

Optimization of plasma-based electron injectors for a linear collider of XFEL

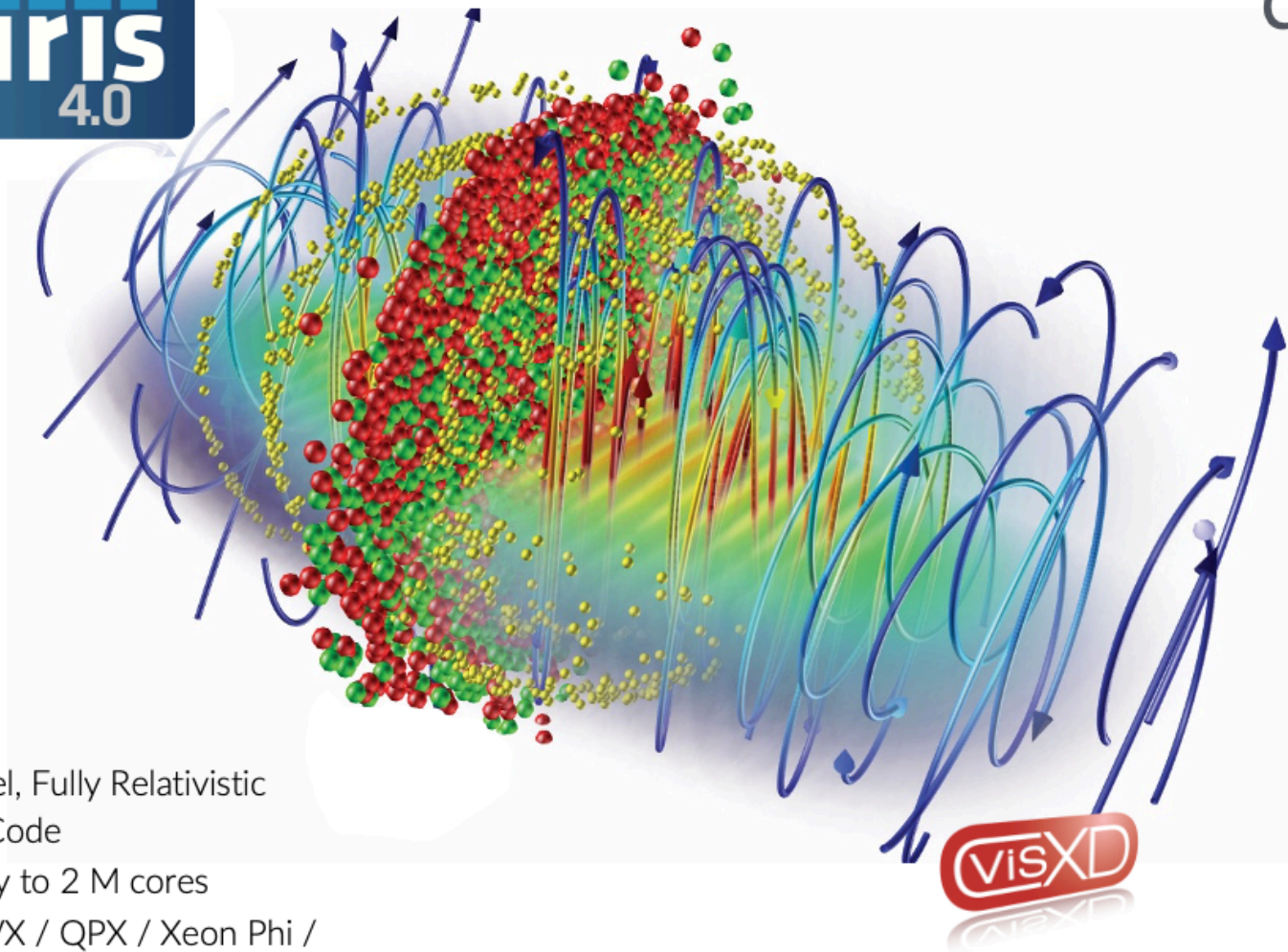
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Advanced Accelerators Concepts
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OSIRIS framework

- 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

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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

Beam generation & optimal acceleration

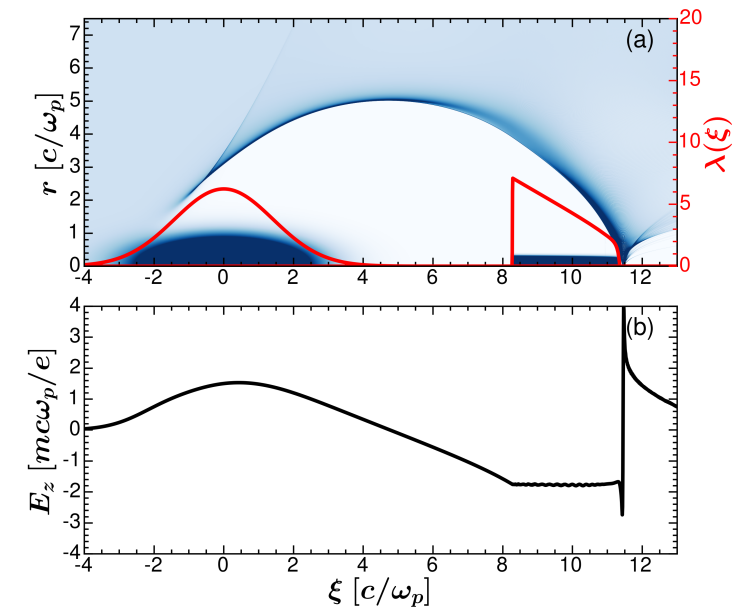
- PBA can enable high gradient acceleration (> 1 GV/cm) and high quality beam generation for next-gen XFEL and LCs.

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

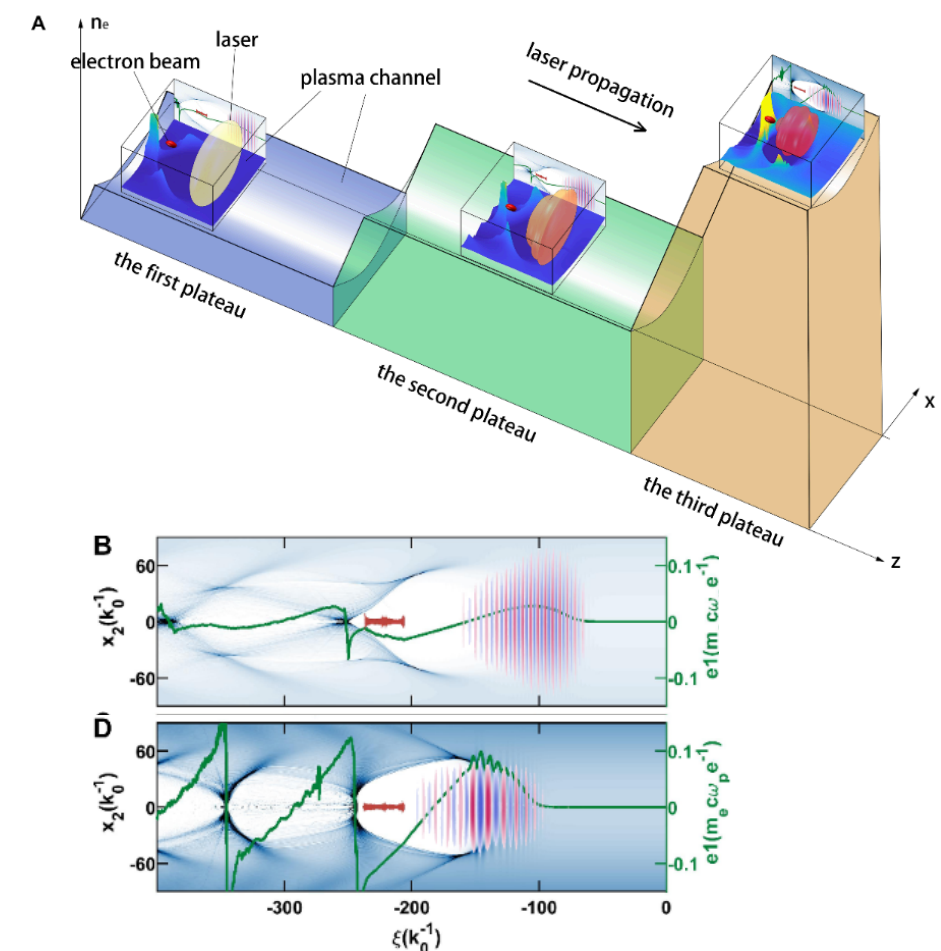
- Main challenge: low energy spread acceleration.
- Ideal loading difficult to realize with injection.
- Dynamic beam loading (DBL) schemes (e.g., tri-plateau plasma) aim to flatten average field

