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Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics

AWAKE Collaboration

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Abstract. New acceleration technology is mandatory for the future elucidation of fundamental particles and their interactions. A promising approach is to exploit the properties of plasmas. Past research has focused on creating large-amplitude plasma waves by injecting an intense laser pulse or an electron bunch into the plasma. However, the maximum energy gain of electrons accelerated in a single plasma stage is limited by the energy of the driver. Proton bunches are the most promising drivers of wakefields to accelerate electrons to the TeV energy scale in a single stage. An experimental program at CERN – the AWAKE experiment – has been launched to study in detail the important physical processes and to demonstrate the power of proton-driven plasma wakefield acceleration. Here we review the physical principles and some experimental considerations for a future proton-driven plasma wakefield accelerator.

1. Introduction

Over the last fifty years, accelerators of ever increasing energy have been used to probe the fundamental structure of the physical world. This has culminated so far in the Large Hadron Collider (LHC) at CERN, Geneva, an accelerator of 27 km in circumference. With this accelerator, the Higgs Boson, the particle of the Standard Model that attributes to particles their mass, was recently discovered [1, 2] in proton–proton collisions. However, although the Standard Model has been incredibly successful at describing fundamental particles and the forces that act between them, there are still several unexplained phenomena that pose some of the big questions in science:

- Why are the masses of the fundamental particles so different, e.g. the top quark and neutrinos?
- Why are there three families of quarks and leptons?
- Where is the anti-matter in the Universe?
- Why does the visible matter constitute only 5% of the Universe and what are dark matter and dark energy that constitute the rest?
- Is there a Grand Unification Theory that merges the fundamental forces into one?

That the Standard Model can not answer all these questions, points towards the need for new theories or phenomena such as Supersymmetry, which unifies the forces at high energies and provides a candidate for dark matter, or extra spatial dimensions, such as required by string theory. Such phenomena are being searched for at high energy using the LHC and any successor. It is widely held that a next energy frontier accelerator should collide electrons and positrons at around the Tera-electron-Volts (TeV) energy scale. As electrons and positrons are point-like, fundamental objects and the centre-of-mass energy is controlled, a significantly cleaner environment can be achieved than at the LHC that collides protons. Such a future electron–positron collider would therefore have the potential to search for new physics as well as being able to measure to high precision new phenomena discovered already at the LHC.

The gradient at which charged particles can be accelerated using today's radio-frequency (RF) or microwave technology is limited to about 100 MeV/m by RF breakdown on and fatigue of the cavity walls. To reach the TeV scale in a linear accelerator, the length of the machine is therefore tens of kilometres. Circular electron colliders are feasible at these energies only at the 100 km scale due to limitations imposed by synchrotron radiation [3]. At these scales it becomes difficult to find a suitable stable geological site and the construction cost of such a machine is estimated to be in the range of ten(s) of billions of Euros. Therefore, a new high-gradient accelerator technology must be developed to ensure that the energy frontier in particle physics can be investigated experimentally within affordable cost, time-scale and space constraints.

Ionized gases, or plasmas, with densities over a thousand times lower than that of the atmosphere, can sustain accelerating gradients (several 10 GeV/m) orders of magnitude larger than RF structures [4]. These large fields are due to the collective

response of the plasma electrons to the electric field of a laser pulse or charged particle bunch driver. The plasma, without initial structure, supports waves or wakes travelling at velocities near the speed of light, ideal to accelerate particles to relativistic energies. These wakefields have a longitudinal component able to extract energy from the driver and transfer it to a trailing witness bunch (of e.g. electrons). The wakes also have transverse wakefield components with focusing strength orders of magnitude larger than that of conventional magnets, allowing for the two beams to remain transversely small over long distances. This combination of large plasma fields and long confined propagation distances can lead to the large energy gain necessary for high-energy physics applications, but over much shorter distances than with today's RF and magnet technology.

The potential of plasma as the medium for high gradient acceleration has been demonstrated with short and intense laser pulse drivers yielding electron bunches of up to 2 GeV energy gain in cm-long channels [5, 6] that corresponds to about 100 GV/m average accelerating fields. High gradients have also been demonstrated with a short, high charge electron bunch driver with an energy gain of 42 GeV in 85 cm, corresponding to 52 GV/m [7].

