Stability of PWFA Injection Schemes in Hybrid Accelerators

Advanced Accelerator Concepts Workshop 2026

Edgar Hartmann, Natascha Thomas, Fahim Habib, Thomas Heinemann, Onur Bilen, Antonio Tarzikhan, Mirela Cerchez, Bernhard Hidding

July 30, 2026

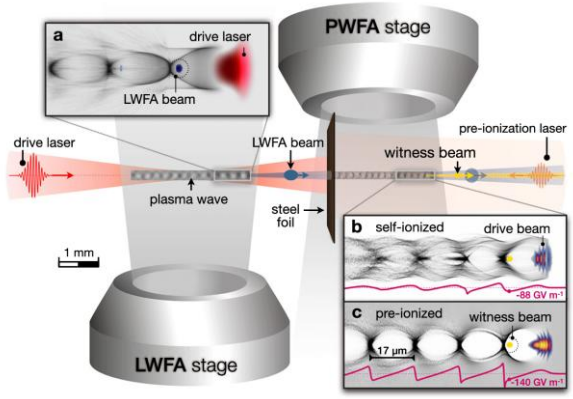
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Outline

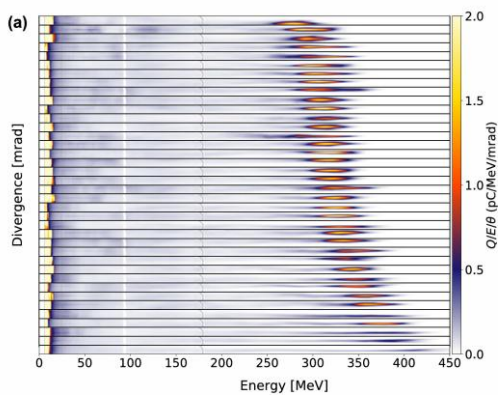
Heinrich Heine
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- Motivation and Introduction: Hybrid LWFA driven PWFA
- PWFA Injection Methods
- Simulation Working Routine
- Results
- Outlook

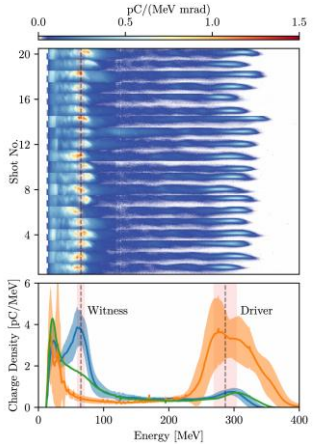
Hybrid LWFA driven PWFA



Kurz, T., Heinemann, T., Gilljohann, M.F. *et al.* Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams. *Nat Commun* **12**, 2895 (2021). https://doi.org/10.1038/s41467-021-23000-7



Susanne Schöbel *et al* 2022 *New J. Phys.* **24** 083034. https://doi.org/10.1088/1367-2630/ac87c9



Foerster, F. M. *et al.* Phys. Rev. X **12**, 041016. https://doi.org/10.1103/PhysRevX.12.041016

- Inherent jitter of the PWFA driver due to laser induced jitter in the LWFA stage
- Simulation based approach that investigated the jitter on the PWFA witness beams

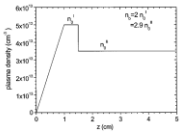
The Hybrid-Collaboration

Selected Density Downramp Injection Milestones in LWFA and PWFA

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Experiments **PWFA** Theory

Suk et al. 2001:
Sharp downramp



Wittig et al. 2015:
Optical plasma torch

1st PWFA realization:
Deng/Karger et al. 2019:
Optical plasma Torch

Zhang et al. 2019
Asymmetric Driver

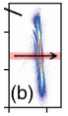
1st Hybrid LWFA-PWFA Downramp:
Couperus Cabadag et al. 2021
Hydrodynamic shock

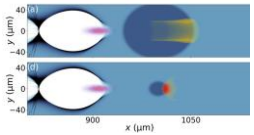


Ullmann et al. 2021:
Optical plasma torch

Knetsch et al. 2021:
Optical plasma torch

Foerster et al. 2022





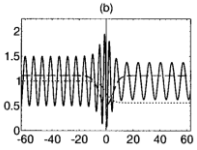
Energy and brightness boost
Zhang et al. 2025

