Published by IOP Publishing for Sissa Medialab

Received: *September 15, 2021*
Revised: *November 12, 2021*
Accepted: *January 17, 2022*
Published: *March 9, 2022*

4th European Conference on Plasma Diagnostics (ECPD2021)
7–11 June, 2021
Online

2022 JINST 17 C03012

A novel technique for an alignment-insensitive density calibration of Thomson scattering diagnostics developed at W7-X

G. Fuchert,[a,*] P. Nelde,[a,c] E. Pasch,[a] M.N.A. Beurskens,[a] S.A. Bozhenkov,[a] K.J. Brunner,[a] J. Meineke,[a] E.R. Scott,[b] R.C. Wolf [a,c] and W7-X team

[a] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*
[b] *University of Wisconsin-Madison, Madison WI, U.S.A.*
[c] *Technische Universität Berlin, Berlin, Germany*

E-mail: golo.fuchert@ipp.mpg.de

Abstract: In most laboratory setups in plasma physics, including magnetic-confinement experiments for fusion research, laser-based Thomson scattering allows for absolutely calibrated density measurements without input from other diagnostics and with high spatial resolution. A common issue is the alignment stability of either the laser beam or the observation optics. Frequent recalibrations are typically required. This is a challenge in particular for larger fusion experiments; while beam paths tend to get longer, the access for alignment and calibration gets more restricted. Therefore, simple, fast and robust calibration methods are required. A novel calibration technique has been developed at W7-X to account for alignment variations in the calibration procedure. This will decrease the pulse-to-pulse variations significantly and allow for a longer time duration before a recalibration becomes necessary. By monitoring the beam position accurately, it could be shown that misalignment leads to deterministic and reproducible changes in the measured density. The introduced density errors can be corrected for by monitoring the laser beam for every individual laser pulse. In the last experimental campaign, this has been done retrospectively by introducing parallel shifts to the laser beam path in order to show the feasibility of this method. It could be demonstrated that the impact of introduced shifts on the electron density can be successfully corrected for. For future campaigns, the beam alignment will intentionally be varied during the absolute calibration in order to cover the full range of expected beam positions. During the actual experiments, the beam positions will be monitored likewise and each density profile will be

*Corresponding author.

https://doi.org/10.1088/1748-0221/17/03/C03012

evaluated with the most suitable calibration factor. While probably not needed for W7-X, vibrations of the observation optics could be included in the same way.

Keywords: Data processing methods; Detector alignment and calibration methods (lasers, sources, particle-beams); Plasma diagnostics — interferometry, spectroscopy and imaging

Contents

1 Introduction

Thomson scattering (TS) refers to the elastic scattering of electromagnetic radiation by free electrons or other charged particles. It is frequently used in plasma physics to measure the electron density and temperature. The density is determined by the intensity of the scattered light and the temperature by its spectrum (caused by the Doppler shift). Early examples are atmospheric studies (e.g. using radar [1]) and fusion research (e.g. the famous measurement of more than 1 keV in the tokamak T3 with a laser-based TS diagnostic [2]). For fusion research, most commonly high-power short-pulse lasers (Nd:YAG or ruby lasers in the near infrared) are employed as light source. The scattered light is collected by observation optics with lines-of-sight that intersect the laser beam path at not too shallow angles. Since the scattered light is only observed in regions where laser beam and lines-of-sight intersect, the measurement is spatially resolved. The observation optics is typically designed such that several spatial points are observed along the beam path. The regions around those points from which the scattered light from the laser beam can be fully observed by the optics are called scattering volumes. Their width is commonly designed to be somewhat larger than the beam width in order to avoid truncation due to misalignment. The relatively high densities in fusion experiments (10^{18}–10^{21} m^{-3}) enable measurements with sufficient photon counts for accurate profile measurements. But with increasing detector sensitivity and laser energy, comparable setups also became useful diagnostic tools for low density laboratory plasmas in applied and basic plasma research.

