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Ion Temperature Measurement by Laser Scattering at 2.8μ

by

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ION TEMPERATURE MEASUREMENT

BY LASER SCATTERING AT 2.8 μ

by

A. W. DeSilva

ABSTRACT

Laser scattering using 2.8 μ radiation is considered as a means of measuring ion temperatures on Scyllac. Both suitable detectors and a laser with sufficient power are presently available. It is concluded that such measurements are certainly feasible. However, the self-imposed restriction that no special windows or ports be allowed in the quartz vacuum vessel makes the rejection of stray light difficult.

I. INTRODUCTION

The wavelengths that may be used for light scattering measurements in the cooperative regime defined by $\alpha \equiv (k\lambda_D)^{-1} \gtrsim 1$ are bounded on the short wavelength side by the practical requirement that the scattering angle be reasonably large ($\sim 5^\circ$) and on the long wavelength side by the transmission properties of the Scyllac quartz vacuum vessel where there is a cutoff at $\lambda = 3 \mu$. The HF laser, with an output at $\lambda = 2.8 \mu$, has adequate power and seems well suited for cooperative scattering measurements.

It is useful at the outset to examine just what may be learned from cooperative light scattering. In this regime ($k < \lambda_D^{-1}$), the electron density fluctuations are due to electrostatic plasma waves. At high frequency near ω_{pe} the electron plasma waves have the dispersion relation

$$\omega^2 = \omega_{pe}^2 + 3k^2 k_B T_e / m \quad (1)$$

and at low frequency the strongly damped ion acoustic waves have the dispersion relation

$$\omega = \frac{k C_s}{(1 + k^2 \lambda_D^2)^{1/2}} \quad (2)$$

Only these low-frequency waves have a dependence on ion temperature that may be exploited. Figs. 1 and 2 show for $\alpha = 1$ and 2, respectively, the spectrum of scattered light expected from a deuterium plasma with Maxwellian ions and electrons of several values of T_e/T_i . For a particular α , the relation between n_e , T_e , and the scattering angle θ is

$$\alpha = \frac{3.23 \times 10^{-6}}{\sin \theta / 2} \sqrt{\frac{n_e}{T_e}} \quad (3)$$

Fig. 1. The spectrum $S_1(\omega)$ of the ion feature for plasmas with Maxwellian electrons and ions having different temperatures.

Fig. 2. As in Fig. 1, with $\alpha = 2$.

For $\alpha = 2$, for example, Eq. 1 shows that for $n_e = 2 \times 10^{16}$ and $T_e = 5 \times 10^6$ °K, the spectra shown in Fig. 2 would be seen for a scattering angle $\theta = 11.7^\circ$. Were the electron temperature 10^7 °K, the spectra of Fig. 2 would be seen at $\theta = 8.3^\circ$.

The width of the spectrum varies about a factor of 2 for a factor of 10 in T_e/T_i , showing that the measurement of spectrum is not a highly sensitive measure of T_i . The integrated intensity under the scattered light feature also varies by about a factor of 2 for a factor of 10 in T_e/T_i . This suggests that perhaps a detailed measurement of the spectrum is not required to obtain T_i , it being sufficient only to measure intensity absolutely. If there are nonthermal fluctuations such as one might expect to find in a plasma having strong currents, however, the intensity can be strongly enhanced, and the intensity measurement is ambiguous.

In order to determine whether or not there is such an enhancement, it is necessary to make some calibration of the scattered light intensity.¹ A direct absolute calibration by Rayleigh scattering is impossible since wall-scattered light will mask the Rayleigh scattering (See Sec. V.A). To get away from this stray light, we must look at scattered light that is Doppler-shifted from the incident wavelength and has no dependence on ion temperature. Light scattered by the electron plasma oscillations seem to offer the only possibility. These oscillations must also not be enhanced above thermal lev-

els if this scattering is to be used as a calibration, but the assumption that they are thermal is probably not too bad if they are observed where current densities are small.² The spectrum $S_e(\omega)$ of scattered light from these oscillations is shown in Fig. 3 for three values of α . There is no dependence of T_e/T_i . It will be noted that the amplitude is much less and the width much greater than is the case for the ion oscillations.

