THE IC/RAL BEAT-WAVE EXPERIMENTS

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ABSTRACT

We report on attempts to detect a relativistic plasma wave excited when the frequency difference between two co-propagating neodymium glass laser beams is close to the plasma frequency. In the first experiment (Jan 86) detection of the plasma wave by monitoring the sidebands formed on the laser light was made impossible due to Raman scattering by atmospheric nitrogen. Further, the plasma formed by a Z-pinch was not reproducible or uniform enough to obtain a resonance. Multiphoton ionisation of hydrogen gas at pressures of a few torr using a frequency doubled neodymium laser was investigated (June 86) and found to produce extremely uniform plasmas, the density corresponding to 100% ionisation. This was used in the last experiment (May 87) where the two I.R. laser beams followed separate paths and were mixed under vacuum. However, detection of the plasma wave was not possible due to the CARS effect in the mixing optics.

1. INTRODUCTION

The need to probe smaller and smaller distances in matter has led to the requirement for huge increases in particle accelerator energy. To accelerate a charged particle to relativistic velocities requires a longitudinal electric field and a phase velocity close to c. A plasma being fully ionised does not suffer from breakdown which limits the maximum fields achievable in a conventional accelerator. It has the major advantage that the maximum longitudinal electric field of a relativistic plasma wave is

$n_e^{1/2}$ (cm^{-3}) Vcm^{-1}, so that for number densities $n_e \sim 10^{20} cm^{-3}$ the maximum field is $\sim 10^{10}$ Vcm^{-1} orders of magnitude greater than a conventional structure. The major disadvantage is that plasmas are inherently unstable. The beat-wave mechanism1) is an interesting method of producing a relativistic plasma wave and requires that two parallel laser beams of slightly different frequencies are focused onto a plasma of resonant frequency $\omega_p = \omega_1 - \omega_0$. Since this is a resonant process the plasma density is required to be reasonably uniform, perhaps for as much as 100m for an accelerator. Using a neodymium glass laser (~1μm) requires the plasma number density be within about 0.5% of the resonance value, compared to the much less stringent condition of a few percent for the CO_2 lasers (~10μm) used by others in this field2,3). However, the phase velocity v_{ph} of the plasma wave, characterised by the Lorentz factor $\gamma = (1-(v_{ph}/c)^2)^{-1/2} = \omega_0/\omega_p$, is much larger ($\gamma$=100) than for a CO_2 laser (γ=10) and so is more relevant to particle acceleration. In order to avoid excessive collisional damping of the plasma wave the plasma temperature should be greater than about 20eV, but not too much higher than this to minimise trapping of background plasma electrons. Preliminary experiments in this field have used DC arc discharges, Z or theta pinches, or air breakdown plasmas. These are recognised as having inadequate homogeneity and reproducibility for accelerator applications. Multiphoton ionisation of hydrogen gas produces exceptionally uniform plasmas with appropriate density and temperature and the technique is scalable to plasmas of arbitrary size4).

2. EXPERIMENTAL ARRANGEMENT

The experiments were conducted at the SERC Central Laser Facility using the Vulcan neodymium glass laser. This was used to give 1.064 μm (YAG) and 1.053 μm (YLF) pump beams each delivering ~50J in a pulse of 200ps full width at half maximum (f.w.h.m.). The first experiment5) (Jan 86) used a Z-pinch to create a preformed plasma into which the pump beams were focused by a 3m lens, f/30 optics. The size of the focal spot was measured with an equivalent focal plane camera to be about 400μm in diameter. A frequency doubled YLF beam (5265 Å) delivering ~10J and of 1ns f.w.h.m. was focused using a 1m lens, f/10 optics, to give a spot size of 200μm diameter and used as a Thomson scattering probe, the scattered light collected at four scattering angles (20,60,120,160 degrees). Light from diametrically opposed channels was fed into the same spectrometer by means of a spherical mirror, the light emerging from the spectrometers was fed into two streak cameras whose time dispersion separated the direct and reflected light components. The experimental arrangement is shown in Fig. 1.

