Simulation Study of an LWFA-based Electron Injector for AWAKE Run II

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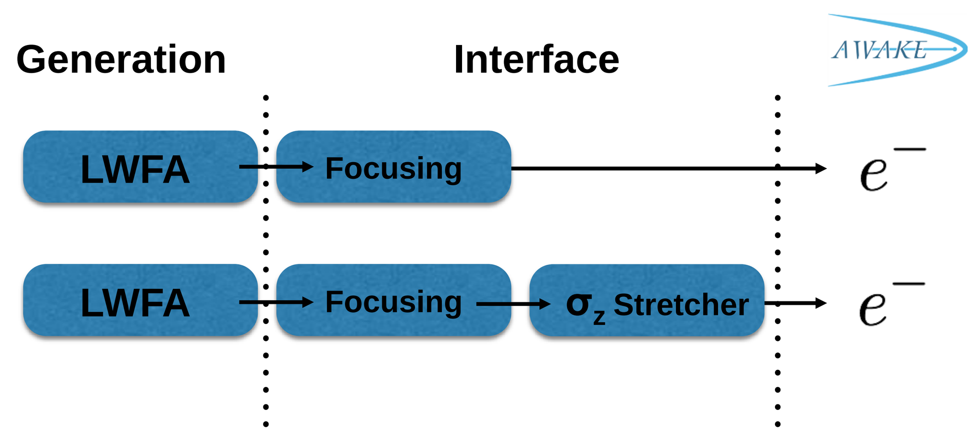
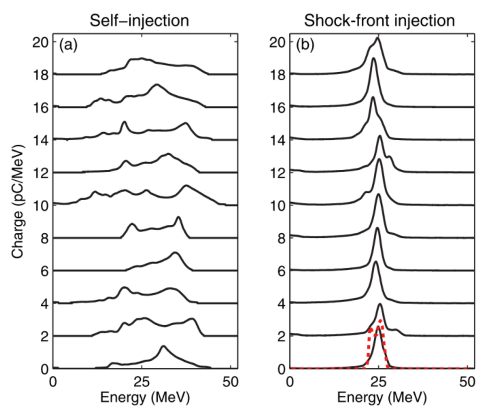
Final Energy Spread Preservation in Run II

- The AWAKE experiment is the world's first proton-driven plasma wakefield accelerator[1]
- Run 2 aims to demonstrate acceleration of high-quality electron beams[2], needed for applications[3]
- Injected bunch should lie entirely within accelerating phase of the p^+PWFA wakefield to preserve energy spread at injection
- With the space available to electron injector beamline this is challenging with the Run 1 electron injector
- An LWFA can provide fs duration bunches in a compact device and satisfies kA current for beam loading p^+PWFA wakefield[4]

Possible LWFA electron beam	
Energy	100 MeV
ΔE/E	10.0 %
Charge	100 – 200 pC
σ_z	100 fs
ε_n	1 mm mrad



