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The electron accelerators for the AWAKE experiment at CERN—Baseline and Future Developments

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ABSTRACT

The AWAKE collaboration prepares a proton driven plasma wakefield acceleration experiment using the SPS beam at CERN. A long proton bunch extracted from the SPS interacts with a high power laser and a 10 m long rubidium vapor plasma cell to create strong wakefields allowing sustained electron acceleration. The electron beam to probe these wakefields is created by an electron accelerator consisting of an rf-gun and a booster structure. This electron source should provide beams with intensities between 0.1 and 1 nC, bunch lengths between 0.3 and 3 ps and an emittance of the order of 2 mm mrad. The booster structure should accelerate the electrons to 16 MeV. The electron line includes a series of diagnostics (pepper-pot, BPMs, spectrometer, Faraday cup and screens) and an optical transfer line merges the electron beam with the proton beam on the same axis. The installation of the electron line started in early 2017 and the commissioning will take place at the end of 2017. The first phase of operation is called RUN1. After the long shutdown of LHC a second phase for AWAKE is planned starting 2021 called RUN2. In this phase the aim is to demonstrate the acceleration of high quality electron beams therefore a bunch length of the order of 100 fs rms is required corresponding to a fraction of the plasma wavelength. The AWAKE collaboration is studying the design of such an injector either based on classical rf-gun injectors or on laser wake-field acceleration. The focus for the RF accelerator is on a hybrid design using an S-band rf-gun and x-band bunching and acceleration cavities. The layout of the current and the future electron accelerator and transfer line, including the diagnostics will be presented.

1. Introduction

The Advanced Wakefield Experiment (AWAKE) [1,2], part of the CERN accelerator complex, aims to demonstrate for the first time proton driven plasma wakefield acceleration. The 12 cm long, 400 GeV proton beam from the SPS at CERN is injected together with a short-pulse high-power laser into a 10 m long rubidium vapor cell. The laser will have a dual function, ionizing the rubidium vapor to create a plasma channel with a density of 7.10^{14} cm^{-3} and seeding a self-modulation within the proton bunch to excite the strong wakefields.

In a first step (called RUN1), a photo injector electron source, reused from the CLIC Test Facility (CTF3) [3,4], will be installed to generate bunches propagating together with the proton beam and the laser beam to demonstrate the concept of plasma wakefield acceleration. Extensive simulations [5] have been done to determine the necessary electron beam parameters for the experiment. The electron bunch will be extending over several plasma wave length ($\lambda_p = 1.3$ mm) therefore only a fraction of about 15% of the injected electrons will be trapped in a suitable acceleration bucket. In a later phase of the experiment called

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Table 1
Awake electron beam parameters for the RUN1 and RUN2 of the AWAKE experiment.

Parameter	RUN1	RUN2
Beam energy	16 MeV	≥50 MeV
Energy spread (RMS)	0.5%	≤1%
Bunch length (σ)	4 ps	50–100 fs
Beam size at focus (σ)	0.25 mm	≤100 mm
Normalized emittance (RMS)	2 mm mrad	<1 mm mrad
Charge per bunch	0.2 nC	0.1–0.2 nC

RUN2, the electron source will be modified to produce a more energetic and shorter electron beam. Beam parameters for RUN1 and RUN2 are summarized in Table 1. More details about the electron source used for the RUN1 can be found in [6].

We will first present the current electron line with the source, the booster structure and all the diagnostics. Then, we will present the studies for the RUN2 electron source, as well as, the new schematic for the injection into the plasma cell.

2. Electron line for the RUN1

The electron accelerator for AWAKE-RUN1 consists of a 2.5 cell rf-gun and a one meter long booster structure both at 3 GHz. A cathode is illuminated with a frequency quadrupled laser pulse which is derived from the main drive laser for the plasma. The laser wavelength used in the photo injector will be 262 nm. The setup includes a load lock system allowing to use different cathodes. A constant gradient accelerating structure is used to boost the energy of the beam up to 16 MeV. The rf-gun and the booster are powered by a single klystron delivering about 30 MW. The operation mode will be single bunch with a maximum repetition rate of 10 Hz. The SPS extraction rate of the proton beam is 0.14 Hz. The beam line is equipped with diagnostics to measure and optimize the beam parameters after the gun, at the end of the accelerator and then downstream the plasma cell. A timing system has been designed allowing the synchronization of the laser, the electron beam and the proton beam at a sub-ps level.

