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A fully plasma based electron injector for a linear collider or XFEL

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Advanced Accelerators Concepts
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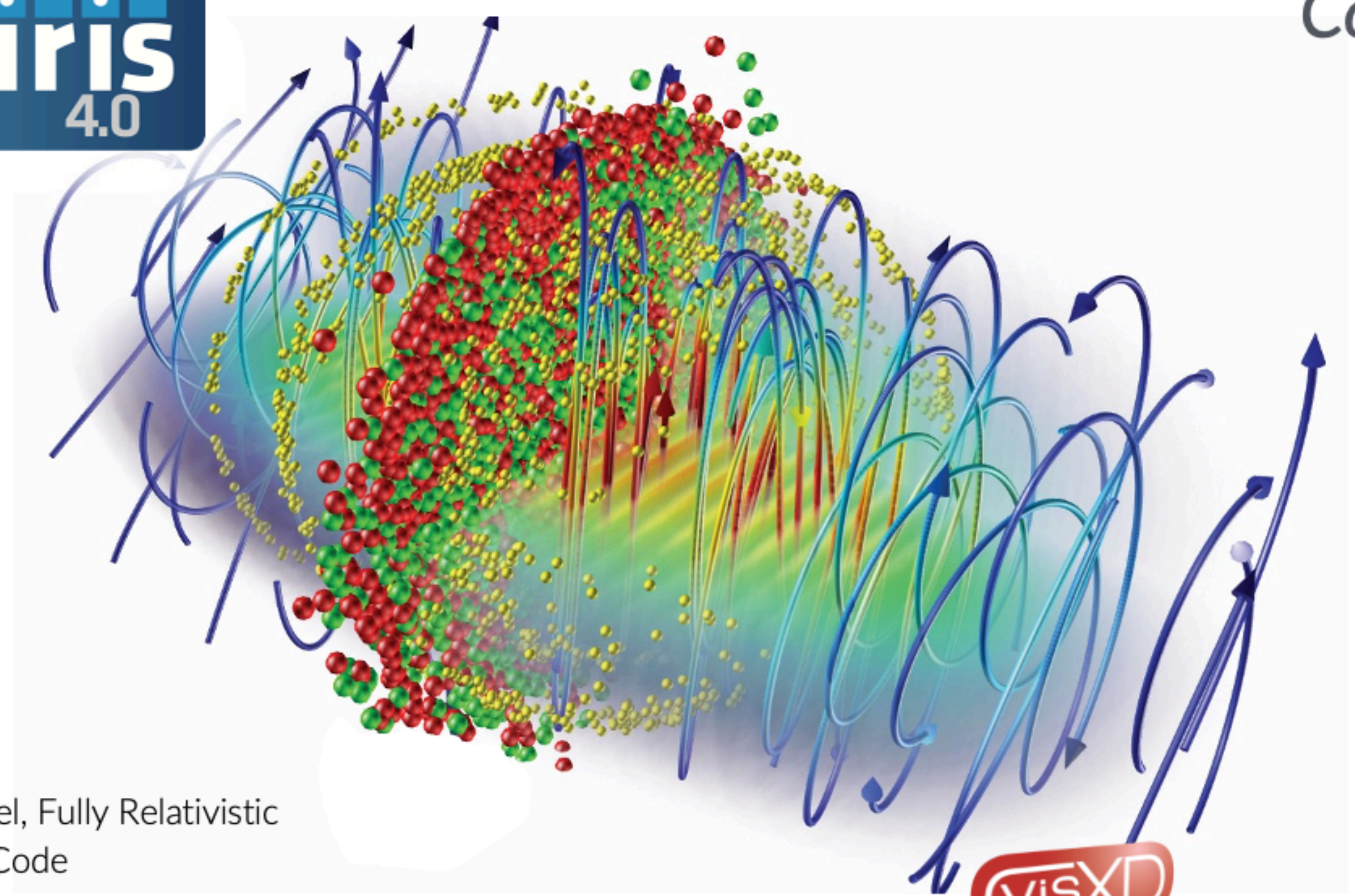
PIC simulations performed using OSIRIS 4.0

Osiris 4.0



Committed to open science

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at: http://epp.tecnico.ulisboa.pt/osiris

Open-source version

- Search osiris-code/osiris on GitHub

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended physics/simulation models

visXD

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Challenges for a PBA-based XFEL or LC

Beam generation & optimal acceleration

- **PBA can enable high gradient acceleration (> 1 GV/cm) and high quality beam generation for next-gen XFEL and LCs.**

$$Q \sim 1 \text{ nC}, \quad \epsilon_n \sim 100 \text{ nm}$$

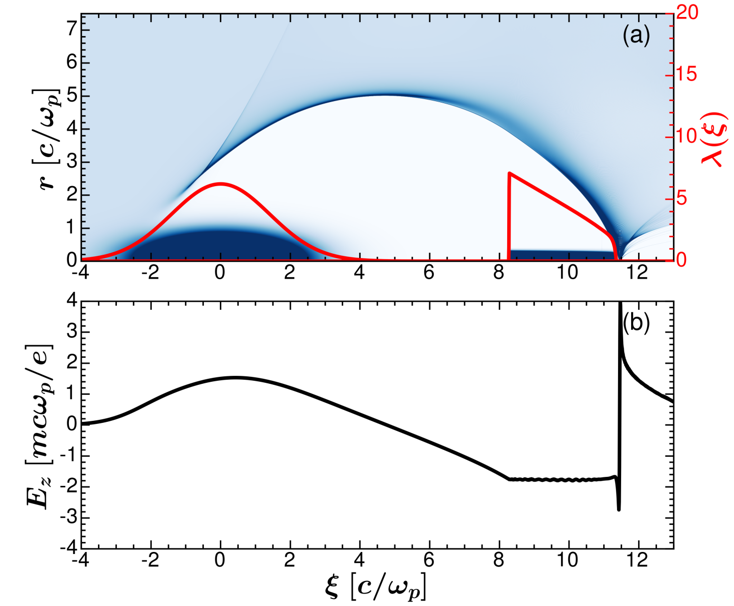
- **Main challenge: low energy spread acceleration.**

- **Ideal loading difficult to realize with injection.**

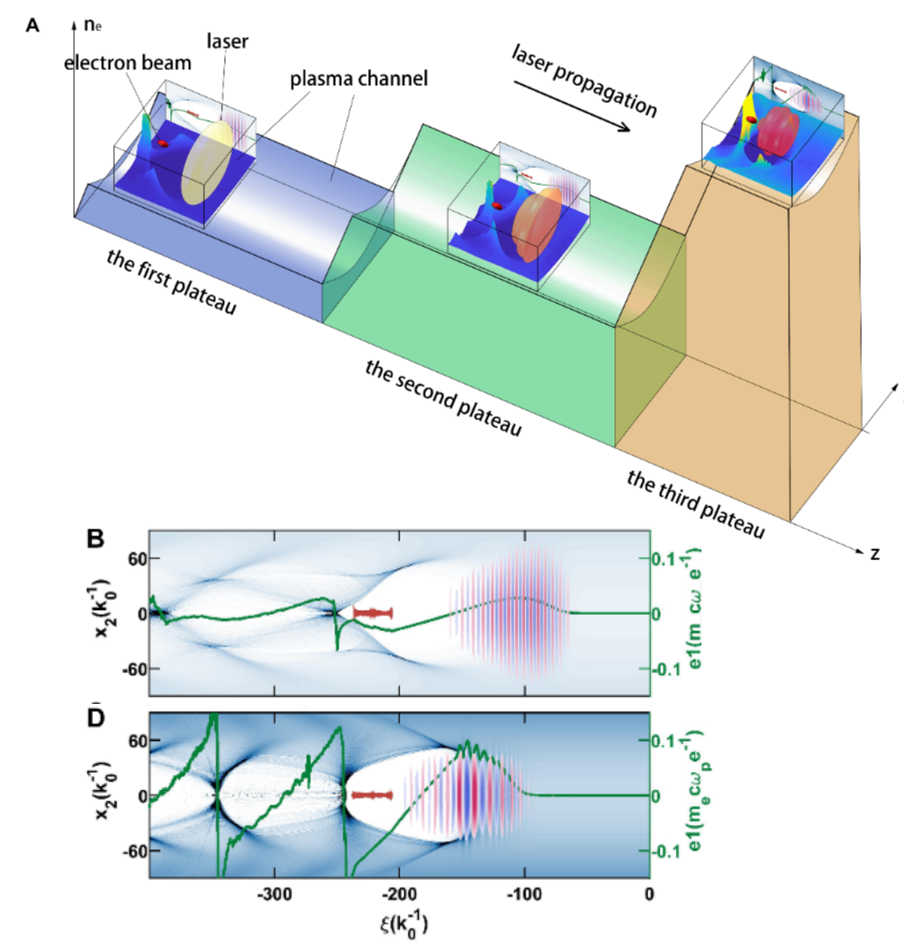
- **Dynamic beam loading (DBL) schemes (e.g., tri-plateau plasma) aim to flatten average field**