The I.R. light emerging from the pinch tube was attenuated by wedged uncoated mirrors and focused into a spectometer, the spectrally resolved light was fed into an S1 streak camera. This channel, known as the cascade,

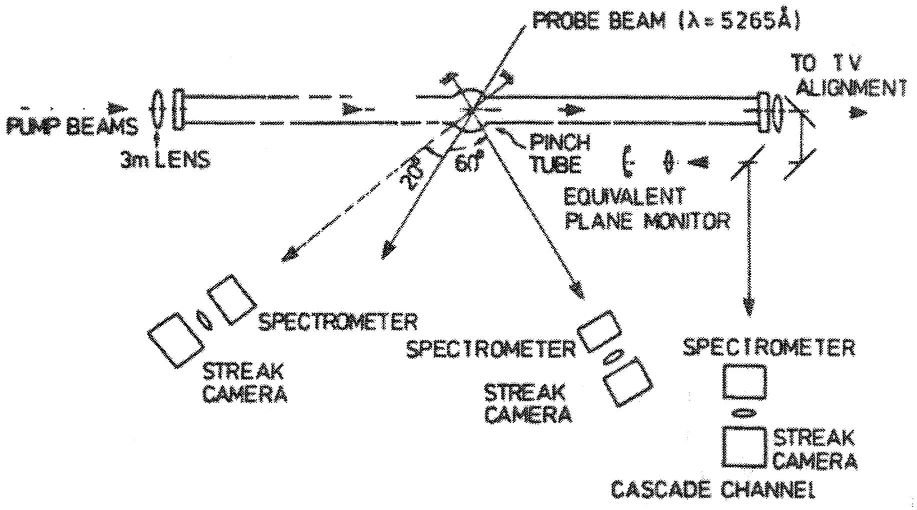

Fig. 1 The experimental layout for the first beat wave experiment

was set up to monitor the development of spectral sidebands on the pump light which are generated by the interaction of the pump beams with the relativistic plasma wave. Unfortunately it was impossible to measure the amplitude of the plasma wave as the simultaneous propagation of both laser frequencies through an air path of ~30m gave rise to strong Raman scattering. A quick fix to attempt to minimise this effect was to use a Michelson arrangement introduced into the beam paths just before the 3m focusing lens, see Fig. 2. The time delay of the two arms of the Michelson arrangement was set to be the same as the deliberate desynchronisation of the laser beams. To further minimise the air region in which both wavelengths were synchronous the Michelson arrangement was enclosed and flushed with argon. In addition a 0.1% transmitting I.R. mirror was placed at the output of the pinch tube. This considerably reduced the amplitude of the sidebands but was not effective enough.

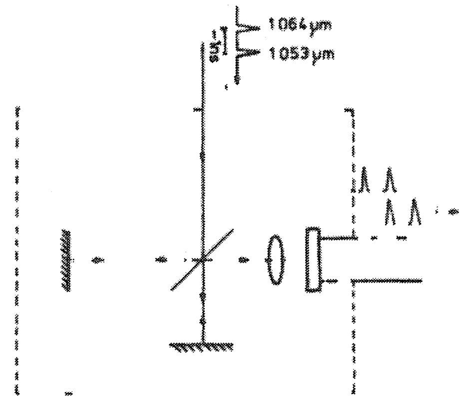

Fig. 2 The Michelson arrangement used to recombine the pump beams

For the multiphoton ionisation experiment$^{6)}$ (June 86) a frequency doubled YLF beam delivering ~10J and of 200ps f.w.h.m. was focused using a 2m lens, f/20 optics onto hydrogen gas at pressures from 0.5-4 torr. The size of the focal spot was measured with an equivalent plane camera to be about 400μm, the focussed irradiances were about 10^{14}Wcm^{-2}. The same beam also acted as a Thomson scattering probe and the scattered light was collected at four angles (20,60,120,160 degrees). The streak camera output was recorded on HP5 film and a calibration wedge was recorded individually for each data shot. The overall layout of the scattering and other diagnostics is shown in Fig. 3. The spectral and temporal resolutions were respectively about 5Å and 100ps. The gas filling pressure was measured with a calibrated MKS baratron head.

