PLASMA ACCELERATORS

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## Introduction

In the continuing quest for the fundamental building blocks of matter, particle accelerators have been indispensable to physicists since the invention of the cyclotron in the 1930's. In contrast to their earliest table-top ancestor, todays synchrotrons are some of the largest machines ever built with their circumference measured in kilometers rather than in meters. It is natural to ask, therefore, if it is possible to achieve far higher accelerating gradients than the current benchmark gradient of 20 MeV/m, thereby permitting machines of ever-increasing energy but reasonable size and cost to be built.

In this talk I shall review recent progress in an emerging area of accelerator technology. This new area is characterized by extremes of the parameter space available for building accelerators. The typical dimensions of the accelerating mode are submillimeter and the accelerating gradients, on the order of 10 GeV/m, are so high that the structure is totally ionized. This area is called "Plasma Accelerators". The source of free energy which drives the accelerating mode in Plasma Accelerators is not rf, but is either in the form of lasers or electron beams.

## Space-charge Waves in a Plasma

The accelerating mode in a plasma is a relativistic electron plasma wave. A relativistic electron plasma wave is basically a space charge wave (in which the electrons are bunched with some periodicity and the ions from a uniform neutralizing background) with a phase velocity approximately the speed of light, c. Relativistic plasma waves have some general properties which are independent of the method of excitation:

Frequency: $\omega_p = (4\pi n_o e^2/m)^{1/2} = 6\times10^4 \sqrt{n_o}$

Wavenumber: $k_p = \omega_p/c$

Maximum amplitude: $eE_{max}/m\omega_p c = 1.$

Here, $\omega_p$ is the natural resonant frequency of the plasma with a density $n_o(cm^{-3})$. $E_{max}$ is the maximum amplitude of the longitudinal field which is used to accelerate particles. $E_{max}$ is conveniently related to the electron density as

$$E_{max} \approx \sqrt{n_o}\ \text{V/cm}$$

This gives rather impressive values of between 10-100 GeV/m for plasma densities in the range $10^{16}$-$10^{18}$ $cm^{-3}$. In practice, as the wave grows it develops harmonics and also traps background electrons from the plasma. Computer simulations show that one might be able to use 0.1 $E_{max}$ without significant harmonic content or self-trapped particles.

## Laser Driven Plasma Accelerators

The basic mechanism for excitation of a longitudinal plasma wave by laser light is illustrated in Fig. 1. In this scheme proposed by Tajima and Dawson[1], two parallel laser beams are co-propagated into a plasma. The difference frequency of the lasers is chosen to match the plasma frequency, so that the ponderomotive force of the beating pattern resonantly drives up the plasma wave. This accelerator is, therefore, named the Plasma Beat Wave Accelerator (PBWA)[2].

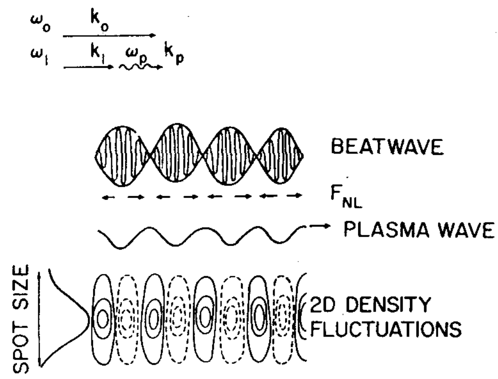


Fig. 1: Schematic of the beat wave idea.

If $\alpha_i = eE/m\omega_i c$ is the normalized amplitude of the laser, it can be shown that the plasma wave exhibits secular growth with amplitude $\varepsilon(t) = n_1/n_o$, given by

$$\varepsilon(t) = \frac{\alpha_1\alpha_2}{4}\omega_p t\,. \quad (1)$$

The maximum amplitude is reached when the plasma wave and the beat wave driver become out of phase with one another due to relativistic detuning[3]. The saturated amplitude is given by

$$\varepsilon_{max} = \left[\frac{16}{3}\alpha_1\alpha_2\right]^{1/3}. \quad (2)$$

Expression (2) is valid in principle for $\alpha_1$, $\varepsilon \ll 1$ but simulations indicate that it is a reasonable approximation for values of $\alpha < 0.5$ and $\varepsilon < 0.8$[4].

