LONGITUDINAL PHASE SPACE DIAGNOSTICS FOR ULTRASHORT BUNCHES WITH A PLASMA DEFLECTOR

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Abstract

The plasma-based deflector is a new method to diagnose the longitudinal phase space of ultrashort electron bunches. It harnesses the strong transverse fields of laser-driven plasma wakefields to streak an electron bunch that is injected off-axis with respect to the driver laser. Owed to the short plasma wavelength and the high field amplitude present in a plasma wakefield, a temporal resolution around or below one femtosecond can be achieved with a plasma length of a few millimeters. Limitations arise from beam loading, synchronization and higher order correlations of the transverse fields. Amongst the possible applications are experiments aiming at external injection into laser-driven wakefields, or the diagnostics of laser-plasma accelerated beams.

INTRODUCTION

Laser Plasma Accelerators (LPA) can provide high accelerating gradients in the order of 10 to 100 GV/m, and the acceleration of electron bunches to several GeV has been shown over few centimeter distances [1, 2]. The technology is therefore a promising candidate especially for drivers of next generation light sources. However, the beam quality is still a major challenge for the field, especially in terms of energy spread, emittance and divergence after the plasma.

In a laser plasma accelerator, a high power laser pulse is focused into a plasma target. Typical laser parameters here are a few Joules pulse energy, several tens of femtoseconds pulse length and a focal spot size around 15 μm. In the plasma, the laser pulse trails a wakefield. The ponderomotive force of the laser pulse causes a charge separation leading to large electric fields both in the longitudinal and in the transverse directions. The characteristic length scale is the plasma period with around 10 to 100 μm length for typical parameter ranges. Short electron bunches can be injected into the wakefield internally, i.e. from the plasma background, or externally from a conventional accelerator [3, 4], which has not been demonstrated so far. The usually large energy spread of plasma accelerated beams can be connected to the finite electron bunch length in combination with the short plasma period. For both injection strategies it is therefore vital to gain access to the longitudinal phase space of the injected bunch, in order to optimize the beam quality.

The bunch length of LPA beams has been measured to around 1.4 to 1.8 fs rms with coherent transition radiation [5] or to 2.5 fs rms employing Faraday rotation of a probe laser [6]. The resolution of a longitudinal phase space diagnostic consequently needs to be around or below one femtosecond, a feat that so far has only been achieved with X-band TDS cavities [7]. The use of those cavities in LPA is extremely challenging, not only due to their large size and cost, but also due to the lack of synchronization of the RF to the LPA driver laser. We therefore proposed [8] to employ the strong fields and short periods in plasma wakefields to streak the electron bunch.

PLASMA BASED DEFLECTOR

In the linear regime, i.e. for a normalized peak vector potential of the driver laser $a_0^2 = (eA/m_e c^2)^2 \ll 1$, the electric fields in the wake exhibit a longitudinally sinusoidal structure [9]. The transverse shape of the longitudinal field follows the laser intensity profile, while the shape of the transverse fields follows the derivative of the laser intensity profile in the respective transverse coordinate. An electron bunch that is injected at a transverse offset with respect to the driver laser and at a phase where the transverse fields have a zero-crossing will then experience streaking fields. For a Gaussian driver laser, the optimum transverse offset is one standard deviation of the laser intensity profile, since there the transverse fields are maximal. An illustration of the setup can be seen in figure 1.

The temporal resolution of the setup can be calculated in a similar manner as for conventional TDS cavities, and is given by

$$\Delta\xi/c \geq \frac{\epsilon_{ny} m_e c}{\sigma_y e k_p V}. \tag{1}$$

Here, ξ is the internal bunch coordinate, ϵ_{ny} is the normalized transverse emittance, σ_y is the rms electron beam size inside the plasma, $k_p = (ne^2/m_e \epsilon_0 c^2)^{1/2}$ is the plasma wavenumber at a density n, and V the effective voltage given by the integral of the peak transverse fields over the plasma length.

The resolution of a plasma-based deflector profits from the short plasma period and consequently large wavenumber, as well as from the strong fields present in the wakefield. Also, a low emittance of LPA beams has been measured with 0.1 - 0.2 mm mrad [10, 11]. On the other hand, a resolution reduction can be expected from the electron beam size σ_y, as it needs to be significantly smaller than the laser spot size, and will consequently be around 10 μm even for large laser spot sizes.

