Test particle injection in the relativistic plasma waves excited by two co-propagating laser beams

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ABSTRACT

We report on a series of experiments aimed at the demonstration of controlled acceleration of externally injected test particles (electrons) by a relativistic plasma wave. The plasma wave is excited resonantly by beaming two co-propagating laser beams at the plasma frequency. The first part of the paper describes the electron linear accelerator and the beam transport system, as well as the particle detection system. The electron macropulse energy spectrum and beam emittance are measured and are shown to be consistent with the requirements of the experiment. The electron beam is passed through a 0-pinch plasma. Although Raman scattering of the incident CO$_2$ laser has shown the plasma to be reproducible in density to within 15% from one shot to the next at peak compression, direct evidence of localized density inhomogeneities due to trapped magnetic fields is found via the deflection of the injected electron beam. The trapped fields persist even as the plasma disassembles following the compression up to the second B=0 point in the 0-pinch cycle.

I. INTRODUCTION

In this paper we shall describe the status of the proof-of-principle experiment designed to demonstrate controlled acceleration of externally injected electrons by a plasma density wave moving nearly at the speed of light. The plasma wave is excited by resonantly beaming two lasers in a plasma in such a wave that their frequency difference $\Delta \omega$ is equal to the plasma frequency $\omega_p$. This scheme is called the plasma beat wave accelerator (PBWA) and has been discussed in numerous previous publications.$^{1,2,3,4,5}$ The parameters of the proposed acceleration experiment are shown in Table 1. In this paper we concentrate on a series of experiments leading up to the proposed electron acceleration experiment. We shall first describe the electron linac and the beam transport system. Detailed particle trajectory calculation have been carried out and have been shown to agree with experimental results on the beam transport without the plasma. We then describe experiments on electron beam transport through the plasma. One such experiment for instance has led to the "observation" of trapped magnetic fields in a 0-pinch plasma.

II. ELECTRON LINAC AND BEAM TRANSPORT

We use a 9 GHz, x-band linac as the injector for our experiment. Since the linac structure must be maintained under better than $10^{-6}$ Torr vacuum, whereas the rest of the experiment is under ~ 100 mTorr, a 6 $\mu$m thick mylar foil is used to separate the linac from the experiment. The linac macropulse is 5 $\mu$s and is expected to contain micropulses each typically 10 ps long separated by ~110 ps. The electron beam exiting the mylar foil has an emittance of 50 $\pi$ mm mrd. Figure 1 shows the trapping threshold vs. wave amplitude for particle making various angles w.r.t. the wave for a $\gamma_p = 10$. It is readily seen that the trapping threshold rapidly increases as the particles' parallel velocity drops because they

![Fig. 1. Injection energy vs plasma wave amplitude for various injection angles.](image-url)
make larger and larger angles w.r.t. the wave. In our experiment we therefore wish to reduce the emittance of the injected particles by beam scraping. We use a solenoidal lens to focus the beam to a spot size of 1 cm. An off-axis parabolic mirror with a 1.5 mm hole is used to reduce the beam emittance to ~ 10 π mm mrad. This mirror is used to focus the laser beam coaxially with the electron beam at the center of the plasma chamber. From the beam current measurements we estimate that the microbunches exiting from the linac contain typically $7 \times 10^6$ electrons; however, this number is down to $2 \times 10^3$ electrons by the time they emerge through the momentum selecting aperture in the focusing mirror. The electron beam transport system is shown in Fig. 2. A second solenoidal lens is used to focus the electron bunches to a spot size of about 1 mm at the center of the 6-pinch.

