LASER-WAKEFIELD ACCELERATION WITH EXTERNAL BUNCH INJECTION AT REGAE*

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Abstract

We present particle-in-cell simulations with the code OSIRIS [1] for future laser-plasma wakefield experiments with external bunch injection at the REGAE accelerator at DESY. The topics of particular interest are: emittance evolution of electron bunches and longitudinal bunch compression inside the wakefield. Results show significant transverse emittance growth during the injection process, if the electron bunch is not matched to its intrinsic betatron motion inside the wakefield. In addition, when externally injected at the zero-field crossing of the laser-driven wake, the electron bunch may undergo significant compression in longitudinal direction and simultaneously be accelerated due to the gradient in the accelerating field. This mechanism would allow for production of high-energy, ultra-short (on the order of one femtosecond) bunches at REGAE.

EXTERNAL BUNCH INJECTION AT REGAE

Laser-plasma acceleration (LPA) is a technology which exploits large electric wakefields created by high-intensity laser pulses in plasma. Such wakes support field gradients which are many orders of magnitude larger than in conventional accelerators and can be used to accelerate particle bunches over short distances. Experiments demonstrated GeV energy gain in centimeter distances [2, 3]. Nevertheless, the energy increase in a single LPA module is limited by energy depletion of the laser pulse. Further energy gain is thus possible by placing LPA modules one after another, i.e. by staging [4], or by using a stronger laser for wakefield generation. LPA might potentially develop into a technology to be used for driving compact and brilliant X-ray sources, and possibly particle colliders. Thus achieving a beam quality sufficient for these demanding applications is of crucial importance.

The injection process of electrons into a plasma wake in the wave-breaking regime is sensitive to fluctuations in laser and plasma parameters, and difficult to manipulate. Our aim is to inject externally accelerated and phase-space tailored beams from a conventional accelerator into a laser-driven wake for full control over the electron-trapping process. These experiments will open numerous opportunities for probing wakefields and exploring fundamental properties of laser-plasma interaction and electron acceleration. Moreover, external injection experiments are of crucial importance for exploring the concept of staging. The aim of external injection is to place electron bunches with a length much shorter than the plasma wavelength, λ_p, and a transverse extent much smaller than the laser spot size in the phase-region of the wake which is both focusing and accelerating.

The Relativistic Electron Gun for Atomic Exploration (REGAE) is a linear accelerator at DESY which produces 2 to 5 MeV velocity-grouped electron bunches of 10-15 fs RMS length, $\sim$1 pC charge, 3-5 μm RMS width, and 0.3 mm mrad emittance. Originally designed for femtosecond electron diffraction experiments, the REGAE injector will be used together with a high-intensity laser and a plasma target for LPA external injection experiments.

EMITTANCE EVOLUTION

External controlled injection is a direct way to study bunch emittance evolution in LPA. Minimising emittance growth during the acceleration process is crucial for most applications. Emittance growth in LPA was earlier investigated in [5, 6, 7]. The transverse trace-space emittance, $\epsilon = \sqrt{\langle x^2\rangle \langle x'^2\rangle - \langle xx'\rangle^2}$ [8], is a figure of merit for the transverse beam quality, where x is the transverse particle position, $x' = p_x/p_z$ is the ratio of transverse and longitudinal particle momenta and $\langle Y^k\rangle = \sum_i^N (Y_i - \overline{Y})^k/N$ the k-th central moment of a discrete variable Y. We consider an electron bunch with transverse properties defined by the emittance ϵ and the Courant-Snyder parameters (CSP)[9] :

$$\beta = \frac{\langle x^2\rangle}{\epsilon}, \qquad \gamma = \frac{\langle x'^2\rangle}{\epsilon}, \qquad \alpha = -\frac{\langle xx'\rangle}{\epsilon}. \tag{1}$$

Combining emittance definition and (1) yields the relation between these parameters, $\beta\gamma = 1 + \alpha^2$.

While being accelerated, the individual particles perform transverse betatron oscillations with a betatron frequency ω_β. Due to the particle oscillations, the ellipse with area $\pi\epsilon$, defined by the CSP (1), $\gamma x^2 + 2\alpha xx' + \beta x'^2 = \epsilon$, rotates according to the single particle trajectories in trace space. Since the transverse field and ω_β are ξ-dependent ($\xi = z - ct$ is a co-moving variable, where z is the longitudinal coordinate, c is the speed of light and t is time), the individual longitudinal slices of the bunch oscillate at different frequencies which leads to a betatron-oscillation phase mixing during the acceleration process, as illustrated in Fig. 1. Slice ellipses develop a tilt with respect to each other which increases the projected area and hence causes emittance growth. Emittance growth due to this mechanism can be suppressed by matching the transverse properties of the electron beam to the intrinsic electron betatron motion in the plasma wake [10, 5]. Expressing the matching con-