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

$$\xi = z - ct$$



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



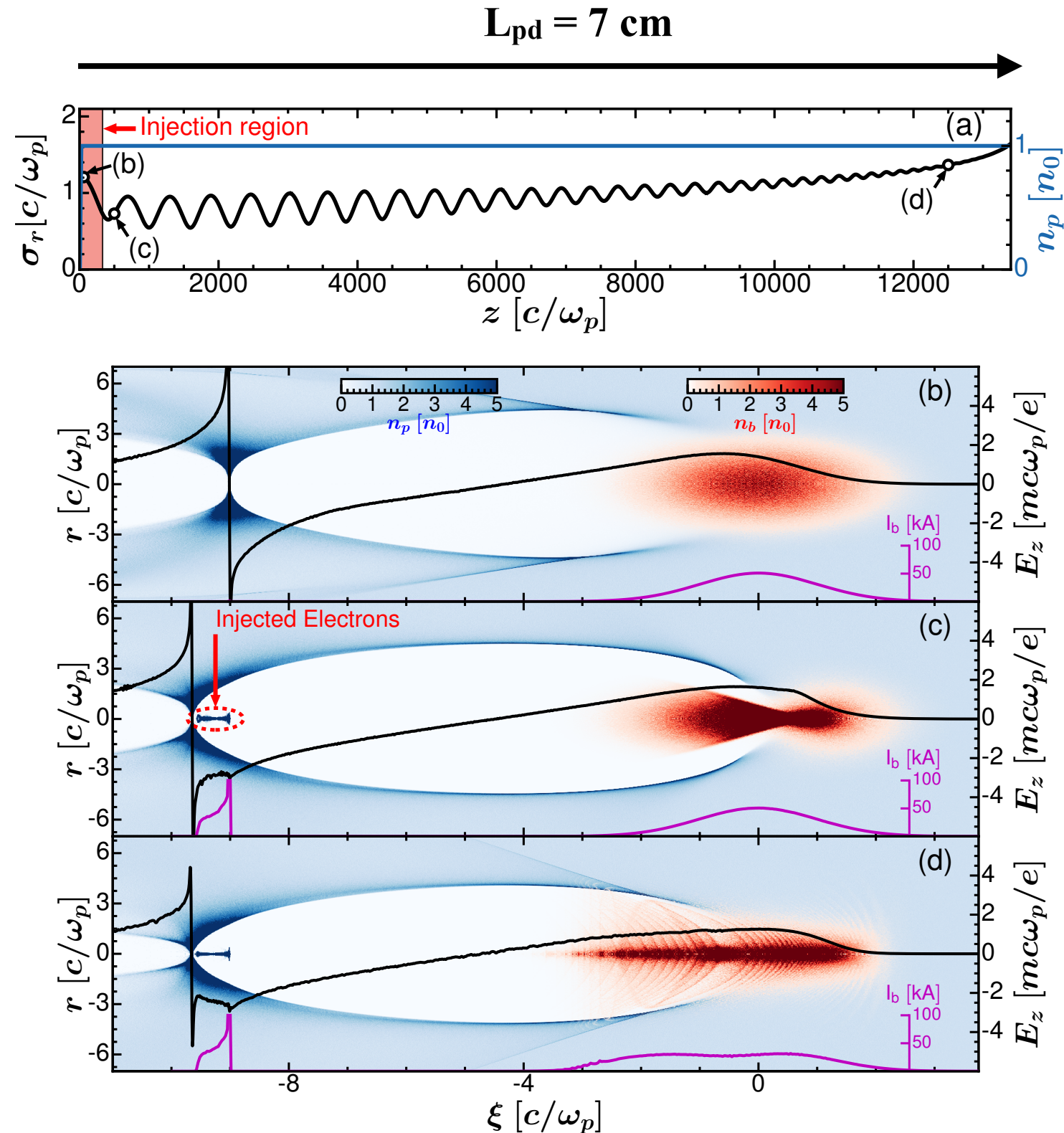
S. Liu, et al., Research, 0, 34133 (2024).

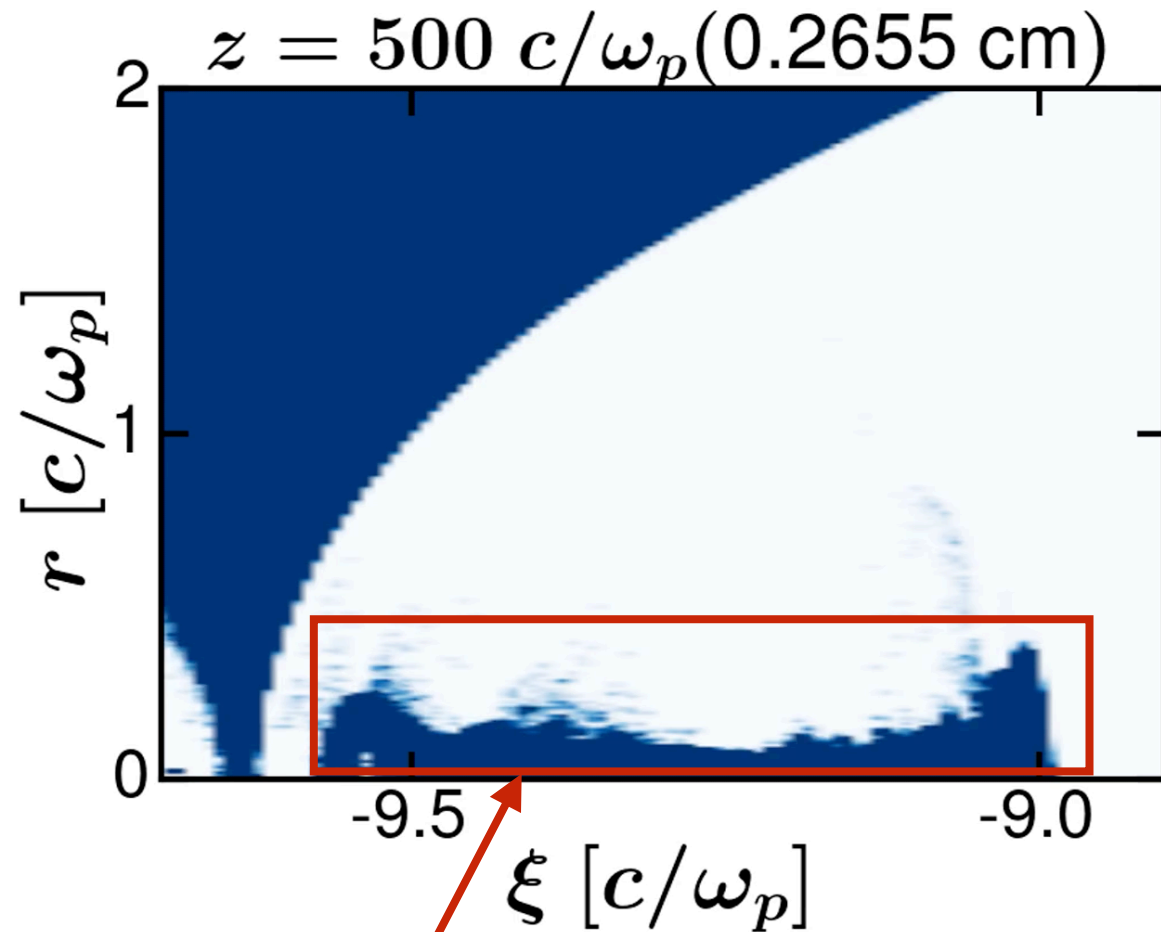
Novel DBL Scheme

- 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, $\sigma_r \simeq 6.5$ μm , $\sigma_z \simeq 5.3$ μm ,
 $\gamma_b = 10\text{GeV}$, $\beta^* = 1.7$ cm, $n_p \simeq 10^{18}$ cm^{-3}



