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LASER AND PLASMA ACCELERATOR WORKSHOP

Laser Ionized Preformed Plasma at SLAC

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Abstract. The Facility for Advanced Accelerator and Experimental Tests (FACET) at SLAC installed a 10-TW Ti:Sapphire laser system for pre-ionized plasma wakefield acceleration experiments. High energy (500 mJ), short (50 fs) pulses of 800-nm laser light at 1 Hz are used at the FACET experimental area to produce a plasma column. The laser pulses are stretched to 250 fs before injection into a vapor cell, where the laser is focused by an axicon lens to form the appropriate plasma column that can be sustained over the desired plasma radius and length. A 20-GeV electron bunch interacts with this preformed plasma to generate a non-linear wakefield, thus accelerating a trailing witness bunch with gradients on the order of a few GV/m. The experimental setup and methods for producing the pre-ionized plasma for plasma wakefield acceleration (PWFA) experiments performed at FACET are described.

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1. Introduction

The Facility for Advanced Accelerator and Experimental Tests (FACET) at the SLAC National Accelerator Laboratory has operated as a National User Facility since 2011. It supports a broad user program in accelerator science, materials science, and other fields of research. The multi-GeV Plasma Wakefield Acceleration Experiments (known as E-200) form the core of the FACET program to demonstrate a single-stage plasma-based accelerator for electrons and positrons. The main goal is to develop a plasma module with beam parameters and energy gain at the level required for novel radiation sources and future linear colliders[1]. The potential applications for plasma wakefield accelerator (PWFA) include Free Electron Laser (FEL) energy doublers and plasma afterburners for a linear collider or a future Higgs factory.

For next generation PWFA experiments, long, uniform, high-density ($> 10^{16}$ e^{-}/cm^{3}) plasmas are required to produce a large energy gain, on the order of tens of GeV. Best performance is achieved when the plasma radius is greater than the blow-out radius. The blow-out radius is on the order of the plasma electron skin depth c/ω_{pe} or about 17μm for the above density. In the SLAC linac, the FACET electron beam is accelerated to 20 GeV with a charge of 3 nC. In E-200 PWFA experiments, a plasma is formed in a heat-pipe oven[2] filled with alkali metal vapor (Li, Rb or Cs). Lithium is utilized as the plasma source due to its relatively low ionization potential (5.4 eV) while also avoiding secondary ionization due to its higher second electron ionization threshold (75.6 eV). As a result, the plasma density reached through field ionization is expected to be equal to the lithium atomic vapor density.

In a beam-driven PWFA, head erosion resulting from a finite beam emittance limits the maximum energy gain[3]. The head of the electron beam is not guided until a plasma is formed; hence a preformed plasma will mitigate the head erosion problem. With a pre-ionized plasma source, energy can be effectively transferred from the beam to the wake. Moreover, in two-bunch PWFA experiments at FACET, the space charge field of the bunch produced for FACET cannot ionize the Li vapor over the required meter-scale distance. Therefore, a laser ionization scheme using axicon focusing has been developed to turn Li vapor into a preformed meter-scale homogenous plasma[4]. The laser ionized plasma electron density drops by a factor of two in approximately 1.5 ns, and thus needs to be synchronized with the electron bunch and controlled to ~100 ps or better to avoid plasma recombination before the arrival of the e-beam.

Full ionization of lithium demands maintaining a high laser intensity larger than ($\sim 4 \times 10^{12}$ Watts/cm^{2}) over the desired plasma radius ($\sim$ 1 mm) and length ($\sim$ 1.5 m). The minimum laser energy required depends on the ionization potential, density, and the volume of the vapor to be ionized. To make a 1.5 m long lithium plasma with a diameter of 1 mm and a density of $\sim 5 \times 10^{16}$ e^{-}/cm^{3}, the minimum laser energy is about 200 mJ, corresponding to a minimum peak power of 4 TW for a 50-fs (FWHM) laser pulse.

