E164

High Gradient Plasma-Wakefield Acceleration Using Ultrashort Electron Bunches

M. J. Hogan[*]*, P. Emma, R. Iverson, C. O'Connell, P. Krejcik, R. Siemann and D. Walz*
Stanford Linear Accelerator Center
B. Blue, C. E. Clayton, C. Huang, C. Joshi[*]*, K. A. Marsh, and W. B. Mori*
University of California, Los Ange*les*
T. Katsouleas[*]*, P. Muggli, and S. Lee*
University of Southern California

I. Introduction

For the past three years, the E157 and E162 collaborations have been studying key issues related to the applicability of plasmas to future high-energy accelerators.(1) In particular we have been examining the beam-driven plasma wakefield accelerator(2) (PWFA) scheme and electron and positron focusing by plasmas(3) in the context of a e^+-e^- linear collider. This is because plasmas can provide accelerating gradients and focusing forces that are orders of magnitude greater than those obtained using conventional technology.

The E157 experiment(4) studied the transverse and longitudinal electron beam propagation issues in a 1.4 meter long plasma that would act as a prototype accelerating stage for an eventual PWFA. The ongoing E162 experiment(5) is continuing the acceleration work with electrons and extending the measurements using positron beams. In the first E162 run conclusive results on focusing of a positron beam have been obtained using an extended plasma lens. The experimental set-up, for observing energy change of the beam particles as they traverse the plasma, has been substantially improved by the addition of an imaging spectrometer. E162 collaboration recently finished its second run. The data from that run is currently being analyzed and we expect to give a status report to the Program Committee on our preliminary findings.

The goal of the original E157 proposal was to demonstrate 1 GeV/m accelerating gradients over a distance of 1 meter or greater using a drive beam with 4 x 10^{10} particles in a .6 mm long bunch. For realizable beam parameters of 2 x 10^{10} electrons in a 0.65 mm long bunch the maximum accelerating gradient was limited to < 425 MeV/m. In spite of this reduced drive bunch charge and a longer bunch length, the E157/E162 experiments have successfully observed many of the predicted phenomena such as 1) multiple betatron oscillations of the beam as the plasma density is increased; 2) propagation of a matched beam through the plasma; 3) sloshing of the tilted beam and the electron hosing instability in an ion column; 4) dynamic focusing of the beam; 5) x-ray emission due to betatron motion in the ion column; 6) focusing of a positron beam and 7) acceleration and deceleration of the drive beam. These results are discussed briefly in Section VI.

In this proposal we would like to revisit our original goal: ultrahigh gradient plasma-wakefield acceleration. Ultrahigh gradient, in this context, refers to peak acceleration gradients of > 10 GeV/m. It is possible to contemplate such an experiment because of the availability of much shorter electron bunches at the FFTB, where the experiments are being carried out. We expect the Ultra-short Bunch Facility (USBF) to deliver σ_z = 100 μm bunches compared to σ_z = 0.6 mm bunches used in E157/E162. Since the accelerating gradient scales as the beam current divided by the bunch length, a factor of six reduction in pulse length translates to a factor of 36 increase in the accelerating gradient. However, a shorter electron bunch requires a higher plasma density source. With a 30 cm long plasma source at the optimum plasma electron density of 5.6 x 10^{15} cm^{-3}, we expect to see energy gains of around 1.75 GeV with some particles gaining as much as 4.4 GeV.

We believe that the successful demonstration of this experiment will be a truly significant and defining accomplishment in the Advanced Accelerator Research field. Since the short pulse capability will be available at the FFTB for only a short period of time, this proposal to do such an ultrahigh gradient plasma wakefield acceleration experiment represents a window of opportunity that cannot be missed. The E164 collaboration has proven ability (see Section VI) and expertise to conduct these experiments. As shown in Fig. 1 most of the experimental apparatus (see Section IV) is already in place as part of the E157/E162 experiments. The experimental work will be carried out in conjunction with theory and simulations programs that are absolutely necessary for the success of the experiments.

