# Towards a soft x-ray PWFA-FEL via Trojan Horse single bunch injection

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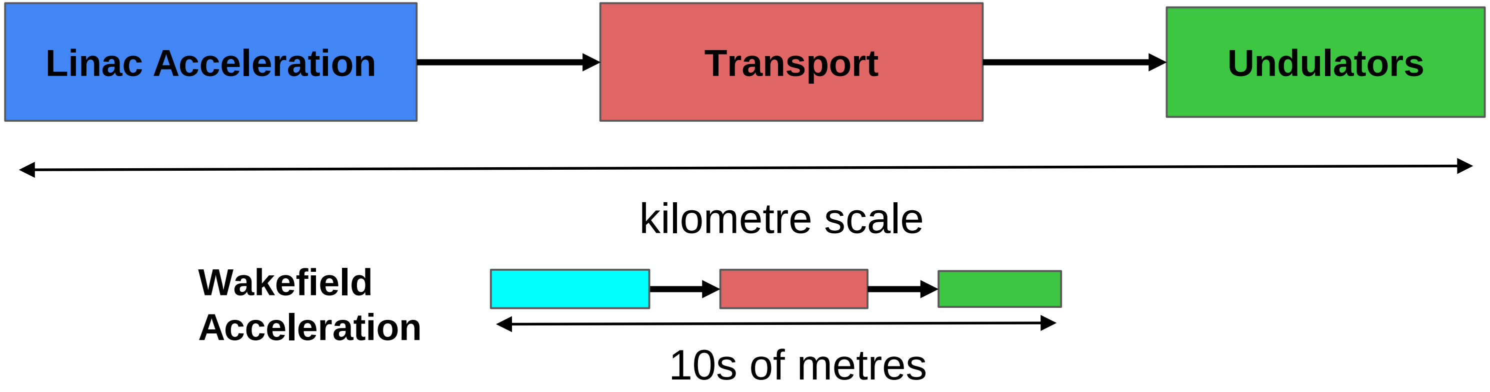
7/11/2022

AAC 2022

# Motivation: shrink XFEL footprint




**First experimental demonstrations towards plasma-based FELs:**

- Exponential gain at 27 nm (XUV) with LWFA**-** Wang, W., Feng, K., Ke, L. *et al.* Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. *Nature* 595, 516–520 (2021)
- Exponential gain at 830 nm (IR) with PWFA - Pompili, R., Alesini, D., Anania, M.P. *et al.* Free-electron lasing with compact beam-driven plasma wakefield accelerator. *Nature* 605, 659–662 (2022)
- Gain in seeded FEL at 270 nm (UV) with LWFA - Labat M, Cadabag JC, Ghaith A, et al. Seeded free-electron laser driven by a compact laser plasma accelerator. Research Square; 2022 (PREPRINT)

**Ultimate goal:** PWFA-XFEL with comparable performance to linac facilities

# Challenges of PWFA-XFEL

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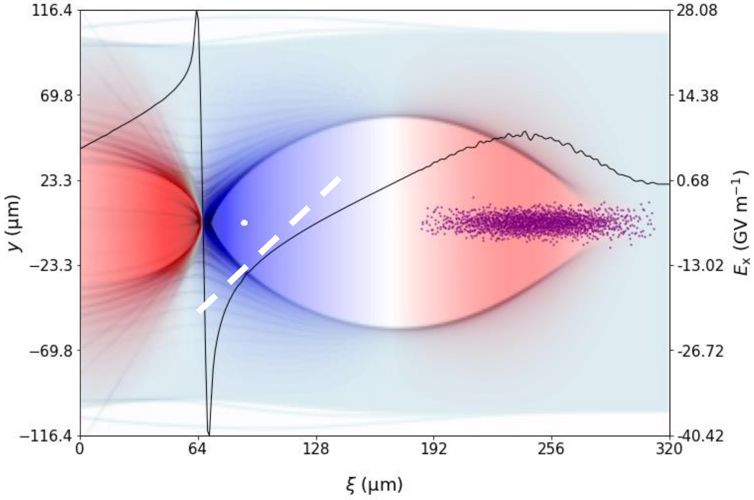
- Need excellent beam quality - low emittance, high current, low energy spread
- Requirements more severe as target wavelength decreases
- PWFA beams naturally chirped - resulting energy spread unacceptable for XFEL