Causality demands that the phase velocity of the plasma wave has to be the same as the group velocity of the light waves. If the laser frequencies are much higher than $\omega_p$, then $v_{ph}$ is very close to c and the injected relativistic particles may stay in phase with electric field of the plasma wave for a significant distance to be accelerated to high energy.

In practice the plasma wave will be driven by laser pulses that have a finite risetime, $\alpha_i(t)$. Onset of plasma turbulence due to ion motion restricts the laser pulse widths that can be used to drive the plasma wave to a duration less than the ion plasma period. This turns out to be ≈ 43 plasma wavelengths for a hydrogen plasma. The group velocity of the plasma wave behind the laser pulse is almost zero; thus the energy remains in the plasma oscillation until it is eventually dissipated by electrostatic wave-wave coupling. The trick in this plasma accelerator scheme is to efficiently beam load the plasma wave just behind the laser pulse to extract as much of the energy as possible, while maintaining the beam quality (energy spread and emittance).

### Plasma Waves Driven by Electron Bunches

An alternative method for exciting a relativistic plasma wave was invented by J. Dawson who realized that the energy density in existing electron or proton bunches can be comparable or exceed that in the most powerful of today's laser beams. In a scheme proposed by Chen, Dawson, Huff and Katsouleas[5], a dense compact bunch is shot through a high density plasma. The space charge force of such a bunch displaces the plasma electrons and leaves behind a wake of plasma oscillations. The phase velocity of this wake, like that of the wake behind a boat, is tied to the velocity of the driving bunch ≈ c. The acceleration mechanism in this scheme is exactly the same as in the PBWA. A trailing beam appropriately phased in this plasma wake can gain energy from it, much in the same way that a surfer gains energy from an ocean wave. This scheme is called the Plasma Wake Field Accelerator (PWFA)[6].

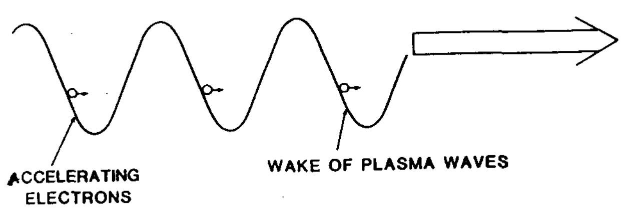


Fig. 2: Schematic of the wake-field idea.

If one uses a single symmetric bunch with a length that is much smaller than the wavelength of the plasma oscillation, the maximum energy gained by the trailing particles (assuming like particles) is limited to $< 2\gamma_b mc^2$ where $\gamma_b$ is the Lorentz factor associated with the driving particles. A solution to this dilemma was pointed out by Bane et al.[7] who showed that by using a properly shaped bunch, the trailing particles could exceed this limit of $2\gamma_b mc^2$ imposed by the "wake-field theorem". The precise shape of the driving bunch is not critical. It should have a ramped density, with a risetime of ten or so plasma wavlengths, with a rather sharp cut-off. The cut-off time should be less than $\omega_p^{-1}$.

The basic mechanism behind obtaining large wake fields with shaped bunches is as follows:[8] When a shaped electron bunch enters the plasma the plasma sees an excess of negative charge. Since the charge builds up slowly, the plasma electrons move out both transversly and longitudinally to neutralize the bunch field. The shielding continues until the tail of the bunch exists the region. Then suddenly the plasma, which was nearly neutral, is left with a non-neutral space charge of amplitude that is equal to the charge density at the peak of the driving beam. Clearly, the peak beam density should not be greater than the plasma density. Each plasma electron at this point acts like a spring pulled out to its maximum amplitude and released, setting up an oscillation at frequency $\omega_p$ and the phase velocity tied to the driving bunch velocity. This scheme is conceptually similar to other wake field transformer schemes[9] which utilize the wake fields of a low voltage, but high current driving beam to accelerate a low current bunch to high energies. In this scheme the plasma rather than a structure, acts as the transformer which has a high transformer ratio.