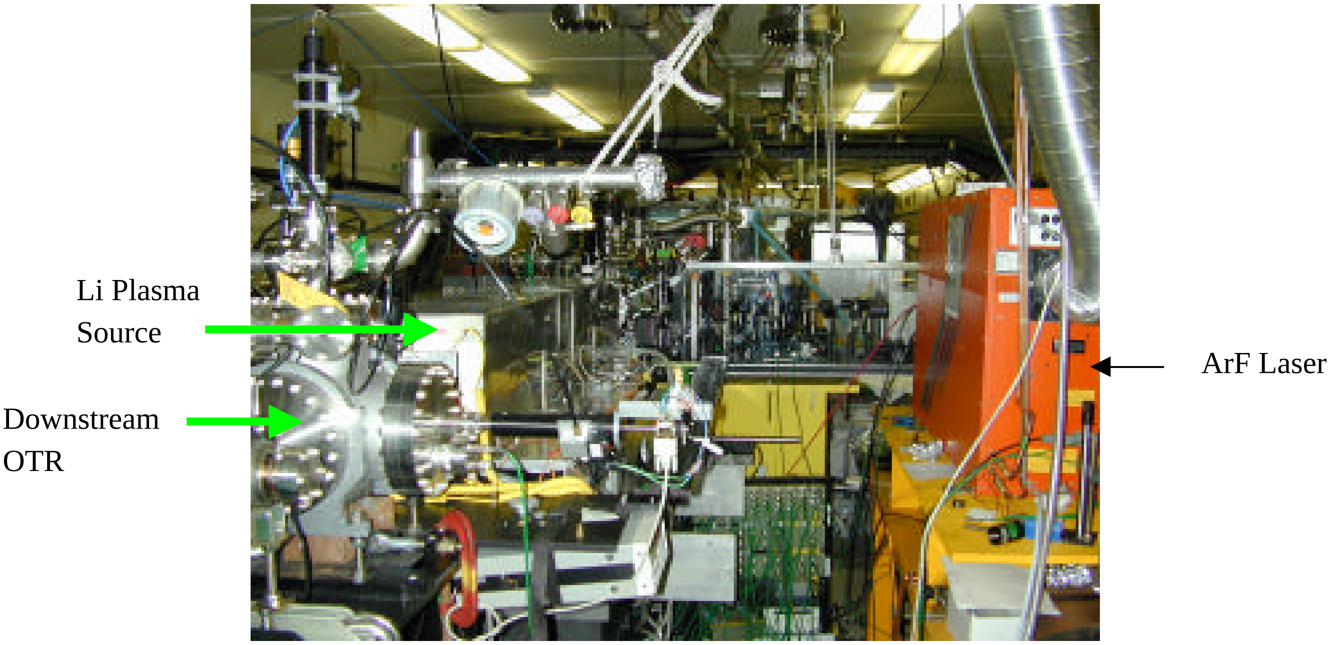


Figure 1. Photograph of the E157/E162 experiment in the vicinity of IP(0) of FFTB.

We begin by defining the symbols used throughout this proposal.

Physical Parameter	**Symbol**
Speed of Light in Vacuum	c
Charge of an Electron	e
Accelerating Gradient	eE, e_1
Plasma Wavenumber	$k_p = \omega_p/c$
Plasma Wavelength	$\lambda_p=2\pi/k_p$
Mass of an Electron	m_e
Number of electrons per Bunch	N, N_e
Drive Beam Density	$n_b=N/(2\pi)^{3/2}\sigma^2_r\sigma_z$
Plasma Density	n_p, n_e
Drive Beam Transverse Size	σ_r
Drive Beam Bunch Length	σ_z
Beam Plasma Frequency	$\omega_{pb}=(n_b e^2/\varepsilon_o m_e)$
Electron Plasma Frequency	$\omega_p=(n_o e^2/\varepsilon_o m_e)$
Beta Function of the Beam	β
Normalized Emittance of the Beam	$\varepsilon_N = \gamma\varepsilon$
Spot Size of the Beam in x, y	σ_x, σ_y
Skin Depth of Plasma	c/ω_p

Table 1: Legend of symbols used in this proposal

II. Motivation

In the beam-driven plasma wakefield accelerator (PWFA), a short but high current electron bunch, with beam density n_b larger than the plasma electron density n_p,(6) expels the plasma electrons as shown in Fig. 2. If however, the length of bunch is approximately half the wavelength of the relativistic plasma wave ($\omega_p = k_p c$), then the expelled plasma electrons rush back in and set-up a large plasma wakefield which has a phase velocity that is exactly the beam velocity c. According to linear plasma theory the wake amplitude is optimized for $k_p\sigma_z \quad \sqrt{2}$ at a value given by

$$(eE)_{\text{linear}} = 240\ \text{MeV/m} \left(\frac{N}{4 \times 10^{10}} \right) \left(\frac{0.6}{\sigma_z(\text{mm})} \right)^2$$

where N is the number of particles in the electron bunch and σ_z is the bunch length.

For the parameter of this experiment, the wake is excited in the so called blow out regime, $n_b > n_p$, where the wake excitation is highly nonlinear. However, 3D Particle-in-Cell (PIC) code simulations (see Fig. 3) have born out this $1/\sigma^2_z$ dependence of the accelerating gradient. For beam and plasma parameters of interest the accelerating field is highly nonlinear (spikey) with a peak value

$$(eE)_{\text{peak}} \qquad 3\text{–}4\ (eE)_{\text{linear}}.$$

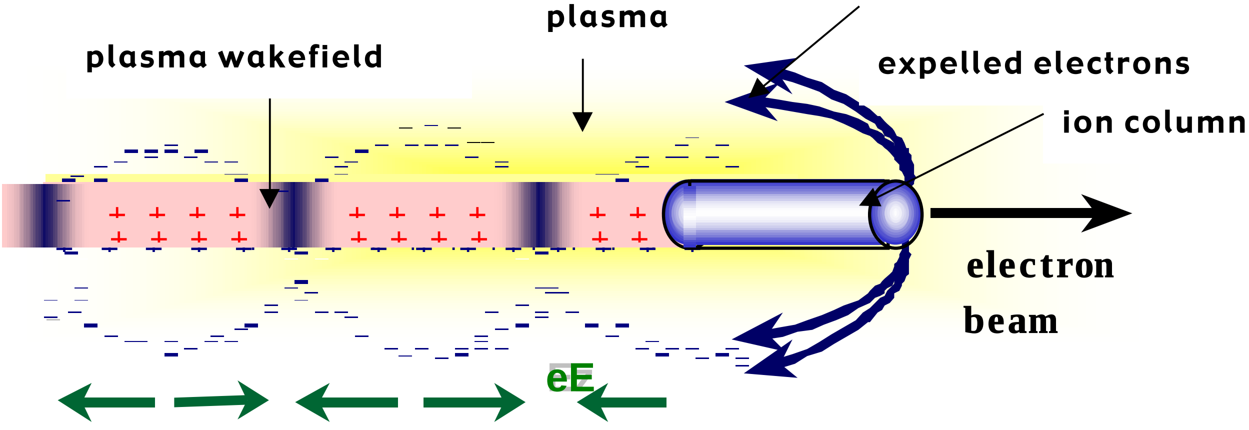


Figure 2. Physical mechanism of the Plasma Wakefield Accelerator.

