THE UW/ANL PLASMA WAKE-FIELD ACCELERATION EXPERIMENT

J. B. Rosenzweig, D. B. Cline,* B. Cole, J. Detra and P. Sealy
Department of Physics, University of Wisconsin - Madison, 1150 University Ave., Madison, Wisconsin 53706

*Present address: Dept. of Physics, University of California at Los Angeles.

Abstract

The University of Wisconsin Accelerator Physics Group, in collaboration with Argonne National Laboratory, has designed and built an experiment to test the physics of the Plasma Wake-field Accelerator using the ANL Advanced Accelerator Test Facility. The facility provides a very short (6 psec) bunch of electrons at 22 MeV which is used to excite large amplitude longitudinal plasma oscillations in a hollow cathode arc plasma. The plasma wave supported electrostatic wake-fields, which can be expected to exceed 100 MeV/m, are probed by a low intensity 15 MeV witness pulse with a variable delay time behind the driving bunch. The energy changes and transverse kicks in both beams are measured by a high resolution, double focusing, broad range magnetic spectrometer. Status of the project is discussed and experimental progress reported.

Introduction

The Plasma Wake-field Accelerator (PWFA) has been the subject of much theoretical discussion in the last few years, due in large part to the possibility of achieving ultra-high accelerating gradients for high energy physics use through this scheme. The predictions of the linear fluid theory and computer simulation[1-3] two dimensions have identified certain issues for experimental study and verification. These include the fundamental excitation of the plasma waves, the concommitant electrostatic fields, and the electromagnetic self-pinching of a high intensity driving beam. The idea for an experimental test of the PWFA at ANL came about because of the existance of an ideal driver: a very short pulse, high intensity linac that has since become the injector for the Argonne Wake-field Test Facility. The present experimental apparatus is designed to address these physical issues, and future modifications are planned to study the effects of longitudinal pulse shaping on the physical mechanisms involved.[4]

Theoretical predictions

The two dimensional linear theory, as formulated by Chen,[5] provides a simple model for calculating the expected performance of the PWFA experiment. This model was used to optimize the experimental parameters to match the beam characteristics at the ANL 22 MeV Linac, which are listed in Table 1. The details of these calculations can be found in a previous publication.

Table 1: ANL Wake-field Test Facility Characteristics

Driving Beam Energy	22 ± 0.8 MeV
Witness Beam Energy	15 ± 0.2 MeV
Emittance	7π mm-mrad
Pulse Frequency	≤ 800 Hz
Pulse Length	6 psec (1.8 mm)
Driving Beam Charge	30 - 60 nC
Witness Beam Charge	≤ 1 pC
Witness Beam Delay	0 - 2.4 nsec
Witness Beam Offset	0 - 1 cm
Driving Beam Radius at Focus	≥ 1.5 mm

The length of both the high intensity driving beam and the low intensity witness beam is 1.8 mm. The characteristic wavelength of the plasma oscillation excited is $\lambda_p = \sqrt{\frac{m_e \pi}{r_e n_0}}$ where n_0 is the unperturbed plasma electron density. If the witness beam is longer than a quarter of a plasma wavelength it will not resolve the effects of distinct longitudinal regions of the plasma wave. This sets a minimum desirable plasma wavelength, $\lambda_p = 7.2\ mm$, or a maximum plasma density of $n_0 = 2 \times 10^{13} cm^{-3}$. The wave is also not excited as efficiently if this density is exceeded, as the plasma electrons have time to react to the presence of the beam, lowering the coupling of the beam charge to the wave. If the beam radius a is large, the amplitude of the plasma waves is diminished because the driving beam charge is less dense. On the other hand, if $a \ll \lambda_p$, then the space charge in the plasma wave is confined to a region small compared to its oscillation length, and the fields become more radial and less useful for acceleration. This is the region of parameter space considered useful, for plasma lenses which are of interest as final focusing methods.[5] The calculated field profiles for an optimized experiment are shown in Figs. 1 and 2. Larger accelerating gradients can be achieved if the radius is smaller and the plasma density is higher, but at the cost of longitudinal and transverse resolution. If on the other hand, the density is lowered significantly the radial effects dominate, and analysis and computer simulations indicate the plasma response may also prove to be fairly nonlinear.[6,7] The experimental parameters given in the Figs. 1 and 2 are a set for which all effects are observed in relative moderation.

