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# Efficient Free-Electron Laser Modelling Using a Lorentz-Boosted Coordinate System

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## Introduction

- Free-electron lasers (FELs) provide ultrashort (femtosecond) radiation with tuneable wavelengths
- FEL simulation codes such as Genesis do not fully capture transverse beam dynamics
- Particle-in-cell (PIC) simulations account for emittance and space charge effects

## Beam matching

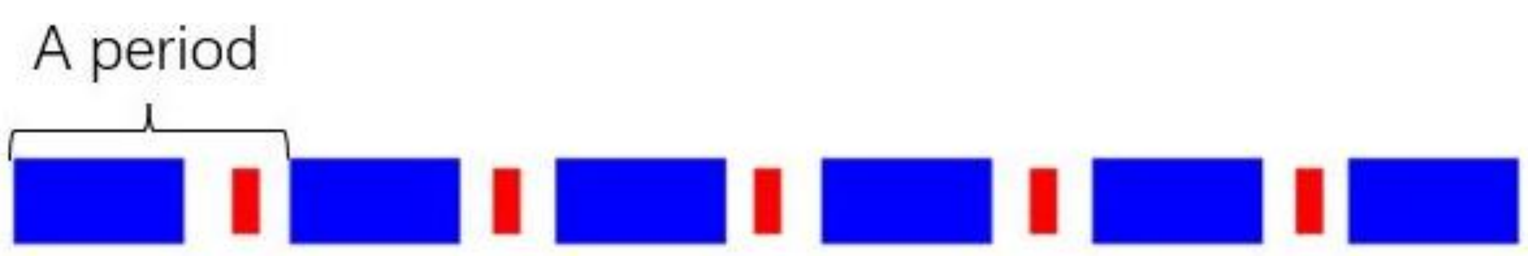


*Figure 1:* Layout of the SPARC FEL beamline, see Pompili et al. (2018) [1]. The blue boxes represent the undulators, and the red rectangles denote the quadrupole magnets.

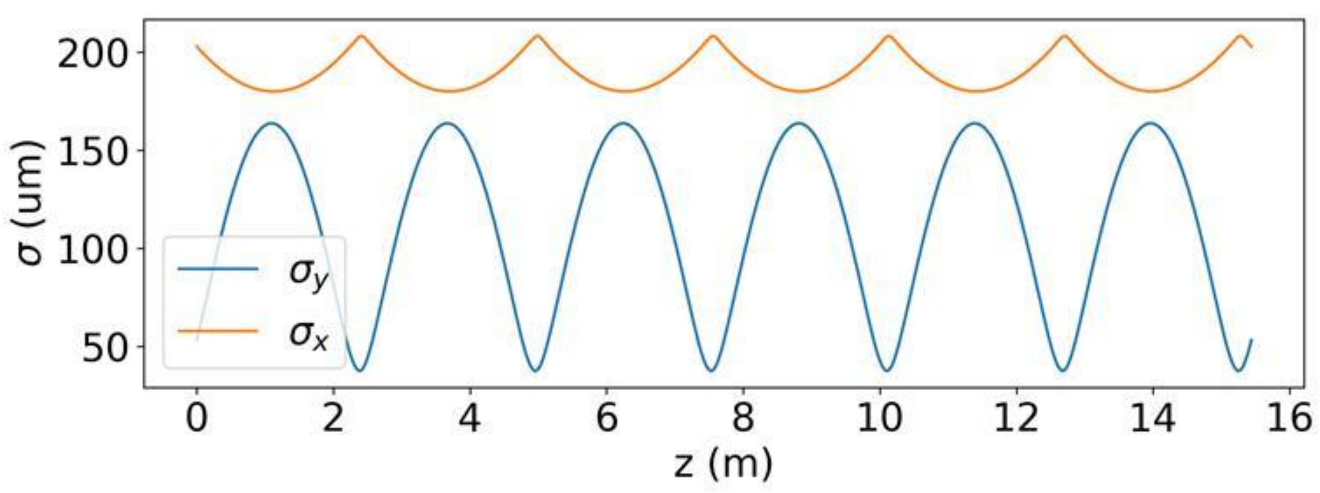


*Figure 2:* Beam matching and optimisation to minimize beam losses and maximize radiation output.

