Review of Scientific Instruments

RESEARCH ARTICLE | AUGUST 16 2024

Calibration techniques for Thomson scattering diagnostics on large fusion experiments

Special Collection: Proceedings of the 25th Topical Conference on High-Temperature Plasma Diagnostics

G. Fuchert ; J. Wagner ; L. V. Henschke ; E. Pasch; M. N. A. Beurskens; S. A. Bozhenkov ; K. J. Brunner ; S. Chen ; J. M. Frank ; M. Hirsch ; J. Knauer ; R. C. Wolf ; W7-X Team

Rev. Sci. Instrum. 95, 083533 (2024)
https://doi.org/10.1063/5.0219161

Review of Scientific Instruments ARTICLE pubs.aip.org/aip/rsi

Calibration techniques for Thomson scattering diagnostics on large fusion experiments

Cite as: Rev. Sci. Instrum. 95, 083533 (2024); doi: 10.1063/5.0219161
Submitted: 15 May 2024 • Accepted: 30 July 2024 •
Published Online: 16 August 2024

View Online Export Citation CrossMark

G. Fuchert,[1,a)] J. Wagner,[1] L. V. Henschke,[1,2] E. Pasch,[1] M. N. A. Beurskens,[1] S. A. Bozhenkov,[1] K. J. Brunner,[1] S. Chen,[1,3] J. M. Frank,[1,2] M. Hirsch,[1] J. Knauer,[1] R. C. Wolf,[1,2] and W7-X Team[b)]

AFFILIATIONS

[1] Max-Planck-Institut für Plasmaphysik (IPP), 17491 Greifswald, Germany
[2] Technische Universität Berlin, 10623 Berlin, Germany
[3] Technische Universität München, 80333 Munich, Germany

Note: This paper is part of the Special Topic on Proceedings of the 25th Topical Conference on High-Temperature Plasma Diagnostics.
[a)] **Author to whom correspondence should be addressed:** golo.fuchert@ipp.mpg.de
[b)] For the complete member list, please refer to T. Sunn Pedersen, Nucl. Fusion **62**, 042022 (2022).

ABSTRACT

Larger fusion experiments require long beam paths for laser diagnostics, which requires mechanical stability and measures to deal with remaining alignment variations. At the same time, due to technical and organizational boundary conditions, calibrations become challenging. The current mid-sized experiments face the same issues, yet on a smaller scale, which makes them ideal testing environments for novel calibration methods, since a comparison with the established best practices is still possible. At the stellarator Wendelstein 7-X, the calibration and operation of the Thomson scattering diagnostic is hampered by beam displacements, coating of windows during operation, and access restrictions while the superconducting coils are active. New calibration techniques were developed to improve the profile quality and reduce calibration time. While positional variations of the laser beam have to be minimized, the remaining displacements can be accounted for during the absolute calibration. An *in situ* spectral calibration has been developed based on Rayleigh scattering, which calibrates the whole diagnostic, including observation windows. In addition, a less accurate but faster method has been developed, which utilizes stray-light of a tunable OPO to perform spectral calibration within minutes and does not require torus hall access. Finally, a workflow has been established to consider finite linewidths of the calibration source in the spectral calibration. While these methods will be used at W7-X to complement existing calibration techniques, they may also solve some of the aforementioned issues expected for even larger and nuclear experiments, where access restrictions are stringent and calibration becomes even more demanding.

I. INTRODUCTION

Currently, the Thomson scattering (TS) diagnostic at Wendelstein 7-X (W7-X) utilizes three Nd:YAG lasers at a wavelength of 1064 nm with a repetition rate of 30 Hz each. Consequently, electron density and temperature profiles are available with a repetition rate of 90 Hz. The beams enter the cryostat and vacuum vessel from the inboard side of the torus, pass through the plasma vessel mostly radially (with a slight tilt downward with respect to the mid-plane) and exit on the outboard side of the torus, resulting in radially resolved profile measurements. Two observation optics measure the scattered light along this beam path, one for the inner half and one for the outer half of the minor radius. These optics are located within immersion tubes through the cryostat vessel and observe the scattered light through a window at the end of the immersion tube. For calibration and maintenance, the optics can be fully retracted from the immersion tube. For a sketch of the entire setup and a more detailed description, we refer the reader to Ref. 1.

