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Absolute calibration of sniffer probes on Wendelstein 7-X

D. Moseev,^{1,a)} H. P. Laqua,¹ S. Marsen,¹ T. Stange,¹ H. Braune,¹ V. Erckmann,¹
F. Gellert,^{1,2} and J. W. Oosterbeek³

¹Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

²Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany

³Eindhoven University of Technology, Eindhoven, The Netherlands

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Here we report the first measurements of the power levels of stray radiation in the vacuum vessel of Wendelstein 7-X using absolutely calibrated sniffer probes. The absolute calibration is achieved by using calibrated sources of stray radiation and the implicit measurement of the quality factor of the Wendelstein 7-X empty vacuum vessel. Normalized absolute calibration coefficients agree with the cross-calibration coefficients that are obtained by the direct measurements, indicating that the measured absolute calibration coefficients and stray radiation levels in the vessel are valid. Close to the launcher, the stray radiation in the empty vessel reaches power levels up to 340 kW/m² per MW injected beam power. Furthest away from the launcher, i.e., half a toroidal turn, still 90 kW/m² per MW injected beam power is measured. [<http://dx.doi.org/10.1063/1.4960349>]

I. INTRODUCTION

Wendelstein 7-X is an optimized stellarator with $n = 5$ toroidal symmetry.¹ Electron cyclotron resonance heating (ECRH) at 140 GHz is used as the main heating mechanism in the machine.^{1–4} The ECRH system will deliver up to 10 MW of microwave power in continuous regime.² The ECRH system is a main source of stray radiation in Wendelstein 7-X and the contribution of ECE is negligible. Estimations using Trubnikov's equation⁵ lead to ECE stray radiation energy fluxes of less than 0.1 kW/m² which are below detectors sensitivity. However, even a relatively small fraction of stray radiation from ECRH may damage diagnostics and device components if they are not properly screened and cooled.⁶ Accurate knowledge of the stray radiation energy flux is vital for proper protection of the collective Thomson scattering diagnostic which is installed or planned on many machines^{7–10} and will be installed in Wendelstein 7-X in the next experimental campaign. Hence a set of diagnostics is installed in order to monitor and control the level of non-absorbed microwave power: sniffer probes, microwave bolometers,⁴ electron cyclotron absorption (ECA) diagnostic,¹¹ (near) infrared (IR) video cameras.¹²

Sniffer probes¹³ belong to the standard set of diagnostics for device safety and are, for example, installed in ASDEX Upgrade,¹⁴ LHD.¹⁵ Typically interlocks are fed with the sniffer probe measurements and the threshold is determined experimentally. However, the steady-state operation requires more accurate knowledge on the distribution of stray radiation and, moreover, on the absolute values of the energy flux in the different parts of the device.

In Section II, the design and the arrangement of sniffer probes on Wendelstein 7-X are described. The absolute calibration of sniffer probes against modeling is explained in Section III. Section IV describes an independent cross-calibration procedure for the sniffer probes. The absolute

calibration and cross-calibration are compared and combined into one calibration curve in Section V. Section VI concludes the paper.

II. EXPERIMENTAL SETUP

There are five sniffer probes in the Wendelstein 7-X stellarator that are equidistantly distributed around the stellarator. Their location in the device is displayed in Fig. 1. A sketch illustrating their design is shown in Fig. 2. On the right panel, a front-end part of the diagnostic is shown: a water-cooled stainless steel shield which is necessary for high performance steady-state experiments. The back-end part consists of a copper tube acting as oversized waveguide. The microwaves pass through a copper tube and a vacuum window (fused silica) and are then focused by a concave teflon lens on a Schröder diffuser.¹⁶ This assembly should ensure the wide angle antenna acceptance pattern. An attenuator is installed between the horn and the diode in order to prevent saturation of the amplifier and data acquisition system.

