TOWARDS AWAKE APPLICATIONS: ELECTRON BEAM ACCELERATION IN A PROTON DRIVEN PLASMA WAKE*

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Abstract

The first phases of the AWAKE experiment will study the wake structure and the potential for electron acceleration in a self-modulated proton driver. In AWAKE Run 2, expected to start after the LHC Long Shut Down 2, electron beam acceleration will be studied. Using a single proton driver and a long acceleration stage, an electron bunch will be accelerated to high energies. Demonstrating beam quality preservation and scalable plasma sources will be a significant step towards using proton driven plasma for applications. We report on the plans and preparations for AWAKE Run 2.

INTRODUCTION

In AWAKE [1,2] the first proton driven plasma wakefield acceleration (PD-PWFA) experiment worldwide, a CERN SPS bunch will drive a plasma wake in a Rubidium plasma with density 7×10^{14} cm^{-3}. The proton bunch, being much longer than the plasma wavelength, will self-modulate [3] generating a train of micro-bunches resonantly driving a strong wakefield. The goal of Phase I of experiments starting towards the end of 2016 [4,5] is to understand the physics of the self-modulation instability, by measuring the effect of the plasma on the proton beam [2]. In Phase II starting towards the end of 2017 the accelerating wakefields will be probed with externally injected electrons [2]. Phase II lasts until the long shutdown 2 of LHC. AWAKE Run 2 will start in 2021, after the shutdown. Many PWFA applications require high-quality electron beams accelerated to high energies. During Run 2 of the AWAKE experiment we aim to demonstrate acceleration of a beam of electrons, and to develop solutions for scaling up the experiment to parameters interesting for applications. A potential application considered is a low-luminosity electron-proton (e- p+) collider, where an electron bunch driven by an SPS or LHC bunch collides with a second LHC bunch [6]. Electron energies similar to those of LHeC (60-100 GeV) [7] could be reachable by using an SPS bunch as driver, while using an LHC bunch as driver could potentially yield electron energies up to TeV [8].

The AWAKE experiment is installed in the tunnel previously used for the CNGS experiment [9]. The available space puts some constraints on Run 2 upgrades. The proton beam line cannot be extended more than $\gtrsim 10$ m until the tunnel containing activated material from CNGS is reached. The space for electron injection is limited to about 5 m beam line. While this is enough to host the injector for Phase II, the space available for Run 2 upgrades is limited. After successful Run 2 proof-of-principle demonstrations, scaled up versions of the experiment could be installed in a new location, geographically compatible with a first PD-PWFA e- p+ collider.

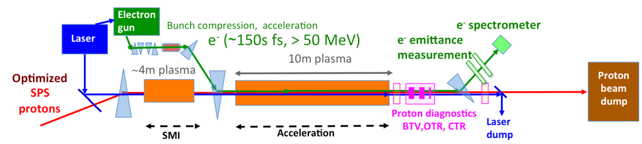

Figure 1: Possible layout for AWAKE Run 2. The proton beam is micro-bunched in the first plasma stage. An electron beam is accelerated in the second plasma stage.

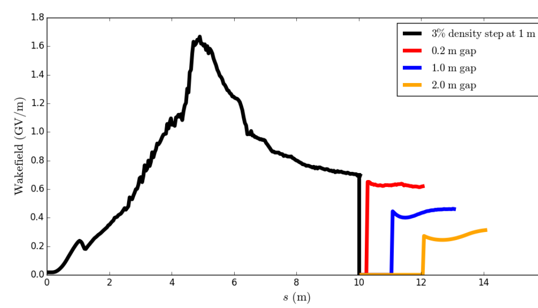

Figure 2: The effect of a plasma interstage on the wakefield amplitude, as function of interstage length, assuming no focusing optics in the interstage. After 1 m of vacuum interstage, the wakefield gradient has decreased by about a factor two.

STAGING

While the self-modulation instability grows and the proton micro-bunches develop, the wakefields change phase rapidly with respect to the beam. The phase change is estimated to about $\sim \lambda_p/8$, before the phase stabilizes after about four meters [10]. Two plasma stages are therefore foreseen for Run 2, a ~4 m plasma stage in which the proton beam self-modulates, followed by electron beam injection in an interstage region, followed by a ~10 m plasma stage which accelerates the injected beam at a stable phase. Figure 1 shows a possible layout for the two stages. Inside the plasma, the proton beam is strongly focused. During vacuum

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propagation between the cells, the beam therefore expands rapidly. Depending on the length of the interstage, the wake may be significantly weaker in the second stage, unless the proton beam is refocused into this stage. The reduction in gradient as function of interstage length is shown in Figure 2. Re-focusing using a triplet built from SPS-type quadrupoles would require about 140 m of beam line. Scaling the magnet aperture down and the gradient up could give shorter interstage lengths. Preliminary estimates indicates that an interstage of about 20 m might be feasible. Another option could be an interstage short enough that refocusing is not necessary. According to Figure 2, an interstage length of 1 m gives a reduction of the gradient of about 50%, which may be acceptable. Whether it is possible to inject an electron beam in a 1 m gap needs to be further studied.