Since TS diagnostics are essentially spectroscopic diagnostics, a relative spectral calibration is required to measure the electron temperature, with an additional absolute calibration needed for the electron density. The spectral calibration is usually performed by observing a tunable light-source with the entire diagnostic. Although many different methods exist, it is rather common that the light-source must be set up in or around the vacuum vessel, which makes these calibrations rather complex. For absolute calibration, it is common to either use Raman[2] or Rayleigh scattering on neutral gases or to cross-calibrate with other diagnostics measuring the electron density. Often, these calibration measurements are time-consuming and require access to the torus hall. This is often in contradiction with the goal to maximize valuable experimental time and mandated access restrictions due to, for example, radiation safety or the operation of superconducting magnets. Furthermore, stability of the diagnostic becomes paramount due to the required long beam paths. Yet, the harsh conditions (mechanical shocks and deformations as well as degradation of optical components) often disturb the system and make frequent recalibrations necessary. Considering these points, it is clear that existing techniques must be adapted and developed further as fusion experiments grow in size in order to provide robust calibrations in less time and, ideally, without requiring access to the torus hall.

While it is considered possible, at least occasionally, to perform Raman calibrations at ITER,[3,4] traditional spectral calibration methods, including torus hall access, and dedicated measurements to characterize all optical components are considered unrealistic. So far, the most promising solution is the so-called self-calibration, where the Thomson scattering spectrum is either observed under different scattering angles (*dual angle TS*[5,6]) or with different laser wavelengths (*dual wavelength TS*[7,8]). From the redundant information, it is possible to infer the spectral calibration. Usually, these methods are restricted to a certain electron temperature range, and it would be preferable if complementary methods were available for validation.

In light of this discussion, the larger experiments of today offer a great opportunity to test novel techniques, while still offering the possibility to benchmark against the classical approaches. In this paper, we present three methods that have been implemented for the Thomson scattering diagnostic at W7-X to improve the quality of the calibrations, to reduce the required time and, if possible, to avoid torus hall access. In Sec. II, we summarize a previous work on a position-dependent Raman calibration and put it into the context of this paper. In Sec. III, we discuss efforts to improve the spectral calibration. First, we summarize the current standard approach and compare it to an alternative using Rayleigh scattering and then discuss a novel approach using only stray-light. For these methods, compromises have to be made to make calibrations faster (or even just possible), leading to a spectral linewidth of the calibration light source larger than the required resolution. The resulting artifacts and their correction are discussed in Sec. IV.

II. POSITION-DEPENDENT RAMAN CALIBRATION

An automated beam-alignment control is currently being implemented for W7-X, but was not available for the previous experimental campaigns. Instead, the beam path was adjusted manually in between experiments using a set of cameras and remotely controlled mirrors. It was observed that even small changes in the laser beam position cause drastic errors in the measured density profiles. In fact, despite the frequent manual beam adjustments, laser misalignment was so far the dominant error source for the density profiles.[9] As a consequence, mechanical structures along the beam-path have been reinforced and an additional Brewster window between the laser room and the torus hall was introduced to reduce air flow along the beam path (leading to mirror vibration). These countermeasures greatly improved the stability of the beam path and, consequently, profile consistency, but the effect of beam misalignment can still be occasionally observed. An example is shown in Fig. 1, which shows three consecutively measured density profiles, one for each of the three lasers. It can be seen that, in this experiment, laser 1 and laser 3 agree well, while the profiles measured by laser 2 show a higher overall density and a larger scatter between neighboring spatial points. Hence, not only the absolute scale of the density profiles is affected, but even their shape[9] (i.e., the profiles cannot be corrected just by rescaling).