In the electron acceleration experiment, the current in Lens 3 is adjusted such that the incident 1.5 MeV particles are focused at the entrance aperture of the electron spectrometer shown in Fig. 2. The magnetic field in this spectrometer is very weak (200 G) and is used to deflect the 1.5 MeV electrons out of the way. The accelerated electrons (6 MeV and above) are only weakly focused by Lens 3 and only slightly deflected by the first electron spectrometer. They exit this spectrometer, which is used only as a beam dump to discriminate the accelerated electrons from the incident electrons, and enter a second spectrometer with a 3 kG magnetic field where they can be detected and energy analyzed. The detectors are an array of Si surface barrier detectors. The output of the detectors is amplified using charge sensitive preamplifiers and then amplifiers. The output can be digitized using A/D converters and then analyzed using a desk top computer. The spectrum of the incident pulse can be recorded by removing the magnetic field in the "dump spectrometer" and readjusting the current in Lens 3 to image the electrons at the entrance aperture of the 3 kG spectrometer. Such a spectrum is shown in Fig. 3. The spectrum is seen to peak around 1.4 MeV with a FWHM of 300 keV. With the beam dump spectrometer operative we have determined that the noise level in the second spectrometer is less than 1 electron. In other words our detection system is capable of detecting single events.

![Fig. 2. Electron beam transport system of the UCLA PBWA Experiment.](image)

![Fig. 3. Photographically measured injected electron spectrum at the output of the electron spectrometer.](image)
III. THE PLASMA SOURCE AND DENSITY MEASUREMENTS

In our proposed experiment the plasma source is a θ-pinch. In a θ-pinch a sheet of current is pulsed into a single turn coil around an insulating tube containing the gas. The gas in our case is either H₂ or He. This current \( I_0 \) induces a magnetic field \( B_z \) which varies in time. From Faraday's law an induced electric field \( E_0 \) arises, causing the gas to break down. A thin sheet of plasma is thus formed and as a result of the diamagnetism of the plasma, a current \(-I_0\) is produced which opposes the circuit current \( I_0 \) keeping the plasma field free. This current crossed with the \( B_z \) generates a radially inward force on the plasma which drives the plasma towards the axis. The moment at which the gas breakdown occurs depends on the type of gas, the filling pressure, any preionization and the external circuit parameters. Maximum compression is obtained when the plasma pressure \( nkT \) balances the magnetic field pressure.

![Graph showing dB/dt vs t signal picked up by the current loop and (b) density vs time as measured by holographic interferometry.](image)

Fig. 4. (a) dB/dt vs t signal picked up by the current loop and (b) density vs time as measured by holographic interferometry.

The parameters of our θ-pinch are listed in Table 2. A typical \( B \) signal picked up by a single turn loop some 50 cm from the coil is shown in Fig. 4a. In He without preionization, plasma breakdown occurs close to the first minimum of the \( B \) and maximum compression follows typically 1 μs thereafter as determined by holographic interferometry. Figure 4b shows the plasma density vs. time. Time \( t = 0 \) is the time of the peak compression. It can be seen that for ±200 ns around this time the density is quite close to the resonance value in 120 mT of He without preionization. A more exact measurement of density can only be obtained by using the Raman scattering technique that we have used in our previous experiments. A preliminary attempt was made to transport the electron beam through the θ pinch plasma. A detailed “ray-tracing” computation was initially carried out to see how the electron beam is influenced by the stray fields of the θ pinch as well as any trapped fields. Details of these calculations are summarized in Fig. 5. Figure 5a shows the on axis magnetic field profiles (top) and the electron beam trajectories (bottom) for 5 electrons starting with a radial displacement of 0.5 mm and with various initial angles from the mylar foil of the electron gun. Figure 5b shows what happens when the pinch is fired and assuming that at the peak of compression a trapped field of 1/10 Bmax exists in the plasma. The electron beam dynamics is now dominated by the θ pinch which acts as a strong solenoidal lens. Electrons make 1/2 of a betatron oscillation and the displacement of the electron with the largest angular spread is such that the electron no longer overlaps with the laser focus which has only a 300 μm radius. In the initial experimental tests we fired the electron beam at the 2nd zero of the magnetic field. Figure 6 shows the results of these tests. A diode placed at the focus of the third lens [or at the output of the electron spectrometer which images this point] shows that an electron pulse only ±50 ns wide is transmitted around the 2nd zero of the magnetic field. We are effectively gating the linac externally. Obviously this way of sharpening the electron pulse has the advantage of reducing the noise level in the spectrometer by a factor of ~50.

