AWAKE: from proof-of-concept towards first particle-physics applications

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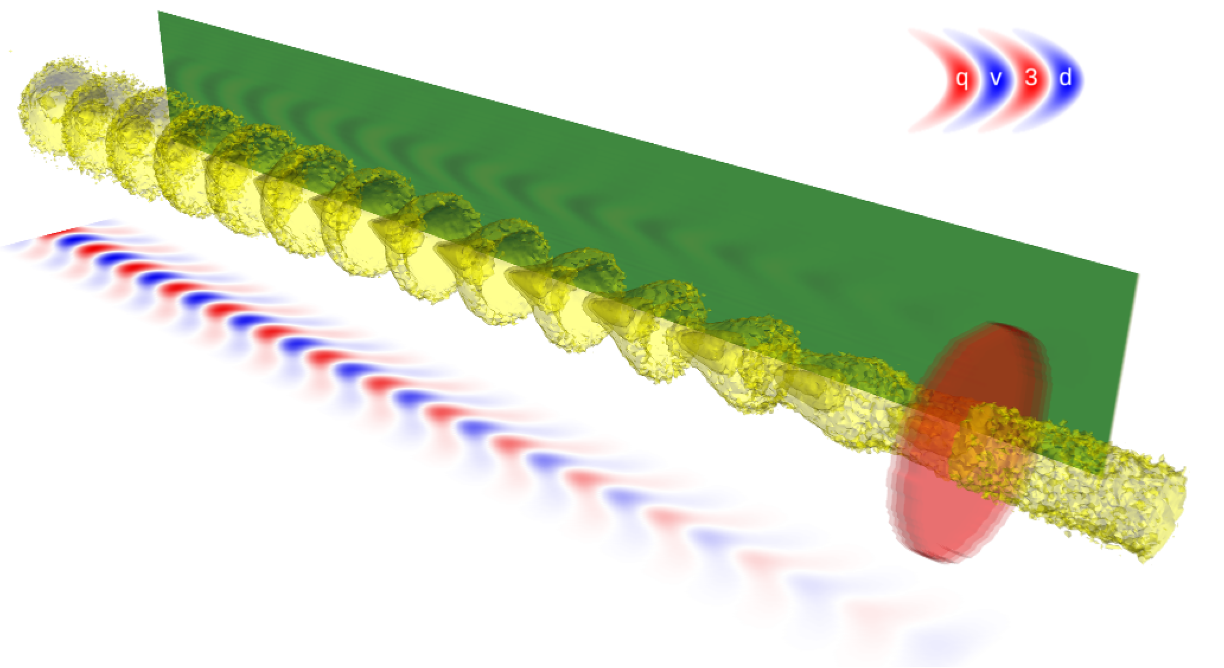
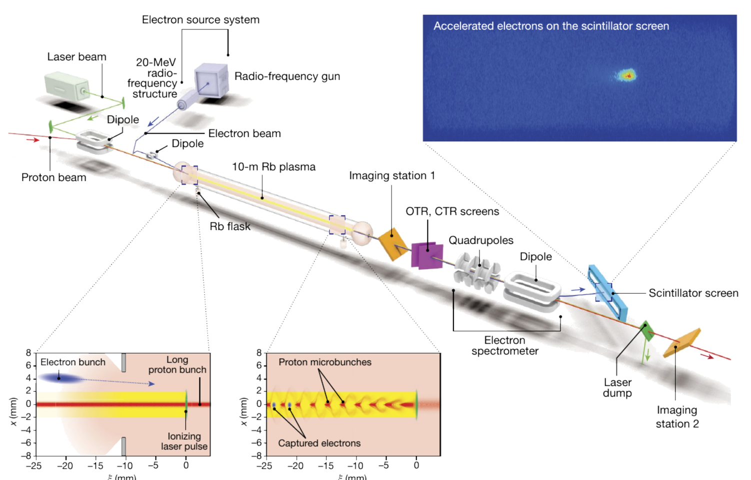
The AWAKE experiment at CERN makes use of a self-modulated proton bunch to excite wakefields and accelerate a witness electron bunch. Run 2c of the experiment will demonstrate stabilization of the wakefield amplitude and control of the witness bunch emittance during injection and acceleration. In this work, we present an overview of the ongoing simulation efforts to support the project as it moves towards controlled acceleration and first particle-physics applications.



