Proton Beam Alignment and Plasma Light Spectrum at AWAKE

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CERN Summer Student Report

15/09/2023

Abstract

This report provides a summary of the activities conducted during my CERN summer student internship within the AWAKE project. The tasks undertaken encompassed diverse aspects of the project. Initially, an examination of the proton beam alignment was performed, recognising its pivotal role in the experiment. Contributions were made towards the implementation of an improved alignment procedure of the proton bunch with respect to the plasma. Secondly, the installation of a spectograph as a diagnostic tool was completed, which allows to validate the integrated plasma light as a measure of wakefield amplitude. The analysis presented strongly indicates no spectral shift for higher wakefield amplitudes. Lastly, a 3D visualisation of a proton bunch undergone self-modulation in 10 m of plasma where ion motion decoheres wakefields at the tail of the bunch is shown.

1 The AWAKE Experiment

Plasma wakefields are one of the great hopes for the future of particle accelerators. They can be used to produce high accelerating gradients which may allow future accelerators to be more compact. The AWAKE project at CERN aims to generate GeV-level electron beams using protons from the SPS at 400 GeV. For a detailed setup of the experiment see [1]. In the current Run 2b a new Rubidium vapour source has been installed which allows for a density step in the plasma. With this new vapour source, the wakefield properties have been investigated with the goal of improving the energy gain of accelerated electrons over long distances.

2 Beam Alignment

One crucial part of the experiment is the alignment of all three beams with respect to each other. There are the laser pulse used for plasma formation; the proton beam driving wakefields and the electron beam undergoing acceleration. In the following, the proton beam alignment will be discussed in detail.

There are two categories of diagnostics for the proton beam position along the beamline: The first category consists of 21 low-resolution, non-invasive Beam Position Monitors (BPMs). In contrast, the second category comprises more precise but invasive Beam Screens (BTVs). During the measurement process, utilising the BTVs situated in front of the plasma is not feasible as the laser can not pass through them. Additionally, the position measurements obtained from BPM352 and 425 (see Figure 1) are compromised by plasma charge dispersing from the cell. Consequently, this discussion addresses two separate scenarios: initial alignment and online monitoring of the proton beam's position.

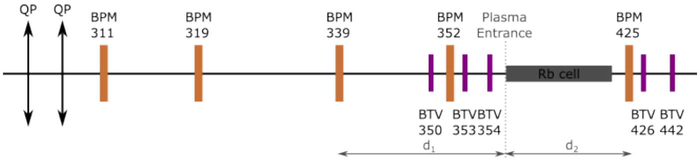

Figure 1: Schematic of the proton beam diagnostics along the end of the AWAKE beamline after the last proton quadrupoles (QP).

The alignment of the proton beam is characterised by the offset of the beam at the entrance of the vapour cell and the angle to the design trajectory in both transverse axes respectively. With AWAKE Run 2c in view, it is required to align the proton beam with a position accuracy of 5 µm to allow for high quality acceleration. Therefore, the current alignment procedure was reviewed and its accuracy has been calculated.

The alignment procedure performed in the previous runs uses 20 measurements at BPM339 and BPM425 to calculate these quantities. In order to estimate the accuracy of this alignment procedure, the resolution of the BPMs was determined using a dataset of 125 events collected on the 08/05/2023. The correlation of the BPM measurements was analysed for both axes using Singular Value Decomposition [2]. By removing the 4 largest contributions, the remaining jitter is attributed to the resolution. The standard deviation of the treated data corresponding to the resolution can be seen in Figure 2. The resolution averages 50 µm to 100 µm, which agrees with previous measurements. In particular, the BPM339 and 425 used for alignment (19 and 21 in Figure 2) have a resolution of $\sigma_1 = 50\,\mu\text{m}$ and $\sigma_2 = 85\,\mu\text{m}$ respectively (average of both axes).

