BEAT WAVE DEVELOPMENT WORK

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ABSTRACT

The first phase of experiments on beat wave acceleration have been completed at UCLA. Here we examined the suitability of a theta pinch as a plasma source. The beatwave was excited to amplitudes providing GeV/m-scale accelerating fields. However, trapped magnetic fields within the theta-pinch plasma hindered the injection of test particles. Optical diagnostics were developed to measure the accelerating gradient-length product which was found to be around 3 MeV. Future plans are also discussed.

INTRODUCTION

The plasma beatwave experiment at UCLA is designed to study wave-particle interaction physics of plasma-based acceleration schemes.\textsuperscript{1,2} The experiment consists of five major systems: (1) the CO\textsubscript{2} laser which drives the plasma wave; (2) the electron linac which provides a source of test particles to probe the plasma wave; (3) the electron detection apparatus with single-electron detection capability; (4) the plasma source, generating the medium which supports the high-gradient accelerating structure; and (5) the optical diagnostics which provide an independent, on-line diagnostic of the state of the plasma and amplitude of the plasma wave. We will briefly describe these systems before presenting the current experimental standing.

EXPERIMENTAL ARRANGEMENT

The five main components of the experiment are shown schematically in Fig. 1. (1) The laser system delivers 200 GW...
Figure 1: A schematic overview of the five main systems comprising the beatwave acceleration experiment.

Pulses consisting of two wavelengths of light—10.27 and 9.56 μm. The pulse duration is about 400 psec FWHM. The laser system is typically fired at 7 minute intervals yielding typically 50 shots per experimental run.

(2) The electron source is an 9.3 GHz linac at 1.5 MeV with an average current of 2-10 mA over a 3 μs macropulse. The approximately 20 psec micropulses contain a few million electrons focused to a spot size of 2σ⊥ = 1 mm. This large spot size is a result of the large emittance introduced when the beam scatters in a 6 μm window at the end of the linac. The electron beam is brought onto the CO₂ beam axis via a few millimeter diameter hole in the off-axis parabolic focusing mirror.

(3) The electron detection apparatus is shown schematically in Fig. 2. A 900 G guiding field brings all the electrons up to the spectrometer and can be adjusted to provide focusing for electrons of the most probable energy (as explained later). The reversed fringing field of the spectrometer is used to dump the large number of micropulses which do not interact with the O(100) psec-lived plasma wave. This external, low-Z plastic beam dump was found necessary to limit X-ray noise on the silicon surface-barrier detectors to below the expected signal for single electrons. The 2.5 mil Teflon window, provided for experimental convenience during the initial phase of this experiment will be eliminated for the next phase.
(4) The difficulty of obtaining a suitable plasma for this experiment has been the biggest roadblock to success. The requirements for the plasma source are quite severe. Beatwave excitation of a plasma wave is a resonant process, requiring hundreds of periods to drive up the wave (at our pump intensity). From the resonance curves of Tang, Sprangle, and Sudan, we find that the plasma must be tuned to the correct density to within 6%. If we include rise-time and phase slippage effects, we find that the density must be within 1% of the resonant density (about $5.8 \times 10^{16} \text{ cm}^{-3}$ in this case) over the acceleration length (about 1 cm) or that the density scale-length must be on the order of meters. A theta-pinch plasma source was chosen for its ability to provide pre-formed, fully ionized plasmas of the requisite spatial uniformity. A generic theta-pinch source is shown schematically in Fig. 3. A capacitive discharge through a low inductance switch (a rail gap) into a single turn coil makes up the simple circuit. The ionizing electric field is due to the time-changing magnetic field. As the
magnetic field rises, the plasma formed at the walls of the inner vacuum tube gets compressed on the axis forming a long, uniform plasma near the time of the maximum of the magnetic field. As the plasma is a good electrical conductor, it is in principle field-free but in practice there is always some trapped magnetic field. As time progresses, the external magnetic field will go through zero at which point we hope to have a truly field free plasma.

