

OVERVIEW AND PROSPECTS OF PLASMA WAKEFIELD ACCELERATION EXPERIMENTS AT PITZ

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Abstract

The Photo Injector Test Facility at DESY in Zeuthen (PITZ) carries out studies of beam-driven plasma wakefield acceleration (PWFA). The facility possesses a flexible photocathode laser beam shaping system and a variety of diagnostics including a high-resolution dipole spectrometer and an rf deflector which enables the observation of the longitudinal phase space of electron beams after their passage through a plasma. Two plasma sources are available: a gas discharge plasma cell and a photoionized lithium vapor plasma cell.

Studies at PITZ include investigations of the self-modulation instability of long electron beams and the high transformer ratio, i.e., the ratio between the maximum accelerating field behind the drive beam and the decelerating field within the beam. This overview includes the experimental results and plans for future experiments.

INTRODUCTION

Beam-driven plasma wakefield acceleration [1] is one of promising technologies for future high-gradient compact accelerators. In this scheme, a relativistic particle bunch traverses a plasma and drives a wakefield in it. A trailing relativistic electron bunch placed at an appropriate distance from the driver bunch samples the wakefield and can be accelerated with a gradient exceeding that of conventional accelerators by orders of magnitude. PITZ has unique capabilities which make it suitable for studying various aspects of PWFA. It is a 1.3 GHz rf photoinjector accelerator, capable of producing electron bunches with charges up to 5 nC, momenta up to 25 MeV/c, and emittances down to 0.7 mm mrad for 1 nC bunches at the repetition rate of 10 Hz [2]. A general layout of the facility is shown in Fig. 1. The photocathode laser was built by the Max-Born Institute and features a pulse shaper – a set of 13 birefringent crystals that enables the production of various temporal pulse shapes from a short Gaussian pulse [3]. An S-band transverse deflecting structure (TDS) [4] allows time-resolved measurements of the electron beam profile; combined with a high resolution electron spectrometer (HEDA2) [5], it enables

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measurements of the longitudinal phase space (LPS). When passing the TDS, the electrons receive a vertical kick according to their longitudinal position within the bunch, in conjunction with the HEDA2 dipole, the electrons are dispersed horizontally according to their energies; hence the transverse projection of the electron bunch on a measurement screen downstream of these two devices represents the LPS of the bunch.

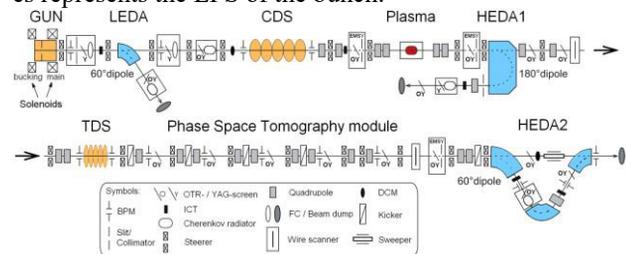


Figure 1: Layout of the PITZ facility. The plasma source is located 6 meters downstream of the photocathode plane.

PLASMA SOURCES

Two plasma sources were commissioned at PITZ: a cross-shaped photoionized lithium heat pipe oven and a gas-discharge plasma cell. Both plasma cells can be installed in the same slot in the beamline 6 meters downstream of the electron gun. Four quadrupole magnets upstream of the plasma source alongside the gun solenoid provide optimal focusing of the electron beam in the plasma channel. Thin polymer foils separate the gas atmosphere of the plasma cells from the ultra-high vacuum conditions of the accelerator beamline, but at the same time introduce a tolerable electron beam scattering of less than 0.2 mrad at the PITZ bunch parameters [6, 7].

Heat Pipe Plasma Cell

Inspired by the SLAC heat pipe source [8], the PITZ heat pipe oven plasma cell has side ionization as a distinctive feature. Thanks to the heat pipe mechanism, a homogeneous lithium vapor column is formed in the central zone of the plasma cell and then ionized by a laser through the side arms, as shown in Fig. 2. The side ionization gives the possibility to manipulate the plasma profile along the electron beam propagations axis – that feature will be used in upcoming experiments [9]. The full length

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of the ionization channel is 8 cm. The initially foreseen plasma density of $1 \cdot 10^{15} \text{ cm}^{-3}$ [10] was not yet achieved in experiment due to technical shortcomings, but the setup was already modified in order to overcome them [6, 11].

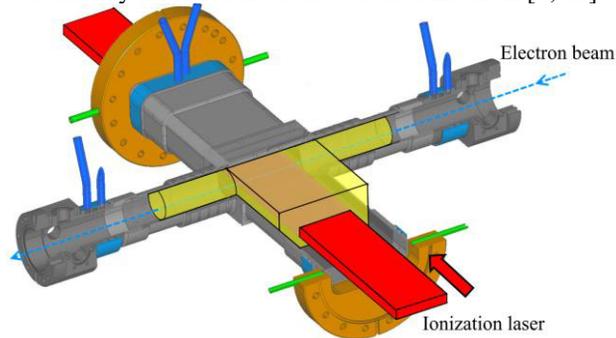


Figure 2: Concept sketch of the PITZ heat pipe oven plasma source.