As shown in Fig. 1, the electron beam line consists of different systems, starting with the rf-gun (top right), then the booster structure (in the middle) and the transfer line including vertical and horizontal bends which connects to the merging point (bottom right), where the electron beam propagates collinear together with the proton beam and the laser beam.

The beam is generated with an S-band RF photo injector [7] using a 2.5 cell standing wave structure. The peak field on the cathode was set to 100 MV/m for the simulations which has been obtained previously with this gun and the laser beam size to 0.5 mm (σ). A Gaussian laser pulse was used with a length of 4 ps (σ). The nominal charge for the AWAKE baseline is 0.2 nC per bunch. These set of parameters allowed in simulation using ASTRA to obtain the target emittance of 2 mm mrad at the end of the injector beam line. Two solenoids around the rf-gun are used for emittance compensation and focusing of the beam towards the traveling wave accelerating structure. CERN has traditionally experience with producing and using Cs_2Te cathodes with a quantum efficiency of $Q_e \approx 10^{-2}$. The possibility to use those cathodes due to a installed load-lock system will give more flexibility in the choice of beam parameters for future experiments. Photo-cathodes are produced at CERN by thin film deposition [8] and transported under ultra-high vacuum conditions in the AWAKE tunnel. However the AWAKE laser system provides enough power to use copper cathodes with a quantum efficiency of $Q_e \approx 10^{-4}$ as an alternative.

Once generated and accelerated up to 5.5 MeV in the 2.5 cell rf-gun, the beam enters a first diagnostics section providing beam current measurements with a Fast Current Transformer (FCT) and a pepper-pot emittance diagnostics developed by Manchester University. Detailed simulations have been performed with PARMELA and ASTRA to design the device [9]. The entire electron beam line is equipped with sensitive Beam Position Monitors (BPMs) developed and contributed by Triumf. In beam tests using the CTF3 facility these monitors were characterized with a resolution of 20 μm at a bunch charge of 100 pC.

In order to achieve the AWAKE requirements for RUN1, the beam is accelerated from 5.5 to 16 MeV in the booster structure. The 1 m long traveling wave structure, simulated and designed by the University of Lancaster, is composed of 30 cells working at 3 GHz. The RF power needed for this structure and the gun is produced by a single klystron. The RF power generated is split to power the rf-gun and the accelerating structure in parallel. A high power phase shifter and attenuator allow to regulate amplitude and phase of both structures independently.

Once it has reached its nominal energy, the beam passes through a set of quadrupole and BPMs and then can be imaged on beam profile monitors (BTVs) with a resolution of 20 μm. This system is used to measure the Twiss parameters and emittance to match the following transfer line correctly. A Faraday cup, developed as well by Triumf will provide accurate charge measurements (10 pC resolution). Following the numerous constraints of the existing tunnel layout a transfer line with vertical and horizontal bending sections brings the beam collinear to the proton beam axis towards the plasma cell [10]. The correct arrival time of the electron beam with respect to the laser can be verified on the last optical diagnostics with a streak camera imaging the beam and the laser right before the entrance of the plasma cell. To measure the electron beam acceleration downstream the plasma cell, a spectrometer has been developed by University College of London (see Fig. 2). This spectrometer consists of a dipole with a maximum magnetic field of 1.6 T and a large scintillator 999 × 64 mm^2. The scintillator is imaged over a distance of around 10 m with a high sensitivity camera. According to the simulations [11] we expect to detect electrons in the range between 1–2 GeV.