The E-200 experiments are the first to utilize the FACET laser to generate a preformed plasma in June and December of 2013. This paper describes plasma formation with the 10-TW FACET laser system and the setup for the first experiments, in which laser pulses were compressed to 250 fs, injected into a vapor cell, and focused by an axicon lens to form the plasma. The interaction of the 20-GeV FACET electron beam with this preformed plasma leads to acceleration in the wakefield with gradients on the order of a few GeV/m.

2. The Laser System

The 10-TW chirped pulse amplified Ti:Sapphire laser system was conceived, designed, installed and commissioned in less than seven months. The laser system consists of the front end laser, preamplifier, main amplifier, 28-meter-long laser transport line, compressor, and timing system, as described in the following subsections. It enhances the FACET experimental program and enables a number of experiments utilizing a high-energy and/or high peak-power laser with the FACET electron or positron beam.

2.1. The Front End Laser System, Preamplifier, and Main Amplifier

The laser oscillator is a Vitara-T from Coherent Inc., which operates at a center wavelength of 800 nm with a spectral bandwidth of 60 nm FWHM and a mode-locking rate of 68 MHz. The oscillator is locked at the 8th harmonic of the 476-MHz radiofrequency (RF) drive of the SLAC linac Main Drive Line (MDL), allowing control of the timing of the laser relative to the FACET beam. The oscillator is followed by a commercial regenerative amplifier (Regen) from Coherent Inc (Legend Elite HE USP), where part of the laser is taken before its compressor to seed the amplifiers.

The Regen is operating at 120 Hz, the maximum repetition rate of the SLAC Linac, and is triggered by the linac timing system. The Regen output laser repetition rate is divided down to 1 or 10 Hz to match the FACET beam repetition rate. One millijoule of the Legend uncompressed output energy is used for the power amplifiers designed at SLAC. The first stage is an intermediate 4 pass preamplifier that delivers 30 mJ to the main amplifier. It is pumped by a Quantel CFR200 YAG flash lamp laser that can produce 130 mJ at 532 nm and 10 Hz. It uses an 8 mm diameter 15 mm long Ti:Sapphire rod that is water cooled.

A 4-pass main amplifier brings the energy up to 1 J using two Thales SAGA YAG lasers that each produces 1.8 J at 532 nm and 10 Hz. In this case, the Ti:Sapphire crystal is a 20-mm-diameter 20-mm-long water-cooled rod. The entire laser amplifier system fits onto two optical tables located in the FACET laser room, at ground level next to the Klystron Gallery at Sector 20 of the SLAC Linac (2 km from the start of the 3-km linac). The laser system layout is illustrated in Fig. 1.

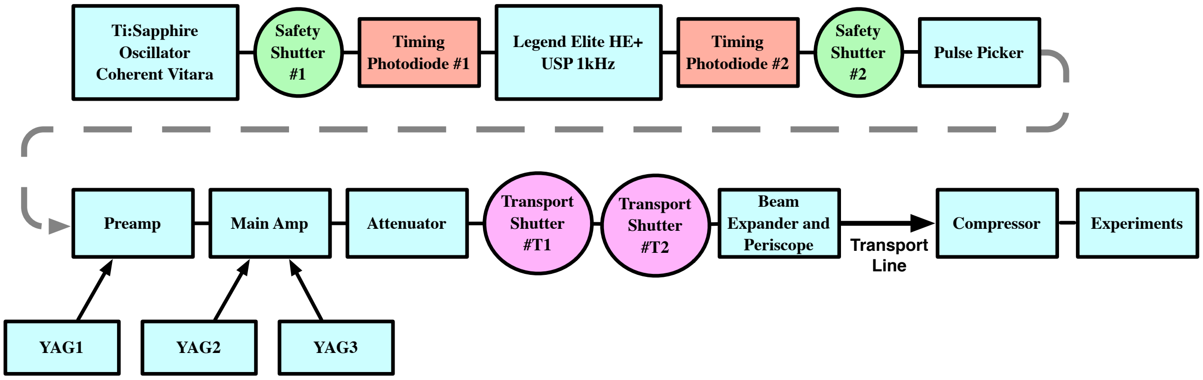

Figure 1: A diagram of the laser system.

