Towards full baseline simulations of Run 2c

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Motivation

Goals

1. Demonstrate energy gain of **3 GeV over 10 m** for Run 2c, as realistically as possible
2. Establish fast **"workhorse" simulations** for subsequent parameter scans and optimization studies

What are we simulating?

→ Consider both **RIF** and **electron seeding**

→ Use (mostly) nominal AWAKE parameters

→ 2D cyl. geometry

Electron bunch

Bunch charge	Q_e	500 pC
RMS longitudinal bunch size	$\sigma_{z,e}$	2.2 ps
RMS transverse bunch size	$\sigma_{x,e} = \sigma_{y,e}$	$250\ \mu$m
Electron energy	E_e	18 MeV
Normalized emittance	ε_N	2 mm mrad

Proton bunch

Bunch population	N_b	3×10^{11}
RMS longitudinal bunch size	$\sigma_{z,p}$	170 ps
RMS transverse bunch size	$\sigma_{x,p} = \sigma_{y,p}$	$200\ \mu$m
Proton energy	E_p	400 GeV
Normalized emittance	ε_N	2.2 mm mrad
Energy spread	$\Delta E_p / E_p$	0.035%
Relativistic ionization front (RIF) position relative to bunch center	$\Delta\xi_{\mathrm{RIF}}$	200 ps
Electron bunch seed position relative to bunch center	$\Delta\xi_{\mathrm{ES}}$	600 ps
Longitudinal profile	$f(\xi)$	cosine
Transverse profile	$g(r)$	Gaussian

Using a realistic plasma density step

→ Step parameters found in previous optimisation studies*

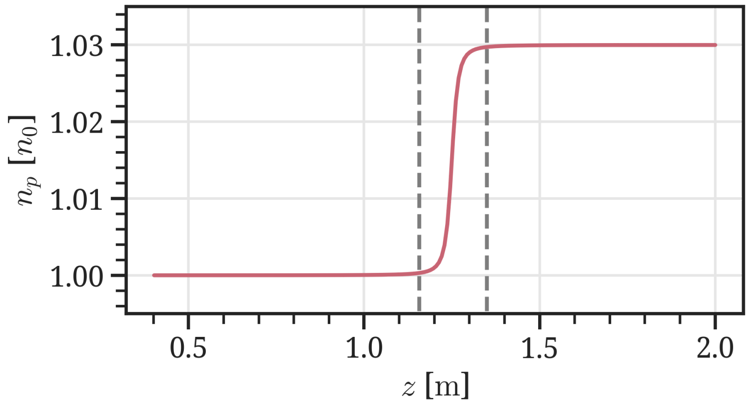
→ Step width was interpolated between 10 cm for +1% and 80 cm for +10%, as suggested by measurements**

→ Assume sigmoid-shaped*** step with width of 18.75 cm:

$$n_p(z) = \frac{n_{\text{step}} - 1}{2} \left[1 + \frac{z - z_{\text{step}}}{A\sqrt{\left(\frac{z - z_{\text{step}}}{A}\right)^2 + \frac{1}{4}}} \right] + n_0$$

Plasma

Plasma density	n_0	7×10^{14} cm^{-3}
Plasma radius	r_p	0.15 cm
Step location	z_{step}	1.25 m
Step height	n_{step}	1.03 n_0
Step width	L_{step}	18.75 cm
Vacuum gap length	Δz_{gap}	1 m



* J. Farmer, "Latest input from simulations II", AWAKE Run 2 Retreat, 31 March 2023

** M. Bergamaschi, "The new Rb vapour source", AWAKE Collaboration Meeting 4-6 October 2023

*** G. Plyushchev, et al., J. Phys. D: Appl. Phys. **51**, 025203 (2018)

General setup

1. RIF/e^{-}-seeded self-modulation (SM′or)
   - plasma density step
2. gap propagation
   - computed externally
3. e^{-} witness injection and acceleration (ACC′or)
   - entrance and exit density ramps

What are some potential challenges?