These laser Thomson scattering diagnostics often suffer from a common issue: since the density is determined from an absolutely calibrated intensity measurement, laser-misalignment directly impacts the density measurement. Careful monitoring and control of the laser beam alignment is, hence, an important part for most Thomson scattering systems (e.g. at ASDEX Upgrade [3], DIII-D [4] or LHD [5]). If every scattering volume is affected in the same way, the profile shape remains intact and the profile can possibly be rescaled (e.g. using an interferometer), but often this is not the case and even the profile shape becomes uncertain. Such effects are well

2022 JINST 17 C03012

known from the experience of many Thomson scattering diagnostics at various fusion experiments. If parts of the laser beam profile are outside of the scattering volumes, the measured density will be smaller than the actual plasma density (or zero in the case of no overlap). In order to prevent this, the scattering volumes are usually designed with a certain margin. If they are chosen too large, however, background radiation becomes an issue. At W7-X, the scattering volumes have a margin of at least 2 mm to either side. Due to divergence and initial focusing of the beam, the beam width varies across the plasma from around 4 to 7 mm (see [6] for details), meaning that different volumes react differently to a small misalignment. But even when the full beam profile is passing through the scattering volume, subtle effects can lead to a positional sensitivity of the measured density. The impact of such effects is small compared to an actual loss of signal, but can still be relevant.

2 Impact of misalignment on density measurements at W7-X

The Thomson scattering diagnostic at W7-X currently uses three Nd:YAG lasers at a wavelength of $\lambda = 1064$ nm and a polychromator-based detection system. A detailed description of the various components, the scattering geometry and the data processing is given in [6, 7]. Specifically for the first experimental campaigns of W7-X, a detailed analysis [8] has revealed that laser misalignment is the dominant source of error in the electron density profiles. By accurately measuring the laser position it was possible to resolve the systematic and reproducible impact of misalignment on the measured density. In order to achieve this, parallel shifts have been introduced to the laser beam path during plasma operation with constant conditions and, hence, density profiles. As an example, figure 1 shows the measured density as a function of the laser position on the Brewster window at the entrance to the W7-X vessel (see [6] for a detailed description and drawings) for one particular scattering volume. The laser position on the entrance window is measured with an infrared camera. The laser pulse itself is visible due to dust and fluorescence in the glass. But depending on the exact angle between the camera and the window, reflections of the laser beam from other glass surfaces are visible and are easier to detect. The setup from the last campaign is depicted in figure 2. Visible is the direct laser spot (1), a bright reflection (2) and a less bright reflection (3). It has been observed that all three spots move together and, hence, they can all be used to determine a relationship between the spot position and the impact on the measured density. This makes it most convenient to measure the position of the brightest reflection by a simple center-of-mass algorithm. The spatial resolution of the images on the window is around 0.16 mm and the time resolution is 33 Hz, making it possible to accurately measure the position of every individual laser pulse.

The laser beam can drift in two different directions with respect to the designed beam path. One is less critical than the other, since the beam stays in the light-cones of the observation optics. Here, the terms *laser position* or *y-direction* refer to the second direction, in which the laser beam moves perpendicular to the observed light-cones. Laser misalignment in this y-direction is most detrimental, since small variations of the beam path lead to loss of signal, since the beam is no longer fully contained in the scattering volumes. In the following, this y-direction is measured relative to an arbitrary reference position on the window, which is called “0”.

2022 JINST 17 C03012

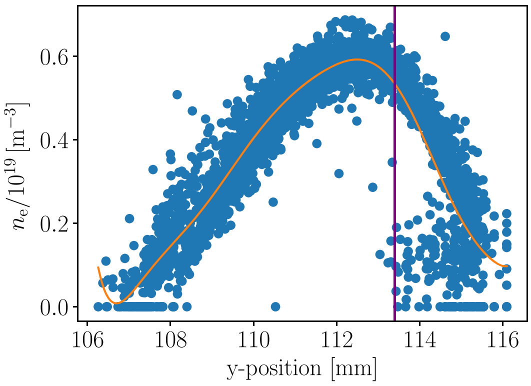

Figure 1. Measured density as a function of the laser position measured on the entrance window (exemplary for scattering volume "45"). The purple line indicates the estimated laser position during the Raman calibration.

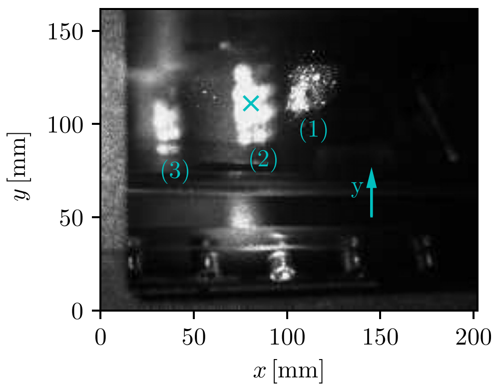

Figure 2. Infrared camera image of the entrance window during a laser pulse. Visible is the direct laser spot (1), a bright reflection (2) and a less bright reflection (3).