The proposed ultra-short bunch facility (USBF) at SLAC(7) gives us a unique opportunity to demonstrate the $1/\sigma_z^2$ bunch length scaling of the accelerating gradient and conduct an ultrahigh gradient plasma wakefield experiment at the FFTB. This can be appreciated immediately by comparing the existing and proposed parameters of the beam at IP(0) of the FFTB shown in Table 2. One can see that with $N = 2 \times 10^{10}$, the accelerating gradient predicted by the linear theory can be increased from 120 MeV/m to 4.3 GeV/m by reducing the bunch length from $\sigma_z = 0.6$ mm (E157 and E162) to 0.1 mm (E164).

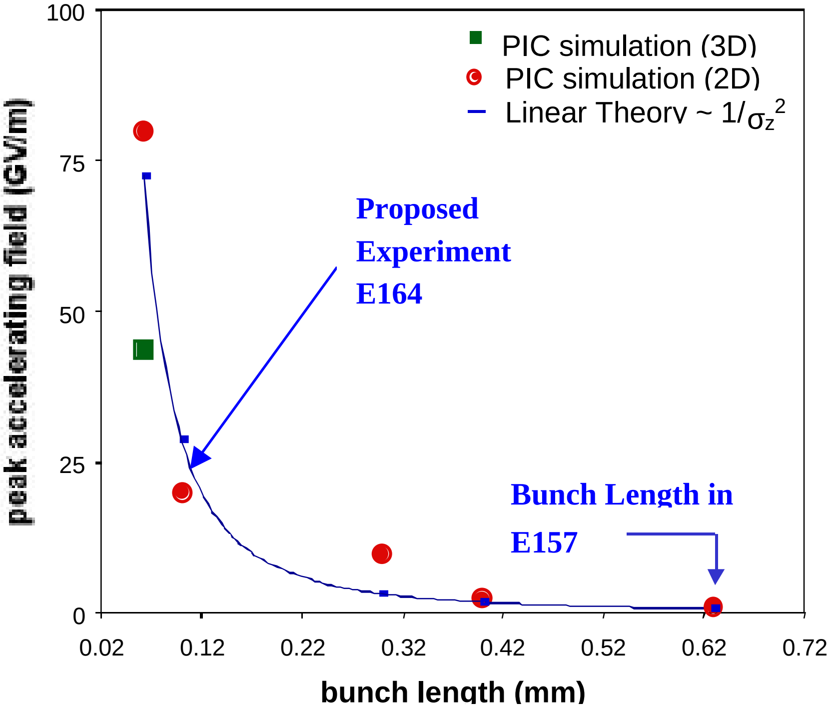


Figure 3. The peak accelerating field vs. the bunch length from PIC simulations and $1/\sigma_z^2$ scaling predicted by the linear theory.

The peak gradient could be as high as 20 GeV/m as shown in Fig. 3. Of course the plasma density has to be increased from present 1.5 x 10^{14} cm^{-3} to 5.6 x 10^{15} cm^{-3} to optimally excite ($k_b\sigma_z \quad \sqrt{2}$) the plasma wakefield. These ultrahigh gradients are comparable to those achieved with short pulse laser beams in plasmas. However, since an electron beam can be self-guided by the ion channel and its natural diffraction length is typically longer than the Rayleigh length of a focused laser beam, the gradient times length product will be much greater in the electron beam case leading to a larger energy gain per stage.

	Current Beam	**Proposed Short-Pulse**
N	2×10^{10}	2×10^{10}
σ_z(mm)	0.6-0.7	0.1-0.15
σ_r(μm)	10-50	20-40
$\Delta\gamma/\gamma$	0.5%	$<$ 1.5%
I_{peak}	1 kA	10 kA
$\gamma\varepsilon_x$	30 μm	50 μm
$\gamma\varepsilon_y$	5 μm	5-50 μm

Table 2: Comparison of the Current and Proposed Short-Pulse Beam Parameters

III. Computer Simulations:

As mentioned earlier for $n_b >> n_p$ the linear plasma theory is not valid. We have developed extensive computer simulations capabilities that allow us to perform one-to-one modeling of the experiment in this highly nonlinear regime. The code used, OSIRIS(6) is a 3-D, fully electromagnetic, relativistic, parallized particle-in-cell (PIC) code that has been benchmarked against other codes and model problems that can be solved numerically. OSIRIS is now the standard tool for simulating the beam plasma interactions in E157/E162 and has successfully predicted many of the observed phenomena in a quantitative manner.

