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Particle physics experiments based on the AWAKE acceleration scheme

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New particle acceleration schemes open up exciting opportunities, potentially providing more compact or higher-energy accelerators. The AWAKE experiment at CERN is currently taking data to establish the method of proton-driven plasma wakefield acceleration. A second phase aims to demonstrate that bunches of about 10^9 electrons can be accelerated to high energy, preserving emittance and that the process is scalable with length. With this, an electron beam of $\mathcal{O}(50 \text{ GeV})$ could be available for new fixed-target or beam-dump experiments searching for the hidden sector, like dark photons. The rate of electrons on target could be increased by a factor of more than 1000 compared to currently available, leading to a corresponding increase in sensitivity to new physics. Such a beam could also be brought into collision with a high-power laser and thereby probe the completely unmeasured region of strong fields at values of the Schwinger critical field. An ultimate goal is to produce an electron beam of $\mathcal{O}(3 \text{ TeV})$ and collide with an LHC proton beam. This very high energy electron–proton collider would probe a new regime in which the structure of matter is completely unknown.

1. Introduction

The Standard Model of particle physics [1–4] is amazingly successful in describing the fundamental particles of nature and their interactions. It has been built up over 50 years of experimentation and theoretical development with the prediction [5–10] and discovery [11,12] of the Higgs boson being the latest compelling success. The Standard Model provides predictions and can describe a wide range of phenomena, some to tremendous precision and/or covering a huge kinematic range.

However, there is still much unexplained for which new experiments are needed. Examples of some of the big questions in particle physics are: Why is there so much matter compared to anti-matter in the Universe? What is the nature of dark matter (and dark energy)? Can we unify the forces? What is the fundamental structure of matter? These and other areas of particle physics have often relied on the use of high-energy particle beams and colliders to resolve and push back the boundaries of our knowledge. The discovery of the Higgs boson, mentioned in the previous paragraph, is one of the latest examples of how particle colliders have been key in elucidating the biggest questions in particle physics.

In the 1960s, electron–positron colliders had a centre-of-mass energy of about 1 GeV and in the 30 years up to LEP II, in the 1990s, the centre-of-mass energy increased up to about 200 GeV. A similar increase was also obtained for hadron colliders, culminating in the Large Hadron Collider (LHC) [13] which collided protons at a centre-of-mass energy of 13 TeV for the first time in 2015. Future electron–positron colliders up to and beyond the TeV scale, such as at the International Linear Collider (ILC) [14] or Compact Linear Collider (CLIC) [15], will extend to 30 – 50 km. The use of RF cavities in conventional accelerators, which are limited to accelerating gradients of at most 100 MV/m, means that increased energy such as the ILC or CLIC requires increased lengths. In order to reduce the length of future colliders, novel acceleration techniques are required in which significantly higher accelerating gradients are obtained.

Plasma wakefield acceleration [16–20] is one such technique that could lead to shorter or higher-energy accelerators. Pioneering experiments have shown that an intense laser pulse [21–24] or electron bunch [25,26] traversing a plasma, drives electric fields of 10s GV/m and above. A recent paper [27] has demonstrated acceleration up to 7.8 GeV using a laser driver in tens of centimetres of plasma. A limitation of laser pulses and electron bunches is their low stored energy, which motivates the use of multiple stages to reach very high energies [20,28]. Given the high stored energies possible in proton bunches, this scheme provides the possibility to accelerate electrons to high energy in one stage [29] and so is well suited to high-energy physics applications. However, plasma wakefield acceleration has a number of challenges to overcome: a high repetition rate and a high number of particles per bunch is needed so as to maximise luminosity; likewise, the bunch spatial extent needs to be small (nm scale) to maximise the luminosity; and the production of beams needs to be efficient and highly reproducible. The ultimate goal of plasma wakefield acceleration is then to have high-quality electron beams at the TeV scale produced over the km length scale.

The advanced wakefield (AWAKE) experiment [30–33] has already demonstrated that protons can drive plasma wakes [34,35] and that electrons can be accelerated to high energies [36] (see Section 2 for more details on the AWAKE experiment). Given this, it is appropriate to think of first, realistic applications of the AWAKE scheme of proton-driven plasma wakefield acceleration. In having an ultimate goal of generating high-quality TeV electron beams, this document considers applications of beams of lower energy and less stringent demands on the quality, whilst making strong use of the current CERN infrastructure. In doing this, the technology will be tested and should enable the ultimate aims to be achieved faster, whilst doing experiments that have a novel and exciting particle physics programme.

