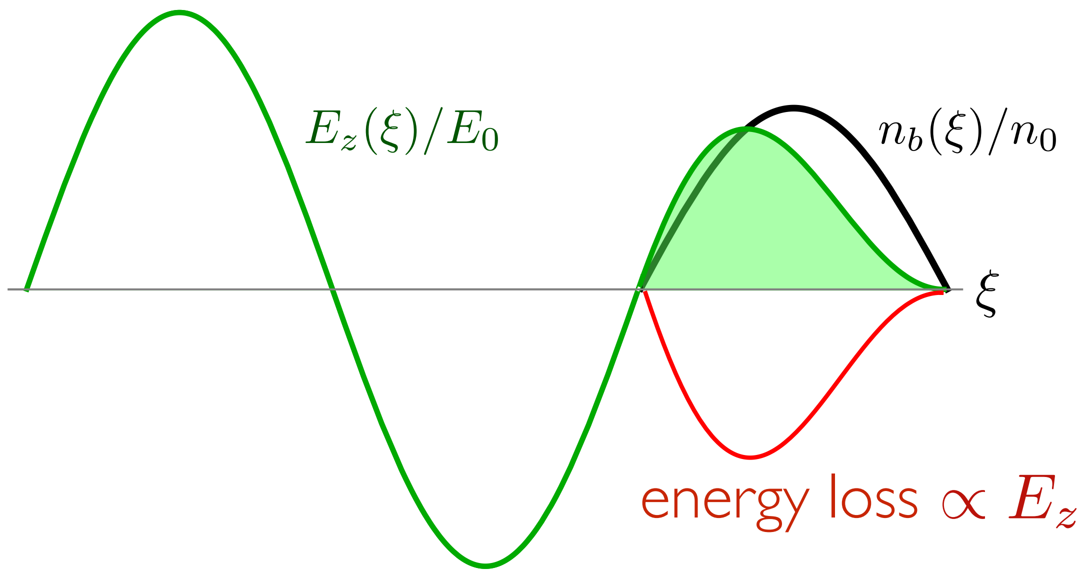
E. Esarey *et al.*, Rev. of Modern Phys. (2009)

- Passive beam dump → beam wakefield
- Active (laser-driven) beam dump → beam + laser wakefield

Passive beam dump

- Beam propagating in a quiescent plasma (with flat density profile) transfers its energy to the self-excited wakefield:

H.-C. Wu *et al.*, PRSTAB (2010)



$$\gamma(\xi, r, s) = \gamma_0 - k_p s \left[\frac{E_{zb}(\xi, r)}{E_0} \right]$$

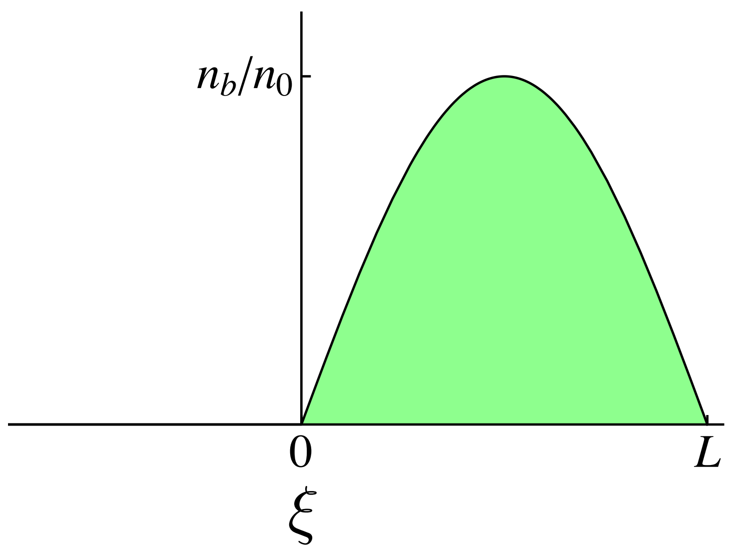
- Energy loss (frozen beam approximation):

$$\frac{U(s)}{U_0} = 1 - k_p s \boxed{\frac{\int_V dV \left[E_{zb}(\xi, r)/E_0\right] \left[n_b(\xi, r)/n_0\right]}{\gamma_0 \int_V dV \; n_b(\xi, r)/n_0}} \quad \frac{dU}{ds} \rightarrow \frac{E_z(\xi)}{E_0} \,,\; n_b(\xi)$$

$$U(0) \equiv U_0 = \gamma_0 \int_V dV \; n_b(\xi, r)/n_0$$

Passive beam dump $1\mathrm{D}$

- e-beam with half-sine longitudinal profile:



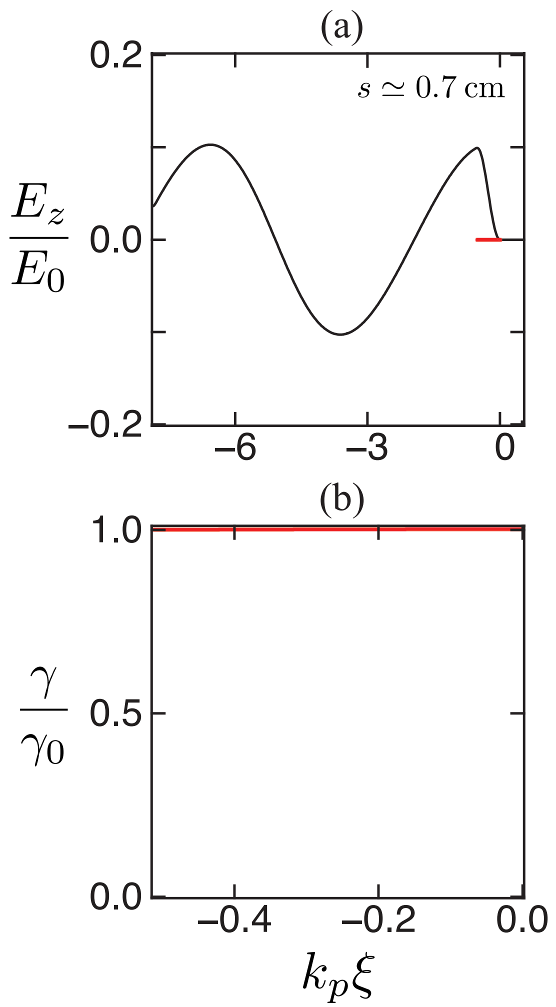
$$n_b(\xi) = \frac{n_b}{n_0} \sin\left(\frac{\pi\xi}{L}\right) \quad , \quad 0 \leq \xi \leq L$$

