TOWARDS REALIZING OPTICAL INJECTION OF ELECTRONS IN RESONANTLY EXCITED PLASMA WAKEFIELDS†

N. Saleh, P. Zhang S. Chen, C. Widjaja, W. Theobald, V. Yanovsky, D. Umstadter
FOCUS Center, University of Michigan, MI 48109, USA

Abstract

The concept of optical injection of plasma background electrons into resonantly driven laser wakefields has been extensively studied theoretically [1]. It was shown that when a strong 1-D wakefield is ponderomotively excited by an ultra-short laser pulse comparable in duration to the plasma wave and a similar transverse laser pulse, but otherwise tightly focused onto the wakefield, is introduced, a relativistic electron bunch with a very narrow (a few %) energy distribution, and very short duration (10's fs) is produced. This concept is actively being investigated experimentally using the University of Michigan's Hercules laser system. We report our progress toward experimentally realizing this concept.

1 INTRODUCTION

Plasma-based laser wakefield accelerators (PBLWFA) have exhibited superiority over conventional RF-based accelerators primarily due to their high field gradients and compactness. Despite the wide array of applications (PBLWFA) have spurred [2][3], they continue to fall short of meeting some modern demanding application. There are two major shortcomings of (PBLWFA) realized so far; first, their acceleration schemes depend on plasma instabilities like Raman scattering [4]. Second, the electron bunches produced have undesirably large longitudinal emittance. To mitigate these shortcomings, a number of schemes were proposed [5-10], some of which are being experimentally investigated [11], and some have reported promising results [12-14]. The general principle of these schemes suggests that a short, intense laser pulse, called pump, with duration comparable to the plasma wave period can resonantly excite a wakefield in the plasma. The short duration of the pump pulse makes the excited plasma wave resilient to laser-plasma instabilities that require several plasma periods to grow. This process merely generates an accelerating structure but does not load the plasma wave with particles. This is so because the electrons carrying the plasma wave oscillate in a certain phase that results in null net motion. In order to load the plasma wave with electrons, either external or internal injection is required. The scheme we experimentally pursue [1], LILAC (Laser Injected Laser Accelerator), utilizes internal injection by means of another equally short intense laser pulse, called injection pulse, synchronized with the pump. The femtosecond synchronization required has been demonstrated in numerous recent pump-probe experiments using ultrafast lasers. This injection method eliminates the jitter problems encountered frequently in RF-accelerators. The injection of the electrons occurs over a duration of a single plasma period and is achieved by the ponderomotive or ionization "kick" of the injection pulse which causes the oscillating electrons to be dephased from the plasma wave and become trapped then accelerated by the excited wakefield.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Laser System

The experiment we describe will use the University of Michigan HERCULES laser system at the FOCUS center [15]. It is a 100-TW class, Ti:Sa CPA-based laser system, whose output wavelength is centered at λ = 810 nm. The 12 fs seed pulse coming out of the system main oscillator is contrast-enhanced, stretched then injected in to a novel large-ring-cavity regenerative amplifier [16]. Two downstream amplification stages increase the final power to a nominal level of 100 TW when parasitic transverse lasing in the amplifiers is subdued. The final amplified beam is split by a 50:50 beam-splitter before compression, each beam is sent to a different compressor. This allows for controlling the pulse durations independently. The final beam diameter is 50 mm, and polarized upward, making all horizontal transport mirrors in S-polarization configuration suitable for the high-damage-threshold, broad-band dielectric mirrors used in the compressors and experiment, and also makes possible producing interference fringes to study interesting physical phenomena like stochastic heating [13].

2.2 Experimental Setup

The experimental setup is illustrated in Fig. 1. After the beam is split, the primary compressor houses the pump pulse, while the secondary compressor houses the injection pulse. The experiment layout has been designed so that the pulses overlap with zero delay in the 1 mm He gas jet target inside the experimental chamber. The pump pulse is focused onto the gas target by an f/10 15^o-off axis gold-coated parabolic mirror, this provides a good approximation to the 1-D focusing geometry desired. The injection pulse is focused tightly by an f/3 90^o-off axis parabolic mirror. The injection parabolic mirror is mounted on a micron-precision 3-D translation stage that permits fine tuning of the spatial overlap of the two pulses. The gas target density can be varied up to 5×10^{19}

