

# LASER-DRIVEN ACCELERATION WITH EXTERNAL INJECTION AT SINBAD

J. Grebenyuk\*, R. Assmann, U. Dorda, B. Marchetti  
Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany

## Abstract

One of the important milestones to make plasma acceleration a realistic technology for user-applications is the demonstration of bunch acceleration inside a plasma wake with minimal degradation of its energy spread and emittance. This can be achieved by means of external injection of conventionally-tailored well-characterised beams into a plasma accelerator. SINBAD (Short INnovative Bunches and Accelerators at DESY) is a proposed dedicated accelerator research and development facility at DESY where amongst other topics laser-driven wakefield acceleration (LWFA) with external injection of ultra-short bunches will be exploited. To minimise energy-spread growth during acceleration, the bunch should occupy a small fraction of the plasma wavelength. In addition it has to be longitudinally synchronised with the laser driver to high accuracy. To avoid emittance growth the transport lattice for the incoming beam has to be matched to the intrinsic beta-function of the plasma. To facilitate matching and synchronisation, acceleration at low plasma densities can be advantageous. We present a preparatory feasibility study for future plasma experiments at SINBAD using simulations with the particle-in-cell code OSIRIS [1]. Field-gradient scaling laws are presented together with parameter scans of externally injected bunch, such as its injection phase, charge and length.

## INTRODUCTION

Plasma-wakefield acceleration (PWA) [2, 3] has proven to be a technology which can be successfully used to generate accelerating cavities with gradients up to 100 GV/m [4, 5]. Beams produced in a single stage of a plasma accelerator reached energies up to 2 GeV [6]. While the quality of those beams improved significantly since early PWA experiments, some of the key parameters, such as energy spread, are still worse than those achieved in conventional accelerators. Limitations on beam quality may arise from laser instabilities, lack of control over the injection process, or due to intrinsic mechanism of correlated energy-spread growth in PWA.

There are two main mechanisms of delivering bunches for acceleration inside a plasma: trapping of the plasma background electrons and external bunch injection. In current studies we consider external injection of electron bunches in the plasma wake owing to its simplicity and controllability and to address the issue of delivering high-quality beams. In order to minimise energy-spread growth during acceleration the bunch length should be significantly shorter than the plasma wavelength which scales as the square root of plasma density,  $n_e$ . For example, for  $n_e = 10^{17} \text{ cm}^{-3}$ , the plasma

wavelength is 106  $\mu\text{m}$ , requiring bunch durations below 10 fs to avoid its significant quality degradation. Such ultra-short bunches require state-of-art accelerators with optimised compression [8–10]. External injection of ultra-short bunches also implies tight constraints on the synchronisation jitter.

Another challenge of external injection is beam matching into the plasma: Twiss parameters of the bunch must be matched to the intrinsic betatron motion inside the plasma to avoid emittance growth due to slice decoherence [11].

Due to tight requirements on bunch length, timing jitter and matching mechanisms, acceleration at lower plasma densities may facilitate control over those issues. On the other hand, accelerating gradients at low-plasma densities are weaker requiring longer stages to reach the same energies as at high densities. Excitation of high-amplitude wakes at low densities also requires longer pulse lengths, i.e. higher laser pulse energies.

## PLASMA ACCELERATION AT SINBAD

SINBAD [7] is a proposed dedicated accelerator research and development facility on site of the DESY laboratory, Hamburg, Germany, where amongst other topics plasma acceleration will be explored. Initial focus of the plasma experiments at SINBAD will be on controlled external injection of conventionally-tailored electron bunches into the accelerating and focusing phase of the laser-driven plasma cavity. External injection allows for precise population of the 6D-phase space and thereby provides possibilities to optimise the following evolution of bunch parameters during the acceleration process. These studies are also important for future tests of staging, i.e. acceleration of bunches in multiple PWA-modules placed one after another.

A compact photo-injector will produce ultra-short electron bunches which will be accelerated in S-band RF-cavities to up to 100 MeV. It will provide beams with 0.5 - few tens of pC charge, sub-femto second - few-fs duration for external injection in a plasma cavity. The wakefield in a plasma will be excited by a laser with 5 J energy and 200 TW peak power which is currently used in DESY at the LAOLA-REGAE facility [8, 12]. The laser will be transferred to SINBAD with an option for possible future upgrade to higher peak powers. Minimal gradients of 200 MV/m are aimed for at SINBAD to obtain reasonable energy gain and usable beam quality at the exit of plasma. We note that many existing conventional linacs operate at gradients of about 20 MV/m.

## SIMULATIONS

A set of 2D particle-in-cell simulations with the code OSIRIS was performed in order to investigate different sce-

\* julia.grebenyuk@desy.de

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scenarios of plasma acceleration with external injection at SINBAD.

