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Citation for published version (APA):

Bakker, L. P., Freriks, J. M., Hoog, de, F. J., & Kroesen, G. M. W. (2000). Thomson scattering using an atomic notch filter. *Review of Scientific Instruments*, 71(5), 2007-2014. <https://doi.org/10.1063/1.1150569>

DOI:

[10.1063/1.1150569](https://doi.org/10.1063/1.1150569)

Document status and date:

Published: 01/01/2000

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Thomson scattering using an atomic notch filter

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(Received 30 November 1999; accepted for publication 21 January 2000)

One of the biggest problems in performing Thomson scattering experiments in low-density plasmas is the very high stray light intensity in comparison with the Thomson scattering intensity. This problem is especially present in fluorescent lamps because of the proximity of the glass tube. We propose an atomic notch filter in combination with a dye laser and an amplified spontaneous emission (ASE) filter as a way of reducing this stray light level. The dye laser produces 589 nm radiation which is guided through the ASE filter that increases the spectral purity. The beam is then guided in the fluorescent lamp, where the Thomson scattering process takes place. The scattered light is collected and guided through a sodium vapor absorption cell, where the stray light is absorbed because it is resonant to the D_2 transition of sodium. The spectral width of the Thomson scattering light is large enough to be transmitted through the absorption cell. In this way we only measure the Thomson scattering light. © 2000 American Institute of Physics.

[S0034-6748(00)02805-7]

I. INTRODUCTION

Thomson scattering is elastic scattering of photons at free electrons. It has been used extensively for the determination of the electron energy distribution function in high-density plasmas like fusion plasmas. Recently, this technique has also been introduced for plasmas with electron densities down to 10^{17} m^{-3} .¹⁻³ Thomson scattering gives reliable results for the electron density and the electron temperature. In contrast with Langmuir-probe measurements, the interpretation of the measurements is straightforward and the results are unambiguous. However, the main difficulty for performing Thomson scattering in low-density plasmas is the low intensity of the scattered signal. The Thomson scattering intensity is very small compared to the intensities of plasma emission, Rayleigh scattering and stray light. In order to increase the Thomson signal, high power lasers such as Nd:YAG lasers are used. However, using more laser power also increases the Rayleigh signal, and the stray light. The wavelength of these two signals is approximately equal to the wavelength of the laser. The spectral width of the Thomson signal, however, is much larger due to the Doppler effect and the movement of the free electrons. This is why normally one can discriminate the stray light (and the Rayleigh scattering) from the Thomson scattering signal by using a grating monochromator. However, due to the instrumental broadening of the monochromator the stray light and the Thomson signal will overlap. Furthermore, the stray light intensity is a few orders of magnitude higher than the Thomson signal, so the Thomson signal will be lost in the noise of the stray light. This is especially the case in a low-density plasma like a fluorescent lamp, where the stray light level is very high due to the proximity of the tube wall.

A notch filter at the laser wavelength will reduce the stray light considerable. However, interference notch filters cannot be used because of the fact that the spectral width of the best interference notch filters available is comparable to the characteristic width of the Thomson signal. One has to look for special notch filters like an atomic absorption cell or a double monochromator. We propose an atomic absorption cell as a notch filter. The biggest problem of using such a filter in a Thomson scattering setup is finding the laser at the right wavelength, with sufficient spectral purity. We will describe a way to introduce an atomic filter in a Thomson scattering setup.

II. EXPERIMENTAL SETUP

This section describes the experimental setup. We will start with an overview of the Thomson scattering setup. After this overview, we will describe the two new components, and the detection branch in detail.

A. Overview of the Thomson scattering setup

The setup we built is basically a standard Thomson scattering setup, except for two components. At first, we used an excimer pumped dye laser with an amplified spontaneous emission (ASE) filter instead of a “standard” Nd:YAG laser. At second, we added a sodium vapor absorption cell in the detection branch of the setup. Figure 1 shows a schematic drawing of the setup.

