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COMPARISON OF FOURIER SIGNAL AND ERROR ANALYSIS TECHNIQUES FOR IDENTIFYING THE SELF-MODULATION FREQUENCY OF A PROTON BUNCH

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Abstract

The AWAKE experiment uses an ultra-high energy proton beam to create large amplitude wakefields for accelerating electrons in plasma. The proton beam is much longer than the plasma wavelength, and must be formed into small, sub-wavelength sized beamlets before it can effectively drive the wake. These beamlets are referred to as micro-bunches and are formed by the plasma self-modulation instability. An important aspect of AWAKE is to measure the depth, frequency, and stability of the modulation, as this provides critical information for establishing the presence of a high-amplitude wakefield driven by a self-modulation proton bunch. This paper discusses Fourier Analysis techniques for measuring the modulation frequency and compares error estimation techniques that work for both small and large datasets.

INTRODUCTION

AWAKE is the world's first proton beam-driven plasma wakefield experiment [1, 2]. AWAKE utilizes the 400 GeV proton beam produced by the SPS accelerator at CERN. The primary advantage of the proton beam is that it stores 20 kJ of energy, or nearly one thousand times the energy stored in electron beams [3] or laser pulses [4] used in previous state-of-the-art plasma acceleration experiments. This implies that the proton bunch can be used to accelerate a trailing electron bunch to extremely high energies in a single plasma cell, thus avoiding the problem of staging [5]. However the length of the proton bunch produced by the SPS is long, typically between 6-12 cm, and the plasma wavelength is short, about 1.2 mm for a plasma density of $n = 7 \times 10^{14}$ cm^{-3}. The proton bunch is incapable of exciting a high-amplitude wakefield because it lacks power at the high frequencies associated with the plasma oscillation. It is nevertheless possible to produce a high-amplitude wakefield as a result of the self-modulation instability (SMI) which can seeded by noise or by a short laser pulse [6]. We refer to the latter case as seeded self-modulation (SSM). In both scenarios, the wakefield grows as the proton beam is alternately focused and defocused at the plasma frequency, producing proton beamlets or ”micro-bunches". The micro-bunches are spaced at the plasma frequency and work together to resonantly drive a high amplitude wakefield.

The AWAKE experiment is composed of several critical systems which must work together to create the plasma wakefield and accelerate a trailing electron beam. These systems include the 400 GeV proton beam [2], a 10 meter-long Rubidium vapor source [7], a terawatt-class ionization laser, an electron beam source [8, 9], and diagnostics for each component. The 2017 experimental run focused on the study, control, and optimization of the plasma wakefield in both the SMI and SSM regimes. For this work, several diagnostics were used to measure the temporal evolution of the proton beam along the co-moving coordinate $\xi = z - ct$. The growth and strength of the wakefield can be inferred from the divergence of the protons as measured along ξ with the streak camera [10], and with a halo monitor that integrates over ξ [11]. The frequency of the modulation is also measured by the streak camera as well with an RF-heterodyne monitor [12]. Since the streak camera is capable of making spatio-temporal observations of the modulated proton beam, it is the primary diagnostic for characterizing the frequency and amplitude of the micro-bunches. In the remainder of this paper, we discuss the streak camera data and analysis pipeline, as well as the procedure for determining statistical and systematic errors of the measurements.

TIME-RESOLVED IMAGE DATA

The proton bunch is modulated into micro-bunches during its transit through the plasma and passes through a metallic foil two meters downstream of the exit of the Rubidium cell. The beam produces Optical Transition Radiation (OTR) as it passes through the foil, and the OTR light has the same spatio-temporal pattern as the bunched beam. The light is sent through a series of lens and mirrors to a dark room where it is imaged onto the aperture of a streak camera. Inside the streak camera, the OTR photons are converted into electrons by a photocathode and accelerated through a ”streak tube" towards a phosphor screen [13]. A time-varying, transverse voltage is applied to the streak tube such that the electrons receive a kick that depends on when they were produced at the photocathode. The electrons arrive at different transverse positions on the phosphor screen and the emitted light is imaged onto a CMOS camera. The streak camera manufacturer provides a calibration of the streak axis so that the vertical dimension of image can be interpreted as the co-moving temporal ξ dimension. The AWAKE streak camera is a Hamamatsu C10910-05 model with 16-bit, 2048×2048 pixel ORCA-Flash4.0 CMOS sensor, binned to 512×512 pixels for streak operation. The streak camera provides time windows ranging from 2 ns down to 72 ps. For the smallest time window, the resolution is limited by the streak dynamics rather than the pixel size and was found to be better than 2 ps [10].

