A HIGH TRANSFORMER RATIO SCHEME FOR PITZ PWFA EXPERIMENTS

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Abstract

In the field of plasma wakefield acceleration (PWFA) significant progress has been made throughout the recent years. However, an important issue in building plasma based accelerators that provide particle bunches suitable for user applications will be a high transformer ratio, i.e. the ratio between maximum accelerating field in the witness and maximum decelerating fields in the driver bunch. The transformer ratio for symmetrical bunches in an overdense plasma is naturally limited to 2. Theory and simulations show that this limit can be exceeded using asymmetrical bunches. Experimentally this was proven in RF-structures, but not in PWFA. To study transformer ratios above this limit in the linear regime of a plasma wake, an experimental scheme tailored to the unique capabilities of the Photoinjector Test Facility at DESY Zeuthen site (PITZ), a 25-MeV electron accelerator, is being investigated. The numerical simulations of beam transport and plasma wakefields, as well as preparatory studies on the photocathode laser system and plasma sources are presented.

INTRODUCTION

The driving bunch in a plasma wakefield accelerator (PWFA) experiences decelerating fields that are correlated with the accelerating wakefields it creates in the plasma. The ratio between the maxima of these two fields defines the maximum energy that a single particle in the witness bunch can gain with respect to the minimum energy of a particle in the driving bunch, before the latter one is lost and the acceleration is degraded. This so called transformer ratio R is limited by the fundamental theorem of beamloading [1] to R<2 for symmetrical driving and witness bunch, which would mean that in a beam driven plasma wakefield, the witness particles can only be accelerated by twice the energy of a driving bunch particle. To enhance this, several methods have been proposed throughout the investigation on PWFA: either the use of asymmetrical bunches [2–4], or symmetric and asymmetric trains of bunches [5–7]. So far, only the use of a ramped bunch train could be verified to produce high transformer ratio (HTR) acceleration in a collinear dielectric-loaded accelerator [8, 9]. No successful HTR acceleration in a plasma wakefield has been reported yet.

The photoinjector test facility at DESY, Zeuthen site (PITZ), which is shown in Fig. 1, has unique capabilities that make it attractive for HTR PWFA studies, e.g. a highly flexible photocathode laser system [10] and well-elaborated diagnostics with several dispersive sections, a transverse deflecting structure and various emittance measurement options. While the longitudinal laser pulse shaping was developed to produce flattop bunches for FLASH and the European XFEL, it is in principle capable of delivering any longitudinal profile formed of 14 Gaussian bunches, which would allow experiments with all above-mentioned HTR scenarios. Nevertheless, due to the facts that the PITZ facility does not include a bunch compressor and that the accelerating field at the photocathode is limited to 60 MV/m, only wakefields in the linear regime at very moderate field strengths are reachable. Therefore, the investigations are mainly aiming at proving different schemes that have been proposed, comparing their capabilities and practicability as well as the applicability of photocathode-shaped bunches for future HTR PWFA facilities.

In the following, the preparations and preliminary simulations of plasma wakefield acceleration with high transformer ratios at PITZ are shown. The presented simulations employ a bunch with a short flat top precursor, followed by a linear current ramp and a sharp cutoff, the so called "doorstep"-profile [2].

UPGRADE OF THE PHOTOCATHODE LASER

The first adaptation of the PITZ facility is the addition of a separate witness bunch to the driver bunch generated by the current photocathode laser. As internal injection mechanisms are not applicable at PITZ, this is the only solution to probe the created wake fields. Figure 2 shows the changes to the photocathode laser system that allow for this additional pulse.

By splitting the incoming Gaussian pulse from the oscillator, a separate treatment of driver and witness bunch is possible. After the beam splitter, the designated driver bunch goes straight into the above-mentioned bunch shaper, that allows for longitudinal combination of 14 virtual Gaussian pulses through 13 birefringent crystals to a flexible final bunch shape. The designated witness bunch is coupled into an optical fibre. The outcoupling optics and the fibre termination are located on a translation stage and can thus be shifted towards the recombination point of driver and witness pulse in the polarising beam splitter. By this, the delay between the two pulses is adjusted.

