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Simulating the Measurement of the Electron Beam Emittance at AWAKE

The AWAKE Collaboration

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Abstract: In preparation for the experiments at AWAKE, simulations were used to determine to what precision the spectrometer is to be able to measure the emittance of the accelerated electron beam. A range of experimental parameters, including bunch size, energy, energy spread, emittance were tested and the degree to which these parameters effect the measurement of the emittance were determined. Systematic errors arising from the discrete pixels on the screen were found to increase the measurement emittance by 1×10^{-8} m rad.

Keywords: plasma wakefield, spectrometer, emittance, electron beam, simulation

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Chapter 1

Introduction

Advancements in quantum and particle physics are driven by experimental observations. They are used for verifying hypothesise based on previous observations or for providing data from which new hypothesise can be drawn. Particle colliders create large amounts of observation data from particle interactions and improvements to these come largely in the form of increasing the energy of the colliding particle beams. Proton beam energies have reached energies of 13 TeV using current synchrotrons, however lepton-lepton colliders have yet to reach the TeV energy scale. Higher energy electron and positron colliders promise much higher precision measurements as they are fundamental, point-like particles and they will be able to interact within a much cleaner environment.

Looking at current accelerators, circular electron or positron accelerators are not possible at these energies unless the accelerator reaches the 100 km scale as electrons at this energy approach the speed of light and since they are accelerating in a circle they will radiate large amounts of their energy. An accelerator at the 100 km scale is impractical due to geographical and financial limitations. Similar problems also arise in linear colliders where current radiofrequency (RF) cavities in a linear collider will have to be tens of kilometers in length to reach the TeV scale, this is with current acceleration gradients of up to $100\,\mathrm{MV\,m^{-1}}$. This urges the development of a new methods for the acceleration of particles.

1.1 Proton Driven Plasma Wakefield Acceleration

The concept of accelerating particles in plasma was promising as plasma is able to sustain large electric fields. The idea being that energy can be transferred to a group of charged particles by injecting them into the plasma wakefield that follows a high energy laser pulse or proton bunch, using the plasma as an energy transfer medium. The witness bunch is then accelerated by the high electromagnetic gradient.

1.1.1 Self-modulation instability

The first challenge in the development of this accelerator was getting the length of the proton driver bunch small enough so that resonance occurs with the electrons in the plasma. Typical proton bunches, i.e. those produced by the CERN Super Proton Synchrotron (SPS), have lengths of $\sim 10\,\mathrm{cm}$ which cannot directly create strong plasma waves at the required wavelength in the mm scale as the Fourier component of the proton beam at the plasma frequency is negligible. Simulations [1] on the compression of these bunches show that reducing the longitudinal phase volume blows up the transverse phase volume. An alternative method would be to split up the proton bunch into a number of micro-bunches to be simultaneously decelerated.

Figure 1.1. Phasing of the electron bunch for increased density (a) correct density (b) and decreased density (c). Figure credit to [5]

An instability between the beam and the plasma arises from the mutual amplification of the rippling of the beam radius and the plasma wave. This instability tends to destroy the plasma wave as the amplification focuses and defocuses selected slices of the beam. This problem was solved by seeding the self-modulated instability (SMI) with a short electron bunch [2], a laser pulse [3] or a sharp cut in the bunch profile[1]. This will promote a single mode and suppress other modes, including the strongest competing modes, the hosing modes [4] and produce well-separated micro-bunches.

1.1.2 Uniform-density plasma cell

The plasma wavelength is $\lambda_{pe} \approx 1.26\,\mathrm{mm}$ meaning that the 10 cm proton bunch will have to be split into ~ 100 micro-bunches in order to be able to drive the wake. Each micro-bunch contributes to the wakefield, and only if the plasma density is uniform will the contribution of each bunch be coherent. Incoherence will cause the electron bunches to arrive at the wrong phase in the plasma oscillation. An increase in the plasma density will shorten the plasma wavelength causing the electron bunch to crest plasma wave it was riding and fall into the defocusing phase of the plasma wave as shown in Fig 1.1(a). A decrease in the plasma density will increase the plasma wavelength causing the plasma wave to fall further behind the electron bunch meaning the electron bunch to fall into the trough of the plasma wave resulting in a deceleration of the electron beam 1.1(c). The electron beam must be in the region of length $\lambda_{pe}/4$ between the defocusing and decelerating phases of the plasma wave.

This requirement of the plasma limits the plasma selection to being uniform rubidium vapor, ionised by a co-propagating laser pulse [6, 7]. Rubidium was chosen due to it's low ionization potential and heavy atomic mass. A heavy element is required to minimize the movement of the plasma's nuclei which causes adverse effects on the plasma's behaviour [8, 9]. The Rubiduim vapor is kept in thermodynamic equilibrium at a constant temperature and volume.

1.1.3 Injection of the witness beam

Due to SMI, the shape of the drive beam changes in the plasma and for the first four meters, the difference between the phase velocity of the wakefield and the proton beam velocity is quite large and this will effect the electron beam in the same manner as having a non uniform plasma, detailed above. To avoid this problem it was suggested that the electrons could be injected into the plasma after SMI had fully developed. The design of the injection method arrived at passing the electron beam through a narrow vacuum tube separated from the plasma by a thin foil. Then after $\sim 4\,\mathrm{m}$ the electrons will be directed into the wakefield close close behind the proton driving beam.

