ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB173

PHYSICS PROGRAM AND EXPERIMENTAL FOR AWAKE RUN 2

P. Muggli*, Max Planck Institute for Physics, 80805 Munich, Germany
on behalf of the AWAKE Collaboration

Abstract

AWAKE aims at exploring the possibility to accelerate externally injected electrons to high energies in wakefields driven by a self-modulated proton bunch. Experiments performed during Run 1 demonstrated and observed a great many of the characteristics of the self-modulation process. They also demonstrated that externally injected, MeV, test electron can be accelerated to the GeV energy level by the wakefields driven by the self-modulated proton bunch. We briefly describe here the physics and experimental program we are developing for Run 2. Run 2 will focus on the external injection of an electron bunch and its acceleration to the multi-GeV energy level with charge, emittance and relative energy spread suitable for applications.

INTRODUCTION

Proton bunches produced by synchrotrons (e.g., CERN SPS) can carry large amounts of energy per particle (400 GeV) and per bunch (≅19 kJ with 3×10^{11} particles). They can thus in principle drive wakefields in plasma [1] over long distances (100's of m). However, these bunches are typically too long (σ_z ≅6-12 cm) to drive wakefields of large amplitude (~ GV/m) following the single bunch scaling: with $\lambda_{pe} = \sigma_z$, the amplitude can reach $E_{WB} = \frac{2\pi m_e c^2}{e}\frac{1}{\lambda_{pe}}$. In a plasma with electron density n_{e0}, $\lambda_{pe} = \left(\frac{\pi}{r_e n_{e0}}\right)^{1/2}$ is the relativistic electron plasma wave wavelength, r_e is the classical radius of the electron. For $\lambda_{pe} = \sigma_z$=10 cm the amplitude of the wakefields is: E_{WB} ≅16 MV/m and the corresponding plasma electron density n_{e0}=2.8×10^9 cm^{-3}.

Increasing the plasma density such that $\lambda_{pe} \ll \sigma_z$ makes the bunch subject to a self-modulation (SM) process [2]. The SM is the result of the action of the low amplitude transverse wakefields driven by the long bunch, modulating the bunch density. More modulation drives larger amplitude wakefields, which generates deeper modulation, a feedback loop for the SM process to grow. The process transforms the continuous bunch into a train of microbunches shorter than, and separated by $\sim \lambda_{pe}$. The train, with each microbunch satisfying the above single bunch condition, can constructively drive wakefields to amplitudes on the order of E_{WB}. We note that each microbunch must also be small in its transverse dimensions ($\sigma_{r0} \ll \lambda_{pe}$).

With baseline AWAKE parameters, σ_{r0}=200 µm, n_{e0}=7×10^{14} cm^{-3}, λ_{pe} ≅1.3 mm, the amplitude of the wakefields can exceed the GV/m.

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* muggli@mpp.mpg.de

RUN 1

In the AWAKE experiments of Run 1 [3], a number of interesting and important results were obtained. These include: The development of a 10 m-long plasma source based on laser ionization of a rubidium vapor providing a very uniform plasma density [4]; The demonstration of the SM of the long proton bunch in the 10 m-long plasma [5]; The demonstration of growth of wakefields along the bunch and plasma [6] and of their saturation before the end of the plasma [7]; The seeding of the SM process that was coined as an instability, i.e., the ability to make the process reproducible from event-to-event [8]; The possibility to manipulate the SM process through the phase velocity of the wakefields with plasma density gradients [9]; The possibility to accelerate externally-injected, test electrons from the MeV to the GeV energy levels [10]; The observation of the hosing instability [11], but only at very low plasma densities [12]. We also observe that there is very good agreement between experimental and numerical simulation results, e.g., Ref. [13].

RUN 2

Based on these results, we have developed a new experimental program and set-up [14] for Run 2 aiming at demonstrating the acceleration of an externally-injected electron bunch to multi-GeV energy, with low emittance (mm-mrad) and relative energy spread (%-level), and sufficient charge (~100 pC) for applications [15]. In these experiments the SM process of the proton bunch is separated from the acceleration of the electron bunch by using two plasmas (Fig. 1). The Run 2 plan is supported by an extensive simulation program, not described here. It is divided in four parts, referred to as a to d, that we briefly describe below.