However, in both of these pioneering experiments the energy gain was limited by the energy carried by the driver (~ 100 J) and the propagation length of the driver in the plasma (< 1 m). The laser pulse and electron bunch driver schemes therefore require staging [8, 9], i.e. the stacking of many $10 - 25$ GeV acceleration, or plasma, stages to reach the ~ 1 TeV energy per particle or equivalently ~ 2 kJ of energy in $\sim 2 \times 10^{10}$ electrons and positrons. The scheme proposed in this paper solves these propagation-length and energy limitations by using a proton bunch to drive the wakefields.

Bunches with 3×10^{11} protons and 19 kJ of energy (the CERN SPS 400 GeV beam), and with 1.7×10^{11} protons and 110 kJ of energy (the CERN LHC 4 TeV beam) are produced routinely today. Because of their high energy and mass, proton bunches can drive wakefields over much longer plasma lengths than other drivers. They can take a witness bunch to the energy frontier in a single plasma stage, as was demonstrated in simulations [10]. This proton-driven scheme therefore greatly simplifies and shortens the accelerator. In addition, because there is no gap between the accelerator stages, this scheme avoids gradient dilution.

2. Self-modulation instability of particle beams in plasmas

Despite the great potential of proton-driven plasma wakefield acceleration, there are a number of challenges to overcome. The major challenge is the length of the existing proton bunches. A plasma can be understood as an ensemble of oscillators swinging at the plasma frequency. To enforce the resonant swinging of these oscillators, the driver must contain a Fourier component close to the plasma frequency. The maximum field

of a plasma wake scales as

$$E_{\max} \approx \sqrt{\frac{n_e[\mathrm{cm}^{-3}]}{10^{14}}}\,\mathrm{GV/m}, \tag{1}$$

where n_e is the plasma electron density. Consequently, plasma densities of at least $n_e \approx 10^{14}\,\mathrm{cm}^{-3}$ are required to reach accelerating gradients of GeV/m and above. The corresponding plasma wavelength is

$$\lambda_p \approx \sqrt{\frac{10^{15}}{n_e[\mathrm{cm}^{-3}]}}\,\mathrm{mm}. \tag{2}$$

At these densities, the plasma wavelength is of the order of a millimetre. On the other hand, proton bunches available today are much longer, $\sigma_z = 3 - 12\,\mathrm{cm}$. Having a nearly Gaussian shape, they are not resonant and thus no strong plasma wakefields can be excited directly.

Fortunately, a mechanism has been discovered that automatically splits the proton bunch propagating in plasma into a number of micro-bunches: the self-modulation instability (SMI) [11, 12]. The instability starts from a seeding wave whose transverse field acts on the beam and modulates its radius. The modulation has a period very close to the plasma wavelength. Its amplitude grows exponentially from head to tail of the bunch and along the propagation distance. The physics of the instability is now well understood, and theoretical predictions agree well with results of simulations [13, 14, 15, 16, 17]. At saturation, the initially long and smooth beam is split into a train of micro-bunches that resonantly excite a strong plasma wave. This plasma wave is inherently weakly nonlinear [18], so the way of its excitation is almost independent of the charge sign of the drive beam. An example of a self-modulated bunch as observed in 3D simulations using the particle-in-cell code VLPL [19, 20] is shown in Figure 1. Numerical simulation of a self-modulating proton beam in the real geometry is a challenging problem, e.g. the resolution must be carefully chosen [21].

3. Uniform-density plasma cell

The second challenge also arises because of a large disparity between the bunch length and the plasma wavelength. The proton bunch must be split into some 100 micro-bunches to drive the high amplitude wake. All these micro-bunches must work constructively. This translates into a very strict requirement on the plasma density uniformity [22]. Simulations show that electron trapping and subsequent stable acceleration are mainly affected by density gradients. The relative plasma density variations must be controlled down to

$$\frac{\delta n_e}{n_e} \approx \frac{\lambda_p}{2\pi\sigma_z}. \tag{3}$$

This means that for realistic proton bunches we have to control the plasma density below 0.5% over distances of many metres [23].