In order to determine if the resonant density of 5.8×10¹⁶ cm⁻³ could be produced at the second B = 0 we carried out an extensive series of measurements. The technique used was Raman scattering of an intense CO₂ laser probe beam. Since the frequency of the Raman backscattered radiation is shifted by the Bohm-Gross frequency we can determine the plasma density rather accurately using this technique. We measured the frequency of the Raman backscattered radiation using an image dissector to disperse the radiation and a He-cooled Ge detector to detect the radiation. We found that at the peak-compression phase of the θ-pin, 120
Fig. 5. Ray-tracing calculations showing trajectories of test electrons without (a), and with (b) the θ-pinch on. The Plasma is assumed to have a trapped field of 1/10 \( B_{\text{max}} \) at the peak of the compression.

Fig. 6. Experimentally measured shape of the transmitted electron pulse shape through the plasma when the electron beam is fired at the second \( B = 0 \).
mT of He at 24 kV produced an intense Raman shifted signal corresponding to the resonant density with only 1 J (in ~ 250 ps) of incident CO₂ laser energy. Furthermore this density could be reproducibly generated shot-to-shot. This is shown in Fig. 7(a). On the other hand at the second B = 0, we needed to increase the fill pressure up to at least 350 mT to obtain a signal at the resonant density. Moreover, the Raman scattering occurred over a wide range of densities from $2.53 \times 10^{16}$ to $1.0 \times 10^{17}$ cm⁻³.

**IV. OBSERVATION OF TRAPPED MAGNETIC FIELDS IN THE PLASMA**

The plasma in a 0-pin device is generally thought to be field free since plasma can shield out magnetic field lines. However, our experiments have determined that a significant fraction of the magnetic field can be trapped by the plasma as it implodes inwards. At peak of the compression the trapped field can produce localized density islands which can be observed interferometrically (Fig. 8). From pressure balance we have determined that up to 4% of the magnetic fields at peak compression can be trapped. Furthermore since the typical diffusion time of the magnetic field is on the order of 1 μs, even at the second B = 0, which occurs 1.5 μs later, the plasma (which is by now quite tenuous) can still have tens of gauss of B field trapped within it.

An independent confirmation of the trapped B field in the plasma was obtained by shooting the electron bunch through the plasma at the second B = 0 with and without the plasma. Two diagnostics were used. The first was a diode placed at the image plane of the third lens and the second was a photographic film placed at this point. Fig. 9 shows the result. Fig. 9(a) shows that, even when no current is flowing through the coil at the second B = 0, the electron signal detected by the diode can be a factor 3-10 less when there is plasma present compared to when there is no plasma. The electron signal is less because of the small kicks the electron beam gets and this is evident in the beam images of Fig. 9(b). One can see that image can shift (usually unpredictably) by one to two diameters when the plasma is present, consistent with a trapped field of 20-30 Gauss over the length of the plasma of 20 cm.

**Fig. 8. Interferogram of the plasma taken at peak compression showing density islands.**

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**Fig. 7. Raman signals at peak compression and at B = 0.**

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V. CONCLUSIONS

In this paper we have described the status of the proof-of-principle experiment designed to demonstrate the controlled acceleration of externally injected test particles by a relativistic space-charge density wave. Initial tests have been carried out on the electron beam transport system. Using the deflection of the injected electrons as a diagnostic we have determined that the θ-pinch plasma can have significant trapped B-fields even when no current is flowing through the coil. A parameter space is systematically being narrowed down in which the acceleration experiment can be reproducibly accomplished.

VI. ACKNOWLEDGMENTS

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