$$\langle d_\xi E_z \rangle_{acc} \approx 0$$

$\xi = z - ct$



T. N. Dalichaouch et al., Phys. Plasmas, 28, 063103 (2021).



S. Liu, et al., Research, 0, 34133 (2024).

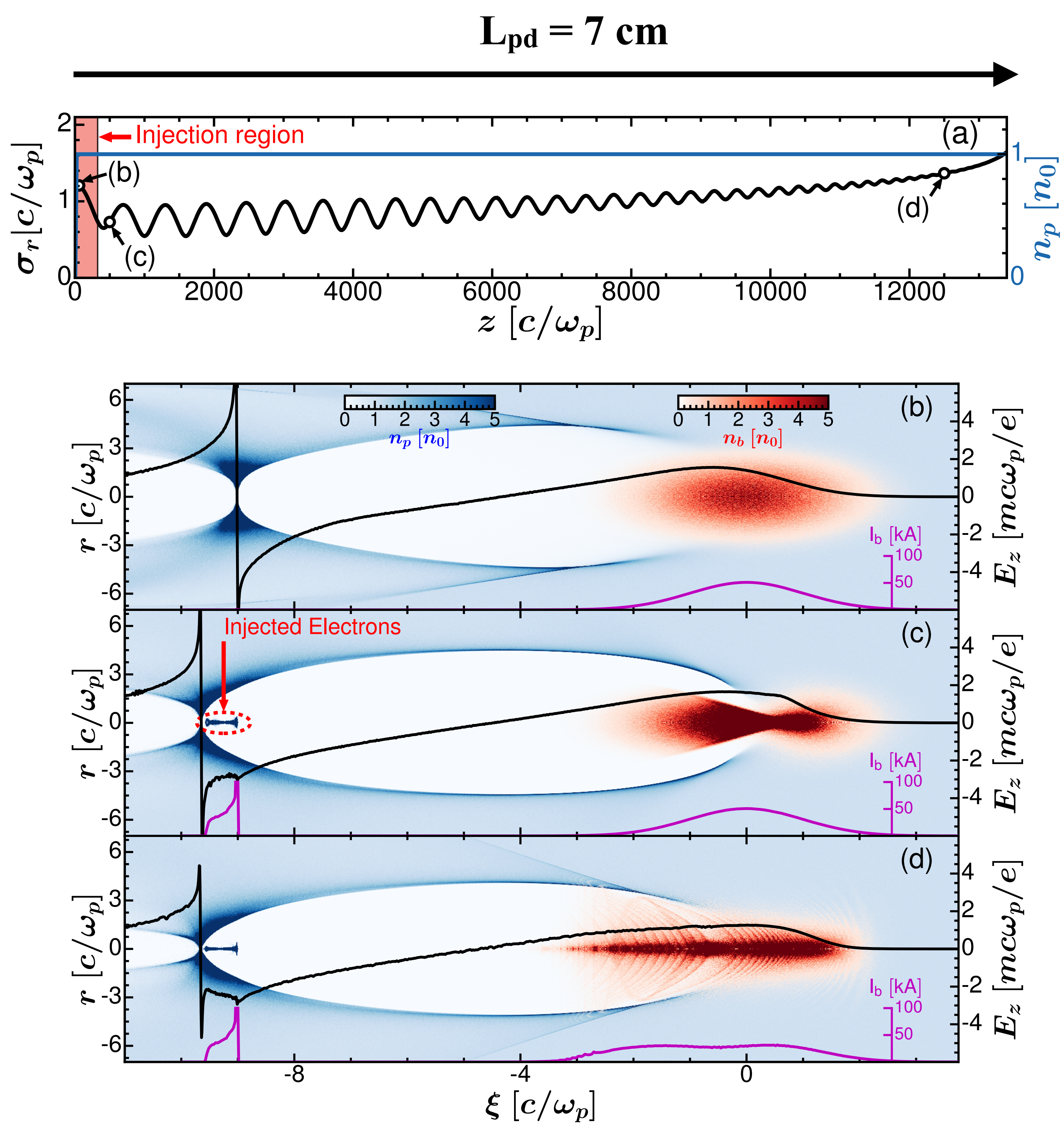
Proposed DBL scheme using PWFA

Proposed Scheme

- **An unmatched e- driver (2.3 nC) self-focuses leading to injection (0.5 nC).**
- **DBL is then induced by wake evolution.**
- **Transitions from underloaded ($d_\xi E_z > 0$) to overloaded $d_\xi E_z < 0$**
- **DBL is dictated by pump depletion.**

Drive/Plasma Parameters

$I_{pk} \simeq 51$ kA, $\sigma_r \simeq 6.5$ um, $\sigma_z \simeq 5.3$ um,
$\gamma_b = 10$GeV, $\beta^* = 1.7$ cm, $n_p \simeq 10^{18}$ cm^{-3}



T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

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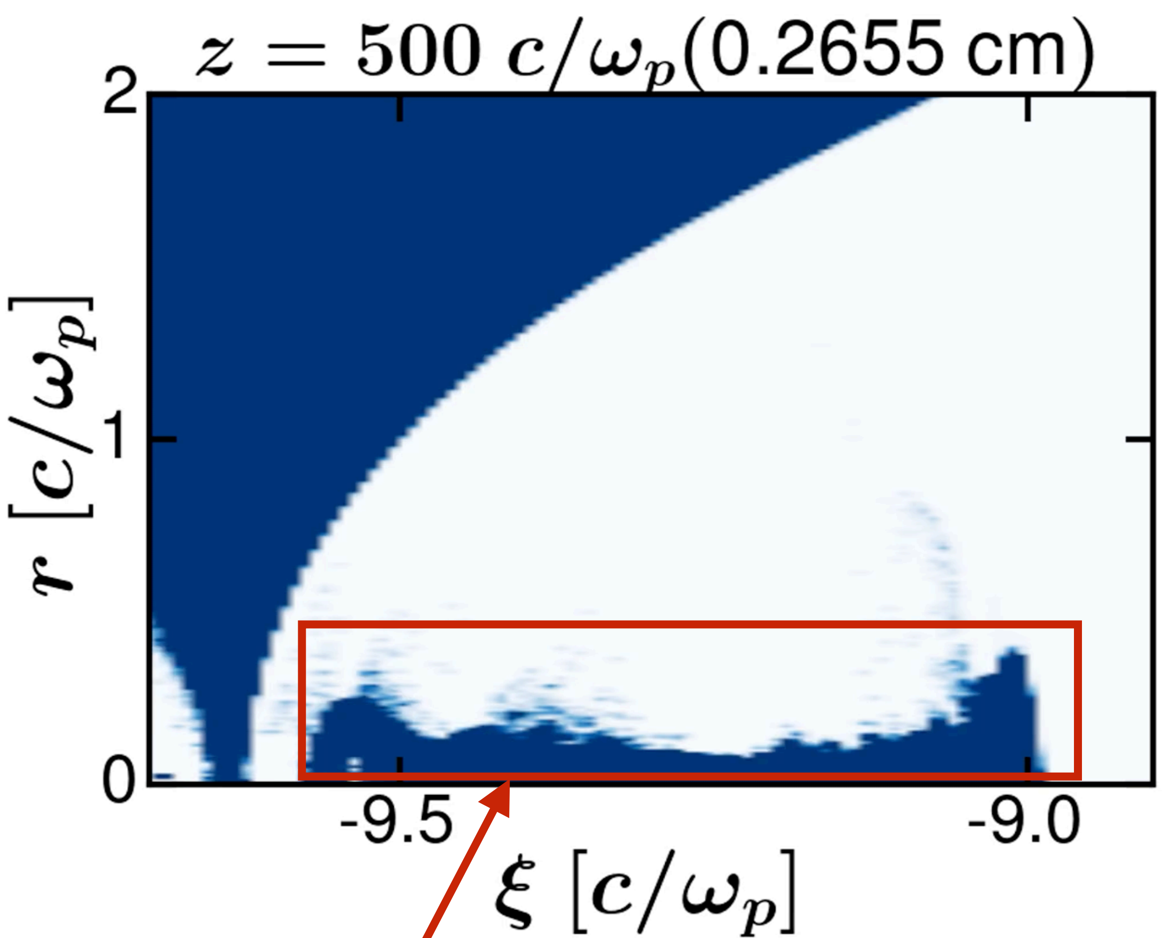
"Bubble" evolution causes DBL



