A SPECTROMETER FOR PROTON DRIVEN PLASMA WAKEFIELD ACCELERATED ELECTRONS AT AWAKE

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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 electron acceleration by use of a proton driven plasma wakefield. The 400 GeV proton beam from the CERN SPS will excite a wakefield in a plasma cell several metres in length. To observe the plasma wakefield, electrons of a few 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. The baseline design makes use of a single dipole magnet to separate the electrons from the proton beam. The dispersed electron beam then impacts on a scintillator screen: the resulting scintillation light is collected and recorded by an intensified CCD camera. The design of the spectrometer is detailed with a focus on the scintillator screen. Results of simulations to optimise the scintillator are presented, including studies of the standard GadOx scintillators commonly used for imaging electrons in plasma wakefield experiments.

INTRODUCTION

New acceleration technology is mandatory for the future elucidation of fundamental particles and their interactions. A promising approach is to exploit the properties of plasmas. Past research has focused on creating large-amplitude plasma waves by injecting an intense laser pulse or an electron bunch into the plasma. However, the maximum energy gain of electrons accelerated in a single plasma stage is limited by the energy of the driver. 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 — has been launched to study in detail the important physical processes and to demonstrate the power of proton-driven plasma wakefield acceleration.

AWAKE will be the first proton-driven plasma wakefield experiment world-wide and will be installed in the CERN Neutrinos to Gran Sasso facility [1]. The conceptual design of the AWAKE experiment is described in [2]: the current status of the project is given in [3]. 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 [4]. 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.

SPECTROMETER DESIGN

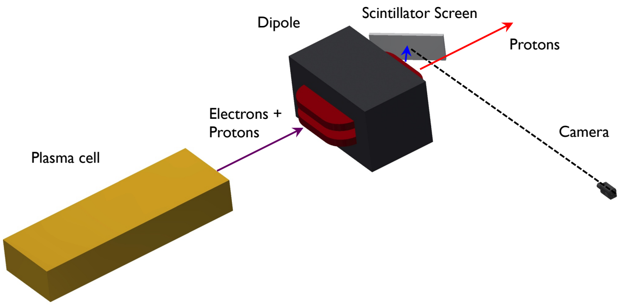

Figure 1: Spectrometer layout showing plasma cell (yellow), magnet (black with red coils), screen (silver) and camera.

The spectrometer has the following requirements:

1. Separate electrons from the drive beam protons.
2. Introduce a spatial distribution into the accelerated beam that is a function of energy.
3. Measure the intensity of the spatially distributed accelerated electrons to allow the mean energy and energy spread to be calculated.
4. Provide sufficient acceptance to prevent significant beam loss of accelerated electrons before the energy measurement.
5. Provide sufficient dynamic range to allow measurement of a range of electron energies from 0–5 GeV.
6. Measure the energy profile of the electron beam with sufficient resolution to demonstrate proton driven plasma wakefield acceleration of witness beam electrons.

The spectrometer layout is shown in Fig. 1. A dipole magnet, located ~2 m downstream of the exit of the plasma

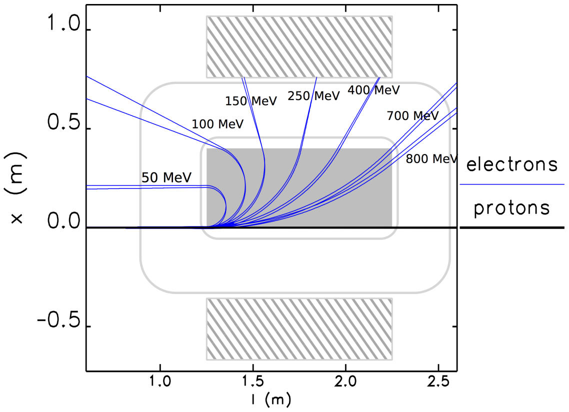

Figure 2: Electron trajectories within the spectrometer dipole for a range of energies.

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cell, introduces dispersion into the witness beam that results in a horizontal spread that is correlated to the electron energy: the resulting electron trajectories are shown in Fig. 2. A CERN MBPS dipole has been identified for use in the AWAKE spectrometer: these have a 1 m-long bore that is 140 mm tall, with a useful field aperture of 300 mm and a maximum field of 1.8 T [5]. Such a field provides measurable spatial electron separation above energies of 5 GeV for the spectrometer layout described here.

