Beam current from downramp injection in electron-driven nonlinear plasma wakefields

C. Hue,[1] A. Golovanov,[1] S. Tata,[1] S. Corde,[2] V. Malka[1]

[1]Weizmann Institute of Science, Rehovot, Israel

[2]LOA, ENSTA Paris, CNRS, Ecole Polychnique, Institut Polytechnique de Paris, France

Abstract

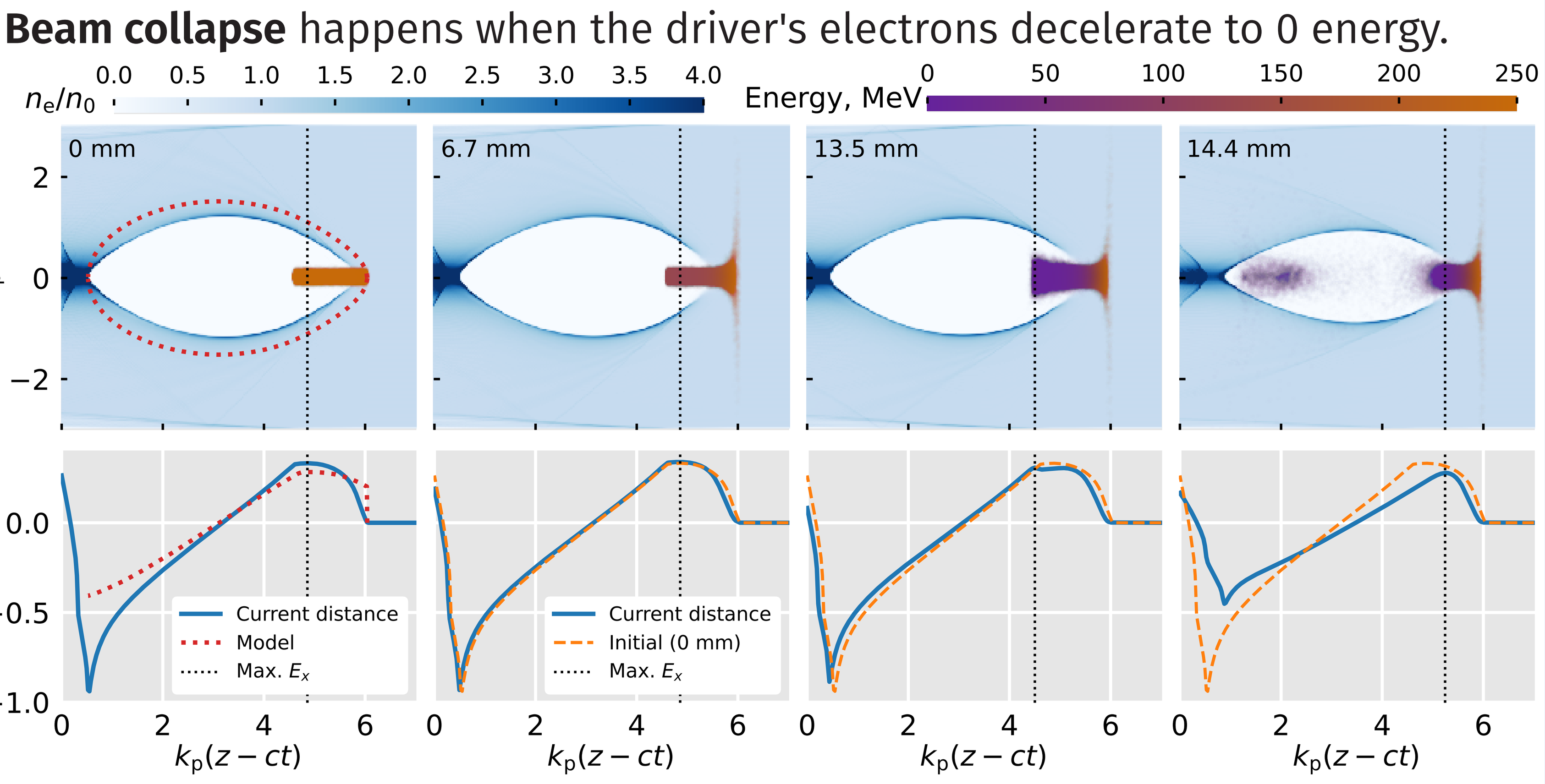
We study the stability of a plasma wake wave and the properties of density-downramp injection in an electron-driven plasma accelerator. Most importantly, we find that the current of the injected bunch primarily depends on just one parameter J_{eff} which combines both the properties of the driver (its current and duration) and the plasma density.

