THE AWAKE PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT AT CERN

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Abstract

We briefly outline the proposed AWAKE plasma wakefield accelerator (PWFA) experiment to be performed with the CERN SPS proton bunches. We focus on the experimental setup, allude to some of the physics involved and describe some of the measurements that are planned.

INTRODUCTION

A new high-gradient acceleration technique for electrons (e^-) and positrons (e^+) is required. Among those currently proposed and explored, plasma-based acceleration has led to the largest energy gain (>40 GeV) over a meter-scale distance [1]. However, producing with plasmas beams with parameters equal to or better than those produced by conventional, RF-based accelerators remains challenging. One of the challenges arises from the energy of the drive bunch that limits the energy gain of the witness bunch. Current short laser pulses or e^- bunches carry less than ~100 J. Therefore, staging of a large number of plasma accelerator sections, with all the ensuing issues (alignment, timing, gradient dilution, etc.), is required to reach the desired energy (TeV range).

Proton (p^+) bunches available today, e.g. at CERN, carry much more energy than that carried by a future e^-/e^+ collider bunches: ~1.6 kJ for 2×10^{10} particles at 500 GeV. With 10^{11} p^+, CERN SPS (400 GeV) and LHC (7 TeV) bunches carry 6.4 and 112 kJ, respectively. However, these bunches are long (σ_z ~10 cm). For single-bunch operation at a plasma e^- density n_{e0} such that the electron plasma wave period $\lambda_{pe} = 2\pi c\left(\epsilon_0 m_e/n_{e0}e^2\right)^{1/2}$ matches the bunch length ($\lambda_{pe} \sim \sigma_z$, as in [1]) would result in a very low maximum accelerating field: $\leq E_{WB} = \left(2\pi m_e c^2/e\right)/\lambda_{pe} \cong 3.2 \times 10^9/\sigma_z(mm)$ ≅32 MV/m in a plasma with $n_{e0} \sim 10^{11}\,\mathrm{cm}^{-3}$. Short p^+ bunches (σ_z ~0.1-1 mm) are thus necessary to reach fields higher than in RF cavities (>200 MeV/m).

P^+-DRIVEN PWFA

The potential for a p^+-bunch driven, plasma-based accelerator to produce a high energy e^- bunch was demonstrated in proof-of-principle simulations [2, 3]. An energy gain of ~500 GeV in a plasma ~500 m-long with a density of $6\times10^{14}\,\mathrm{cm}^{-3}$ with a σ_z ~100 μm-long drive bunch was achieved. A train of short bunches can be produced out of a long bunch ($\sigma_z \gg \lambda_{pe}$) by the plasma itself through a transverse self-modulation instability (SMI) [4]. Thanks to the periodic focusing/defocusing fields of the initial wakefields, the SMI produces a train of $\sim \lambda_{pe}/2$-long bunches separated by $\sim \lambda_{pe}$ that can then resonantly drive the wakefields to large amplitudes. Interestingly, the amplitude of the wakefields is comparable the one that would be driven if all the charge were in a single short bunch. However, using the long bunch and the SMI to drive wakefields brings new challenges.

When the SMI grows from noise it needs a long plasma length to saturate. Also, the final relative phase of the wakefields is unknown and varies from event to event, which prevents the deterministic injection of the witness bunch into the accelerating and focusing phase of the wakefields. Over this long propagation distance the long bunch is subject to a competing, but asymmetric transverse instability, the hose instability (HI) [5]. The HI can break-up the bunch before the SMI can grow or before the witness bunch can gain large amounts of energy. Calculations and simulations indicate that the growth length of the SMI can be shortened, the phase of the wakefields determined and the occurrence of the HI mitigated by seeding the SMI with a signal of large amplitude [6] and known phase. They also indicate that in certain regimes the full bunch self modulation can effectively prevent the HI from developing over the acceleration region [7].

Even when seeded, the phase velocity of the SMI is slower than that of the drive and witness bunch during the growth phase of the SMI [8]. This leads to dephasing of the witness bunch with respect to the wakefields and to its loss through strong defocusing. The witness bunch must therefore be injected after the SMI has saturated and the bunch is fully self-modulated.

The SMI also grows along the bunch (convective instability) and the witness bunch must be injected many plasma periods behind the start of the wakefields ($\sim 1\sigma_z \gg \lambda_{pe}$). Therefore the proper position within the drive bunch for the witness bunch to be focused and accelerated ($\sim \lambda_{pe}/4$) over a long distance is rather sensitive to plasma density variations since $\delta\lambda_{pe}/\lambda_{pe} = -\frac{1}{2}(\delta n_{e0}/n_{e0})$. When injecting the witness bunch $N \sim \sigma_z/\lambda_{pe}$ periods after the start of the wakefields the density uniformity requirements becomes $|\delta n_{e0}/n_{e0}| \leq (1/2N)$ (for a $\leq \lambda_{pe}/4$ phase shift). This requirement must be met over the plasma length, but only over the time scale of the interaction ($\sim \sigma_z/c$).

