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# Towards experimental investigation of hosing instability mitigation at the PITZ facility

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**Abstract.** Beam-driven plasma wakefield acceleration (PWFA) allows for high gradient acceleration of electron beams and hence is a promising candidate for compact and cost-efficient drivers of applications demanding high brightness beams. One of the main challenges in these accelerators is to control beam-plasma instabilities with rapid growth rates which are induced by the strong transverse components of the wakefields. The hosing instability, a growing transverse oscillation of the beam centroid caused by coherent coupling between bunch slice centroids and transverse wakefields, was predicted to set severe limits on the possible acceleration distance in PWFAs. Several methods have been proposed to damp or even suppress the hosing of the beam, prevent beam-breakup and thus allow stable operation. Here, we present preparations and simulation studies aiming at the experimental investigation of hosing suppression mechanisms at the PITZ facility.

## 1. Introduction

Acceleration of particles in beam-driven wakefields in a plasma (plasma wakefield acceleration, PWFA) [1, 2] has received broad interest in recent years due to the prospects of acceleration of high-brightness particle beams with accelerating gradients exceeding those of conventional technology by orders of magnitude. In PWFA a driver particle bunch traveling with ultra-relativistic velocity enters a plasma, where it pushes the plasma electrons from their equilibrium positions due to its space charge. The displaced plasma electrons will subsequently be pulled back by the space charge force of the ion background left behind and will start oscillating around their equilibrium position. Plasma ions are usually assumed to be static due to their much larger mass. A wake of net negative and positive plasma particle charge excess regions is formed by these oscillations behind the driver and the strong electric fields that are present between these net charges can be used to accelerate a second, trailing particle bunch, called witness.

To preserve the beam quality (i.e. emittance) of the witness beam throughout the acceleration in the plasma, PWFAs are usually designed to operate in the non-linear regime of interaction [3, 4], where all plasma electrons are expelled from the propagation axis by the driver, and the remaining pure ion column provides a linear, constant focusing field for the witness bunch. Positive feedback between transverse asymmetries in the driver bunch and the wakefield that it forms can lead to rapid amplification of the bunch centroid offsets with respect to the propagation axis. This so-called hosing instability (HI) was first described in the scope of the ion-channel laser [5] and is sometimes also called beam-breakup in analogy to similar effects in conventional



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accelerators. Due to the large growth-rate of the instability, HI would limit the maximum length of a PWFA significantly, prohibiting significant energy gain in such a setup [6, 7, 8]. Recently, several methods to mitigate the growth of HI, which would allow stable operation of a PWFA, have been proposed and investigated in theory [9, 10, 11, 12, 13]. All the described methods are based on breaking the coherence of the betatron oscillations of the bunch particles, which results in negative interference of the detuned centroid oscillations and therefore prevents growth and in some cases even provides damping of the beam centroid offsets. Proposed methods to achieve a sufficient decoherence include acquired or initial correlated and uncorrelated energy spreads [9, 12], variation of the focusing forces by operating in the mildly nonlinear regime for at least part of the acceleration [10, 13] and also variation of the focusing forces along the bunch due to motion of the plasma ions in very intense driver beam scenarios, i.e. in the extremely nonlinear regime [11].

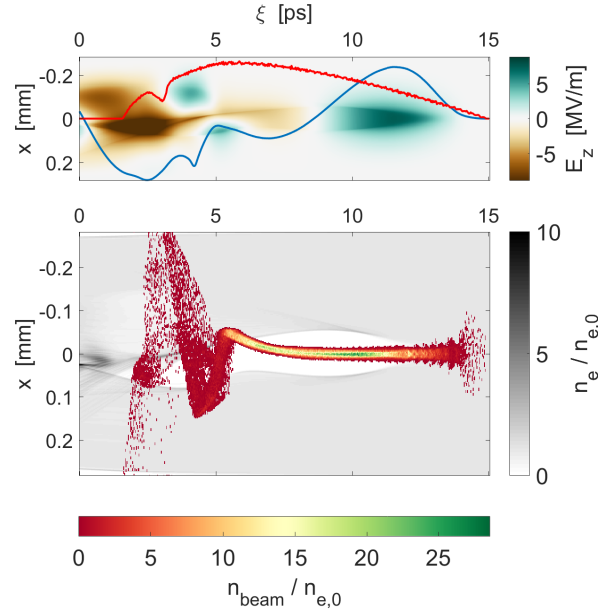
Thus far these methods lack experimental verification, which is why an experiment is proposed to study mitigation of the hosing instability at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) [14, 15]. In this work we discuss results of simulation studies for such an experiment and report on the status of the experimental preparations.

