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SELF-MODULATION INSTABILITY OF ELECTRON BEAMS IN PLASMA CHANNELS OF VARIABLE LENGTH

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Abstract

The self-modulation instability (SMI) of long (in respect to the plasma wavelength) charged particle beams passing through plasma enables the use of currently existing high energy charged particle beams as drivers for plasma wakefield accelerators. At the Photo Injector Test Facility at DESY in Zeuthen (PITZ) the SMI of electron beams is studied [1, 2].

An enhanced experimental setup includes a plasma channel of variable length which allows to investigate in detail the development stages of the SMI by measuring the instability growth rate and phase velocity as a function of propagation distance in the plasma. In this contribution we present the experimental setup improvements, experimental plans and supporting beam dynamics simulations.

INTRODUCTION

The self-modulation instability of long relativistic charged particle beams is of great interest in the context of creating compact single stage GeV-scale electron accelerators utilizing currently available high-energy driver beams. The instability mechanism is a feedback between the transverse wakefields in plasma and the bunch radius. An initial, low-amplitude seed wakefield (generated by a sharp density offset of the particle beam or plasma) creates periodic regions of focusing and defocusing which modulate the bunch transverse profile with a period equal to the plasma wavelength λ_p, and then the wake is amplified by the modulated beam. The process leads to a formation of a train of short ($\sigma_z < \lambda_p$) bunchlets, that resonantly drive wakefields and can serve as a driver in plasma wakefield acceleration (PWFA) schemes. The instability formation can be split into phases: initial phase, where the beam profile is modulated by the initial wakefields, the non-linear growth stage, where the feedback between the wakefield and the transverse profile leads to a rapid increase of the wakefield amplitude, then the amplitude decreases fast and reaches a certain established level. During the nonlinear stage, the phase velocity of the instability is lower than that of the driver bunch [3]. This effect not only complicates the phase synchronization between the driver and witness bunches [4] but is also responsible for charge loss in the self-modulated driver: the defocusing phase of the wakefield travels back along the long particle bunch and "kicks out" a substantial share of particles [5]. It was shown that a positive plasma density gradient along the plasma accelerator can result in a better phase lock between the driver and witness, and consequently in a higher effective acceleration gradient [6, 7].

Experiments at PITZ are intended to improve understanding of the underlying physics of the SMI, confirm the theoretical models and provide input for more accurate simulations. In this report, we present preparation studies for the experiment aimed to observe and characterize the growth of the SMI.

EXPERIMENTAL SETUP

The general layout of the PWFA experiments at PITZ is described in [8]. A flexible photocathode laser system allows generating flattop electron bunches with a FWHM length of about 24 ps and rise and fall times of less than 2 ps. The bunches are then accelerated to a momentum up to 25 MeV/c. Typical bunch charges for the PWFA experiments at PITZ are from 100 pC to 1 nC. Time-resolved transverse profile and longitudinal phase space (LPS) measurements are available downstream of the electron bunch-plasma interaction point. Observing the momentum modulations on the LPS of the long electron bunch after passing different lengths of plasma will allow inference of such parameters of the SMI as the travelled distance in plasma required to start of the nonlinear stage of the instability and its duration, and the established acceleration gradient after the instability is developed. For this experiment, the existing cross-shaped heat pipe plasma cell setup [9, 10] was upgraded. A homogeneous lithium vapor column is generated in the central part of the plasma cell and ionized by a UV laser pulse coming through side arms, as shown in Fig. 1. A Coherent COMPexPro 201 ArF excimer laser is used for the ionization. The beam at the laser output has dimensions of 24x10 mm^2. The laser pulse is transversally stretched by a pair of prisms and ionizes an 80x10 mm^2 column of the metal vapor. After passing through the plasma cell, the laser pulse is reflected back for a second ionization pass. A

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modification to the setup is a mask installed on a remotely controlled linear stage in front of the prisms pair. The mask can partially or completely block the ionization laser profile and thereby vary the plasma channel length from 0 to 80 mm.