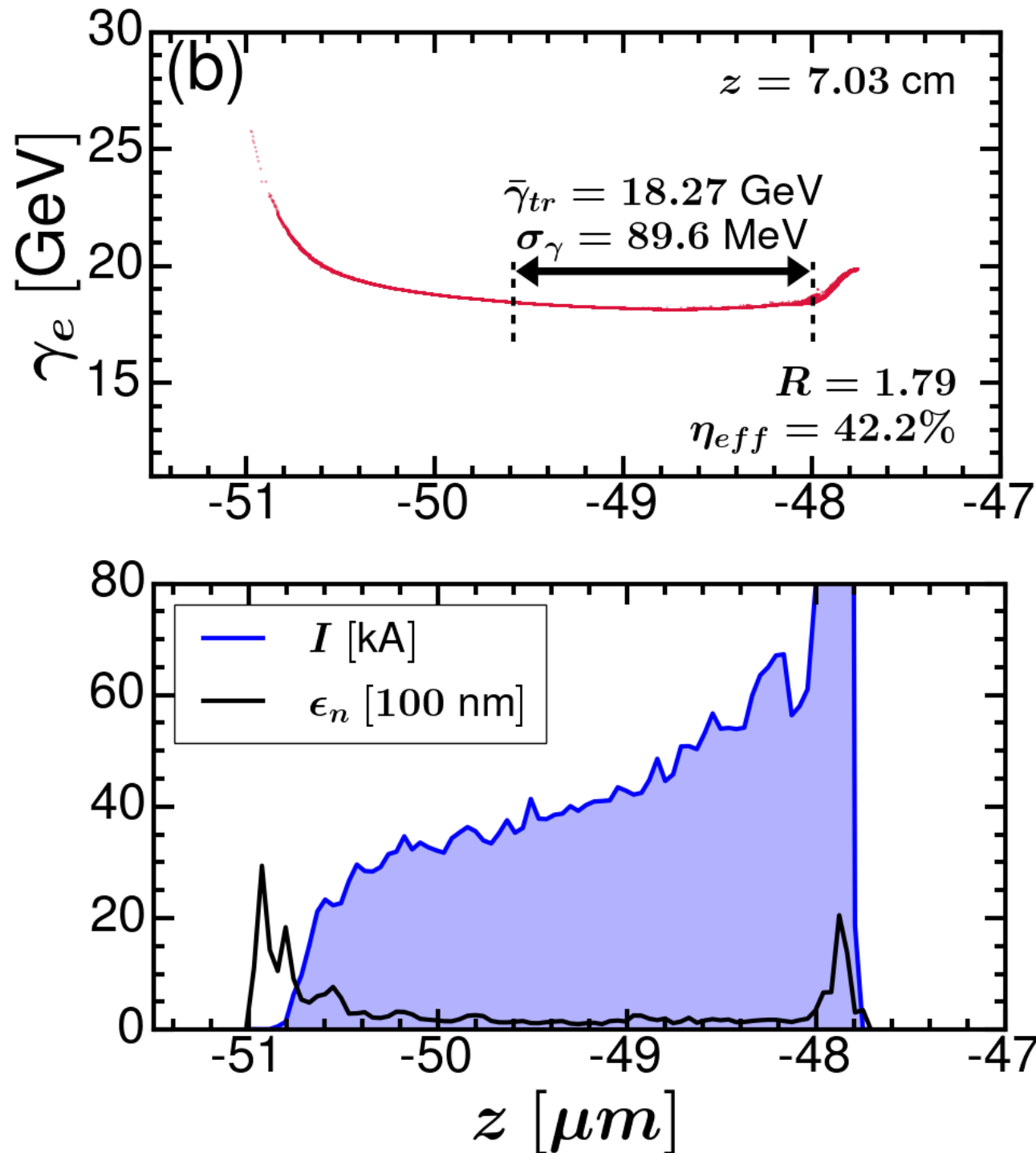


Nonlinear theory

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

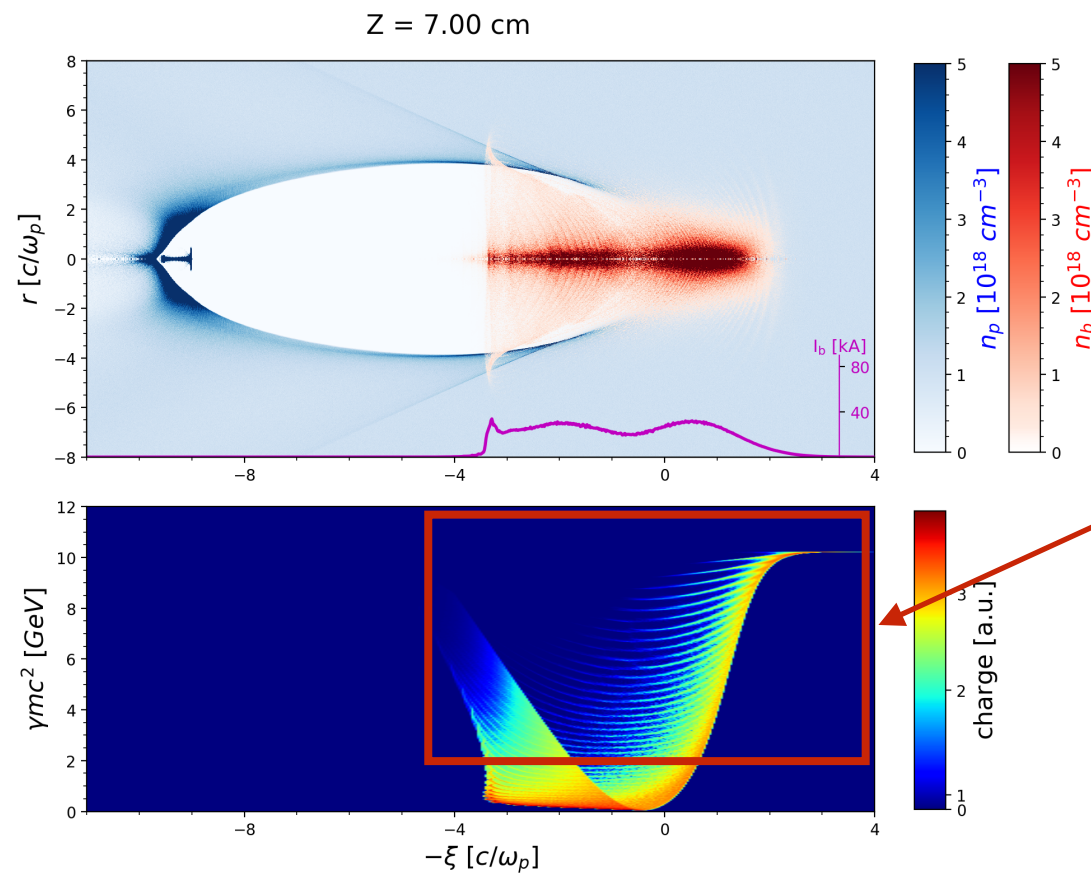
$$\frac{dE_z}{d\xi} = \frac{1}{2} + \frac{1}{2} \left(\frac{dr_b}{d\xi} \right)^2 - \frac{\lambda(\xi)}{r_b^2}$$

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

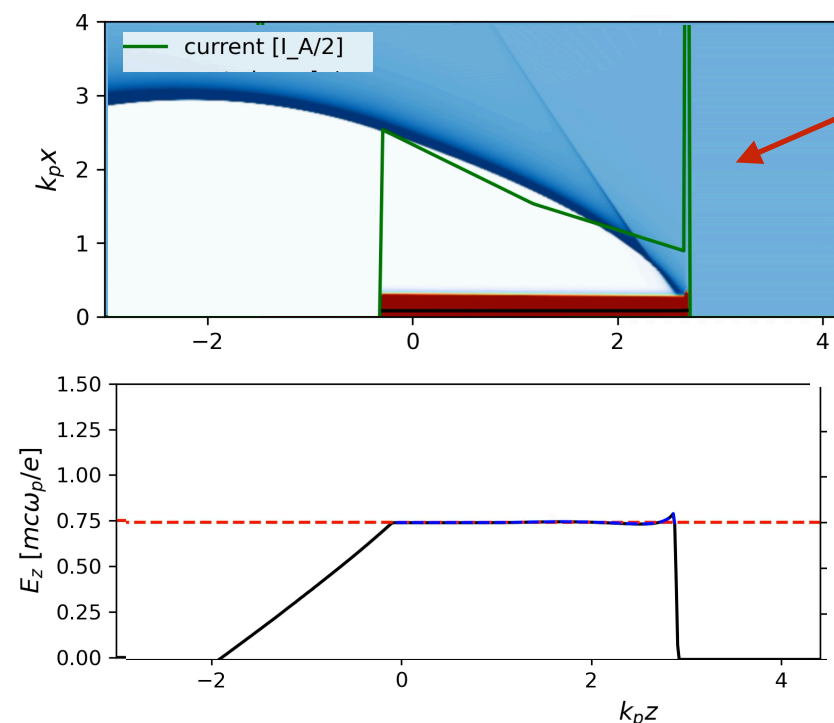


- Beam extracted with $\sim 18.3 \text{ GeV}$ and $\sim 90 \text{ MeV}$ (0.49%) after 7 cm propagation distance.
- High efficiency acceleration 42.2% and high transformer ratio ~ 1.8 .

Energy/Brightness Booster		
	Drive	Trailing
Energy	10.2 GeV	18.3 GeV
Emittance	$\sim 50 \text{ }\mu\text{m}$	$\sim 100 \text{ nm}$
Bn [A/m ² /rad ²]	10^{14}	10^{19}



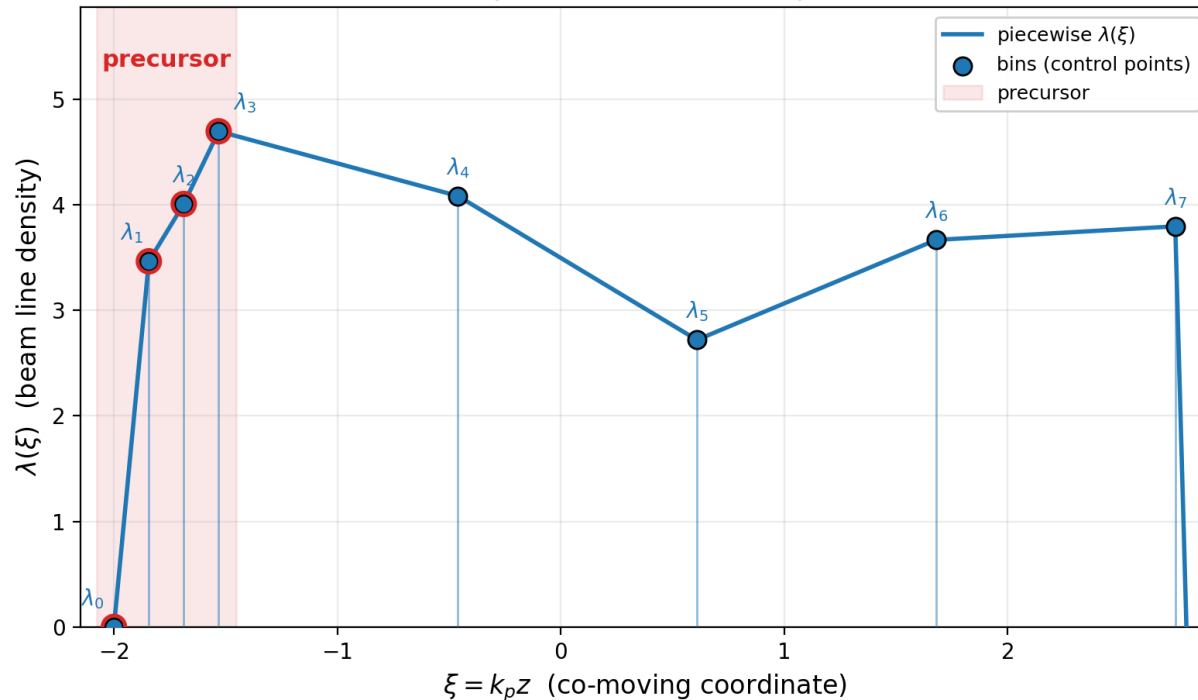
- For Gaussian profile, significant energy left in beam charge (about 25% remaining).



- Shaping driver for uniform deceleration.
- Optimization algorithms exist to optimize profile for single snapshot in time. [1]
- More complicated because driver evolves.