Paper: C. Hue et al. arXiv:2307.00515 (submitted to JPP)

Driver evolution in PWFA

There are several limiting factors for plasma-wakefield acceleration (PWFA):

- **Head erosion** is important mostly when the target is not pre-ionized and leads to the loss of the head of the bunch.
- **Hosing instability** can be suppressed by driver's non-uniform deceleration.
- **Beam collapse** happens when the driver's electrons decelerate to 0 energy.



Simulation with QuickPIC. Analytical model from Golovanov et al. *PRL* 2023. Bunch: 250 MeV, 137 pC, $\xi_b = 13.4\,\mu$m (flattop), $\sigma_r = 0.52\,\mu$m (Gaussian). Plasma density $n_0 = 3.125 \times 10^{17}$ cm^{-3}.

The main limitation is the **beam collapse**. It happens at the distance $L_{\text{col}} = mc^2\gamma/eE_{\max}$ when the electrons which feel the peak field $E_{\max}$ lose their kinetic energy and cannot keep up with the wake.

			L_{col}[mm]		η, %	
n_0[cm^{-3}]	n_b/n_0	$k_p\xi_b$	sim.	model	sim.	model
2.5×10^{18}	15	3.99	4.8	6.0	65	73
1.875×10^{18}	20	3.45	5.5	7.1	71	81
1.25×10^{18}	30	2.82	6.7	8.1	76	87
6.25×10^{17}	60	1.99	9.4	11.6	77	93
4.17×10^{17}	90	1.63	11.6	14.1	75	93
3.125×10^{17}	120	1.41	13.5	16.4	73	92