Gas-discharge Plasma Cell

The centerpiece of this source is a 10 cm long quartz glass tube with copper electrodes on both ends (Fig. 3). A pre-ionization DC glow discharge is maintained through the cell. A plasma channel is formed when a 2.4 kV, 330 A, 2 μs long discharge is applied to the electrodes. The discharge jitter is minimized through optimizations of the electrical circuit parameters and by maintaining constant gas flow through the plasma cell to remove outgassing hydrogen [12]. Plasma densities in the range of about $1 \cdot 10^{12}$ - $1 \cdot 10^{16} \text{ cm}^{-3}$ can be generated by varying delay between the discharge and the electron bunch arrival.

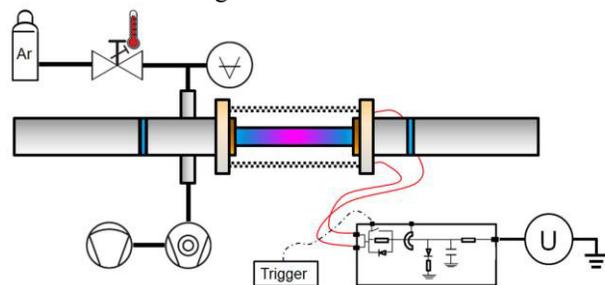


Figure 3: Concept sketch of the PITZ gas discharge plasma source. Source: [12].

SELF-MODULATION INSTABILITY

One of the advantages of using proton drivers in plasma wakefield accelerators is that the stored energy of the proton driver can be much higher compared to an electron beam driver, and thus it is possible to accelerate the witness electron bunches to very high energies in a single stage [13], whereas a laser wakefield accelerator requires a sophisticated multistage approach due to the driver depletion and or dephasing [14].

In order to excite wakefields in plasma efficiently, the driver bunch size should be matched to the plasma wavelength λ_p . A process called self-modulation instability enables the use of long (on the plasma wavelength scale) particle drivers for PFWA: the long particle bunch is split

in a train of short equidistant bunchlets that can then resonantly drive high-amplitude wakefields.

The self-modulation instability is the cornerstone of the AWAKE experiment, whose goal is to generate multi-GV/m acceleration gradients in a plasma using a long self-modulated proton driver beam and utilize them for electron acceleration [15]. At PITZ, a proof-of-principle experiment was conceived to demonstrate the self-modulation instability of a long electron beam in plasma [10].

The instability occurs in an overdense plasma (i.e., the plasma density is higher than the electron beam density $n_p/n_b > 1$) due to a coupling between the transverse wakefield and the bunch radius evolution [13, 16, 17]. The initial transverse wakefield periodically focuses and defocuses parts of the long bunch on λ_p and then the wake is amplified by the modulated bunch. Eventually, the bunch is split into a train of focused bunchlets with defocused slices in between. The transverse and longitudinal wakefield components are 90° phase-shifted with respect to each other, so when the bunchlets are formed, they are partially accelerated and decelerated. The characteristic SMI properties, such as growth rate and dephasing [17] can be evaluated via observation of the LPS of the electron bunch after passing the plasma.

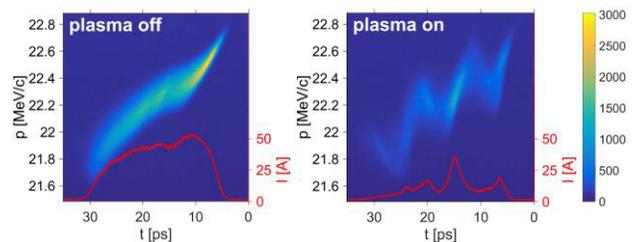


Figure 4: Self-modulation of the long flattop electron bunch passing through a plasma. Bunch momentum and transverse distribution are modulated, as seen in the LPS and the charge profile. The bunch head is on the right.

First time-resolved measurements of the electron bunch being self-modulated in a plasma were conducted at PITZ [18]. A flattop bunch with a charge of 970 pC, a FWHM length of 24 ps, and a rise time of 2 ps was passed through a plasma and its LPS was recorded downstream. The bunch momentum without interacting with plasma was 22.3 MeV/c with an rms momentum spread of 0.1 MeV/c. After passing through an 8 cm long channel of the photoionized lithium plasma the electron bunch exhibited evidence of self-modulation: a momentum modulation with an amplitude of about 200 keV/c (Fig. 4). The plasma density of $1.3 \cdot 10^{14} \text{ cm}^{-3}$ was deduced from the periodicity of the modulation. Although theory and beam dynamics simulations indicate that the momentum and transverse profile modulations are caused by the SMI, only 3 modulation periods observed in the experiment do not allow to directly assess the wakefield amplitude growth. A follow-up experiment is in preparation with a goal to observe the stages of the SMI development and also to study effects of longitudinal plasma profiles. For this experiment, the existing setup was modified to

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achieve higher plasma density and a device to vary the length of the plasma channel was implemented [9].