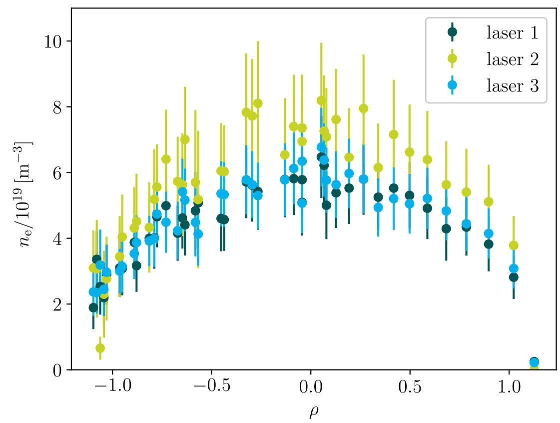

FIG. 1. Consecutive density profiles from the three lasers of the TS diagnostic at W7-X for the experiment 20 230 323.034 at $t = 2.6$ s. While the measured profile is consistent between laser 1 and 3, laser 2 is affected by beam misalignment.

It is obvious that no large fusion experiment will operate a Thomson scattering diagnostic without an automated alignment control system. However, even with such a system, the beam alignment could vary for a number of reasons: first, for a pulsed laser and a long beam path length, as a consequence of larger experiment sizes, the beam-pointing stability of the laser leads to small pulse-to-pulse variations that cannot be corrected for; second, due to the harsh environment, active parts of the alignment system could fail during a campaign and access restrictions to the torus hall could prevent a timely repair; and third, due to external forces, the beam position monitors, defining the coordinate system in which the beam position is kept constant, could be displaced, leading to a different beam path in torus hall coordinates. Without additional diagnostics, such a system would not be able to compensate a motion of the detectors themselves. Consequently, it would be preferable to ensure a sufficient profile quality even if the laser alignment is not perfectly stable. One solution is to make the position-dependence explicit in the absolute calibration.

At W7-X, where Raman scattering on nitrogen gas is used for the absolute calibration[10] (*Raman calibration*), it was shown in a previous work that a position-dependent calibration factor can drastically improve the quality of the density profiles.[11] For this, accurate monitoring of the beam position is required. For each individual laser pulse during the calibration, the beam position is determined together with the signal level of the Raman scattering raw data. Ideally, the beam position is varied in a controlled way, but a stochastic approach (e.g., by imposing vibrations) is also sufficient. This way, a correct calibration factor is obtained for each position.

While such an approach requires a lot of dedicated time for the calibration measurements, it prolongs the time between recalibrations, since small drifts of the beam path are accounted for in the calibration dataset. The position dependence can also be obtained from machine learning with a sufficient amount of profile data as training data. This may be a viable solution for even larger experiments, where extensive calibrations could be difficult to achieve or if faulty beam monitoring hardware cannot be replaced immediately. A detailed description of such an algorithm is out of the scope of this paper and will be published separately.

III. SPECTRAL CALIBRATION

The standard spectral calibration[10] for W7-X is performed by retracting both observation optics from their immersion tubes and placing a white scattering disk in front of them. By shining the light of a tunable laser-based light source onto the scattering disk, the spectral response of the entire optical setup and the detectors is calibrated. Since a SuperK supercontinuum light source from NKT photonics is currently used for this, we will simply refer to this calibration procedure as the *SuperK method* in the following. The resulting calibration has a high reproducibility and, since the measurement duration is only limited by practical boundary conditions (e.g., torus hall availability), statistical errors can be minimized. There are, however, three main disadvantages with this method.