## Beam evolution

- Simulated a 100MeV beam propagating through a 2m long undulator
- Significant emittance and space charge effects in the wiggling plane
- Genesis underestimates the beam expansion

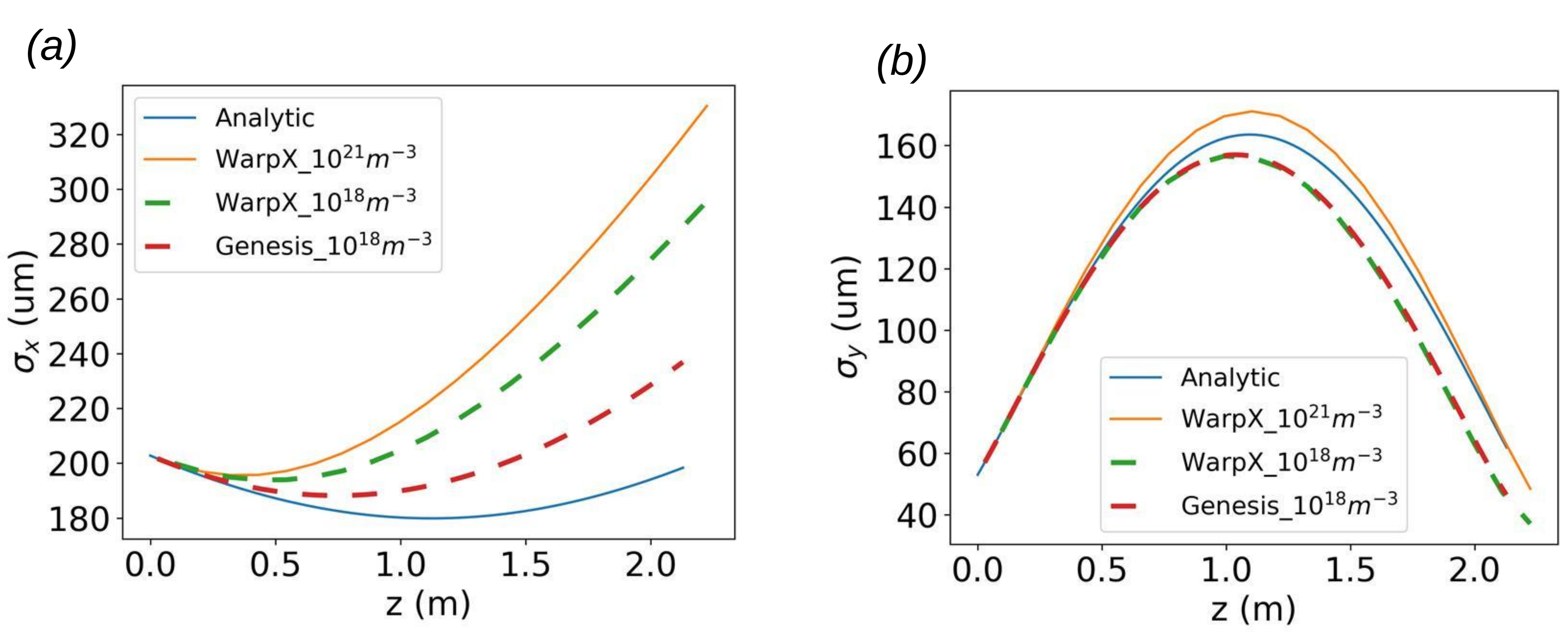


*Figure 3:* Comparison of simulated beam dynamics at different electron number densities- transfer matrices (analytic), boosted frame PIC, and Genesis [2] (FEL-code). Highlights discrepancies due to space charge and emittance effects.

## Radiation

- Beam expansion washes out microbunching
- Genesis overestimates the radiation power

