Update on Seeded SM-LWFA and Pseudo-Resonant LWFA Experiments – (STELLA-LW)

W. D. Kimura,[1] N. E. Andreev,[4] M. Babzien,[2] D. B. Cline,[3] X. Ding,[3]
S. M. Hooker,[7] E. Kallos,[9] T. C. Katsouleas,[9] K. P. Kusche,[2]
S. V. Kuznetsov,[4] P. Muggli,[9] I. V. Pavlishin,[2] I. V. Pogorelsky,[2]
A. A. Pogosova,[4] L. C. Steinhauer,[5] D. Stolyarov,[2] A. Ting,[8]
V. Yakimenko,[2] A. Zigler,[6] and F. Zhou[10]

[1]*STI Optronics, Inc., Bellevue, WA 98004 USA*

[2]*Brookhaven National Laboratory, Upton, NY 11973, USA*

[3]*UCLA, Los Angeles, CA 90095, USA*

[4]*Institute for High Energy Densities, Russian Academy of Sciences, Moscow 125412, Russia*

[5]*University of Washington, Redmond Plasma Physics Laboratory, Redmond, WA 98052 USA*

[6]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

[7]*University of Oxford, Oxford, OX1 3PU, United Kingdom*

[8]*Naval Research Laboratory, Washington, DC 20375, USA*

[9]*University of Southern California, CA 90089, USA*

[10]*Stanford Linear Accelerator Center, Stanford, CA 94025, USA*

Abstract. The Staged Electron Laser Acceleration – Laser Wakefield (STELLA-LW) experiment is investigating two new methods for laser wakefield acceleration (LWFA) using the TW CO_2 laser available at the Brookhaven National Laboratory Accelerator Test Facility. The first is seeded self-modulated LWFA where an ultrashort electron bunch (seed) precedes the laser pulse to generate a wakefield that the laser pulse subsequently amplifies. The second is pseudo-resonant LWFA where nonlinear pulse steepening of the laser pulse occurs in the plasma allowing the laser pulse to generate significant wakefields. The status of these experiments is reviewed. Evidence of wakefield generation caused by the seed bunches has been obtained as well as preliminary energy gain measurements of a witness bunch following the seeds. Comparison with a 1-D linear model for the wakefield generation appears to agree with the data.

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BACKGROUND

Progress in laser wakefield acceleration (LWFA) research is quickly reaching the point where system issues are becoming more important, e.g., maintaining good *e*-beam quality (low emittance, monoenergetic, high charge) and staging multiple LWFA devices to enable reaching high total energy gain. These require the ability to

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control the electron bunch position with respect to the wakefield phase. It is the aim of the Staged Electron Laser Acceleration – Laser Wakefield (STELLA-LW) experiment to realize this type of control in LWFA by demonstrating two new LWFA schemes. The first is called seeded self-modulated LWFA (seeded SM-LWFA) [1], in which an ultrashort electron beam (*e*-beam) bunch acts as a seed in the plasma to generate a wakefield. The laser pulse immediately follows and amplifies the wakefield via a self-modulated process. The second is pseudo-resonant LWFA (PR-LWFA) [2] where nonlinear steepening of the laser pulse occurs while traveling through the plasma. This helps bring the laser pulse in closer resonance with the plasma, thereby, permitting generation of appreciable wakefields. An update on the seeded SM-LWFA and PR-LWFA modeling is given elsewhere in these proceedings [3]. These two methods may also make it easier to control the wakefield phase, which will allow us to stage LWFA devices in future experiments.

DESCRIPTION OF OVERALL EXPERIMENT

STELLA-LW is being performed at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) and utilizes the ATF TW CO_2 laser, which currently delivers 1 TW peak power (5 J in 5 ps). The experiment will be the first to use 10.6 μm to drive the LWFA process, where the longer wavelength has certain advantages over shorter wavelength lasers [4]. The plasma source for the experiment is a capillary discharge: an ablative (polypropylene) capillary or a gas-filled capillary.

Figure 1 shows a schematic layout of the experiment. The *e*-beam source is a photocathode, microwave-driven linear accelerator typically operated at 45-65 MeV. Entering the beamline from the right, the *e*-beam is focused into the capillary using various quadrupole magnets. The capillary is housed inside a vacuum chamber, which has input and output windows for the high-power CO_2 laser beam. Various *e*-beam diagnostics are available including beam position monitors (BPM), a coherent transition radiation (CTR) interferometer, and two electron energy spectrometers. Due to the large changes in the *e*-beam energy during our experiments, we primarily use the spectrometer at the end of the beamline, which has a wide energy acceptance.