Numerical:

- Accurately simulating evolution of electron bunch driver with larger timesteps (quasistatic codes) – *see K. Lotov, V. Yarygova*
- Accuracy of simulations with a varying plasma density (quasistatic codes)
- Numerical convergence over long windows

Physics:

- Finding an optimum (emittance, energy, charge) – *see K. Lotov, J. Farmer*
- Realistic (potentially non-axisymmetric) electron bunches (i.e. produced by MAD-X, taking scattering from foils into consideration etc.)
- Effect of exit density ramp on accelerated witness bunch – *see J. Pucek, P. I. Morales Guzmán*
- Sensibility to transverse offsets – *see M. Weidl, T. Wilson, K. Lotov*
- Effect of lower density uniformity in accelerator stage

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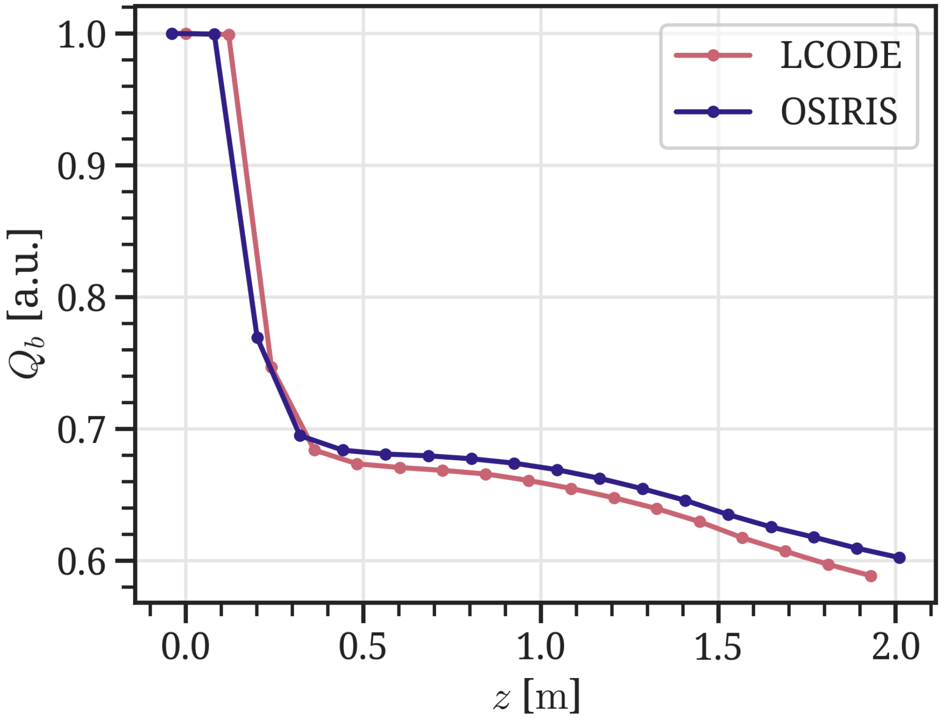
Comparison for a short window, electron bunch only

