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HETERODYNE DETECTION OF RUBY LASER LIGHT SCATTERED IN A THETA PINCH PLASMA

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ABSTRACT

Ruby laser light scattered by a 10^{16}cm^{-3}, 5 eV deuterium theta pinch plasma has been detected and its frequency and wavelength spectra measured by heterodyne techniques using a vacuum photodiode as a mixer, stray light radiation as the local oscillator, and a UHF communications receiver as a frequency analyser.

Scattered light came predominantly from $\underline{k}$ vectors parallel to the magnetic field. Frequency and wavelength distributions showed maxima at 680 MHz and 4×10^{-3} cm respectively, consistent with scattering by an ion acoustic wave corresponding to plasma temperature 8 eV. The temperature deduced from the plasma diamagnetism was 4.8 eV.

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1. Introduction

The circumstance that collectively scattered electro-magnetic radiation is influenced by most plasma parameters including the electron and ion temperatures[1] makes it an attractive candidate for diagnostic purposes. Collective scattering is only observable however when the plasma Debye length λ_D is less than the scattering scale length as determined by the incident radiation wavelength λ, and the angle of scattering θ, viz

$$\alpha \equiv \frac{1}{k\lambda_D} = \frac{\lambda}{4\pi\lambda_D \sin\theta/2} \gtrsim 1 . \qquad \ldots(1)$$

Although collective scattering experiments designed to verify theory have been performed at angles of only a few degrees with ruby lasers, thus corresponding to scale lengths of a few μm, magnetically confined plasmas of interest in current fusion research have λ_D of the order of 100 μm. The unusually long scale length implied by this value can be reached only by accepting scattered light from very small scattering angles, or by turning to radiation sources, usually lasers, whose wavelengths are very much longer than the familiar ruby or even CO_2 TEA system. Attempts to detect scattered radiation at very small scattering angle are always complicated by the intense stray laser radiation which increases with decreasing scattering angle, and this has made very small angle scattering seem prohibitively difficult.

At the Xth Conference on Phenomena in Ionised Gases[2], we proposed a means of overcoming these difficulties through the use of heterodyne detection in which stray light would play the role of local oscillator. An experiment based on this proposal was performed and a short description subsequently presented by us at the XIth Ionised Gas Conference[3]. The purpose of this paper is to put on record a more detailed account of that experiment.

Briefly, pulsed ruby laser light, scattered at angles as small as 0.5° in a theta pinch plasma, was collected by a lens and appropriate focal plane stops, and directed onto a photocathode where it was mixed with stray light at the laser wavelength. This generated an electric signal at the beat frequency which was analysed by conventional electronic means.

Methods of this kind had already been used at visible wavelengths, but CW, not pulsed, to study for example, Brillouin scattering in liquids [4]. CW heterodyne methods have also been applied in plasma physics both in the microwave region [5] and at 10 μm [6]. Very recently a CW FIR laser at 1.22 mm has been used to measure density fluctuations in the University of California Microtor tokamak [7].

Because the foregoing experiments were conducted on a CW basis, their application for diagnostics is confined to plasmas whose lifetime is unrestricted or at least very long. The authors believe the experiment described in the present paper and briefly reported earlier [3] was the first to apply heterodyne methods to scattered radiation from a pulsed laser, certainly a pulsed ruby laser.

Before the pulsed ruby heterodyne experiment was performed on a plasma, a preliminary investigation was undertaken in which the scatterer was a train of ultrasonic waves in liquid paraffin, driven by a 10 MHz quartz crystal oscillator. The purpose was to demonstrate that the heterodyne apparatus would respond to the short laser pulses in such a way as to yield the correct frequency distribution. The positive results of this exercise encouraged us to proceed to the plasma experiment.

2. Heterodyne Detection; Signal-to-Noise Ratios

The theory of heterodyne detection [8] shows that when a weak optical field having its intensity distributed over frequency according to some function $I_s(\nu)$ and a strong local oscillator at a fixed unique frequency $\nu_{\ell o}$ are superimposed on a photocathode under conditions which meet the requirements of the vanCittert and Zernike coherence theorem [9], the resulting photocurrent i has a power spectrum $P_i(\nu)$ proportional to $i_{\ell o}$, the photocurrent due to the local oscillator alone, and to $I_s(\nu-\nu_{\ell o})$ the intensity spectrum of the weak radiation, transposed to the beat frequency $\nu-\nu_{\ell o}$.

