FIRST MEASUREMENTS OF TROJAN HORSE INJECTION IN A PLASMA WAKEFIELD ACCELERATOR *

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Abstract

Plasma accelerators support accelerating fields of 10-100's of GV/m over meter-scale distances and routinely produce femtosecond-scale, multi-kA electron bunches. The so called Trojan Horse underdense photocathode plasma wakefield acceleration scheme combines state-of-the-art accelerator technology with laser and plasma methods and paves the way to improve beam quality as regards emittance and energy spread by many orders of magnitude. Electron beam brightness levels exceeding 10^{20} Am^{-2} rad^{-2} may be reached, and the tunability allows for multi-GeV energies, designer bunches and energy spreads <0.05% in a single plasma accelerator stage. The talk will present results of the international E210 multi-year experimental program at SLAC FACET, which culminated in successful first demonstration of the Trojan Horse method during FACET's final experimental run in 2016. Enabling implications for applications, including high performance plasma-based 5th generation light sources such as hard x-ray FEL's, for which preliminary start-to-end simulations are presented, and for high energy physics are discussed.

INTRODUCTION

Plasma wakefield acceleration provides electric accelerating fields on the order of tens of GV/m or more. This is three to four orders of magnitude more than state-of-the-art, and nurtures prospects of shrinking down the size of accelerators correspondingly. Electron energy gains up to ~ 4 GeV via laser-driven wakefield acceleration (LWFA) [1,2] and >40 GeV via electron beam driven plasma wakefield acceleration (PWFA) [3,4] have been demonstrated in single stages of sub-meter lengths. However, not only the energy gain, but also the quality of the accelerated electron beams, as well as controllability and tunability of the acceleration process is crucial. The ultra-high fields in plasma wakefield acceleration are due to collective plasma Langmuir oscillations, and on the flip side imply small, typically sub-mm sizes of the co-moving plasma cavities, and corresponding ultrahigh field gradients. This gives rise to a strong sensitivity of the plasma acceleration process with regard to fluctuation of drive beam and plasma parameters, and a variety of injection pathways of background plasma electrons into the plasma wave, especially when the driver pulse travels with a velocity $< c$. In practice, this can easily blur the boundaries between unwanted dark current and controlled injection, and limits the producible electron beam quality and stability.

The development of photocathodes has revolutionized radiofrequency-driven linacs, and has enabled the construction of hard x-ray free-electron lasers such as the LCLS, e.g. by reduction of normalized electron bunch emittance and increase of bunch brightness. A novel plasma photocathode wakefield acceleration strategy, known as Trojan Horse [5], has been devised to strongly decouple the electron bunch generation process from the generation of the accelerating plasma cavity, and to allow a further step change as regards obtainable electron beam quality and stability. In this concept, the driver excites a plasma wave based on a low ionization threshold (LIT) plasma component, which serves as the accelerating structure. A synchronized laser pulse is then focused to just above the ionization threshold to release electrons from a higher ionization threshold (HIT) component within the plasma wave. These electrons are then immediately subject to tens of GV/m accelerating fields, which strongly limits space charge-related transverse emittance growth. Further, in order to excite a strong plasma wave oscillation, a typical Ti:Sapphire drive laser pulse as used in state-of-the-art LWFA must have an intensity in the relativistic ~10^{18} W/cm^2 range – many orders of magnitude larger than typical ionization thresholds. The reason is that the rapidly transversally oscillating field structure of an electromagnetic laser wave does not directly push plasma electrons away from axis to excite the longitudinal plasma oscillation in the sense of a unidirectional Coulomb force, but does so more indirectly and complicatedly via the ponderomotive force. In turn, the oscillating field nature is an asset for generating ultracold electrons in the plasma photocathode process, as it limits the residual transverse momentum which is imparted to the HIT plasma electrons *in statu nascendi* from tunnelling ionization, which is switched on at intensities of the 10^{14} W/cm^2

