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PROSPECTS FOR ION TEMPERATURE MEASUREMENTS IN JET BY THOMSON SCATTERING OF SUBMILLIMETRE WAVES

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INTRODUCTION.

The dimensions and properties of the JET plasma will probably preclude the measurement of ion temperatures by techniques which have been used on smaller Tokomaks (eg. neutron flux measurements, and analysis of charge-exchange neutrals emanating from the plasma). In principle, Thomson scattering of submillimetre waves could be used to measure the ion temperature. The principal concern here will be the practical limitations imposed by the availability of high power pulsed sources and sensitive detectors - and noise due to plasma emission at submillimetre wavelengths (bremsstrahlung and electron cyclotron emission). Coherent scattering from plasma waves (eg. ion acoustic waves and electron drift waves) with millimetre and submillimetre waves will be considered briefly. The reader is referred to refs. 1 and 2 for the theory of Thomson scattering in general and ref. 3 for more information on collective scattering of submillimetre waves by a Tokamak plasma.

CHOICE OF WAVELENGTH AND SCATTERING ANGLE FOR JET.

We consider irradiating the plasma with a monochromatic beam of radiation of wavelength λ_o and observing the Doppler broadening of radiation scattered by thermal fluctuations in the density of plasma electrons, at a small angle to the incident beam (forward scattering). If the incident wave has a wave vector $\underset{\sim}{k}_o$ (of magnitude $k_o = 2\pi / \lambda o$) and the scattered wave has a wave vector $\underset{\sim}{k}_s$ ($k_s \simeq k_o$ because the Doppler shift will be small compared with the laser frequency) the scattering vector is defined by $\underset{\sim}{k} = \underset{\sim}{k}_s - \underset{\sim}{k}_o$ (Fig.1). It follows that $k \simeq 2\, k_o \sin \theta/2$. The importance of the scattering vector is that the spectrum of the scattered signal is just the spectrum of components of electron density fluctuations with wave vector $\underset{\sim}{k}$. If the ion temperature of the plasma is to be measured, the spectrum of the scattered radiation must be dominated by ion thermal motion, so $1/k$ must be large compared with the plasma Debye length λ_D. Quantitatively it is required that the "scattering parameter", defined by

$$\alpha = \frac{\lambda_o}{4\pi\lambda_D \sin\ /2} ,$$

be greater than about 3 [2]. For a typical JET plasma ($N_e = 5\times10^{13}$ cm^{-3} ; $T_e = 5$ keV) the Debye length is 75 μm. It follows that scattering angles somewhat less than 0,1° would be required to measure T_i with visible lasers (eg. Ruby, $\lambda_o = 0{,}7$ μm) or less than 0,5° with infrared lasers (eg. CO_2, $\lambda_o = 10{,}6$ m) but angles of the order of 10° to 20° could be used if the source were a 337 μm HCN laser or a 496 μm CH_3F laser. In a visible scattering experiment the viewing direction would lie well within the angular divergence of the probe beam and would be impossible to resolve. With a CO_2 laser it may be possible to distinguish a scattered signal at $\simeq 0{,}5°$ to the probing beam but spatial resolution in the direction of the probing beam would not be very good (eg. 50 cm). Nevertheless, scattering at 10,6 μm is worth consideration as a means of measuring ion temperature in JET - details of the sort of system that would have to be envisaged are to be found in ref. 4. However forward scattering at 10° with an HCN laser or a CH_3F laser would be simpler in principle and should give better spatial resolution (eg. 10 cm in the direction of the probing beam for a feasible beam diameter of 2 cm).

FORWARD SCATTERING WITH A SUBMILLIMETRE LASER : SPECTRUM OF THE SCATTERED SIGNAL.

