LATEST PLASMA WAKEFIELD ACCELERATION RESULTS FROM THE FACET PROJECT *

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Abstract

SLAC's new Facility for Advanced Accelerator Experimental Tests (FACET) had its second user run in April–June, 2013. Several new milestones were reached during this run, including the achievement of beam driven plasma wakefield acceleration of a discrete witness bunch for the first time, and energy doubling in a noble gas plasma source. The FACET beam is a 20 GeV electron bunch with a charge of 3.2 nC that can be compressed and focused to a size of $20\,\mu\mathrm{m} \times 20\,\mu\mathrm{m} \times 20\,\mu\mathrm{m}$ rms. To create the two-bunch, drive/witness beam structure, a chirped and over-compressed beam was dispersed horizontally in a chicane and a bite was taken from its middle with a tantalum finger collimator, corresponding to a longitudinal notching of the beam due to the head-tail energy correlation. A new 10 terawatt Ti:Sapphire laser was commissioned and used during this run to pre-ionize the plasma source in order to increase the efficiency of energy transfer from the beam to the wake. Ultimately, a witness beam of hundreds of pC in charge was accelerated by a drive beam of similar charge in a pre-formed lithium plasma with a density of $5 \times 10^{16}\,\mathrm{cm}^{-3}$, experiencing gradients reaching several GV/m in magnitude.

INTRODUCTION

The field of plasma wakefield acceleration (PWFA) has long been motivated by a need for new technologies that can provide higher accelerating gradients than conventional microwave powered metallic structures in order to make multi-TeV energies and beyond accessible to future generations of linear colliders. A conceptual design was recently developed for a plasma wakefield powered linear collider with a center of mass energy of 1 TeV that is extendible to the multi-TeV regime [1]. The main linac consists of modular plasma accelerator stages into each of which a fresh electron beam is injected to drive a wake over a meter-scale plasma source to provide an energy gain of 25 GeV per stage to the primary collider beam. Besides the high average gradient of such a collider design, the wall-plug efficiency is another very attractive feature, estimated to be well over ten percent. Current research efforts in beam driven plasma wakefield acceleration are largely devoted to creating a single plasma accelerator stage akin to what would be used in a collider, first as a proof-of-concept, and then as a test bed for studying the complex dynamics involved in the beam-plasma interaction.

In order to achieve accelerating gradients on the order of 10 GV/m with a GeV-scale drive beam, plasma densities on the order of $10^{17}\,\mathrm{cm}^{-3}$ are required. This sets the plasma wavelength, and thus the scale of the longitudinal spacing between the drive and witness bunch, to distances on the order of $150\,\mu\mathrm{m}$ (= 500 fs temporal spacing). The drive beam must have a density that is > 1.8 times the background plasma density in order to produce a nonlinear blowout [2], which sets the scale for the peak current to the kA scale with a transverse size on the order of a few tens of microns, which is ultimately focused down to several microns by the strong fields generated in the plasma. FACET is the only facility in the world that can meet these demanding beam requirements, as well as produce a witness beam of several hundred pC or more to sample the large magnitude fields.

Previous electron-beam-driven plasma wakefield acceleration experiments that were performed at SLAC's Final Focus Test Beam (FFTB) facility have shown that the PWFA mechanism can produce accelerating gradients in excess of 50 GV/m by observing the energy gain in the low charge tail of the wake-driving electron beam. The tail trailing behind the head of the beam sampled the accelerating phase of the plasma wake, finally doubling the energy of the 42 GeV electrons [3]. What remained to be demonstrated, however, was the acceleration of a coherent beam of electrons, rather than individual particles. FFTB lacked the capability to produce a distinct drive and witness electron beam with the required temporal spacing, on the order of 500 fs from center to center. Several years after the FFTB was decommissioned, FACET was designed and constructed with this goal in mind, leveraging the knowledge gained from the FFTB experiments and the linac infrastructure available at SLAC [4]. Now, FACET has finally been able to fulfill the experimental requirements needed to study the acceleration of actual beams via

* Work supported by DOE contracts DE-AC02-76SF00515, DE-AC02-7600515, DE-FG02-92-ER40727, and NSF contract PHY-0936266.
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ISBN 978-3-95450-138-0