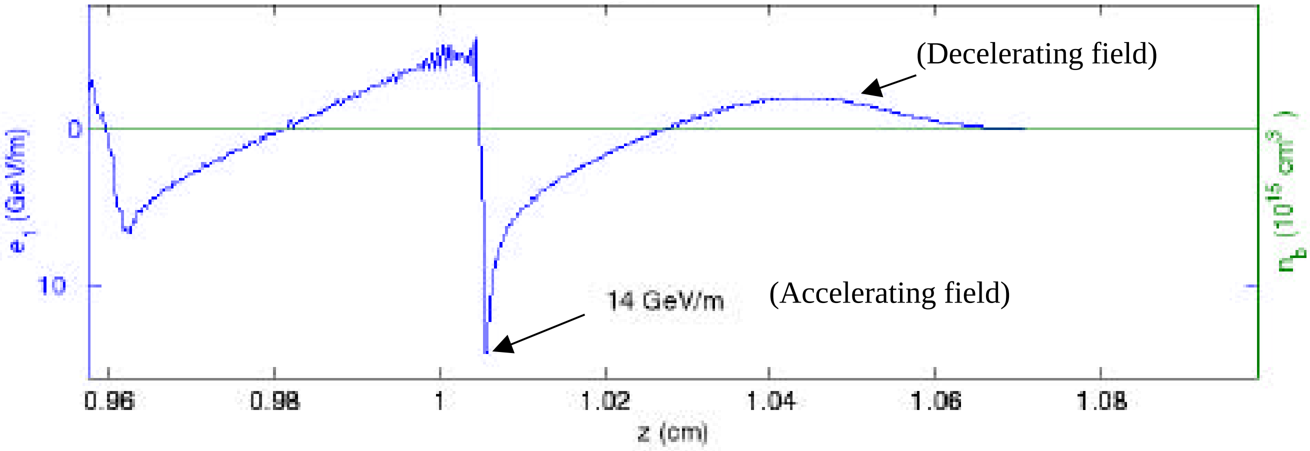
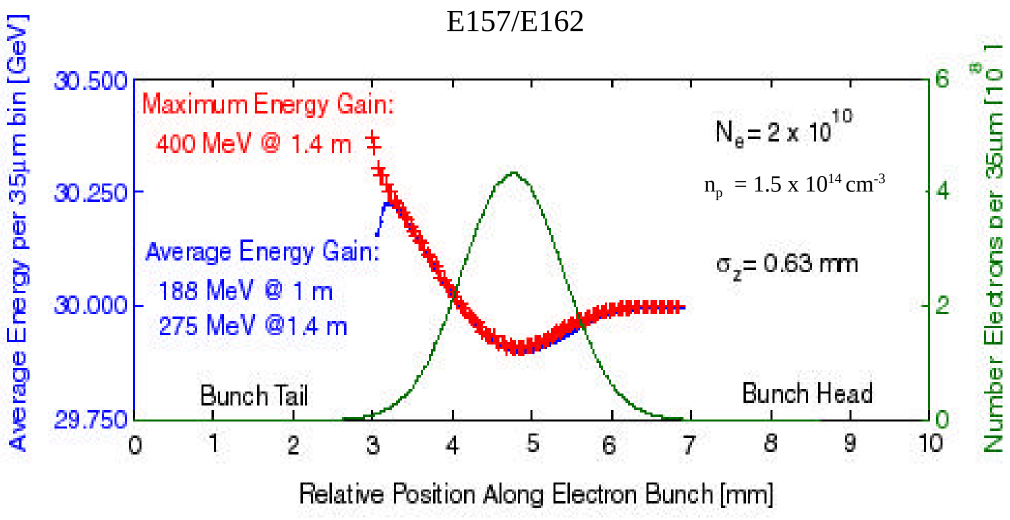
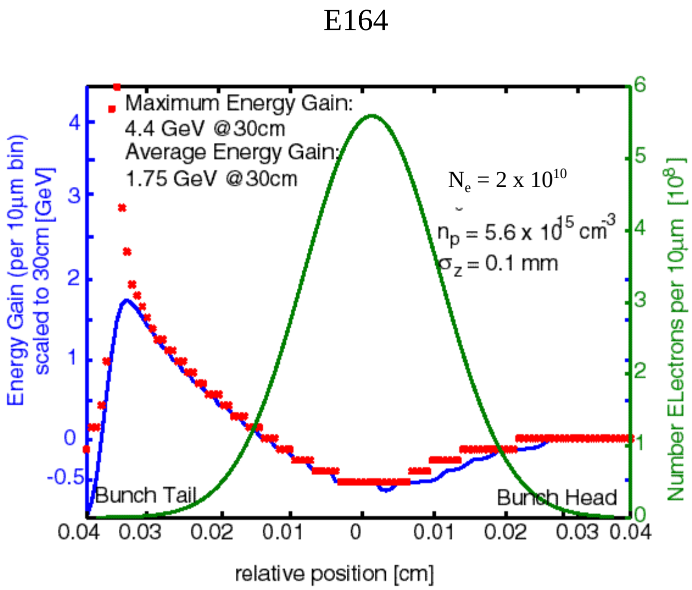


Figure 4: The decelerating and the accelerating field on axis of the wake field induced in the plasma by a .1 mm long electron bunch containing 2 x 10^{10} particles: OSIRIS simulations.

Figure 4 shows 2D simulation results from OSIRIS of a 100 μm bunch containing 2 × 10^{10} electrons propagating through a 5.6 × 10^{15} cm^{-3} plasma. The peak accelerating gradient is 14 GeV/m. Figures 5(a) and (b) show the energy loss and gain by the beam electrons using the E162 experimental conditions and proposed E164 experimental conditions. One can see that in the present E162 experiment, the maximum expected


E157/E162

(a)


E164

(b)

Figure 5. The expected energy change of the electrons in the beam in the present E162 experiment and in the proposed E164 experiment: OSIRIS simulations.

energy gain is about 400 MeV over 1.4 meters. This is to be contrasted to the experiment proposed here. We expect an energy loss of the main part of the beam of 0.6 GeV and a gain of > 1.75 GeV (average energy of a slice in the tail) and perhaps as large as 4.4 GeV (for the highest energy particles) in just 30 centimeters. There is one other critical experiment that can be carried out as part of this work. This is the electron beam hosing(8) experiment. The ability to propagate short bunches stability without breakup due to the hosing instability is critical to the future application of this method of acceleration as a possible afterburner to a linear collider. The increase in the displacement of the centroid of the beam can be measured as a function of plasma density to determine the extent of the hosing growth.

IV. Method

This experiment requires a 30 cm long, 5.0×10^{15} cm^{-3} plasma density source. The existing Lithium source(9) is unable to give the necessary density because the high absorption cross-section of Lithium (2×10^{-18} cm^2 at 193 nm) leads to a large axial density gradient. Rubidium with its first ionization potential of 4.17 eV and absorption cross-section of 2×10^{-20} cm^2 however is able to produce the required density plasma, over 30 cm length using a 265 nm laser focused to give a fluence of 30 Jcm^{-2}. We shall therefore construct a Rubidium source that will give the necessary parameters for this experiment.

