Wakefield regeneration in a plasma accelerator

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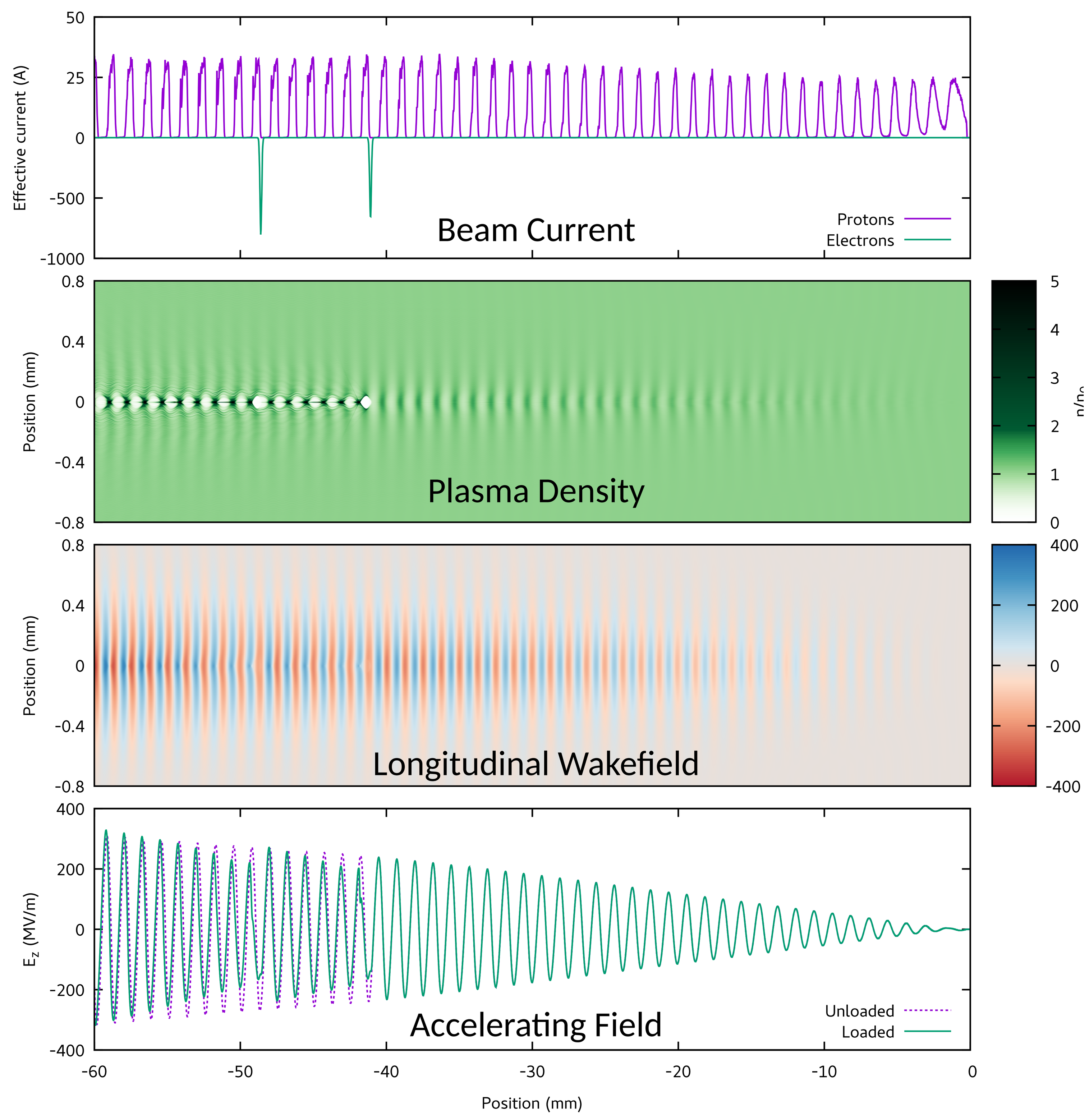
MULTI-BUNCH INJECTION



Beam loading in a plasma wakefield accelerator introduces a trade-off between **energy gain, energy spread** and **accelerated charge** [1]. In order to generate high-quality beams, only a fraction of the wakefield energy can be extracted by the witness bunch, resulting in significant energy deposited in the plasma.