3. Studies for the RUN2 electron source

One goal of the second phase of experiments with AWAKE at CERN is to demonstrate the sustained acceleration of high quality electron beams in the proton driven plasma wakefield. A schematic view of the preferred scenario for RUN2 can be seen in Fig. 3. To accelerate high quality beams it is necessary to separate the formation of the micro bunches in the proton beam using self-modulation seeded by the ionization laser and the pure acceleration in the generated high plasma wakefield. Therefore two plasma cells will be used and the electron witness beam has to be injected in a short gap of less than 1 m between the two cells. Extensive simulations [12,13] are ongoing to determine the most suitable input parameters for the electron beam in order to obtain emittance conservation during the acceleration and an energy spread of the order of 1%. In particular a bunch length below 100 fs, a fraction of the plasma wavelength is needed. The peak current is important to obtain a correct beam loading which is necessary to achieve a small energy spread and emittance conservation. Simulations showed a peak current around 500 A with a Gaussian profile would achieve this goals. Finally the electron bunch needs to be focused to a spot size smaller than 100 μm to match the good focusing and acceleration region within the plasma wakefield. The main parameters used for the conceptual design of the RUN2 injector can be found in Table 1. To be able to produce such a beam and transport it its energy probably has to be higher than 50 MeV.

In addition the injector should be extremely compact to match the existing space constraint in the experimental area.

The design consists of a 2.5 cell S-band rf-gun, a X-band adiabatic bunching section and a X-band high-gradient accelerator. The S-band rf-gun allows to start off with a moderate bunch length of 2 ps and a laser spot-size of 1 mm very similar to the first phase injector presented earlier. This S-band gun is not extremely sensitive to laser alignment or higher order modes compared to an X-band version. The use of X-band accelerators afterward allows for a compact design. The whole

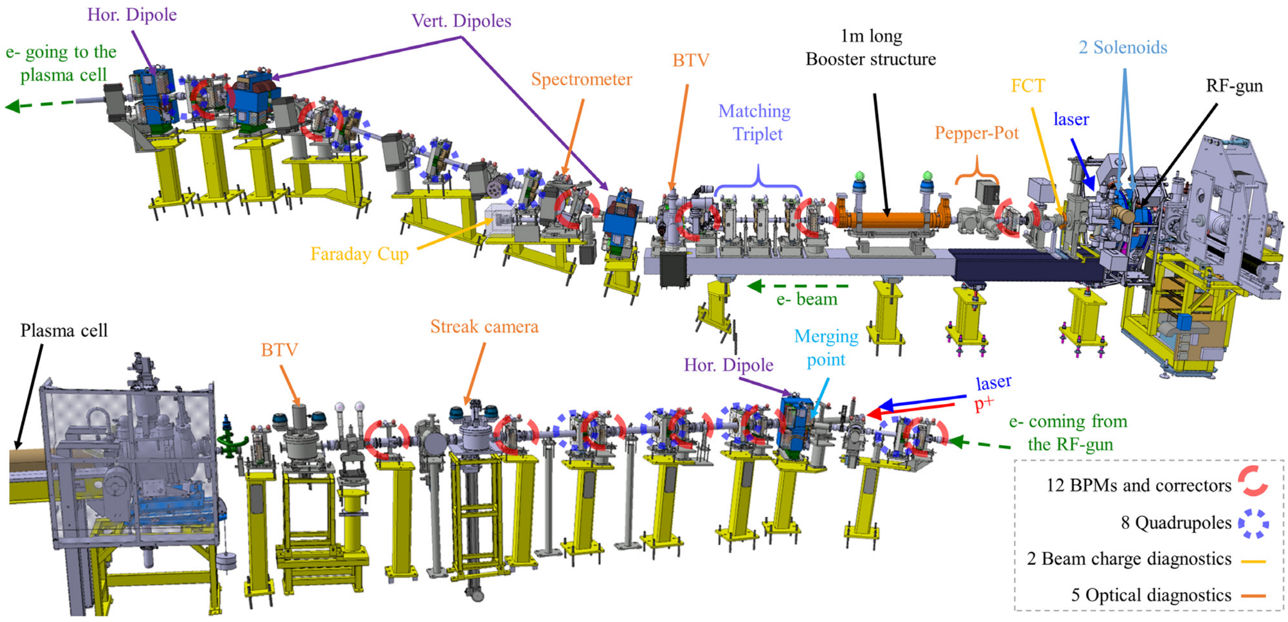

Fig. 1. Layout of the electron line. The electron source starting with the rf-gun (top right corner) can be seen together with the accelerating and focusing elements as well as the different beam diagnostics. The beam transfer line starts with a vertical achromat followed by two horizontal bends to bring the beam on the same axis as the proton beam and its ionization laser toward the plasma cell (lower left corner).

