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THE AWAKE, PROTON-DRIVEN PLASMA WAKEFIELD EXPERIMENT AT CERN

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Abstract

We briefly describe the current status of the AWAKE experiment in terms of physics and experimental program.

INTRODUCTION

Plasma wakefield acceleration has made remarkable progress since it was proposed [1] and plasma wakefields were first observed [2]. In particular, very large accelerating gradient ($\sim 50\,GeV/m$) and energy gain ($\sim 42\,GeV$) where measured in a meter-scale plasma [3]. A witness electron bunch was accelerated with a narrow energy spread ($\sim$ %) and a significant energy transfer efficiency ($\sim$ 30%) [4].

The AWAKE experiment at CERN [5] aims at exploring the possibility of using a proton (p^+) bunch to drive large amplitude wakefields ($\sim\ GV/m$) in plasmas. Proton bunches are interesting because they carry large amounts for energy (kilojoules). It was shown in numerical simulations that a single LHC p^+ bunch could potentially be used to accelerate electrons to TeV scale energies, in a single plasma stage with GeV/m accelerating gradient [6].

The large momentum p^+ bunches ($\sim 400\,GeV/c$ at SPS and $\sim 7\,TeV/c$ at LHC) are long ($\sigma_z \cong 10-12\,cm$). In order to reach $\sim\ GV/m$ accelerating fields, the plasma density n_{e0} needs to be in the $10^{14}-10^{15}\,cm^{-3}$ range since their amplitude is on the order of $E_{WB}=m_ec\omega_{pe}/e$. Here $\omega_{pe}=\left(n_{e0}e^2/\epsilon_0 m_e\right)^{1/2}$ is the plasma electron (angular) frequency. At these electron plasma densities the plasma wave or wakefields wavelength ($\lambda_{pe}=2\pi c/\omega_{pe}$) is on the order of $1\,mm$. A relativistic charged particle bunch traveling in a plasma with wakefields period much shorter than its length ($\lambda_{pe}\ll\sigma_z$) is subject to the self-modulation instability (SMI) [7].

The SMI is a transverse instability that arises from the interplay between transverse components of the plasma wakefields locally increasing (decreasing) the bunch density through focusing (defocusing), and the wakefields being driven stronger (weaker) by regions of larger (smaller) bunch density. The modulation period is $\cong\lambda_{pe}$ and the modulated bunch resonantly drives the plasma wakefields. In order to avoid another transverse instability, the current filamentation instability (CFI) [8], the bunch must be focused near the entrance of the plasma to a transverse size σ_r smaller than the cold plasma collisionless skin depth c/ω_{pe}: $\sigma_r\le 168\,\mu m$ for n_{e0} up to $10^{15}\,cm^{-3}$.

The occurrence of the SMI can be detected by characterizing the structure of the p^+ when exiting the plasma, the corresponding plasma density modulation and the wakefields this density modulation supports through the acceleration of externally injected electrons.

Experiments will start in late 2016 with the first goal of observing and characterizing the SMI of the p^+ bunch, including seeding of the SMI, in a single, $10\,m$-long plasma. Experiments scheduled for mid 2017 will focus on the external injection of electrons into the wakefields. Acceleration from $\sim\ 20\,MeV$ to over $1\,GeV$ is expected. Later experiments will use two plasmas, the first one for seeding and SMI development, and the second one for acceleration. The second one can be very long thanks to the high energy of the p^+ bunch that is thus able to drive wakefields over many tens of meters [9].

PROTON BUNCH

In the AWAKE experiment, the $\sim\ 400\,GeV/c$, $\sigma_z\ \cong\ 12\,cm$ SPS bunch with $1-3\times10^{11}$ p^+ is focused to $\sigma_r\ \cong\ 200\,\mu m$ near the entrance of the plasma. The p^+ bunch has a low normalized emittance, $3.5\,mm-mrad$ and a small relative momentum spread of 0.35%. Its focused beta function is $\cong 5\,m$, half the plasma length.