Figure 1 shows the strong impact of the laser position on the measured density. Depending on the position, a shift by one millimeter can reduce the measured density by as much as 50%. There seem to be some measurements at positions above 113 mm which do not follow the deterministic trend. At larger y-values (around 115 mm) the laser beam is truncated somewhere along the beam path, which makes the determination of the beam position less reliable (obviously these regions should be avoided during operation), meaning that the position is incorrectly measured at y-values below 115 mm. Comparing with figure 1, it would have been beneficial to shift the laser to lower y-values to prevent truncation and to have a weaker response of the measured density on positional variations. It is very likely, however, that the drifts that affected the Thomson scattering operation were already changing the laser position before and during the Raman calibration, bringing the laser into this unfavorable position. Furthermore, at a given location there is still a rather larger variation of measured densities larger than 10%. The current hypothesis is that this is caused by angular variations of the beam path due to observed mirror vibrations [8]. Angular variations can in principle be accounted for, but would require a second camera observing the exit window in order to be resolved. Two cameras are sufficient to determine all degrees of freedom of the laser beam and, hence, all possible misalignments can be corrected for. A second camera will be added to the setup for future campaigns, but is not available for the existing profile data. With those two cameras it will be possible to test whether angular variations alone are enough to explain the remaining density error or if other effects have to be considered in the calibration as well (e.g. vibrations of the observation optics).

In order to demonstrate a successful correction already with the existing data, a proof-of-principle correction has been made for parallel shifts only. The first step was the position scan in which the laser beam was shifted parallel to the designed beam path and for every individual volume the dependence of the measured density on the position was determined. This yields calibration curves like the one shown in figure 1 for every scattering volume and every laser. The second step was to estimate the laser position during the Raman calibration (described in the next section), which relates the measured signal level to the density. This step is necessary to know the reference position (shown as purple line in figure 1), to which the density has to be corrected to. The last step is the actual correction. For every density profile measured by Thomson scattering, the laser position is measured and the density is corrected for every individual scattering volume by multiplying with a correction factor, which is the ratio of the density at the Raman reference position and the respective position of that particular measurement, $n(y_{\mathrm{Raman}})/n(y_{\mathrm{profile}})$.

3 Proof-of-principle correction

3.1 Estimating the laser position during the Raman calibration

In the past, the laser position has not been measured during the Raman calibration. In order to demonstrate the potential of the positional calibration, the reference position during the Raman calibration needs to be known. Determining it retrospectively was possible, since it has been observed [8] that the "noise" in the density measurements (i.e. the pulse-to-pulse variation) also depends strongly on the laser position. Qualitatively speaking the laser position during the Raman calibration can be estimated by characterizing the scatter in each volume for different laser positions and compare these characteristics to the scatter during the calibration. In order to quantify this, the distribution functions of Raman intensities, I, and TS densities, n, are determined. In the case of the Raman calibration, one distribution function is obtained per scattering volume and laser. For the position scan there is one distribution for every scattering volume, laser and scanned laser position. Figure 3 shows such distributions for three different positions as an example, comparing them to the Raman calibration. Now, for every scanned laser position, the overlap integral of the TS and Raman distribution function is calculated. High values of these integrals represent comparable distribution functions. For every scanned position, the resulting values for all scattering volumes are multiplied and one single value for each laser position is obtained. The position with the maximum value is the most likely laser position during the Raman calibration. It is clear that for future campaigns the position has to be measured during the calibration in the same way it is measured during the profile measurements, but for a proof-of-principle this approach gives us the required reference position.

2022 JINST 17 C03012

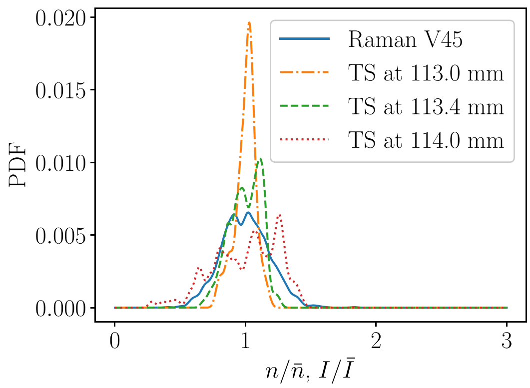

Figure 3. Shown are the distribution functions (PDF) of measured densities (Thomson scattering) and intensity measurements (Raman calibration). Every individual laser pulse results in one density measurement, n, during plasma operation or one intensity measurement during the Raman calibration, I. At any average laser position, small alignment changes lead to variations in the measured quantities, making the distribution characteristic for that position.