- Energy loss:

$$\frac{U(s)}{U_0} = 1 - k_p s \, \frac{\pi^3 k_p L (n_b/n_0) \cos^2(k_p L/2)}{\gamma_0 (\pi^2 - k_p^2 L^2)^2}$$

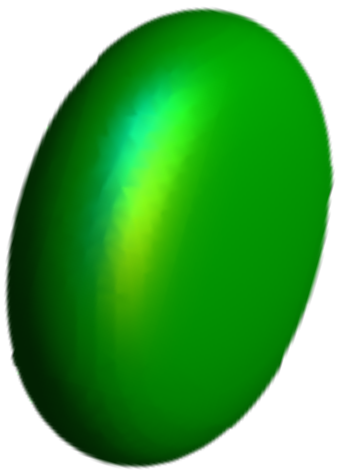
Passive beam dump $1\mathrm{D}$ - analytical model vs. PIC (Warp)

$$n_0 = 10^{18}\mathrm{cm}^{-3}\,,\ L = 2.7\,\mu\mathrm{m}\,(k_p L \simeq 0.5)\,,\ n_b/n_0 = 0.315\,(E_z/E_0 = 0.1)\,,\ \gamma_0 = 1000$$



Passive beam dump $2D$ axi-symmetric

- Half-sine (longitudinal) , parabolic (transverse):



$$n_b(\xi, r) = \frac{n_b}{n_o}\,\sin\left(\frac{\pi\xi}{L}\right)\left(1 - \frac{r^2}{r_b^2}\right)\;,\;\left[\begin{array}{l} 0 \leq \xi \leq L \\ 0 \leq r \leq r_b \end{array}\right.$$

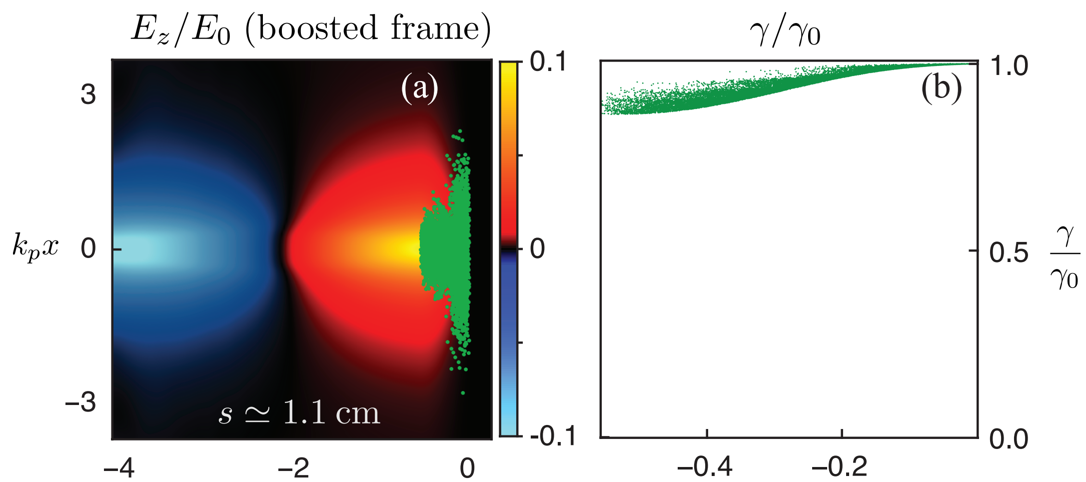
- Energy loss:

$$\frac{U(s)}{U_0} = 1 - k_p s\,\frac{\pi^3 k_p L\,(n_b/n_0)\cos^2(k_p L/2)}{\gamma_0(\pi^2 - k_p^2 L^2)^2}\,\frac{2}{3}\left[\frac{k_p^2 r_b^2 - 6 + 24\,I_2(k_p r_b)K_2(k_p r_b)}{k_p^2 r_b^2}\right]$$

Passive beam dump $2\mathrm{D}$ axi-symmetric: analytical model vs. PIC 3D (Warp)

$$n_0 = 10^{18}\mathrm{cm}^{-3}\,,\; L = r_b = 2.7\,\mu\mathrm{m}\,(k_pL = k_pr_b \simeq 0.5)\,,\; Q = 10\,\mathrm{pC}\,,\; \gamma_0 = 1000$$

