AWAKE++: the AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN

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1 Abstract

The AWAKE experiment reached all planned milestones during Run 1 (2016-18), notably the demonstration of strong plasma wakes generated by proton beams and the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields.

During Run 2 (2021 - 2024) AWAKE aims to demonstrate the scalability and the acceleration of electrons to high energies while maintaining the beam quality.

Within the Physics Beyond Colliders (PBC) study AWAKE++ has explored the feasibility of the AWAKE acceleration scheme for new particle physics experiments at CERN. Assuming continued success of the AWAKE program, AWAKE will be in the position to use the AWAKE scheme for particle physics applications such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.

With strong support from the accelerator and high energy physics community, these experiments could be installed during CERN LS3; the integration and beam line design show the feasibility of a fixed target experiment in the AWAKE facility, downstream of the AWAKE experiment in the former CNGS area. The expected electrons on target for fixed target experiments exceeds the electrons on target by three to four orders of magnitude with respect to the current NA64 experiment, making it a very promising experiment in the search for new physics.

Studies show that electrons can be accelerated to 70 GeV in a 130 m long plasma cell installed in an extended TI 2 extraction tunnel from SPS to the LHC and transported to collision with protons/ions from the LHC. The experiment would focus on studies of the structure of matter and QCD in a new kinematic domain.

The AWAKE scheme offers great potential for future high energy physics applications and it is the right moment now to support further development of this technology leading to unique facilities.

Input to the European Particle Physics Strategy Update

December 2018

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2 Introduction

The AWAKE collaboration is investigating future applications of the proton-driven plasma wakefield acceleration concept, which has been demonstrated at CERN. The AWAKE experiment uses a self-modulated SPS proton beam to resonantly drive a strong wakefield in plasma, producing accelerating gradients at the order of $1\,\mathrm{GVm}^{-1}$ [1]. An electron bunch is externally injected into the wakefield and accelerated up to multi-GeV energies over a distance of 10 m. Due to the large stored energy in a single SPS proton bunch, this scheme can naturally be extended to plasma distances on the order of 100 m, offering accelerated electron energies of approximately 70 GeV. This electron bunch can then be used in a multitude of high energy physics experiments including an extension of the current NA64 experiment [2] looking for dark photons and also a future electron-proton or electron-ion collider.

This document describes the beam line design and the integration proposals of two experiments, i.e. a fixed target experiment in the AWAKE facility and PEPIC, a plasma electron-proton/ion collider, which both use an SPS proton beam to drive wakefields and which are first applications that could already be start installation after a successful AWAKE Run 2 and during LS3 at CERN. The expected electron energies that can be achieved with the AWAKE electron acceleration scheme using the SPS proton beam as drive beam is presented as well as the feasible electron rate for the fixed target experiments and luminosity considerations for PEPIC. The detailed physics program pursued with these electron beams are described in a separate submission [3, 4].

2.1 The AWAKE Experiment

AWAKE is an accelerator R&D experiment and had an outstandingly successful Run 1: In 2016/2017 AWAKE achieved a major milestone and observed the strong modulation of high-energy proton bunches in a 10 m long plasma; the results represent the first ever demonstration of strong plasma wakes generated by proton beams. In May 2018 AWAKE demonstrated for the first time the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields [5]. The aims of AWAKE Run 2 (2021 - 2024) are to achieve high-charge bunches of electrons accelerated to high energy, about 10 GeV, while maintaining beam quality through the plasma and showing that the process is scalable. Details of AWAKE Run 2 are described in [4]. 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 proposed in this document.

3 Proposed Particle Physics Experiments Using the AWAKE Scheme

Currently, high energy electrons ($\geq$50 GeV) are only possible as part of the secondary SPS beam and at low rate. With the AWAKE acceleration scheme electron energies up to 70 GeV can be achieved and the rates can be significantly higher and therefore provide the highest energy, high charge electron bunches in the world. AWAKE++ includes the following particle physics experiments:

- Fixed target experiments are the first applications of these electrons from the AWAKE scheme and could be realized already during LS3; the electron beam quality is in reach of the experimental requirements and less stringent than for high energy electron/positron linear colliders. An interesting fixed target experiment is the search for dark photons: currently the NA64 experiment uses high-energy electrons on a target from the SPS secondary beam line. Electrons from the AWAKE scheme to an NA64-like experiment could make a real impact as the number of electrons is expected to be several orders of magnitude higher. Figure 1 shows the promising physics [6] reach with this experiment. Details of the physics and the experiments are described in [3].
- Another viable application is an electron-proton or electron-ion collider in order to investigate deep inelastic scattering of electrons off protons or ions in order to study the fundamental structure of matter. Electrons accelerated in a wakefield driven by the SPS proton beam collide with LHC protons and ions, this collider is called 'PEPIC' (Plasma Electron-Proton/Ion Collider). The