The excimer pumped dye laser (Lambda Physik LPX 315, and FL 3002) produces a laser beam with a wavelength of 589.0 nm. The pulse energy is at maximum 60 mJ at a repetition frequency of 150 Hz. The pulse width is 30 ns. The laser beam is focused in a fluorescent lamp by a lens with a focal distance of 800 mm. The laser wavelength is equal to the wavelength of the sodium D_2 transition. This means that, given the fact that the intensity is not too high

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FIG. 1. Schematic drawing of the experimental setup.

and the spectral width of the laser is small enough, the laser radiation will be absorbed by sodium vapor. On the other hand, the Thomson signal, which is Doppler broadened, will be transmitted through sodium vapor.

There is one problem with this setup: The laser not only produces radiation at 589.0 nm, but also a broadband signal called ASE. This ASE signal has the same spectral width as the dye-tuning curve. The spectrally integrated ASE level is typically 1%–1% of the laser power. Because of the fact that it is a broadband signal, it will not be absorbed by sodium vapor. So we need a bandpass filter with a spectral width smaller than the spectral width of the sodium vapor absorption cell. To accomplish this, we will make the spectral width of the ASE filter as small as reasonably possible and we will increase the spectral width of the sodium vapor absorption cell sufficiently. Then, the stray light reduction will be equal to the rejection of the ASE filter multiplied by the ASE level of the laser.

In the next subsections we will discuss the ASE filter, the sodium absorption cell, and the detection branch of the setup, respectively.

B. The ASE filter

The ASE filter consists of two spatial filters and a configuration of 20 prisms. The design of the filter is discussed in Ref. 4. Here we will briefly discuss its characteristics.

A schematic overview of the filter is given in Fig. 2. The first spatial filter creates a parallel beam, which is guided through the 20 prisms. After passing the prisms, the laser beam is focused on a second pinhole that selects the wavelength. The transmission of the ASE filter is measured with a single-mode ring dye laser. The normalized transmission profile is shown in Fig. 3. The transmission for the central wavelength of the filter is approximately 80%, which is very high, considering the fact that the beam passes 40 prism surfaces. The 1% transmission width of the filter is 0.19 nm.

FIG. 2. Schematic drawing of the ASE filter.

FIG. 3. Normalized transmission profile of the ASE filter.

All the components are mounted on a vertical breadboard. This vertical orientation has two advantages: At first, we do not need to change the polarization of the laser beam, and at second a vertical breadboard needs less space in the laboratory. The lenses have a focal distance of 400 mm. The pinholes are produced by focusing the laser on a piece of aluminum tape. In this way we “drilled” a hole which exactly matched the laser focus. The diameter of the pinholes was $320 \pm 20 \mu\text{m}$.

We note that by changing the position of the second pinhole, the central wavelength of the bandpass filter can be changed. We used the filter at 589 nm.

The next objective is to design an absorption cell with a spectral width that matches the spectral width of the ASE filter. In Sec. II C we will discuss the design of our sodium vapor absorption cell.

C. The sodium vapor absorption cell

This subsection describes the design and the characteristics of the sodium vapor absorption cell. This absorption cell has to absorb all the stray light. On the other hand, the Thomson scattering signal has to be transmitted through the cell without being absorbed. We can define four criteria for the absorption cell:

- (1) the absorption of the stray light has to be very large, even when saturation of the transition is present;
- (2) the excited atoms should lose their energy before the next laser pulse arrives;
- (3) the transmission width has to be larger than the width of the ASE filter; and
- (4) the transmission of nonresonant light should be as high as possible.

Note that the transmission width is defined as the spectral width of the transmission profile of the absorption cell. This width is much larger than the width of the absorption lines. The first two criteria determine the atom density in the cell and the absorption length. We start with the first criterion. Absorption without saturation can be described by Lambert–Beer’s law. However, due to the high power radiation, we have to consider saturation. A very simple way of treating saturation in the resonant absorption of a nanosecond scale high power laser pulse is considering the saturation