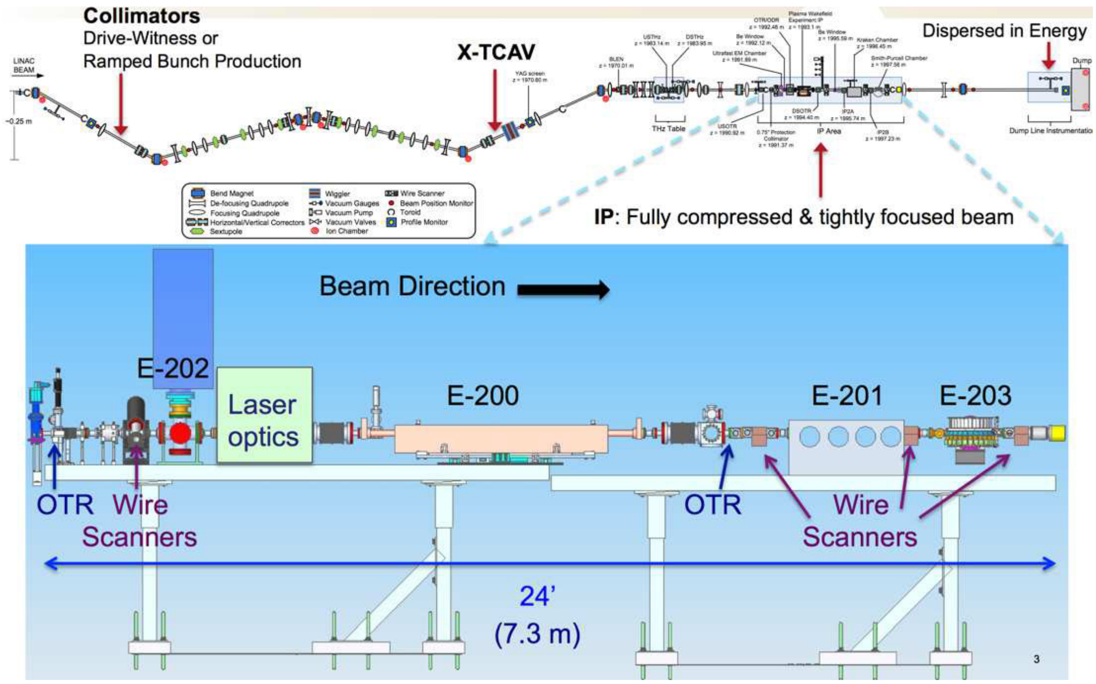

Figure 1: Top: The FACET beamline. Bottom: Detail of experimental area. The text “E200” marks the location of the plasma source.

beam-driven plasma wakefields, and has also continued to explore new dynamical regimes of plasma wakefield acceleration.

ELECTRON BEAM

The data presented here were taken by the E200 experiment from June 2013 during the second User Run of FACET. The first two kilometers of the main SLAC linac were used to provide a 20.35 GeV electron beam with a charge of up to 3.2 nC. In the final 100 m of the beamline a chicane provided the final compression of the beam, with a minimal bunch length of 20 μm rms, corresponding to a peak current of 20 kA. A final focusing section focused the beam down to the desired transverse dimensions at the entrance to the plasma source, approximately 20 μm $\times$ 20 μm Gaussian rms in x and y. An imaging spectrometer transported the beam from the exit of the plasma source to the final diagnostic area and ultimately to the beam dump. Figure 1 shows a schematic view of the final 100 m of the FACET beamline with a detail of the experimental area where the plasma source is located.

The two-bunch beam structure was generated by bisecting a linearly chirped, horizontally dispersed beam using a tantalum finger collimator. Jaw collimators were also employed to remove the spectral tails at the horizontal extrema, where the energy spread was uncorrelated with longitudinal position. The beam was then over-compressed in the chicane, placing one portion of the remaining beam in front of the other with the desired spacing optimized for PWFA experiments.

Two diagnostics were used to measure the longitudinal phase space of the beam after collimation. The first was a wiggler spectrometer that measured the X-ray intensity profile generated by the beam in a low field triplet of wiggler magnets. The wiggler spectrometer is located at a point in the chicane with the same large magnitude of dispersion as the point where the beam is notched by the tantalum collimator further upstream, thus it provided direct feedback on how the beam is being notched in space and in energy on a shot-by-shot basis.

