# NONLINEAR TRANSVERSE BEAM DYNAMICS IN AWAKE RUN 2C

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## *Abstract*

The AWAKE experiment harnesses the 400 GeV proton beam from the CERN SPS to drive plasma wakefields, which in turn accelerate a witness bunch of electrons to high energy. Upgrades are currently being carried out to facilitate the experimental programme of Run 2c, which includes control of the witness bunch quality during acceleration. In this work, particle-in-cell simulations are used to investigate the wakefields excited by the proton driver. We find that nonlinearities in the plasma response result in “wakefield tearing”, a shift in the relative phase of the focusing and accelerating regions of the wakefield. We demonstrate that tearing can have a significant impact on the witness energy gain which can be achieved while simultaneously maintaining witness quality, with shorter drive bunches offering a path to mitigate the effect. These simulations inform the choice of parameters for the experiment.

## INTRODUCTION

Plasma wakefield acceleration has attracted considerable attention due to the high fields which plasma can support, potentially leading to a significant reduction in the length, and hence the cost, of linear accelerators [1]. A plasma wave is excited by a driver, with the plasma acting as a transformer to couple energy from the driver to a co-propagating witness bunch. Currently available electron and laser drivers have limited energy, and so multiple acceleration stages would be required to reach high energies. Proton-driven wakefield acceleration offers the potential to accelerate a witness bunch of electrons to the energy frontier in a single stage [2].

To effectively excite a large amplitude wakefield, the drive bunch should be short, on the scale of the plasma skin depth $1/k_p$, with $k_p = (ne^2/\varepsilon_0 mc^2)^{1/2}$ the plasma wavenumber. Here, $n$ is the plasma number density, $-e$ and $m$ the electron charge and mass, $c$ the vacuum speed of light and $\varepsilon_0$ the vacuum permittivity. Currently available proton beams have a typical length of a few centimetres, too long to drive high-amplitude wakefields. One solution is to develop methods for generating short proton bunches at high repetition rates [3], as pursued by the ALiVE project, which would open the path towards the high luminosities required collider applications [4]. Alternatively, plasma instabilities can be harnessed to modulate currently available proton beams, as in the AWAKE experiment at CERN [5].

Figure 1a shows the longitudinal profile (in terms of the effective current, $I_{\mathrm{eff}}$ [6]) of a proton drive beam with $\sigma_z \gg 1/k_p$. The associated longitudinal wakefields are shown in Fig. 1b in terms of the characteristic field amplitude $E_c = mc^2k_p/e$. The initial wakefields are small, but the plasma response also generates transverse fields which are sufficient to “self-modulate” the long drive bunch into a train of microbunches over a distance of a few metres [7, 8]. The beam profile and associated wakefields after 10 m of plasma propagation are also shown. At this point, the proton beam is fully modulated and the wakefields are much larger and increase along the length of the beam.