Injected bunch

Nonlinear theory

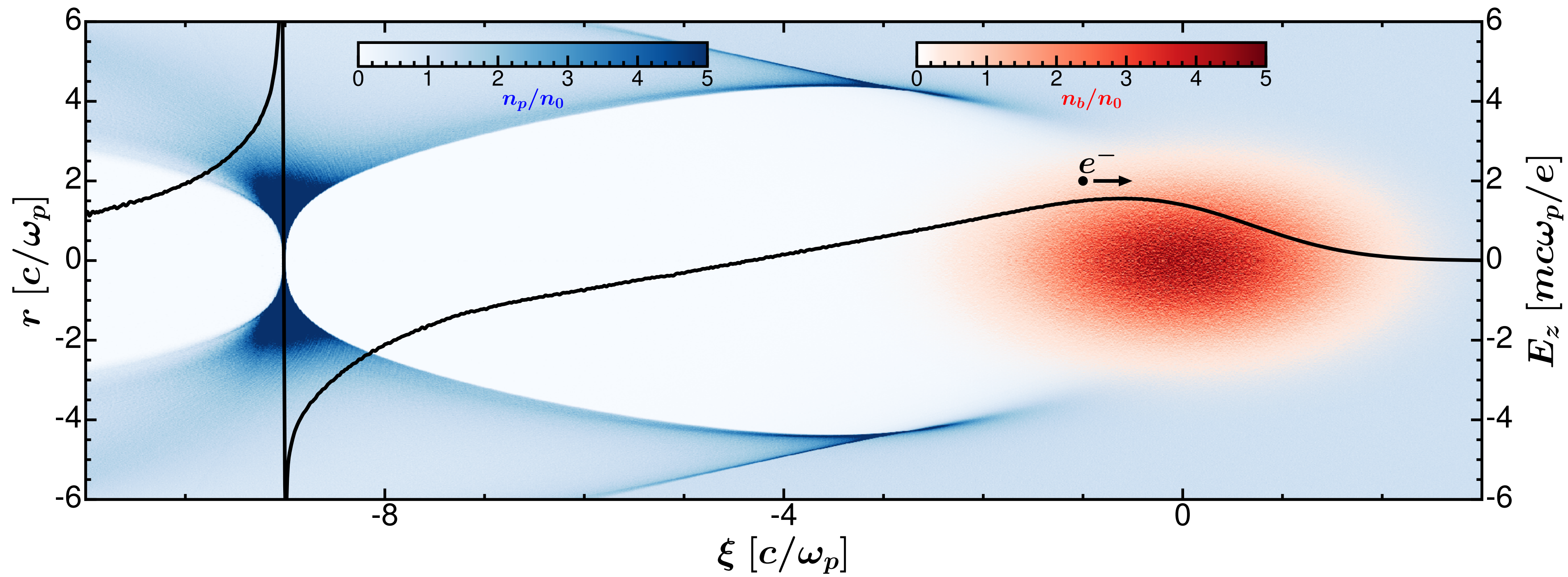
- **The loading of the wake depends on the bubble radius** $r_b(\xi)$ **and beam current** $\lambda(\xi)$

$$\frac{dE_z}{d\xi} = \frac{1}{2} + \frac{1}{2}\left(\frac{dr_b}{d\xi}\right)^2 - \frac{\lambda(\xi)}{r_b^2}$$

- **DBL induced by wake evolution: rb decreases, space-charge force increases.**
- $d_\xi E_z$ **changes sign from positive to negative.**

T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

Drive beam dynamics responsible for DBL



Transverse dynamics

$$x''(z) + \frac{\gamma_b'(z)}{\gamma_b} x'(z) + k_\beta(z)^2 x(z) = 0$$

$$\boldsymbol{x}(z) \approx \boldsymbol{x_i} \left[\frac{\gamma_{bi}}{\gamma_b(z)}\right]^{1/4} \cos(\phi)$$

Longitudinal dynamics

$$\frac{d\xi}{cdt} = \frac{v_z}{c} - 1 \approx -\frac{|\boldsymbol{x}'|^2}{2}$$

$$\Delta\xi(z) \approx \frac{-k_p^2 r_i^2 z}{4\gamma_b(1+\sqrt{\gamma_{bi}/\gamma_b})}$$

$$k_\beta(z) = \frac{k_p}{\sqrt{2\gamma_b(z)}} \qquad \phi = \int_0^z k_\beta ds$$

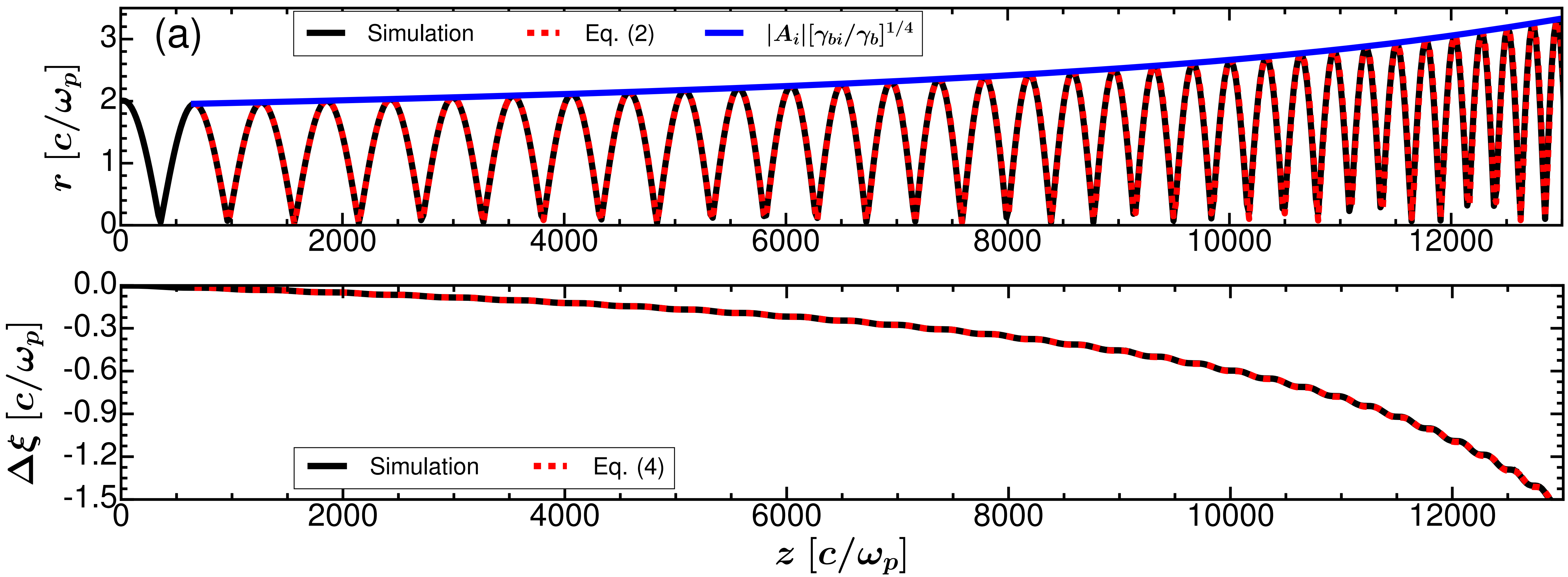
Trans/long dynamics coupled to energy

T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

Example drive beam electron motion

$$\boldsymbol{x}(z) \approx \boldsymbol{x_i} \left[\frac{\gamma_{bi}}{\gamma_b(z)} \right]^{1/4} \cos(\phi) \quad (2)$$