2.2. Laser Synchronization to the e-Beam

The laser needs to be synchronized with the FACET e-beam for PWFA experiments. A photodiode is used to time the laser to the electron beam within 1 ns. The photodiode is placed at a location on the beam line where both the laser signal and optical transition radiation from the electron bunch can be detected. The timing of the laser is adjusted to place the laser pulse about 1 ns before the arrival of the electron beam. The resolution is limited to 1 ns by the photodiode, long cables, and the oscilloscope. Fine timing to ensure the e-beam arrives before the plasma density decays is done with the plasma acceleration signal itself. The laser timing is stepped in 100 ps increments until there is no evidence of beam-plasma interaction on downstream beam imaging diagnostics, and thus the laser pulse is known to arrive after the electrons. Then the laser timing is moved back $<$ 100 ps before the e-beam.

The FACET laser is locked by an RF synchronization and phase stabilization system developed at SLAC. The timing system makes use of custom modular components designed to fit into a simple off-the-shelf chassis, thereby enabling flexible controls system requirements. The locking system consists of an RF downmixer, a phase detector, a frequency multiplier, a phase shifter and controller, a feedback unit, and a trigger re-synchronizer, as illustrated in the block diagram of Fig. 2. The RF system locks the 56th harmonic (3808 MHz) of the 68 MHz mode-locked oscillator to the 8th harmonic of the 476 MHz accelerator master reference source. The laser oscillator pulse time relative to triggers is controlled by adjusting the cavity length of the Vitara oscillator via the Phase Shifter to delay the oscillator relative to the accelerator RF system. The laser jitter has been measured to 70 fs or better in a bandwidth from 10 Hz to 10 kHz. Long-term drift over days has been estimated at $<$ 2 ps.

2.3. Laser Transport

The laser pulses are transported from the laser room to the FACET experimental area located in the linac tunnel, 10 m below ground. The transport tubes pass through the wall from the laser lab to the Klystron Gallery, along and across the Klystron

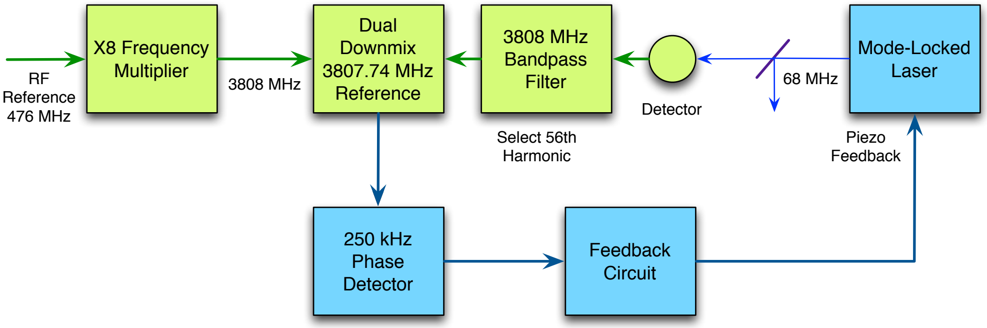

Figure 2: A block diagram for the laser locking system.

Gallery and down through a penetration to the linac tunnel. To avoid beam quality degradation along the long transport beam line due to the high peak power and thus possible optics damage, the uncompressed laser is transported through a system of five evacuated stainless steel tubes with a diameter of 6 inches (150 mm).

The main amplifier output plane is relay-imaged to the entrance plane of the compressor. There are two imaging stages: the magnification of the first stage is 3:1 and that of the second is 1:1. Each stage of the imaging system produces a focus in the laser transport line. Therefore, it is essential to keep the transport tubes under vacuum to avoid air breakdown at the focal points that would cause laser shape and phase instabilities. The 28-meter-long transport line is evacuated to a vacuum pressure of 10^{-5} Torr. A vacuum also avoids laser pointing instabilities from air convection driven by uncontrolled temperature changes in the Klystron Gallery. The output of the imaging system preserves the collimated input laser qualities.

There are five dielectric turning mirrors in the transport line, and each is controlled remotely to align the laser. To aid the alignment, a network camera is installed behind each of the turning mirrors. Each camera is placed outside the vacuum and allows observation through a viewport of the laser spot on a thin glass diffuser mounted directly behind the dielectric transport mirror.