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range – four orders of magnitude less than typical laser pulses suitable to excite plasma waves. In order to drive a plasma wave, one needs to impart a *large* transverse momentum to plasma electrons, whereas to generate a cold electron bunch one wants to impart a *low* transverse momentum to plasma electrons. At non-relativistic intensities required for tunnelling ionization, the transverse electric laser fields are of the same order of magnitude as the plasma wakefields, i.e. ~tens of GV/m, only. The combination of localized release volume due to the confined laser focus, the greatly minimized transverse momenta, and the rapid acceleration in the plasma wave leads to dense phase space packets, which can have ultralow normalized transverse emittance ε_n of the order of nm rad. In combination with inherently short, femtosecond duration and multi-kA currents I, this results in ultrahigh 5D-brightness $B \approx I/\varepsilon_n^2$. This means that plasma-based electron bunch generation has prospects to not only exceed the accelerating fields, but also the obtainable beam quality of state-of-the-art accelerators in terms of emittance or brightness by orders of magnitude.

The TH concept and related schemes can in principle be realized also by two laser pulses, one to drive the plasma wave via LWFA and another one to release electrons [6-11]. However, relativistic electron beam driven PWFA-TH conceptually combines desirable benefits of both LWFA and PWFA and for example harnesses the unipolar electric field nature of particle bunch drivers, which allows to use LIT/HIT combinations in a wide range and with especially low ionization thresholds, dephasing-free and dark current-free operation and a comparably robust acceleration cavity with fixed phase relation over extended distances.

E210 TROJAN HORSE AT SLAC FACET

At SLAC, a pioneering experimental plasma wakefield acceleration R&D program has been carried through since the 1990's at FFTB and FACET [12]. This made FACET the ideal test facility to aim for experimental development of the TH technique. The "E210: Trojan Horse PWFA" experiment was approved at FACET in 2011 and embarked as an expanding multi-institutional collaboration of international academic groups (Strathclyde/UCLA/Hamburg/Oslo/Austin), research centers (SLAC/DESY) and industry (RadiaBeam/Tech-X/RadiaSoft) in 2012. In parallel, the confidence level regarding feasibility and prospects, as well as understanding of TH increased, based on further theoretical and simulation-assisted works by various groups [13-17].

Continuous efforts have been devoted on developing the experimental capabilities at FACET over the years, some of general use for various experimental programmes of the multi-purpose facility, many to support plasma experiments and some very specifically for plasma photocathode TH exploration and E210. In 2012, for example, the state-of-the-art at FACET was using alkali metal vapour ovens, in which the heated alkali metals such as Li or Rb were self-ionized by the FACET electron beam driver on the fly. This is possible due to the low ionization thresholds of alkali metals and the high charge densities of the FACET electron beam. However, to allow for controlled acceleration in plasma media which are gaseous at ambient conditions and therefore much more manageable, to enable the use of widely tunable multi-component gas mixtures, and in order to allow for broad optical accessibility of the plasma, e.g. for active probing diagnostics for visualization, timing studies and for the TH photocathode injection laser, optical ionization capability is highly desirable. A multi-TW Ti:Sapphire laser system was therefore procured, installed and commissioned in proximity to the plasma source and the interaction area at SLAC linac sector 20 and synchronized to the tens of ps level to the FACET electron beam. This is sufficient in order to preionize the gas, as recombination takes place on orders of magnitude longer timescales. Preionization of the plasma along the axis over metre-scale length with a Gaussian laser pulse requires long Rayleigh lengths and hence a spatial footprint which is not compatible with a compact setup as required for FACET. Furthermore, selective preionization is crucial. The hydrogen needs to be ionized ideally fully, while the helium component should remain neutral, which means "hot spots" are to be avoided both in the laser intensity profile as well in the generated plasma wave structures [18]. Additionally, the plasma channel should be wide enough to allow propagation of the plasma wave without boundary effects compromising or even disrupting the plasma blowout in a harmful way. This is a real bottleneck, and the importance of the mentioned preionized plasma channel features for PWFA in general cannot be overemphasized. At FACET, axicons and axilenses were explored and used in E210 to generate suitable plasma channels with selective ionization of hydrogen. Figure 1 shows a corresponding laser intensity profile (a) and resulting hydrogen plasma profile (b). In fig. 1 b), the laser pulse travels from left to right along the electron driver beam axis *z*.

