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OPTIMISATION OF HIGH TRANSFORMER RATIO PLASMA WAKEFIELD ACCELERATION AT PITZ

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Abstract

The transformer ratio, the ratio between maximum accelerating field and maximum decelerating field in the driving bunch of a plasma wakefield accelerator (PWFA), is one of the key aspects of this acceleration scheme. It not only defines the maximum possible energy gain of the PWFA but it is also connected to the maximum percentage of energy that can be extracted from the driver, which is a limiting factor for the efficiency of the accelerator. Since in linear wakefield theory a transformer ratio of 2 cannot be exceeded with symmetrical drive bunches, any ratio above 2 is considered high. After the first demonstration of high transformer ratio acceleration in a plasma wakefield at PITZ, the photoinjector test facility at DESY, Zeuthen site, limiting aspects of the transformer ratio are under investigation. This includes e.g. the occurrence of bunch instabilities, like the transverse two stream instability, or deviations of the experimentally achieved bunch shapes from the ideal.

INTRODUCTION

Wakefield acceleration in plasma is one of the most promising techniques for future high energy, high brightness accelerators. In the beam driven plasma wakefield accelerator (PWFA) [1] one of the key figures of merit is the transformer ratio (TR), defined as the ratio between accelerating field strength in the witness bunch and decelerating field strength in the driver bunch [2]. It defines the maximum energy gain for the witness bunch in a PWFA. As the fundamental theorem of beamloading [3] limits the transformer ratio to below 2 for symmetrical bunches in linear wakefield theory, several asymmetrical drive bunch shapes and asymmetrical trains of bunchlets have been proposed to increase the transformer ratio [2, 4, 5]. Due to the TR limitations faced by bunchlet-train based methods [6] and advanced phase space manipulation capabilities, research focus has recently shifted towards production and application of long, ramped bunches [7, 8, 9, 10]. The TR in a PWFA employing such bunches directly depends on the ratio of driver bunch length to characteristic /plasma wavelength, i.e. how many plasma wavelengths the bunch is long. A high TR (HTR, i.e. a transformer ratio > 2) can usually be achieved with driver bunch lengths at least on the order of the plasma wavelength. Due to the inherent, strong transverse wakefields in a plasma, such bunches are subject to various beam-plasma instabilities, such as the self-modulation instability [4, 11, 12] or the hosing instability [13], the growth lengths of which also depend on bunch length. To mitigate these instabilities, control of the bunch phase space [14] and operation in the nonlinear regime of the PWFA [15] are required. In this contribution we will discuss limitations for the transformer ratio in the PWFA experiments at the Photoinjector Test Facility at DESY, Zeuthen site (PITZ), imposed by bunch shape deviations and beam-plasma instabilities.

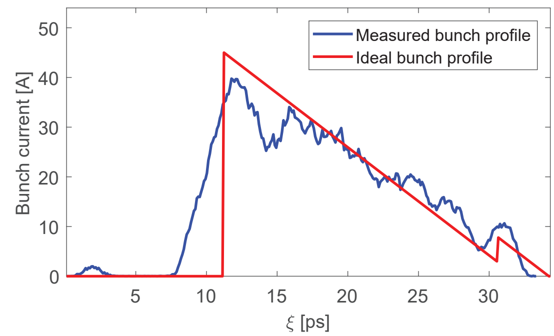

Figure 1: Exemplary measured and ideal bunch current profiles for PITZ HTR experiments.

BUNCH SHAPE LIMITATIONS

The main limitations for the TR in a PWFA are the length of the driver bunch and the accuracy of the bunch current shape [4]. Energy gain of the witness is then limited by the energy and stability of the driver bunch. PITZ is a 25 MeV photoinjector RF-accelerator, which can produce electron bunches of flexible shape and transverse emittances as low as 0.1 mm mrad. The advanced photocathode-laser pulse shaping schemes also allow the production of HTR-capable bunches [10, 16]. Figure 1 shows a measured and an ideal bunch current profile of similar length and current. The achieved bunch shape deviates significantly from the ideal, especially at the falling edge at the tail of the driver (Fig 1, ~ 11 ps) and at the precursor at the bunch head (Fig 1, ~ 32 ps). Results from [4] predict a maximum ratio of the PITZ driver bunch length to the plasma wavelength of ~ 1 for the measured bunch current tail length. Even for an otherwise ideally shaped driver bunch the TR would thus be limited at ~ 6.

