ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FROXGD1

A METHOD FOR OBTAINING 3D CHARGE DENSITY DISTRIBUTION OF A SELF-MODULATED PROTON BUNCH

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Abstract

The Advanced Wakefield Experiment (AWAKE) at CERN is the first plasma wakefield accelerator experiment to use a proton bunch as driver. The long bunch undergoes seeded self-modulation (SSM) in a 10 m-long plasma. SSM transforms the bunch into a train of short micro-bunches that resonantly drive high-amplitude wakefields. We use optical transition radiation (OTR) and a streak camera to obtain time-resolved images of the bunch transverse charge density distribution in a given plane. In this paper we present a method to obtain 3D images of the bunch by scanning the OTR across the entrance slit of the streak camera. Reconstruction of the 3D distribution is possible because with seeding self-modulation is reproducible. The 3D images allow for checking the axi-symmetry of SSM and for detecting the possible presence of the non-axi-symmetric hosing instability (HI).

INTRODUCTION

Plasma-based acceleration is a promising alternative to conventional one, as plasma can sustain accelerating fields several orders of magnitude higher than the RF cavities. Acceleration of electron bunches up to 8 GeV [1] and 42 GeV [2] has already been demonstrated in laser wakefield and beam-driven wakefield experiments, respectively.

The Advanced Wakefield Experiment (AWAKE) uses a long relativistic proton bunch as driver. This long bunch, propagating in plasma, undergoes self-modulation instability (SMI). SMI transforms the bunch into a train of short micro-bunches that drive high-amplitude wakefields. In order to control SMI we use a relativistic ionization front (RIF) or a short electron bunch preceeding the proton bunch that creates initial seed wakefields. When seeded, self-modulation (or SSM) yields reproducible outcome [3,4].

Seeding of the self-modulation that is an axi-symmetric process with the electron bunch relies on the alignment of the electron and proton bunches with respect to each other. When misalignment is present, SSM is accompanied by the non-axi-symmetric hosing instability (HI). HI occurs in the plane of misalignment and, in case this plane is different from the main plane of observation, additional diagnostic is required in order to detect this instability.

In this paper we present a method that allows simultaneous observation of the proton bunch evolution in two perpendicular planes and, by extension, in any plane. We use a streak camera that yields time-resolved images of slices of the proton bunch charge density distribution [5,6]. From the slices we obtain a 3D charge density distribution, which gives the possibility to detect whether HI is present in the plane perpendicular to the main plane of observation.

OPTICAL SETUP

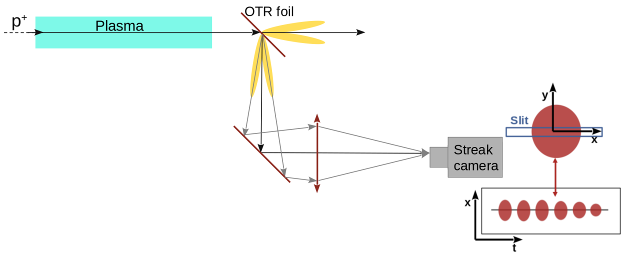

Figure 1: Simplified schematic of OTR transport line.

After exiting the Rubidium (Rb) vapor source, where plasma is created, the proton bunch propagates through a 280 µm-thick Silicon waver coated with 1 µm mirror-finished Aluminium foil, see Fig. 1 [6]. The emitted backwards optical transition radiation (OTR) contains information of the spatio-temporal proton bunch charge distribution. It is collected and guided in free-space using optical relay imaging to the streak camera room, where it is imaged onto the slit of the streak camera. The field of view of the imaging system is ∼ ± 4 mm [7]. The streak camera yields light intensity distribution as a function of time and position.

The streak camera can operate with various slit widths and in different time windows. The choice of these parameters affects the temporal resolution of the resulting images. We measure the time resolution in two time windows, 73 ps and 210 ps respectively, and in the range of slit widths from 10 µm to 200 µm, using a 120 fs-short laser pulse. We define time resolution as the standard deviation in time of the intensity of the measured much shorter signal. The optimal resolution value is obtained with the slit width of 20 µm with minimum loss of signal, therefore this width is used in all the measurements. In the measurement presented below we use 1 ns time window in order to capture the full proton bunch charge density distribution. Corresponding time resolution value is ∼ 4.79 ps.

The spatial resolution of the imaging system is measured using a 1951 USAF resolution target illuminated with the

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uniform blue light. Assuming a Gaussian response of a point light source, we do a convolution of the response with the square signal reproducing the selected target element. We find modulation transfer function (MTF) as a function of a ratio between the standard deviation of the Gaussian response and the line width of the selected element. We define spatial resolution as the standard deviation of the response function corresponding to the MTF of the signal. We obtain a resolution value of ~ 0.18 mm.

METHOD AND RESULTS

The streak camera produces time-resolved images of the transverse proton bunch charge density distribution. Under normal operation conditions the proton bunch OTR is centered on the slit of the camera to obtain the slice of the distribution around the bunch propagation axis. In order to detect potential transverse instabilities it is possible to offset the OTR with respect to the slit, thus to produce images of the proton bunch charge density at different transverse positions across its distribution. In the experiment we change the OTR position on the slit with the last reflecting mirror of the transport line in front of the streak camera (shown in Fig. 1). The distance between the mirror and the slit is ~ 0.93 m, while the maximum OTR offset introduced is ~ 1.1 mm, thus the effect of change in angle (maximum angular offset is ~ 1.18 mrad) is negligible. We can consider the variation of the OTR position with respect to the slit as equivalent to the change of the slit position across the transverse proton bunch distribution. A graphic overview of the method summarizing the discussion above is given on Fig. 2a).