## 2. Hosing mitigation scheme for PITZ

The PITZ facility consists of a 1.3 GHz photocathode radiofrequency gun with a nominal accelerating field of 60 MV/m at the cathode, a 1.3 GHz booster cavity, which increases electron energies up to 25 MeV, several quadrupoles, an experimental beamline slot for insertion of e.g. a plasma cell and various diagnostics, among them also a transverse deflecting structure (TDS) for longitudinal bunch profile measurements.

Within the scope of a dedicated hosing experiment at PITZ first the seeding of HI will be demonstrated by introducing an intentional transverse asymmetry of varying strength to an electron bunch. The transverse profile in the direction in which the asymmetry is introduced, is then measured for cases without and with interaction with a plasma to observe an increase of the initial asymmetry in the beam-plasma interaction. As hosing grows along the bunch that drives the wakefield, the bunch length should be as long as possible. Practically, the bunch length is limited to about one plasma wavelength though, as longer bunches are prone to other instabilities, e.g. self-modulation [16, 17]. At PITZ the seed asymmetry is intended to be introduced by intentionally misaligning the bunch trajectory in the booster cavity of the linac with respect to its symmetry axis. Measurements presented below show that this produces a time-dependent transverse kick of the bunch, which results in a controllable tilt (i.e. linear x-z correlation) in the bunch.

After demonstrating the seeding of HI, one of the above-mentioned methods to mitigate it will be applied to the bunch. Ideally one parameter of the bunch at the plasma entrance would be varied, which is predicted to lead to slice betatron decoherence in the plasma wake, and consequently a reduction in the transverse asymmetry after the plasma would be observed. In case of the PITZ facility, this is mainly possible with the transverse bunch size at the plasma entrance, corresponding to the method described in Ref. [13]. Other methods (e.g. introducing a correlated energy spread by off-crest acceleration in the booster cavity) make it difficult to maintain the small transverse bunch size at the plasma entrance at the moderate beam energies at PITZ, whereas this is mandatory to access the nonlinear regime of interaction in the plasma. Lowering the plasma density leads to an increased betatron length, which can make the observation of HI impossible due to insufficient growth in the given plasma length. Slight, symmetrical changes of the transverse bunch size at the plasma entrance on the other hand are easily achieved by changing the current in the main gun solenoid in the PITZ beamline.



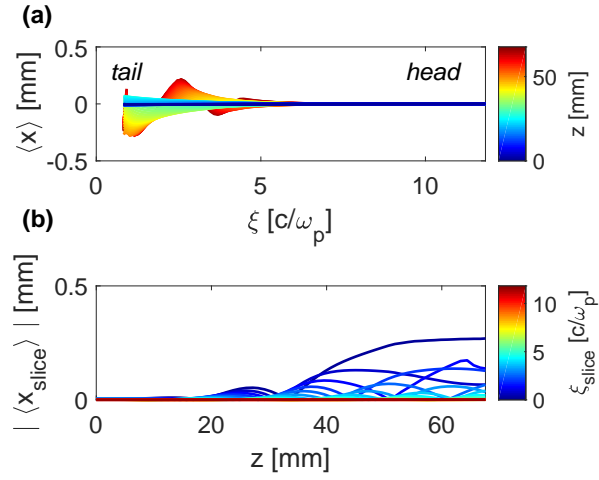
**Figure 1.** Simulation results for the PWFA interaction of a 500 pC triangular driver bunch with a plasma of unperturbed electron density  $n_{e,0} = 2 \times 10^{14} \text{ cm}^{-3}$  in the co-moving frame ( $\xi = z/c - t$ )  $\sim 67$  mm into the plasma at a main solenoid current of 351 A. The top plot shows the electrical field distribution in the  $x$ - $\xi$ -plane close to the axis (colour scale), bunch current profiles (red line) and longitudinal fields on axis (blue line, shares axis of colour bar). The lower plot shows beam (colour scale) and plasma electron densities (grey scale) in the  $x$ - $\xi$ -plane close to the axis. The bunch is propagating from left to right.

### 3. Simulation studies

Numerical simulations were conducted to identify suitable beam and plasma parameters for the proposed experiment. PITZ electron bunches were simulated using ASTRA [18] until the entrance into the plasma medium. Simulations in the plasma were conducted with HiPACE [19] for a simulated co-moving volume of  $4.5 \times 0.55 \times 0.55 \text{ mm}^3$ , resolved with a  $z$ - $x$ - $y$  grid of  $512 \times 256 \times 256$  cells.

