A FULL-ENERGY ELECTRON INJECTOR FOR THE EIC BASED ON PROTON-DRIVEN PLASMA-WAKEFIELD ACCELERATION

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Abstract

The Electron-Ion Collider (EIC) is presently under construction at Brookhaven National Laboratory, and will collide electrons with an energy of up to 18 GeV with hadrons of up to 275 GeV. In this work we evaluate the feasibility of using proton-driven plasma wakefield acceleration (PWFA) to accelerate electron bunches to full energy for injection into the EIC Electron Storage Ring. Particle-in-cell simulations are used to identify a scheme which allows the acceleration of electron bunches with high charge and low energy spread, building on previous studies which investigated the potential energy gain.

The RHIC "BLUE RING", which accelerates hadrons in the same direction as the electrons of the EIC, can be exploited to drive the plasma wakefields, offering the potential to significantly reduce the capital cost of the EIC facility. We show that by increasing bunch population to 3×10^{11}, and moderate compression of the drive bunch to 2.5 cm, high accelerating fields can be achieved by exploiting the self-modulation of the proton beam, as harnessed by the Advanced Wakefield Experiment (AWAKE) project at CERN. To facilitate the use of a plasma discharge, we consider the possibility of using different ions, instead of rubidium.

INTRODUCTION

The Electron-Ion Collider (EIC) is a new collider which is planned to be built at Brookhaven National Laboratory, and will re-use some infrastructure of the existing Relativistic Heavy Ion Collider (RHIC) [1]. Currently, RHIC is composed of two ion accelerator/storage rings. The construction of the EIC would involve adding an electron accelerator ring, which would allow collisions between electrons with energy up to 18 GeV and protons with energy up to 275 GeV. This addition would involve significant changes to the layout of the collider, which will be expensive to complete. To offer a lower-cost alternative, this work investigates the feasibility of proton-driven plasma wakefield accelerator for injection of electron bunches into the EIC electron storage ring. The scheme is based on technology developed at the AWAKE experiment at CERN [2], and investigated using LCODE particle-in-cell simulations [3].

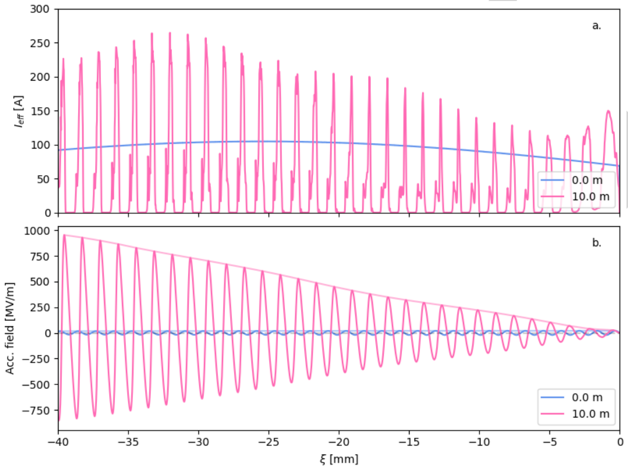

Figure 1: a) Effective current of the drive beam, b) the associated longitudinal wakefields, with the envelopes of the field shown. Both are pictured as the beam first enters the plasma (blue) and after 10 m after the start of the plasma (red).

PROTON-DRIVEN PWFA

This scheme is based on the planned design for Run 2c of AWAKE at CERN [4]. AWAKE is a proof-of-concept accelerator facility, which uses a proton bunch from the CERN Super Proton Synchrotron (SPS) to drive wakefields in plasma. Plasma can support high fields, and therefore has the potential to significantly reduce the length of linear accelerators [5,6]. Using a proton driver has the significant advantage of higher driver energy compared to electron or laser drivers [7].

Most often, the bunch used as the driver in a plasma wakefield accelerator is shorter than the plasma wavelength. Using a short bunch is preferable, and other studies have investigated the use of a short proton bunch as a driver [8]. For injection into a storage ring, considered in the present work, high average current from the injector is not required, and so it may be possible to avoid significant compression of the proton bunch, greatly reducing the cost. While it is possible to increase the plasma wavelength, such that the length of the bunch is comparable to it, it is undesirable, as it decreases the maximum fields the plasma can sustain [9].

