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CALIBRATION OF THE AWAKE ELECTRON SPECTROMETER WITH ELECTRONS DERIVED FROM A PARTIALLY STRIPPED ION BEAM

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Abstract

The electron spectrometer for the Advanced Wakefield (AWAKE) experiment at CERN has been tested using an electron beam derived from partially-stripped ions accelerated in the Super Proton Synchrotron (SPS). The remaining electrons are stripped by passage of the beam through a thin screen upstream from the spectrometer, and using knowledge of the ion beam charge and energy, models of the spectrometer response could be verified.

INTRODUCTION

Plasma wakefield acceleration is a promising technology for future particle accelerators in terms of both energy gain and reduction in size and cost. Using wakefields driven by protons delivered by the Super Proton Synchrotron (SPS) at CERN in a Rb laser-ionized plasma, the Advanced Wakefield (AWAKE) experiment is a proof-of-principle plasma wakefield accelerator with demonstrated energy gains for injected electrons of up to 2 GeV over the 10 m length of the plasma [1].

The electron Spectrometer

The diagnostic spectrometer for accelerated electrons at AWAKE comprises a quadrupole doublet followed by a large-acceptance dipole. The magnet arrangement directs the electron bunch onto a 1 m DRZ High scintillating screen (Mitsubishi), which is observed, via a system of mirrors, from 17 m away by an Andor image-intensified CCD camera. More details of the technical specifications of the spectrometer may be found in Reference [2]. Briefly, the bending dipole transforms differences in energy into horizontal displacement on the screen, and the quadrupoles, which have a 6% strength difference, provide focussing up to a maximum of 1.3 GeV. Using simulations performed with the Beam Delivery Simulation (BDSIM) software [3], a polynomial fit function for screen position to beam energy for various dipole currents was calculated. Additionally, simulations to predict the variation of beamspot size in both horizontal and vertical planes have been performed at various quadrupole currents.

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ELECTRON BEAMS FROM PARTIALLY-STRIPPED IONS TO AWAKE

As part of the Gamma-Factory project [4] machine development (MD) runs, partially stripped Pb ions (PSI) were accelerated in the SPS. Usually, ion acceleration in the SPS is performed with fully-stripped ions. In order to study the stability of high energy atomic beams, in these MD runs Pb^{81+} and Xe^{39+} were accelerated up to rigidity-equivalent energies to 400 GeV protons, that is, the total relativistic energy E_{ion}:

$$E_{ion} = \sqrt{Z^2 E_p^2 \beta_p^2 + E_{0(ion)}^2} \tag{1}$$

where Z is the ion charge, E_p the proton energy (400 GeV in this case), β_p the β for the proton beam, and $E_{0(ion)} = m_0 c^2$, the rest mass energy of the ion. For the AWAKE PSI run, only $^{208}Pb^{81+}$—hydrogen-like Pb—was used, meaning the ions were accelerated to 32.40 TeV, or 155.7 GeV/n. The utility of these ion beams for AWAKE calibration is that the remaining electron can be stripped by passing the beams through a thin foil or screen, to produce electron beams with well defined energies and narrow energy spreads. The energy of the resultant electron beam can be calculated from simple kinematic arguments; the binding energy of the electron being ignored, the ions and ionized electrons have the same Lorentz factor γ, so

$$E_e = \frac{E_{ion}}{E_{0(ion)}} E_{0(e)} \tag{2}$$

or 85.46 MeV for H-like Pb ($E_{0(e)} = 0.511$ MeV).

Determination of Energy Distribution, Angular Distribution and Bunch Population

In order to produce a fit for the electron optics of the spectrometer, the energy distribution of the test electron beam must be determined. The above calculation (Equation 2) predicts only the initial energy of the stripped electrons, however, as they are stripped inside a foil, the electrons can subsequently interact with the material of the foil which will worsen the energy distribution. Furthermore, the position in the foil that stripping process occurs affects how much material the electrons must subsequently pass through. In order to determine this position, the stripping cross-section must

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be known—this also in principle allows a charge calibration of the scintillator screen, as the amount of charge reaching the screen can then be determined from the ion beam charge, which is measured on entry to the AWAKE experimental zone. Finally, in order to make predictions about the electron optics, the angular distribution of the electron beam must be known; this is also affected by the passage of the beam through material.