Integrations of the equations of motion, assumimg that the driving beam profile changes little during the plasma region (L = 15 cm), indicate that the rear of the driving beam self-focuses and the resulting divergence of the beam at the end of the plasma is about 100 m-rad. The divergences in the witness beam may be even stronger, dependent on the initial delay between the pulses. The driving beam shows energy loss of about 12 MeV and the witness pulse shows a maximum gain of about 18 MeV, or an acceleration gradient of 120 MeV/m, as expected. This calculation method has been compared to 2-D simulations and gives similar results for short plasmas, although the maximum field on axis calculated in simulation shows enhancement due to the pinching of the driving beam.

Experimental Status

The experimental work at both UW and ANL has progressed to the point of tuning the beam line and measuring the charateristics of the plasma. This section provides an overview of the experimental scheme and its status as of March 1987.

The Wake-field Test Facility

The construction of the double beam line facility at the ANL Chemistry Division 22 MeV linac has been finished and the optics are being tuned. The facility layout is shown in Fig. 3. The core of the high intensity 6 psec beam pulse delivered from the bunching system is intercepted just before the first bend, producing a lower energy spray which is separated from the primary by the bend and a small momentum and emittance bite is then accepted into the low energy beam line. The high energy beam is transported through the

CH2387-9/87/0000-0083 $1.00 © IEEE

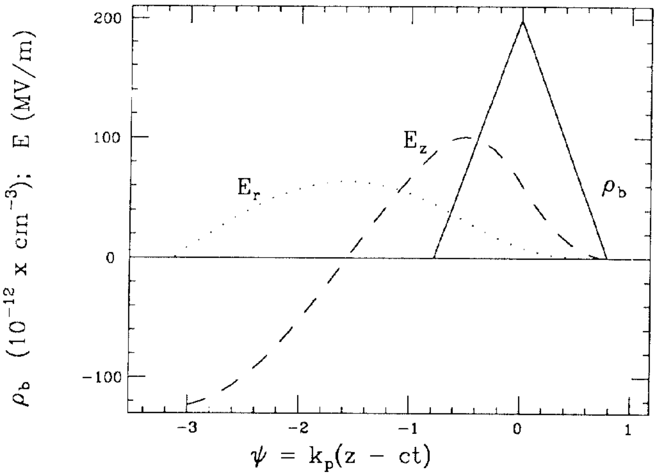

Fig. 1. Longitudinal driving beam density ρ_b profile on axis and maximum wake-fields for optimized PWFA eperiment with $n_0 = 2 \times 10^{13}\ cm^{-3}, a = 1.2\ mm$, and $N = 10^{11}$.

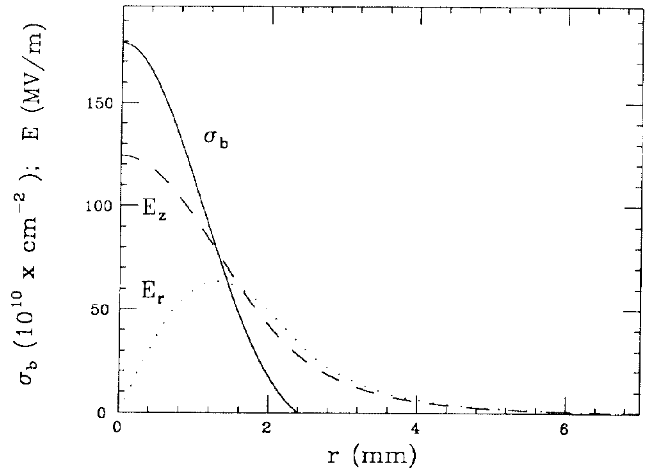

Fig. 2. Radial driving beam surface charge density $\sigma_b = \int \rho_b dz$ profile and maximum wake-fields for optimized PWFA experiment.

fixed isochronous line with the 270° bend. The low energy beam traverses a trombone leg which provides an adjustable delay (0 - 2.4 nsec) behind the driving beam when they are recombined at the final bend. The low energy line is also nearly isochronous for its stated range of delays. Both lines are designed also for zero dispersion. The witness beam trajectory can also be offset (0 - 1 cm) from that of the driver at focus to permit measurement of transverse wakes.