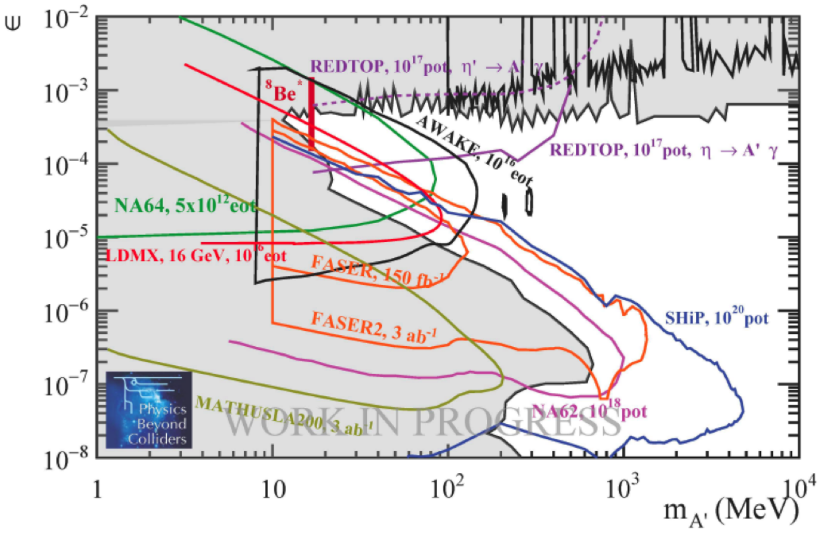

Figure 1: Projected sensitivities to the dark photon visible mode (BC1) of PBC projects. The filled area corresponds to already excluded regions.

experiment would focus on studies of the structure of matter and QCD in a new kinematic domain, in particular at low value of Bjorken x where the event rate is high.

Other applications, which are not part of this document include strong-field QED experiments where high energy electrons at the order of 50 GeV, as provided with the AWAKE scheme, collide with high-power lasers. This regime has never been tested so far, and therefore the AWAKE scheme could provide more sensitivity and probe different kinematic regimes. Future applications of the AWAKE scheme could use LHC protons to drive wakefield and could lead to multi-TeV electron bunches, i.e. 3 TeV electron acceleration achieved in 4 km of plasma. The physics potential of these proposals is described in [3].

4 Using the SPS Proton Beam to Drive Wakefields

4.1 Possible Plasma Length and Electron Energy Reach

The feasibility of a plasma wakefield accelerator for particle physics applications using the SPS proton beam as a driver has been studied using particle-in-cell (PIC) simulations in LCODE [7,8]. Initial proton beam and plasma parameters are taken from the proposed AWAKE Run 2 experiment: plasma density $n_p = 7 \cdot 10^{14}\ \mathrm{cm}^{-3}$, proton energy is 400 GeV, proton bunch length $\sigma_z = 6$ cm, number of protons in the bunch $N_p = 3 \cdot 10^{11}$. Earlier AWAKE Run 2 studies [9] have shown that by using the plasma density step technique [10, 11] it is possible to stabilize the self-modulated proton beam in around 10 meters from the start of the plasma section. The resulting train of proton micro-bunches drives the plasma oscillations with an amplitude close to 1 GV/m and the wakefield stays stable around 800-900 MV/m for approximately 150 m.

However, using the 400-450 GeV SPS proton beam to drive plasma wakefields limits the plasma length and therefore the accelerated electron energy. This is caused by the dephasing of electrons with respect to the plasma wakefield, which is moving at the speed of the proton beam: the dephasing effect between electrons and the 400 GeV protons over 70 m leads to a shift of electron bunch phase by 16% of the plasma wavelength. Therefore in a longer plasma section electrons move into a decelerating phase of the wakefield and as a consequence the energy of the accelerated electrons is limited [1].

In addition, due to the dephasing the achievable accelerated electron beam energy spread is limited, as the electron bunch is accelerated in wakefields with different amplitudes. However, simulations show that with certain beam loading settings and electron bunch charges, the energy spread can be minimized (energy spread $\sim 1\%$ with a bunch charge of around 100 pC).

proton energy	**plasma length**	**electron energy**	**electron charge**
400 GeV	50 m	33 GeV	107 pC
400 GeV	100 m	54 GeV	134 pC
450 GeV	130 m	70 GeV	134 pC

Table 1: Electron energies and optimal electron bunch charge with $\sim$2$-$3% electron energy spread for different plasma length, proton energy.