- [1] Q. Su et al., Phys. Plasmas 30, 053108 (2023)

Beam representation: control points λ_i



Driver Constraints

Longer Beam : $L \simeq 25 \text{ um}$ ($k_p L \approx 5$)
 Higher Charge: $Q_d = \sum \lambda_i \Delta \xi_i \simeq 2.8 \text{ nC}$

Bayesian Optimization Formulation

- Find current profile that optimizes acceleration distance & energy transfer.
- Piecewise-linear profile:

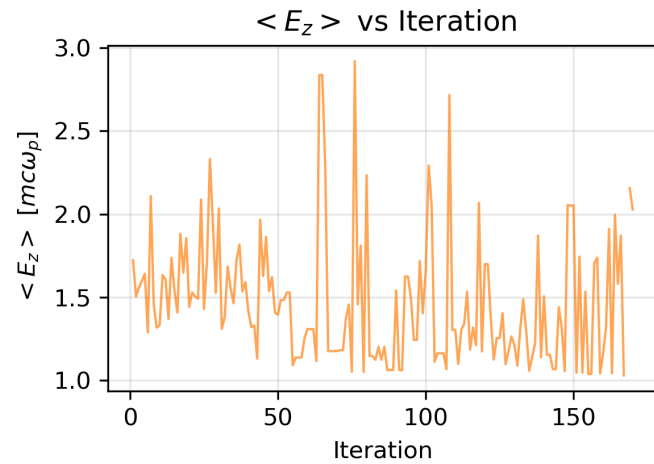
$$h(\xi_i \leq \xi \leq \xi_{i+1}) = \lambda_i + \frac{\lambda_{i+1} - \lambda_i}{\xi_{i+1} - \xi_i}(\xi - \xi_i)$$

Objective Function

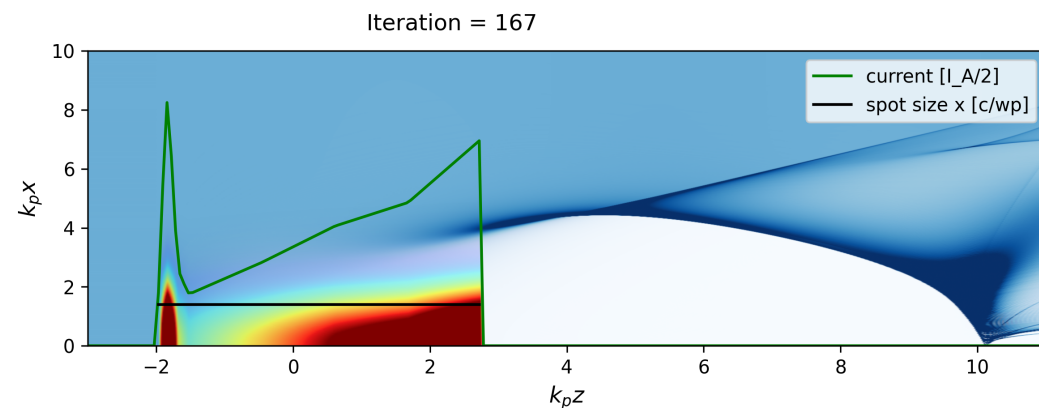
- Maximize acceleration distance and minimize max energy loss

$$f = \frac{z}{\max(\Delta \gamma_d)} \sim \frac{1}{\max(\langle E_z^+ \rangle)}$$

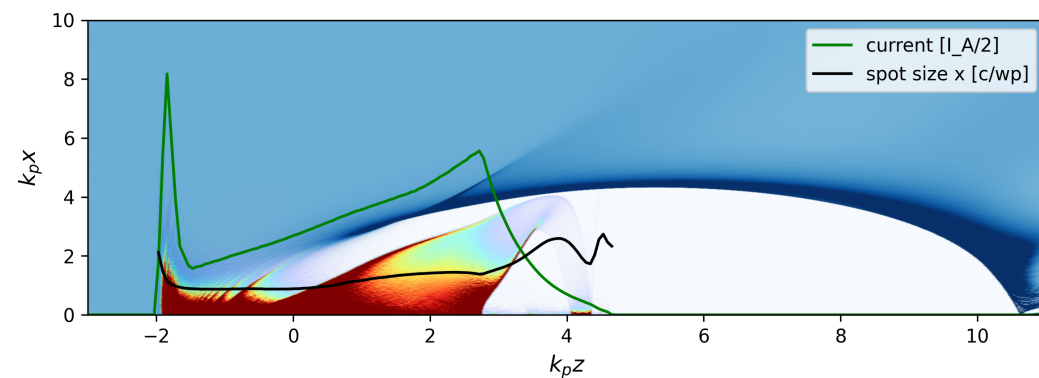
- Evaluations use QPAD (Quasi-static code) to simulate driver to pump depletion.



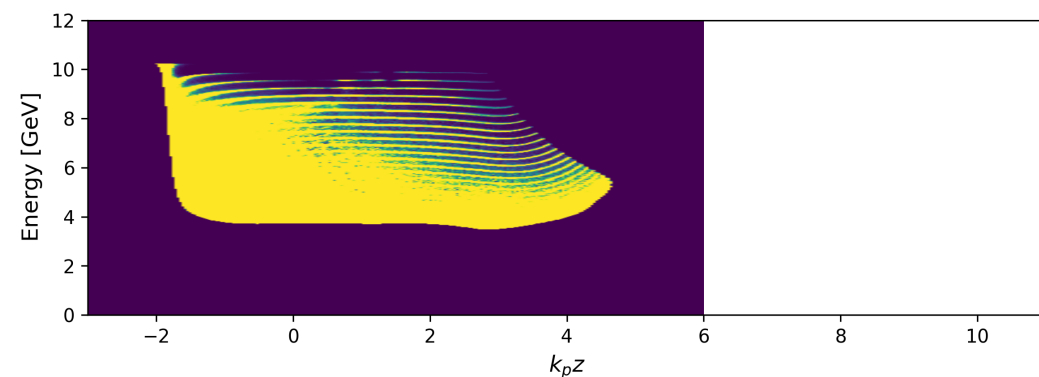
- **BO for 170 evaluations.**
- **Max decelerating field drops from $\langle E_z \rangle \sim 1.7$ to $\langle E_z \rangle \sim 1$**
- **Best result shown below for objective $f \sim 1/\langle E_z \rangle$.**



Initial driver/wake at $z = 0.1$ cm



Driver/wake at $z = 6$ cm



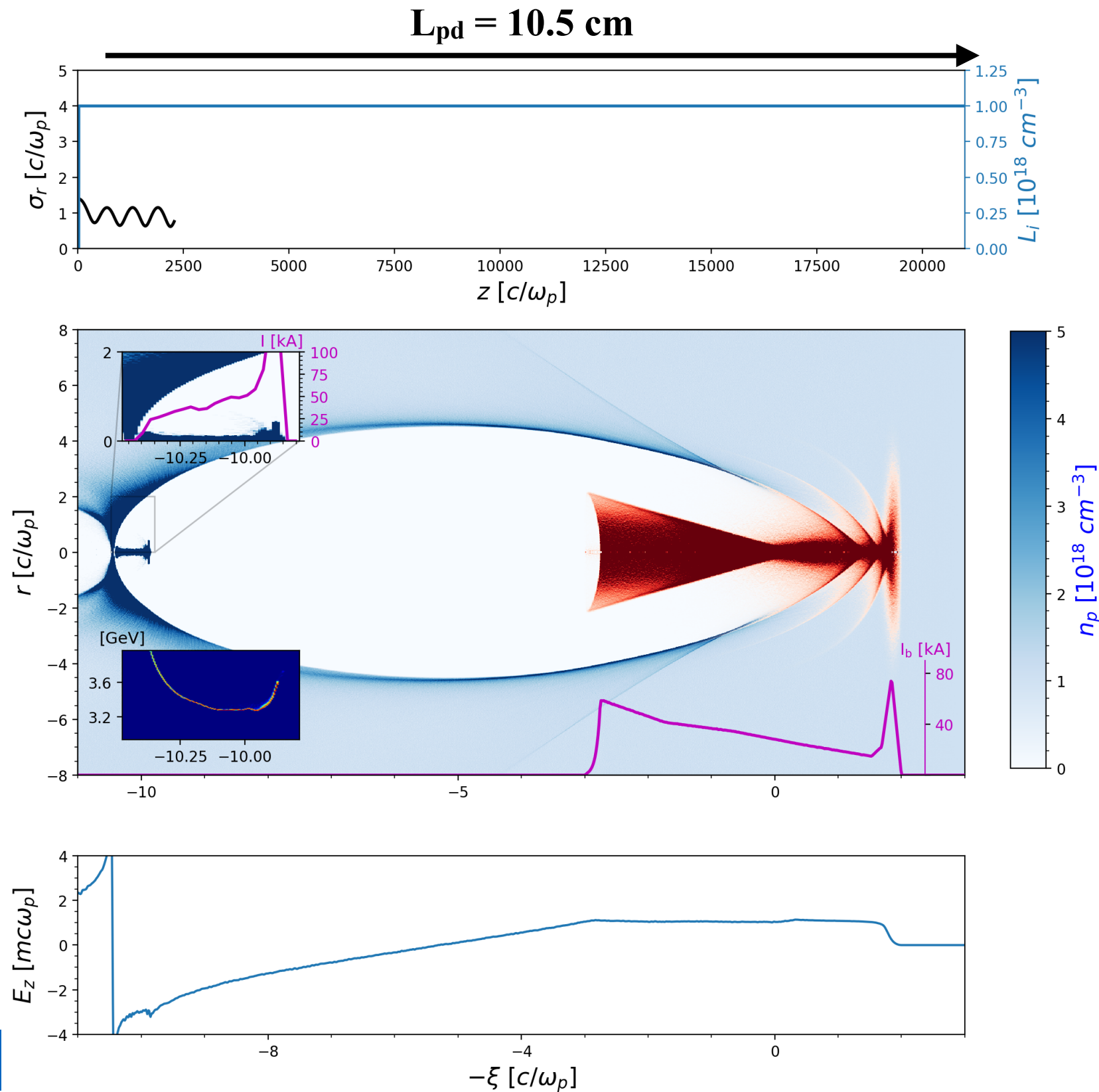
Drive Energy distribution at $z = 6$ cm

DBL with Shaped Driver

- Plug shaped driver back into OSIRIS to simulate self-injection and dynamic beam loading.
- Unmatched electron driver (2.8 nC) injects high quality beam (0.5 nC).
- Pump depletion extended to > 10 cm, energies up to 26.6 GeV.
- Driver shape changes throughout simulation.