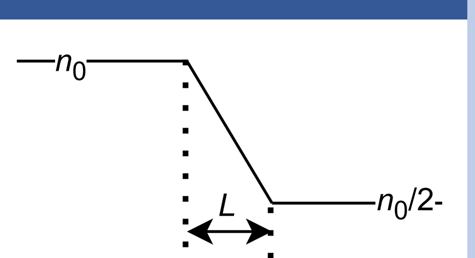
The efficiency of acceleration is

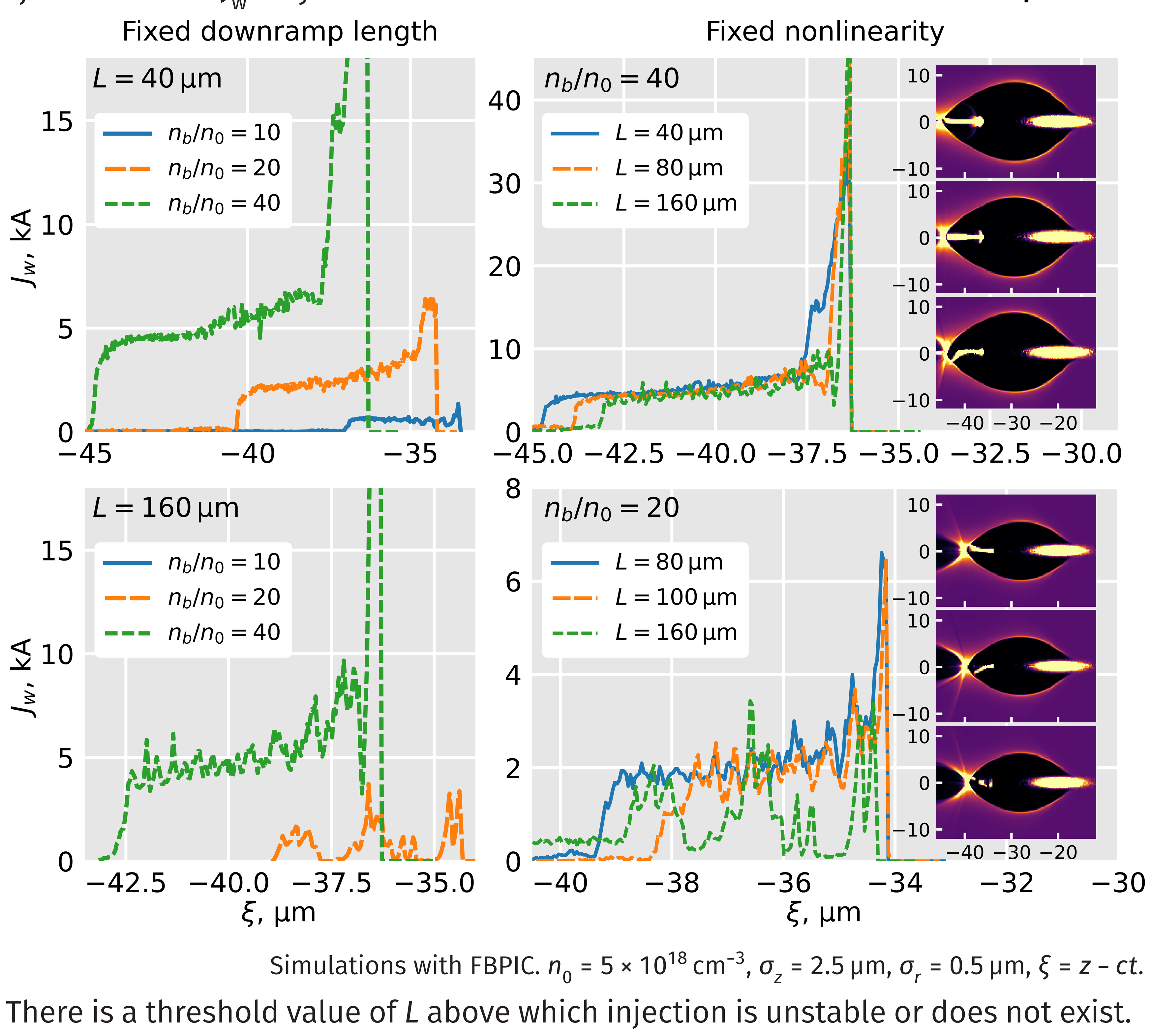
$$\eta = \frac{\langle\gamma\rangle_0 - \langle\gamma\rangle_{\text{col}}}{\langle\gamma\rangle_0} \approx \frac{\langle E_z\rangle}{E_{\max}}$$

There is an optimum plasma density for highest efficiency η.

Influence of bubble nonlinearity and downramp length

We consider injection in a linear density downramp. If we increase the nonlinearity of the bubble n_b/n_0, the injected current J_w increases. If we change the downramp length L, the injected current J_w stays almost the same.





Simulations with FBPIC. $n_0 = 5 \times 10^{18}$ cm^{-3}, $\sigma_z = 2.5\,\mu$m, $\sigma_r = 0.5\,\mu$m, $\xi = z - ct$.

There is a threshold value of L above which injection is unstable or does not exist.

Scaling of the injected beam current

The introduce the **power of the bubble** $\Psi(\xi) = \int (cW - S_z)\,d^2\mathbf{r}_\perp$. In the absense of drivers and witness, $\Psi(\xi) = \text{const}$ is an integral. It serves as the measure of the nonlinearity of the bubble.