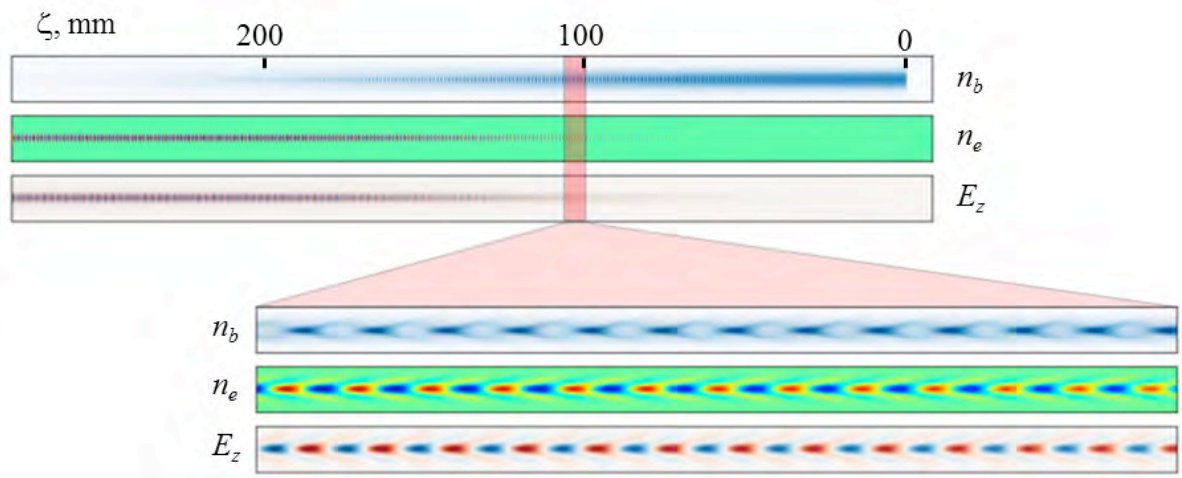

Figure 1. Proton beam density n_b, plasma electron density n_e, and the longitudinal component of the wakefield E_z after 4 m of propagation in plasma. The coordinate $\zeta = ct - z$ is counted from the bunch head. The region 10 cm behind the bunch head is zoomed in.

The best option to achieve the high density uniformity is to fill an evacuated vessel with a neutral gas and ionize it instantaneously with a laser. The laser pulse must be short, shorter than λ_p. If the laser co-propagates together with the proton bunch, the fast creation of plasma inside the bunch has the same effect as a sharp leading edge of the bunch would have; it reliably seeds the self-modulation.

4. Injection and acceleration of the witness beam

The third challenge is a detailed understanding of the interactions of the proton bunch with the plasma to optimize the injection capture efficiency (maximize the size of the stable longitudinally focusing and accelerating phase-space "bucket") and properties (minimize the phase space volume) of the accelerated electrons. Theory and simulations show that the witness beam should not be injected before the self-modulation instability reaches saturation [13, 14]. The reason is the low phase velocity of the wake during the self-modulation linear growth stage. One might split the plasma cell in two parts: the proton bunch would self-modulate in the first part and witness particles could be injected into the second, accelerating plasma cell. Yet, injecting the witness bunch axially into the second plasma cell is technologically difficult. It is expected that the plasma density will not be uniform in the first centimetres behind the cell entry. The irregular wake in the plasma density gradient can easily scatter low energy ($10 - 20$ MeV) electrons foreseen from an injector.

The solution is the side injection of particles into the wake of an already modulated bunch [13, 24]. In this case, the witness electrons propagate at a small angle with respect to the driver and are gradually "sucked-in" at the right phase by the wake's transverse fields (see Figure 2). Simulations show that this leads to high quality quasi-