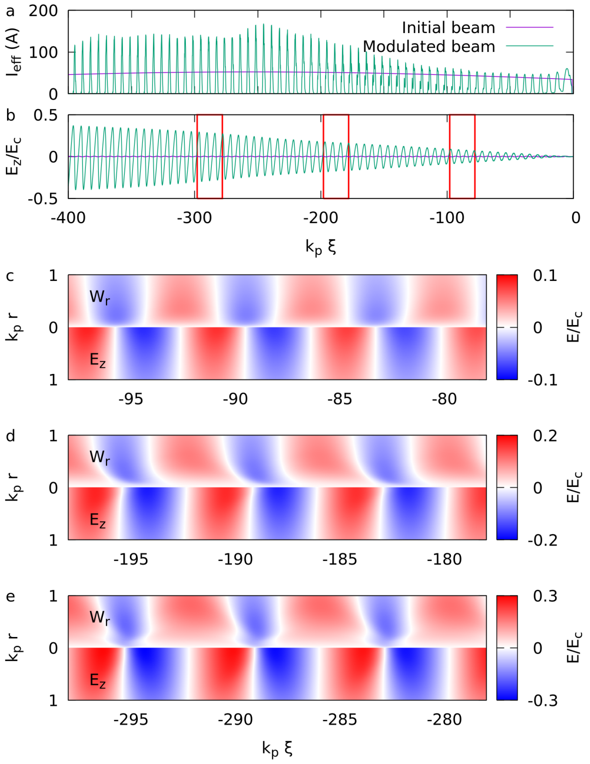

Figure 1: a) Effective current of the proton drive beam (propagating right) and b) the associated on-axis longitudinal wakefield, for the initial beam and for the modulated beam after 10 m of plasma propagation. c-e) the radial dependence of $W_r = E_r - cB_\theta$ and $E_z$ after 10 m propagation at different positions along the beam, indicated by red boxes in (b).

The use of a train of microbunches requires that the wakefields persist over many plasma periods. Small changes in the local plasma frequency, which can arise due to the relativistic shift in the mass of plasma electrons and the influence of the driver charge, can then lead to significant phase shifts, which ultimately lead to the destruction of the microbunch

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train. A plasma density step allows a partial compensation of the phase shift [9], allowing the microbunch train to survive over long distances [10, 11].

In this work we use particle-in-cell (PIC) simulations to investigate the impact of the nonlinear plasma response on the structure of the excited wakefields. We find that for a train of drive bunches, “tearing” of the transverse wakefields can disrupt the phase relation between the focusing and accelerating fields, limiting the injection regions where a witness bunch can attain high energy while maintaining low emittance. We demonstrate that the use of a shorter driver increases the energy gain which can be achieved. These simulations inform the choice of parameters for the forthcoming AWAKE Run 2c.

## WAKEFIELD TEARING

Simulation parameters used to produce the results shown in Fig. 1 are chosen to be similar to those in the AWAKE Run 2b campaign, with a drive beam from the CERN SPS of $3 \times 10^{11}$ protons at 400 GeV, an RMS length of 170 ps, a transverse normalised emittance of 2.2 μm and a waist size of 200 μm. The beam was cut 170 ps ahead of its centre to model the effect of seeding the self-modulation with a relativistic ionization front [12]. The plasma density is $7 \times 10^{14}$ cm$^{-3}$, corresponding to $1/k_p = 200$ μm and $E_c = 2.5$ GeV/m, with a 3.5% density step at 1.75 m. Static ions are assumed, with the impact of ion motion discussed in the next section. Simulations were carried out with the 2D axisymmetric quasistatic code LCODE [13, 14].

Shifts in the local plasma frequency can modify the structure of the wakefields [15–17], as shown in Figs. 1c-e. The top half of each plot shows the transverse wakefield $W_r = E_r - cB_\theta$, and the bottom half the longitudinal field $E_z$. For a witness electron bunch to be focused and accelerated, $W_r$ should be positive and $E_z$ negative. Near the front of the drive train, shown in Fid. 1c, the plasma response is essentially linear, with the focusing and accelerating regions of the wakefields offset by a phase of $\pi/2$. This alternating pattern, similar to a stretcher bond in masonry [18], results in a quarter period where the wakefields are both focusing and accelerating. In practice, only the head of the witness beam needs to be focused, as the witness will drive its own wake capable of keeping the tail focused [19, 20].

Further back in beam ($\xi \approx 200/k_p$, Fig. 1d), the transverse wakefields develop a radial phase dependence. Close to the axis, this “wakefield tearing” results in focusing fields which predominantly overlap with the decelerating phase, making this region unsuitable for electron injection. Still further back, ($\xi \approx 300/k_p$, Fig. 1e), the increased amplitude of the plasma wave results in focusing regions which are significantly larger than the defocusing regions [21], and regions suitable for acceleration can again be found.

## SIMULATION VALIDATION

To confirm whether the development of wakefield tearing is physical, comparisons were made with the 3D quasistatic PIC code HiPACE++ [22], and the electromagnetic PIC code OSIRIS [23], operating with a 2D axisymmetric geometry. To reduce the computational overhead, the wakefields were compared after a propagation distance of 6 m, where the wakefield amplitude has not yet stabilised, and tearing can be observed closer to the leading edge of the driver.