Wood et al. 2026

Efficiency record
Foerster et al. 2026

Experiments **LWFA** Theory

Bulanov et al. 1998:
Gentle downramp



1st LWFA Realization
Geddes et al. 2008

Routine injection method in LWFA
(mostly sharp downramps)

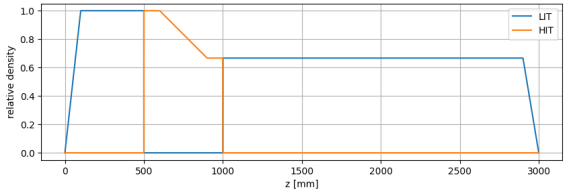
FEL lasing at 27nm
Wang et al. 2021

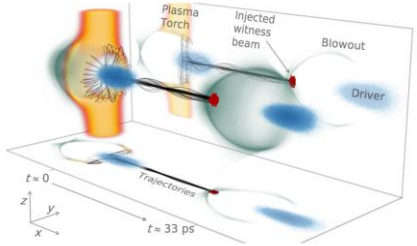
Xu et al. 2023:
Downramp + self-injection

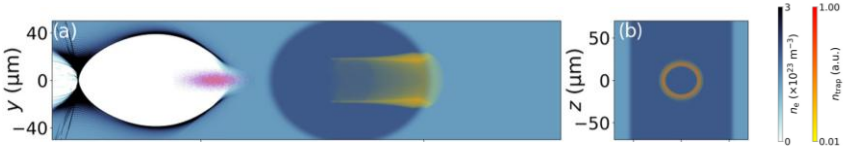
Injection methods

Two injection schemes are considered:

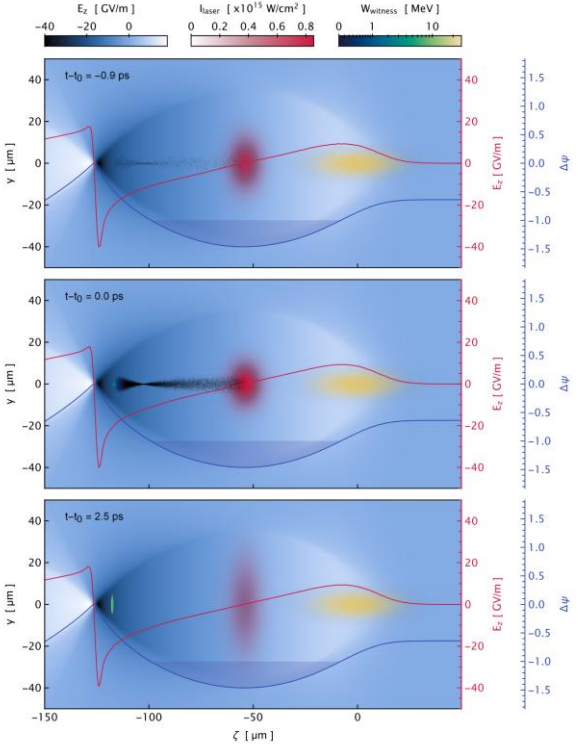
- Trojan Horse injection
- Density downramp injection (DDRI)
  - Sharp DDRI / Wide Torch







Ullmann, D., Scherkel, P. et al. Phys. Rev. Research **3**, 043163
https://doi.org/10.1103/PhysRevResearch.3.043163



Heinemann, T., PhD Thesis 2025

Working routine

Use fixed driver parameter:

- 500pC
- 1.5 GeV
- rms width 5 µm
- rms length 15µm
- lambda_p = 100µm

And highlight pitfalls in this routine

Optimize injection-relevant parameter via Bayesian optimization

FBPIC

R. Lehe et al. A spectral, quasi-cylindrical and dispersion-free Particle-In-Cell algorithm, Computer Physics Communications, Volume 203, 2016, Pages 66-82, ISSN 0010-4655, https://doi.org/10.1016/j.cpc.2016.02.007

S. Jalas, et al. Accurate modeling of plasma acceleration with arbitrary order pseudo-spectral particle-in-cell methods. *Phys. Plasmas* 1 March 2017; 24 (3): 033115. https://doi.org/10.1063/1.4978569

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A. Ferran Pousa et al. 2023, Phys. Rev. Accel. Beams **26**, 084601, https://doi.org/10.1103/PhysRevAccelBeams.26.084601