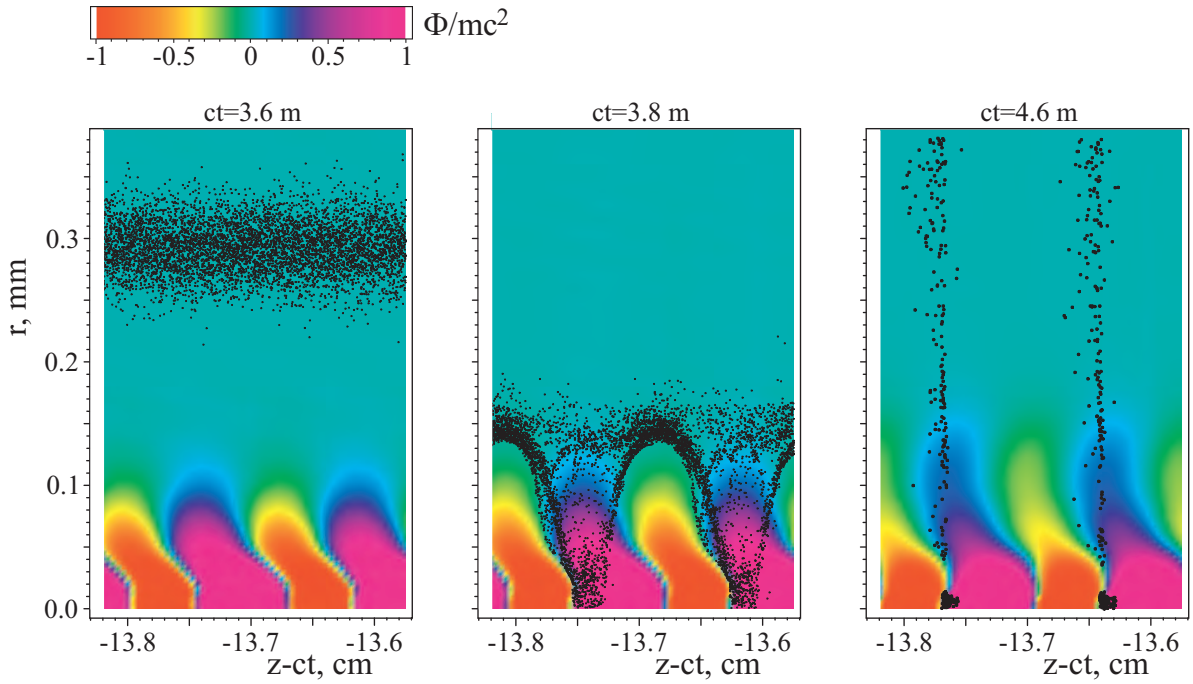

Figure 2. Maps of the wakefield potential at three positions along the plasma. The relative size of the wakefield potential is indicated by the colour map. At $z = 3.6$ m (left image), the low energy electrons (shown as black dots) are injected from the side, at an angle of 9 mrad, (top on the figure) towards the wakefield. At $z = 3.8$ m (middle image) the electrons have reached the wakefield potential wells, some are reflected while some reach the axis and can be trapped. At $z = 4.6$ m (right image), two trapped electron micro-bunches are visible near the axis ($r = 0$) and a few electrons are still drifting out radially.

monoenergetic acceleration of electrons.

To maximize the capture efficiency of externally injected electrons into the stable longitudinally focusing accelerating bucket, it will be necessary to have an electron injector with the flexibility of tuning the injection energy from 5 MeV to 20 MeV, as well as the capability to change the phase-space volume of the "cold" electron source (charge and emittance) in order to understand the dynamics of the plasma wakefield channel, electron capture and acceleration. Such flexibility is offered by a radio-frequency electron gun (RF gun) fitted with a laser-driven photocathode as the emitter.

5. AWAKE experiment at CERN

To address these challenges, the AWAKE experiment at CERN [25] will be the first proton-driven plasma wakefield experiment world-wide. The conceptual design of the proposed AWAKE experiment is shown in Figure 3: The laser and proton bunches are made co-linear. The laser ionizes the metal vapor in the first plasma section and seeds the self-modulation instability. The self-modulated proton bunch (shown in the left hand side inset) enters a second plasma section where it drives the plasma wakefield