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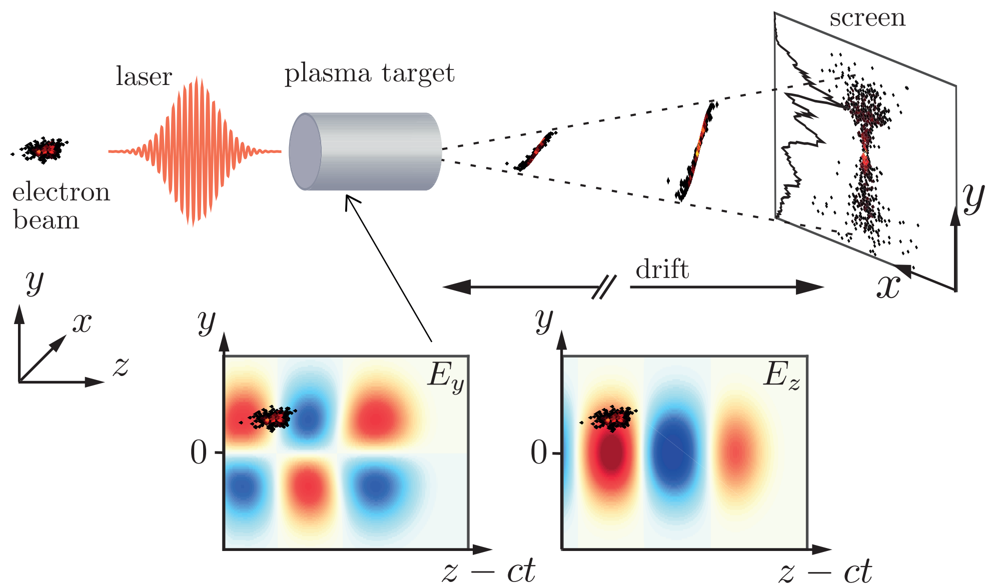

Figure 1: Sketch of the plasma deflector setup. A high power laser pulse drives a linear plasma wakefield, and the probed electron bunch is injected off-axis with respect to the driver laser propagation axis. The wakefield for a Gaussian driver laser is given below in arb. u. The optimum bunch position in the wake is at the transverse maximum and the longitudinal zero-crossing of E_y. In a drift or beam optics after the plasma, the transverse momentum change is transfered into a change of position, carrying the time information.

LIMITING EFFECTS

Several effects can limit the resolution and applicability of the plasma-based deflector. Due the finite electron beam size compared to the wakefield width, which is determined by the laser spot size, the electron bunch will sample over part of the curvature of the transverse fields. Particles at the side of the bunch will experience a smaller streaking slope than those in the center. The loss of resolution depends on the position within the bunch, assuming its center is at the longitudinal zero-crossing of E_y, and can be calculated to

$$\Delta\xi \geq \sqrt{\frac{5}{2}} \left(\frac{\sigma_y}{\sigma_r}\right)^2 |\xi|, \tag{2}$$

with the rms width of the Gaussian laser intensity denoted as σ_r. To reduce the influence of this effect, the laser spot size needs to be chosen much larger than the electron beam size.

Another limitation arises from beam loading, i.e. the electron bunch driving its own wakefield in the plasma. This will modify the streaking fields, and sets a limit on the maximum beam charge. This effect is especially pronounced at the tail of the bunch, where the beam-driven wake is already built up, while at the head of the bunch the influence of beam loading is small. If this is a dominant effect, a transversally larger driver laser allows to increase the electron beam size and reduce the bunch density, thereby suppressing beam loading without pronouncing the resolution reduction from higher order correlations of the streaking field.

The arrival time of the probed electron bunch needs to be synchronized to the driver laser. An electron bunch injected internally in LPA will be intrinsically synchronized to the driver laser of this stage. Applying the plasma deflector to such a beam allows to use part of the same laser system for both stages, thereby keeping the intrinsic synchronization. The plasma deflector is therefore well suited for beams from previous LPA stages. In the case of electron beams from conventional accelerators, the plasma deflector might best be suited for experiments aiming at external injection. There, a sophisticated synchronization system between the RF and driver laser is required anyway for the timing of the external injection experiment, in addition to a high-power laser system and a plasma target. The plasma deflector then would not require any additional equipment.

The tolerable arrival time jitter is given by the plasma period, which is typically in the range of 100 fs. A synchronization to the 10 fs level then needs to be achieved. However, this constraint can be relaxed by decreasing the plasma density, which leads to an increase of the plasma period like $\lambda_p \propto n^{-1/2}$.

CONCLUSION

Due to their short bunch length, laser plasma accelerated beams call for novel diagnostics concepts. One option to gain access to the longitudinal phase space is the plasma deflector, which, owing to the short plasma period and high fields, can achieve a theoretical temporal resolution below one femtosecond. In order to achieve a high resolution, detrimental effects like the transverse field curvature or beam loading have to be minimized.

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