length concept. We assume the absorption in the vapor to be high. When a high power laser pulse enters the vapor, it will excite the atoms in the vapor. The upper state of the atoms will be populated. We will divide the laser pulse in N equal parts. The first part of the pulse excites part of the atoms along a certain length in the absorption cell. This part of the cell is called the saturated region. In this region, the excited atom density will be so high that the probability for stimulated emission from the excited state will be equal to the probability for absorption from the ground state. Therefore, when the lifetime of the excited state is much higher than the length of the laser pulse, then the second part of the laser pulse will be transmitted through the part saturated by the first part of the pulse without losing photons. When the second part of the pulse arrives at the end of the saturated region, then it will excite the atoms in the subsequent part of the cell, thereby extending the saturated region. This process will repeat for the N parts of the pulse. After the whole pulse is absorbed, the number of excited atoms in the vapor will be equal to the number of photons in the pulse. In this way we can relate the number of photons N_p in the pulse to the number of excited atoms in the saturated region.

$$N_p = \frac{1}{g_1/g_2 + 1} \cdot n_a A l_s, \quad (1)$$

where g_1 and g_2 are the statistical weights of the lower and the upper state of the transition, n_a is the atom density, A is the area of the light beam, and l_s is the saturation depth. We assume that A is equal to the cross section of the absorption cell. We can rewrite this expression

$$l_s = N_p \cdot \left(\frac{1 + g_1/g_2}{n_a A} \right) = E_p \cdot \frac{\lambda}{hc} \cdot \left(\frac{1 + g_1/g_2}{n_a A} \right), \quad (2)$$

where E_p is the pulse energy, λ is the wavelength, h is Planck's constant and c is the velocity of light. In order to have sufficient absorption, the length of the absorption cell has to be larger than the saturation length.

The second criterion deals with transport of resonance radiation. We will make a very rough approximation of the characteristic time for de-excitation of the atoms in the vapor cell. We assume that the radiation transport can be described as a diffusion process of excited atoms. The diffusion coefficient D for this process is

$$D = \frac{1}{\sigma^2 \tau n_a^2}, \quad (3)$$

where σ is the cross section for absorption and τ is the lifetime of the upper state. We neglect quenching so the only loss of excited atoms (photons) is at the walls. In this way we estimate the upper limit of the characteristic time for de-excitation of the atoms in the vapor cell. The expression for this characteristic time is

$$\tau_d = \frac{\Lambda^2}{D} = \sigma^2 \tau n_a^2 \Lambda^2, \quad (4)$$

where Λ is the characteristic length of diffusion. In a long cylinder with a circular cross section, this length is equal to $R/2.4$, where R is the radius of the cylinder.

TABLE I. The characteristic quantities of the sodium vapor absorption cell.

Quantity	Value 1	Value 2
Absorption length	17 cm	17 cm
Cell radius	2.5 cm	2.5 cm
Argon pressure	1 bar at 20 °C	1 bar at 20 °C
Sodium pressure	0.27 Pa	2.12 Pa
(temperature)	(250 °C)	(300 °C)
Saturation length per pulse energy	70 mJ	8.9 mJ
Characteristic time for de-excitation	7 μ s	421 μ s
Theoretical 1% transmission width	0.17 nm	0.50 nm

The third criterion can be met by adding argon gas to the vapor. We thereby introduce pressure broadening of the resonant absorption lines.

The fourth criterion is met because of the fact that atomic absorption lines have very steep profiles. However, keeping the windows clean is an important issue.

The atomic vapor in the absorption cell is sodium. Sodium is chosen because of its strong D lines at 589.0 and at 589.6 nm. At these wavelengths we can use the Rhodamine 6G dye, which is cheap, relative stable, and efficient. The sodium D₂ line at 589.0 nm is more suitable than the D₁ line at 589.6 nm. The D₂ line is stronger, and its transmission width is larger. We chose the cell radius and the absorption length in such a way that we have met the requirements mentioned above, and in such a way that we could use standard ConFlat (CF) vacuum components. In Table I, the values for the absorption length, the cell radius, and the argon pressure are given. This table also shows two different sodium pressures and the values for the saturation length, the characteristic time for de-excitation, and the 1% transmission width. This width is calculated from the sodium vapor pressure⁵ and the collisional broadening cross-section for the sodium D₂ line by argon.⁶ It seems that both sodium pressures can be used: both the saturation length and the characteristic time for de-excitation are small enough. Furthermore, both the transmission widths are large enough. Note that the saturation length is not long enough for the direct absorption of the laser pulse. However, the cell has to absorb the scattered radiation only. The pulse energy of this scattered radiation will be more than two orders of magnitude lower than the laser pulse energy. Due to this, the absorption length for the scattered radiation will be smaller than the length of the absorption cell. Concerning the de-excitation of the atoms in the cell, we can draw an interesting conclusion. The de-excitation takes place on a microsecond scale. The Thomson scattering signal is present during the 30 ns of the laser pulse. So when we open the detector during the laser pulse and close it when the pulse is terminated, then the photons emitted during the de-excitation of the atoms in the vapor cell will not be detected.