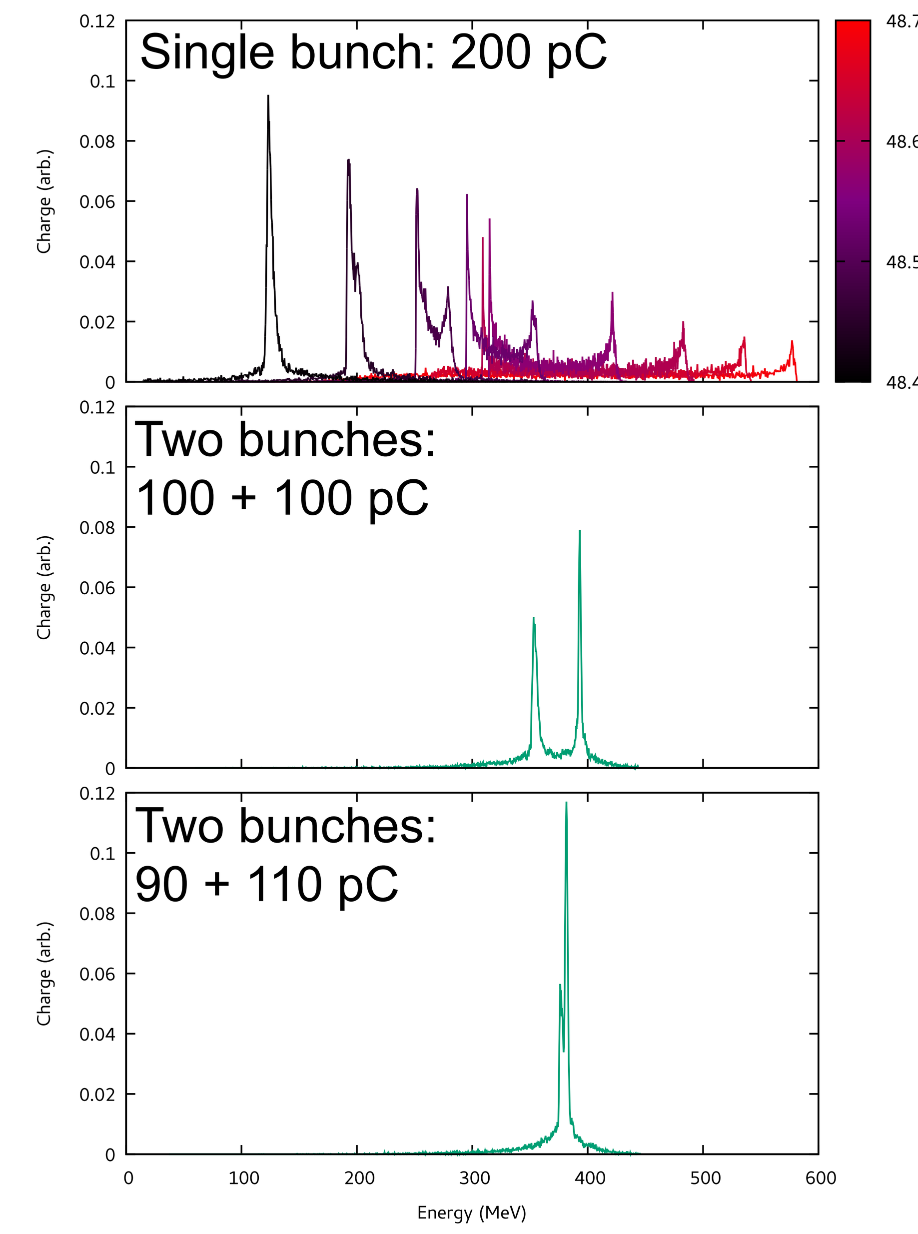
In this work we use simulations to demonstrate that **a train of drive bunches can regenerate the wakefield** after the witness bunch, allowing a second witness to be accelerated with the same energy gain.