For the purpose of calculating typical figures HCN laser (f_o = 890 GHz) scattering at a forward angle of 10° is considered. A pulsed experiment is assumed. In this case the scattering parameter would be of the order of 3 and the spectrum of scattered radiation would be dominated by ion thermal motion . The width of the ion spectrum is of the order of the Doppler shift due to scattering by a particle moving in the direction of the scattering vector k with the ion thermal speed v_{th}. This width Δf_i is thus given by

$$\Delta f_i = f_o \frac{v_{th}}{c} \quad \text{with} \quad v_{th} = \sqrt{\frac{2k\ T_i}{m_i}} \ .$$

For T_i = 3 keV Δf_i is approximately 400 MHz. In order that frequencies of (say) one tenth of this should be resolvable the source line-width should be no greater than 40 MHz and the minimum pulse duration would be about 30 nsec. The form of the scattered spectrum will depend on the orientation of the scattering vector $\underset{\sim}{k}$ with respect to the Tokamak's toroidal magnetic field $\underset{\sim}{B}$. Two configurations will be considered (Fig.2) ; one in which $\underset{\sim}{k}$ is parallel to $\underset{\sim}{B}$ and one in which $\underset{\sim}{k}$ is perpendicular to $\underset{\sim}{B}$.

(a) $\underset{\sim}{k} \parallel \underset{\sim}{B}$ - Fig. 2a.

In this case the form of the scattered spectrum is the same as in the absence of magnetic field [2]. In general for a plasma with $T_e \geqslant T_i$ the scattered spectrum is dominated by a peak at the frequency of the ion-acoustic resonance [2]. Due to negative Landau damping of this resonance by the plasma electrons the amplitude of this peak increases with T_e - its frequency also increases with T_e in accordance with the dispersion relation for ion-acoustic waves [1]. There is generally one such peak for each mass species in the plasma. The amplitude of the peak associated with each impurity ion [6] increases with concentration and degree of ionization. The frequency of an impurity peak is zero for low concentration or degree of ionization and tends to the appropriate ion-acoustic resonance frequency as these parameters increase. Some of these general trends are illustrated in Fig. 3.

(b) $\underset{\sim}{k} \perp \underset{\sim}{B}$ - Fig. 2b.

In this case the features of the scattered spectrum associated with the ion-accustic resonance shoud be suppressed by the magnetic field and the spectrum should be Gaussian with a width corresponding to the ion Doppler shift Δf_i. Heavy impurities would contribute small superimposed peaks at the centre of the spectrum which may or may not be of diagnostic use. In any case, the impurity contribution should not hinder a measurement of the width of the ion spectrum. Superimposed on this spectrum there would be a modulation at the ion cyclotron frequency ($\simeq$ 50 MHz for hydrogen, B = 30 kG), the depth of modulation depending strongly on the angle between the scattering vector and the total magnetic field in the scattering volume [5].

DETECTION AND SPECTRAL ANALYSIS OF THE SCATTERED SIGNAL.

In order to calculate the laser power required for a submillimetre wave Thomson scattering experiment it is necessary to know the minimum signal power that can be detected. It will be seen that with suitable precautions the fluctuations in plasma emission at the laser wavelength arriving at the detector could be kept less than or of the order of the noise equivalent power of the most sensitive far-infrared detection systems available. It is not sufficient to simply detect the scattered radiation, it is necessary also to conceive a system for analysing its spectrum which would have a width of 1 GHz ($\simeq 2\Delta f_i$) about a centre frequency of (for example) 890 GHz. A possible solution is a heterodyne detector using a small part of the laser signal as local oscillator (there are other possibilities - eg. a harmonic of a microwave oscillator - but the principle remains the same). The scattered signal would thus be transformed into a spectrum of electrical noise in the bandwidth 0 - 1 GHz at the output of the detector. This could then be analysed by electrical means (eg. Fig. 4). In fact, since the sensitivity of far-infrared detectors is limited by internal electrical noise a heterodyne system is necessary in order to achieve maximum sensitivity. Of the existing detectors with a bandwidth of 1 GHz or more the two most promising candidates are the room-temperature Schottky diode [7] and the liquid helium cooled Josephson junction [8] with corresponding noise equivalent powers for heterodyne detection at 337 μm (NEP_h) of 10^{-15} W/Hz and 10^{-17} W/Hz respectively.