Run 2a

Run 2a experiments will use essentially the same experimental setup as that of Run 1. In Run 1, seeding of the SM process was obtained by using a relativistic ionization front created by a short ($\ll \lambda_{pe}$) and intense laser pulse ionizing a rubidium vapor, and placed within, and traveling with the proton bunch [5, 8]. Seeding makes the SM process reproducible. This seeding method leaves the front of the long bunch, traveling in the neutral vapor, not modulated (Fig. 2 (a)). We also observed that in a pre-ionized plasma, e.g., by placing the laser pulse ahead of the proton bunch (Fig. 2 (b)) the SM process is not reproducible, i.e., it is in an instability regime. The front of the bunch emerging from the first plasma (Fig. 2 (c)) could thus experience SM in the instability regime in the second, pre-ionized plasma (Fig. 2 (d)) of the two-plasma configuration of Run 2. The development of the instability in the front of the bunch could

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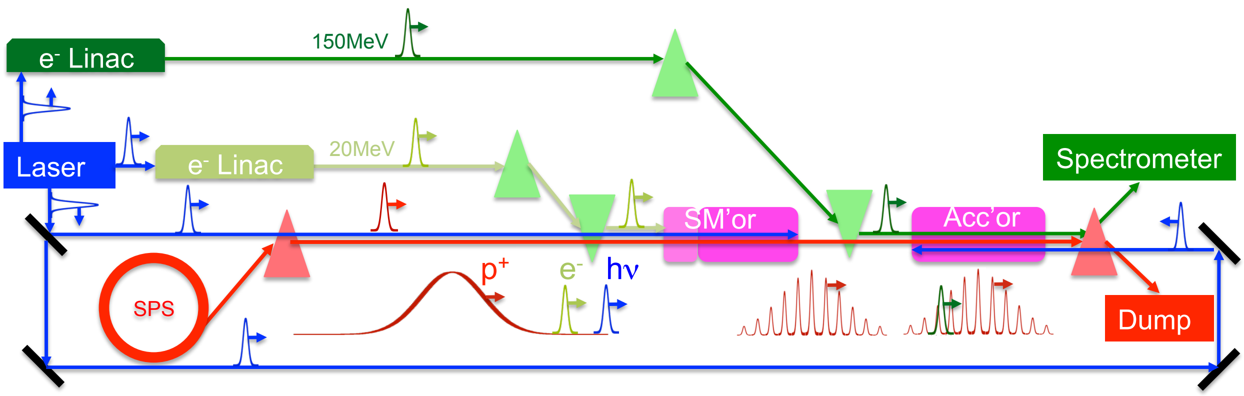

Figure 1: Schematic set-up for Run 2 experiments showing the plasmas (pink colors) for SM (SM'or) with the density step, and for acceleration (Acc'or), as well as the two linacs and beamlines (green colors) for the seeding electron bunch (20 MeV) and the bunch for acceleration (150 MeV). The various bunches (protons in red) and laser pulses (blue color) are also schematically shown. Not to scale.

interfere with the seeded wakefields driven by the core of the bunch, and thus interfere with the acceleration process. We will therefore test seeding of the SM process with an electron bunch preceding the proton bunch [16] (Fig. 2 (e)). An initial simulation and experimental program to study the driving of (seed) wakefields by the electron bunch has started [17]. The advantage of this seeding method is that the entire long bunch exits the plasma self-modulated (Fig. 2 (e)) and can drive wakefields in a following pre-ionized source without the risk of interference described here above. A witness electron bunch can then be injected in the reproducible wakefields driven in a second plasma, ionized for example by a backward-propagation laser pulse (Fig. 2 (f)).

The above interference possibility can also be tested experimentally, for example by placing the seed electron bunch within the proton bunch, and the ionizing laser pulse some distance ahead of it. We can use the diagnostic for the SM process reproducibility of Ref. [8] for two configurations. First, with the laser pulse placed just ahead ($< \lambda_{pe}$) of the seed electron bunch, in which case one expects only reproducible SM of the proton bunch to occur (behind the seed). Second, with the laser pulse a variable distance ahead ($> \lambda_{pe}$) of the electron bunch, in which case one could expect the SM between the laser pulse and the electron bunch to be not-reproducible and to interfere with the otherwise reproducible SM of the back of the bunch. One can then determine whether SM remains reproducible after the electron bunch.