$$\frac{d\xi}{cdt} \approx -\frac{|\boldsymbol{x}'|^2}{2} \quad (4)$$



- **Betatron oscillations and pump depletion lead to defocusing+dephasing.**

T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

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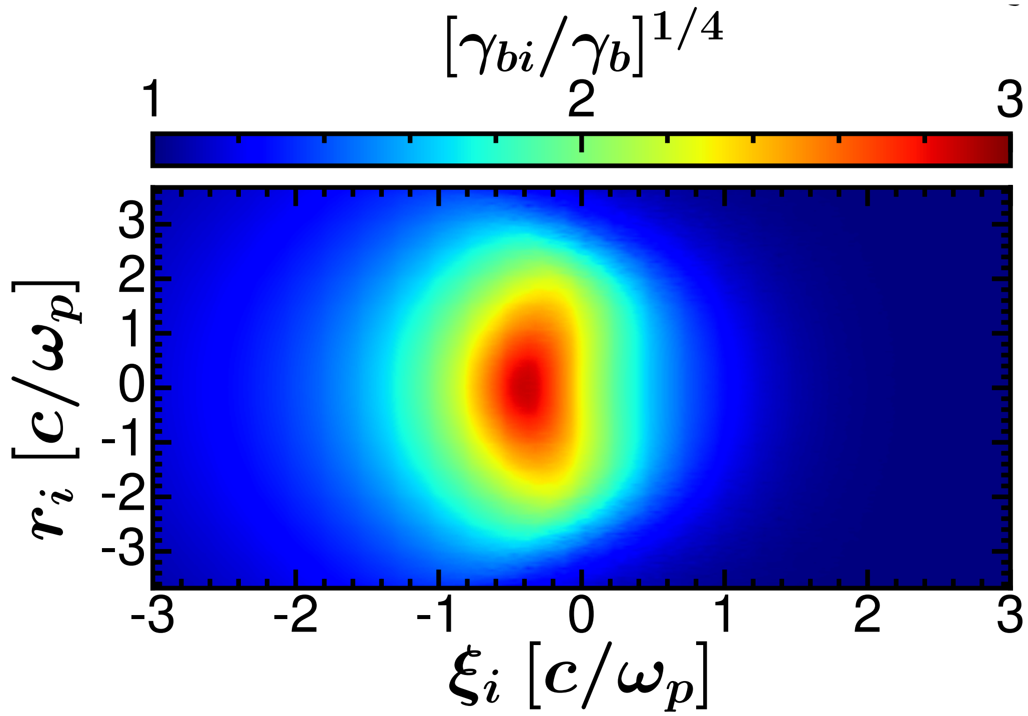
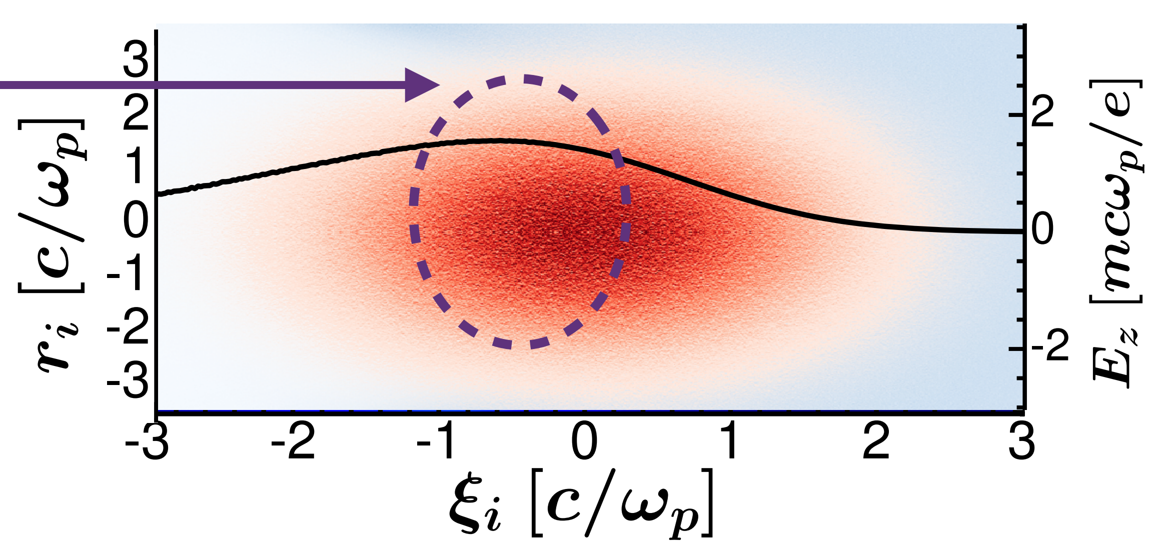
Which beam components drive defocusing?

- **Energy factor $x(z) \sim \left[\gamma_{bi}/\gamma_b(z)\right]^{1/4}$ for drive beam electrons shown after 6.9 cm (13000 c/wp)**

- **Spot size expansion driven by significant pump depletion (93%+ energy loss) behind the centroid** $(-1 \lesssim k_p\xi_i \lesssim 0)$

- **Strong defocusing where decelerating field is large.**





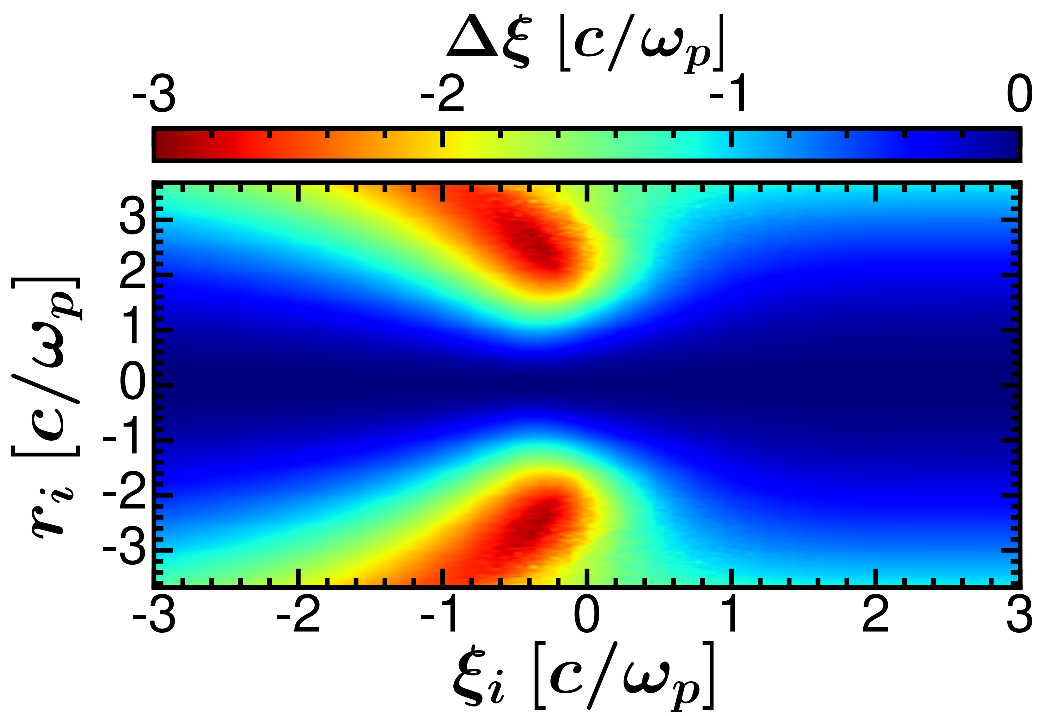
T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

Which beam components drive dephasing?

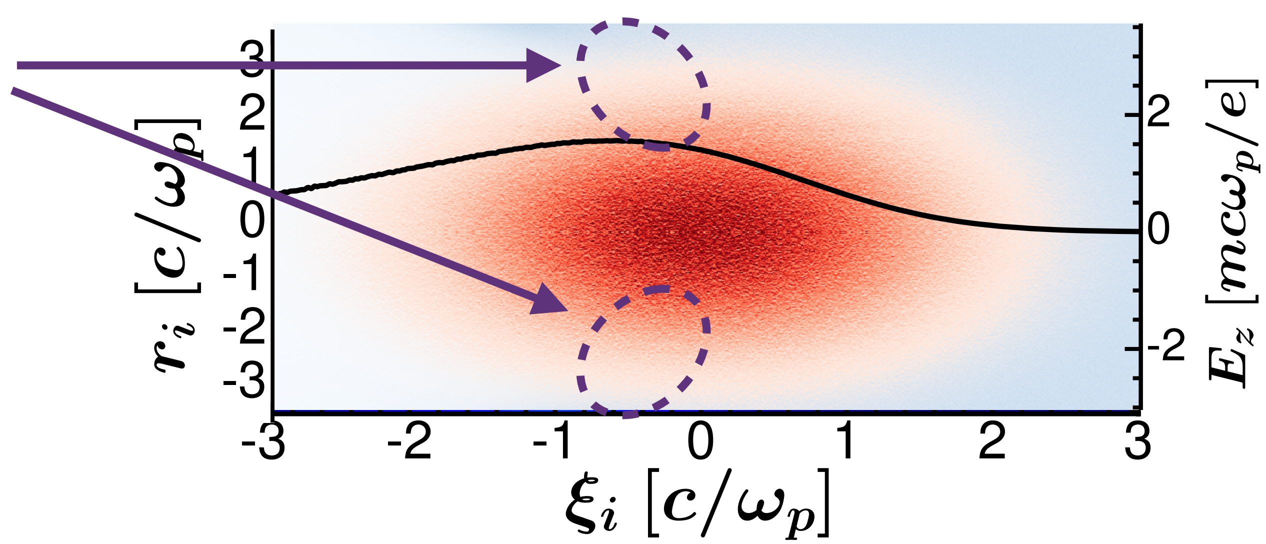
- **Dephasing $\Delta\xi$ shown for driver beam electrons after z = 6.9 cm (13000 c/wp) in plasma.**

$$\Delta\xi(z) \approx \frac{-k_p^2 r_i^2 z}{4\gamma_b(1+\sqrt{\gamma_{bi}/\gamma_b})}$$