### Computer Simulations of Plasma Wave Excitation

#### Plasma Beat Wave Accelerator

Figure 3 shows the results of a 1-D, relativistic, self-consistent particle simulation[10] in which the beating lasers are injected from the right. In 3(a) the beating pattern of the two lasers (which are rising in intensity from left to right) is clearly visible. In 3(b) we see the longitudinal electric field pattern of the plasma wave. The peak amplitude of the laser fields was 100 GeV/m, whereas the beat excited plasma wave saturated due to relativistic detuning at 55 GeV/m. The results of the numerical solution to the fluid equation[3] are also shown for comparison with the particle code prediction. The two are seen to be in excellent agreement.

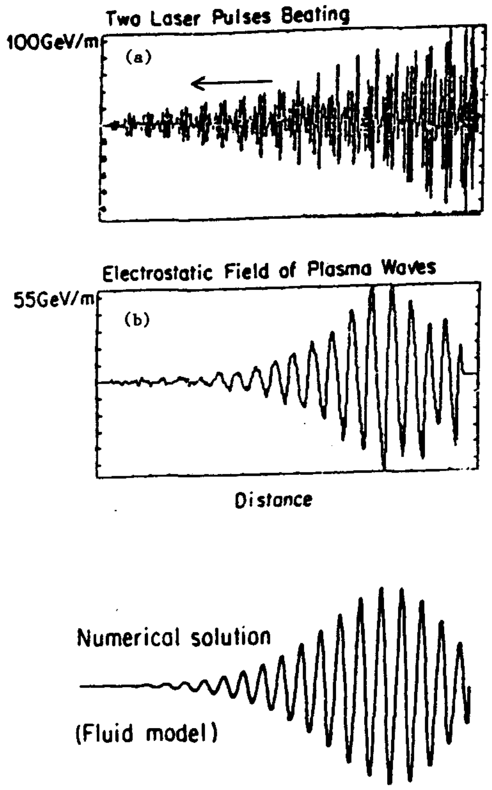


Fig. 3: 1D Particle simulation results of beat excitation of a plasma wave.

Recently the computer models have been extended to 2D[4,11] to examine the transverse stability of the lasers and the plasma wave. A parameter regime has been identified which essentially reproduces the 1D results. Basically, if the laser beams are less than $\omega_{p_i}^{-1}$long, then the ion motion is not too worrysome and one can obtain a fairly planar plasma wave right up to saturation. There are 2D effects that influence particle acceleration such as the radial electric fields, but these are common to both the PBWA and the PWFA will be discussed later.

#### Plasma Wake Field Accelerator

Figure 4 shows the numerical solutions of 1D wake fields produced by various bunch shapes. The ideal bunch shape is one for which the retarding field within the bunch is uniform[8]. Such an ideal situation can only be reproduced by placing a delta function precursor in front of a triangular bunch. Without such a precursor, the wake field inside the triangular bunch $E_-$, although much smaller than the wake field behind it $E_+$, is a displaced sinusoid. Defining the transformer ratio R as $E_+/E_-$ we can see that it is now possible to obtain large values of R.

The linearly ramped and sharply cut-off bunches can only be approximated in an experiment. A more realistic driving bunch would have a long Gaussian rise time and a short Gaussian fall time.