The hose instability has often been posited as imposing limitations on the acceleration quality and length in plasma-based accelerators. We will thus pursue previous studies [12], with additional emphasis on hosing at long wavelengths ($\gg \lambda_{pe}$). We observe the occurrence of the instability using time-resolved images from a streak camera. This instrument provides bunch density distributions in only one transverse direction of the bunch, while hosing can occur in any direction. We will thus use multiple streak cameras to observe two perpendicular transverse directions

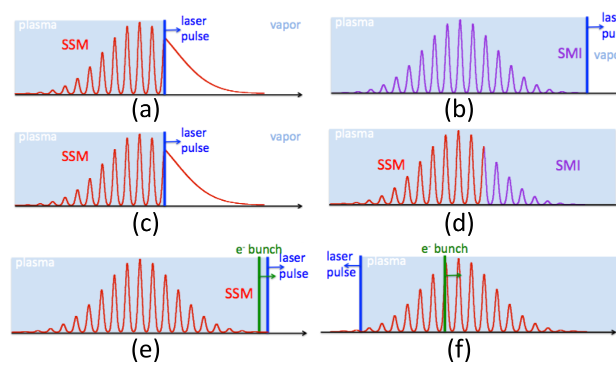

Figure 2: Schematics of some of the configurations for the various bunches and pulses of Run 2a. (a) Relativistic ionization front (RIF created by the laser pulse) seeding of Run 1 leading to reproducible SM of the proton bunch (red line). Front of the bunch not self-modulated. (b) RIF ahead of the proton bunch, SM is not reproducible (purple line). (c) Same as (a) in the first plasma, goes into a second pre-formed plasma (d), and the front self-modulation is not reproducible (purple line) and could interfere with the reproducible modulation in the back (red line). (e) Electron bunch seeding leads to reproducible self-modulation of the entire proton bunch in the first plasma. (f) In the second plasma, preformed (e.g., by a backward-propagating laser pulse), the fully self-modulated bunch drives reproducible wakefields. The externally injected electron is also shown.

of the bunch, as well as on different time scales (ps and ns) to be able to simultaneously observe possible occurrence of hosing at the plasma period and much longer bunch duration scales.

We will also study in more details the parameters of the self-modulated bunch, in particular improving the time resolution to detect variations in the length of the microbunches predicted by simulation results, but masked by the limited time resolution of the Run 1 setup (~1.5 ps).

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Run 2b

Numerical simulations [18] indicate that in a constant density plasma, the amplitude of the wakefields decreases after the saturation point of the SM process. They also show that when imposing a density step in the early stage of the SM process, wakefields can maintain a large amplitude beyond their saturation point [19]. This is of course essential for high-gradient acceleration over long distances. Studying these two predictions will be the main focus of Run 2b.

We are developing a prototype of rubidium vapor source including a temperature step whose position and amplitude can be varied. The vapor source transforms the temperature step into a vapor density step. The laser ionization process transforms the vapor step into a plasma density step. In order to observe the effect of the plasma density step on wakefields, we are developing a THz shadowgraphy diagnostic [20]. Since it is the electron plasma density perturbation that supports wakefields, changes in the amplitude of the wakefields are imprinted on the amplitude of the density perturbation.

We are also investigating plasma light diagnostics to detect changes in the amplitude of the wakefields.

Run 2c

Run 2c is essentially an external injection experiment, aiming at showing that an electron bunch can be injected on-axis, after the plasma for self-modulation, including electron-bunch seeding (Run 2a) and plasma density step (Run 2b), and into the plasma for acceleration [21] (Fig. 1). For these experiments, the electron bunch must be shorter than the period of the wakefields ($\ll \lambda_{pe}$, e.g., 60 µm) and synchronized with them. The bunch parameters are adjusted to reach the blow-out of plasma electrons not achieved by the SM process, load the wakefields and match the ion column focusing fields [22]. In this case, a significant fraction of the bunch charge (e.g., 70%) can be accelerated with a small final relative energy spread, and have its incoming emittance preserved. We note here that producing a short and tightly-focused bunch at the entrance of the second plasma requires electrons with an energy of ~150 MeV [23,24]. The electron bunch for SM seeding can have a lower energy, ~20 MeV.