III. ABSOLUTE CALIBRATION OF SNIFFER PROBES

The absolute calibration of sniffer probes is performed independently from the cross-calibration of the probes. Gyrotrons C1 (module 1) and D5 (module 5) are used as sources of stray radiation. The gyrotrons are not used simultaneously. The underlying principle of the absolute calibration is the intrinsic estimation of the quality factor of the Wendelstein 7-X vacuum vessel using calibrated sources. One of the biggest problem of the method is the large variance of the sniffer probe signal, the reasons for which are discussed later in the text. It is overcome by multiple averaging over:

- gyrotron frequency chirp,
- time,
- gyrotron polarization.

^{a)}Electronic mail: dmitry.moseev@ipp.mpg.de

FIG. 1. Sketch showing a top view of Wendelstein 7-X. Green ports at the top denote the location of the C1 and D5 launchers used as sources of stray radiation. Red circles show the location of ports where the sniffer probes are installed.

A. Gyrotron modulation

Gyrotrons are sources of coherent high-power microwave radiation. We use gyrotrons as sources for the absolute calibration of the sniffer probes. As the radiation is coherent, strong interference patterns form in the vacuum vessel. Due to the frequency chirp of gyrotrons, the resulting interference pattern is not stationary. The strongly non-uniform heat distribution in the wall due to the interference pattern from the gyrotrons is observed by IR cameras during the experiments in the MISTRAL chamber.³ Fig. 3 shows an IR picture with 5 ms exposure time which is taken after a 1 ms long gyrotron pulse into the chamber. The thermal signature of the interference pattern of a mm-scale can be observed with such a short experimental timing as thermal transport due to heat conduction happens on a longer time scale and the gyrotron frequency chirp is not significant.

The existence of these interference patterns is a problem for sniffer probe calibration. The actual reading of the diagnostic depends whether it measures in the minimum or maximum of the interference picture. During a plasma

FIG. 3. Snapshot from IR camera in the MISTRAL chamber, the flakes are showing the fine-grained heat distribution due to the interference pattern of the gyrotron radiation. The gyrotron pulse duration is 1 ms, and the picture is taken after the pulse. The exposure time is 5 ms. The spatial scale of the interference pattern is in the order of the wavelength, i.e. approx. 2 mm.

discharge, there will be no interference pattern since the plasma destroys the coherence of the radiation. Hence we need to minimize the impact of the interference pattern in the calibration experiments. Here we exploit the fact that the gyrotron frequency changes when the power is modulated. We modulated the gyrotron power by 90%. The modulation frequency of the accelerating voltage in the range 66-78 kV is 10 kHz. This power modulation on this short time scale results in frequency chirps of about 30 MHz. The gyrotrons are modulated for 10 ms corresponding to 100 modulation cycles.

One could argue that the frequency changes by less than 1% and that it is not significant; however, after numerous reflections, the difference of optical paths of interfering waves can easily reach one wavelength. Sniffer probe amplifiers are equipped with low-pass filters with a cutoff frequency of 5 kHz. Therefore the signal on data acquisition cards is intrinsically averaged over the frequency chirp.

For quantitative analysis of the gyrotron stray radiation, the gyrotrons are calibrated in the modulated regime by calorimetry measurements. Steerable mirrors in the transmission lines for the C1 and D5 gyrotrons² redirect microwaves into the water load instead of the vacuum vessel of the stellarator. The power-voltage curves of the gyrotrons are shown in Fig. 4. The upper and lower values of the accelerating voltage are shown on x-axis and the average power is shown on y-axis.

FIG. 2. A sketch of the sniffer probe design for Wendelstein 7-X. Water-cooled stainless steel shield is mounted in the front-end part (left). The back-end part (on the right) has a copper-made oversized waveguide, a biconcave teflon lens, a Schröder diffuser, and a detection diode.

FIG. 4. Calibration curves for the gyrotrons C1 and D5 in the modulation regime. Lower and upper values of the acceleration voltage are shown on X axis and corresponding average power is depicted on Y axis.

B. Averaging of the sniffer probe signals

The sniffer probes should provide absolute power levels of stray radiation during plasma discharges. Our calibration is, however, performed by launching the microwave beam into the empty vacuum vessel. In addition to the intrinsic frequency averaging due to the 5 kHz low-pass filter and power modulation, we average over the polarization of the injected microwave power by turning the polarizer plates. This has to be done as stray radiation in a plasma experiment is arbitrarily polarized whereas the injected microwave power in the calibration is polarized. We averaged over five different polarizer settings. The polarization vector of gyrotron radiation is changed from -90° to $+90^\circ$ with 45° steps.