The scintillator screen, nominally 1 m in length, is mounted at 45° to both the proton beam axis and the exit face of the dipole magnet, level with the downstream face of the dipole coils. In common with other plasma wakefield experiments, Terbium-doped Gadolinium OxySulfide screens[1] (Gd_2O_2S:Tb) have been selected for use in the AWAKE spectrometer. Extensive simulations have been carried out to confirm that the light output of these screens is sufficient to measure an electron energy spectrum: these are described later.

An Andor iStar 340T intensified CCD camera [6] is then used to record the light emitted by the accelerated electrons impacting on the scintillator: this is mounted at 45° to the surface of the screen and therefore 90° to the proton beam axis. The original design placed the camera looking at the upstream face of the screen, as shown in Fig. 1: however, more recent simulations have indicated the camera is better placed viewing the downstream side. Since the camera is not designed for high radiation environments, a trade-off exists between moving the camera closer to the screen to improve light capture and moving it further away to reduce radiation damage: the nominal distance from screen to camera of 4 m may be reduced if simulations suggest the camera will survive closer to the beamline, since this will improve the signal-to-noise ratio. Normally used for spectroscopy applications and capable of single photon counting, the use of a 25 mm intensifier provides a pixel resolution of 1850×512: careful selection of the lens system will be necessary to ensure that the full width of the CCD is utilised for imaging the screen. At 4 m, a 50 mm diameter Nikon F-mount lens provides a fractional coverage of $\sim 10^{-5}$ over 4π steradians: work is ongoing to design an optical system to increase the light capture at large distances.

SCINTILLATOR SIMULATIONS

A Geant4 simulation of the scintillator screen has been written in order to simulate the output and spatial distribution of the emitted photons as part of a complete start-to-end simulation of the spectrometer system. The relevant electromagnetic and physics processes are turned on. The simulation includes electromagnetic processes in order to model the energy deposition in the screen. In addition, the scintillation process is activated. This process emits optical photons isotropically in a given spectrum, with an energy yield proportional to the deposited energy. In addition, relevant optical processes are activated. The screen is composed of a backing layers with a front scintillation layer of phosphor grains in an adhesive binder. Therefore an approximation of Mie scattering is included, which describes light scattering from spherical particles. Optical absorption is included — all photons are stopped after traversing 7 mm of the phosphor layer — this limits the simulation time but does not have a significant impact on the number of photons emitted from the front of the screen and only about 20% of the light escapes [7] from the front of a 300 µm thick screen. The most important optical processes included are reflection and refraction at boundaries of changing refractive index which significantly affect both the light output and the angular distribution of the emitted photons.

Table 1: GadOx Physical Properties

ρ [g cm^{-3}]	7.44
ϵ [%]	0.20
Peak E_γ [eV]	2.240
Yield Y [MeV^{-1}]	8.9×10^4
Grain size a [µm]	8.5
I_R	1.82

Table 2: GadOx + Binder Mixture Bulk Physical Properties

Packing fraction	0.5
ρ [g cm^{-3}]	4.25
$l_{abs.}$ [mm]	O 70 (7 mm used in sim.)
Phos. coat. thickness t [µm]	300
I_R	1.50

The microscopic density profile of the screen is approximated by composing the screen of layers of pure GadOx interleaved with layers of pure binder material. However, the bulk material in the simulation has a constant refractive index, thereby maintaining the bulk optical properties of the material. It is assumed that half of the front layer of phosphor grains protrude from the binder material. Therefore the front layer of phosphor will consists of a layer of hemispheres of phosphor directly coupled to the air and will therefore emit light isotropically within approximately ±45° (beyond this angle photons begin to refract through neighbouring grains). Therefore, the front layer of GadOx is given a refractive index of 1. The numerous physical and optical properties needed to describe the screen such as yield, refractive index, particle size, phosphor thickness, density *etc.* were compiled from various sources [7–14]. The most important parameters are listed in Tabs. 1 and 2.

The simulated angular distribution as a function of screen thickness (figure 3) and the simulated light output in one hemisphere of the screen as a function of energy (figure 4) both show reasonable agreement with measurement [13, 14].