Having performed this theoretical estimation, the design of the sodium cell seems straightforward. However, it is not. Sodium is very reactive, it is a very strong reducing agent. Special care has to be taken in choosing materials of the cell that can be in contact with the sodium vapor. The absorption

TABLE II. The materials used for the sodium vapor absorption cell.

	Material	Sodium resistance	Reference
Windows	sapphire	Resistant to Na, at least up to 500 °C	7
Glass to metal seals	Sealing ceramic: oxide mixture also called the sealing frit	Used for high pressure sodium lamps up to 1500 K	8–10
Metal to metal junction	Kovar	Resistant to Na up to 500 °C, corrosion resistance better than Fe, worse than stainless steel.	10,11
Vessel	304 stainless steel	Used with Na up to 1500 K	9
Gaskets	silver and copper	Silver used up to 300 °C, Copper up to 500 °C.	7,12
Gas fill	argon	No reaction	13
Pollution	Metal oxides from vessel, and water from Argon impurity.	React with sodium	13

cell can be divided into six parts: the windows, the glass to metal seal, metal to metal junction, the vessel, the gaskets, and the gas fill. Note that the metal to metal junction is necessary to match the thermal expansion of the window material to the vessel. Apart from these six parts, there is also some pollution. After having studied the literature carefully, we chose suitable materials for every part of the absorption cell. Table II shows the materials we used, along with their resistance to sodium as has been found in the literature. We note that we do not claim to give a complete overview of the resistance data.

The purity of the argon gas was 99.999%. This means that we introduce 10^{-5} bar = 1 Pa of impurities, mostly water in the cell. This “pollution pressure” is higher than the sodium vapor pressure. So before the cell can be used as an atomic notch filter, it has to be “neutralized”, i.e., the pollution has to react with the sodium vapor.

The design of the absorption cell is shown schematically in Fig. 4. It consists of a standard CF 63/40 reducer tee (a), with two sapphire windows mounted on CF 63 flanges (b₁ and b₂). On the other flange, a CF 40 full nipple is mounted (c), with a cooling block (d) and an ampule crusher (e). At the end of this nipple, a CF mini valve (f) with a glass pipe (g) is mounted. The valve is covered with heat-isolating ceramic material in order to prevent it from being the coldest part of the setup. The ampule crusher is a thin stainless steel

pipe. In this thin pipe, a closed sodium ampule is placed. By bending the tube, the glass will break, and the sodium is released.

The cell is placed in an oven with four compartments: two compartments containing the sapphire windows (1 and 2), one compartment containing the reducer tee (3), and one compartment for the nipple (4). This part is called the cold part. The oven has two windows to decrease the heat losses (h₁ and h₂). These windows are antireflection coated. The sapphire windows are heated by heating elements on their flanges, and by air heating in compartments 1 and 2. The temperature of the cold part is controlled by a heating element, which is placed in between the CF mini valve (f) and the cooling block (d). Furthermore, we can cool compartments 3 and 4 by opening the oven at three positions (i₁, i₂, and i₃). The heating of the four compartments is controlled by a microprocessor based controller.

The temperature of the coldest part of the setup determines the sodium vapor pressure. At this cold spot the sodium vapor condenses. In our case the liquid sodium is at the position of the cooling block. The controller sets the cold-spot temperature, and the temperature difference of the windows with respect to the real temperature of the cold spot. Using this scheme, the windows can never get colder than the cold-spot.

