Exploring a Path to High-Quality, High-Charge LWFA Beams

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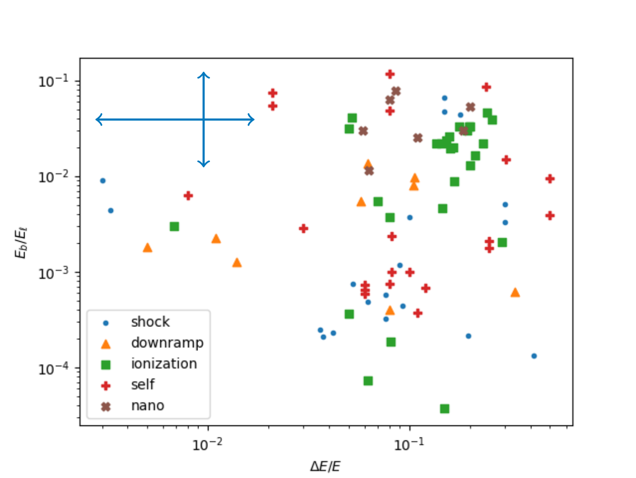
Last time: can we have good efficiency and high quality?

Is it a physics limitation preventing us from having both $E_b/E_L \gtrsim 1\%$ and $\Delta E/E \lesssim 2\%$?



[L. Labun et al 2025]

Beam-Quality Requirements

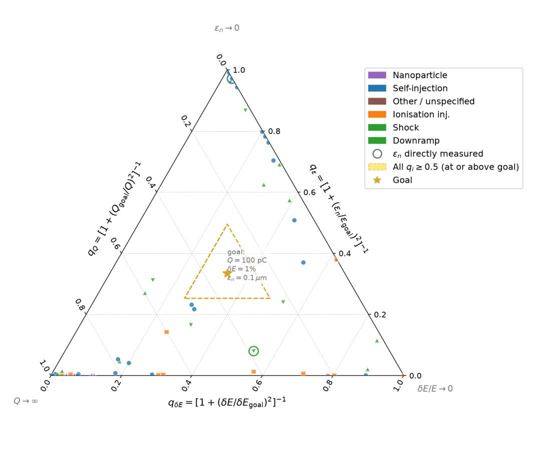
Target (loosely based on FEL reqs.)

- Centroid energy: 4-10 GeV
- Charge: $Q \gtrsim 100\,\mathrm{pC}$
- Slice energy spread $\delta E/E < 0.1\%$
- Normalized emittance $\varepsilon_n < 0.1\,\mathrm{mm\,mrad}$

Each metric has been demonstrated individually, but not in combination.

Why simultaneous optimization is hard:

Beam generation depends on $L_{\mathrm{inj}} \gg c\tau_b$
Largely determines transverse phase-space
Downstream correction works on longitudinal



The Infinite-Money Solution

Gedankenexperiment:
no resource limitations $\Rightarrow$ build the biggest laser

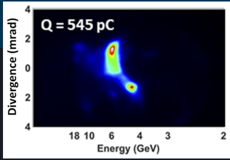
Concrete base case: TPW + nanoparticles

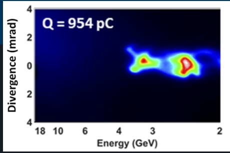
- Nanoparticle-enhanced injection > 500 pC
- $\Delta E/E \gtrsim 2\%$ and $\varepsilon_n \gtrsim 1$ mm mrad

$\Rightarrow$ Chicane and pinhole to throw away $> 90\%$

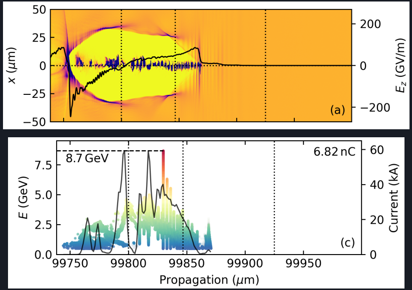
This does not scale:

- Large wall-plug energy per useful pC
- 10 kHz not yet possible
- Efficiency $\lesssim \frac{\Delta E_{\rm goal}}{\Delta E_{\rm LPA}} 0.03$

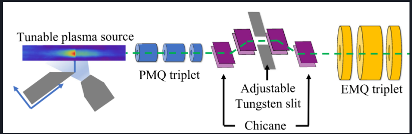




[Aniculaesei et al, MRE 2023]



[O. Labun, et al arXiv:2605.18968]



[Barber et al 2025]

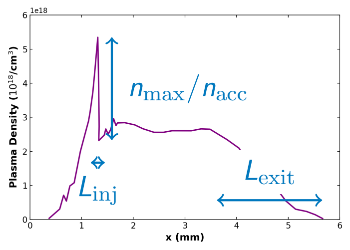
Improve efficiency by producing target phase-space volume at injection

Self-injection (Threshold trapping plasma electrons)
Uncontrolled in phase ⇒ broad spectrum, large emittance. High charge is easy.