That this is plausible can be seen by taking the beat frequency component of the photodiode current to be proportional to the square of the sum of the electric fields associated with the signal and with the local oscillator,

i.e. $i \sim |E_s+E_{\ell o}|^2 = I_s + I_{\ell o} + 2\sqrt{(I_s I_{\ell o})} \cos 2\pi(\nu-\nu_{\ell o})t$.

The frequency analyser in turn produces an output which is proportional to the square of the beat frequency term:

$$i_{out} \sim i^2 \sim I_{\ell o} I_s \sim i_{\ell o} I_s \quad .$$

The vanCittert and Zernike condition ensures that mixing takes place by requiring the etendu = area x solid angle $\leq \lambda^2$ at every stage in the collection optics, for example on the photocathode.

The signal-to-noise ratio in the frequency analyser output current is given by [8]

$$S = \frac{s}{1+s} \sqrt{(1 + \Delta\nu_{IF}\ T)}$$

where s is the signal-to-noise ratio immediately following the photodiode, i.e. at the input of the IF amplifier, $\Delta\nu_{IF}$ is the bandwidth of that amplifier and therefore defines the spectrum resolution interval, and T is the integration time.

Possible noise sources that could contribute to s include intensity fluctuations in the laser output, plasma light, amplifier noise, and local oscillator shot noise. It is desirable that the latter should dominate all the rest, because then

$$s = \frac{P_s}{P_{np}} = \frac{I_s}{\left(\frac{h\nu}{\eta}\right)}$$

where P_s is the signal, P_{np} the pulsed noise, and η the photocathode quantum efficiency. Estimates of the strengths of all the above contributions have been made for our experiment, and we conclude that while shot noise is probably dominant, a CW noise component cannot be ignored. We thus define

$$s = \frac{P_s}{P_{np} + P_{nc}}$$

identifying P_{nc} with this continuous amplifier noise.

It is also convenient to introduce the idea of the visibility D to measure the amplitude of the pulsed signal with respect to the prevailing CW noise level, and this is

$$D \equiv \frac{P_s}{P_{nc}} \sqrt{(1 + \Delta\nu_{IF}\ T)} = \frac{P_s/P_{np}}{P_{nc}/P_{np}} \sqrt{(1 + \Delta\nu_{IF}\ T)}\ .$$

The futility of using a laser brighter than that necessary to make $s = 1$ is plain from the foregoing, for if $s = 1$, then $S = \frac{1}{2}\sqrt{(1 + \Delta\nu_{IF}\ T)}$, but if s is made to increase without bound, S only doubles at most.

If continuous noise P_{nc} were negligible by comparison with shot noise, the laser power necessary to perform a pulsed heterodyne detection experiment would be given by setting the scattered power per unit frequency interval I_s equal to $^{h\nu}/_{\eta}$.

Using $I_s d\omega = I_o r_e^2 n_e L\Omega \, S(k,\omega)\, d\omega = \frac{h\nu}{\eta} \frac{d\omega}{2\pi}$

where L is the length of beam over which scattering takes place, Ω is the collection solid angle, I_o is the incident laser power, and the other symbols have their usual meanings, applying the etendu = λ^2 condition for heterodyning, and substituting $n_e = 10^{16}$ cm^{-3}, T_i = 4 eV, η = 0.03 electrons per photon, $\theta = 1^\circ$ and $\Delta\theta = 0.1^\circ$, we find the minimum laser power necessary to make s=1 to be 0.5 MW.

3. Experimental Assembly

A diagram of the experimental assembly is presented in Figure 1. The plasma produced in a theta pinch discharge was illuminated across a diameter by a narrow beam of pulsed ruby laser light. Radiation scattered by the plasma in the near forward direction fell on the fast photodiode where it mixed with some of the stray incident laser light. The resulting photocurrent was spectrally analysed on a shot by shot basis by means of a UHF communications receiver, the output of which was displayed on an oscilloscope. The receiver and the oscilloscope were housed in an electrically screened room.

3.1 The Plasma

This was a theta pinch discharge in a 10 cm diameter quartz tube fitted with two diametrically opposed side arms which terminated in optically flat quartz windows mounted at Brewster's angle with respect to the side arm axis. The quartz tube was located within a 20 cm long single turn coil through which the 6 μF capacitor was discharged. Charging voltage was 30 kV and the resulting ringing current wave form had a half period of 5 μs, producing a peak axial magnetic induction of 1.1 tesla in the second half-cycle.