1. The necessary preparations for the calibration take time and require access to the torus hall. Calibrating both observation optics currently takes about three days.
2. The scattering disk is located on top of the immersion tube, and hence, the observation window at the entrance to the plasma vessel is not covered by the calibration. The window transmission is measured separately and then combined with the measured spectral calibration. This approach is problematic if the spectral transmission of this plasma-facing window changes throughout an experimental campaign due to coating.
3. The light spot on the scattering disk is larger than the light-cone observed by the optics. The full numerical aperture of the optical fibers from the observation optics is used, which could lead to differences in the response between the calibration and the actual Thomson scattering measurements. Such a scenario could arise if, for example, a polychromator is not perfectly aligned and the light-cone were to overfill certain avalanche photodiodes during calibration, but not during TS operation.

So far, however, the latter is only a hypothetical possibility, while the calibration time and the omission of the window transmission are known drawbacks of the current approach.

As an alternative, a novel calibration method is being developed at W7-X. Rayleigh scattering in argon is used in combination with a tunable optical parametric oscillator (OPO, here from the manufacturer InnoLas) to perform an *in situ* spectral calibration, mimicking the diagnostic setup during plasma operation as much as possible.[12,13] Importantly, the plasma-facing window in front of the observation optics is included in the calibration, and, with the source geometry being similar to the Thomson scattering measurements, possible errors due to overfilling the detectors are no longer a concern. It was found that 300 mbar of argon in the plasma vessel give a sufficiently large scattering signal for a calibration with the current setup. It is planned to improve the calibration procedure, such that only 100 mbar will be required (the maximum pressure allowed in the W7-X plasma vessel during experimental campaigns). A detailed description of this *Rayleigh calibration* has already been published[12,13] and is not repeated here. Rather, we highlight a new development making use of one particular aspect of this method that makes the Rayleigh calibration itself challenging, but may offer an additional path for very fast recalibrations during experimental campaigns without torus hall access: Since Rayleigh scattering occurs at the incident laser wavelength, performing a spectral calibration requires a scan over the wavelength range relevant for the detectors. For wavelengths that are in the transmission bands of the different interference filters, not only is the scattering signal measured but also the stray-light originating from windows, metal surfaces, and optical components along the beam path. These sources of stray-light lead to a substantial background signal, which is larger than the Rayleigh scattering signal itself. Therefore, a careful characterization of the stray-light background in vacuum is required. In practice, this is achieved by starting the calibration with argon gas in the plasma vessel, reducing the pressure step-wise (to show the linearity of the signal with pressure) and finally concluding with a vacuum measurement, which represents the background measurement for subtraction. After this, the stray-light in vacuum alone offers the possibility to diagnose severe changes in the diagnostic, allowing for fast health checks during experiment operation. In fact, if the spectrum of the stray-light was known, the stray-light itself would be sufficient for a spectral calibration.

As a proof-of-principle, we assume that the effective reflectivity of all the components involved in creating the stray-light is independent of the wavelength. This assumption can be relaxed by either a second, independent calibration method or by a dedicated diagnostic to measure the spectral composition of the stray-light at the observation optic. However, even with the assumption of a flat spectrum, the background measurement alone yields a spectral calibration close to the one obtained with the SuperK method. Figure 2 illustrates this by showing the results of both the methods for one example poylchromator. Here, response refers to the combined effect of the transmission of all the optical components and the wavelength-dependent sensitivity of the avalanche-photodiodes used as detectors. Between the two methods, most filters agree within 10%. A clear qualitative difference is only seen in the spectral channel between 750 and 920 nm. It is not yet clear if the observed differences are purely explained by the incorrect assumption of a flat spectral dependence of the stray-light or if they indicate issues with either of the two methods. Spectroscopic measurements with a light source in the vacuum vessel indicate that these deviations are not explained by window coating. An important question is how reproducible the stray-light is. While individual pulses vary noticeably, the average over several pulses has been observed to be stable.