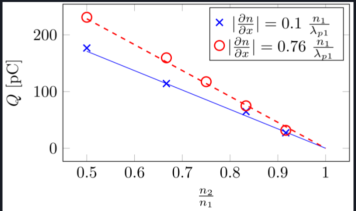
Shock/downramp (lowers wake v_{ph})
Control trapping window time and phase: *steeper ramp both injects more charge and lowers emittance*, via stronger beam loading damping transverse oscillation

[de la Ossa et al. 2017, Ekerfelt et al. 2017]

Colliding-pulse/Trojan Horse (external trigger)
Small injectable population by design. Great phase-space control but limited charge



[adapted from Jin et al 2026]



[Ekerfelt et al 2017]

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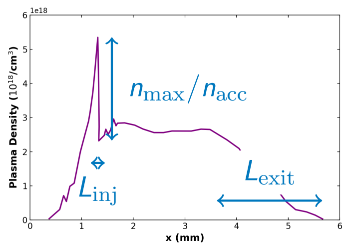

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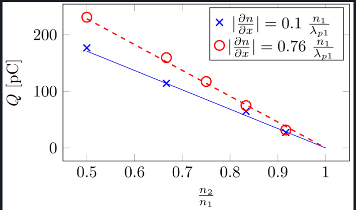


[Ekerfelt et al 2017]

Punchline

Shock injection can push in the *right direction on all three metrics* by steepening the ramp but has engineering tension with high-rep-rate gas targets

Engineering current profile and energy spread via Beam Loading

Low charge: wakefield slope dE_z/dz means head and tail of bunch gain different energy, broadening spectrum

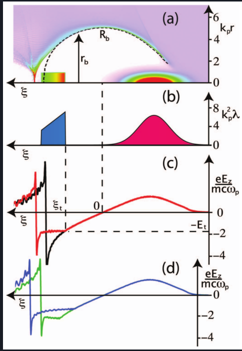
High charge modifies the wake (beam loading): Optimal $J(\zeta)$ compensates wake slope

[Tzoufras et al 2008,2009]

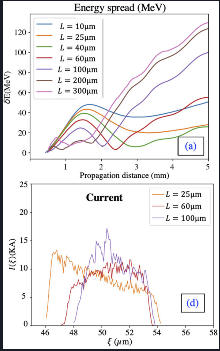
Peaked profile locally overloads $\Rightarrow \delta E/E \uparrow$

Experiments see an optimal charge Q_b

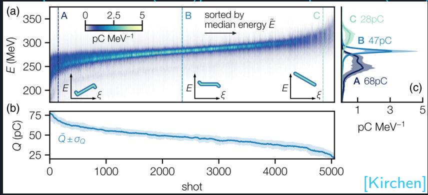
[Couperus et al. 2017; Kirchen et al. 2021; Jin et al 2026]



[Tzoufras et al (2009)]



[Hue et al (2022)]



[Kirchen]

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[Tzoufras et al 2008,2009]

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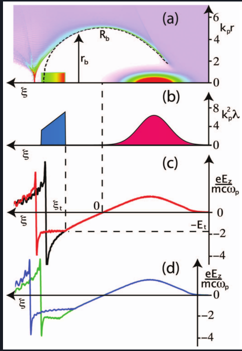
Unfortunately How-to not settled:

- ramp length sets trapping duration
- Current profile affected by density contrast and prior laser evolution [Hue et al. 2022]
- Optimum charge $Q_{\mathrm{opt}}(P_L, a_0, n_e(z))$

full chain, downramp $\rightarrow J(\zeta) \rightarrow \delta E/E$, control not yet closed experimentally



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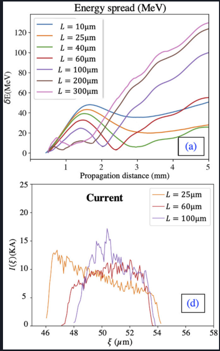

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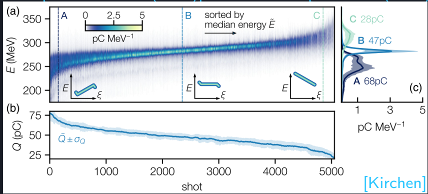
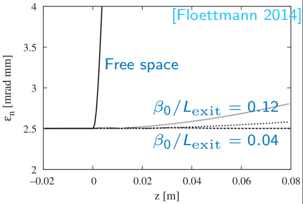