THE AWAKE EXPERIMENT

The AWAKE collaboration proposed an experiment to be performed at CERN to study the physics of self-modulation of long p^+ bunches in plasmas, to determine the potential of plasma-based accelerators driven by self-

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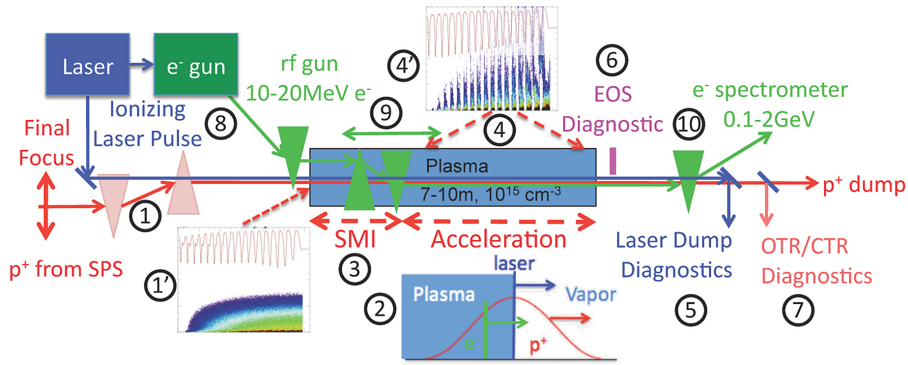

Figure 1: (1) p^+ bunch extracted from SPS. (1') p^+ bunch charge distribution when entering the plasma and transverse wakefields (red line). (2) Time sequence showing the p^+ and e^- bunch and the ionizing laser pulse. (3) Region of the plasma where self-modulation occurs. (4) Region of the plasma where acceleration occurs. (4') p^+ bunch charge distribution when exiting the plasma and transverse wakefields (red line). (5) Laser beam dump. (6-7) EOS and OTR-based p^+ bunch diagnostics. (8) e^- beam for injection into wakefields. (9) Dipole magnets to "side-inject" the witness e^-. (10) Magnetic energy spectrometer for the e^-. Note: the schematic is not to scale and a shorter e^- bunch is used for illustration in 1' and 4'.

modulated p^+ bunches and to explore the possibility of using short p^+ bunches to accelerate e^- to very high energies.

The baseline parameters for the AWAKE experiment using the p^+ bunches from the CERN SPS-CNGS beam line [9] are given in Table 1. A schematic of the experiment is shown in Fig. 1. Note that many standard beam line diagnostics are not shown (alignment screen, beam position monitors, toroids, etc.) [9]. The bunch is extracted from the SPS and transported to the CNGS beam line with an energy of 400 and up to 3×10^{11} p^+. It is focused to a rms radius σ_r^*=200 μm ($\beta^* \cong 5\ m\ \beta^* \cong$5 m) near the entrance of a 10 m-long ($\sim 2\beta^*$) plasma. After the plasma the p^+ bunch free streams to the beam dump. The plasma density can be varied in the $10^{14} - 10^{15}$ cm^{-3} range to keep $k_{pe}\sigma_r^* \leq 1$ ($k_{pe} = 2\pi/\lambda_{pe}$) in order to avoid beam transverse filamentation [10]. The plasma is created by laser field-ionization of a rubidium (Rb) vapor. The vapor with a very uniform density is created in a Rb vapor source with a very uniform temperature [11]. The seeding of the SMI is insured by propagating the short ($\ll \lambda_{pe}$) laser pulse within the p^+ bunch itself [12] (see (2) on Fig. 1). Note that the interaction between the three beams (p^+, e^- and laser) is locally over after approximately one p^+ bunch length ($\sim$12 cm or $\sim$400 ps). Therefore the plasma once locally created by the laser pulse within the p^+ bunch needs to remain uniform only over that time scale. Long-term plasma evolution through diffusion, recombination, etc. common to most other sources is therefore avoided. Over the first few meters of plasma (typically $\sim$4) the SMI develops, saturates and the bunch becomes self-modulated (see (4') on Fig. 1).

The focus of the first experiments will be the study of the SMI. Simulations indicate that with the parameters of Table 1 the SMI does not develop unless seeded. The radial modulation of the p^+ bunch will be measured using various diagnostics. The p^+ bunch will emit incoherent optical transition radiation (OTR) when traversing a thin metal foil placed downstream from the plasma. The OTR light can be time resolved, for example with a streak camera, to directly measure the period of modulation through its intensity variations and perhaps to obtain information about the bunch transverse size. The modulation period and the depth of modulation can also be inferred from electro-optic (EO) measurements. Since there is a large number of modulation periods within the bunch ($\sim 100/\sigma_z$) EO measurements can be made in the frequency rather than in the time domain. EO measurement can either sample the coherent