In order to achieve the best possible accelerated electron parameters, the optimal electron beam parameters at plasma injection are motivated by a small transverse beam size of several microns in order to minimize its emittance while the charge of the bunch and its length should have such values that initially the wakefield is overloaded and later underloaded; the input parameters for the injected electrons used here are: $\sigma_r = 2.4\ \mu$m, $\epsilon_n = 1.5$ mm*mrad, 130 pC, σ_z= 32μm. This allows minimizing the energy spread blow-up due to electron beam dephasing with respect to the slower proton-driven plasma wakefield. Typical expected accelerated electron beam parameters after 100 m are then (see Table 1): electron energy= 54 GeV, electron bunch size $\sigma_r = 2.4\ \mu$m, r.m.s. bunch length $\sigma_z = 32\mu$m, bunch charge = 130 pC, $\epsilon_n = 12$ mm*mrad.

Note that preliminary studies [13] indicate that emittance can be preserved at the level of several mm*mrad. Note also that the considered applications of the AWAKE scheme are much less sensitive to beam emittance (requirements at the order of 1 - 50 mm*mrad) than for example the electron-positron collider requiring nm-size beam at the collision point. Demonstrating 10mm*mrad emittance is a goal for AWAKE Run 2.

Table 1 summarizes the dependencies between the proton and electron energy and the plasma length. Note that the plasma lengths might become even shorter, when further optimizing plasma and beam parameters. We see that with the SPS proton beam as drive beam typical plasma source lengths at the order of up to 130 m can be used. A 450 GeV proton beam is advantageous for any future experiment. However, further simulation studies are required to define the parameters specifications in more detail and to understand the complex plasma wakefield effects.

4.2 Limitations from the Plasma Sources

The AWAKE setup uses a 10 m long cylindrical cell in which the Rb plasma is formed and the acceleration process takes place. At present, a laser pulse co-propagating with the proton beam ionizes Rb vapour to form the plasma and, in the process, seeds the self-modulation of the proton bunch. This seeding effect ensures that self-modulation is the dominant process that causes evolution of the proton bunch rather than non-axisymmetric modes such as hosing that can cause the proton bunch to break up transversely [14]. If a future AWAKE-based accelerator were to seed self-modulation of the proton bunch in the same way, it would be limited by the relaxation and recombination time of the plasma. From current measurements in the AWAKE experiment we assume relaxation times at the order of $\sim\ \mu$s [15], but this

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[1] Note however, that using the LHC protons as drive beam with 7 TeV energy would avoid this effect; simulations have shown that an LHC-type proton beam of 1 TeV would accelerate electrons to more than 500 GeV in 500 m plasma [12], i.e. reaching an average wakefield of 1 GV/m.

might increase to the ms-scale if more energy is deposited in the plasma. In addition it would be also limited by the repetition rate of the laser system used; at present, the laser system is operated at 10 Hz but future systems could operate at kHz rates.

Research into alternative plasma sources where no laser for seeding and ionization is required is already underway [16]; these new methods include helicon plasma cells or discharge plasma cells. In addition to this, alternative methods for seeding self-modulation such as using a second electron bunch to provide the charge density perturbation necessary have been proposed [17].

If it were possible to extract single bunches from the SPS bunch train, a kHz repetition rate could be sufficiently high to allow optimal luminosity to be achieved assuming a $\sim$ ms plasma relaxation timescale. Extracting a full proton bunch train from the SPS, with bunches separated by 25 ns, would be only possible with new methods to produce and refresh the plasma and seed the self-modulation, which must be further developed. The plasma effects need to be studied in more detail before hard limits on the luminosity of a future plasma wakefield acceleration based accelerator can be placed. Experiments are currently being undertaken at AWAKE in an attempt to begin to understand these processes.

5 Fixed Target Experiment Using the AWAKE Scheme

5.1 Electron Acceleration Beam Line Layout

The electron acceleration process in the proton driven plasma wakefield scheme for a fixed target experiment is similarly done as for AWAKE Run 2; The proton beam passes through a first several meter long plasma source in order to self-modulate before entering the accelerating plasma source into which the electrons will be injected and accelerated. During the process of proton beam self-modulation in the first several meters of the plasma section a large fraction of the proton beam is defocused with a maximum angle around 1 mrad. Without external focusing such protons would have a diameter of 10 cm in a 50 m long accelerator while the size of the accelerated electron beam will be measured in microns. The installation of external focusing quadrupoles on top of the plasma cell is studied to avoid proton beam loss along the plasma section and in the electron/proton separator optics, which is required to bring the electron beam to the fixed target experiment.