The simplest measurement to make for calibration would be observation of the integrated intensity of the electron feature $\int S_e(\omega) d\omega$, for comparison with the integrated intensity of the ion feature $\int S_i(\omega) d\omega$. For a plasma with Maxwellian electrons and ions these integrated intensities are given by Salpeter³ as

$$I_i \sim \int S_i(\omega) d\omega = \frac{\sqrt{\pi} \omega_{pi}^4}{(1 + \alpha^2)(1 + \alpha^2[1 + T_e/T_i])} \quad (4)$$

$$I_e \sim \int S_e(\omega) d\omega = \frac{\sqrt{\pi}}{1 + \alpha^2} \quad (5)$$

Owing to their dependence upon α , some determination of α is required. This could be by ruby laser scattering. If α is near unity, the shape of the spectrum $S_e(\omega)$ is sensitive to α so a detailed observation of $S_e(\omega)$ can also serve to determine α .

We now turn to a discussion of the hardware requirements to successfully perform a scattering measurement at 2.8 μ . We will assume the Scyllac conditions to be $n_e = 2 \times 10^{16}$ cm⁻³ and $T_e \sim 500$ eV.

Fig. 3. The spectrum $S_e(\omega)$ of the electron feature for various α .

II. LASER

An HF laser is to be used having output power of about 10 MW, with pulse length ~ 100 ns. It is assumed that the beam divergence is small enough so a focal spot ~ 1 mm diameter may be achieved. The presence of outputs at wavelengths other than the primary one (assumed to be 2.8μ) is an annoyance that should be controllable by means of filtering in the laser, or failing that, in the dispersive optics of the scattered light collector. For reference, we note that for this laser wavelength:

$$\begin{aligned}\lambda &= 2.8 \times 10^{-4} \text{ cm} \\ \omega &= 6.73 \times 10^{14} \text{ s}^{-1} \\ \nu &= 1.07 \times 10^{14} \text{ s}^{-1} \\ h\nu &= 0.446 \text{ eV} = 7.14 \times 10^{-20} \text{ J}\end{aligned}\quad (6)$$

III. SCATTERED POWER

We assume for the moment that whatever dispersive element (grating, Fabry-Perot) is used, it will have an aperture sufficiently large to utilize all the light we can collect from the plasma. The scattered power is⁴

$$dP_S = I_0 N r_0^2 (1 - \sin^2 \theta \cos^2 \phi) S(\omega) d\Omega d\omega, \quad (7)$$

where θ is scattering angle, ϕ the angle between $\vec{E}$ and the plane defined by incident and scattered rays, N is the total number of scatterers, I_0 the incident intensity,

$$r_0^2 = 7.9 \times 10^{-26} \text{ cm}^2,$$

and $d\Omega$ is the solid angle subtended by the light collection optics. $S(\omega)$ is the spectral function and is defined so

$$\int S(\omega) d\omega \approx 1 \text{ for } \alpha \ll 1. \quad (8)$$

For forward scattering θ is small, and the angular factor is approximately unity. If the laser beam has radius s and is viewed over a length ℓ , then $N = \pi s^2 \ell n_e$. Noting that

$$I_0 \pi s^2 = P_I, \quad (9)$$

the incident power, we have

$$dP_S = P_I \ell n_e r_0^2 S(\omega) d\omega d\Omega. \quad (10)$$

The solid angle $d\Omega$ will depend upon the access through coil slots. Assuming the scattering volume is 12 cm from the 1-cm-wide slot, the maximum angular width is 0.083 rad. For forward scattering at 10° , α varies directly with scattering angle so α must not vary more than $\sim \pm 10\%$. Such a variation will produce an uncertainty of $\sim 50\%$ in the determination T_{i1} . Taking the angular spread to be 2° , we have $d\Omega \sim 3.5 \times 10^{-3}$ sr. (This figure may be reduced if the monochromator aperture is too small.) Now assume the disperser throws 10% of the light into a typical channel, so $S(\omega) d\omega = 0.1$. ℓ is determined by a distance over which the plasma conditions are nearly constant, say 1 cm. So far, we have assumed no losses in the light collection system. Estimating such losses to be 95%, we have