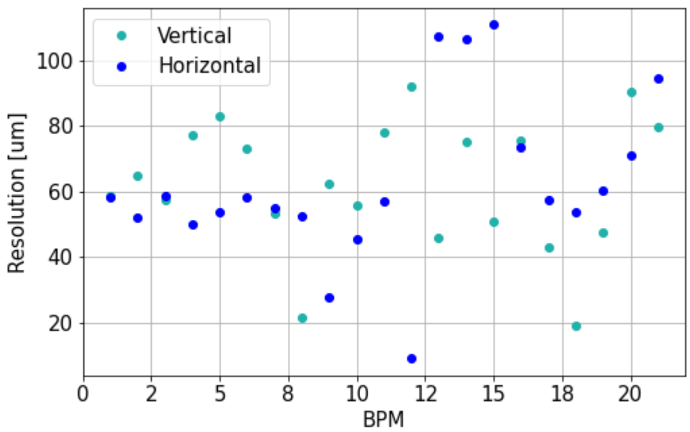

Figure 2: Vertical and Horizontal resolution for all 21 BPMs along the AWAKE transfer line.

Using these numbers the accuracy of the alignment procedure can be calculated as follows for one transverse plane. The distances from the BPMs to the plasma entrance for which these numbers will be calculated are given by $d_1 = 7.98\,\text{m}$ and $d_2 = 11.87\,\text{m}$, see Figure 1. For the accuracy of the position at the plasma entrance $x = x_1 + \frac{d_1}{d_1+d_2}(x_2 - x_1)$, the error can be propagated as

$$\sigma_x = \frac{1}{d_1 + d_2}\sqrt{(d_2\sigma_1)^2 + (d_1\sigma_2)^2}$$

. For small angles, the error of the angle at the plasma entrance $\theta \approx (x_2 - x_1)/(d_1 + d_2)$ can be estimated as

$$\sigma_\theta \approx \frac{1}{d_1 + d_2}\sqrt{\sigma_2^2 + \sigma_1^2}$$

. An alignment based on a single shot would therefore have an accuracy of 45 µm in position and 5 µrad in angle.

For $n = 20$ shots used in the alignment procedure, the position resolutions σ_1 and σ_2 improve by a factor of $1/\sqrt{20}$ assuming the BPM resolution is limited by statistical errors. This leads to an accuracy of 10 µm and 1 µrad, respectively. Thus, the alignment employing the BPMs does not meet the accuracy requirements for run 2c.

The resolution of the BTVs can be estimated by assuming the projection of the proton beam on the screen to be an accumulation of several (independent) position measurements of (macro) particles. Therefore, the uncertainty of the mean is given by $\sigma/\sqrt{N}$ where σ is the width of the distribution and N is total signal. For BTV354 with a pixel size of 41.2 µm, a beam of 3×10^{11} protons has approximately a beam size of 1 mm. The total number of counts is on the order of 1.3×10^7 after a background removal. Thus the position resolution can be estimated around 300 nm. This agrees with the variance of the mean of the gaussian fit on the projection.

Performing a similar analysis on the BTVs shows clear correlations for the beam positions on different BPMs. Thanks to the small resolution, we can use the BTVs to estimate the proton jitter. A linear drift subtraction on the beam position is performed to exclude mid-term changes of the position. This analysis was first performed by V. Bencini [3]. Using the same dataset, the analysis was performed for BTV354. The proton jitter has been determined to be 5 um in the vertical and 24 um in the horizontal, after subtracting a drift of 5 µm h^{-1} in the vertical plane and none in the horizontal. plane This agrees with the data for BTV350 from V. Bencini. The larger horizontal jitter most probably originates from the jitter of the SPS septum extraction kicker. A similar study has been performed by V. Hafych in 2021 [4]. While this proton jitter is sufficient for the current run, it does not meet the requirements for Run 2c and needs to be improved.

