IMPROVED ELECTRON BEAM QUALITY FROM EXTERNAL INJECTION IN LASER-DRIVEN PLASMA ACCELERATION AT SINBAD

M. K. Weikum*[1], R. W. Assmann, U. Dorda, A. Ferran Pousa, T. Heinemann[1,2], B. Marchetti, E. Svystun, P. A. Walker, DESY, 22607 Hamburg, Germany
F. Y. Li, Z. M. Sheng[3], SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK
[1]also at SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK
[2]also at University of Hamburg, 20146 Hamburg, Germany
[3]also at Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

External injection into laser wakefield accelerators is one of the possible routes towards high energy, high quality electron beams through plasma acceleration. Among other reasons this is due to the increased control over the electron beam parameters and overall experimental setup when compared to other plasma schemes, such as controlled self-injection. At the future SINBAD (Short INnovative Bunches and Accelerators at DESY) facility at DESY this technique is planned to be tested experimentally through injection and acceleration of a sub-femtosecond electron beam, produced from a conventional RF-injector, with a charge of around 0.7 pC and initial mean energy of 100 MeV at the plasma entrance. A summary of optimisation steps for the potential experimental setup is presented in this paper, including considerations regarding effects of electron beam self-fields and matching of the beam into the plasma stage. The discussion is complemented by first start-to-end simulations of the plasma accelerator setup based on these findings.

INTRODUCTION

Laser wakefield acceleration (LWFA) is a promising technique in novel accelerators standing out through high accelerating field gradients on the order of GV/cm [1,2]. Although immense developments have been made in the field in the last decade, among others reaching new records in energy gain up to 4.2 GeV [3], its main limitation, especially compared to conventional systems, remains the acceleration stability and, related to this, electron beam quality. In general, LWFA-accelerated beams are characterised by a large correlated energy spread on the order of few percent due to the gradient of the accelerating wakefield, and, in particular for self-injected beams, by a normalised emittance of a few micrometres. In addition, instabilities in the experimental setup, such as laser power variations, pointing errors, jitter and fluctuations in the plasma profile, can lead to further reductions in the beam quality as well as reproducability. Since most controlled self-injection setups are affected quite strongly by the latter due to their reliance on, for example, specific plasma profiles or multiple interacting laser pulses, a reduction of this effect is proposed by externally injecting a pre-accelerated electron beam into the plasma allowing for better control over the initial electron pulse parameters and possibly a simpler accelerator setup.

The SINBAD (Short INnovative Bunches and Accelerators at DESY) project at DESY, Hamburg, Germany, is one location where such external injection LWFA experiments are planned [4]. This dedicated research and development facility, currently under construction, will feature, among others, an S-band photo-injector and linac to produce, through different bunching techniques, ultrashort electron pulses of sub-femtosecond to femtosecond duration with charge on the order of 0.5 to few tens of pC and energy up to 100 MeV [5]. For the plasma experiments planned at the facility, it is additionally foreseen to have a high power Ti:Sapphire laser available with 5 J energy and 200 TW peak power as a driver for the plasma wakefield.

POSSIBLE OPTIMISATION STEPS IN THE PLASMA SETUP

After initial studies by Grebenyuk et al. [6] to prove the capability of the SINBAD setup for plasma acceleration experiments, a number of two-dimensional simulations were completed with the particle-in-cell (PIC) code OSIRIS [7] to optimise the setup with regard to different aspects of the acceleration process, in particular the effect of electron beam self-fields, the transverse development of the electron beam in the plasma and the laser evolution. In all cases, the parameters of the injected witness beam were defined as shown in Table 1, based on simulation results by Zhu et al. [8] with the particle-tracking code ASTRA [9].

Table 1: Possible electron beam and laser pulse parameters for planned external injection experiments at SINBAD. The electron beam properties are based on simulations by Zhu et al.

Beam charge	0.7 pC
Beam energy	(99.70 ± 0.37) MeV
Beam longitudinal RMS duration	774 as
Beam transverse RMS size	5.1 µm
Beam beta-function	0.03 m
Laser power	196.6 TW
Laser spot size	42.5 µm
Laser duration (FWHM)	25 fs

* Corresponding author: maria.weikum@desy.de

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Effect of Self-fields

Due to its short duration and high density of around $4.6 \times 10^{22}\ \mathrm{m}^{-3}$, the externally injected electron beam generates its own wakefield, which in low density plasma, is on the same order of magnitude as the local gradient of the laser-driven wakefield at the beam position. A simple one-dimensional model for optimisation of this beamloading effect in the weakly nonlinear wakefield regime to compensate the wakefield gradient through variation of the electron beam - laser offset was hence derived based on [10,11].