The stripping cross-section was calculated using the plane-wave Born approximation, following the method of References [5–7]. This defines the cross-section σ_s as the sum of two components, corresponding to a Coulomb interaction (σ_{Coul}) and a transverse interaction (σ_{trans}), with:

$$\sigma_{Coul} = f\left(\eta_k\right) \frac{4\pi a_0^2 Z_t^2 \alpha}{Z_p^2} \tag{3}$$

and

$$\sigma_{trans} = 5.23 \times 10^3 \left(\frac{Z_t}{Z_p}\right)^2 \left(\frac{\log \gamma^2 - \beta^2}{\beta^2}\right) \tag{4}$$

defined in barns, where Z_t, Z_p are target and projectile atomic number, $\eta_k = \left(\frac{\beta}{Z_p \alpha}\right)^2$, and f is a slowly varying factor precalculated and tabulated for interpolation in [7]. It can be seen that the transverse interaction will eventually come to dominate the cross-section (as is already the case here) as σ_{Coul} approaches a constant and $\sigma_{trans} \propto \log \gamma^2$. This observation is not borne out by experiment [8,9], and a correction [10] to this calculation by defining a critical value for γ,

$$\gamma_c \sim \frac{60\left(\alpha Z_p\right)^2}{Z_t^{1/3}} \tag{5}$$

is used to compensate for this. Using this approximation for the stripping cross-section, a new discrete process was implemented in Geant4 [11–13] for ion stripping in order to calculate both the energy spread of the resulting electron beam and its beam divergence distribution.

Ion stripping occurs in two locations in this calibration run: first at an upstream vacuum window separating the SPS from AWAKE (200 μm Al foil), and second at a beam observation station (BTV, 300 μm Si) after the AWAKE plasma cell. This arrangement means that much of the ion beam is in fact fully stripped by the time it reaches the BTV station, with the electrons being lost in transport from the upstream foil. While this might seem disadvantageous at first, since it naturally reduces the H-like population available for stripping at the desired position, it has a beneficial side effect of allowing the cross-section calculated in the previous section to be determined experimentally as well. The mixed charge state ion beam passes through a dipole bend—usually used at AWAKE for merging the proton and laser beams so that they then co-propagate—and the difference in charge leads to their separation at the BTV station. Imaging the two beam spots to determine the relative intensity can then lead

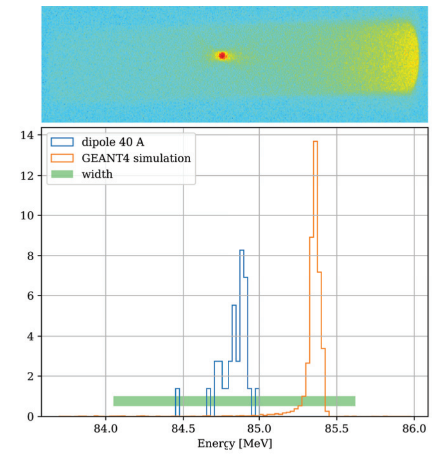

Figure 1: Above: PSI electron beam spot on the spectrometer screen. The asymmetry across the screen is the background arising from the ion beam. Below: predicted and measured energies, including the apparent width of the observed energy distribution.

to the cross-section (for Pb–Al interactions, at least) via the Beer–Lambert law:

$$\sigma_{s(Al)} = \frac{-\log P}{n_{Al} l} \tag{6}$$

where P is the proportion of ions that remain in the 81+ state, n_{Al} is the number density of the target (Al in this case) and l the target thickness.

