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# HIGH TRANSFORMER RATIO PLASMA WAKEFIELD ACCELERATION DRIVEN BY PHOTOCATHODE LASER SHAPED ELECTRON BUNCHES

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*Abstract*

Particle beam driven wakefield acceleration in plasmas (PWFA) are among the most promising candidates for novel, compact accelerators. Several aspects of PWFA are under investigation at the Photoinjector Test facility at DESY in Zeuthen (PITZ). One of the main characteristics of these accelerators is the ratio between field strength usable for acceleration and decelerating field strength in the driver bunch, the so called transformer ratio. To reach high transformer ratios, usually shaped bunches, e.g. with ramped current profiles and lengths on the order of or longer than the plasma wavelength are employed as drivers. Due to their length, such bunches have been predicted to be subject to beam-plasma instabilities like hosing and self-modulation. Here, we give an overview of experimental results on PWFA with high transformer ratios at PITZ with a focus on the production of the required electron bunches by shaping the photocathode laser pulses of a photoinjector. Further developments on the shaping technique, allowing highly flexible electron bunches for future plasma wakefield accelerators are also introduced.

## INTRODUCTION

Since the proposal of utilising wakefields in plasmas driven by high energy particle beams to accelerate electron or positron witness particles with high gradients [1, 2], the method has made significant advancements. High gradient beam-driven plasma wakefield acceleration (PWFA) has been demonstrated as well as the achievement of enhanced efficiency [3, 4]. Only recently, it was also demonstrated that a high ratio of the acceleration of the witness beam to the deceleration of the driver beam can be achieved [5]. This so-called transformer ratio [6–8] defines the maximum achievable witness particle energy for a given driver particle energy, or similarly the minimum required driver beam energy for a target witness energy. Furthermore, it can be shown that achieving a high transformer ratio (HTR) requires a homogeneous decelerating field within the driver bunches. As homogeneous deceleration is a prerequisite for extracting the maximum amount of energy from a driver bunch with low initial energy spread, achieving high transformer ratios is similar to enabling high efficiency PWFA.

In the linear regime of plasma wakefields and for longitudinally symmetrical driver bunches the transformer ratio is limited to below 2 by the fundamental theorem of beamloading [6, 9, 10]. To surpass this limit, several longitudinally asymmetrical bunch shapes, usually consisting of a linear current ramp — sometimes with a precursor — and a sharp drop at the tail (also called "triangular"), have been proposed [8, 11–14]. As bunches that typically emerge from conventional photoinjectors do not exhibit such asymmetrical bunch shapes, additional measures have to be taken to deliver such bunches to PWFAs. In this work we will give brief overviews of currently available bunch shaping schemes and of the status of HTR wakefield acceleration. We will introduce the bunch shaping scheme in use at the photoinjector test facility at DESY in Zeuthen (PITZ), show some recent results on HTR PWFA with shaped bunches achieved at PITZ and discuss limitations of the bunch shaping for achieving stable acceleration of finite length witness bunches.

## SHAPING SCHEMES FOR PICOSECOND RAMPED ELECTRON BUNCHES

Shaping of triangular bunches was achieved with various methods. These methods are based on either the introduction of nonlinear modifications to the longitudinal phase space (LPS) of a bunch , which are subsequently transferred into the longitudinal profile in a magnetic chicane [15,16], cutting parts of the bunch distribution from the LPS [17, 18], introduction of nonlinear transverse fields to a dispersed bunch [19] or transverse masking of parts of the bunch and consequent transverse-to-longitudinal emittance exchange [20–22]. Nevertheless, all the above-mentioned methods exhibit some intrinsic drawbacks as e.g. the necessity for additional, dedicated beamline elements. Some schemes also lead to distortion of the transverse phase space which limit further application of the shaped bunches [19], others imply large charge losses within the vacuum of the accelerator beamline [18, 22]. While the latter is of limited concern at low repetition rates, the supply of high repetition rate shaped bunches for wakefield accelerators will necessi-