- A shock-front injected LWFA can meet parameter requirements reproducibly

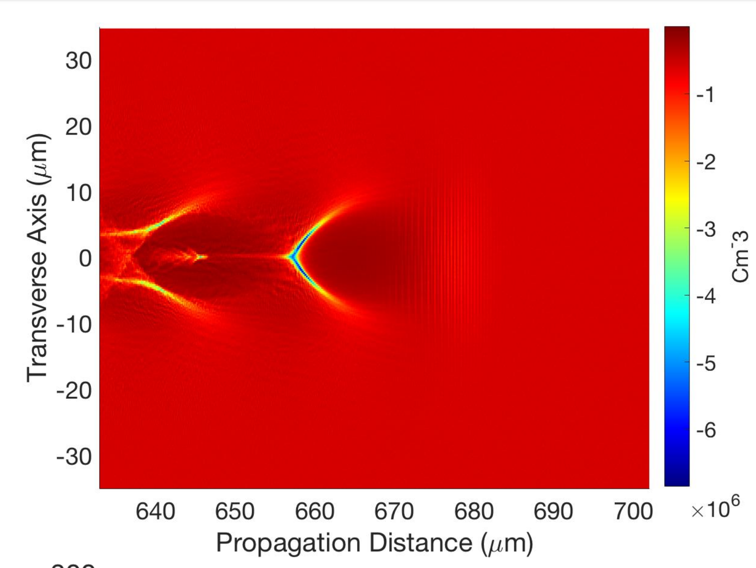


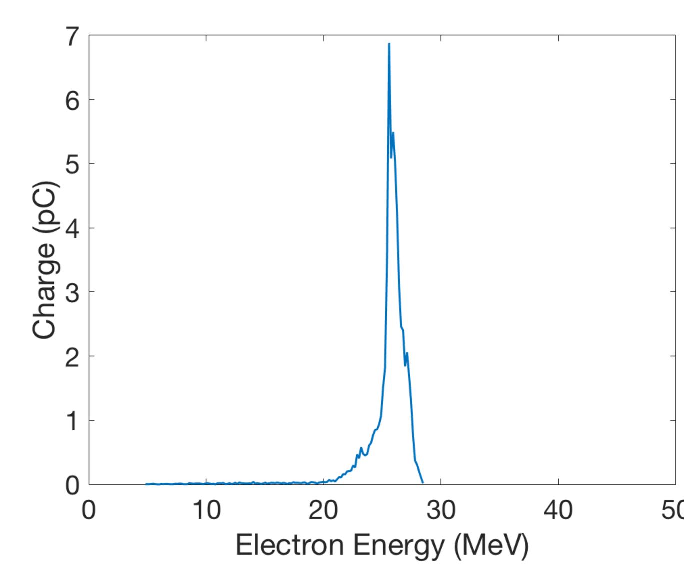
Buck, A. *et al. Phys. Rev. Lett.* **110,** 185006 (2013).

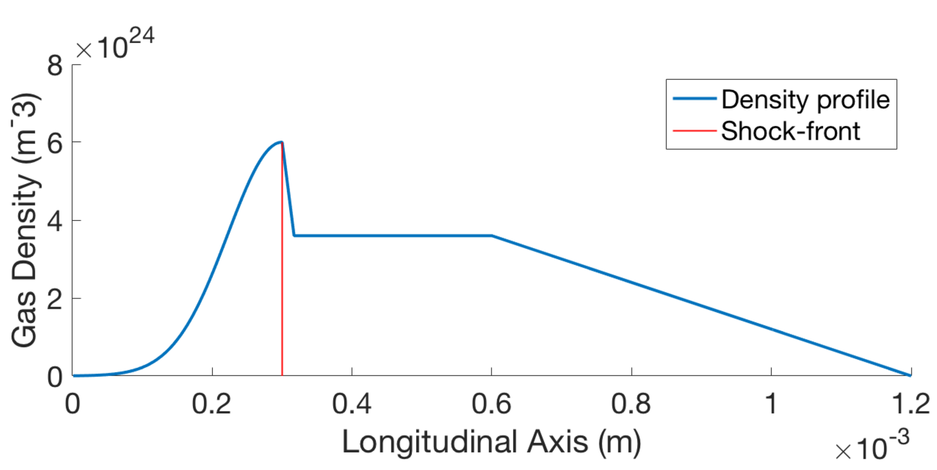
- Injection relies on a transition from a high density to low density region that occurs over a scale λ_p
- Bunch duration of LWFA beam may be very short (≦10 fs)
- A high electron density could drive its own wake; bunch stretching is needed
- How are these parameters met and optimised with an LWFA?

Beam Generation

- To evaluate possible schemes a 2D simulation using PIC code EPOCH has been developed and compared with experimental work in Buck, A. *et al. Phys. Rev. Lett.* **110,** 185006 (2013)
- Includes a model of gas jet density profile used in experiment
- Matlab routines have been written to analyse output; they characterise the energy spectra, charge, emittance and profile of the electron beam from the simulation
- The simulation successfully reproduces experimentally observed electron beam, confirms bunch length