Polarization averaging can be replaced by averaging over gyrotron launching directions, which has a similar effect. In the discussed experiments, polarization averaging is performed using gyrotron C1 as a source; direction averaging is performed using the D5 gyrotron as a source. The impact locations are shown in Fig. 5 by red circles. The beam impact positions are located in half-modules 51 and 50.

This figure shows that the variations in launching angles are quite small: the distance between neighboring safe launch positions is 10-15 cm.

Lastly, to increase the signal-to-noise ratio, we average over 10 ms. The averaging duration is restricted by the total energy which is allowed to be injected into the empty vessel.

FIG. 5. Beam impact positions for the D5 gyrotron on the back side of the inner wall of Wendelstein 7-X are shown as red circles. The green line depicts magnetic axis. The typical linear size of each tile is approx. 10 cm.

Stray radiation scales linearly with the injected microwave power. To verify our averaging procedure, we performed a power scan using the C1 gyrotron. Fig. 6 shows the readings from sniffer probes in modules 1-5, where for a single data point, signal averaging over gyrotron frequency, polarization, launch angle, and time is performed as described above. We find close to linear responses of the sniffer probe voltages to increases in gyrotron power. The deviation from a linear monotonic response of sniffer probe to the input power seen on the left panel of the graph is due to proximity of the launcher to this particular sniffer probe. A possible direct reflection of a part of the ECRH beam into the diagnostic causes a rise of the signal at low power. To illustrate the importance of polarization averaging, Fig. 7 shows an example for just one polarizer angle setting. Here the polarization of the wave leads to a strongly non-linear, even non-monotonic response.

The polarization-averaged time traces of sniffer probes in modules 1-5 are shown in Fig. 8. The source of stray radiation is the C1 gyrotron in module 1.

FIG. 6. Raw signal of sniffer probes as a function of gyrotron power. C1 gyrotron is used as a source. From left to right: sniffer probes in modules 1-5.

FIG. 7. Raw signal of sniffer probes as a function of gyrotron power. D5 gyrotron is used as a source. Polarization averaging is not performed. From left to right: sniffer probes in modules 1-5.

C. Modeling of the ECRH stray radiation distribution

A model for describing the distribution of the stray radiation is presented in Ref. 17. In this model, the stellarator is represented as a number of interconnected volumes—“resonators.” Stray radiation in the model is considered isotropic, uniform, and arbitrarily polarized in each resonator. The stray radiation energy flux is determined by the power balance. Therefore, the stray radiation level in resonator k can be found by solving the following equation:

$$P_{in,k} = \sum_{i=abs.surfaces} p_k A_i \eta_i + \sum_{j=neighbours} (p_k - p_j) S_{jk}, \quad (1)$$

here $P_{in,k}$ (W) denotes the input power in the resonator k , p_k (W/m²)—the stray radiation energy flux in the resonator k , index i runs through microwave absorbing surfaces in the resonator k , A_i (m²) is a surface area of the absorber i , η_i is its absorption coefficient, index j runs through all other resonators in the system, p_j (W/m²) is the stray radiation energy flux in the resonator j , S_{jk} is the interface area between the resonator k and the coupled resonator j .

A model of the Wendelstein 7-X vacuum vessel is taken from the in-vessel components database. For the stray

radiation modeling, we assume that the vacuum vessel of Wendelstein 7-X consists of ten identical units, or half-modules in the Wendelstein 7-X terminology. Although every half-module is unique, this model closely resembles the reality because the relevant parameters, i.e., surface area, materials they are made of, and the cross section areas are similar. The cross section areas named S_{jk} in (1) are taken from the computer-aided drafting (CAD) model. The wall absorption, which is responsible for the quality factor of the vessel, $\sum_{i=abs.surfaces} p_k A_i \eta_i$ in (1), is found by forward modeling.