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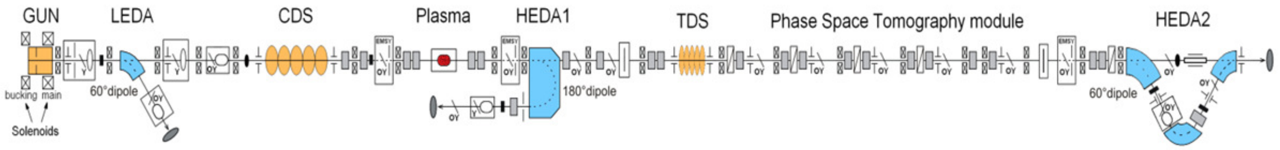

Figure 1: Layout of the PITZ beamline.

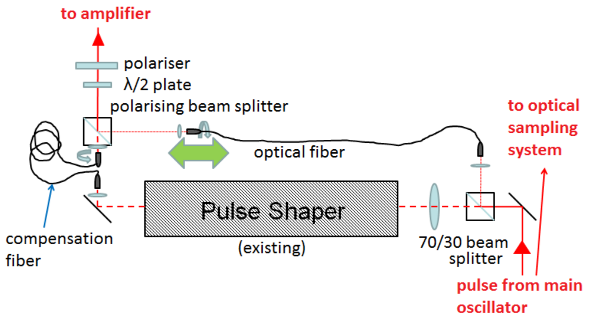

Figure 2: Schematic of the witness bunch addition to the PITZ photocathode laser system.

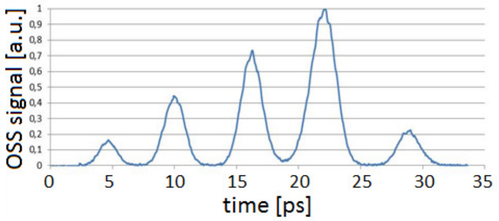

Figure 3: Ramped bunch train photocathode laser pulse, measured at PITZ.

PRIOR STUDIES

The flexibility of the bunch shaper has already been proven in various experiments. In Fig. 3, a cross-correlation measurement of the shaped laser pulse is shown. The crystals were adjusted to create a ramped bunch train out of the single Gaussian laser pulse of the main oscillator. A train of 3 bunchlets with a ramped charge profile has already been transported successfully through the PITZ beamline to the transverse deflecting structure and was measured on a subsequent screen. Clear separation of the bunches could be achieved at a position after the plasma cell position, where a similar profile can be assumed.

PLASMA CELL INVESTIGATIONS

In addition to the studies on a cross-shaped, laser-ionised Lithium heatpipe oven based plasma cell [11], investigations on an Argon gas discharge plasma cell have been conducted. First results have already proven the stability of the plasma in the designed cell, which fits into the plasma cell beamline slot at PITZ. This development is important for the planned HTR experiments as due to the rather low accelerating field strength a longer plasma column might be favourable for precision measurements, which is hard to realise with the transversely ionised Lithium vapour cell. Figure 4 shows a picture of the discharge plasma, which is currently under investigation at PITZ.

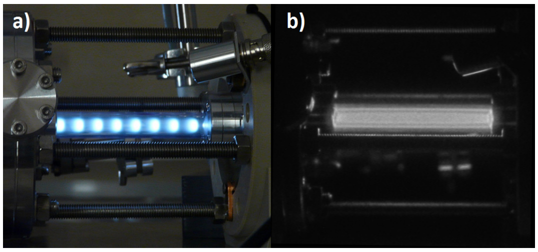

Figure 4: Pictures of the Argon gas discharge under investigation for use in PWFA experiments at PITZ: a) preionisation glow discharge, b) a 240 ns picture during the peak of the 550 A, 6 μs current pulse in 0.5 mbar Argon.

BEAM TRANSPORT SIMULATIONS

The beam transport through the PITZ beamline has been simulated using ASTRA [12], a particle tracking code including space charge forces, and Space Charge Optimiser (SCO), a rms-envelope-solver based, slice-wise optimisation algorithm including linear space charge forces, developed at Helmholtz-Zentrum Berlin. SCO is only used for optimisation of beam optics, the final beam transport is simulated using ASTRA only.