Drive/Plasma Parameters

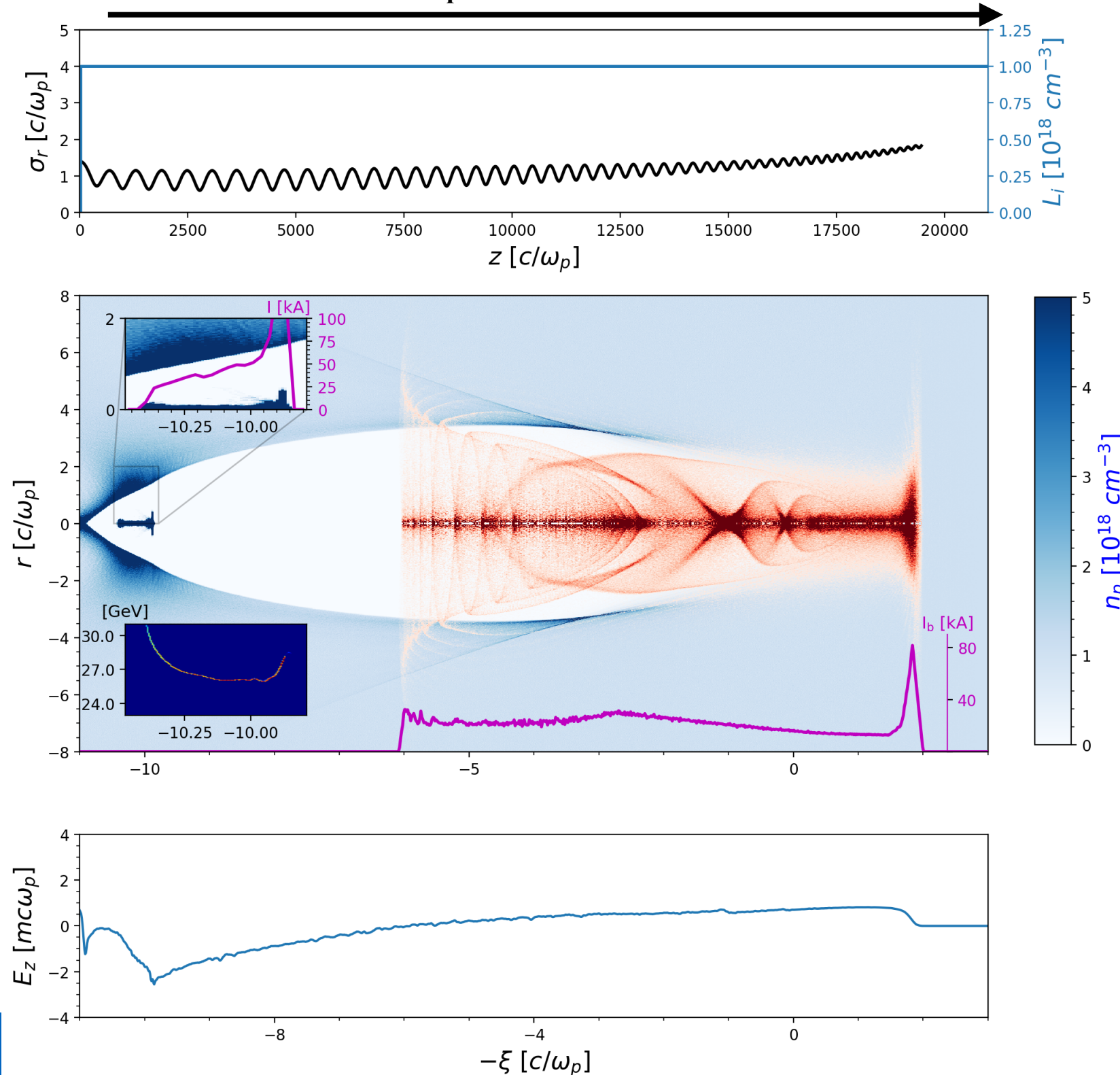
$Q_d \simeq 2.8$ nC, $\sigma_r \simeq 7.4$ μm , $L \simeq 25$ μm
 $\gamma_b = 10$ GeV, $\beta^* = 5.1$ cm, $n_p \simeq 10^{18}$ cm^{-3}



DBL with Shaped Driver

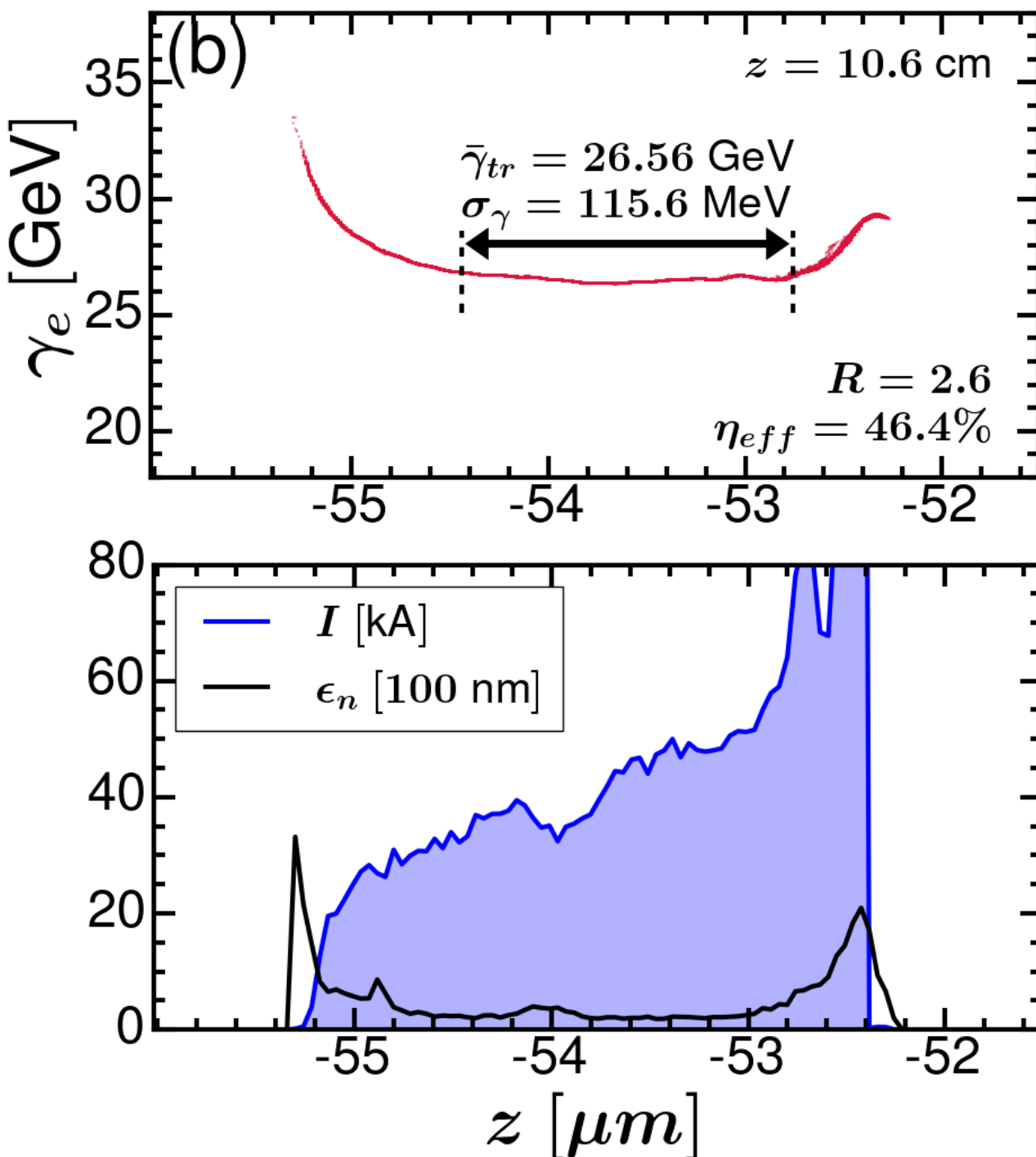
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- Driver shape changes throughout simulation.