The distribution of sources in the stray radiation model is difficult to measure directly since there is no clear transition from directed (reflected) beam and stray radiation. In the calibration experiments, we postulate (due to the symmetry) that the input power from the gyrotron converts to the stray radiation in the two nearest to the launcher half-modules with a 1:1 ratio. Although this assumption is reasonable, it is not entirely correct and the inability to find a correct source distribution in the system is the main limiting factor for the quality of the fits presented later in the manuscript.

D. Forward modeling

For the modeling of the C1 gyrotron experiments, the input power is scaled to 1 MW and the sniffer probe readings are scaled accordingly. The data from the nearest sniffer probe to the launcher are ignored. The readings of the other sniffer probes are calibrated against the modeled stray radiation energy flux at their locations. The quality factor of the vacuum vessel determines the dumping of the stray radiation level as a function of the distance from the source. We make an implicit search of the Q factor of the vacuum vessel by assigning the effective microwave absorption area to each half-module (the same for each of ten), $A_{eff} = \sum_{i=abs.surfaces} p_k A_i \eta_i$. The modeling scheme is illustrated in Fig. 9 and consists of the following steps:

- An initial guess about the effective surface area.
- Simulations of two experiments where the gyrotrons C1 and D5 are used as sources of stray radiation.
- Sniffer probes are calibrated against the computed stray radiation level where they are installed, for

FIG. 8. Average time traces from all five sniffer probes installed in modules 1-5. The gyrotron power is modulated by 90% with 10 kHz frequency.

FIG. 9. Schematic with the logic of sniffer probe calibration against the experiments and modeling. Here the sniffer probes are calibrated in the experiments using the C1 gyrotron as a source.

the experiments with the C1 gyrotron as a source. The calibration is done for all sniffer probes but one, the closest to the source because of the direct beam irradiation.

- Stray radiation level is computed in the simulation considering the D5 gyrotron as a source.
- Apply the obtained calibration coefficients to the sniffer probe readings from the experiments with the D5 gyrotron as a source.
- Compare measured and simulated stray radiation levels in the case of the D5 gyrotron used as a source.
- Update the effective absorption area in order to minimize the difference.

In the absolute calibration scheme shown in Fig. 9, the C1 gyrotron can be replaced by the D5 gyrotron and the D5 gyrotron replaced by the C1 gyrotron. The calibration is performed with gyrotron D5 as the source of stray radiation whereas the optimization of the absorption coefficient is done with gyrotron C1 as the source of stray radiation.

Both procedures resulted in very similar effective absorption areas and slightly different calibration coefficients for sniffer probes. The calibration coefficients for three sniffer probes, situated remotely both from the launchers of the C1 and D5 gyrotrons, can be compared directly to each other, see Fig. 10. The best fits shown in this graph differ due to the roughness of the assumption of the distribution of sources of the stray radiation in the model. The problem of source distribution is that it is not possible to spot where in the vacuum vessel and after how many reflections the directed gyrotron beam is scrambled enough, so that the resulting stray radiation can be described by our model.

The calibration coefficients for sniffer probes in modules one and five cannot be obtained simultaneously by two methods. Calibration for sniffer probe 1 can only be provided in calibration against simulations with the D5 gyrotron as a

source; calibration for the sniffer probe 5—in the case of using the C1 gyrotron as a source. The calibration coefficients for the sniffer probes in modules 2–4 are defined as mean values of the coefficients depicted in Fig. 10. The errorbars for the sniffer probes 2–4 are defined as a deviation of the calibration coefficients obtained in two different ways from their mean value,

$$\delta = \frac{\text{abs}(k_{2...4} - k_{2...4}^{C1})}{k_{2...4}}, \quad (2)$$

here $k_{2...4}$ is a mean calibration coefficient for sniffer probes in modules 2–4, respectively, $k_{2...4}^{C1}$ is a calibration coefficient for sniffer probes in modules 2–4 obtained in the experiments with the C1 gyrotron as a source. Due to symmetry with respect to the mean, $k_{2...4}^{C1}$ can be replaced by $k_{2...4}^{D5}$ without changing the result.

The complete calibration curve is shown in Fig. 11.