The glass tube is used to fill the cell with sodium and argon. At first the cell is heated and pumped down in order to remove impurities. After that, the sodium ampule is crushed by bending the thin pipe (e). Then, the cell is flushed a few times with argon, and the valve (f) is closed.

The choice of materials is not the only difficulty with the sodium cell. The dynamic behavior of the cell is very slow, due to the high argon pressure and the fact that all the transport in the cell is governed by diffusion. The characteristic diffusion time is on the order of 4 min, which means that the transport of sodium is very slow. The heating up and cooling down of the cell needs special attention due to this slow transport of sodium.

The transmission of the cell is measured with a single-mode ring dye laser. It is measured in the same way as described in Ref. 4. We measured the transmission at a cold-

FIG. 4. Schematic drawing of the sodium absorption cell: (a) stainless steel reducer tee, (b₁ and b₂) flanges with sapphire windows, (c) stainless steel full nipple, (d) cooling block, (e) ampule crusher, (f) valve, (g) glass tube, (h₁ and h₂) antireflection coated windows, (i₁, i₂, and i₃) air inlets, (1–4) four different compartments of the oven.

FIG. 5. Normalized transmission profile of the sodium absorption cell at two different sodium pressures.

spot temperature of 250 °C with a window temperature of 325 °C, and at a cold-spot temperature of 300 °C with a window temperature of 330 °C. The out of band transmission of the cell is 60%. The normalized transmission profile is shown in Fig. 5. It is clear in this picture that the 250 °C profile is more suitable than the one at 300 °C. The wings of the 300 °C profile extend much further. This means that a significant part of the Thomson scattering signal will be absorbed. In contrast to this, only a small part of the Thomson signal will be absorbed when we heat the sodium cell to 250 °C.

D. The detection branch

The detection branch is the last part of the setup we have to discuss. This detection branch consists of two lenses, the sodium cell, a spectrograph, and an intensified charge coupled device (ICCD) camera. The two lenses form an image of the Thomson scattering signal onto the entrance slit of the spectrograph. The focal distance of these lenses is 500 mm and their diameter is 50 mm. The sodium cell is placed in between the lenses. In front of the slit of the spectrograph, a polarizer is placed in order to reduce the plasma emission. We built a 30 cm single optical element spectrograph with a 1500 lines/mm holographic aberration corrected concave grating (type IV). The width of the input slit of the spectrograph is 500 μm ; its length is 12 mm. The slit orientation is parallel to the laser beam, so we have a scattering length of 12 mm. At the exit slit of the spectrograph, an Andor Technology ICCD camera is mounted. This camera is able to detect the spectrum from 580 to 600 nm in one go. The quantum efficiency of the photocathode is on the order of 10%. The amplification of the intensifier is at maximum 10^4 counts/photoelectron. This high gain enables us to use photon counting, which improves the signal to noise ratio. The CCD is cooled to -30 °C in order to reduce the dark current. A pretrigger pulse from the excimer laser triggers the intensifier. This trigger pulse is created by the remote control of the laser. The intensifier is gated for 150 ns around the laser pulse. The necessary electronic delay in order to match the gating of the camera with the laser pulse is created by a Stanford Research Systems DG535 delay generator. The ICCD camera is read out in the full vertical binning mode

every second. If necessary, several spectra can be accumulated during the measurements.

In order to measure the amount of laser power used for the measurement of a Thomson scattering spectrum, an Ophir 30A-P laser power meter is placed behind the fluorescent lamp.

The description of the detection branch completes the experimental setup section. The next section describes the first measurements we performed with the setup.

III. FIRST SCATTERING RESULTS

This section describes the first measurements we performed with the setup described in the preceding section. We will start with the measurement of the stray light reduction, then discuss the Raman scattering measurements and end with the first Thomson scattering measurement ever performed in a fluorescent lamp.

