INJECTION OF A LWFA ELECTRON BUNCH IN A PWFA DRIVEN BY A SELF-MODULATED PROTON BUNCH

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Abstract

We briefly describe a scheme in which an electron bunch produced by a laser wakefield accelerator is injected in a proton-driven plasma wakefield accelerator. This bunch can be short (fs), carry high current (kA) and could be ideal to load the wakefields driven by a self-modulated bunch and thereby produce an accelerated bunch with narrow final energy spread. In the AWAKE experiment the injected bunch is also inherently synchronized with the seed of the wakefields.

INTRODUCTION

Plasma-based accelerators operate at large accelerating gradients by replacing the fields of a standing wave accelerating structure by those resulting from local charge separation in a plasma. This charge separation sustains large longitudinal accelerating/decelerating as well as transverse focusing/defocusing fields. These fields are known as plasma wakefields and can be driven by a charged particle bunch [1] or a laser pulse [2]. One of the characteristics of current plasma wakefield experiments is the relatively small size of the accelerating structure, 10's-100's μm as opposed to 10's of cm for RF structures. This small size is the result of the scaling of accelerating field ($E_{acc} \cong n_e^{1/2}$) and plasma wave wavelength ($\lambda_{pe} \cong n_e^{-1/2}$) with plasma density n_e. The bunch that has to fit in the structure has to be proportionally small ($\sigma_z \leq \lambda_{pe}$) to avoid large energy spread and emittance dilution due to non-negligible variations of the wakefield amplitudes across the (accelerated) bunch. This is particularly true when the bunch to be accelerated is externally injected and not self-generated, for example through trapping of plasma electrons. AWAKE [3] is a plasma wakefield acceleration (PWFA) experiment using a long CERN-SPS proton bunch to drive the wakefields. A train of "short" bunches resulting from the saturation of the self-modulation instability (SMI) [4] of the long proton bunch in the "high-density" plasma ($\sigma_z \gg \lambda_{pe}$) drives wakefields to the GV/m amplitude. However, the plasma density ($n_e = 7 \times 10^{14}\,cm^{-3}$, typical) is relatively low, when compared to other PWFA experiments: $10^{16} - 10^{17}\,cm^{-3}$ [5, 6], which means at the accelerating structure is mm in size and that external injection of electrons within one wakefield period is easier (spatio-temporal alignment). Initial AWAKE experiments will use a long ($\sigma_z \approx (1-3)\lambda_{pe}$ or ≈1-4 mm) electron bunch and trapping will select a subset of injected particles that will be accelerated. However, to reach large capture efficiency and produce a good quality accelerated bunch, a short electron bunch is required ($\sigma_z \sim \lambda_{pe}/10 - \lambda_{pe}/20$). It is difficult to produce low energy (10-20 MeV), sub-picosecond bunches with an RF-gun/linac system, such as the one envisaged for initial acceleration experiments. In addition, since the externally injected bunch is not expected to be very short when compared to the wakefield period, beam loading will be necessary to reach low final energy spread.

Plasma-based, laser wakefield accelerators (LWFA's), routinely produce 10-100 MeV, kA, few fs-long, low emittance electron bunches [7]. These are ideal for injection in a SMI-driven-PWFA such as that of AWAKE since the SMI is also seeded by an ionizing laser pulse. Having the initial phase of the wakefields and the laser pulse that generates the electron bunch in the LWFA derived from a single laser oscillator pulse yields the best possible synchronization ($< 100\,fs$ or $< \frac{1}{25}(\lambda_{pe}/c)$).

PROPOSED SCHEME

During the growth of the SMI the phase velocity of the wakefields is lower than that of the drive bunch. [8]. In order to deterministically inject a relativistic electron bunch into the accelerating and focusing phase of the wakefields, the injection point must be located *after* saturation of the the SMI. It is therefore natural so split the plasma into a *self-modulation* and an *acceleration* section. The relative phase of the wakefields is expected not to change along the the acceleration plasma section. We consider placing a short (a few mm) gas-jet LWFA section driven by a multi-TW-power level laser pulse between the two PWFA sources (see Fig. 1). The electron bunch to be accelerated is generated by trapping of plasma electrons and accelerated to ~50 MeV. It is either directly injected or re-focused into the second PWFA section where the self-modulated proton bunch drives GV/m accelerating fields. General requirements for the electron bunch, the plasma sources and the LWFA injector are briefly described below.

