Absolute calibration of LIDAR Thomson scattering systems on large fusion devices

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Abstract. Two lasers of different wavelengths could be used in the ITER LIDAR Thomson scattering system. This raises the possibility that absolute calibration from one laser could be used to calibrate the other laser system. Lower laser wavelengths have the advantage that the Raman cross section increases, \( \sigma_{\text{Raman}} \propto \frac{1}{\lambda_0^4} \). However at lower laser wavelength the spectral width of the scattered spectrum decreases \( \Delta \lambda_{\text{Raman}} \propto \lambda_0^2 \) making measurement closer to the laser wavelength necessary. The choice of calibrating gas presents a number of trade offs. Raman calibration using a hydrogenic molecule produces a broad spectrum, useful since it is not close to the laser wavelength. However, Raman calibration in Nitrogen or Oxygen produces a far greater number of scattered photons for the same calibrating gas pressure. The f-number of scattered light collected by a LIDAR system varies significantly with plasma major radius. The large change in collected solid angle changes the angle of incidence of the scattered light onto the detector and hence the spectral transmission of the optical filter. This change in spectral transmission must be very accurately measured to determine the detected cross section of Raman or Rayleigh scattered light. In the case of Raman scattering, uncertainty in the absolute calibration can be reduced by collecting both Stokes and anti-Stokes lines with a number of different optical filters.

1. Introduction

Calibrating LIDAR Thomson scattering systems to produce reliable electron density profiles presents a number of challenges. The accuracy of the absolute calibration is strongly dependent on the spectral calibration of the spectrometer and the gas temperature of the calibrating molecule. As well as the various permutations of laser wavelength and calibrating gas, engineering constraints must also be considered. While it is possible to put 150mbar of calibrating gas in smaller Tokamaks, this is not always possible on large devices due to interaction with cryo-pumping and cooled components. At low pressure the overall number of collected scattered photons may limit the feasibility of certain calibration techniques. Although only Raman calibration is considered in this paper, Rayleigh calibration is also a possibility. However, Rayleigh calibration is subject to stray laser light and would require an optical filter at the laser wavelength that would not be useful for Thomson scattering.

The design of a core ITER LIDAR Thomson scattering system is detailed in [1]. The performance of one such system based on a 1064nm laser is analysed in [2]. This 1064nm laser system would benefit from an additional laser of a different wavelength. The use of an additional laser was originally proposed by [3] with a focus on spectral calibration. In this paper the absolute calibration of a Thomson scattering system for ITER using both 532nm and 1064nm lasers is discussed. The absolute calibration from an auxiliary 532nm laser could be extended to provide absolute calibration of a standard 1064nm laser system.
2. Raman Calibration

2.1. Calibration Laser Wavelength

The proposed Thomson scattering system could be calibrated in Nitrogen, Oxygen, Hydrogen or Deuterium depending on which gases are allowed in the ITER vacuum vessel. Currently the technology for detectors in the visible regions is available [4]. Detectors are also available in the infrared region, but have relatively poor effective quantum efficiency (EQE). The detectors in the visible region will allow measurement of Thomson scattered light from a 1064nm laser for a broad range of electron temperatures, but currently only low EQE detectors can detect Raman scattered light from a 1064nm laser. Frequency doubling a 1064nm laser would allow the high EQE detectors to detect the Raman scattering from the 532nm laser pulse. This Raman scattering from the 532nm pulse could be used to provide an absolute density calibration that could be scaled to the 1064nm laser system.

The Raman cross section scales with laser wavelength $\lambda_0$ as:

$$\sigma_{\text{Raman}} \propto \frac{1}{\lambda_0^4}$$  \hspace{1cm} (1)

and hence there is 16 times more Raman scattered light from a 532nm laser than from a 1064nm laser of equivalent energy. Due to the strong scaling of scattered light with laser wavelength, even if high EQE fast infrared detectors are developed absolute calibration from a 532nm laser will remain an attractive option. A similar scaling of cross section occurs for Rayleigh scattering.

At lower laser wavelength the separation between Raman lines decreases. The wavelength of the Raman line resulting from the $j\rightarrow j-2$ transition [5] is in general given by:

$$\lambda_{j\rightarrow j-2} = \frac{1}{\lambda_0 + B_0(4J-2)} \text{ for } j = 2, 3, ...$$  \hspace{1cm} (2)

which may be approximated as in [6] to:

$$\lambda_{j\rightarrow j-2} \approx \lambda_0 - \lambda_0^2 B_0 (4J-2)$$  \hspace{1cm} (3)

where $B_0$ is the rotational constant[5, 7, 8], which is 198.96m$^{-1}$ in N$_2$, 143.8m$^{-1}$ in O$_2$, 2991.05$^{-1}$ in D$_2$ and 5933.9m$^{-1}$ in H$_2$. The gap between subsequent Raman lines $\Delta \lambda = \lambda_{j+1\rightarrow j-1} - \lambda_{j\rightarrow j-2}$ is given by:

$$\Delta \lambda \approx -4B_0 \lambda_0^2$$  \hspace{1cm} (4)

which for Nitrogen and Oxygen evaluates to $\Delta \lambda = 0.6 - 0.8\, \text{nm}$ for a scattering wavelength of 1064nm and $\Delta \lambda = 0.15 - 0.2\, \text{nm}$ for a scattering wavelength of 532nm. For this reason, the Raman scattered lines from a 532nm laser are quite close to the laser wavelength. Optical filters must have good transmission to within 2-3nm from the laser wavelength to detect this spectrum, while at the same time good blocking at the laser wavelength. The spectral broadening of the laser wavelength should be small, since it will have a significant affect on the Raman cross section in a spectral channel.

2.2. Calibration Gas

Raman calibration in H$_2$ or D$_2$ gas overcomes the difficulty of proximity to the laser wavelength and reduces the strong dependency of calibration accuracy on the accuracy of the filter transmission. This is a strong advantage, since the optical filter transmission will vary with collection solid angle across the plasma. A further advantage of calibration using a Hydrogenic molecule is that broadening of Raman lines due to non-monochromatic laser pulses will not affect the cross section since the lines are not at the edge of the filter.

There are fewer spectral lines for Hydrogenic molecules. There are four strong Stokes lines corresponding to transitions $j=0\rightarrow 2$, $j=1\rightarrow 3$, $j=2\rightarrow 4$ and $j=3\rightarrow 5$. There are two strong anti-Stokes lines corresponding to the transitions $j=3\rightarrow 1$ and $j=2\rightarrow 0$. Due to the smaller number lines a much lower
Figure 1. The top plots show the Raman spectrum for scattering from a 532nm laser from gases at 298K. The bottom plots, whose scale a factor of 10 lower, show the spectrum from a 1064nm laser.

Table 1. Number of detected photoelectrons from Raman scattering at a gas pressure of 10mbar from both Stokes and anti-Stokes lines. Optical transmission 10.7%, f/12, scattering length 67mm, EQE 4%.

|               | H₂   | D₂   | N₂   | O₂   |
|---------------|------|------|------|------|
| 1.25J, \(\lambda_0 = 532\text{nm}\) | 249  | 260  | 1493 | 3845 |
| 2.5J, \(\lambda_0 = 1064\text{nm}\) | 29   | 31   | 186  | 480  |

The number of scattered photons are detected for the equivalent gas pressure relative to Raman scattering from N₂ or O₂. The accuracy of the calibration is sensitive the gas temperature, since this changes the relative population of the different rotational states and hence the intensity of the different lines. A further practical consideration is that Hydrogenic gases are explosive in reaction with air and so may pose a safety risk which translates to a low allowable pressure.

The number of detected photoelectrons from Raman scattering at a gas pressure of 10mbar for a variety of molecules are given in table 1. There are significantly more scattered photons from the high Z elements, however scattering from Hydrogenic molecules would produce detectable results from a 532nm laser. The spectral distribution of the scattered photons is shown in figure 1. Oxygen provides a greater number of scattered photons than Nitrogen, although both elements produce scattered spectra close to the laser wavelength.

2.3. Collecting both Stokes and anti-Stokes lines

The collection f/number of the ITER core lidar system varies from f/6 at the outboard edge of the plasma to f/18 at the inboard edge of the plasma. The variation in the position of the scattered light collected relative to the focal length of the collection lens can cause a variation in angular distribution of light on the optical filters in the spectrometer. The resulting spectral distortion can skew the radial density profile if not correctly calibrated out.

Collecting both Stokes and anti-Stokes lines provides robustness against systematic errors due to
change in collection position within the plasma. This is illustrated in figure 2 for Raman scattering from Nitrogen gas from a fundamental harmonic YAG laser. The results shown in this figure use a shift in the central wavelength of the filter as a simple model for the variation in the angular distribution of light on the optical filters. Applying the same wavelength shift to the filters capturing Stokes lines and anti-Stokes lines causes a change in the number of detected photoelectrons in one filter to compensate for the change in the number of detected photoelectrons in the other filter.

3. Conclusions

Absolute calibration of LIDAR systems can be achieved using a number of different choices of gas and laser wavelength. Oxygen is not a likely choice of gas since it will pollute the vacuum vessel. The combination of Nitrogen gas and a 1064nm laser would work well and is already widely used on current TS systems. Another option is calibrating using a Hydrogenic gas at low pressure. This has the advantage that it might be considered cleaner for the vacuum vessel and Raman lines are further from the laser wavelength than for Nitrogen. The lower cross section could be partially compensated by use of a 532nm wavelength laser.

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