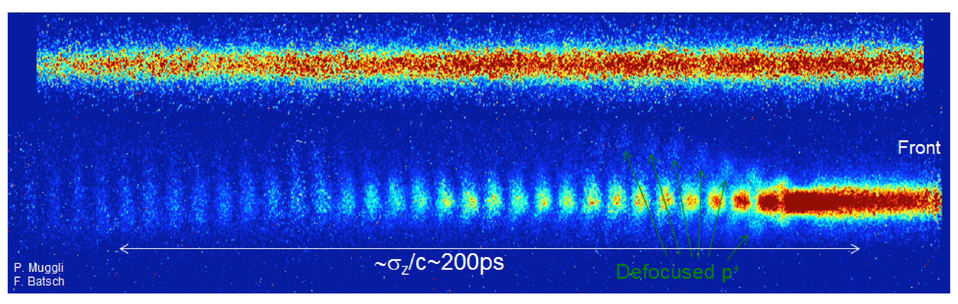
Right: The self-modulation of a proton beam (yellow) is seeded by a co-propagating laser pulse, which causes a step in the plasma density (rear projection). This allows the generation of a plasma wakefield (bottom projection) with a reproducible phase, suitable for acceleration of a witness electron bunch.

AWAKE Run 1 – Run 2b (2016-2024)



AWAKE has demonstrated that the self-modulation of the proton bunch in plasma can be controlled [1,2], creating a train of microbunches suitable for acceleration [3].

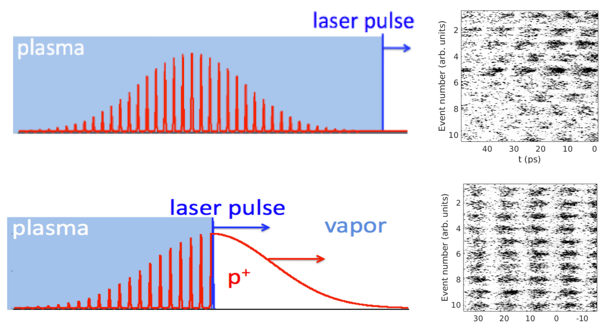
Agreement between experimental results and simulations provide confidence that simulations can be used to develop the expectations for the experiment as we move towards Runs 2c and 2d.



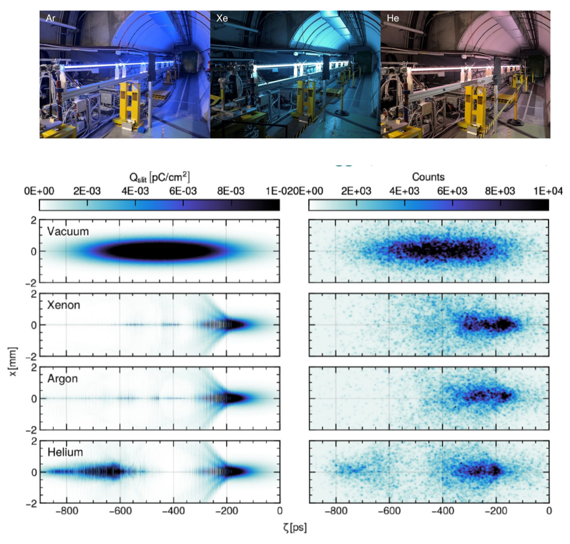
Top left: experimental configuration in Runs 1-2ab.

Left: self-modulation of a proton beam in plasma.

Right: demonstration of wakefield phase control [1].