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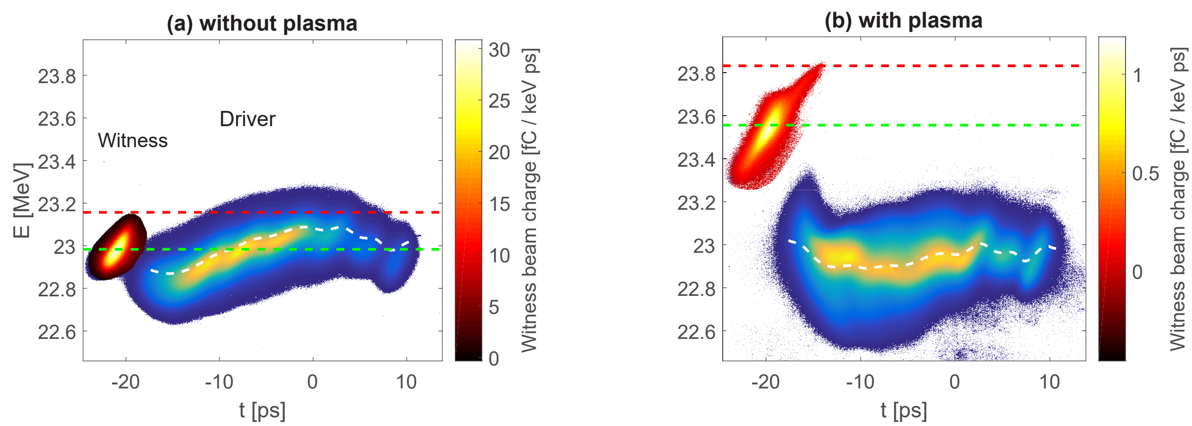


Figure 1: Longitudinal phase spaces of driver and witness bunches measured without (a) and with (b) a plasma of $(1.2 \pm 0.4) \times 10^{13}\,\mathrm{cm}^{-3}$ electron density. The witness bunch ($t \approx -20$ ps) was measured with a different camera gain than the driver. Dashed lines indicate witness mean (green) and maximum (red) energies and the driver mean slice energies (white).

tate the removal of large amounts of heat from the masks in vacuum and will lead to high radiation doses in the shaping section of the beamline.

Shaped driver bunches for PWFA experiments at PITZ are therefore supplied by shaping of the temporal intensity profile of the ultraviolet laser pulse that is utilised to extract the electron bunch from the photocathode in the electron gun. No additional beamline elements are required for this shaping method. The current photocathode laser at PITZ includes a shaping section based on a Šolc fan filter, which allows the production of longitudinal intensity distributions that can be formed from 14 partially overlapping Gaussian quasi-pulses [23–25]. As shaping is achieved by the delay of parts of the laser intensity, the transverse profile of the laser pulse remains unchanged.

## STATUS OF HIGH TRANSFORMER RATIO WAKEFIELD ACCELERATION

As stated above, several methods of achieving high transformer ratios in beam-driven wakefield acceleration have been proposed in the literature. After early proposals of bunches with linear ramps and lengths on the order of or longer than the characteristic wavelength of the wakefield (e.g. plasma wavelength in plasmas) [8, 11], methods based on different trains of driver bunches have been proposed and pursued [26, 27]. This change of paradigm was motivated by the limited availability of bunch shaping on the necessary scales at that time. First successful demonstration of enhanced and high transformer ratio in a dielectric wakefield accelerator was also achieved with trains of driver bunches at Argonne National Laboratory [28, 29]. With several experimental demonstrations of shaping ramped bunches with the parameters required for high gradient wakefield acceleration (see also previous Sec.) experiments again concentrated on single, shaped bunches due to the limitations of schemes based on bunch trains (see e.g. [30]).

Recently, acceleration with transformer ratios of ~ 5 with single, shaped driver bunches was shown in a dielectric wakefield accelerator [31] and in a plasma [5] at the Argonne National Laboratory and at DESY Zeuthen, respectively. While the concept of achieving high transformer ratios has thus been validated experimentally, no experiment has so far demonstrated high transformer ratio acceleration at gradients and with a final witness bunch quality relevant for applications.

Several projects are ongoing which are aiming to demonstrate the driving of high transformer ratio wakefields at high gradients. In the case of plasma-based wakefields, current projects are

1. SPARC at INFN, where a train of driver bunches created by stacking of UV photocathode laser pulses shall be used to drive GV/m-scale wakefields in a quasi-nonlinear regime PWFA [32],

2. FLASHForward at DESY Hamburg, where triangular bunches produced in a superconducting linac with a third harmonics cavity will be utilised to drive wakefields in the 10 GV/m-range [33],

3. and AWA at Argonne National Laboratory, where triangular bunches shaped in a transverse-to-longitudinal emittance exchange beamline are being employed to drive wakefields on the order of 100 MV/m [34].