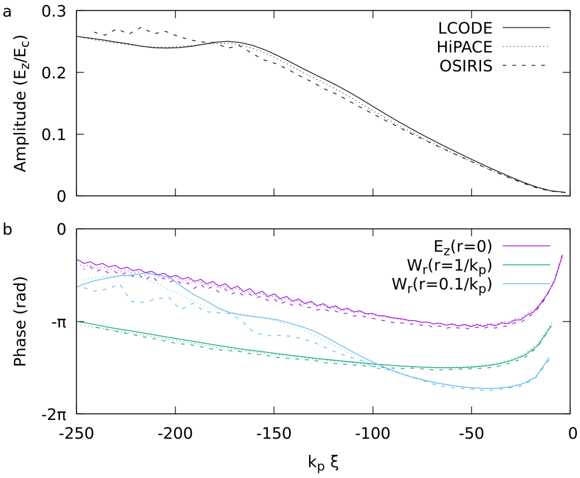

Figure 2: a) amplitude of the on-axis accelerating field, and b) phase of $E_z$ on axis, and $W_r$ at $r = 1/k_p$ and $r = 0.1/k_p$.

Figure 2a shows the wakefield amplitude, taken as the magnitude of the trough $E_z$, and Fig. 2b shows the phase of fields: $E_z$ on axis, and $W_r$ at $r = 1/k_p$ and $0.1/k_p$. The phase is calculated from the zero-crossings of the field relative to a harmonic wave [6]. For the transverse fields, where the relative size of the focusing and defocusing regions varies significantly, every second zero crossing is used.

Excellent agreement is seen between the three codes, demonstrating that wakefield tearing is indeed a physical effect. Small differences in the fields are attributed to numerical differences arising due to choice of resolution. LCODE has the lowest computational overhead, as it assumes both an axisymmetric geometry and quasistatic plasma response, and so is best converged.

## TEST PARTICLE SIMULATIONS

AWAKE Run 2c will make use of two plasma sources with a gap between, allowing the witness electron bunch to be injected into the second plasma on axis [5]. The large focusing fields in plasma result in a witness electron bunch which is much more tightly focused than the proton driver.

It can be seen from Figs. 1 and 2 that the effect of tearing is predominantly limited to small radii, and so only the witness is expected to be strongly impacted. High-quality acceleration therefore requires injection regions to be identified where the wakefields retain the correct phase over the entire acceleration length. Full simulations of electron injection and acceleration are computationally intensive due to the disparate scales of the driver and witness. For this reason, previous works have considered either a simplified model for the driver [20] or a masking technique applied to the wakefields to identify regions where the wakefields

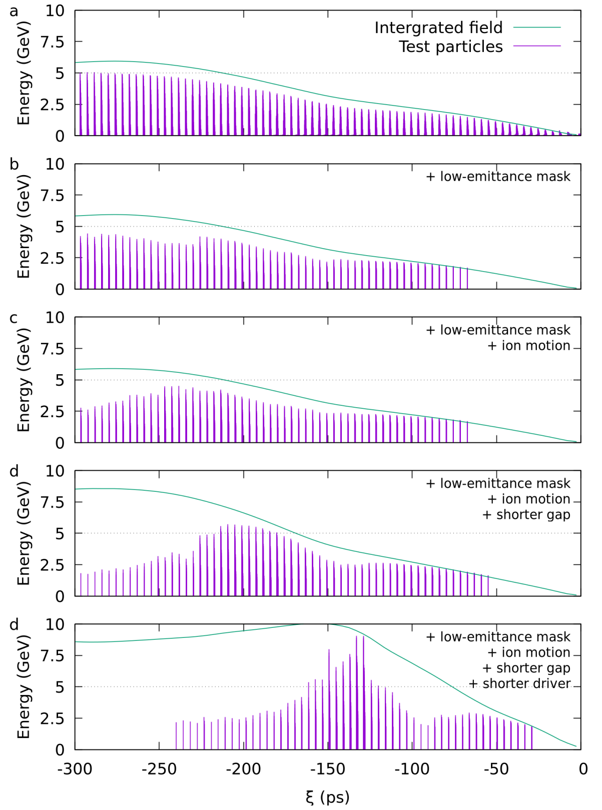

Figure 3: Comparison of integrated accelerating field and mean energy of test particles after acceleration. a) All surviving test particles. b) After applying a mask for low emittance. c) As (b), but using mobile rubidium ions. d) As (c), but with a reduced gap between the modulation and acceleration stages. e) As (d), but with a driver length of 85 ps.