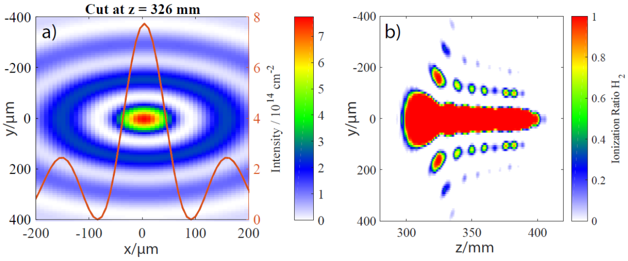

Figure 1: Calculation of transverse axilens intensity distribution at *z*=326 mm including the central lineout (a). The longitudinal cut of the ionization ratio for hydrogen ionization shows an expected plasma length of *z*~1 m (b).

The plasma wakefields constitute a further important boundary condition. On the one hand, the plasma wave must be strong enough to allow for trapping of electrons which are released by the plasma photocathode process. This is easily achieved at FACET, due to its ultrahigh drive beam current capability. On the other hand, the drive beam and wake must not be too strong because then wakefields may ionize or even trap helium electrons, thus

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generating dark current. Drive beam fields can be reduced e.g. by operating at reduced drive beam charge or with longer driver bunches and/or reduced drive beam focusing, and wakefields can be decreased by operating at reduced plasma densities. The latter is advantageous also because then the blowout region is larger, and spatiotemporal alignment and synchronization requirements for the injection laser are relaxed. However, the transverse channel width limits the latitude in this regard. Figure 2 visualizes the effect of reduced plasma densities (corresponding to increased plasma wavelength λ_p) and/or reduced driver charge Q.

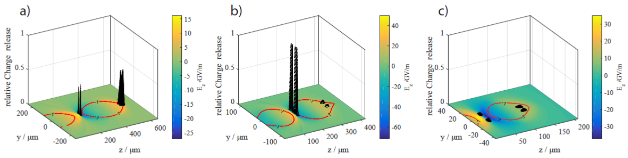

Figure 2: Charge release calculated from ADK rates for a) drive beam charge Q = 3 nC, λ_p = 333 µm σ_z = 25 µm, σ_r = 7 µm, b) λ_p = 149 µm, c) Q = 1.1 nC, λ_p = 100 µm $\sigma_z = \sigma_r$ = 14.1 µm. The red line indicates where the trapping condition $\psi < -1$ is fulfilled, and the black peaks represent the longitudinal derivative of the ionization rate, normalized by the final ionization ratio.

At FACET, a tight sweet spot could be found, taking into account the above considerations and boundary conditions. Increasing the preionization channel width, without losing selective ionization capability is a key objective for future R&D. On the other hand, the flexibility to shape the channel width as a function of propagation distance by the use of diffractive optics opens up interesting opportunities to exploit channel-blowout boundary effects.

In any case, the spatiotemporal alignment and other challenges involved with delivering a precisely ionizing laser pulse into the centre of a relativistically propagating blowout are substantial, and maybe the biggest challenge of the TH technique. Fortunately, the need for alignment precision on the fs and µm scale is one shared with many areas of modern laser-particle beam interaction, for example for various pump-probe setups, FEL seeding and diagnostics etc. For example, various methods for measuring and optimizing the time-of-arrival of laser or electron beams have been developed, such as electro-optical sampling. At E210, it was crucial to implement these state-of-the-art methods, but also to amend them with completely new methods which harness the plasma response to intersecting laser and electron beams. These were an experimental breakthrough and allowed to diagnose and steer the interaction on-the-fly and with extremely high accuracy and robustness. This accelerated data taking and scientific output involved with various plasma experiments, especially those involving multiple beams, dramatically. For example, it allowed for the first time to take reliable data even after sunrise, when usually using only state-of-the-art methods did not allow to complete the complex alignment procedures due to substantial thermal drifts in the interaction area. The new enabling method of plasma response based spatiotemporal alignment in particular has shown an excitingly high performance and robustness, and is a very promising technique of very general applicability even far beyond the plasma accelerator area.

