Molecular Rayleigh Scattering as Calibration Method for Thomson Scattering Experiments

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This work presents the results obtained with Rayleigh scattering as method of calibration for the Thomson scattering diagnostic in the determination of density and temperature on the field-reversed theta-pinch TC-1 at UNICAMP. The methods employed to reduce the presence of stray light, as well as quest for best scattering geometry, are also described.

I. Introduction

The Thomson scattering[1,2,3] is the most straightforward technique used for local measurements of electron temperatures (T_e) and densities (n_e) in pulsed plasma devices. It consists basically on the measurement of the scattered light induced by a high power laser on the electrons of the plasma. A ruby laser ($\lambda_i =$ 694.3 nm) is commonly used for this purpose. The scattered light can be coherent or incoherent, depending on the a parameter α parameter ($\alpha = \lambda_i/4\pi\lambda_D \sin(\theta/2)$), where λ_D is the Debye length and θ is the angle between incident and scattered wavenumber vectors. For $\alpha \geq 1$, the coherent case, the scattered spectrum is influenced by the interaction between electrons and ions in the plasma. For the incoherent case, ($\alpha \ll 1$), this spectrum reflects the thermal electron motion, resulting in a Gauss profile for most laboratory plasmas. For scattering in plasma with maxwellian electron velocity distribution, as in this experiment, the signal S_{th} measured by a photomultiplier corresponding to the scattered light in a small observation solid angle $\Delta\Omega$ around a fixed angle Ω can be written as[1]:

$$\frac{dS_{\mathrm{Th}}(\lambda_s)}{d\lambda_s} = \frac{D \cdot P_i \cdot c \cdot n_e}{2 \cdot \sqrt{\pi} \cdot \lambda_i \cdot \sin(\theta/2)} \cdot \left(1 - \frac{7 \cdot (\lambda_s - \lambda_i)}{2 \cdot \lambda_s}\right) \cdot \left\{ \frac{1}{a} \cdot \left| 1 - \frac{G_e}{\epsilon} \right|^2 \cdot e^{-X_e^2} + \frac{1}{b} \cdot \left| \frac{G_e}{\epsilon} \right|^2 \cdot e^{-X_i^2} \right\} , \qquad (1)$$

where:

$$G_e = \alpha^2 \left(1 - 2 \cdot X_e \cdot e^{-X_e^2} \cdot \int_0^{X_e} e^{p^2} dp - i \cdot \pi^{1/2} \cdot X_e \cdot e^{-X_e^2} \right) ,$$

$$G_i = \alpha^2 \frac{z \cdot T_e}{T_i} \left(1 - 2 \cdot X_i \cdot e^{-X_i^2} \cdot \int_0^{X_i} e^{p^2} dp - i \cdot \pi^{1/2} \cdot X_i \cdot e^{-X_i^2} \right) ,$$

$$\epsilon = 1 + G_e + G_i \ ,$$

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$$X_e = \frac{c \cdot (\lambda_s - \lambda_i)}{2 \cdot \lambda_i \cdot \sin(\theta/2) \cdot a \cdot \left(1 + \frac{\lambda_s - \lambda_i}{\lambda_i}\right)^{1/2}}$$

and

$$X_i = \frac{c \cdot (\lambda_s - \lambda_i)}{2 \cdot \lambda_i \cdot \sin(\theta/2) \cdot b \cdot \left(1 + \frac{\lambda_s - \lambda_i}{\lambda_i}\right)^{1/2}} \ ,$$

and D is a calibration constant, P_i is the incident laser power, c is the light velocity, T_i is the ion velocity, Z is the ion charge number and a and b are the electron and ion thermal velocities, respectively.

The constant D depends on parameters of the collection optics and detector:

$$D = T \cdot \eta \cdot G \cdot L_s \cdot \Delta\Omega \left(\frac{d\sigma_T}{d\Omega}\right)_{\Delta\Omega} \ , \qquad (2)$$

where the total transmission of the collection optics T, the quantum efficiency η and the gain G of the detector, are assumed to be constant along each measured wavelength region of the scattered spectrum. L_s and $(d\sigma_T/d\Omega)_{\Delta\Omega}$ are the length of the scattered volume and the electron differential cross section, respectively.

