A triple spectrograph system for low stray light Thomson scattering measurements

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Introduction
Thomson scattering is scattering of photons by the electrons in a plasma. From the scattering spectrum, the electron temperature and density ($T_e, n_e$) of the plasma can be deduced. In the past decade, the development of high power lasers and sensitive detection devices has made Thomson scattering a powerful diagnostic tool for small laboratory plasmas. However, measurements on plasmas close to a plasma applicator or contained in glass (e.g. gas discharge lamps) suffer from an excessive amount of stray light [1]. For plasmas with a low electron density and temperature, this is a serious problem; in fact, stray light often determines the detection limit. This paper discusses the design of a dedicated triple spectrograph detection branch to reduce the disturbing effect of stray light on Thomson scattering spectra.

Stray light redistribution
Because of the high electron velocities in a plasma, Thomson scattered photons are Doppler shifted. The resulting spectrum, reflecting the electron temperature, is a few nanometres wide for common laboratory plasmas. In contrast, stray light is scattered on the surroundings of the plasma and is therefore virtually monochromatic. The scattering spectrum thus consists of a relatively broad Thomson scattering contribution and a narrow stray light contribution in the centre of the spectrum.

If the spectrograph that is used to disperse the scattered radiation were ideal, the shape of the recorded spectrum would be identical to that of the scattering spectrum. However, in practice the narrow stray light peak in the centre of the spectrum is redistributed somewhat by the spectrograph. This redistribution is described by the instrumental profile of the spectrograph (its response to monochromatic light). Because the stray light intensity can be huge compared to the Thomson scattered intensity, the wings of the redistributed stray light peak can obscure a significant part of the Thomson spectrum, thus making the results useless, see Figure 1.

A solution to this problem is to filter the narrow-banded stray light away with a notch filter. The filter must have a very narrow spectral range (~ 1 nm) so as to transmit the major part of the Thomson spectrum. Such narrow a notch filter cannot be obtained commercially, but it can be constructed from a subtractive double spectrograph [2,3].

A subtractive double spectrograph as a notch filter
A subtractive double spectrograph consists of two identical spectrographs, the second cancelling the dispersion of the first. In principle, the spectrum exiting the double spectrograph is thus the same as the spectrum that entered. However, the spectrum that is
formed between the two spectrographs can be manipulated by a mask that blocks part of the spectrum. In this way, the subtractive double spectrograph acts as a notch filter, whose width can be chosen by the width of the mask. This principle is sketched in Figure 2.

The shape of the filter profile can be calculated from the instrumental profiles of both spectrographs. For ideal spectrographs, which have a Dirac delta-function instrumental profile, the transmission at wavelength $\lambda_0$ is zero and the spectral width of the notch filter can be chosen arbitrarily narrow. However, with an ideal spectrograph the incident spectrum is not redistributed and a notch filter is not necessary. A non-ideal double spectrograph does not block light of wavelength $\lambda_0$ entirely, but choosing a wider mask can always lower the transmission at this wavelength. For a better double spectrograph (narrower instrumental profiles), the required mask width for a certain stray light reduction is smaller, resulting in narrower filter profiles. A bandpass $\Delta\lambda_{bp}$ (full width at half maximum of the instrumental profile) on the order of 0.3-0.4 nm can be shown to be small enough for sufficient stray light reduction (factor $10^6$) and a sufficiently narrow filter profile ($\sim 1$ nm) [4].

Design of a triple spectrograph system
In order to use a subtractive double spectrograph efficiently with the ‘primary’ spectrograph used to disperse the scattering spectrum, we decided to design a complete, dedicated detection branch for scattering experiments.

A spectrograph consists of a grating and two imaging elements that collimate the incident light for the grating and focus the diffracted light onto the spectrograph’s exit plane [5]. The design parameters of a spectrograph, shown in Figure 3, are the focal length $f$ and size $\phi$ of the optics, the length $a$ of the collimated beam, the grating constant $n$, and the angle of deflection by the grating, $\delta$, which is the result of the angle of incidence $\alpha$ and the angle of reflection $\beta$. In addition, the imaging elements can be chosen to be either lenses or mirrors.

The choice of the design parameters determines single spectrograph properties as the dispersive power $d$, the bandpass or width of the instrumental profile $\Delta\lambda_{bp}$, and the opening angle of the system $\Delta\Omega$. The dispersion must be such that the iCCD detector that is used can cover the entire Thomson spectrum; a dispersion of one to two mm/nm is satisfactory. As discussed above, the required bandpass is $\Delta\lambda_{bp} \approx 0.3$ nm or better.
The opening angle must be as large as possible to collect as much light as possible, but at least \(f/10\) (0.008 sr).