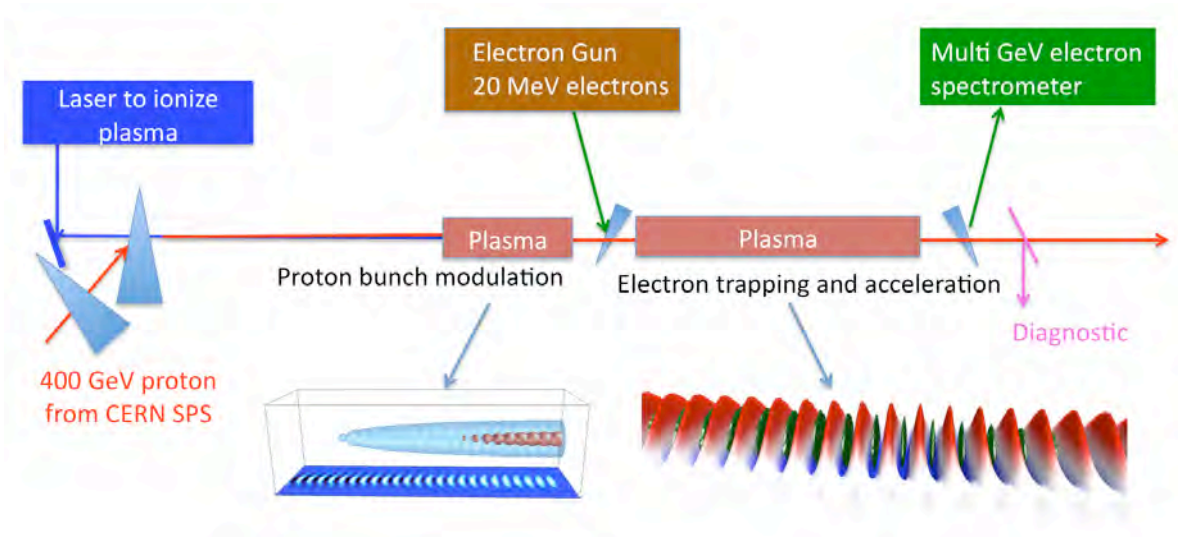

Figure 3. Conceptual design of the AWAKE experiment, showing the major sections and description of expected effects.

structure (shown in the right side inset). The electrons are injected in the wakefields and their multi-GeV energy is measured with an electron spectrometer.

The AWAKE experiment will be installed in the CERN Neutrinos to Gran Sasso (CNGS) facility [26]. A design of the experimental setup is shown in Figure 4. Nominally a proton bunch with intensity of the order of 3×10^{11} protons, a length of 12 cm and energy of 400 GeV is extracted every 30 s from the SPS and transported along more than 800 m of beam line towards the AWAKE experimental area that will be installed in the upstream part of the (previous) CNGS facility. The focused transverse beam-size at the plasma cell is $\sigma_r = 0.2$ mm and the transverse normalized emittance is $\epsilon_N = 3.5$ mm mrad. The laser beam is merged with the proton beam ~ 20 m upstream of the entrance of the plasma cell in a junction system. The area downstream of the plasma cell houses the beam diagnostics systems and the electron spectrometer. The proton beam will be dumped in the existing CNGS hadron stop, $\sim 1,000$ m downstream of the experimental area, thus avoiding any backscattering of particles and radiation into the AWAKE experimental area.

The plasma cell technology which best fulfills the requirements of the experiment is an alkali metal vapor source, as alkali metals have been used in previous experiments [27] and have low ionization potentials (e.g. 4.2 eV for the first electron of rubidium). The vapor is therefore relatively easy to ionize with a laser pulse, with the threshold intensity being as low as 1.7×10^{12} W/cm^2. Rubidium has a large ion mass, which makes the plasma less sensitive to ion motion [28].

Figure 5 shows an example of an electron bunch energy spectrum as obtained from numerical simulations using the simulation tool LCODE [29] for the side injection case and the nominal proton bunch parameters. A simulation of what would be seen on a scintillator screen in the electron spectrometer downstream of the plasma cell is also

