An Electron Spectrometer for Proton Driven Plasma Accelerated Electrons at AWAKE: Predicted Resolution of Energy and Emittance Measurements

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***Abstract*—The Advanced Wakefield Experiment (AWAKE), to be constructed at CERN, 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. Under certain conditions it is also possible to use the spectrometer to measure the transverse beam emittance. The expected resolution of these measurements is investigated for various beam distributions, taking into account an optimised vacuum chamber and scintillator screen design and results of beam and optical tests.**

***Index Terms*—AWAKE, plasma wakefield acceleration, electron spectrometer, emittance measurement**

I. Introduction

THE AWAKE electron spectrometer system [1]–[3] will be installed at the AWAKE experiment in order to measure the energies of the accelerated (witness) electrons. For future applications such as colliders, beam emittance will be an important quantity. This will depend on the details of the electron injection and plasma acceleration scheme. In the initial phase of the AWAKE experiment, the electron beam will be injected co-propagating with the proton beam, and self-modulation and acceleration will occur in the same channel. According to plasma simulations, this will impart a large emittance growth and energy spread to the beam [4]. In future iterations of the AWAKE experiment ("Run II" and beyond) [5], a modification to the beam line is proposed, using two separate plasma cells. The first cell will induce the self-modulation instability in the proton beam in order to split the beam into the micro-bunches needed to excite the plasma wakefield. In a second plasma cell the micro-bunched proton beam will excite a plasma wakefield and accelerate injected witness electrons. In such a scheme electrons will be injected directly into the second cell, bypassing the first cell, which could improve the energy spread and emittance of the accelerated witness beam, as the electrons will not experience the plasma wakefield during microbunching.

The possibility of using the electron spectrometer system to measure emittance in addition to the energy has been outlined, and a function to extract the beam emittance from the spectrometer data has been shown via simulation to work under ideal, low noise conditions [1]. The advantage of such a scheme is that the proposed electron spectrometer system can be used without modification - the vertical emittance can be determined by analysing the two-dimensional beam distribution at the scintillator screen. However, there are limitations to this method; for example, we will show that a certain amount of energy spread is required in the witness beam. In this extended abstract we outline the emittance measurement scheme being proposed. We then briefly outline a method of estimating the uncertainty associated with the emittance measurement, including estimates for all known sources of noise, using a Monte-Carlo simulation, and present the results. In future iterations of AWAKE the energy spread is likely to be reduced [5]. We calculate the measurement uncertainty as a function of energy spread in order to indicate the range of energy spreads that can yield a useful measurement. This will provide an indication of wether or not the method could be used at AWAKE Run II and beyond. Finally, we suggest further parameters to be investigated. More details will be provided in a paper to be submitted to IEEE Transactions on Nuclear Science.

II. Spectrometer Layout

The layout of the spectrometer system [1]–[3] is shown in figure 1. The system begins with the first quadrupole 4.06 metres downstream of the plasma cell. The system comprises two quadrupoles which focus the beam onto a scintillator screen via a dipole magnet. The energy distribution is inferred from the spatial distribution on the scintillator screen.

III. Method

A. Beam size function and effective quadrupole scan

The beam transfer matrix was calculated using the thick lens component transfer matrices [6] from the upstream face of the first quadrupole to the screen. The quadrupole strengths were allowed to vary as functions of energy in the transfer

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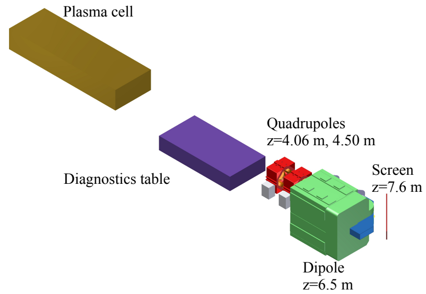

Fig. 1. A 3D CAD image of the spectrometer system annotated with distances along the z direction from the exit of the plasma cell to the magnetic centers of magnets, and the center of the scintillator screen.