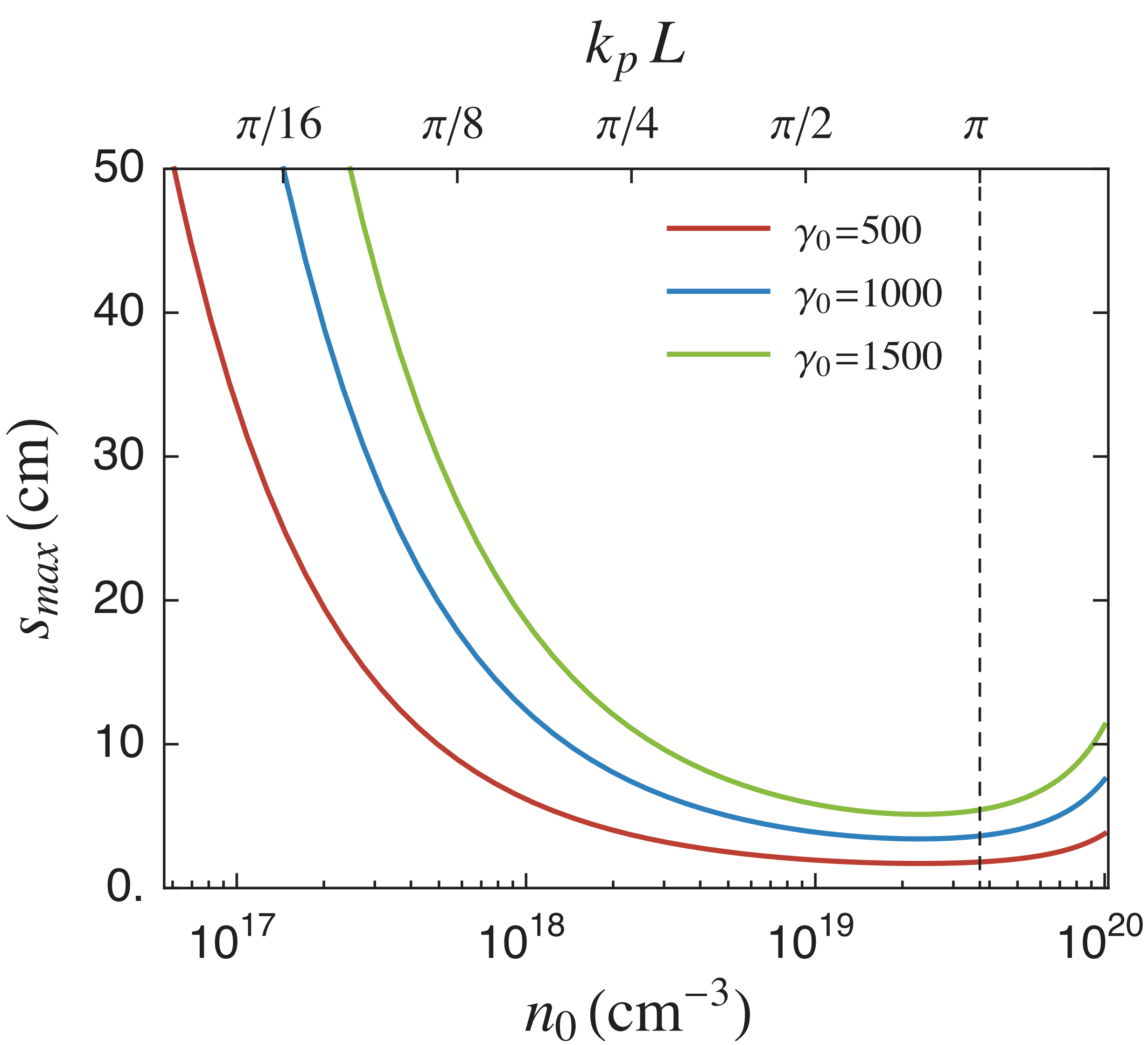
$$\epsilon_x = \epsilon_y = 0.35\,\mu\mathrm{m\,rad}$$