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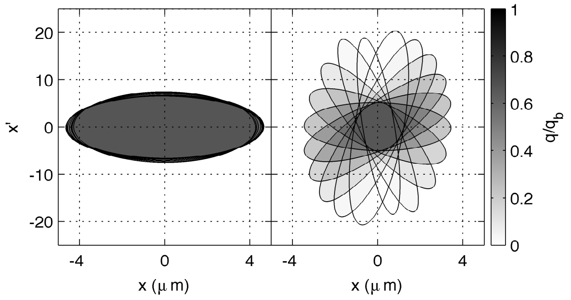

Figure 1: Ellipses representing bunch slices from PIC simulation C2 (see below) at position $z = 0.72$ mm (left) and $z = 2.10$ mm (right). The gray-scale of the ellipse was chosen according to the ratio of the charge in a slice q and total bunch charge q_b.

ditions in terms of the CSP in the relativistic limit gives

$$\beta_m \simeq \frac{c}{\omega_\beta}\,, \qquad \gamma_m = \frac{1}{\beta_m} \simeq \frac{\omega_\beta}{c}\,, \qquad \alpha_m = 0\,, \qquad (2)$$

so that particle oscillations follow the ellipse defined by the CSP of the beam.

3D PIC simulations were performed to study emittance growth. Laser, bunch and plasma parameters listed above correspond to expected experimental conditions at REGAE. Electron bunches with an initial normalised emittance of $\epsilon_{n,\mathrm{init}} = 0.3\,\mu\mathrm{m}$ propagate collinear to laser pulse of 5 J energy, $\tau_0 = 25$ fs FWHM pulse duration, $\lambda_0 = 800$ nm central wavelength, and a peak-normalised vector-potential of $a_0 = 1.8$. The Rayleigh-length of the laser is long compared to the betatron length and the waist of the pulse is 50 μm FWHM, where the transverse profile is a Gaussian and the temporal profile is a symmetric polynomial. Electron beams have a charge of 1 pC, mean energy of 5.5 MeV an energy spread of 32.5 keV, RMS length of 10 fs, and an RMS transverse size of 3μm. The charge is sufficiently low to neglect space-charge forces as well as beam loading at the accelerating and focusing phase of the plasma wave. The plasma target has a flat-top longitudinal profile with an electron density of $n_0 = 10^{17}\mathrm{cm}^{-3}$.

We compare PIC simulations with different sets of CSP that result from different focussing geometries of the same electron beam:

- *matched case (CM)*: beam with matched CSP;
- *miss-matched case (C1)*: beam with matched beta function at focus but with miss-matched focal position;
- *miss-matched case (C2):* beam with miss-matched beta function but matched focal position.

Fig. 2 depicts the emittance evolution during acceleration for the three mentioned cases. If matched, the bunch ellipse will not oscillate after injection and the emittance will not grow. For the non-matched cases the betatron phase is completely mixed at $z \approx 3.5$ mm and emittance growth is saturated at that position.

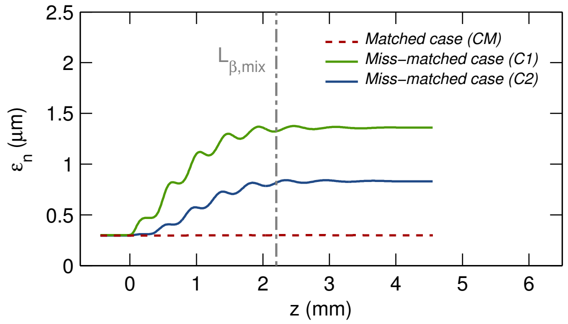

Figure 2: Evolution of the normalised emittance $\epsilon_n = \epsilon \bar{p_z}/m_e c$ in PIC simulations for the three considered cases. The total betatron-phase mixing length relative to the initial position is indicated by the dash-dotted line.

The consequences of the presented simulations for multi-stage acceleration are discussed in the following. We derive the propagation distance during which the betatron phase of a bunch becomes completely mixed. Assuming the bunch with the length L_b and the relativistic gamma-factor γ_b is injected and fixed to the maximum accelerating field phase of a quasilinear plasma wave driven by a laser pulse with a spot diameter on the order of λ_p, we find an expression for the total betatron-phase mixing length:

$$L_{\beta,\mathrm{mix}} \simeq \frac{\lambda_p}{a_0}\sqrt{\frac{8\pi\gamma_b}{k_p L_b}}\,. \qquad (3)$$

where $k_p = c/\omega_p$ is a plasma skin depth. This suggests that total betatron phase mixing occurs within $\lesssim$1 m scale stages for electron energies of up to one TeV for a plasma density of 10^{17} cm^{-3}, 3 μm long bunches and a laser pulse with $a_0 = 2$. This might introduce the necessity to include beam-matching sections upstream of each plasma-accelerator section with fundamental implications on the design of staged laser wakefield accelerators.

