The electron accelerator for the AWAKE experiment at CERN

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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 vapour plasma cell to create strong wakefields allowing sustained electron acceleration. The electron bunch to probe these wakefields is supplied by a 20 MeV electron accelerator. The electron accelerator consists of an RF-gun and a short booster structure. This electron source should provide beams with intensities between 0.1 to 1 nC, bunch lengths between 0.3 and 3 ps and an emittance of the order of 2 mm mrad. The wide range of parameters should cope with the uncertainties and future prospects of the planned experiments. The layout of the electron accelerator its instrumentation and beam dynamics simulations are presented.

Keywords: Electron gun, Accelerators, Charged particle beams in accelerators, Diagnostics

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1. Introduction

The Advanced Wakefield Experiment (AWAKE) [1] at CERN aims to demonstrate for the first time proton driven plasma wakefield acceleration. The 400 GeV proton beam form the SPS at CERN will be injected together with a short-pules high-power laser into a 10 m long rubidium vapour cell. The laser will have a dual function, ionizing the rubidium laser to create a plasma channel and seeding a self-modulation instability within the proton bunch to excite the strong wakefields.

In order to probe the generated wakefields and to demonstrate plasma wakefield acceleration an electron beam will be injected into the plasma wake excited by the proton bunch. The wavelength of the plasma wave is expected to be 1.26 mm for a plasma density of 7.10^{14} cm^3. Details of the wakefield and self-modulation instability in the AWAKE experiment can be found in [2]. Extensive simulations [3] have been done to determine the necessary electron beam parameters for the experiment. The electron bunch will be extending over several plasma wave periods therefore only a fraction of about 15 % of the injected electrons will be trapped in a suitable acceleration “bucket”. The emittance of the beam has to be small enough to allow a tight focusing of the beam to match the transverse dimensions of the plasma channel and the wakefield wave. Furthermore it seems, an oblique injection of the electron beam with respect to the proton beam is advantageous to reduce defocusing effects caused by the plasma density transition at the entrance of the plasma cell [4]. The beam parameters for the electron beam are summarized in Table 1. The central column has the baseline parameters chosen to start the experiments while the right column describes possible future evolutions towards higher charge and shorter bunches. Of course not all parameters can be realized simultaneously.

The electron accelerator for AWAKE 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 wavelength used in the photo injector will be 262 nm. The setup includes a load lock system allowing the use of copper or Cs_2Te as a cathode material. A constant gradient accelerating structure is used to boost the energy of the beam up to 20 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 and at the end of the accelerator. A timing system has been designed allowing the synchronization of the laser, the electron beam and the proton beam at a sub-ps level.

2. Electron accelerator beam dynamics

The beam is generated with an S-band RF photo injector using a 2.5 cell standing wave structure. The accelerating gradient was set to 100 MV/m for the simulations and the laser beam size to 0.5 mm (σ). A Gaussian laser pulse was used in the simulations and has a length of 4 ps (σ). The nominal charge for the AWAKE baseline is 0.2 nC per bunch. Under these conditions the beam is space charge dominated out

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Table 1: Awake electron beam parameters

Parameter	Baseline	Possible Range
Beam energy	16 MeV	10-20 MeV
Energy spread	0.5 %	0.5 %
Bunch length (σ)	4 ps	0.3-10 ps
Beam size at focus (σ)	250 µm	0.25-1 mm
Normalized emittance (RMS)	2 mm mrad	0.5-5 mm mrad
Charge per bunch	0.2 nC	0.1-1 nC

of the gun and requires special care for transport and diagnostics. Two solenoids around the RF-gun are used for emittance compensation and focusing of the beam towards the travelling wave accelerating structure. A 30 cell travelling wave structure was designed by Lancaster University to boost the energy with a constant gradient of 15 MV/m. The beam dynamics was studied using PARMELA. A smooth focusing keeps the beam envelope below one millimeter avoiding strong focusing. The beam emittance at the exit of the RF-gun can be roughly preserved through acceleration and transport. The normalized emittance is 1.3 mm mrad at the end of the short beam line [5]. Figure 1 shows the emittance and beam size evolution for the nominal beam parameters. The influence of timing jitter at the gun on the final bunch length and emittance has been studied assuming a Gaussian jitter with 300 fs standard deviation and found to be acceptable for the base line parameters [5]. The most critical parameter is actually the effect of the energy spread on the final spot size caused by chromatic effects in the electron transport line [6]. Additional work would be needed to insure the proper transport of sub-ps bunches.

