PHYSICS OF THE AWAKE PROJECT

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Abstract

We briefly describe the physics goals of the AWAKE experiment proposed at CERN. AWAKE is a plasma wakefield acceleration (PWFA) experiment using the SPS proton bunch as a PWFA driver. These goals include the study of the self-modulation instability of the proton bunch propagating along the plasma, the sampling of the accelerating wakefields by witness electrons, the acceleration of an electron bunch as well more long term issues, such as the generation of very long plasmas and of very short proton bunches.

INTRODUCTION

Proton (p^+) bunches are interesting for driving wakefields in plasmas because they carry large amounts of energy, e.g., with $3\times10^{11}p^+$/bunch $\sim 19\,kJ$ for a CERN SPS bunch at $400\,GeV$ and $336\,kJ$ for a LHC bunch at $7\,TeV$. These energies are much larger than those typical of a future e^-/e^+ linear collider, e.g., $\sim 1.6kJ$ for $2\times10^{10}e^-$ at $500\,GeV$. Experiments have demonstrated that electron and positron bunches, i.e., negatively and positively charge bunches, about one plasma wavelength long ($\sigma_z \approx \lambda_{pe} = 2\pi c/\omega_{pe}$ with $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$) drive plasma wakefields with approximately the same amplitude [1, 2]. Experiments also demonstrated that accelerating gradients in excess of $50\,GeV/m$ can be sustained over m-scale plasmas, leading to an energy gain of $\sim 42\,GeV$ by trailing electrons of a single $42\,GeV$ bunch [3].

Simulation results show that a LHC-like p^+ bunch ($1\,TeV$, $10^{11}\,p^+$) can accelerate an incoming $10\,GeV$ electron bunch to more that $500\,GeV$ in $\sim 500\,m$ of plasma with an average gradient $> 1\,GeV/m$ [4]. However, these simulations use a $100\,\mu m$-long proton bunch. Such short, high current ($\sim 20\,kA$) bunches do not exist today at this energy.

It was recently proposed that the self-modulation instability (SMI) of long proton bunches in dense plasmas, i.e., with $\sigma_z \gg \lambda_{pe}$, can lead to the formation of a a bunch train with approximately the plasma period that can resonantly drive wakefields to large amplitude [5]. The long particle bunch excites transverse wakefields with periodic focusing/defocusing fields. These wakefields lead to periodic larger/smaller density regions along the bunch, which then reinforce the wakefields amplitude and provide the feedback for the SMI to grow. The SMI is a convective instability that grows both along the bunch and along the plasma. It is important to understand that the resulting periodic longitudinal bunch density modulation results from transverse effects and not from longitudinal bunching of the relativistic particles.

In this context, the AWAKE experiment at CERN is being proposed. The general parameters for the experiment are given in Table 1. The experiment will use the $\sigma_z \approx 12\,cm$ SPS bunches with $3\times10^{11}p^+$ at $400\,GeV$. The p^+ beam will be focused to $\sigma_r \approx 200\,\mu m$ near the entrance of a $10m$-long plasma with a density adjustable in the $10^{14}-10^{15}\,cm^{-3}$ range. This density range keeps $k_{pe}\sigma_r \leq 1$ ($k_{pe} = 2\pi/\lambda_{pe}$) in order to avoid the possible occurrence of the transverse current filamentation instability when $k_{pe}\sigma_r \gg 1$ [6]. The best location available at CERN to perform the AWAKE experiment is the CNGS beam line [7].

Table 1: General AWAKE Experiment Parameters

Parameter & Symbol	Value
Plasma density, n_e	$7\times10^{14}\,cm^{-3}$
Plasma length, L_{plasma}	10 m
p^+ bunch population, N_b	3×10^{11}
p^+ bunch length, σ_z	12 cm
p^+ bunch radius, σ_r	$200\,\mu m$
p^+ bunch energy, W_b	400 GeV
p^+ bunch energy spread, δW_b	0.35%
p^+ bunch normalized emittance, ϵ_{bn}	3.6 mm mrad
e^- beam population, N_e	1.25×10^9
e^- beam length, σ_{ze}	0.25 cm
e^- beam radius at injection point, σ_{re}	$200\,\mu m$
e^- beam energy, W_e	~16 MeV
e^- beam normalized emittance, ϵ_{en}	2 mm-mrad
e^- beam injection angle, α_0	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m

AWAKE EXPERIMENT MAIN PHYSICS GOALS

The main physics goals of the experiment are:

- to study the physics of self-modulation of long p^+ bunches in plasma as a function of beam and plasma parameters. This includes radial modulation and seeding of the instability;
- to probe the longitudinal (accelerating) wakefields with externally injected electrons.This includes mea-

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suring their energy spectrum for different injection and plasma parameters;

- to study injection dynamics and the production of multi-GeV electron bunches, either from side injection or from on-axis injection (with two plasma cells). This will include using a plasma density step to maintain the wakefields at the GV/m level over meter distances;
- to develop long, scalable and uniform plasma cells and develop schemes for the production and acceleration of short p^+ bunches for future experiments and accelerators.