Mirrors are the common imaging element in most spectrographs since they do not exhibit chromatic aberration and can thus be used for a wide range of wavelengths. However, since mirrors have to be used off-axis, they suffer from astigmatism, i.e. the effect that the focal planes of optimal spatial resolution and optimal spectral resolution do not coincide. For our application, spatial resolution is strongly desirable and spectral resolution is indispensable for high stray light reduction. Therefore, we chose to use lenses, which can be used (almost) on-axis and thus suffer less from astigmatism. Lenses do suffer from chromatic aberration, but the spectral range we are interested in is only a few nanometres wide. A more serious problem is spherical aberration. Achromatic doublet lenses, which are also corrected for spherical aberrations and astigmatism, eliminate this problem sufficiently. The design discussed in this work uses achromatic doublet lenses as imaging elements.

The grating constant \(n\) was chosen to be 1800 grooves/mm. This results in a large dispersion, yielding a narrow instrumental profile. The deflection angle of the spectrograph was taken \(\delta=30^\circ\), being a convenient angle for a compact setup. The corresponding angles of incidence and reflection for light of 532 nm are \(\alpha=15^\circ\) and \(\beta=45^\circ\). In order to achieve a sufficiently small bandpass and sufficiently large dispersion, the focal length of the lenses was taken \(f=600\) mm. Their size is \(\phi=95\) mm, which is about the maximum size that can be used before aberrations start playing a significant role. The single spectrograph properties that result from these values of the design parameters are listed in Table 1 [6,7]. Because of the absence of severe image aberrations, the bandpass \(\Delta\lambda_{bp}\) is mainly determined by the entrance slit width \(s\), which must be broader than the width of the laser beam used in the Thomson scattering experiment. The calculated bandpass is based on an entrance slit width of \(s=250\) \(\mu\)m.

Ray-trace simulations were performed to verify the calculated characteristics of the spectrograph system and to determine its spatial and spectral resolution. The spatial resolution ranges from 35 to 100 \(\mu\)m, depending on the position along the entrance slit and the wavelength of the incident light; the optimal condition (on-axis use of all lenses) is light of wavelength \(\lambda=532\) nm at the centre of the entrance slit. The spectral resolution equals the calculated bandpass (0.22 nm) and is in all cases determined by the entrance slit width.

The final design of the triple spectrograph system is shown in Figure 4. The entrance slit is horizontal (parallel to the laser beam) for simultaneous measurements at different positions in the plasma. In order to keep the optical axis of the system horizontal as well, a 90° image rotator, consisting of three flat mirrors, is used. One additional flat mirror in front of the mask compacts the system. The iCCD camera is placed on a stand that can be moved to the mask position. In this way, it is possible to choose between a triple spectrograph system for efficient stray light suppression and a single spectrograph system for a higher transmission, which results in a lower detection limit if stray light is not the main problem.

### Table 1: The chosen design parameters and resulting single spectrograph properties.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Single spectrograph properties</th>
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<tbody>
<tr>
<td>(f = 600) mm</td>
<td>(d = 1.54) mm/nm</td>
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<tr>
<td>(\phi = 95) mm</td>
<td>(\Delta\lambda_{bp} = 0.22) nm</td>
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<tr>
<td>(a = 600) mm</td>
<td>(\Delta\Omega = 0.0198) sr ((f/6.3))</td>
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<tr>
<td>(n = 1800 ) mm(^{-1})</td>
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<tr>
<td>(\alpha = 15^\circ)</td>
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<td>(\beta = 45^\circ)</td>
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<td>(s = 250) (\mu)m</td>
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Conclusions
Thomson scattering experiments on low electron density plasmas close to a plasma applicator or contained in glass suffer from a huge amount of stray light. Combined with the non-ideality of the spectrograph that disperses the scattering spectrum, this can be a severe restriction to the detection limit. In order to get around this problem, a narrow notch filter can be used to filter the stray light. In this work, a dedicated triple spectrograph system with a notch filter in the form of a subtractive double spectrograph was designed. An image rotator is used to allow for spatial resolution. The triple spectrograph system reduces the effect of stray light by six orders of magnitude compared to a detection system based on a single spectrograph. The opening angle of the system is $f/6.3$ (0.0198 sr) and its transmission is 15%. The spatial and spectral resolutions are estimated from ray-trace simulations at about 100 µm and 0.22 nm respectively.

References