2.4. Laser Compressor

The laser pulses are compressed using a grating compressor in a vacuum chamber at the end of the transport line. The compressor chamber is adjacent to the FACET beamline.

The stretched pulses coming out of the main amplifier have a spectral bandwidth of 24 nm FWHM and can be compressed down to less than 50 fs FWHM. The compressor is a two-grating compressor with a vertical retro-reflector. Because of the high peak power reached after compression (up to 10 TW), the compressor chamber has to be under vacuum. To avoid self-phase modulation when passing through the optics in the Interaction Point (IP) chamber, the compressor (separation of the gratings) is detuned to increase the pulse length to ~ 250 fs. At the output of the chamber, an anti-reflective coated window isolates the vacuum between the compressor and the FACET beam line.

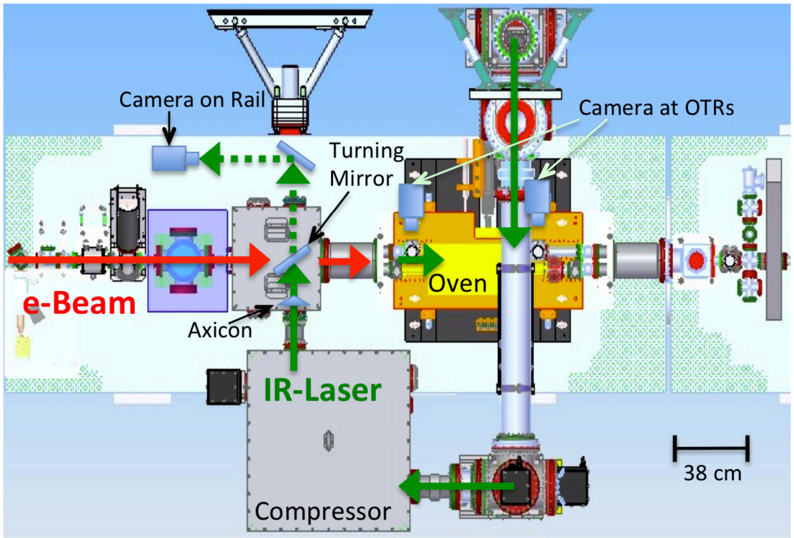

Figure 3: A top view of the laser transported to the experiment. The turning mirror and axicon lens are not drawn to scale. The dashed path is used for laser diagnostics when the turning mirror is extracted to allow the laser pulses to be brought outside of the chamber for equivalent plane imaging.

The total transmission efficiency of the laser transport line and compressor has been measured to be about 60%.

2.5. Integration of Particle and Laser Beams

The laser pulses leaving the compressor are sent into a chamber on the FACET beam line. Figure 3 shows a top view of the beam path at the location of the PWFA experiment and the two optics inside this chamber. The compressed laser pulses pass through a 2″ (50 mm) diameter, 1.5° axicon lens with a mask of 3/8″ (9.5 mm) diameter. The turning mirror is gold-plated and has a 4-mm diameter central hole to pass the electron beam, thus allowing the laser pulses to travel collinearly with the electron beam.

Laser pulses injected into the vapor cell are focused by the axicon lens to form the plasma. A conventional spherical lens cannot produce a uniform high-intensity profile over a meter-scale distance but an axicon lens can[5]. Figure 4 illustrates the laser ray tracing and the focal region where laser ionization leads to plasma formation. Another advantage of using the axicon lens is that it prevents damage from focused high-intensity laser pulses. After the line focus, the laser diverges and is dumped onto a glass neutral density filter, rather than onto the beryllium vacuum window used to isolate experimental vacuum region from the linac vacuum.