Although the parameters T, η and G can be measured absolutely by using standard light sources and L_s, $\Delta\Omega$ and $(d\sigma_T/d\Omega)_{\Delta\Omega}$ can be determined from the geometry of observation as well as P_i can be measured directly, the individual determination of these parameters is a difficult task and large sistematic errors can appear in the theoretical calculation of S_{Th}. In practice, the determination of D as whole is done more easily by using molecular Raman or Rayleigh scattering. The same optics as for Thomson scattering is used, eliminating the problems with the estimation of the scattered volume, losses with the optical elements, detectors calibration and laser pulse measurement.

The Raman scattering is inelastic, and basically consists in changes on the vibrational and rotational states of the molecule, induced by the laser, originating spectral lines at both sides of the incident frequency[4,5]. Rayleigh scattering is elastic and occurs due to a dipole oscillation of the molecule with the same incident frequency. The light of the Raman scattering has an intensity of a factor of thousand less than that of Rayleigh scattering. It is specially recommended when the excessive stray light level makes Rayleigh scattering difficult or impossible to be measured. Calibration using Rayleigh scattering is done in this experiment after a carefull stray light suppression.

This work presents and discusses the results obtained by using Rayleigh scattering as calibration method for the Thomson scattering diagnostic implanted recently on the TC-1 device of UNICAMP. The techniques used to reduce stray light for this diagnostic are also discussed.

II. Experimental set up

The TC-1 device[6,7] is a field reversed theta-pinch with a coil length of 65 cm and 14 cm in diameter. It works with three capacitors banks, which are discharged in a pre-determined sequence. A maximum magnetic field of 0.36 T is reached after a rise time of 5 ms from the beginning of the main bank discharge with 1 mTorr of hydrogen gas. More details can be found in references 6 and 7.

For a first kind Thomson scattering experiment, the laser light was injected axially in the discharge tube of the TC-1 device. Apropriate entrance and exit windows were constructed for minimization of the stray-light. Details of this set up can be seen in Fig. 1. The ruby laser, working with a Pockel cell and generating 3 J pulse in 40 ns, was polarized vertically, i.e., perpendicular to the paper plane in Fig. 1. The beam diameter was reduced from 1 cm to 3 mm in the center of TC-1 by means of a 1 m focal length lens. The outgoing beam ended in a dump consisting of a curved Pyrex cone. The scattered light was observed perpendicularly to the the injection beam. A set of 3 plane mirrors was used to rotate the image in 90° in order to obtain a best matching between the observed plasma region and the entrance slit of the spectrometer (SPEX - 75 cm - 1.1 nm/mm). The alignment of the laser beam is very

critical and special care must be taken in the construction of stable supports to avoid misalignment due to temperature changes and external vibrations.

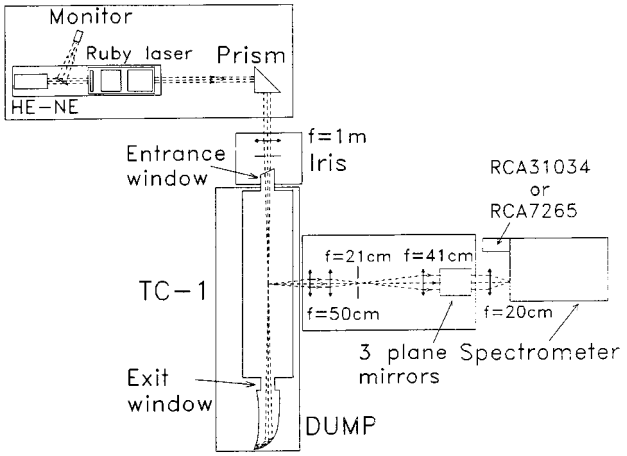

Figure 1: Experimental set up for axial Thomson Scattering.

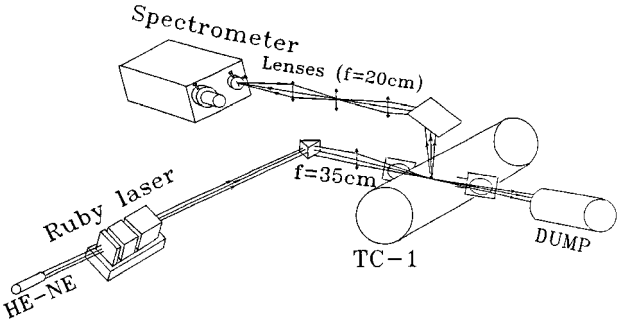

Figure 2: Experimental set up for radial Thomson Scattering.