The plasma density was measured using a calibrated streak camera [10] to observe the radiated visible continuum, and the resulting radial density profile at the peak of the second half cycle turns out to be parabolic with peak density 1.1×10^{16} electrons cm^{-3}, while at a radius of 1.8 cm, the density had fallen by one order of magnitude.

The plasma energy was measured by the diamagnetic loop method [11] and gave an average value of plasma $\beta = 0.3$, and an average temperature $\frac{1}{2}(T_e+T_i) = 4.8$ eV .

3.2 The Laser

The laser used in this experiment consisted of a 4"x $^9/_{16}$" ruby in an oscillator configuration, followed by one stage of amplification using a 9"x $\frac{3}{4}$" rod. The laser pulses used in this experiment were 50 ns long and 70 MW average power.

Oscillograms of the laser pulses measured with the fast photodiode and displayed on a Tektronix 519 oscilloscope were comparatively smooth with only a trace of modulation associated with inter-mode beating. This suggested that the laser output was predominently single mode. This low intensity mode structure of the pulse was examined by measuring its homodyne spectrum using the communications receiver. The resulting beat frequency distribution was found to consist of a sequence of pulses located at approximately 150 MHz intervals across the whole bandwidth under examination, that is, over about 1 GHz. The principal peak at zero frequency shift was unobservable owing to a characteristic of the frequency analyser, but the amplitudes of the peaks that could be measured were similar within a factor of 2 or 3 .

When scattered radiation was observed, it was apparent that the beat frequency signal produced by it was about two orders of magnitude weaker than the adjacent laser peaks, taking into account the nonlinear response of the receiver, which must have been approaching saturation at the voltage levels reached in these peaks.

This observation, taken together with the comparatively smooth, fast time-resolved pulse oscillograms, leads to the conclusion that the laser output was confined mainly to a single strong longitudinal mode, and that the homodyne spectrum is generated by beating between a succession of very much weaker modes and this intense fundamental. The fundamental can likewise be regarded as alone responsible for the scattered light signal. No evidence for other transverse modes was found.

3.3 The Optics

The laser beam was focused into the plasma by a f=100 cm lens so that the optical aperture was approximately F/50. After entering and leaving the plasma vessel through Brewster angle windows, the beam was directed onto an OB10 blue glass dump.

Light scattered into the forward direction between 0.5° and 2.65° passed through the same exit window as the unperturbed beam but missed the beam dump and was collected by a 50 cm lens located 80 cm from the plasma mid-plane. A stop having a variable annular aperture was located in the focal plane of this lens and served to select the range of scattering angles as well as to define the collection solid angle. Following this, in the plane where the plasma was imaged a distance of 133 cm from the lens, was another stop immediately in front of the photodiode. By masking the annular focal plane aperture in azimuth, it was possible to select the range of azimuthal angles φ from which scattered light was accepted. In this way, the azimuthally-stopped annular aperture served to define the differential scattering vector $\underline{k}$ not only in amplitude, but also in direction.

The range of scattering angles $\Delta\theta$ contributing to the collection angle actually used at any time was about 0.3°, while the range of azimuth was $\varphi = 45^{\circ}$. The resulting collection solid angle

$\Delta\Omega \sim \varphi\ \theta\ \Delta\theta = 7\text{x}10^{-5}$ steradians, corresponding to a coherent collection area = $7\text{x}10^{-5}$ cm^2. As the actual collection area, defined by the image in the plasma of the stop on the detector, was more than an order of magnitude larger than this the measured signal strength will have been correspondingly larger than that expected for a single coherent etendu, but the value of the signal-to-noise ratio s will have been the same as if only one coherence etendu had contributed [8].

Stray light, unshifted in frequency, and scattered probably on the entrance or exit windows of the plasma vessel, was able to reach the photodiode through the collection optics. It was this light, together perhaps with some contribution from the skirt of the diffracted laser focal spot that served as local oscillator to generate the beat frequency spectrum.

3.4 The Detector System

Scattered light mixed with local oscillator radiation on the S20 photocathode of an Instrument Technology Ltd (Kenley, Surrey) vacuum photodiode. This had a nominal risetime of 0.2 ns, and a sensitivity quoted as 1.8×10^{-4} amp watt^{-1} at 0.7 μm wavelength, corresponding to a quantum efficiency η=0.032 electrons per photon. A 100Ω transmission line conveyed the photocurrent to the Eddystone 990S UHF communications receiver. The latter was calibrated over the range 230 to 870 MHz, and had an IF bandwidth of 12 MHz.