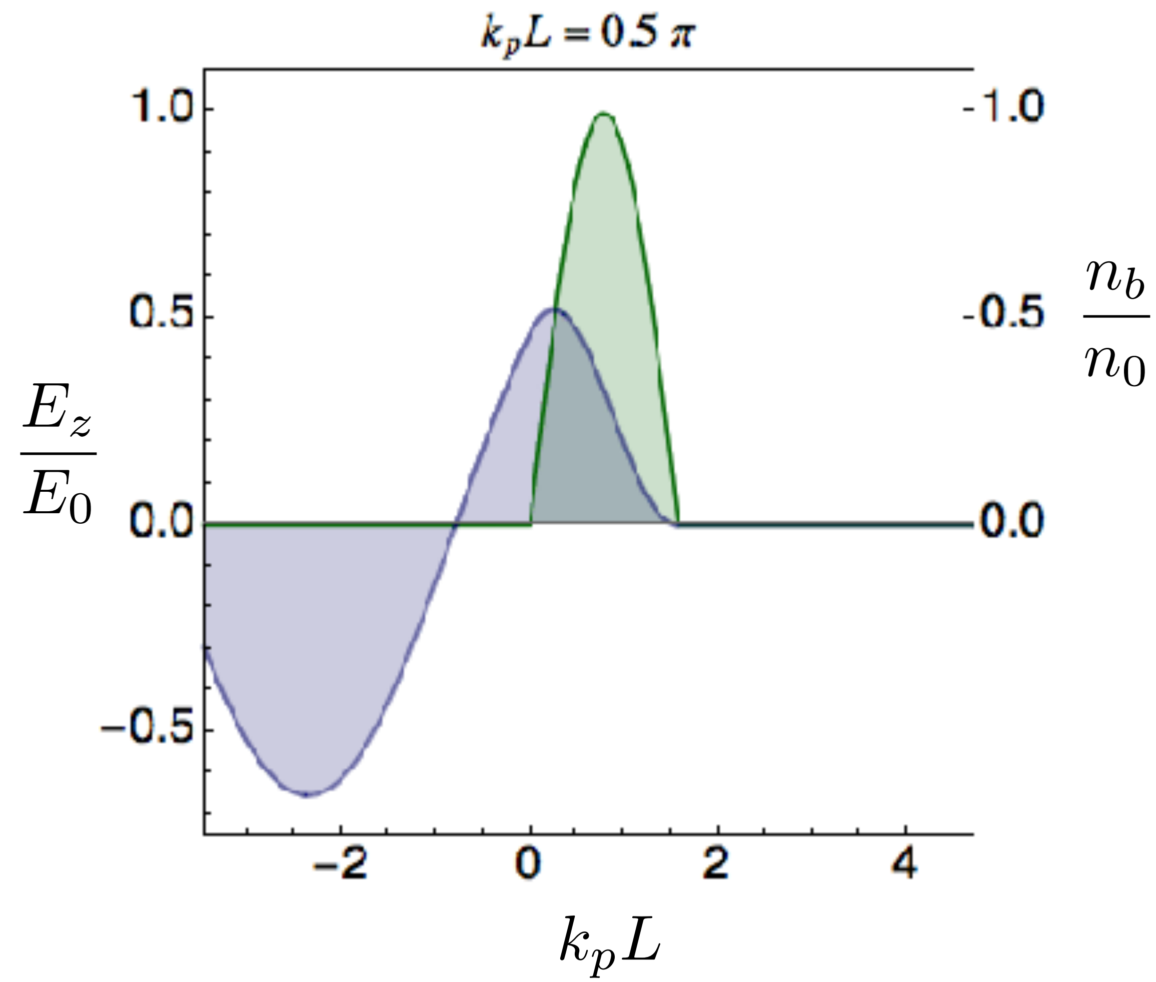


s_{max}

Passive beam dump $2\mathrm{D}$ axi-symmetric:
s_{max} as an estimate for the deceleration length

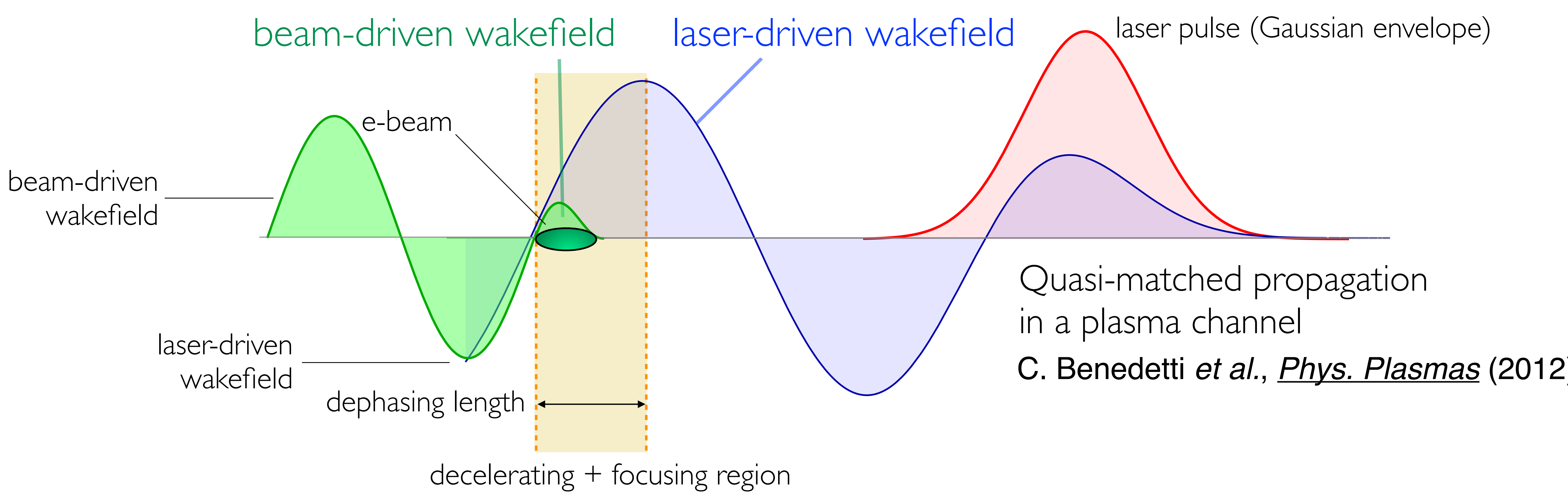
$$s_{max}(n_0, \gamma)\ ,\ (L = 2.7\,\mu\mathrm{m}\,,\ r_b = 2.7\,\mu\mathrm{m}\,,\ Q = 10\,\mathrm{pC})$$





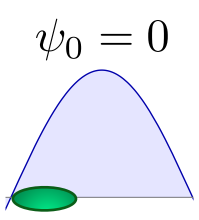
Active beam dump:
laser wakefield reduces energy chirp

- Frozen e-beam propagating in the wake of a laser pulse ($v_b \simeq c$):



- Laser wakefield:

given by pulse shape and duration



Relative phase between beam and laser wake

$$\frac{E_{z\ell}(\xi, r, s, \psi_0)}{E_0} = \frac{E_{max}^{z\ell}}{E_0} \sin\left[k_p \xi + \frac{k_p s}{2\gamma_g^2} + \boxed{\psi_0}\right]\left[1 - \frac{2r^2}{r_w^2}\right] \quad , \; r_b \ll r_w$$

Phase slippage

Active beam dump $1\mathrm{D}$

- General expression for the evolution of the beam total energy (active beam dump scheme):