BEAM LOADING

Beam loading is simply the combination of the witness bunch wakefields with those of the accelerator structure to produce more constant wakefields through the witness bunch. Most beam loading calculations are performed for plasma wakefields driven by a single bunch. The rules of

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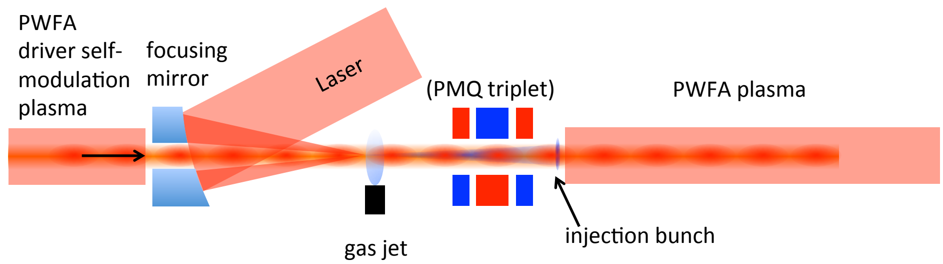

Figure 1: Poor man's sketch of a proposed LWFA-based PWFA injector: A gas jet with shock-front injection (2 not shown in detail) injects a freely diverging or collimated electron beam into the focusing and accelerating phase space of a PWFA. Permanent magnet quadrupoles may be used to collimate the electron beam prior to the main plasma to match the beam divergence.

thumb obtained from linear PWFA theory are that the witness bunch must be short when compared to the length of the accelerating structure ($\ll \lambda_{pe}$) and carry a charge of a fraction that of the drive bunch ($\approx 1/3$).

The case of the SMI-driven PWFA is quite different because the wakefields are driven by a train of (a large number of) drive bunches. Therefore, the charge necessary to beam-load the wakefields can be many times that of each drive bunch and, as a result, the witness current much larger than that of the (long) drive bunch and its charge comparable.

We use expressions obtained from linear PWFA theory considering a wide ($\gg c/\omega_{pe}$) and short ($\ll \lambda_{pe}$) [9] driver to evaluate the characteristics of the witness bunch that could beam-load typical wakefields expected in AWAKE. In this case, the number of particles necessary to fully beam-load the wakefields is given by: $N_W \sim 5 \times 10^5 \frac{n_1}{n_{e0}} \sqrt{n_{e0}} A$ and the corresponding bunch current is: $I_b \sim N_W ec/\sigma_z$. Here, n_1 and n_{e0} are the drive bunch and background plasma electron density, respectively. Using typical AWAKE parameters, i.e., considering $n_1/n_{e0} = E_z/E_{WB} \sim 0.35$ and a beam transverse area $A = \pi\sigma_r^2$, one obtains $N_W \sim 5.9 \times 10^9 e^-$ or ~1 nC and I_b ~2.4 kA for $\sigma_z = \lambda_{pe}/10$ or ~400 fs. Note that these numbers are indeed comparable to the charge effectively driving the wakefields, i.e., ~ 34% (within $1\sigma_z$) of 50% (because of self-modulation) of 50% (because of the ionizing laser pulse is in the middle of the bunch) of the total bunch population (3×10^{11}). As expected, the current is on the order of the bunch current multiplied by number of micro-bunches driving the wakefields (~100). Simulations of the SMI show that, because of the evolution of the wakefields during the SMI growth (first plasma section), not all the protons initially in the focusing phase of the wakefields are finally focused toward the beam axis, i.e., not all the bunch current participates in the wakefields driving. However, since the final radius of the micro-bunches is smaller than the initial bunch radius, the on-axis bunch density increases and wakefields are driven harder ($E_z \sim n_b$).

PLASMA SOURCES

Self-modulation Plasma Source

The self-modulation plasma source must allow for seeding of the SMI. One option is to keep a source similar to that developed for the first experiment [10]. It consists of a metallic vapor source photo-ionized by a short and intense laser pulse that also provides the seeding of the SMI. Other option would be considered if this source did not perform as expected during the first AWAKE experiments.

Acceleration Plasma Source

The aim of the second plasma source is to produce a preformed, uniform and long plasma with a density matching that of the first source so the self-modulated structure imprinted in the proton beam can resonantly excite wakefields in the acceleration section. One option is to use a discharge source. The plasma is produced in a stable pure argon background with controlled pressure (close to 10^{-2} mbar for plasma densities considered here) by ionizing it to Ar^+ with an ionization fraction close to 100%. The ionization is achieved by a pulsed high-voltage capacitive discharge applied over a DC simmer discharge. The pre-existing plasma produced by the simmer discharge makes the main discharge more reliable and reproducible. The simmer discharge, with a current ¡1 mA, can easily be produced by the off current of the switch used for the main high-current discharge or more reliably by a high-ohmic resistor in parallel with that switch. For a stable gas pressure background, the main parameters of the discharge: applied voltage, peak current and pulse duration can be controlled by the capacitor charge voltage, circuit resistance, capacitor size and switching pulse. By using 1 μs-duration high-voltage pulses, a high level (close to 100%) ionization fraction of argon is achieved with a current density of ≈1 kA/cm^2. This current density can be reduced by using a longer pulse. The use of a semiconductor switch (arrays of IGBTs) allows for control of the energy deposited in the plasma and also avoids discharge ringing (present with gas switches), thereby reducing electromagnetic noise. The discharge is produced between two hollow metallic elec-

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trodes (to allow for the electron and proton beams passage) placed at the ends of a glass tube containing the gas. It is important to use a positive (anode) and a ground (GND cathode) electrode to assure that the discharge does not exist between the anode and some other close and grounded metal part through some residual gas background. Therefore, for reliable operation the anode needs to be isolated from close-by metallic parts by high-pressure (1 atm) or high vacuum ($< 10^{-4}$ mbar). Plasmas with length up to 3 m have been demonstrated using voltages up to 9 kV indicating that scaling to 10 m is possible by using 40 kV discharges.

