BNL - 73208-2004-CP
ATF-04C

Laser Wakefield Acceleration Driven by ATF CO_2 Laser (STELLA-LW)

W. D. Kimura,[1] N. E. Andreev,[4] M. Babzien,[2] I. Ben-Zvi,[2] D. B. Cline,[3] C. E. Dilley,[1] S. C. Gottschalk,[1] S. M. Hooker,[6] K. P. Kusche,[2] S. V. Kuznetsov,[4] R. H. Pantell,[9] I. V. Pavlishin,[2] I. V. Pogorelsky,[2] A. A. Pogosova,[4] L. C. Steinhauer,[7] A. Ting,[8] V. Yakimenko,[2] A. Zigler,[5] and F. Zhou[3]

September 2004

Presented at "11th Advanced Accelerator Concepts Workshop (AAC2004)", Stony Brook, New York, June 21-26, 2004.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Laser Wakefield Acceleration Driven by ATF CO_2 Laser (STELLA-LW)

W. D. Kimura,[1] N. E. Andreev,[4] M. Babzien,[2] I. Ben-Zvi,[2] D. B. Cline,[3] C. E. Dilley,[1] S. C. Gottschalk,[1] S. M. Hooker,[6] K. P. Kusche,[2] S. V. Kuznetsov,[4] R. H. Pantell,[9] I. V. Pavlishin,[2] I. V. Pogorelsky,[2] A. A. Pogosova,[4] L. C. Steinhauer,[7] A. Ting,[8] V. Yakimenko,[2] A. Zigler,[5] and F. Zhou[3]

[1]*STI Optronics, Inc., Bellevue, WA 98004-1495, USA*
[2]*Brookhaven National Laboratory, Upton, NY 11973 USA*
[3]*University of California at Los Angeles, Los Angeles, CA 90095 USA*
[4]*Institute for High Energy Densities, Russian Academy of Sciences, Moscow 125412, Russia*
[5]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
[6]*University of Oxford, Oxford, OX1 3PU, United Kingdom*
[7]*University of Washington, Redmond Plasma Physics Laboratory, Redmond, WA 98052 USA*
[8]*Naval Research Laboratory, Washington, DC 20375, USA*
[9]*Stanford University, Stanford, CA 94305 USA*

Abstract. A new experiment has begun that builds upon the successful Staged Electron Laser Acceleration (STELLA) experiment, which demonstrated high-trapping efficiency and narrow energy spread in a staged laser-driven accelerator. STELLA was based upon inverse free electron lasers (IFEL); the new experiment, called STELLA-LW, is based upon laser wakefield acceleration (LWFA). The first phase of STELLA-LW will be to demonstrate LWFA in a capillary discharge driven by the Brookhaven National Laboratory Accelerator Test Facility (ATF) terawatt CO_2 laser beam. This will be the first time LWFA is conducted at 10.6-μm laser wavelength. It will also be operating in an interesting pseudo-resonant regime where the laser pulse length is too long for resonant LWFA, but too short for self-modulated LWFA. Analysis has shown that in pseudo-resonant LWFA, pulse-steepening effects occur on the laser pulse that permits generation of strong wakefields. Various approaches are being explored for the capillary discharge including polypropylene and hydrogen-filled capillaries. Planned diagnostics for the experiment include coherent Thomson scattering (CTS) to detect the wakefield generation. This will be one of the first times CTS is used on a capillary discharge.

INTRODUCTION

Laser wakefield acceleration (LWFA) is a promising method for achieving high acceleration gradients [1]. The aim of the Staged Electron Laser Acceleration – Laser Wakefield (STELLA-LW) experiment is to demonstrate for the first time LWFA driven by 10.6 μm laser light. STELLA-LW will also be investigating an interesting pseudo-resonant LWFA operating regime [2] where the laser pulse length is too long

for resonant LWFA and too short for self-modulated LWFA. STELLA-LW is located at the Brookhaven National Laboratory Accelerator Test Facility (ATF).

The ultimate goal of advanced accelerator research is to build practical accelerator systems. Such systems must accelerate a reasonable amount of charge with narrow energy spread. This requires grouping the electrons into a microbunch whose length is short enough to be trapped within the ponderomotive potential well ("bucket") of the accelerating field. Staging of the acceleration process is also generally needed in order to obtain high net energy gain.

With this in mind, the STELLA-LW experiment builds upon the successful STELLA experiment where efficient trapping with narrow energy spread in a staged system was demonstrated [3]. STELLA used inverse free electron lasers (IFEL) as the laser acceleration mechanism; however, the STELLA approach of creating and trapping microbunches can be applied to other acceleration schemes. Hence, the STELLA-LW experiment is being designed to apply the STELLA approach to LWFA.

