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An ep collider based on proton-driven plasma wakefield acceleration

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Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. This scheme could lead to a future ep collider using the LHC for the proton beam and a compact electron accelerator of length 170 m, producing electrons of energy up to 100 GeV. The parameters of such a collider are discussed as well as conceptual layouts within the CERN accelerator complex. The physics of plasma wakefield acceleration will also be introduced, with the AWAKE experiment, a proof of principle demonstration of proton-driven plasma wakefield acceleration, briefly reviewed, as well as the physics possibilities of such an ep collider.

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1. Introduction

A high (TeV-scale) energy electron–proton collider would complement the proton–proton physics programme at the LHC and the planned electron–positron physics programme at the ILC. The rich physics programme of the Large Hadron–Electron Collider (LHeC) is given in detail elsewhere [1], with only a brief discussion given here. The cross section for Higgs production at LHeC is similar to that at the ILC and so with sufficiently high luminosity (10^{34} cm^{-2} s^{-1}), precise measurements of in particular the triple-gauge boson couplings can be made. Measurements of inclusive deep inelastic scattering at these high scales should allow a full flavour decomposition of the parton densities in the proton and eliminate assumptions currently used as well as significantly reducing the uncertainty on their determination, often a limiting factor in the search for exotic physics at the LHC. As well as considering the highest energy scales, the property of saturation at the very lowest Bjorken x values will be probed. At low x, the nuclear structure is very poorly known and so an eA physics programme will investigate an unmeasured region for $x < 0.01$.

In order to investigate such a wide-ranging physics programme of precision and potential discovery, the LHeC would use the 7 TeV proton beam from the LHC and requires a new electron accelerator with energies of about 60 GeV, giving a centre-of-mass energy of 1.3 TeV. To achieve such an electron energy, the favoured solution, based on conventional acceleration using radio frequency cavities, is a 9 km long “racetrack" complex. Such a large accelerator is needed due to the limitation in the maximum accelerating gradient to about 100 MV m^{-1} due to the onset of ionisation of the metal cavities. Given this size, it is sensible to look at alternative technologies which could significantly reduce the length of the electron accelerator. In these proceedings, such a technology, based on proton-driven plasma wakefield acceleration, is described. Plasma wakefield acceleration is a scheme originally proposed at the end of the 1970s [2] and is, in principle, applicable to all uses of accelerators and not just the LHeC. The use of proton-driven plasma wakefield acceleration has applications in general to the acceleration of particles to high energies [3] and so could also lead to a future e^+e^- machine of much reduced size.

2. Proton-driven plasma wakefield acceleration

Plasma wakefields occur when a drive beam, a laser pulse or particle beam, enters a plasma and disturbs the free electrons. In the case of a proton beam, the free electrons are attracted to the proton bunch, accelerate towards it, overshoot, are attracted back by the region of high positive charge density formed by the stationary ions, and hence form an oscillating system which creates large electric fields with an accelerating gradient in the direction of the incoming beam. In the case of a laser pulse or an electron bunch as the driver, accelerating gradients of up to 100 GV m^{-1} have been observed [4].

Given the limitations of the initial energies of the laser pulse or electron beam, multiple acceleration stages would be required in order to accelerate electrons to the scales required for energy frontier machines. As current proton beams have up to O(100) kJ of energy, the beam can propagate for long distances in a plasma and so act as a powerful driver of plasma wakefields. Simulations demonstrated that electrons could be accelerated from 10 GeV to 500 GeV in about 300 m of plasma using a proton beam of 1 TeV [5], with a maximum accelerating gradient of 3 GV m^{-1}.

3. The AWAKE experiment at CERN

The Advanced Wakefield (AWAKE) collaboration was formed to perform a proof-of-principle experiment at CERN, showing that protons can drive strong plasma wakefields and that these can be used to accelerate electrons, in an initial phase, up to the GeV-scale in under 10 m [6]. The AWAKE experiment will use the SPS beam with an energy of 400 GeV to drive the wakefields, however, in strong contrast to the concept of proton-driven plasma wakefield acceleration [5], where the beam length considered was $\sigma_z = 100\,\mu$m, the length of the SPS proton bunch is 12 cm. Given the strength of the wakefield generated is proportional to $1/\sigma_z^2$, the strength of the wakefield for the SPS beam is potentially very low. This is overcome by relying on the self-modulation instability (SMI) [8] in which transverse fields in the plasma split the long proton bunch into micro-bunches, spaced at the plasma wavelength. These higher densities act constructively to create wakefields with an accelerating gradient of about 1 GV/m. Witness electrons will be injected behind the proton bunch and a fraction of the electrons (up to 10% of the bunch) will be accelerated from about 16 MeV to about 2 GeV in 6 m of plasma.