It is clear that the spectrum of the stray-light must be known before it can be used for a reliable spectral calibration. Two possible ways to achieve this are (1) with a dedicated diagnostic measuring

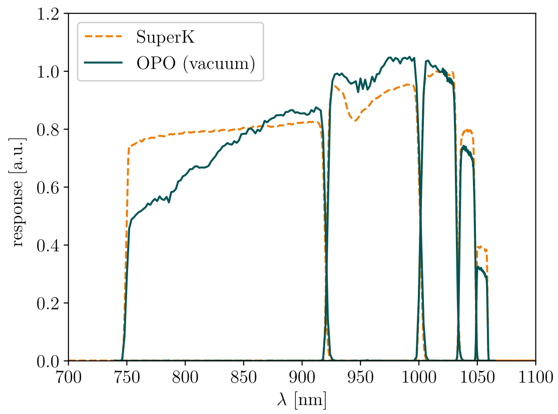

FIG. 2. Comparison of two spectral calibrations, one measured with the traditional SuperK method, the other inferred just from stray-light of an OPO light source fired through the plasma vessel along the beam path of the Nd:YAG lasers used for TS.

the stray-light spectrum close to the observation optics or (2) with a second, independent calibration method. By comparing the stray-light calibration with a reference calibration (e.g., from the SuperK method or employing Rayleigh scattering), an effective spectrum of the stray-light can be calculated such that the two calibrations agree. With that calculated spectrum, recalibrations would be possible until the stray-light spectrum noticeably changes (e.g., due to surface coating during plasma operation). For future campaigns at W7-X, it is planned to perform a quick recalibration on every experiment day. The measurements can be completed within a few minutes and serve as a quick health check of the diagnostic and allow us to investigate on which time scale the stray-light background remains unchanged.

IV. WAVELENGTH ACCURACY OF THE SPECTRAL CALIBRATION

For a spectral calibration with a tunable light-source, the wavelength-dependent linewidth should ideally be smaller than the wavelength resolution of the measurement. Otherwise, the steep gradients in the transmission curves (see Fig. 2) will appear flatter than they really are. Furthermore, if the spectral line shape has a strong tail to either side, the overall calibration curve can be shifted to higher or lower wavelengths, respectively. For most calibration methods typically used for TS, both errors are small and only lead to negligible differences in the inferred electron density and temperature. The same is not true for absolute Raman calibration, since the rotational Raman spectrum consists of a series of discrete lines. For a given spectral calibration, the integral of these lines can be calculated for each spectral channel and the result is then compared to the measured signal. For spectral lines close to the filter edges, errors in the calibration affect the weight with which a certain line is included in the calculation of the integral value for that spectral channel (or whether it is included at all). This can lead to noticeable errors of the absolute calibration.

These errors affect all the TS diagnostics, independent of the experiment size. However, if new methods are developed to reduce the calibration time or to make calibrations possible in the first place, compromises on the spectral linewidth may be required. For W7-X, the linewidth of the SuperK method is typically between 0.2 and 0.3 nm, but almost a factor of 1.5 larger for the OPO light source. The required spectral resolution, however, is only 0.1 nm. Hence, it is expected that errors arising from the finite spectral width of the calibration light-source need to be measured and corrected for. In the following, such a correction will be presented for the SuperK method. The same method can be applied to the OPO, but the necessary measurements to characterize the wavelength-dependent line shape for that setup are still a work in progress.

For the SuperK, the spectral line shape was measured in the relevant wavelength range. An example line shape is shown in Fig. 3 for a wavelength setting of 1050.0 nm. The line shape has a noticeable left tail (i.e., toward smaller wavelengths) and an overall width of around 0.3 nm (wavelength-dependent), which is empirically well described by an asymmetric Voigt profile. The observed linewidth is larger than the desired spectral resolution of 0.1 nm (the employed monochromator, a Spex 750M, allows for wavelengths setting with sub-Ångström resolution). Furthermore, due to the wider left tail, the intensity-weighted average wavelength is shifted with respect to the set value of the monochromator. In combination, that leads to a slight flattening of the filter edges and, more importantly, a shift of the spectral calibration of around 0.3 nm. The shift itself is also observed to be wavelength dependent and increases with the wavelength.