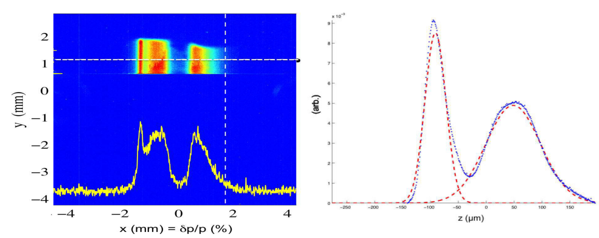

Figure 2: Specral profile of the elecron beam (left) and longidutinal profile of the electron beam (right) after notch collimation and before entering the plasma source.

The second diagnostic used to measure the longitudinal phase space of the beam was an X-band transverse deflecting structure. This device streaked the beam itself onto an optical transition radiation screen located near the plasma source, roughly 25 m downstream. The streaking process precludes the beam from having an optimal profile for PWFA, however, so this method of measuring the longitudinal profile is limited to statistical studies of the beam profile used in the experiment. Figure 2 shows a typ-

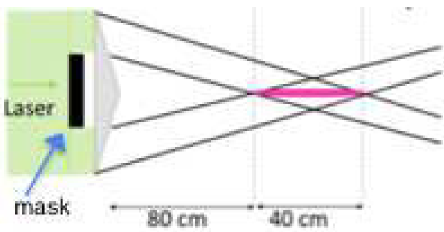

Figure 3: Schematic depiction of the axicon lens focusing the laser.

ical spectral and longitudinal measurement for a two-bunch beam prior to entering the plasma source for PWFA experiments.

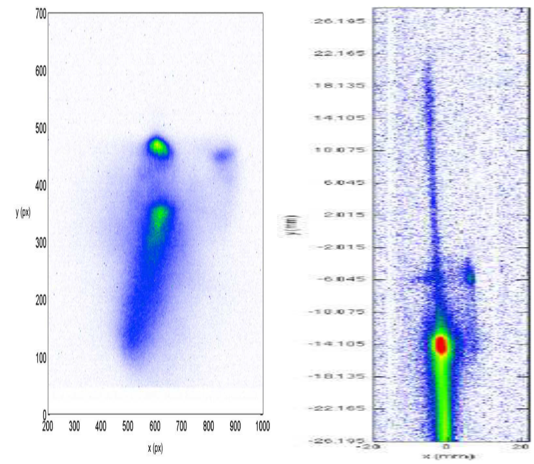

Figure 4: Left: Accelerated witness beam (top feature) with decelerated drive beam (bottom feature) produced in a pre-formed lithium plasma. Right: Energy doubled tail with decelerated beam core produced in self-ionized plasma generated in argon gas. In both plots energy increases with height.

PLASMA SOURCE

The plasma was generated by ionizing a lithium vapor, which was generated inside a heat pipe oven roughly 40 cm in length. A room temperature buffer gas of argon was used to contain the lithium vapor and also completely filled a parallel bypass line, which was able to be inserted into the beamline in lieu of the lithium oven for control measurements. The density and length of the lithium vapor can be controlled by adjusting the heat applied to the oven and the pressure of the buffer gas. The choice of a noble gas for the buffer is motivated by its high ionization threshold, which drastically reduces the likelihood of generating plasma outside of the lithium region.

A new 10 TW, 800 nm Ti:Sapphire laser system was installed and commissioned for the 2013 FACET User Run. The primary purpose of the laser system was to ionize the lithium vapor in the heat pipe oven, generating a wide column of plasma before the arrival of the electron beam. Though it has been shown that if the electron beam is dense enough, it can itself tunnel-ionize the outer shell electrons of a metal vapor and still subsequently drive a non-linear wake [5], using the laser to generate the plasma reduces the demand on the electron beam delivery somewhat. Preforming the plasma also leaves more energy available in the drive beam to be transferred to the plasma wake, which ultimately means a higher efficiency of energy transfer from the drive to the witness beam. Finally, a preformed plasma will also mitigate the head-erosion of the drive beam, allowing for much longer plasma interaction lengths [3, 6].

The laser was focused into the plasma using an axicon lens [7], which focuses the laser toward the central axis at the same convergent angle over all radii. Figure 3 shows a schematic demonstrating the axicon focusing method. This produces a radial intensity distribution that follows a Bessel function of the zeroth order and persists for over a meter of length before the laser diverges away from the axis in a ring shape and is dumped into an annular neutral density filter. A circular mask just before the axicon lens is used to control the start of the line focus, and the diameter of the laser beam determines the end of the line focus.