$L_{pd} = 10.5$ cm



Drive/Plasma Parameters

$Q_d \simeq 2.8$ nC, $\sigma_r \simeq 7.4$ μ m, $L \simeq 25$ μ m
 $\gamma_b = 10$ GeV, $\beta^* = 5.1$ cm, $n_p \simeq 10^{18}$ cm⁻³

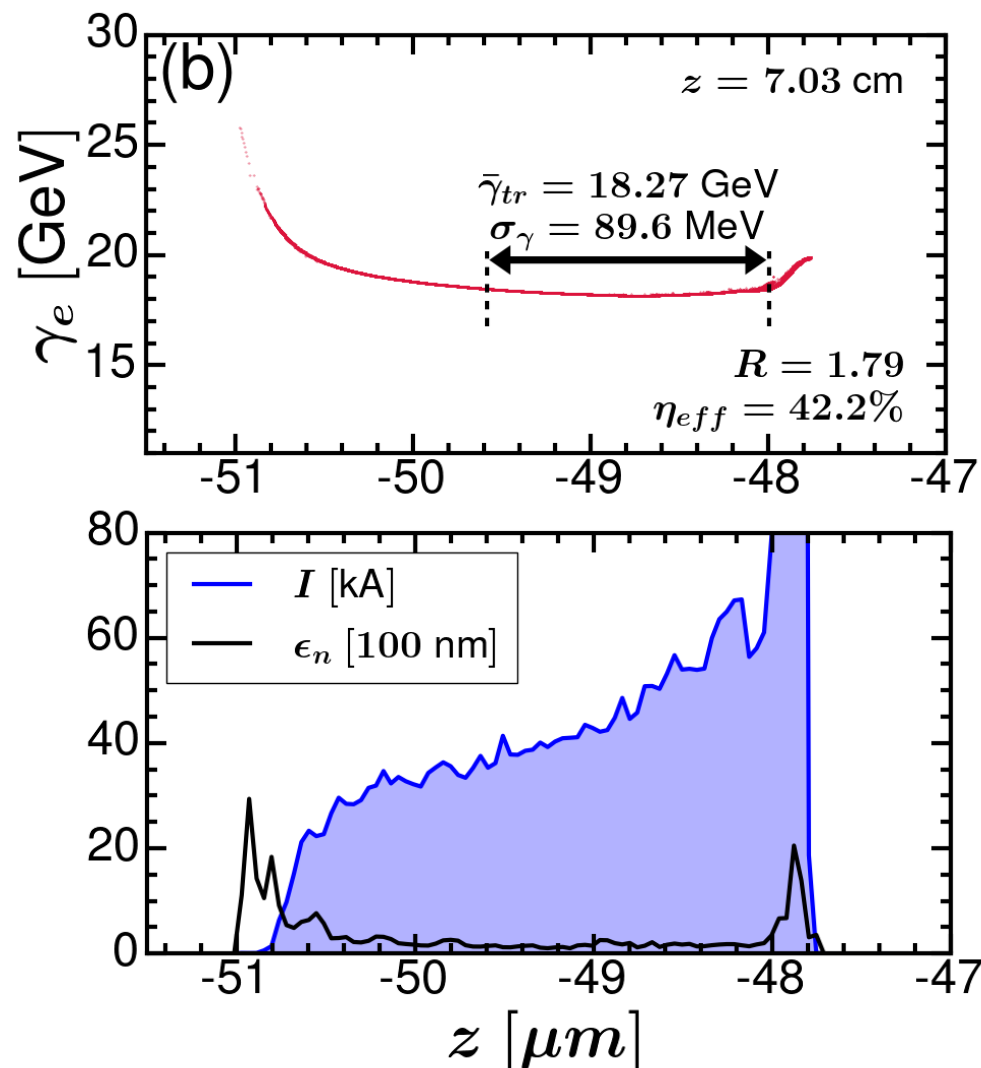


- Beam extracted with $\sim 26.6 \text{ GeV}$ and $\sim 115.6 \text{ MeV}$ (0.43%) after 10.6 cm prop distance.
- High efficiency acceleration 46.4% and high transformer ratio ~ 2.6 .

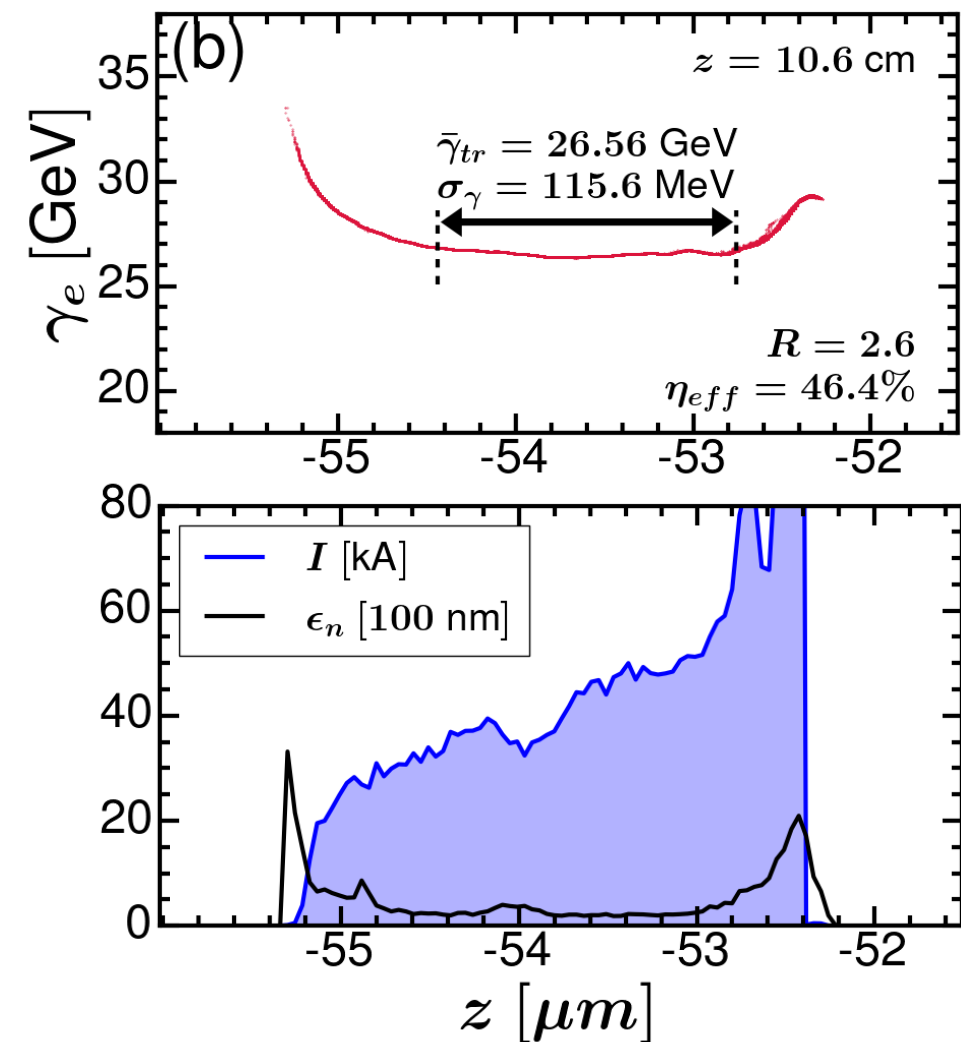
Energy/Brightness Booster		
	Drive	Trailing
Energy	10.2 GeV	26.6 GeV
Emittance	$\sim 20 \text{ um}$	$\sim 100 \text{ nm}$
Bn [$\text{A/m}^2/\text{rad}^2$]	10^{14}	10^{19}

Summary of Results (10 GeV Drivers)			
	Gaussian (2.2nC)	Shaped (2.8 nC)	Improvement
Trailing Charge	0.5 nC	0.5 nC	~ 1x
Trailing Energy	18.3 GeV	26.6 GeV	~ 1.45x
Transformer Ratio	1.8	2.6	~ 1.45x
Efficiency	42.2%	46.4%	~ 1.1x

Gaussian Driver



Shaped Driver



- Energy Efficiency improvement primarily driven by higher drive-to-wake transfer efficiency.

$$\eta_{eff} = \eta_{dr \rightarrow wake} \eta_{wake \rightarrow tr}$$

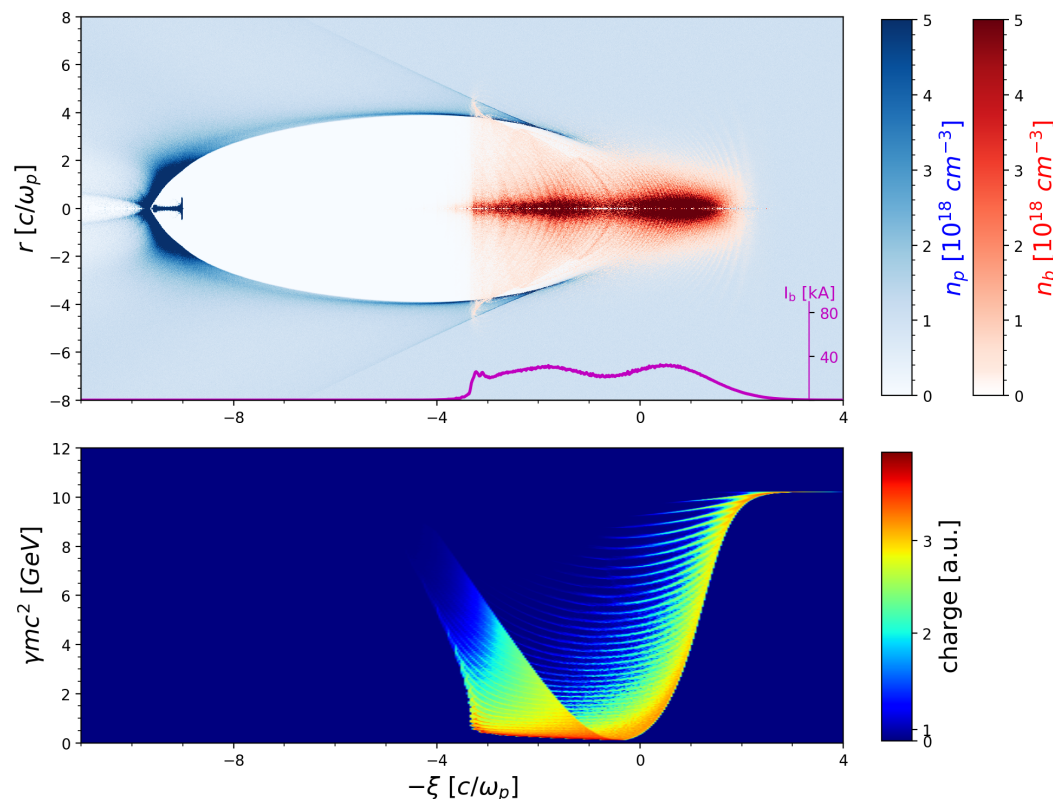
- Room for further efficiency improvement by collimating non-participating precursor charge.