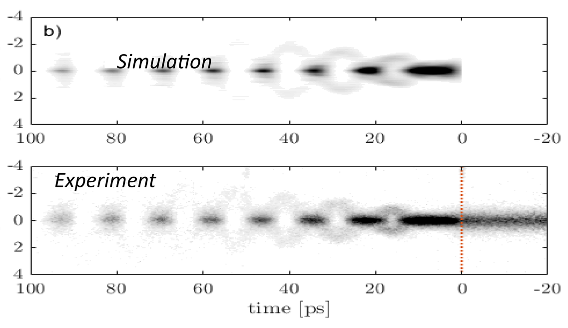
Simulations and experiment

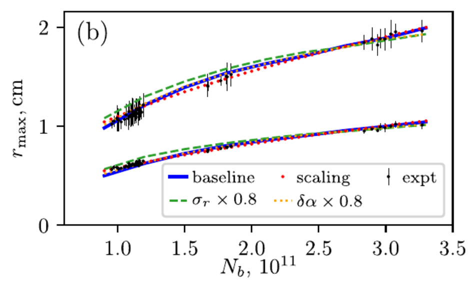


Top left: impact of ion motion on self-modulation in simulation and experiment [4].

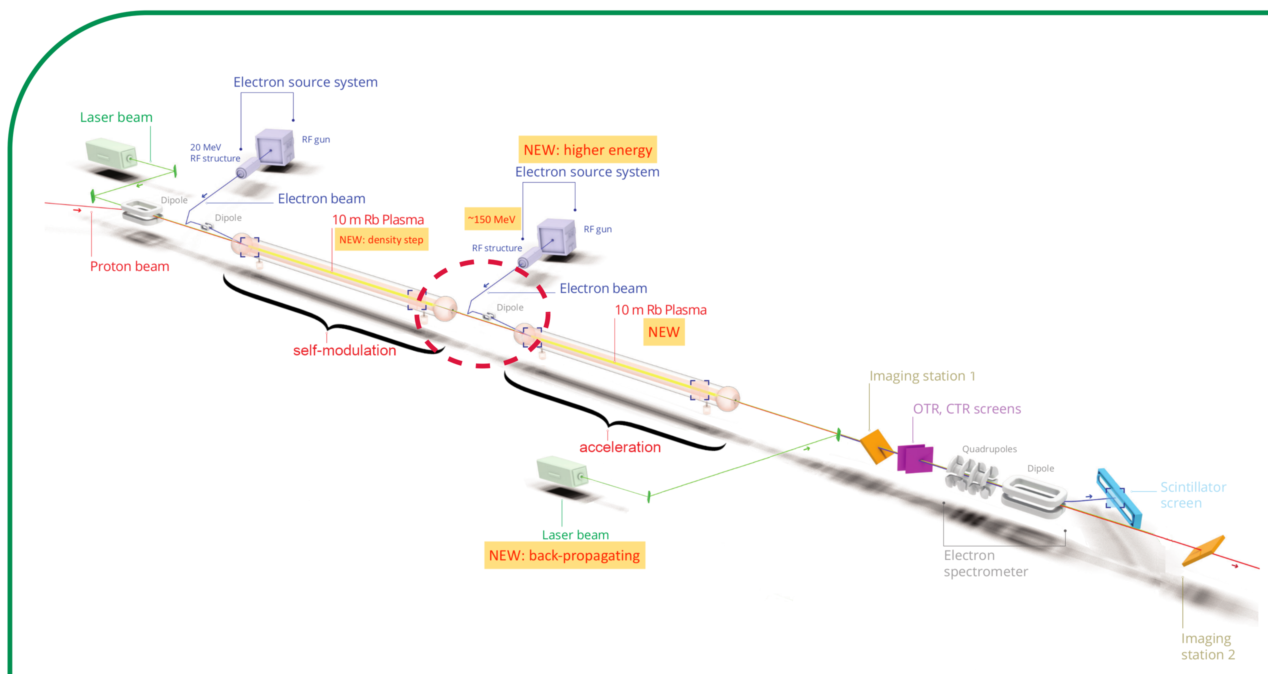
Bottom left: development of microbunch train in simulation and experiment [5].