PROPOSED LWFA INJECTOR

Laser wakefield accelerators have demonstrated their potential for delivering reproducible, low-emittance electron beams with energies in the few 10 MeV to few GeV range (for a review, see [11]). Depending on the primary injection mechanism into the laser-driven wakefield, bunches with a narrow energy spread, between a few and 10%, are routinely produced. As an example, Fig. 2 shows the result of an experiment carried out at MPQ by firing a 60 TW laser pulse into an supersonic gas jet (for details, see [12]). The jet featured a density down-step created by a shock front, localizing the electron trapping position and allowing for tunability of the bunch parameters.

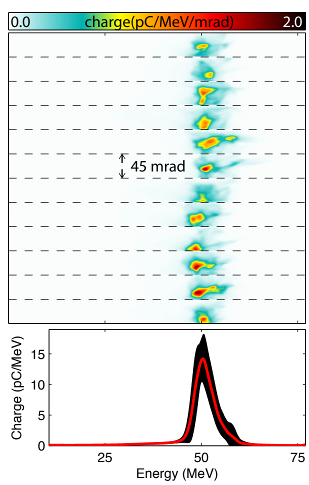

Figure 2: Spectra of consecutive electron bunches (from top to bottom) accelerated with the shock-front injection scheme. The shock position was chosen to select 50 MeV bunch energy. The average bunch charge was 90 pC, with little shot-to-shot fluctuations, as indicated in the line-out. Image taken from [12] with permission from APS.

As the beam divergence amounts to ≈ 10 mrad, after an $\approx$10 cm propagation the electron beam has diverged sufficient to fill the transverse extent of the PWFA plasma wave. If needed, permanent magnet lenses [13] can be used to collimate the electron beam into the main accelerator. The pulse duration of LWFA electron bunches has been measured (e.g.[14], [15], own measurement) as ≈ 5 fs FWHM, ensuring that the injected pulse indeed only occupies a very small fraction (10^{-3}) of the wave period. Even at this very short duration, the above injection bunches exhibit a density of $3 \times 10^{14}\ cm^{-3}$ after diverging to match the PWFA wavelength, which is still below the PWFA's electron density. However, its 18 kA peak current is above the required beam loading current. Therefore, temporal manipulation of the bunch may be necessary to optimize beam loading. The necessity to stretch or collimate the injection beams is currently studied numerically.

Even current LWFA electron beam parameters are a very attractive and simple route for meeting some of the requirements for an injected bunched matched PWFA, namely with small emittance, short duration and high current. We note here that thorough numerical studies are necessary to determine the final parameters of the scheme. In particular, the distance between the two plasma sources, the parameters of the electron bunch at the plasma entrance, the stability of the wakefields phase against variations in initial parameters need to be determined. In addition, the adjustment of the two plasma sources density is a practical challenge.

SUMMARY

We are considering injecting a LWFA-generated electron bunch into a PWFA driven by a long proton bunch. This bunch can be very short, carry high current and is also inherently synchronized with the laser pulse that creates the plasma and seed the SMI for the AWAKE experiment. Such bunches may allow for effective beam loading of the wakefields, thereby enabling narrow energy spread of the electron bunch emerging from the accelerator at TeV energies. These plasma-based accelerators are also very compact.

REFERENCES

[1] P. Chen, et al., Phys. Rev. Lett. 54, 693 (1985).
[2] T. Tajima, et al., Phys. Rev. Lett. 43, 267 (1979).
[3] AWAKE Collaboration, Plasma Phys. Controlled Fusion (submitted 2013), E. Oz et al., R. Tarkeshian et al., these Proceedings.
[4] N. Kumar *et al.*, Phys. Rev. Lett. 104, 255003 (2010).
[5] E. Kallos et al., Phys. Rev. Lett. 100, 074802 (2008).
[6] I. Blumenfeld *et al.*, Nature 445, 741 (2007).
[7] LWFA
[8] C. B. Schroeder *et al.*, Phys. Rev. Lett. 107, 145002 (2011); A. Pukhov *et al.* Phys. Rev. Lett. 107, 145003 (2011).
[9] S. Wilks *et al.*, IEEE Trans. Pl. Sci., PS-15(2), (1987).
[10] E. Oz, P. Muggli, Nucl. Instr. Meth. Phys. Res. A 740, 197 (2014), see also these Proceedings.
[11] E. Esarey *et al.*, Rev. Mod. Phys. 81, 1229 (2009).
[12] A. Buck *et al.*, Phys. Rev. Lett. 110, 185006 (2013).
[13] S. Becker *et al.*, Phys. Rev. STAB 12, 102801 (2009).
[14] O. Lundh *et al.*, Nat. Phys. 7, 219 (2011).
[15] A. Buck *et al.*, Nat. Phys. 7, 543 (2011).

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