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CHARACTERIZATION OF SELF-MODULATED ELECTRON BUNCHES IN AN ARGON PLASMA

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Abstract

The self-modulation instability is fundamental for the plasma wakefield acceleration experiment of the AWAKE (Advanced Wakefield Experiment) collaboration at CERN where this effect is used to generate proton bunches for the resonant excitation of high acceleration fields. Utilizing the availability of flexible electron beam shaping together with excellent diagnostics including an RF deflector, a supporting experiment was set up at the electron accelerator PITZ (Photo Injector Test facility at DESY, Zeuthen site), given that the underlying physics is the same. After demonstrating the effect [1] the next goal is to investigate in detail the self-modulation of long (with respect to the plasma wavelength) electron beams.

In this contribution we describe parameter studies on self-modulation of a long electron bunch in an argon plasma. The plasma was generated with a discharge cell with densities in the 10^{13} cm^{-3} to 10^{15} cm^{-3} range. The plasma density was deduced from the plasma wavelength as indicated by the self-modulation period. Parameter scans were conducted with variable plasma density and electron bunch focusing.

INTRODUCTION

Motivated by the ongoing experiments of the AWAKE collaboration [2] the self-modulation instability [3] is investigated at the electron accelerator PITZ. This effect was demonstrated for the first time by utilizing a lithium heat pipe oven plasma cell [1]. Flat top electron bunches with a FWHM length of about 20 ps and with rise/fall times of <2 ps were generated by impinging similarly shaped photocathode laser pulses [4] onto a Cs_2Te photocathode. The bunches were accelerated with an L-band electron gun and a subsequent booster linac to a momentum of 22.3 MeV/*c*. A gun solenoid and four quadrupole magnets were used to focus these bunches into a heat pipe oven which provided a lithium plasma with densities up to ≈10^{14} cm^{-3}. The sharp transition of charge density at the head of the bunch triggers a plasma wake which is seeding the self-modulation instability along the electron bunch. Since the bunch is several plasma wavelengths long this results in a periodical bunch diameter and energy modulation. These modulations were observed on Ce:YAG and LYSO scintillation screens by resolving the temporal charge distribution with an RF deflector and the energy distribution with a dipole spectrometer.

Here we describe a follow-up experiment using the same setup with the only difference that the lithium heat pipe oven was replaced with a discharge plasma cell [5].

EXPERIMENTS

The setup used for these experiments is depicted in Fig. 1. Argon plasma was generated with a 2.4 kV, 250 A discharge pulse of 2 µs length. The timing of the discharge pulse is adjustable with respect to the electron bunch arrival at the plasma cell. Since the plasma is recombining after the discharge pulse has ended, this variable delay translates into a scan of the plasma density which the electron bunch is experiencing. The bunch charge is adjustable by tuning the pulse energy of the photocathode laser, while the focusing of the bunch into the plasma cell can be scanned by changing the drive current of the gun solenoid.

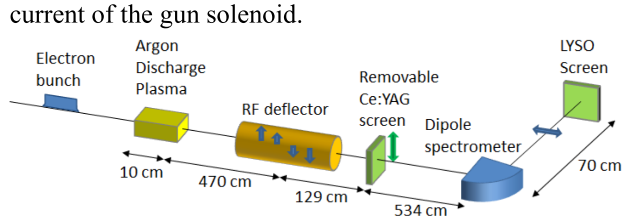

Figure 1: Experimental setup.

Streaked Bunch

For the first set of experiments a removable Ce:YAG screen was inserted to observe the electron bunches which are vertically streaked with an RF deflector [6]. Results of a timing scan are shown in Fig. 2. The bunch charge was 600 pC and the main solenoid current 390 A. The horizontal axis shows the horizontal size of the bunch while the vertical axis is the axis of RF streaking, which is

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calibrated to the temporal evolution of the bunch; the bunch head is located at the bottom of the figure. The signal density (proportional to the electron density) is color-coded with yellow indicating high density and blue indicating low density.

