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# Photon acceleration by laser produced wakefields on Astra

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## Introduction

In refraction, it is well known that a spatially varying refractive index brings about a change in the wavevector, which we call k, without altering the frequency, termed $\omega_0$, of the incident light. We can think of the situation where the refractive index changes in time but not in space and call it 'time refraction'. In this symmetric situation, the wavevector, k, remains unchanged while the frequency changes to satisfy the dispersion relation. For a plasma the dispersion relation is given by:

$$\omega_0^2 = k^2c^2 + \omega_p^2 \qquad (1)$$

With $\omega_p$, the plasma frequency, varying as the square of the electron charge, e, and the root of the plasma density $n_e$, thus:

$$\omega_p^2 = \left(\frac{e^2 n_e}{\varepsilon_0 m_e}\right) \qquad (2)$$

If we generalize these two types of refraction, we can formulate a theory encompassing all space and time variations in refractive index. The frequency shifting associated with this is commonly referred to as photon acceleration[1)].

The term 'photon acceleration' was first used in a simulation based paper by Wilks *et al.*[2)]. He noted that photons can exchange energy with a plasma through the action of the ponderomotive force. It was noted that the frequency shifts experienced by the laser were dictated by gradients, both in time and space, in the local refractive index and hence plasma density.

Simulation and theory has suggested that photon acceleration in plasma waves could be used to characterize plasma waves in regimes where other techniques cannot operate[3)]. The regime we have chosen is one of increased interest due to recent work on the production high quality electron beams[4 - 6)].

If the driving laser pulse is shorter than half the plasma wavelength, the whole of the laser pulse acts to increase the wakefield amplitude. This energy transfer to the plasma results in redshifting of the laser beam, or photon deceleration. However, if the laser pulse is made longer than this, the tail of the pulse will experience an upshift in energy. Up-shifted photons stay in the accelerating phase of the wakefield longer than decelerated photons. Hence, due to this non-linear dispersion, a characteristic asymmetry arises, with greater frequency blueshifts than redshifts.

We report for the first time photon acceleration from longitudinal wakefields. This can be seen as a proof of principal for the first non-intrusive diagnostic for the accelerating structure in a laser wakefield accelerator.

## Experimental Setup

The experiment was conducted using the Ti-Sapphire Astra laser at the Rutherford Appleton Laboratory. The laser delivered pulses of wavelength 790 nm (bandwidth 20nm FWHM), energy 360 mJ and pulse duration $\tau$ = 40 fs to target. The 60 mm-diameter laser beam was focused onto a supersonic helium gas jet target with an f/17 off-axis parabolic mirror, giving a focal spot of 25 μm (FWHM). An equivalent plane monitor indicated that 50% of the delivered laser energy was within this focal area. The intensity on target was $I\lambda^2 =$ 5.7x10$^{17}$ Wcm$^2$μm$^2$, corresponding to a peak normalized vector potential $a_0$ of 0.8. The gas jet, when ionised, produced uniform plasmas with densities in the range 1x10$^{19}$ cm$^3$ and 3x10$^{19}$ cm$^3$. Over this range, the characteristic period of plasma oscillation ($2\pi/\omega_p$) is from 0.5 $\tau$ to 0.75 $\tau$. The supersonic gas jet ensures that the laser impinges on the gas target within one Rayleigh length of its maximum intensity.

Transverse optical imaging revealed an interaction length of $\delta x$ ~ 650 μm. The light transmitted through the helium gas target was collected and collimated using a 0.44 m-focal length on-axis parabolic mirror, steered out of the vacuum chamber using flat silver coated mirrors and then focused onto the entrance slit of a 0.25 m optical spectrometer, equipped with a 150 lines per millimetre diffraction grating. A 16-bit CCD camera recorded the dispersed spectra on a single shot basis.

## Experimental Results and Discussion

Figure 1 shows an example optical spectrum taken at a plasma density of 1.8x10$^{19}$ cm$^3$. The dotted line indicates the central frequency of the initial laser spectrum, $\omega_0$. Several features are noticeable. First, the spectra are shifted to both lower and higher frequency with respect to $\omega_0$. However there is a clear asymmetry, with the light displaced furthest from $\omega_0$ being more intense on the 'blue' side. Second, distinct Raman scattered peaks are visible at lower frequencies. The separation of the peaks did increase with increasing density as expected. They provide an unambiguous measure of the plasma density n, since they are separated from $\omega_0$ by the plasma frequency which can been seen in Equation (2) above.

There are also Raman peaks shifted by half the plasma frequency, as have been predicted[7)].

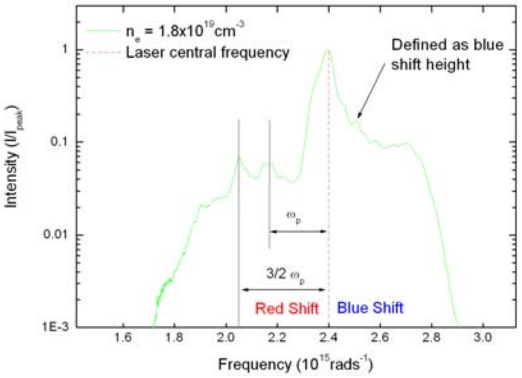

**Figure 1.** Optical spectrum. The blue shift is seen as a broad shoulder to the main pulse. The plasma density is retrievable from the Raman sidebands.