LWFA has better scaling characteristics than IFELs; in particular, IFELs have smaller acceleration gradients and the gradients decrease as the electron beam (*e*-beam) energy increases. For the condition being explored in STELLA-LW, LWFA has a longer accelerating wavelength (~300 μm) instead of 10.6 μm. This is because the CO_2 laser beam creates 300-μm plasma wakes. Hence, the LWFA microbunch length will be of order 30 μm instead of 1 μm or, equivalently, 100 fs instead of 3 fs. The potential advantage with the longer microbunch length is less susceptibility to longitudinal space-charge spreading and emittance degradation due to coherent synchrotron radiation (CSR). The longer accelerating wavelength may also ease the alignment and stability requirements of a staged LWFA system where it is necessary to rephase the microbunches with the wakefields in each stage.

Despite these advantages, implementation of the STELLA approach to LWFA poses several challenges. Like a tapered wiggler in an IFEL, there is a minimum laser intensity needed to drive the wakefield. This minimum intensity is orders of magnitude higher for LWFA than for IFEL; thus, placing new demands on the laser and optics. Unlike a wiggler, which is a passive device, the plasma in LWFA is a dynamic medium whose characteristics must be carefully controlled and reproduced from shot to shot. A key question is whether the wakes produced in the plasma can be controlled sufficiently to permit reliable phase synchronization with microbunches entering each LWFA stage.

Tackling these issues will be done in multiple phases during the STELLA-LW program. The goals of the first phase (Phase I), which is currently underway, are to design and construct the plasma source (i.e., capillary discharge), assemble the needed diagnostics (e.g., coherent Thomson scattering), and observe LWFA-induced energy modulation of the *e*-beam driven by the CO_2 laser beam. In future phases, the aim will be to demonstrate an LWFA buncher, where the LWFA-modulated *e*-beam creates microbunches, and to develop a high-gain LWFA accelerator. This LWFA accelerator would have a long plasma length (e.g., many centimeters) to provide high acceleration and would be fed by the microbunches produced by the LWFA buncher. Hence, the combination of the LWFA buncher and LWFA accelerator is precisely analogous to the STELLA IFEL buncher and IFEL accelerator. And, just like in

STELLA, the goal of the LWFA buncher and accelerator experiment would be to demonstrate high trapping efficiency and narrow energy spread.

The rest of this paper describes in more details the plans for the STELLA-LW Phase I experiment.

DESCRIPTION OF STELLA-LW PHASE I EXPERIMENT

The main objective of the Phase I program is to demonstrate modulation of the *e*-beam energy. This modulation will be accomplished by sending the electrons through the plasma wakes created in a capillary discharge by the terawatt ATF CO_2 laser. Figure 1 depicts the basic concept for the experimental layout. The laser beam is focused into the capillary tube using a 90° parabolic mirror that contains a central hole for transmission of the *e*-beam. This same focusing arrangement has been successfully used at the ATF for Compton scattering experiments [4]. Another parabolic mirror downstream of the capillary tube extracts the spent laser beam while allowing the *e*-beam to continue to the energy spectrometer.

Besides creating the necessary plasma density for formation of the wake, the capillary discharge can also channel the laser radiation as was demonstrated at the ATF for the CO_2 laser beam [5]. This permits focusing the laser beam to a small waist inside the plasma to create high laser intensities for driving the LWFA process, while not being limited by the short Rayleigh range Z_R of a tiny focus. For example, in STELLA-LW the desired laser waist is ~100 μm, so that Z_R = 3 mm. However, appreciable energy gain requires the plasma length to be several centimeters long.

The wakefields in the plasma also possess strong radial fields, which can defocus the *e*-beam. One way to avoid these radial forces is to the focus the *e*-beam into a small radius in the center of the capillary. Preliminary estimates indicate that the *e*-beam radius should be less than 40 μm. This is within the capabilities of the ATF *e*-beam; however, this small size can only be sustained over ≈3 cm [6].