Beyond the AWAKE baseline with the aim to demonstrate the acceleration by the proton driven plasma wakefields to an energy above 1 GeV we looked at possible evolutions for the electron injector.

Obviously very short bunches would be attractive to inject and possibly trap the entire beam in a single plasma acceleration bucket. Therefore the electron bunch length should be of the order of 200 fs. This requires an excellent synchronization of laser and RF as well as careful optics design to generate and transport the beam. The synchronization system for the baseline is based on a phase looked loop between a 6 GHz master oscillator and a harmonic signal from the laser obtained from a photo diode. The system is specified to obtain a phase jitter below 100 fs in the range of 1 to 10 Hz.

Beam dynamics simulations indicate that with the present S-band RF-gun bunches with a rms length of 300 fs could be achieved with bunch charges $\leq$ 0.2 nC with some emittance growth compared to the nominal beam parameters. The emittance was found to increase to about 2 mm mrad compared to the baseline parameters.

How to create shorter bunches in the order of 100 to 200 fs is currently studied and requires probably a different injector. A combination of a high frequency rf gun and active bunching methods is being investigated.

High bunch charge can be produced using the Cs_2Te cathodes at the expense of a larger emittance and very small laser beams could be used together with a lower charge to access smaller emittances. A severe limitations for these variations is the laser ablation threshold while using a copper cathode. The quantum efficiency of Cs_2Te is at least a factor 100 higher compared to copper which allows to lower laser densities on the cathode.

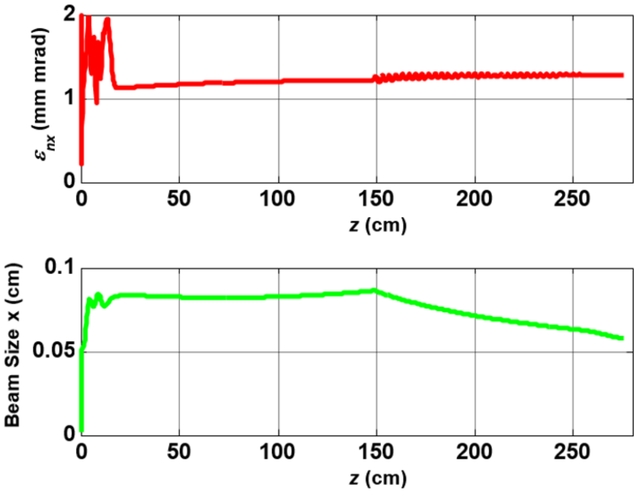

Figure 1: Beam size and emittance evolution along the electron source.

3. Electron beam layout

(a): Electron source and accelerating structure. The AWAKE experiment will be installed in a tunnel used before for the Neutrino program (CNGS). The area has limited space and numerous constraints presenting quite a challenge to integrate all the necessary equipment for the electron accelerator and the experiment. The concept for the electron source was developed around the existing RF-gun (PHIN) [7] from the CLIC study and a new booster structure. The accelerator will be installed in a shielded area as shown in Fig.2. This electron beam line with a length of only 4 m will consist of four parts. The PHIN photo injector will be placed on the left, it is composed of a RF cavity at 3 GHz and two solenoids for the emittance compensation and to ensure a vanishing magnetic field on the cathode. Upstream of the solenoids the cathode loading chamber with it's manipulators which is used to change the cathode under vacuum can be seen. The booster structure will be located in the middle to increase the beam energy to the required 16 MeV. Finally, before the beam transfer to the merging point in the proton tunnel,

a quadrupole triplet will be installed to match the beam into the transfer line. Beam diagnostics distributed along the beam line will allow to set up and control the beam.

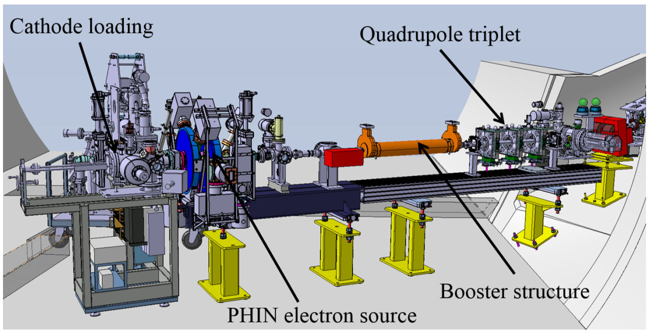

Figure 2: Electron source and accelerating structure layout.