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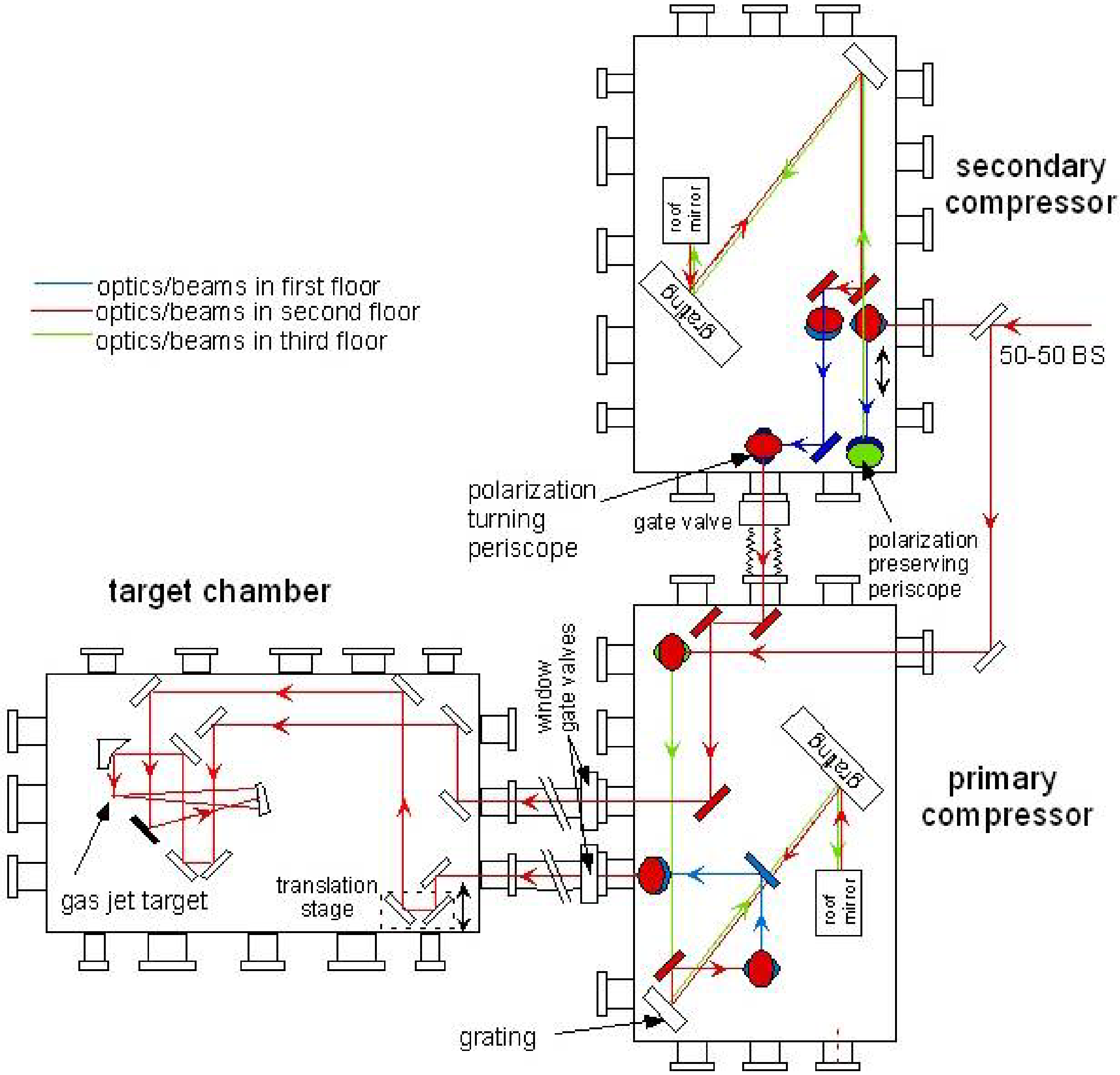

Figure 1: Layout of the LILAC experiment.

electrons/cm^3 by changing the backing pressure of the solenoid-activated supersonic nozzle assembly. The produced e^- beam is diagnosed by an integrating coil transformer for the charge measurement, and a Kodak LANEX scintillating screen for transverse spatial profile and the emittance measurement (using the pepper pot technique [17]), this screen is imaged with a 12-bit CCD camera. The spatio-temporal overlap of the two pulses is monitored from the top through the observation of the Thomson scattering of the fundamental laser wavelength. The e^- beam momentum is measured by inserting a dipole sector magnet between the source (nozzle) and the scintillating screen, and imaging the dispersed trace of the e^- beam.

2.3 Experimental Procedure

In order to determine the proper point of injection in the phase space, the parameter space of the experiment should be set at the threshold of the pump beam self-trapping, where the dark current (the electron signal from the pump alone before injection) diminishes. This should occur close to the resonant regime, $\tau_{laser} \sim 2\pi / \omega_{plasma}$. A target density scan will be performed to achieve that. At the optimum injection point, the injection beam is turned on and further fine-tuning of the beams overlap is performed if needed. The effect of injection beam on pump e^- is then studied.

3 PRELIMINARY RESULTS

A preliminary run with only one beam was taken at 10 TW and peak intensity in excess of 10^{19} W/cm^2. Fig. 2. shows the electron beam profile measured with the laser pulse off-resonance at $\tau_{laser} \approx 2.5\ \tau_{plasma}$. The electron beam measured has a superior divergence solid angle of about 15 μSr, (~ 0.25^o). To our knowledge is the smallest divergence angle achieved with laser accelerators to date.