1. Emittance criterion

$$\varepsilon_n \leq \frac{\gamma \lambda_r}{4\pi}$$

1. Energy spread criterion

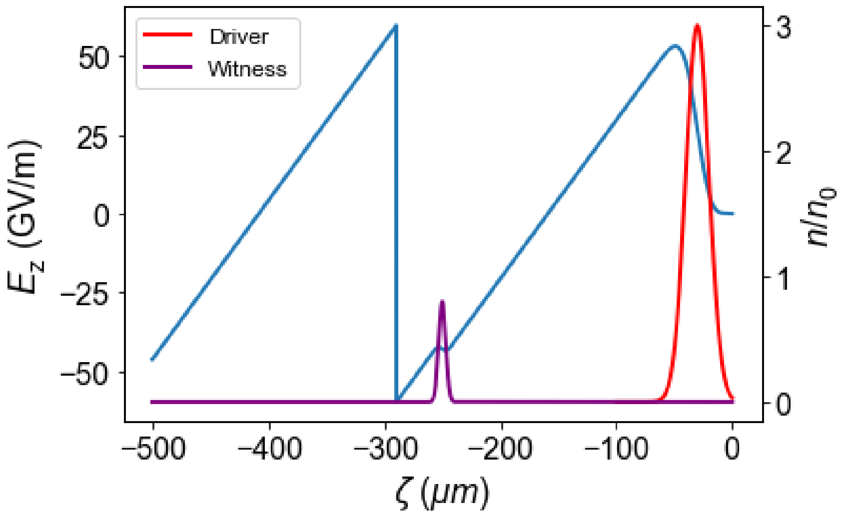
$$\sigma_\gamma < 0.5\,\rho_{\mathrm{FEL}}$$

1. Diffraction criterion

$$Z_R \geq 2L_{1D}$$

# Chirp suppression with Trojan Horse injection

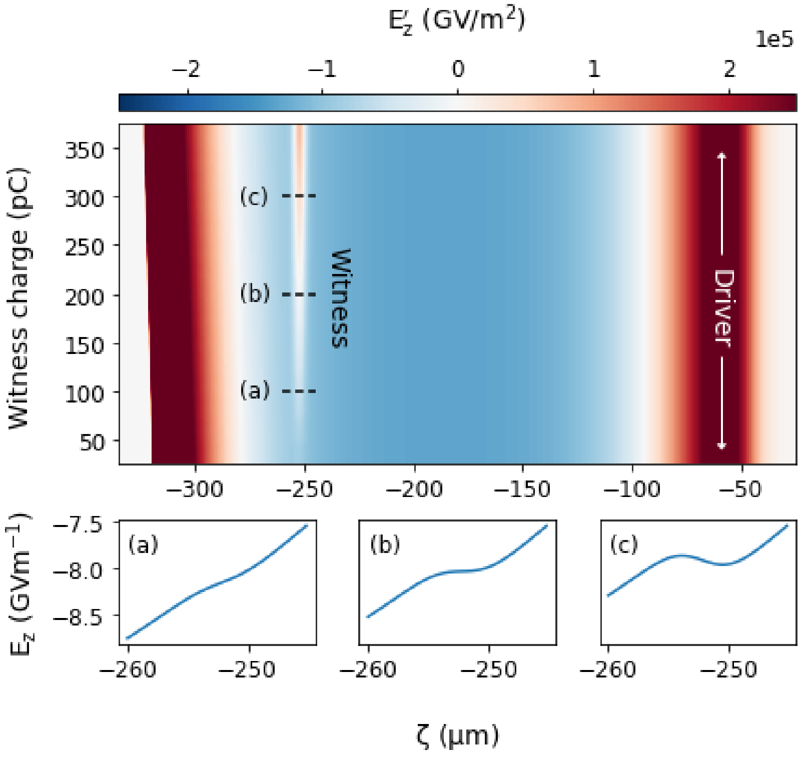
- Low-charge regime (few pC): few 10s nm rad emittance + 0.01% level energy spread possible - multibunch approach required for dechirping (G.G. Manahan et al., Nat Com 2017)
- Chirp suppression with single bunch of higher charge via beam-loading - locally flatten field
- Achievable using planned E310 setup in collinear configuration
- Optimisation of bunch properties:
  - ✓ Increased peak current
  - ✓ Reduced projected energy spread
  - ✗ Increased emittance due to space charge