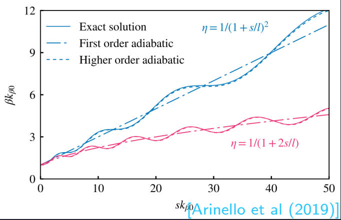
[Kirchen]

Controlling Emittance Growth at the exit



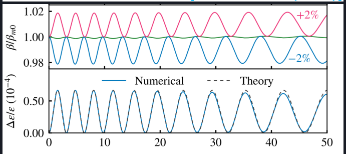
Inside the plasma, the beam is confined by the ion channel. Beam size and divergence are related:

$$\sigma^2 = \frac{\varepsilon_n}{\gamma k_\beta}, \qquad k_\beta = \frac{k_p}{\sqrt{2\gamma}} \sim \sqrt{n}, \qquad \sigma' = k_\beta \sigma$$



Abrupt plasma boundary ($L_{\mathrm{exit}} \lesssim 2\pi/k_\beta$)

- Transverse momentum converts to angular spread $\Rightarrow$ large divergence
- chromatic phase mixing $\Rightarrow$ emittance growth



Gradual exit ramp ($L_{\mathrm{exit}} \gg 2\pi/k_\beta$)

- emittance conserved: $\sigma \uparrow$ adiabatically as $k_\beta \downarrow$
- $\sigma' \sim \gamma/\varepsilon_n \sigma$ decreases

[Floettmann 2014; Ariniello et al. 2019; Zhao et al. 2020]

Parameter Dependences and Design Constraints

Parameter	Change	Q	$\delta E/E$	ε_n	σ_θ	Constraint
Injection ramp L_{inj}	Steeper	↑	↓	↓	—	Gas load at rep rate
Density contrast $n_{\mathrm{max}}/n_{\mathrm{acc}}$	Higher	↑	sensitive	sensitive	—	Need to control current profile
Laser power P_L	Higher	↑ Q_{opt}	↓ at opt.	neutral	—	Self-injection threshold; average power cost
Exit ramp L_{exit}	Longer	—	—	↓	↓	Increases dephasing and pump-depletion length

Ramp geometry and laser/plasma parameters are coupled: they jointly set the injected charge, current profile, and phase-space volume and should be optimized together rather than sequentially.

Wavelength Scaling of the Design Parameters

Design parameters scale with plasma density, depends on laser wavelength via matching: $n_e \propto \lambda_L^{-2}$, $k_p^{-1} \propto \lambda_L$ and bubble radius $r_b \propto \lambda_L$. Scaling scheme defined by P^η with $a_0 =$const

Quantity	This talk	Direction	Fix n_e $\eta=-2$	Notes
n_e	λ_L^{-2}	↓	λ_L^0	Allow n_e to drop with λ_L
$Q_{\rm opt}, Q_{\rm max}$	λ_L^1	↑	λ_L^0	$Q_{\rm opt} \sim 1/E_t$, $Q_{\rm max} \sim n_e V$
$\varepsilon_n^{\rm inj}$	λ_L^0–λ_L^1	—	—	beam-loading, a_0; possible small k_p^{-1} effect [de la Ossa 2017]
$L_{\rm exit} \propto \lambda_\beta$	λ_L^1	↑	λ_L^0	easier engineering
$P_{\rm peak}$	λ_L^0	const.	λ_L^{-2}	
E_L	λ_L^1	↑	λ_L^{-2}	driven by $P\mathcal{T}$

At $\eta=0$: same peak power and number of stages; Mid-IR moves Q into the 100 pC range for the same peak laser power. Cost is pulse energy $\propto \lambda_L^1$.

Summary

1. Large-laser baseline with phase-space selection is physically valid but not efficient enough for high-rep-rate applications. Controlling injection is necessary.
2. Shock/downramp injection improves charge, energy spread, and emittance simultaneously as the ramp steepens, but gas system may be an engineering challenge at high rep rate.
3. Beam-loading optimum couples injected charge to energy spread through the current profile.
4. Relevant design parameters scale with λ_L. Mid-IR drivers could shift Q_{opt} into the 100-pC range using the same injection and acceleration physics. The open problem is mid-IR laser development at sufficient pulse energy and repetition rate.
5. Emittance vs charge scaling needs to be studied more carefully; a few competing optimization effects can keep emittance small or grow with wavelength.