EXPERIMENTAL INVESTIGATION OF HIGH TRANSFORMER RATIO PLASMA WAKEFIELD ACCELERATION AT PITZ

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Abstract

Plasma wakefield acceleration (PWFA), the acceleration of particles in a plasma wakefield driven by particle bunches, is one of the most promising candidates for a future compact accelerator technology. A key aspect of this type of acceleration is the ratio between the accelerating fields experienced by a witness beam and the decelerating fields experienced by the drive beam, called the transformer ratio. As for longitudinally symmetrical bunches this ratio is limited to 2 by the fundamental theorem of beam-loading in the linear regime, a transformer ratio above this limit is considered high. This can be reached by using a modulated drive bunch or a shaped train of drive bunches. So far, only the latter case has been shown for wakefields in a RF-structure. We show the experimental setup, simulations and first, preliminary results of high transformer ratio acceleration experiments at the Photoinjector Test Facility at DESY in Zeuthen (PITZ).

INTRODUCTION

Due to the superior accelerating field strength reachable in plasma wakefields, the plasma wakefield accelerator (PWFA) in which a wakefield in a plasma is driven by a relativistic driving particle bunch, has received significant attention throughout recent years.

As the driving bunch has to be accelerated by other, complex means (conventional RF-structures, laser driven wakefield, etc.) beforehand, the efficient usage of the driver's energy is of vital importance in the PWFA. One of the parameters influencing the efficiency is the homogeneity of the decelerating field inside of the driving bunch. This homogeneity is also directly connected to the ratio between the maximum accelerating fields behind the drive bunch and the maximum decelerating field inside of the drive bunch [1], the so called transformer ratio. As in linear wakefield theory the transformer ratio is limited to maximally 2 for (most common) symmetric drive bunches [2], a ratio above 2 is considered high.

Such high transformer ratios (HTR) can be reached in a nonlinear wakefield or by using shaped drive bunches [1, 3, 4] or trains of drive bunches [5], where the latter was proposed to circumvent driver instabilities, which were found to prevent the transport of drive bunches longer than the plasma wavelength [6]. Since the favourable focusing conditions of the ion channel in a nonlinear or quasi-nonlinear wake have been discovered [7, 8], shaping the drive bunch to e.g. a double triangular shape [4] is the most promising way to reach HTR.

To demonstrate and investigate such a HTR PWFA, experiments have been set up at the Photoinjector Test facility at DESY, Zeuthen site (PITZ) [9, 10].

EXPERIMENTAL SETUP

A sketch of the PITZ beamline is shown in Fig. 1. Bunches of up to 4 nC are created by a UV-laser pulse from a Cs-Te photocathode and accelerated in the L-band gun and booster cavities to a maximum energy of 25 MeV. The photocathode laser shaping available at PITZ [11] allows the creation of bunch shapes able to drive HTR wakefields directly at the photocathode by splitting a single Gaussian, 1 ps rms laser pulse 13 times in birefringent crystals, forming various shapes of the 14 Gaussian quasi-pulses.

The plasma cell is inserted in the high energy section of the accelerator after the cut-disk booster cavity (CDS) and before the transverse deflecting structure (TDS), which allows time resolved measurements of the bunches after beam/plasma-interaction. In combination with the second high energy dispersive section (HEDA2), the longitudinal phase space can be measured.

As a plasma source the gas discharge cell shown in Fig. 2 is used. The cell consists of two electrodes at the end of a glass tube, filled with Argon gas. The pressure of 0.2-8 mbar is separated from the accelerator vacuum by thin polymer foils. By applying a high voltage between the electrodes the gas is ionised and conducts a high current pulse ($\leq$ 600 A of several µs length, which heats the plasma and increases ionisation. Plasmas with densities of up to 5×10^{16} cm^{-3} at a plasma column length of 100 mm can be created. Changing the delay between plasma ignition and beam arrival time allows the user to adjust the plasma density during interaction.

SIMULATIONS

Simulations of the experiments were conducted with ASTRA [12] until the entrance of the plasma and using PAMASO [13] and HiPACE [14] for simulating the beam-plasma-interaction.

