INVESTIGATING THE KEY PARAMETERS OF A STAGED LASER- AND PARTICLE DRIVEN PLASMA WAKEFIELD ACCELERATOR EXPERIMENT

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Abstract

Plasma wakefield accelerators can be driven by either a powerful laser pulse (LWFA) or a high-current charged particle beam (PWFA). A plasma accelerator combining both schemes consists of a LWFA providing an electron beam which subsequently drives a PWFA in the highly nonlinear regime. This scenario explicitly makes use of the advantages unique to each method, particularly exploiting the capabilities of PWFA schemes to provide high-brightness beams, while the LWFA stage inherently fulfils the demand for compact high-current electron bunches required as PWFA drivers. Effectively, the subsequent PWFA stage operates as beam brightness and energy booster of the initial LWFA output, aiming to match the demanding beam quality requirements of accelerator based light sources. We report on numerical studies towards the implementation of a proof-of-principle experiment at the DRACO laser facility at Helmholtz-Zentrum Dresden-Rossendorf (HZDR).

INTRODUCTION

Plasma wakefield accelerators [1] driven by a high-current electron beam [2] or an intense laser pulse [3,4] share the same working principle, but inherit some fundamental differences. Utilizing a highly relativistic particle beam to drive a PWFA in the blowout regime results in a stable phase relation between the wakefield and the accelerated witness bunch, in contrast to the significant dephasing in LWFA schemes [5]. Without dephasing it is in principle possible to match ideal conditions for beam loading that result in a substantial reduction of the correlated energy spread of the witness beam [6]. Novel injection techniques specifically developed for PWFA, such as the underdense plasma photocathode [7,8] (Trojan Horse) and wakefield induced ionization (WII) injection [9] promise to deliver ultra-low emittance witness beams and precise control of the injected charge to optimize the beam-loading conditions for low energy spread. Enabling trapping of electrons generated by ionization of a dopant gas in PWFA typically requires compact, high peak-current (> 5 kA) drive beams to reach a strong blowout regime [10]. These beam requirements often impose challenging operating conditions for conventional linacs upon compressing and transporting the beam, raising the need for a sophisticated large scale accelerator. In contrast, LWFA accelerators are naturally capable of generating highly compressed beams with peak-currents well above 10 kA [11]. Additionally, it has been recently proven that a sizeable energy spread in the PWFA driver substantially mitigates the hosing instability [12]. Therefore, LWFA generated beams potentially offer ideal properties sought-after as PWFA drivers. Exploiting the complementary advantages of both methods enables a staged LWFA and PWFA setup to operate as an energy and quality (in terms of beam brightness and monochromaticity) transformer, potentially offering a working scenario towards a future plasma-based accelerator capable of producing high-quality electron beams suitable for accelerator-driven light sources with a small spatial footprint. Such a compact plasma-based accelerator of enhanced quality and energy is currently aimed for within the EuPRAXIA [13] design study, where staged LWFA to PWFA concepts are subjected to investigation through a dedicated working package [14]. Several milestones towards an experimental realization have been achieved already [15-18], and theoretical studies demonstrate the great potential such a hybrid staging offers [9,19].

We present an outline of a proof-of-principle experiment to be conducted at HZDR Dresden using the DRACO [20] laser system for the LWFA stage and the thereby produced electron beam as driver for a subsequent PWFA stage. One crucial component towards an experimental realization of such a staging experiment is the transition from the LWFA to the PWFA process, particularly the recapturing of the initially diverging LWFA output in the following plasma section. We report on numerical studies of an idealized transition process, aiming for defining a working point for the anticipated experiment.

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EXPERIMENTAL SETUP

The experiment consists of two gas jets, each featuring injection and acceleration of an individual electron beam, as shown in Fig. 1. While the first stage is operated by a high power laser, the second stage utilizes the LWFA output to subsequently drive a PWFA, wherein the final witness electron beam in this setup is generated by means of wakefield-induced ionization injection. Ultimately, the resulting PWFA output is ought to feature a substantially higher energy and brightness in comparison with the initial LWFA beam. The two stages can be strictly separated by an optional laser block.