To achieve the small *e*-beam focus, a short-focal-length, permanent-magnet (PM), adjustable-field quadrupole (quad) can be positioned just upstream of the parabolic mirror as illustrated in Fig. 1. Together with conventional electromagnet quads upstream of the PM quad (not shown in Fig. 1), the *e*-beam can be focused to the

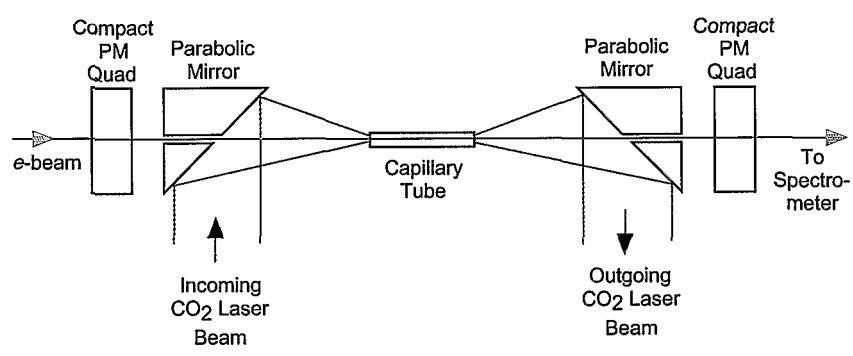

FIGURE 1. Conceptual layout for STELLA-LW experiment.

requisite small size. STI Optronics manufactures remotely-tunable PM quads, which may be suitable for this application [7].

Detection of the modulated *e*-beam energy spectrum will be measured using existing spectrometers. The first is a variable-angle spectrometer (4°-8°) that is capable of wide energy acceptance (~20%). This is the spectrometer that was primarily used during STELLA. The second is a 90° spectrometer with much higher resolution (0.013%), but more limited energy acceptance (~2%). This latter instrument is especially useful for detection of small energy modulations.

CAPILLARY DISCHARGE

Model simulations [2] indicate for the anticipated conditions of the ATF CO_2 laser (i.e., 5 J, 2-ps pulse length) that good wakefield generation occurs at a plasma density of ~10^{16} cm^{-3}. This density is 10-100× smaller than previous work with capillary discharges, which used either ablative mechanisms to produce the plasma medium [8] or gas-filled capillaries [9]. Achieving a stable and reproducible low plasma density is an important issue during the Phase I program.

The ATF used a polypropylene capillary, where ablation of the wall by the discharge provided material for the plasma, and demonstrated 10^{17} cm^{-3} densities [5]. A drawing of the channeling apparatus from Ref. 5 is given in Fig. 2(a). Using a larger tube diameter can reduce the plasma density [8]. However, it may be difficult to achieve a stable, reproducible plasma as the diameter increases.

A gas-filled capillary [9] utilizes an alumina or sapphire tube rather than polypropylene. Figure 2(b) shows a sketch of this type of capillary. Hydrogen gas is injected into the tube and provides the material for the plasma. One advantage of this method is that the tube diameter is not dependent on the required plasma density. Instead the diameter can be chosen to ensure proper channeling of the laser beam for a given laser beam focus size. There is still an issue whether the low gas pressure will yield a stable and reproducible plasma.

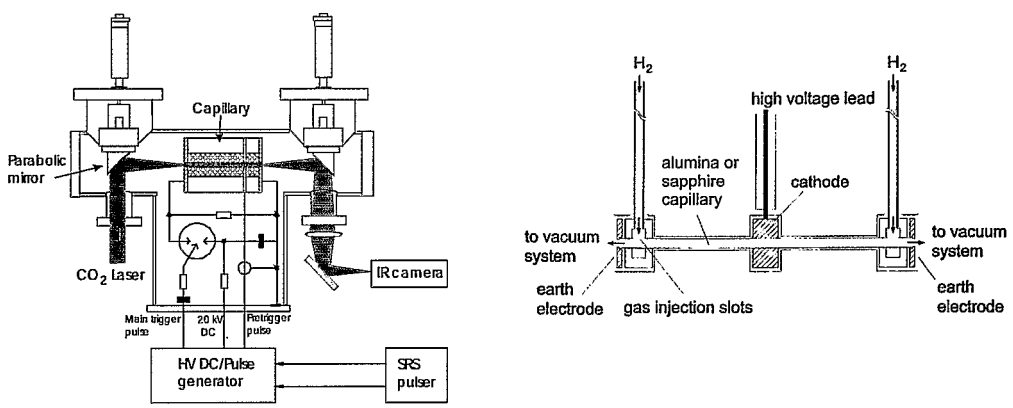

FIGURE 2. Examples of capillary discharges to be tested during STELLA-LW. (a) Channeling experiment using polypropylene capillary [5]. (b) Gas-filled capillary based on Ref. 9.

