IMPROVEMENTS FOR THE THIRD GENERATION PLASMA WAKEFIELD EXPERIMENT E-164 AT SLAC

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Abstract

The E-164 experiment at the Stanford Linear Accelerator Center is the third in a series investigating Plasma Wakefield Acceleration where the wake is driven by electron bunches. A collaboration between SLAC, UCLA and USC, E-164 has up to $2\text{x}10^{10}$ electrons at 28.5GeV in 100 micron long bunches. These bunches enter a 30cm long Lithium plasma with density of $6\text{x}10^{15}$ electrons/cm^3, where the transfer of energy from the head of the bunch to the tail takes place. In addition to acceleration, strong focusing, refraction of the electron beam and "betatron X-ray" production are all investigated. E-164 builds on related prior experiments, and its apparatus has evolved considerably. A third Optical Transition Radiator has been added for real time Twiss Parameter measurements which include the effects of scattering. The plasma cell is moved to the focus of the Final Focus Test Beam facility in order to increase bunch electron density. Spectrometry is extended with an upstream chicane in a dispersive region to produce synchrotron X-rays. Performance of these improvements and status of the experiment are discussed.

INTRODUCTION

In the last few years, a series of experiments have been performed at SLAC demonstrating significant energy gain by particles traversing a plasma. In these experiments, known as E-157 and E-162, a single electron or positron bunch both excites the plasma wake and provides the witness particles to observe the large accelerating fields of order 150 MV/m [1]. E-164 will increase these gradients with shorter and more intense electron beams in dense plasmas. The new regime of energy gain requires several changes to the experimental setup and diagnostics, as discussed below.

ELECTRON BEAM

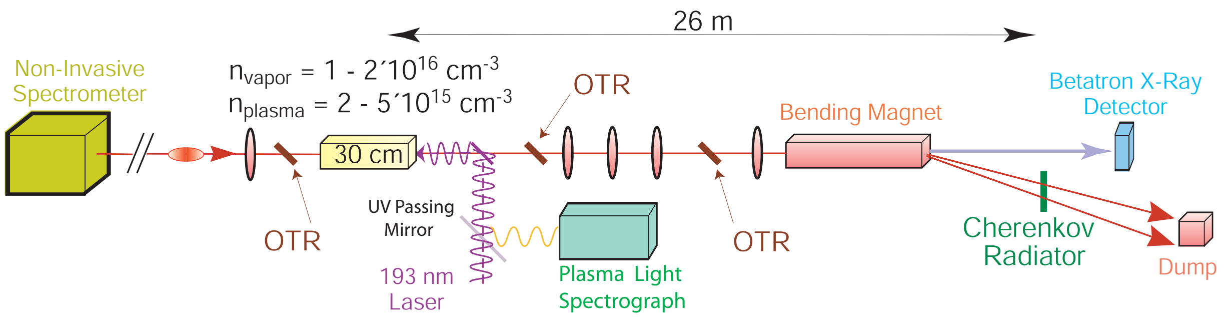
Move of Experimental Setup to IP0

Since the E-157 experiment, the plasma interaction region has been moved to IP0 of the FFTB tunnel at the end of the SLAC linac. This enables the plasma cell to be closer to final quadrupoles and permits smaller spot sizes to be achieved at the plasma entrance. We currently have spot sizes of 20 by 20 microns at the entrance to our plasma cell. The greater electron density in the beam allows the creation of a clean wake in our much denser plasma. In such dense plasma wakes, intense accelerating fields are created. We expect to produce gradients over distances of approximately 30cm that exceed several GeV/meter.

Electron Optics Setup

To verify our small spot sizes, during setup we insert two Optical Transition Radiator (OTR) foils at the locations where the plasma entrance and exit planes will subsequently be. The foils are 25 micron thick Titanium with an optical quality finish on the observed surface. Titanium is resistant to beam damage, but we still observe occasional perforation, and then must move the foil relative to the beam.

These two OTR foils are additionally necessary because, as discussed below, we use an imaging spectrometer to observe the energy spread induced in our electron bunches. Setup of the spectrometer optics to



guarantee an imaging condition requires direct observation of beam spot sizes at the locations for the plasma entrance and exit. When the optics setup is complete, the foils are removed and the plasma oven placed in the beam at the same location.