Take optimized simulation settings from each injection scheme

Explore stability of injection scheme for variations in Driver parameter

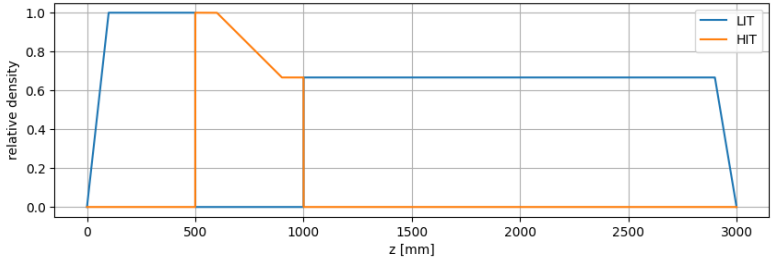
Density Downramp Optimization

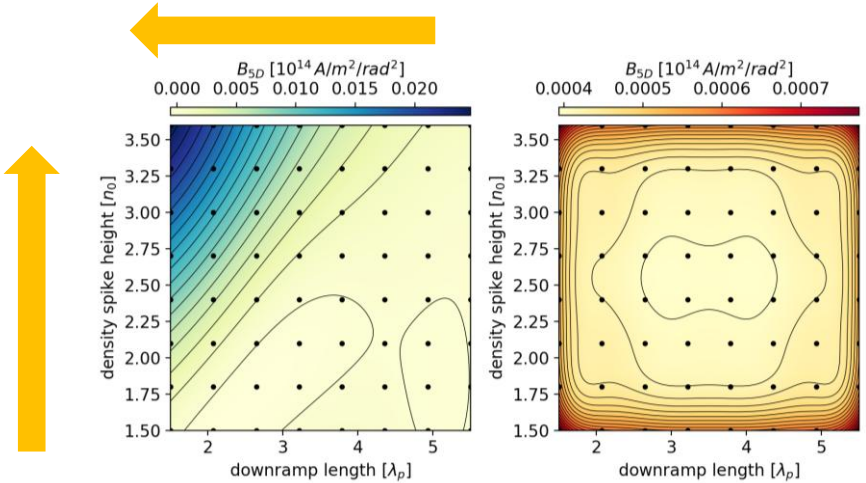
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Parameter space for optimization:

- downramp length ∈ $[0.5\ \lambda_p,\ 6\ \lambda_p]$
- density spike height ∈ $[1.5\ n_0, 3.5\ n_0]$

Optimization objective: $B_{5D} = \frac{I_{peak}}{\epsilon_{n,x}\epsilon_{n,y}}$





A smooth downramp never yielded a converging result in terms of the optimization objective