SMI-based Plasma Density Measurement

A new method to measure the plasma density using the self-modulation instability was proposed and tested at PITZ [19]. The method relies on the fact that the energy modulation periodicity is determined by λ_p . The periodicity is found via Fourier-transformation of the energy modulations appearing on the LPS of the electron bunch after passing through a plasma. The self-modulation of long flat-top bunches passing through the gas-discharge generated plasma was measured. The bunch charge was varied from 400 pC to 1 nC, and the delay between the discharge and bunch arrival time was scanned from 0 to 250 μs , which yielded a plasma density range from ca. $1 \cdot 10^{16} \text{ cm}^{-3}$ down to few times 10^{12} cm^{-3} . Errors of the method were examined by means of beam dynamics simulations. It was found that the measurement accuracy may be affected by the phase velocity drop during the SMI development stages. However, if the nonlinear growth of the instability is not yet started or already finished, the errors can be as low as a few percents. The experimentally obtained values with the SMI-based method were validated, where possible, by spectroscopic measurements (based on the Stark broadening of the Balmer- α line) carried out with the same plasma cell. The SMI-based method requires no additional equipment besides the diagnostics for PWFA experiments and allows to evaluate the plasma density directly at the moment and location of the charged particle bunch passage. However, beam dynamics simulations are necessary in order to estimate errors for a specific beam and plasma parameters combination.

HIGH TRANSFORMER RATIO

Transformer ratio (TR), the ratio between the maximum accelerating field in the witness bunch and the maximum deceleration field in the driver bunch, is another important aspect of PWFA acceleration. Producing higher transformer ratios would allow accelerating witness bunches to higher energies using the same driver, reducing space requirements and costs of PWFA setups. The fundamental theorem of beam-loading limits the transformer ratio to 2 for longitudinally symmetric bunches. Transformer ratio can be increased if a constant (flat) deceleration field is maintained along the driver bunch [20], and asymmetrical bunches were proposed to achieve that [21].

At PITZ, a transformer ratio of $4.6^{+2.2}_{-0.7}$ was measured using a ramped current profile driver bunch passing through the gas-discharge plasma [22]. The driver of a “double triangle” (Fig. 5) shape was generated with the photocathode laser pulse shaper, while the witness bunch was obtained by splitting the incoming Gaussian laser pulse from the oscillator before entering the pulse shaper and merging the beam paths again before projecting them onto the photocathode. The delay between the driver and witness was adjustable by varying the optical path length between the two laser pulses. The driver length was 20 ps

from the first peak to the last peak and its charge was ca. 500 pC, while the witness length was 0.7 ps rms, with a charge of ca. 10 pC, and the plasma density was $2 \cdot 10^{13} \text{ cm}^{-3}$. The interaction took place in the nonlinear regime ($n_p/n_b < 1$) – this allows to mitigate the accompanying instabilities which would otherwise occur due to strong transverse wakefields generated by the long asymmetrical driver bunch. The current photocathode laser provides only longitudinal pulse shaping, so the space charge forces along the generated electron bunch are inhomogeneous which results in an uneven focusing along the bunch at the plasma channel position and limits the charge density. An advanced photocathode laser pulse shaping technique using spatial light modulators [23] can minimize space-charge related distortions of the phase space of the electron bunch, allow higher bunch densities and result in higher transformer ratios [24].

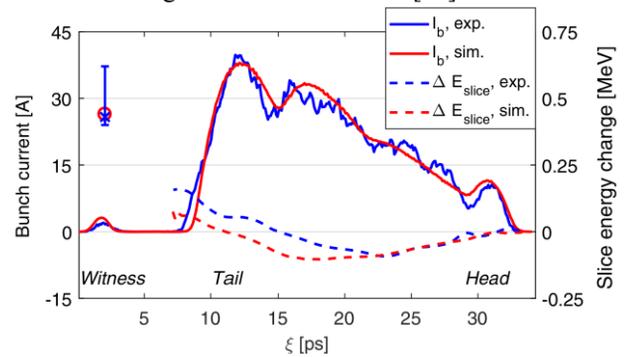


Figure 5: Measured and simulated bunch current profiles (solid lines) and deceleration within the driver bunch (dashed lines). Blue cross and red circle represent the maximum energy gain within the witness in the experiment and simulation, respectively. Source: [22].

CONCLUSION

PWFA studies at the PITZ facility are presented. Observations of the SMI and HTR are important steps toward future compact beam-driven plasma accelerators. Further studies include detailed characterization of the SMI development phases and improvement of the HTR by advanced driver bunch shaping techniques. Among possible hardware improvements are implementation of arbitrary longitudinal plasma density profiles using attenuation masks for the ionization laser of the heat pipe plasma source and commissioning of a longer gas discharge source.

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