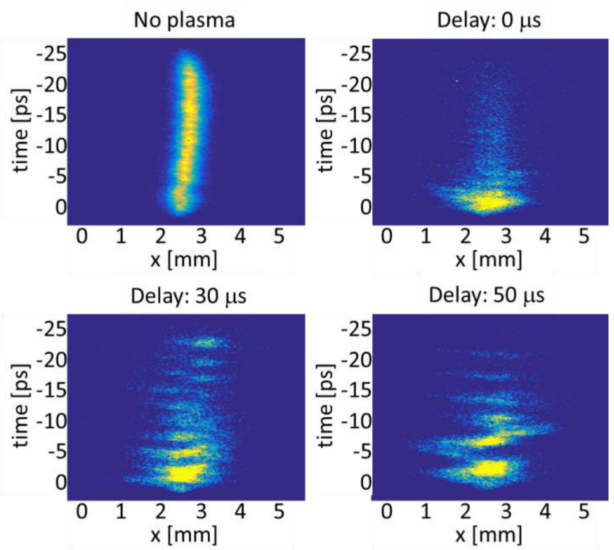

Figure 2: Streaked bunch measurement for varying delay of bunch arrival w.r.t. discharge pulse. The color scale is different for the measurement without plasma in comparison to the others to have good visibility for all cases.

When there is no plasma, the electron bunch propagates through the argon gas without changing its longitudinal shape and the original flat top is measured. At a delay time of 0 μs (maximal achievable plasma density) the bunch head is clearly visible at the bottom of the graph as a region of high electron density. This compression zone is caused by the Coulomb force when repelling the free plasma electrons and further deceleration of the beam electrons due to their energy loss by seeding the plasma wake. This zone is also visible with similar shape for longer delays. Behind the head a zone of low electron density can be seen, which is governed by the self-modulation instability: beam electrons in the defocusing regions are driven strongly away from the beam propagation axis and are partially lost during transport to the observation screen. The electrons in the focusing regions are near the beam axis, but the sub-bunch structure is not resolved due to the very small plasma wavelength at this high plasma density [3]. For a delay time of 30 μs the effect of the self-modulation is clearly visible: the long electron bunch is split into sub-bunches with the distance between two sub-bunches given by the plasma wavelength. Note here the difference to our earlier experiments at lower plasma densities [1]: In those experiments in lithium plasma of 10^{14} cm^{-3} plasma density we could see the envelope of the defocused electrons. Due to the much stronger electric fields in this case (the plasma density for this delay is ~10^{15} cm^{-3} – see below) the electron density in the defocusing regions is lowered below the detection threshold of the measurement system. The plasma wavelength is inversely proportional to the square root of the plasma density, which is clearly visible in comparison with the next measurement at 50 μs delay. Ongoing recombination reduces the plasma density, thereby increasing the plasma wavelength: the distance between the sub-bunches is increased accordingly. Also visible here is the effect of hosing [7], leading to a horizontal displacement along the bunch axis. This is most likely caused by a slight tilt of the bunch to the propagation axis which is visible in the measurement without plasma.

Longitudinal Phase Space

For the second set of experiments the removable screen was extracted. In that configuration the electron bunches are additionally deflected horizontally in a dipole spectrometer [8]. This enables the direct observation of the longitudinal phase space on a LYSO screen behind the dipole: the horizontal axis in the following figures indicates the electron momentum. Some measurements of a timing scan are shown in Fig. 3. The bunch head is at the bottom; red color indicates high density and blue indicates low density. The bunch charge was 600 pC and the main solenoid current was 370 A. The green line indicates the mean energy for a given time bin.

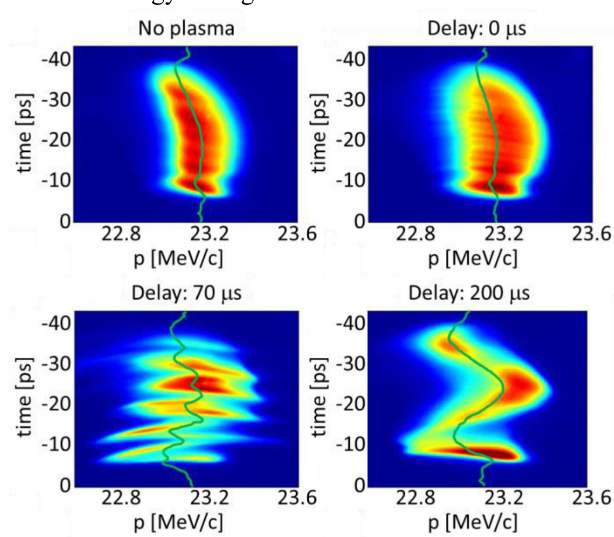

Figure 3: Longitudinal phase space for varying delay of bunch arrival w.r.t. discharge pulse.