$$\frac{d\xi}{cdt} \approx -\frac{|\boldsymbol{x}'|^2}{2}$$

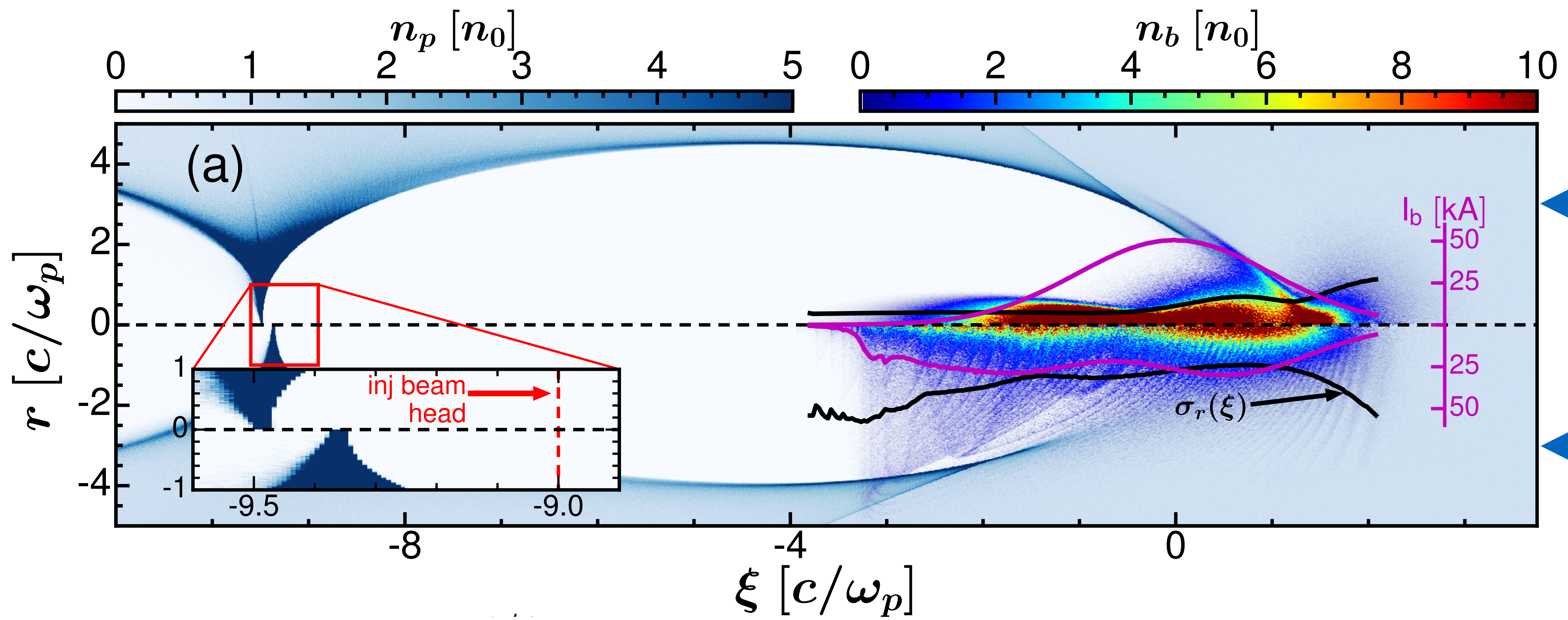


- **Dephasing is most prominent for particles with high frequency, large betatron oscillations.**



T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

Unloaded wake evolution over pump depletion



z = 0.5 cm
7% energy loss

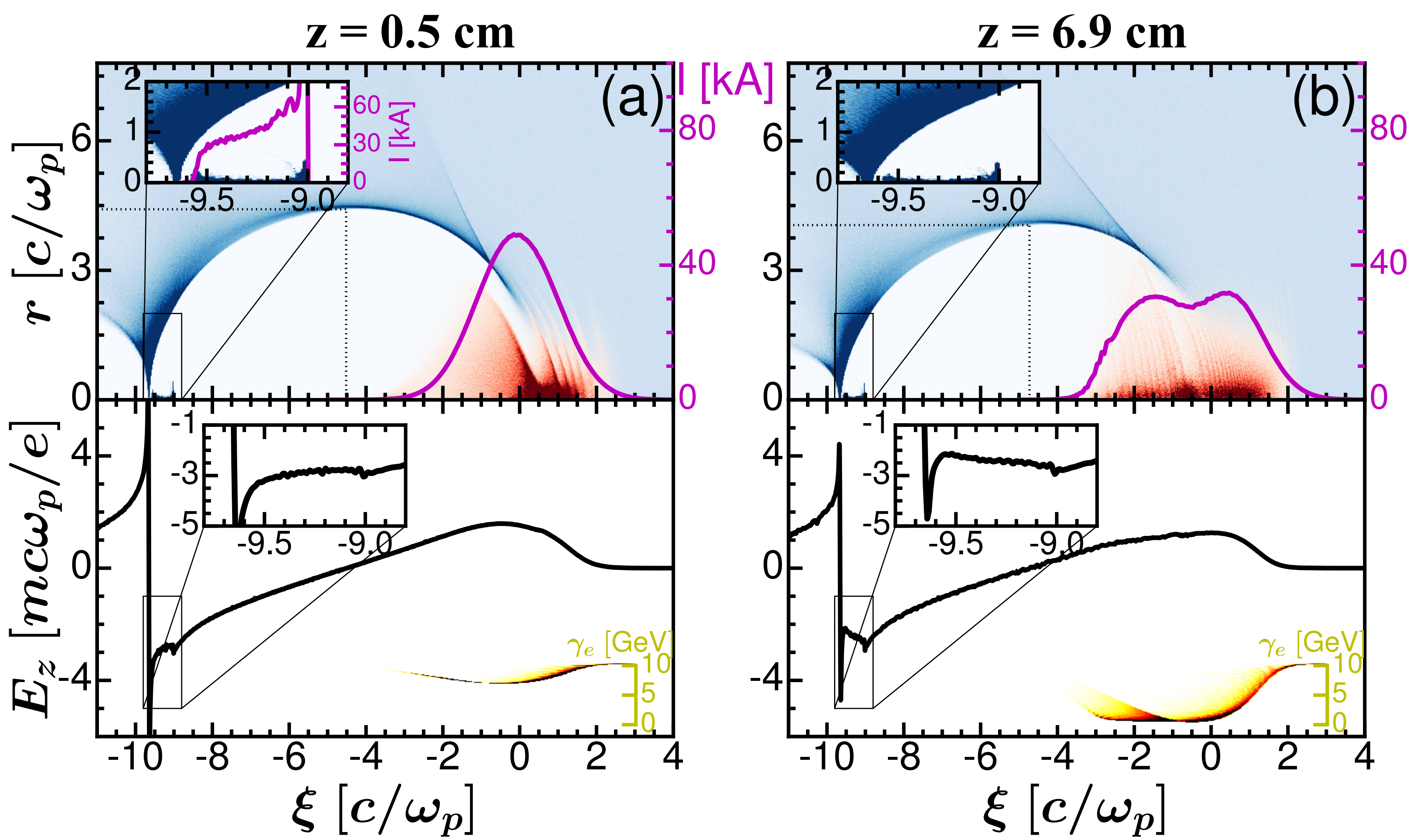
z = 6.9 cm
93% energy loss

Wake evolution w/out trailing beam

- **Spot size defocusing reduces the wake length.**
- **Dephasing reduces peak current and blowout radius** $k_p r_m \approx 2\sqrt{\Lambda}$
- **Smaller** $r_b(\xi)$ **along injected beam leads to stronger loading.**

T. N. Dalichaouch et al., arXiv:2406.04585 (2024).

Loaded wake evolution over pump depletion



- **Loaded wake remains fully expanded due to the space-charge force.**
- **Beam force $\lambda(\xi)/r_b$ increases ($r_b \downarrow$) and slope $dr_b/d\xi$ decreases ($|p_\perp| \downarrow, \psi \uparrow$).**

$$\frac{dE_z}{d\xi} = \frac{1}{2} + \frac{1}{2}\left(\frac{dr_b}{d\xi}\right)^2 - \frac{\lambda(\xi)}{r_b^2} \qquad \frac{dr_b}{d\xi} = \frac{-p_\perp}{1+\psi}$$