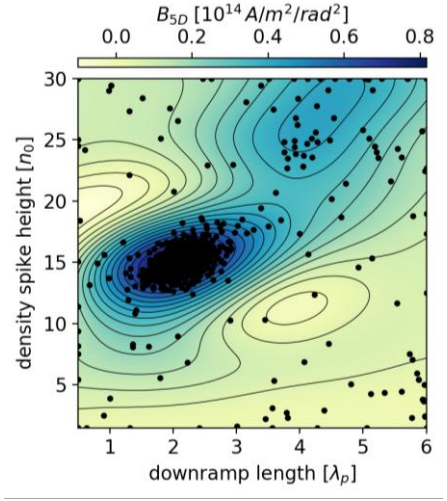
Optimization: Wide Torch

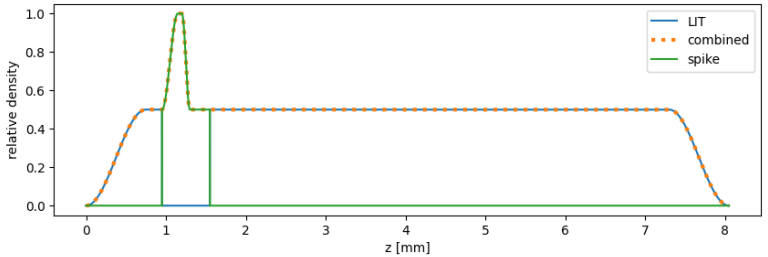
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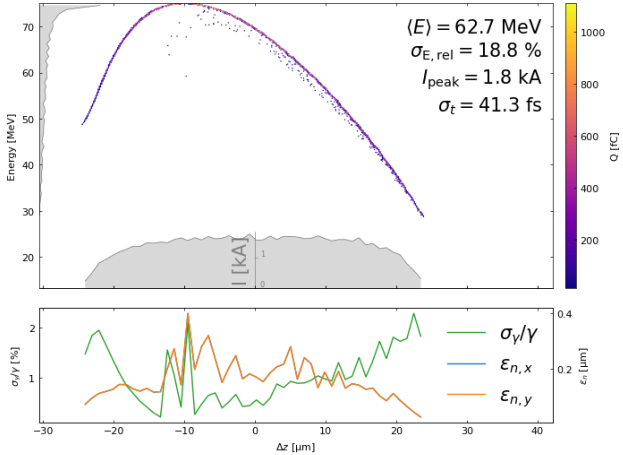
Parameter space for optimization:

- downramp length ∈ $[0.5\ \lambda_p,\ 6\ \lambda_p]$
- density spike height ∈ $[2\ n_0, 30\ n_0]$

Optimization objective: $B_{5D} = \dfrac{I_{peak}}{\epsilon_{n,x}\epsilon_{n,y}}$







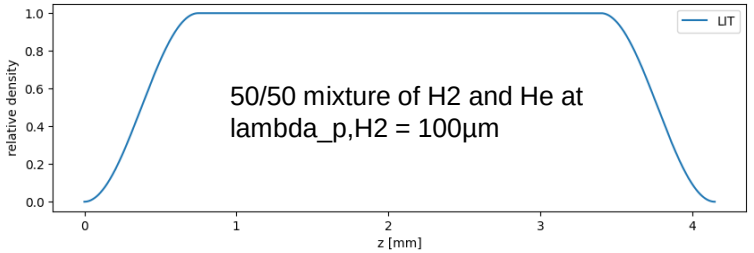
Optimization: Trojan

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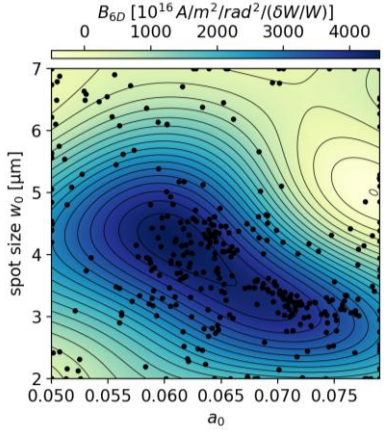
Parameter space for optimization:

- $w_0 \in [2\ \mu m, 7 \mu m]$
- $a_0 \in [0.05, 0.08]$
- $\tau_0 \in [20\ \text{fs}, 50\ \text{fs}]$
- Laser distance behind driver $z_0 \in [0.1\ \lambda_p, 0.5\ \lambda_p]$

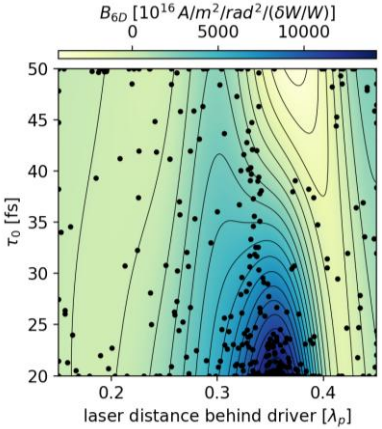
Optimization objective: $$B_{6D} = \frac{I_{peak}}{\epsilon_{n,x}\epsilon_{n,y}\left(\frac{\delta W}{W}\right)}$$