While the bunch head accuracy could be improved by thorough tuning and ultimately by improved shaping meth-

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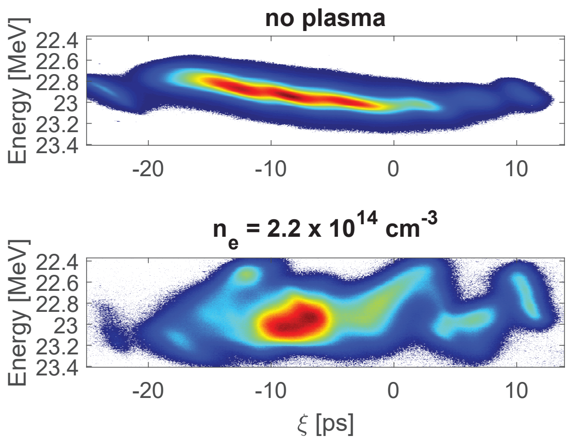

Figure 2: Longitudinal phase space of a ramped bunch and a small witness bunch (left, ~ -23 ps) without and with a plasma of density n_e, exhibiting clear signs of self-modulation instability.

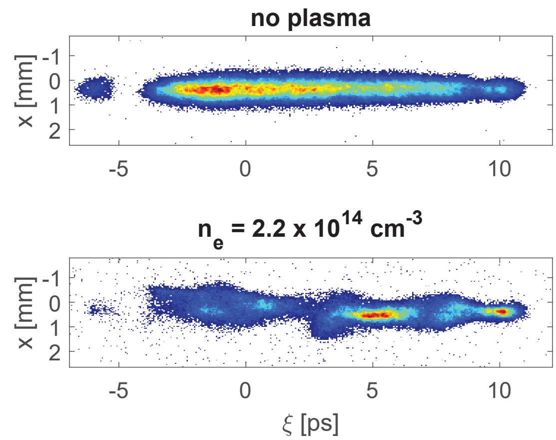

Figure 3: Bunch profile of a ramped bunch, showing self-modulation in a plasma of density n_e.

ods [10], the slope and therefore the length of the falling edge at the bunch current tail are limited by diffraction of the photocathode-laser pulse and by space charge effects during the extraction of the bunch from the photocathode. Even by larger laser spot sizes these deviations from an ideal bunch shape cannot be mitigated completely. Nevertheless simulations presented in [10] already show a significantly improved shape, raising the maximum possible TR at PITZ to ~ 8.5, even though not being optimised in this regard. This might also be increased further by longer photocathode-laser pulse (i.e. bunch) lengths.

BEAM-PLASMA INSTABILITY LIMITATIONS

As mentioned above, bunches that drive HTR wakefields have to be transported over a substantial length in the wakefield structure/medium to transfer significant amounts of energy to the witness bunch. As beam-plasma instabilities and TR both increase with the ratio of bunch length to plasma wavelenghts, ways of mitigating these instabilities have to be found to enable HTR PWFA.
Figures 2 and 3 show the interaction of ramped bunches with a similar profile as shown in Fig. 1 with a ~ 10 cm long plasma of density n_e. The modulations introduced to the longitudinal phase space of the bunch (Fig. 2, bottom) are a clear sign of the self-modulation instability (SMI) [17]. The transverse modulation and break-up of the bunch into short bunchlets can be seen in Fig. 3.

The appearance of SMI was averted by operating at lower plasma density. At densities where the beam density locally exceeds the plasma density, nonlinear PWFA theory applies, which predicts purely focusing transverse forces along the driver bunch. Nevertheless, lower plasma density again implies a lower number of plasma wavelengths in the driver (i.e. lower TR) and also lower acceleration gradients. To operate at high plasma densities and still achieve nonlinear interaction, the bunch density has to be increased. This can either be achieved by higher bunch charge, which is partially constrained by the TR-limitations discussed in the previous section, or by longitudinal and transverse compression of the driver bunch. The latter can be achieved by lower geometrical emittance or a bunch compression stage. As the PITZ linac does not include a bunch compressor and the final bunch energy is limited to ~ 25 MeV, decreasing the emittance of HTR-capable bunches at the photocathode is the only option. Further simulations and experiments will study the impact that an increasing bunch charge has on the bunch current profile and on the bunch phase space.

CONCLUSION

We have presented considerations on the limit for the transformer ratio in plasma wakefield acceleration at PITZ. With the current bunch shaping capabilities, deviations of the achievable driver bunch shapes from ideal HTR-driver shapes were found to limit the TR to ~ 6. Mitigation of beam-plasma instabilities, that were shown to inhibit stable driver bunch transport, was achieved by operating at low plasma densities, where the bunch densities exceed the plasma densities locally, and thus the interaction takes place in the nonlinear regime of PWFA. The possibility to improve driver bunch parameters to achieve transformer ratios beyond the values presented in [16] in PITZ PWFA experiments will be the subject of further studies.
The presented limits do not represent general limits for photocathode-laser based bunch shaping techniques, as different laser pulse shapes, acceleration gradients at the photocathode, final beam energy and other parameters can influence the achievable transformer ratios significantly and a similar assessment needs to be done for every individual case.

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