PRELIMINARY TARGET PARAMETERS

For a demonstration of electron beam acceleration, the following quantities are of importance: accelerating gradient, total energy gain, amount of charge accelerated, final energy spread, final emittance and shot-to-shot stability. We here suggest target parameters for Run 2. Some parameters are guided by a potential first applications, some are guided by constraints of the plasma acceleration process. PD-PWFA should demonstrate beam acceleration with a gradient of >0.5 GV/m, much higher than for CLIC. In a 10-20 m plasma cell, the corresponding energy gain would be >10 GeV. Successful demonstration, combined with a solution to scale up the experiment, would demonstrate the potential of high-gradient acceleration. An energy spread of a few percent and a final normalized emittance of $\lesssim 10$ μm may be sufficiently small for an e- p+ collider application [7]. If this level of beam quality could be demonstrated, it would be a significant step towards applications. The e- p+ collider luminosity is proportional to the amount of electron charge accelerated, so charge should be maximized. In a plasma accelerator, the peak current, the energy spread and the emittance of the accelerated beam are related; in order to accelerate a beam with low energy spread, the beam current must be adjusted to load the wakefield correctly. Although beam loading has been studied for the linear regime [11] and the blow-out regime [12], it is not known how to optimally load the resonant wake of a self-modulated proton driver. Studies of this are on-going in the AWAKE collaboration [13]. Preliminary beam loading study results are shown in Figure 3. They indicate that a $\sigma_z = 40$–60 μm long bunch, with peak current of 200–400 A, corresponding to 67–200 pC bunch charge, result in reasonable beam loading and relatively low energy spread. The injection energy should be high enough that the phase slip $L_{\text{plasma}}/\gamma_i\gamma_f \ll \sigma_z$, is small; at least 50 MeV. With the above considerations, in Table 1 we suggest a set of preliminary Run 2 electron beam target parameters, as a guideline for further work.

Table 1: Preliminary Run 2 Electron Beam Target Parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

ELECTRON INJECTOR

For Phase II an S-band gun with an S-band accelerating structure will be used [14], generating a long ($\sigma_z \sim \lambda_p$) electron beam with sub-nC charge, energy of ~16 MV/m and an emittance of ~2 μm. In order to meet the target parameters in Table 1 this beam should be compressed by a factor ~10 and the energy increased by a factor ~3. The Phase II injector occupies most of the available space, and neither the required bunch compression nor the energy increase is possible with S-band technology without enlarging the injector area.

X-band technology is more compact than S-band, and accelerating structures of ~100 MV/m have been proven [6]. Replacing the S-band booster structure with an X-band structure, easily provides ≥50 MeV electrons. X-band gun R&D has been performed at SLAC [15]. According to [15, 16] replacing the S-band gun with an X-band gun, and using an

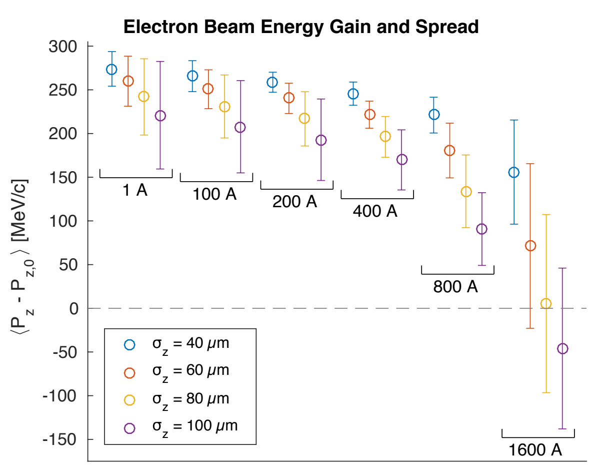

Figure 3: Preliminary beam loading studies [13], showing the energy gain and spread (the error bar) for electron bunches of different lengths and peak currents, accelerated in a pre-modulated proton wake. The results indicate that a peak current of 200–400 A optimally loads the wake for bunch lengths of 40–60 μm.