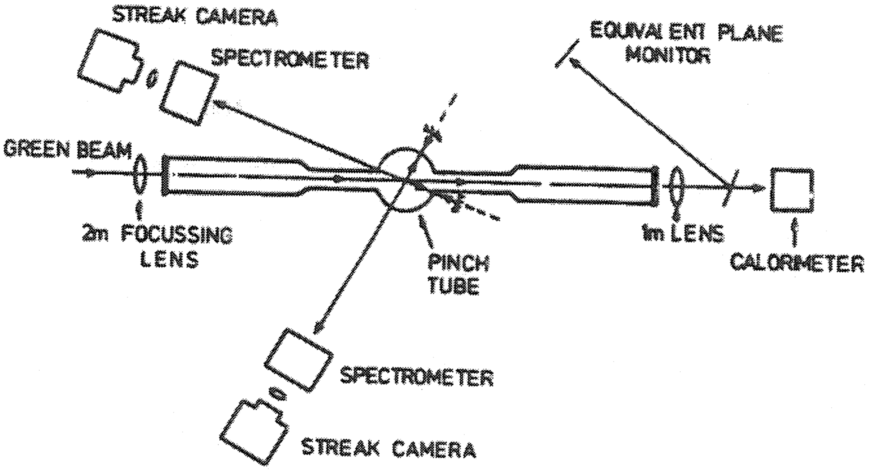

Fig. 3 Schematic arrangement of the multiphoton ionisation expt

The experimental arrangement used in the last experiment (May 87) is shown in Fig. 4. The pump beams each delivering ~50J and of 200ps f.w.h.m. were focused by a 2m lens, f/20 optics, to give a 250μm diameter spot size. The plasma was preformed by a frequency doubled YLF beam delivering ~10J and of 200ps f.w.h.m., focussed using the same 2m lens as for the I.R. beams and a negative correcting lens to give a focal spot at the same location as the I.R. beams of size 400 μm. The target chamber was filled with hydrogen gas at pressures from 1-2 torr. The two pump beams were amplified using different rod chains, followed separate air paths and were orthogonally polarised, finally being mixed together under vacuum and their polarisations matched. A 0.1% transmitting I.R. mirror was placed at the output of the target chamber, the emerging light further attenuated by wedged uncoated mirrors before being focused onto a Bentham spectrometer and then an S1 streak camera. These precautions were taken in order to avoid Raman scattering by atmospheric nitrogen. Thomson scattered light was collected from the preionising green beam and from a separate green probe beam whose relative timing could be varied. The scattered light was collected at four scattering angles for both the preionising beam (40,58,122,140 degrees) and the probe beam (18,64,116,162 degrees). Using this arrangement the plasma conditions could be determined both before and after the pump beams had passed through the plasma.

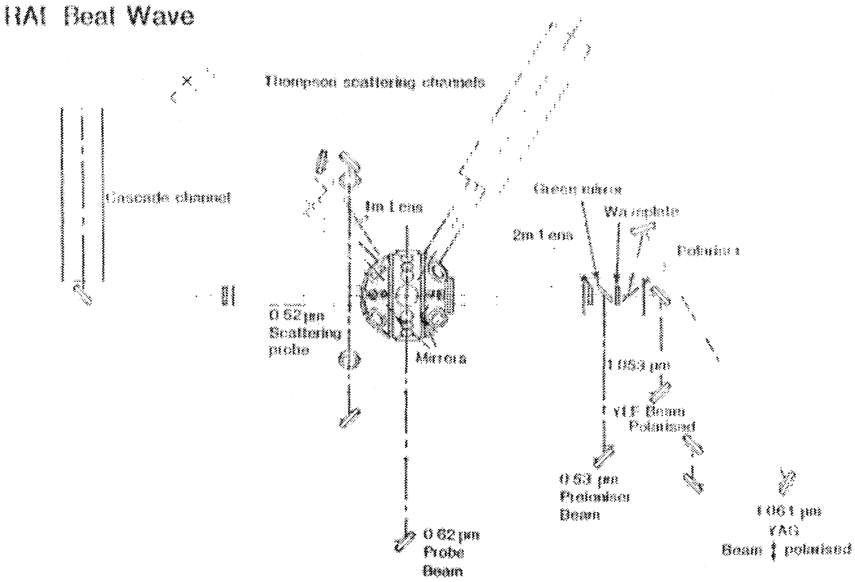

Fig. 4 Experimental layout for the second beat wave experiment

3. EXPERIMENTAL RESULTS

The planned use of the cascade channel in the first experiment was made impossible by the unexpected near coincidence of the difference frequency of the pumps =98.2 cm^{-1}, with the S(11) rotational line of nitrogen at 99 cm^{-1}. The resulting strong Raman scattering gives the spectrum shown in Fig. 5, two Stokes and two anti-Stokes lines can be seen on the originals. These sidebands were not observed at the output of the laser amplifiers and were a consequence of the air propagation path. The Michelson arrangement very substantially reduced the Raman scattering but this was still large enough to compete with the expected plasma wave signal. To assist in detecting the weak sidebands the pump lines were masked off by an ND2 strip before entering the streak camera. A typical time resolved spectrum using the Michelson arrangement is shown in Fig. 6, notice that there are still sidebands when only the second YLF pulse is present. The Michelson arrangement is inefficient in that only one quarter of the laser energy is effective in driving the plasma wave.