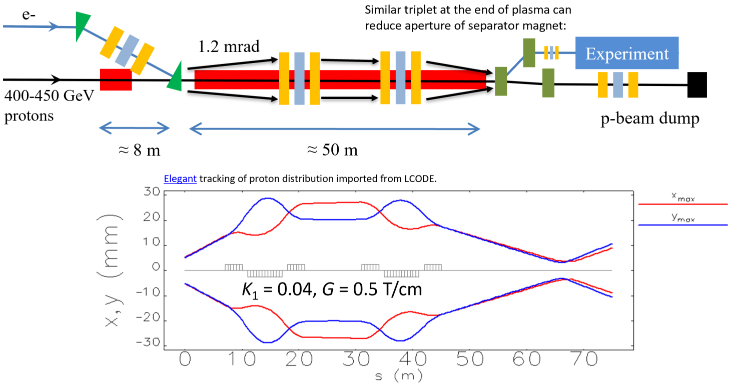

Figure 2: Top: Sketch of the experimental layout of a fixed target experiment in the AWAKE area. Bottom: Maximum proton deviation from the center as effect from the external quadrupole around the plasma source.

As shown in Figure 2 such quadrupoles, with a typical normal conducting quadrupole gradient of 0.5 T/cm and an aperture of several cm, can occupy a small fraction of the total length of the plasma cell. The proton beam can be focused near the exit from the plasma cell to below 1 cm which can reduce the apertures of the electron-proton separator magnets dramatically and avoid any proton beam losses before the experiment. This might be especially important for background reduction in the fixed target experiments located shortly after the proton driven accelerator.

At the exit of the plasma source the electron beam is separated from the proton beam: first studies show that with two 2 m long 1.5 T dipoles it is possible to separate a 33 GeV electron beam and 450 GeV protons by 16 cm in a 10 m long beamline. With an additional 10-m long final focus the electron beam size at the target can be kept around 1 mm. This simulation was done using Elegant [18] taking into account synchrotron radiation induced blow-up of electron beam emittance. To further progress, additional beam line and magnet design studies are needed. Details of the experimental layout are described in [3].

5.2 Integration of the Experiment in the AWAKE Facility

It is proposed to install the fixed target experiment searching for dark photons in the current AWAKE underground area: The AWAKE experiment today is installed just upstream of the 100 m long CNGS target cavern; an electron gun has been installed at the downstream end of the access gallery and the experiment fits in the area upstream of the former CNGS target, leaving the entire 100 m CNGS target and secondary beam line in place, albeit behind a shielding wall. Clearing the $\sim$100 m long CNGS target cavern would allow the houseing of a $\sim$50 m long plasma cell for electron acceleration to $\sim$33 GeV (baseline) followed by an up to 50 m long NA64-like experiment. Details of the NA64-like experiment can be found in [3]. Modifications necessary for the electron source and beam line (see [4]) are already planned for AWAKE Run 2 after LS2 and would be used also for the fixed target experiment.

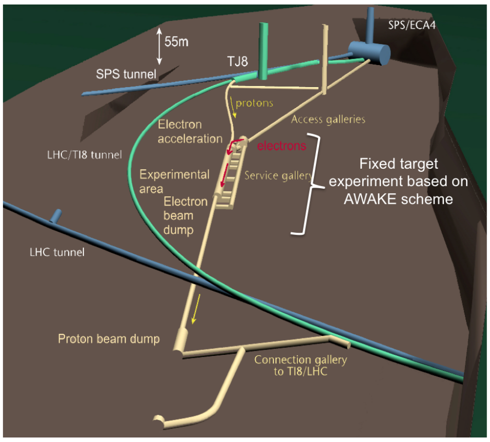

Figure 3: AWAKE facility and proposed fixed target experimental area.

The most time-consuming interventions to prepare the facility is the dismantling of the CNGS target area: A first study estimates the time needed to fully empty and decontaminate CNGS's target area at 14 months. This duration is defined by the required complex work in this radiation area. The dismantling of the CNGS target area involves a specialized nuclear dismantling team that will also ensure the correct packaging of all material to be removed from the area. Handling of heavy objects in the target cavern as well as logistics of all material from the target area to radioactive waste repositories is required. Installation of new general services is estimated at 4 months of work. Additional civil engineering to widen the area might be required to integrate infrastructure needs for the plasma sources, laser system, diagnostics etc. However, the works could be done during LS3, so that the experiment could be realized after LS3.