PLASMA SOURCE

The plasma source consists of a rubidium (Rb) vapor ionized by a short ($\cong 100\,fs$) and intense laser pulse [10]. Rubidium was chosen because it has a low ionization potential ($4.177\,eV$) for its first electron and a relatively large one for the second ($27.28\,eV$). Since the appearance intensity for ionizations scales with the fourth power of the laser intensity [11], only about $1.3\times10^{11}\,W/cm^2$ are necessary to free the first electron, while a 1984 times larger intensity is required to ionize the second one. Note that in this case the p^+ beam impact or field ionization fraction is very small. Rubidium also has a relatively large ion mass, which makes the experiment less sensitive to ion motion [12]. This is important since the useful wakefields span many plasma wavelengths behind the ionizing laser pulse and the start of the wakefields. The Rb vapor with density $n_0=10^{14}-10^{15}\,cm^{-3}$ is created in an oil heat-exchanger and can accommodate either a very uniform constant density that may be necessary for external injection [13] or a (linear) density gradient. The density is reached at oil and vapor temperatures between 150 and 200^o C. The vapor column is $40\,mm$ in diameter and $\cong 10\,m$-long. The vapor density is measured using the hook method [14].

Since field-ionization is a threshold process, the plasma density and its uniformity are equal to those of the Rb vapor. At the densities considered here, the plasma radius needs to be everywhere at least one millimeter ($\ge c/\omega_{pe}$). Sim-

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ple calculations show that this can be achieved with only $\cong 70\,mJ$ of laser energy. However, propagation considerations indicate that a larger energy may be required. The laser has a maximum energy of $\cong 450\,mJ$. Propagation and ionizations studies are currently underway [15].

Simulation results [16] show that at the plasma entrance the transition between vacuum and full plasma density must occur over less than $10\,cm$ in order not to completely lose the injected electrons by plasma defocusing by the wakefields wavelength changing in the ramp. Flow simulations indicate that a cm-long transition can be obtained with a continuous vapor flow through a small diameter aperture ($\cong 10\,mm$) [17]. Flow at both ends, with two vapor sources, allows for control of the vapor density gradient along the plasma, while a single source at one end of the vapor source with a fast opening valve at the other allows for very uniform density but a long plasma ramp.

SMI SEEDING

Numerical simulations of the SMI development indicate that without seeding the SMI does not develop over the $10\,m$-long plasma and the AWAKE parameters [18].

The SMI is seeded by using the abrupt creation of the plasma by the intense laser pulse with a length $\cong 100\,fs$ much shorter than the plasma period, typically a few ps. Seeding of the SMI fields by a sharp rise time of the particle bunch, an equivalent seeding method, was demonstrated experimentally [19]. In the AWAKE case, where the bunch is much longer than the plasma wavelength and the SMI grows over many tens of them, the laser ionization seed serves to set the start phase of the wakefields. Controlling the start of the wakefields is important experimentally to deterministically inject external electrons at a phase corresponding to a large accelerating field and in the corresponding focusing region of the wakefields (only 1/4 of the wakefields period in linear theory) by adjusting the laser pulse to electron bunch delay.

SMI DIAGNOSTICS

The first round of experiments will focus on the observation and study of the occurrence of the SMI. A number of diagnostics are being developed and integrated in the experimental layout.

The first diagnostic is based on optical transition radiation (OTR). OTR is prompt and its time structure reflects that of the bunch charge density hitting the radiator foil placed in the beam path. Time integrated images of the OTR can reveal the focussing/defocusing action of the SMI development on the p^+ bunch [20]. Using multiple screens can yield information about the angular divergence of the bunch particles and about some details of the development of the SMI [21]. The time structure of the light and p^+ bunch can be characterized using a $\cong 1\,ps$-resolution streak camera. In particular, the period of the modulation (expected to be that of the plasma wave) can in principle be measured up to frequencies of $\cong 300\,GHz$, as was demonstrated in test measurements [22]. For the AWAKE plasma densities, the plasma and modulation frequency range is $100-300\,GHz$.

The modulated p^+ bunch also emits coherent transition radiation (CTR), whose spectrum reflects the bunch longitudinal (Gaussian with $\sigma_z \cong 12\,cm$ or $f \cong 3\,GHz$, untouched by the transverse SMI action) and transverse structure (radial modulation with longitudinal period approximately that of the plasma wave). Therefore CTR emission at the plasma frequency from the radially modulated p^+ bunch can in principle be detected. The long p^+ bunch radiation can be filtered out by a section of wave guide in cut-off (high-pass filter) and the high-frequency time evolution of the radiation detected using a fast Schottky diode ($\sim 200\,ps$ rise time). In particular CTR emission at high frequency should be correlated with the ionizing laser position within the p^+ bunch, i.e., with the SMI seed.