Hard to optimize due to small number of macro particles at low w_0



This trend is trivial and not necessary to be optimized

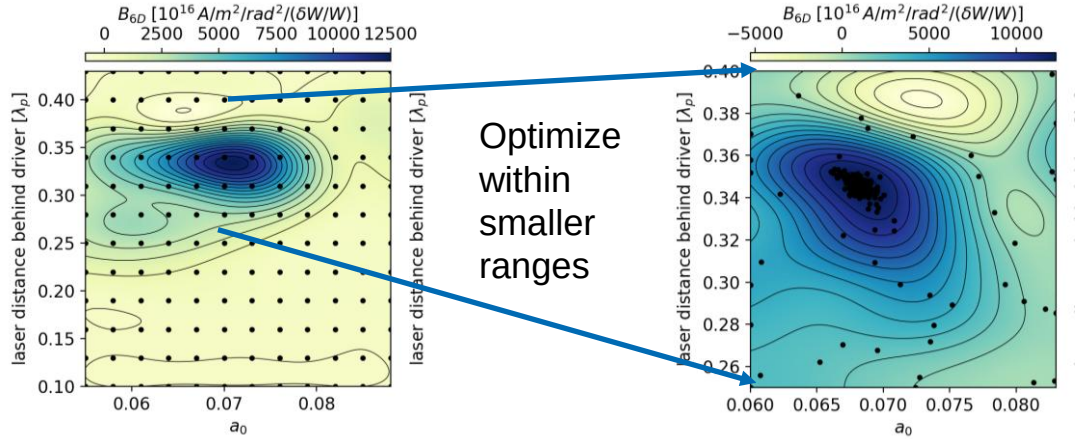


Optimization: Trojan

Choose a constant w0 = 4µm and tau = 30fs and use the **reduced parameter space** for optimization

- $a_0 \in [0.05, 0.08]$
- Laser distance behind driver $z_0 \in [0.1\ \lambda_p, 0.5\ \lambda_p]$

Scan the parameter space:



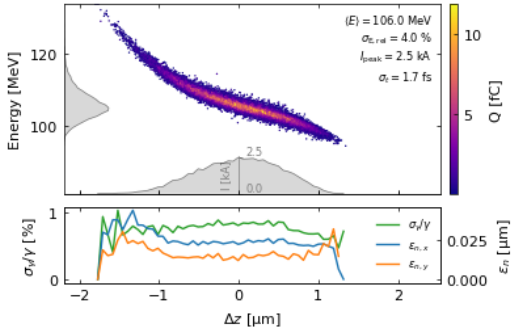
Optimize within smaller ranges

Best trial at:

- $a_0 = 0.068$
- $z_0 = 0.345\ \lambda_p$

Resulting in:

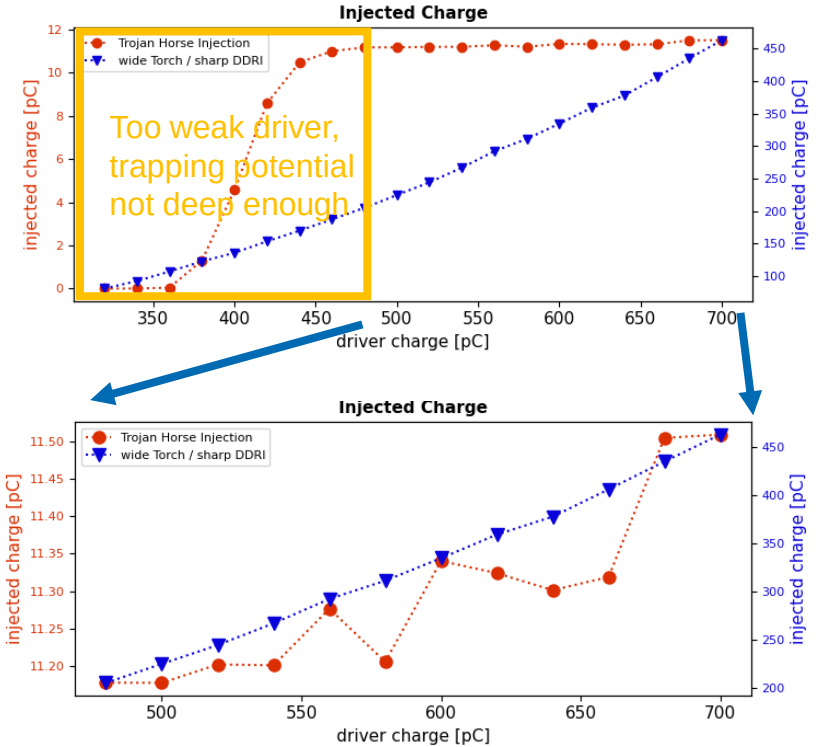
- $Q = 11.2$ pC
- $\varepsilon_{n,x} = 28.6$ nm
- $B_{6D} = 13.7\ 10^{19} A/m^2 rad^2 (\frac{dW}{W})$