$$P_S \approx 3 \times 10^{-7} \text{ W}. \quad (11)$$

This represents a flux of about 4×10^{12} photons per second, or 4×10^5 photons in the 100-ns interval. Thus the photon statistics look good.

IV. DETECTORS

Possible detectors include photovoltaic HgCdTe, InAs, InSb, or photoconductive Ge:As. All must be operated at 77° K to obtain low noise. The required detector area is determined by the étendue of the light collection system. Assuming that the detector can be illuminated in a solid angle of $d\Omega_d = 0.25$ sr ($f/2$), then the detector area A_d is

$$A_d = \frac{d\Omega}{d\Omega_d} A, \quad (12)$$

where A is the effective radiating area of plasma seen by the detector and is dependent upon the focal diameter of the laser beam, and $d\Omega$ is the solid angle of light collection optics. The focal diameter for a diffraction-limited beam focussed by a 1-m focal length lens is ≈ 0.7 mm. Let us assume a somewhat worse case, where the beam diameter is 1.5 mm. The length viewed is 1 cm, but projected at 10° , gives an effective length 1.7 mm. Thus, we obtain $A \approx 2.55 \text{ mm}^2$, and detector area $A_d \sim 3.5 \times 10^{-4} \text{ cm}^2$. The noise equivalent power is proportional to $(A_d)^{\frac{1}{2}}$, so it is desirable to make the detector no larger than necessary.

TABLE I
COMPARING DETECTIVITIES AT 2.8 μ

Detector	D*	Source
HgCdTe	$2 \times 10^{11} \frac{\text{cmH}}{\text{W}}^{1/2}$	(A. D. Little)
InAs	1.2×10^{11}	(Texas Inst.)
InSb	4×10^{10}	(Texas Inst.)
Ge:Au	1×10^9	(Raytheon)

All the detectors have their frequency response limited on the high side by junction capacity, except for Ge:Au. For HgCdTe, the junction capacitance is, according to A. D. Little Co., about 2.5×10^{-9} F/cm², whereas it is four times that for the indium crystals. Thus HgCdTe appears best as a high-frequency response detector. Ge:Au is claimed to have response better than 2 ns,⁵ but the detectivity is comparatively low.

On both counts, D* and time response, HgCdTe appears to be best. This assumes the HgTe-CdTe ratio is adjusted to give near-peak detectivity at 2.8 μ . According to A. D. Little Co., research near 3 μ is not active now, and so there is not much available. It would be difficult, therefore, to get multi-element detectors at this time from them. S.A.T. is an alternative source for detectors.

The detector operates into a load resistor R_L . Johnson noise current in this resistor is

$$\langle i_n^2 \rangle = \frac{4kT\Delta f}{R_L} \quad (13)$$

so it is desirable to make R_L large for low noise. The upper limit for R_L may be due to two effects. When R_L equals the junction resistance R_J of the crystal, then further increases in R_L avail nothing. In InSb, for example, a typical junction resistance for $A_d = 10^{-3}$ cm is $R_J = 10^4$ ohms, so R_L should be no larger than this. The detector risetime τ is determined by the RC time of the parallel combination of R_L and R_J with the junction capacitance, so the second upper limit on R_L is the requirement that

$$\frac{R_L R_J}{R_L + R_J} C_J \lesssim \tau \quad (14)$$

For example, InAs has a high resistance, $R_J = 1\text{M}$ for $A_d = 10^{-3}$ cm, and $C_J = 10^{-8}$ F/cm². Here, R_L could be increased to $\sim 1\text{M}$ if it were not for the risetime requirement that limits R_L to about 2.5 K for $\tau = 10^{-7}$ s. InSb has similar junction capacitance per unit area and is similarly limited, but HgCdTe appears to have about four times lower capacitance per unit area.