X-band booster structure, Table 1 bunch lengths and emittances may be reached for peak currents close to the requirements. A solution more comfortably producing the target peak current could include a second X-band structure as a velocity buncher. In principle these three X-band components could be powered by a single klystron with phase shifters and power dividers. A disadvantage of X-band is the four times higher demands on phase stability with respect to S-band. The feasibility of using an X-band gun for AWAKE should be studied in more detail, including understanding the lessons learned from the SLAC gun [15].

Laser wakefield accelerators (LWFA) today routinely produce very short (fs), high current (kA), high-energy (GeV) electron beams. Based on experimental scalings, a ~40 TW laser system is needed to produce ~100 MeV electron beams. The shot-to-shot stability of LWFA is not as good as for RF guns. Following initial studies [17], more detailed investigations on how to utilize a state-of-the-art LWFA system as a Run 2 electron injector, are planned.

An alternative to external injection (all of the above) is to inject charge directly inside the plasma. One method is ionization injection where electrons are ionized and trapped inside the plasma wake [18]. Since these electrons are injected at the accelerating phase of the wake, tolerances on timing jitter and plasma density variations are eased [19]. A disadvantage is that bunch parameters at injection are not observable. It may therefore be challenging to separate eventual problems arising in the injection process from eventual problems in the acceleration process. While we plan to study ionization injection further, we currently consider this as a mechanism that will be tested in addition to an external injector.

PLASMA SOURCES

A single LHC proton bunches is energetic enough to accelerate an electron or positron bunch to TeV-energies [8]. Using a single plasma stage, which would have to be ~km long, is advantageous since defocusing and re-focusing of beams between plasma cells may be necessary. Focusing optics would drive down the effective gradient of a plasma accelerator [20]. The tolerances on density variation along the plasma cell are tight, estimated to $\delta n_{\mathrm{max}} \sim 0.25/N$ [19] where N is the number of driving micro-bunches, order of 100 for AWAKE. For AWAKE Phase I and II, a 10 m Rubidium vapor cell, ionized with a 5 TW Ti:Sa laser, will be used as plasmas source. The measured temperature stability is better than 0.2%, fulfilling the density variation requirements. In order to extend the length of such the Rubidium vapor cell significantly, additional ionization laser systems are needed, which are expensive, and need to be coupled into new cells, necessarily creating gaps in the plasma. Long, or easily scaleable plasma sources with this small density variation are currently not available. Therefore, the development of scalable plasma sources is part of the AWAKE Collaboration efforts.

A Helicon plasma source prototype has been developed within the AWAKE collaboration [21]. The plasma is generated by a Helicon RF wave, driven by external antennas. The length is readily extended by adding RF antennas longitudinally, with no interruption in the plasma. No ionization laser is needed. Plasma densities of 7×10^{14} cm^{-3} have been demonstrated [22]. The spatial and temporal density uniformity is still relatively far from the requirements. Further technical development is planned to improve the uniformity.

A prototype discharge plasma source, where plasma is generated by sending a high current pulse through a gas, has been developed for AWAKE at Imperial College London. The maximum cell length is probably limited to some 10s of meters. Density uniformity tolerances will be challenging to fulfill. The effect of the discharge current on the beam must be further studied. However, this technology is very simple and cost effective and also planned to be further studied within the AWAKE collaboration.

For the first phases of Run 2, Rubidium vapor sources could be used, while the technology development for more scalable sources continues in parallel. The Rubidium cell from Phase I could be re-used as the second stage for Run 2. A new, shorter Rubidium cell, with possibilities for a flexible density profiles, would then be added as the first plasma stage.

LONGER TERM UPGRADES

When the proton bunch is micro-bunched by self-modulation, the larger part of the charge does not contribute to building up the wakefield; protons are instead defocused or accelerated. By optimally bunching the proton beam longitudinally instead, a much larger part of the charge would drive the wakefield. Longitudinal modulation could be achieved by energy modulating the beam at the bunching frequency, by about 0.5 GeV, followed by magnetic compression. Since the plasma wavelengths of interest are mm-scale, the RF frequency for the modulation needs to be of order 100 GHz. Accelerator technology at this frequency is currently at the R&D stage, and to build a mm-wavelength 0.5 GeV linac is out of the scope for Run 2, however, this could be an option for later AWAKE runs.

SUMMARY

Plans for AWAKE Run 2 are underway. A two-stage experiment is considered. The proton beam is fully bunched by the self-modulation instability in the first stage. An electron bunch, optimized for beam loading, is injected between two plasma stages. S-band, X-band, LWFA and ionization-based injectors are being studied. Plasma source technology that scales well to long lengths is being developed. Very strict tolerances on plasma density variations are a challenge for the plasma source development.

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