It is important to determine whether fluctuations in the plasma emission near the laser wavelength arriving within the solid angle of the detector could be greater than the noise equivalent powers quoted above. Two sources will be considered; plasma bremsstrahlung and electron cyclotron emission. The following estimates are based on the maximum étendue for heterodyne detection ($[A.\Delta\Omega]_{max} \simeq \lambda_0^2$) which should be quite feasible for JET. In this case the fluctuations in radiation from a source of brightness equal to that of a black body at temperature T (at the same wavelength) are of the order of kT WHz^{-1} (in one polarization - a heterodyne system normally only accepts one polarization). If, for example, the plasma were to radiate at the laser frequency like a black body at the plasma electron temperature the noise power at the detector would be $\simeq 10^{-15}$ WHz^{-1} (for $T_e = 5$ keV ; wavelength independent for $\lambda \gtrsim 0{,}1$ mm), so the full sensitivity of the Josephson junction could not be used. It is to be hoped that the plasma will not radiate so strongly at all frequencies although it will be seen shortly that it might even radiate more strongly than a black body at some frequencies.

The calculated signal due to bremsstrahlung for a pure deuterium plasma at 5 keV is of the order of only 10^{-21} WHz^{-1} (independent of wavelength in the submillimetre region). This should be multiplied by a factor of (say) 100 in accordance with the anomalously high bremsstrahlung than can be observed at optical frequencies. If a viewing dump were not used the cavity effect of the reflecting walls of the vacuum vessel could increase the level of radiation arriving at the detector by a factor of up to 100. Even with these overestimates the bremsstrahlung level would only just equal the heterodyne noise equivalent power of a Josephson junction (10^{-17} WHz^{-1}) so it may be concluded that bremsstrahlung would not increase the minimum detectable signal.

Fluctuations of the plasma emission in the vicinity of harmonics of the electron cyclotron frequency could also contribute to noise at the scattering wavelength. Experimental observations on the CLEO tokamak by Costley et al [9] have shown that the spectrum of the emission does not always conform to the predictions of the theory of electron cyclotron emission and the emission at some frequencies can be an order of magnitude greater than the level of black body emission corresponding to the plasma electron temperature.

The authors suggest that this high level emission may be due to runaway electrons, in which case it might not be polarized, whereas electron cyclotron emission should be. Indeed, the observed emission is unpolarized, but this could be due to "scrambling" of the polarization by multiple reflections inside the torus. It seems unsafe to assume that with a viewing dump the emission would be linearly polarized and could be largely eliminated by suitable orientation of the polarization in a scattering experiment.

Reasonable estimates of upper limits on the fluctuations of electron cyclotron emission arriving at the detector, based on calculations by Brossier and Costley and assuming reasonable levels of enhanced emission [10] are tabulated below. Since the reflecting walls of the torus constitute a cavity at submillimetre wavelengths the levels of emission seen with and without a viewing dump are expected to be quite different. Results are given for both cases, for frequencies corresponding to the HCN laser and the CH_3F laser.

Source frequency	605 GHz- CH_3F	890 GHz - HCN
Upper limit for noise power at detector without viewing dump (WHz^{-1})	3×10^{-15}	10^{-16}
Upper limit for noise power at detector with viewing dump (WHz^{-1})	10^{-16}	10^{-18}

These figures are for a hydrogen plasma with $N_e = 5 \times 10^{13}$ cm^{-3}, $T_e = 5$ keV and B = 30 kG. It should be noted that at 605 GHz, a detector without a viewing dump could see up to three times the noise due to a black body at the plasma electron temperature. As the CH_3F and HCN laser frequencies correspond to quite high harmonics of the electron cyclotron frequency the emission drops quite rapidly with frequency in this region. Thus although a viewing dump would seem necessary for scattering at 605 GHz (CH_3F) it may not be so at 890 GHz (HCN).

It may be concluded that if a viewing dump were used the full sensitivity of a Josephson junction (10^{-17} WHz^{-1}) could be used in a scattering experiment at 890 GHz, whereas electron cyclotron emission might increase the minimum detectable signal by an order of magnitude (to 10^{-16} WHz^{-1}) at 605 GHz. In either case the use of a Josephson junction would appear to be justified. Because it is a point contact device, and operates at liquid helium temperatures, this detector is not convenient to operate but it can be used routinely if sufficient attention is paid to mechanical details [11]. On the other hand, recent advances in the performance of the more convenient Schottky diodes have been quite rapid [12] and it is conceivable that their noise equivalent power may get closer to that of the Josephson junction in the near future. An important problem is the coupling of an incident wave field to the whisker antennae of these diodes, and improvements in performance should be possible simply by improving this coupling.