The quantum efficiency of all these detectors is 50–100%, so their current responsivity is about $S = 1 \text{ A/W}$. Then the noise equivalent power (NEP) for Johnson noise is

$$\text{NEP} = \sqrt{\frac{4kT\Delta f}{R S^2}} \quad (15)$$

For $\Delta f = 10$ MHz, $T = 77^\circ \text{K}$, $R = 10^4 \Omega$, we obtain $\text{NEP} = 2 \times 10^{-9} \text{ W}$. Using an area of $4 \times 10^{-4} \text{ cm}^2$ and $\Delta f = 10^7$, the D* that would produce the same noise power is

$$D^* = 1 \times 10^{10} \frac{\text{cmH}}{\text{W}}^{1/2} \quad (16)$$

A detector having D* greater than this value (for $A_d = 4 \times 10^{-4} \text{ cm}^2$) will be limited by Johnson noise, and thus offers no advantage.

We conclude that due to its lower junction capacitance, HgCdTe can operate into a larger load resistor than the indium crystals (about 10^4 ohms) and still have risetime $\tau = 10^{-7}$ seconds. The overall detectivity is then determined by Johnson noise, and $\text{NEP} \sim 2 \times 10^{-9} \text{ W}$. If the load resistor is at room temperature, NEP rises to about $4 \times 10^{-9} \text{ W}$.

V. OPTICAL SYSTEM

A. Elimination of Stray Light

Assuming that no special windows are allowed in the vacuum vessel, the laser light is scattered by the quartz tube in passing in and out of the plasma region, and this wall-scattered light is transmitted by total internal reflection to the viewing window where it is scattered out to merge with the plasma scattered light. Figure 4 shows the model. The scattered intensity for each scattering process is

$$I_s = \frac{V}{r^2} I_0 R_v \quad (17)$$

Fig. 4. Model assumed in computing intensity of light scattered by quartz tube into light collection optics.

where R is the scattering coefficient, r is distance of observer from scattering volume V , and I_0 is incident intensity.⁶ R is dependent upon material, and for pure materials without inclusions is proportional to λ^{-4} , where λ is wavelength. For the problem at hand, we are concerned with light that has scattered twice--once from the laser beam into the quartz, and then from the quartz out into the light collection optics. The power scattered out into solid angle $d\Omega$ from the quartz in (Fig. 4) is

$$dP_s = V_2 I(z_2) R d\Omega, \quad (18)$$

where $I(z_2)$ is intensity of once-scattered light within the quartz at the position z_2 where the second scattering occurs. Because this light is effectively only spreading out in two dimensions within the quartz due to total internal reflection,

$$I(z_2) = I(z_1) \frac{z_1}{z_2}, \quad (19)$$

$I(z_1)$ is determined by the first scattering process at the point where laser light traverses the quartz tube.

$$I(z_1) = \frac{V_1}{z_1} I_0 R, \quad (20)$$

where V_1 is illuminated volume and z_1 is determined by the conditions for total internal reflection:

$$z_1 = \frac{t}{2\sqrt{n^2-1}}; \quad (21)$$

n is here the index of refraction of the quartz. Combining, we have

$$dP_s = \frac{2AV_2 R^2 I_0 \sqrt{n^2-1}}{z_2} d\Omega, \quad (22)$$

where we have set $V_1 = tA$, and A is the laser beam area and t is the thickness of the quartz wall.

Taking n for quartz at 2.8 μ to be 1.42, noting $I_0 A =$ incident power P_1 , and setting $d\Omega = 4 \times 10^{-3}$ sr,

$$P_s \approx \frac{2P_1 V_2 R^2}{z_2}. \quad (23)$$

Using Fabelinskii's value of $R = 1.93 \times 10^{-9}$ at 2.8 μ , and with reasonable values for other quantities, we see

$$P_s \sim 10^{-11} \text{ W}, \quad (24)$$

which is negligible.