Single Shot Twiss Parameter Determination

During normal experimental running, we have three OTR foils which can be inserted to help characterize the electron beam. As shown in Figure 1, there is a foil before the plasma cell, one immediately after, and a third foil downstream of a series of quadrupoles. These locations are chosen to have unique betatron phase.

Using MATLAB, we model beam transport including scattering. This code allows single shot determination of the beam Twiss parameters when the plasma is turned off.

The second OTR foil is additionally useful, because it provides a snapshot of the electrons shortly downstream of the plasma cell. As observed in previous experiments at SLAC, [2] we expect a time dependent focusing force on the electron bunch: the plasma wake evolves for various longitudinal positions in the bunch. We believe that the large faint halo in Figure 2 corresponds to the strongly overfocused tail of the electron bunch, while the majority of the electrons are only modestly focused.

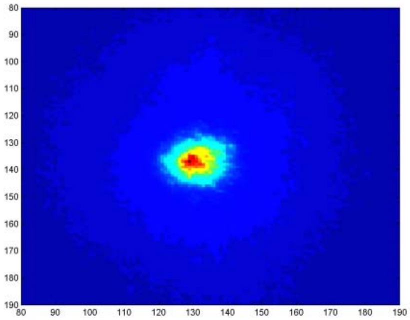


Figure 2: Second OTR Image of Beam

PLASMA SOURCE

Lithium Oven

As shown in Figure 3, the first phase of E164 uses a 30cm long Lithium oven operating at over 800 degrees Celsius with a Lithium vapor pressure of 1 to 3 torr. This temperature and pressure corresponds to a maximum Lithium vapor density of 5x10^{16} per cubic centimeter.

Temperature differentials drive a convection cycle in the Lithium to provide a sharp density profile cutoff as the hot vapor encounters the cold Helium buffer gas. [3]

To ionize our Lithium vapor, we use a 100mJ Ultraviolet laser at 193nm, which has good mode quality. This laser enables photoionization of approximately 20% of the lithium atoms illuminated by the laser.

However, preliminary results from the first half of E164 indicate substantial tunnel ionization of the Lithium, in addition to the expected photoionization. This arises because the intense electric fields associated with our tightly focused electron beam can strip the outermost electron from the Lithium atoms. A problem with tunnel ionization is that for our beam parameters, it occurs near the middle of the bunch, when the fields are the largest.

To create a plasma wake useful for acceleration, the gas must already be ionized before the majority of the electron bunch particles arrive to drive the wake. For the second run of E-164, we are considering the use of Cesium, which ionizes more readily. This allows rapid ionization before the main body of the electron bunch arrives. Dispensing with the ionization laser would greatly simplify alignment, but because tunnel ionization ionizes all Lithium atoms in a volume, we cannot change ion density except by adjusting the vapor density, and that is a slow process, making some measurements difficult.

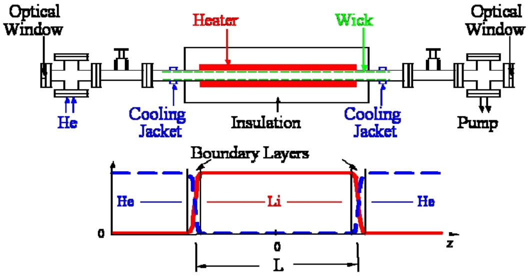


Figure 3: Heat Pipe Oven Layout. L is 30cm.

Plasma Diagnostics

For direct observation of plasma density and plasma decay rate, we use an optical spectrograph to observe the several emission lines of Lithium as the ions recombine.

As discussed above, there appears to be substantial tunnel ionization of the Lithium. We see the Lithium recombination lines when ionizing by the UV laser and also see them under the condition that the laser is turned off, but the electron beam is focused to a tight spot.

Because the plasma acts as a strong lens in X and Y, there is also a possibility that the electron beam will focus to a very small spot inside the plasma. The associated fields of the beam could ionize Lithium a second time, or ionize the Helium buffer gas. Our spectrograph could allow observation of characteristic emission lines in Li$^+$ and Helium if this effect occurs.