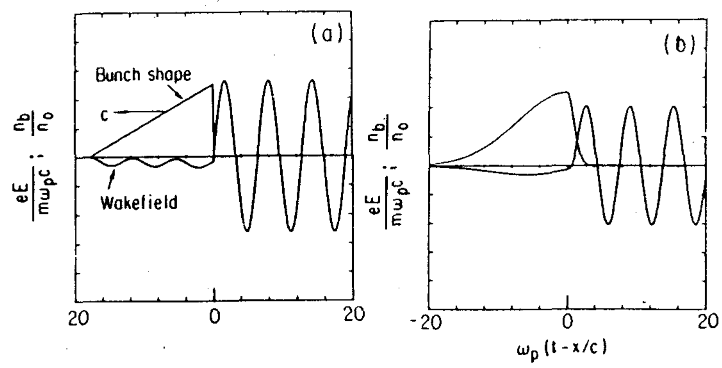


Fig. 4: Wake fields in a plasma excited by a triangular bunch and a Gaussian bunch.

Such a bunch turns out to be more desirable. The retarding field $E_-$ inside the Gaussian bunch is smoother. The driving beam particles, therefore, will slow down roughly at the same rate leading to less distortion of the bunch. The sharp cut-off of the driving bunch is not too critical as long as it is shorter than $c/\omega_p$.

The beam shaping and cut-off requirement may prove to be one of the toughest technological challenge in realizing the PWFA. For example in a plasma density of $10^{15}$ cm$^{-3}$, the cut-off time must be on the order of one picosecond.

Acceleration Mechanism and Limit to Energy Gain

In the PBWA, the phase velocity of the plasma wave is $c(1 - \frac{1}{2}\omega_p^2/\omega_o^2)$, where $\omega_p$ is the plasma frequency and $\omega_o$ is the frequency of the laser. The ratio $\omega_p^2/\omega_o^2$ is equal to the ratio $n_o/n_c$, where $n_o$ is the electron density and $n_c$ is the critical density at which $\omega_o = \omega_p$. The relativistic factor associated with this phase velocity $\gamma_{ph} = \omega_o/\omega_p$. In the wave frame a particle can only see an accelerating and focusing field for a maximum distance of quarter of a wavelength. In the lab frame, after Lorentz transformation, this turns out to be $\frac{1}{4}\gamma_{ph}^2 c/\omega_p$ . Since the longitudinal accelerating field is Lorentz invariant, the maximum energy gain limited by this dephasing is $\int \underline{E}\cdot\underline{dl} = \varepsilon/4\sqrt{n_e}\ \gamma_{ph}^2 c/\omega_p$, where $\varepsilon$ is the fraction of the density perturbation.

For optimum energy gain we want the plasma density to be as high as possible. At the same time the waves should have a high phase velocity. In other words, the ratio of $\omega_o/\omega_p$ should be as large as possible. An example based on using a KrF laser, shown below, gives a maximum energy gain of 16 GeV limited by phase slip which is probably the best that can be done in a single stage.

**Table 1: Single Stage Parameters for tne PBWA**

| | |
|---|---|
| **Laser wavelength** | **0.25 μm** |
| **Plasma density** | **$10^{17}$ cm$^{-3}$** |
| **$E_z$** | **3 GeV/m** |
| **$\varepsilon$** | **0.1** |
| **Length** | **5.4 m** |
| **Energy gain** | **16.2 GeV** |
| **Plasma wavelength** | **100 μm** |

What are the laser requirements for such a compact accelerator? There are considerable uncertainties at present in evaluating this. The main uncertainty is in estimating the laser to plasma wave coupling efficiency. At a first glance it would appear that the maximum efficiency is simply $\omega_p/\omega_o$ as demanded by the Manley-Rowe relation for a three wave process, or the conservation of wave action. This is fortunately not the case. In the beat excitation process, we get a series of frequency upshifted (anti-Stokes) and frequency downshifted (Stokes) sidebands, each shifted in frequency from its neighbor by $\omega_p$. If we could preferentially excite the frequency downshifted sidebands, while for each cascade transfer $\omega_p/\omega_o$ amount of energy to the plasma wave, we might improve the efficiency. In principle the two original electromagnetic waves will cascade until they downshift to frequencies close to $\omega_p$. Unfortunately, because of dispersion, the group velocities of the cascaded waves are not the same and the cascades might actually broaden the k spectrum of the plasma wave. Only experiments will determine this important issue. Nevertheless, we give some idea of what might be required from the laser. These are to be taken as non-optimized parameters.