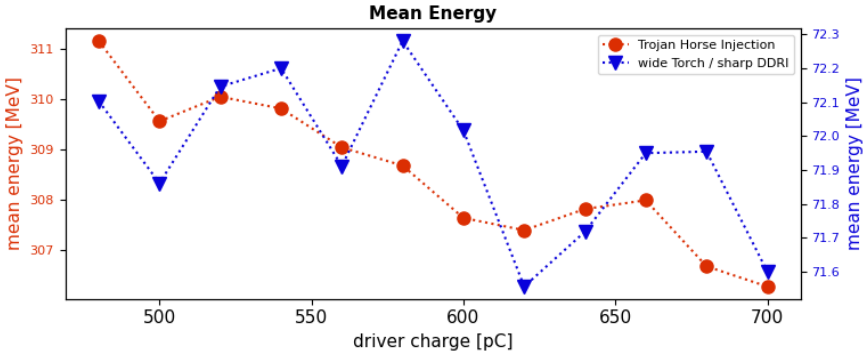
Note: optimization result depends on plasma length

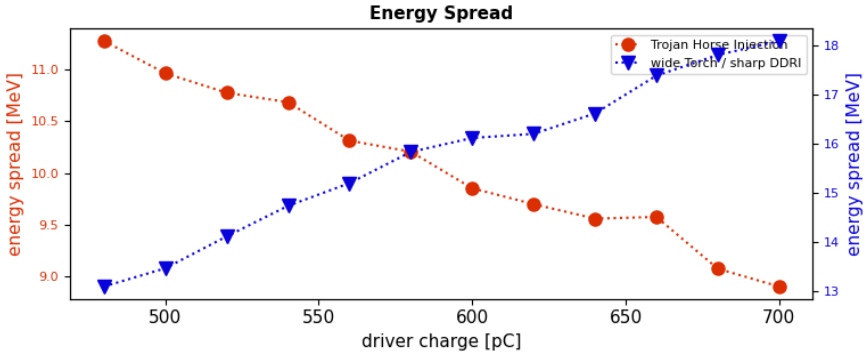
Results of Driver Jitter scan

- Taking the optimized scenarios from the Bayesian Optimization
- Vary the charge of the Drive beam
- Results:
  - Trojan Horse Injection traps little charge < 480 pC driver charge
  - Sharp downramp injected charge and energy spread scales linearly with driver charge

