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MOLECULAR ORIGIN OF BACKGROUND LIGHT
IN THOMSON SCATTERING MEASUREMENTS

By

D.H. McNeill

JUNE 1986

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MOLECULAR ORIGIN OF BACKGROUND LIGHT
IN THOMSON SCATTERING MEASUREMENTS

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ABSTRACT

The plasma background light in Thomson scattering measurements is often far higher than expected for a pure hydrogen plasma. The spectral distribution of light from three plasmas (duration: 1 ms to steady state; electron density: below 10^{12} to over 10^{14} cm⁻³; temperature: below 20 to over 1000 eV) and signal-to-noise and intensity data from the Thomson scattering systems used on them are compared with analytic estimates to show that in two of these plasmas molecular light dominates the spectrum, while in the other, molecular light is present, but bremsstrahlung is usually more intense. Knowledge of the mechanism for background light can aid in designing detection systems for Thomson scattering and provide information on the neutral species composition and effective charge of the plasma.

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I. INTRODUCTION

It is customary to treat the electron-ion bremsstrahlung continuum as the major source of background light in designing Thomson scattering systems for plasma experiments.¹⁻⁵ This is done primarily for ease of mathematical analysis, but also because edge regions of hot plasmas are assumed to contain negligible amounts of impurities and molecular hydrogen. Many hydrogen plasmas, however, emit light that is far more intense than pure hydrogen bremsstrahlung at the wavelengths of interest in Thomson scattering using ruby lasers (wavelength 694.3 nm). The bremsstrahlung continuum may be supplemented by impurity line emission. However, it was pointed out by Engelhardt⁶ that the line spectrum of molecular hydrogen might be a major contributor to the "enhanced continuum" background observed in some scattering measurements. In this paper the observed ratios of Thomson scattered signal to plasma background signal for three plasmas (EBT, S-1, and PLT) are compared with the ratios calculated using approximate formulas for the scattered signal, bremsstrahlung emission, and molecular emission. Spectral data from these plasmas show that hydrogen line emission dominates the background light in the first two examples, while it is present, but not usually dominant, in the third. Knowledge of the mechanism for the background signal in a Thomson scattering measurement can aid in designing the detection system and in statistical evaluation of the data obtained from it, as well as provide information on the properties of the plasma.

The Dieke tables list roughly 12000 emission lines of the H_2 and D_2 molecules in the wavelength interval from 500-750 nm.^{7,8} Although individual molecular lines are generally very weak compared with the Balmer lines of atomic hydrogen or strong impurity lines, their large number and closeness make them appear as a low-level continuum at the ≥ 1 nm resolution of the spectrum analyzers used in most scattering systems. Figure 1 shows the spectrum of a hydrogen discharge in the steady-state ACT-I plasma device,⁹ in which excitation and ionization are caused primarily by an electron beam propagating toroidally in the plasma. The structure of the H_2 spectrum produced by electrons with energies above 30 eV is well illustrated in this figure: the Fulcher alpha bands, centered near 600 nm, can be seen, along with emission at all other wavelengths, some of which appears to be a continuum at this resolution. (The true continuum of H_2 lies in the range 165-500 nm.)

The average number of photoelectrons produced in a detector with quantum efficiency η at the output end of a polychromator channel of width $\Delta\lambda_c$ (nm) centered near the ruby laser line by photons scattered from a plasma

volume with electron temperature T_e (eV) and density n_e (cm^{-3}) is roughly¹⁻⁵

$$S_S = 4.05 \times 10^{-8} E n_e 16 \Omega \Delta \lambda_c \tau \eta / (T_e^{1/2} \sin \theta / 2), \quad (1)$$

where E (J) is the laser pulse energy, l (cm) is the projected length of the viewed scattering volume normal to the collecting optics, $\delta \Omega$ (sr) is the solid angle of the collecting lens relative to the scattering volume, θ is the scattering angle, and τ is the fractional transmission of the optical system. Here it is assumed that the entire focussed laser beam is seen by the viewing optics, the scattering is incoherent and relativistic effects are negligible so that the full-width-half-maximum of the Gaussian scattered spectrum is given by $\Delta \lambda_{1/2} \approx 4.57 T_e^{1/2} \sin \theta / 2$, $\Delta \lambda_c \ll \Delta \lambda_{1/2}$, and the detector gate width (Δt_D , s) is wide enough to include all of the laser pulse.