The properties of the plasma column depend on the parameters of the axicon lens and of the laser beam. The geometry of the lens determines the plasma length. Using an axicon lens with a smaller apex angle increases the plasma length by the ratio of the angles of the lenses. For example, reducing the axicon angle from a 2° to 0.5° lengthens

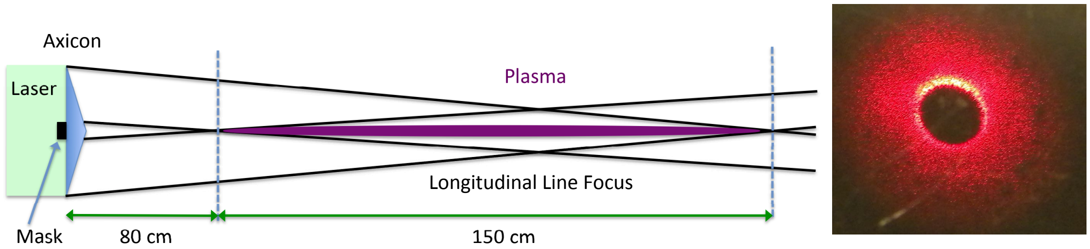

Figure 4: Laser ray tracing (left, not drawn to scale) and picture of laser dump after line focus (right).

the plasma from 40 cm to 160 cm, but requires proportionally more laser energy. The radius of the axicon lens and the mask size control the ionization length, since they determine where the focal region begins and ends, as also illustrated in Fig. 4. The mask blocks the central laser rays that define the start of the line focus. Adjusting the outer diameter of the laser light determines the location of the end of the line focus. The laser energy delivered at the IP was about 140 mJ for the first experiments in June 2013; and it was 480 mJ in December 2013 after a laser energy upgrade.

The E-200 experiments also require spatial overlap of the laser and the electron beam. A phosphor screen is mounted on the back of the turning mirror in Fig. 3 to aid in beam positioning. To align the electron beam and the laser along the axis of the oven, a motorized translation stage moves the oven to the side and substitutes a bypass line with two optical transition radiation (OTR) targets; they can be inserted approximately at the locations corresponding to the ends of the plasma. A 500-μm-thick titanium disc generated OTR from the electrons and also reflected light from the laser pulse; both profiles are measured by a CCD camera at each OTR location. The laser pulses propagate through the axicon lens and form a Bessel transverse intensity profile when aligned as expected.

3. Results

In the E-200 experiments with the 1.5° axicon lens, 480 mJ, 42 mm diameter laser pulses are stretched to 250 fs. The beam-plasma interaction is insensitive over the pulse range scanned. The laser-ionized plasma column has a diameter about 1.2 mm, measured by translating the turning mirror and hence the laser pulse parallel while observing the accelerated feature of the beam.

After the laser and axicon lens are aligned, the turning mirror is extracted to allow the laser pulses to be brought outside of the chamber for equivalent plane imaging. A CCD camera on a rail (Fig. 3) is positioned at the equivalent locations of the entrance and exit of the oven. The transverse laser profiles captured by the camera shown in Fig. 5 confirm that a Bessel profile is maintained to the end of the oven. More importantly, the laser intensity is high enough ($> 4 \times 10^{12}$ W/cm^2) to fully ionize Li vapor.