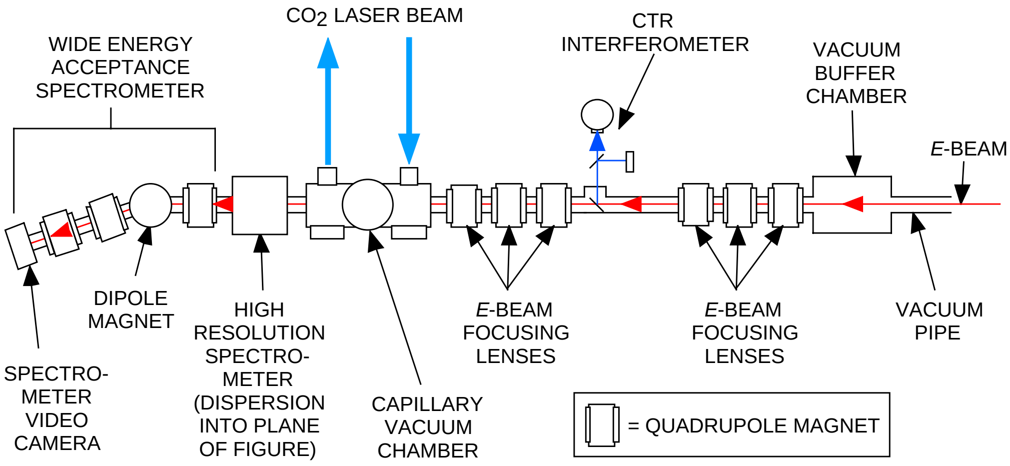

FIGURE 1. Diagram of STELLA-LW experiment.

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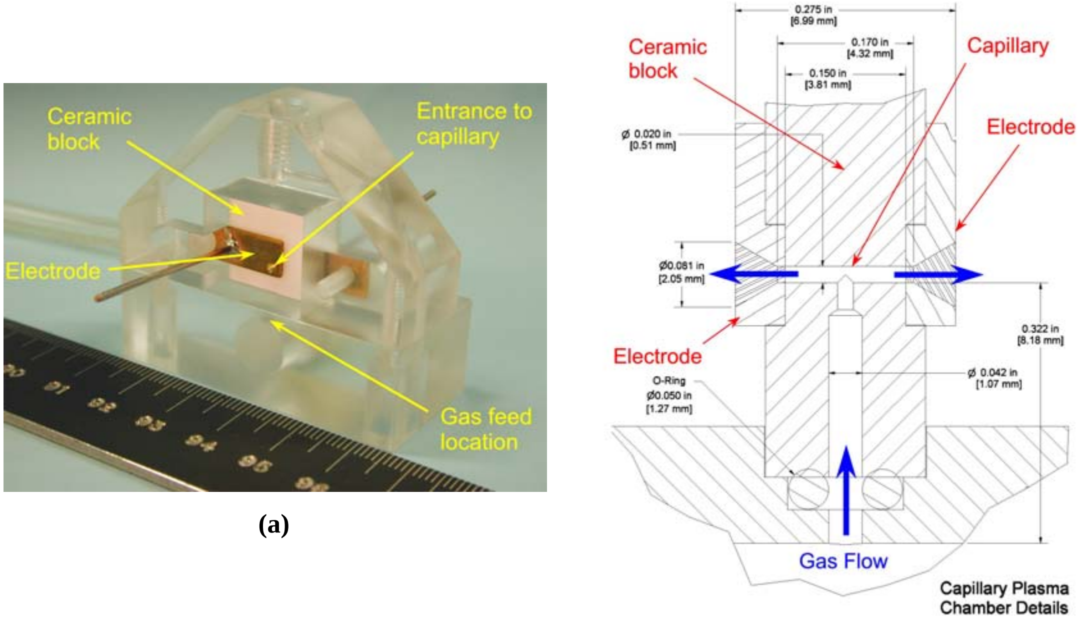
The polypropylene capillary follows the design developed by A. Zigler [5] and its operational range has been extended to very low plasma densities, i.e., $<10^{15}$ cm^{-3}. For the STELLA-LW experiments we need to operate at plasma densities between $10^{16} – 10^{17}$ cm^{-3}, which is well within the plasma density range of the polypropylene capillary. Most of the experimental data presented in this paper was taken using a 6-mm long polypropylene capillary.