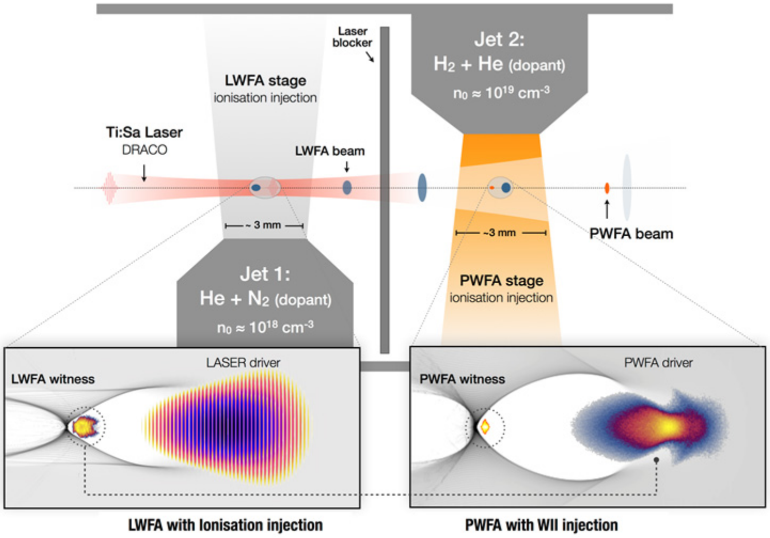

Figure 1: Conceptual setup of the proposed experiment, where the LWFA driven by the DRACO laser system provides the drive beam for the subsequent PWFA stage, generating the final witness beam. Beams propagate from left to right.

LWFA Stage

The LWFA section is operated in the highly non-linear regime, driven by the ~100 TW class DRACO laser system at the HZDR facility. It consists of a supersonic gas jet of 3 mm length featuring a gas mixture of Helium (He) and Nitrogen (N_2) as dopant gas, operating at a gas density of order 10^{18} cm^{-3}. Electron bunch generation relies on ionization injection of the Nitrogen component. Recent results [20] show its capability of producing an electron beam on the order of ~300 pC charge with bunch duration below 10 fs (FWHM), providing a peak current up to ~50 kA, deeming it a suitable PWFA driver. While the spot size of the beam leaving the LWFA stage is estimated to be on the order of ~1 µm, it shows a divergence of several mrad, leading to an increased growth in transverse size upon propagation towards the second stage.

PWFA Stage

The PWFA stage is positioned close to the LWFA stage to reduce the effective transverse size growth of the LWFA output beam to a minimum. It also consists of a supersonic gas jet of 3 mm length, with a gas mixture composed of Hydrogen (H_2) with He as dopant gas. It is operated at significantly higher density compared to the LWFA stage, on the order of 10^{19} cm^{-3} to operate close to the resonance condition accounting for the short drive beam. This aims for optimized conditions for a) refocusing and capturing of the LWFA output, and b) trapping and acceleration performance, featuring a high transformer ratio. Providing a plasma in the PWFA stage relies either on optical pre-ionization or self-ionization due to the electric field of the bunch.

LWFA TO PWFA TRANSITION

One crucial process of the presented setup is the transition between the two stages. Ideally, the initially diverging LWFA beam is re-focused in the early propagation in the second stage, thus being captured upon its transition into the plasma and continuously driving a plasma wave in the second stage. The predominant parameter defining the effective width of the LWFA beam at the entrance of the second stage is the separation distance between the two stages. We chose a specific scenario where the two stages are separated by 1 mm, and use particle-in-cell (PIC) simulations to investigate the re-focusing process and the resulting trapping and acceleration capabilities for several plasma densities in a pre-ionized and a self-ionizing scenario.

Numerical Studies

Our PIC simulations consider an idealized setup where the initial LWFA generated beam is approximated by purely Gaussian distributions in size and momentum. The beam parameters have been chosen to represent the estimated LWFA output at the beginning of the second gas jet after a 1 mm long drift in vacuum and are presented in Table 1.