Initial numerical simulations [25] show that the bunch final parameters are sensitive to the transverse alignment of the electron and proton bunches at the plasma entrance. Multiple beam diagnostics must be developed (e.g., novel beam position monitors [26]) to monitor and control the input and output parameters of the beams and bunches.

Run 2d

The length of a rubidium, laser-ionized plasma source is limited by the ionization process (laser pulse energy depletion, etc.). In the general context of AWAKE we are therefore also developing plasma sources whose length can be extended to the hundreds or thousands of meters necessary for the electron bunch to reach the 100 GeV to TeV energy levels. We are studying helicon [27] and discharge sources. The challenge for these sources is to provide the plasma density uniformity and reproducibility (e.g., $\delta n_e/n_{e0} < 0.2\%$) necessary for the acceleration process over long distances. After the successful injection experiments of Run 2c, the second plasma source will be replaced by one of the new sources. The self-modulation source will remain of the vapor source type to produce the density step.

SUMMARY

The success of the Run 1 program provided essential information for the development of the general Run 2 physics and experiment program presented here. The design of the facility that will host these experiments is in progress [14]. The goal of Run 2 is to demonstrate that the acceleration scheme based on wakefields driven in a single, long plasma by a self-modulated proton bunch can produce an electron bunch with parameters suitable for applications, for example to fixed target or beam dump experiments. The program is strongly supported by numerical simulations. Besides programmatic goals, we will perform studies of the various aspects of the physics involved in these experiments.

REFERENCES

[1] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, "Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma", *Phys. Rev. Lett.*, vol. 54, p. 693, 1985. doi:10.1103/PhysRevLett.54.693

[2] N. Kumar, A. Pukhov, and K. Lotov, "Self-Modulation Instability of a Long Proton Bunch in Plasmas", *Phys. Rev. Lett.*, vol. 104, p. 255003, 2010. doi:10.1103/PhysRevLett.104.255003

[3] P. Muggli *et al.*, "AWAKE readiness for the study of the seeded self-modulation of a 400GeV proton bunch", *Plasma Phys. Control. Fus.*, vol. 60, no. 1, p. 014046, 2018. doi:10.1088/1361-6587/aa941c

[4] E. Öz, P. Muggli, "A novel Rb vapor plasma source for plasma wakefield accelerators", *Nucl. Instr. Meth. Phys. Res. A*, vol. 740, p. 197, 2014. doi:10.1016/j.nima.2013.10.093

[5] AWAKE Collaboration, "Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities", *Phys. Rev. Lett.*, vol. 122, p. 054802, 2019. doi:10.1103/PhysRevLett.122.054802

[6] M. Turner *et al.*, "Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch", *Phys. Rev. Lett.*, vol. 122, p. 054801, 2019. doi:10.1103/PhysRevLett.122.054801

[7] M. Turner *et al.*, "Experimental Study of Wakefields Driven by a Self-Modulating Proton Bunch in Plasma", *Phys. Rev. Accel. and Beams*, vol. 23, p. 081302, 2020. doi:10.1103/PhysRevAccelBeams.23.081302

[8] F. Batsch *et al.*, "Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma", *Phys. Rev. Lett.*, vol. 126, p. 164802, 2021. doi:10.1103/PhysRevLett.126.164802

[9] F. Braunmueller *et al.*, "Proton Bunch Self-Modulation in Plasma with Density Gradient", *Phys. Rev. Lett.*, vol. 125, p. 264801, 2020. doi:10.1103/PhysRevLett.125.264801

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[10] AWAKE Collaboration, "Acceleration of electrons in the plasma wakefield of a proton bunch", *Nature*, vol. 561, p. 363, 2018. doi:10.1038/s41586-018-0485-4