5.3 Achievable Electrons on Target

Considering an example case of an NA64-type fixed target experiment using electron bunches accelerated by AWAKE, the achievable estimated number of electrons on target has been calculated for two different drive beam setups. The results are summarised in Table 2. The electrons on target calculations assume a 12 week experimental period with a 70% SPS duty cycle.

The CERN SPS today extracts 450 GeV protons to the LHC and 400 GeV protons to the North Area and to AWAKE. The SPS is fed by the CERN PS and PS Booster, the operation of which applies limitations to the number of bunches that can be injected into the SPS. Today the AWAKE scheme uses one proton bunch per cycle. However, it is possible that a maximum of eight AWAKE-type bunches could be present in the SPS ring at once; in this case, the PS Booster would need to be operated in its second harmonic, reducing the maximum intensity and increasing the emittance of each bunch. The bunches would then be sent from the CERN PS, which has a total length of $2\,\mu$s, to the SPS. Some RF manipulation would need to be performed to equally space the proton bunches around the $23\,\mu$s SPS ring so that a maximum of eight current AWAKE-type proton bunches can be accelerated and extracted in a single SPS cycle. The AWAKE-upgrade-type calculation assumes that eight proton bunches are accelerated and extracted within each cycle, with two cycles per SPS supercycle, which has a total length of 40 s. Further detailed studies on the RF and extraction systems are needed.

The electron rates expected with this AWAKE-upgrade scheme is $\sim 4.1 \times 10^{15}$ electrons, already three orders of magnitude higher than what NA64 hope to accumulate in its current setup in its lifetime [2] ($\sim 3 \times 10^{12}$ electrons).

Parameter	**AWAKE-upgrade-type**	**HL-LHC-type**
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

Table 2: Potential achievable number of electrons on target for an AWAKE-based fixed target experiment for two different drive beam configurations. Assumes a 12 week experimental period with a 70% SPS duty cycle.

Another option would be to use an LHC-type proton beam to drive the wakefield. By the time an AWAKE-based experiment is operational, the High Luminosity Upgrade to the LHC is expected to have been completed, meaning the proton bunch produced by the SPS would also have different parameters, see third column of Table 2. This beam has a lower population and would not be longitudinally compressed to the same extent as the current AWAKE beam, but would offer a significant reduction in transverse size and therefore higher bunch density. This beam would drive stronger wakefields with higher gradients, making it more ideal for electron acceleration. If the HL-LHC-type beam were to be used as the drive beam, there are two options for extraction:

Firstly, the current extraction magnets could be used to extract the entire bunch train from the SPS. This would contain four bunch trains, each separated by 200 ns, with each train made up of 80 individual bunches separated by 25 ns. However, due to the limitations in the plasma relaxation times (currently at the order of ~ 100 ns) this might not be possible, but more detailed studies need to be performed.

The second option would be to modify the extraction kicker system such that single bunches could be extracted from within the train. At present, the extraction kicker cycle has a duration of $\sim 8\,\mu$s, with the option to reduce it to a few μs, but cannot be made shorter than this so is not suitable for single bunch extraction. However, options are being explored to reduce the extraction cycle to the order of the separation between single bunches, i.e. < 25 ns, which would present the opportunity to extract bunches from the train at the required repetition rate of the plasma relaxation time. In that case the electrons delivered to the fixed target experiment would even reach $\sim 2 \times 10^{17}$ electrons.

6 PEPIC, Plasma Electron Proton/Ion Collider, Using the AWAKE Scheme

The Plasma Electron Proton/Ion Collider requires a 450 GeV proton beam from the SPS to drive plasma wakefields and an electron beam, accelerated in the plasma wakefield and transported to the LHC in order to perform collision experiments with LHC protons or LHC ions. Possible locations of the plasma acceleration beam line have been studied [19] considering using already existing extraction channels and tunnels from the SPS to the LHC, avoiding large deflection angles for a 70 GeV electron beam and providing a minimum required length of straight section to house the plasma wakefield acceleration line. In addition it is assumed that the LHC stays fully operational as a pp collider. As a consequence the PEPIC equipment would need to share space with existing equipment in the LHC and the transfer line. The parameters relevant for the studies are the following: plasma length for self-modulation = 10 m, plasma length for acceleration = 130 m, electron energy after plasma acceleration = 70 GeV, proton beam energy = 450 GeV. The outcome of this study shows that the only possible location situated at an existing beam line for PEPIC is in the downstream part of TI 2, see Figure 4.