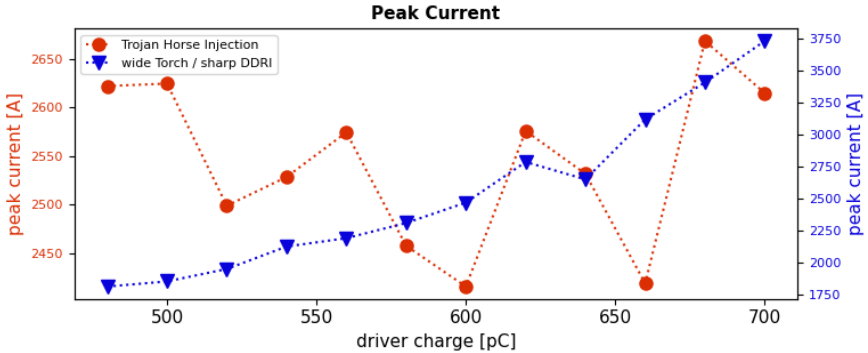


Energy and Peak Current



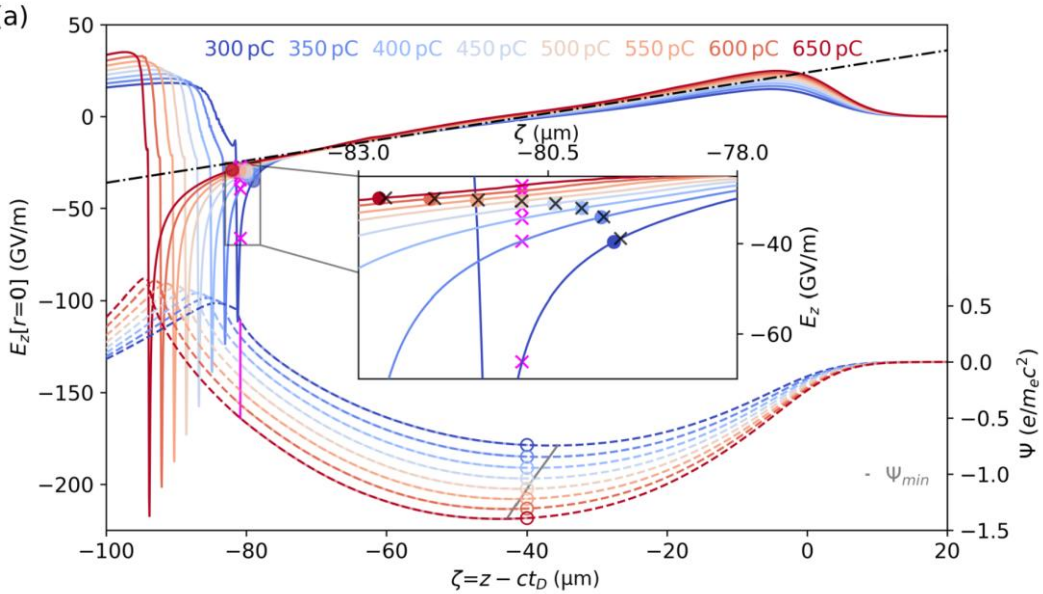


- Mean energy mostly decoupled
- Energy spread weak dependence on driver charge
- Peak current has a strong dependence on driver charge for sharp DDRI



Trojan Self-adaptive Stability

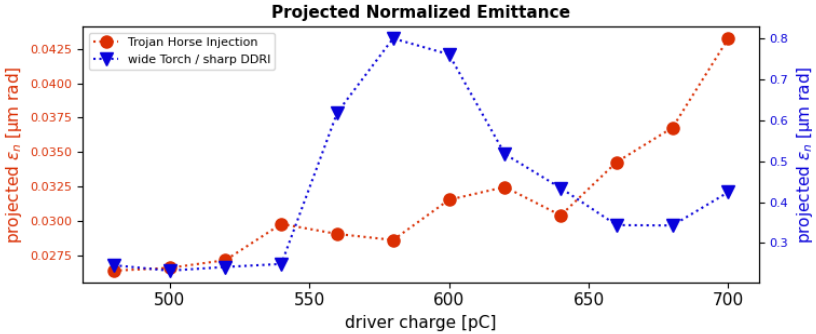
- With variations in the driver charge, the trapping position of the witness changes
- Trapping occurs at similar Ez across a wide range of driver charges
- A detailed study:
  - D. Campbell *et al.* Phys. Rev. Research **8**, 013273 (2026) https://doi.org/10.1103/p6ss-vgq5

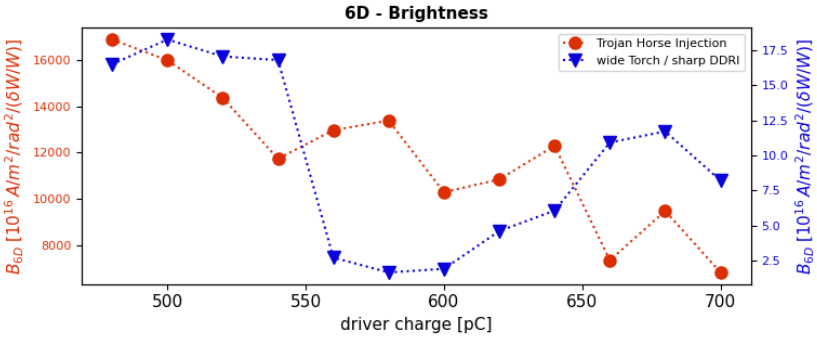


D. Campbell *et al.* Phys. Rev. Research **8**, 013273 (2026) https://doi.org/10.1103/p6ss-vgq5

Emittance and Brightness

- **Sharp DDRI**: Relatively constant emittance at low driver charge resulting in B_{6D} to be within a factor of 5 over ~40% driver charge increase
- **Trojan Horse Injection**: emittance *within a factor of 2* for witness beams with strong driver
- Trojan Horse witness beam B_{6D} is ~3 orders of magnitude higher when charge is injected