We also checked the obtained calibration to the retrospective experiments where the D5 gyrotron is used in a

FIG. 10. Comparison of absolute calibration coefficients for sniffer probes in modules 2, 3, and 4. The blue bars show calibration of sniffer probes in the experiments with the C1 gyrotron as a source; the red bars show calibration of sniffer probes in the experiments with the D5 gyrotron as a source.

FIG. 11. Calibration curve of the sniffer probes installed in modules 1-5.

FIG. 12. Comparison of calibrated sniffer probe measurements with the modeling of an independent experiment in the Wendelstein 7-X vacuum vessel with the D5 gyrotron used as a source and working in a different regime as one described in Sec. III. Dashed lines show depict upper and lower errorbars.

different regime (another accelerating voltage modulation, no polarization scan, position scan over points different to those described in Section III). The results of the comparison of modeling of those experiment and actual measurements with calibrated sniffer probes are shown in Fig. 12. The dashed lines denote the errorbars. The observed disagreement between the modeling and the measurements is most likely due the difficulty in choosing the correct distribution of sources of the stray radiation. Additionally, when doing launching direction averaging instead of polarization averaging, the change of the impact location of the gyrotron beam on the inner wall may change the reflections significantly due to the finer structure of the tiles of the inner and the distribution of sources may vary from one gyrotron pulse to another.

After the quantification of the effective absorption area of the vacuum vessel, the expected levels of stray radiation during the start-up phase (without plasma) are identified. The modeling showing the case of injection from module 1 is displayed in Fig. 13 and demonstrates the stray radiation levels in the range from 90 kW/m² to 340 kW/m² per MW of input power.

IV. CROSS-CALIBRATION OF SNIFFER PROBES

Four out of five sniffer probes are cross-calibrated in the laboratory, so that their measurements can be compared directly. The sniffer probe 5 is damaged during the unmounting from the stellarator and the RF diode with the attenuators are changed, therefore the cross-calibration and the absolute calibration for this sniffer probe cannot be

FIG. 13. Stray radiation levels in the vacuum vessel of Wendelstein 7-X assuming the microwave injection from module 1. The levels range from 90 kW/m² to 340 kW/m² of stray radiation per MW of input power.

compared. The back-end parts of sniffer probes from modules 1-5 are unmounted from Wendelstein 7-X and cross-calibrated in the setup shown in Fig. 14 and its schematic in Fig. 15. The front-end part of the sniffer probes is the same for all five of them and therefore have no influence on cross-calibration. The back-end part of the probes uses different RF diodes and attenuators, each of them is individual. The sniffer probes are irradiated in each measurement for more than 2 s, the data from the last 2 s of acquisition are taken for the analysis. Each of the sniffer probes is measured 22 times in order to average out sensitivity of microwave diodes to the polarization of microwaves. In order to demonstrate reproducibility of the measurements, the entire cross-calibration procedure is

FIG. 14. Photo of the cross-calibration setup. The schematic is shown in Fig. 15. (a) Microwave source, delivering approximately 10 W at 140 GHz; (b) back-end part of the cross-calibration setup, including high-voltage power supply, microwave source from panel (a), hidden behind metal sheets for security reasons, microwave antenna that emits into the oversized waveguide with built-in diverging teflon lenses; (c) front-end part of the cross-calibration setup displaying the end of the oversized waveguide and a sniffer probe on the holder.

FIG. 15. Schematic that illustrates how the cross-calibration experimental setup is built. The photo of the setup is shown in Fig. 14.

FIG. 16. The average sniffer probe signals from independent experiments show the reproducibility of measurements.

repeated at the next day and the measurements are similar, see Fig. 16.

The cross-calibration coefficients are dimensionless and are computed with respect to the sniffer probe from module 2, see Fig. 17. The value is computed as the mean value of two independent experimental sessions and the errorbars represent the discrepancy between the computed coefficients. The errorbars are not shown, the uncertainties are below 10%.