Bottom right: beam radial size after self-modulation in simulation and experiment [6].



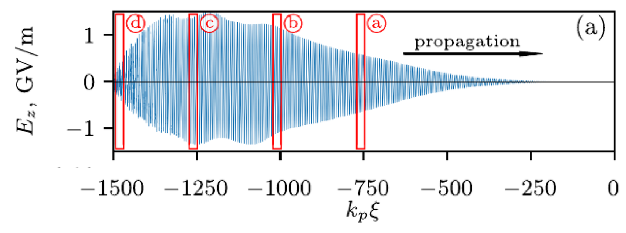


AWAKE Run 2c (2028-)

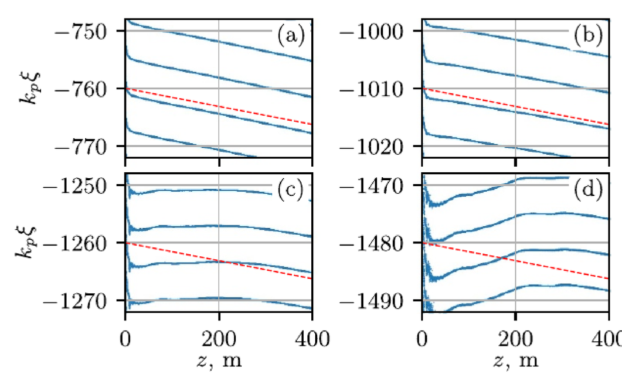


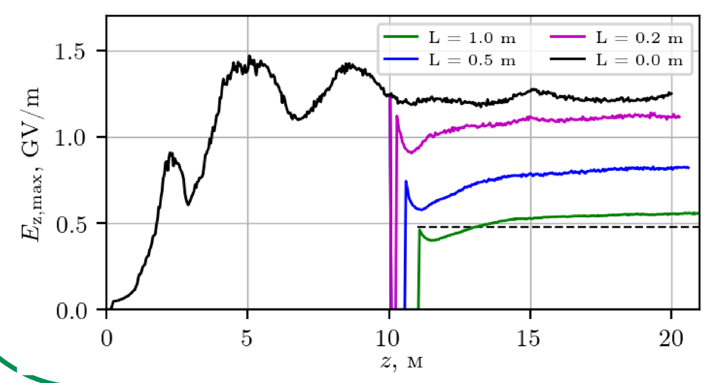
Starting with Run 2c (2028), AWAKE will use a separate plasma stage for self-modulation of the proton bunch [7]. The witness bunch will be injected into a second plasma for acceleration, allowing its emittance to be controlled during acceleration.

The proven ability of simulations to reproduce experimental results means that they can provide a quantitative basis for decisions about the experimental implementation.



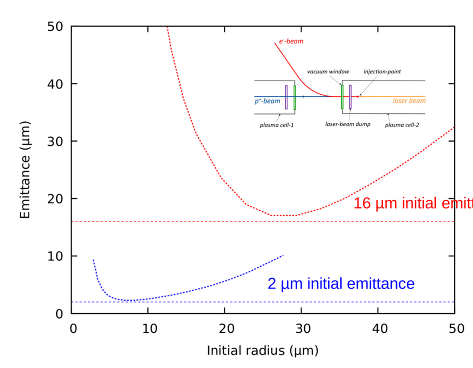
The evolution of the proton microbunch train allows acceleration over long propagation distances [11].