The imaging spectrometer developed by the E162 collaboration is absolutely necessary for making these measurements. With a vertical energy dispersion of 300 MeV/mm a total energy gain of up to 3 GeV can be measured using the time integrated Cherenkov camera. We therefore need to reduce the length of the plasma source to about L=30 cm in order to be able to measure a total energy change of up to 2.35 GeV (loss of 0.6 GeV and gain of 1.75 GeV) as the bunch length is decreased to .1 mm.

Existing Experimental Apparatus

Figure 6 shows the schematic of the experimental set up for E162. The FFTB beam traverses two, 12.5 μm thick titanium optical transition radiation (OTR) foils before and after going through the plasma source placed at IP(0). The OTR foils allow monitoring of the electron beam profile and give information needed to tune out any beam tails.

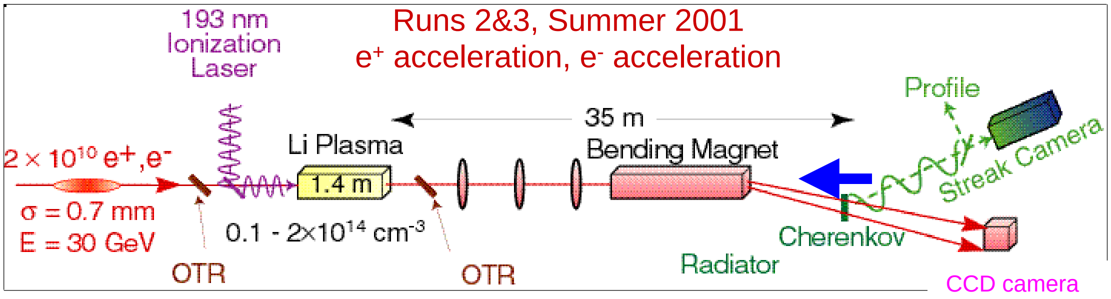


Figure 6. Schematic of the experimental set-up used for the E162 experiment. In the proposed experiment the plasma sources and geometry used for laser ionization may be different. In particular the ionizing laser will be injected through the photon beam line indicated by the thick blue arrow in the above figure.

The quadruples downstream of IP(0) in conjunction with the FFTB dipole dump magnet form an imaging spectrometer as shown in Fig. 7. The beam after exiting the spectrometer traverses an aerogel Cherenkov emitter. The Cherenkov radiation is recorded using a CCD camera and also simultaneously image relayed to the outside of the FFTB bunker where it is time resolved in both planes. In addition to these diagnostics the beam position is monitored throughout the FFTB by a series of beam position monitors.

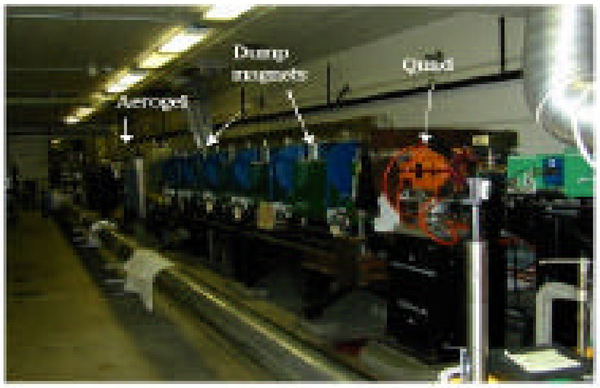


Figure 7. Photograph of the downstream portion of the imaging spectrometer used in E162.

Data is acquired by shot-by-shot correlations. The upstream and downstream OTR images, the time integrated Cherenkov image, the two (x vs. t) and (y vs. t) streak camera images and laser and beam data are acquired on each shot and information from these diagnostics can be combined for filtering and sorting of data.

Experimental Issues For E164

Although the experimental arrangement for the proposed E164 experiment is qualitatively similar to that for E162 there are some crucial differences:

First, since the drive beam is only $\sigma_z = 100$ μm long, the Cherenkov radiation will no longer be time resolved using the streak camera. The change in energy spectrum in this experiment is expected to be large enough that we should be able to resolve it easily on the time-integrated Cherenkov CCD camera

Second, the ionizing laser pulse will be provided by a frequency quadrupled, Nd:YAG laser rather than an ArF laser. This change in laser is needed to obtain the required fluence and mode quality. Since Lithium cannot be ionized by this laser we will change the vapor to Rubidium which has an ionization potential of 4.17 eV.

Third, the ionizing laser will no longer be injected off a thin pellicle upstream of the plasma source. Instead it will be injected through the photon beam line (see Fig. 6). The focusing telescope will be placed just after the electrons are bent away using the dipole magnet. The spot size of the beam w_o is expected to be about 300 μm throughout the plasma leading to a very homogeneous longitudinal plasma profile. Transversely we will try to obtain as smooth and flat top a profile as possible

Fourth, the 35 m space between the exit of the plasma and IP(2) will be filled with ~ 1 Torr of He. This is not the case in the present E162 experiment where two 75 μm Be foils, one on either side of the plasma source confine the helium buffer gas. However, preliminary measurements made on beam propagation through 3 meters of Helium of up to 20 torr pressure during the second E162 run suggest that 35 torr × m of He that will be used in E164 should not cause severe problems for the beam due to either collisional ionization or scattering.