In practice, however, inclusions, bubbles, and dirt on the inner wall are the most likely sources of scatter. We can make some rough estimate of the scattering coefficient R for inclusions, assuming, say, a density of 40 inclusions per cm^3 of a size about 0.1 μ . We obtain $R \sim 3 \times 10^{-6}$, which is five orders larger than the density fluctuation value, and produces a twice-scattered signal 10^{10} times larger:

$$P_s \sim 0.1 \text{ W}. \quad (25)$$

This is 3×10^5 times larger than the expected plasma-scattered signal. Since the stray light occupies only a narrow frequency band, however, it may be eliminated by a high-rejection band-elimination filter. This scheme unfortunately renders calibration by Rayleigh scattering impossible.

The technique developed by Stemon⁷ based on the varioillumination principle offers a reasonable solution. Before discussing this, however, we must first consider the more fundamental question of the proper type of dispersers to use in analysis of the scattered light.

B. Disperser

A choice must be made between a Fabry-Perot interferometer or grating as the primary disperser. The Fabry-Perot, in general, is preferred for high-dispersion systems such as this one, but does not

lend itself well to use of the varioilluminator principle. Also, rejection of unwanted nearby sidebands is generally poorer in the Fabry-Perot. We therefore consider first whether a grating is suitable as regards (1) dispersion, (2) resolution, (3) étendue, and (4) scattered light.

In order to make use of all available light, the spectrometer must have étendue E_g equal to or greater than the étendue E_c of the light collection optics. An approximate value for E_c is implied from previous sections, since we have assumed the emitting area is $A = 2.55 \text{ mm}^2$, and the light collection optics subtend a solid angle $d\Omega = 3.5 \times 10^{-3} \text{ sr}$. Thus,

$$E_c = A d\Omega \approx 9 \times 10^{-5} \text{ cm}^2 \text{ sr}. \quad (26)$$

The grating étendue E_g is the slit area times the inverse of the instrument focal ratio f :

$$E_g = \frac{hw}{f^2}, \quad (27)$$

where w and h are slit width and height, respectively. We define $a = h/w$, and use the grating equations to find

$$w = 2 F \tan \theta \frac{\Delta\lambda}{\lambda}, \quad (28)$$

where θ is the angle of incidence of light on the grating, F is the focal length of the spectrograph, and $\Delta\lambda$ is the desired wavelength resolution. F may be written in terms of the grating height H as $F = H/\sin \theta$. If the grating width is D , we require $H = D \cos \theta$ in order that the focal ratio not be restricted by the grating tilt angle. We find

$$E_g = 4a \left(\frac{\Delta\lambda}{\lambda} \right)^2 H^2 \frac{1 - (H/D)^2}{(H/D)^2}. \quad (29)$$

We see from this expression that the spectrometer light-gathering power is dependent on the resolution $\frac{\Delta\lambda}{\lambda}$, the grating size H , and the slit shape factor a . The focal ratio of the instrument has fallen out. We may make use of this by making the focal ratio large in order to reduce stray light, without paying any penalty in E_g .

For commercially obtainable gratings, $H/D \approx 0.75$ and the largest H is about 15 cm. The optimum grating angle is about 40° , and it should have about

470 rulings/mm. We require $\frac{\Delta\lambda}{\lambda} = 7 \times 10^{-5}$ to obtain 2 Å resolution. Thus

$$E_g = 3.43 \times 10^{-6} a. \quad (30)$$

To obtain a , we must consider the details of the light collection optics. Of course, if fiber optics image shapers were available, " a " could be made arbitrarily large, limited only by the étendue E_c of the light collection optics. If we restrict our considerations to what can be done with lenses, we can utilize the rectangular light collection aperture to realize some gain in a . The effective source is almost square, about 2 mm x 2 mm, and the light is collected through a rectangular aperture at 12 cm radius, measuring about 1 cm wide (coil slot width) by a height which determines the $d\Omega$ in the scattering angle ϕ . We can use two cylindrical lenses to focus the light into a rectangular aperture (Fig. 5) such that the light is uniformly divergent emerging from the aperture. Under this condition, it is easily shown that the shape factor (width/height) of the light collection aperture is the same as a . The étendue of the light collection system is, under this restriction,