As Fig. 1 – depicting the energy distribution across the beam in z and x for an optimised (a) and non-optimised (b) scenario – shows, the beamloading can indeed reduce the correlated energy spread along the z-axis. In this case, though, the energy spread along the x-axis is increased as the beam is moved closer to the end of the wave bucket where the gradient of the accelerating wakefield in the transverse direction becomes steeper. Due to the small longitudinal size of the beam, this transverse effect is on the same order as the potential longitudinal spread hence leading to a similarly sized energy variation of 0.348 % compared to 0.319 % without optimisation. As the spread in both cases is within the limits required for advanced applications, such as Free-Electron Lasers (FELs), though, further extensions of the optimisation model to include transverse effects on the beam energy distribution have not been implemented yet.

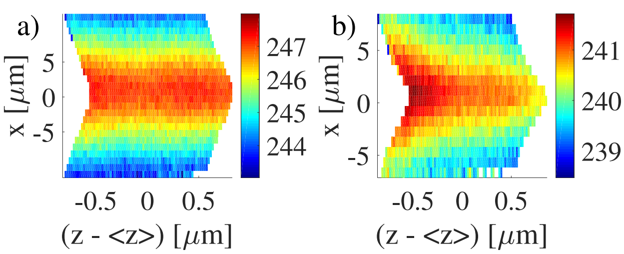

Figure 1: Energy distribution (in MeV) across the witness beam in z and x for a beamloading optimised case (a) and a non-optimised case (b).

Matching into the Plasma

To avoid emittance growth in the plasma due to betatron decoherence, the electron beam needs to be matched in its transverse properties to the plasma, such that the spread due to the beam emittance is fully compensated by the wakefield focusing forces [12]. In this context, the ultrashort duration of the beam is a disadvantage, as beam focusing is limited due to space-charge forces to beta functions at the plasma entrance of more than one order of magnitude larger than the matched value [8]. With a set of 2D OSIRIS simulations, it was therefore tested to reduce the emittance growth in the plasma by gradually reducing the beam size using a density upramp, as proposed in [13-15]. Unlike in previous studies, however, a realistic plasma ramp profile, based on OpenFoam simulations of a plasma cell translated to different ramp lengths, was investigated in this case, the effect of which on the emittance growth is shown in Fig. 2.

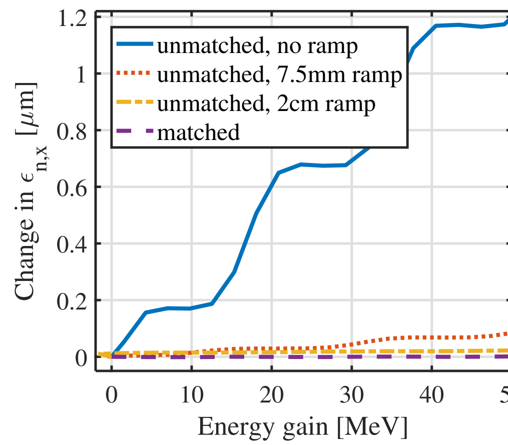

Figure 2: Emittance evolution during acceleration of matched and unmatched beams with plasma profiles with varying density upramp lengths.

By introducing a ramp at the beginning of the plasma and focusing the laser pulse into the latter, the emittance growth can be mitigated with an increasing ramp length leading to a smaller emittance rise. A ramp of length 7.5 mm, for example, reduces the normalised emittance increase over 50 MeV energy gain already to around 0.08 µm instead of 1.2 µm without the ramp. Further, with a density increase of 2 cm length a small emittance rise is observed during the first part of the ramp, where the shape of the laser wakefield changes due to the varying density, but the final emittance settles with an overall growth of around 0.02 µm.

Whereas long acceleration stages, such as up to 1 GeV, thus require cm-long density ramps to mitigate the emittance growth, ideally also at the end of the stage for the adiabatic extraction of the beam [13], for shorter plasma targets even mm-scale ramps can provide sufficient control over the final emittance to stay well below 1 µm, as required for many applications. Note that, despite the small beam charge, the Lehe solver [16] was employed for the calculation of the electromagnetic fields for the simulations shown, as the standard Yee solver generates strong numerical Cherenkov radiation and consequently an artificial increase in beam emittance.

