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PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATION FOR HIGH-ENERGY LEPTON BEAMS

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Abstract

Future colliders with discovery potential for particle physics rely on increasing the parton centre of mass (pCM) energy, with the recent P5 report calling for a 10 TeV pCM collider. However, the development of such schemes using conventional accelerator technology would result in ever-larger facilities. High-gradient plasma wakefields driven by proton beams allow the transfer of energy to a witness bunch over a short length scale, and so offer a potential method to transform high-energy proton beams into high-energy lepton beams while requiring relatively little additional civil engineering.

The application of this concept to a Higgs factory driven by 400 GeV protons was recently proposed. In the present work, we discuss the ongoing efforts to address the challenges to realising such a scheme, and possible upgrade paths to particle physics applications beyond a Higgs factory.

INTRODUCTION

Plasma wakefield acceleration is a potential basis for future high-energy accelerators, due to the extremely high fields that plasma can support. A driver, either a charged particle beam or a laser pulse, excites a plasma wave which can be used to accelerate a witness bunch. However, even with the large gradients supported by plasma, an electron beam or a laser pulse does not have sufficient energy to drive wakefields over a sufficiently long distance for a witness bunch to reach the energy frontier. One approach is to make use of multiple acceleration stages, each with a fresh driver [1], but adequate coupling of the witness bunch between stages is technically challenging and remains unproven. The alternative is to make use of a proton driver [2], as proton beams with energies in the kilo- to mega-Joule range are already available at circular accelerator facilities across the world.

In order to generate a wakefield amplitude approaching the plasma wavebreaking limit $E_c = k_p mc^2/e$, with $1/k_p$ the plasma skin depth, c the vacuum speed of light, and m and $-e$ the electron charge and mass, the drive bunch should have a duration on the order of the plasma skin depth. In this way, a 500 μm driver should drive wakefields approaching 1 GV m^{-1}. However, currently available proton drivers typically have durations on the order of 5 cm, too long to drive a high gradient wakefield. One approach is to make use of plasma instabilities to modulate the beam into a train of microbunches [3], as successfully pursued by the AWAKE collaboration [4]. The ALiVE project (Advanced Linear accelerator for Very high Energies) seeks to develop an alternative approach based on the generation of short proton bunches suitable for future collider schemes, opening the path to the increased efficiency necessary for high luminosity. The use of a proton driver is attractive, as the accelerator facility to provide the drive beams could likely make use of existing infrastructure, reducing both the cost and carbon footprint of a future collider facility.

We here outline the physics of a wakefield accelerator based on a short proton drive beam, and detail some of the key challenges that must be overcome in order to realise such a facility [5]. We then discuss some of the potential physics applications at different energies which would exploit the synergies with the proton accelerator complex.

PROTON-DRIVEN WAKEFIELD ACCELERATION

As a short proton bunch propagates in plasma, it perturbs the local density of the plasma electrons, as shown in Fig. 1.

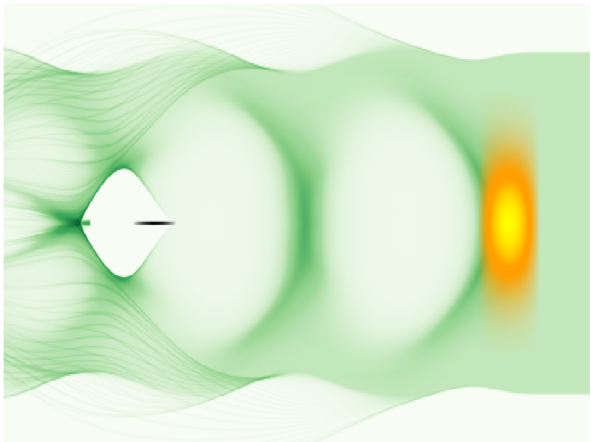


Figure 1: A short proton driver (yellow/orange), propagating to the right, excites a density wave of the plasma electrons (green). The associated wakefields can be used to accelerate a trailing witness, in this case an electron bunch (black), to high energy.

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The plasma electrons remain in motion after the passage of the drive bunch, leading to periodic oscillations of the plasma density. A witness bunch trailing the drive beam can be placed such that it suppresses the wakefield, gaining energy in the process.

The wakefields also provide strong transverse fields. In AWAKE, these fields are sufficient to modulate the 400 GeV proton beam over a few metres [6]. In order to avoid rapid pinching, a drive bunch with a tailored emittance profile can be used, with higher emittance towards the bunch tail, allowing stable propagation of the driver over sufficiently long distances to achieve the desired acceleration.