After a thorough characterization, the effect of the finite linewidth can be taken into account during the spectral calibration. A forward model was developed, which simulates how the measurement of a spectral calibration would look like, given the wavelength-dependent linewidth. The measured spectral calibration is taken as an initial guess for the actual calibration and is then var-

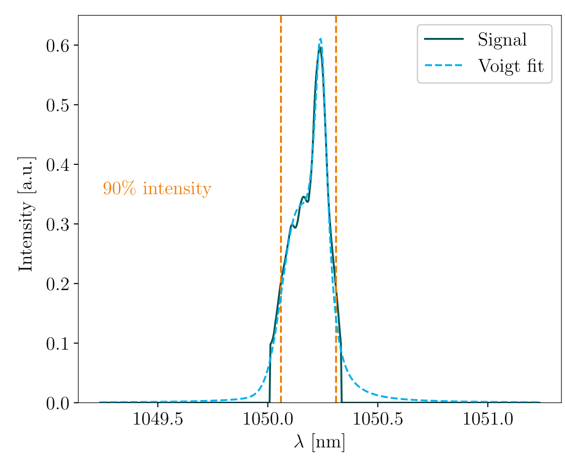

FIG. 3. Line shape of the SuperK light after the monochromator (wavelength setting of 1050.0 nm), together with a fitted asymmetric Voigt profile. The linewidth is indicated by the full-width covering 90% of the total integrated intensity (0.25 nm). There is a shift of ~0.2 nm between the monochromator set value and the intensity-weighted average wavelength (1050.2 nm). The drop at low signal values is caused by noise suppression to improve the fit quality.

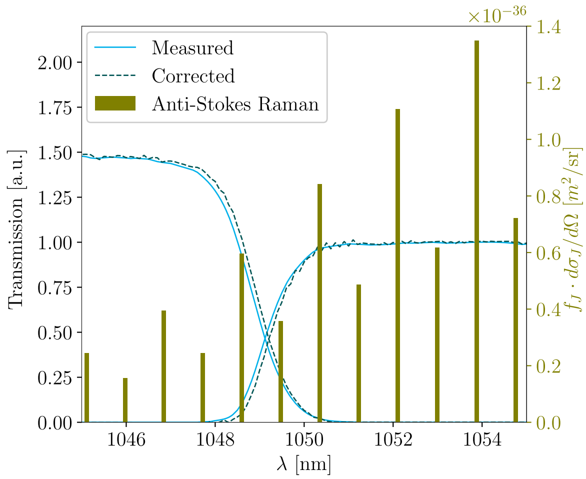

FIG. 4. Comparison of the measured and corrected spectral calibration. Due to the discrete nature of the Raman scattering spectrum (superimposed to the calibration curves), even small differences can lead to noticeable differences in the absolute calibration.

ied in an optimizer loop until the output matches the experimental observations. This procedure has been repeated for each of the W7-X polychromators and the Raman calibration has been performed both with the measured and the corrected spectral calibration. As an example, the result for one of the polychromators is shown in Fig. 4.

For most polychromators, using the uncorrected calibrations resulted in an error in the Raman calibration (and, hence, the electron density) between 1% and 2%. This can still be considered as a small error, but, as discussed above, will likely be higher for the OPO calibration (currently under investigation).

V. SUMMARY AND CONCLUSION

W7-X is a mid-sized fusion experiment and one of the two largest stellarators in the world (together with LHD). Experiment time is valuable and during experimental campaigns, torus hall access is restricted due to safety reasons connected to the operation of the superconducting magnets. For the same reason, the lasers for Thomson scattering are located outside the torus hall, which allows for maintenance without torus hall access, but requires long beam paths. In this situation, calibration measurements are becoming more challenging compared to smaller experiments, but have to be performed in less time. For future, even in larger fusion experiments, this issue will only become worse. Hence, improved calibration methods for the Thomson scattering diagnostic are needed in order to reduce required measurement time while, at the same time, increase their accuracy. This involves the minimization of the required torus hall access or, if possible, the development of fully remote calibrations.