# Beam-loading

Aim to inject charge for optimum loading - i.e. field is flattened. Loading depends on witness charge density

Analytical models* - estimate the charge density needed for beam-loading → **Optimum peak witness charge density ~ 1e19 /cm$^3$**




*A. A. Golovanov, I. Yu. Kostyukov, J. Thomas, and A. Pukhov, "Analytic model for electromagnetic fields in the bubble regime of plasma wakefield in non-uniform plasmas," *Physics of Plasmas*, vol. 24, no. 10, p. 103104, Oct. 2017

*A. A. Golovanov, I. Y. Kostyukov, A. M. Pukhov, and J. Thomas, "Generalised model of a sheath of a plasma bubble excited by a short laser pulse or by a relativistic electron bunch in transversely inhomogeneous plasma," *Quantum Electron.*, vol. 46, no. 4, pp. 295–298, Apr. 2016

# Beam-loading

Aim to inject charge for optimum loading - i.e. field is flattened. Loading at a given wakefield strength and plasma density depends on witness charge density

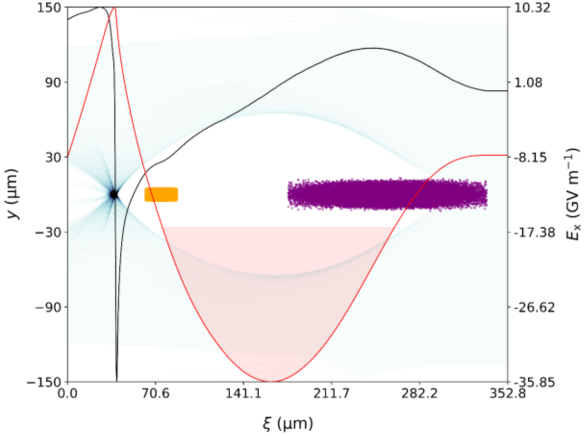
Use PIC simulations for increased accuracy - witness bunch (orange) loaded in as external Gaussian beam with fixed dimensions and charge is varied

**Optimum peak witness charge density ~ 0.4-0.5 e19 /cm$^3$**

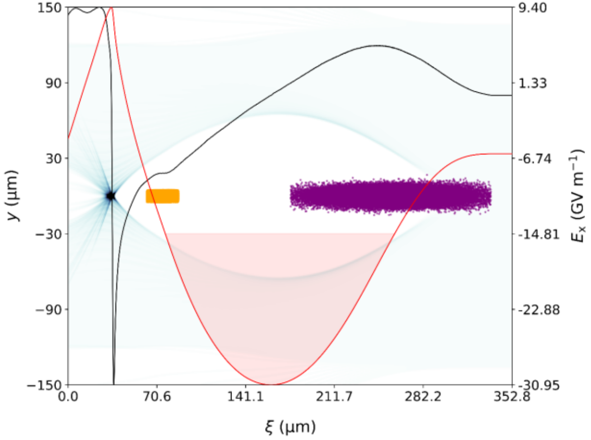
**For likely witness dimensions, $Q_w$ < 100 pC**