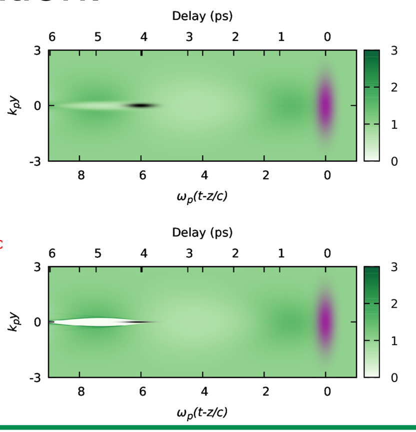




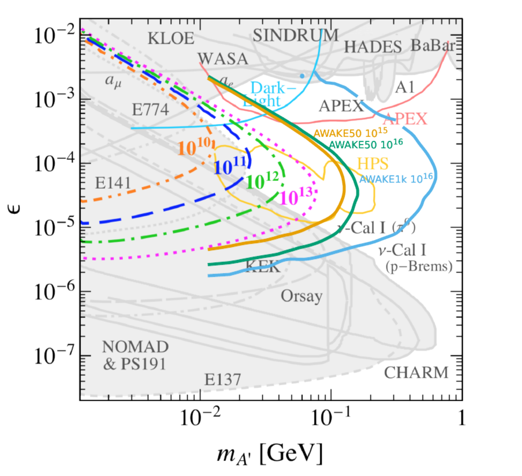
Left: The length of the gap between the self-modulation and acceleration stages modifies the the wakefields in the second plasma cell [8].

The witness emittance at injection [9] influences the plasma dynamics. However, emittance control can be achieved even when a blowout is not formed by correctly choosing the bunch radius [10].

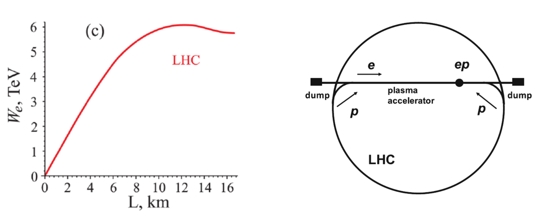




First particle physics



Left: limits on dark-photon decay to an e⁻-e⁺ pair mass from previous and proposed experiments.

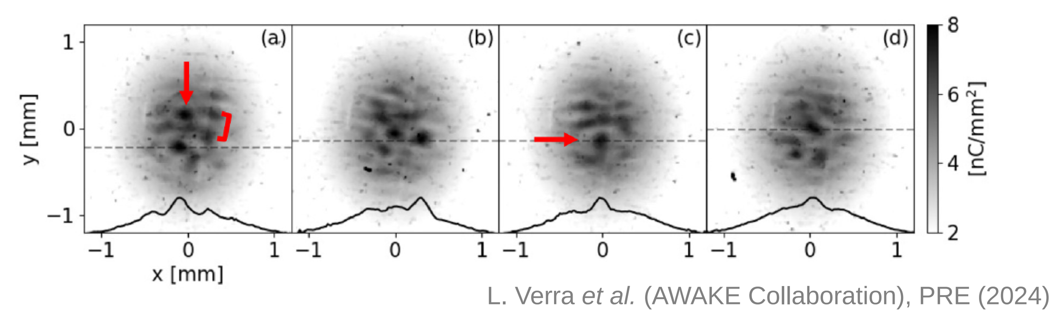


AWAKE offers significantly more electrons-on-target than secondary beam schemes. A first application would be a beam-dump experiment for appearance mode dark-photon searches [12].

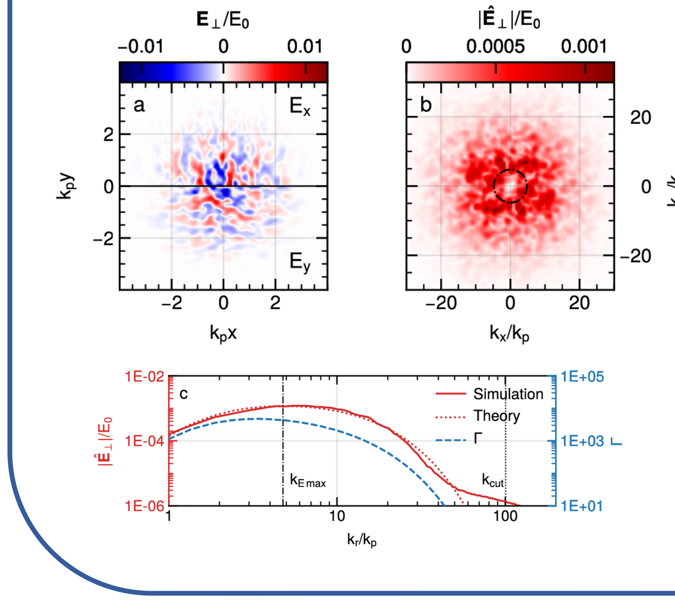
Beyond AWAKE Run 2, an LHC-like driver would allow electron acceleration to TeV energies [13]. This could also be applied to an electron-proton collider [14].