The modulation frequency can in principle be determined using a heterodyne measurement system, mixing the RF modulation signal of unknown frequency with a known local oscillator frequency in a crystal that generates the difference or intermediate frequency. By choosing the frequencies and crystal one can bring the intermediate frequency within the measurement range of a wide bandwidth oscilloscope ($\leq 10-40\,GHz$).

Other diagnostics involving electro-optic sampling are also considered to obtain more detailed information [23].

Complementary diagnostics such as Smith-Purcell radiation yielding the modulation radiation frequency in a single event and photon acceleration yielding information about the plasma density perturbation associated with the bunch charge modulation are also under consideration.

EXTERNAL INJECTION

Various schemes for external injection of electrons are investigated for AWAKE. The initial injection scheme called side injection [24] aims at avoiding the effect of the wakefields changing phase velocity during the growth of the SMI [25]. In this scheme the electrons propagate outside of and parallel to the plasma and are bend towards the wakefields to be trapped and accelerated after the point where the SMI has reached saturation. Numerical simulations show that with this scheme, a narrow electron energy spread (a few %) around $\sim 2\,GeV$ can be reached. However, this scheme was deemed too complex for the first AWAKE external injection experiments.

The current injection scheme is a simple on-axis injection, at the plasma entrance [16]. Initially, the injected electron bunch will be at least one plasma period long (typically $4\,ps$ or $1.2\,mm$) in order to avoid precise timing of a much shorter electron bunch with respect to the wakefields. In this scheme the trapping efficiency of electrons is very sensitive to the length of a possible density ramp at the plasma entrance, whereas that of positrons is not [13]. In all cases the trapping efficiency is less than $\sim 10\%$. Numerical simu-

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lations show that with this scheme, a finite electron energy spread (tens of %) around ~ 1.3 GeV can be reached.

For those injection schemes the plasma density needs to be very uniform, on the order of 0.2% over the 10 m plasma. However, recent simulation results suggest that a plasma density ramp along the beam path may be beneficial for trapping or acceleration [26].

Deterministic injection of a short bunch (when compared to the plasma period or ~ 300 fs) is also considered for later experiments.

Another injection scheme considers the case of two plasmas: seeding and development of the SMI in the first one and driving of the wakefields and acceleration in the second. In this case the injected electrons could be generated by an RF electron gun or a laser wakefield accelerator (LWFA) [27].

ELECTRON BEAM

The electron source is the PHIN radio-frequency gun used at CERN for the CTF3 project. It produces an ≅ 4 MeV electron bunch with up to 1 nC charge (typically 200 pC), and a low normalized emittance of ≅ 2 $mm-mrad$ and low energy spread ~ 0.5%. The energy is boosted to between 10 and 20 MeV in a traveling wave structure powered by the same klystron as the gun. The 10 − 20 MeV range is necessary for optimum trapping and acceleration in the wakefields [16]. The electron bunch is focused to a radius of 250 μm near the entrance of the plasma. The parameters of the laser pulse for the RF gun allow for producing bunches a few picoseconds long for injection in an entire plasma bucket for the initial experiments, down to 300 fs for injection within one bucket. The electron transport line is described in these proceedings [28].

ELECTRON ACCELERATION

Ultimately, the purpose of the experiment is to accelerate the externally injected electrons. A magnetic spectrometer was developed with a relatively large energy acceptance, from a few hundred MeVs to a few GeVs [29]. It is based on a C-shape magnet existing at CERN and providing a B-field integral $Bdl = 1.3 - 1.6\,Tm$. The spectrometer system includes a quadrupole doublet in a point-to-point imaging configuration to focus the beam exiting the plasma onto the spectrometer screen to increase the energy resolution. The light produced on a ScintiMax screen is transported to a low-radiation area and captured by a CCD camera. Calculations show that a %-level energy resolution can be achieved with a signal to noise ratio larger than 1000:1.