An interesting aspect of this analysis is that the distribution functions observed for a certain laser position are also an experimental measurement of the error distribution of the density for every scattering volumes. All effects that can affect the measured intensity, even if they are not known, are determined this way and can be used as precise estimate of the uncertainty. It is planned to exploit this in future experimental campaigns of W7-X.

Another important observation is that already the distribution function from the Raman calibration itself shows clear signs of alignment variations (broad distribution with local maxima). This indicates that the calibration factor itself is not perfectly correct. We find that for some scattering volumes there is a difference between the mean and the median of the distributions of around 5%. This underlines the importance of reducing the vibrations along the laser beam path (counter measures are described in [8], especially improving mechanical stability of mirror mounts and reduction of airflow in the beam tubes due to pressure differences) and further motivates the need for a calibration method that accounts for any remaining misalignments.

3.2 Applying the correction

The actual correction is performed by determining the position of the laser beam spot from the camera data for every pulse and for every scattering volume a correction curve like the one shown in figure 1 is used to correct the measured density. A different way to look at this is that the Raman calibration factor itself is a function of the laser position.

An example for such a correction is shown in figure 4. In (a), the uncorrected profiles are shown. The three different profiles are measured with the different lasers available in the last campaign. Two of the lasers (1 and 2) have been misaligned intentionally, while laser 3 is unchanged with respect to normal Thomson scattering operation. It serves as a reference, even though it has to be kept in mind that it is also affected by similar positional variations. Most obvious is the strong variation between neighboring spatial points and the very different profile shape measured by laser 2. This is a consequence of the deliberate change of the laser alignment and exaggerates the deviations that are observed during normal operation in order to demonstrate the capabilities of this method. The correction with the position-dependent calibration is shown in (b). Most striking is how much closer the profile of laser 2 is now matching the others. But also the scatter between neighboring points within one profile is reduced. There is one obvious outlier in the profile measured by laser 2, which does not benefit from the correction. The reason for this outlier is the low signal-to-noise ratio caused by the low density in the edge combined with the intentional laser misalignment. Its large statistical error bar indicates that for this particular point the signal level was too low for a reliable measurement. It can also be seen, however, that this proof-of-principle correction does not result in perfectly smooth profiles. In the following, the reasons for remaining errors are discussed and why they are not expected to be an issue in the future implementation at W7-X (or any other device).

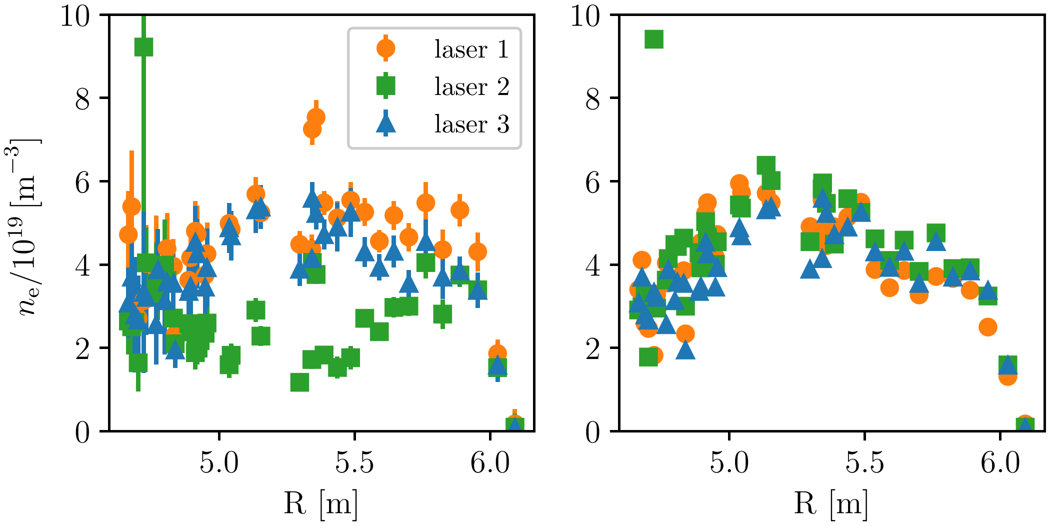

Figure 4. Density profiles changed by deliberate misalignment of laser 1 (shifted by −2.7 mm compared to the Raman calibration) and 2 (shifted by −2.3 mm). (a) Radial single pulse profiles for the three different lasers during constant plasma conditions before correction. (b) The same three profiles after performing the correction. The error bars (only shown in the left plot for clarity) indicate the uncertainty due to photon (shot) noise and are much smaller than the changed caused by the misalignment.