Both types of capillaries will be investigated during the Phase I program. It is anticipated that the STELLA-LW capillaries will be designed with extra flexibility to permit easy exchange of different sized capillaries, probing the capillary with diagnostic laser beams (see next section), and adding capillaries in series.

COHERENT THOMSON SCATTERING DIAGNOSTIC

There are several methods that have been used to detect the wakefields generated in plasmas. For various reasons many of these methods are not appropriate for the STELLA-LW experiment. One method that does appear suitable is coherent Thomson scattering (CTS). In CTS a probe laser beam is directed either along the discharge or orthogonal to it. This probe beam can be a different wavelength than the pump beam, which helps eliminate noise from the pump beam. The plasma wave acts like a grating, which scatters light from the probe beam. This light is sent into a spectrometer for analysis of its sidebands. Existence of anti-Stokes (AS) light corresponds to formation of a wakefield traveling at near the speed of light. (Stokes light corresponds to the incorrect type of wakefield for acceleration.) The amplitude of the AS light is directly related to the amplitude of the wakefield. It is also possible to determine the plasma density from this measurement. This technique has been used extensively by UCLA [10]-[11] and others [12]-[13]. Although it requires fairly large amplitude waves, e.g., $\Delta n/n \sim 10\%$, the LWFA modeling analysis for the ATF CO_2 laser predicts amplitudes as large as ~100% [2].

The ATF uses a Nd:YAG laser to drive both the linac photocathode and to provide laser pulses for temporally slicing the CO_2 laser pulse via semi-conductor switching. As part of this process, the ATF Nd:YAG laser generates two pulses at 1.06 μm separated in time with variable time delay. The first pulse is sent to the CO_2 laser system and the second pulse is converted to 266 nm and sent to the photocathode. The variable time delay permits the *e*-beam pulse and amplified laser pulse to arrive at the experiments at the same time.

For the wakefield generation experiments, the *e*-beam will not be needed. This means the entire energy from the second 1.06-μm laser pulse could be made available as the probe beam for the CTS diagnostic. A Pockels cell can be used to extract out the second laser pulse, which can be directed to the capillary discharge with its arrival time controlled by the variable time delay. This pulse could be doubled into the green (i.e., 0.532 nm) and used as the probe instead of the 1.06-μm beam. This may have advantages because the total scattered signal intensity relative to the probe intensity scales as λ_L^{-2} [11] and the pulse length will also shorten to <10 ps. A shorter pulse helps improve the signal-to-noise ratio since less of the scattered light is from portions of the laser pulse that do not temporally intersect the wakefield. However, the pulse energy will also decrease when converting to the green.

Figure 3 shows a possible arrangement for directing the 1.06-μm probe beam collinear with the TW CO_2 laser beam inside the capillary discharge. The 1.06-μm probe beam passes through the central hole in the entrance parabolic mirror, travels

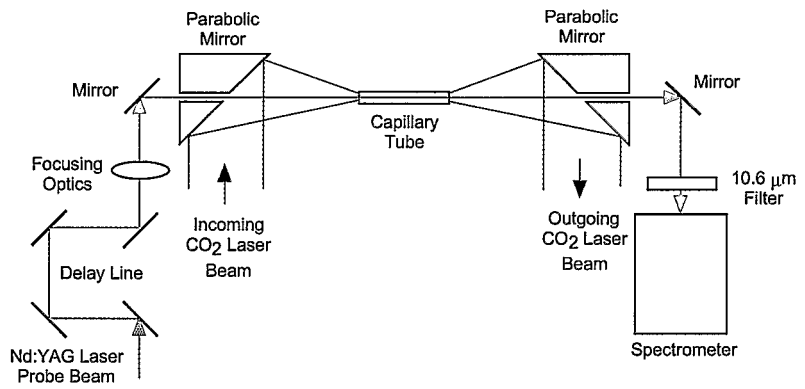

FIGURE 3. Possible scheme for introducing Nd:YAG laser probe beam for coherent Thomson scattering diagnostic.

through the capillary tube, and traverses through a hole in the exit parabolic mirror. The beam is then sent to a spectrometer. A more elaborate optical filtering system before the optical spectrometer shown in Fig. 3 may be needed. A UCLA CTS system used a Fabry-Perot etalon and spatial filtering [14].

