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RESULTS FROM PLASMA WAKEFIELD EXPERIMENTS AT FACET*

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Abstract

We report initial results of the Plasma Wakefield Acceleration (PWFA) Experiments performed at FACET - Facility for Advanced aCcelertor Experimental Tests at SLAC National Accelerator Laboratory. At FACET a 23 GeV electron beam with 1.8×10^{10} electrons is compressed to 20μm longitudinally and focused down to 10μm $\times 10\mu$m transverse spot size for user driven experiments. Construction of the FACET facility completed in May 2011 with a first run of user assisted commissioning throughout the summer. The first PWFA experiments will use single electron bunches combined with a high density lithium plasma to produce accelerating gradients $>$ 10 GeV/m benchmarking the FACET beam and the newly installed experimental hardware. Future plans for further study of plasma wakefield acceleration will be reviewed.

FACET BEAM COMMISSIONING

FACET, the Facility for Advanced aCcelertor Experimental Tests, was first commissioned in June 2011. The beam parameters archieved to date are presented in Table 1, as compared to their nominal design values. The beam is focused to an interaction point (IP) for plasma wakefield acceleration (PWFA) experiments, one of the major programs at FACET. The goal is to demonstrate high-gradient acceleration with low energy spread and high efficiency that can apply to future advanced accelerators and/or colliders.

To help with beam tuning, beam diagnostics techniques are developed and implemented at FACET with details provided in [1]. The beam trajectory and current are measured by beam position monitors (BPM) and Toroids while the bunch length and transverse spot size are measured by bunch length monitor and optical transition radiation (OTR) profile monitors, respectively. The OTR profile monitors (USOTR and DSOTR) are located upstream and downstream of the PWFA experiments to provide measurements of the beam size before and after the beam-plasma interaction. An example of the beam spot size with Gaussian fits to its profile projections is shown in Fig. 1. A chicane in a plane of large horizontal dispersion deflects the beam vertically. X-rays from the resulting stripe of synchrotron radiation are intercepted by an off axis scintillator crystal made of Cerium doped Yttrium Aluminum Garnet (YAG:Ce). The X-ray intensity is proportional to the beam intensity giving a measurement of the beam energy spectrum. Figure 2 is an image captured by a UNIQ CCD camera with 1392×1040 active pixels, and the energy spread is measured to be about 1%.

Table 1: FACET beam requirements and corresponding plasma parameters at the interaction point (IP) for PWFA experiments in single bunch operation.

Parameter	**Design**	**Achieved**
Particle Type	e^- or e^+	e^-
Beam Energy	23 GeV	∼20 GeV
Energy Spread (r.m.s.)	1.5%	∼1%
Dispersion (η)	$< 10^{-5}$ m	≥ 0.014 m
Charge per Pulse	3.2 nC	3 nC
Bunch Length (σ_z)	20μm	$> 70\mu$m
Beam Size ($\sigma_{x,y}$)	13μm, 5μm	$> 58\mu$m, $> 40\mu$m
Peak Current	22 kA	5 kA
Repetition Rate	$1 - 30$ Hz	$1 - 10$ Hz
Plasma Type	Lithium or Cesium	Lithium
Vapor Density (cm^{-3})	$(0.1 - 3) \times 10^{17}$	$(0.5 - 2.5) \times 10^{17}$
Plasma Length	$20 - 100$ cm	$30 - 40$ cm

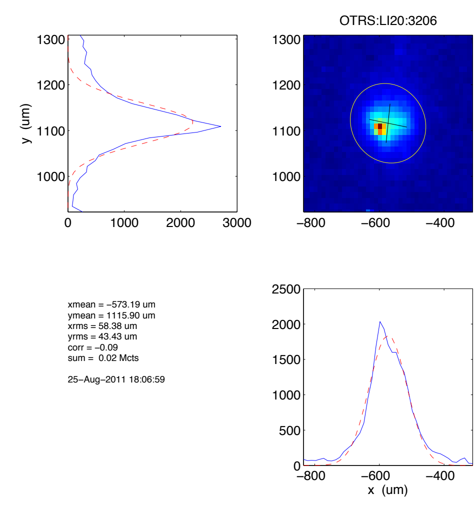

Figure 1: An image from the downstream OTR profile monitor provides a measurement of the transverse beam size $\sigma_x = 58.38\mu$m and $\sigma_y = 43.43\mu$m.