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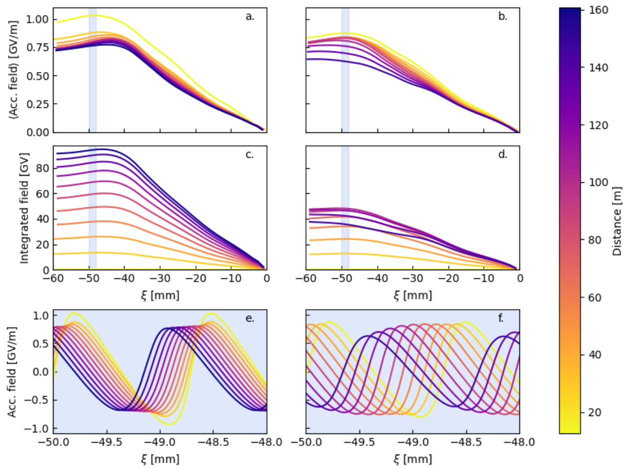

Figure 2: Figure shows the evolution of wakefield for different propagation distances. Instantaneous wakefield envelopes (a. and b.), summed longitudinal wakefields (c. and d.), and instantaneous wakefields for a short range of lengths along the beam (e. and f.) in the accelerating cell. An example of a field envelope is also shown in Fig. 1b. Figures a., c., e. show fields for drive beam with energy 400 GeV, and b., d., f. for drive beam with energy 275 GeV.

One option to overcome this limitation is to make use of Self Modulation (SM) of the bunch in plasma [10], illustrated in Fig. 1a. This is the case in AWAKE, which uses a bunch with length of 2.5 cm to 5 cm, in plasma with wavelength $\approx$ 1 mm. When the bunch passes through plasma it drives both longitudinal and transverse wakefields. The transverse wakefields act on the bunch to periodically focus and defocus it, creating a train of "microbunches", separated by the plasma wavelength, which resonantly drive wakefields with increasing amplitude, as seen in Fig. 1b. The wakefields after 10 m of bunch propagation in plasma are significantly higher than those immediately after the beginning of the plasma.

The SM process described above takes place within the first 10 m of the plasma. Numerical simulations show that placing small, positive plasma density step during the SM process prevents fast decay of the wakefield amplitude, and allows a high accelerating gradient to be sustained over a longer distance than in uniform plasma [11]. The modulated beam then propagates through a 30 cm gap into a second cell, where it excites wakefields in which the electrons can be accelerated. The plasma is separated into two cells to allow electrons to be injected into the accelerator on-axis.

SCALING AWAKE

The drive beam in AWAKE Run 2c is planned to be a 400 GeV proton bunch, with population 3×10^{11}, and length down to 85 ps ($\approx$ 2.5 cm). The EIC proton bunches have energy 275 GeV, bunch population of 6.9×10^{10}, and length $\approx$ 200 ps (6 cm) [12]. To avoid lengthy optimisation, we assume the population and bunch length used in AWAKE could be achieved in the EIC, and the other parameters were kept the same.

As the energy of the proton bunch in the EIC is 18 GeV, the bunch will modulate more quickly than in the AWAKE case. As mentioned above, the first cell includes a positive plasma density step, which helps preserve high wakefield amplitude. The position and height of the step was optimised for the parameter set for AWAKE Run 2c [13], so the position of the optimised step was scaled to match the energy of the proton beam, by a factor of $\sqrt{\gamma}$, with γ being the Lorentz factor [14].

DEPHASING

The accelerating fields in the second cell (between 10 m and 160 m) can be seen in Fig. 2. The instantaneous accelerating fields along the plasma show very little change in the case of the 400 GeV beam (Fig. 2a). In the case of the 275 GeV beam (Fig. 2b) the field amplitude drops by 30 % over 150 m of plasma. This is due to the lower energy of the drive beam. As it loses a larger fraction of its total energy during propagation, its ability to drive wakefields will reduce over the plasma propagation length.