This paper is organised as follows. The AWAKE experiment, its results and plans are briefly given in Section 2 to outline how the scheme will mature towards a useable technology. The main body of the paper, Section 3, outlines possible particle physics experiments that could be realised using the AWAKE scheme, some on timescales of within the next 10 years. Some possibilities are just stated, with the more promising possibilities discussed in more detail. The ideas are then briefly summarised in Section 4.

2. An AWAKE-like beam for particle physics experiments

The AWAKE experiment is a proof-of-principle project, approved by CERN in 2013, to demonstrate proton-driven plasma wakefield acceleration for the first time. A special extraction

of the Super Proton Synchrotron (SPS) provides bunches of 400 GeV protons, containing a charge of about 3×10^{11} protons, up to every 7 sec to the experimental area. Experimentation started in 2016 and continued in 2017 in which the proton bunch was injected into a rubidium vapour plasma source (with density, $n_{pe} = (1 - 10) \times 10^{14} \text{ cm}^{-3}$). Given the length of the SPS proton bunches, $\mathcal{O}(10 \text{ cm})$, the experiment relies on the self-modulation effect which splits the long proton bunch into shorter higher density micro-bunches, spaced by the plasma wavelength. The micro-bunching of the protons was seen in the first data-taking period and the effect has recently been published [35]. The effect of self-modulation also leads to the transverse expulsion of protons, which was also measured in the first data-taking period as an expanded beam halo downstream of the plasma cell and also recently published [34]. At the end of 2017 and during 2018, experiments were performed in which an external bunch of electrons were injected in the wake of the proton beam and accelerated. At low plasma densities, clear and consistent signals of accelerated electrons were seen at energies around 500 – 800 MeV; at higher densities, the number of electrons accelerated was smaller, but acceleration up to 2 GeV was observed [36]. These results [37] demonstrate proton-driven plasma wakefield acceleration for the first time and motivate further experimentation to develop the AWAKE scheme as a useable acceleration technique.

The AWAKE Run 1 programme finished in November 2018, at which point the CERN accelerator complex shut down for two years for upgrade and maintenance. The SPS will start up again in 2021 and run for four years until 2024 and an ambitious AWAKE Run 2 programme is being developed for this period. The final goal by the end of AWAKE Run 2 is to be in a position to use the AWAKE scheme for particle physics experiments. In order to achieve this, the aims of AWAKE Run 2 are to have high-charge bunches of electrons accelerated to high energy, about 10 GeV, maintaining beam quality through the plasma and showing that the process is scalable. The parameters are summarised in Table 1 [38]. This will require development of the initial electron source, beam and plasma diagnostics as well as development of the plasma technology which can fulfil these ambitious goals.

Table 1. Preliminary AWAKE Run 2 electron beam parameters.

Parameter	Value
Accelerating gradient	$> 0.5 \text{ GV/m}$
Energy gain	10 GeV
Injection energy	$\gtrsim 50 \text{ MeV}$
Bunch length (rms)	40 – 60 μm
Peak current	200 – 400 A
Bunch charge	67 – 200 pC
Final energy spread	few %
Final emittance	$\lesssim 10 \mu\text{m}$

3. Possible particle physics experiments

A high-energy electron beam with high-charge bunches from tens of GeV up to TeV energies has many potential applications. Three are outlined in detail in the following sub-sections, but other possibilities are briefly discussed here. A condition of any application is that the particle physics goals must be new, interesting and do something not done elsewhere. An oft mooted application of plasma wakefield acceleration is the development of a high energy, high luminosity linear e^+e^- collider. However, such a collider is a challenge for conventional accelerators and so to have this as the first application of plasma wakefield acceleration is ambitious. Hence, the approach taken here is to consider experiments, such as fixed-target experiments and an electron–proton collider,

which have less stringent requirements on the quality of the beam. A natural progression would be to build such accelerators before attempting to develop a high energy, high luminosity linear e^+e^- collider. In this way, the accelerator technology can be developed whilst still carrying out cutting-edge particle physics.

