A SPECTROMETER FOR PROTON DRIVEN PLASMA ACCELERATED ELECTRONS AT AWAKE - RECENT DEVELOPMENTS*

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Abstract

The AWAKE experiment is to be constructed at the CERN Neutrinos to Gran Sasso facility (CNGS). This will be the first experiment to demonstrate proton-driven plasma wakefield acceleration. The 400 GeV proton beam from the CERN SPS will excite a wakefield in a plasma cell several meters in length. To probe the plasma wakefield, electrons of 10–20 MeV will be injected into the wakefield following the head of the proton beam. Simulations indicate that electrons will be accelerated to GeV energies by the plasma wakefield. The AWAKE spectrometer is intended to measure both the peak energy and energy spread of these accelerated electrons. Results of beam tests of the scintillator screen output are presented, along with tests of the resolution of the proposed optical system. The results are used together with a BDSIM simulation of the spectrometer system to predict the spectrometer performance for a range of possible accelerated electron distributions.

INTRODUCTION

Proton bunches are the most promising drivers of wakefields to accelerate electrons to the TeV energy scale in a single stage. An experimental program at CERN — the AWAKE experiment [1, 2] — has been launched to study in detail the important physical processes and to demonstrate proton-driven plasma wakefield acceleration.

AWAKE will be the first proton-driven plasma wakefield experiment world-wide and is currently being installed in the CERN Neutrinos to Gran Sasso facility [3], with data taking with the proton beam phase scheduled to take place summer 2016 [4]. An electron witness beam will be injected into the plasma to observe the effects of the proton-driven plasma wakefield: plasma simulations indicate electrons will be accelerated to GeV energies [5]. In order to measure the energy spectrum of the witness electrons, a magnetic spectrometer will be installed downstream of the exit of the plasma cell. The design of the spectrometer was outlined in [6] and in [7] an updated spectrometer design along with estimated energy resolution for various quadrupole and magnet settings was presented. In this paper the resolution of the system and minimum detectable bunch charge under various beam conditions are discussed.

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SPECTROMETER DESIGN

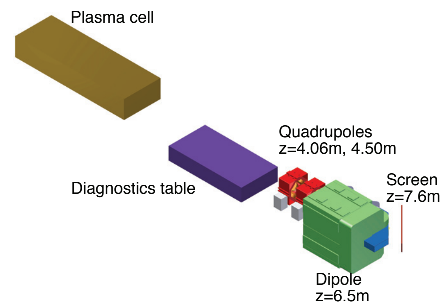

Figure 1: A 3D CAD image of the spectrometer system annotated with distances along the z direction from the exit of the plasma cell to the magnetic centers of magnets, and the center of the scintillator screen.

RESOLUTION

Optical System

The resolution of the energy spectrometer will ultimateley depend on the resolution of the optical system imaging the screen. Due to the radiation environment, the intensified CCD camera (Andor iStar 340T) will need to be located 17 m away in an adjacent tunnel. The light will be reflected to the camera using a series of mirrors. In order to collect as much light as possible whilst maintaining good spatial resolution, a large diameter, 400 mm focal length, f#/2.8 lens has been selected (Nikon 400 mm f/2.8 FL ED VR). This lens was tested by imaging various targets back-lit with green with various line widths, and the modulation transfer function was calculated. Mirrors of varying quality were tested. Tests were carried out with the screens at various distances from the camera and at various positions within the image plane of the camera. From 17 m away the smallest resolvable bar width was 1 mm and a bar width of 0.5 mm was not resolvable. This result was independent of whether or not a mirror was used, the type of mirror used, and the transverse position of the target. This indicates that a low quality mirror could be used, the resolution is good across the image plane, and the indicated resolution of the optical system of is $\sim \sigma = 1.0$ mm. The resolution of the system finally installed at AWAKE will depend on the optical transfer line finally installed and tests are planned during the commissioning stages.

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Screen

Studies are currently ongoing to optimize the vacuum chamber window thickness. The point spread function of the screen will depend on the finally chosen window/screen thickness. Studies are ongoing. For the purposes of this study we assume the line spread function of the screen will be negligible compared to the optical system.

Emittance

The resolution of the spectrometer will depend on the beam size of the accelerated electrons at the screen which in turn will depend on the beam parameters and the magnetic beam line components which will be used to focus the beam.

