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Witness injection via laser-solid interaction for plasma wakefield accelerators

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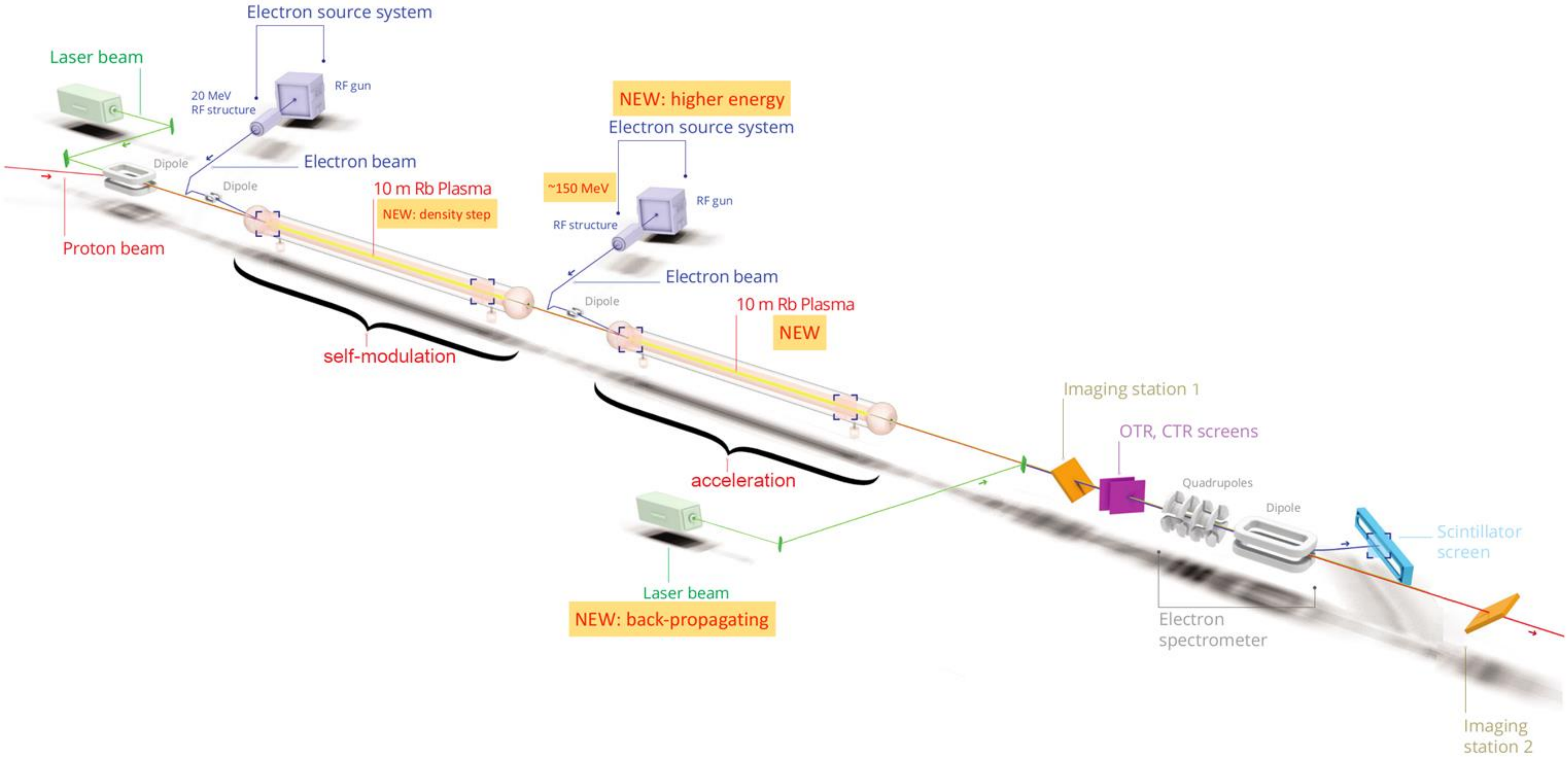
Talk structure

1. Motivation, introduction to the AWAKE experiment
2. The "toy model" & simulation design
3. Simulation results
4. Wrap-up

