AWAKE, THE ADVANCED PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION EXPERIMENT

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Abstract

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) aims at studying plasma wakefield generation and electron acceleration driven by proton bunches. It is a proof-of-principle R&D experiment at CERN and the world's first proton driven plasma wakefield acceleration experiment. The AWAKE experiment is currently being installed in the former CNGS facility and will use the 400 GeV/c proton beam bunches from the SPS to drive the wakefields in the plasma. The first experiments will focus on the self-modulation instability of the long (rms $\sim$ 12 cm) proton bunch in the plasma. These experiments are planned for the end of 2016. Later, in 2017/2018, low energy ($\sim$ 15 MeV) electrons will be externally injected to sample the wakefields and be accelerated with GeV/m gradients. The main goals of the experiment will be summarized. A summary of the AWAKE design and construction status will be presented.

INTRODUCTION

Wakefields can be driven in plasmas by short and intense laser pulses in a scheme known as the Laser Wakefield Accelerator (LWFA) or by short and dense, relativistic charged particle bunches in a scheme known as the Plasma Wakefield Accelerator (PWFA). The LWFA and the PWFA usually use a single pulse or bunch to drive the wakefields. The pulse or bunch need to be short because the typical amplitude of the wakefields scales with the square of the plasma electron density n_e and the wavelength with the inverse of the square root. The wakefield amplitude is a fraction of the wavebreaking field $E_{WB} = m_e c\omega_{pe}/e$, where $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$ is the plasma electron angular frequency. It can be written as $E_{WB}[\mathrm{GV/m}] \cong 100\sqrt{n_e[10^{14}\,\mathrm{cm}^{-3}]}$, showing that 1 to 100 GV/m accelerating fields can be reached with plasma densities in the 10^{14} to 10^{18} cm^{-3} range. The pulse or bunch need to be small transversely because the transverse size of the accelerating structure scales with the plasma skin depth c/ω_{pe}, i.e., as $n_e^{-1/2}$. In the case of the PWFA driven by a single bunch, the charge of the bunch needs to be large since the fraction of the wavebreaking field is n_{b0}/n_e, where n_{b0} is the initial bunch density. Note that the above scaling comes from linear PWFA theory, but the trends remain essentially correct even in the nonlinear PWFA regime.

However, these pulses or bunches carry limited amounts of energy, typically less than 100 J, thereby limiting the distance over which wakefields can be driven and also the maximum energy gain. Recent PWFA experiments have shown that the acceleration process can be sustained over typical distances of 1 m, leading to energy gain (per particle) on the order of the drive bunch particles energy (20 − 40 GeV). In order to reach energies relevant for high energy physics applications, energies larger than 60 GeV for an e^-/p^+ collider or than 250 GeV for an e^-/e^+ collider are desired. Therefore, staging of multiple plasma sources driven by multiple bunches would be necessary. Staging introduces complexity in the accelerator system and leads to gradient dilution. The average accelerating gradient, that is equal to the energy gain per plasma cell divided by the distance between cell entrances, becomes much lower than the gradient within each cell [1].

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AWAKE

AWAKE, the Advanced WAKefield Experiment aims at exploring the use of proton bunches to drive plasma wakefields [2]. Proton bunches are interesting because bunches available today, for example from the CERN SPS or the LHC, carry large amounts of energy, from a few to hundreds of kJ. They can therefore in principle drive wakefields over a very long single plasma, leading to large energy gain for a witness bunch (e^- or e^+). This potential was demonstrated in simulations with a 1 TeV, 100 µm-long p^+ bunch [3]. However, p^+ bunches delivered by the SPS or the LHC are 10−12 cm-long (rms length σ_z), and, according to the scaling summarized above for a single bunch, would drive very low amplitude wakefields in correspondingly low density plasmas.

AWAKE therefore relies on a transverse beam/plasma instability, the Self-Modulation instability (SMI) of long charged particle bunches in dense plasmas that was recently proposed to drive plasma wakefields [4]. This instability transforms the long bunch ($\sigma_z \gg \lambda_{pe}$) into a train of shorter bunches separated by approximately the wakefield' s wavelength $\lambda_{pe} = 2\pi c/\omega_{pe}$. The train can then resonantly drive wakefields to large amplitude, on the order of 1 GV/m for AWAKE, over very long plasma distances, potentially kilometers, leading to TeV energy gain for a witness e^- bunch [5].