V. COMPARISON OF THE ABSOLUTE CALIBRATION AND CROSS-CALIBRATION OF THE SNIFFER PROBES

Cross-calibration and absolute calibration data can be compared when the latter is normalized to the sniffer probe calibration coefficient from module 2. The choice of the reference sniffer probe is in principle arbitrary, in this case the sniffer probe 2 is used because its absolute calibration coefficient computed in Section III D has the smallest errorbar, i.e., the discrepancy for the calibration coefficient computed using the gyrotrons C1 and D5 as sources of the stray radiation is the smallest. The comparison is shown in Fig. 17. One can see there a good agreement between cross-calibration coefficients (blue bars) and normalized absolute calibration coefficients (red bars). A relatively large disagreement for the sniffer probe from module 1 is due to the absolute calibration procedure: the absolute calibration coefficients are the average coefficients, obtained in the procedures using the gyrotrons C1 and D5 as sources. The averaging is needed in order to minimize the effect of the distribution of sources for the stray radiation. However, the averaging cannot be performed for sniffer probes from modules 1 and 5 because each of them has only one value which is computed when the gyrotron in another module is used as a source.

Unfortunately the sniffer probe from module 5 got damaged during the procedure of unmounting from the

FIG. 17. Comparison of cross-calibration (blue bars) and absolute calibration coefficients (red bars) of the sniffer probes. All values are shown with respect to the calibration coefficient of the sniffer probe 2. The sniffer probe from module 5 is excluded from the analysis.

FIG. 18. Combined normalized calibration coefficients for sniffer probes from modules 1-4 and their errorbars scaled to the absolute values.

device and its microwave diode and an attenuator have to be replaced before the cross-calibration. Therefore, the data are not comparable and not presented in the Fig. 17.

For the combined calibration coefficient, the normalized shape is taken from the cross-calibration measurements. The scaling factor is the absolute calibration coefficient of sniffer probe 2, computed in Section III. Errorbars are estimated in the following way:

$$\delta_{combined,i} = \sqrt{\delta_{abscalib,2}^2 + \delta_{xcalib,i}^2}, \quad (3)$$

where $\delta_{combined,i}$ is an errorbar on combined calibration coefficient for sniffer probe i , $\delta_{abscalib,2}$ is an errorbar on the absolute calibration coefficient for sniffer probe 2, and $\delta_{xcalib,i}$ is an errorbar on the cross-calibration coefficient for sniffer probe i .

The combined normalized calibration coefficients can be scaled back to their absolute values, as shown in Fig. 18.

VI. CONCLUSIONS

In this paper, we present a systematic approach to calibrate sniffer probes. Large variability of sniffer probe signals is overcome by averaging over time, frequency chirp, and polarization or launching direction.

The stray radiation model is validated in the Wendelstein 7-X vacuum vessel and is used for the absolute calibration of the sniffer probes. The calibration method is based on implicit estimation of the Q factor of the vacuum vessel of Wendelstein 7-X with calibrated sources. The method allows absolute calibration of sniffer probes or any other diagnostic

that measure stray radiation, i.e., microwave bolometers. The weakest part of the method so far is difficulty in obtaining the correct distribution of sources of the stray radiation in the device. This is a limiting factor for the quality of fits which we can obtain.

Independently, cross-calibration is performed and the normalized absolute calibration coefficients are compared to the cross-calibration coefficients. Both methods show good agreement for the sniffer probes located in the modules without ECRH launchers. The obtained calibration coefficients are applied retrospectively to the experiment in the vessel with the D5 gyrotron as a source, working in a different regime than discussed in the paper. The measurements reasonably agree with the modeling of the experiment.

The distribution of stray radiation in the modules of Wendelstein 7-X is conducted using computed average absorption coefficient for the vacuum vessel. This distribution assumes no plasma and the C1 gyrotron as a source. These conditions are typical for the start-up phase of the stellarator. The stray radiation energy flux ranges from 340 kW/m² per MW to the launcher, the stray radiation in the empty vessel reaches power levels up to the launcher, the stray radiation in the empty vessel reaches power levels up to the launcher, the stray radiation in the empty vessel reaches power levels up to of input power in module 1 (where the source is placed) to 90 kW/m² per MW of input power in module 3, the most remote module from the source.

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