For the multiphoton ionisation experiment the Thomson scattering results were in the form of four simultaneous time resolved spectra. The 20 degree scattering channel is predominantly sensitive to electron density which it gives by direct measurement of the frequency separation of the plasma satellites. The 160 degree channel is mostly sensitive to electron temperature but in the two other channels the shape of the scattered light spectrum is dictated by both parameters and a fitting procedure is required. The photographic data were corrected for film response, spectrometer and streak camera sensitivity and finally fitted in a least squares sense to the

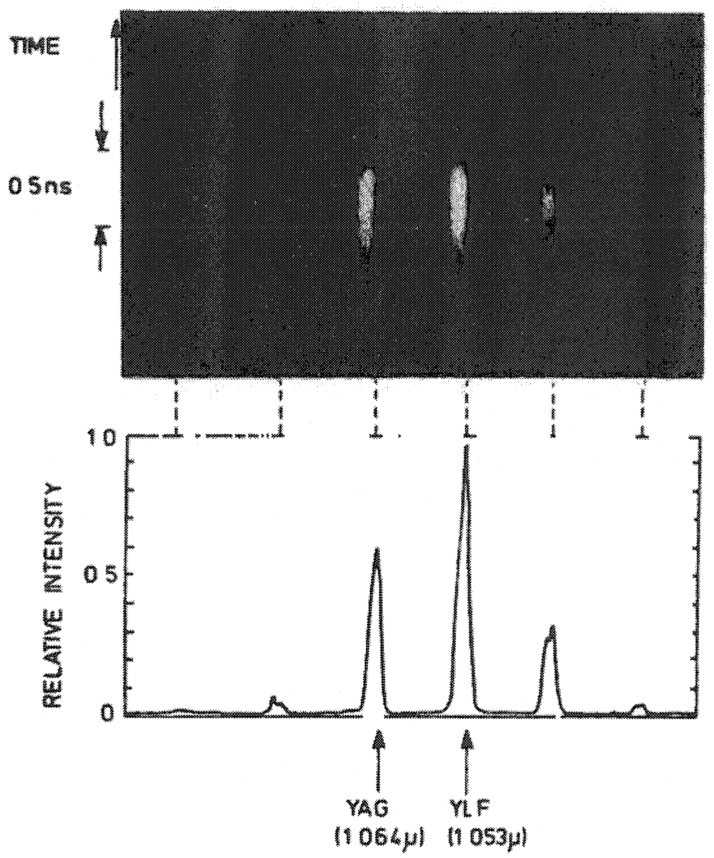

Fig. 5 Spectrum of I.R. pump lasers due to Raman scattering

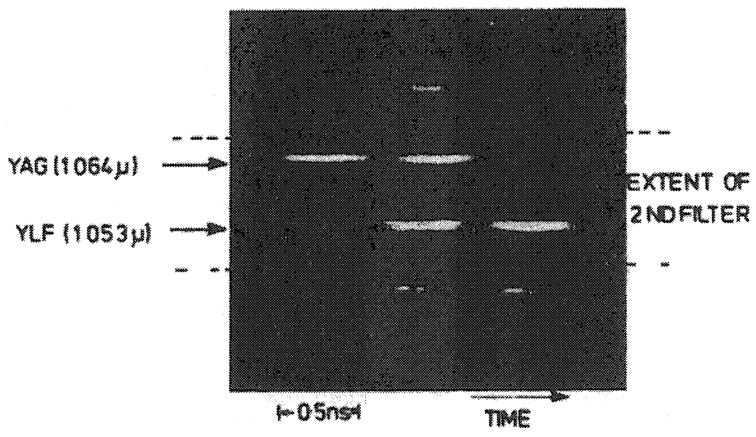

Fig. 6 Spectrum obtained with Michelson interferometer in place

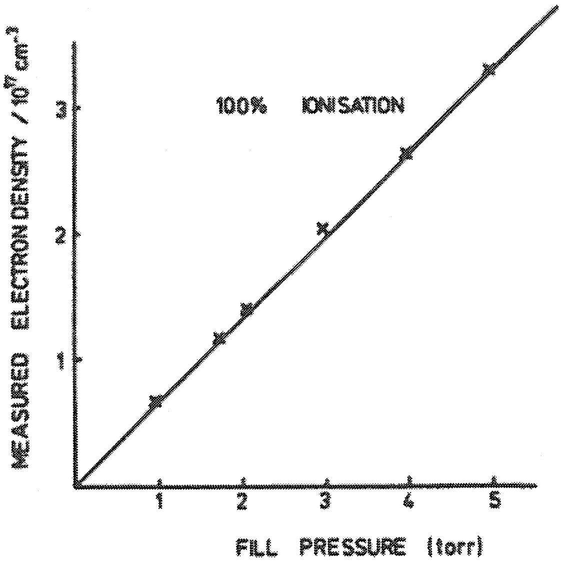

Fig. 7 Electron density as a function of fill pressure

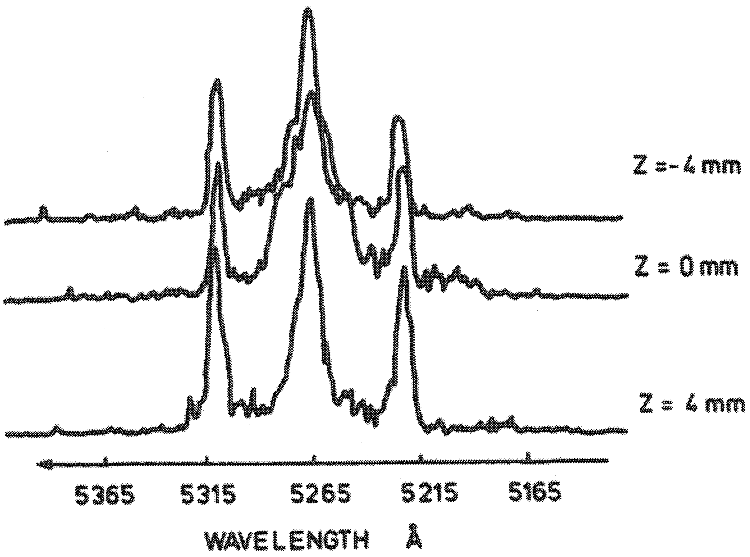

Fig. 8 20 degree scattering signals from three axial positions theoretical Thomson scattering profiles. For all the data, the electron density did not vary with laser irradiance. The measured electron density as a function of gas fill pressure is shown in Fig. 7. The electron density is proportional to fill pressure, and corresponds to 100% ionisation to within the measurement error. Fig. 8 shows the results of defocusing the input lens by +4,-4mm axially while keeping the scattering volume fixed in space. This has the effect of measuring the electron density variations along the axis of the main focusing lens. The densitometer scans show that there is no measurable variation of ω_p at the 2% level, corresponding to a 4% uncertainty in n_e. The electron temperature is measured to be about 8-10eV.

In the last experiment use of the cascade channel to detect the plasma wave was impossible due to the CARS effect in the optical components where the pump beams were together. This resulted in sidebands several times larger than those expected due to a plasma wave, giving spectra similar to Fig. 5. Four simultaneous Thomson scattered signals were obtained for both the preionising green beam and the green probe beam, and by varying the timing of the probe beam it was possible to study the time evolution of the plasma. Typical spectra obtained are shown in Fig. 9. By comparing the scattered light profiles of the 160 degree (preioniser) and 120 degree (probe) channels the heating of the plasma by the pump beams can be determined. Typical profiles are given in Fig. 10. and show a temperature increase from ~12eV to ~25eV, in this example the probe was delayed 400ps with respect to the pump beams. The theoretical profile, which assumes a Maxwellian distribution, does not fit the scattered signal from the heated plasma as well as the fit obtained with the signal from the preformed plasma. This suggests that the heated plasma is non-Maxwellian or turbulent. The measured increases in temperature due to the pump beams show only a slight dependence on the preformed plasma density, there being no indication of large increases corresponding to a particular resonant density which would be expected if a large amplitude plasma wave were driven and then decayed into thermal energy. The analysis of the data from this experiment is not yet complete.