To evaluate the suitability of the wakefields for acceleration, the integrated fields at different plasma propagation distances are considered. They are the sum of all fields up to a given propagation distance, and are a metric for possible energy gain. While the real energy gain of an electron bunch will be lower due to beam loading [15], they are useful for finding the set of parameters where the energy gain would be the highest.

The integrated fields for the 400 GeV beam increase over the entire length of propagation and reach a maximum of $\approx$ 100 GV (Fig. 2c). However, the integrated wakefields for the 275 GeV beam reach only 50 GV (Fig. 2d), which is much lower than the instantaneous wakefield over the same distance would suggest. Additionally, they reach a maximum after 100 m instead of increasing continuously. This is caused by dephasing, as the phase velocity of the wakefields is lower than the velocity of an electron injected into them.

Electrons injected into the wakefields rapidly become strongly relativistic, and remain at a fixed point in the co-moving frame $\xi = z - ct$. The proton driver, and therefore the wakefields which it excites, are slower than the electron bunch. This effect can be seen in Fig. 2e and 2f, where the peak of the wakefields shifts backwards by 0.5 mm and 1 mm respectively, while the amplitude of the field remains high (as also seen in Fig. 2a and 2b). Due to this an electron bunch which would initially experience an accelerating field will eventually start experiencing a decelerating one as it propagates through the plasma, and after a certain plasma length the amount by which the fields dephased prevents further energy gain. As a result, the length of acceleration is limited by the dephasing. This can be seen in Fig. 2d, where the optimal length for second plasma cell in this case is shown to be 90 m.

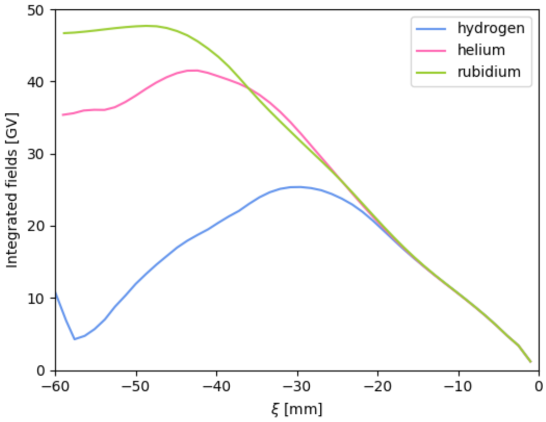

Figure 3: Sum of accelerating wakefields in the second cell up to 100 m from the start of the plasma for hydrogen, helium and rubidium plasma.

IMPACT OF ION MASS

AWAKE Run 2c will use laser-ionised rubidium [2], which limits the possible length of the accelerating cell. Using a discharge plasma would offer the option of using longer accelerating distances, which limits the choice of gases in the source, as some are better suited for the purpose than others [16]. Additionally, plasma has a shorter recovery time when using lighter ions, opening the possibility of operating at a higher repetition rate [17].

However, ion motion can suppress SM. This suppression increases with decreasing ion mass [18]. The effect of the ion mass on the cumulative fields was therefore investigated. The results are shown in Fig. 3, where hydrogen, helium and rubidium plasmas were used. It can be seen that helium plasma offers integrated fields 14 % lower than Rb, while offering significantly better recovery times. Additionally, it would be easier to extend the length of the plasma, which would result in a higher energy gain, despite lower integrated fields here.

CONCLUSION

The feasibility of an electron acceleration scheme for the EIC based on Run 2c of the Advanced Wakefield Experiment (AWAKE) is considered, and simulations of proton-driven plasma wakefield acceleration were conducted. The results show significant integrated accelerating fields can be achieved using the proton beam from the EIC as the driver. These results motivate full acceleration simulations, which include the effects of beam loading, and allow the evaluation of the electron-bunch charge that could be accelerated. The effect of using different plasmas is also considered. Results suggest that the instantaneous fields that can be achieved using helium plasma are comparable to those in rubidium. Using helium plasma would be preferable due to a larger possible acceleration length and increased repetition rate.

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