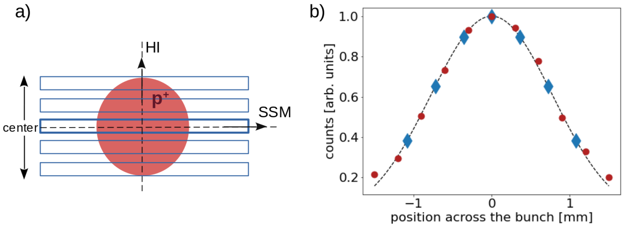

Figure 2: a) Schematic overview of the scanning procedure. In order to detect HI that occurs in the plane perpendicular to the slit it is possible to vary the OTR position with respect to the slit. It is equivalent to change of the slit position across the transverse proton bunch distribution. Blue rectangles indicate various slit positions. b) Average sum of counts of the images of the time-integrated proton bunch charge density distribution as a function of the position across the bunch. Red points – data, black dashed line – gaussian fit, blue diamonds – positions across the bunch where the slices are obtained in the experiment.

We determine the central position of the proton bunch OTR on the slit and locate the edges of the distribution by varying the mirror angle and obtaining corresponding images of the time-integrated charge density distribution that is produced without streaking. We plot the average sum of counts of the images (red circles on Fig. 2b) as a function of the position across the bunch. The transverse proton bunch distribution is Gaussian, therefore we perform a Gaussian fit. We use the mirror angular offset corresponding to the maximum of the Gaussian as the initial position. The rms size of the proton bunch at the OTR screen is $\sigma_p = 0.73$ mm. We vary the mirror angle so that we record sets of bunch slices every 0.36 mm or $\sim 0.5\sigma_p$ (blue diamonds on Fig. 2b). This step size is also larger than the spatial resolution of the system.

In the experiment we start the measurement from the central position of the proton bunch OTR on the slit and we vary the mirror angle in a way described above to obtain 3 slices above and 3 slices below the central one (see Fig. 2b). We record 5 events per slice and obtain the average time-resolved image of the proton bunch charge density distribution for each of them. We then produce a 2D distribution containing the average sum of all the slices and a 3D distribution consisting of the slices placed in order in a linear rectangular grid. We test the method by reconstructing the charge density distribution of the un-modulated (incoming) proton bunch propagating in the Rb vapor, that is as if in vacuum. Results are shown on Figs. 3 and 4.

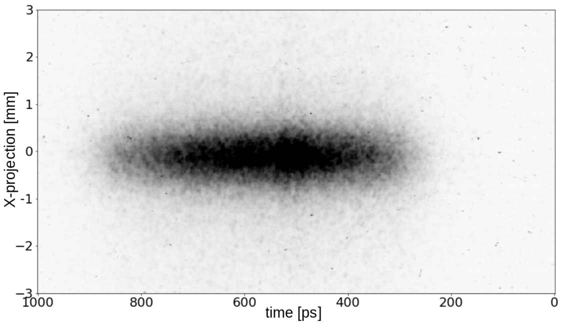

Figure 3: Proton bunch charge density distribution containing an averaged sum of all the slices as a function of time and position in the slit plane. The bunch propagates from left to right.

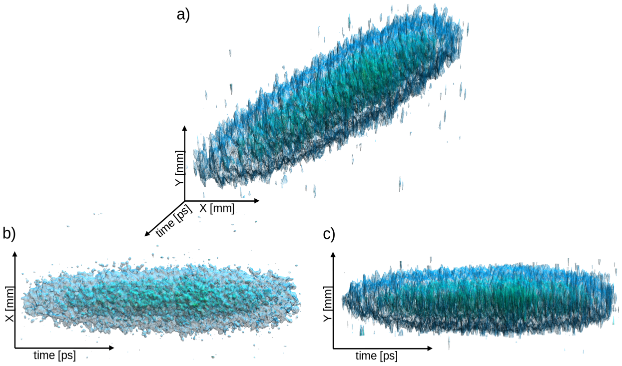

Figure 4: 3D reconstruction of the proton bunch charge density distribution: a) isometric view, b) projection of the slit plane, c) projection of the plane perpendicular to the slit plane. Slices separated by $0.5\sigma_p$ are placed in a linear rectangular grid. On b) and c) the bunch propagates from left to right.

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CONCLUSION

In the AWAKE experiment a long proton bunch propagating in plasma undergoes SMI. This instability can be controlled by placing a short electron bunch that creates initial wakefields ahead of the proton bunch and on its axis. Misalignment between the two bunches causes HI to occur in addition to SSM. HI develops in the plane of misalignment and SSM occurs in the perpendicular plane. It is important to be able to detect HI (if it occurs) when the system is supposed to be well aligned and therefore to develop a tool that allows simultaneous observation of two planes. We will purposely misalign the two bunches to induce HI and to study its characteristics.

We introduced a method that allows to reconstruct time-resolved 3D charge density distribution of the proton bunch using a streak camera. We tested the procedure by obtaining the distribution of the incoming proton bunch propagating in the Rb vapor. We will use the method in the upcoming measurements of the proton bunch evolution in plasma.

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