![Diagram of theta-pinch plasma source](image)

**Figure 3:** Simplified picture of a theta-pinch plasma source. A quartz vacuum tube sits inside the coil.

(5) The optical diagnostics are in three parts: those which monitor the operation of the laser system, the backscatter diagnostics, and the forward scatter diagnostics. One component of the backscattered light is due to stimulated Raman scattering. In this process, a pump photon decays into a "plasmon" and a frequency-shifted, backscattered photon. The magnitude of the frequency shift is equal to the characteristic frequency of the plasmon which is essentially the local plasma frequency. By measuring the spectrum of this backscattered light, we can infer the spectrum of plasma densities within the focal volume of the CO$_2$ laser. This is the means by which we measure the plasma density for every laser shot.
An estimate of the amplitude of the plasma wave (the beatwave) can be obtained on given shot by measuring the power in one of the forward scattered sidebands to the laser frequencies. The generation of the Stokes (downshifted) and anti-Stokes (upshifted) sidebands at frequency shifts of integer multiples the beatwave frequency is necessarily part of the beatwave process. One can think, for example, of the first Stokes sideband as arising when the lower frequency pump Thomson scatters off the plasma wave. Thus, the Stokes level is a function of the amplitude and length of the plasma wave as well as the level of the lower frequency pump. We will use this fact to arrive at an estimate of the amplitude-length product of the beatwave later on.

RESULTS

Theta Pinch Parameters

A summary of the operating modes of the theta-pinch plasma source is shown in Table 1. All three conditions produced the resonant density, resulting in significant levels of excitation for the beatwave. The first condition is the standard operating mode of a theta pinch. This is when the plasma first collapses onto the axis of the pinch tube. This condition produced the most uniform plasma, as evidenced by the Raman backscatter diagnostic, but, as mentioned before, the plasma is not truly field free at this point. Also, the external circuit produced non-axisymmetric components to the magnetic field. As a result, the 1.5 MeV electron beam could not be transmitted through this plasma.

The second condition was at the point in time where the external circuit field went through zero (the "B = 0" point). This is about 1.5 μsec after the peak of compression. To achieve the resonant density at this point, one must over-fill the pinch to have higher-than-resonant density at the peak compression and then let the plasma expand until resonant density occurs at B = 0. At the same time, any trapped magnetic field will have time to diffuse out of the plasma so that the plasma will be field free. Unfortunately, there remained some residual trapped field, on the order of tens of Gauss, which itself was shot-to-shot irreproducible. This trapped field was probed by observing the deflections of the transmitted 1.5 Mev electron beam.
Table 1: Summary of theta pinch operating modes which produced resonant density.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fill Pressure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Peak of compression</td>
<td>120 mT He</td>
<td>pinch produces a uniform, dense plasma column but ~ kG trapped fields.</td>
</tr>
<tr>
<td>2. B = 0, 24 kV</td>
<td>750 mT He</td>
<td>pinch over compresses the plasma which expands to give the resonant density at B = 0; still has tens of gauss trapped fields.</td>
</tr>
<tr>
<td>3. B = 0, 14 kV</td>
<td>1750 mT He</td>
<td>pinch acts as preionization source and one must rely on laser to fully ionize: poor homogeneity.</td>
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</tbody>
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The third and most promising operating condition of the theta pinch was to use a very high fill pressure and use the electric field of the theta pinch as a source of preionization. In this case, heating from the laser beam contributes significantly to the plasma density but the data from Raman backscatter indicated that the plasma was not nearly as homogeneous as one would like, with inferred density variations of 50% from resonant density. Nevertheless, the Stokes sideband measurements\(^8\) indicated that the level of the beatwave was sufficient perhaps to observe some accelerated electrons as will be discussed shortly. The timing of the theta pinch, linac, and laser is shown in Fig. 4. The transmitted electrons were measured on-axis at the output end of the guiding field. The guiding field was optimized to collect electrons when the pinch field is off so that electrons coming before or after the B = 0 point are simply defocused out of the acceptance angle due to strong solenoidal focusing. Only a 100 nsec FWHM burst of electrons are transmitted near B = 0. The 400 psec laser pulse is then timed to occur within the transmission window of the electrons.
Stokes Measurement