SIMULATION USING BDSIM

BDSIM [15] is a Geant4 and C++ based particle tracking for beam line simulation. It combines fast particle tracking

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[1] GadOx screens are more commonly known by the trade names LANEX, DRZ or P43.

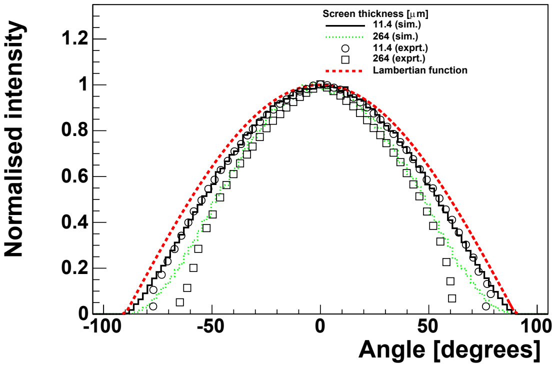

Figure 3: Angular distribution of photons emitted from the screen - simulation vs. measurement.

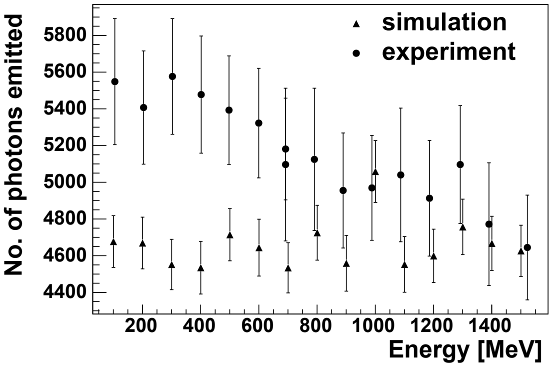

Figure 4: Number of photons emitted from the front of the screen - simulation vs. measurement.

routines with a powerful geometry description framework using a high level description language, GMAD. BDSIM includes standard parametrised geometry and field descriptions for many common accelerator components such as magnets and collimators. It also allows user-defined beam line elements using either the GMAD description or users can directly create new components by writing a class in C++ inheriting from the BDSAcceleratorComponent base class. The AWAKE spectrometer is simulated using BDSIM by defining the beam line from the exit of the plasma cell to the CCD camera. Standard "drift" and "quadrupole" components are used for the upstream drifts and quadrupoles. Then the MBPS dipole magnet geometry including the vacuum chamber was user-defined using the high-level geometry description language. A uniform dipole field was used, by a non-uniform field map has been obtained from field measurement data for use in further studies. Finally, a parameterised C++ class was written to describe the geometry from the scintillator screen to the camera (including the upstream part of the vacuum chamber and its window), including parameters such as screen angle, screen thickness, vacuum window thickness *etc.* to allow the setup to be tuned by altering just a few parameters in the GMAD file. Particle sampling planes were placed at possible camera locations for post-analysis of simulated camera readout response.

SPECTROMETER RESPONSE

A possible witness electron spectrum was tracked from the exit of the plasma cell through the entire geometry to the scintillator screen including any secondary interaction processes along the way such as electromagnetic showers in the beam pipe walls, residual vacuum gas and other materials using a preliminary vacuum chamber geometry. 1.27×10^6 particles were fired from a sample spectrum 1% of that size. In reality, the witness bunch population post-plasma-cell could be of the order of 10^7. The resulting particle distributions (including optical photons) were recorded at the entrance and exit of the scintillator screen and at the camera. The histograms were binned according to the camera pixel size, and the resulting energy spectra were reconstructed.

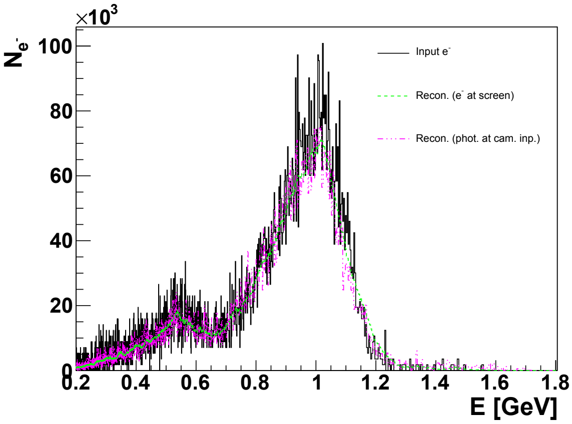

Figure 5: Energy reconstruction. Black line: actual spectrum. Green line: spectrum reconstructed from electrons at screen. Magenta line: spectrum reconstructed from photons entering CCD camera lens assuming a perfect optical system with CCD camera pixel binning.