BUNCH COMPRESSION

Ultra short bunches are of high interest for coherent X-ray generation and ultrafast pump-probe experiments. The longitudinal electric field in the laser-driven wake has a ξ-dependence and can be used for simultaneous acceleration and compression of the externally injected electron bunch. The accelerating force in longitudinal direction acting on the front part of the bunch is weaker than at the back part, such that after propagation in the plasma wake the bunch can undergo significant size reduction. The compression of the bunch in the wakefield was analytically analysed in [12, 13] and was proposed to minimise energy spread growth in multi-staged LPA. Bunch compression occurs in LPA if the following conditions are fulfilled:

- the bunch should experience the strongest negative gradient of the accelerating force, i.e. to be injected at the maximum of the wakefield potential (at the zero-field crossing);
- low initial bunch energy to ensure maximum change in

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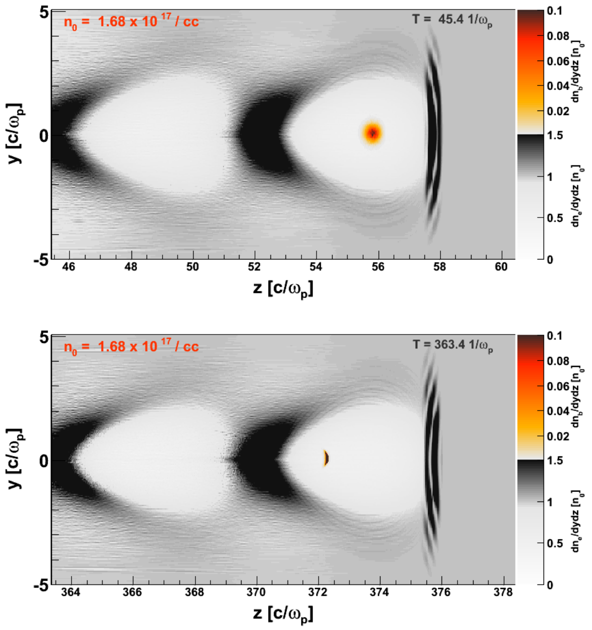

Figure 3: Plasma and externally injected bunch charge densities from PIC simulations at an early position (top) and after 8 mm of propagation inside plasma (bottom). Significant reduction in longitudinal size is observed.

velocity between the front and the back of the bunch;
- sufficiently low initial bunch charge, i.e. the electron-number density in the bunch should be smaller than the plasma density, $n_e \ll n_p k_p^{-3}$, to avoid space-charge effects;
- initial length of the bunch should be much smaller than λ_p. For sufficient compression the bunch length should not exceed k_p^{-1} [12];
- initial transverse size of the bunch should be significantly smaller than the laser-spot size in order to ensure constant transverse accelerating fields along the bunch.

Current studies focus on investigating the effect of longitudinal bunch compression by means of 2D PIC simulations. The compression factor depends on the gradient of the longitudinal field, therefore a more intense laser-pulse is advantageous. In the following, simulations in homogeneous plasma of $n_0 = 1.68 \times 10^{-17}$ cm^{-3} density are presented with a laser of $a_0 = 5$, $\lambda_0 = 800$ nm, $\tau_0 = 25$ fs FWHM, waist $w_0 = 24$ μm RMS. An electron bunch with the same parameters as listed in the previous section, was externally injected into a wake on the laser axis at the zero-field crossing. The transverse properties of the beam were matched to the intrinsic betatron motion to suppress emittance growth [10]. Fig. 3 shows the plasma charge density together with the externally injected electron bunch in the initial and final position of propagation inside the plasma. It can be seen that strong compression occurs after 8 mm distance. The final bunch length was 1.2 fs RMS (which corresponds to a compression factor of 8.3), energy of 37 MeV with relative energy spread of 6%. Bunch energy grows steadily during propagation while the absolute energy spread saturates when the bunch reaches the point of maximal compression, which leads to a steady reduction of the relative energy spread. This suggests that acceleration to higher energies would reduce the relative energy spread even more, though this would require laser guiding in a parabolic plasma channel for acceleration over longer distances.

One of the crutial factors for efficient bunch compression is injection at exactly or near to the zero-field crossing. Injection phase scans showed that strong compression still occurs if the bunch is injected within ~10 fs from its optimal injection phase. This puts strong restrictions on the synchronisation between the laser and electron-injection system. The level of synchronisation at REGAE experiments is expected to be ~10 fs RMS which should allow for the experimental observation of bunch compression. Furthermore, space-charge effects were studied by injecting bunches of higher charge density. Simulations showed that compression did not occur for charges of 5 pC and above.

SUMMARY

PIC simulations matching future experimental conditions of LPA experiments at REGAE were performed and two major topics are covered in present studies: electron-bunch emittance growth and bunch compression. It was shown that the emittance of externally injected electron beam grows if the beam parameters are not matched to the intrinsic betatron length in the plasma wake. If matched, the emittance remains constant during the acceleration process. We also presented the mechanism of longitudinal bunch compression due to the gradient in the longitudinal field inside the plasma wake. This effect is sensitive to the injection phase, initial bunch energy, energy spread, length and charge.

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