SPECTROMETER

We use an imaging spectrometer which provides a magnified image of the beam as it exits the plasma cell. In the vertical plane, imaging ensures that the spot size is dispersion dominated, giving the best energy resolution.

An aerogel slab approximately 1mm thick is placed at the focal plane of the spectrometer 26 meters downstream of the plasma. The beam produces a bright Cherenkov wake in a cone with opening angle of 7^o. Using a standard Nikon 105mm lens, we image a portion of this light cone onto a Princeton Instruments scientific grade CCD camera with 512x512 pixels. This camera digitizes with 16 bit resolution. The high dynamic range is important, as our acceleration is expected to be seen by a relatively few electrons at the tail of the bunch, and ability to distinguish them is critical.

Dispersion is 10mm at Cherenkov screen and the imaging of the light to the CCD camera used to observe the Cherenkov light is such that the energy resolution is 20MeV per pixel, or 0.07%. A sample spectrometer image is below. Note the large energy spread of 2.5GeV due to strong plasma interaction.

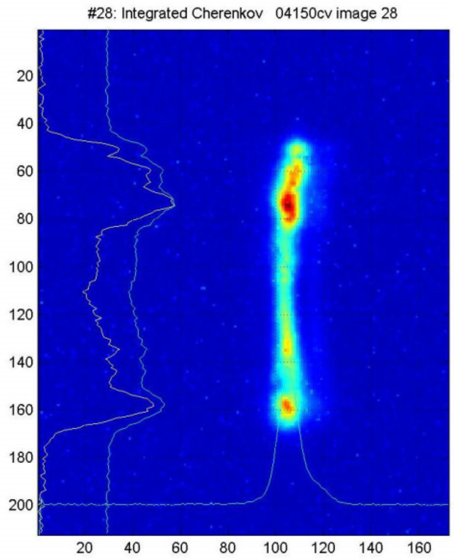


Figure 4: Energy Spectrometer Image

FUTURE ADDITIONS

Synchrotron X-Ray Spectrometer

The short electron bunches used in E-164 mean that the time dependent energy spectrum is impossible to resolve with most techniques. For example, our 150fs bunches cannot be resolved by even the best streak cameras.

To get around this difficulty, we plan to compare the energy spectrum of the beam as it comes into the FFTB with detailed simulations of the linac. Those simulations give full longitudinal phase space, and allow us to infer the bunch profile with confidence.

The main goal is to know the energy spectrum of the bunches before and after the plasma cell for shot-by-shot measurement of energy gain.

Thus for several reasons we desire a non-invasive spectrometer upstream of the plasma cell. There is a region at the beginning of the FFTB with 8cm of dispersion. To do a non-disruptive measurement, we will place a vertical chicane in this dispersive region.

The incoherent synchrotron radiation power produced as the electrons traverse the chicane is in direct proportion to the number of electrons at a given energy, and allows non-invasive measurement of the electron energy spread with expected resolution of 0.2%. This design is adapted from a similar spectrometer at SLAC. [4]

Betatron X-Ray Measurements

The transverse oscillations of the electron beam as it propagates through the strongly focusing plasma lead to intense production by synchrotron radiation of high energy X-Rays. [5]

For E-164 and future experiments, we plan to do spectroscopy on the extremely broadband radiation produced by the electron beam. Theoretical calculations indicate that, for our expected parameters, photons with energies from approximately 100keV to 80MeV will be produced.

There will also be a position-energy correlation in the cone of radiation, so a spectrometer capable of resolving energies at each of a number of positions transverse to the beam is required.

Single photon calorimetry/spectroscopy is well understood, but the extremely intense photon fluxes expected from the synchrotron radiation require special techniques to resolve individual photon energies. Studies of the best setup to achieve this are ongoing, but are expected to use Bragg reflections and surface barrier detectors in conjunction with detectors suited for high energy gamma ray detection such as scintillator crystals connected to photomultiplier tubes.

CONCLUSION

The special requirements of E-164, specifically the dense plasma and very short electron bunches, lead to a need for a number of new diagnostic techniques which are suitable for characterizing the many unusual parameters of the experiment.

Recent and planned improvements are expected to allow the accurate determination of the beam properties in all three dimensions necessary for demonstrating the intense acceleration of our beam in plasma.

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