For a needle-like flat-top electron driver, it can be calculated as (see Golovanov et al. *PPCF* 2021)

$$\Psi \approx \frac{\sqrt{2}mc^2 J_A}{e}\left(\frac{J_{\text{eff}}}{J_A}\right)^{3/2}\left[1 - \frac{(k_p\xi_b)^{4/3}}{\sqrt{128 J_{\text{eff}}/J_A}}\right]$$

$J_A = 4\pi\varepsilon_0 mc^3/e \approx 17$ kA is the Alfvén current, and the effective current is intoduced

$$J_{\text{eff}} = J_b(k_p\xi_b)^{2/3}$$

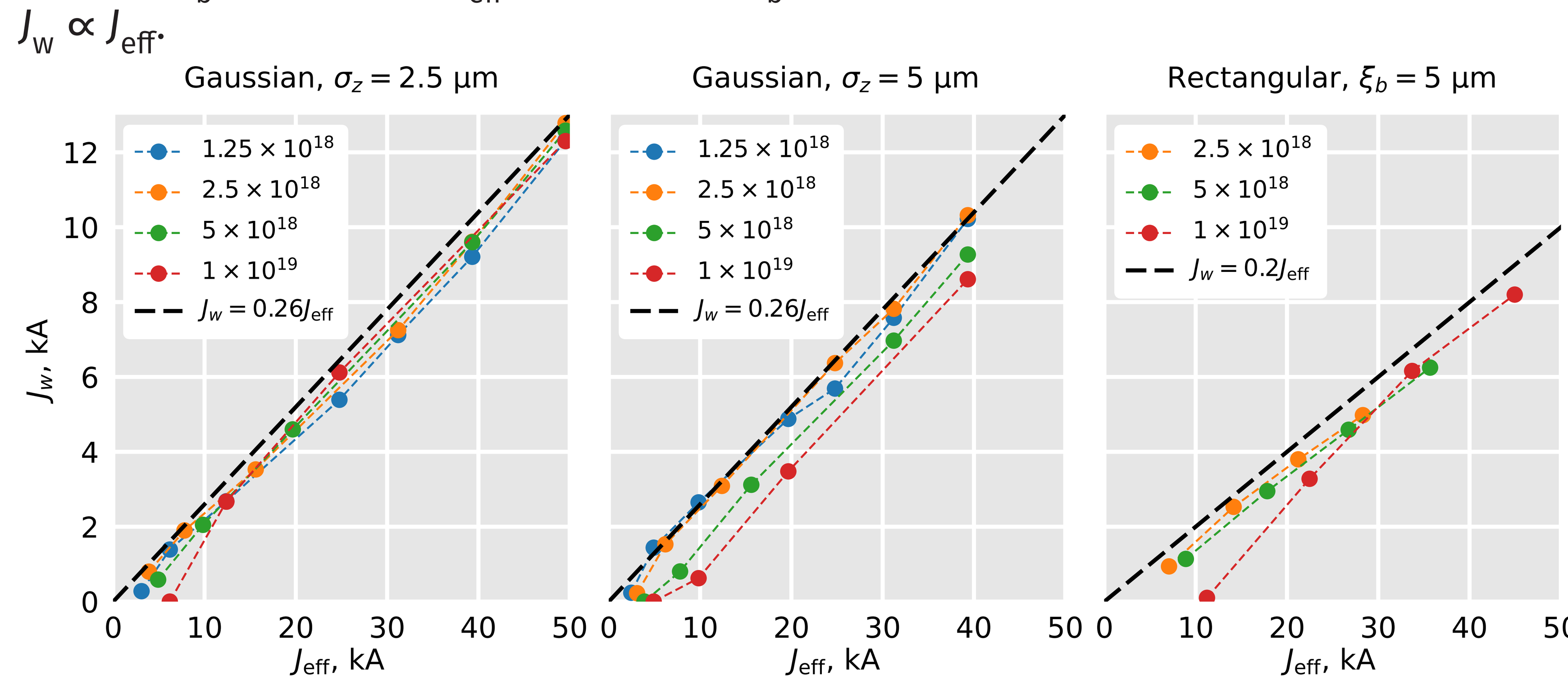
For short high-current drivers, $\Psi \propto J_{\text{eff}}^{3/2}$, thus **$J_{\text{eff}}$ is the main parameter determining the properties of the bubble**.

We expect that the injected current J_w is fully determined by Ψ and therefore J_{eff}, $J_w = f(\Psi) = \tilde{f}(J_{\text{eff}})$.