## RECENT HTR PWFA EXPERIMENTS AT PITZ

At PITZ, the experimental focus lies on the shaping of bunches by shaping of photocathode laser pulses and the experimental investigation of PWFA characteristics and phenomena at low plasma densities. In the scope of these experiments, the driving of a PWFA by a triangular bunch with a transformer ratio of 4.6 was achieved and reconstructed in numerical simulations [5]. In later measurements, a TR

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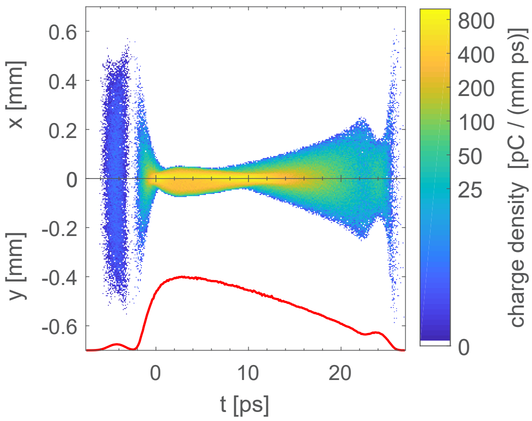

Figure 2: Charge projection in x-t (top) and y-t (bottom) planes for 700 pC double triangular driver and Gaussian witness bunches at the PITZ plasma cell entrance simulated with ASTRA [35]. The normalised bunch current profile is shown in red.

of $5.0^{+1.5}_{-0.4}$ could be achieved. The corresponding measurement is shown in Fig. 1. Longitudinal phase spaces of the $(29 \pm 1)$ pC witness and $(700 \pm 19)$ pC driver bunches are measured without and with plasma interaction. The change in the maximum energy of the witness bunch (red dashed lines) is divided by the maximum change of the slice-wise mean energy in the driver bunch (white dashed lines) to calculate the transformer ratio. Maximum energies of the witness bunches are taken into account, as the witness bunch experiences a wide range of phases of the wakefield and the time resolution in these measurements was not sufficient to resolve the witness slice energy. One of the main shortcomings of the experiment, which is visible in Fig. 1, is the large loss of witness bunch charge. In the shown measurement only ~ 4 % of the witness charge was recorded at the measurement screen when the plasma was switched on. The large loss of charge is attributed to defocusing of the majority of witness bunch particles in the plasma and consequent particle loss on the exit aperture of the plasma cell. As described above, the shaping method based on the Šolc fan filter does not change the transverse size of the laser pulse. Hence, the transverse bunch size at the photocathode during extraction is similar for all slice of the bunch, i.e. also for the witness bunch. Due to the strongly varying charge in the slices of the driver bunch as well as in the witness bunch, the slices' transverse phase spaces are oriented differently [23]. Figure 2 illustrates this: While the high charge slices of the driver bunch ($-2$ ps< $t$ < 28 ps) are well focused, the low charge slice of the driver and the witness bunch are defocused.

Furthermore, stable transport of the bunches through the plasma was only achieved at plasma densities < $10^{14}$ cm$^{-3}$. At higher densities the driver bunch is severely deteriorated by the self-modulation instability, a transverse instability in which small differences in the transverse wakefields of bunches with lengths on the order of a plasma wavelength lead to periodic focusing and defocusing along the bunch profile [36–38]. In simulations of the experiment stable transport was achieved at densities up to $2 \times 10^{14}$ cm$^{-3}$. The discrepancy between simulation and experiment is addressed to non-ideal bunch shaping with the current PITZ photocathode laser pulse shaper. Shaping of the bunches was found to be very sensitive to small variations of the shaping crystal orientations and thus required long tuning times. Slow drifts of the shaper led to spikes in the longitudinal laser pulse profile, which increase the slice charge differences and thus amplify the focusing inhomogeneities described above.

Another issue caused by the uneven focusing of different slices of the driver are oscillations of the phase that the witness bunch experiences in the wakefield. Matching conditions of transverse size to the transverse wakefields can only be adjusted for part of the driver bunch due to the varying slice focus. The other parts of the bunch undergo betatron oscillations along the plasma medium. As the interaction is nonlinear, the longitudinal size of the plasma bubble depends on the driver bunch density. Slice envelope oscillations therefore change the phase of the wakefield at the position of the witness bunch. In these oscillations witness particles can slip to defocusing phases of the wakefield and are lost from further acceleration.