REQUIRED LASER POWER.

a) Thomson scattering from thermal density fluctuations.

For forward angle scattering the scattered power P_s is related to the incident laser power P_o by

$$P_s = P_o \, \sigma_T \, N_e \, L \, \Delta\Omega$$

where σ_T is the Thomson scattering cross-section (8×10^{-26} cm^2), N_e is the electron density, L is the length of the scattering volume ($L \simeq d/\sin\theta$ where d is the diameter of the laser beam) and $\Delta\Omega$ is the solid angle within which the scattered radiation is collected. A reasonable beam diameter for the 337 μm or 496 μm laser wavelengths would be 2 cm (at 1/e of the intensity distribution) which gives $L \simeq 10$ cm for $\theta = 10°$. Then for $N_e = 5 \times 10^{13} \mathrm{cm}^{-3}$ and $\Delta\Omega_{max} \simeq 3 \times 10^{-4}$ sr. ($\Delta\Omega_{max} \simeq \lambda_o^2/$source area - for heterodyne detection) it is found that $P_s \simeq 1{,}2 \times 10^{-14}\, P_o$. This scattered power would be spread throughout the range of frequencies from $f_o - 2\,\Delta f_i$ to $f_o + 2\,\Delta f_i$ approximately (f_o is the laser frequency) and then folded about zero frequency by heterodyne detection to give a bandwidth $0 - 2\,\Delta f_i$. For HCN laser scattering (f_o = 890 GHz) and the properties of the JET plasma $\Delta f_i \simeq 400$ MHz, so the power per unit bandwidth at the detector output would be

$$\frac{P_s}{B_{if}} \simeq \frac{1{,}2 \times 10^{-14}\ P_o}{2 \times 400 \times 10^6} \quad WHz^{-1}$$

$$= 1{,}5 \times 10^{-23}\ P_o \quad WHz^{-1}$$

For an instantaneous signal to noise ratio of 1 in the post detector amplifier the required laser power P_o can be calculated by equating the above expression to the detector noise NEP_{het} (= 10^{-17} WHz^{-1} for a Josephson junction).

In practice the signal to noise ratio could be improved by integrating during the duration τ of the laser pulse, to give a final signal to noise ratio :

$$\frac{S}{N} = \frac{P_s}{NEP_{het} \cdot B_{if}} \quad (2\ B_{if} \cdot \tau)^{1/2}.$$

This value applies to the case of a single integrator following the intermediate frequency amplifier - a system which would detect the scattered signal without spectrally analysing it. If the band B_{if} were divided into (say) ten consecutive bands (channels) by a series of filters, each one followed by an integrator (as in Fig.4) the signal to noise ratio would be worse by a factor $\sqrt{10}$. (This assumes equal signal power in each channel which is, of course, an over-simplification). At the end of the laser pulse the outputs of the integrators would give a histogram of the scattered spectrum.

Table 1 shows the HCN and CH_3F laser powers as a function of pulse duration which would be required to give a signal to noise ratio of 1 with a Josephson junction. The scattered power is assumed to be uniformly distributed in ten channels.

Pulse Duration τ	50 nsec	1 μsec	20 μsec	10 msec	1 sec	Min. det. signal
Required laser power for unity signal to noise ratio	250 kW	50 kW	10 kW	500 W	50 W	10^{-17} WHz^{-1} (HCN)
	2 MW	400kW	80 kW	4 kW	400 W	10^{-16} WHz^{-1} (CH_3F)

TABLE 1

For scattering at the CH_3F wavelength the required powers are larger by a factor 8 corresponding to a minimum detectable power of 10^{-16} WHz^{-1} (as set by plasma emission) instead of 10^{-17} WHz^{-1} and a decrease in bandwidth of $\sqrt{337/496}$. The threshold for resolving the scattered spectrum would be about ten times the power for unity signal to noise ratio.

b) Coherent scattering from plasma waves.