A high-energy electron beam could be used as a test-beam facility for either detector or accelerator studies. There are not many such facilities world-wide and they are often over-subscribed. The characteristics of the electron beam which would make it rather distinct is the high energy which can be varied; a pure electron beam with low hadronic backgrounds; a high bunch charge; and longitudinally short bunches. These properties may not be ideal or will be challenging for detector studies which usually rely on single particles. However, as an accelerator test facility the bunched structure and flexibility in energy will be useful properties.

A natural avenue of study with a high-energy electron beam is the deep inelastic scattering of electrons off protons or ions in order to study the fundamental structure of matter [39]. The simplest experimental configuration is where a lepton beam impinges on a fixed target and many such experiments have been performed in the past. So far only one lepton–hadron collider, HERA [40], has been built. Potential physics that could be studied at a future deep inelastic scattering experiment are to measure the structure of the proton at high momentum fraction of the struck parton in the proton, which could be valuable for the LHC, and to understand the spin structure of the nucleon, which is still poorly known [41]. A thorough survey of previous as well as planned experiments must be carried out to assess the potential of a deep inelastic scattering fixed-target experiment based on a high-energy electron beam ($\mathcal{O}(50)$ GeV) from AWAKE.

(a) Experiment to measure strong-field QED at the Schwinger critical field

The theory of electromagnetic interactions, quantum electrodynamics (QED), has been studied and tested in numerous reactions, over a wide kinematic range and often to tremendous precision. 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, $E_{\text{crit}} \sim 1.3 \times 10^{18}$ V/m, QED becomes non-linear and these values have so far never been achieved in controlled experiments in the laboratory. Even with modern high-power lasers, the fields are still well below the Schwinger critical field. However, in combination with a high electron energy beam the critical field can be reached where an invariant $\chi = E'/E_{\text{crit}}$, characterises this. Here the electric field of the laser, E , is modified in the electron's rest frame to $E' = \gamma_e E$, where γ_e is the relativistic factor of the electrons, relating energy and mass. 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.

In the presence of strong fields, rather than the simple $2 \rightarrow 2$ particle scattering, e.g. $e^- + \gamma \rightarrow e^- + \gamma$, multi-particle absorption in the initial state is possible, e.g. $e^- + n\gamma \rightarrow e^- + \gamma$, where n is an integer (see Fig. 1). Therefore an electron interacts with multiple photons in the laser pulse and a photon can also interact with multiple photons in the laser pulse to produce an e^+e^- pair, also shown in Fig. 1. For more details on the processes and physics, see a recent review [42]. The different regions are characterised by the invariant, $\xi = eE/m_e\omega$ where e is the magnitude of the electron's charge, m_e is the mass of the electron and ω is the laser frequency. For values $\xi \ll 1$, the fields are weak and the processes proceed via single-photon scattering on an electron, i.e. in the perturbative regime. As ξ approaches and exceeds unity, multi-photon absorption processes become possible.

The E144 experiment [43] at SLAC investigated electron–laser 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, i.e. χ was less than one. They did, however, reach values of ξ close to unity and so observed multi-photon absorption processes. With the advances in laser technology over the last 20 years, these strong fields ($\chi > 1$) are now in reach [44]. The current highest-energy electrons are delivered by the European XFEL at 17.5 GeV and the AWAKE

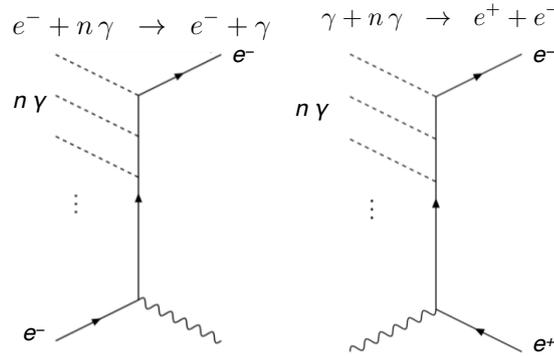


Figure 1. A Feynman diagram representation of (a) Compton scattering of an electron and (b) production of an e^+e^- pair in the field of a high-power laser in which absorption of multiple photons has taken place.

scheme has the possibility to provide a higher-energy electron beam which would then be more sensitive to the e^+e^- pair production process, with a higher value of χ , thereby probing a different kinematic regime.