As mentioned before, one can arrive at an estimate of the amplitude of the beatwave by measuring the level of forward-scattered Stokes radiation. To see why this is so, we start with the wave equation for the scattered (Stokes) electric field

\[
\left( \frac{\partial^2}{\partial t^2} + \omega_p^2 - c^2 \nabla^2 \right) E_s(r,t) = -4\pi \frac{\partial J(r,t)}{\partial t}.
\]

The source current density \( J \) is due to the coupling of the plasma wave density fluctuations \( \tilde{n} \) (oscillating at the plasma frequency) with the transverse quiver velocity \( v_0 \) of the plasma electrons in the electric field \( E_0 \) of the lower frequency pump laser (at frequency \( \omega_0 \)). That is,

\[
J = -e\tilde{n}v_0 = -e\tilde{n}\frac{eE_0}{mc\omega_0}.
\]

From these beginnings, one can derive the well-known "Bragg scattering" formula\(^9\) for the scattered power \( P_s \) in terms of the
incident power $P_0$, the amplitude $\bar{n}$ and length $L$ of the wave, and the wavelength of the scattered light $\lambda_s$;

$$P_s = P_0 \left( \frac{\pi n_o}{2 n_c} \frac{\bar{n}}{n_0} \frac{L}{\lambda_s} \right)^2. \quad (1)$$

To apply this formula to the experimentally measured quantities, we must examine the geometry of the experiment to determine what solid angles are involved. A sketch of the model used shown in Fig. 5. In this model, the grey volume in the center represents the spatial location of the beatwave having an area $A_s$ presented to the laser beam which itself has an area of $A_o$. The detection plane where the collection lens (of area $A_{det}$) is located is roughly 1 meter from the scattering volume. We assume that the divergence angle of both the laser

![Figure 5](image_url)

Figure 5: A sketch of the model used to calibrate the level of forward scattered Stokes radiation in terms of beat wave amplitude times interaction length.

beam and the scattered light beam are determined by diffraction from their respective "apertures" such that

$$\frac{A_o'}{A_s'} = \frac{A_s}{A_o}. \quad (2)$$

Let $P_s'$ and $P_0'$ be the scattered and incident powers measured through the collection lens. Also, $P_0$ does not refer to the full
laser power $P_{\text{laser}}$, but only that portion which "sees" the beatwave. We therefore have the relations:

$$P'_{s} = P_{s} \frac{A_{\text{det}}}{A_{s}^{'}} \quad P_{o}' = P_{\text{laser}} \frac{A_{\text{det}}}{A_{o}'} \quad P_{o} = P_{\text{laser}} \frac{A_{s}}{A_{o}}$$

(3)

With these, Eq. (1) becomes

$$P_{s}' \equiv P_{o}' \left( \frac{A_{s}}{A_{o}} \right)^{2} \left( \frac{\pi n_{o}}{2 n_{c}} \frac{\bar{n}}{n_{o}} \frac{L}{\lambda_{s}} \right)^{2}.$$  

(4)

For pulse durations less than half of a nanosecond, our detectors cannot resolve the pulse shapes of the radiation but rather produce a characteristic pulse the height of which is proportional to the energy of the radiation pulse. Let $U_{s}'$ and $U_{o}'$ represent the measured (through the collection lens) energies of the scattered and incident light pulses and $\tau_{s}$ and $\tau_{o}$ represent their pulse durations. We can then substitute the expressions

$$P_{s}' = \frac{U_{s}'}{\tau_{s}} \quad P_{o}' = \frac{U_{o}'}{\tau_{o}}$$

into Eq. (4) and solve for $(\bar{n}/n_{o})L$:

$$\frac{\bar{n}}{n_{o}} L = \left( \frac{U_{s}'}{U_{o}'} \right)^{1/2} \left( \frac{\tau_{o}}{\tau_{s}} \right)^{1/2} \left( \frac{A_{o}}{A_{s}} \right) \left( \frac{\pi n_{o}}{2 n_{c}} \frac{1}{\lambda_{o}} \right)^{-1}$$  

(5)

The four factors on the RHS of Eq. (5) are measured or estimated as follows.