- **Beam term dominates so chirp becomes negative (overloaded).**

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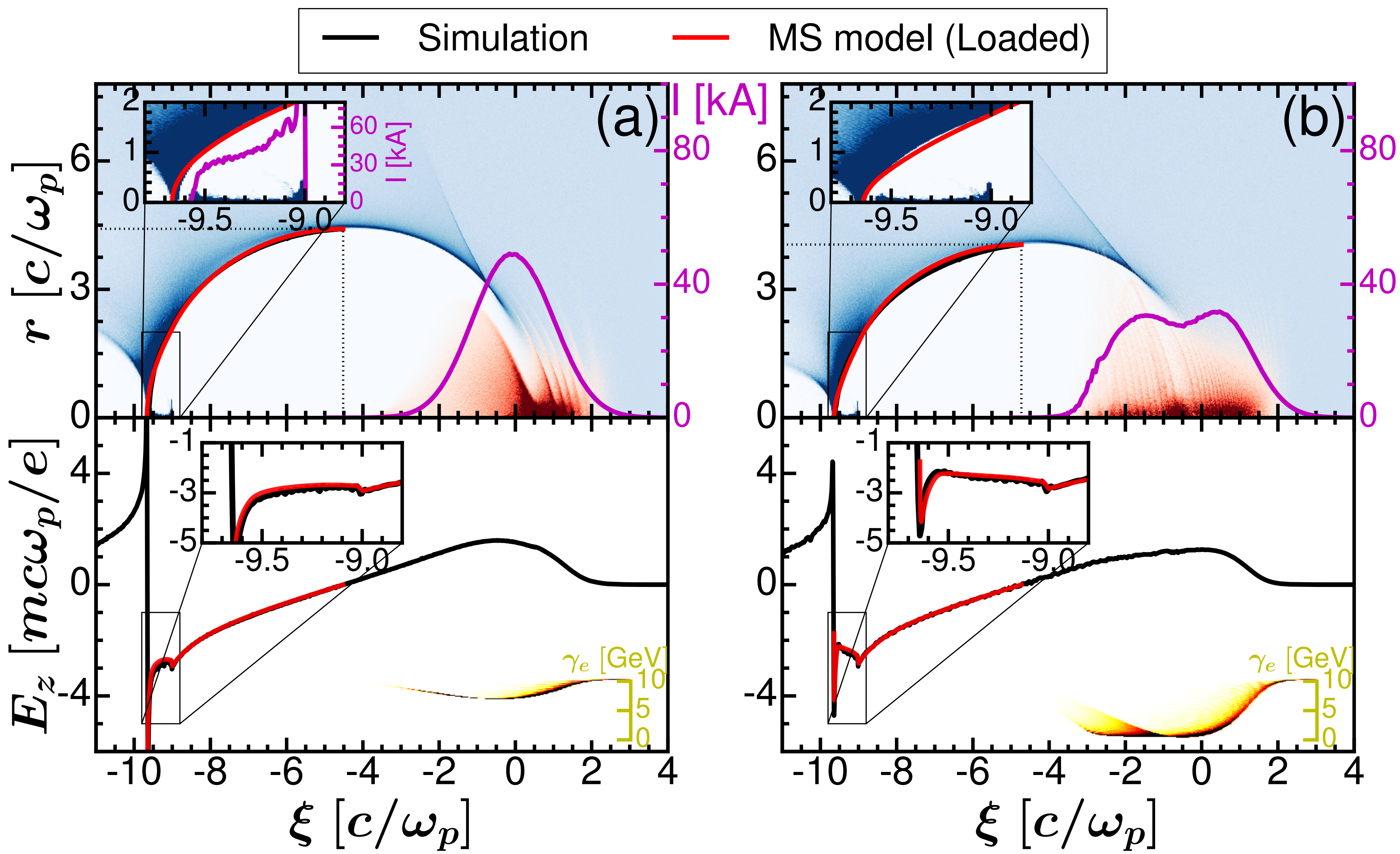
DBL effect verified by multi-sheath model



Multi-sheath model

Verified this DBL effect using multi-sheath model for wake potential. Bubble radius and electric field obtained from 2nd order pde

$$\psi_0(\xi) = (1+\beta')r_b^2/4, \quad E_z(\xi) = d\psi_0/d\xi$$

MS Model Ref - T. N. Dalichaouch et al., PoP 28 (063103), 2021.

Energy spread evolution of injected beam

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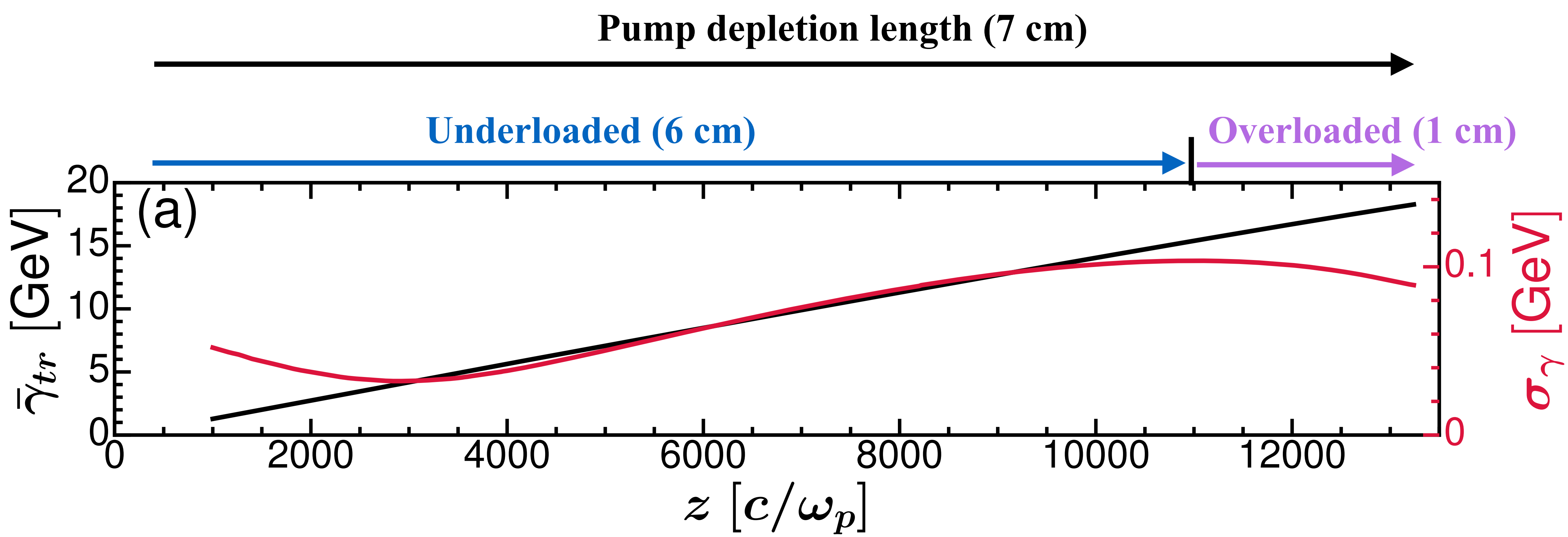

- **Wake is underloaded until final 10-20% of pump depletion distance**
- **Energy spread deviates (sub 0.1 GeV) due to strong overloading.**
- **Normalized energy spread** $\hat{\sigma}_\gamma = \sigma_\gamma / \langle \gamma \rangle \sim \langle d_\xi E_z \rangle$ **is minimized**

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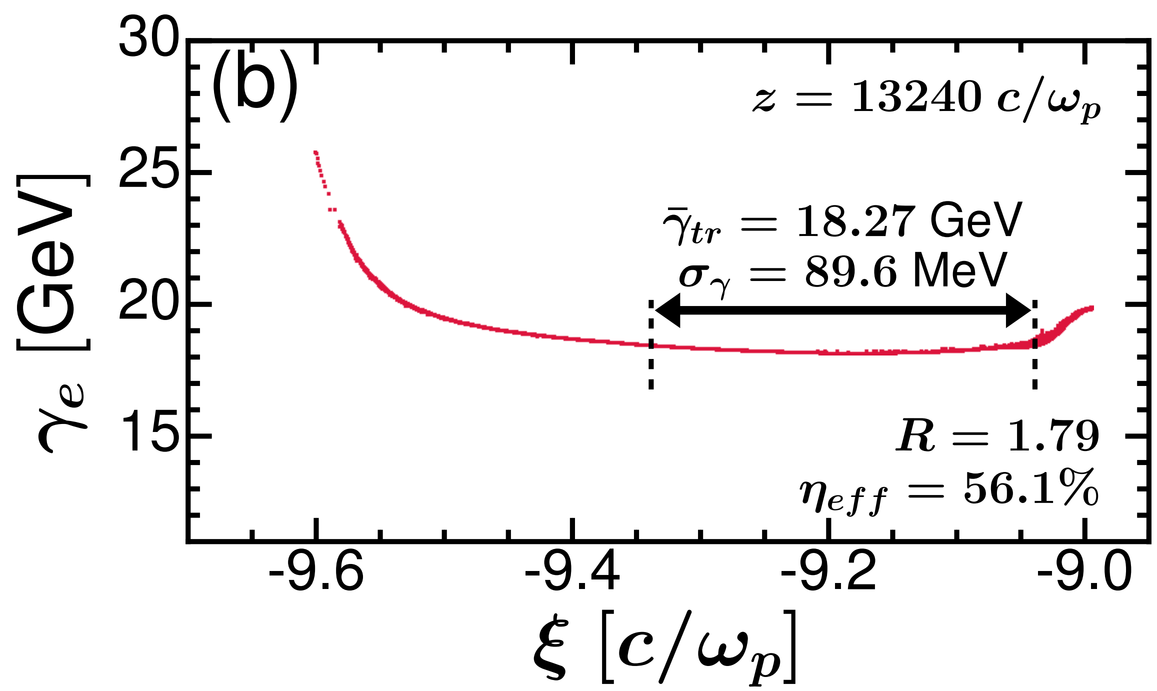
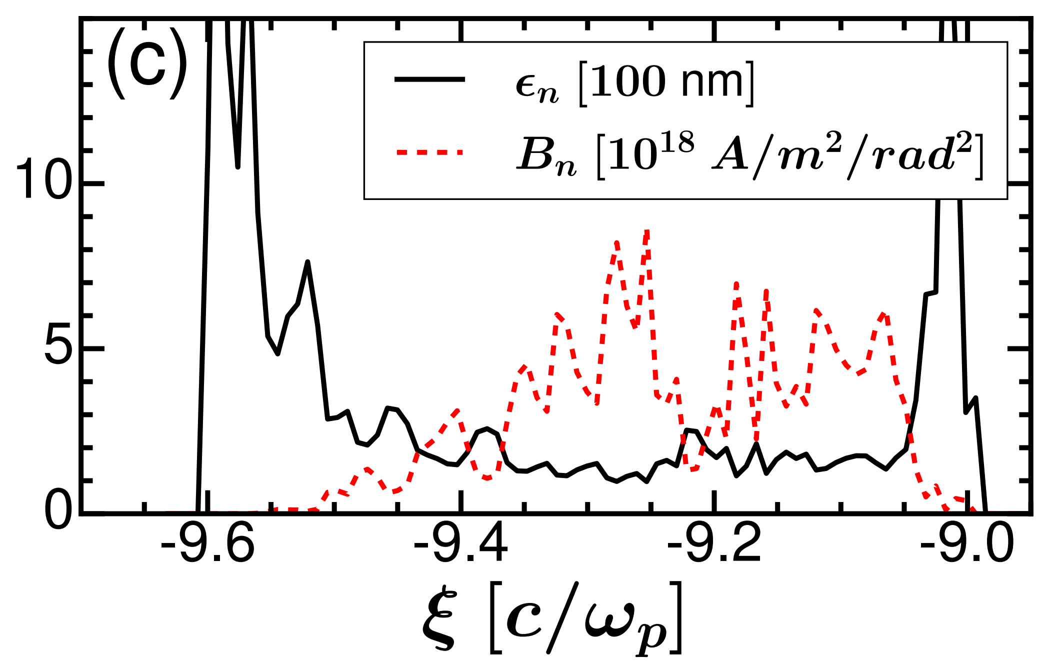
Energy and final beam slice parameters (7 cm)