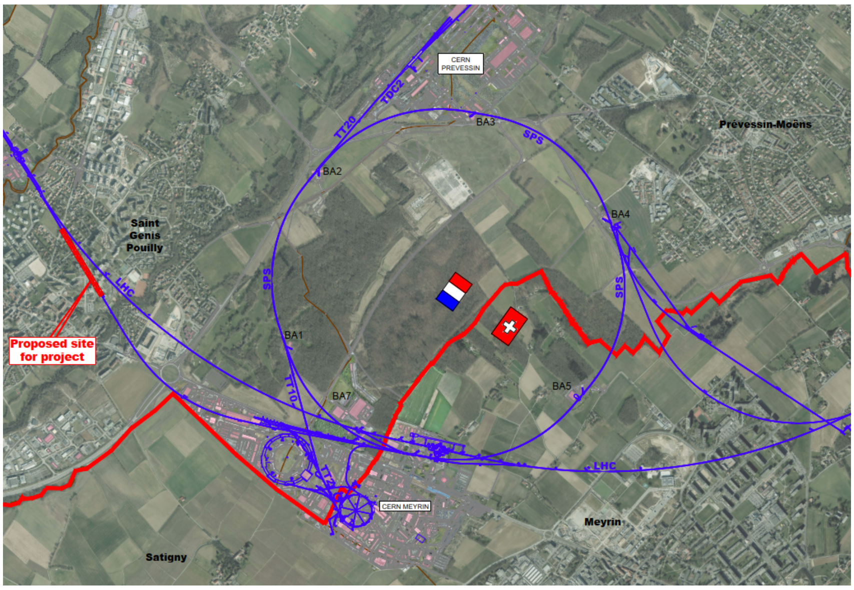

Figure 4: Location plan showing the proposed site of the scheme in relation to existing CERN infrastructure and the wider geographic context.

6.1 Beam Line Layout

The downstream part of the TI 2 beam line contains a long straight section equipped only with quadrupoles, correctors and beam instrumentation elements in a regular FODO lattice. This part of TI 2 can provide enough space for installing the plasma sources and other equipment. Nonetheless, an extension of the TI 2 tunnel and an additional cavern is required to house the electron source, the electron beam line, the proton beam dump, diagnostics and infrastructure equipment.

This scheme would leave the TI 2 beam line optics untouched and the beam could be rapidly switched between proton and plasma accelerated electron beam. The electron beam line is foreseen to be installed parallel to the AWAKE++ proton beam line with a dogleg injection chicane at its end as shown in Fig. 5. To be able to capture, separate and transport the proton beam after the plasma cell to a dedicated beam dump, an external focusing around the plasma cell as proposed for the fixed target experiment is mandatory, since otherwise the beam diameter would be too large. With such a system the separation of the proton and electron beam downstream the plasma cell looks feasible and the electron beam could be injected into the TI 2 beam line. This would allow use of the existing TI 2 beam line for transporting the 70 GeV electron beam to the LHC and physics experiment. This would be a great advantage with respect to a dedicated electron transfer line to the LHC, as it minimizes costs and integration issues.

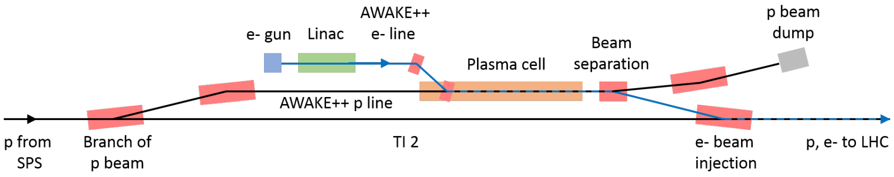

Figure 5: Schematic layout of the AWAKE++ PEPIC facility (not to scale).

This study is limited up to the transport of the electron beam to the LHC. Injection into the LHC and transport to the experiment has to be looked at in more detail in a future study. However, with the proposed usage of TI 2 for the electron beam transport this should be much easier to achieve than with a separate beam line. An unpolarized electron beam has been assumed for this study. For a polarized electron beam the spin dynamics would need to be studied in detail, in particular inside the plasma cell. If the electron spin with an arbitrary direction does not experience a rotation inside the plasma or experiences a rotation in a deterministic way, a Wien filter installed directly after the gun could compensate the spin rotation in the downstream elements.

In this study the bending angles for the high-energy electron beam have been chosen as low as reasonably possible. The total energy loss is still low. However, the produced synchrotron radiation has a high peak power above 1 GW, due to the ultra-short electron bunches and it might be worth investigating if this synchrotron radiation can cause any damage on the accelerator equipment.