Fifth, the Rayleigh range of the laser beam $2Z_R$ is expected to be about 2 m. The peak energy density will exceed 30 J/cm^2. This means that there can be neither any transmitting optic nor Ti OTR foils in the way of the laser beam. Once the electron beam and the laser beam are aligned using two phosphor screens, both will be retracted. We will not have an online OTR image of the beam. However, we will place two additional beam position monitors upstream and downstream of the plasma, respectively to monitor the position of the beam centroid with and without the plasma.

Sixth, ionization induced refraction is not a serious issue for L=30 cm long plasma with a peak density less than 5.6×10^{15} cm^{-3}. As the laser beam ionizes the Rb vapor it will begin to slowly refract because the plasma column it produces will act as a negative lens. As the intensity of the beam drops due to refraction, the ultimate density that can be achieved will be capped at some maximum value. A rough estimate of the maximum density that can be obtained is given by $(n_p/n_c)_{max} < \lambda/L$. Taking L = .3 m and λ = 0.25 μm, $n_c = 1.6 \times 10^{22}$ the maximum plasma density turns out to be 1.3×10^{16} cm^{-3}.

V. Experimental Program Schedule

This is an ambitious and difficult experiment. It can only be carried out after it is demonstrated that short bunches can be delivered at IP(0) with the parameters stated in Table. 2. Assuming that this will be realized around October 2002, we would like to request 3 separate runs, each lasting 4 weeks.

We will also need access to FFTB for a period of several weeks after the Summer shutdown in 2002 for installing the laser and making in-situ beam transport measurements. The Rb plasma source will be developed and diagnosed at UCLA as soon as the experiment is approved. Some preliminary work could also be done, while the ultra-short beam facility is being commissioned, on beam transport through 24 meters of helium buffer gas as well as testing the properties of the imaging spectrometer under simulated plasma exit conditions.

VI. Results from E157/E162 Experiments

E157 experiment called, " One GeV Beam Acceleration in a One Meter Long Plasma Cell," was proposed in 1997, began running in the Summer of 1998 and concluded data taking in the Spring of 2000. It was a truly pioneering experiment as there had never been any work done on the interaction of GeV class electron bunches with plasmas in the past. The experiment yielded an enormous amount of data some of which is still being analyzed. Nevertheless, several papers (See Section VIII) have been either published or submitted while several more are still under preparation.

E162 experiment called, "Positron and Electron Dynamics in a Plasma Wakefield Accelerator" was approved in the Winter of 2000. It had a very successful first run that demonstrated dynamic focusing of a 28 Gev positron beam and a second run on electron acceleration in the PWFA that was completed at the end of July 2001. The data from these runs is still being analyzed.

We describe below highlights of some of the results that have been obtained by the E157/E162 collaborations.

1) Focusing of Positron Beams by an Extended Plasma Column:

We have obtained time integrated and time resolved measurements of the focusing of a 28 GeV positron beam as it traverses a 1.4 m long plasma column. The beam size at two different locations downstream of the plasma as a function of plasma density has been measured over a wide range of plasma densities. A maximum demagnification on the order of 2 has been demonstrated.

Time Integrated Focusing of a Positron Beam

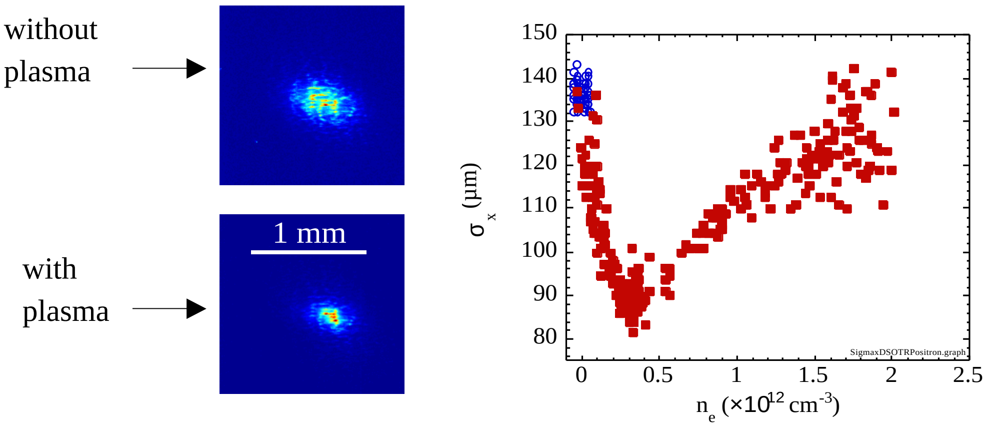
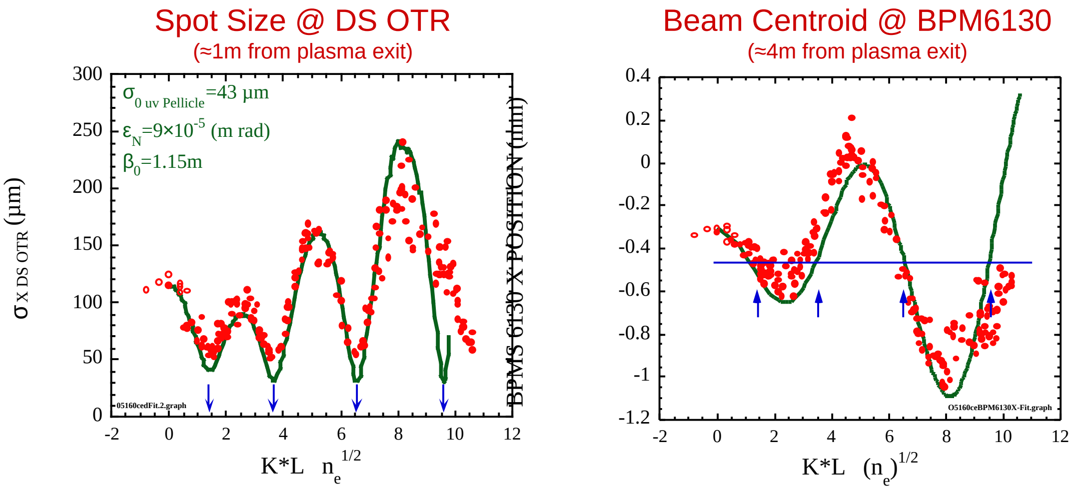


Figure 8. Time integrated images on the downstream OTR without and with the plasma indicating positron beam focusing and spot size variation on the downstream OTR as a function of plasma density.