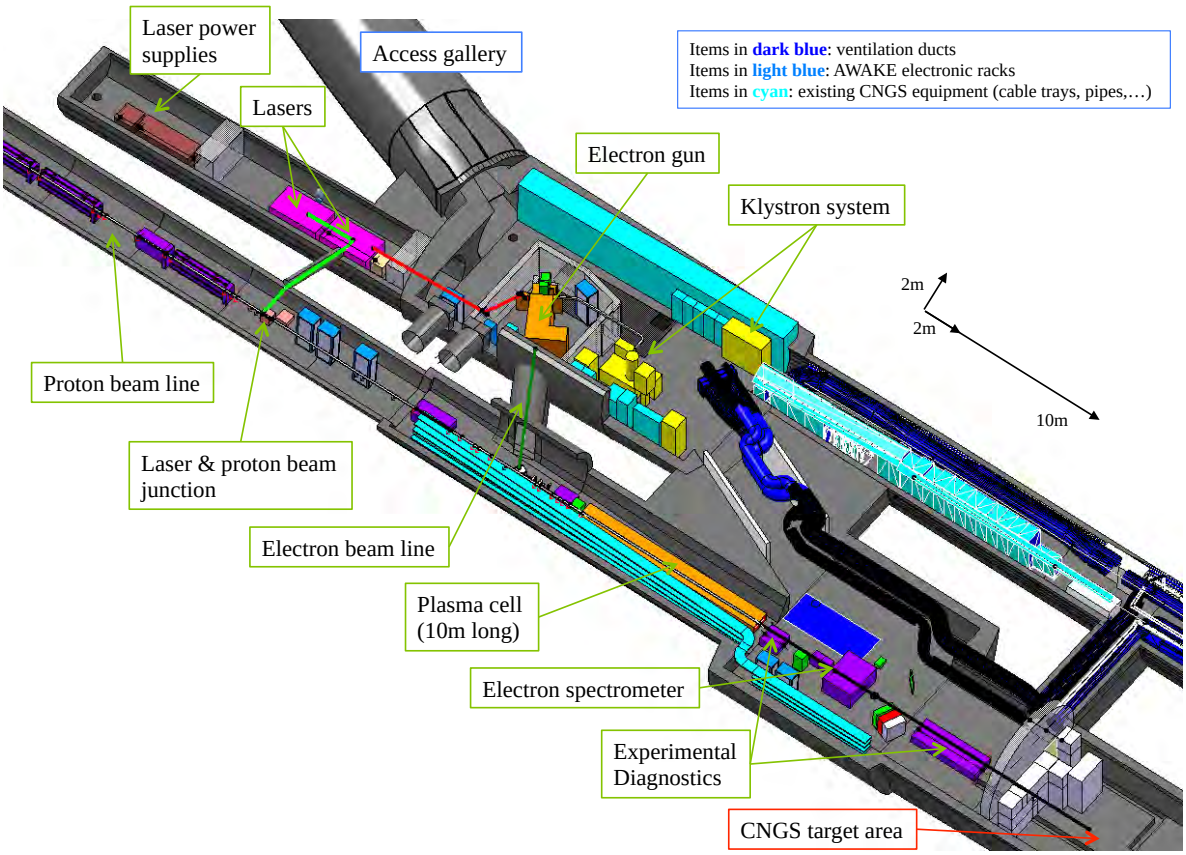

Figure 4. Design of the layout of the AWAKE experiment.

shown as well as the energy reconstructed from this spatial spread. Electron bunches of energy 16 MeV, charge 0.2 nC, and length $\sigma_{ze} = 2.5$ mm are side injected after 3.9 m of plasma. Approximately 5% of electrons are trapped and accelerated to the end of the 10 m plasma. This amount of charge is not high enough to observe beam loading, but sufficient to characterize accelerating gradients. The final energy spread is $\sim 2\%$ r.m.s., which can be accurately reconstructed by the electron spectrometer, indicating that percent level energy spread can be reached. The peak gradient seen in this simulation is above 1 GeV/m, and the average gradient witnessed by the electrons is 350 MeV/m.

In addition to the electron spectrometer, several other diagnostic systems will be used to characterize the beams and plasma so as to better understand the physics of self-modulation and acceleration of electrons in the wake of the proton beam [30]. Examples are shown in Figure 5c) in which a proton beam passes through a metal foil, thereby producing a cone of optical transition radiation that will be measured using a streak camera. Additionally, transverse coherent transition radiation will be produced and detected using electro-optical sensors; this will be the first experimental use of this recent concept [31].

First protons to the experiment are expected at the end of 2016 and this will be followed by an initial $3-4$ year experimental program of four periods of two weeks of