A. Stray light reduction

The purpose of the sodium cell in combination with the ASE filter is the reduction of stray light (and Rayleigh scattering). At first we will calculate the theoretical stray light reduction from the transmission profile of the ASE filter, and the ASE level of the laser. We define the stray light reduction η as

$$\eta = \frac{\eta_{\text{ASE}}}{\Delta\lambda_{\text{dye}}} \cdot t_{\text{ASE filter}}, \quad (5)$$

where η_{ASE} is defined as the ratio of the total ASE power to the laser power, $t_{\text{ASE filter}}$ is the rejection of the ASE filter, and $\Delta\lambda_{\text{dye}}$ is the width of the dye tuning curve. In this way, η describes the amount of stray light that is measured per nanometer. We can compare this η to the normalized apparatus profile of the spectrograph. We assume $\eta_{\text{ASE}} = 10^{-2}$, $t_{\text{ASE filter}} = 10^{-5}$, and $\Delta\lambda_{\text{dye}} = 40$ nm. Then the stray light reduction η is equal to $3 \times 10^{-9} \text{ nm}^{-1}$. Note that the definition of the stray light reduction assumes a uniform dye tuning curve: this is an approximation.

We also measured this stray light reduction. We did this by comparing the stray light level from a discharge tube at two laser wavelengths: 589 and 588 nm. The alignment of the ASE filter is changed in order to let it transmit the 588 nm radiation. At 589 nm, the absorption cell absorbs the stray light; at 588 nm it does not. Both stray light spectra were normalized to the total scattered signal at 588 nm. The results of these measurements are shown in Fig. 6. The curve for $\lambda = 588$ nm is basically the normalized apparatus profile of the spectrograph. The curve for $\lambda = 589$ nm shows no maximum at 589 nm; from this we can conclude that the laser beam is totally absorbed in the absorption cell. The curve is much higher than we would expect from the transmission of the ASE filter and the absorption cell. The most likely explanation for this is that the transmission of the ASE filter for wavelengths other than 589 nm is higher than the 10^{-5} shown in Fig. 3. This can be due to the fact that the prism surfaces are not as clean as during the measurements

FIG. 6. Stray light signal per unit wavelength at two different laser wavelengths.

in Ref. 4. A second possible reason is the fact that the detection branch was not sufficiently shielded from the ASE filter and the laser, which results in extra stray radiation. A third possible reason is the fact that the ASE level of the laser is not known; due to bad alignment, it can be higher than the specification of the manufacturer.

B. Raman scattering

The electron density in a plasma can be deduced from the total Thomson scattered power. Therefore, we need the sensitivity of the detector and the transmission of the detection branch. The total Thomson scattered power P_T is equal to

$$P_T = P_{\text{in}} \cdot \left(\frac{d\sigma}{d\Omega} \right)_T \cdot n_e \cdot L \delta\Omega \theta, \quad (6)$$

where P_{in} is the laser power, the factor in between the square brackets is the differential cross section for Thomson scattering, n_e is the electron density, L is the scattering length, $\delta\Omega$ is the solid angle in which the scattered radiation is captured for the measurements, and θ is the transmission of the optical system from the incoming laser beam up to the ICCD camera, including the sensitivity of the camera. The product of the last three terms in expression (6) can be obtained by performing an intensity calibration.

The intensity calibration of the Thomson scattering setup cannot be performed using Rayleigh scattering. This is because the sodium absorption cell absorbs the Rayleigh scattering signal. On the other hand, using Raman scattering in nitrogen, it is possible to calibrate the setup. We made a glass tube similar to the discharge tube, filled with 900 mbar nitrogen. Using this tube the rotational Raman scattering spectrum in nitrogen is measured. However, the apparatus profile of our spectrograph is too broad to resolve the individual rotational Raman lines. Therefore, we used the wavelength integrated Raman scattering signal for the calibration. The total cross section for this scattering process can be obtained by summing over all the rotational lines, and integrating over the wavelength. The total measured scattered power of all the rotational Raman transitions is equal to¹⁴

FIG. 7. Raman scattering signal, used for the intensity calibration of the setup.