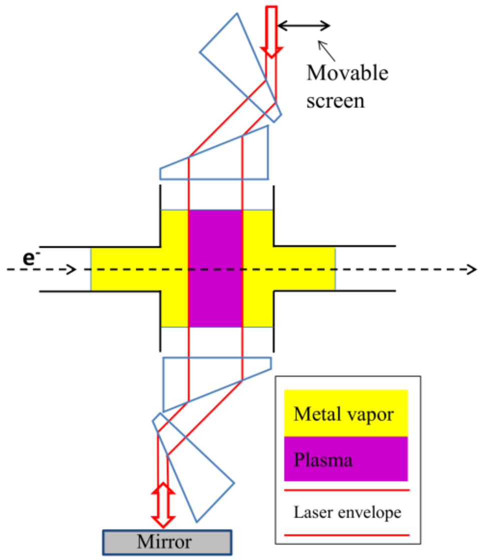

Figure 1: Lithium heat pipe plasma cell ionization scheme. The incoming ionization laser pulse is stretched by a pair of prisms and generates an 80 mm long plasma channel, passes through another set of prisms and reflected back for a second ionization pass.

BEAM DYNAMICS SIMULATIONS

3D particle-in-cell simulations were carried out using the quasi-static code HiPACE [11]. For the simulations, the following parameters were assumed:

- Plasma density: $1\cdot10^{14}..2\cdot10^{15}$ cm^{-3}
- Plasma length: 80 mm
- Bunch profile: flattop
- Bunch length: 24 ps FWHM
- Bunch rise and fall time: 1.7 ps
- Bunch transverse size: 50..200 µm
- Bunch charge: 100..1000 pC
- Mean bunch energy: 23 MeV
- Uncorrelated energy spread: 5%

The simulation used a 512x256x256 grid and a moving box of 12x2x2 mm^3. Due to the phase velocity drop, the same slice within the electron bunch can be subjected to different phases of the SMI development, so the net momentum modulation after travelling the full length of the plasma channel will not represent the wakefield amplitude evolution along the plasma channel. Instead, a maximum slice momentum change per simulation step is accounted (for most of the simulations, the beam distributions were saved each 10 mm in plasma).

Figure 2 shows the evolution of the maximum deceleration longitudinal electric field E_z at the tail of the bunch (solid line) calculated from the slice momentum change and the maximum deceleration longitudinal electric field E_z at the tail of the bunch obtained directly from the simulations (dashed lines). The first peak at z=20 mm corresponds to the formation of the instability. During next few simulation steps, the wakefield amplitude remains at a high level, but its phase velocity is slower than that of the electron bunch, so the wakefield travels back with respect to the bunch and partially defocuses the freshly formed bunchlets. At the position z=40 mm a substantial fraction of the bunchlets are defocused, and the wakefield amplitude begins to decrease. At the beginning of the instability development, the growth of the calculated values starts later than that of the values obtained directly from the simulations; however, both values start to decrease simultaneously at the moment the instability growth is over. The values calculated from the bunch momentum distribution are systematically lower than that obtained directly from the simulations by 45-50%.

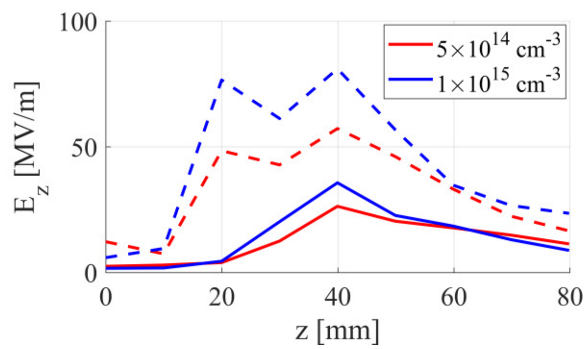

Figure 2: Maximum decelerating longitudinal electric field as a function of the distance propagated in plasma for a 1 nC bunch. The dashed lines indicate the values obtained directly from simulations, and the solid lines indicate the values obtained calculated from the bunch momentum modulations.