There are substantially different requirements on the multi-TW preionization laser arm, and on injection and diagnostics laser arms. For example, the high power, multi-TW class Ti:Sapphire preionization laser pulse requires a vacuum compressor, and at the same time, especially for robust full but selective preionization of hydrogen it is desirable to use comparably long laser pulses in the region of 100 fs or more. The latter is due to the well-known (double) ionization dynamics of hydrogen [19]. In contrast, for the injection and probe beams it is in principle ideal to operate with short or ultrashort pulse durations. In any case, it is highly desirable to have injection, diagnostic and probe beams as independently tunable as possible from the main preionization laser beam. This involves timing, pulse duration, intensity, polarization, wavelength etc. However, being the pioneering and only multi-GeV facility for plasma and other accelerator experiments and the very high demand for beamtime, FACET necessarily operated in simultaneous multi-experiment mode. This implies a highly complex, milestone-driven and evidence-based sequential experimental schedule aiming to maximize research output. In this context, early attempts at achieving injection in E210 have operated with a split-off injector laser pulse off the compressed main laser pulse and explored two photon absorption as a means to achieve synchronization of upstream and downstream laser arms. Later, continuously developed setups have profited enormously from the installation of a separate air compressor for the injector and diagnostic laser beams, from a dedicated injection chamber which was developed jointly with Radiabeam Technologies and which was informally known as “Picnic Basket” at FACET, and a fully motorized off-axis parabola for injection. These dedicated improvements, in addition with the combination of plasma-based spatiotemporal alignment techniques and state-of-the-art diagnostics, have paved the way for successful Trojan Horse injection campaigns on the final leg of FACET’s lifetime in 2016. As a complementary stepping stone towards TH injection, the so called Plasma Torch laser-triggered injection scheme [20,21] has been demonstrated. The latter technique had been theoretically developed as a multi-purpose injection and beam manipulation technique which allows, amongst other things, an all-optical generated plasma density downramp injection mode with strongly relaxed temporal synchronization requirements. These injection techniques both are the first truly tunable, laser-triggered injection demonstrations in PWFA. They have at the same time both proven to be remarkably robust as a result of the decoupling of wakefield excitation and injection, mainly limited only by the inherent shot-to-shot temporal jitter of the SLAC driver electron beam, which originates from the thermal cathode and large compression requirements. Key publications discussing the many scientific

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firsts achieved in the E210 program are in preparation. The decoupled and robust underlying physics have allowed to utilize and tune up to 5 laser pulses (including the plasma wakefield probing laser beam from the E224 experiment) simultaneously for mapping and steering the interaction of the main drive electron beam with the dual-component plasma, thus constituting one of the most advanced and flexible plasma wakefield acceleration experiments to date.

The lessons learned during E210 have significantly influenced also the design of FACET-II [12] and will be useful for many other future incarnations and further developments of the TH technique also at other facilities such as currently discussed for FACET-II [22], DESY [23], BNL ATF-II [24], CLARA [25] and INFN. For example, experiments at FACET-II will be fundamentally further improved e.g. by the use of a) a photocathode to deliver the drive beam, which implies strongly improved stability of the drive beam and wakefield, including an improved temporal jitter by an order of magnitude, b) wider plasma channels, c) collinear experimental setup, whereas the 2016 E210 realization has used a 90° geometry due to the necessity to include robust Plasma Torch density downramp injection and due to experimental boundary conditions at FACET, and d) windowless on-axis interaction to extract low-emittance electron witness beams without compromising the emittance due to small-angle scattering. Finally, it shall be noted that apart from the preionization laser pulse, the other laser pulses involved require only few-mJ or sub-mJ laser pulse energies. In the future, this in principle allows substantial improvements of the quality and stability of those lower energy laser pulses, and potentially even to harness fibre laser pulses as completely independent laser pulses as one of the early uses of fibre lasers for plasma wakefield acceleration. The synchronization structure of the preionization laser beam (few ps or tens of ps before the electron beam) and the injection and probe beams (fs-scale) allows this.