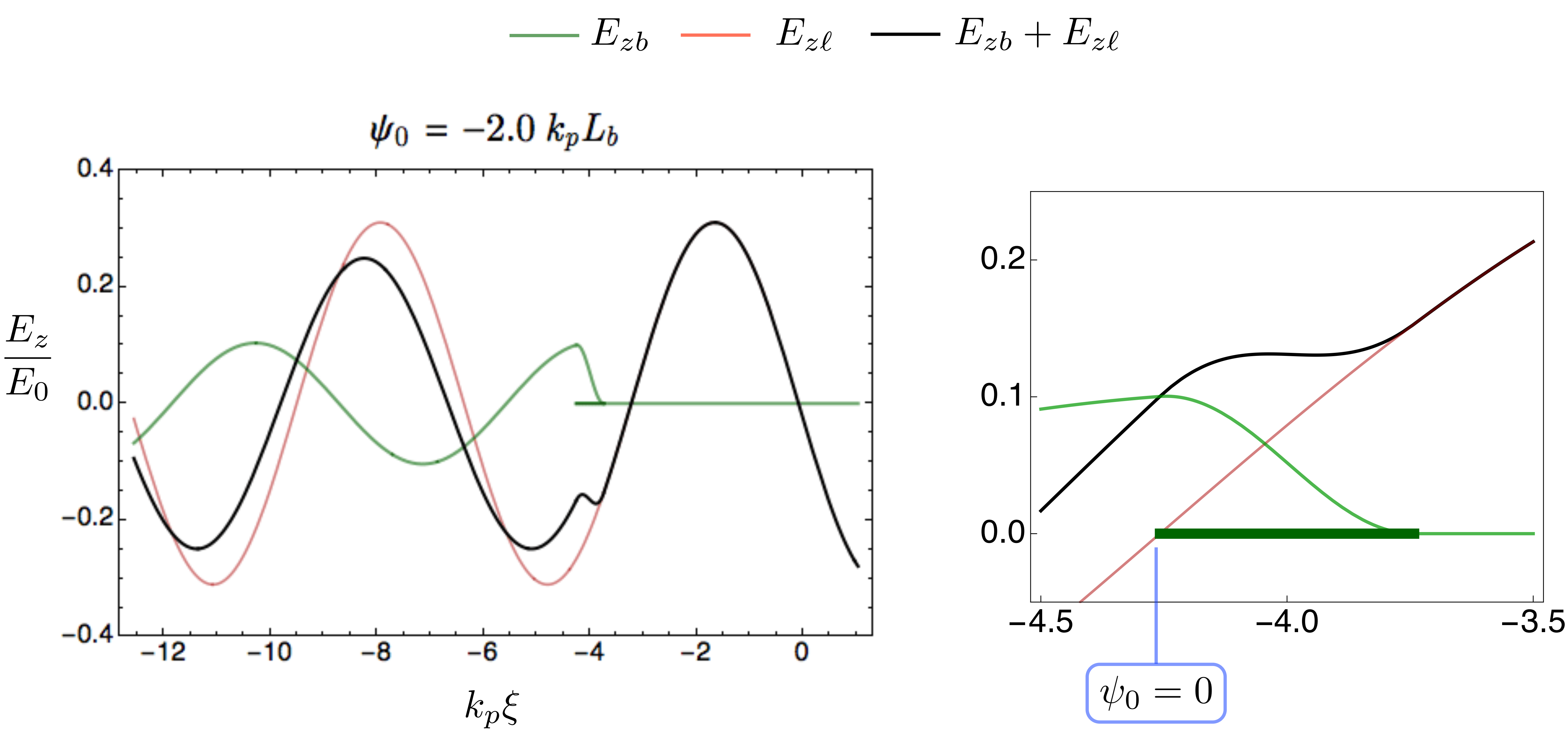
$$\frac{U(s,\psi_0)}{U_0} = 1 - k_p s \, \frac{\int_V dV \left[E_{zb}(\xi,r)/E_0\right]\left[n_b(\xi,r)/n_0\right]}{\gamma_0 \int_V dV \; n_b(\xi,r)/n_0}$$
$$-k_p \frac{\int^s ds' \int_V dV \left[E_{z\ell}(\xi,r,s',\psi_0)/E_0\right]\left[n_b(\xi,r)/n_0\right]}{\gamma_0 \int_V dV \; n_b(\xi,r)/n_0}$$

- 1D case: e-beam with half-sine longitudinal profile:

$$\frac{U(s,\psi_0)}{U_0} = 1 - k_p s \, \frac{\pi^3 k_p L \, (n_b/n_0) \cos^2(k_p L/2)}{\gamma_0(\pi^2 - k_p^2 L^2)^2}$$
$$- \frac{4\pi^2 \gamma_g^2 (E_{max}^{z\ell}/E_0) \cos(k_p L/2)}{\gamma_0(\pi^2 - k_p^2 L^2)} \sin\!\left[\frac{k_p s}{4\gamma_g^2}\right] \sin\!\left[\frac{k_p L}{2} + \frac{k_p s}{4\gamma_g^2} + \psi_0\right]$$

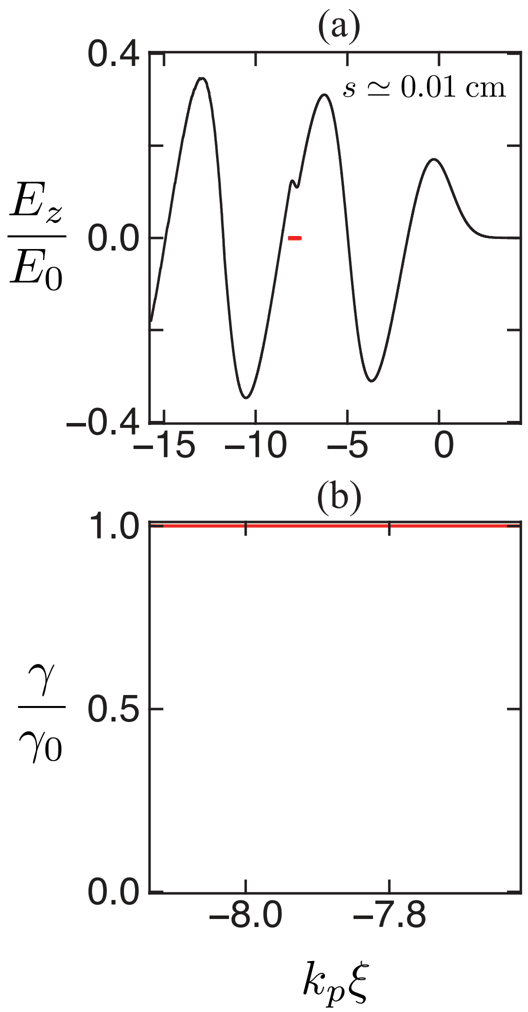
Active beam dump: laser wake can flatten Ez along the beam