While in experiment the bunch tilt which seeds HI is achieved by off-axis propagation in the PITZ booster cavity, the  $x$ - $z$ -correlation is manually introduced to the bunches in simulations at the conventional beamline/plasma interface.

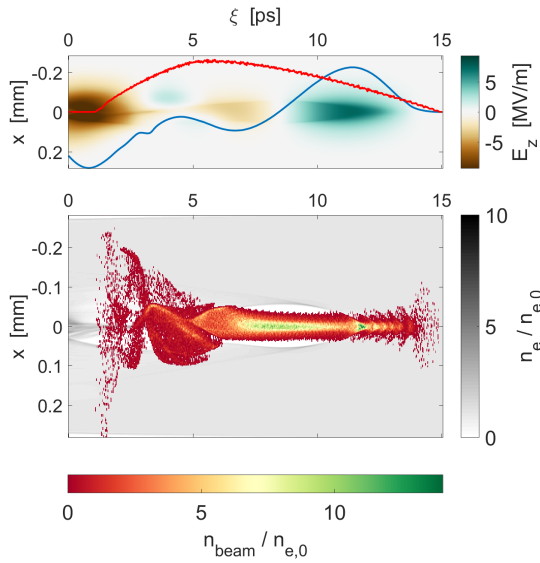
Figure 1 shows a bunch, that is subject to the hosing instability after  $\sim 67$  mm propagation in the plasma. The bunch was extracted from the photocathode by a laser pulse with a linearly rising intensity and a sharp drop at the tail (so-called triangular shape). Transverse spot size varies along the pulse, according to the integrated flux in the longitudinal slice [20]. Plasma density, bunch charge and length were chosen such, that the bunch length covers as many plasma wavelengths as possible, while nonlinear interaction is maintained and simulations without an initial hosing seed show stable transport of the bunch. An initial bunch tilt of  $1 \mu\text{m}/\text{mm}$  was applied to the bunch at the simulated entrance into the plasma. The slice centroid evolution of the bunch is shown in Fig. 2: the front slices do not oscillate significantly, as is expected from hosing, which grows along the bunch. Slices in the back of the bunch (low  $\xi_{\text{slice}}$ ) oscillate with partially detuned frequencies beginning at ca. 30 mm into the plasma. This is caused by a residual energy spread in the bunch and by slice particles leaving the wakefield blowout region and therefore experiencing different transverse forces. Beam hosing is fully developed at the end



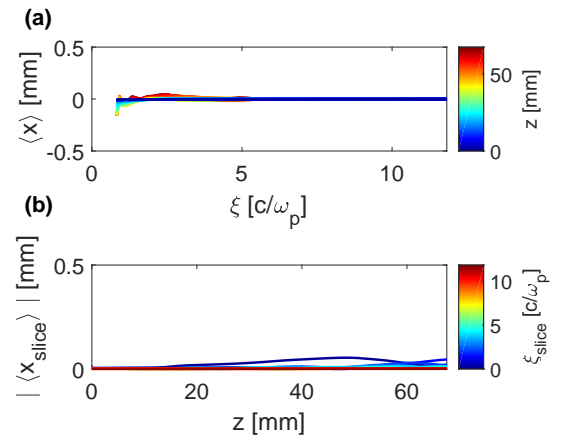
**Figure 2.** Evolution of the bunch slice centroid offsets for the simulation depicted in Fig. 1. (a) Slice centroid along the bunch at different positions along the plasma (colour scale). (b) Slice centroid positions along the plasma for different slices (colour scale).

of the simulated interaction: bunch particles have partially left the blowout region, the wakefield is distorted such that no acceleration of a witness bunch would be possible (see Fig. 1).

The results for a similar simulation with a bunch that is slightly overfocused at the entrance of the plasma are shown in Figs. 3 and 4. By increasing the main gun solenoid current by 2 A to 353 A, the transverse RMS size of the bunch is increased from  $13\ \mu\text{m}$  to  $23\ \mu\text{m}$ . While there are still asymmetric structures apparent in the transverse profile of the bunch in Fig. 3 and the wakefield shape is also clearly distorted, the bunch centroid oscillations shown in Fig. 4 have been reduced significantly compared to Fig. 2. This is considered a first evidence of hosing



**Figure 3.** Simulation results for bunch and plasma parameters described in Fig 1 at a main gun solenoid current of 353 A.