6.2 Integration and Civil Engineering Impact

Widening of the TI 2 tunnel and an additional cavern is required to house the electron source, the electron beam line, the proton beam dump, diagnostics and infrastructure equipment. For the favoured setup with a 130 m long plasma cell the enlarged tunnel needs to accommodate a proton bypass beam line for the plasma cell requiring tunnel widening over a distance of approximately 500 m. Major civil engineering work will be required to provide the necessary space to accommodate PEPIC, which would be located on and adjacent to the existing alignment of TI 2: an injection tunnel built for the LHC. The geology in this area consists of Moraines overlying Molasse. The works for PEPIC would be situated within the Molasse. The Molasse is broadly considered good rock for tunnelling since it is relatively dry and stable without being prohibitively hard. Detailed geological records exist following the design and construction of TI 2. TI 2 is a horseshoe shaped tunnel and measures 3 m across and 2.5 m in height between tunnel invert and crown as shown in Figure 6. The following civil engineering works are proposed:

- Widening of TI 2 from 2.22 m width at floor level to 5.2 m over a length of 494 m.
- Widening to 6.2 m over 11 m length to accommodate a beam dump and shielding arrangement.
- A 60 m long, 6 m wide cavern parallel to TI 2 to house a laser lab, klystrons and other electronic equipment with two 4 m wide tunnels and up to three 500 mm diameter cores linking tunnels.

The civil engineering works should not pose feasibility issues since generally they will be implemented by standard techniques in an area which is geologically well understood. Access will also need to be considered further; at this stage, shaft PMI2 at Point 2 of LHC is considered likely to be the best access

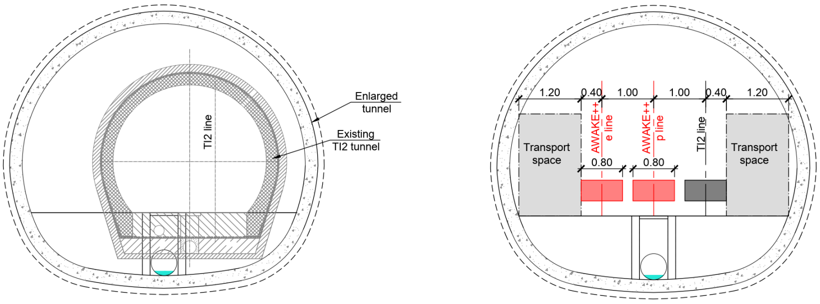

Figure 6: Typical cross-sections showing existing TI2 and widened tunnel profiles required (left) and the proposed beam-line arrangement necessitating changes (right)

point. This will be key to spoil removal and will generate a significant number of wagon movements for waste disposal. The civil engineering study carried out has been appropriate to a concept design. To make further progress with PEPIC, a number of additional studies will be required including radiation protection testing of concrete and soil, integration studies, ground investigation gap analysis, condition survey of TI 2 and a drainage survey.

6.3 Luminosity Considerations

Considering beam parameters as shown in Table 2 for the HL-LHC-type case and assuming $\epsilon_p = 2.5\,\mu$m, $\beta_p^* = 0.15$ m, γ_p =7460 for the proton beam, the PEPIC luminosity [2] is $\mathcal{L}_{\rm PEPIC} = 1.46 \times 10^{27}$ cm^{-2} s^{-1}. Assuming a running period of about 10^7 s per year this would give an integrated luminosity of about 10 nb^{-1}. So although PEPIC would have the same energy reach as the LHeC project, but with luminosities several orders of magnitude lower, this collider could though be an interesting option for CERN should the LHeC not be realized. As such, it would focus on studies of the structure of matter and QCD in a new kinematic domain, in particular at low value of Bjorken x where the event rate is high. In addition further studies should be performed to investigate possibilities to increase the luminosity by improving the number of electrons per bunch, the SPS bunch frequency or proton bunch size.

7 Summary

The AWAKE collaboration is well supported and excellent progress has been made over the last years; AWAKE observed the strong modulation of high-energy proton bunches in plasma and demonstrated for the first time the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields. During Run 2 (2021 - 2024) AWAKE aims to demonstrate the scalability and the acceleration of electrons to high energies ($\sim$10 GeVs) while maintaining the beam quality (at the order of ϵ_n=10 mm*mrad). Accelerating electrons over short distances to high energies with the AWAKE technology is a promising scheme for particle physics applications. Possible experiments using the AWAKE electron acceleration scheme includes the search for dark photons, measurement of quantum electrodynamics in strong fields and high-energy electron-proton/ion collisions. The requirements on the beam emittance are less stringent (at the order of 1 - 50 mm*mrad) for these experiments and demonstrating 10mm*mrad emittance is a goal for AWAKE Run 2.