$$E_c = A d\Omega_1 d\Omega_2, \quad (31)$$

where A is the 2 mm x 2 mm source area, $d\Omega_1 \approx 1/12$ is the angular width of scattered light, and $d\Omega_2$ is the angular height (along the scattering angle ϕ). Setting

$$\frac{d\Omega_1}{d\Omega_2} = a \quad (32)$$

and equating E_g to E_c , we find that $d\Omega_2$ is about 0.5° , and $a = 7.6$, so

$$E_g = 2.6 \times 10^{-5} \text{ cm}^2 \text{ sr}. \quad (33)$$

This represents the largest solid angle that can be used that will not throw away light in the monochromator under the assumed restrictions.

If fiber optics were used, we could increase a to about 30, the limitations being the allowable size of $d\Omega_2$, which is about 0.10 . This realizes an increase in available light by a factor of over 4, less, of course, any losses in the light fibers.

Fig. 5. System of cylindrical lenses that will convert a square source radiating into a rectangular source radiating into a square.

A third alternative light collecting system makes use of only conventional lenses, but with the grating tilted far enough that its projected area matches the rectangular light collection aperture. In this case, we again have

$$E_g = \frac{hw}{f^2} . \quad (34)$$

Since the source has an approximately square cross section (2 mm x 2 mm), $h \approx w$. The grating equation may be used to find the relation between slit width w and wavelength resolution $\Delta\lambda$ in terms of the focal length F of the instrument and the angle of incidence θ of light onto the gratings:

$$w = 2F \tan \phi \left(\frac{\Delta\lambda}{\lambda} \right) . \quad (35)$$

Plugging into Eq. 34 above, we have

$$E_g = \frac{4F^2 \tan^2 \phi}{f^2} \left(\frac{\Delta\lambda}{\lambda} \right)^2 . \quad (36)$$

We further note that the length H of the grating rulings is F/f , so

$$E_g = 4H^2 \tan^2 \phi \left(\frac{\Delta\lambda}{\lambda} \right)^2 . \quad (37)$$

For the experiment at hand, $\Delta\lambda \approx 2\lambda$ and the largest H commercially available is ~ 15 cm. Then

$$E_g = 4.59 \times 10^{-6} \tan^2 \phi . \quad (38)$$

Now, light is collected through a coil slot 10-mm wide from a scattering volume about 12 cm away. This corresponds to an angular aperture $d\theta_1 \approx 0.083$ rad (toroidal direction). The angular aperture $d\theta_2$

in the poloidal direction must be as large as possible, but not to exceed an angle $d\theta_2^* \approx 0.10$ so that the scattering angle is well-defined. If we define

$$\gamma \equiv \frac{d\theta_1}{d\theta_2^*} , \quad (39)$$

then it can be shown easily that the grating tilt angle ϕ that will allow the grating to be just filled with light is defined by

$$\tan \phi = (\gamma^2 - 1)^{1/2} , \quad (40)$$

assuming the ruled area is square. (If the ruled width is δ times the height, replace γ^2 by $\gamma^2 \delta^2$). Thus we have

$$E_g = 4.59 \times 10^{-6} (\gamma^2 - 1) . \quad (41)$$

The light collection étendue is

$$E_c = A d\theta_1 d\theta_2 = \frac{A d\theta_1^2}{\gamma} , \quad (42)$$

and equating $E_g = E_c$ yields $\gamma = 4$, or $\theta = 75.5^\circ$, and

$$E_g = 6.9 \times 10^{-5} \text{ cm}^2 \text{ sr} . \quad (43)$$

The grating equation then shows that the grating must be ruled with about 700 rulings/mm, for operation in first order. It may prove too difficult to obtain such a grating ruled and blazed properly.