Gaussian Bunch

$$\eta_{eff} \approx 42.2 \%$$

$$\eta_{dr \rightarrow wake} \approx 75.3 \%, \quad \eta_{wake \rightarrow tr} \approx 56.1 \%$$

Z = 6.95 cm

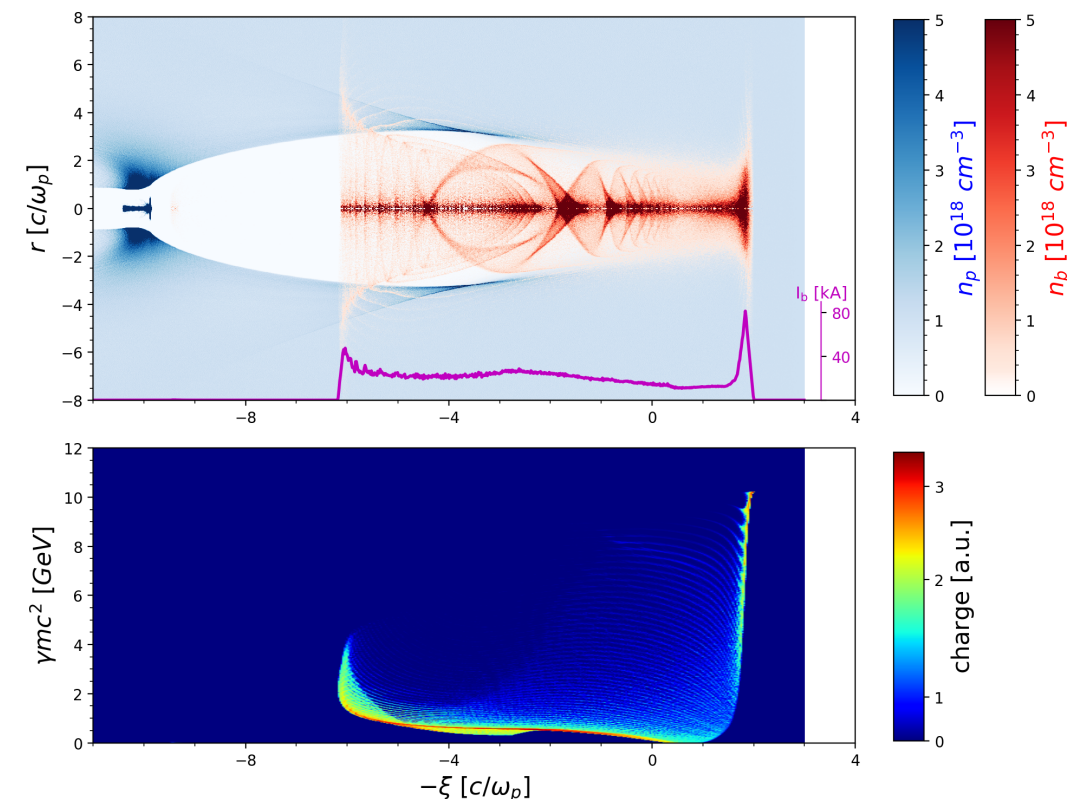


Shaped Bunch

$$\eta_{eff} \approx 46.6 \%$$

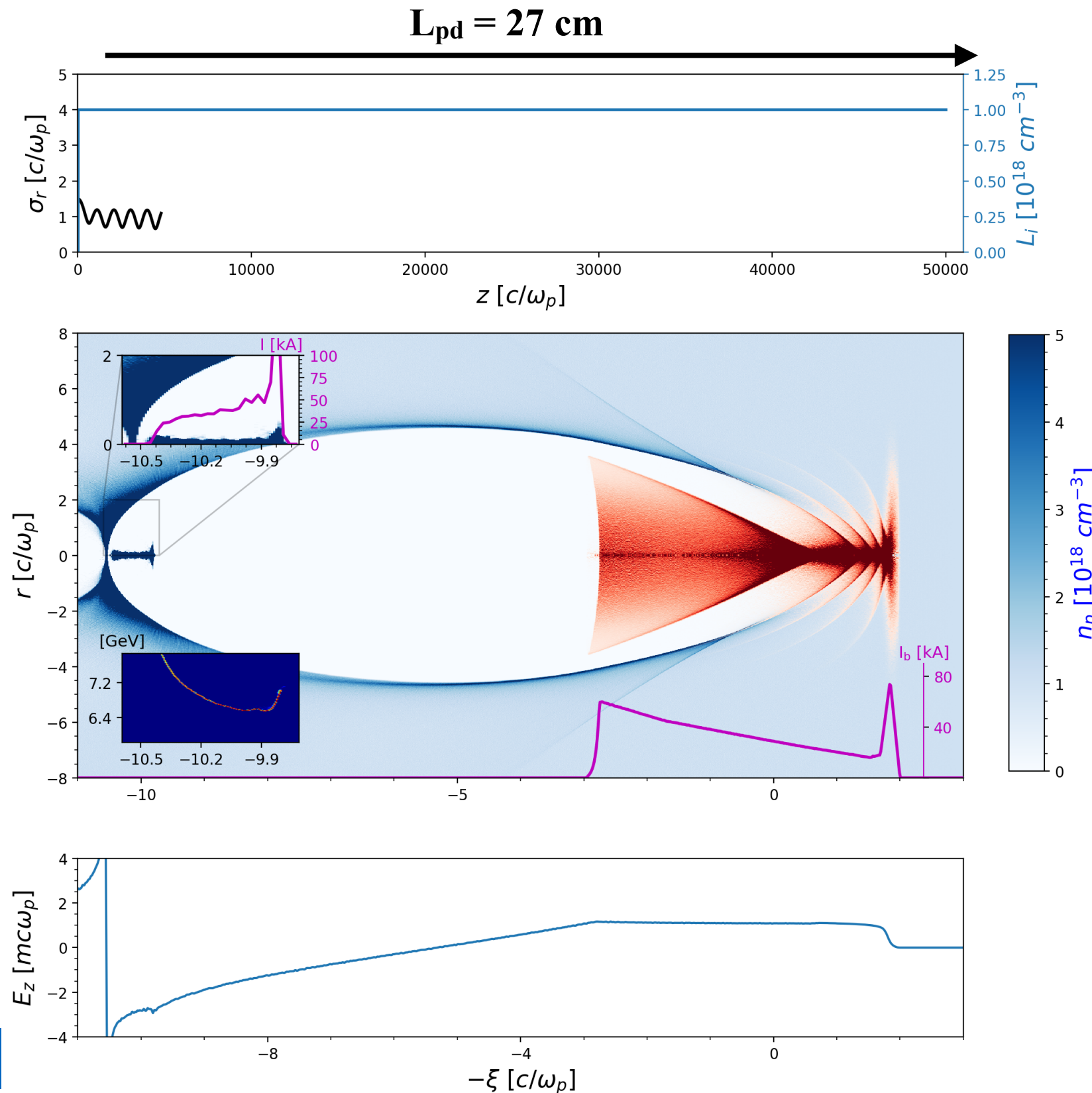
$$\eta_{dr \rightarrow wake} \approx 83.3 \%, \quad \eta_{wake \rightarrow tr} \approx 55.7 \%$$

Z = 10.6 cm



25 GeV Driver Results

- Repeated BO to shape drive beam with higher energy (25 GeV).
- OSIRIS sims demonstrate injection-DBL concept scales with energy.
- Similar injected bunch (0.5 nC).
- Pump depletion extended to > 27 cm, energies up to 63.15 GeV.