With the future runs in mind, a new alignment procedure using the BTVs was implemented in the current run. This was made possible through previous efforts from G. Zevi della Porta and L.Verra, who developed the BTV alignment code in 2022 and installed the new BTV354 which has a higher reproducibility when flipping the screen in and out of the beam line. [5] The new alignment procedure uses 5 consecutive shots on BTV354 and BTV426 to calculate the alignment. Using the much better resolution for the position diagnostic of 300 nm, this new alignment procedure has a position and angle resolution of 130 nm and 20 nrad, respectively. This assumes ideal conditions, e.g. no noise and a Gaussian distribution of the proton bunch. As this is well below the proton jitter and accuracy of the orthogonal beamline steering, it satisfies the alignment goals while also requiring fewer shots. The procedure has been implemented starting from August 2023.

Despite the new alignment procedure has an improved resolution, the BTVs can not be used for an online monitoring. It has been also shown that monitoring on a shot-to shot basis is not feasible using the current BPMs as they don't resolve the proton jitter. However, an online drift analysis can be performed and has been tested. For that, the floating average of 21 events is calculated and this data series fitted with a linear drift. If several BPMs show a correlated drift, this can be used as an indication to check the alignment using the BTVs.

During testing of this procedure, it has been found that this does not improve the drift detection much to human operators. Firstly, sudden changes are only shown in the drift detection after a certain time due to the floating average. Secondly, any drifts in the SPS are usually noticed and corrected by their operators, leading to a oscillating change of the floating average rather than a drift. A comparison with SPS data may be subject of further investigation.

3 Plasma Light Spectrum

Plasma light intensity is the key quantity to investigate the wakefields in the new vapour source. In addition to Photo Multiplier Tubes (PMTs) measuring the plasma light intensity as a function of time and fast cameras providing a spatially resolved image, a spectograph measures the spectrum of the plasma light. The light from a viewport located 6.5 m from the start of the vapour source is coupled into an optical fibre using a fibre coupler. Behind a concrete shielding, the fibre light is dispersed using an ANDOR SR-750 spectograph and imaged with a gated CCD camera. The maximum wavelength range recordable for one shot is about 120 nm. In Figure 3, the full spectrum of the plasma light can be seen, which has been stitched together from multiple shots with 1 ms exporsure.

The full spectrum is dominated by two Rb atom (RbI) lines at 780.0 nm and 794.8 nm respectively [6]. Additionally, several smaller lines in particular around 450 nm are visible which can be attributed to Rubidium ions (RbII).

The spectrograph as a diagnostic tool is imple-

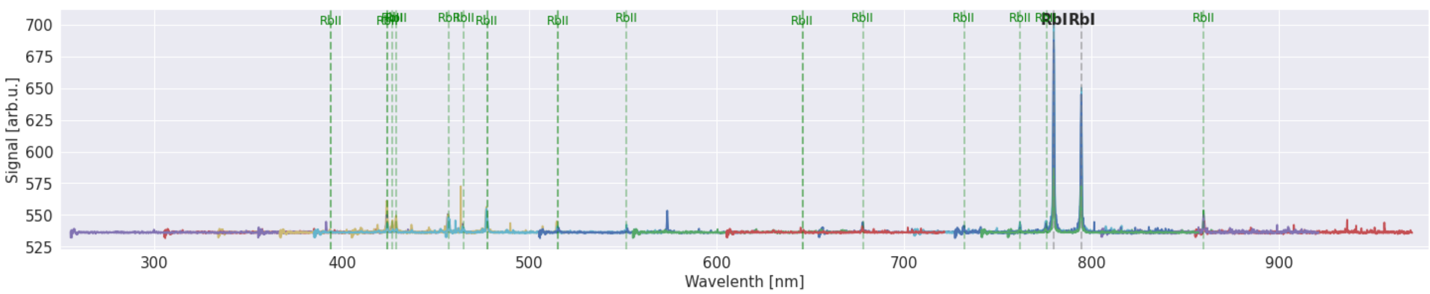

Figure 3: The full detectable spectrum of the plasma length stitched together from multiple shots.

mented to prove the assumption that the spectrally integrated light, captured by the PMTs, serves as a measure of the wakefield amplitude. It has been experimentally shown for a different plasma, that the energy loss of the driver is proportional to the intensity of a specific spectral line [7]. However, the relative height of the lines with respect to each other may change, leading to a shift in the spectrum which reduces value the of the PMT measurements. Therefore, the spectra of different plasma settings have been compared.