Beam Parameters The accelerated electron beam has been simulated in plasma simulations using LCODE [8, 9]. The phase space distribution of the accelerating beam is non-Gaussian with long tails. It also appears to be composed of a number of distinct phase space ellipses with different orientations. In this study we approximate the overall phase ellipse using the overall RMS position and angular distributions. The resulting beam parameters at the exit of the plasma cell are give in table 1. The parameters were calculated by assuming twiss parameter $\alpha = 0$, corresponding to an unrotated phase ellipse, which is true for the central part of the phase space (figure 3). Emittance was estimated from the RMS area of the phase ellipse i.e. $\epsilon = \sigma_x \sigma_{x'}$.

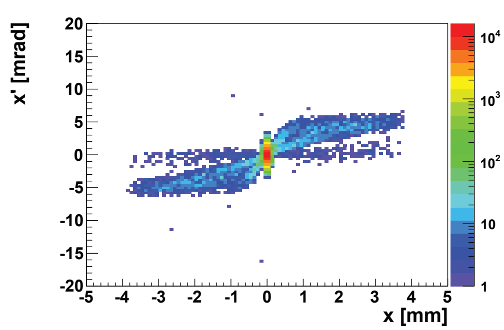

Figure 2: A sample of the simulated phase space distribution of the witness electron beam.

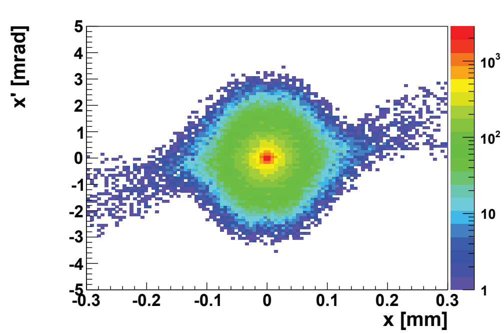

Figure 3: Central region of a sample of figure 2 (rebinned)

Table 1: Predicted beam parameters for the accelerated electron beam at the plasma cell exit calculated from the simulated phase space distribution (figure 2)

σ_x [μm]	327.1 ± 0.6
$\sigma_{x'}$ [mrad]	1.048 ± 0.002
ϵ [μm]	0.34280±0.0009

Beam Line The beam line down stream of the plasma cell will consist of the components listed in table 2. The 7% offset between the strengths of the two quadrupoles causes the horizontal and vertical foci to coincide at the screen [7].

Table 2: Beam Line Components Downstream of Plasma Cell. **l** is magnetic length. **k** is the magnet focusing strength.

Name	Type	**l** [m]	**k** [m^{-1}]
qf0	quad.	0.31	-4.2900
d1	drift	0.185	
qd0	quad.	0.31	3.9897
d0	drift	~3 m (energy dependent)	

Based on the above parameters, a transfer matrix was calculated analytically using the thick quadrupole transfer matrices [10] to transfer the beam from the upstream face of qd0 to the screen. As the quadrupole strengths and the length of d0 vary as a function of energy, these were left as functions of energy in the transfer matrix. $l_{d0}(E)$ was determined from a tracking simulation using BDSIM [11–14]. The quad focusing strengths are simply scaled linearly with energy. As the position on the screen is a function of energy, it was possible to derive a function (*beam size function*) describing beam size (and therefore energy resolution) as a function of position (and therefore energy) using the energy dependent transfer matrix and the estimated beam parameters.

Overall Resolution

The resolution due to the emittance, when combined with the resolution of the optical system of 1.0 mm by adding the beam size due to emittance and the optical resolution in quadrature, is plotted in figure 4. The result for the nominal emittance in plotted, together with emittances 10 and 100 times smaller/larger. The resolution in the experiment could be estimated by measuring the vertical beam size on the screen and assuming a circular beam.

