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MEASURING THE DIRECTIONAL EMISSIVITY OF PLASMA FACING COMPONENTS AT HIGH TEMPERATURES WITH A NEW SETUP, MAGRYT

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ABSTRACT. Directional emissivity is a key thermal property critical for applications in thermal radiation modeling, material characterization, and energy systems. It defines a surface's ability to emit thermal radiation as a function of temperature and observation angle. This paper introduces a new measurement system, so-called MAGRYT, tailored for fusion devices (tokamak), where extreme conditions such as high temperatures [200-3600°C] and plasma-wall interactions demand precise emissivity data to ensure reliable infrared temperature monitoring. The setup includes a vacuum chamber to simulate tokamak conditions, a CO₂ laser for controlled heating, a rotative sample holder, and an infrared camera for directional flux measurement. This system enables emissivity measurements in the 3–5 μm spectral range for viewing angles between 0° and 83° at temperatures up to 1000°C. First experimental measurements with this setup on metallic samples at 450°C are presented. These measurements prove the high angular dependency of emissivity, leading to temperature errors of up to 100°C in wide-angle views of the future tokamak ITER.

1. INTRODUCTION

Emissivity is a fundamental property that describes the ability of a surface to emit thermal radiation as a function of temperature. It plays a critical role in various scientific and industrial domains, particularly in non-destructive testing using thermography systems. The term "emissivity" is commonly used to denote emissivity at normal incidence. This paper focuses on the directional emissivity dependent on the observation angle. This is to be distinguished from hemispherical emissivity, which is the integral of the spectral emissivity over all directions and all wavelengths. Accurate measurement of emissivity is particularly demanding, as it requires a controlled environment to monitor all parameters that can change the surface state and, consequently, the emissivity value, such as temperature gradients and environmental conditions (e.g., vacuum, humidity).

Developing reliable measurement systems is therefore essential to advance our understanding of thermal phenomena in highly demanding contexts. This is particularly true in infrared (IR) thermography applications for nuclear fusion. In this case, infrared thermography is used to monitor the surface temperature of Plasma Facing Components (PFCs) over a wide range of temperature [200-3600°C] for ITER [1]. Nevertheless, the surface temperature measurement is not straightforward due to the low and variable emissivity of in-vessel components and the resulting presence of reflection. Added to this is the fact that the imaging systems used are wide-angle systems that observe the thermal scene from all angles, including normal and grazing angles. This can cause significant errors on temperature higher than 100% for the lowest temperature (< 400 °C) and between 30-100% for the highest temperature

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(≥ 400 °C) [2]. Characterizing the directional emissivity of materials is an essential step towards a better understanding of IR images and more accurate measurements for safe plasma operations.

The directional emissivity can be measured using two main approaches: the direct method and the indirect method [3]. The indirect method involves directing a light beam from an external source onto a sample and then measuring its reflectivity and transmittivity to deduce the absorptivity [4]. The directional emissivity value can then be deduced according to Kirchhoff's law, which states that the spectral directional emissivity and absorptivity are equal for a material in thermal equilibrium. The indirect method enables measurements of samples at low temperatures and low emissivity, as it does not rely on detecting the thermal radiation emitted by the sample itself. The direct method calculates emissivity by comparing the thermal radiation emitted by the sample with a blackbody reference. The direct method is particularly well suited for measurements at high temperatures, as the signal-to-noise ratio is higher under such conditions, which simplifies the differentiation between the thermal radiation emitted by the sample and any reflected radiation from the surroundings. The direct method also requires fewer complex calculations, as emissivity is measured directly as the ratio of the sample's emitted radiation to that of a black-body reference. In addition, the direct method is often more practical for directional emissivity measurements, since it involves the rotation of only one component, either the sample or the radiation collecting optics, making the experimental setup simpler and more efficient compared to the indirect method.

Several direct measurement devices for directional emissivity have already been presented in the literature. These systems enable direct measurements at low temperatures [5, 6], high temperatures [7, 8] and over a wide spectral range [9]. However, we needed a bench dedicated to our field of research.

This paper presents a new system for measuring directional emissivity, designed to address the specific challenges posed by tokamak environments. Section 2 describes the test bed MAGRYT and the experimental method for measuring the directional emissivity. The experimental results, especially the temperature and angular dependence of emissivity of different samples are discussed in section 3. Section 4 shows an application of fitted experimental emissivity measurements on simulated IR images of the future tokamak ITER and the impact on the interpretation of IR images.