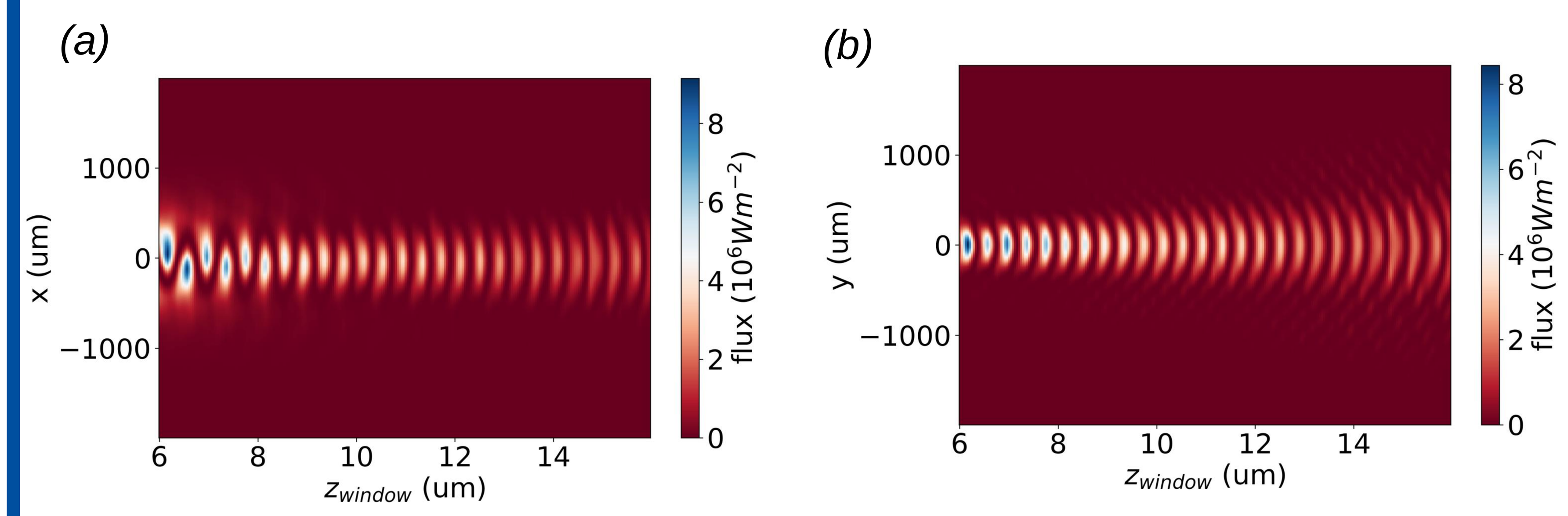


*Figure 4:* Transverse snapshots of the radiation flux 1m in the undulator for $n_e = 10^{18}\text{m}^{-3}$.

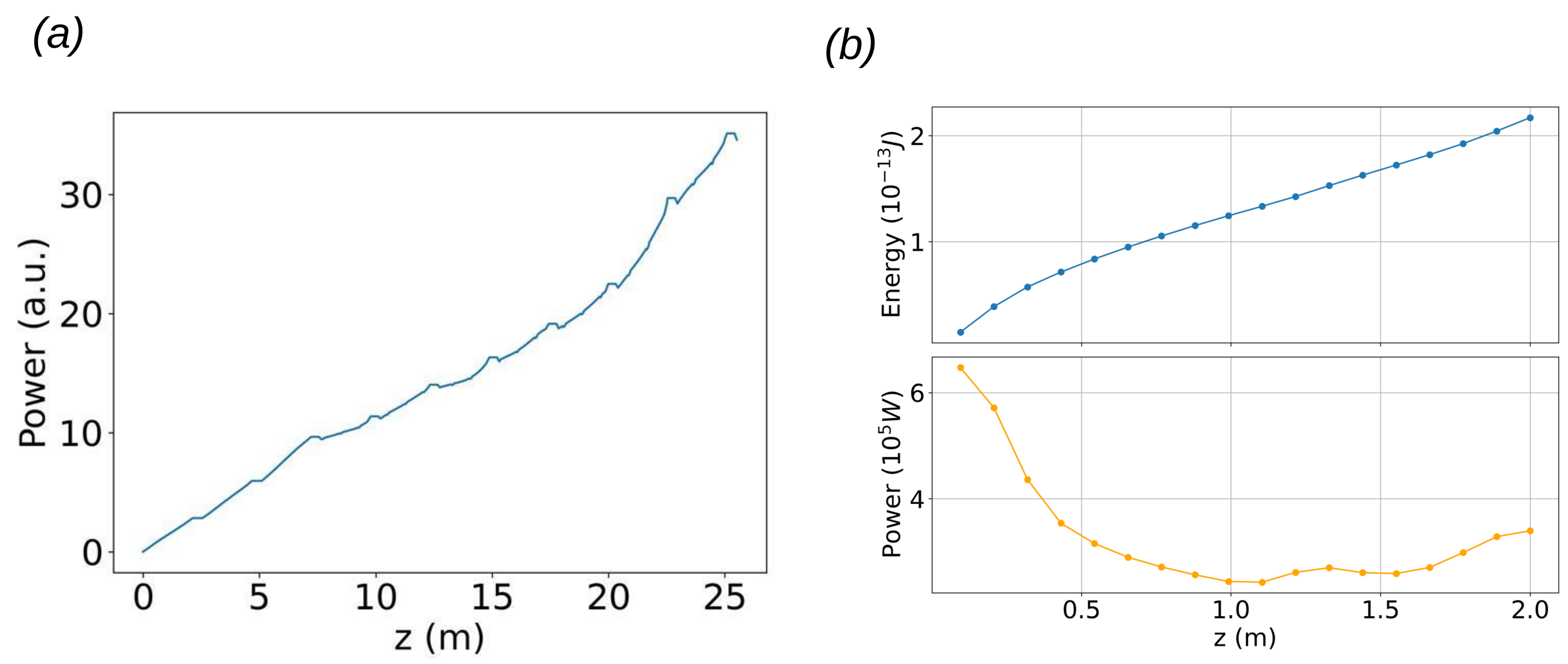


*Figure 5:* Comparison of simulated radiation power from (a) Genesis (ten undulator periods) and (b) boosted-frame PIC simulation (one undulator section, $n_e = 10^{18}\text{m}^{-3}$). The PIC simulation predicts lower energy.