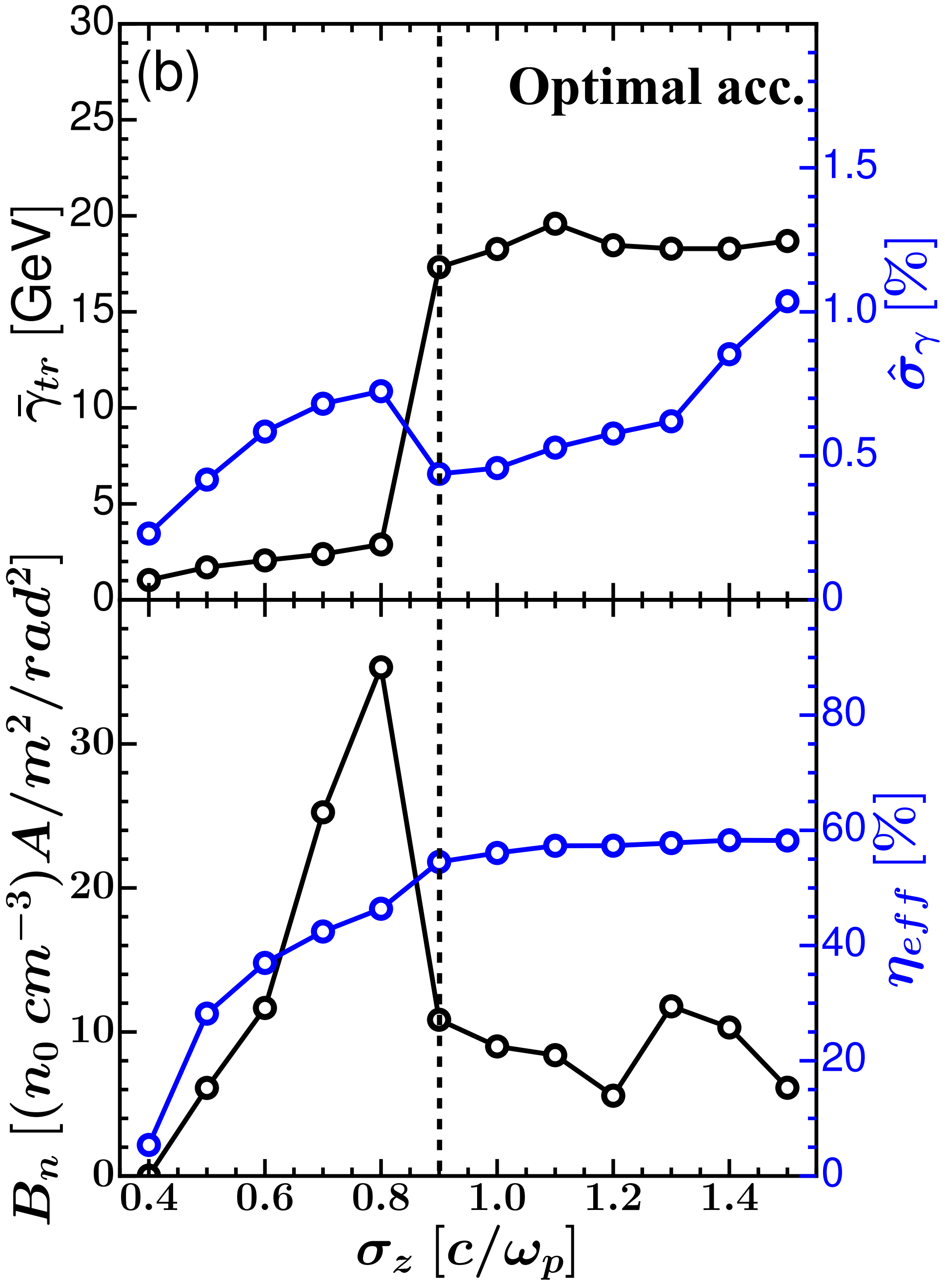


- **Beam extracted with ~18.3 GeV and ~90 MeV (0.49%) after 7 cm propagation distance.**
- **High efficiency acceleration 56% and high transformer ratio ~1.8.**



Energy/Brightness Booster	Drive	Trailing
Energy	10 GeV	18.3 GeV
Emittance	~ 50 um	~ 100 nm
Bn [A/m²/rad²]	10^{14}	10^{19}

Longer drivers that generate optimal DBL



- **Parameter scans show optimal DBL can be achieved by using longer drivers** $\sigma_z \gtrsim 0.9\ c/\omega_p$

- **Can produce high quality multi-GeV beams:**

- **20 GeV energies,**
- **sub-1% energy spreads.**
- **High efficiency (> 50%)**
- **High brightness (10^{19} A/m²/rad²)**

Thank you for your time!

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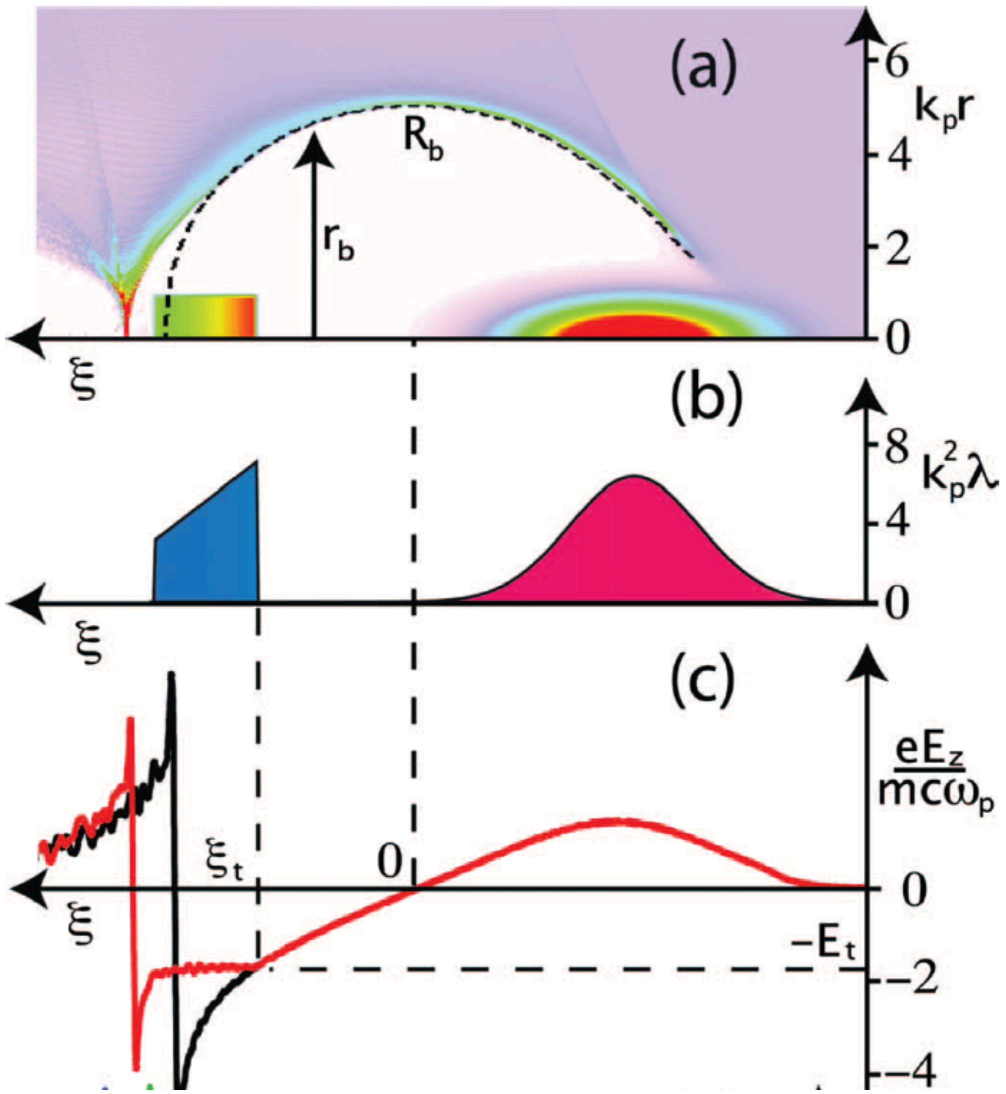
Conventional beam loading



Tzoufras et. al, Phys. Plasmas 16, 056705 (2009).

