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PLASMA WAKEFIELD EXPERIMENTS AT FACET*

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Abstract

FACET, the Facility for Advanced Accelerator and Experimental Tests, is a new facility being constructed in sector 20 of the SLAC linac primarily to study beam driven plasma wakefield acceleration beginning in summer 2011. The nominal FACET parameters are 23GeV, 3nC electron bunches compressed to ~20µm long and focused to ~10µm wide. The intense fields of the FACET bunches will be used to field ionize neutral lithium or cesium vapor produced in a heat pipe oven. Previous experiments at the SLAC FFTB facility demonstrated 50GeV/m gradients in an 85cm field ionized lithium plasma where the interaction distance was limited by head erosion. Simulations indicate the lower ionization potential of cesium will decrease the rate of head erosion and increase single stage performance. The initial experimental program will compare the performance of lithium and cesium plasma sources with single and double bunches. Later experiments will investigate improved performance with a pre-ionized cesium plasma. The status of the experiments and expected performance are reviewed.

THE FACET FACILITY

FACET, the Facility for Advanced Accelerator and Experimental Tests, is a new facility being constructed in sector 20 of the SLAC linac primarily to study beam driven plasma wakefield acceleration beginning in summer 2011. Beam time is allocated through a peer-reviewed proposal driven process. FACET will operate independently of the LCLS and run for approximately four months per year over approximately five years. The nominal FACET parameters are 23GeV, 3nC electron bunches compressed to ~20µm long and focused to ~10µm wide delivered with a repletion rate from 1-30Hz. The nominal FACET beam parameters are given in Table 1.

SCIENTIFIC CASE

The overall goal of the FACET PWFA program is to demonstrate the high-gradient acceleration of a witness bunch with low energy spread and high beam loading (energy extraction efficiency). Furthermore, the emittance dilution mechanisms for an electron drive and electron witness bunch will be measured. Next, our collaboration will use FACET to characterize high-gradient positron acceleration using first a positron drive beam and then an electron drive beam. After understanding the options, a positron acceleration scheme will be selected and demonstrated at FACET with high gradient, low energy spread and high beam loading. This ambitious program will be carried out over roughly five years and this paper describes the first phases of this program.

Table 1: The nominal FACET beam parameters at the focal point (IP) for single bunch operation and corresponding plasma parameters.

Parameter	**Nominal Value**
Energy	23GeV
Energy Spread (r.m.s.)	1.5%
Species	electrons or positrons
Charge per Bunch	3.2nC
Bunch Length	20µm
Transverse Size (x, y)	13µm, 5µm
Peak Current	20kAmps
Repetition Rate	1-30 Hz
Plasma Type	lithium or cesium
Plasma Density	$10^{16} – 3x10^{17}$ e^-/cm^3
Plasma Length	Variable, 20 – 100cm

THE FIRST TWO YEARS

Single Bunch in Field-ionized Lithium Plasma

The dramatic increase in the maximum particle energy produced by PWFA is a direct result of the advent of high-intensity drive bunches at SLAC. There are two factors involved in achieving the high intensities needed for exciting large-amplitude wakes—a high peak current and a small transverse size. The nominal FACET beam parameters of 23GeV, 3nC, 20µm bunch length and <100µm^2 transverse area are ideal for driving large amplitude wakefields in a plasma. Similar beams are not available anywhere else in the world.

FACET will produce beams with properties similar to those that have worked successfully in the past at the

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SLAC Final Focus Test Beam Facility (FFTB) and will allow this work to now be continued. As part of the FFTB program, this collaboration has developed unique apparatus for studying beam-plasma interactions. The majority of this existing apparatus including the plasma source and associated diagnostics will be relocated to the FACET facility allowing these experiments to pick up where they left off. Thus, the natural first phase of the proposed experimental program is to use the FACET beam with the newly installed experimental apparatus to reach again multi-GeV plasma wakefield acceleration in a field ionized lithium plasma. This measurement is the single most comprehensive way to ensure that all of the necessary ingredients for the proposed PWFA program have been brought together and commissioned successfully.

Single Bunch in a Field-ionized Cesium Plasma

In addition to high-intensity beams, producing a large energy gain requires uniform, high-density meter-scale plasmas. When the current density of the electron bunch is high enough, the Coulomb field of the relativistic electron bunch can create a plasma in a tube of vapor through field (a.k.a. tunnel) ionization. The ionization is accomplished by leading particles of the drive bunch, so the majority of that bunch and any trailing bunches encounter a fully ionized plasma. Field ionization allows the production of long, uniform, high-density alkali metal (Li, Rb or Cs) plasmas with no timing or alignment issues [1]. This technique may also allow the production of uniform high-density plasmas that are 10 m or more in length, which have been envisioned for future plasma-based colliders.

Alkali vapor is created in a heat pipe oven [2] where neutral vapor density and length are controlled by the pressure of a buffer gas (He, Ar, etc) and heating power to the oven. The buffer gas confines the hot alkali vapor at both ends. Lithium, for instance, has a relatively low ionization potential for the first electron (5.4 eV), allowing complete ionization of lithium vapor to generate densities of up to 4×10^{17} cm^{-3} over a broad range of beam parameters. The larger ionization potential of the second electron of the Li atom (75.6 eV) ensures that the plasma density does not evolve significantly along the bunch due to secondary ionization. The plasma density is then equal to the lithium vapor density.