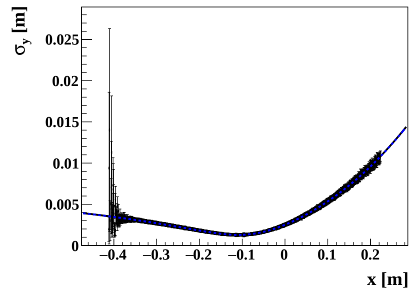

Fig. 2. A fit of the beam size function to the simulated spectrometer output. The black line is the input function. The dashed blue line is the fit (the lines are almost entirely overlapping)

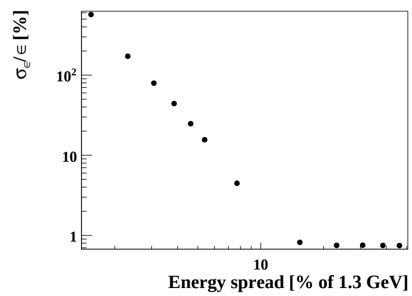

Fig. 3. Calculated uncertainty of the simulated emittance measurement vs. energy spread.

matrix. As the position on the screen is a function of energy, a function was derived (beam size function) giving beam size (and therefore energy resolution) as a function of energy using the energy dependent transfer matrix and the estimated beam parameters. With a large enough energy spread, a single bunch emittance measurement could be possible using the spectrometer system. The procedure is as follows: plot the vertical beam size as a function of energy. 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 upstream beam parameters, including emittance.

B. Monte-Carlo simulation

To determine the resolution of the emittance measurement, simulated spectrometer camera outputs were randomly generated. The simulation assumes a Gaussian beam profile with the parameters approximately equal to those expected for the AWAKE witness beam. An algorithm was written to take account of sources of noise and provide an estimate of the uncertainty of the emittance measurement. Realistic camera noise parameters were used, derived from tests to the CCD camera. The screen output was estimated based on previous measurements using MeV electrons, simulations and the known properties of the scintillator. The background was estimated based on simulations of proton interaction with an upstream aperture (the plasma cell iris). The point spread function of the imaging system was estimated based on modulation transfer function measurements carried out using the lens. The following steps were carried out:

1) An energy distribution is generated representing the accelerated electron energies.
2) The corresponding position histogram is filled, with positions convoluted with the point spread function of the system.
3) Electrons are randomly converted to photons taking account of screen efficiency and imaging system acceptance.
4) A uniform background and camera noise is added to the distribution. This distribution simulates the spectrometer raw data.
5) Background is subtracted.
6) Beam size (standard deviation of position) and error calculated for each vertical strip of pixels.
7) The resulting graph is fit to the beam size function by minimising χ^2. The error of the emittance fit gives the error on the emittance measurement (figure 2).

IV. Results

A. Baseline parameters

The fit with the baseline parameters is shown in figure 2. This gives an uncertainty on the emittance measurement of $\sim$0.8%. This assumes a 1.3 GeV beam with 0.4 GeV energy spread and 1 um emittance.

B. Reduced energy spread

A beam with a narrower energy spread increases the uncertainty of the measurement because the fit is less well constrained. Emittance measurement uncertainty vs. energy spread is plotted in figure 3. The uncertainty rapidly increases to over $\sim$10% for relative energy spreads less than $\sim$5%.

V. Conclusion

An estimate of the energy measurement resolution was previously presented [1], together with an outline of a possible method for measuring the emittance using a single bunch. Some constraints on the use of this method have now been estimated; with the baseline parameters the uncertainty on the measurement will be $\sim$0.8%. The measurement requires a relatively wide energy spread, and the uncertainty increases to over 10% for energy spreads less than 5%. The simulation framework described here will be used to determine the dependence of the emittance measurement uncertainty on various parameters such as:

- Radiation background
- Camera thermal noise
- Emittance
- Quadrupole field
- Coupled and/or non-Gaussian beam distribution
- Bunch charge

This will provide more information on the limitations of this emittance measurement method.

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