For a plasma of diameter D (cm) with effective average electron temperature $\bar{T}_e$ and electron and ion densities $\bar{n}_e$ and $\bar{n}_i$, the average number of photoelectrons produced by bremsstrahlung emission from the plasma at wavelength λ (nm) during Δt_D is roughly⁷⁻⁸

$$S_B = 8.38 \times 10^{-15} \bar{n}_e \bar{n}_i \bar{Z}^2 \lambda^{-1} \bar{T}_e^{-1/2} \exp(-1240/\lambda \bar{T}_e) l w D \delta \Omega \times \\ \times \Delta \lambda_c \Delta t_D \tau \eta. \quad (2)$$

Here $\bar{Z}$ is the effective ion charge of the plasma for bremsstrahlung and w (cm) is the width of the volume viewed by the collecting optics in the object plane.

An estimate of the intensity of light from H_2 can be made by assuming that all molecules entering the plasma are absorbed.¹⁰ The probability of emission of a photon in the interval $\Delta \lambda_c$ by electron impact on a molecule is given approximately by $\langle \sigma_{mol} \rangle \Delta \lambda_c / \langle \sigma_{loss} \rangle$, where $\langle \sigma_{mol} \rangle$ denotes the rate coefficient for emission of photons at a given wavelength per unit wavelength ($\text{cm}^3 \text{s}^{-1} \text{nm}^{-1}$) and $\langle \sigma_{loss} \rangle$ is the rate coefficient for loss of H_2 by electron impact reactions (the sum of the rates of ionization, dissociative excitation into all states of the product atoms, and dissociative ionization). $\langle \sigma_{mol} \rangle$ can be evaluated by scaling the cross section data of Khayrallah¹¹ for $\lambda = 668$ nm to $\lambda = 694$ nm using emission spectra of H_2 such as that of Fig. 1. The ratio $f_m = \langle \sigma_{mol} \rangle / \langle \sigma_{loss} \rangle$ obtained in this way is approximately $1.2 \times 10^{-4} \text{ nm}^{-1}$ for $T_e \geq 20$ eV.¹⁰ The number of photoelectrons produced in the detection system by a flux Φ ($\text{cm}^{-2} \text{s}^{-1}$) of hydrogen entering both sides of the plasma is given by the product of the number of molecules per unit time entering the surfaces seen by the collecting lens and the probability of photon emission within the observation

passband, times the quantum efficiency and various transmission and solid angle factors:

$$S_M = 0.16 \Phi_{\text{MW}} \Omega \Delta \lambda_c \Delta t_D \tau \eta. \quad (3)$$

For a short-lived (i.e., less than the transit time for a thermal molecule across the vessel) discharge in a vacuum vessel with a filling pressure p (Torr) of H_2 at room temperature, the flux is given roughly by $\Phi = 1.5 \times 10^{21} p$ ($\text{cm}^{-2}\text{s}^{-1}$). For longer-lived discharges, the neutral pressure at the plasma edge is not isotropic, so it is more appropriate to deal directly with the flux produced by a gas feed or by release of trapped gas from the wall.

II. SPECTROSCOPIC ANALYSIS OF BACKGROUND LIGHT

This section describes spectral analyses of the background light from three plasma devices: EBT, S-1, and PLT. The purpose was to determine the amount of molecular light in the background. Numerical estimates of the signal to noise characteristics of the Thomson scattering measurements on these devices are given in the conclusion of this paper.