For a fixed plasma density, there are two ways to change J_{eff}: by changing the current J_b and by changing the driver length ξ_b. We run FBPIC simulations with drivers with two different shapes, rectangular and Gaussian, and explore the dependence of J_w on J_{eff}.

Fixed driver length

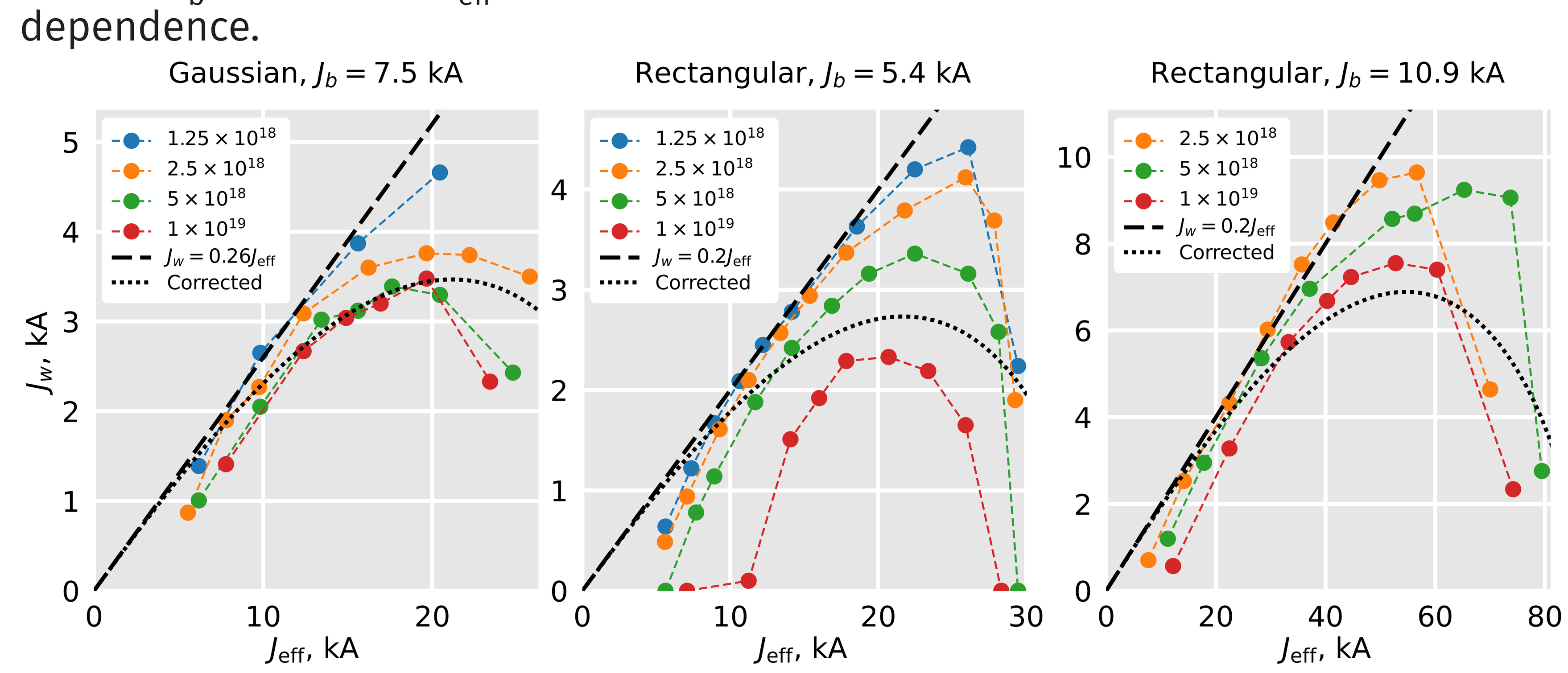
If we fix ξ_b and change J_{eff} by changing J_b, we observe a linear dependence, $J_w \propto J_{\text{eff}}$.



For the Gaussian driver, we defined J_{eff} by setting $\xi_b = \sqrt{2}\sigma_z$.