2) Propagation of Matched and Unmatched Beams Through An Ion Column:

We have shown that when the beam is match to the plasma ($\beta_{beam} = \beta_{plasma}$) it propagates through it without significant oscillations of its beam envelope over a wide range of densities. This matched propagation also minimizes the sloshing of the beam tail thereby reducing the transverse momentum imparted to the particles in the beam tail. When the beam is not matched, the beam can undergo multiple betatron oscillations of its envelope within the plasma. Experimentally, these oscillations are observable as an oscillation of the spot size of the beam on a screen downstream of the plasma as the plasma density is increased.


Spot Size @ DS OTR

(≈1m from plasma exit)

Beam Centroid @ BPM6130

(≈4m from plasma exit)

Figure 9. Oscillations of the beam envelope and the beam centroid as observed on the downstream OTR due to betatron motion of the electrons: E157 experiment.

3) *Experimental Test for the Electron Hosing Instability*

Stable propagation of the drive bunch is essential to the operation of the PWFA. Of concern is the electron hose instability which can lead to the growth of transverse perturbations on the beam due to the nonlinear coupling of beam electrons to the plasma electrons at the edge of the ion channel through which the beam propagates. We have carried out an experiment to measure the extent of the electron hose instability by sending a beam with a known initial tilt through the plasma column. The center of mass of the beam is seen to oscillate at the betatron frequency with the maximum exit angle of the beam scaling as the square root of the plasma density as expected. The beam tail is seen to experience some growth of its transverse displacement due to hosing. However, the growth is much less than predicted by theory.

4) Observation of Betatron X-ray Emission from a Plasma Wiggler

Synchrotron light sources use magnetic undulators to obtain high brightness photon beams in the x-ray region. Here we have utilized an ion channel in a plasma to wiggle an ultra-relativistic, 28.5 GeV, electron beam instead of a magnetic wiggler/undulator. The quadratic density dependence of the spontaneously emitted betatron x-ray radiation, the absolute x-ray yield at 6.4 ± 0.13 KeV of $(2 \pm 1)\times 10^{7}$ photons and the divergence angle of 10^{-4} radian of the forward emitted x-rays as a consequence of wiggling in the ion channel are in good agreement with theory.

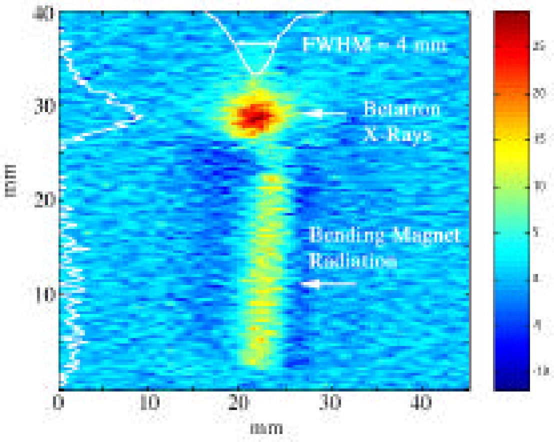


Figure 10. Betatron x-ray radiation and bending magnet radiation recorded using a fluoresor at the end of the photon beam line: E157 experiment.

5) Refraction of the Electron Beam at a Plasma-Gas Interface

We have observed the collective refraction of a 30 GeV beam of electrons at a plasma/gas interface that is orders of magnitude larger than would be expected from single electron consideration and that is unidirectional. The electron beam exiting the plasma is bent away from the normal to the plasma-neutral gas interface in analogy with light exiting a high index medium at an interface between two dielectric media.

The physical reason for this effect observed for the first time with a particle beam is as follows. While the beam is fully in the plasma, the space charge at the head of the beam repels the plasma electrons out to a radius $r_c \sim (n_o/n_e)^{1/2} r_b$ where r_b is the radius of the beam, n_b is the peak density of the beam, and n_e is the plasma density. The remaining plasma ions constitute a positive charge channel through which the latter part of the beam travels. The ions provide a net focusing force on the beam. When the beam nears the plasma boundary, the ion channel becomes asymmetric producing a deflecting force in addition to the focusing force. This asymmetric plasma lensing gives rise to the bending of the beam path at the interface. The bending of the beam by the collective effect of the (passive) medium at the boundary is the particle analog to refraction of photons at a dielectric boundary.

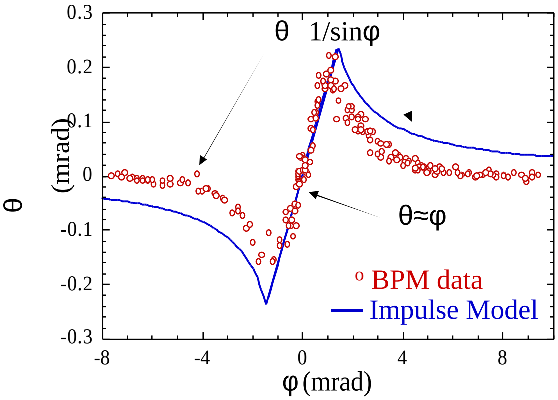


Figure 11. A plot of beam deflection (θ) measured with the beam position monitor versus angle between the laser and the beam (φ). For incident angles φ less than 1.2 mrad, the beam appears to be internally reflected.