- Total wakefield (black line):



Active beam dump $1\mathrm{D}$ - analytical model vs. PIC (Warp)

$$n_0 = 10^{18}\mathrm{cm}^{-3}\,,\; L = 2.7\,\mu\mathrm{m}\,(k_p L \simeq 0.5)\,,\; n_b/n_0 = 0.315\,(E_z/E_0 = 0.1)\,,\; \gamma_0 = 1000$$
$$a_0 = 1\,(\mathrm{lin.\ pol.})\,,\; \lambda_0 = 0.8\,\mu\mathrm{m}\,,\; \sigma_\ell \simeq 7.5\,\mu\mathrm{m}\,(k_p\sigma_\ell = \sqrt{2})$$



Active beam dump 2D axi-symmetric

- Half-sine (longitudinal) , parabolic (transverse):

$$n_b(\xi, r) = \frac{n_b}{n_o} \sin\left(\frac{\pi\xi}{L}\right)\left(1 - \frac{r^2}{r_b^2}\right) \ , \ \left[\begin{array}{l} 0 \leq \xi \leq L \\ 0 \leq r \leq r_b \end{array}\right.$$

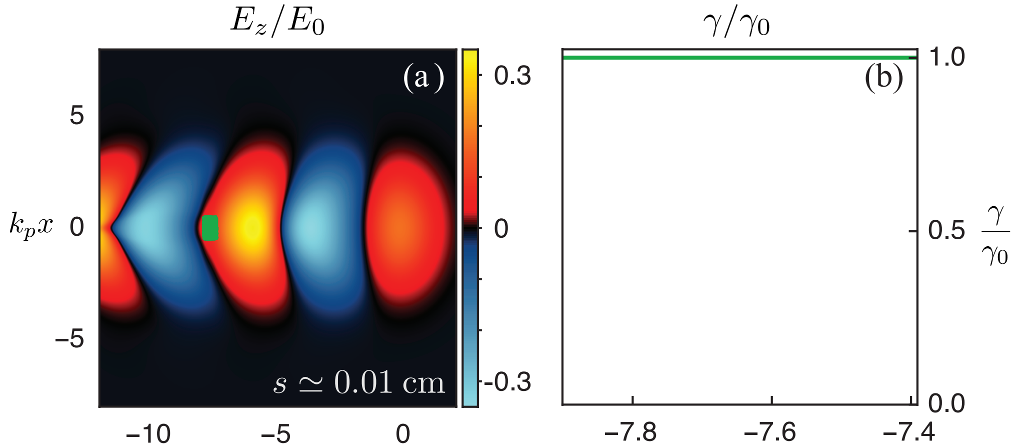
- Energy loss:

$$\frac{U(s)}{U_0} = 1 - k_p s \, \frac{\pi^3 k_p L \, (n_b/n_0) \cos(k_p L/2)^2}{\gamma_0(\pi^2 - k_p^2 L^2)^2} \left[\frac{2}{3} \frac{k_p^2 r_b^2 - 6 + 24 \, I_2(k_p r_b) K_2(k_p r_b)}{k_p^2 r_b^2}\right]$$
$$- \frac{4\pi^2 \gamma_g^2 (E_{max}^{z\ell}/E_0) \cos(k_p L/2)}{3\gamma_0(\pi^2 - k_p^2 L^2)} \left[3 - 2\frac{r_b^2}{r_w^2}\right] \sin\left[\frac{k_p L}{2}\right] \sin\left[\frac{k_p L}{2} + \frac{k_p s}{4\gamma_g^2} + \psi_0\right]$$