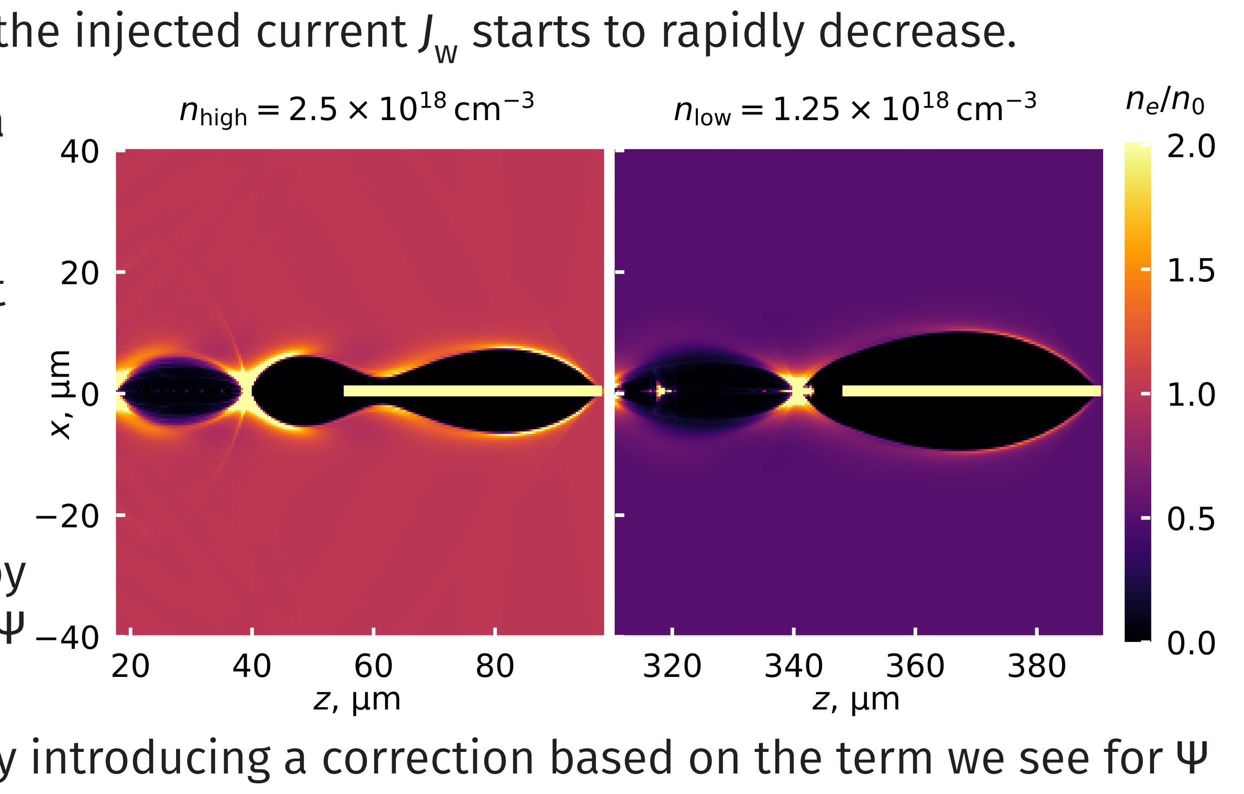
Fixed driver current

If we fix J_b and change J_{eff} by changing the length, initially there is a linear dependence.



When ξ_b is increasing, the injected current J_w starts to rapidly decrease.

This happens because a long bunch does not drive the bubble efficiently, and part of it accelerates instead. Long enough drivers cannot even fit in the bubble. This effect is reflected by the second term in the Ψ definition.



We can describe this by introducing a correction based on the term we see for Ψ

$$J_w = c_1 J_{\text{eff}}\left[1 - c_2\frac{(k_p\xi_b)^{4/3}}{\sqrt{128 J_{\text{eff}}/J_A}}\right]^{2/3}$$

However, this correction cannot explain a more complex behavior during the downramp injection.

e-mail: anton.golovanov@weizmann.ac.il