A second type Thomson scattering experiment was done with side-on injection of the laser beam, horizontally polarized, i.e., in the axial direction of the discharge tube. With the proximity between entrance and exit windows the alignment became easier, but the problems concerning stray light increased. In this case, some modifications in the entrance and observation optic were necessary in order to reduce stray light to desirable levels. Windows constructed in Brewster angle were used to diminish the reflections. Black tubes inside the entrance and exit windows serve as protection against reflections and conduction of light throughthe discharge glass tube. The dump was better elaborated. A black paper was installed between the solenoid and the discharge tube to reduce the back reflections. Finally, the collection optic was protected by a black tube to avoid the captation of light comming from other parts of the experiment.

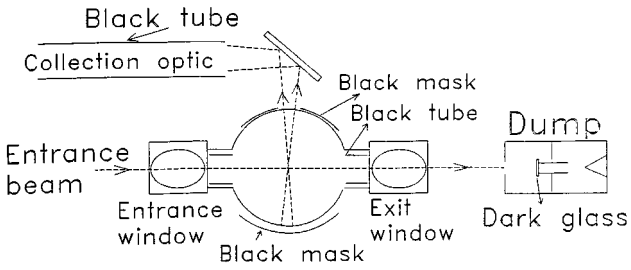

Figure 3: Details of the radial injection.

Rayleigh scattering for calibration of the Thomson scattering experiment was done after evacuation of the discharge tube by a mechanical pump, and insertion of nitrogen gas. The nitrogen gas system of injection must be previously evacuated and cleaned with a nitrogen flow of gas to avoid that heavy particles be suspended during the laser shots. Since these particles have a bigger cross section, they can contribute to increase the level of stray light introducing large errors in the measurements.

III. Rayleigh Scattering

Since the Rayleigh scattering is performed at room temperature, the width of the scattered profile is much less than the instrumental profile of the spectrometer. The Rayleigh signal S_{Ray} will correspond to the integrated spectrum over all relevant wavelength region inside the angle of observation ($\Delta\Omega$):

$$S_{\mathrm{Ray}} = \left(\frac{d\sigma_R}{d\Omega}\right)_{\Delta\Omega} \cdot n_R \cdot L_s \cdot \Delta\Omega \cdot T \cdot \eta \cdot G \cdot P_i \ , \quad (3)$$

where n_R is the density of the gas molecules and $(d\sigma_R/d\Omega)_{\Delta\Omega}$ is the differential cross section for the used gas. The normalization in eqs. (1) and (3) of S_{Th}, S_{Ray} and P_i with the monitor signal of a photodiode, arbitrarily proportional to P_i, eliminates problems concerning changes on the laser power from shot to shot. In this way, the constant D (equation 1) can be written as:

$$D = \frac{S_{\mathrm{Ray}}}{n_R} \cdot \frac{(d\sigma_T/d\Omega)_{\Delta\Omega}}{(d\sigma_R/d\Omega)_{\Delta\Omega}} \quad (4)$$

The ratio between Thomson and Rayleigh cross sections is known for several gases and listed in table 1 [8]:

Gas	σ_T/σ_R
N_2	380
H_2	1769
CH_4	177
O_2	462

Table 1: Ratio between Thomson and Rayleigh cross section[8].

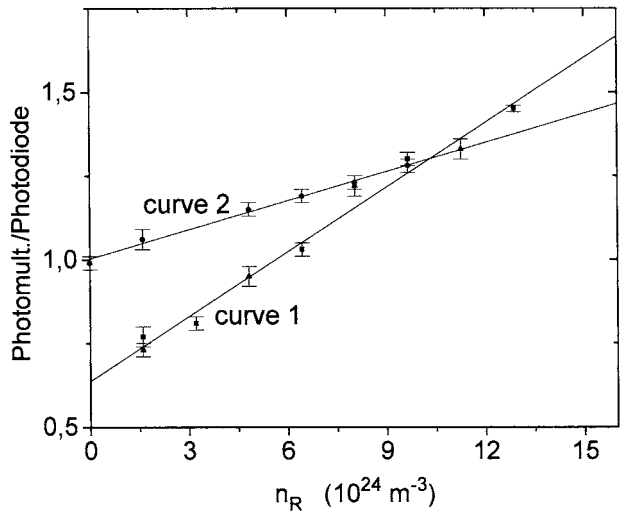

Figure 4: Molecular Rayleigh scattering with nitrogen gas, curve 1, 2 - axial and radial set up, respectively.