**Table 2: Laser and Plasma Wave Parameters for Example in Table 1**

| | |
|---|---|
| **Laser-Plasma wave coupling efficiency** | **≈ 10%** |
| **Build-up time of the plasma wave** | **15 ps** |
| **Laser pulse-width (square pulse)** | **15 ps** |
| **Laser beam diameter** | **500 μm** |
| **$\alpha = v_o c$** | **0.04** |
| **Laser energy** | **200 J** |
| **Plasma wave diameter (plane wave)** | **500 μm** |
| **Plasma volume** | **1 cm$^3$** |
| **Plasma wave energy** | **16.65 J** |

Clearly a proof-of-principle experiment to a few GeV level is not impossible with a modest extrapolation of todays KrF laser technology. In order to gain more energy one has to either contemplate staging or invent a scheme for phase-locking the particles[12].

In the PWFA, the situation is somewhat better. Here the requirement that the driving bunch to truncated in a time < $\omega_p^{-1}$ means that plasma densities must be at most $10^{16}$ cm$^{-3}$. This assumes that 1 ps is probably the sharpest cut-off time that can be achieved. The phase velocity of the wave; however, can be arbitrary depending on the beam energy. For beams with low energy, as shown in Fig. 5, dephasing still limits the maximum energy gain but for high energy beams pump depletion limits the energy gain.

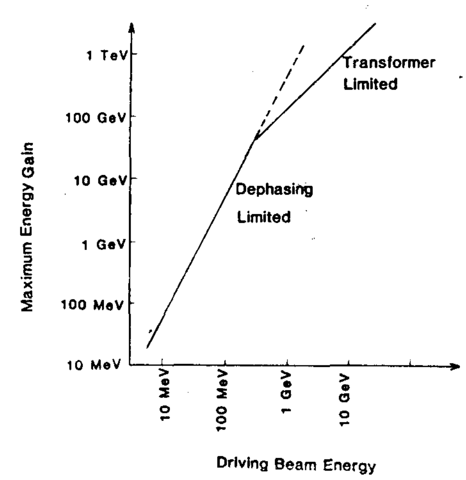


Fig 5: Maximum energy gain for a fixed beam current of 125 amps in PWFA. The spot size is assumed to be $c/\omega_p$.

The useful design equations which describe the acceleration gradient and final energy which can be gained in the PWFA are:

$$eE = \varepsilon\sqrt{n_e} \quad \text{eV/cm} \quad ,$$

$$\Delta\gamma = N\pi\varepsilon\gamma_b \; \frac{\varepsilon\gamma_b}{N + \varepsilon\gamma_b} \quad ,$$

where $\varepsilon$ is defined as the ratio of the peak driving beam density to the plasma density ($\varepsilon = n_b/n_e < 1$) and N is the length of the driving bunch normalized to the plasma wavelength. The two other design criteria are the spot size ($2\,r_b$) and the cut off time ($\tau$) of the driving bunch :

$$2r_b > c/\omega_p \approx 5 \times 10^5/\sqrt{n_e} \quad \text{cm} \; ;$$

$$\tau < \pi/\omega_p \approx 5 \times 10^{-5}/\sqrt{n_e} \quad \text{sec.}$$

If the spot size is chosen to match $c/\omega_p$, the normalized bunch density $n_b/n_e$ can be calculated in terms of the current I (Amps)

$$\frac{n_b}{n_e} = 10^{-3}\, I \; .$$

Thus, $n_b/n_e = 1$ for $I = 1$ kA. The corresponding wake field amplitude is simply

$$eE = (n_b/n_e)\sqrt{n_e} \;\; \text{V/cm} = 10^{-3}\, I(\text{amps})\sqrt{n_e(\text{cm}^{-3})} \;\; \text{V/cm.}$$