The first factor is the level of Stokes measured at 11.06 $\mu$m compared to the level of the 10.27 $\mu$m light in the pump. For the third operating condition from Table 1 above, the maximum level of Stokes observed corresponded $U_{s}'/U_{o}' \approx 2.8 \times 10^{-4}$. These levels occurred only when resonant density was present in the Raman diagnostic and were at least 20× greater than the largest spurious background signal ever observed when the density was apparently not resonant.

The second factor in Eq. (2) is greater than unity because we expect the beatwave to lose its coherence within two or
three plasma ion periods or about 100 psec. We therefore take $\tau_0/\tau_s \approx 4$. This does not include the fact that the energy sensitivity of the detection electronics is dropping with shorter and shorter pulses, a factor which would increase this term.

The third factor reflects two contributions. One is the fact that the growth rate for the beatwave is different at different radii of the pump wave so that only the center of the pump exhibits the rapid growth. The second contribution is a result of the different solid angles of the scattered and incident beams. We estimate a ratio of diameters of two so that $A_0/A_s = 4$.

The last factor is measured as about 0.1 mm. Putting these all together, we find that the maximum product $(\hat{n}/n_0)L$ is about 0.13 mm. We need an independent measurement of the length $L$ to extract the wave amplitude. One possible way to infer the length of interaction is to use the Raman backscatter spectral width and assume that it results from scattering in a linear density gradient over the 1 cm focal depth of the laser. If one then has a theory for the amplitude of the beatwave as a function of plasma density, one could construct the expected interaction length. Rough estimates of this kind indicate that the interaction length is closer to 1 mm than to 1 cm so that $\hat{n}/n_0$ is in the neighborhood of 13%. However, to get an estimate of the maximum energy an injected electron could gain in this wave, we don't need to know specifically how large is $L$ or $\hat{n}$. This is because the energy gain is also a function of the product $\hat{n}L$, as is the Thomson scattering.

Let us express the wave amplitude as $\varepsilon = \hat{n}/n_0$. We can apply Gauss' Law to find

$$\nabla \cdot E_a = 4\pi \rho$$

or

$$E_a = \frac{4\pi \varepsilon \hat{n}}{k_\rho} \equiv \varepsilon \sqrt{n_0} \text{ V/cm}$$

which for $n_0 = 5.8 \times 10^{16} \text{ cm}^{-3}$ gives

$$E_a \equiv \varepsilon \times 24 \text{ MeV/mm.}$$
If we plug in our experimentally inferred value of $\varepsilon L = 0.13$ mm, we find

$$(E_aL)_{\text{max}} = 3 \text{ MeV}.$$
the magnetic fields in the vicinity are a quite manageable 10's of Gauss. We have tested this and similar cathodes and find, photographically, that the plasma is quite uniform over the 2 cm long electrode. We have yet to measure the density of this plasma.

If it turns out that we cannot get a density of $5.8 \times 10^{16}$ cm$^{-3}$ from this arc plasma, then we still have two options. One is to use the arc as a preionization for a laser-heated plasma using either a pre-pulse from the Mars laser or else the main pulse itself. The second option is to switch the experiment over to run on 10.6 and 10.3 $\mu$m which requires a resonant density of only $1 \times 10^{16}$ cm$^{-3}$. The arc plasma will certainly work at this density. The drawback is that the Lorentz factor associated with that beatwave will be $\gamma_{ph} = 35$ so that the trapping threshold will be substantially higher to trap the 1.5 MeV electrons.

Another improvement is to increase the current and energy of the linac. By switching to a more powerful magnetron source and improving the performance of the gun, we expect that we can increase the current by perhaps an order of magnitude and the energy from 1.5 to 2 MeV. Also, by focusing onto the 6 $\mu$m Mylar window, we can reduce the emittance and therefore the spot size at the interaction point by a factor of 3. These changes will increase the flux of electrons at the interaction point by 1 or 2 orders of magnitude, taking us out of the single particle regime.

REFERENCES