Hosing of a long proton bunch induced by an electron bunch

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Abstract

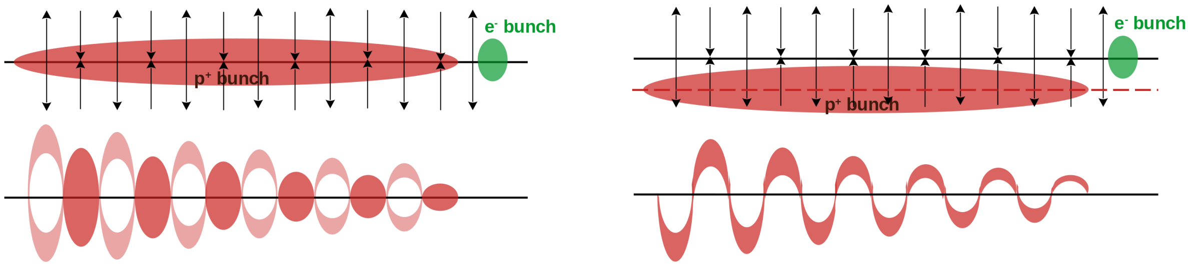
We study hosing that we observe as a centroid oscillation of a long relativistic charged particle bunch induced by an electron bunch. In the experiment we use a long proton bunch. We introduce misalignment between the trajectories of the bunches, therefore the effect of initial seed wakefields on the proton bunch is not axi-symmetric. As a consequence, the proton bunch centroid starts to oscillate. Results show that hosing occurs at the same time as self-modulation (SM) and takes place in the plane of electron bunch misalignment, while SM is observed in the perpendicular plane. Both the phase of the modulation and of the centroid oscillation along the bunch are reproducible.

Introduction

The Advanced Wakefield Experiment (AWAKE) at CERN studies proton-driven plasma wakefield acceleration. A long proton bunch propagating in plasma undergoes self-modulation instability (SMI) which transforms it into a train of short micro-bunches [1]. These micro-bunches are capable of resonantly driving high-amplitude wakefields.

When the proton bunch propagates in a pre-formed plasma, SMI grows from noise (irregularities in bunch distribution or in plasma, Schottky noise etc.), therefore the phase of the wakefields is distributed randomly from event to event. In order to control SMI we seed it (seeded self-modulation, SSM), that is we trigger the start of its growth such that the phase of the wakefields is reproducible. Two seeding schemes are used in AWAKE. In the first scheme a laser pulse that ionizes the Rubidium (Rb) vapor and creates plasma, co-propagates within the proton bunch. This leads to a sudden onset of beam-plasma interaction and provides a seed for self-modulation (SM). In the second scheme a short electron bunch propagates ahead of the proton bunch in a pre-formed plasma and drives initial seed wakefields. Both schemes yield reproducible outcome [2], [3]. Seeding with the electron bunch is currently under further study.

In the context of the electron bunch seeding scheme, alignment between the electron and proton bunches is important. Figure 1(a) shows a schematic of seeding when the proton bunch propagates on the axis of the electron bunch. In this case the initial wakefields created by the electron bunch are axi-symmetric for the proton bunch, therefore the net force on its centroid is zero. The transverse focusing/defocusing force leads to SM and to the formation of the micro-bunches. When the two bunches are misaligned, as shown on Figure 1(b), the initial wakefields are not axi-symmetric for the proton bunch. The force on the proton bunch centroid is no longer zero, leading to oscillation of the centroid position. This oscillation is referred to as hosing [4]. Initial wakefields cause focusing/defocusing effect, therefore hosing and SSM occur simultaneously and thus with the same frequency.



(a) (b)

Figure 1: (a) Schematic of seeding when the electron and proton bunches are aligned. In this case only SSM is observed. Black arrows indicate wakefields' force acting on the proton bunch. (b) Schematic of seeding when misalignment is present between the electron and proton bunches. The wakefields are not symmetric with respect to the proton bunch axis, which leads to hosing development simultaneously with SSM.

To zeroth order, hosing develops in the plane of misalignment of the two bunches, SSM – in the perpendicular plane. Both processes are reproducible, as they are induced by the same seed wakefields.

Hosing induced by an electron bunch

A simplified schematic of the experimental setup is shown on Figure 2. After exiting the plasma the proton bunch hits a Cr_2O_3 (Chromox) screen. The emitted light is collected by the imaging system that yields time-integrated images of the transverse proton bunch charge distribution in its core and halo [5]. These images are used to detect the plane in which hosing develops. The proton bunch then propagates through a Silicon waver coated with 1 µm mirror-finish Aluminium [1]. The bunch emits optical transition radiation (OTR) that contains information about its spatio-temporal charge distribution. The backward emitted OTR is transported via an in-air optical relay line to the entrance slit of a streak camera. The streak camera yields time-resolved images of the proton bunch transverse charge density distribution and is used for the direct observation in time of evolution of hosing and SSM.