4. Experimental Results and Their Interpretation

Photo-mixed signals from the detector are shown in Figure 2. The bottom oscilloscope trace shows the signal when the plasma is present but the laser has not been fired, the middle trace when the laser was fired but no plasma was present, and the top trace when the laser was fired into plasma. These show that radiation scattered or refracted by the plasma is being detected.

The frequency spectrum of the detector photocurrent was constructed from a sequence of laser and plasma discharges, and the distribution from 550 to 780 MHz is shown in Figure 3 . The most striking features are the peaks near 600 and 750 MHz. These and others like them appear at 150 MHz intervals throughout the whole frequency range accessible to the analyser. Since they appear even when the plasma is absent, it seems reasonable to attribute them to beating of pairs of longitudinal laser modes.

The smaller, broader, feature located between 650 and 700 MHz appears only when the laser beam traverses the plasma, and is accordingly interpreted as due to scattered light. There is also evidence of scattered light at other frequencies, but it appears most reproducible near 680 MHz. This feature, frequency shifted from the wavelength of the incident laser light, is convincing evidence that the light being observed has actually experienced Thomson scattering, and has not been merely refracted by the plasma.

Although the signal amplitude at the frequency analyser output was rather irreproducible, it was up to an order of magnitude more intense than the prevailing continuous noise level at 680 MHz, and could readily be distinguished from it. This is the property we have called the "visibility" D , and allows us to estimate $P_s/P_{nc} \sim 8$, since we know $\sqrt{(1+\Delta\nu_{IF}\ T)} \sim 1.25$. Now the laser power was greatly in excess of the minimum required, indeed,

$I_s / \frac{h\nu}{\eta} > 100$, hence $s = \frac{100}{1 + 100/8} = 7.4$, leading finally to $S = \frac{7.4}{1 + 7.4} \times 1.25 \approx 1.1$. Thus the ease with which we could observe signal in the presence of continuous noise is consistent with what is nevertheless a very poor signal-to-noise level. The latter could have been improved either by using a significantly longer laser pulse, perhaps not feasible with the theta pinch plasma, or by repeating the measurements many times and averaging the results.

As well as being peaked in frequency, the scattered light spectrum was found to be peaked in wavelength too. This was shown by measurements of the frequency spectrum made at a series of scatterin angles from 0.65° to 1.35° , corresponding to varying the scale length from 6.1×10^{-3} cm to 2.9×10^{-3} cm. This variation was brought about by changing the annular stop defining the scattering angle, in such a way that the stray light signal on the detector was kept constant. As the beat frequency signals are proportional to $i_{\ell o} I_s$, the changes in the power spectrum observed with different stops must be due to changes in I_s alone.

The scattered intensity collected near θ , corrected for solid angle and area variations, is plotted as a function of θ for the frequency 680 MHz, in Figure 4. A distinct peak in the neighbourhood of $\theta = 1^\circ$ is apparent. Moreover suitable masking in azimuth demonstrated that scattered light originated predominantly from the horizontal plane. No signal was detected when light scattered near the vertical plane alone could reach the detector. This result served to demonstrate that the observed signal originated in components of the density fluctuation whose $\underline{k}$ vectors lie parallel to the axis (and the magnetic field) of the plasma.

If the fluctuation spectrum giving rise to our observations is an intense ion-acoustic wave obeying a dispersion relation like $k\ v = \Delta\omega$, then the velocity determined by the measurements is 2.7×10^6 cm $\sec^{-1}$, corresponding to a temperature of 8 eV for deuterium. This bears comparison with the 4.8 eV deduced from the plasma diamagnetism.

No satisfactory conclusions could be drawn about the intensity of the scattered light signal, ruling out comparison between theory and experiment except as regards the shapes of the frequency and wavelength spectra. The latter would not be inconsistent with scattering from a thermal collective ion feature where the temperature for the electrons exceeds that for the ions by perhaps 10 times. But such an interpretation fails to account for the observed anisotropy which indicates a wave directed preferentially along the theta pinch axis.

5. Conclusions

Ruby laser light scattered by a theta pinch deuterium plasma has been detected and its frequency spectrum measured by heterodyne techniques using a vacuum photodiode, a local oscillator provided by stray laser light, and an Eddystone communications receiver as a frequency analyser.