Baseline parameters: 250 μm blowout, driver 10 GeV + 1.5 nC, H/He gas mix

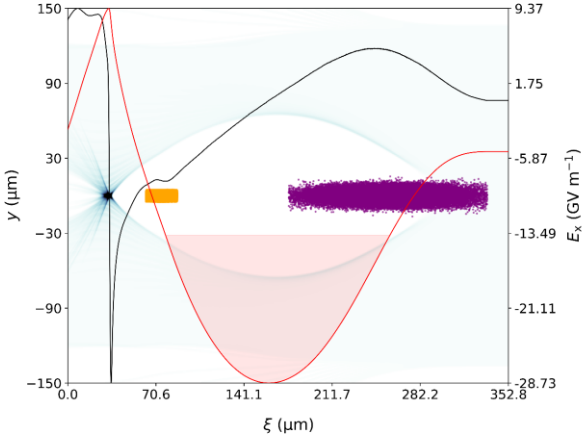
$n_w/n_0$ = 170




$n_w/n_0$ = 280



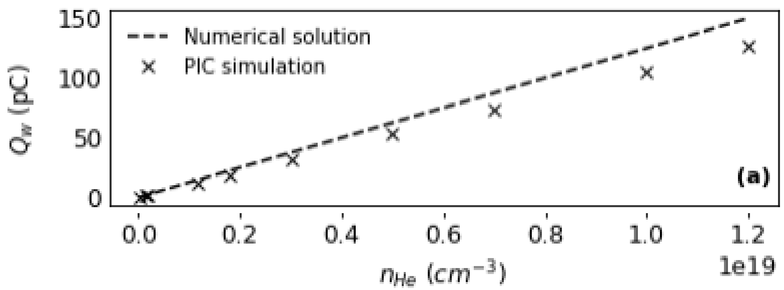

$n_w/n_0$ = 450

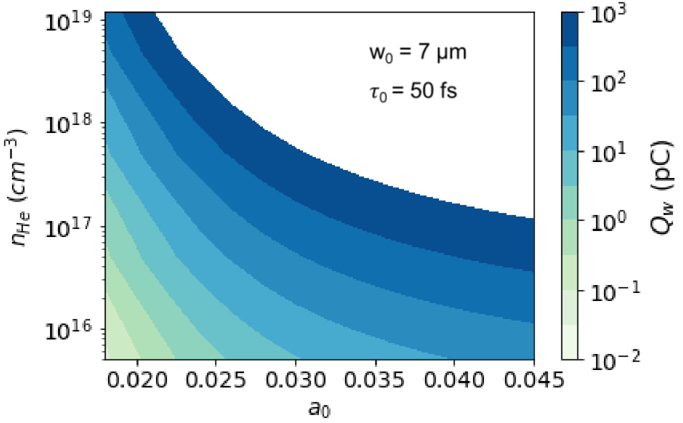


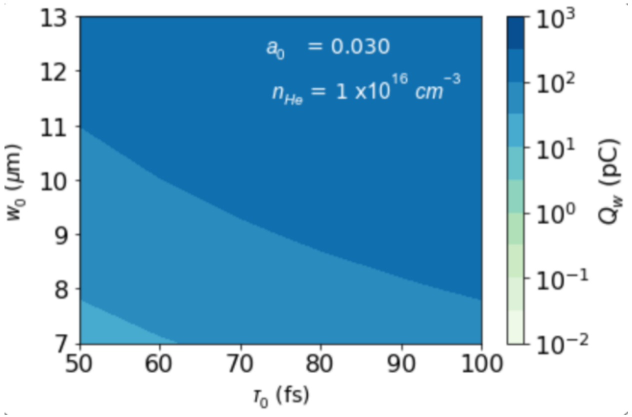
# Tuning released charge via plasma photocathode

4 degrees of freedom with which to tune injected charge:

- Photocathode laser amplitude $\mathbf{a_0}$
- Photocathode laser waist $\mathbf{w_0}$
- Photocathode laser pulse duration $\boldsymbol{\tau_0}$
- HIT gas density $\mathbf{n_{HIT}}$



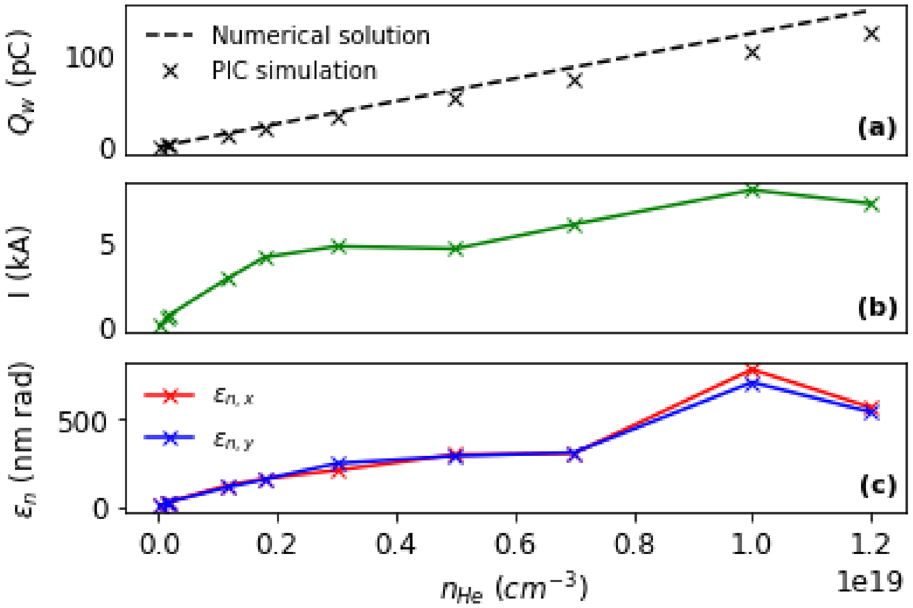
# Initial simulation results

- Initial scan of witness charge via increasing HIT density at medium resolution and 200 um plasma wavelength

- Allows likely witness properties to be examined

- Resolving beam loading requires increased resolution and significantly increased computational resources

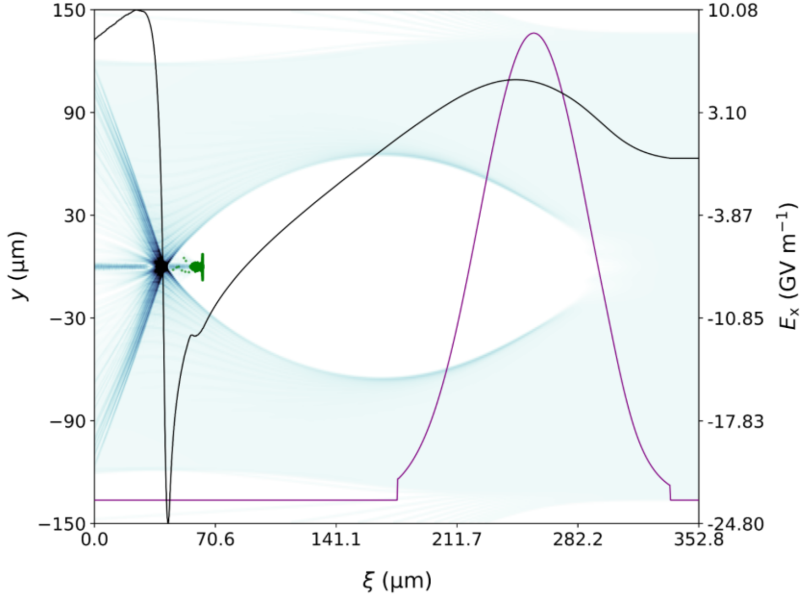
- Initial results show that it should be possible to inject a bunch capable of sufficient beam loading that maintains < 300 nm rad emittance and > 5kA peak current