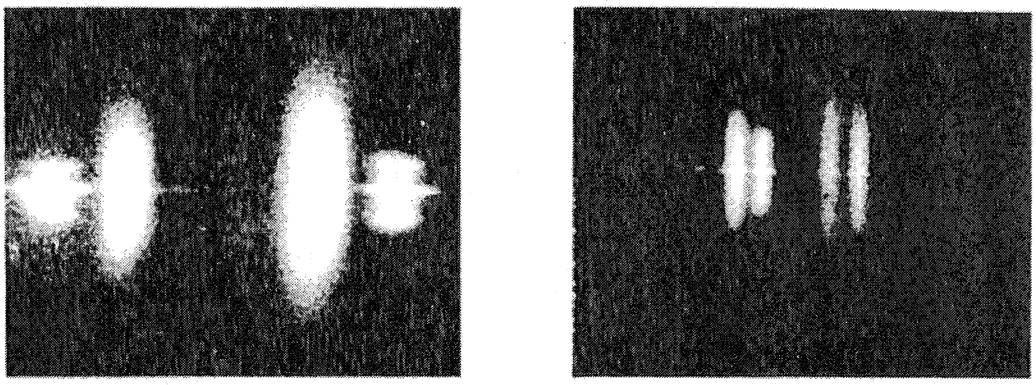
(18,140,162,40 degrees) (64,58,116,122 degrees)