FROM 5D TO 6D BRIGHTNESS

The TH technique allows generation of ultrashort and multi-kA current, ultralow emittance electron beams and thus ultrahigh 5D-brightness $B \approx I/\varepsilon_n^2$. However, a fundamental disadvantageous side-effect of the ultrahigh wakefields realizable in plasma accelerators in general is the ultrahigh accelerating field gradients. These lead to a substantial energy chirp of the produced witness bunches, which in turn can compromise or even prevent not only performance of key applications such as free-electron lasers, but also can compromise the emittance during extraction from the plasma stage. It is therefore crucial to control and optimize the energy spread of the electron output from plasma accelerators, which typically is of the order of few percent to few tens of percent. A step change was achieved in 2004 [26-28], when for the first time quasi-monoenergetic electrons instead of Maxwellian distributions could be produced from plasma accelerators. A similarly fundamental step change would be highly desirable today in order to improve the energy spread obtainable from plasma accelerators to levels where for example the Pierce parameter requirements can be clearly fulfilled, in order to allow high-gain FEL lasing into the x-ray region. Ideally, such a mechanism would be compatible with and decoupled from the plasma photocathode ability to produce ultrahigh 5D brightness. Together with reduced energy spread $\Delta W_{\mathrm{rms}}/W$, this would constitute ultrahigh 6D-brightness, defined as $B_{6D} \approx B_{5D} / 0.1\% \, \Delta W_{\mathrm{rms}}/W$. Such a mechanism has recently been found based on a novel approach utilizing the production of tailored “escort” electron beams [29]. This escort bunch technique promises to allow to reduce the energy spread from head to tail by orders of magnitude, leaving basically only the residual energy spread inherent due to bunch generation. A scaling law to describe the residual energy spread has been found and is in good agreement with 3D PIC-simulations which were carried through with VSim [30]. Fortunately, these considerations indicate that the energy spread can be further reduced by operation at reduced plasma densities, in addition to the natural relative energy spread damping with increasing energies. This is synergistic with better timing stability at reduced plasma densities, and may allow a breakthrough as regards realization e.g. of hard x-ray light sources at electron energies which are straightforwardly achievable even in a single stage, whereas usually the typical energy spread and chirp is a showstopper due to the strict Pierce parameter requirements.

The advancements are being amalgamated in a novel approach called *NeXource*, aiming at ultrahigh 6D-brightness in a single PWFA-driven stage. Figure 3 shows theoretical projected 6D-brightness values of this approach in various incarnations, compared to existing or upcoming state-of-the-art XFEL facilities. The main message here is that *NeXource* may be able to exceed the 6D-brightness values (taken from [31]) by two or more orders of magnitude or more.

HYBRID PLASMA WAKEFIELD ACCELERATION

The use of linac-generated electron beam drivers for TH-PWFA such as at FACET stands out because of the unrivaled stability and reproducibility of electron beams and the straightforward availability of high repetition rate. Next to linac-driven PWFA, there is a perspective to also utilize LWFA systems for PWFA research in general, as proposed e.g. in [32,5,33] or for TH-PWFA in particular [5,33]. The latter is especially attractive because one needs a synchronized laser pulse for ultracold witness bunch generation in any case. Here, the LWFA system would produce a dense electron bunch which would then be used as a driver for an attached TH-PWFA stage, and a fraction of the LWFA laser pulse would be used for injection and witness bunch conditioning in the PWFA stage [5,33] (the latter then constituting a “double hybrid” approach). These R&D approaches had been supported by DFG since 2012 [34]. A DOE-funded R&D programme

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(RadiaBeam), ultimately aiming at hybrid LWFA→(TH-)PWFA, has substantially supported the E210 experiment at FACET since 2014 in the US [35]. In Europe, the EuPRAXIA project [36], which was kicked off in 2015, has a dedicated work package on "Hybrid Laser-Electron-Beam Driven Acceleration", which explores hybrid LWFA→PWFA. Experimental exploratory work in this context has been already performed e.g. at FSU Jena [37], and plans are underway to use DRACO at HZDR Dresden [38], the Scottish Centre for the Application of Plasma-based Accelerators SCAPA, and other facilities. Linac-generated electron bunches, energy-boosted in an LWFA stage [39], may be a third alternative to generate the driver bunches which are required to drive a PWFA suitable for TH.