(b) Experiment to search for the dark sector

Dark photons [45–47] are postulated particles which could provide the link to a dark or hidden sector of particles. This hidden sector could explain a number of issues in particle physics, not least of which is that they are candidates for dark matter which is expected to make up about 80% of known matter in the Universe. Dark photons are expected to have low masses (sub-GeV) and couple only weakly to the Standard Model particles and so would have not been seen in previous experiments. The dark photon, labelled A' , is a light vector boson which results from a spontaneously broken new gauge symmetry and kinetically mixes with the photon and couples to the electromagnetic current with strength $\epsilon \ll 1$. Recently, experimental and theoretical interest in the hidden sector has increased and is discussed in recent reviews on the subject [48,49].

A common approach to search for dark photons is through the interaction of an electron with a target in which the dark photon is produced and subsequently decays. This process is shown in Fig. 2 in which the dark photon decays to an e^+e^- pair. The NA64 experiment is already searching for dark photons using high-energy electrons on a target [50–52], initially measuring the dark photon decaying to dark matter particles (“invisible mode”) and so leaving a signature of missing energy in the detector. Although high-energy electrons of 100 GeV are used, a limitation of the experiment is the rate of electrons is below about 10^6 electrons per second as they are produced in secondary interactions of the SPS proton beam.

The NA64 experiment is already making significant progress investigating new regions of phase space for dark photons and as shown in Fig. 3 will cover much new ground in the $\epsilon - m_{A'}$ plane. Given the limitations of the number of electrons on target, the AWAKE acceleration scheme could make a real impact as the number of electrons is expected to be several orders of magnitude higher. Assuming a bunch of 10^9 electrons produced every 5 s and a running period of 3 months gives 10^{15} electrons on target and this along with a range of other values is shown in Fig. 3. Further studies are ongoing and a higher number of electrons on target should be possible depending on the SPS injection scheme as well as the success of AWAKE in accelerating bunches of electrons. The extra electrons on target provide extra reach into an unexplored region in the $\epsilon - m_{A'}$ plane.

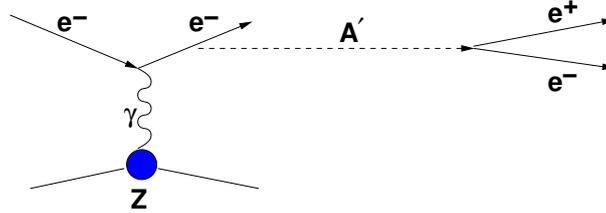


Figure 2. A representation of the production of a dark photon, A' , in a fixed-target experiment with an electron beam. The dark photon subsequently decays to an e^+e^- pair.

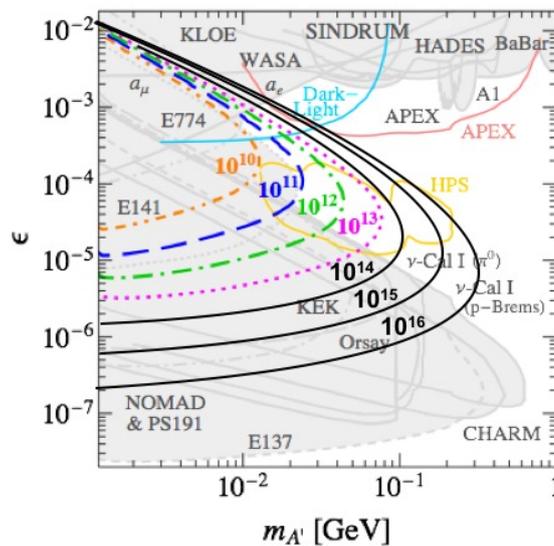


Figure 3. Limits on dark photon production decaying to an e^+e^- pair in terms of the mixing strength, ϵ and dark photon photon mass, $m_{A'}$, from previous measurements (light grey shading). The expected sensitivity for the NA64 experiment is shown for a range of electrons on target, $10^{10} - 10^{13}$. Rough estimates are also shown for $10^{14} - 10^{16}$ electrons on target which could be provided to an NA64-like experiment by a future AWAKE accelerator scheme.