Fig. 3 shows the target density scan up to the density corresponding to a few plasma periods. Full characterization of the electron beam from the pump alone is actively underway.

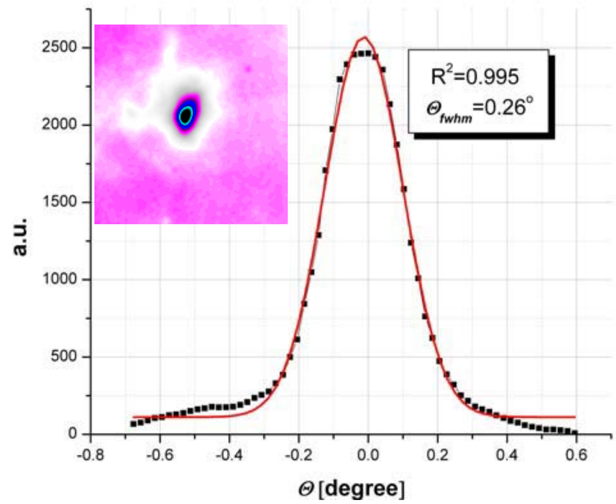

Figure 2: Lineout of the e^- beam produced by the one laser beam off-resonance. Inset is the corresponding LANEX image.

4 CONCLUSION AND FUTURE WORK

We have developed a 100 TW class CPA laser system and setup the LILAC experiment including successfully overlapping two laser pulses to within 30 fs and a few microns. Preliminary data of the one beam alone show that the dark current diminishes close to the resonance regime, while off-resonance an electron beam with superior divergence is obtained. Further characterization of the electron beam before injection is underway. The laser power level is being maximized by further subduing the parasitic transverse lasing in the amplifier media. The effect of the injection beam on the pump electron beam will be studied in the immediate future. Full characterization of the electron beam obtained with optical injection will be performed and compared to theory and simulation.

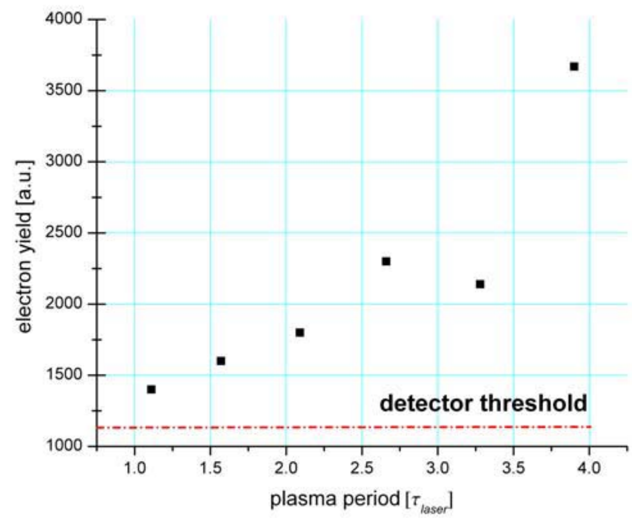

Figure 3: e^- beam yield from the pump alone vs target density measured in plasma periods.

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6 REFERENCES

[1] D. Umstadter *et al.,* Phys. Rev. Lett. **76**, 2073 (1996).
[2] N. Saleh *et al*., Rev. Sci. Instr. **71**, 2305 (2000).
[3] D. Umstadter, J. Phys. D **36** R151-R165 (2003).
[4] P. Bertrand *et al.*, Phys. Rev. E. **49**, 5656 (1994).
[5] E. Esarey *et al.,* Phys. Rev. Lett. **79,** 2682 (1997).
[6] B. Rau *et al.,* Phys. Rev. Lett **78,** 3310 (1997).
[7] G. Hemker *et al*., Phys. Rev. E. **57**, 5920 (1998).
[8] C. Moore *et al.,* Phys. Rev. Lett. **82**, 1688 (1999).
[9] S. Bulanov, Plasma Phys. Rep. **25**, 468 (1999).
[10] H. Suk *et al.,* Phys. Rev. Lett. **86**, 1011 (2001).
[11] Kaganovitch *et al.,* these proceedings.
[12] W. Leemans *et al.,* in the 44th Annual Meeting of the Division of Plasma Physics www.aps.org/meet/DPP02/baps/abs/S1800110.html
[13] N. Saleh *et al*., AIP conf. Proc., **647**, 690 (2002).
[14] P. Zhang *et al*., submitted to Phys. Rev. Lett.
[15] V. Yanovsky *et al.*, Technical Digest of CLEO 2000, 288 (2000).
[16] V. Yanovsky *et al*., App. Phys. B **74**, 181 (2001).
[17] P. Ostroumov *et al*., Rev. Sci. Instr. **73**, 56 (2002).