RESULTS

A comparison of the calculated energy and that measured by the spectrometer is shown in Figure 1. A small discrepancy is observed between the prediction and measurement, which is attributed to the uncertainty of the undeflected axis position (this is typically included in calculation of accelerated electron energy at AWAKE). The width of the observed peak is shown as a band on the plot, for comparison with the expected width of the distribution. This is most likely dominated by other effects, primarily affecting the optical line from screen to camera.

To understand the electron optics, a fit was performed of the vertical and horizontal beam size (measured as the FWHM of the peak, corrected by a factor of 2.355) as a function of quadrupole current assuming Gaussian beam, but also including the energy-to-position transformation of the dipole. This is shown in Figure 2, with the best fit returning values for the angular distribution width of $\sigma_{xp} = 4.98$ mrad, $\sigma_{yp} = 2.63$ mrad—significantly at variance with the Geant4 prediction of 9.50 mrad for both directions. The difference is accounted for by the angular acceptance of the beampipe between BTV screen and spectrometer, which leads to beam loss from the tails of the momentum distribution. This effect is dependent on quadrupole current, and is illustrated in Figure 3. Note that the fits in Figure 2 include the resolution of the optical system in addition to the electron optics and beam parameters.

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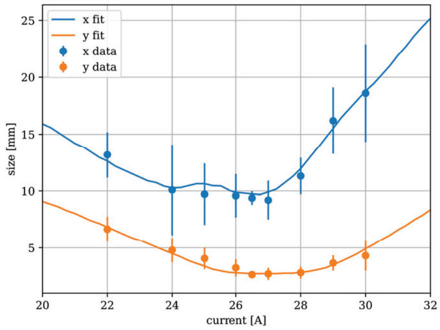

Figure 2: Fits to beam size as a function of quadrupole current. The best fit values for the beam divergence width are $\sigma_{xp} = 4.89$ mrad and $\sigma_{yp} = 2.63$ mrad.

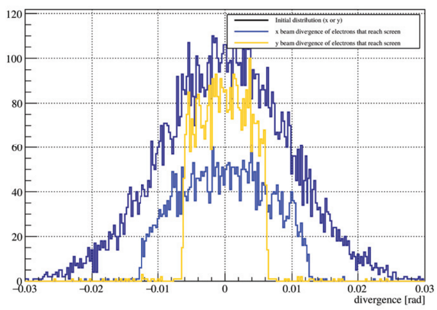

Figure 3: Effect of angular acceptance for one particular quadrupole current. It differs in x and y owing to the alternate focussing or defocussing effect of quadrupole lenses.

Figure 4 shows the asymmetric beamspot recorded on the BTV/stripping screen. The asymmetry arises from the superposition of two Gaussian beamspots corresponding to the two charge states present in the beam. A fit of two rotated Gaussian peaks to this data produces an estimate of the $^{208}\mathrm{Pb}^{81+}$–Al ion ionization cross-section of $1.24(11) \times 10^{-25}$ m^2, where the uncertainty is statistical, from combining multiple BTV images and from fitting parameter uncertainty estimates. The results of Eqs. 3 and 4, with the correction of Eq. 5, predict a cross-section for this process of $1.093(2) \times 10^{-25}$ m^2, where the uncertainty in the calculation comes from the energy spread of the ion beam. An additional uncertainty of 10–20% might be expected in the calculation [10]. The difference between the measured and calculated values could also arise from incorrect assumptions about the thickness, density and composition of the upstream stripping foil.

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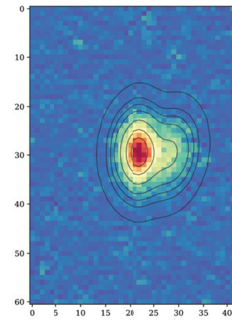

Figure 4: Double ion beamspot at downstream stripping position, showing the contours of the fitted double Gaussian. One pixel unit is approximately 100 μm.