Though post detection signal-to-noise ratio was about 3, short laser pulse length combined with the narrow IF bandwidth of the receiver to limit output signal-to-noise to around unity. Nevertheless, the pulsed output signal could be discriminated from the prevailing CW background, and an estimate of its value as a function of frequency deduced. The scattered light frequency spectrum passed through a maximum at 680 MHz.

By varying the scattering angle, the wavelength spectrum of the scattered light was measured. This proved to peak near 1°, corresponding to 40 μm scale length. Azimuthal masking of the collection lens focal plane stop showed the direction of the scattering $\underline{k}$ vector to be parallel to $\underline{B}$, rather than isotropic as would be expected for thermal fluctuations.

A superthermal wave interpretation of our observations is further supported by the fact that the estimated wave velocity corresponds to a plasma temperature of 8 eV, close to the value of 4.8 eV measured by the balanced magnetic loop method.

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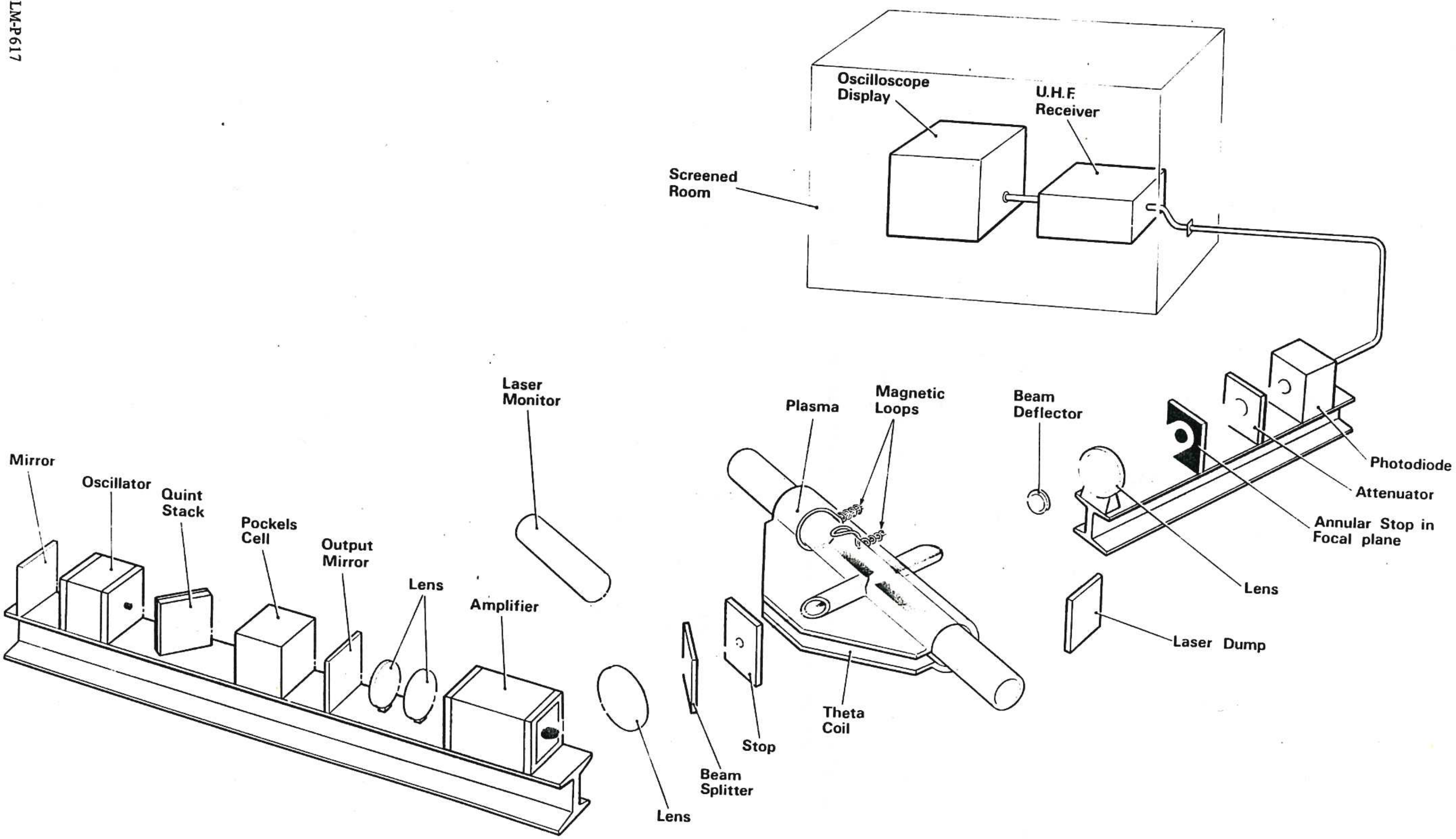