START-TO-END SIMULATIONS

Combining the conclusions presented above, a full 2D start-to-end simulation of the external injection of a SINBAD-like beam into a 2.75 cm long plasma target with maximum density $1 \times 10^{23}\ \mathrm{m}^{-3}$ was investigated, as shown in Figure 3. The laser pulse with the same parameters as in Table 1 is unguided with its focal plane positioned at the centre of the plasma at 1.39 cm. Although test simulations showed an increase in the required acceleration length by 18 % and an energy spread increase of 16 % for an energy gain of 100 MeV with respect to a similar setup with laser guiding in a plasma channel, these limitations are accepted based on the major simplification of the experimental setup that the unguided scenario provides. The density profile is given by the black, dashed line in Fig. 3, consisting of a

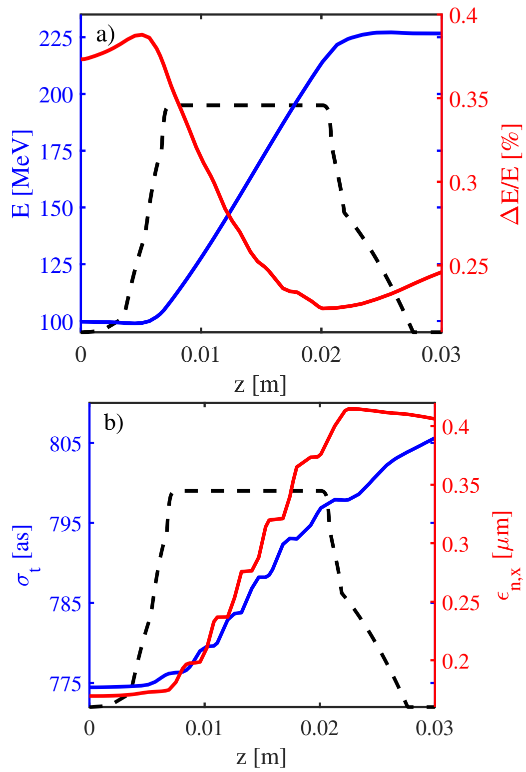

Figure 3: Evolution of the electron beam properties during acceleration in an external injection LWFA plasma setup based on a 2D OSIRIS simulation. The black, dashed line represents the shape of the plasma density profile.

plateau of length 1.25 cm and surrounded by 7.5 mm long up- and downramps with shapes defined from the previously described OpenFoam simulations. The offset of the electron beam to the laser pulse is 52.7 µm and not optimised for on-axis beamloading compensation.

As Fig. 3 a) shows, the energy gain is almost linear between about 6.9 mm and 2.13 cm despite the focusing and defocusing of the drive laser pulse; a guiding of the laser is indeed not necessary over this limited plasma length. Moreover, the relative energy spread decreases along the main region of acceleration and, despite some increase at the beginning and the end of the plasma stage, stays below 0.25 %. The two phases of energy spread increase coincide with the low density regions along the up- and downramps, where the beamloading fields are dominant in the effective wakefield gradient over the laser-driven field.

In Fig. 3 b) the RMS bunch duration and the normalised emittance in x throughout the plasma propagation are presented. The increase in σ_t is small on the order of 4 % and exhibits an oscillatory behaviour which is equivalent to the small betatron oscillations of the beam transversely. The longitudinal oscillations are a consequence of the reshaping of the beam, as the off-axis electrons experience weaker wakefields and due to their longer path lengths during the transverse oscillations thus fall back within the beam. With regard to the beam emittance, a similar rise is visible from the end of the upramp, although, as shown in Fig. 2, to a much smaller extent than without the ramp. From the beginning of the downramp the emittance also slowly decreases again which has been associated with the emittance compensation effect described by [14,17]. While in their case, both the sides and the head are eroded away at first and finally re-aligned in phase space, in this case it is mostly the sides towards the back of the beam which become re-matched with the betatron oscillations of the main beam on the downramp.

Overall, the final beam a few millimetres behind the plasma target has very promising properties with mean energy of 226.6 MeV, energy spread below 0.25 %, bunch duration around 805 as and normalised emittance of 0.41 µm. It should be noted that, due to the superluminal group velocity of the laser pulse with the Lehe solver, used to avoid numerical emittance growth, artificial dephasing between the laser and electron beam of 6 µm is observed which may influence the evolution of beam energy and spread to a small extent. Moreover, a Gaussian beam shape was assumed in the 2D simulation; a longitudinal energy chirp as well as slightly larger transverse size in the y-direction, as observed from the full 6D phase space distribution of the pre-accelerated SINBAD bunch from ASTRA and not considered here, may also have some effect on the beam evolution and acceleration. Simulations in 3D with the full beam distribution are planned to understand these effects better.

SUMMARY

The successful external injection and acceleration of a sub-femtosecond electron beam in low density plasma was demonstrated through two-dimensional PIC simulations. The ultrashort bunch duration allows for a small final energy spread limited by the transverse rather than the longitudinal gradient of the accelerating wakefield. Due to space-charge limitations, matching the beam into the plasma target is a considerable issue; however, mitigation of the emittance growth to a tolerable level can already be achieved with density ramps of millimetre length. While the beam energy presented here is too low for FEL interaction, further studies will investigate an extension of this setup to the GeV level with the required inclusion of longer matching ramps and laser guiding mechanisms.

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