To reach the quasi-nonlinear regime, the beam has to be focused tightly into the plasma at comparably low densities of about 10^{14} cm^{-3}. In terms of transformer ratio, a double triangular bunch shape [4] was found to be optimal for

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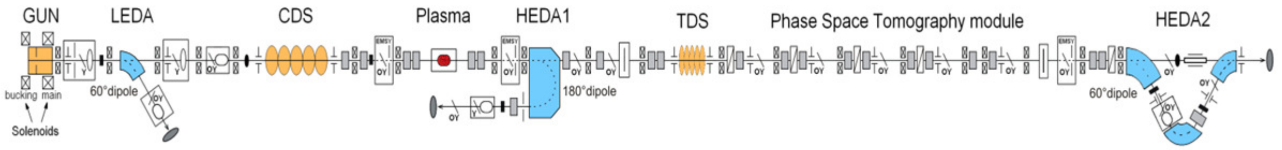

Figure 1: Layout of the PITZ beamline for the PWFA experiments.

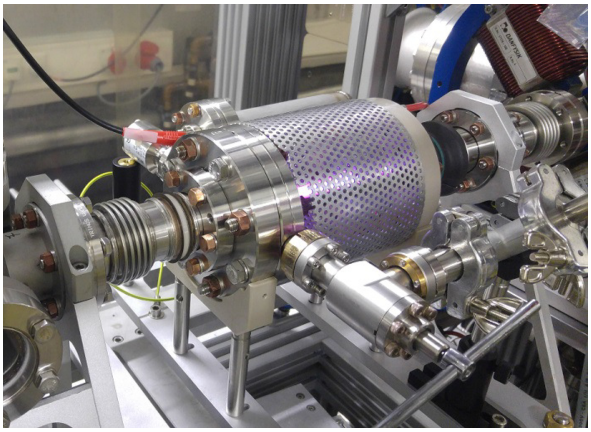

Figure 2: PITZ gas discharge plasma cell inserted into the accelerator beamline.

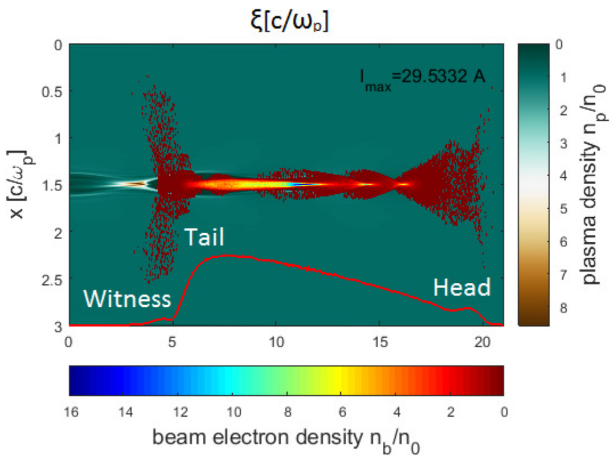

Figure 3: Simulated charge distribution of a 500 pC double triangular bunch in a 10^{14} cm^{-3} plasma after 43 mm of propagation. ω_0 is the plasma frequency, ζ the longitudinal coordinate in the comoving frame z-ct, n_0, n_p and n_b are the undisturbed plasma density, the actual plasma density and beam electron density respectively. The red line represents the bunch current.

the PITZ case. Figure 3 shows a 500 pC bunch during propagation in the plasma. The approximately double triangular bunch current is also shown. The probe bunch is present in the long tail of the driver. The interaction is clearly nonlinear, with both beam density, as well as plasma electron density well above the unperturbed plasma electron density n_0, even at the comparably low currents of maximally ca. 30 A.

The evolution of maximum accelerating field and transformer ratio along the plasma length can be seen in Fig. 4. The strong variations are caused by beam envelope betatron oscillations in the driver bunch, which could in principle be avoided by matching of the driver bunch to the plasma [15], whereas in simulations of the PITZ experiments this proves to be difficult because of the low energies of about 22 MeV and also due to the varying space charge forces along the bunch at the photocathode that result in slice mismatch.