Associated physics

AWAKE also offers the opportunity to investigate physics beyond acceleration, such as and filamentation [15, 16].



L. Verra *et al.* (AWAKE Collaboration), PRE (2024)

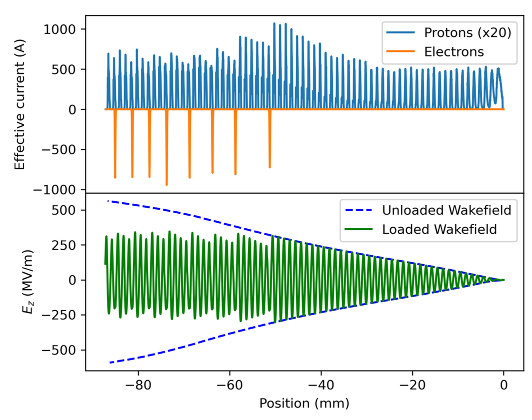


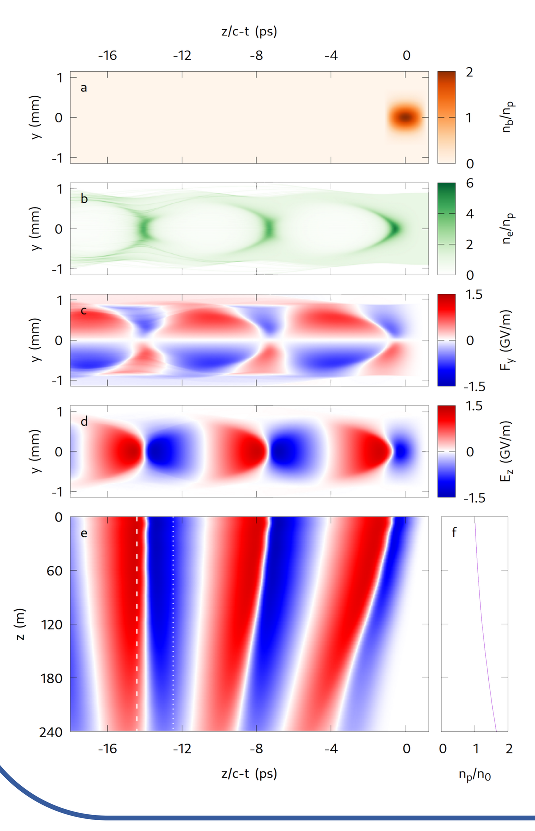
Top: increasing the width of the proton beam allows the development of beam filamentation [15].

Left: The study of a fireball beam in simulations allows self-modulation and filamentation to be isolated [16].

Beyond AWAKE Run 2

Simulations also allow studies of acceleration schemes beyond the scope of Run 2.





Above: the long train of microbunches can be harnessed to regenerate the wakefields, allowing the acceleration of multiple witness bunches [17].

Left: a short proton driver could be used to accelerate both electrons and positrons for use in a Higgs factory [18].

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[2] L. Verra *et al.* (AWAKE Collaboration), Phys. Rev. Lett. **129**, 024802 (2022).
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[5] A-M. Bachmann, PhD Thesis (2021).
[6] A. Gorn *et al.* (AWAKE Collaboration), Plasma Phys. Control. Fusion **62** 125023 (2020).
[7] E. Gschwendtner *et al.* (AWAKE Collaboration), Symmetry **14**, 1680 (2022).
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