AWAKE Run 2 Overview



Self modulation of the proton beam

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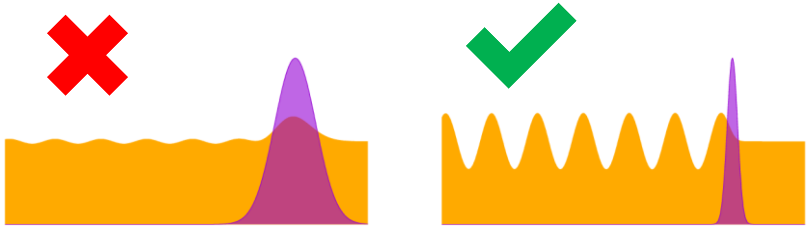
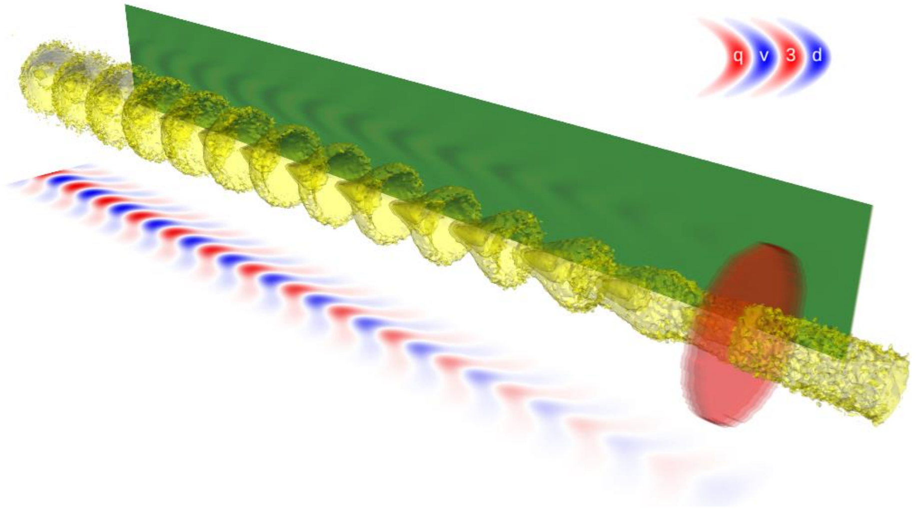
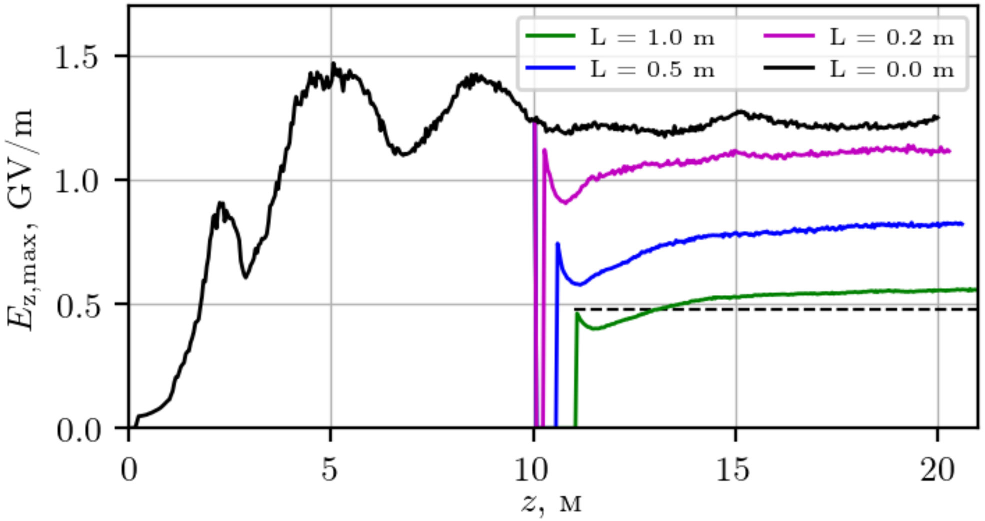
The SPS beam is long (7cm), and long beams damp their own wake



The modulation stage exists so the proton beam can organise itself into short microbunches via the transverse two-stream instability.