At high energy, dephasing between the driver and witness can limit the energy gain, as the low mass of the witness bunch means it begins to catch up with the driver. For a short driver, this can readily be remedied by tailoring the plasma density along the acceleration distance. A higher plasma density results in a shorter plasma skin depth, reducing the wavelength of the plasma oscillation. This allows the witness bunch to remain at a point of constant phase in the wakefields, even as the absolute distance between the witness and driver decreases [7].

Proof of principle simulations have been carried out for such a scheme using a 400 GeV drive beam, the same energy as used in the AWAKE experiment. By combining the above techniques, a drive bunch with a root-mean-square driver length of 150 μm and a population of 10^{11} protons was used to accelerate a witness bunch of 10^{10} electrons or positrons to 125 GeV in 200 m. Such beams would form the basis of a e^-e^+ Higgs factory [2].

However, such short proton bunches are not currently available. Furthermore, the repetition rate would need to be orders of magnitude higher than current proton accelerators in order to attain competitive luminosity for a Higgs factory. A suitable plasma source, with sufficent length and repetition rate, would need to be developed, as would techniques for the acceleration of high-quality beams. We address these issues in the next section.

KEY CHALLENGES

Proton Accelerator Complex

We assume that with moderate optimisation, for example by shaping the witness bunch current profile [8], bunches of 2×10^{10} electrons and positrons can be accelerated to 125 GeV. Assuming this energy gain can be achieved while maintaining a normalised emittance of ~ 100 nm (discussed in more detail below), and final-focus optics similar to the ILC or CLIC, a collision rate of at least 5 kHz would be required to reach a luminosity of ~ 10^{34} cm^{-2} s^{-1}. Bearing in mind that a proton driver is required for each arm of the collider every collision, this gives a required proton bunch extraction rate of ~ 10 kHz, with bunches alternately delivered for e^- and e^+ acceleration.

Recent developments in high-temperature superconductors [9] led to the renewed interest in short proton drivers, as a fast-ramping synchrotron could potentially deliver drive beams at a suitable rate. However, significant further development of this technology is still required before the mass production of suitable magnets could be envisaged. Recently, the ALiVE collaboration has been investigating fixed-field alternating gradient accelerators (FFAGs, also known as FFAs) as an alternative method to deliver proton bunches at a high constant rate. In this scheme, the guiding and focussing magnetic fields are fixed in time but vary radially, with the radius of the bunch orbit increasing during acceleration towards stronger magnetic fields [10]. Since each bunch follows the same path during acceleration, FFAGs are well suited to providing a continuous stream of bunches.

Initial investigations suggest that an FFAG is feasible as a source of suitable drive bunches [5], but an R&D program would be required to develop magnets with a suitable field profile, as well as a superconducting RF accelerating system with sufficiently high voltages to allow the creation of short bunches.

Plasma Source

In order to reach the energy frontier, a suitable plasma source is also required. Laser-ionized plasmas with a length of 10 m have been demonstrated in the context of the AWAKE project [6], but scaling to longer distances is challenging due to the required laser power. A discharge plasma source has also been demonstrated [11], with this technology having the benefit that a series of discharge plasmas could be added in sequence to reach the required length. The Run 2d of the AWAKE project will seek to demonstrate this technique [4].

The acceleration of collider-relevant bunches to high energy brings additional challenges, as the strong focussing fields from the plasma leads to witness bunches with an extremely tiny radius, and the resulting space charge could lead to secondary ionization of the plasma species, spoiling the witness quality. The development of new discharge technologies based on alkali vapour is therefore being pursued [5].

Witness Quality

In the absence of ion motion, control of the witness emittance is straightforward for an electron bunch. The witness rapidly drives its own "blowout" [12], a cavitated wake free of plasma electrons [13], as illustrated in Fig. 1. Within this region, the plasma ions provide a linear focussing field, allowing emittance to be conserved. Ion motion can become significant for low emittance beams at high energy [14], but initial studies suggest that self-matching of the witness bunch to the slow evolution of the focussing field can greatly reduce the emittance growth [15]. The plasma response can lead to emittance coupling between the transverse planes [16], meaning that plasma acceleration is most suited to the acceleration of round beams. The use of suitable final optics can be used to give a somewhat flattened beam at the interaction point, reducing disruption [5].

For positrons, the case is much more difficult, with focussing fields varying on the scale of the witness radius,

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resulting in deleterious emittance growth. The acceleration of positrons has been identified as one of the "grand challenges" of plasma-based acceleration [17], with several groups working towards possible solutions, typically based on structured plasmas [18].

BEYOND THE HIGGS

For the proton driver discussed for the Higgs factory [2], the acceleration length (and so the energy gain) is not limited by this initial energy spread, but the correlated energy spread which the driver develops as it loses energy to the wakefields it excites. Longitudinal dispersion leads to a lengthening of the drive bunch, reducing how effectively it can excite plasma wakefields.