We conclude that the best light-gathering power will be realized if a fiber optics image-shaper were available. If not, the third alternative using conventional lenses is next best, but suffers from a lack of flexibility for future work in which the aperture restrictions are different. The first two methods require cylindrical lenses which may be difficult to obtain.

Using any of these systems to introduce light into a grating instrument, we may then follow the method of Siemon⁷ using the varioilluminate principle to "notch out" the stray light.

A Fabry-Perot interferometer can easily provide the aperture and dispersion required to analyze the scattered light. Plates only 1 cm in diameter would have étendue sufficient to utilize all light that could be collected through the coil slot with $d\theta_2 = 2^\circ$. However, F-P is poor in rejection of nearby sidebands, such as the stray laser light.

For example, an instrument having finesse (defined in the usual way as free spectral range divided by line half width) of 50 offers a rejection of only 0.01 at a wavelength 1/5 of a free spectral interval from the line. In a case of practical interest, we would want a 2Å resolution and free spectral range of about 40Å. To obtain a rejection ratio of 10^{-6} at λ_c from a strong line would require 3 F-P interferometers in series.

VI. DAMAGE IN QUARTZ

There seems to be little experimental data on damage to transparent materials due to high-energy infrared radiation. An article by Bliss⁸ lists a number of sources of radiation-induced damage in transparent dielectrics. These include bulk absorption, absorption in color centers or inclusions, multiphoton and electron avalanche breakdown, stimulated Brillouin scattering (SBS), and the effects of self-focusing. Of these, it appears that the breakdown processes and self-focusing should be much less important for the long-wavelength laser. The effects of inclusions are difficult to assess, and an experimental determination of the damage threshold in a sample quartz tube is needed. SBS produces high-intensity acoustic waves whose stresses fracture the quartz. An article by Ritus and Manenkov⁹ claims that observed fractures in fused quartz cannot possibly be due to SBS. They give a threshold of 220 J/cm² for damage to fused quartz under laser radiation, without identifying the mechanism. Zverev¹⁰ presents data that indicates there is little dependence of this threshold on laser wavelength, at least for long wavelengths.

VII. SUMMARY

There does not appear to be any single overwhelming objection to a forward scattering measurement of T_i using 2.8-μ laser radiation. The restriction that the primary laser beam must pass through the vacuum vessel wall renders the problem difficult, however, since it means that a complex system will be required for elimination of stray light at the laser wavelength, and that due to this system, the calibration procedure becomes cumbersome. If entrance and exit ports of only 2 or 3 mm

diameter could be fitted to the tube, the stray light problem would be greatly relieved, and calibration would become far easier, since a Rayleigh scattering calibration could be performed using, e.g., pentane.

Even under the pessimistic assumption of only 5% efficiency in the light collection system, it appears that the scattered signal in one channel of the detector should be 10 to 100 times the minimum detectable signal, and that this represents enough photons so that statistical variations are small. A grating spectrometer can be used to provide both the stray light rejection and spectral dispersion, although availability of gratings having the proper number of rulings and blaze is in question.

The spectrum measured will distinguish somewhat coarsely between various T_i , a factor of 10 in T_i representing a change of only a factor of about 2 in spectral width for $\alpha \sim 1$. For large α or large T_i/T_e , the spectral width goes as $T_i^{1/2}$. An independent measure of n_e and T_e is almost certainly necessary in interpretation of infrared scattering data.

Two single experiments are necessary before further work on design can be done. Both are due to the requirements that the laser beam traverse the tube wall. The first is to determine how much light is scattered by the quartz tube wall under realistic conditions, in order that estimates may be made of the magnitude of the stray light problem.

The second experiment is to determine the damage threshold of the quartz in the tube wall due to the primary laser beam. This will determine the laser power and focal spot size allowable in a scattering experiment.

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