Once modulated, the wakefield maintains a constant amplitude and phase into the acceleration stage, even with the gap between stages





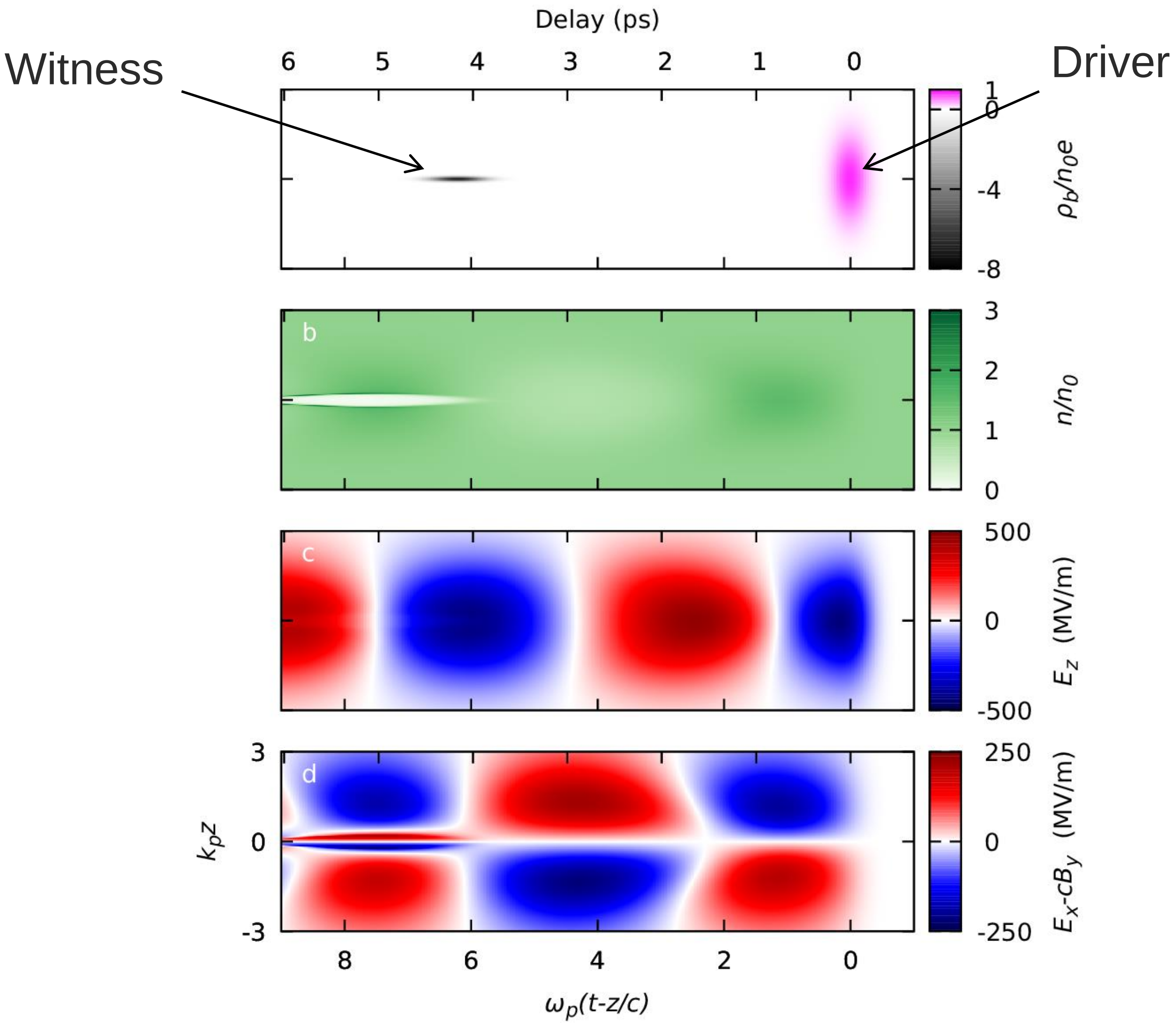
V. Yarygova (2023)

Toy model for acceleration studies

Simulating the full beam is very expensive, but with the assumption that the wake structure is fixed after modulation, we can employ a 'toy model'.