MINIMUM DETECTABLE CHARGE DENSITY AND SCREEN LINEARITY

Method

Beam line tests were carried out to determine the minimum detectable charge density of the system. A 5.5 MeV electron beam was used from the PHIN beam line [15]. A 850 μm thick terbium-doped gadolinium oxysulphide scintillator screen was placed after a 0.2 mm aluminum window at the end of the beam line. The electrons passed through

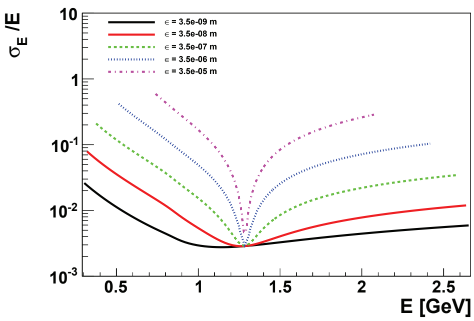

Figure 4: Fractional energy resolution as a function of energy for various beam emittances.

the back of the scintillator screen emitting photons from the front. The resulting image, after reflecting at 45 degrees in a mirror, was captured with the CCD camera using a 50 mm diameter lens. The iStar CCD camera was placed 17 metres from the screen in order to mimic the AWAKE setup. The bunch charge was measured using Faraday cup and a fast current transformer. The number of photons detected was then plotted as a function of bunch charge. The background fluctuation was measured directly from each CCD camera image by looking at a dark area of the image. The camera image intensifier gain curve was measured using a standard light source and plotting the ADC counts in the camera as a function of micro channel plate (MCP) voltage.

Minimum Detectable Charge Density

From the above measurements the response (ADC counts as a function of charge) was derived, and from the response and the pixel size the minimum visible charge density was derived. The results are summarized in table 3

Table 3: Results Relating to Minimum Visible Charge Density of the System, Using a 50 mm Diameter Lens. Minimum visible charge is estimated as response/(2×dark noise)

Dark noise [ADC counts]	6.91±0.02
Response [counts/nC]	$1.11{\pm}0.04{\times}10^{9}$
Min. vis. charge [nC]	$1.25{\pm}0.05{\times}10^{-8}$
CCD pixel area at screen [mm^2]	5.9±0.6
Min. vis. charge dens [nC/mm^2]	2.1 ± 0.2
Min. vis. charge dens [electrons/mm^2]	130 ± 20

Using the values in table 3 and the *beam size function* the minimum detectable charge/emittance can be determined. As a rough comparison, a large emittance and energy spread witness beam, with a uniform spatial distribution on the screen of 50cm wide and 1cm tall would have a charge density of about $5{\times}10^{-5}$ [nC/mm^2], which is about 2000 times the minimum detectable charge density. The real awake beam will have a smaller capture efficiency, about 30%, but will not be uniformly distributed. However, a 50 mm diameter lens was used for this beam test - the large diameter Nikon 400 mm f/2.8 lens planned to be used at AWAKE, with a diameter of 143 mm has an acceptance 8 times larger than the small lens.

EMITTANCE MEASUREMENT

It may be possible to use the electron spectrometer image to provide an emittance measurement in a single shot. This will be useful to study the quality of the beam that is accelerated at AWAKE. The procedure is to plot the vertical beam size, which is provided in the vertical beam axis, as a function of horizontal position (or energy), which is given in the horizontal axis of the image. The *beam size function* is then fit to the data. This energy-dependent function yields an effective "quadrupole scan", and the parameters of the fit give the vertical beam matrix upstream, from which the emittance can be derived. An example fit to a simulated beam is shown in figure 5, and the results of the fit are given in table 4. The simulation assumes a perfect optical system (every electron position is recorded, perfect optical resolution). The fit parameters agree well with the input, demonstating emittance measurement in a single pulse under the described beam conditions. Further study is required to determine the limitations of the method.

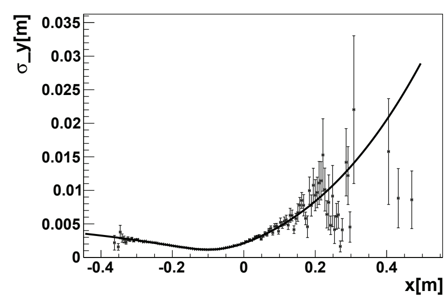

Figure 5: Fit of a simulated electron beam to the *beam size function*.

Table 4: Input and fit result for the emittance measurement simulation.

	Input	**Result**
bin width [camera pixels]	10	
N_{electons}	$1{\times}10^{5}$	
σ_y^2 [mm^2]	1.004±0.005	0.92±0.02
$\sigma_{y'}^2$ [10−6]	1.247±0.006	1.271±0.009
ϵ [μm]	1.004±0.005	1.016±0.018

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