When comparing the line heights for the ion lines around 400 nm, it can be seen that all lines scale equally for different density step heights. This is expected as the ion distribution can be assumed to be thermal and therefore an increase in temperature does not shift the spectrum discernibly. However, the thermal distribution of atoms can be considered as independent from the ions and thus the line ratio of RbI to RbII lines is not governed by that mechanism.

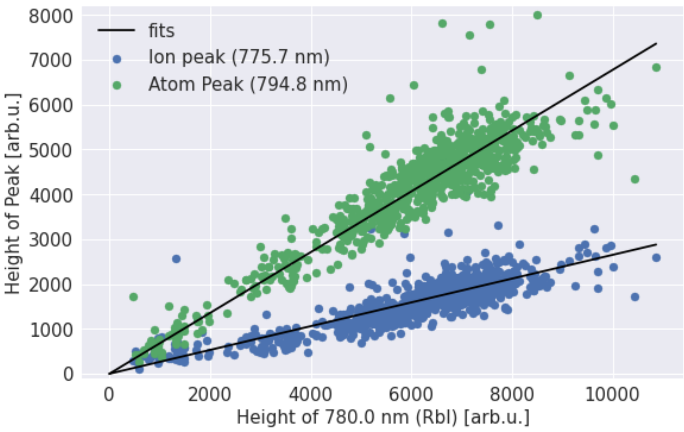

Figure 4: Heights of atom and ion peaks vs. the height of the largest peak in the spectrum (RbI) accumulated over various plasma settings.

In Figure 4, the peak heights of an exemplary atom peak and ion peak are shown with respect to the height of the 780 nm peak (RbI). For this measurement, the timing of the proton bunch with respect to the laser was altered resulting in greatly differing amounts of light. It can be seen that both atom and ion lines show a clear proportionality. While there is a small non-linear trend in the ion line, it is small compared to the linear trend. This indicates no significant spectrum shift. As these measurements cover almost the entire range of plasma light amplitude expected under the desired conditions this can be used to back the PMTs as valid diagnostics.

The spectrum was further investigated using two fibres at different positions along the beam line. Preliminary analysis shows no significant difference between both fibres, backing the described findings.

4 3D reconstruction

Furthermore, a tomographic measurement of the proton bunch after propagation through 10 m of Helium plasma was performed using an optical transition radiation (OTR) screen, a remote controlled mirror and a streak camera with a slit. This data was visualised using the python library *mayavi* [8]. The final result can be seen in Figure 5. It shows clearly defocused protons in the middle of the bunch which originate from large wakefields that cause ion motion towards the back of the bunch. This is visible from the bunch tail. A paper on this phenomenon is in preparation.

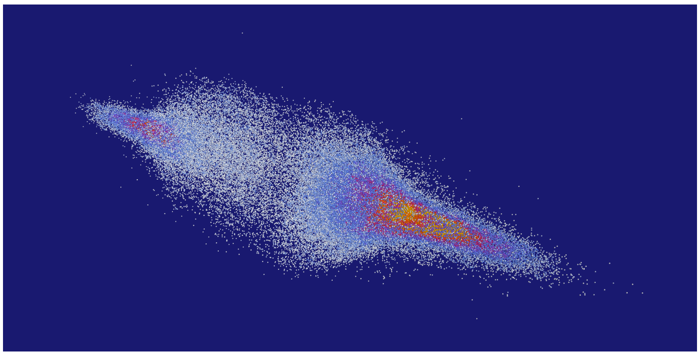

Figure 5: A 3D rendering of a measured proton bunch undergone large wakefields.

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