Table 1: Initial Bunch Parameters for PIC Simulations

beam charge	300 pC
mean energy	250 MeV
rel. energy spread	10 % (rms)
bunch rms length	1 µm
bunch rms width	5 µm
norm. emittance	5 µm-rad

For the purpose of studying the initial transition of the beam into the second stage, the ambient gas consists of pure Hydrogen. The density profile is implemented approximating the experimental gas jet and is shown on top in Fig. 2 and 3. In the pre-ionization scenario a cylindrical plasma channel of 40 µm diameter is implemented along the propagation axis of the beam, while the simulation box is filled with neutral gas in the self-ionizing case. 3D simulations have been performed with the PIC-code VSim, using symmetric cell dimensions of 0.5 µm, modelling the beam with 125 macroparticles per cell (PPC) and using 8 PPC for the ambient medium. Each scenario has been investigated for plasma densities of 0.1, 0.5 and 1.0×10^{19} cm^{-3}, respectively. Figures 2 (pre-ionized case) and 3 (self-ionizing case) show, against propagation distance, the resulting peak accelerating field in a) and the trapping condition in b), that is if the wakefield potential ψ fulfils $\Delta\psi \cdot e/(m_e c^2) < -1$ [21]. This condition is visualized by the filled area below the dashed line. Subfigures c) show the evolution of mean energy (solid line) and rms deviation (filled area) of the decelerated beam slice trailing 2 rms-lengths from the initial beam center.

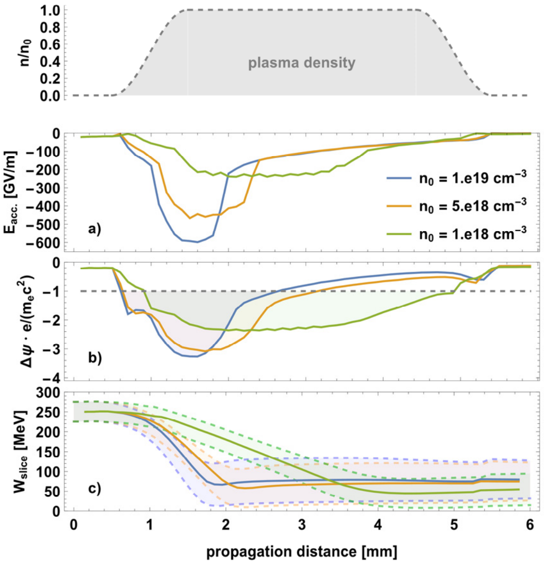

Figure 2: Pre-ionized scenario showing in a) the peak accelerating field, b) the trapping potential and c) the slice mean energy and the rms energy deviation.

Both scenarios show successful recapturing of the drive beam and high accelerating fields emerging for all investigated plasma densities. Furthermore, each simulation indeed features a finite region where trapping of particles is possible. The maximum achievable accelerating field, although generally less in the self-ionized case, naturally increases for higher densities (shorter plasma wavelengths), yet the driver depletes more rapidly due to the also higher decelerating fields in the driver's region.

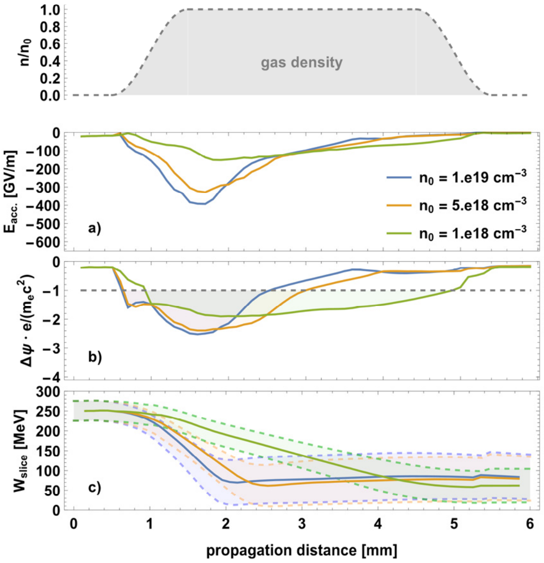

Figure 3: Self-ionized scenario, showing in a) the peak accelerating field, b) the trapping potential, c) the slice mean energy and the rms energy deviation.

CONCLUSION

A conceptual setup for a LWFA driven PWFA experiment, accompanied by numerical studies investigating the transition between the two stages for pre-ionized and self-ionized cases have been presented. For the chosen parameters, both scenarios show a successful transition. The results indicate that the ambient gas density is one of the key parameters to tune in the experiment, as thereby the peak electric field influencing the ionization rate and trapping region can be adjusted to optimize the amount of injected charge in a scenario using WII injection. As a trade-off, tuning the plasma density also allows to match the depletion length close to the actual length of the gas jet, in order to enable stable acceleration conditions over the whole plasma distance, which potentially results in an increased energy gain and a reduced correlated energy spread.

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