Table 1: AWAKE Experiment Baseline Parameters

Parameter & Symbol	Value
p^+ bunch ...	
Population, N_b	3×10^{11}
Length (rms), σ_z	12 cm
Radius (rms), σ_r^*	200 μm
Energy, W_b	400 GeV
Normalized emittance, ϵ_N	3.6 mm mrad
Beta function, β^*	4.7 m
Plasma ...	
Density, n_{e0}	$7 \times 10^{14}\ cm^{-3}$
Wavelength, λ_{pe}	1.2 mm
Frequency, f_{pe}	239 GHz
Length, L_{plasma}	10 m
Density uniformity, $\delta n_{e0}/n_{e0}$	$\leq 0.25\%$
Relative ...	
Bunch density, n_b/n_{e0}	6×10^{-3}
Bunch length, $k_{pe}\sigma_z$	597
Bunch radius, $k_{pe}\sigma_r^*$	1
Plasma length, $k_{pe}L_{plasma}$	50,000
Plasma length, L_{plasma}/β^*	~ 2

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transition radiation (CTR) emitted by the p^+ bunch or the transverse CTR recently proposed [13]. Measurements of the CTR frequency using cut-off waveguides or heterodyne microwave systems (f_{pe}=239 GHz with n_{e0}) will be used to detect the occurrence of SMI and measure the frequency of the bunch self-modulation as a function of n_{e0}.

The wakefields themselves will be sampled by externally injecting e^-. These e^- will be produced by an RF photo-injector gun driven by a laser pulse derived from the ionization laser system [9]. This is necessary to be able to chose the injection position of the e^- bunch with respect to the p^+ bunch and to the wakefields (see (2) on Fig. 1), i.e., at their peak and in the accelerating and focusing phase. First injection experiments will use side-injection [14]. This method avoids splitting the plasma source in two, as necessary for on-axis injection thereby avoiding issues related to local plasma density non-uniformities and precise density adjustment between sources. Also, it can be realized with a long e^- bunch ($> \lambda_{pe}$) letting the wakefields trap a fraction of the incoming e^-. Simulations show that e^- with an energy of ~15 MeV crossing the p^+ bunch path at an angle of a few mrad can be trapped when injected along the plasma after SMI saturation (>4 m). Bunches with energies larger than 2 GeV and an energy spread of a few % have been observed after the plasma in simulations with the parameters of Table 1. Note that inherently short (a few fs), high-current (kA) e^- bunches routinely produced by laser-driven plasma-based accelerators (LWFAs) could also be considered for injection.

Later experiments will use two plasmas for on-axis injection of the e^- bunch and accelerator physics experiments. The first source will be a laser-ionized alkali metal vapor source to preserve the SMI seeding ability. However, the second source, used exclusively for e^- acceleration in the wakefields resonantly driven by the modulated p^+ bunch can be of a different, simpler type. Discharge and helicon sources are possible candidates. These sources can be scaled to very long lengths, while the length of the laser-ionized source does not scale well. An interesting option afforded by the two-source scheme (but also with single vapor sources with two heating systems [11]) is the possibility of introducing a step in the plasma density. Simulations suggest that a step up of a few percent during the growth of the SMI can help mitigating the decrease in wake amplitude generally observed after SMI saturation [3]. This decrease is due to the continued evolution of the bunch train and wakefields structure and is most pronounced with positively charged bunches.

OUTLOOK

Using the SMI to produce a train of short bunches and resonantly drive wakefields to large amplitudes is an attractive method when single bunches with suitable properties are not available. However, with the SMI a large fraction of the long initial bunch (at least half) is defocused and does not contribute to the wakefields generation. Another fraction is excluded by the seeding mechanism chosen here. The long distance along the bunch it takes for the SMI to saturate forces the injection of the e^- many plasma periods into the wakefields. This in turn leads to a very tight requirement on the plasma density uniformity. Some of these issues can me mitigated, for example by compressing the bunch and thereby reducing its relative length ($k_{pe}\sigma_z$). Compressions by a factor of a few is possible in the SPS ring and will be explored [9] as a means of increasing wakefields and better understanding SMI physics. However, methods to produce short p^+ bunches (~100 μm) will also be explored to reach the single-bunch non-resonant regime of PWFA excitation and circumvent the issues related to the use of SMI.

SUMMARY

The AWAKE plasma wakefield accelerator experiment is in its preparation phase. We described the high-level experimental set-up, some of the physics involved as well as planned and possible measurements that will be used to test the physics of the SMI and of the acceleration of externally injected e^- in the wakefields driven by the long p^+ bunch. These experiments are tentatively scheduled to start at the end of 2016. These will be the first p^+-driven PWFA experiments and will explore PWFA in a low density range with $\sim GV/m$ accelerating fields that can be sustained over many meters of plasma and potentially accelerate e^- to very large energies in a single (or a few) plasma section [2]. Operation at lower density decreases the accelerating gradient (~1 vs. 100's GeV/m) and increases the plasma length for reaching a fixed final energy. However, operating with a larger accelerating structure ($\sim \lambda_{pe}^3 \propto n_e^{-3/2}$) simplifies the drive and witness bunch production as well as the spatial and temporal alignment of the two bunches. It also increases the beam beta function matched to the plasma focusing force ($\beta_{matched} \propto n_e^{-1/2}$ in the blow out regime) and makes it easier to capture the bunch exiting the plasma.

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