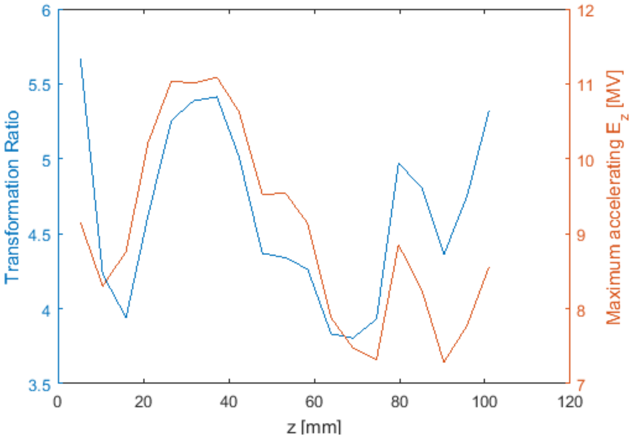

Figure 4: Evolution of maximum accelerating field and transformer ratio calculated from the momentary wakefields [1] along the beam/plasma-interaction length.

Due to these oscillations and field changes, a field-weighted transformer ratio R_w is used as a figure of merit for the optimisation of the interaction

$$R_w = \frac{\int_0^{l_p} E(z)R(z)dz}{\int_0^{l_p} E(z)dz} \tag{1}$$

where R(z) is the transformer ratio directly calculated from de-/accelerating fields [1], E(z) is the maximum accelerating field and l_p is the acceleration/plasma length. For the case shown above the weighted TR is 4.7. The accelerating field averaged over all maximal fields along the acceleration path is 9.04 MV/m. The maximum slice energy loss of the drive bunch is 0.11 MeV after the simulated acceleration length of 100 mm, which is well within the energy resolution of the dispersive section of PITZ. Division of the averaged maximal accelerating field by the maximum slice energy loss yields a ratio of 8. The disparity to the transformer ratio directly calculated from the fields is caused by the fact that the field distribution in the driver bunch is changing, i.e.

there is no specific slice which always experiences maximum deceleration. Division of the maximum energy gain in the witness bunch by the maximum slice energy loss in the driver results in a transformer ratio of 6.2. The deviation of this "effective" transformer ratio to the previous one shows, that also no witness particle experiences the maximum wakefield throughout the acceleration, either because of transverse betatron oscillation or phase instability.
Nevertheless, as the actual energy loss of the drive bunch and the maximum possible energy gain behind the driver are important for the acceleration efficiency, the latter would be the number defining the efficiency and it would also be the parameter measured in experiment.

EXPERIMENTAL RESULTS

It was observed in experiments that double triangular bunches could be transported through the 100 mm plasma column without showing typical signs of instabilities like oscillations in the longitudinal phase space (self-modulation instability) or transverse kicks (hosing instability).
Energy gain of the witness beam was also measured. Figure 5 shows a typical bunch profile measurement without plasma interaction. Total charge is 500 pC.

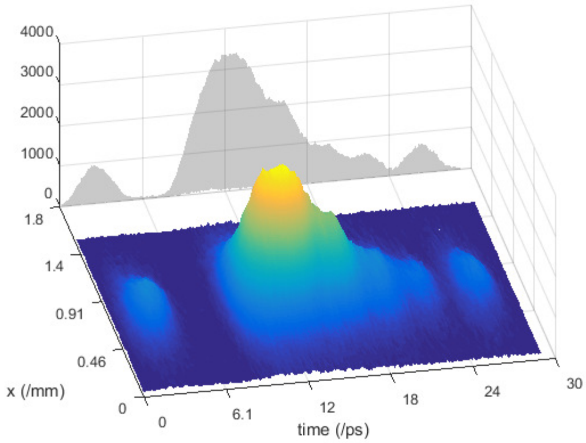

Figure 5: Measured driver (right) and witness beams (left) at PITZ.

SUMMARY AND OUTLOOK

First experiments of HTR PWFA have been succesfully conducted at PITZ and detailed experimental results will be published soon. Possible improvements on beam diagnostics as well as on the discharge plasma cell performance have been discovered during the experiments and are being addressed before further PWFA experiments will be performed. The next experimental period will then concentrate on the optimisation of the transformer ratio and comparison of different driver bunch shapes.

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