More detailed work is also ongoing to provide more robust estimates of the sensitivity as well as the ultimate number of electrons on target. A crucial difference to NA64's current set-up is that AWAKE produces short bunches of high charge. This is one reason why the decay to e^+e^- pairs is considered rather than the invisible mode. Other channels such as the decay to a $\mu^+\mu^-$ pair should also be considered. Other aspects which need to be studied are optimising the experimental set up, re-assessing the backgrounds, particularly given the higher number of electrons on target, and considering the optimal beam energy.

(c) High-energy electron–proton/ion colliders

A high-energy electron–proton/ion (ep/eA) facility could be the first application of plasma wakefield acceleration to particle colliders. In such collisions, the electron generally emits a photon of virtuality Q^2 and strikes a parton carrying a fraction, x , of the proton's momentum. The higher the Q^2 , the smaller the probe and hence the more detailed structure can be seen; also low values of x probe low momentum particles and hence the dynamic structure of quark and gluon radiation within the proton. As such, ep/eA collisions provide a detailed picture of the

fundamental structure of matter and investigates the strong force of nature and its description embodied within quantum chromodynamics (QCD). Some of the open issues to be investigated in ep/eA collisions are: when does this rich structure of gluon and quark radiation stop or "saturate" as it surely must otherwise cross sections would become infinite; in general, the nature of high-energy hadronic cross sections; and is there further substructure or are partons fundamental point-like objects.

Such an ep collider would be more easily achieved than a high-luminosity, high-energy e^+e^- collider for a number of reasons: the proton bunches used in collisions are available in the CERN accelerator complex; an ep machine could make use of positrons, as well as electrons, although this is not absolutely necessary; electron bunches of small transverse extent (nm-scale) are not necessary as the proton bunches are at the micron-scale; and certain processes and kinematic regions in ep physics do not require high luminosity and so the physics case is still strong at low luminosity values. Initial collider designs [53] considered generating electron bunches via the AWAKE scheme with electrons up to about 100 GeV. This has been formulated into the PEPIC (Plasma Electron-Proton/Ion Collider) project in which the SPS protons are used to drive wakefields and accelerate electrons to about 50 GeV which then collide with LHC protons. This would have essentially the same energy reach as the LHeC project [54], but with luminosities several orders of magnitude lower. As such, it would focus on studies of the structure of matter and QCD, in particular at low values of x where the event rate is high.

Plasma simulations have shown the the LHC proton bunches can be used as a drive beam and accelerating gradients of just under 1 GV/m are possible for long distances, leading to the possibility of accelerating electrons up to 6 TeV in under 10 km [55]. Such values are unrealistic with conventional RF accelerators. Given these promising results, a very high energy electron-proton (VHEeP) [56] collider has been proposed in which LHC bunches are used to drive wakefields and accelerate electrons to 3 TeV in under 4 km, which then collide with the counter-propagating proton (or ion) bunch, creating electron-proton collisions at centre-of-mass energies, \sqrt{s} , of over 9 TeV. The energies of the electrons could be varied, although the distance of 4 km fits comfortably within the circumference of LHC ring, so although there maybe an upper energy limit, lower energies should be achievable. Such centre-of-mass energies represent a factor of 30 increase compared to HERA which allows an extension to low x and to high Q^2 of a factor of 1000. The luminosity is currently estimated to be around $10^{28} - 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ which would lead to an integrated luminosity of 1 pb^{-1} per year. Different schemes to improve this value are being considered such as squeezing the proton (and electron) bunches, multiple interaction points, etc. However, even at these modest luminosities, such a high-energy electron-proton collider has a strong physics case.

The physics potential of VHEeP was discussed in the original publication [56] and discussed further at a dedicated workshop [57] on the subject. An example and updated result is shown in Fig. 4, in which the total γp cross section is shown versus the photon-proton centre-of-mass energy, W . This is a measurement which relies on only a modest luminosity and will be dominated by systematic uncertainties. As can be seen from the expected VHEeP data, the measurement is extended to energies well beyond the current data, into a region where the dependency of the cross section is not known. Some models are also shown and they clearly differ from each other at the high energies achievable at VHEeP. These data could also be useful in understanding more about cosmic-ray physics as such collisions correspond to a 20 PeV photon on a fixed target.