### Field Gradients at Low Plasma Densities

The maximum-achievable accelerating gradient depends on plasma density and laser strength and pulse length [13]. It scales as following:

- The cold non-relativistic wavebreaking field,  $E_0$  (and thereby a maximum achievable field gradient), scales with plasma density,  $n_e$ :  $E_0[\text{V/m}] \approx 94\sqrt{n_e}[\text{cm}^{-3}]$ . For example, for density of  $10^{18} \text{ cm}^{-3}$  the fields may reach 94 GV/m, while for  $10^{16} \text{ cm}^{-3}$  they are on the order of 9.4 GV/m;
- The amplitude of the excited wake,  $E_z$ , in terms of a fraction of the  $E_0$  depends on the laser strength, i.e. its normalised vector potential,  $a_0$ . For a flat-top pulse in the non-linear regime  $E_z$  is [14]:  $E_z/E_0 \propto a_0^2 / (2\sqrt{1 + a_0^2/2})$ . For the a laser with  $a_0 = 1.8$  we therefore obtain an amplitude of  $E_z \approx E_0$ ;
- The laser-pulse length,  $L_{\text{RMS}}$ , should be matched to the plasma period for a resonant wakefield excitation. The maximum field amplitude can be reached for pulses of approximately  $L_{\text{RMS}} \approx k_p^{-1}$ , where  $k_p^{-1} = c/\omega_p \propto 1/\sqrt{n_e}$  is the plasma skindepth,  $\omega_p$  is the plasma frequency and  $c$  is the speed of light. Therefore at lower plasma densities, i.e. larger wavelengths, longer pulses are required for maximal wake amplitudes.

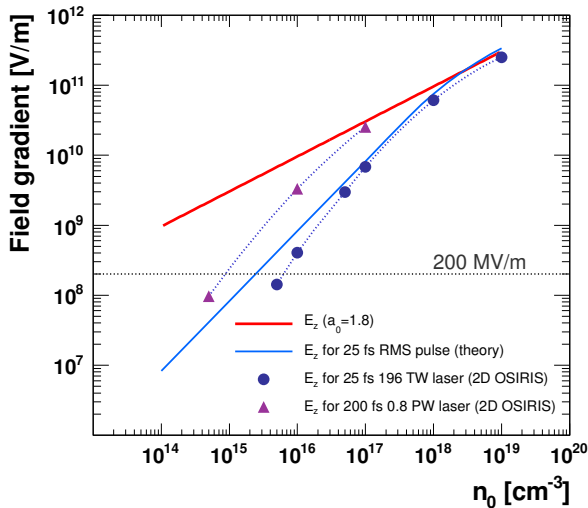


Figure 1: Achievable field gradients for various plasma densities and 196 TW and 0.8 PW lasers of 25 fs and 200 fs pulse lengths, correspondingly. The dots represent 2D OSIRIS simulations, the red line is  $E_z$  for a laser with  $a_0 = 1.8$  and the blue line is a prediction for 196 TW case.

A set of 2D OSIRIS simulations with various laser parameters and plasma densities was performed to test the expected

scaling of field gradients. The dimensions of the simulated box were  $218 \mu\text{m} \times 269 \mu\text{m}$  with  $6000 \times 600$  grid points corresponding to the resolution of  $0.036 \mu\text{m} \times 0.44 \mu\text{m}$ . The following laser parameters were simulated:  $a_0 = 1.8$ , pulse length 25 fs FWHM, spot size  $50 \mu\text{m}$  FWHM, 800 nm frequency, 5 J energy, which corresponds to 196 TW peak power. Simulated parameters approximately match the laser operating in plasma experiments at LAOLA-REGAE. Additional case of 784 TW laser with 200 fs pulse FWHM length and  $100 \mu\text{m}$  spot size FWHM was simulated. The range of scanned plasma densities was  $0.5 \times 10^{16} - 10^{18} \text{ cm}^{-3}$  with simulated 4 particles per cell.

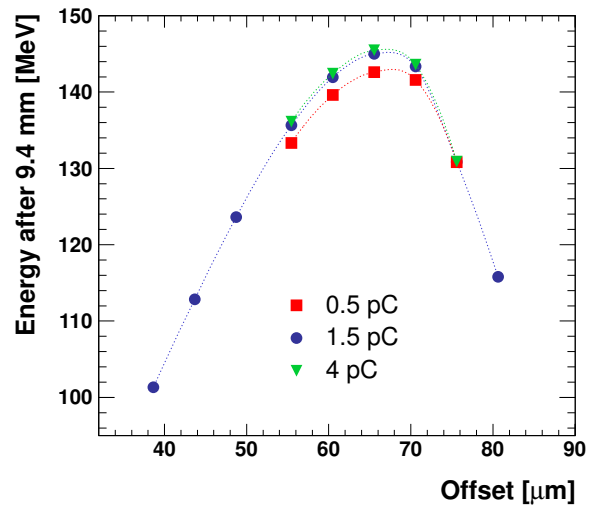


Figure 2: Energy of an externally injected 100 MeV bunch after 9.4 mm of propagation in a plasma of density of  $10^{17} \text{ cm}^{-3}$  as a function of injection phase for 0.5, 1.5 and 4 pC bunch charge. The phase offset is given with respect to the laser centre.