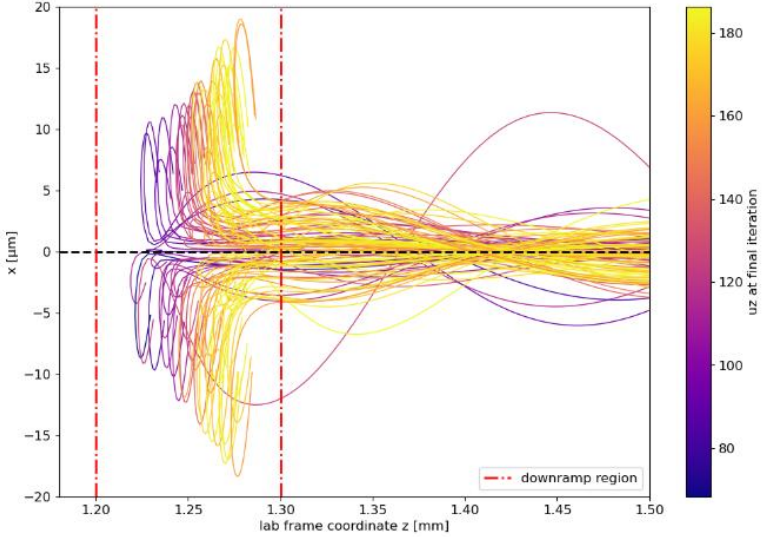




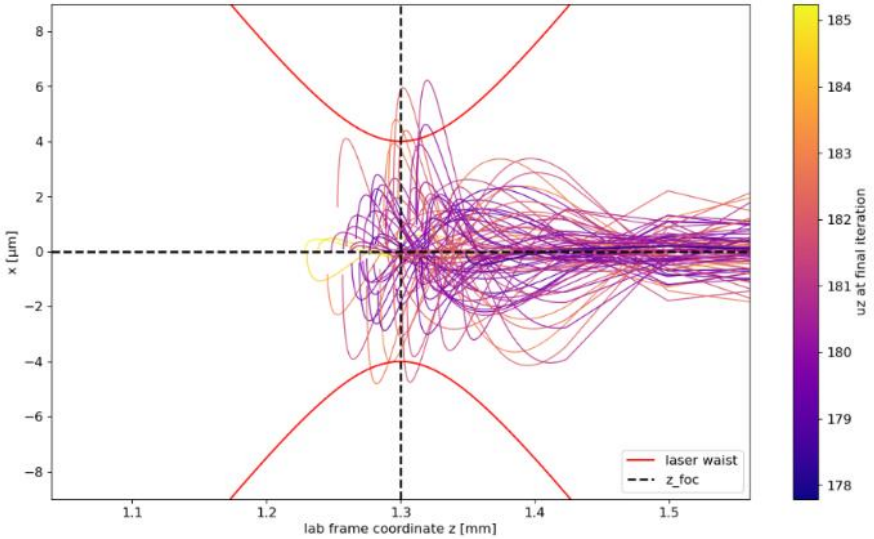
Injection coupling

- Tracking electrons during injection shows (de-) coupling to the wake

Sharp Downramp Injection



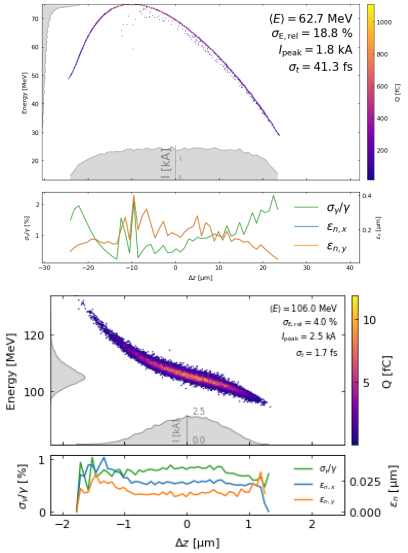
Trojan Horse Injection



Outlook and Summary

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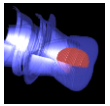
- Simulation approach for Hybrid PWFA witness beams presented
  - Pitfalls in working routine highlighted
- Sharp DDRI injected witness charge is depended on driver charge, which in turn leads to stable mean witness energies
- Trojan injection is decoupled from the wake excitation and injects stable witness beams if a strong wake is excited
- More optimization runs needed for different initial Driver parameters
- Broader Driver parameter scans needed (size, duration, shape, etc.)



Thank you to everyone who contributes to open-source software!

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