Fig. 9 Typical Thomson scattering spectra

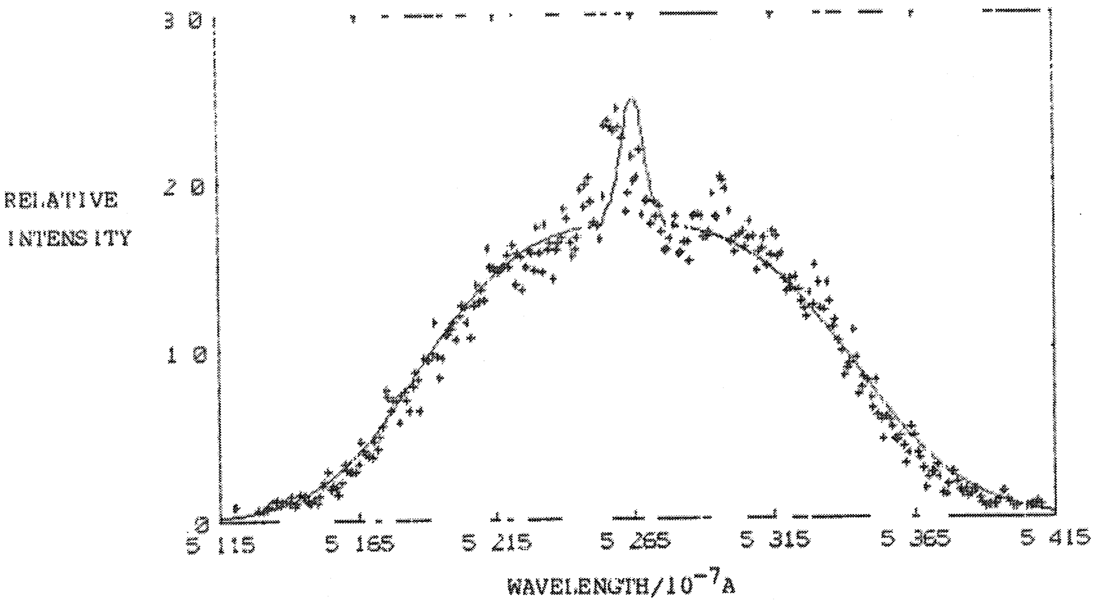

Fig. 10a Computer generated best fit to the 140 degree signal, T_e=12eV

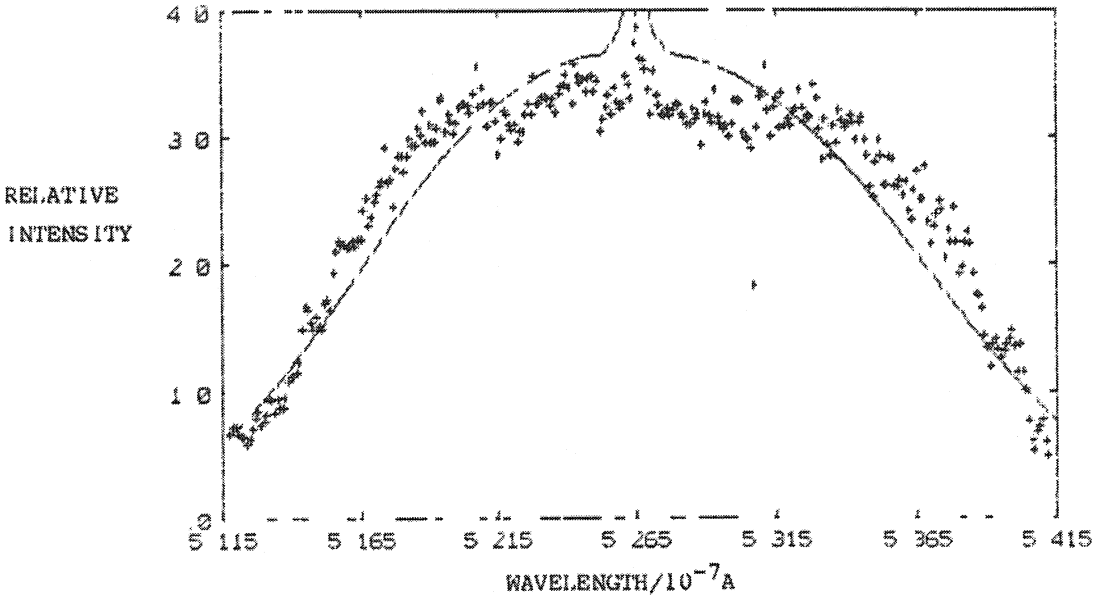

Fig. 10b Computer generated best fit to 162 degree signal, T_e=25eV

4. DISCUSSION

We have modelled the plasma heating with a single one-dimensional (cylindrically symmetric) computer code, modelling inverse bremsstrahlung absorption, thermal conduction, ion electron equilibration and hydrodynamic expansion. The classical absorption cross section is modified to allow for the reduction in collision frequency[7,8] when the electron oscillation velocity in the light wave $v_{osc}=eE/m\omega_p$ exceeds the thermal speed $v_e=(k_BT_e/m)^{1/2}$. The electron thermal conductivity is limited by the electron free streaming limit. The model gives very good agreement to the data obtained from the multiphoton ionisation experiment using the standard value of the flux limit[9] $f=0.1$ and the modified inverse bremsstrahlung cross section.

5. CONCLUSIONS

We have studied the laser ionisation of molecular hydrogen, using Thomson scattering techniques to measure the time and space resolved density and temperature. Our results show the gas is fully ionised over a length of at least 1cm using 2m focusing optics. The uniformity of the plasma is very high and appears to be more than adequate for performing future beat wave experiments. However, we have as yet been unable to detect the presence of a relativistic plasma wave.

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6. REFERENCES

1) Tajima T, Dawson J M, Phys. Rev. Lett. 43, 267 (1979)
2) Clayton C E, Joshi C, Darrow C, Umstadter D, Phys. Rev. Lett. 54, 21, 2343 (1985)
3) Ebrahim N A, Martin F, Brodeur P, Heighway E A, Matte J P, Pepin H, Lavigne P, Proceedings 1986 Linear Accelerator Conference Stanford Ca.
4) Dangor et al., IEEE Trans. on Plasma Sci. 2, 161 (1987)
5) Dangor et al., RAL Annual Report RAL-86 046, A1.1 (1986)
6) Dangor et al., RAL Annual Report 1987 (to be published)
7) Pert G J, Journal of Physics A 5, 506 (1972)
8) Rand S, Phys. Rev. B 136, 231 (1964)
9) Bell A R, Evans R G, Nicholas D J, Phys. Rev. Lett. 46, 243 (1981)

Discussion

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Have you taken into account the density shift needed to account for the fact that the plasma wave is not many wavelengths wide?

Reply

No. However, the target gas pressure and hence the plasma density was varied from 1 to 2 Torr (resonance at 1.67 Torr expected with a large spot size) Most shots were at about 1.67 Torr No heating resonance was observed but not all results are yet analysed.