The condition for coherent scattering from density waves is that the laser wavelength and scattering angle satisfy the Bragg-condition, as shown in Fig. 5. In other words scattering will take place from waves with wave vector equal to the scattering vector $\underset{\sim}{k}$. In this case the total scattered power can be considerably enhanced and is given by the expression [13]

$$P_s = P_o \sigma_T \; n_e^2 \, L^2 \lambda_o^2$$

Here n_e is the electron density amplitude of the wave. For an incident plane wave (and an infinite plasma) all the scattered power is radiated at the scattering angle - in practice the divergence in the scattering direction would be determined by diffraction from the scattering volume.

Using the equation above, it may be calculated that waves of amplitude 5×10^{-7} cm^{-3} - one millionth of the density expected in JET - would scatter 1000 times more power than the thermal fluctuations in a quiescent plasma. It will be seen later that scattering from waves of such an amplitude could readily be observed using existing lasers and detectors.

EXISTING PULSED SOURCES AT 337 μm AND 486 μm.

Apart from power considerations the principal requirements of a source for Thomson scattering are that it be essentially monochromatic (say $\Delta f \lesssim 40$ MHz for JET) and have a sufficiently long duration (say $\tau \gtrsim 30$ ns for JET). These are minimum requirements imposed simply by the desired spectral resolution. In addition, if the source is to be used as local oscillator (as in Fig.4) it should present a flat wave front over the detector surface and have a much higher monochromaticity than indicated above. This is because heterodyne detection of components far into the the wings of the local oscillator spectrum could produce spurious beat signals at the same level as the wanted signal. Thus the conditions imposed on a high power scattering source, when it is also used as local oscillator, are quite stringent. For extreme forward scattering with CO_2 lasers, such conditions have been satisfied by a special hybrid laser [14], but this is essential because the use of stray light as local oscillator signal cannot be avoided. With submillimetre lasers and scattering angles of 10° or more it would probably be possible, and may be much easier, to use a separate continuous laser as local oscillator. Then only the local oscillator would need to be very monochromatic, the limitation on source linewidth being relaxed to the value dictated by the desired spectral resolution. A further advantage with a separate local oscillator is that its level would be constant and it could be adjusted for optimal heterodyne detection.

a) Pulsed 337 μm HCN laser.

A typical pulsed HCN laser is excited by an electrical discharge (eg. 0,5 μF charged to 15 kV) in a flowing mixture of nitrogen and methane ($\simeq 1$ l.s^{-1} at $\simeq 1$ torr) in a pyrex tube ($\simeq 5$ m long × 15 cm dia.) [15,16,17]. The highest power so far obtained with pulsed HCN lasers is of the order of 500 W for 20 μs [15]. The pulse shape can be quite clean and since there is only one emission line at 337 μm the linewidth is less than the width of this line - about 10 MHz. The principal source of broadening is chirping by the time - varying electronic refractive index of the decaying discharge [18]. Thus the instantaneous linewidth is much less than 10 MHz. It is possible to concentrate all the pulse energy into one TEM_{00} mode so a part of the laser beam (eg. stray light) could be used as local oscillator for the heterodyne detector.

Table 1 shows that a pulsed power of 500W for 20μs would give a signal to noise ratio of 0,05 only, so with existing detectors anHCN laser two hundred times more powerful would be required for ion temperature measurements on JET. It seems certain that longer lasers would produce more power, the inconvenience being that a

500 W laser is already quite long ($\gtrsim$5m). However the HCN laser is very simple and the parts required to build a giant laser are not expensive so some increase in length could be considered. In the case of JET, the minimum detectable signal would be determined by detector noise so improvements in detector performance (eg. of a Josephson junction) could reduce the required laser power.

b) Pulsed optically pumped 496 µm CH_3F sources.

A pulsed CH_3F source consists of a tube (≃1 m long × ≃5 cm dia.) of CH_3F gas at a pressure between 0,1 and 20 torr, optically pumped by a pulsed CO_2 laser operating on the 9,55 µm line [19]. The CH_3F molecule has an absorbtion band at 9,5 µm corresponding to excitation of (for example) the first excited state of the C-F bond stretching mode ($\nu_3 = 0 \rightarrow 1$) for a molecule with total angular momentum number J = 12. The de-excitation of this state starts by the rotational transition $J = 12 \rightarrow 11$ (in the $\nu_3 = 1$ state) which occurs essentially spontaneously. There are several such transitions at wavelengths near 496 µm. There are two ways in which this emission may be used : superradiantly or in a resonant cavity.

b.1) Super-radiant emission at 496 µm.