As it can be inferred from equations 1, 3 and 4, the power ratio between nitrogen Rayleigh scattering and Thomson scattering for typical θ-Pinch plasmas with n_e = 1x10^{21} m^{-3}, T_e = 100 eV, and for perpendicular scattering $\theta = 90^0$ in the wavelength range of $\lambda_s = \lambda_I \pm 11$ Å, is $P_{\mathrm{Ray}}/P_{\mathrm{Th}} = 4 \times 10^{-2} \frac{n_R}{n_e}$. In order to obtain Rayleigh signals comparable or greater than the stray light level of this experiment, it has been necessary to operate with nitrogen molecule densities in the range of 1.5x10^{24} m^{-3} to 1.5x10^{25} m^{-3}, i. e., a factor of 1000 to 10000 greater than the electron density. The voltage supply of the photomultiplier was also reduced from its normal operation value (1800 V or 2010 V) to 1350 V in order to prevent signal saturation. The photomultiplier signals obtained during Rayleigh scattering were corrected by the correspondent factor due to the changes in the gain, as measured from light emission diodes.

Fig. 4 shows the results obtained with the Rayleigh scattering. In this figure, the normalized S_{Ray} is plotted as function of the nitrogen gas pressure. The curve 1 corresponds to the axial set-up (Fig. 1). In this curve triangle and square dots have been taken with five days of difference, indicating a very good alignment stability. The curve 2 of Fig. 4 corresponds to the radial set-up (Fig. 2) . Each point of these curves correspond to a mean of 4 to 6 shots. As the nitrogen fill pressure is directly related to nR inside the tube at room temperature, it is possible to obtain the relation S_{Ray}/n_R from the inclination of these curves. The signal at vacuum ($n_R = 0$) corresponds to the stray light level of the system. One observes from these curves that the stray light level for axial injection has a factor of 3.7 lower than the side-on measurements within 25% error, when the mean value and the standard deviation of the laser monitor, different for each curve, are considered for all shots. The numerical difference on the inclination of curves (1) and (2) is mainly due to different normalization factors from the photodiode, and some differences on the respective collection optics. The great advantage in using this method of calibration is that absolute measurements on the laser power are not necessary as well as, measurements on the observation solid angle, transmission of the optical set up, and parameters related to the gain of the photomultiplier. Measurements along the Thomson spectrum, specially for high electron temperatures when it's profile is very broad, require relative calibration of the detector (or detectors) due to the variation of it's sensibility along the wavelength. This calibration can be done by using a calibrated tungsten lamp.

IV. Conclusions

A simple and practical method for calibration in Thomson scattering experiments using Rayleigh scattering is described. This method was used for experiments with axial and side-on light injection on the theta-pinch plasma of the TC-1 device. The stray light level for axial injection (Fig. 1) was about a factor of 3.7 less than for side-on injection (Fig. 2), as obtained from curves 1 and 2 of Fig. 4. This result reveals the influence of the reflections at the windows and the conduction of the laser light through the glass tube of the

vacumm chamber. The techniques employed to reduce the stray light (Fig. 3) were decisive to obtain the signals with the assembly of Fig. 2. The stable optical alignment can be confirmed by the results of curve 1 in Fig. 4. High pressures for Rayleigh scattering calibration are not recommended because gas breakdown can occur. Moreover, the vacumm chambers are generally not constructed to operate in such conditions. The linear increasing of the scattered signal with the pressure (or molecular density), demonstrate a good matching of the experimental data to the predictions of eq. (3).

The great advantage in using this method of calibration is that the absolute measurements on the laser power are not necessary as well as measurements on the observation solid angle, transmission of the optical set up, and parameters related to the gain of the photomultiplier.

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