A gas-filled capillary design has also been developed based upon the work of S. Hooker [6]. Unlike the alumina or sapphire waveguides used by [6], the STELLA-LW gas-filled capillary is constructed from a machinable ceramic called Macor™. Macor™ has dielectric properties similar to alumina and sapphire, and appears to be an acceptable substitute as evidenced by the successful operation of the capillary.

Figure 2(a) is a photograph of the assembled gas-filled capillary. Acrylic is used as the mounting fixture for the ceramic block. The electrodes on the opposing faces of the block are offset from each other to discourage tracking along the surface of the ceramic and the plastic mount. Figure 2(b) is a cross-sectional, close-up view of the assembled capillary showing how the gas enters the waveguide. The capillary system has been designed so that the ceramic block can be easily replaced without changing the mounts. It can also accommodate longer waveguides without modifying the mounts or the electrodes.

Knowing the plasma density accurately inside the capillary is a critical aspect of the experiment. We are using a Stark broadening diagnostic developed for the multibunch plasma wakefield acceleration (PWFA) experiment [7]. This diagnostic is described



(a)

(b)

FIGURE 2. (a) Photograph of assembled gas-filled capillary showing ceramic block secured to acrylic mounting fixtures. (b) Cross-sectional, close-up view of assembled gas-filled capillary shown in (a).

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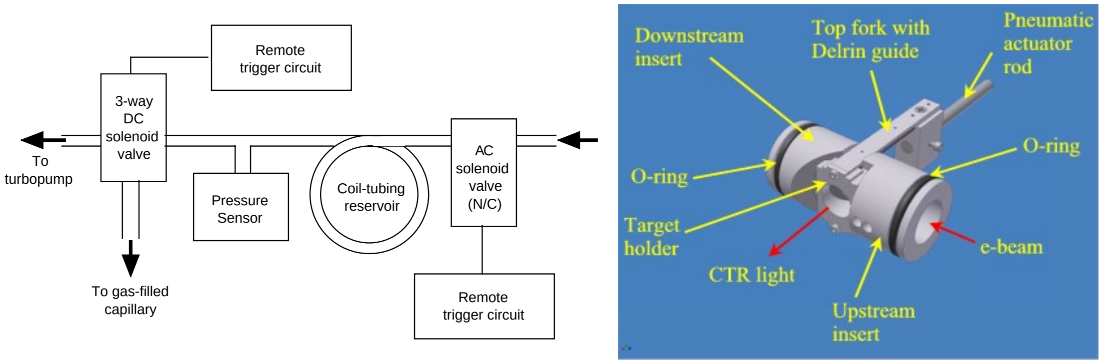


(a) **(b)**

FIGURE 3. (a) Schematic of gas manifold system for gas-filled capillary. (b) 3-D drawing of pellicle/CTR BPM in the inserted position with the 1-μm Ti foil sealed inside the cylindrical holder.

elsewhere in these proceedings [8]. A recent modification to the gas-filled capillary, not shown in Fig. 2, is the insertion of an optical fiber to collect light from the center of the waveguide. This fiber is used in conjunction with the Stark broadening diagnostic.

Also built for the gas-filled capillary is a gas-manifold system for controlling the injection of gas into the capillary. A schematic of the gas-manifold system is depicted in Fig. 3(a). This system uses a gas reservoir, which is preloaded with an amount of gas. This gas is then released into the capillary using a fast-acting solenoid valve. The valve is a three-way device configured so that in its off-position, the capillary inlet gas line is being constantly pumped on by the vacuum system. This helps remove residual gas inside the capillary after a shot is completed.

The gas-filled capillary has been successfully tested over the range of plasma densities of interest (i.e., 10^{16} – 10^{17} cm^{-3}). Based upon the Stark broadening measurements [8], it appears that the ionization is less than 100% at these low densities. However, this is also at relatively low discharge voltages (16.5 kV). Operation at higher discharge voltages may rectify this situation. The drive circuit for the gas-filled capillary is being upgraded, which will permit driving the capillary with higher voltage and currents.