The ELMO Bumpy Torus (EBT) was a steady-state microwave heated plasma in a toroidal vacuum vessel with a major radius of 150 cm and minor radius of 12-25 cm.^{10,12} In this plasma the average electron density is approximately $1 \times 10^{12} \text{ cm}^{-3}$ and the bulk electron temperature, roughly 100 eV. The evolution of the Thomson scattering system on this device has been discussed by Cobble.¹² During early measurements (with a repetitively pulsed ruby laser and a rotatable interference filter for spectral analysis), it was found that the plasma background light was many orders of magnitude greater than bremsstrahlung.¹³ Figure 2 shows a spectrum over 595-605 nm from a deuterium plasma in EBT together with a comparison spectrum¹⁴ from a gas discharge tube. The O I 604.6 nm line is the only significant impurity line that can be seen. Similar agreement with comparison spectra was obtained for hydrogen discharges. In addition, the spectral distribution of plasma light obtained with the Thomson scattering detection system (a rotatable interference filter with a passband of 12 nm) agreed well with that calculated⁸ for a 12-nm-wide rectangular passband crossed with the line intensities given in the H_2 wavelength table of Gale, Monk, and Lee.¹⁵ This spectrum showed a minimum near the laser wavelength (as in Fig. 1) and a contribution from the Al II triplet near 706 nm. Spectral and intensity data of the type described here showed clearly that H_2 (D_2) line emission dominated the plasma light, and that

significant amounts of molecular hydrogen were present at the edges of the plasma.

The S-1 Spheromak is a pulsed discharge (plasma lifetime ≤ 1 ms), with $n_e \approx 0.3\text{--}2 \times 10^{14} \text{ cm}^{-3}$ and, depending on the filling pressure, peak average T_e of 8–25 eV without stabilizing coils¹⁶ (as in the data discussed here) and ≈ 45 eV with stabilizing coils.¹⁷ The plasma is produced in a vacuum vessel with a roughly oblate ellipsoidal shape and a mean diameter of slightly more than 2 m. During design of the single-point scattering system for S-1, the background light level was estimated under the assumption that hydrogen gas would flow into the plasma throughout its lifetime. When the expected molecular line emission from this gas was included, the calculated background level was within a factor of two of that observed in the experiment. Measurements were subsequently made to determine the actual contributions of molecular and impurity radiation to the background. Figure 3 shows traces of the photomultiplier signal from two of the seven channels of the Thomson scattering polychromator during a typical mid-range shot. The five remaining channels had the same waveform as the lower trace, which, in turn, was closely matched¹⁸ by the time variation of the H_α line and, for example, of the 463.4 nm line of H_2 . The channel centered at 679.8 nm had strong peaks in the main part of the discharge (0.15–0.40 ms) which were highly variable from shot to shot. These peaks were similar in duration and time of appearance to those from visible C II lines,¹⁸ and the additional structure in this channel can be attributed to the C II 673 nm multiplet. The absolute intensity of the background light viewed by the collecting optics was determined from a comparison between the background and the Thomson scattered signal, and found to equal the value given by Eq. (3) to within 40% (the measurement error) for a flux corresponding to the initial filling pressure. These conclusions about the origin of the background light in S-1 are consistent with careful background measurements made by Wysocki¹⁹ on the smaller Proto-S-1-C device, which operates with lower T_e and higher n_e and filling pressures.

The PLT tokamak is larger and hotter than the above examples, with discharge minor and major radii of roughly 40 and 140 cm, respectively, and central electron temperatures above 1 keV.^{20,21} Figure 4 shows simultaneous traces of the intensity of H_α (0.3 nm fwhm detector channel) and of light at 594 nm (10 nm fwhm interference filter) along the same optical path during a PLT discharge shortly after the beginning of a series of runs with ion Bernstein wave resonance heating.²⁰ The optics view tangentially to the toroidal magnetic field past a gas inlet near the Thomson scattering port. The peaks labelled 1, 2, and 3 correspond to the times gas was fed into the vacuum vessel. (The relative