A system for obtaining super-radiant emission can be as simple as a glass tube of CH_3F gas sealed at its ends by an NaCl window and a TPX window. The 9,55 µm CO_2 pumping beam enters through the NaCl window, is partly absorbed on its first passage through the CH_3F, partly absorbed and partly reflected (but not transmitted) by the TPX window, and so on. The 496 µm emission is transmitted by the TPX window only, the NaCl window being partly reflecting and partly absorbing at this wavelength. Typical pump energies of 10 to 100 Joules in 100 ns pulses have be used and super-radiant emission follows essentially temporally. In early experiments [20] with an 8J pumping pulse a train of 30 kW spikes with durations of the order of 10 ns were obtained. Recent experiments at Culham with 70 Joules of pump energy have produced cleaner pulses with peak powers near 1 MW and durations of about 50 ns [21]. Table 1 shows that this power level would give a signal to noise ratio of 0,5. The linewidth was about

250 MHz which is of the same order as the halfwidth of the spectrum to be measured (≃ 400 MHz). In some circumstances it might be possible to unfold the source contribution to the width of the spectrum of the scattered radiation but interpretation would be difficult because fine structure due to impurities and the ion-acoustic resonance would be lost.

It seems likely that further increases in the level of CH_3F super-radiant emission will be achieved so the problem for JET would not be one of source power, but of linewidth. A natural approach to this problem is to put the CH_3F gas in a laser resonator -some results of such experiments are described below.

b.2) Laser operation at 496 μm.

For laser action the CH_3F gas is contained in a resonant cavity formed by two mirrors, with a coupling system designed to let a certain fraction of the radiation in the cavity escape after each round-trip. The gas can be pumped either transversely, or longitudinally by means of an appropriate 9,55 μm - input/496 μm - output coupling system. The high Q cavity limits the rate of change of the stored energy at 496 μm - partially smoothing the spikes of emission. Stimulated emission builds up fastest in the lowest loss mode(s), saturating the gain and tending to reduce emission in other modes. In this way the spectral width of the emission is much reduced.

Using a transverse - optically - pumped (TOP) laser, with an 8 J 9,55 μm pump pulse, Brown et al [22] have obtained clean 500 W pulses at 496 μm with a duration of 50 ns and a linewidth ≲ 30 MHz. Similar experiments at Culham (but using longitudinal pumping) with a 70 J pumping pulse have recently produced ≃ 10 kW in clean pulses with a duration of 1 μsec and a linewidth of 100 MHz [21]. Table 1 shows that with 1 μs duration a pulse power of 200 kW would be required for a signal to noise ratio of one - so two orders of magnitude increase in the power would be required for doing scattering on JET. The 100 MHz linewidth is somewhat larger than the required resolution of 40 MHz. However the experiments on laser-type operation at 496 μm are recent and already the emission is better suited for scattering than the super-radiant emission. Two orders of magnitude increase in the product of the pulse power and the square root of the pulse duration (which determines the final signal to noise ratio) and a reduction of linewidth by a factor 3 seem quite possible. This approach to the use of 496 μm CH_3F emission as a source for scattering is more promising than the use of super-radiant emission.

CONCLUDING REMARKS.

1 - Submillimetre laser scattering for ion temperature measurements.

With existing submillimetre lasers and heterodyne detectors measurement of the ion temperature in JET by Thomson scattering is just outside the bounds of possibility. However if suitable development were undertaken such measurements should be possible within the next few years. The information presented in this paper suggests two possible approaches :

- If scattering on JET were to be done with a pulsed HCN laser a detector with a lower heterodyne noise equivalent power could be used to advantage. Such an improvement seems possible for the Josephson junction but it seems unlikely that the Schottky diode could attain the required performance. The narrow linewidth and the possibility of single mode operation of the HCN laser would permit the use of a part of the laser beam (eg. stray light) as local oscillator. Depending on the future reduction achieved in the NEP of a Josephson junction an increase of laser power of up to two orders of magnitude would be required.