The Plasma Source and Diagnostics

The plasma source for this experiment is a DC hollow cathode arc (HCA). A prototype of the final source has been constructed and is currently being tested at Wisconsin. The arc and plasma characteristics are summarized in Table 2. A plot of plasma density profiles obtained with electrostatic probes on a test stand prototype

Table 2: Plasma Source Parameters

Electron Density n_0	$10^{12} - 10^{14}\ cm^{-3}$
Plasma Wavelength λ_p	3 - 30 mm
Interaction Length	10 - 30 cm
Typical Arc Voltage	≤ 100 V
Typical Arc Current	≤ 50 A
Neutral Pressure	≤ 1 mTorr

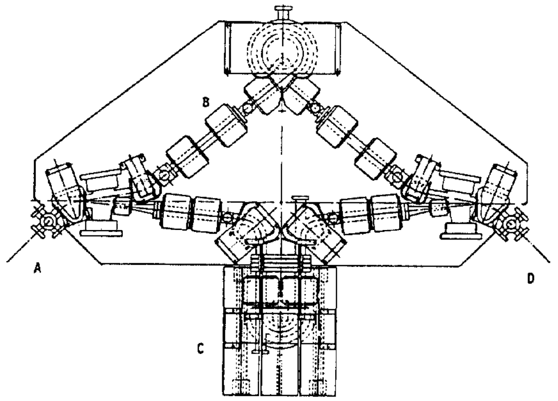

Fig. 3. Advanced Accelerator Test Facility beam lines. (A) Witness beam generated by driving beam on target, (B) high energy beam line, (C) low energy beam line with adjustable length trombone leg, (D) experimental area ($\leq$ 1 m long).

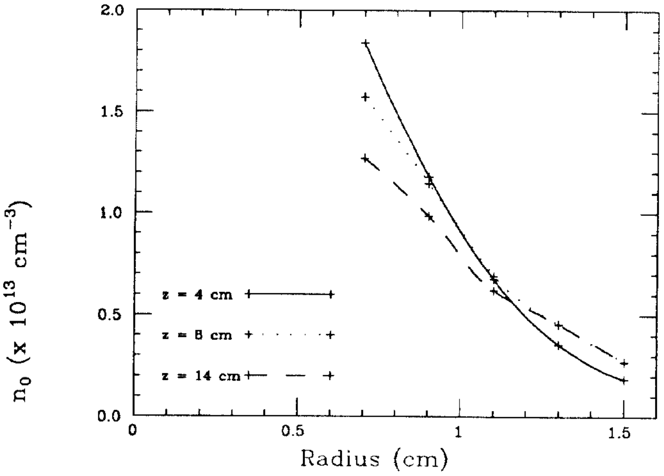

Fig. 4. Plasma density profiles from electrostatic probe measurements. The coordinate z is the distance from the cathode and $kT_e \simeq 4\ eV$.

The plasma source for the PWFA experiments is presently nearing completion at Wisconsin. The major unique feature of this source is that the cathode consists of two concentric thin wall (0.5 mm) tantalum tubes, with nitrogen gas flowing at about 1 Torr-l/sec through the annular region between the two. This scheme allows the beams to enter the plasma without suffering multiple scattering from a relatively high density gas. Gas is also fed in at the anode, to ameliorate pressure and density gradients that destabilize the arc and are undesirable for the experiment. The plasma is formed at the hot spot ($T \geq 2000^o K$) a few diameters from the end of the tubes. This dense plasma then flows into the interelectrode space, and is confined by an axial magnetic field (400 - 800 G) generated by a pair of coils in an approximately Helmholtz geometry, with an iron yoke around them to contain the return flux. The cathode and the anode are both placed in the fringe field region. The length of the plasma column can be changed by moving the anode and its associated magnet coil. The plasma density is adjusted by varying the arc current, gas flow and magnetic field strength.

The arc is ignited through the abnormal glow regime with argon gas flowing through the central tube, and power supplied by a 1200 V, 20 A DC supply. When the tantalum is hot enough to support an arc, the discharge voltage is less than 100 V and the power is then provided by a 150 V, 130 A supply. The gas feed is switched over to nitrogen. The arc source has been tested at up to 65 A.

Pumping is provided at 1500 l/sec by a turbomolecular pump, yielding a vessel pressure of ≤ 1 mTorr. The neutral density is slightly less than the plasma density. This situation tends to stabilize the arc, but is not expected to affect the high frequency plasma waves being studied on a 10 psec time scale. Differential pumping is provided back towards the beam lines by the poor conductance of the tantalum tubing followed by a 280 l/sec turbo pump.

The plasma diagnostics that are to be used during the PWFA experiments consist of electrostatic probes for measuring local densities and temperatures and a 70 GHz microwave interferometer for a line integral of the density across the column. The probes are of standard double and triple tip design. The interferometer is able to measure electron densities up to cutoff, $n_c = 6 \times 10^{13} cm^{-3}$. The phase information in the interferometer output is digitized at 1 MHz and stored in on-board memory using a CAMAC module originally designed at Princeton and used widely in much tokamak research. The plasma diagnostics are to be integrated into the facility's computer control and data taking system.