$$P_{\text{RM}} = P_{\text{in}} \cdot \left[\sum_{J=0}^{\infty} \left(\frac{d\sigma_{J \rightarrow J'}}{d\Omega} \right) \cdot \frac{n_J}{n_{N_2}} \cdot \int G(\lambda - \lambda_{J \rightarrow J'}) d\lambda \right] \cdot n_{N_2} L \delta\Omega \theta = P_{\text{in}} \cdot \left[\sum_{J=0}^{\infty} \left(\frac{d\sigma_{J \rightarrow J'}}{d\Omega} \right) \cdot \frac{n_J}{n_{N_2}} \right] \cdot n_{N_2} L \delta\Omega \theta, \quad (7)$$

where P_{in} is the laser power, $d\sigma_{J \rightarrow J'}/d\Omega$ is the differential cross section for the rotational transition $J \rightarrow J'$, n_J is the density of the rotational state J , n_{N_2} is the nitrogen density, and $G(\lambda)$ is the normalized apparatus profile. Note that the product $L \delta\Omega \theta$ has the same value as in expression (6) when we use the same scattering geometry for the Thomson and the Raman measurements. The expression in between the square brackets can be defined as the total rotational Raman scattering cross section σ_{RM} :

$$\sigma_{\text{RM}} = \sum_{J=0}^{\infty} \left(\frac{d\sigma_{J \rightarrow J'}}{d\Omega} \right) \cdot \frac{n_J}{n_{N_2}} = 4.18 \times 10^{-34} \text{ m}^2/\text{sr}, \quad (8)$$

where the numerical value is obtained using the value for the anisotropy of the polarizability tensor measured by Penney *et al.*¹⁴ We used the right angle scattering geometry with polarization parallel to the laser polarization. The gas temperature is assumed to be 295 K. We measured the wavelength integrated rotational Raman spectrum with the ICCD camera, along with the laser power needed to take this spectrum. Using these two values, we can calculate the factor $L \delta\Omega \theta$ in expression (6). Note that we corrected the value for the total rotational Raman scattering cross section for the transmission of the sodium cell. The value we used is slightly lower than the value in expression (8).

Figure 7 shows an example of a rotational Raman spectrum measured in nitrogen. Note that we can calibrate the pixel-sensitivity of our ICCD camera with this spectrum, by comparing the experimental spectrum with the theoretical one. It is also possible to obtain the apparatus profile of the spectrograph, and to calibrate the wavelength axis using the individual peaks of the measured Raman spectrum. In conclusion, we can calibrate the wavelength axis, the pixel sensitivity, and absolute scattering intensity of the setup by measuring one rotational Raman spectrum.

FIG. 8. The first Thomson scattering measurement, along with the plasma emission and the stray light signal.

C. The first Thomson scattering experiment in a fluorescent lamp

After the calibration is done with Raman scattering, the Thomson scattering experiments can be performed in a fluorescent lamp. We used a fluorescent lamp filled with 10 mbar neon and approximately 2 Pa mercury. The diameter of the lamp was 26 mm, its length 50 cm. At the ends of the tube we placed Brewster windows, as shown in Fig. 1. The current through the lamp was 380 mA. We used a Philips BRC411/01 35 kHz ballast to produce this current. The biggest additional problem we had to deal with in the Thomson scattering experiments is the extremely low signal level. It is not possible to align the setup using this Thomson signal. Therefore, we aligned the setup with the nitrogen tube. The intensity of the rotational Raman spectrum from this tube was high enough to align the detection branch and the laser beam. When we exchanged the nitrogen tube with the fluorescent lamp, we did not have to change this alignment. In addition to the low signal level, measuring the Thomson scattering profile, gives rise to another problem: the plasma emission. In our case, we detected a lot of neon and mercury lines in the region of the Thomson scattering spectrum.

We measured the Thomson scattering signal for 1 h. During this measurement, the dye efficiency decreased significantly. The average power of the dye laser decreased from 2.5 to 1.8 W. The transmission of the optics up to the discharge was on the order of 50%. At the position of the discharge, the laser power averaged over the measurement time was 0.98 W. The result of the measurement is shown in Fig. 8, where we also plotted the plasma emission and the stray light. It is clear that the stray light is negligible compared to the Thomson scattering signal. However, without using the sodium cell the stray light level will be on the order of 10^{10} – 10^{11} on the scale of Fig. 8. It is also clear that the plasma emission is the dominant source of noise in the Thomson spectrum. We can see the spectral lines of neon at 585.25, 588.19, 594.48, and 597.55 nm. The spectral lines of mercury are at 576.96, 579.07, 585.93, and 587.20 nm. Note that we only detected the wings of the 576.96 and 579.07 nm lines, which extend in our detection region due to the instrumental broadening of the spectrograph.