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IMAGE ANALYSIS AND FREQUENCY IDENTIFICATION

The goal of the streak image analysis is to identify the frequency of the micro-bunching. Once an image has been selected for processing, it enters the analysis pipeline. The steps are as follows:

1. Apply a median filter to remove noisy pixels.
2. Identify a region of interest.
3. Project the image data along the time axis to create a one-dimensional time-amplitude signal.
4. Apply a Hann window to suppress edge effects.
5. Zero-pad the projection.
6. Apply a Fast Fourier Transform (FFT).

Note that by zero-padding the projection, we increase the resolution of the FFT, resulting in a smoother distribution and a more accurate determination of the measured frequency, but the absolute resolution of the FFT is still limited by the length of the initial time window.

In some cases, the peak of the FFT is less pronounced. Simply identifying the maximum of the spectra may produce an erroneous result due to bias from from the DC beam distribution or high-frequency noise. A more robust technique for identifying peaks in the Fourier spectra is to use purpose built algorithms.

ERROR ANALYSIS

The goal of the analysis is to identify the micro-bunching frequency in the Fourier spectra. Once the frequency is identified, we need to ascertain the associated measurement error. The statistical error on the mean defined as

$$\sigma_m = \frac{\sigma}{\sqrt{N}} \tag{1}$$

where σ is the standard deviation of the measured frequency values and N is the number of measurements.

It is often the case at AWAKE that we are working with small datasets of dissimilar data. This is because the repetition rate of the experiment is roughly once per thirty seconds, limiting the experiment to a couple thousand shots per day. After cuts are applied to the data, there may only be a handful of events that meet the criteria for cross-comparison. In this case, σ is likely to be large and N is small, so the error on the mean will be quite large, even in the peak frequency is clearly determined from the image. Is it still possible to discuss a statistical uncertainty in the measurement for this scenario?

One approach is to take the FFT of each column of pixels in the image, rather than taking the FFT of the projection. This results in a large number of Fourier spectra corresponding to the number of columns identified in the region of interest. For each spectrum, we identify the peak frequency and create a histogram.

CONCLUSIONS

AWAKE utilizes an advanced streak camera diagnostic with picosecond-level resolution to measure the self-modulation of a proton beam by a plasma. The process for extracting a modulation frequency from a streak camera image is described, and the peak prominence algorithm is identified as most robust tool for finding the spectral peak.

The data rate at AWAKE is roughly 0.033 Hz, which results in selected data samples that might contain many similar events or perhaps just one event. We described techniques for identifying the statistical uncertainty on the measurement in both cases.

REFERENCES

[1] R. Assmann et al., Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics, PPCF 56 084013, (2014).

[2] E. Gschwendtner et al., AWAKE: The Advanced Proton Driven Plasma Wakefield Experiment at CERN, Nucl. Instrum. Methods Phys. Res., A 829 76-82, (2016).

[3] M. Litos et al., High-efficiency acceleration of an electron beam in a plasma wakefield accelerator. Nature, 515(7525), 92-95, 11 (2014).

[4] W.P. Leemans at al., Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime, PRL 113, (2004).

[5] A. Caldwell et al., Proton-Driven Plasma-Wakefield Acceleration, Nature Physics, DOI:101038/NPHYS1248 (2009).

[6] N. Kumar et al., Self-Modulation Instability of a Long Proton Bunch in Plasmas, Phys. Rev. Lett. 104, 255003 (2010).

[7] E. Oz, P. Muggli, A novel Rb vapor plasma source for plasma wakefield accelerators (2014).

[8] K. Pepitone et al., The electron accelerator for the AWAKE experiment at CERN, Proceedings of EAAC (2015).

[9] J. Schmidt et al., The AWAKE Electron Primary Beam Line, Proceedings of IPAC (2015).

[10] K. Rieger et al., GHz Modulation Detection using a Streak Camera: Suitability of Streak Cameras in the AWAKE Experiment, Review of Scientific Instruments 88, 025110 (2017).

[11] M. Turner et al., Upgrade of the Two-Screen Measurement Setup in the AWAKE Experiment, IOP, Proceedings of IPAC (2017).

[12] F. Braunmüller et al., Novel diagnostic for precise measurement of the modulation frequncy of the Seeded Self-Modulation via Coherent Transition Radiation in AWAKE, NIM A, Proceedings of EAAC (2017).

[13] Hamamatsu Corporation, Guide to Streak Cameras, `https://www.hamamatsu.com/resources/pdf/sys/SHSS0006E\_STREAK.pdf`, (2008).