Accuracy of simulations with a varying plasma density

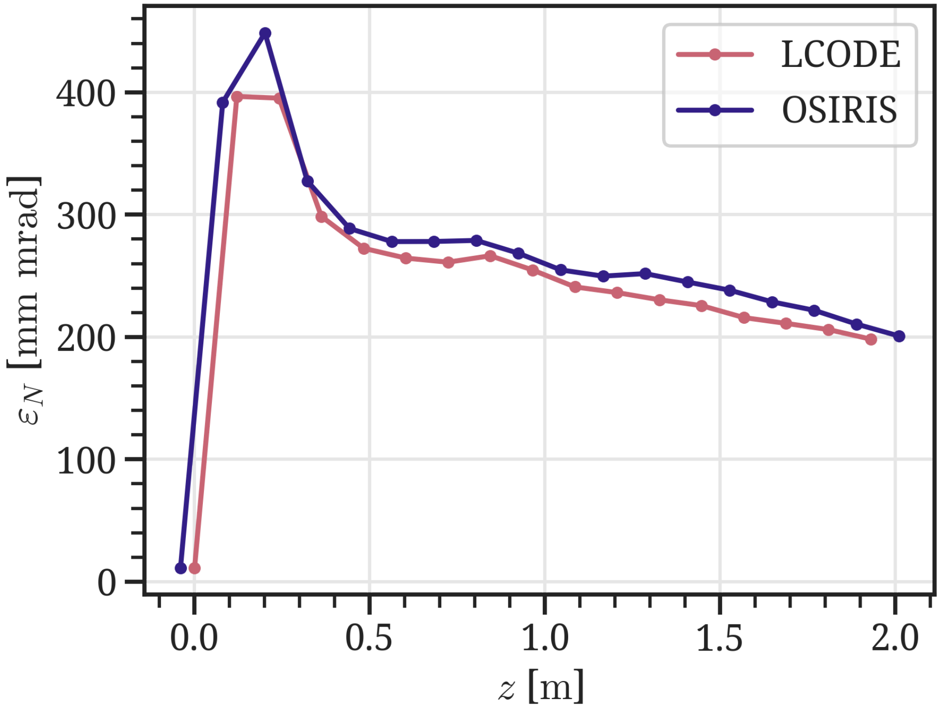
Electron bunch evolution

Total electron bunch charge



The fact that charge is lost at the plasma boundary in LCODE was taken into account.

Electron bunch emittance



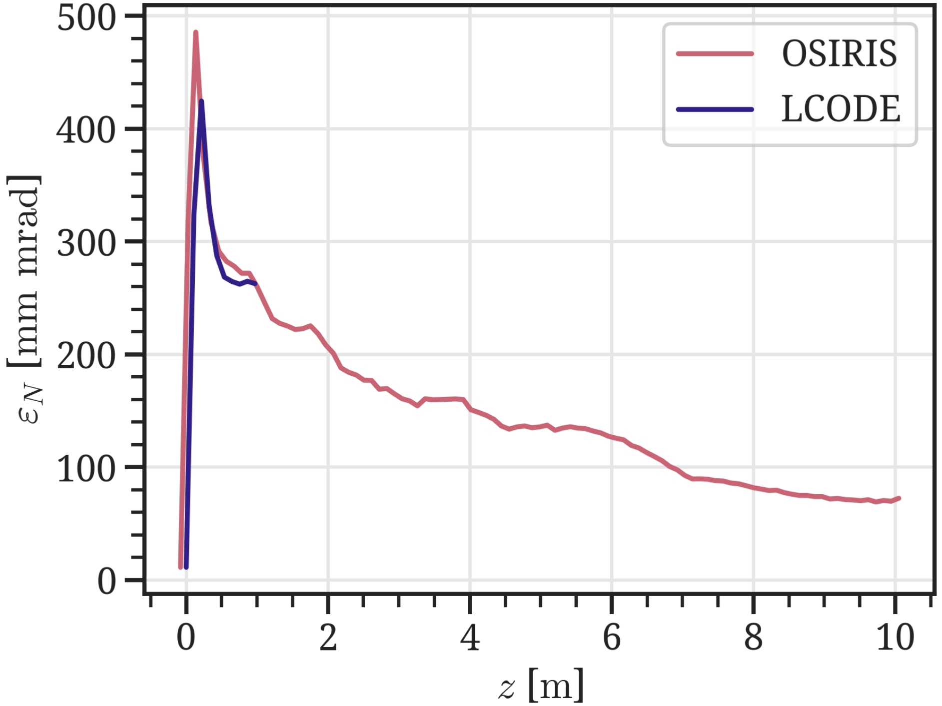
Normalized effective (Lapostolle) emittance.

2

Comparison for a long window

Numerical convergence over long windows
Accurately simulating evolution of electron bunch driver with larger timesteps (quasistatic codes)

Electron bunch emittance - long window



Normalized effective (Lapostolle) emittance.

Conclusion

- Simulations are crucial for the success of Run 2c
- Work is ongoing to obtain realistic, baseline simulations
- Please reach out if you think of further risks that should be considered!