## Transverse Effects and Instabilities

In addition to the longitudinal $E_z$ accelerating field the plasma wave in the PBWA has a significant radial field component $E_r$. This force is associated with the transverse variation of the plasma density due to the spatial intensity variation of the pump beams. The radial fields are both focusing and defocusing and the relative magnitude of $E_r$ compared to $E_z$ depends on the transverse dimensions of the plasma wave. Figure 6 shows radial variation of $E_r$ and $E_z$ for a Gaussian laser beam of size $k_pR = 3$. One can see that the maximum value of $E_r$ is $0.5E_z$. Figure 7 shows $E_z$ and $E_r$ variation with z. It can be seen that the accelerating particles will see a focusing and an accelerating field over only a quarter of the wavelength.

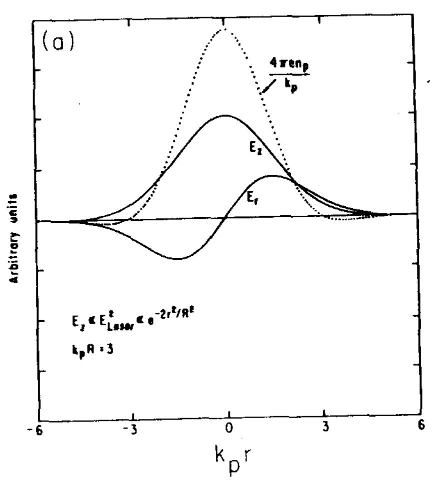


Fig. 6: Self-consistent longitudinal, $E_z$, and transverse, $E_r$, electric field profiles of the plasma wave.

In the beat wave accelerator it is of some importance to know not only the field distribution in the focal plane of the lasers but also their phase variation. This is particularly true if diffraction limited beams are not used.

In both the PBWA and the PWFA most of the usual laser or beam plasma instabilities are avoided by using driving beams that are only a few picoseconds long. An extensive discussion of the possible instabilities is found in Ref. (4) and (11). We note here that in the case of the PBWA, one instability that cannot be suppressed by simply going to very short laser pulses is the relativistic self- focusing. The threshold for this instability ($10^{12}$ W for $CO_2$) is rather high. It may be possible to actually use this instability to keep the laser beams focused over a distance greater than the Rayleigh length, thus utilizing the laser energy more efficiently.

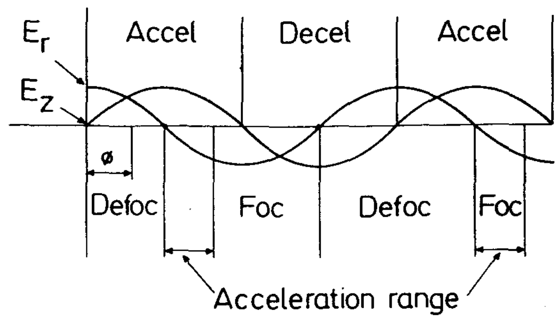


Fig. 7: Schematic of the variation of $E_z$ and $E_r$ with z.

## Beam Loading and Efficiency

The term "beam loading" refers to the fraction of the energy in the accelerating mode that can be transferred to the accelerating beam. Clearly, we want to maximize this while keeping the energy spread and the emittance of the beam as small as possible. Because of the extremely small size of the accelerating buckets in the plasma accelerators, efficient beam loading consistent with emittance and energy spread requirements is going to be a challenge to achieve.

Katsouleas et al. have calculated the beam loading achievable in both the beat wave and the wake field case[13]. In the former case, we assume that a very short laser pulse excites the plasma wave and the accelerating bunch or bunches are injected immediately behind the laser pulse before the plasma wave looses its coherence. In the wake field case, the second bunch should ideally be immediately behind the driving bunch.