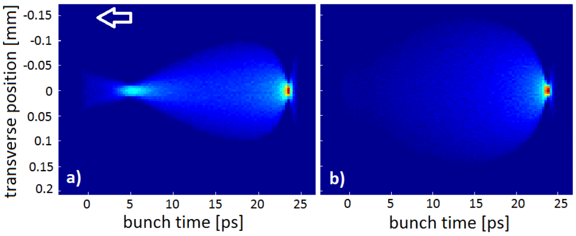

Figure 5: Simulated normalised charge distribution of a 60 pC, doorstep-profile bunch transported trough the PITZ beamline in x-t (a) and y-t (b) projection. The arrow indicates the direction of flight.

Figure 5 shows the shape of a bunch with the "doorstep" current profile introduced above, that was focused at the plasma cell position of the PITZ beamline. As the typical density for PITZ-PWFA experiments is 10^{15} cm^{-3}, the focused beam easily fits into half a plasma wavelength. Due to the strong space charge forces at the comparably low energies the beam is not homogeneously focused but the focus points differ for the different bunch slices. The effect of this uneven focusing is discussed in the next section. In Fig. 6, the bunch current of the focused bunch depicted in Fig. 5 is shown. The current profile could be preserved from the photocathode until the plasma. Total bunch charge for these simulations was 60 pC. Preservation of the longitudinal bunch profiles could be verified for bunch charges up to 1 nC at a laser spot rms-size of 0.7 mm on the photocathode.

PLASMA WAKEFIELD SIMULATION

The interaction of the focused bunch shown in Fig. 5 with a plasma was also simulated using HiPACE [13]. The excited wakefields, the bunch particle positions and the bunch current are shown in Fig. 6. The wakefield amplitude is not flat, which could be an indicator that either the uneven focusing for the bunch slices with different charge is degrading the wakefield formation or the doorstep profile is not optimally matched to the plasma density so far. Nevertheless this simulation already shows an unloaded transformer ratio of nearly 7 at a plasma density of 0.8×10^{15} cm^{-3}.
The very moderate electric field of slightly less than 1 MV/m would result in a maximum energy gain of around 100 keV in the 10 cm long plasma. While this would be measurable in the dispersive sections of the PITZ facility, the field strength can be enhanced e.g. with higher bunch charges. As stated above, the bunch charge could be increased by a factor of 12 from the 60 pC used in this simulation without significant degradation of the longitudinal bunch shape.

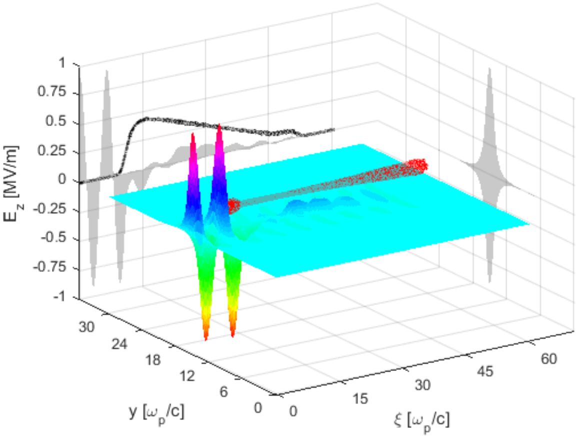

Figure 6: Accelerating/decelerating field, simulated with HiPACE. In grey, the projections of the electric fields are shown, the red dots show the bunch particles, the black line indicates the current profile, which peaks at ca. 5 A. The bunch is moving from left to right.

CONCLUSION

High transformer ratio plasma wakefield acceleration experiments are under preparation at PITZ. Simulations have shown the potential of the facility to demonstrate high transformer ratios in different experimental schemes. Optimisation of the accelerator operation parameters with simulations and commissioning of necessary equipment is ongoing. First experiments are foreseen in the next run of PITZ this year. Even though the experiments will not yield high energy results or wakefield strengths high enough for future accelerators, the investigations are aiming at contributing detailed experimental data on the promising high transformer ratio, beam-driven plasma wakefield acceleration and the investigation of photocathode-shaped bunches for this purpose.

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