- For scattering with a CH_3F laser the NEP of a Josephson junction is more than adequate because a relatively high level of plasma emission is expected at 496 μm. It seems possible that the performance of Schottly diodes could be improved to the point where the noise equivalent power is set by plasma emission (even with a viewing dump). The power output of the CH_3F laser would need to be improved by about two orders of magnitude and its linewidth would have to be reduced by a factor of 3 or so. Of course, a separate local oscillator would be required.

2 - Coherent scattering from plasma waves.

As shown earlier coherent scattering from plasma density waves could enhance the detected signal by many orders of magnitude and, in view of the comments in the previous section, appears quite feasible with existing lasers and detectors. With HCN or CH_3F wavelengths, at scattering angles of 10° to 90°, fluctuation wavelengths in the approximate range 0,3 mm to 1,5 mm could be investigated. The obvious candidate in JET would be ion-acoustic waves propagating parallel to the magnetic field, and driven by the plasma current.

Owing to the large scattered power from plasma waves, microwave scattering could also be considered for investigating longer wavelength phenomena, eg. electron drift waves which are thought to contribute to an anomalous electron thermal conductivity in Tokamak plasmas [23]. To reduce plasma refraction the use of a probing wavelength as short as 1 mm would have to be envisaged. This would allow plasma wavelengths between about 1 mm and 5 mm ($10° \leqslant \theta \leqslant 90°$) to be investigated. Such an experiment using 2 mm microwaves is being prepared for TFR [23]. Other details of, and possible requirements for a possible system for JET should be more easily determined when the system on TFR comes into operation.

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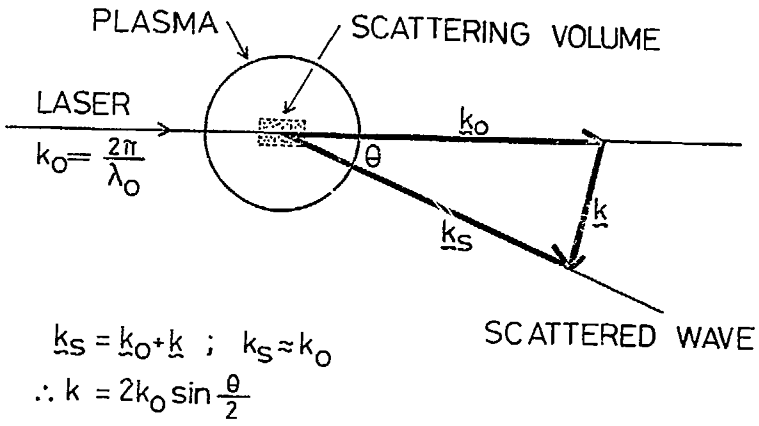