The pressure in the gas jet was varied to allow different plasma densities to be studied. The most noticeable feature of this scan was that the blue shoulder decreased with increasing plasma density. For consistency, the first prominent peak to the blue side of the fundamental (as indicated in Figure 1) was taken as indicative of the blue shifted intensity. The results of four shots are summarised in Figure 2. The values are in dimensionless units normalised to the peak intensity.

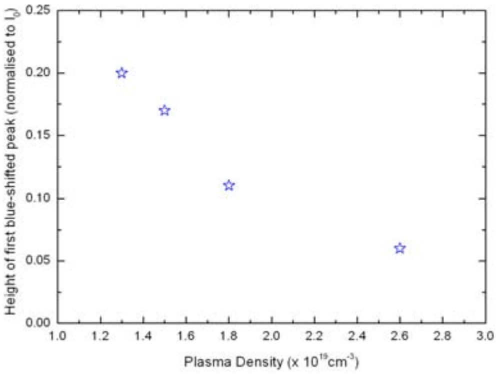

**Figure 2.** The variation of blue shift intensity with plasma density.

This decrease in blue shift intensity with increasing plasma density serves as evidence contrary to much previously published work.

In the past, such blue shifting has been attributed solely to changes in density due to rapid optical field ionisation8). If this were the case, it could be expected that the blue shift would increase as the gas density increased, which is not observed. A fall in normalized blue shift intensity with increasing density was observed at high density in one study. This was attributed to preferential scattering of the up-shifted light out of the collection optics9). The wavelength shift observed in this case was less than 0.5% (1 nm at 249 nm).

Other studies have reported greater shifts of up to 10% (>100 nm at 1054 nm)10) but in all of these previous measurements, the pulse length was significantly longer than the plasma wave length ($c\tau >> \lambda_p$). Also the interaction length was much longer than the Rayleigh length and so these previous experiments can expect ionistion to begin when the pulse is far from the focal volume. This means that a significant amount of the laser pulse can be blueshifted by ionisation effects.

In our experiment, however, ionisation effects cannot explain the decreasing level of blueshifts with increasing density or the blueshifting of almost half of the laser energy. Here, the pulse has an intensity close to $10^{18}$ Wcm$^{-2}$ over the whole interaction length; the foot of the laser pulse should be able to fully ionise the helium at intensities just above $10^{16}$ Wcm$^{-2}$. Note that use of a supersonic gas jet, which has a density ramp 500 µm, means that the peak of the pulse cannot ionise gas at much lower intensity when it is far from focus. Finally, ionisation cannot account for the observed redshift, since over the timescale of the laser pulse, the plasma density can only increase due to optical field ionisation.

Figure 3 shows what happens to the optical spectrum at higher laser intensities. It should be noted that this graph is on a linear scale to allow better observation of the splitting in the main spectral peak. This split appears in place of the Raman peaks which were present at lower laser intensity. Still, a large portion of the light has been shifted.

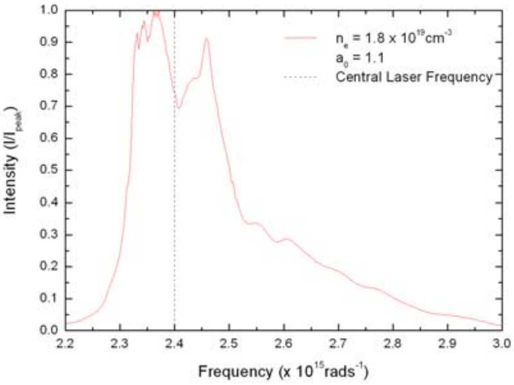

**Figure 3.** Optical spectrum taken at higher laser intensity. The red shift appears a split in the fundamental.

The best explanation for this is that the higher laser intensity causes the wakefield to grow rapidly. This rapid growth causes a large number of photons at the front of the pulse to be compressed and, as a result, red-shifted. This effect would normally continue as before resulting in Raman peaks appearing as the light is shifted further to lower frequencies. The absence of such shifting implies that the light (which moves backwards in the wave as it is red-shifted) is no longer in a plasma gradient. That is, the wave is so non-linear that all of the plasma gradients are at the extremes of the wavebucket. Such nonlinear waves are highly susceptible to breaking and indeed electrons were observed on this shot.

Simulations have been carried out which appear to back-up these hypotheses and can be found elsewhere in this report11).

## Conclusions

We have shown that frequency upshifting by photon acceleration in laser produced wakefields has been observed. We can show that the rate at which a plasma wave grows and the amplitude it reaches are parameters intimately connected with the spectrum of the transmitted light from the driver pulse. We have proven, in principal, that observing photon acceleration may be used as a non-intrusive diagnostic for relativistic plasma waves of interest to particle acceleration.

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