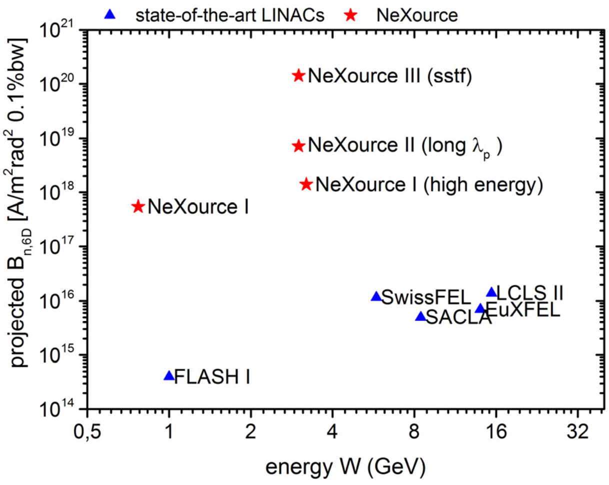

Figure 3: Theoretical normalized 6D-brightness performance of the *NeXource* technique in comparison to existing or upcoming XFEL facilities [31].

These three types of intense electron beam sources can be used as PWFA drivers. The TH stage then would act in multiple ways to improve the electron beam quality: a) electron energy boost (depending on the transformer ratio by a factor of 2+), b) energy spread minimization (two orders of magnitude), c) emittance minimization (two or more orders of magnitude), d) brightness maximize (three or more orders of magnitude), and e) to tune the output in a wide range, and to stabilize the overall output. The latter point is predominantly relevant to electron bunches from LWFA systems. The electron bunch improvement capabilities of the plasma photocathode are impressive. The TH/*NeXource* stage may therefore evolve into a gateway enabling advanced photon science via realization of 5th generation light sources e.g. on free-electron laser (FEL), inverse Compton scattering (ICS) or ion channel laser (ICL) basis, or for electron diffraction at low energies etc. These applications would profit in particular from a minimized emittance (e.g. Pellegrini criterion), energy spread (e.g. Pierce parameter), and brightness (gain). Next to such key applications for natural, material and life sciences, TH/*NeXource* could also fertilize high energy physics, for example by using TH/*NeXource* as a low emittance electron injector. Figure 4 visualizes this approach conceptually.

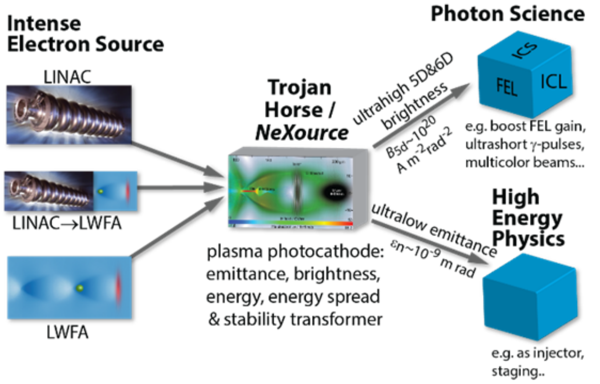

Figure 4: Driven for example by electron bunches from linacs, LWFA or LWFA-boosted linacs, TH/*NeXource* can be a gateway to advanced photon science (free electron lasers, inverse Compton scattering, ion channel laser) and HEP.

CONCLUSION AND OUTLOOK

The Trojan Horse technique, the Plasma Torch technique, and many novel, partially enabling alignment techniques have been experimentally explored and discovered in the "E210: Trojan Horse PWFA" program at SLAC FACET. At the same time, theoretical work has been ongoing which further nurtures prospects of not only producing ultrahigh 5D brightness beams, but also ultrahigh 6D brightness electron beams, both advancing the state-of-the-art substantially. The surprising stability of the laser-triggered injection mechanisms achieved in the E210 program, jointly with expected significant improvements expected from FACET-II, and via the hybrid plasma acceleration avenue, are highly promising as regards future incarnations of the TH and the *NeXource* 6D brightness scheme and its potentially transformative application.

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