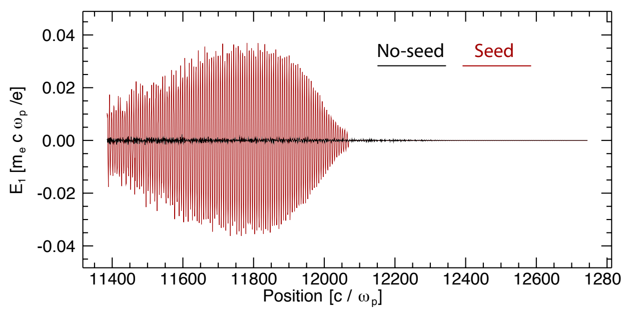

Figure 1: Longitudinal electric field (E_1 in units of the wave breaking field $m_e c\omega_{pe}/e = 0.96\,GV/m$) along the p^+ bunch after propagation in $\sim 6.5\,m$ of plasma in the case of the unseeded, full length p^+ bunch (black line). The bunch (not shown) is propagating to the right, is centered at $\sim 12050c/\omega_{pe}$ (where the ionizing laser pulse is placed) and is $\sigma_z \approx 22.6c/\omega_{pe}$-long ($c/\omega_{pe} = 530\,\mu m$, $n_e = 10^{14}\,cm^{-3}$). Other parameters are $N_b = 11.5\times10^{10}$, $W_b = 450\,GeV$ and those of Table1. Simulations with the OSIRIS code [8].

SMI Seeding

Numerical simulation results in 2D cylindrical geometry show that with the parameters of Table 1 and the full length p^+ bunch propagating in a pre-formed plasma the SMI does not grow to a measurable level along the $10\,m$ plasma (see Fig. 1, black line). The SMI must therefore be seeded, i.e., wakefield of sufficient amplitude must be driven for it to grow and saturate over the plasma length. Seeding can be achieved for example through driving wakefield with a preceding laser pulse or particle bunch with duration $\leq 2\pi/\omega_{pe}$. Seeding can also be achieved by shaping the p^+ bunch with a sharp, rising edge, typically $\leq 2\pi/\omega_{pe}$. However, shaping methods [9] are very difficult to implement with high energy p^+ bunches. Therefore, the seeded method uses a relativistic ionization front [10] created by a moderately intense ($< 10^{13}\,W/cm^2$) and short laser pulse co-moving with the p^+ bunch and ionizing a rubidium vapor. The sharp plasma/vapor boundary effectively seeds the instability as shown on Fig. 1 by the red line and allows it to reach full saturation over a few meters of plasma. Note that this seeding method does not allow the plasma to evolve, i.e., it density to become non uniform or to become unstable. With a witness bunch placed $\sim 1\sigma_z$ behind the ionizing laser pulse, at the location of maximum accelerating field, the useful lifetime of the plasma is only about $400\,ps$. The development of the SMI leads to the beam and plasma density structures shown on Fig. 2. The protons sit in the regions of excess plasma electron density. The seeding of the SMI by the ionization front and its dependency on the position of the ionization front along the p^+ will be studied. The plasma density, as well as the plasma length will also be varied in order to study the dependency of the SMI development on these parameters. The bunch radial self-modulation will be studied using coherent (CTR) and incoherent (OTR) transition radiation as well as transverse CTR (TCTR) [11]. The OTR will be time resolved using a sub-ps resolution streak camera. This measurement will reveal the bunch radial modulation structure, the dependency of the modulation period on plasma density, as well as the growth of the SMI along the bunch. Electro-optic sampling will be used with CTR as well as with TCTR. For example first side bands in the laser pulse spectrum will yield the bunch modulation period, while higher order side band will yield information about the modulation depth.

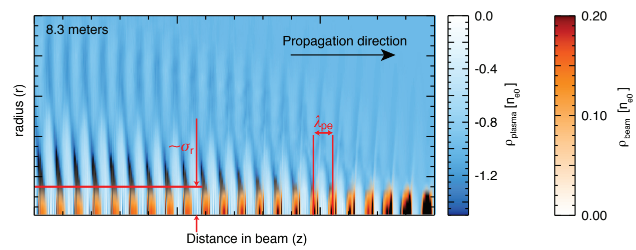

Figure 2: Longitudinal section of the self-modulated p^+ bunch resonantly driving plasma wakefields sustained by the plasma density perturbation. The plasma electron density is shown increasing from white to blue and the proton density increasing from yellow to dark red. The bunch and plasma modulations period is approximately the wakefield period λ_{pe}. Simulation with the OSIRIS code [8].

Wakefields Sampling

The SMI is driven by transverse wakefields. However, longitudinal wakefields can be used to accelerate witness particles (Fig. 1). Since the phase velocity of the wakefields is lower than that of the bunch during the growth of the SMI [12, 13], witness electrons must be injected at a position along the plasma after the SMI has saturated. Initial experiments will use a single long plasma cell and the electrons will be "side-injected" into the plasma wave that will trap and accelerate them [14]. The electrons must have an energy around $16\,MeV$ to be trapped and cross the wakefields at an angle of a few $mrad$. Simulation results show that side injection of an electron longer than the wakefields period can produce a train of short electron bunches with an energy spread of a few percent around $\sim 2\,GeV$.