This work was published in Nature and a more detailed version is accepted for publication in PRSTAB.

6) *Electron Acceleration in a Meter Long Plasma via the Plasma Wakefield Acceleration Technique: E157 Experiment.*

Analysis of the time-resolved Cherenkov emission after the dispersion plane had indicated that there were indeed energy changes in different slices of the beam. However, transverse oscillations of the beam made interpretation of this data ambiguous. To eliminate this ambiguity during the second E162 run, the E157/E162 set-up was moved from IP(1) to IP(0) in the FFTB tunnel. An imaging spectrometer was commissioned successfully to allow imaging of the beam from the plasma exit plane to the spectrometer image plane at IP(2). Moving the experimental setup to IP(0) allowed focusing of the beam to a much smaller spot ~ 0(10 μm) at the plasma entrance allowing the beam to be matched to the plasma. The data is currently being analyzed and we expect that preliminary results will be presented to the PAC committee.

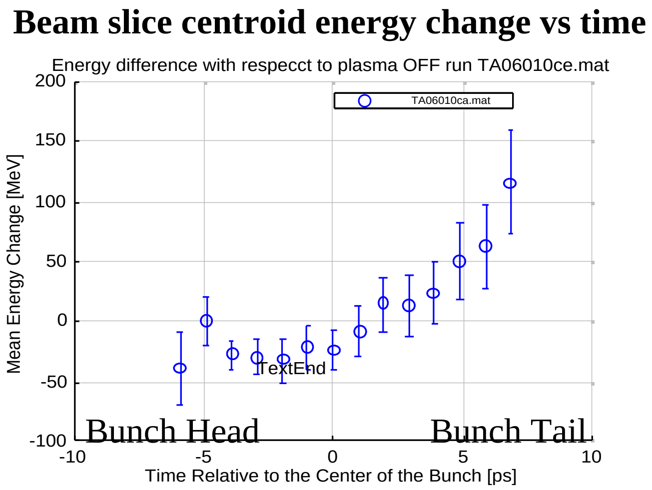


Figure 12. Preliminary measurements on the change in energy of picosecond slices of the electron beam at the resonant plasma density: E157 experiment. With the addition of an imaging spectrometer the uncertainty introduced by beam tail oscillations in interpreting this data should be greatly reduced.

VII. References

1. T. Katsouleas et al., " An Energy Doubler for Linear Colliders, submitted for publication on *PRSTAB.*
2. P. Chen et al., *Phys. Rev. Lett.* **56**, 1252 (1986).
   T. Katsouleas et al., *Phys. Rev. A* **33**, 2056 (1986).
   J. Rosenzweig et al., *Phys. Rev. Lett.* **61**, 98 (1988).
   R. Ruth et al., *Particle Accelerators* **17**, 171 (1985).
3. P. Chen, *Particle Accelerations* **20**, 171 (1987).
   J. B. Rosenzweig et al., *Phys. Rev. A* **44**, 6189 (1991).
4. M. J. Hogan et al., *Phys. Plasmas* **7**, 2241 (2000).
5. M. J. Hogan et al., " E162: Positron and electron dynamics in a plasma wakefield accelerator," SLAC-ARDB-242, Oct. 2000.
6. R. Hemker et al., *PRST:AB* **3**, 061301 (2000).
7. P. Krejcik, P. Emma, and R. Iverson: Private Communication.
8. D. Whittum et al., *Phys. Rev. Lett.* **67**, 991 (1991).
9. P. Muggli et al., *IEEE Trans. Plasma Science* **27**, 791 (1999).

VIII. Publications of the E157/E162 Collaboration

1. M. Hogan et al., “E157: A 1. 4m-long plasma wakefield acceleration experiment using a 30 GeV electron beam from Stanford Linear Accelerator Center,” ***Phys. Plasmas***, Vol. 7, 2241 (2000).
2. P. Muggli et al., “Refraction of a particle beam,” ***Nature***, Vol. 411, 43 (2001).
3. S. Lee, T. Katsouleas, R. Hemker, W. B. Mori, "Simulations of a meter-long plasma wakefield accelerator," ***Phys. Rev. E***, Vol. 61, 7014 (2000).
4. P. Catravas et al., "Measurements of radiation near an atomic spectral line from the interaction of a 30 GeV electron beam and a long plasma," accepted by ***Phy. Rev. E (Rapid Communications).***
5. T. Katsouleas, S. Lee, and P. Muggli, "Refraction of a beam of electrons at a plasma-gas interface," accepted by ***PRSTAB***.
6. T. Katsouleas et al, “ An Energy Doubler for Linear Colliders, submitted to ***PRSTAB***.
7. S. Wang et al., “Demonstration of Betatron X-ray emission Using a Plasma Wiggler,” to be submitted to ***Physical Review E (Rapid Communications)***
8. C. E. Clayton et al, “Transverse dynamics of a 28 GeV beam in a meter long plasma,” to be submitted to ***Physical Review Letters***.
9. P. Muggli et al., "E-157: A Plasma Wakefield Acceleration Experiment," Proceedings of the LINAC 2000 Conference, August 21-25, 2000, Monterey, CA.
10. S. Wang et al., "Observation of Spontaneous Emitted X-Ray Betatron Radiation in Beam-Plasma Interactions," Proceedings of the Particle Accelerator Conference, June 17-22, 2001, Chicago, IL.
11. B. Blue et al., "Test of the Electron Hose Instability in the E157 Experiment," Proceedings of the Particle Accelerator Conference, June 17-22, 2001, Chicago, IL.