This method can be used to **increase the luminosity and efficiency** of a resonantly-driven plasma wakefield accelerator.

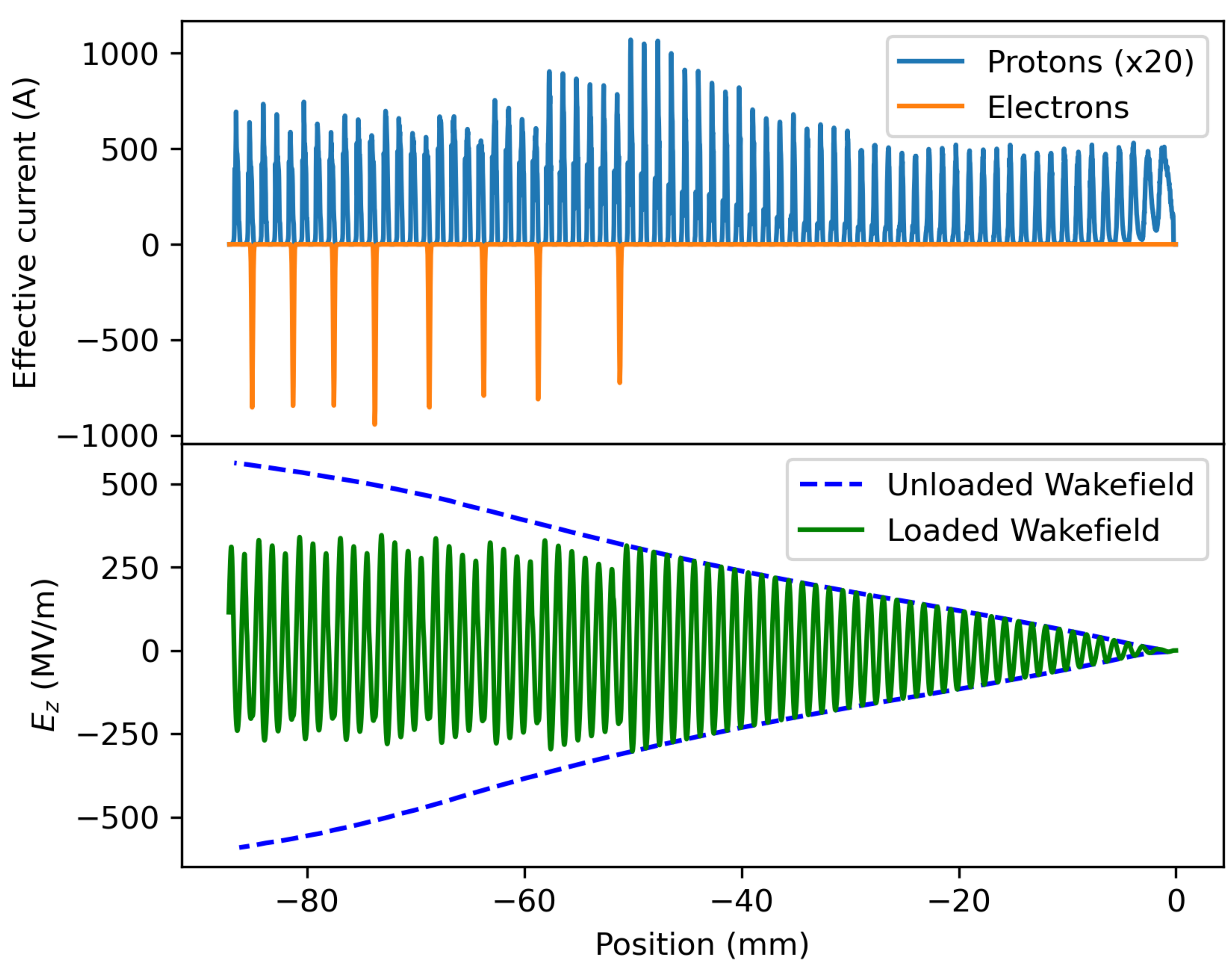
<u>Left:</u> Response of the plasma to the drive beam and witness bunches. <u>Top:</u> effective current (sum $K_0(k_p r)q/\Delta t$) of a self-modulated proton drive bunch and two witness electron bunches. <u>Middle</u>: 2D slices showing the (saturated) plasma density and longitudinal wakefields. <u>Bottom</u>: on axis accelerating field, with and without the witness bunches. Simulated using LCODE [2,3].