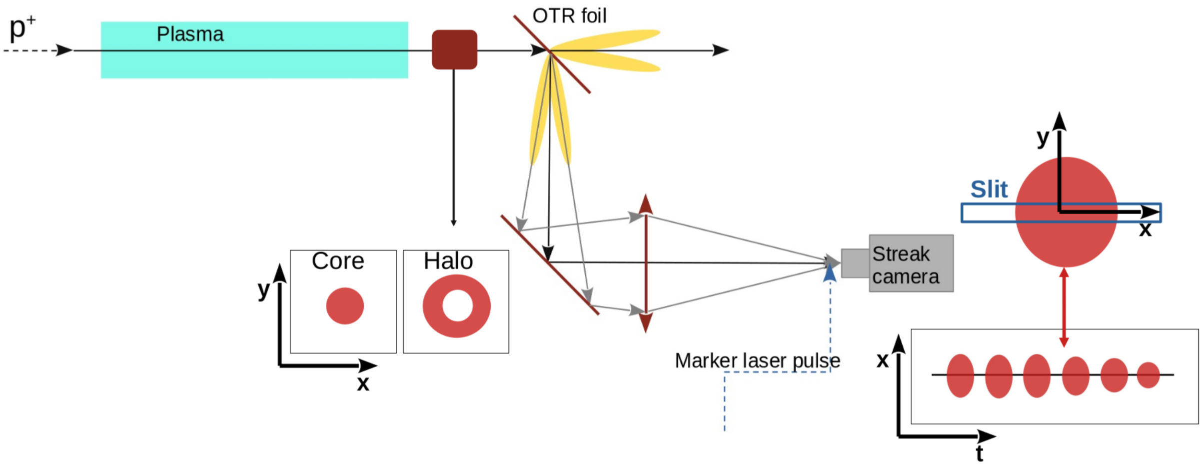


Figure 2: A simplified schematic of the experimental setup showing the main relevant diagnostics.

The experimental setup allows for purposely misaligning the electron bunch in a way shown on Figure 3. This will allow for simultaneous observation of hosing and SSM using the streak camera and time-integrated core/halo imaging system.

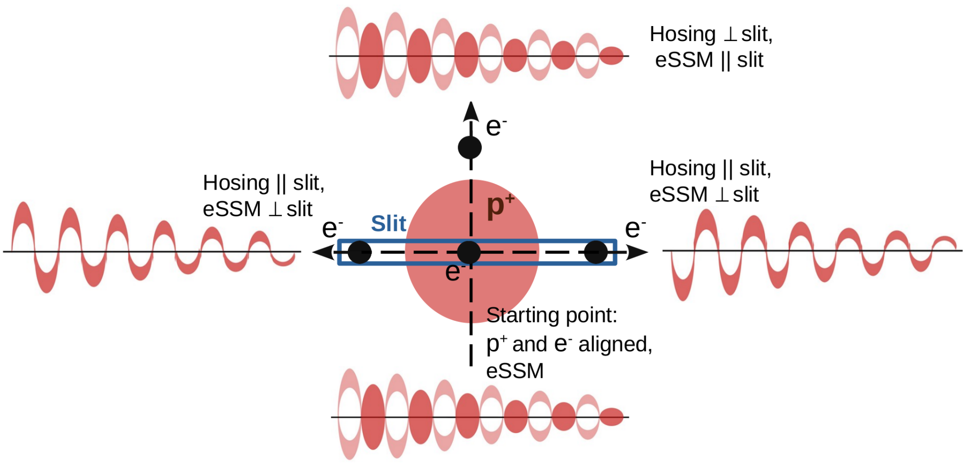


Figure 3: Schematic of electron bunch misalignment implemented in the experiment for simultaneous observation of hosing and SSM.

In order to demonstrate the occurrence of hosing and SSM one can start from aligning the electron bunch on the proton bunch trajectory. This should yield the observation of SSM on the streak camera images and a symmetric time-integrated distribution on the core/halo images. One can then offset the electron bunch to both sides with respect to the proton bunch in the plane of the streak camera slit. This would induce hosing in the slit plane, therefore it would be visible on the streak camera images. We expect the centroid oscillations in these two cases of misalignment to be in the opposite phase, due to the force of the wakefields having opposite directions on the two sides of the electron bunch axis (Figure 1(b)). In addition one would observe a clear asymmetry in the slit plane in the time-integrated proton bunch distribution that is particularly pronounced in the halo. Finally, one can offset the electron bunch in the plane perpendicular to the streak camera slit. In this case only SSM would be visible on the streak camera, while the time-integrated images would show core/halo elongation in the plane perpendicular to that of the slit.

Conclusion and outlook

In the AWAKE experiment a long proton bunch propagating in plasma undergoes SMI. We introduced a scheme to purposely misalign the electron bunch with respect to the proton bunch that will allow simultaneous observation of hosing and SSM using time-resolved and time-integrated core/halo images.

We will use this scheme to study the dependence of hosing on the electron bunch misalignment offset. We expect the force on the centroid to follow the radial dependence of the transverse wakefields. The amplitude of the initial wakefields can be increased/decreased by increasing/decreasing the electron bunch charge. We will also vary the charge and the size of the proton bunch. The growth rate of hosing is expected to be higher with higher charge and with smaller size of the proton bunch. Variation of the aforementioned parameters may allow a comparison of hosing observed in the experiment with the linear theory predictions [6]. This requires sufficiently low charge of the electron and proton bunches as well as the low plasma density, that is low plasma electron frequency. Experimental results will be also compared to the numerical simulations results. In addition, using the optical system we will scan across the proton bunch transverse charge density distribution with the streak camera slit [7]. This would allow to reconstruct the 3D distribution of the bunch and therefore simultaneously observe hosing and SSM. We will introduce misalignment in the plane between the slit plane and the perpendicular one, the plane where a combination of hosing and SSM should be observed.

References

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