intensity of the H_{α} light and the light passing through the interference filter at 694 nm is 60 ± 15 at these times.) Depending primarily on the sticking probability for H atoms at the walls, the ratio of H_{α} photons to H_2 photons in a 10 nm band centered at 694 nm emitted from a flux of H_2 molecules entering a hot, dense plasma can be estimated to be 45 ± 20 .²² The intensity ratios in peaks 1-3 of Fig. 4, therefore, suggest a molecular origin for the light during gas injection into the machine. The H_{α} signal obtained from a radially viewing collimator with a viewing dump at the Thomson scattering port has a time history similar to that of the H_{α} trace of Fig. 4, but with lower peaks during gas injection. These data, and absolute measurements of the H_{α} intensity, indicate that when gas is fed into the discharge most of the background light in the Thomson scattering system is from molecular emission. The molecular light at the Thomson scattering port is enhanced because this port is close to a gas feed port and gas enters the field of view at levels in excess of wall recycling. (The H_{α} signal on the opposite side of the torus shows none of the peaks of Fig. 4 during gas injection and, except at the limiter, the intensity is roughly uniform around the torus when the gas feed is off.)

The behavior of the background light during moderate power auxiliary heating (with ion Bernstein waves in the traces of Fig. 4) and when no gas is being fed into the discharge is somewhat different from that described above. The time labelled RF in Fig. 4 corresponds to application of ≈ 230 kW of rf power at 30 MHz. At this time the gas puff is off, so that the H_{α} signal is low; however, the signal at 694 nm rises substantially during the rf pulse. Furthermore, in the wide-band 694 nm trace, the intensity at the base of the peaks is higher relative to the peaks than in the H_{α} trace. Both the intensity rise during the RF pulse and the higher baseline in the 694 nm trace appear to be caused by two factors related to the influx of impurities: increased line emission by impurity species (e.g., C and Cr, many lines of which lie in this range) and an enhancement of the effective charge $\bar{Z}$ to values above 1. The relative increase in the signal at 694 nm during the rf pulse corresponds roughly to the square of the relative density increase (by a factor of about 1.5) during that time, suggesting that the increase is caused by bremsstrahlung (cf. Eq. (2)) with $\bar{Z} = \text{const}$. During rf heating and during Ohmic heating with the gas supply turned off, therefore, impurity-related emission dominates the background light in the Thomson scattering system on PLT.

III. SIGNAL-TO-NOISE CALCULATIONS. CONCLUSION

The signal-to-noise ratio for a given detector channel can be defined

in a number of ways.^{1,23} For simplicity of comparison among the preceding examples, it is defined here as the ratio of the intensities of scattered and background light. The Table lists typical signal-to-noise characteristics of the three experiments discussed above. Listed there are the electron density and temperature in the scattering volume, their averages over the plasma volume, and various parameters of the scattering system, together with the observed signal-to-noise ratio $(S/N)_0$, the calculated signal-to-noise ratio for bremsstrahlung $(S/N)_B = S_B/S_B$ [Eqs. (1) and (2)], the entering flux of H_2 , and the calculated signal-to-noise ratio for molecular emission $(S/N)_M = S_S/S_M$ [Eqs. (1) and (3)]. In all cases the observed S/N is substantially lower than the bremsstrahlung S/N for $\bar{Z}=1$, i.e., for a pure hydrogen plasma. The spectral measurements and the data in the Table show that the background light in EBT and S-1 is primarily caused by hydrogen molecular line emission. In PLT, on the other hand, the hydrogen emission measured around the torus is not sufficient to explain the observed background level and bremsstrahlung (with some impurity line emission) provides most of the background. When gas is being fed into the discharge, however, the level of molecular emission detected by the scattering system is higher and may dominate the background.