1.1.4 AWAKE

The aim of this experiment is to provide a proof of concept for proton driven plasma wakefield acceleration. An overview of the experiment is as follows:

The SPS will provide the 400 GeV proton driver beam with a bunch length of $\sigma_z = 12\,\mathrm{cm}$ and an intensity of $\sim 3 \times 10^{11}$ protons/bunch. This will travel down the 750 m long CNGS transfer line and be focused to $\sigma_{x,y} = 200\,\mu\mathrm{m}$ and enter a 10 m long Rubiduim vapor plasma cell with an adjustable density at the 10^{14} to 10^{15} electrons/cm^{-1} scale.

The proton driver will self modulate at the plasma wavelength λ_{pe} after being seeded by a high powered $\approx 4.5\,\mathrm{TW}$ laser pulse that is co-axial and co-propagating with the proton driver beam. This laser also serves the purpose of ionising the Rubidium vapor. These two beams need to be

Figure 1.2. Phase space ellipse with x or y on the horizontal axis and x' or y' on the vertical axis. (credit to [11])

synchronous to within 100 ps and the focal point of the proton beam is required to be $\leq$ 100 µm and $\leq$ 15 µrad so they are co-axial for the full length of the plasma cell.

The electron witness beam will be created via photo-emission by an illuminating cathode electron source and accelerated by a 2.5 cell RF-gun and a meter long booster at 3 GHz.

1.2 Emittance

The beam emittance is a quantity that describes the collective motion of all the particles in the beam, providing a qualitative way of describing the quality of the beam. It is a conserved quantity in the absence of a z component (i.e. in the direction of the beam) in the magnetic field and when the beam is not being accelerated.

The position of each particle in Cartesian coordinates is not sufficient in describing the state of a beam so each beam particle is represented in six-dimensional phase space with coordinates (x, p_x, y, p_y, z, p_z) where $p_x \approx\ p_0 x'$ and $p_y \approx\ p_0 y'$ are the transverse momenta, z is the position along the beam trajectory, p_z is the longitudinal momentum and x' and y' are the trajectory angles to the horizontal and vertical planes. Since the transverse momenta, and therefore x' and y', are generally quite small we can approximate $\sin(x') \approx x'$ and $\sin(y') \approx y'$. We can then project this six-dimensional volume into three independent two-dimensional phase planes, because in this approximation there is no coupling between those degrees of freedom.

The horizontal emittance of the beam is defined by considering the ellipse in the $x' - x$ phase space that contains 95% of all the particles [10]. The area contained by this ellipse divided by π is defined as the emittance in units of π-mm-mrad.

$$\int_{ellipse} \mathrm{d}x\mathrm{d}x' = \pi\varepsilon$$

Fig. 1.2 shows a beam projected onto a two dimensional phase plane. The emittance can be described by the equation of the ellipse:

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

where α, β are γ are ellipse parameters that determine the ellipse's shape and orientation and are related by this equation

$$\beta\gamma - \alpha^2 = 1$$

It follows that the beam matrix is

$$\sigma = \begin{pmatrix} \sigma_{1,1} & \sigma_{1,2} \\ \sigma_{2,1} & \sigma_{2,2} \end{pmatrix} = \begin{pmatrix} \beta\varepsilon^2 & -\alpha\varepsilon^2 \\ -\alpha\varepsilon^2 & \gamma\varepsilon^2 \end{pmatrix}$$

such that $\varepsilon = \det\sigma$, $\sigma_{1,1}$ is the besm size and $\sigma_{1,2}$ is the orientation in phase space. We can relate the beam matrix after passing through quadrupoles, σ_1, to the original beam matrix, σ_0, as follows

$$\sigma_{1,11} = c^2(k)\sigma_{0,11} + 2c(k)s(k)\sigma_{0,12} + s^2(k)\sigma_{0,22}$$

where we plot the final beam size $\sigma_1, 11$ against the quadrupole strength k. σ_0 is determined from the fit and it's determinant will then give the emittance.

Chapter 2

Project outline

The development of this experiment has been heavily simulation driven. For example, simulation code had to specifically be developed for the simulation of the plasma which needed to be able to resolve for time scales of ω_p^{-1}, (where ω is the frequency of the plasma wave) and length scales of down to c/ω_p, as existing codes were not tuned to resolve at these scales. Different simulation softwares are tuned to be used for different sections of the AWAKE experiment.

I will be working on simulating the electron spectrometer using BSDIM [12], simulation software in active development, designed to simulate and track particle beams passing through accelerators and detectors. It is built on top of the Geant4 toolkit [13] for the simulation of particles through matter, which also provides the graphical user interface for a visualisation of the simulation. Event data is stored using ROOT [14], an advanced statistical analysis and visualisation framework designed to work for petabyte scale data storage.

More specifically, I will initially be looking at calculating the emittance of the accelerated electron beam using data from simulated accelerated electron beams. Recent simulations of the spectrometer used an idealised electron beam [15] and I will be continuing this line of investigation. The electron beam profile and other properties immediately after it leaves the plasma cell will be provided by separate simulations using LCODE. This data is used as input for the BDSIM simulation where we will simulate the beam passing through dual focusing quadrupoles in both the horizontal and vertical planes. The simulation will be able to provide all the raw data about the final state of the electron beam, however, in reality we will not be able to simply query the beam properties. The measurement of the energy spectrum will be carried out by using a magnetic dipole downstream of the dual quadrupoles, and observing the horizontal spread of the electron beam on a screen. This screen will also be sumulated with BDSIM taking into account the screen resolution and detection rates.

I will also be working on the modeling and simulation of the background radiation from the plasma cell and other sources using real world data to help build an accurate model. All of these simultions along with real data will help in finding optimal parameters for each component of the spectrometer, including the strength of the quadrupoles and the dipole, the lens parameters of the camera and the properties of the screen.

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