Beam Diagnostics

The electron momenta are analyzed by a double focusing, broad range magnetic spectrometer constructed at ANL, a flat field dipole ($B \simeq 700\ G$) preceded by a vertically focusing quadrupole, which is the standard 10 cm long quad used in the beam lines. Vertical focusing may be adjusted by varying current to the quad. The dipole exit angle is -45^o, which provides telescopic (parallel) reference orbits for all momenta within the design range. The dispersion as a function of momentum is equal to the radius of curvature ($\rho = p/eB = 0.5 - 1.5\ m$) in the dipole. The exit angle is also strong focusing lens for the horizontal motion, giving a tight focus and, with large dispersion, high momentum resolution on the order of $R = p/\delta p = 1000$. The dipole bend is rotated 90^o out of the beam line horizontal plane so that the effects of a witness beam offset in that plane can be measured in the spectrometer's vertical plane. The vertical focusing has chromatic dependence, but is approximately point-to-parallel. This arrangement should also reduce the noise from stray electrons in the detectors. The beam spots in the focal plane are to be detected by scintillator and imaged by video cameras.

The longitudinal profile of the beam pulses will be measured by a streak camera of ≤ 2 psec resolution. This equipment is currently being acquired. The transverse beam profiles are diagnosed by imaging of inserted phosphor plates.

Computer Control and Data Acquisition

The control and data aquisition for the Wake-field facility is based on an IBM PC/XT equipped with CAMAC interface and frame grabber boards. The CAMAC system is used to control and monitor magnet power supplies, position beam line diagnostics and read out plasma diagnostics. The phase digitizer can be read at up to 1 MHz and a data logger samples data from the electrostatic probes at up to 40 KHz with 12 bit accuracy. Displays of data and FFT's are available on-line.

The beam lines and spectrometer are instrumented with glass plates coated with commercial color TV phosphors. Since these diagnostics are destructive, they are moved into the beam as require under computer control. The phosphor plates are viewed by standard CCTV cameras. Signals from the cameras are then digitized for further analysis using the frame grabber, with 256 x 240 pixel resolution and a 64 level gray scale. Lower intensity signals can be enhanced with an image intensifier.

Experimental Goals

The examples given in the previous section are illustrative of experiments designed to measure high gradient acceleration by short beams of moderate beam radial extent ($a \simeq \lambda_p/3$). A feature of this sort of experiment is that most of the witness beam distribution leap-frogs in energy over the driving beam distribution. This is, of course, not the only type of experiment one can attempt using this experimental design. The adjustable delay of the witness beam can be exploited to study the different regions of the plasma wave: accelerating, decelerating, focusing and defocusing. The transverse effects can be measured as a function of radius by utilizing the horizontal beam offset. If less dramatic energy gains and deflections are to be studied, the beam current can be scaled back accordingly, and the driving beam distribution will be kept above the witness distribution.

The effects of longitudinal beam shaping will be investigated in the future after the facility is upgraded to include another RF cavity. This will allow generation of longer, ramped beam pulses that have been predicted to give higher transformer ratios[4] (the transformer ratio, or the maximum accelerating field in the wake over the maximum decelerating field inside the driving beam, for the present experiments are expected to be somewhat less than two, as in Fig. 1). A longer plasma column is desirable for this type of experiment. Small modifications on the existing source should provide this, with appropriate plasma densities. The previously described self-pinching of the driving beam will also be studied closely in future experiments, with the goal of the use of a plasma lens as a final focus in present and future linear colliders.[8]

REFERENCES

1. R. D. Ruth, A. Chao, P. L. Morton, and P. B. Wilson, *Particle Accelerators* **17** (1985) 171
2. T. Katsouleas, *Phys. Rev. A* **33** (1986) 2056.
3. P. Chen, *Particle Accelerators* **20** (1985) 171.
4. K. L. F. Bane, P. Chen, P. B. Wilson, *IEEE Trans. Nucl. Sci.* **32** (1985) 3524.
5. J. B. Rosenzweig, D. B. Cline, B. Cole, J. Detra, and P. Sealy *Proceedings of the Symposium on Advanced Acceleration Schemes, Madison, Wisconsin - 1986*, edited by D. Cline and F. Mills, AIP (1987).
6. R. Keinigs and M. Jones, to be published in *IEEE Trans. Plasma Sci.*
7. J. B. Rosenzweig, *Phys. Rev. Letters*, **58** 1987.
8. D. B. Cline, B. Cole, J. B. Rosenzweig and J. Norem, these proceedings.