An important issue in FACET experiments will be beam head erosion resulting from nonzero beam emittance [3] in the tunnel-ionized plasma. This effect was identified as the limiting factor for maximum energy gain in the FFTB experiments. The generation of two bunches, needed to perform a drive beam/witness beam experiment at FACET, will reduce the peak current in the drive beam compared to the E167 experiment [3]. This may delay the onset of field ionization and exacerbate beam head erosion in a lithium plasma. To mitigate this effect, we are planning on using lower-ionization-potential alkali atoms such as rubidium or cesium, and are also exploring the use of pre-ionized laser-produced plasma columns.

For FACET beam parameters the erosion rate can be limited by using a vapor with lower ionization energy than lithium. The heat pipe oven source of lithium vapor is mechanically robust, scalable, stable, and produces a uniform vapor density over extended distances. By changing to an alkali metal with lower ionization potential, in this case cesium, head erosion will be minimized while maintaining the benefits of the heat pipe oven. The second phase experiment will replace the lithium oven that has been used successfully in the past with a similar heat pipe oven producing cesium vapor. The erosion rate for the cesium plasma will be measured as a function of beam parameters, contrasted with the lithium plasma and used to refine our analytic and computational models of this important process.

Two Bunches

For both the FFTB and FACET, the sub-ps long bunches are generated through a three stage compression process that continually manipulates the longitudinal phase space of the electron bunch to exchange energy spread for bunch length. We will add a collimation system within the final compression stage where the beam has a large energy spread correlated with position along the bunch. Collimation in the transverse plane will then result in structures in the temporal distribution of the final not-fully compressed bunch(es). This technique has recently been used to generate bunch trains in low energy accelerators [4]. We will use this technique at FACET to produce a so-called drive and witness bunch suitable for plasma wakefield accelerator research [5]. In the plasma, the drive bunch will loose the majority of its' energy driving the plasma wave and the witness bunch will sample the resulting accelerating fields. For the third phase of this proposal we will install and commission the collimation system and demonstrate the production of two bunches [6].

Two Bunches in Field-ionized Cesium Plasma

Once the collimation system has been commissioned, the two bunches will be combined with the cesium plasma source for the first PWFA experiments using a drive-witness bunch combination. By adjusting the charge and duration of the witness bunch, the FACET experiments will be able to transition from the previously studied regime of negligible beam loading to beam acceleration with strong wake loading. By loading down or flattening the accelerating wakefield, we will go from accelerating a continuum of particles to accelerating a discrete bunch of particles with a narrow, well-defined, energy spread [7]. The goals of this first round of experiments are to characterize the witness bunch energy and energy spread as a function of drive beam, witness beam and plasma parameters. Computer simulations with the code QuickPIC [8] predict witness bunch energy gain on the order 5GeV with r.m.s. energy spread on the order of 5%, depending on the plasma density, typically mid 10^{16} e^-/cm^3 [7].

OVER THE NEXT FIVE YEARS

Pre-ionized Plasmas

In the first two years the beam and plasma parameters for maximum energy gain with narrow energy spread will be identified. The witness bunch emittance will be compared with the incoming emittance and the mechanisms of emittance dilution (if any) will be characterized. The ultimate goal of this series of experiments is to double the energy of the witness bunch in a single plasma stage. If head erosion becomes a limiting factor even in the cesium plasma, we are pursuing options to return to a pre-ionized plasma in the 10^{17} e^-/cm^3 range. Simulations indicate a pre-ionized cesium plasma results in roughly six times the energy gain of the field ionized case [7]. The larger gain is the result of higher wake amplitude combined with a longer propagation distance not limited by head erosion.

High Transformer Ratio

Such a pre-ionized plasma will open up additional avenues of research such as higher transformer ratios [9,10]. The transformer ratio is defined as the ratio of the peak-accelerating field to the peak de-accelerating field. For symmetric beams this value is always less than two, and for the FFTB experiments, was on the order of 1-1.5 depending on the operating parameters. By adjusting the collimation system installed for dive/witness beam operation, we can create a drive bunch with a current profile that ramps up in intensity over several plasma periods, then terminates abruptly in much less than one period. This type of current profile can theoretically have a transformer ratio of 5 or more. By definition, the leading edge of such a current profile has a low peak current; so low in fact that it will not tunnel ionize the vapor to create the necessary plasma. For this type of high-transformer ratio experiment, a pre-ionized plasma is essential.

Positron Acceleration

For the plasma wakefield accelerator to find successful application in the field of high energy physics, a regime of operation must be found that accelerates positrons with high gradients, good efficiency and preserved beam quality. When FACET has successfully installed and commissioned the upgrade of the sector 10 bunch-compressor chicane, experiments at FACET will be able to study the wakefields driven by compressed positron beams for the first time. Although the plasma electron response for positron drivers is quite different than for electron beams, simulations indicate that compressed positron beams can still produce wakefields with multi-GeV/m gradients [5]. Yet another alternative is to accelerate the positrons on the appropriate phase of a wake generated by an electron drive beam. This collaboration has proposed a technique to demonstrate this idea in principal [5, 11]. The possible upgrade of the FACET S20 beamline to accommodate the top half of the so-called sailboat chicane would allow this idea to be fully explored by combining independent bunches of electrons and positrons overlapped in time and space at the plasma entrance.

SUMMARY

The FACET Facility is being constructed in sector 20 of the SLAC linac primarily to study beam driven plasma wakefield acceleration. The facility will begin commissioning in summer 2011 and conduct an experimental program over the coming five years to study electron and positron beam driven plasma acceleration with strong wake loading in the non-linear regime. The FACET experiments aim to demonstrate high-gradient acceleration of electron and positron beams with high efficiency and negligible emittance growth.

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