ACCELERATION OF A WITNESS BEAM

An imaging spectrometer comprising a quadrupole doublet and a 1 m dipole was used to disperse the beam at the experimental dump table while imaging a plane at the exit of the plasma source. The imaging condition only holds for a given (adjustable) energy, however, so portions of the beam above and below the set energy are defocused. CCD cameras were used to image the Cherenkov light produced by the dispersed beam as it traveled through the air from the beam pipe exit window to the dump.

A drive beam with a peak current of 1.2 kA and a witness beam of several hundred pC trailing 126 μm (420 fs) behind it were sent into a pre-formed lithium plasma on the order of $\sim$40 cm in length with a density of $5.0 \times 10^{16}\,\mathrm{cm}^{-3}$. The witness beam was accelerated by a few GeV over this distance, corresponding to average accelerating fields on the order of $\sim$5 GV/m. Portions of the drive beam were decelerated by as much as several GeV, and nearly all of the electrons in the drive beam lost at least some energy, an indication of efficient energy transfer to the wake. Figure 4 shows a typical shot of two-bunch PWFA, where the vertical axis corresponds to energy with higher energy toward the top.

ENERGY DOUBLING IN A NOBLE GAS

The FACET beamline can accommodate many different beam optics profiles, one of which is tailored to provide the highest possible compression of a single bunch. With this configuration in place, it was found that the density of the electron beam could reach values that were high enough to ionize the noble gas buffer medium in the oven bypass line. Further, the beam produced a strong wakefield in the plasma it generated, drastically decelerating the bulk of the

ISBN 978-3-95450-138-0

beam and accelerating the rear tail of the beam to more than double its initial energy. Figure 4 shows the dispersed beam after driving a wake in argon gas over about 20 cm. The estimated longitudinal field strength inside the wake was on the order of $\sim 150\,\mathrm{GV/m}$.

The ability to drive a wake in a noble gas was due to a self-focusing process that the beam underwent as soon as it began to ionize even a small fraction of the argon gas. The wake produced in the low density plasma focused the beam transversely, and as the beam density increased, it ionized a larger fraction of the gas, which in turn led to a higher plasma density and larger focusing forces in the plasma wake. The process continued on in a positive feedback loop like this until eventually reaching a point where the beam could drive a non-linear wake in the blowout regime, after having nearly reached the matching condition for the plasma [8]. This description of the evolution of the beam was supported by simulations in the quasi-static 3D particle-in-cell code QuickPIC [9].

After focusing to its minimum size, on the order of a few microns, the beam could drive a fully non-linear wake, and experienced virtually no head erosion. Thus, it was able to continue to drive the wake over a very long distance, limited by the betatron function of the unfocused head of the beam that provided the ionized plasma medium. The avoidance of the head erosion limitation that is predicted in the literature [10] is particularly interesting because it may loosen the previously presumed high density requirement for an electron beam to drive a self-ionized plasma wake. In addition, a plasma stage made from a room temperature gas is far simpler and cheaper than an alkali metal vapor which must be maintained at hundereds of degrees Celcius. Further, a room temperature gas can have a perfectly flat longitudinal density profile throughout the stage, which is impossible with an alkali metal vapor inside a heat-pipe oven due to the density ramps near the oven boundaries.

SUMMARY AND OUTLOOK

FACET has succeeded in accelerating a distinct witness beam of electrons with multi-$\mathrm{GV/m}$ fields produced in a non-linear plasma wake produced by a high current drive beam in a pre-formed lithium plasma. This is the first experimental demonstration of acceleration of a high energy, high charge beam via beam-driven PWFA. FACET has also demonstrated that through the self-focusing mechanism, an under-dense beam can evolve through interaction with the plasma to achieve densities sufficient to drive a non-linear wake over long distances, even in media with high ionization potentials, such as noble gases. This result shows that head erosion is able to be suppressed without having to generate an over-dense, pre-matched drive beam before sending it into the plasma stage, which could open new possibilities for the design of a more optimal particle beam driver. It could also lead to the design of simpler, cheaper plasma stages, eschewing the heat pipe oven for a plain tube of gas.

The next FACET run will begin in late 2013 and will continue where the previous run left off by studying the effects of beam loading on the acceleration of the witness beam, as well as the ability to preserve the beam's emittance and minimize the final energy spread. Further, an upgrade in the ionization laser and a longer heat pipe oven will allow the plasma wake to be driven over much longer distance than in previous runs, which should lead to significantly higher net energy gain in the witness bunch. Improved diagnostics will also allow for better measurements of the beam before and after entering the plasma source, allowing for a deeper insight into the beam-plasma interaction in all of the PWFA experiments.

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