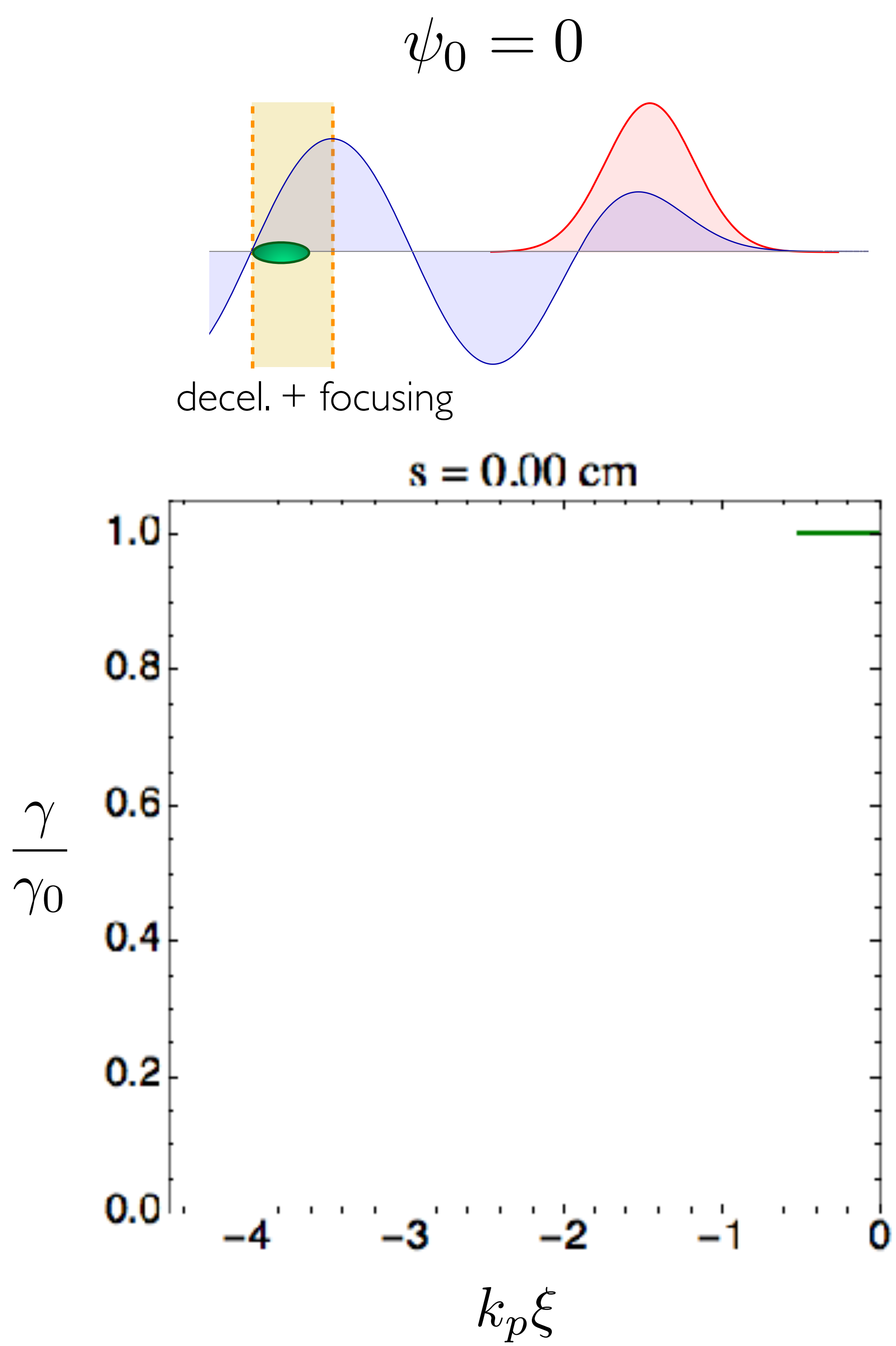
Active beam dump 2D axi-symmetric: analytical vs. PIC (INF&RNO)

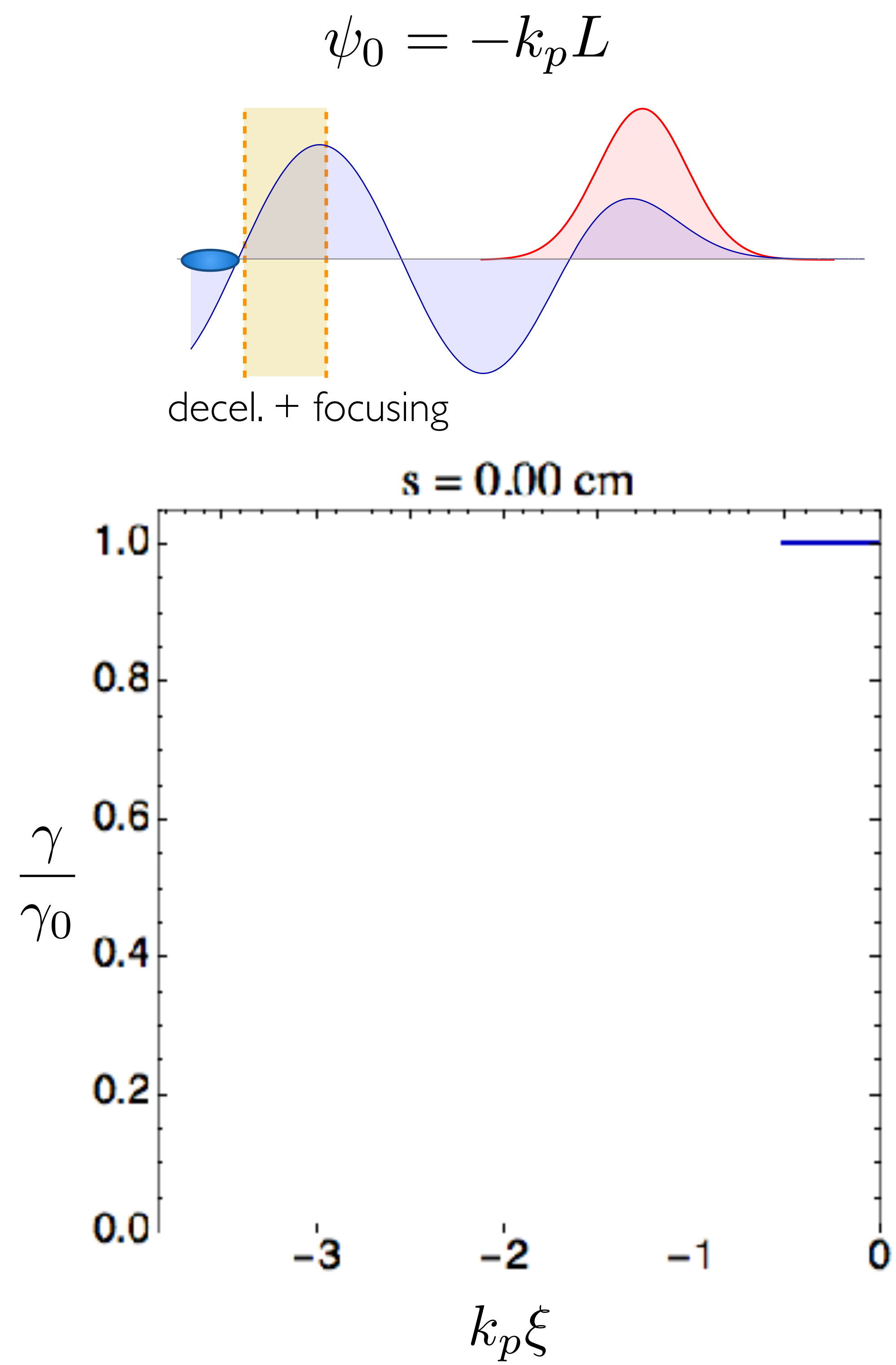
$$n_0 = 10^{18}\mathrm{cm}^{-3}\,,\; L = r_b = 2.7\,\mu\mathrm{m}\,(k_pL = k_pr_b \simeq 0.5)\,,\; Q = 10\,\mathrm{pC}\,,\; \gamma_0 = 1000$$