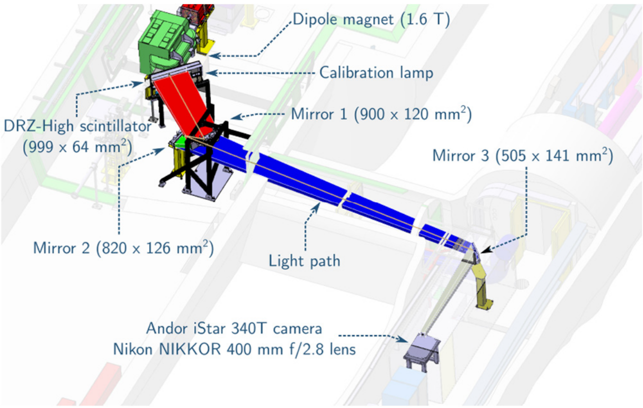

Fig. 2. Spectrometer and light path layout to measure the plasma wake-field accelerated electrons.

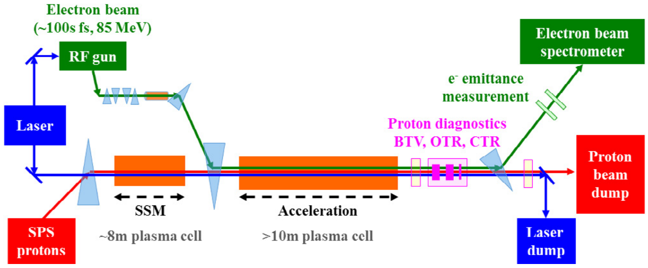

Fig. 3. RUN2 injection scheme with two plasma cells and electron injection in between.

accelerator proposed is less than 5 m long. The 25 cm long bunching section is placed at the transverse focus of the emittance compensated beam coming from the rf-gun and uses a moderate gradient of 22 MV/m. Finally the accelerating structures are starting at the position of the longitudinal focus after the bunching section. We have studied two variants one with a one meter long accelerator operating at 80 MV/m and as an alternative two structures at 40 MV/m to reduce the power requirements. Existing designs of CLIC prototype accelerating structures have been used to model this accelerator while the rf-gun is assumed to be the one used in the RUN1 injector described before. Fig. 4 shows the simulation results obtained with ASTRA for the version with two X-band accelerating structures. We obtain a bunch length of 80 fs at the end of the accelerator at an energy of 85 MeV. The RMS energy spread is very reasonable and below 1%. The whole accelerator is assumed to be embedded in a solenoidal magnetic field. The field profile was obtained in an iterative approach using envelope equations. The goal was to obtain and maintain a small transverse beam size of 0.2 mm which would minimize the emittance growth. An RMS emittance below 1 μm could be maintained along the accelerator like this. Further studies of this scheme continue to validate the concept. A challenging problem will be the transport and injection into the plasma of such a beam. The corresponding studies only recently started and will give certainly feedback to the accelerator design.

4. Conclusion

The installation of the electron source, laser system and RF equipment for RUN1 of AWAKE has been finished. Commissioning started in October 2017 and will continue until the end of the year. During the year 2018, we foresee to accelerate low energy electrons externally injected into the sample wakefields to the GeV level.

In addition we are studying a new electron injector which can provide the range of beam parameters required for the second phase of AWAKE (RUN2). This injector should provide a higher beam energy, a bunch length below 100 fs and an emittance of 1 mm mrad. First simulation results of a hybrid approach using a S-band rf-gun followed by X-band bunching and acceleration show very promising results. In parallel the AWAKE collaboration looks as well into the possibility to realize such an injector based on laser wakefield acceleration [14].