The results are summarised in Fig.1. Each point correspond to a maximum field amplitude obtained in a 2D PIC simulation. Gradients of 200 MV/m can be achieved with the 196 TW ( $L_{\text{FWHM}} = 25 \text{ fs}$ ) laser at a plasma density of about  $10^{16} \text{ cm}^{-3}$ . Increasing  $L_{\text{FWHM}}$  up to 200 fs would allow to achieve the same gradients at the density of  $10^{15} \text{ cm}^{-3}$ .

In the studies above a Ti:Sa laser was assumed with a typical frequency of about 800 nm. CO<sub>2</sub> lasers [15], which operate at one order of magnitude higher frequencies, were proposed as an alternative to Ti:Sa lasers for plasma acceleration [16]. CO<sub>2</sub> lasers can provide longer pulses and the power required for more efficient acceleration at low plasma densities can be reduced significantly.

### External Injection

In order to investigate the evolution of bunch properties during the acceleration process in plasma, a set of 2D simulations was performed. The wakefield was generated by the 196 TW laser focused at a plasma of  $10^{17} \text{ cm}^{-3}$  density.

The externally-injected bunch initial parameters were the following: 100 MeV energy, 0.1 % energy spread, 3  $\mu\text{m}$  RMS length (10 fs duration), 5  $\mu\text{m}$  transverse RMS, 0.5 - 4 pC charge, 0.03 mm mrad transverse normalised emittance. The beam size was not matched to the plasma beta-function.

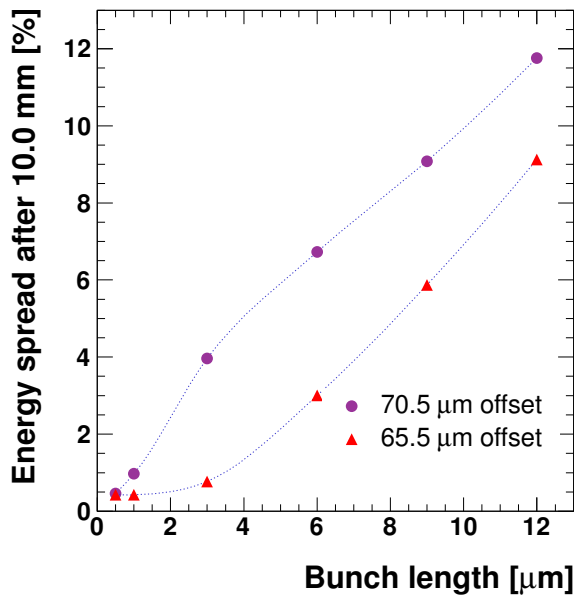


Figure 3: Energy spread of an externally injected bunch with initial energy spread of 0.1 % after 10 mm of propagation in plasma for two different injection phases. The phase offset is given with respect to the laser centre.

The dependence of bunch-phase-space evolution was studied with respect to the injection phase. The delivered bunch energy after 9.4 mm propagation distance as a function of injection phase is depicted in Fig. 2. The defocusing phase was observed for offsets larger than 70.56  $\mu\text{m}$ . Simulations show that a laser-bunch synchronisation jitter on the order of 20 fs would be sufficient to operate in stable accelerating and focusing regime. However, in order to keep the shot-to-shot energy variation below a couple of percent, a jitter of 5 fs will be necessary. Lowering plasma density would allow to relax those requirements. Simulations with different bunch charges showed marginal difference in accelerating gradients for bunches from 0.5 to 4 pC. Depending on the injection phase, the energy spread after 9.4 mm of propagation varied from a below-percent values if injected at optimal phase of the accelerating field, up to 8 % if injected further from the maximum gradient. In all cases when the bunch was injected in the focusing and accelerating phase there was an emittance growth up to 0.5-1 mm mrad after 9.4 mm suggesting that matching will be crucial to overcome this issue.

The induced energy-spread was analysed as a function of injected bunch length. Bunches in a range of 0.5 - 12  $\mu\text{m}$  longitudinal RMS were simulated, corresponding to 0.005 - 11 % of plasma wavelength. The bunch charge density

was kept constant for all cases. The results for two different injection phases are shown at Fig. 3: the final energy spread decreases linearly with decreasing bunch length and saturates for very short bunch durations at values below 1 %. At low densities, i.e. larger plasma wavelengths, energy spread for identical bunches is expected to be smaller.

## SUMMARY

SINBAD is a proposed accelerator research and development facility at DESY with primary goal to combine state-of-art linear accelerators for ultra-short-bunch production and plasma accelerators. In order to relax future experimental tolerances operation at low plasma densities can be advantageous. Plasma wakefields will be excited with the 196 TW laser which is already operating in one of the DESY experimental areas. 2D OSIRIS particle-in-cell simulations showed that the accelerating gradient of 200 MV/m can be achieved with the existing laser for plasmas with  $n_e = 10^{16} \text{ cm}^{-3}$ . Upgrading the laser to 0.8 PW would allow the same gradients at  $n_e = 10^{15} \text{ cm}^{-3}$ . Simulations of external bunch injection showed that the phase-space evolution strongly depends on the injection phase and bunch length. It is seen that matching is necessary to avoid emittance growth.

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