Although the AS signal can be emitted at a different angle with respect to the 1.06-μm probe beam, we are only interested in the AS signal emitted collinear with the probe beam, i.e., at 0°. This is because the 0°-signal originates from direct-forward-propagating wakefields with phase velocity close to the speed of light. Due to the geometry of the plasma, the wakefields can be non-one-dimensional and the wakefield velocities can have transverse components. However, we are only interested in the direct-forward-propagating wakefields since these are the ones that accelerate the electrons. Fortunately, in the case of a capillary discharge, the plasma channel acts like a waveguide and the wavefronts of the wakefields are primarily parallel (i.e., quasi-1D). Therefore, there should be less transverse features except at the ends of the capillary.

For a plasma density of 10^{16} cm^{-3} we estimate the AS signal will be shifted approximately 3.3 nm from the fundamental. Other wavelengths can be detected; in particular, the presence of higher-order AS signals would be an indication of very high amplitude wakefields because these higher-order features originate from the nonlinear waveform of a large amplitude wave.

PHASE I EXPERIMENTS

The first Phase I experiments will concentrate on demonstration of the required low plasma density. A CO_2 laser interferometer may be one method for measuring the density; although, it may require multiple passes of the laser beam through the capillary.

The next step is demonstration of wakefield generation and detection by the CTS diagnostic. For the purposes of verifying the CTS diagnostic performance, it may be better to form wakes using some other means than the ATF CO_2 laser beam. One

option is to send the *e*-beam through the capillary to create wakefields. This has already been demonstrated at the ATF in an earlier plasma wakefield acceleration (PWFA) experiment using the polypropylene capillary [15]. However, using the *e*-beam would necessitate a different method for generating the CTS probe laser beam.

Capillary/laser tests can begin before 2-ps laser pulses are available. This will allow addressing issues such as aligning and focusing the laser beam into the capillary, and confirming channeling. Analysis is being performed to understand how strong the pseudo-resonant LWFA effect is when the laser pulse length is longer than 2 ps.

Once the CO_2 laser is producing 2-ps laser pulses at 5 J, then measurement of the *e*-beam modulation can be done. Preliminary estimates are that a 3-cm long capillary will have a peak modulation energy of $\approx$8 MeV [6].

CONCLUSIONS

Phase I of the STELLA-LW experiment to demonstrate LWFA driven by CO_2 laser light is underway. Different capillary discharge approaches are being pursued for achieving the needed low plasma density. A CTS diagnostic is being designed, which will be one of the first times such a diagnostic is used on a capillary discharge.

Pacing the experiment schedule will be the time needed to upgrade the ATF CO_2 laser to produce 2-ps laser pulses. In the meantime, measurements will be performed to characterize the capillary discharge, including the possibility of generating wakes using the ATF *e*-beam.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Grant Nos. DE-FG02-04ER41294, DE-AC02-98CH10886, and DE-FG03-92ER40695.

REFERENCES

1. W. Leemans, "Progress in Laser Driven Accelerator R&D," in these Proceedings.
2. N.E. Andreev, *et al.*, Phys. Rev. Spec. Topics – Accel. Beams **6**, 041301 (2003).
3. W. D. Kimura, *et al.*, Phys. Rev. Lett. **92**, 054801 (2004).
4. I. V. Pogorelsky, *et al.*, Phys. Rev. ST Accel. Beams **3**, 090702 (2000).
5. I. V. Pogorelsky, *et al.*, Appl. Phys. Lett. **83**, 3459 (2003).
6. W. D. Kimura, *et al.*, "Pseudo-Resonant Laser Wakefield Acceleration Driven by 10.6 μm Laser Light," submitted to IEEE Trans. Plasma Phys. for publication in special ICOPS'04 issue in Feb. 2005.
7. S. C. Gottschalk, D. H. Dowell, W. D. Kimura, in 2001 IEEE Part. Accel. Conf. Proceedings, IEEE Cat. No. 01CH37268C, 3218-3220 (2001).
8. D. Kaganovich, *et al.*, Appl. Phys. Lett. **71**, 2925 (1997).
9. A. Butler, D. J. Spencer, and S. M. Hooker, Phys. Rev. Lett. **89**, 185003 (2002).
10. C. E. Clayton, C. Joshi, D. Darrow, and D. Umstadter, Phys. Rev. Lett. **54**, 2343 (1985).
11. C. E. Clayton, *et al.*, Phys. Rev. Lett. **70**, 37 (1993).
12. F. Amiranoff, et al., Phys. Rev. Lett. **68**, 3710 (1992).
13. A. Ting, *et al.*, Phys. Rev. Lett. **77**, 5377 (1996).
14. C. V. Filip, *et al.*, Rev. Sci. Inst. **74**, 3576 (2003).
15. V. Yakimenko, *et al.*, Phys. Rev. Lett. **91**, 014802 (2003).