remain focusing and accelerating [10]. Here we demonstrate an alternative method to rapidly characterise the suitability of different injection regions.

A continuous beam of test electrons is injected at the beginning of the second plasma, in which acceleration will take place. These particles have an initial energy of 150 MeV, the same as the Run 2c witness bunch, with an initial radius of 11.5 µm and an emittance of 2 µm. The current is chosen to be negligibly small, i.e. the test particles generate no wakefields. The energy gained by these particles over the 11 m accelerating length provides a metric for the magnitude of the accelerating field. For a real witness bunch, beamloading will reduce the accelerating field [20].

Figure 3a shows the mean energy of test particles after 11 m acceleration as a function of position along the beam, for the case of a 1 m gap between the two plasma sources. As can be seen, the initially continuous witness beam becomes modulated due to the periodicity of the wakefields. For comparison, the integrated wakefields over the same distance are also shown. The peak energy gained by test particles is slightly lower than the integrated fields, showing that test particles at the position of the maximum accelerating field are lost over the acceleration length.

To identify regions where high-quality acceleration can be achieved, a mask is applied to consider only regions where the emittance of the test-particle beam remains low. Test particles which have undergone significant dephasing are first discarded, and then only beam slices for which at least 20% of test particles remain and where the emittance remains below 16 µm are considered. It can immediately be seen from Fig. 3b that this leads to a further reduction in the energy of test particles, demonstrating the difficulty in simultaneously achieving high energy gain while maintaining the quality of the witness bunch.

In Fig. 3c, the motion of plasma ions is included in the simulation. The motion of rubidium ions has little impact on the proton beam evolution [24, 25], and the integrated fields are essentially unchanged. However, changes in the plasma ion density close to the axis modify the evolution of the tightly focused witness bunch. Using the same masking technique, it can be seen that ion motion reduces the energy gain which can be achieved for larger injection delays.

Retaining ion motion and again applying the masking technique, the effect of reducing the length of the gap between plasmas to 30 cm is shown in Fig. 3d. This leads to a more–tightly–focused proton beam, resulting in larger fields [5], as seen from the integrated field. It can be seen that the shorter gap allows test particles to reach higher energies.

Finally, we investigate the impact of reducing the length of the proton drive beam from 170 to 85 ps while maintaining the bunch population. A 5.5% density step at 0.75 m was used to stabilize the wakefields, with other parameters as for Fig. 3d. The resulting wakefields grow more rapidly along the beam, as seen from the integrated field in Fig. 3e. The shorter beam also significantly increases the energy gain test particles can achieve while maintaining low emittance.

Further work is required to better understand how the beam parameters influence both wakefield amplitude and tearing. The results here suggest that a shorter driver allows the wakefield amplitude to grow more rapidly than the nonlinear effects which cause tearing. Full simulations of a realistic witness beam have also been carried out to verify the results shown here, and will be published elsewhere.

## CONCLUSIONS

AWAKE Run 2c will accelerate a witness bunch of electrons in the wake of a self-modulated proton drive bunch while controlling the witness quality. The nonlinear plasma response can lead to “tearing” of the plasma wakefields, which may limit the injection regions where high energy gain and low emittance growth can be simultaneously achieved.

We demonstrate a new method to rapidly identify suitable injection regions, applying a mask to test-particle simulations. The results indicate that a shorter proton driver can mitigate the impact of tearing. These simulations inform the choice of parameters for full acceleration simulations, and motivate the development of techniques to compress SPS proton bunches ahead of Run 2c [26].

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