Hydrogen gas released into the beamline vacuum must be evacuated as quickly as possible and prevented from propagating upstream to the linac. Additional pumping capacity was added along the beamline to help remove the gas. Nevertheless, the gas-loading can be significant and may exceed the maximum acceptable vacuum level. To circumvent this potential problem, we also built a dual-function pellicle/CTR BPM. This BPM consists of a 1-μm thick titanium foil that can be inserted at 45° to the *e*-beam trajectory. Moreover, when inserted the foil also makes a vacuum-tight seal inside the beamline pipe preventing gas from traveling upstream. Thus, this BPM serves both as a vacuum-isolating pellicle, which still permits transmission of the *e*-beam through the foil, and a CTR foil. Figure 3(b) is a 3-D drawing of the pellicle/CTR BPM. The BPM is designed to seal within a standard Conflat 4-way vacuum cross.

UPDATE ON SEEDED SM-LWFA EXPERIMENT

The ATF linac system has a chicane for compressing the *e*-beam bunch to ~100 fs. As explained elsewhere in these proceedings [9], rather than producing a single compressed bunch, two ~100 fs bunches are created separated in energy by ≈1.8 MeV and in time by 0.5-1 ps. We identify the higher energy bunch as the "high-E" seed and the lower energy bunch as the "low-E" seed. This phenomenon was new and unexpected. Consequently, progress on the seeded SM-LWFA experiment was delayed while the double-bunch seed beam was studied in order to determine its impact on the experiment.

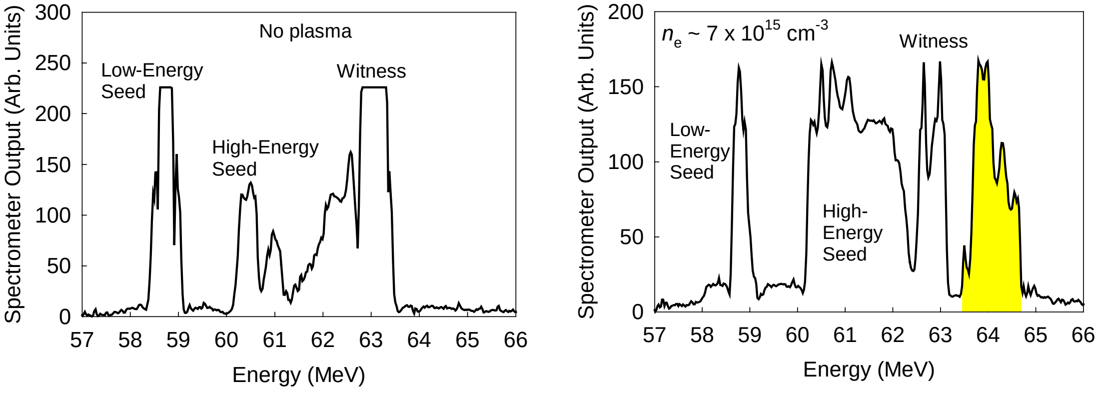
The seeded SM-LWFA experiment needs a wakefield that can be amplified by the laser pulse. In principle, it does not matter whether this wakefield is created by a single seed bunch or two bunches. Therefore, a key question is does the double-bunch beam still produce wakefields and, if so, how might they be utilized to perform the seeded SM-LWFA experiment? To attempt to answer this question, the double-bunch beam was sent through the polypropylene capillary plasma.

As shown in [9], indirect evidence that the double-bunch seeds are generating wakefields is their loss of energy as a function of the plasma density. In fact, as explained in [9], the energy loss data indicates the wakefields produced by the high-E seed are affecting those produced by the low-E seed, thereby giving strong evidence that the high-E seed precedes the low-E seed.

A 1-D PWFA model developed for the multibunch PWFA experiment [7] was run with only two bunches rather than many in order to simulate our double-bunch seeds. The model indicates that the net wakefield produced by the bunches depends on their relative charge, temporal separation, and the plasma density. This can then affect the amount of energy gain or loss of the low-E seed. For example, for the situation when the low-E seed gains energy while in the wakefield of the high-E seed, at 10^{16} cm^{-3} density the model predicts approximately a factor of two difference in the amount of gain depending on whether the ratio of the charges of the high-E seed to the low-E seed is 2:1 or 1:2. This would be expected if the energy loss by the low-E seed is neglected and there is no wake loading. Then the energy gain by the wakefield should be proportional to the drive beam charge. During measurements of the energy gain or loss of the low-E seed at 10^{16} cm^{-3}, we indeed observed a difference in the amount of gain or loss depending on the charge ratio.