[11] D. H. Whittum, W. M. Sharp, S. S. Yu, M. Lampe, and G. Joyce, "Electron-hose instability in the ion-focused regime", *Phys. Rev. Lett.*, vol. 67, p. 991, 1991. doi:10.1103/PhysRevLett.67.991

[12] M. Huether, M. Moreira, and P. Muggli, "The Hosing Instability of a Long Proton Bunch in Plasma", *Bulletin 62nd APS-DPP Conference*, vol. 65, no. 11, p. VO03.00006, 2020. https://meetings.aps.org/Meeting/DPP20/Session/VO03.6

[13] A. Gorn *et al.*, "Proton beam defocusing in AWAKE: comparison of simulations and measurements", *Plasma Phys. Control. Fus.*, vol. 62, p. 125023, 2020. doi:10.1088/1361-6587/abc298

[14] E. Gschwendtner, "Awake Run 2 at CERN", in *Proc. 12th International Particle Accelerator Conference (IPAC'21)*, Campinas, SP, Brazil, May 24-28, paper TUPAB159.

[15] A. Caldwell, M. Wing, "VHEeP: a very high energy electron–proton collider", *Eur. Phys. J. C*, vol. 76, p. 463, 2016. doi:10.1140/epjc/s10052-016-4316-1

[16] M. Huether and P. Muggli, "Seeding of the self-modulation in a long proton bunch by charge cancellation with a short electron bunch", *Nucl. Instr. Meth. Phys. Res. A*, vol. 909, p. 67, 2018. doi:10.1016/j.nima.2018.02.084

[17] G. Zevi Della Porta Gschwendtner, L.Verra, P. Muggli, and K. Moon, "Preparation for Electron-Seeding of Proton Bunch Self-Modulation in AWAKE", in *Proc. 12th International Particle Accelerator Conference (IPAC'21)*, Campinas, SP, Brazil, May 24-28, paper TUPAB160.

[18] A. Caldwell and K. Lotov, "Plasma wakefield acceleration with a modulated proton bunch", *Phys. of Plasmas*, vol. 18, p. 103101, 2011. doi:10.1063/1.3641973

[19] K. Lotov, "Controlled self-modulation of high energy beams in a plasma", *Physics of Plasmas*, vol. 18, p. 024501, 2011. doi:10.1063/1.3558697

[20] A. Gopal *et al.*, private communication.

[21] V. K. B. Olsen *et al.*, "Emittance preservation of an electron beam in a loaded quasi-linear plasma wakefield", *Phys. Rev. Accel. and Beams*, vol. 21, p. 011301, 2018. doi:10.1103/PhysRevAccelBeams.21.011301

[22] J. Farmer, P. Muggli, E. Gschwendtner, M. Weidl, and L. Liang, "Electron Witness Constraints for AWAKE", in *Proc. 12th International Particle Accelerator Conference (IPAC'21)*, Campinas, SP, Brazil, May 24-28, paper TUPAB158.

[23] L. Verra *et al.*, "Electron beam characterization with beam loss monitors in AWAKE", *Phys. Rev. Accel. and Beams*, vol. 23, p. 032803, 2020. doi:10.1103/PhysRevAccelBeams.23.032803

[24] R. Ramjiawan, S. Doebert, E. Gschwendtner, F. M. Velotti, L. Verra, P. Muggli, and J. Farmer, "Design of the Proton and Electron Transfer Lines for AWAKE Run 2c", in *Proc. 12th International Particle Accelerator Conference (IPAC'21)*, Campinas, SP, Brazil, May 24-28, paper MOPAB241.

[25] M. Weidl and J. Farmer, private communication.

[26] A. Curcio *et al.*, "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation", *Phys. Rev. Accel. and Beams*, vol. 23, p. 022802, 2020. doi:10.1103/PhysRevAccelBeams.23.022802

[27] B. Buttenschön, N. Fahrenkamp, and O. Grulke, "A high power, high density helicon discharge for the plasma wakefield accelerator experiment AWAKE", *Plasma Phys. Control. Fus.*, vol. 60, no. 7, p. 075005, 2018. doi:10.1088/1361-6587/aac13a