Several other possible measurements were presented in the original paper [56] in which the current theories of QCD are completely inadequate and where this new collider will significantly constrain our understanding of the fundamental structure of matter. As for Fig. 4, cross sections must at some point stop rising and cannot be arbitrarily large at high energies. Exactly when a different behaviour will occur is not easy to predict, but there are strong indications that VHEeP energies will be sufficient to observe changes in several cross-section measurements such as the production of vector mesons and the inclusive γp and $\gamma^* p$ cross sections. The theory of hadronic

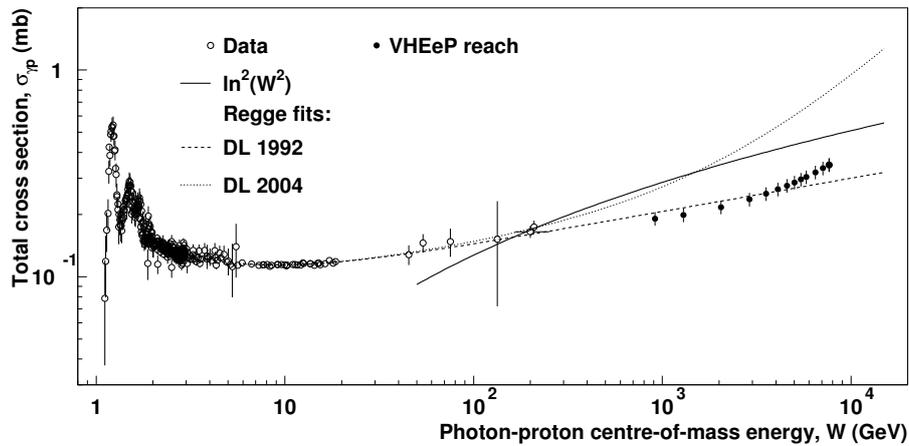


Figure 4. Total γp cross section versus photon–proton centre-of-mass energy, W , shown for data compared to various models [58–60]. The data is taken from the PDG [61], with references to the original papers given therein. The highest VHEeP data point is shown at $y = 0.7$ (where $y = W^2/s$); the cross section at this point is assumed to be double the ZEUS value. The other VHEeP points assume different values of y down to 0.01 and are plotted on a straight line (linear in W) between the ZEUS and highest VHEeP point. All VHEeP points have the same uncertainty as the ZEUS point: a systematic uncertainty of 7.5% and a negligible statistical uncertainty. The ZEUS measurement is at $\sqrt{s} = 209$ GeV and used a luminosity of 49 nb^{-1} . This result has been updated from the original paper [56] with the addition of newly-calculated points for VHEeP.

interactions at high energies and the nature of QCD and structure of matter was also extensively discussed at the dedicated workshop on the subject [57].

At the very highest Q^2 values, searches for high energy phenomenon beyond the Standard Model will be possible. Higher luminosities will allow a comprehensive search to complement those at the LHC; however, even with modest luminosities, some specific processes can be investigated with higher sensitivity at VHEeP than at the LHC. As an example, the production of leptoquarks, which would be produced on mass shell, is possible up to the kinematic limit of the centre-of-mass energy, i.e. 9 TeV. Other examples of physics that could be investigated at VHEeP were presented and discussed at the workshop [57]. It was discussed how high-energy ep collisions are sensitive to new descriptions and general theories of particle interactions [62] as well as having connections with black holes and gravity [63].

4. Summary

The AWAKE collaboration has during 2018 successfully demonstrated proton-driven plasma wakefield acceleration for the first time. A programme of R&D is being developed to be able to apply this scheme as a useable accelerator technology, hence the emphasis is the use of the CERN proton accelerators to drive wakefields and in general how this can fit into the CERN infrastructure. Given this, realistic applications of particle physics experiments are being considered, most notably: the investigation of QED in strong fields; a beam-dump experiment to search for dark photons; and an electron–proton collider at the highest energies to investigate the fundamental structure of matter. As well as being able to integrate these into the CERN accelerator complex and providing a testing ground for the accelerator technology, it is important that the experiments will also investigate new areas of particle physics. Overall, this paper presents a path in which a new accelerator technology of ever-increasing performance, such as high energy or luminosity and better beam quality, can be applied to a new generation of particle experiments.

Data Accessibility. The article has no additional data.

Competing Interests. The author declares that they have no competing interests.

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