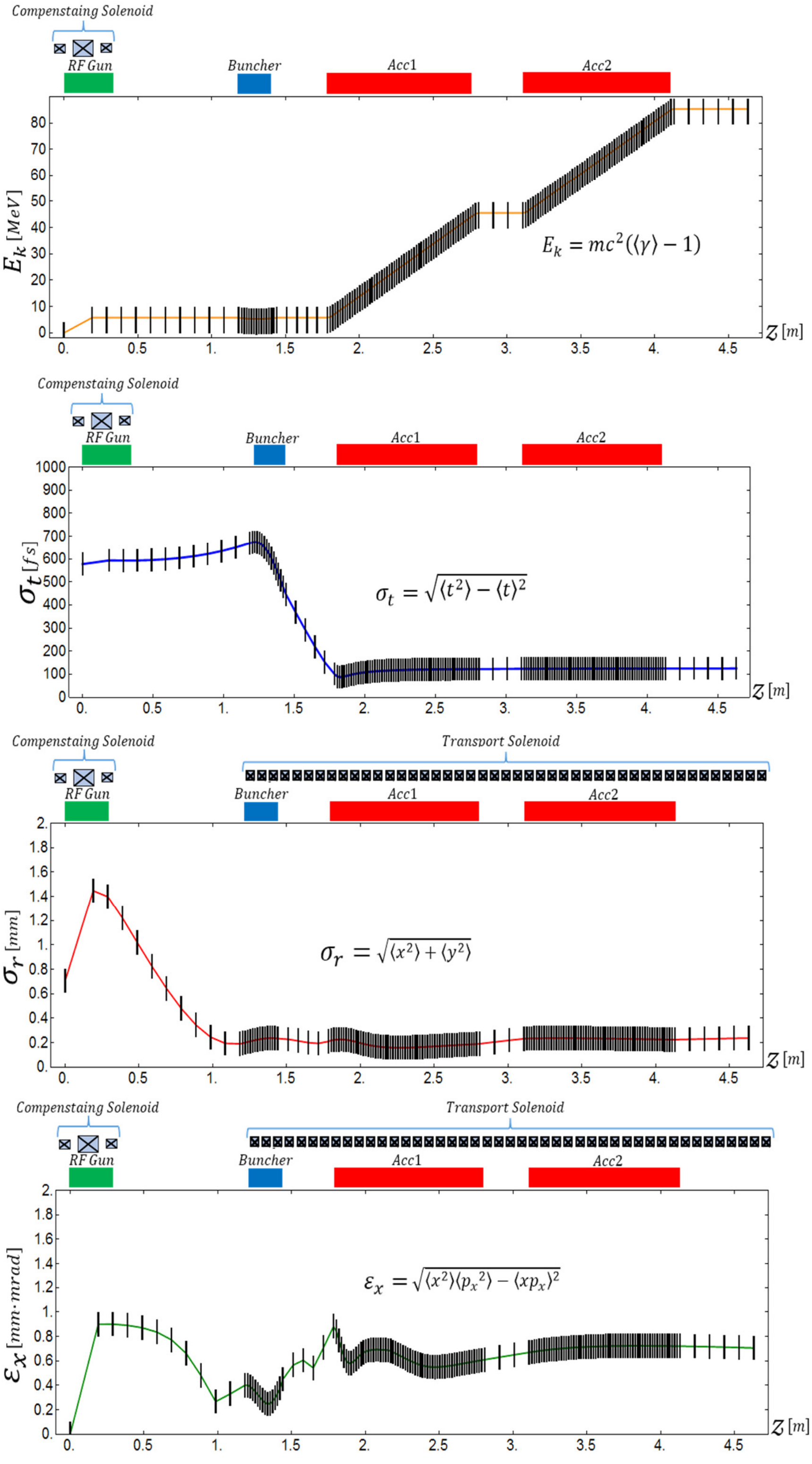

Fig. 4. RUN2 simulations results using ASTRA. The plots show the evolution of key beam parameters along the beam line (from the top to the bottom: Beam energy, bunch length, beam size, and transverse emittance).

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