Preliminary simulations show that with a 400-450 GeV SPS proton beam as a drive beam it is possible to accelerate a 100 pC electron bunch up to 50-70 GeV in a 100-130 m long plasma cell. The integration of a fixed target experiment at CERN is feasible in the AWAKE facility, where the plasma cell and the experiment can be installed in the former 100 m long CNGS target area that must be emptied beforehand. The expected electrons on target for fixed target experiments with the scheme exceeds the

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[2] The standard formula was used: $\mathcal{L}_{\rm PEPIC} = \frac{1}{4\,\pi}\,\frac{P_e}{E_e}\,\frac{N_p}{\epsilon_p^N}\,\frac{\gamma_p}{\beta_p^*}$, with the electron beam power $P_e = N_e\,E_e\,n_b\,f_{\rm rep}$

electrons on target by three to four orders of magnitude with respect to the NA64 experiment, making it a very promising experiment in the search for new physics.

A plasma electron proton/ion collider (PEPIC) is proposed: By widening the extraction line tunnel TI2 from the SPS to the LHC, the SPS proton beam can be used to drive wakefields in a $\sim$130 m long plasma cell in TI2 in order to accelerate electrons that collide with LHC protons. Although the luminosities reached would be several orders of magnitude lower than for the LHeC project, PEPIC could though be an interesting and cost-effective option for CERN should the LHeC not be realized, studying the structure of matter and QCD in a new kinematic domain. Further studies should be performed to investigate possibilities to increase the luminosity by improving the number of electrons per bunch, the SPS bunch frequency or proton bunch size. Assuming a successful AWAKE Run 2 the installation of these first particle physics experiments could start during CERN Long Shutdown 3 so that the experiments could start commissioning and operation once LS3 is finished.

Bibliography

[1] P. Muggli et al. (AWAKE Collaboration), Plasma Phys. Contr. Fusion 60 (2018) 014046.

[2] S. Gninenko, NA64 Status Report 2017, Technical Report CERN-SPSC-2017-018, SPSC-SR-212, CERN, Geneva, June 2017.

[3] M. Wing et al., Particle physics applications of AWAKE acceleration scheme, Input to the European Particle Physics Strategy Update 2018-2020, CERN-PBC-REPORT-2018-004, 2018.

[4] A. Caldwell et al., AWAKE - on the path to particle physics applications, Input to the European Particle Physics Strategy Update 2018-2020 (2018).

[5] E. Adli et al. (AWAKE Collaboration), Nature 561, (2018) 363–367.

[6] J. Beacham et al., Report of the BSM Working Group of the Physics Beyond Colliders at CERN, Input to the European Particle Physics Strategy Update 2018-2020 (2018).

[7] `www.inp.nsk.su/~lotov/lcode/`

[8] K. V. Lotov, A. Sosedkin and E. Mesyats, Simulation of Self-modulating Particle Beams in Plasma Wakefield Accelerators // Proceedings of IPAC’2013 (Shanghai, China), p. 1238.

[9] AWAKE Status Report (2016), CERN-SPSC-2016-033, https://cds.cern.ch/record/2221183/

[10] A. Caldwell and K. V. Lotov, Plasma wakefield acceleration with a modulated proton bunch. Physics of Plasmas 18 (2011) 103101.

[11] K. V. Lotov, Physics of beam self-modulation in plasma wakefield accelerators. Phys. Plasmas 22, 103110 (2015).

[12] K. Lotov, Phys. Rev. ST-Accel. Beams 13, 041301, 2010.

[13] V. Olsen, E. Adli and P. Muggli, Phys. Rev. Accel. Beams 21, 011301, 2018.

[14] D.H. Whittum et al., Electron-hose instability in the ion-focused regime, Phys.Rev.Lett., 76:991-994, 1991.

[15] S. Gessner et al. (AWAKE Collaboration), Measurement of the plasma recombination rate by modulation of a high-energy proton beam, in preparation.

[16] B Buttenschön, N Fahrenkamp, and O Grulke, Plasma Physics and Controlled Fusion 60, 075005 (7pp), 2018.

[17] M. Hüther and P. Muggli, Nucl. Instrum. Meth. A 909, 67 (2018).

[18] M. Borland, “Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287, September 2000.

[19] E. Gschwendtner (ed.) et al., AWAKE++: Feasibility Study of the AWAKE Acceleration Scheme for New Particle Physics Experiments at CERN, EDMS Nr. 2061121.