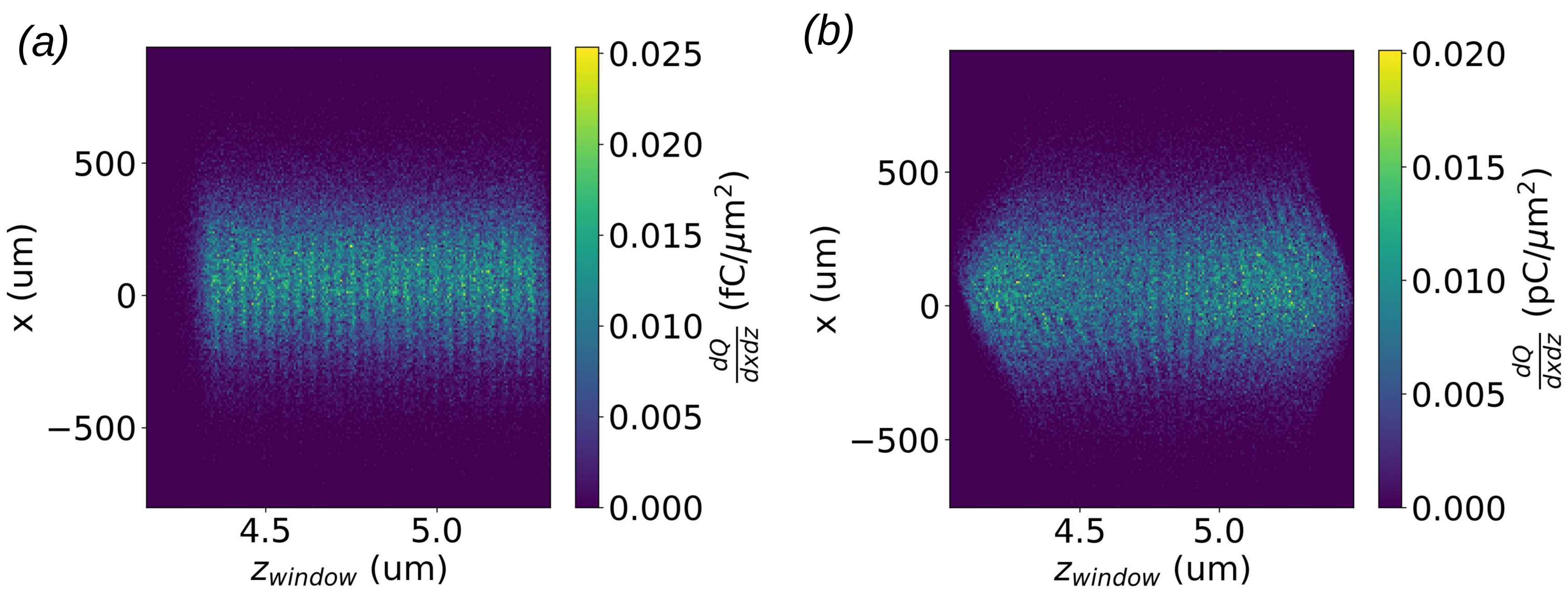


Figure 6: Transverse beam distribution at 0.66 m in the undulator showing microbunching structure for (a) $n_e = 10^{18}\text{m}^{-3}$ and (b) $n_e = 10^{21}\text{m}^{-3}$. The bunching structure is washed out for a higher electron density.

## Conclusion

- Genesis underestimates emittance driven beam expansion
- PIC code fully captures the emittance and space charge effects
- Boosted frame simulation reduce computation time from a month to a few hours
- Future work will include quadrupoles in the boosted frame simulations

1. Pompili et al., 2022, Free-electron lasing with compact beam-driven plasma wakefield accelerator, Nature, 605: 659–662.

2. S. Reiche, 1999, Genesis 1.3: a fully 3D time-dependent FEL simulation code, Nucl. Instrum, Methods Phys. Res. A, 429, 243-248