A short, rigid driver generates a wake with known, constant properties E_z = 480 MV/m, γ_{p+} = 427 designed to mimic the AWAKE wake

Allows for efficient parameter scans



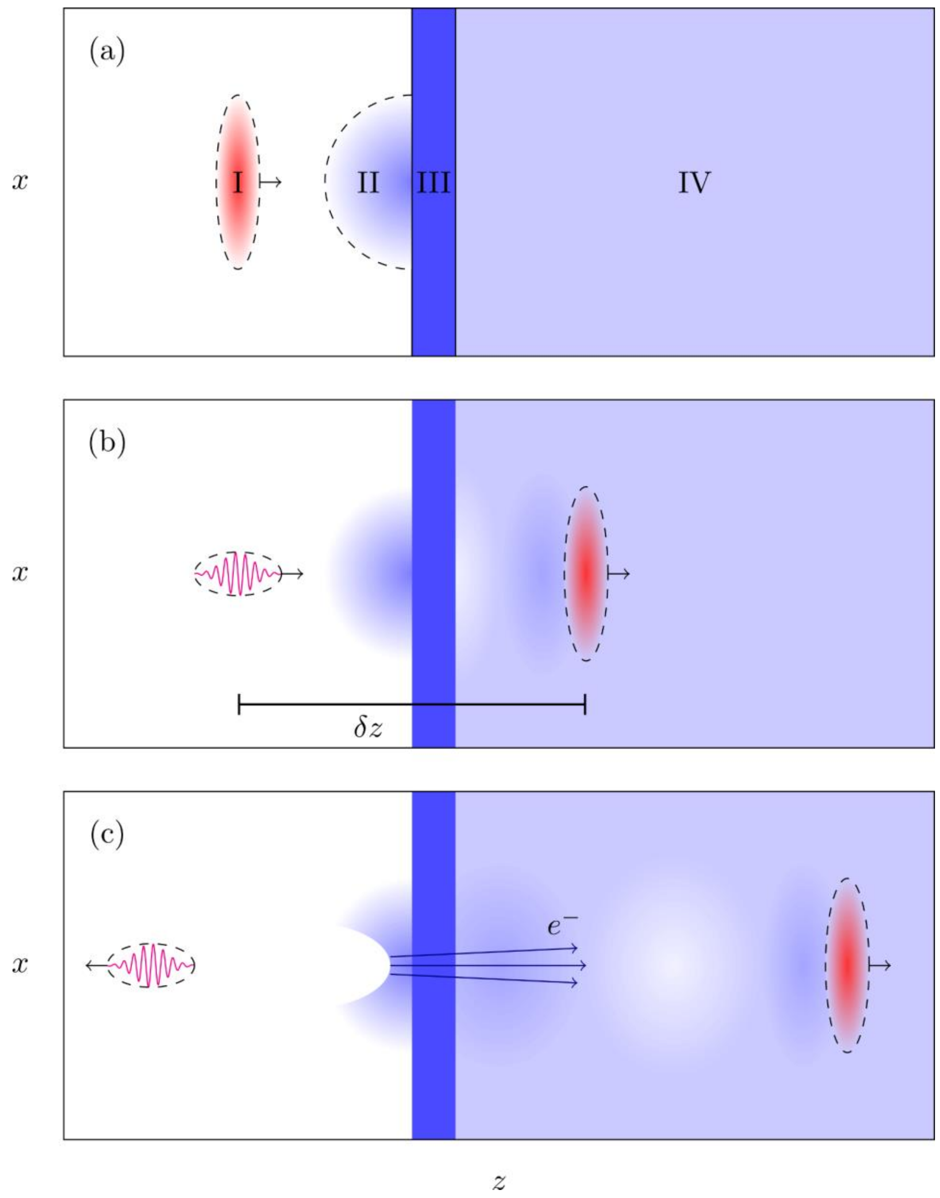
V. Olsen *et al.*, PRAB (2018)
J. Farmer *et al.*, *in preparation*

The laser-solid injection scheme

a) We place a foil in between a vacuum and a plasma, it is assumed to already have a preplasma in front of it

b) The driver passes through the foil and into the bulk plasma, exciting a quasilinear wake

c) The laser trails the driver, and reflects off the foil, shooting hot electrons into the plasma in the process



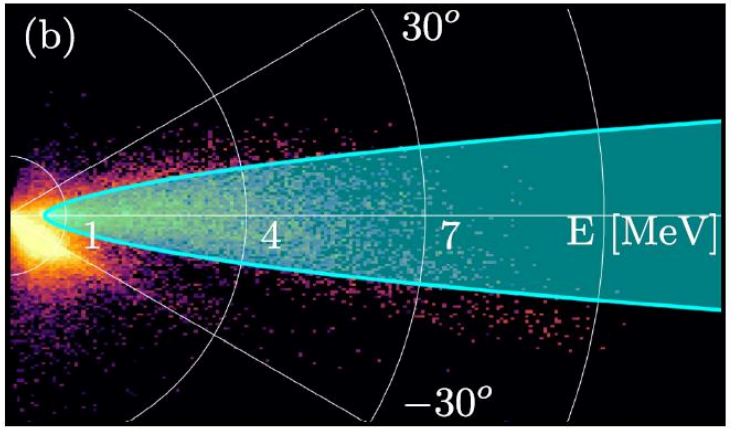
Electron trapping and delay timing

Intuition says we should inject into the centre of the wake, theory and simulations agree