In order to reduce the energy spread of the beam without lowering the beam loading efficiency, the use of an accelerating bunch that is ramped down in density has been suggested[13]. In the 2D analysis beam loading efficiencies of up to 20% appear feasible[13]. Of course, beam loading efficiency is only one of the factors determining the overall efficiency of the plasma accelerator. The efficiency $\eta$ is given by

$$\eta = \eta_1\, \eta_2\, \eta_3 \; ,$$

where
- $\eta_1$ = wall plus to laser (10% maximum) or wall plug to driver beam from linac (30%)
- $\eta_2$ = laser to plasma wave (10% for $\omega_o/\omega_p \approx 30$) or beam to plasma wave (50%)
- $\eta_3$ = plasma wave to accelerated beam (20%)

Thus

$$\eta_{\text{beatwave}} \approx 2 \times 10^{-3} \text{ and } \eta_{\text{wake-field}} \approx 3 \times 10^{-2}.$$

## Experiments

Experiments are being carried out at UCLA[15], Rutherford Laboratory[16] (U.K.), ILE (Japan)[17], INRS (Canada)[18], and elsewhere on the reproducible excitation of the relativistic plasma wave by beating lasers and controlled acceleration of externally injected test particles by the plasma wave. In a recent UCLA experiment[15], the relativistic plasma wave was excited by beating the 9.6 μm and 10.6 μm lines of a $CO_2$ laser, with a modest intensity of $2\times10^{13}$ W/cm$^2$, in a $10^{17}$cm$^{-3}$ density plasma. The plasma wave electric field was inferred from Thomson scattering of a probe laser beam to be $10^3$ MeV/m, a substantial improvement over the current benchmark gradient for accelerators. The results of the UCLA experiment that conclusively demonstrated the excitation of the relativistic plasma wave by beating lasers are shown in Fig. 8.

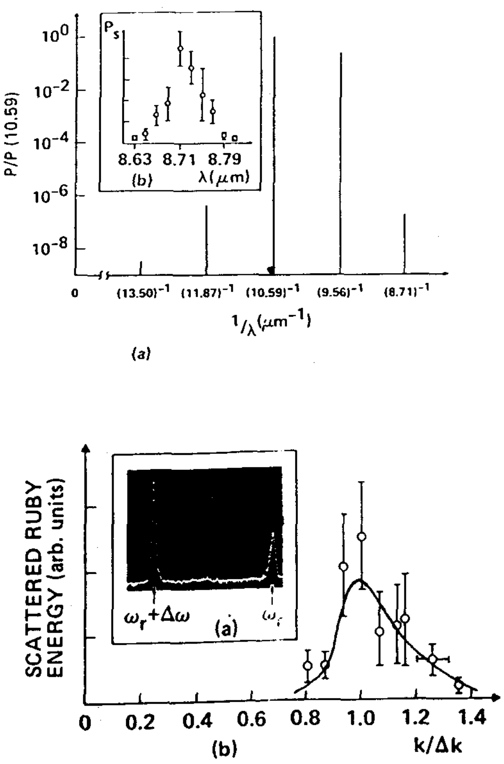


Fig. 8: Infrared scatter spectrum (a) showing Stokes and anti-Stokes sidebands in the forward direction and ruby Thomson scattering (b) of the probe beam showing frequency shifted signal by $\omega_p = \omega_{beat}$. (UCLA experiment[15])

A new mechanism which saturates the beat-excited plasma wave in this parameter regime was discovered[19]. The relativistic plasma wave saturates, on the time scale of a few picoseconds, by coupling to other plasma modes which have a much lower phase velocity, via an ion ripple due to stimulated Brillouin scattering of the laser beams. A scaled up experiment which will demonstrate controlled acceleration of injected electrons is currently underway at UCLA. Experiments on the wake field concept are planned at UCLA and at Wisconsin.

