Hybrid LWFA-PWFA staging as a beam energy and brightness transformer

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Introduction

Plasma-based accelerators are one of the most promising technologies to overcome the accelerating gradient limit of current radio-frequency (RF) accelerators. Driven either by an ultra-intense laser pulse (LWFA) or a relativistic charged particle beam (PWFA), a trailing plasma-density wave with gigavolt-per-centimeter accelerating fields is excited, where a so-called witness beam can be injected and accelerated to relativistic energies. Nowadays compact LWFAs, hosted in widely accessible high-power laser facilities, are routinely capable of generating high-peak current electron beams at the sub-GeV energy level [1,2]. Yet, the witness beam parameters still have to be substantially improved for quality-demanding applications while the maximum attainable energy is inherently limited by dephasing. On the other hand, PWFAs operating in the blowout regime have advantages in wakefield stability, providing an ideal environment for dephasing-free and emittance-preserving acceleration, while persistent beam-loading conditions can be exploited to obtain high quality witness beams at ultrahigh energies. PWFA is therefore particularly attractive for high-energy physics, e.g. linear colliders, and photon science applications, e.g. FELs. However, the limited availability of the required high-peak current drive-beams has constrained PWFA research to a few dedicated RF-facilities, hampering a more rapid development. Therefore, considerable research and development is still necessary to address fundamental and practical challenges.

Both approaches have inherent benefits and disadvantages. Recognizing fundamental complementarities, a collaboration that brings together LWFA and PWFA experts was formed on a mission to combine and explore the unique advantages of each acceleration method circumventing their individual limitations in a compact hybrid Laser-driven Particle Wakefield Acceleration (LPWFA) scheme. Here electron beams from an LWFA stage are deployed to replace the km-long conventional accelerators as the driver for a secondary PWFA stage. In fact, LWFA electron beams are well suited for this task. Their peak-currents exceeding tens of kiloamperes and ultrashort bunch durations enable PWFAs to be downscaled and operated at high plasma densities of above 10^{18} cm^{-3}, where accelerating gradients higher than 100 GV/m can be generated [3]. In addition, their finite energy bandwidth and emittance are beneficial to suppress the driver hosing instability and facilitate longer propagation distances in a PWFA module. For the advanced accelerator community, such a hybrid approach offers a two-fold potential:

LPWFA as complementary PWFA development platforms

The possibility to operate PWFAs at an extremely broad plasma density range provides a powerful platform to study the driver-to-witness transfer efficiency [4] and the emittance preservation for extended acceleration distances closer to the driver depletion length. The capability of LPWFAs to generate a dedicated and tunable driver-witness pair from the LWFA stage [5] can be utilized to explore staging concepts aiming to boost beam energy and to improve charge capture efficiency while maintaining beam quality, important issues for high-energy physics applications. Furthermore the readily available and powerful optical tools can provide a new insight into plasma wave and ion dynamics [6].

LPWFAs as compact sources of high brightness electron beams

In addition to the role as a development platform, LPWFAs also hold promise as transformational electron bunch sources. The possibility to excite a strong and stable plasma wakefield as well as the absence of strong laser fields in the PWFA stage allows for the implementation of novel cold-injection schemes, based on either selective ionization [7,8,9,10] or plasma density down-ramp transitions [11,12], specially designed for the generation of ultralow-emittance beams. Furthermore, the inherent laser-to-beam synchronization, unique to the LPWFA scheme, offers a key advantage for utilizing auxiliary laser pulses for improved injection control [13].

Experimental implementation

Initial experiments were performed mostly in a transition regime from pure laser- to beam-driven modes inside a single LWFA stage. As laser pump-depletion sets in, the LWFA electron bunch drives its own wakefield. For high-density plasmas and acceleration longer than the laser depletion length, an enhanced x-ray emission [14] and electron energies beyond the LWFA dephasing limit [15,16] were observed. Because this regime relies on an interplay of nonlinear processes, the generation of stable beam-driven wakefields is very hard to control. Therefore, employing two separated accelerators (see Fig.1), operating as the LWFA and PWFA stages, decouples the two acceleration mechanisms enabling the independent control and optimization to fully explore the aforementioned potential provided by laser-based PWFAs. A milestone was reached as beam-driven plasma waves and the associated ion motion in the PWFA stage were captured by ultrafast shadowgraphy [6], demonstrating that high-peak current LWFA electron bunches are indeed capable of driving strong wakefields. Recently, the demonstration of witness beam acceleration within a millimeter-PWFA module, revealing accelerating gradients exceeding 100 GV/m, and the successful implementation of a controlled driver-witness pair scheme set a new landmark in the development and the realization of this hybrid plasma acceleration concept [17]. These results substantiate that a variety of PWFA scenarios can be implemented into typical LWFA facilities, which makes PWFA research and applications more accessible.

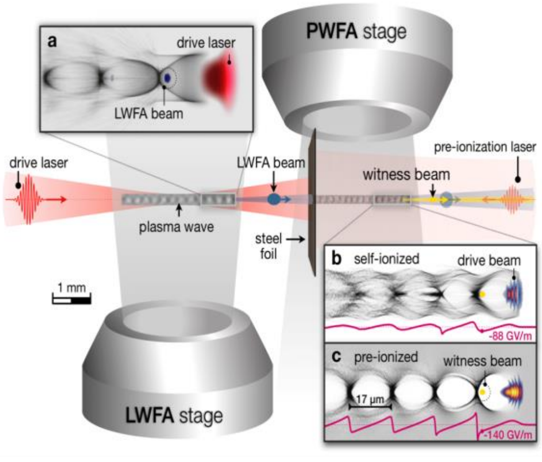

***Fig.1. Schematic of hybrid LPWFA setup**. From left to right, a high intensity laser pulse drives an LWFA in the first stage, producing a high peak-current electron beam. As the spent laser is reflected by a thin foil, the electron beam propagates into the second stage to drive a PWFA regime. A witness beam, either originating from the background plasma in the second stage (internal injection) or carefully prepared in the first stage (external injection), is trapped in the beam-driven wakefield and then accelerated towards high energies. An auxiliary laser pulse can be applied to pre-ionize the second jet, providing a plasma environment prior to the arrival of the drive beam. These two accelerators are completely independent, featuring a full flexibility over a broad parameter range and geometrical setting to allow thoroughly optimization and tuning of individual accelerator necessary for exploration of PWFA physics.*

Summary

Hybrid LPWFAs, where high-peak current ultra-short electron bunches from LWFAs are utilized as driver in a subsequent PWFA, offer a powerful platform to conduct fundamental studies of PWFA concepts at widely accessible high-power laser facilities, complementary to RF-based PWFA facilities. The high wakefield amplitudes and the inherent laser-to-beam synchronization enable the study of advanced injection schemes for the generation of ultralow-emittance electron beams, compliant with beam quality demands of compact light sources such as free-electron lasers. It is anticipated, on the long term, that the future implementation of LPWFAs can be used as beam brightness and energy transformers towards TeV energies while maintaining a compact setup.

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