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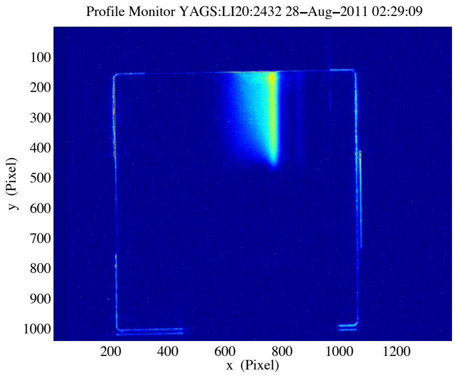

Figure 2: An image from the x-ray based energy spectrometer provides a measurement of energy spread.

With the relevant beam diagnostics in place, the first PWFA experiments will use single electron bunches combined with a high density lithium plasma to benchmark the FACET beam and the newly installed experimental hardware. The first goal is to demonstrate energy doubling similar to the previous experiments performed with the Final Focus Test Beam (FFTB) [2][3] before exploring further plasma wakefield accelerations in later phases of the experimental program at FACET.

EXPERIMENTAL SETUP

The experimental setup for the PWFA experiments is located on the IP optical table in Sector 20 at FACET. An elevation view of the oven on the table is shown in Fig. 3.

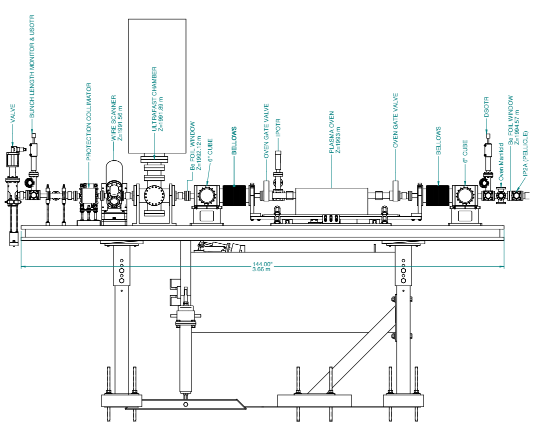

Figure 3: An elevation view of the experimental setup where the beam incident from left to right.

Field ionized lithium vapor is the plasma source for the first PWFA experiments at FACET. The lithium vapor is produced in a heat pipe oven consisting of a wick, a lithium tube, two heaters (30cm and 15cm long), five thermocouples, and thermal insulating bricks. The five thermocouples (TC1, TC2, TC3, TC4, and TC5) inside the oven provide measurements of the temperature along the oven for a profile of plasma column. The heat-pipe oven is filled with helium buffer gas to constrain lithium vapor to a hot zone inside oven. Water jackets are mounted to each end of the oven to provide cooling to the helium. Two beryllium windows isolate the helium gas from the main beamline vacuum, with one on each side of the beam pipe. The helium pressure controls the lithium vapor pressure whose density can be calculated from the following equation:

$$n[cm^{-3}] = \frac{9.66 \times 10^{18} \times P}{T \times 10^{3}} \times 10^{-17}, \qquad (1)$$

where T is the temperature in kilo Kelvin, P is the vapor pressure in Torr and n is the plasma density in units of $10^{17}\mathrm{cm}^{-3}$.

RESULTS OF FIRST COMMISSIONING

The PWFA experimental hardware was commissioned with the FACET beam on August 26^{th}, 2011. The lithium density profile is studied in a teststand setup in UCLA as shown in Figure 4. Similar results were obtained for the oven parameters after the Li oven was installed to the FACET beamline and heated up to $\sim$ 900°C, as illustrated in Table 2. The vapor density is $\sim 1 \times 10^{17}$ cm^{-3}. A number of profiles are available for various plasma densities and lengths. The set of operating condition was chosen to have long interaction length and to be compatible with the beam size of $\sim$60 microns.

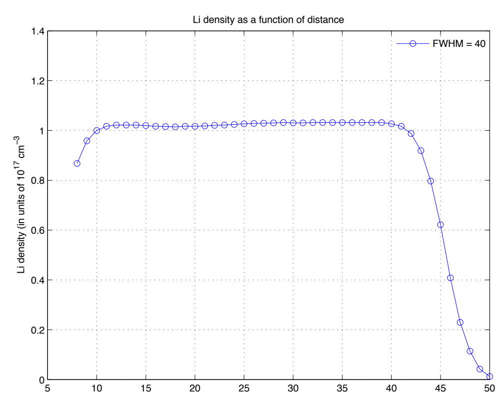

Figure 4: The lithium density as a function of distance measured from the edge of the heater. Note: beam travels from right to left in the x-axis.