<u>Right:</u> Energy spectra of a 150-MeV, 200-fs-duration witness bunch after 2 m of acceleration. <u>Top</u>: a 200 pC witness beam overloads the wakefields, resulting in either low energy gain or large energy spreads. <u>Middle</u>: splitting the witness into two 100 pC bunches, placed in buckets of similar amplitude, allows each bunch to have a narrow energy spread. <u>Bottom</u>: by tailoring the relative charge of the two bunches, the same energy gain can be achieved for both, giving a narrow total energy spread.

ENERGY GAIN AND SPREAD



INCREASED LUMINOSITY

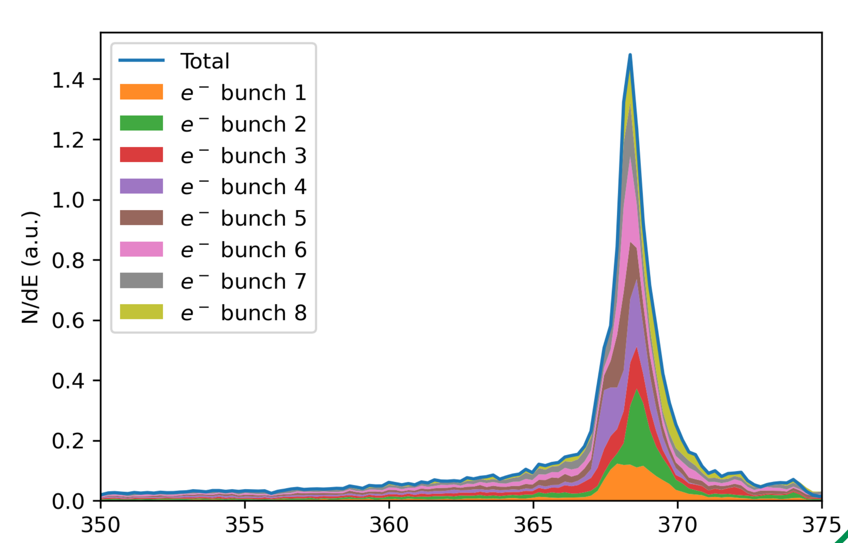


Simulations carried out for a train of witness bunches show that the regeneration of the plasma wakefields is robust. This allows the scheme to be used to increase the achievable luminosity.