The limitation imposed by dispersion naturally lends itself to higher energy drivers, with the stable acceleration length scaling as $\gamma_D^{3/2}$, with γ_D the energy of the driver. A number of other applications would become available at different witness energies. We here discuss two examples which capitalize on the synergies with the proton accelerator complex. Furthermore, both require only the acceleration of electrons in plasma, avoiding the challenges associated with positrons.

LEP3 Upgrade

LEP3 is a proposed e^+e^- Higgs factory which would be situated in the LHC tunnel [19]. Due to the radius of LHC main ring, the collider is envisaged as operating at energies up to 230 GeV, allowing detailed studies of the Z, W and Higgs bosons, but falling short of the $t - \bar{t}$ threshold. However, with a method to generate suitably energetic electron bunches, an asymmetric collider scheme could be envisaged, allowing higher energies to be accessed. With 115 GeV positrons from the LHC tunnel, electrons at 290 GeV would be required to operate at a centre-of-mass collision energy 365 GeV, allowing the $t - \bar{t}$ threshold to be studied.

Since LEP3 would not require the SPS tunnel at CERN, this could potentially be refitted to provide suitable proton drive bunches. Scaling from the preliminary study of the proton-driven Higgs factory [2], which used 400 GeV protons to accelerate electrons and positrons to 125 GeV, 290 GeV electrons should be possible with a 700 GeV proton driver. We note that this energy is rather high to be feasible within the SPS tunnel, which currently accelerates protons to 450 GeV for injection into the LHC. However, further optimisation of the acceleration scheme should allow a reduction in the driver energy. Since only electrons are required, a more nonlinear plasma wake can be tolerated than in the original study which required the acceleration of both electrons and positrons. This may provide a path towards decreasing the required driver energy.

e-P/A Collider

An electron acceleration scheme based on PDPWA would allow for much higher center-of-mass energy collisions for e-P/A collisions than ring-based schemes. We previously discussed AWAKE-like schemes of modulating long proton bunches [20] and using the modulated proton bunch to drive the plasma wakefield. Using short proton bunches where additionally high repetition rates could be achieved, as discussed for the Higgs Factory above, leads to much higher luminosities. The accelerated electrons would be collided, e.g., with LHC protons and ions to produce very high energy eP and eA collisions. An FFA scheme is expected to yield short proton bunches of 10^{11} protons/bunch. We have evaluated an $E_p \simeq 550$ GeV per proton scheme at a rate of $\simeq 20$ kHz which would be possible from a re-use of the SPS tunnel. With protons of this energy, we expect that bunches of $2 \cdot 10^{10}$ electrons can be accelerated up to $E_e \simeq 250$ GeV in a plasma section, yielding $E_{\mathrm{cm}} \simeq 2650$ GeV for collisions with LHC protons. The emittance of electron bunches will be adequate such as to allow a match of the bunch transverse dimensions to the proton bunch size at the IP. Using the proton bunch parameters from the LHeC studies, a luminosity of 10^{32} cm^{-2}s^{-1} will be possible. The kinematic range that will become available for DIS experiments using the SPS as proton drive beam will be extended by approximately two orders of magnitude relative to HERA. If eventually also the LHC tunnel can be used to house the proton driver accelerator, considerably higher final lepton energies will be available, and CoM energies of $E_{\mathrm{cm}} = 9000$ GeV can be reached [20]. As an example, Fig. 2 shows an evaluation of the reach for photon-proton cross section measurements.

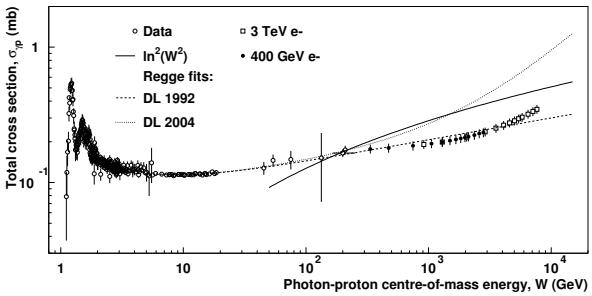


Figure 2: Total photon-proton cross section for different centre-of-mass energies, comparing existing data, analytical models, and energy ranges that would become available by colliding 7 TeV protons with electrons with energy up to 400 GeV and 3 TeV.

CONCLUSIONS AND OUTLOOK

Recent developments in high-temperature superconductors have re-ignited interest in the use of short proton bunches as drivers for wakefield acceleration. Significant progress has been made in a relatively short period or time, with a preliminary study on a Higgs factory [2], and the development of the ideas necessary to support such a facility and on the scaling to higher energies [5]. The use of a proton driver also opens several possibilities for particle physics programmes exploiting synergies with the proton accelerator complex. Significant challenges to the realisation of this technique remain, but the potential physics reach motives the continuing efforts to find solutions to these challenges.

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