Electron Bunch Acceleration

In order to produce high charge, high quality electron bunches, the witness bunch can be injected into the plasma onto the p^+ bunch axis, again at a point after the SMI has saturated. This on-axis injection requires the plasma source to be spilt between a "modulation section" where the SMI is seeded and develops, and an "acceleration section" in which the fully self-modulated p^+ bunch can drive GV/m, synchronous accelerating gradients. In this case the first plasma cell still needs to include seeding of the SMI. This is essential to allow for deterministic injection of the short (when compared to λ_{pe}) witness electron bunch into the accelerating and focusing phase of the wakefields. The ionizing laser pulse and electron bunch relative timing, within a fraction of the plasma period ($\approx 4\,ps$), will be controlled and varied. The ionizing pulse and the pulse generating the electron bunch of the RF-gun photo-cathode are derived from the same laser oscillator. Even though the SMI goes through an exponential growth to reach saturation, initial simulation results show that the phase of the wakefields with respect to the ionizing laser pulse is a weak function of the initial beam and plasma parameters.

Accelerating Gradient Maximization

Simulations indicate that the maximum electric field amplitude along the bunch grows exponentially to saturation. However, even after the SMI has saturated the transverse wakefields keep acting of the bunch radial distribution and, as a result, the wakefield amplitude decreases after saturation. This effects is usually stronger in the case of positively charged bunches, as was shown in [15]. However, it was also shown that it is possible to maintain the accelerating gradient to an amplitude very close to its SMI saturation value by introducing a small ($\sim\%$) step in the plasma density at a location along the growth of the instability [16]. This possibility will be explored numerically first, and then implemented in the experiment.

Long Plasmas - Short p^+ Bunches

In the SMI regime shorter bunches with constant charge generally lead to larger peak wakefield amplitudes. However, they also drive the final wakefield parameters farther away from the linear regime of plasma wakefields. In the more non-linear regime the phase of the wakefields favorable to the focusing and acceleration of positively charged particles becomes smaller. These two effects may counter each other in reaching larger energy gain. This can be tested experimentally by using "beam gymnastics" in the SPS [17] to shorten the p^+ bunch. Compression of by a factor of a few seems possible.

Much shorter bunches ($\sigma_z \sim 100\,\mu m$) will have to be generated to reach the single bunch PWFA regime with GeV/m-level accelerating gradient studied in [4]. Therefore, new techniques to produce this kind of p^+ bunches, unavailable today with high charge and high energy, will be studied. These could include injecting laser created p^+ bunches in conventional RF cavities or other advanced techniques.

Large energy gains are possible only in long plasmas [4, 16]. We will investigate and develop other plasma sources that may scale to very long lengths. Those include discharge sources as well as helicon sources. Discharge sources are in principle technically relatively simple and can be many meters long. High densities have been reached, however, density uniformity and reproducibility are still open questions. Helicon sources offer in principle the advantage of being stackable to make very long plasmas ($> 100\,m$). Radiation loss from the plasma becomes significant when the source is operated at the high densities required for the AWAKE experiment. Plasma density uniformity in the longitudinal direction is also an open question, while in the transverse direction the plasma is much larger than the plasma skin depth or the beam radius and radial uniformities should not be an issue.

SUMMARY

The AWAKE experiment is in its final proposal phase and the physics program is expected to start in late 2015.

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REFERENCES

[1] P. Muggli et al., Phys. Rev. Lett. 93, 014802 (2004).

[2] B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).

[3] I. Blumenfeld et al., Nature 445, 741 (2007).

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

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

[6] B. Allen et al., Phys. Rev. Lett. 109, 185007 (2012).

[7] C. Bracco et al., "Beam transfer line design for a plasma wakefield acceleration experiment (AWAKE) at the CERN SPS", TUPEA051, E. Gschwendtner et al., "AWAKE - The Proton Driven Plasma Wakefield Acceleration Project at CERN", TUPEA053, these proceedings.

[8] R.A. Fonseca et al., Lect. Notes Comp. Sci. vol. 2331/2002, (Springer Berlin / Heidelberg (2002).

[9] P. Muggli et al., Phys. Rev. Lett. 101, 054801 (2008).

[10] D. Gordon et al, PRE, 64 046404 (2001).

[11] A. Pukhov et al., Phys. Rev. ST-AB 15, 111301 (2012).

[12] A. Pukhov et al., Phys. Rev. 107, 145003 (2011).

[13] C. Schroeder et al., Phys. Rev. 107, 145002 (2011).

[14] K.V. Lotov, J. Plasma Physics 78(04), 455 (2012).

[15] J. Vieira et al., Phys. Plasmas 19, 063105 (2012).

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

[17] T. Argyropoulos et al., CERN-ATS-Note-2013-006 MD, H. Timko et al., "Short High-intensity Bunches for Plasma Wakefield Experiment AWAKE in the CERN SPS", TUPWA049, these proceedings.