Without plasma the longitudinal phase space (LPS) of the undisturbed electron bunch is measured. The LPS is nearly linear with minimal energy chirp. A modulation along the bunch is visible which is caused by a slight variation of the photocathode laser intensity. With increasing delay the plasma wavelength is increasing, which manifests as a change of the energy modulation period. This energy modulation is caused by the longitudinal electric field, which is accompanying the transverse field causing the bunching of the electrons. To investigate the time evolution of the plasma density in more detail the plasma density was evaluated for a range of measured delays as shown in Fig. 4.

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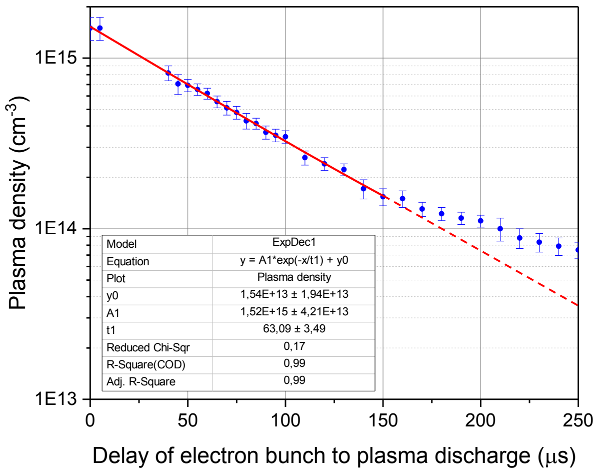

Figure 4: Plasma density vs. delay of the electron bunch with respect to the discharge pulse.

The plasma density was determined from the measurements as shown in Fig. 3 by the following method. The time of occurrence of two energy peaks was determined manually from a LPS plot. The distance was chosen to be as big as possible under the condition that both peaks and all peaks in between were clearly visible (the first peak at the bunch head was never taken due to the special conditions there as explained above). The plasma density was then calculated from the distance between those energy peaks divided by the number of modulations in between using eq. (10) of [9]. For delays between 5 µs and 40 µs the energy peaks could not be determined because the signal was washed out. The maximal usable delay was 250 µs; for longer delays only one energy peak was in the visible range. The solid red line is a linear fit to the data points between 0 and 150 µs delay, indicating an exponential decay in that range. Afterwards the decay appears to slow down with the measured densities positioned well above the extrapolated fit (dashed line) [10].

In a last experiment the LPS was measured for a range of solenoid currents, which translates into different beam densities at the plasma channel entrance. Measurements of a solenoid scan are shown in Fig. 5. The bunch charge was 600 pC and the delay of electron bunch to the discharge pulse was fixed at 50 µs.

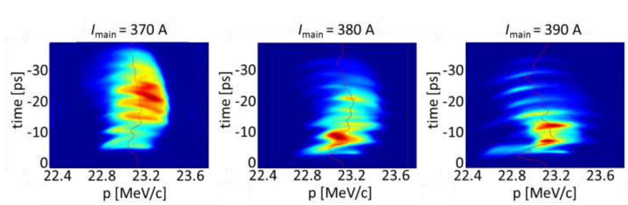

Figure 5: Longitudinal phase space for three different currents of the focusing solenoid.

The effect of the self-modulation is visible for all three cases with the modulation depth being the highest for 390 A.

CONCLUSION

Measurements of the self-modulation of a long electron bunch in an argon plasma are presented here. The plasma was produced with a discharge plasma cell; the modulated electron bunches were characterized utilizing an RF deflector and a dipole spectrometer. The effective plasma density was adjustable by controlling the delay between the discharge pulse and the arrival of the electron bunch at the plasma cell. Observing the streaked bunches for a range of delays shows separation of the electron bunch into sub-bunches with varying modulation period; there is also some hosing visible. The development of the plasma density over time was characterized by measuring the plasma wavelength. This was done by evaluating the bunch energy modulation in the longitudinal phase space. For the first 150 µs after the discharge pulse this follows an exponential decay while the decay is slowing down for longer delays. The next step is a comparison with simulations to gain a better understanding of these experimental results.

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