$$a_0 = 1\,(\text{lin. pol.})\,,\; \lambda_0 = 0.8\,\mu\mathrm{m}\,,\; \sigma_\ell \simeq 7.5\,\mu\mathrm{m}\,(k_p\sigma = \sqrt{2})\,,\; r_w \simeq 17\,\mu\mathrm{m}\,(k_pr_w = \pi)$$

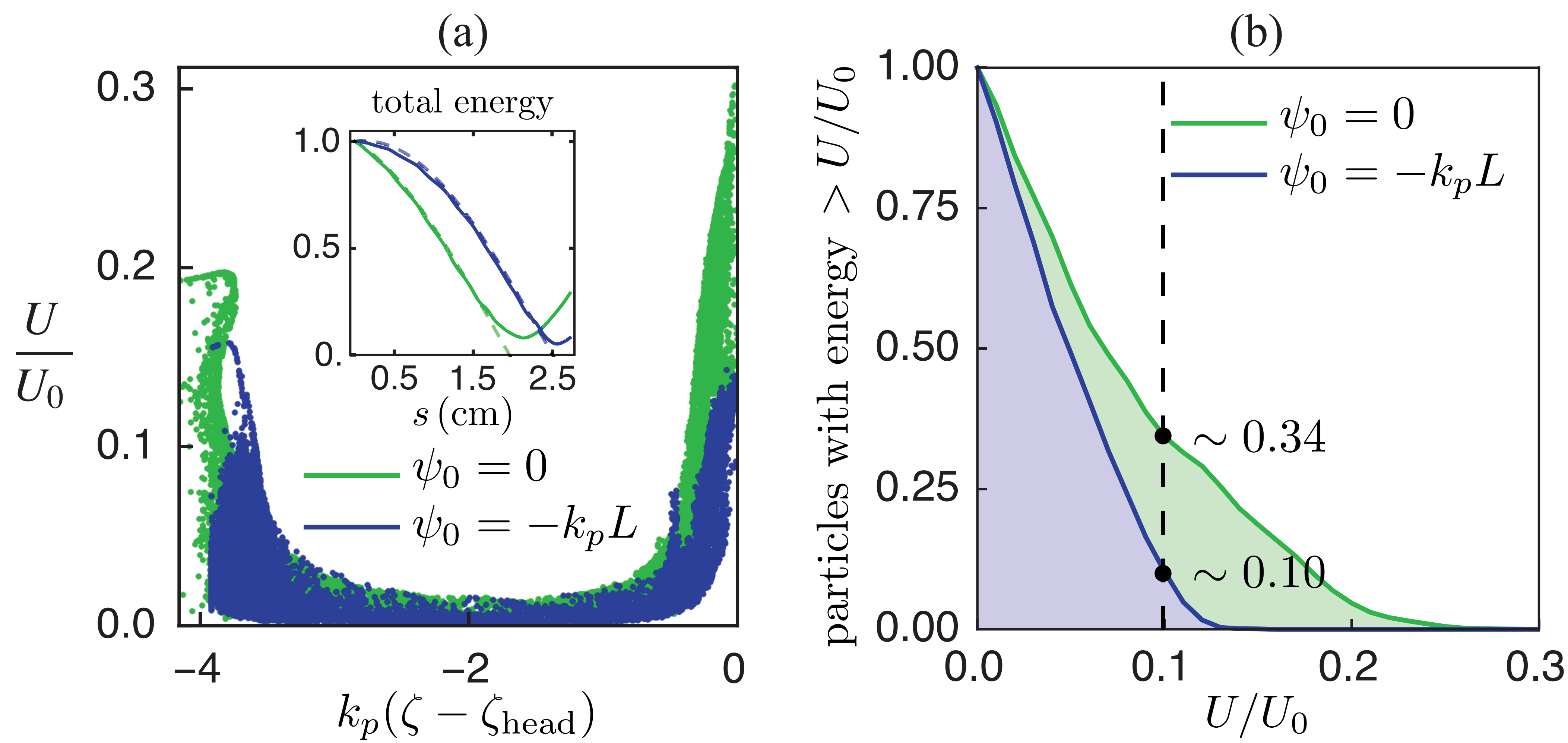


Active beam dump: the energy extraction can be improved by changing the phase





Active beam dump: the energy extraction can be improved by changing the phase



$$\frac{U(2.1\,\mathrm{cm})}{U_0} \simeq 0.08 \qquad \frac{U(2.6\,\mathrm{cm})}{U_0} \simeq 0.05$$

Summary

- Plasma-based beam dumps are a promising method to decelerate e-beams with ~GeV energies over centimeter-scale distances.
- This could be used to mitigate the requirements of conventional beam dumps and/or to go to higher rep-rates.
- Analytical models derived for the evolution of the beam total energy show good agreement while the adopted assumptions remain valid.
- Passive beam dump: head-to-tail variation of the beam-driven wakefield causes a strong beam energy chirp.
- Active beam dump: laser-driven wake flattens the total wakefield along the beam, greatly reducing the beam energy chirp.
- Energy extraction still can be improved (beam phasing, plasma density tailoring).