One method that has shown to be important at W7-X is a position-sensitive absolute calibration. Beam position information has been included in the absolute Raman calibration to improve the quality of the electron density profiles while prolonging the time between recalibrations. Furthermore, spectral calibration methods are developed, which calibrate the entire diagnostic and minimize torus hall access. Rayleigh scattering on argon is being developed further to eventually replace the time-consuming and less complete SuperK method. Furthermore, it is currently investigated if just the stray-light from an OPO (employed for the Rayleigh calibration) is sufficient for a spectral calibration. Initial experiments show promising results, but additional diagnostics may be required to turn this into a stand-alone calibration method for larger fusion experiments. In both cases, an accurate characterization of the spectral properties of the light source is required to minimize uncertainties in the absolute Raman calibration.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200—EUROfusion). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

G. Fuchert: Conceptualization (lead); Data curation (supporting); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (lead); Project administration (equal); Resources (equal); Software (equal); Supervision (lead); Validation (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **J. Wagner**: Data curation (equal); Formal analysis (equal); Investigation (equal); Software (equal); Validation (equal). **L. V. Henschke**: Data curation (equal); Formal analysis (equal); Investigation (equal); Software (equal); Visualization (equal). **E. Pasch**: Conceptualization (supporting); Methodology (supporting); Project administration (lead); Resources (lead); Supervision (equal). **M. N. A. Beurskens**: Methodology (supporting); Project administration (supporting); Supervision (supporting). **S. A. Bozhenkov**: Methodology (supporting); Project administration (equal); Supervision (supporting). **K. J. Brunner**: Data curation (equal); Formal analysis (supporting); Investigation (supporting); Project administration (supporting); Software (equal); Supervision (supporting). **S. Chen**: Formal analysis (equal); Methodology (supporting); Software (supporting); Validation (equal). **J. M. Frank**: Conceptualization (supporting); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal). **M. Hirsch**: Project administration (equal); Resources (equal); Supervision (supporting). **J. Knauer**: Methodology (supporting); Project administration (supporting). **R. C. Wolf**: Project administration (lead); Resources (lead); Supervision (equal).

DATA AVAILABILITY

Raw data were generated at the W7-X large scale facility. Derived data supporting the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] E. Pasch *et al.*, Rev. Sci. Instrum. **87**, 11E729 (2016).
[2] J. Howard, B. W. James, and W. I. B. Smith, J. Phys. D: Appl. Phys. **12**, 1435 (1979).
[3] R. Scannel *et al.*, Rev. Sci. Instrum. **81**, 045107 (2010).
[4] L. Giudicotti and R. Pasqualotto, Plasma Phys. Control. Fusion **57**, 035001 (2015).
[5] E. Yatsuka *et al.*, J. Plasma Fusion Res. SERIES **9**, 12 (2010).
[6] H. Tojo *et al.*, Plasma Fusion Res. **6**, 1302018 (2011).
[7] O. R. P. Smith *et al.*, Rev. Sci. Instrum. **68**, 725–727 (1997).
[8] O. McCormack *et al.*, Plasma Phys. Control. Fusion **59**, 055021 (2017).
[9] P. Nelde *et al.*, J. Instrum. **18**, P09019 (2023).
[10] S. A. Bozhenkov *et al.*, J. Instrum. **12**, P10004 (2017).
[11] G. Fuchert *et al.*, J. Instrum. **17**, C03012 (2022).
[12] S. A. Bozhenkov *et al.*, Rev. Sci. Instrum. **90**, 033505 (2019).
[13] E. R. Scott *et al.*, J. Instrum. **14**, C10033 (2019).