# Initial simulation results

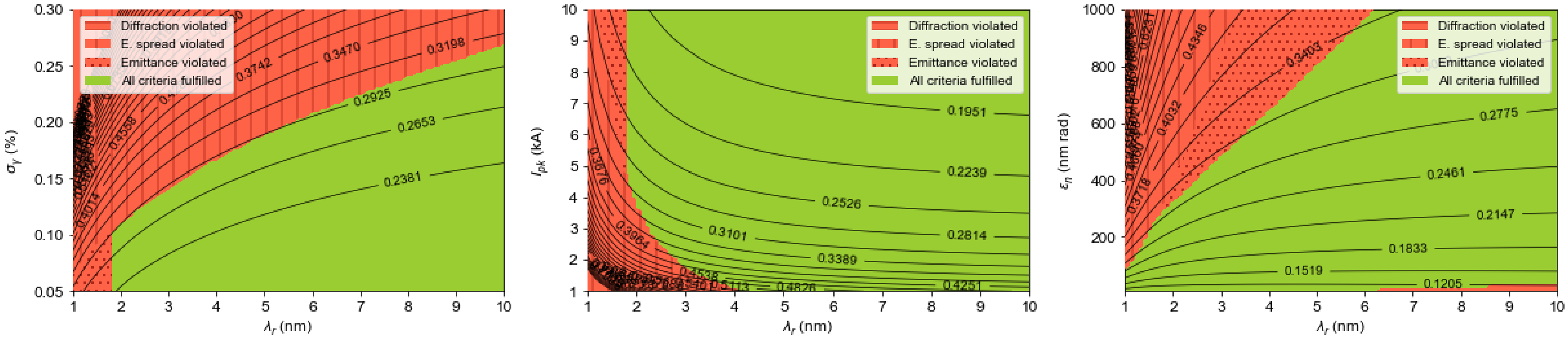
**Increased resolution to resolve beam-loading:**

- First high resolution simulations at target 250 um plasma wavelength have demonstrated witness injection leading to beam-loading near optimum
- At 10 % of target energy (i.e. 100 MeV) witness properties as follows:
    - Charge = 63 pC
    - Peak current = 3.2 kA
    - Projected emittance = 136 nm rad
    - Projected energy spread = 1.19 %
    - Slice energy spread 0.3 %
- At full energy slice and projected energy spread should be further reduced, and emittance slightly increased



# Application to soft XFEL

The Xie parametrisation can be used to examine the prospects for a witness bunch with 5 kA peak current, 300 nm rad emittance, < 0.2 % slice energy spread and negligible chirp. Such a bunch should allow most of the soft x-ray regime to be accessed.



# Next steps

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- Progress 250 um plasma wavelength simulations at high resolution to target beam energy of 1 GeV
- Scan photocathode laser parameters and determine effect on beam properties
- Choose optimum working point - minimised energy spread, maximised current
- Start-to-end simulations of soft x-ray production
- Demonstrate beam-loading experimentally eith **E310 collinear setup**
- Accepted proposal at FACET-II, to be carried out experimentally subsequent to successful injection at E310 - **E313: Multibunch dechirper for ultrahigh 6D brightness beams.** Aims to demonstrate chirp removal of **low-charge** witness bunches while maintaining **10s nm rad emittance and 0.01% level energy spread**

# Summary and outlook

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- Trojan Horse could have the potential to produce beams in the **‘high charge’ regime** (10s pC) with **multi-kA current, few 100 nm rad emittance and few 0.1 % slice energy spread** using chirp-suppression via beam-loading

- Such beams should have sufficient quality to produce XFEL radiation in the soft x-ray region. This will be the subject of upcoming start-to-end simulations

- Beam-loading with Trojan Horse could be demonstrated using the planned E310 setup in collinear geometry simply by changing photocathode laser parameters and gas density