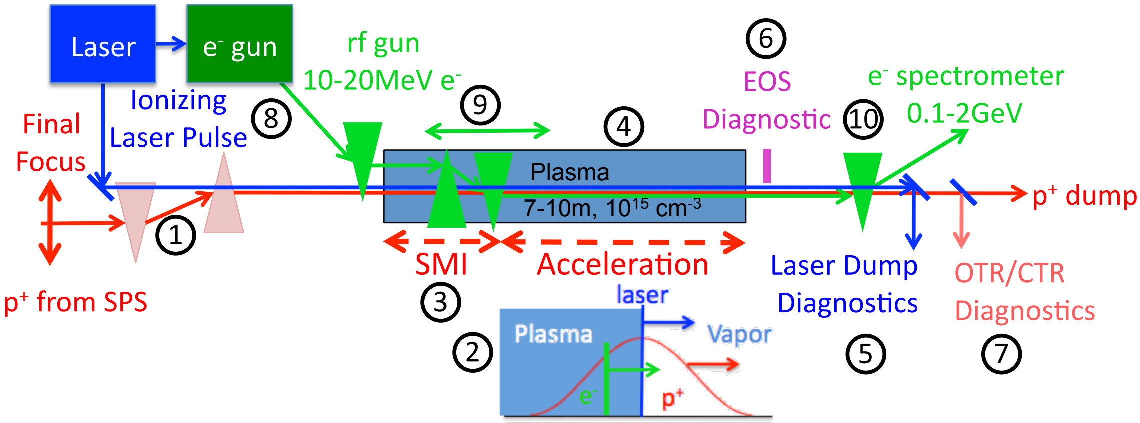

Figure 1: Baseline design of the AWAKE experiment: The proton bunch extracted from the SPS is injected with the ionising laser pulse (1). The laser pulse and the proton bunch travel together through the metal vapor cell. The co-propagating ionisation front shown in (2) provides the seeding of the SMI. Growth of the SMI and the resulting self-modulation of the proton bunch occurs over the first $3-5$ m of plasma (3). The modulated bunch resonantly drives wakefields over the remaining length of plasma (4). The laser pulse is dumped (5) and the proton bunch radial modulation is measured using electro-optical sampling (EOS) diagnostics (6) and optical transition radiation diagnostics (7). An RF-gun driven by a laser pulse derived from the ionizing laser produces a witness electron bunch (8). The electron bunch can be side-injected into the wakefield after the SMI has saturated (9). Downstream of the plasma, the electron bunch energy spectrum is measured using a broad acceptance magnetic spectrometer (10).

The AWAKE experiment will be housed in the CNGS facility at CERN. The general layout of the experiment is shown in Fig. 1. The proton beam propagates through a 10 m long plasma cell, excites the wakefield and becomes modulated by this wakefield. The short laser pulse propagates collinearly with the proton beam and serves the dual function of creating the plasma and seeding the SMI. The electron bunch enters the plasma cell parallel to the proton beam with an initial offset of about 1 cm and is merged into the wakefield several metres downstream as soon as the proton

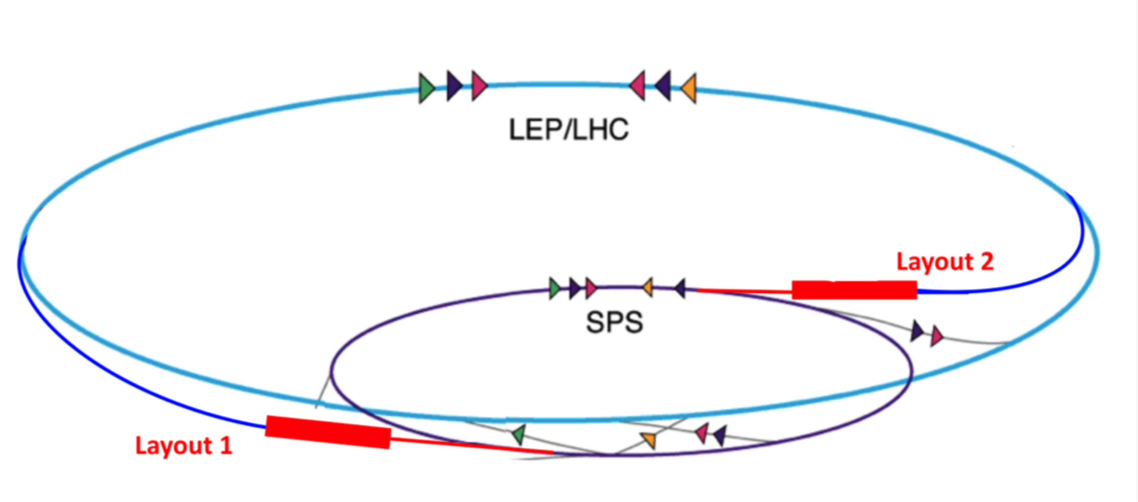

Figure 2: A schematic of a possible *ep* collider using the CERN accelerator complex and the SPS proton beam to drive plasma wakefield acceleration. Electrons would be accelerated in the wakefields and collide with protons in the LHC.

beam is modulated by the SMI. A configuration in which the electron beam is collinear with the proton beam is now considered the default mode of running and although a beam of lower energy and larger energy spread is expected, this mode will have a higher capture efficiency. Modulation of the proton beam radius is measured by electro-optical sampling (EOS) and optical and coherent transition radiation (OTR/CTR) diagnostics. The accelerated electron beam is characterised with a magnetic spectrometer.

