High energy physics applications of the AWAKE acceleration scheme[1]

The use of proton bunches to drive plasma wakefields has the potential to accelerate particles to high energies in one acceleration stage and in significantly shorter distances than is possible in conventional RF accelerators. The AWAKE experiment at CERN [1] is a proof-of-principle project investigating proton-driven plasma wakefield acceleration and the possible high energy particle physics experiments this could enable. In AWAKE's Run 1, the experiment successfully demonstrated the seeded self-modulation of the proton bunch [2] in which the long proton bunch was split into many micro-bunches which then acted as the wakefield driver. Electron bunches were externally injected into the wake and accelerated from 19 MeV to 2 GeV in under 10 m [3]. The AWAKE collaboration is now embarking on a new R&D programme ("Run 2") [4] in which higher energy acceleration is achieved and emittance preservation of the electron bunch is maintained as well as pursuing the development of scalable plasma sources.

Based on the success of AWAKE so far, several possible applications of proton-driven plasma wakefield acceleration have been proposed and are here discussed [5, 6]. The possibilities include experiments to search for dark photons, to investigate QCD in multi-TeV-scale deep inelastic scattering (DIS), as well as a possible electron injector for the electron–ion collider (EIC). Electron beam energies of about 50 GeV, in which the SPS is used as the proton drive beam, are discussed here and could be possible after the completion of AWAKE Run 2. The possibility of TeV scale electron energies, in which the LHC protons are used as the drive beam is also discussed. All experiments which are applications of the AWAKE scheme have particle physics goals that are new and unique. Although primarily discussing proton drivers to accelerate electron bunches, other ion drivers could also be considered and the acceleration of muons for a muon collider is also a possibility and merits further investigation.

Search for dark photons. Dark photons are postulated particles which could provide the link to a dark or hidden sector of particles, with several experiments investigating their possibility. The NA64 experiment at CERN has the unique feature of using electrons up to 100 GeV from the secondary beams and the AWAKE scheme promises similar high energy. AWAKE expects to produce bunches of electrons rather than electrons via single extraction and so a different experimental setup will be required although similarities with NA64 are also present. Simulations show that with 10^{16} electrons on target and with an initial energy of 50 GeV, an AWAKE beam will allow searches for dark photons up to higher masses than is currently possible at NA64 and will be competitive with other proposed experiments [7]. Assuming 1 TeV electrons, the sensitivity extends up to dark photon masses of almost 1 GeV at couplings of 10^{-4}, into a large region uncovered by any current or proposed experiment.

Strong field quantum electrodynamics. The collision of a high-energy electron bunch with a high-power laser pulse creates a situation where QED is poorly tested, namely in the strong-field regime. In the regime around the Schwinger critical field, $\sim 1.3 \times 10^{18}$ V/m, QED becomes non-linear and these values have so far never been achieved in controlled experiments in the laboratory. Investigation of this regime could lead to a better understanding of where strong fields occur naturally such as on the surface of neutron stars, at a black hole's event horizon or in atomic physics. The E144 experiment at SLAC investigated electron–laser

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collisions in the 1990s using bunches of electrons, each of energy about 50 GeV, but due to the limitations of the laser, they did not reach the Schwinger critical field in the rest frame of the electrons. With the advances in laser technology over the last 20 years, these strong fields are now in reach. However, the current highest-energy bunches of electrons of high charge are delivered by the European XFEL at 17.5 GeV and the AWAKE scheme has the possibility to provide a higher-energy electron beam which would then be more sensitive to the e^+e^- pair production process and probe a different kinematic regime.

High-energy electron–proton collisions. Using the LHC proton bunches as wakefield driver, electrons of 3 TeV or more would be available, allowing for fixed-target experiments in the EIC energy range. An *ep* collider, using the LHC proton beams to collide with electrons accelerated to 50 GeV (SPS driver) or 3 TeV (LHC driver) would reach centre-of-mass energies of 1.2 TeV and 9.2 TeV, respectively. The latter, the very high energy electron–proton (VHEeP) collider [8], in particular, would access a new region of QCD where little is know about the nature of the strong force. Even though the luminosity would be modest ($10^{29}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), regions at low proton momentum fraction, x, would still be measured to high precision. In this region, saturation of the cross section is expected to occur and valuable insight into the fundamental underlying physics at the heart of the high energy dependence of hadronic cross sections should be gained. Such high energies would also yield sensitivity to new physics such as leptoquarks.

A compact electron injector using the RHIC-EIC proton beam. The RHIC proton beam is of similar energy and intensity to the SPS proton beam used at AWAKE. Proton bunches at the EIC will be of significantly smaller spatial extent than the SPS proton bunches and can hence drive higher wakefields than currently observed or planned at AWAKE. Simulations have shown [6] that electron bunches could be accelerated to the required EIC energy of 18 GeV in only 16 m of plasma, with the potential that this can be significantly shortened by introduction of an optimised plasma density step. This would allow electrons to be injected at full energy into the EIC. Not only does this show a potential direct application of the AWAKE scheme to the EIC, it also demonstrates that the RHIC proton bunch has excellent characteristics for development of proton-driven plasma wakefield acceleration.

In summary, the AWAKE scheme of proton-driven plasma wakefield acceleration could lead to new particle physics experiments within this decade. The AWAKE facility itself could be extended for fixed-target experiments and ideas of including a collider within the CERN infrastructure have been put forward [8, 9]. Simulations show that the RHIC proton beam can also drive strong wakefields and could be utilised for further R&D or experimentation.

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