## Prospects of a Plasma Accelerator

So what are the prospects of building a future collider using either the PBWA or the PWFA scheme? Clearly it is too early to tell. Even if the proposed proof-of-principle experiments demonstrate high-gradient, controlled acceleration, thereby confirming the promise of these schemes, several important technological issues still need to be addressed. The first, is the effect of plasma fluctuations on the reproducibility of the acceleration process, and on the ability to collide two beams that must be aligned to within a few angstroms of one another. The second, is the efficiency of the accelerator. It is clearly not enough to miniaturize the accelerator; it must also be cheaper. Staging is another important issue, particularly for the PBWA.

## Acknowledgements


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## Discussion

A.A.Kolomensky. What is your opinion about tolerancy on plasma uniformity or on the plasma density as a function of longitudinal coordinate?

C.Joshi. There are effects, both detrimental, of the variation of plasma density from its resonant value at $\omega_{beat} = \omega_p$. The first is, as the plasma density drops, the amplitude of the space-charge wave drops. An estimate of this can be obtained from looking at the Q of the beat wave resonance. From fluid theory the density perturbarian $\varepsilon = n_1/n_0 = (16/3 \cdot V_0/c)^{2/3}$ for equal intensity lasers. It is reasonable to think that a ramped decrease in density if $O(\varepsilon)$ can be tolerated. The situation is different if there is a density increase from the resonant value. The relativistic detuning effect can now be compensated leading to an enhanced response at certain densities.

There is another effect of the plasma fluctuations. The group velocity of the lasers can increase or decrease as the density decreases or increases. The phase velocity of the plasma wave is equal to the group velocity of the lasers. The accelerating parameters therefore slip forward or backward as the density increases or decreases. This will give energy spread and emittance spread to the beam. The quantitative estimate of how much of a density variaring one can tolerate is now being calculated.

A.A.Kolomensky. Were in your laboratory or in other USA laboratories the measurements have done of the electron energy spectrum after passage through the plasma, exited by the laser beam?

C.Joshi. We have concentrated on understanding the basic physics of the beat wave exitation and competing phenomena. Our accomplishments are the first demonstration of relativistic space charge waves, saturation of these waves by electrostatic mode coupling. Recently we have been looking at plasma wave axcitation due to $\omega_{beat} = 2\omega_p$ instability. Our scaled - up experiment is designed to demmonstrate the acceleration of 1.5 MeV electrons, injected from a linac, to about 20 MeV using a $5.8 \cdot 10^{16}$ cm$^{-3}$ plasma excited by 9.6$\mu$m and 10.3$\mu$m lines of a 100 ps long $CO_2$ laser.

There are experiments at ILE (Japan) and IPJRS (Canada) on beat wave acceleration.

S.O.Schriber. Would you comment on INRS, University of Quebec measurements on accelerating electrons in plasma devices?

C.Joshi. In a recent experiment at INRS, Quebec, a $CO_2$ laser operating on 10.6$\mu$m and 9.6$\mu$m lines was focussed in a gas jet target to both produce the plasma and excite the space-charge wave. A fraction of the laser energy was diverted and focussed on a solid target to produce a jet of high energy electrons. Electrons with energies in the range 500 KeV were energy selected and focussed in the plasma using a focusing spectrometer. The electrons exciting the plasma were momentum analysed. Their preliminary results show evidence of particle acceleration and further confirmance of these results is awaited with interest.

S.P.Kapitza. Apart for lasers and electron beam have you considered the use of free electron lasers for exciting plasma waves for accelerating particles?

C.Joshi. A group at the University of Wisconsin has suggested the use of a two frequency FEL driven by a pelletron as a driver for PBWA. Development of a high repetitional rate (1-5 kHz) driver delivering lops long pulses containing 100 joules is essential for realizing a working PBWA. Of couse an FEL is attractive because of its potential for high efficiency.