Fig.1 Experimental assembly. Heterodyne detection etendu is defined by the annular stop in the focal plane of the collection lens, and the photodiode aperture. The latter is focused into the plasma.

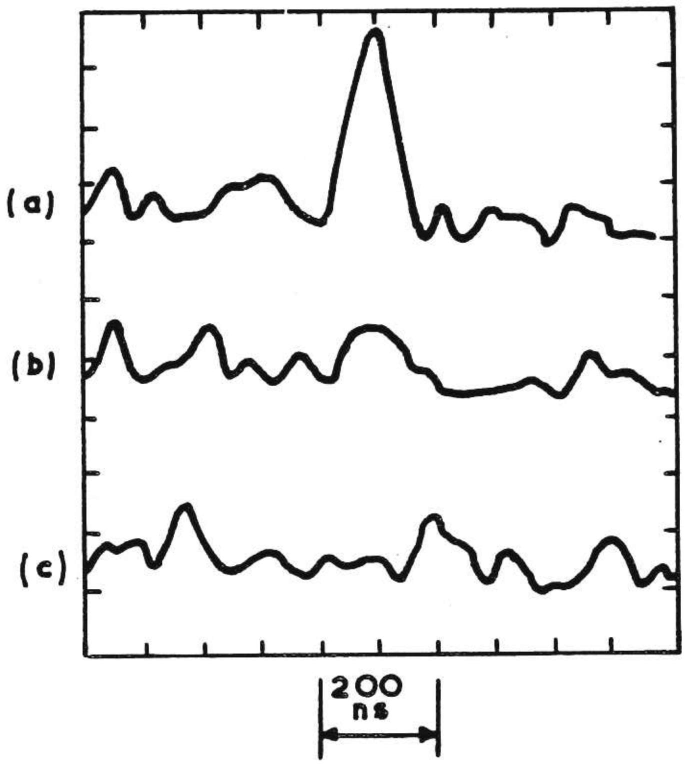

Fig.2 Photodiode current traces of photomixed light. (a) laser fired into plasma; (b) laser fired, plasma absent; (c) plasma present, no laser.

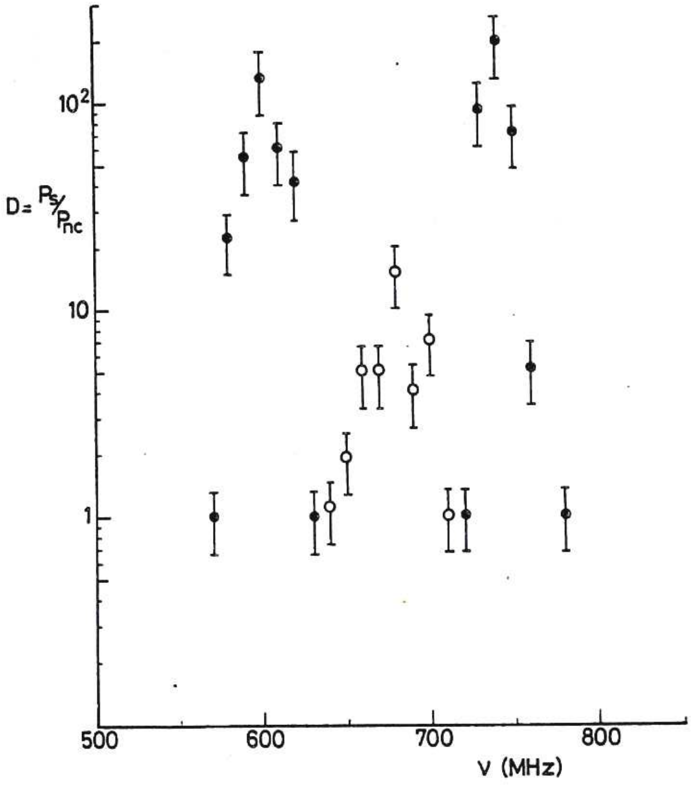

Fig.3 Frequency spectrum of photodiode current from 550 MHz to 780 MHz. Peaks near 600 MHz and 750 MHz are due to beating between longitudinal laser modes. The feature located between 650 and 700 MHz is due to scattered light. The vertical scale is visibility, D, i.e. signal P_s normalised to continuous noise level P_{nc}. Error bars reflect statistics of averaging several measurements.