4. An *ep* collider: design and issues

Assuming that the AWAKE experiment will demonstrate proton-driven plasma wakefield acceleration and that simulations correctly describe the physics of the process, application of the accelerator technology can be considered for a future *ep* collider. Aiming for similar energies to those proposed for the LHeC, a schematic of a possible *ep* collider is shown in Fig. 2. The SPS proton beam is used to drive the wakefield and accelerate a trailing electron bunch to 100 GeV in 170 m of plasma. These electrons then collide with the LHC proton beam, creating an *ep* mode which runs parasitically with the LHC proton–proton collisions. The basic sub-systems of the *ep* collider are: the transfer and matching of protons to the plasma section; the electron source; the plasma section; the beam delivery and final focus; and the beam dump and/or recycling. As this scheme utilises existing CERN infrastructure, there is the prospect of realising a high energy, cost-effective collider.

Although on the face of it this concept is very attractive, with a centre-of-mass energy of $\sqrt{s} = 1.67$ TeV achieved with the a relatively short new electron beam line, there are a number of issues and challenges to be overcome in order to make this realisable [3].

Phase slippage (or dephasing) occurs because there are particles travelling at different velocities and is a limiting factor of proton-driven plasma wakefield acceleration. For a velocity of the wakefield which is the velocity of the proton driver, γ_p and a velocity of the accelerating electrons,

γ_e, the value of γ_e can soon be greater than γ_p and so the electrons overrun the wakefield and hence dephase. The distance of the plasma accelerating section is therefore limited and for the SPS beam this is 170 m; for the LHC beam as the driver, due to the higher energy, it is about 4 km with electrons accelerated to 1 TeV. Such a scheme where the LHC is the drive beam can be used for an e^+e^- linear collider with collisions at the TeV energy scale.

The proton beam will at some point become too spread and will not be able to drive a strong wakefield. A way to compensate for this is to use external quadrupole magnets which will provide transverse focusing of the beam. Additionally, the wakefields themselves have a focusing component and this may be enough to guide the proton beam. Also given the highly relativistic nature of the proton beams, variations of the momentum spread will not be significant over the lengths being considered.

The witness electrons can scatter off the plasma ions or electrons. To assess this effect in detail, a model is being developed using a plasma simulation code and GEANT.

At AWAKE, the witness bunch will be electrons, but a similar controlled acceleration of positrons is necessary for a future linear collider, but also preferable at an *ep* collider where the possibility to change between an electron and positron beam allows the electroweak sector to be probed. Recent simulations have shown that a bunch of positrons can also be continuously accelerated to the TeV scale in a $\sim$ 1 km long plasma [9].

The luminosity of an *ep* machine is given by

$$\mathcal{L}_{ep} = \frac{P_e N_p \gamma_p}{4\pi E_e \varepsilon_p^N \beta_p^*} ,$$

where E_e is the electron beam energy, N_p is the number of particles in the proton bunch, ε_p^N is the normalised emittance of the proton beam, γ_p is the Lorentz factor and β_p^* is the beta function of the proton beam at the interaction point. The electron beam power, P_e, is given by

$$P_e = N_e E_e n_b f_{\rm rep} ,$$

where N_e is the number of particles in the electron bunch, n_b is the number of bunches in the linac pulse and $f_{\rm rep}$ is the repetition rate of the linac. Using the LHC beam parameters, $N_p = 1.15 \times 10^{11}$, $\gamma_p = 7460$, $\beta_p^* = 0.1$ m, $\varepsilon_p^N = 3.5\,\mu$m, and assuming electron beam parameters, $N_e = 1.15 \times 10^{10}$, $E_e = 100$ GeV, $n_b = 288$ and $f_{\rm rep} = 15$, gives a luminosity of, $\mathcal{L}_{ep} = 1 \times 10^{30}\,{\rm cm}^{-2}\,{\rm s}^{-1}$. This luminosity value is significantly below that of conventional LHeC designs and so raises the question as to whether this can be increased, by e.g. increasing the repetition rate or decreasing the size of the electron beam at the interaction point. Alternatively, physics at high energy, but lower luminosity should be considered. As plasma wakefield acceleration has clearly demonstrated high accelerating gradients, there are prospects for a future *ep* of e^+e^- collider at the high energy frontier, but possibly with reduced luminosity than can be achieved with RF acceleration. Brief studies have started [10] considering the physics that could be investigated at such colliders, such as classicalisation in electroweak and gravity, and should be further pursued.

5. Summary

The concept of proton-driven plasma wakefield acceleration and its application to a future *ep* facility has been presented. A proof-of-principle experiment, AWAKE, will start taking data in 2016 to demonstrate proton-driven plasma wakefield acceleration for the first time. Based on such a scheme, simulations show that the current CERN accelerator complex could be used to generate a 100 GeV electron beam in about 170 m and along with the LHC proton beam have *ep* collisions at a centre-of-mass energy of 1.67 TeV. Many challenges remain before such a collider could be realised, such as high luminosity and the acceleration of positrons, but further studies and the results of the AWAKE experiment will help to address these challenges.

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