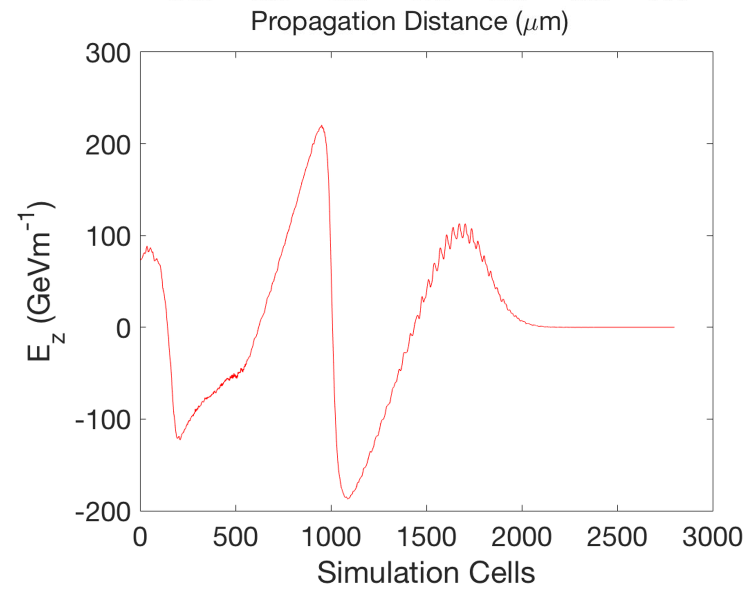






Simulation Parameters	
Box size	70 x 70 µm
Long. resolution	0.025 µm (= 0.2 / k_0)
Trans. resolution	0.025 µm (= 0.1 / k_p)
Macroparticles per cell	10
Global macroparticles	7.84e6

Computing resources provided by STFC Scientific Computing Department's SCARF cluster



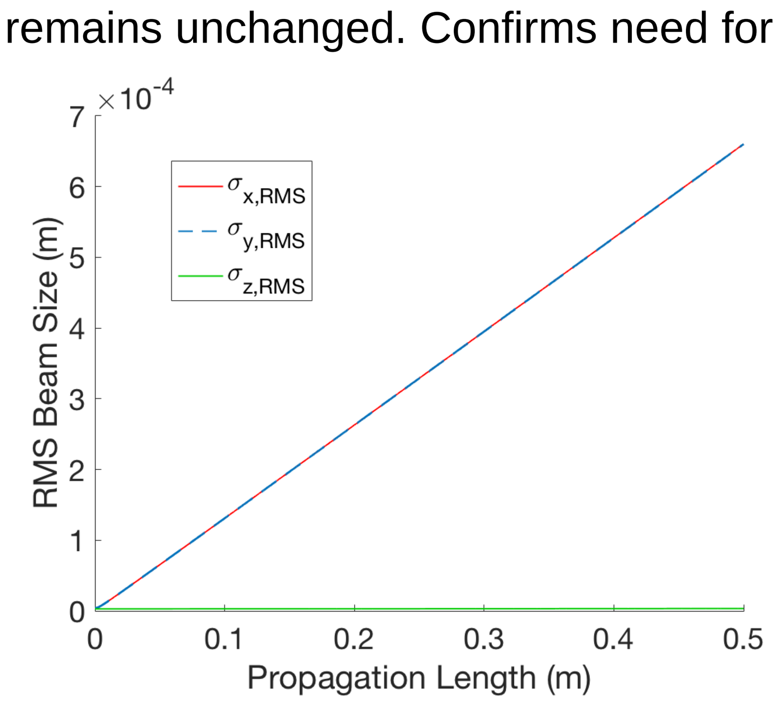
Parameter	PIC output beam
Energy	25.5 ± 0.17 MeV
ΔE/E (FWHM)	8.23 %
Q_{peak} (2D est.)	6.88 pC
Q_{total} (2D est.)	62.2 pC
$\varepsilon_{n,x,y}$	2.98 mm mrad
σ_z	10 fs