Basic idea & Limitations

- **The loading of the wake depends on the bubble radius $r_b(\xi)$ and beam current $\lambda(\xi)$**

$$\frac{dE_z}{d\xi} = \frac{1}{2} + \frac{1}{2}\left(\frac{dr_b}{d\xi}\right)^2 - \frac{\lambda(\xi)}{r_b^2}$$

- **Convetional picture: wake is "static" and trapezoidal beam flattens Ez.**

- **Does not work if wake evolves**

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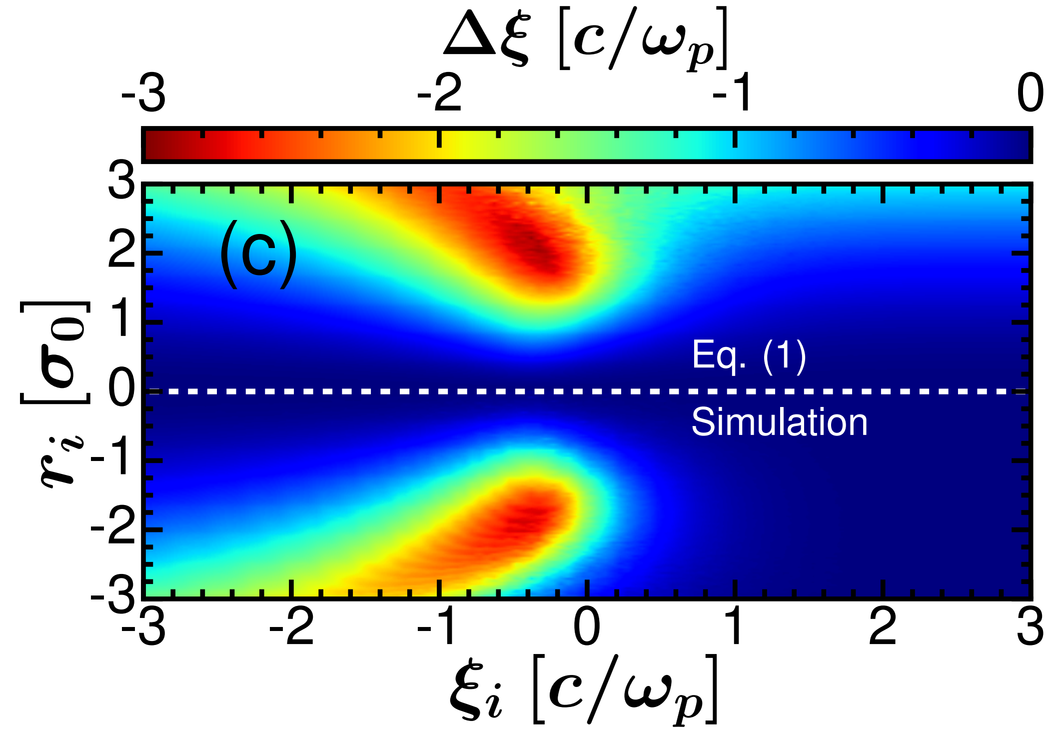
Dephasing: Simulation vs Theory

- **Dephasing theory vs simulation shown for drive beam electrons after z = 6.9 cm (13000 c/wp) in plasma.**

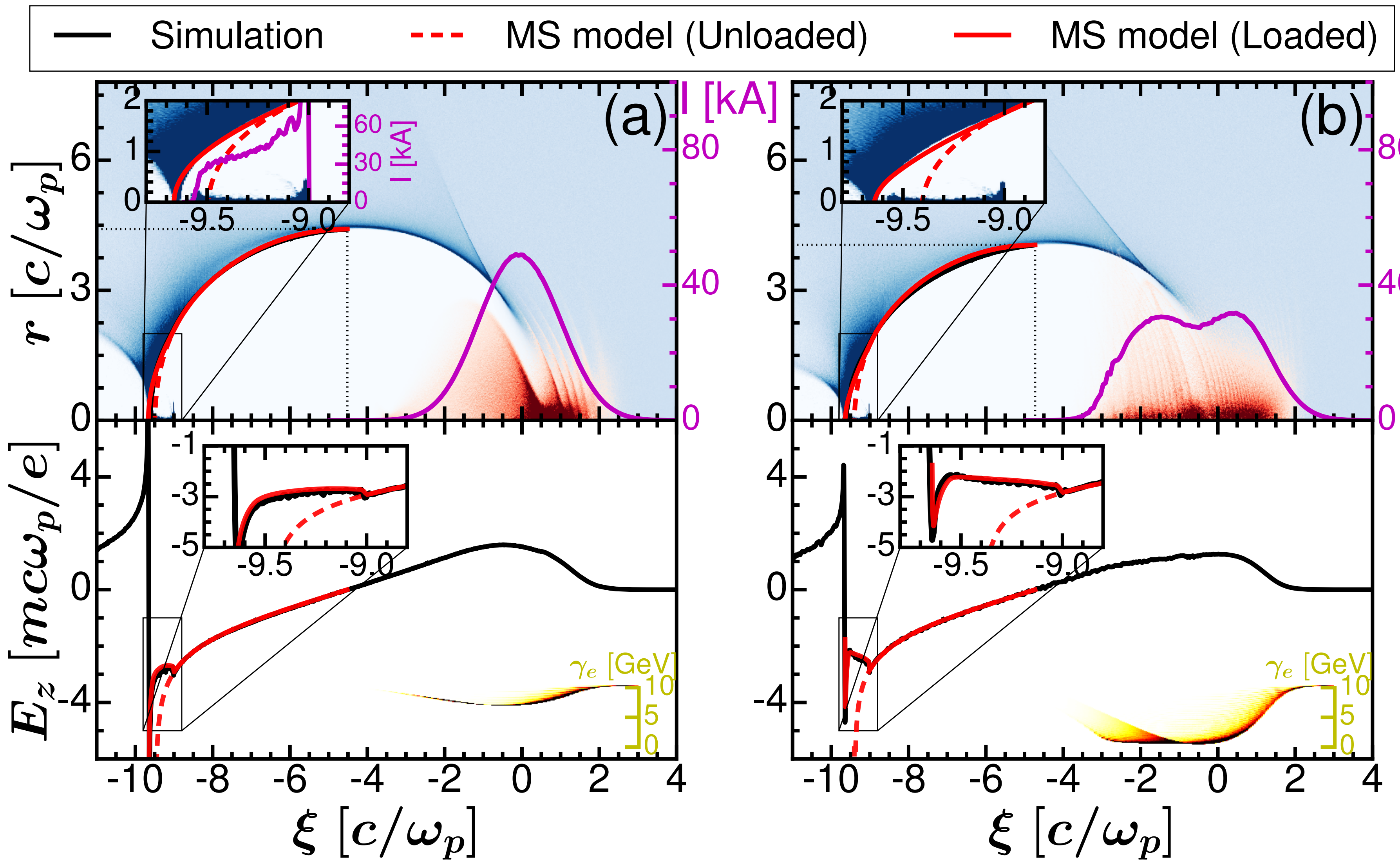
- **Strong agreement along most of driver except at front.**

- **This is because Eq. (1) assumes linear focusing force which is not valid at beam head.**



$$\Delta\xi(z) \approx \frac{-k_p^2 r_i^2 z}{4\gamma_b(1+\sqrt{\gamma_{bi}/\gamma_b})} \quad (1)$$

Modeling unloaded wake



Multi-sheath model

Can calculate the bubble radius and electric field using the multi-sheath model for the wake potential

$$\psi_0(\xi) = (1 + \beta')r_b^2/4, \quad E_z(\xi) = d\psi_0/d\xi$$

Model Ref - T. N. Dalichaouch et al., PoP 28 (063103), 2021.