CONCLUSIONS

A Geant4 simulation of the scintillator screen has been tuned to give reasonable agreement with measurements of the light output as a function of beam energy and angular distribution. Preliminary results using an earlier, less exact screen and vacuum chamber simulation, of the spectrum generated by the system in response to a possible witness electron distribution have been generated and appear to reconstruct the input spectrum. However, in future studies upstream sources of background such as particle scattering in the plasma cell and other diagnostic components must be tested, and appropriate shielding designed. The scattering of the drive beam photons in the updated vacuum chamber geometry as a function of vacuum pressure should be verified, but preliminary results show backgrounds are negligible at typical vacuum pressures.

REFERENCES

[1] E. Gschwendtner *et al.*, "Performance and Operational Experience of the CNGS Facility", IPAC'10, THPEC046, p. 4164–4166 (2010), `http://jacow.org/IPAC10/papers/thpec046.pdf`

[2] A. Caldwell *et al.*, "AWAKE Design Report", CERN Technical Design Report CERN-SPSC-2013-013 (2013), `http://cds.cern.ch/record/1537318`

[3] E. Gschwendtner *et al.*, "The AWAKE Experimental Facility at CERN", IPAC'14, MOPRI005, these proceedings (2014).

[4] K. Lotov *et al.*, "Natural noise and external wakefield seeding in a proton-driven plasma accelerator", Phys. Rev. ST Accel. Beams **16** (4), 041301 (2013), `http://link.aps.org/doi/10.1103/PhysRevSTAB.16.041301`

[5] `http://sba.web.cern.ch/sba/Documentations/docs/Magnets/MBP/MBP-1PageSummary.PDF`

[6] `http://www.andor.com/scientific-cameras/intensified-camera-series/istar-340t`

[7] T. Radcliffe *et al.*, "Monte Carlo optimization of metal/phosphor screens at megavoltage energies", Med. Phys. **20** (4), 1161 (1993), `http://dx.doi.org/10.1118/1.596970`

[8] G. E. Giakoumakis and A. J. Pallis, "On the Cathodoluminescence of Gd_2O_2S:Tb", Solid State Commun. **70** (4), p.419–421 (1989), `http://dx.doi.org/10.1016/0038-1098(89)91071-5`

[9] G. E. Giakoumakis *et al.*, "Absolute efficiency of Gd_2O_2Si:Tb Screens Under Fluoroscopic Conditions", Phys. Med. Biol. **34**, 673 (1989).

[10] Y. Glinec *et al.*, "Absolute Calibration for a Broad Range Single Shot Electron Spectrometer", Rev. Sci. Instr. **77**, 103301 (2006), `http://dx.doi.org/10.1063/1.2360988`

[11] A. Buck *et al.*, "Absolute Charge Calibration of Scintillating Screens for Relativistic Electron Detection", Rev. Sci. Instr. **81**, 033301 (2010), `http://dx.doi.org/10.1063/1.3310275`

[12] S. Agostinelli *et al.*, "Geant4 — a simulation toolkit", Nucl. Instr. Meth. A, **506** (3), p.250–303 (2003), `http://dx.doi.org/10.1016/S0168-9002(03)01368-8`

[13] G. E. Giakoumakis and D. M. Miliotis, "Light angular distribution of fluorescent screens excited by x-rays", Phys. Med. Biol. **30** (1), p.21–29, (1985), `http://dx.doi.org/10.1088/0031-9155/30/1/003`

[14] K. Nakamura *et al.*, "Electron Beam Charge Diagnostics for Laser Plasma Accelerators", Phys. Rev. ST Accel. Beams **14**, 062801 (2011), `http://dx.doi.org/10.1103/PhysRevSTAB.14.062801`

[15] S. T. Boogert *et al.*, "Beam Delivery Simulation (BDSIM): A Geant4 Based Toolkit for Diagnostic and Loss Simulation", IBIC'13, WEPC46, p. 799–802 (2013), `http://jacow.org/IBIC2013/papers/wepc46.pdf`