Plasma Density Steps

It was shown in [5] that a positive step in plasma density introduced at the distance in plasma where the transition to the nonlinear instability growth happens will result in a higher established wakefield amplitude after the complete development of the instability. In order to study the influence of the density steps for PITZ conditions, the relative step amplitude δn_p and the density step position z_s were scanned for bunches with the transverse rms size of 100 µm, charges of 500 and 1000 pC and plasma densities of $5\cdot10^{14}$ and $1\cdot10^{15}$ cm^{-3}. Figure 3 shows the maximum longitudinal electric field E_z at the end of the plasma channel for the aforementioned conditions. No clear pattern for optimum density step amplitude and position emerged from the simulations. In the optimal case, the density step compensates the phase velocity drop, and the formed bunchlets have a higher current compared to that in the flattop plasma. The train of the higher current bunchlets coherently drives a higher amplitude wake. The density step makes the plasma wavelength shorter, and one additional bunchlet is formed, as can be seen in Fig. 4.

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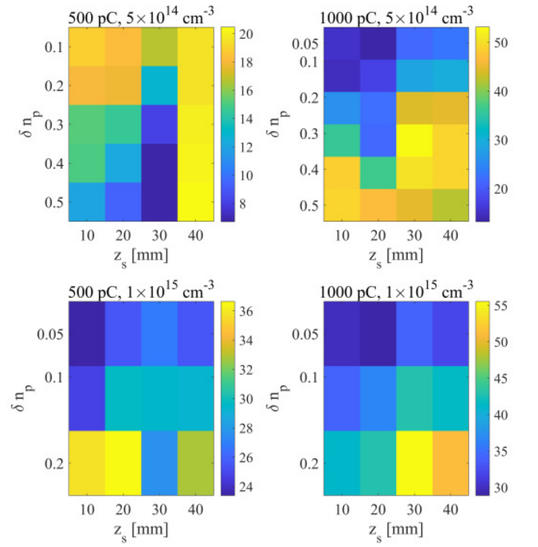

Figure 3: Longitudinal electric field at the end of the plasma channel as a function of the relative plasma density step and its position.

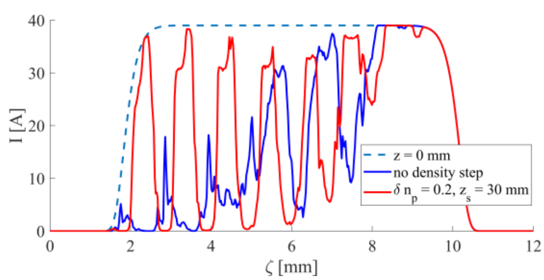

Figure 4: Bunch current on the propagation axis at the end of the plasma channel (z = 80 mm) for the bunch charge of 1 nC and the plasma density of $1 \cdot 10^{15}$ cm^{-3}. The bunch head is on the right.

The transverse ionization scheme at PITZ allows in principle to generate such sharp plasma density profile steps, however, this option was not implemented yet. The existing setup can be modified by mounting the mirror which reflects the ionization laser (Fig. 1, on the bottom) on a movable stage. When the ionization laser pulse is reflected by the mirror, it makes a second ionization pass through the plasma cell. If only a part of the ionization profile is reflected, then there is a single-pass ionization region and a double-pass ionization region along the plasma channel. For the PITZ plasma cell parameters, the density difference between these two regions can reach 10-15%. Another option is to generate plasma density steps by introducing an attenuator mask which overlaps with a part of the incoming laser profile and decreases its intensity. Such an attenuator can consist of air gapped thin quartz glass plates stacked together. The Fresnel equations predict about 6% reflectance on each air-quartz interface at normal incidence for the 193 nm light.

CONCLUSION

The variable plasma channel length setup at PITZ is presented. Simulations confirm that the growth of the SMI can be observed with the variable plasma channel length setup. Further simulation studies include analysis of the wake phase velocity during the instability growth. The variable plasma channel length setup also gives a possibility to study the accuracy of the SMI-based plasma density measurement [2] depending on the SMI development stage, and to investigate possibilities of using the energy loss at the bunch head of diagnostics. When the plasma density profile control is implemented, the setup can be used to examine ways of maximizing gradients in SMI-driven PWFA.

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