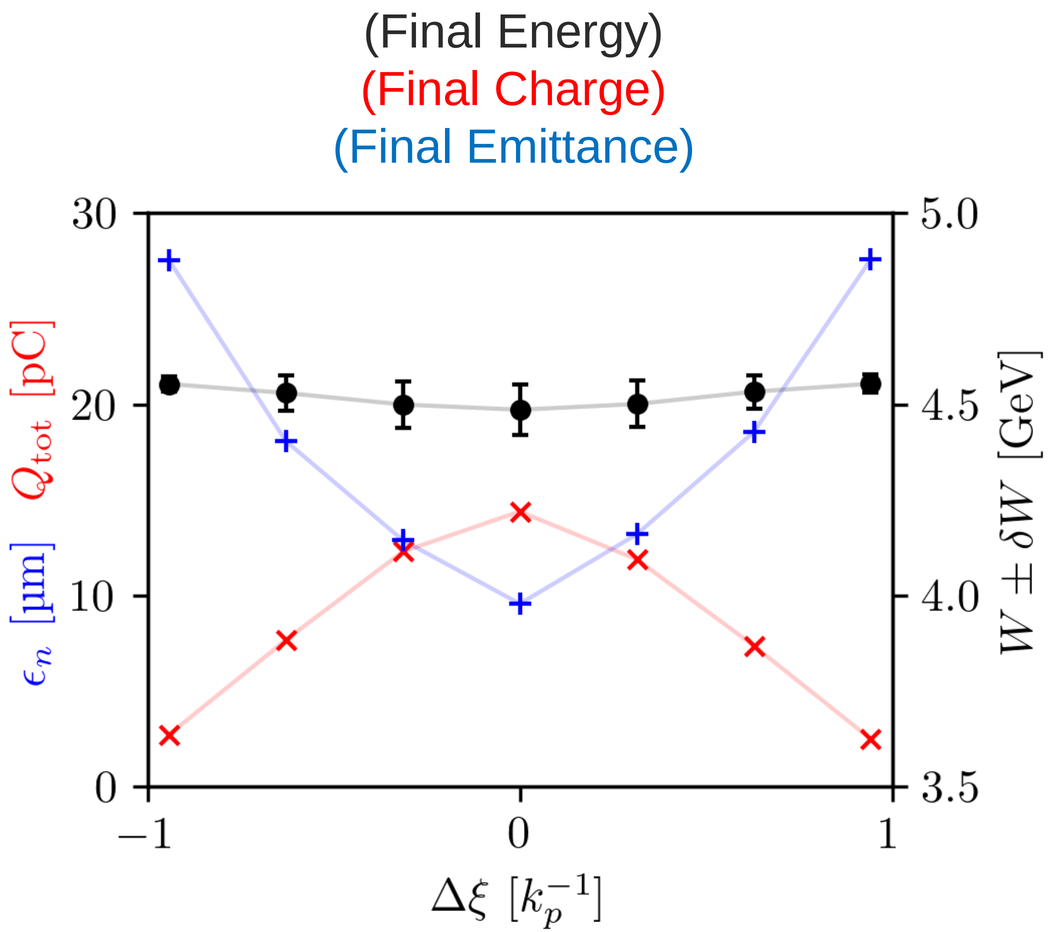
$$\frac{(p_z - p_c)^2}{a^2} + \frac{p_r^2}{b^2} < 1$$

Maximum trapping is found at the centre of the wake within certain momentum limits.

a, *b*, p_c are constants related to the wake potential ϕ_0



V. Khudiakov and A. Pukhov, PRE (2022)



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Hybrid simulation setup

The laser-solid interaction portion is performed with the cylindrical, fully electromagnetic PIC code FBPIC

The newly-injected witness is allowed to evolve for several centimetres in order to gain some momentum

The particles are then saved, and transferred to the 3D, quasistatic PIC code QV3D for the rest of the acceleration stage