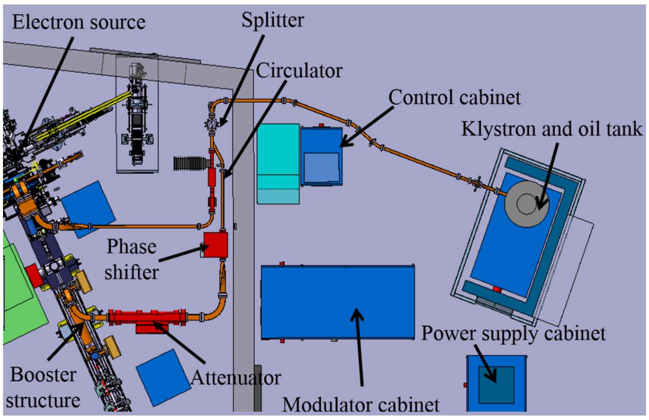

Figure 3: Klystron and waveguides layout.

(b): RF power source. A 40 MW klystron will be used to supply the necessary 3 GHz RF power to the 2.5 cell RF gun and booster structure. The high voltage modulator and the klystron will be located in a room adjacent to the electron source together with all related equipment. The modulator producing 42 kV and 4 kA is discharged by a thyratron, through a high voltage triaxial cable to power the klystron. In order to increase the voltage and reach the required 320 kV, a transformer with a 1:15 ratio is connected between the triaxial cable and the klystron. The RF power generated in a short pulse of a few microseconds is transmitted using high power waveguides and components (splitters, phase shifter, attenuator and circulator). These elements are recovered from the CTF3 [8] facility and arranged as shown in Fig.3.

In this layout, the RF power is splitted equally in two branches allowing to adjust amplitude and phase for the RF gun and the structure independently. Both cavities need up to 15 MW nominally.

(c): Load lock cathode system and transport carrier. A significant effort went into the integration of a existing cathode load lock system allowing to transfer cathodes under ultra high vacuum. The electron beam is produced via photo-emission by illuminating the cathode with an UV laser beam. The baseline will use copper cathodes with a quantum efficiency of $Q_e \approx 10^{-4}$. The AWAKE laser system provides enough power to produce the necessary beam charge but the ablation threshold of copper limits the minimum beam size on the cathode. CERN has traditionally experience with producing and using Cs_2Te cathodes with a quantum efficiency of $Q_e \approx 10^{-2}$. These cathodes will give more flexibility in the choice of beam parameters for future experiments. Photo-cathodes are produced at CERN by thin film deposition [9] and transported under ultra high vacuum conditions in the transport carrier (TC) to the AWAKE area. The transport carrier is an existing element from CTF3 which can contain 4 cathodes. Studies, in order to use it with the electron source in the shielded area of the vacuum chamber are ongoing.

Once the TC is connected to the vacuum chamber, the system supporting the cathodes is pushed inside. A manipulator arm, installed behind the vacuum chamber holds the cathode and places it in the cathode holder (between the two solenoids). Manufacturing of the cathodes, transportation and installation are performed in an environment where the vacuum is of the order of 10^{-11} mbar.

4. Beam instrumentation

To monitor and control the beam during operation, optical and electrical diagnostics will be installed along the beam line. Existing diagnostics will be recovered from CTF3. Three stripline beam position monitors (BPMs) have been developed by Triumf with a resolution of 50 µm to control the beam position. The beam charge can be measured by a fast current transformer with a resolution of 10 pC just outside the RF gun and a Faraday Cup developed by Triumf at the end of the beam line. Two emittance measurement stations will be installed. A pepper pot diagnostics developed by the University of Manchester allowing to measure the space charge dominated beam out of the gun and a screen at the end of the beam line for quad-scans. This screen can be as well used to determine the bunch length together with a streak camera. Finally a spectrometer will be available to measure the energy and energy spread taking advantage from a dipole magnet in the following beam transport line.

5. Conclusion

The electron beam requirements are clearly defined now and the corresponding electron source and accelerator has been designed. The challenging integration of the system into the congested AWAKE area is well advanced. Work is ongoing to explore the possibilities of the accelerator for a range of beam parameters to be possibly used in the future. Clearly interesting will be higher charge, shorter bunches and energy upgrades. The electron source is being developed with numerous contributions from the AWAKE collaboration. The booster structure was designed and will be contributed by Lancaster University. Triumf is manufacturing BPM's and a Faraday Cup. Manchester University is working on a pepper pot emittance meter to be installed in the electron source. Installation, commissioning and first experiments with the electron beam are planned for 2017.

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