Images (such as the one in Fig. 5) from the Cerenkov light based energy spectrometer [1] were used to verify any energy changes resulted from the plasma wake. No evidence of acceleration or decceleration is observed due to the longer bunch and larger beam size than expected in this first commissioning run. Scans of linac phase were performed to vary compression and beam waist location, but no beam-plasma interaction is observed. In order to ionize Li to create long, uniform, and high density plasma, the following criterion needs to be satisfied:

$$\sigma_z[\mu m]\sigma_r[\mu m] \leq \frac{1}{2}\frac{11.5Q[pC]}{\varepsilon_i^{1.73}[eV]}. \qquad (2)$$

Table 2: Measurements of Plasma Oven Parameters

Parameter	Teststand	FACET
Buffer Gas Pressure	12.61 Torr	12.65 Torr
Heater Power	739 W	720 W
Voltage	120 V	120 V
Current	6.16 A	6 A
TC1	910.4°C	907.5°C
TC2	911.7°C	909.1°C
TC3	912.0°C	910.1°C
TC4	911.9°C	910.6°C
TC5	907.0°C	902.6°C

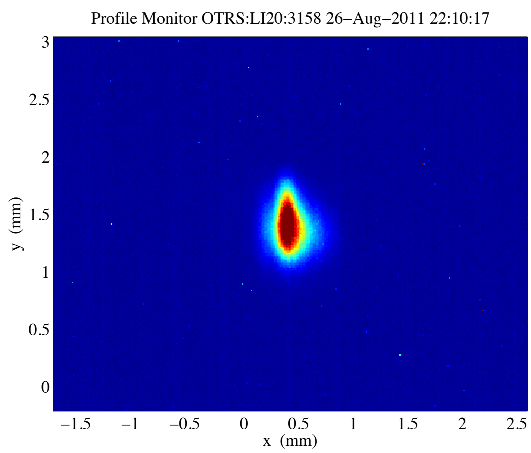

Figure 5: An image from the Cerenkov light based energy spectrometer. Any energy loss will show up toward the right side of the spectrum and energy gain will be on the left. No energy gain or loss is observed.

Simple calculations suggest that it requires $\sigma_r[\mu m]\sigma_z[\mu m] \leq 1000$ to reach ionization and to drive the wakefield for $Q = 3$ nC and $\varepsilon_{i,Li} = 5.39$ eV. Therefore, with the beam parameter achieved in Table 1, no ionization is expected to occur yet. Plasma particle-in-cell (PIC) simulations (Fig. 6) show a few options for ionization to occur. One way is to have the beam size and bunch length smaller than 40μm and 20μm or vice versa since the field needs to be greater than 6 GV/m to ionize Li. In order to perform many of the planned experiments the FACET beam parameters must be close to the design parameters in Table 1.

SUMMARY AND PLANS

The experimental hardware and operation of the plasma heat-pipe oven have been successfully commissioned. Plasma wakefield acceleration was not observed because the electron bunch density was insufficient to ionize the lithium vapor. The remaining commissioning time in summer 2011 will be dedicated to delivering the FACET design parameters for the experimental programs which will begin in early 2012. PWFA experiments require the shorter bunches and smaller transverse sizes to create the plasma and drive large amplitude wakefields. Low emittance and high energy will minimize head erosion which was found to be a limiting factor in acceleration distance and energy gain. We will run the PWFA experiments with the design single bunch conditions in early 2012.

Future PWFA experiments at FACET are discussed in [5][6] and include drive and witness bunch production for high energy beam manipulation, ramped bunch to optimize tranformer ratio, field-ionized cesium plasma, pre-ionized plasmas, positron acceleration, etc.. We will install a notch collimator for two-bunch operation as well as new beam diagnostics such as the X-band TCAV [7] to resolve the two bunches. With these new instruments and desired beam parameters in place next year, we will be able to complete the studies of plasma wakefield acceleration in the next few years.

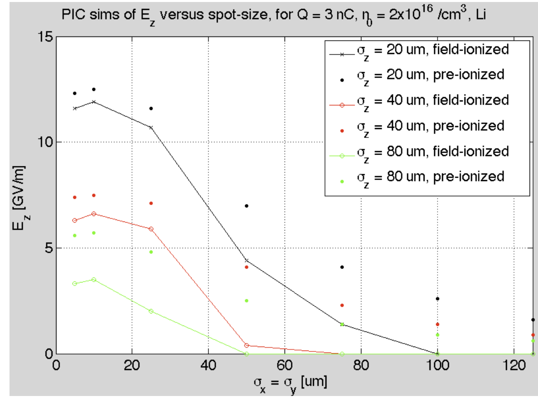

Figure 6: Wakefield amplitude vs beam spot size from PIC simulations for field-ionized and pre-ionized cases.

ACKNOWLEDGEMENT

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