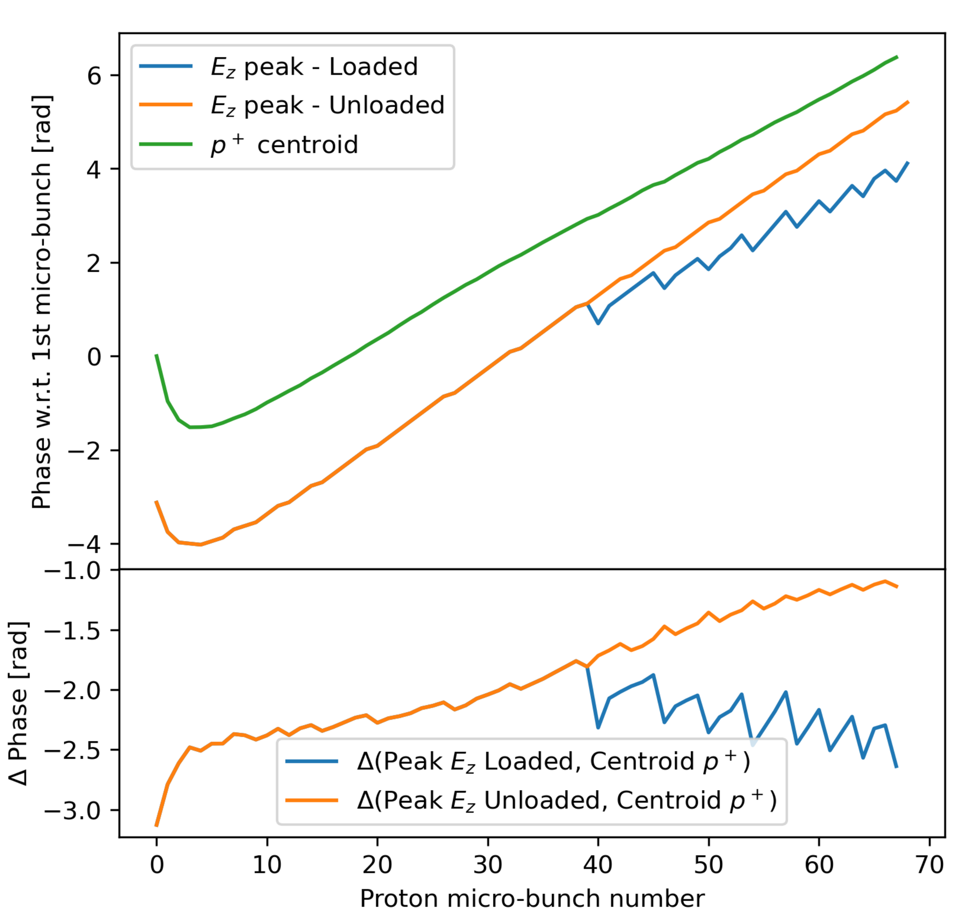
Here, eight witness bunches are injected, for a total witness charge of 0.9 nC. 60% of the charge is within +/-0.5% of the peak after 1m of acceleration, with an energy gain of over 200 MeV. Only the first half of the SPS proton bunch is used for the drive beam, allowing further witness bunches to be added.

<u>Top:</u> A train of witness bunches injected into the plasma alongside the driver bunch train. Each microbunch loads the wakefield.

<u>Right:</u> Energy distribution of all witness bunches after 1m of acceleration. The correct choice of parameters for the witness bunch train allows each bunch to be accelerated to the same energy, increasing the luminosity of the accelerator.