AWAKE PARAMETERS

AWAKE sits in the former CNGS area and uses the 400 GeV/c, $\cong$ 12 cm-long p^+ bunch with $1-3\cdot10^{11}$ particles delivered by the SPS [6–8]. The single bunch with low normalized emittance (3.5 mm-mrad) [9] and low energy spread (0.035%) is focused to $\sigma_r \cong 220$ µm near the entrance of the plasma. A TW, $\cong 100\,fs$ laser pulse ionizes a rubidium (Rb)

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vapor to create the plasma [10]. The laser operates at a 10 Hz repetition rate [11]. Rubidium was chosen because of its low ionization potential (4.177 eV for the first e^-) and relatively large vapor pressure. The laser intensity threshold for field-ionization of the first Rb e^- is around only $1.7 \cdot 10^{12}$ Wcm^{-2}. The baseline electron plasma density is $7 \cdot 10^{14}$ cm^{-3}, but can be adjusted in the $1 - 10 \cdot 10^{14}$ cm^{-3} range by adjusting the vapor density in the same range through the source temperature (150-200^o C). The laser ionization occurs within the p^+ bunch for the abrupt creation of the plasma to seed the SMI and to set the start of the wakefields (phase reference). The plasma source is based on a continuous Rb flow system with two Rb reservoirs. Rubidium flows are temperature controlled, allowing for linear density gradients to be generated [12]. The vapor and plasma column are $\cong$ 10 m-long, about two β^* of the p^+ bunch. This plasma source also meets the requirements for external injection that are briefly specified below.

For the above parameter range, the plasma frequency ($\omega_{pe}/2\pi$) is in the 100-300 GHz range, the plasma period between 10 and 3 *ps* and the wakefields wavelength between 3 and 1 mm. These are also the scales for the p^+ modulation and plasma density modulation that sustains the wakefields, i.e. the accelerating structure.

Simulation results indicate that the SMI grows and saturates over $\sim$ 4 m of plasma [2, 13]. They also show that without seeding by the abrupt ionization the SMI does not grow to significant wakefield amplitudes over the 10 m plasma length.

AWAKE, RUN I, PHASE I

The Phase I of AWAKE, starting at the end of 2016, will focus on the study of the physics of the SMI. It will be centered around p^+ bunch diagnostics located downstream of the plasma.

Transverse Bunch Size

The occurrence of the SMI is expected to transform the time integrated Gaussian transverse profile of the incoming p^+ bunch into a tight core surrounded by a halo of defocused particles. The SMI is driven by the transverse wakefields alternatively focusing/defocusing along the bunch, with the wakefields period. Detailed analysis of the transverse bunch profiles acquired from two screens at $\sim$ 8 m distance should yield important information about the SMI development [14].

Optical Transition Radiation

Transition radiation is prompt radiation emitted when a charged particle crosses the boundary between two dielectrics, such as vacuum and metal. Its spectrum is limited by the screen size on the long wavelength end and the plasma frequency of the metal on the high frequency side (except for x-rays). For wavelengths shorter than the typical bunch size the radiation is incoherent. In the visible range it is known as Optical Transition Radiation (OTR). The OTR can be imaged and can either be time integrated, to obtain the same transverse information as explained above, or time resolved. Time resolution is obtained using a *ps*-resolution streak camera. On a slow *ns* time scale, the effect of SMI seeding as a function of the position of the ionizing laser pulse along the p^+ bunch can be evidenced. On a fast *ps* time scale, the period of the modulation of the p^+ bunch density near its propagation axis can be measured as a function of plasma density. Initial measurements of modulated laser light, obtained from beating and gating two laser beams in an optical fiber, showed the suitability of the streak camera for that measurement. This streak camera setup will also be used to properly time the p^+ bunch and the laser pulse, through a dedicated screen/streak camera system located upstream from the plasma.

Coherent Transition Radiation

For wavelengths longer than the typical bunch spatial features the radiation is coherent. For the plasma densities of AWAKE the CTR is in the microwave range. Its frequency can in principle be measured with a heterodyne mixing system: the CTR with unknown frequency is mixed with radiation with known frequency and the difference measured, at much lower frequency, with a large bandwidth oscilloscope (10-40 GHz). The known frequency radiation, in the 100-300 GHz range, can be generated by standard microwave harmonic generation of a low frequency signal, or by rectification of the two laser beams radiation (as for the OTR-like light generation) on a Schottky diode [15]. Calculations also show that the CTR peak emission angle changes with the plasma frequency and that its peak power is in the kilowatt range [15].

AWAKE RUN I, PHASE II

The Phase II of AWAKE, starting mid-2017, will focus on the external injection of e^- to sample the accelerated fields generated by the SMI.