SUMMARY

The AWAKE experiment will, for the first time, use a p^+ bunch to drive wakefields in a plasma. The first experiments, scheduled to start in late 2016, will aim at studying the development and seeding of the SMI of the p^+ bunch in a ~ 10 m, $10^{14} - 10^{15}\,cm^{-3}$ electron density plasma. Later experiments scheduled for 2017 will study the injection of a RF-gun produced, long electron bunch in the wakefields and its acceleration to GeV energies. Future experiments will use two plasma sources and an ultra-short electron bunch to address accelerator related issues [30]. Long term prospects include using a short p^+ bunch to drive wakefields without resort to SMI with the possibility of accelerating electrons to very high energies, possibly the energy frontier.

REFERENCES

[1] P. Chen, *et al.*, Phys. Rev. Lett. 54, 693 (1985).

[2] J.B. Rosenzweig *et al.*, Phys. Rev. Lett. **61**, 98 (1988).

[3] I. Blumenfeld *et al.*, Nature **445**, 741 (2007), P. Muggli *et al.*, New J. Phys. **12**, 045022 (2010).

[4] M. Litos *et al.*, Nature **515**, 92 (2014).

[5] AWAKE Collaboration, Plasma Phys. Control. Fusion **56** 084013 (2014).

[6] A. Caldwell *et al.*, Nature Physics **5**, 363 (2009).

[7] N. Kumar *et al.*, Phys. Rev. Lett. **104** 255003 (2010).

[8] Y. Sentoku *et al.*, Phys. Rev. Lett. **90**, 15 (2003); B. Allen *et al.*, Phys. Rev. Lett. **109**, 185007 (2012).

[9] A. Caldwell *et al.*, Phys. Plasmas **18**, 103101 (2011).

[10] E. Oz *et al.*, Nucl. Instr. Meth. Phys. Res. A **740**(11), 197 (2014).

[11] S. Augst *et al.*, Phys. Rev. Lett. **63**, 2212 (1989).

[12] J.B. Rosenzweig, *et al.*, Phys. Rev. Lett. **95**, 195002 (2005); R. Gholizadeh *et al.*, Phys. Rev. Lett. **104**, 155001 (2010); J. Vieira *et al.*, Phys. Rev. Lett. **109**, 145005, (2012).

[13] K V. Lotov *et al.*, Phys. Plasmas **20**, 013102 (2013).

[14] F. Batsch, Diploma Thesis, Technical University Munich (2014).

[15] J. Moody *et al.*, "Laser Propagation Effects during Photoionization of Meter Scale Rubidium Vapor Source", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper WEPWA006, these Proceedings.

[16] K.V. Lotov *et al.*, Phys. Plasmas **21**, 123116 (2014).

[17] R. Kersevan *et al.*, private communication.

[18] J. Vieira, private communication.

[19] Y. Fang *et al.*, Phys. Rev. Lett. **112**, 045001 (2014).

[20] P. Muggli *et al.*, Phys. Rev. Lett. **101**, 055001 (2008).

[21] M. Turner, A. Petrenko, private communication.

[22] K. Rieger, Master Thesis, Technical University Munich (2014).

[23] O. Reimann and R. Tarkeshian, "Dispersive Fourier-transform Electrooptical Sampling for Single-shot Modulation Measurement in a Proton-driven Plasma Wakefield Accelerator", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper TUPC39, p. 467.

[24] K.V. Lotov, Journal of Plasma Physics **78**(04), 455 (2012).

[25] A. Pukhov *et al.*, Phys. Rev. Lett. **107**, 145003 (2011); C.B. Schroeder *et al.*, Phys. Rev. Lett. **107**, 145002 (2011).

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA007

[26] A. Petrenko, private communication.

[27] P. Muggli *et al.*, "Injection of a LWFA Electron Bunch in a PWFA Driven by a Self-modulated-proton-bunch", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, paper TUPME048, p. 1470.

[28] J.S. Schmidt *et al.*, "The AWAKE Electron Primary Beam Line", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper WEPWA006, these Proceedings.

[29] L. Deacon *et al.*, private communication.

[30] V.K. Berglyd Olsen *et al.*, "Loading of a Plasma Wakefield Accelerator Section Driven by a Self-Modulated Proton Bunch", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper WEPWA026, these Proceedings.