The background light in ruby laser Thomson scattering measurements on two types of plasma (EBT and S-1) with densities of $\approx 10^{12}$ and 10^{14} cm^{-3} has been shown to be caused almost entirely by hydrogen molecular line emission, with a small contribution from impurity line radiation. In the larger PLT tokamak, impurity line emission and, especially, enhanced bremsstrahlung are responsible for most of the background except during gas injection, when molecular line emission may predominate. The contribution of the impurity sources rises as the power applied to the discharge increases. It may, therefore, be expected that in large tokamaks with minor radii approaching 1 m, such as TFTR, the background light observed in Thomson scattering measurements is mainly impurity-related radiation. If the background in scattering measurements on these plasmas can be shown to be caused primarily by bremsstrahlung, an upper limit to the effective charge $\bar{Z}$ of the plasma can be determined from the scattering data.

This discussion has dealt with ruby laser scattering; however, the same background source would be active for any laser operating between the near infrared and near ultraviolet. Besides helping to explain the nature of the large background seen in many Thomson scattering experiments, detailed measurements of the plasma background light have the additional benefit of providing information on the amounts of neutral and atomic hydrogen at the edges of hot plasmas.

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SIGNAL-TO-NOISE RATIOS IN THREE THOMSON SCATTERING EXPERIMENTS

DISCHARGE:

	EBT	S-1	PLT
Parameter:			
T_e (eV) ^a	80 (40)	20 (20)	1500 (600)
n_e (cm ⁻³) ^a	8×10^{11} (8×10^{11})	1×10^{14} (1×10^{14})	3×10^{13} (2×10^{13})
E (J)	1.3	5	10
w, l (cm)	0.5, 0.5	0.6, 1.5	0.4, 1.2
$\delta\Omega$ (sr)	0.018	0.016	0.015
$\Delta\lambda_c$ (nm)	10	1.0	7
τ, η	0.05, 0.08	0.03, 0.05	0.07, 0.06
θ (deg)	90	120	90
$\bar{Z}$	1	1	1, 3.5 ^b
D (cm)	30	50	80
Δt_D (s)	50×10^{-9}	80×10^{-9}	100×10^{-9}
Φ (cm ⁻² s ⁻¹)	5×10^{15} ^c	2.2×10^{18} ^d	$\leq 5 \times 10^{15}$ ^e , $\leq 2 \times 10^{16}$ ^f
S_S	2.4	190	230
$(S/N)_O$	2	4	25
$(S/N)_B$	7600	83	710, 58 ^b
$(S/N)_M$	2.8	2.6	≥ 120 ^e , ≥ 29 ^f

Notes: (a) The values in the scattering volume are given first and average values in parentheses; (b) the bremsstrahlung signal-to-noise ratio is calculated for two values of $\bar{Z}$ in PLT; (c) derived from direct measurements of the H_2 intensity;¹⁰ (d) given by $nv/4$ where n is the density of deuterium molecules at a filling pressure of 2 mTorr and v is their thermal speed at room temperature; (e) estimated from the H_{α} intensity when the gas puff is off; (f) local value estimated from the H_{α} intensity during gas injection.

FIGURE CAPTIONS

Fig. 1. The spectrum of a hydrogen discharge in the ACT-1 device. The multiplicative sensitivity factor (dotted curve) may be used to scale the observed spectral intensity. The scanning monochromator had a triangular instrument profile with a base width of 3.1 ± 0.1 nm. The maximum intensity of the H_{α} line (656 nm) was roughly 25 on the left-hand scale, and the peak at 777 nm is from an impurity (O I triplet).

Fig. 2. The spectrum of a deuterium discharge in EBT with a filling pressure of 1.6×10^{-5} Torr (uncalibrated ionization gauge reading) and an applied microwave power of about 35 kW at 18 GHz with a comparison spectrum from a gas discharge tube¹³ (lower trace).

Fig. 3. Traces of the signal from two polychromator channels on the S-1 Thomson scattering system. The lower trace has the same waveform as that of the other five channels, while at its peak the upper trace includes a strong contribution from a C II multiplet.

Fig. 4. Traces of emission from the PLT tokamak seen through a 10 nm fwhm interference filter centered at 694 nm (top) and through a 0.3 nm fwhm monochromator centered at the D_{α} wavelength.

Fig. 1.

Fig. 2.

#84X0126

Fig. 3.

#86X0735

Fig. 4.

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