Fig. 1. ARRANGEMENT OF FORWARD SCATTERING EXPERIMENT

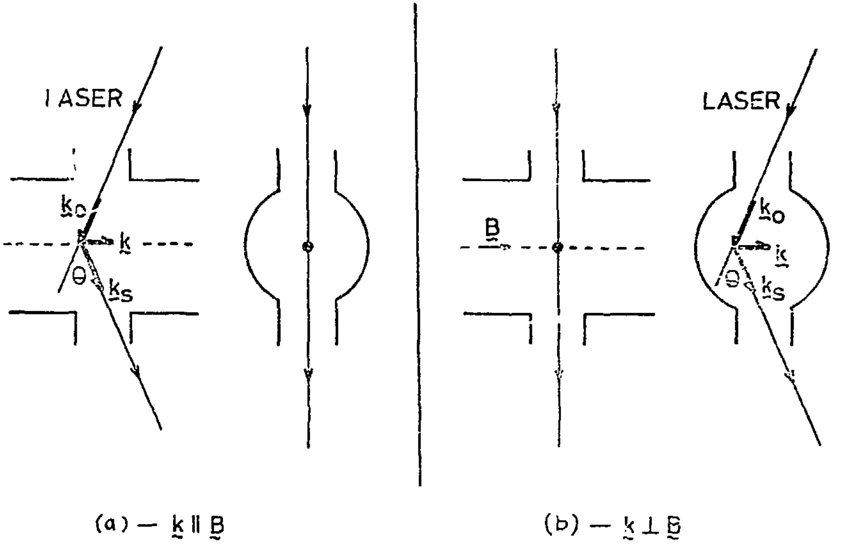


Fig. 2. POSSIBLE CONFIGURATIONS OF FORWARD SCATTERING ON A TOKAMAK

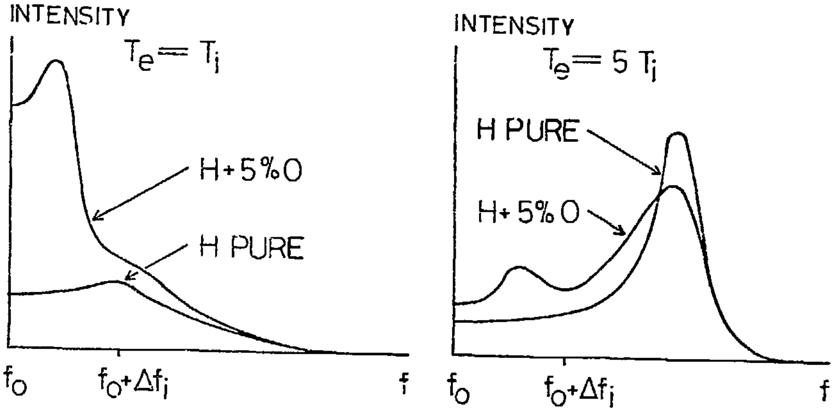


Fig.3. EFFECT OF IMPURITIES ON THE ION SPECTRUM

These curves show the effect of 5% of oxygen (fully ionised) on the spectrum of radiation scattered by a hydrogen plasma with $T_e=T_i$ and $T_e=5T_i$ (5). They are for $\alpha=\infty$ but the form of the spectrum is essentially the same for $3 \leqslant \alpha < \infty$.

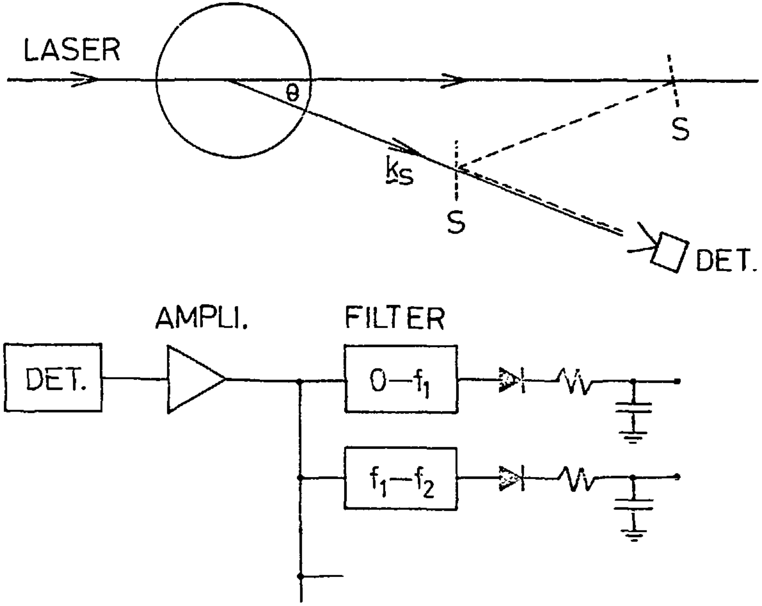
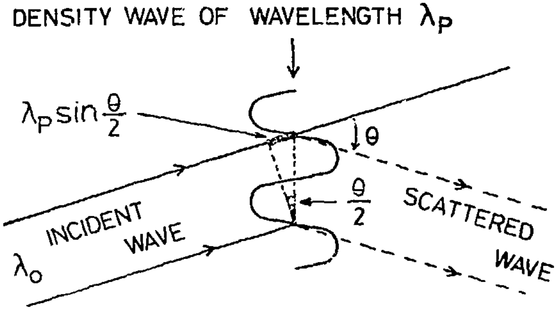


Fig. 4. HETERODYNE DETECTION OF SCATTERED SIGNAL



$$\boxed{2 \times \lambda_p \sin\frac{\theta}{2} = \lambda_0}$$

Fig.5. COHERENT SCATTERING FROM A DENSITY WAVE