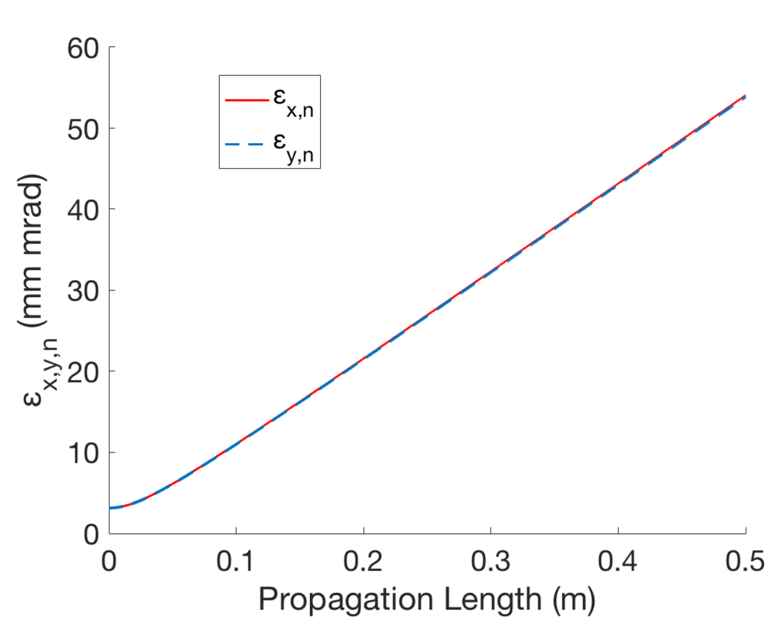
Initial focusing

- In order to optimise the beam parameters prior to injection focusing will be required, as well as a dispersive beamline to stretch the electron bunch
- As a first step in designing the focusing elements the free propagation of a shock-front injected LWFA electron beam is simulated in space-charge tracking code ASTRA, scanned over different σ_z
- Simulation and analytical inspection of envelope equation[5,6] show space-charge to be negligible

$$\sigma'' + \sigma' \frac{\gamma'}{\beta^2\gamma} + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\varepsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0$$

- Divergence of 1.3 mrad leads to growth of spot diameter to 0.66 µm in the case of σ_z = 10 fs, which remains unchanged. Confirms need for focusing





- Normalised emittance of LWFA-type beams has been shown to grow intrinsically during drift[7]
- ε_n has a dependence on energy spread σ_E, transverse bunch size σ_x, and divergence $\sigma_{x'}$, which in parameter regimes of LWFA electron beams can dominate

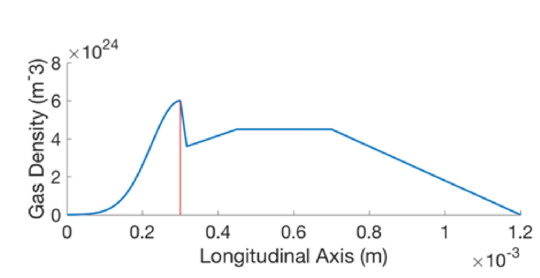
$$\varepsilon_n^2 = <\gamma>^2 \left(\sigma_E^2\sigma_x^2\sigma_{x'}^2 + \varepsilon^2\right) \ [7]$$

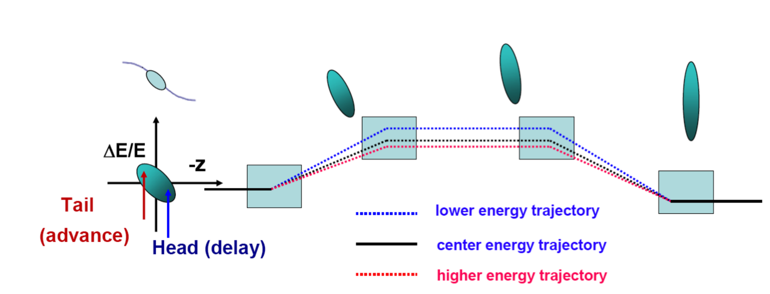
Conclusions

- PIC simulation a useful tool to conduct further studies
- 'off the shelf' shock-front injected LWFA electron beam will be too short (≦10 fs)
- Required charge and energy needs a tailored design
- Focusing needed to suppress large divergence, irrespective of beam parameters

Future Work

- Optimse LWFA Design in PIC simulations
- Add dopant to gas mixture, increasing shot-to-shot stability[8]
- Design LWFA scheme to produce longer σ_z at generation
- Design Quadrupole doublet / triplet focusing in ASTRA
- Energy spread and short duration provides opportunity for phase rotation; operating bunch compression in reverse could be used to increase σ_z





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