After the turning mirror is inserted, another CCD camera captures an image of a

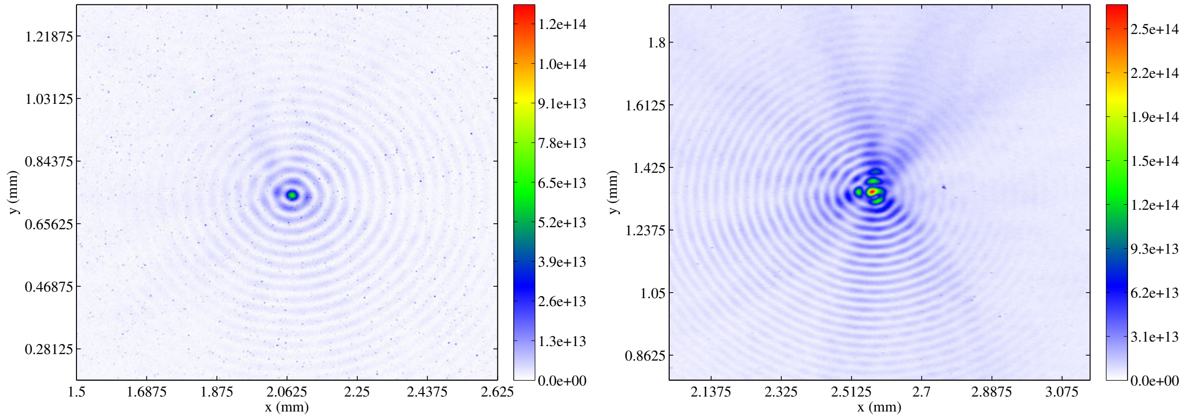

Figure 5: Images for laser transverse profile: at the entrance of the oven (left), and the exit of the oven (right). The color bars indicate laser intensities in unit of W/cm^2 and clearly showed that both profiles contain the required intensity $> 4 \times 10^{12}$ W/cm^2 for full ionization of Li.

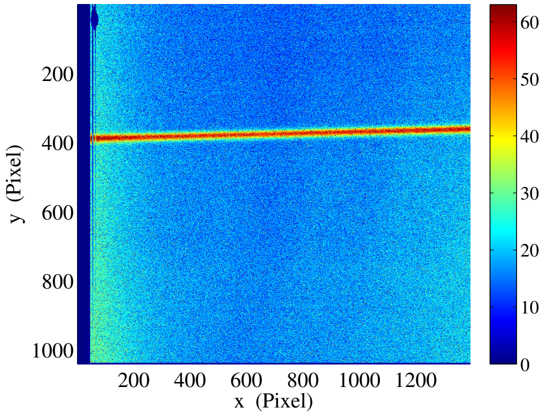

Figure 6: Image taken at the beginning of the axicon focal point shows a laser ionization filament in the argon gas.

laser ionization filament (Fig. 6) through the viewport in the oven bypass line where only argon gas is present. It shows that the laser was able to ionize argon. The compressed electron beam created also strong enough field to ionize the argon[6] where similar ionization filament was observed. When the laser and electron beam are spatially aligned, the two filaments would overlap.

The latest E-200 experiments observed a clear difference between lithium plasmas ionized by the electron beam and those generated by the laser[7]. More energy gain and more participating charge were observed in the laser-ionized plasma. This was a good indication that the electron beam was going through a laser ionized lithium plasma. In the two-bunch experiments, the witness bunch was accelerated due to a larger beam-plasma interaction in a laser-ionized plasma, whereas only decelerated particles were observed in a beam-ionized plasma due to reduced beam fields.

The laser intensity required for full ionization of lithium, hydrogen, and argon is $\sim 4 \times 10^{12}$ W/cm^2, $\sim 1 \times 10^{14}$ W/cm^2, and $\sim 1.7 \times 10^{14}$ W/cm^2, respectively. Since the ionizations of argon and lithium were observed, one can expect that hydrogen can also be ionized. This shows that PWFA experiments performed with hydrogen gas are feasible. There is only one ionization for hydrogen, and thus experiments can avoid the potential problem of secondary excitation in the case of lithium and argon, for example. The ease of bringing hydrogen gas to and from the experimental chamber and lack of residual or mixed waste are some of the added advantages that make it an attractive choice for future PWFA experiments.

4. Conclusion and Outlook

A laser system for the first laser-ionized plasma wakefield acceleration experiments has been successfully commissioned and operated at FACET. The use of an axicon lens was demonstrated to focus a laser that ionizes the vapor to form a 40-cm plasma column suitable for PWFA. The E-200 experiments performed at FACET used this technique for plasma formation and yielded good physics results[7]. These experiments used lithium because it is easy to ionize. However, a laser intensity of $> 10^{14}$ W/cm^2 is sufficient to ionize a hydrogen-filled gas cell as well. Therefore, future PWFA experiments can potentially use hydrogen.

Most recently, good quality axicon profiles have been created over a 1.5 m distance. In the next E-200 experimental run, the 40 cm long Li oven will be replaced with one of a 1.5 m length. A smaller angle axicon lens will be used for plasma formation over the increased length. The expectation is that these changes to the FACET PWFA experiments will result in energy gain of more than 10 GeV.

Acknowledgments

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