The pure Thomson scattering spectrum can be obtained

FIG. 9. Thomson scattering measurement, along with a Gaussian profile, a Gaussian profile multiplied by the transmission of the sodium absorption cell, and a Gaussian profile multiplied by the transmission of the absorption cell, convoluted with the apparatus profile of the spectrograph.

by subtracting the plasma emission from the spectrum with the laser and the plasma on. The result of this calculation is shown in Fig. 9. In this figure, we also added a Gaussian profile, this Gaussian profile multiplied by the transmission of the sodium cell, and this profile convoluted with the apparatus profile of the spectrograph. This last profile is fitted to the measurements, which resulted in an electron temperature of 0.9 eV and an electron density of $1.3 \times 10^{18} \text{ m}^{-3}$.

IV. DISCUSSION

The main conclusion that can be drawn from the measurement we performed is that the stray light level can be reduced considerably by introducing a sodium vapor absorption cell in a Thomson scattering setup. The theoretical stray light reduction is not yet achieved. However, the results we obtained are promising.

The stray light reduction is limited by the rejection of ASE by the ASE filter. The ASE that passes the ASE filter is mainly due to scattering of the laser beam at the surface of the prisms, and at dust on the surface of the prisms. This means that we can improve the rejection of the filter by filtering the laser beam twice. In order to do this, we need an extra, third spatial filter in the setup, as proposed in Ref. 4. An intermediate solution is to insert one dispersion prism as a predisperser, and to use the first spatial filter as a bandpass filter. In this way we obtain a two-stage ASE filter. The rejection of this filter will be five orders of magnitude in the spectral bandpass region of the first filter, and more than five orders of magnitude in the rejection region of this first filter.

The atomic notch filter we built can also be used for metal vapors other than sodium. Using other metal vapors, the wavelength for Thomson scattering can be changed. This can be interesting when the plasma emission in the 589 nm region is too large for Thomson scattering. Since we used the same materials as Neuman *et al.*,¹⁰ the cell we built is applicable of containing strontium (460.7 nm) and rubidium (780.0 and 794.8 nm). By evaluating the electrochemical activity of the other alkali metal and alkaline earth metals, we believe that the cell is robust enough to contain metal vapors like barium (553.5 nm), potassium (766.5 and 769.9 nm),

and calcium (422.7 nm). Due to their extreme aggressiveness, cesium (852.1 and 894.4 nm) and lithium (670.78 and 670.79 nm) will probably react at least with the glass to metal seal. Furthermore, we should note that the vapor pressure of lithium and calcium is too low to have sufficient absorption at a reasonable temperature.

Regarding the detection limit, we have shown that it is possible to detect Thomson scattering at an electron density of 10^{18} m^{-3} . We needed 3500 J of laser energy in the lamp to measure this Thomson spectrum. By optimizing the setup, we believe that we can measure down to 10^{16} m^{-3} . This optimization includes using the photon-counting mode, increasing the detection solid angle, optimizing the dye laser and the ASE filter alignment, lowering the gate width, and lowering the wavelength resolution by resolving the Thomson spectrum in 20 channels instead of 400 channels. On the other hand, the spatial resolution can be increased by changing the ICCD read-out mode from full vertical binning to imaging. Then we can choose the spatial and spectral resolution we want by either integrating vertically or horizontally on the ICCD chip.

ACKNOWLEDGMENTS

This research is supported by the Technology Foundation STW and Philips Lighting Eindhoven, The Netherlands. The cooperation with the Technical Department (GTD) of

the Eindhoven University of Technology is greatly appreciated. The authors are very grateful for the assistance of D. van den Akker in performing the measurements.

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