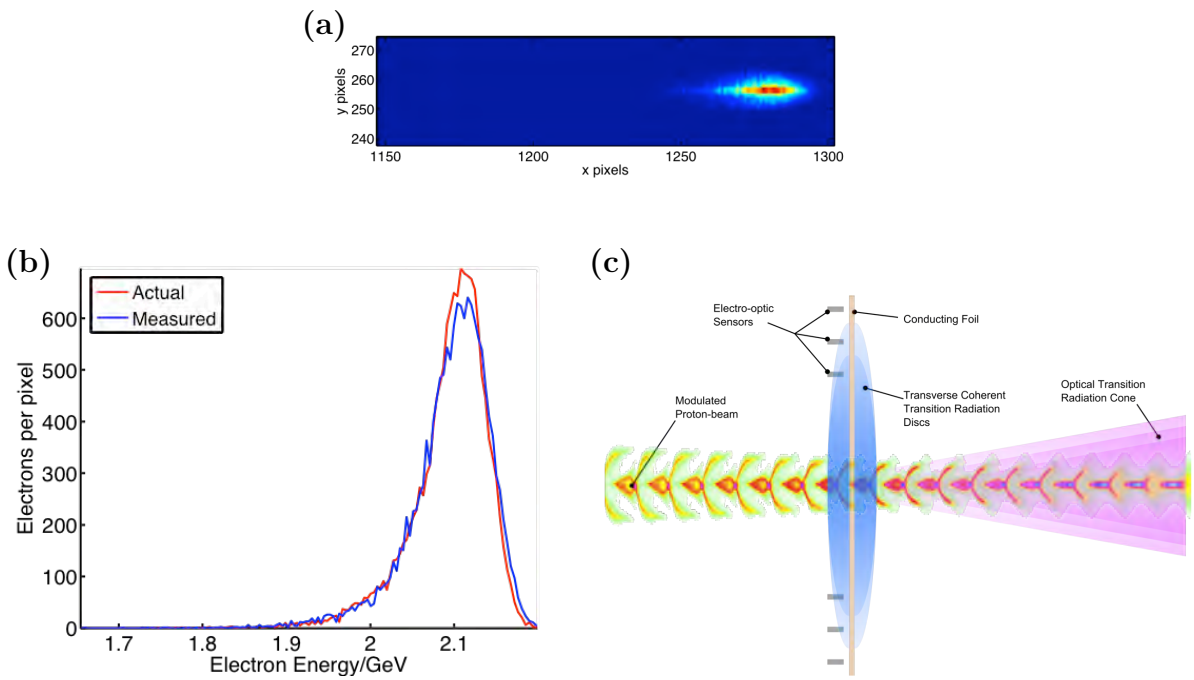

Figure 5. a) Simulated impact position of accelerated electrons on a scintillator screen having passed through a magnetic spectrometer. b) The electron energy spectrum reconstructed using the energy spectrometer (blue line) compared with the energy distribution exiting the plasma cell (red line). c) A modulated proton beam passing through a conducting foil, leading to transition radiation, detected using a streak camera and electro-optic sensors.

data taking.

6. Towards the TeV Frontier

The AWAKE experiment at CERN will test the principle of proton beam self-modulation in plasma and electron acceleration in the excited wake. However, the future use of proton-driven plasma wakefield acceleration as the energy-frontier technique requires additional research effort. The keys here are a scalable plasma source and shorter proton bunches.

Metal vapor plasma sources, ionized with lasers, routinely reach plasma densities of the order of $10^{17}\,\mathrm{cm}^{-3}$ but suffer from limitations of available laser power and are difficult to scale. A solution could be a helicon-wave plasma cell or discharge plasma cell that are potentially scalable in length over very long distances. These types of plasma cell follow a strictly modular concept although have a number of challenges such as density uniformity which are being addressed by an R&D program.

Shorter proton bunches will allow plasma wakes to be driven with either far fewer micro-bunches (via the SMI) or directly with an un-modulated bunch. This would dramatically reduce the uniformity requirements on the plasma, simplify the plasma cell technology, and improve the overall energy efficiency of the scheme [10]. Various

schemes within the current set-up of the CERN accelerators are being considered [32] as well as compression via magnetic chicanes [33] and the production of short proton bunches at source [34].

The results of the AWAKE experiment will inform future larger-scale R&D projects on proton-driven plasma wakefield acceleration and could lead to future high energy colliders for particle physics. Simulations have already shown [16] that electrons can be accelerated to the multi-TeV scale (e.g. 3 TeV after 4 km) using the 7 TeV LHC proton beam which is modulated prior to electron acceleration, following the scheme to be investigated by the AWAKE experiment. An alternative initial application is to provide the electron beam for the LHeC project [35] in which it is planned to collide a 50 GeV electron beam with the LHC proton beam. The SPS or LHC beams could be used to accelerate electrons using proton-driven plasma wakefield acceleration which are then used as the electron beam or as the injector to it. Some of the key issues in designing a compact electron–positron linear collider and an electron–proton collider based on existing CERN accelerator infrastructure have been identified [36].

7. Outlook

The AWAKE experiment at CERN will be the first proton-beam driven plasma wake field acceleration experiment worldwide. Its success will open a pathway towards a revolutionary plasma-based TeV lepton collider. This revolution will then enable groundbreaking particle physics discoveries.

Acknowledgments

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