The ATF is also able to generate a bona fide second electron bunch from its photoinjector gun by sending a second laser pulse to the photocathode. This second bunch serves as the witness bunch for probing the amplified wakefield. Adjusting the time delay between the laser pulses permits varying the delay time between these two bunches. The nominal delay time is 20 ps. Because of this delay, the two bunches intersect the RF field at different phases and, therefore, gain different amounts of energy. This results in approximately 2-3 MeV energy difference when they leave the linac.

Preliminary data has been taken with the witness bunch following the double-bunch seed in the polypropylene capillary. Because the three bunches have three different mean energies and have partially overlapping energy profiles, the resulting energy spectrum is complex. Figure 4(a) shows the spectrum of the three bunches when no



(a)

(b)

FIGURE 4. Energy spectrums of double-bunch seeds with witness bunch. (a) With no plasma discharge. (b) With a plasma density of ~7 × 10^{15} cm^{-3}.

plasma is present. The three bunches are identified in the figure. The witness and low-energy seed bunch spectrums are saturated in order for the spectrometer camera to have enough sensitivity to detect the weaker high-energy seed signal.

At roughly 7 × 10^{15} cm^{-3} density [Fig. 4(b)], electrons appear with energies >1 MeV higher than the witness (shaded portion of spectrum). There is insufficient information in this particular set of data to determine whether these accelerated electrons originated from the witness or low-E seed electrons. If they came from the witness, then this represents an acceleration gradient of >200 MeV/m. If they came from the low-E seed, then the corresponding gradient is >1 GeV/m. Clearly, more measurements are needed to confirm their origin.

Nevertheless, these preliminary results indicate wakefields are being produced that are capable of accelerating electrons. It also appears these wakefields are suitable for amplification by the laser pulse.

Our plan is to block one of the bunches of the double-bunch seed using a high-energy slit located downstream of the beamline chicane. Unfortunately, this will also block the witness bunch produced at the photoinjector. Therefore, in order to measure the amplification of the wakefield by the laser beam, we shall detect the Raman-shifted laser radiation that is forward-scattered off the wakefield [10].

UPDATE ON PSEUDO-RESONANT EXPERIMENT

In principle, PR-LWFA is a simpler experiment to perform compared to seeded SM-LWFA. It requires only a witness *e*-beam bunch following the laser pulse and the bunch length can be its nominal 3-5 ps duration. However, in order for the nonlinear pulse steepening effect to occur, it does require at least 3 TW peak power from the CO_2 laser delivered into a plasma at a density ~10^{16} cm^{-3}. This was confirmed with additional PR-LWFA modeling as explained in these proceedings [3]. As mentioned, the ATF CO_2 laser currently produces 1 TW. Although we can operate at plasma densities much less than 10^{16} cm^{-3} to help compensate for operation at 1 TW, this operating regime is essentially a linear one where insufficient pulse steepening occurs.

In order to reach 3 TW, the ATF is upgrading the Nd:YAG laser system used to drive the photoinjector and provide the laser pulses for slicing the CO_2 laser pulse to picosecond durations. When completed in the early part of 2008, it should provide a ~500 fs laser pulse for slicing the CO_2 laser pulse. However, since this amount of peak power has never been achieved before from a CO_2 laser, we can expect it will still be a challenging task to realize the full peak power with the shorter slicing pulse.

Once the 3 TW is available, the PR-LWFA experiment can be performed. In the meantime, STELLA-LW will focus its efforts on the seeded SM-LWFA experiment.

CONCLUSIONS

Despite the unexpected discovery of double-bunch seed generation, we are ready to perform the integrated seeded SM-LWFA experiment in the near future. With the laser beam following a single seed bunch, an increase in the Raman signal is anticipated indicating amplification of the wakefield by the laser beam. Once this is confirmed, then the more complicated arrangement of sending the double-bunch seed and witness bunch through the plasma can be attempted. An energy modulation of the witness electrons of approximately ±1 MeV is expected assuming 0.5 TW laser peak power [3].

Performing the pseudo-resonant LWFA experiment must await the availability of 3 TW from the ATF CO_2 laser system. Tentatively, our first opportunity to perform PR-LWFA may be sometime in 2008.

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