FBPIC – R. Lehe *et al.* (2016)
QV3D – A. Pukhov (2016)

Baseline results

Now in a position to run the scheme from start to end, the baseline results

The toy model matches to the AWAKE Run 2c parameters

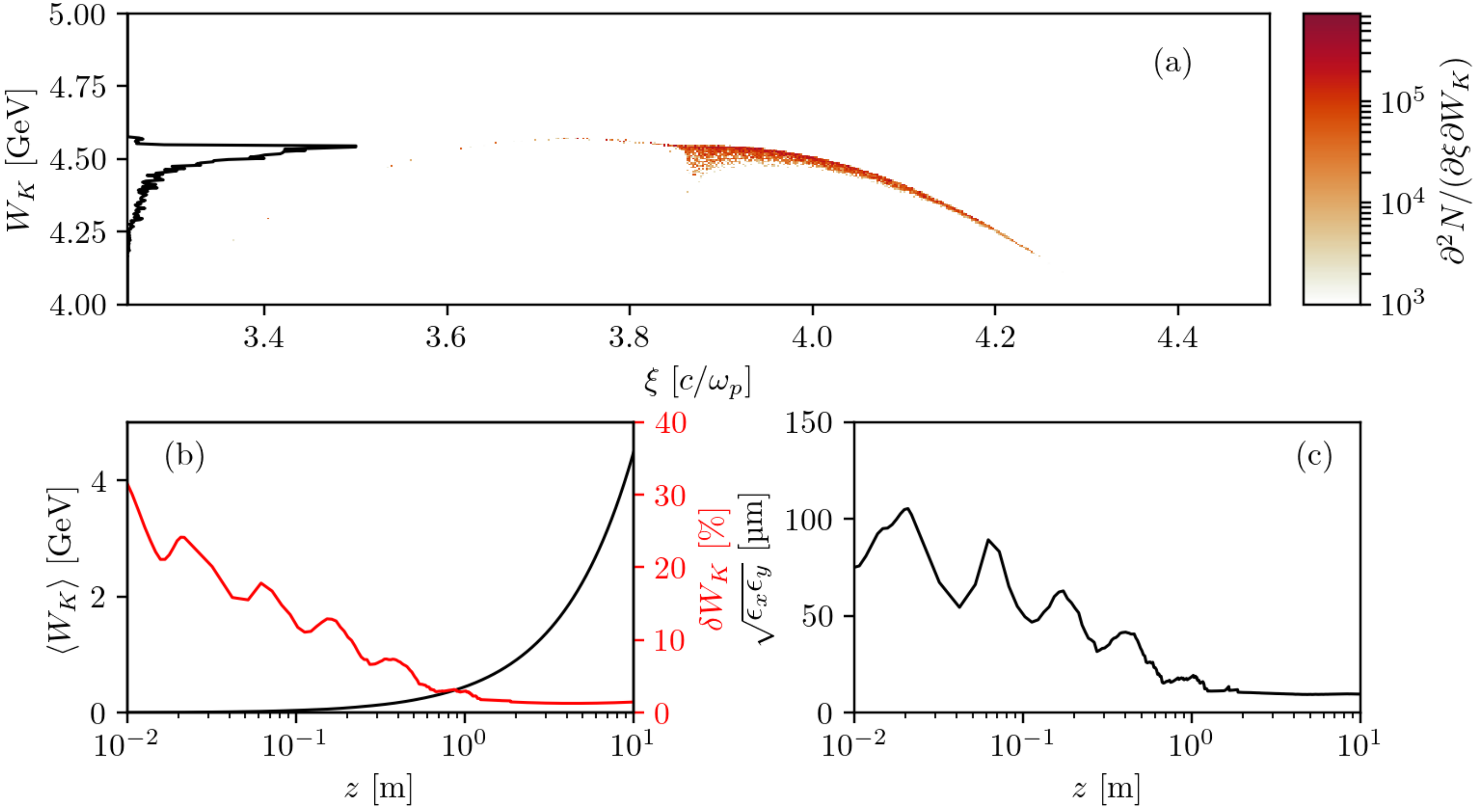
Results

Q_{tot} = 14.40 pC

W_K = 4.49 GeV ± 1.48%

ε_n = 8.49 μm

Final phasespace



energy and energy spread

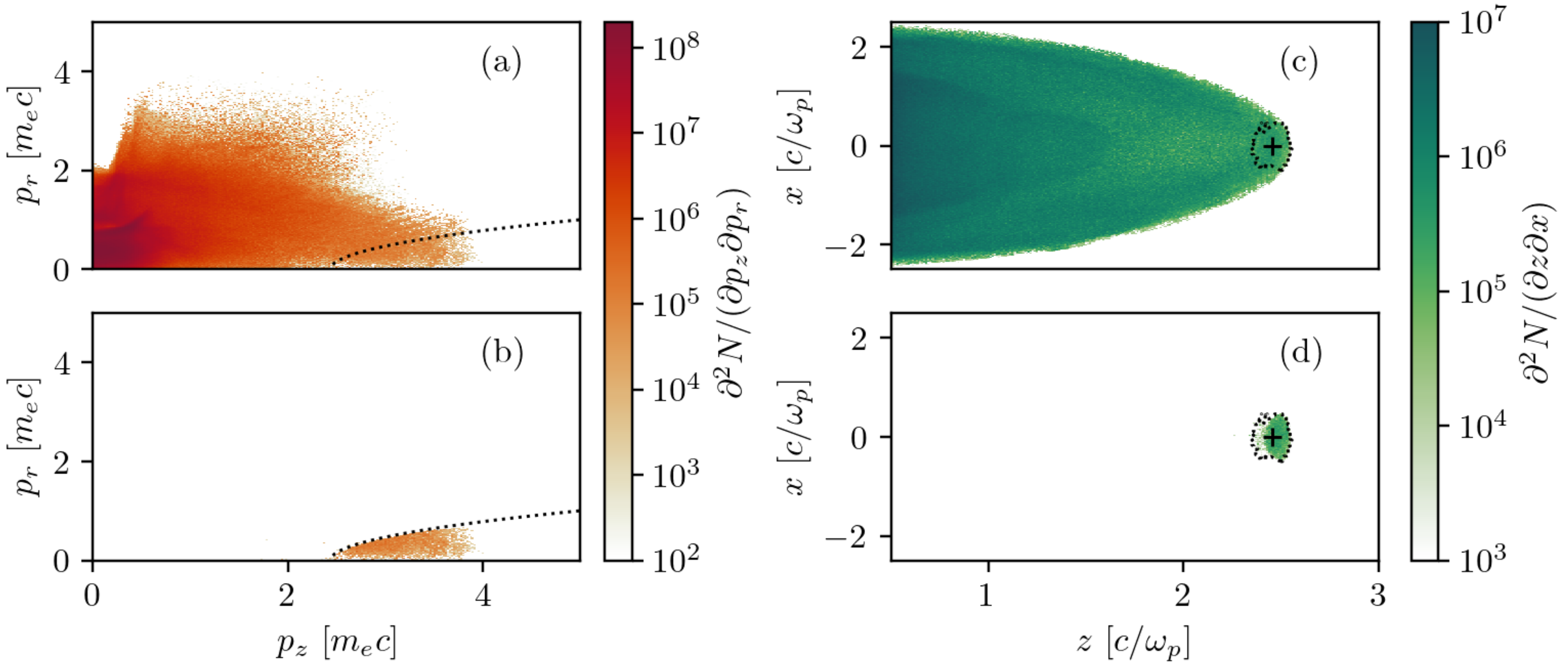
normalised emittance

Trapping evaluation

We can also check how well the trapping conditions agree with theory

Entire electron plume on entry to the plasma

Particles remaining after 10 m



Momentum space

Real space

Parameter exploration

The parameter space is extremely broad, so this is represents only a few possible avenues

	Baseline Case	20 μm (0.1/k_p) Misaligment	Double Length Preplasma (10 μm)	High Wake (2.5x)
Charge (pC)	14.40	13.97	36.37	518.49
Energy (GeV)	4.49 ± 1.48%	4.49 ± 1.46%	4.34 ± 1.83%	8.54 ± 6.03%
Emittance (μm)	8.49	10.35	12.54	30.93

Key take-aways

- Robust to misalignment
- Preplasma scale tunes total charge
- Wake strength scales charge very strongly

Summary

- Colinear laser-assisted injection concept demonstrated
- We study this in the context of AWAKE, but the scheme is general to PWFA
- Several avenues of further work are indicated
  - Preplasma scale and shape
  - low-charge vs high-charge witness dynamics under acceleration
  - Refinements to the trapping criteria – spatial dependence
  - (Too) many other free parameters