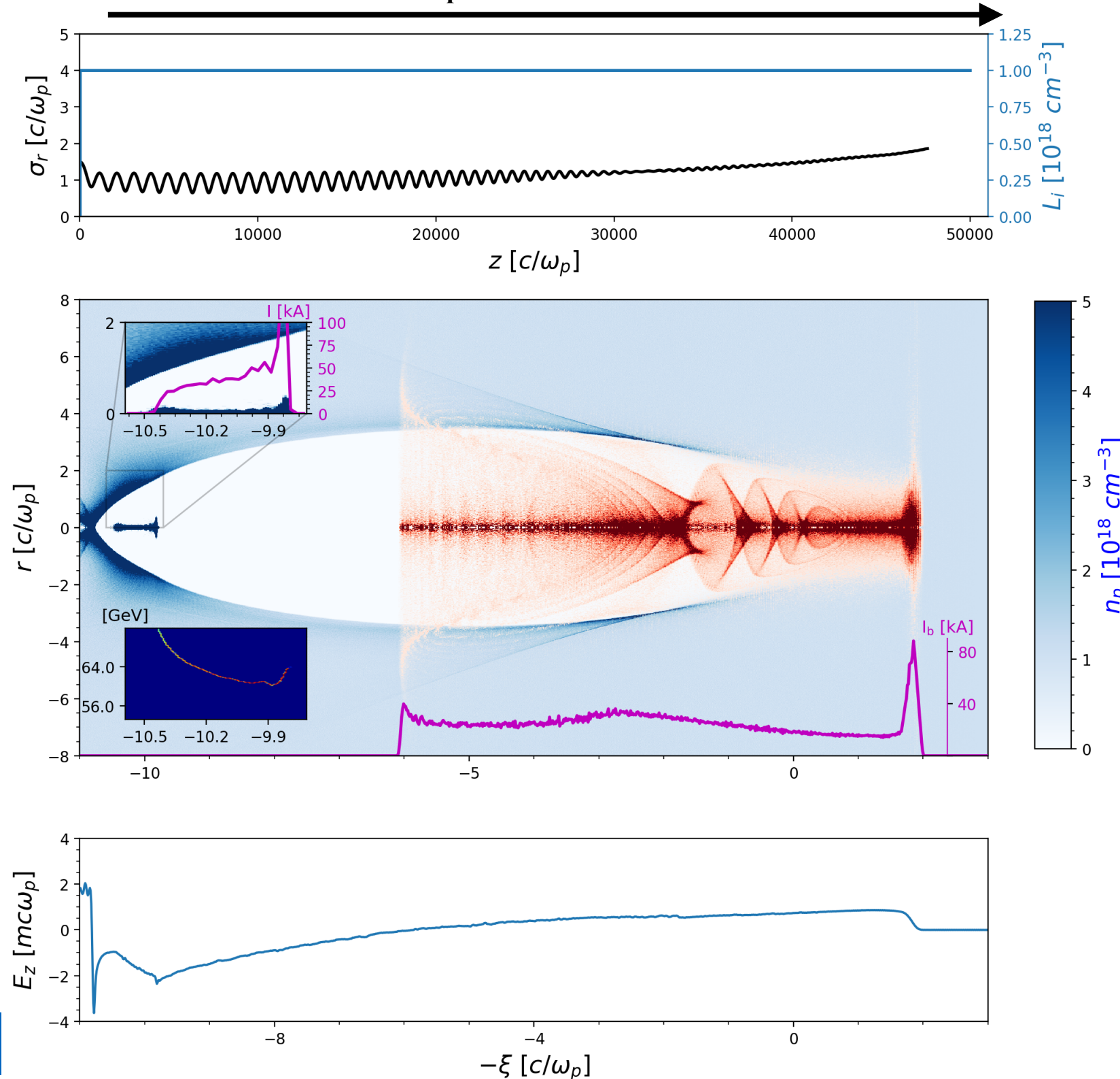
Drive/Plasma Parameters

$Q_d \simeq 2.9$ nC, $\sigma_r \simeq 8$ μm , $L \simeq 25$ μm ,
 $\gamma_b = 25$ GeV, $\beta^* = 11$ cm, $n_p \simeq 10^{18} \text{ cm}^{-3}$

25 GeV Driver Results

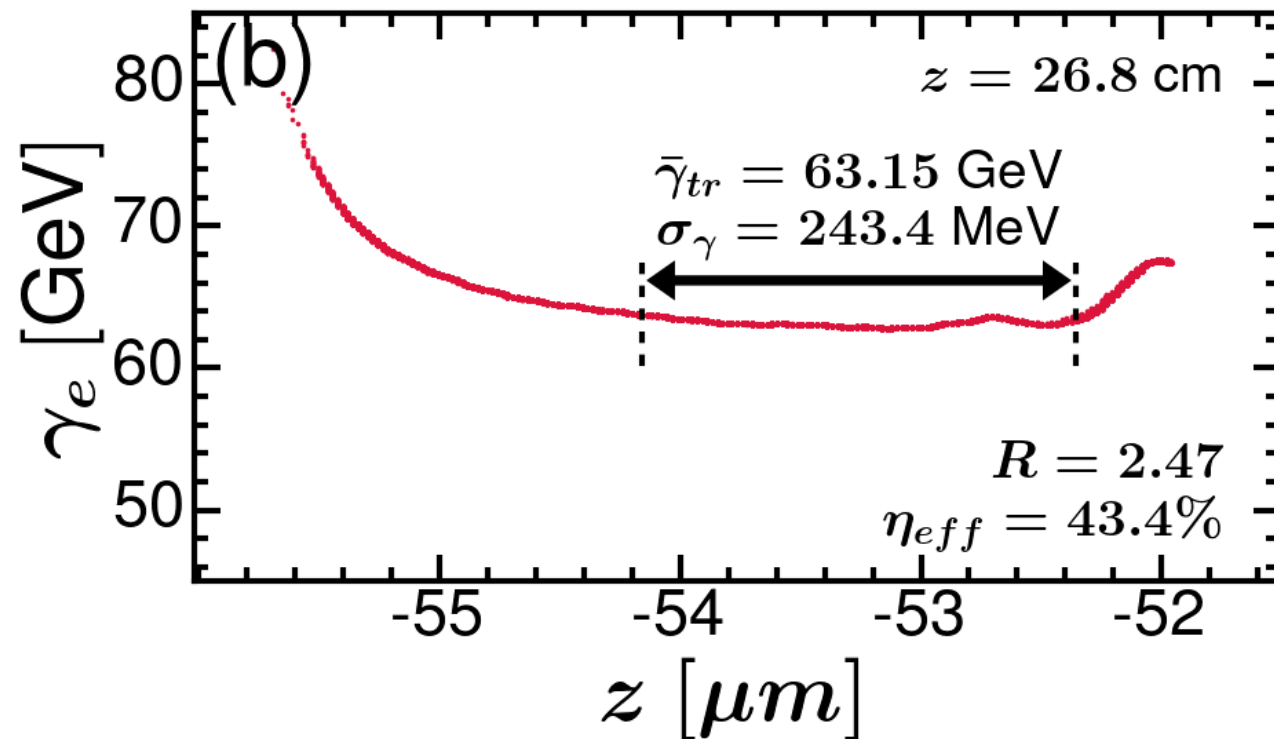
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$L_{pd} = 27$ cm



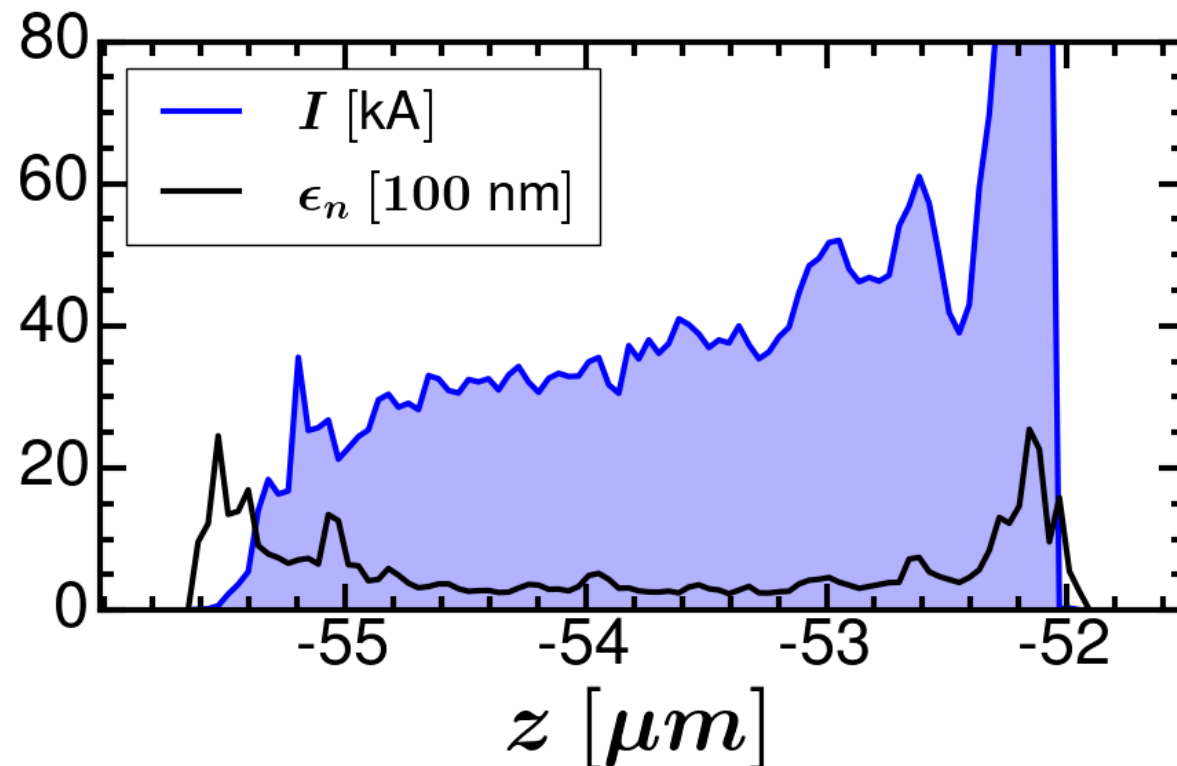
Drive/Plasma Parameters

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 $\gamma_b = 25$ GeV, $\beta^* = 11$ cm, $n_p \simeq 10^{18} \text{ cm}^{-3}$



- Injected beam accelerated to $\sim 63.15 \text{ GeV}$ and with energy spread $\sim 243.4 \text{ MeV}$ (0.38%) after 26.8 cm prop distance.

- High efficiency 43.4% and high transformer ratio ~ 2.5 .



- Low slice emittance $O(\sim 100 \text{ nm})$ leads to high peak brightnesses $\sim 10^{19} \text{ A/m}^2/\text{rad}^2$.

	Summary of Results		
	10 GeV Gaussian	10 GeV Shaped	25 GeV Shaped
Driver Charge	2.2 nC	2.8 nC	2.9 nC
Trailing Charge	0.5 nC	0.5 nC	0.5 nC
Trailing Energy	18.3 GeV	26.6 GeV	63.15 GeV
Efficiency	42.2%	46.4%	43.4%
Transformer Ratio	1.8	2.6	2.5
Bn [A/m ² /rad ²]	10 ¹⁹	10 ¹⁹	10 ¹⁹

- Demonstrated self-injection of high brightness beams with low energy spread acceleration (via DBL) using shaped driver.
- Improved efficiencies (up to 46.4%) & transformer ratios (up to 2.6) for drive beam energies up to 25 GeV.
- Room for further optimization of drive-to-wake energy transfer (> 90%) and total efficiency >50%.

Thank you for your time!