**Figure 4.** Bunch slice centroid evolution for simulation results in Fig. 3. Depiction as in Fig. 2.

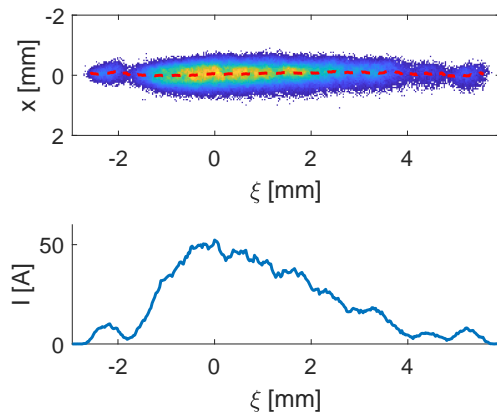
instability mitigation even though stable acceleration of a witness bunch would still not be possible in this case. A clear improvement of the situation would be achieved by increasing the size of the blowout region compared to the bunch size. As no longitudinal bunch compression is available at PITZ and bunches are focused transversely as tightly as possible, the only option is a further reduction of the plasma density. Simulations with lower densities are ongoing, as are preparations of a longer plasma cell to compensate for the increased betatron length (and hence reduced number of HI growth lengths in the given plasma channel length) at lower plasma densities.

#### 4. Experimental preparations

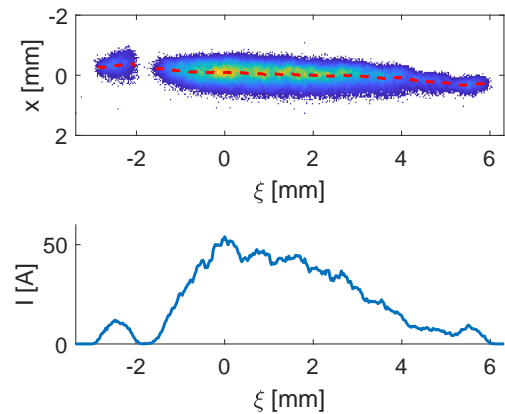
As available plasma sources at PITZ can thus far only provide plasma media with a length of around 70 mm at the plasma densities required for the experiment discussed here [21, 22] an extended Argon discharge plasma cell has been set up. This will allow to reduce the plasma density while still providing a sufficient number of growth lengths for HI to develop. First plasmas with lengths of up to 200 mm have been produced and the stability and shape of the plasma profile is currently being investigated.

A new photocathode laser is being commissioned at PITZ, which will allow three-dimensional shaping of the produced pulses and hence also of the extracted electron bunches [23]. First electrons have been produced and the system is currently prepared for bunch shaping experiments. Simulations have shown that with the expected shaping capabilities bunches suitable for hosing experiments can be produced.

Finally, measurements of the transverse-longitudinal profile of bunches with different



**Figure 5.** Transverse longitudinal projection of a triangular bunch with  $\sim 620$  pC charge and low  $x$ - $z$  correlation (top). Profile of bunch current  $I$  (bottom).



**Figure 6.** Transverse longitudinal projection of a triangular bunch with  $\sim 700$  pC charge and high  $x$ - $z$  correlation (top). Profile of bunch current  $I$  (bottom).

trajectories through the PITZ booster cavity have been performed, to observe hosing seeds of different strengths. These profiles are measured with a transverse deflecting structure (TDS), which is placed downstream of the booster cavity and the beamline spot, where a plasma cell can be installed [24]. Bunches are transported and focused with 4 quadrupole duplets between booster and TDS to the measurement screen  $\sim 1.3$  m downstream of the TDS cavity. As the bunches are deflected in the vertical directions, only the horizontal displacement of the beam slices is considered. Figures 5 and 6 show two such measurements. Bunch slice centroids are shown by the red dashed lines. By small variations in steering magnet deflections upstream of

the booster cavity the bunch tilt could be increased from  $4.8\ \mu\text{m}/\text{mm}$  in Fig. 5 to  $55.3\ \mu\text{m}/\text{mm}$  in Fig. 6. This validates the tunability of the hosing seeds at PITZ. Bunches were not tuned for minimisation of the tilt in this experiment.

## 5. Conclusion

The hosing instability is considered one of the main limitations for high energy particle acceleration in beam-driven plasma wakefield accelerators. Detailed understanding of the beam-dynamics of bunches that are subject to it and of the mitigation of the instability will be decisive for building stable future accelerators based on PWFA. Theoretical models about this are at hand but so far lack experimental validation. Simulations with the beam parameters of the PITZ facility suggest that experiments to investigate the hosing instability can be performed here. Seeding of the instability and its subsequent mitigation have been achieved in simulation. First preparatory experiments have been completed and the delivery of bunches with profiles appropriate for the experiment is being prepared.

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