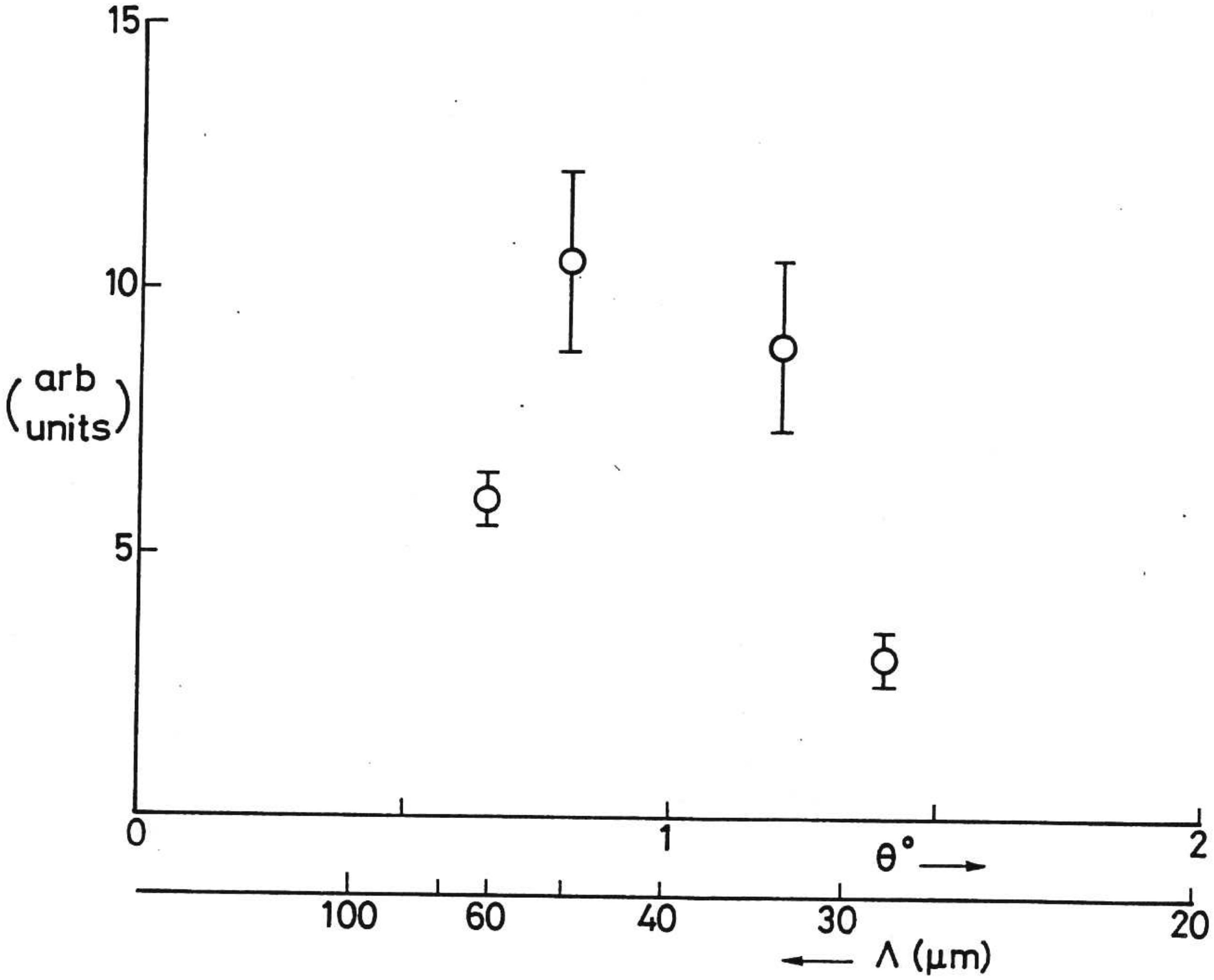

Fig.4 Peak scattered light signal near 680 MHz, as a function of median scattering angle θ. Each point is the average of several measurements.