Electron Injector

The electron injector is the PHIN radio-frequency, photo-injector gun driven by a UV laser pulse and developed and operated for the CTF program at CERN. It can produce bunches with typical charge of 200 pC. The typical normalized emittance and bunch length are 2 mm-mrad [16] and 4 ps (1.2 mm), respectively. The gun is followed by an S-band RF structure [17], driven by the same klystron as the gun, which takes the e^- bunch from its 4-5 MeV to energies between 10 and 20 MeV. The e^- bunch is transported to the plasma where it can be focused to a transverse size of $\sim$250 µm. The timing between the electron bunch and the ionizing laser pulse is obtained by deriving the two laser pulses from the same laser oscillator and phase-locking the laser mode locker (at $\sim$ 88 MHz) and the RF source for the gun (at $\sim$2997 MHz) to a low phase noise oscillator at $\sim$6 GHz. Typical sub-ps rms jitter between the ionizing laser pulse and the injected electron bunch is expected at the

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plasma entrance [18]. Jitter between the laser/e^- bunch and the p^+ bunch is expected to be around 15 ps rms, limited by the p^+ bunch synchrotron oscillation in the SPS accelerating bucket. This jitter is still small when compared to the p^+ bunch length (1.2 ns-rms). This synchronization will be obtained by locking the RF of the SPS (at ~200 MHz) to the laser/gun RF system during a 500 ms constant energy plateau after the p^+ bunch has reached the full energy in the SPS. The minimum time to generate the 400 GeV/c p^+ bunch is 7.2 s, but the bunch will initially be delivered to AWAKE every 30 s.

Injection Schemes

As the SMI evolves, the phase velocity of the wakefields is changing, going from slower than the ionizing laser pulse and p^+ bunch to superluminal. Numerical simulation results [19] show that this leads to relative dephasing between the injected electrons, resulting in defocusing and loss of these e^-. In addition, changes in plasma density along the plasma also lead to relative dephasing. In order for injected electrons to remain in the accelerating and focusing phase of the wakefields, the plasma density uniformity needs to be on the order of 0.2% along the 10 m plasma. This requirement can be fulfilled by the vapor source that showed relative temperature uniformity of better than 0.3^{o}C at 230^{o}C, i.e. better than 0.2%. Temperature uniformity directly translates into neutral vapor density uniformity for an ideal gas without flow, which is in turns turned into plasma density uniformity by the laser field ionization process.

However, the wakefield period is also changing along the density ramps located at the ends of the plasma source. This also leads to relative dephasing and defocusing of the e^- to be accelerated, especially at the entrance side where they have low energy (typically 15 MeV). Wakefield numerical simulation results show that a density ramp shorter than ≅10 cm is necessary not to lose all the electrons. Vapor flow simulation results show that with a flow of Rb from the 40 mm-diameter source tube, through a 10 mm-diameter aperture into a 25 cm-diameter expansion volume at room temperature, the length scale of the density ramp is that of the aperture, again meeting the requirement.

The e^- beam line allows for delivery of the e^- bunch either on the p^+ bunch axis, at an angle with this axis and some distance within the plasma, and parallel to the p^+ bunch axis. Experiments will aim at determining which injection geometry produces the largest e^- bunch energy and smallest energy spread.

Since the e^- bunch length is on the order of the wakefields wavelength, injection will occur in the entire wakefield bucket and the plasma will select particles that are trapped. This also relaxes the timing requirement between wakefield and e^- bunch.

Wakefield simulations results show that, with this setup e^- energies around 1 GeV can be expected with few %-level relative energy spread and up to 50% capture efficiency. An electron spectrometer has been developed to measure the expected spectrum [20].

AWAKE, RUN II AND BEYOND

AWAKE Run I will last till the LHC long shutdown 2 (LS2), scheduled to start at the end of 2018. The AWAKE collaboration is preparing the scientific program for experiments after LS2. This program will probably start with operation with two plasma cells. One cell that allows for SMI seeding and development, possibly including a plasma density step to help maintaining large wakefield amplitudes over long plasma distances. This first source, most likely again a Rb plasma source as described here above, will be only ~4 m-long. The second cell could be of the same type, or could be replaced by a discharge or helicon plasma source, for acceleration over a distance of ~10 m or more.

The Run II program will also address the issue of injection of an e^- bunch short when compared to λ_{pe}, with sufficient charge to produce low final energy spread through loading of the wakefields and possibly preserve its incoming emittance. The e^- injector could be an S-band photo-injector with bunch compression, and X-band photo-injector, or possibly a LWFA injector that then naturally produces a short, high-energy, time synchronized e^- bunch.

At the same time, mid-term plans for an intermediate energy (10s of GeV), p^+ bunch-driven PWFA electron accelerator will be developed. This accelerator should serve as a testbed for issues related to a collider-type accelerator and potentially serve for test-beam applications or fixed-target experiments [21].

Long term applications of the p^+ bunch-driven, PWFA electron accelerator will be explored. These include a e^-/p^+ collider, possibly with a TeV e^- bunch to take advantage of the increase in cross-section of e^-/p^+ reaction with energy [22].

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