The first issue is that, even though the calibration data set only consists of parallel shifts, there is likely an angular displacement between the laser alignment during the profile measurements and the Raman calibration. This leads to an incorrect calibration curve, even though the angle is kept constant during the deliberate misalignments. Furthermore, the vibrations present in the last campaign also introduce further angular variations. In order to correct for those, a second camera is required to measure all degrees of freedom of the misalignment. With the two cameras that are planned for future campaigns, both the Raman calibration and the TS profile measurement can be performed spatially resolved. In that case there is one particular Raman calibration factor for one particular laser-alignment, making it a four dimensional function (two coordinates on the camera observing the entrance and two coordinates observing the exit window).

3.3 Generalization

At W7-X, the total calibration of the Thomson scattering diagnostic is done using Raman scattering on nitrogen gas. Other methods commonly applied are Rayleigh scattering (currently also under investigation at W7-X [9]) or a cross-calibration with other diagnostics. Obviously, the method of the absolute calibration does not influence the impact of misalignment on the observed signal level and the described calibration technique can equally well be used for Rayleigh scattering and cross-calibration with other diagnostics. Furthermore, every other source of error that can be represented as a measurable quantity with a deterministic effect on the measured intensity could be included in the calibration procedure in the same way. If, for example, the observation optics would be subject to vibrations, a sensor or laser tracker could be used to quantify those and their impact could be considered in the calibration procedure.

4 Summary

Measurements of the electron density using Thomson scattering are sensitive to the laser alignment. This is especially true for large experiments with long beam paths (like W7-X) and at some point even the beam-pointing stability may lead to noticeable errors in the measured densities. A new calibration method has been developed to deal with this. By measuring the laser position both during the calibration and the actual profile measurements, the impact of misalignments are quantified and can be taken into account during the profile evaluation, leading to a resilience of the density profiles against changes in the laser position. Since the misalignment is determined purely experimentally, no knowledge on the source of the alignment variations is needed. In order to demonstrate the potential of the described calibration technique, a proof-of-principle correction has been performed for a set of experiments in which the plasma conditions were constant and the laser beam has been shifted deliberately without changing its angle. In that case, one camera is sufficient to describe the misalignment. The measured profiles were improved greatly by applying the position-dependent correction and we are confident that this method will increase the quality of the TS density profiles in the coming experimental campaigns and could achieve the same also for other fusion experiments.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under Grant Agreement Number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

2022 JINST 17 C03012

References

[1] E.E. Salpeter, *Electron density fluctuations in a plasma*, *Phys. Rev.* **120** (1960) 1528.

[2] N.J. Peacock, D.C. Robinson, M.J. Forrest, P.D. Wilcock and V.V. Sannikov, *Measurement of the electron temperature by Thomson scattering in tokamak T3*, *Nature* **224** (1969) 488.

[3] H. Murmann, M. Jakobi, B. Kurzan, H.B. Schilling and the ASDEX Upgrade team, *Dynamic laser alignment control for Thomson scattering on ASDEX Upgrade*, *Rev. Sci. Instrum.* **74** (2003) 4310.

[4] T.N. Carlstrom, C.L. Hsieh, R. Stockdale, D.G. Nilson and D.N. Hill, *Initial operation of the divertor Thomson scattering diagnostic on DIII-D*, *Rev. Sci. Instrum.* **68** (1997) 1195.

[5] I. Yamada, K. Narihara, K. Yamauchi and H. Hayashi, *Active control of laser beam direction for LHD YAG Thomson scattering*, *Rev. Sci. Instrum.* **72** (2001) 1126.

[6] E. Pasch, M.N.A. Beurskens, S.A. Bozhenkov, G. Fuchert, J. Knauer, R.C. Wolf and the W7-X Team, *The Thomson scattering system at Wendelstein 7-X*, *Rev. Sci. Instrum.* **87** (2016) 11E729.

[7] S.A. Bozhenkov et al., *The Thomson scattering diagnostic at Wendelstein 7-X and its performance in the first operation phase*, 2017 *JINST* **12** P10004.

[8] P. Nelde, *Influence of Systematic Errors on the Electron Density and Temperature Measured with Thomson Scattering at W7-X (IPP 2021-07)*, Max-Planck-Institut für Plasmaphysik, Garching (2021), http://hdl.handle.net/21.11116/0000-0007-DDF7-A.

[9] E.R. Scott et al., *Demonstration of an absolute Rayleigh scattering spectral calibration on the W7-X Thomson scattering system*, 2019 *JINST* **14** C10033.

2022 JINST 17 C03012