## PROSPECTS OF PHOTOCATHODE LASER BASED BUNCH SHAPING

Due to the issues of the Šolc filter based laser pulse shaping discussed in the previous section, a new, more direct, transverse and longitudinal shaping of the electron bunches is required for further optimisation. A photocathode laser system with shaping based on partial masking of laser pulses in the frequency domain is currently being set up at PITZ, which is supposed to meet these requirements [23, 39]. In this shaping scheme, infrared (IR) laser pulses with a linear correlation between time and wavelength $\lambda$ ("spectral chirp") are dispersed by a grating and then focused in the dispersion plane. A spatial light modulator (SLM) is utilised to mask parts of the spectrum of the pulse that is dispersed in frequency (which is coupled to time) as well as in one transverse direction. After realignment of the spectral components of the pulse in a second, downstream grating, the masking process is repeated in the other transverse direction.

This method allows to shape any longitudinal intensity profile that can be cut from the original (Gaussian) distribution. Due to the decoupled shaping in the x-$\lambda$- and the y-$\lambda$-planes the transverse profile of the shaped bunches is always rectangular.

Shaping of IR pulses from the laser frontend has already been commissioned at PITZ. A measurement of a triangularly shaped IR laser pulse in the frequency domain is shown in Fig. 3. The pulse profile already quite well resembles the required triangular bunch profile. Nevertheless, longitudinal profile measurement in the time domain and conversion of the laser pulse to the fourth harmonics frequency with

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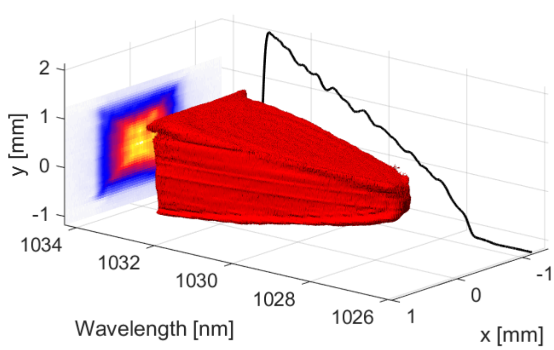


Figure 3: Three-dimensional envelope (red) of a laser pulse shaped to a triangular longitudinal profile (black line) with the SLM-based pulse shaping setup at PITZ, measured in the frequency domain. The intensity was kept constant within every longitudinal slice, while the transverse size is increased gradually. The rectangular transverse projection of the pulse is shown on the left.

preservation of the achieved pulse shapes still has to be commissioned. Even though this was shown to be possible [40], it was also found to be a non-trivial task and measurements at PITZ will first focus on the detailed characterisation of the resulting ultraviolet laser pulses in time and frequency domain, before first electron bunches will be generated.

## CONCLUSION

The transformer ratio is an important figure of merit of a wakefield accelerator, which describes the achievable energy gain of particles in such an accelerator for a given driver bunch particle energy. While methods to achieve high transformer ratios have been proposed already in the beginning of research on wakefield-based acceleration, their experimental demonstration has proven to be very complex, especially due to the required bunch shaping of high brightness electron bunches. Only recently, the driving of high transformer ratio wakefields has been demonstrated in dielectric wakefields as well as in plasmas. Transformer ratios up to ~ 5 have been achieved, which already exceeds the linear limit of 2 significantly. Even though these proof-of-principle experiments have up to now only operated at low accelerating gradients, bunch shaping methods are available to supply bunches for high gradient, high transformer ratio acceleration.

Bunch shaping based on shaping of the photocathode laser pulses of a photoinjector, which offers flexible and efficient manipulation of electron bunch profiles, has been shown to deliver bunches capable of driving high transformer ratio plasma wakefields. Shortcomings of this method in its current implementation have been identified and a new shaping system, that can overcome these shortcomings, is being commissioned at PITZ. First bunches from the system are expected this autumn. Other projects relying on different bunch shaping methods are underway and are also expected to show results in the near future.

After the demonstration of e.g. high gradient acceleration in plasmas, the achievement of high transformer ratios marks another important milestone on the way to the application of high gradient, compact plasma wakefield accelerators. Current efforts are aiming to expand the present capabilities of controlling the transformer ratio to high energy acceleration and ongoing developments promise the availability of highly flexible, high repetition rate shaping methods for future plasma wakefield accelerator facilities.

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