REPHASING THE WAKEFIELDS

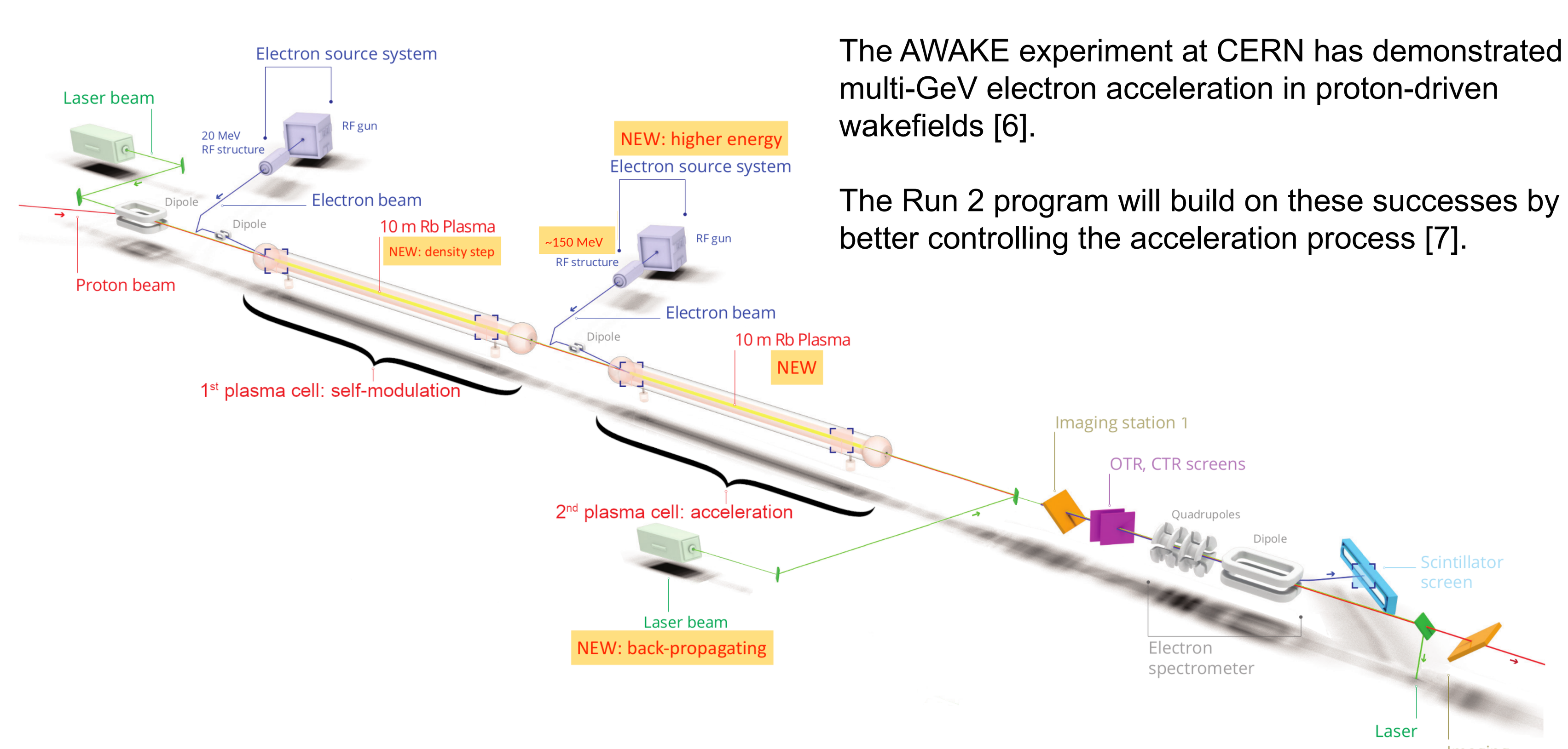


Plots showing the phase of the drive train and the wakefields after 1m acceleration, for both the loaded and unloaded cases (including and excluding the witness train).

Acceleration in resonantly-driven wakefield schemes is limited by nonlinearities. These lead to detuning between the driver and the excited wakefield, which leads to saturation [4,5].

Correctly loading the wakefield shifts the wakefield phase, bringing the system back into resonance. This allows the drive train to regenerate the wakefields, improving the efficiency.

AWAKE EXPERIMENT



The AWAKE experiment at CERN has demonstrated multi-GeV electron acceleration in proton-driven wakefields [6].

The Run 2 program will build on these successes by better controlling the acceleration process [7].

Starting with Run 2c (2028) AWAKE will use a separate plasma stage for self-modulation of the proton bunch. The witness electron bunch will be injected into a second plasma for acceleration.

Multiple witness bunches could be used to increase the luminosity

[1] R. Maeda et al., *Possibility of a multibunch plasma afterburner for linear colliders*, Phys. Rev. ST Accel. Beams **7**, 111301 (2004).

[2] K. V. Lotov, *Fine wakefield structure in the blowout regime of plasma wakefield accelerators*, Phys. Rev. ST Accel. Beams **6**, 061301 (2003).

[3] See https://lcode.info for code description and manual.

[4] K. V. Lotov, *Excitation of two-dimensional plasma wakefields by trains of equidistant particle bunches*, Phys. Plasmas **20**, 083119 (2013).

[5] M. N. Rosenbluth and C. S. Liu, *Excitation of Plasma Waves by Two Laser Beams*, Phys. Rev. Lett. **29**, 701 (1972).

[6] AWAKE Collaboration, *Acceleration of electrons in the plasma wakefield of a proton bunch*, Nature **561**, 363 (2018).

[7] E. Gschwendtner et al., *The AWAKE Run 2 programme and beyond*, Symmetry **14**, 1680 (2022).

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