2. IR MONITORING ISSUES ON TOKAMAK.

Nuclear fusion machines, known as tokamaks, require continuous thermal monitoring to prevent material degradation due to component overheating. To this end, some tokamaks, such as WEST and in the future ITER, use infrared cameras to measure the temperature inside the vacuum vessel during a plasma pulse. However, IR quantitative thermography in a fully metallic environment is not trivial due to the presence of parasitic light (reflected flux) and changes in surface state (emissivity and reflectivity) [2]. Inverse radiative models are currently being developed to obtain reliable surface temperature measurements from IR images that have been filtered for reflections and do not require prior knowledge of the target emissivity [10, 11]. All of these methods are based on robust simulations (direct models) of the entire IR measurement chain, from the thermal scene to the sensor. This includes, in particular, a better characterization of the thermal radiative properties of surface materials under different conditions to adjust the input data used in the simulations. The initial results of the angular dependency of emissivity are shown in one IR view of the future ITER device, focusing on the most critical component, the divertor (the floor of the machine). As shown in Fig. 1, this component is observed from the median port plug in a bird's-eye view, which favors grazing angles. Figure 2 shows a ray-tracing simulation of the apparent temperature of a tokamak section for different directional emissivities. Directional emissivities, shown in insets in the figures, are derived from the Bidirectional Reflectivity Distribution Function (BRDF) according to Kirchhoff's law [12]. These BRDFs are implemented using Phong's model [13] which is not convenient with experimental data but allows to put on light the impact of directional emissivity. Three simulation cases are considered, each with the same normal emissivity: 0.2 for the divertor and 0.5 for the wall. The directional

emissivity model varies for each case. The directional emissivity was tuned by varying the specular component of the BRDF, specifically through adjustments of the KS parameters in the Phong model. These images were simulated without any reflection, considering a uniform temperature of 450 °C for the divertor and 200 °C for the wall. These simulations demonstrate that changes in the directional emissivity model can result in temperature measurement differences of up to 100°C. This highlights the importance of accounting for directional emissivity models to obtain reliable surface temperature measurements. The MAGRYT test bed is designed to characterize the directional emissivity of samples as a function of temperature (up to 1000°C) and within the infrared range of 1-5 μm .

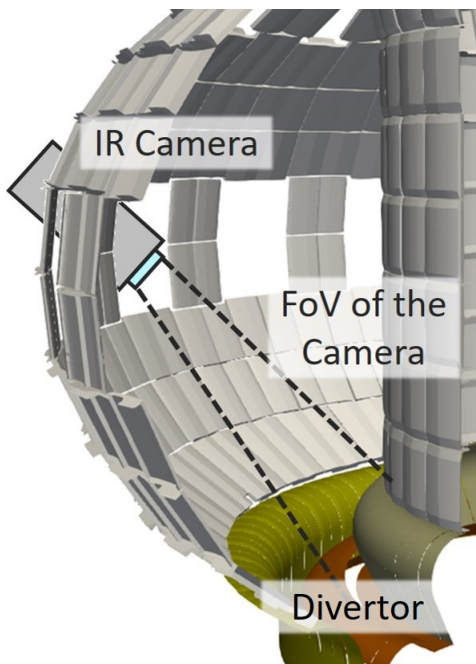


Figure 1: CAO model of the ITER tokamak with the field of view of the simulated IR camera.

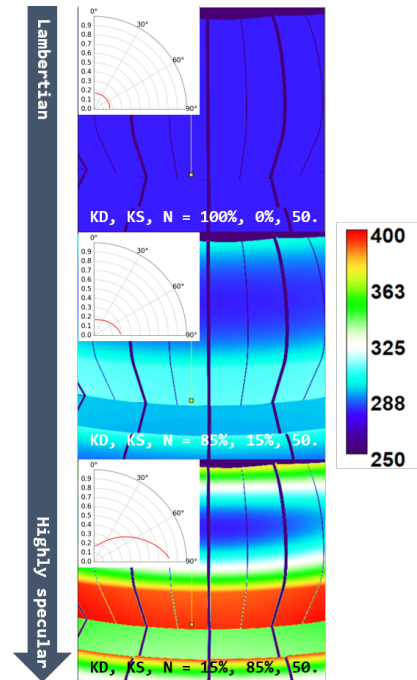


Figure 2: Comparison of temperatures simulated with a ray tracing method with different directional emissivities.

3. EXPERIMENTAL METHOD

3.1 MAGRYT experimental setup

MAGRYT is a new system dedicated to IR quantitative thermography with two main objectives: characterizing the thermal properties of in-vessel components in tokamaks and testing advanced numerical approaches for measuring surface temperature in perturbative but controlled environments. As illustrated in Figure 3, this new set up includes a vacuum chamber in order to reproduce the tokamak environment, a CO₂ laser to heat the sample, a rotative sample holder and an infrared camera to measure the emitted flux. This system enables directional emissivity measurements between 3 and 5 μm for incident angles from 0 to 83° up to 1000 °C.

The sample is placed inside a vacuum vessel (diameter 350 mm) capable of dropping to a pressure of 10⁻⁵ Pa. The vacuum is necessary to prevent oxidation of the samples under study during the temperature rise, and thus reproduce the pressure conditions inside the tokamak. The sample is held in the center of the vacuum chamber by a sample holder that can be rotated 360° around the x-axis. The sample is heated from the rear by a 50 W CO₂ laser (ULR-50, Universal laser system inc.) with a wavelength of 10.6 μm . The laser beam enters the vacuum vessel through a ZnSe window and enables tungsten samples just a few centimeters square and 2 mm thick to be heated

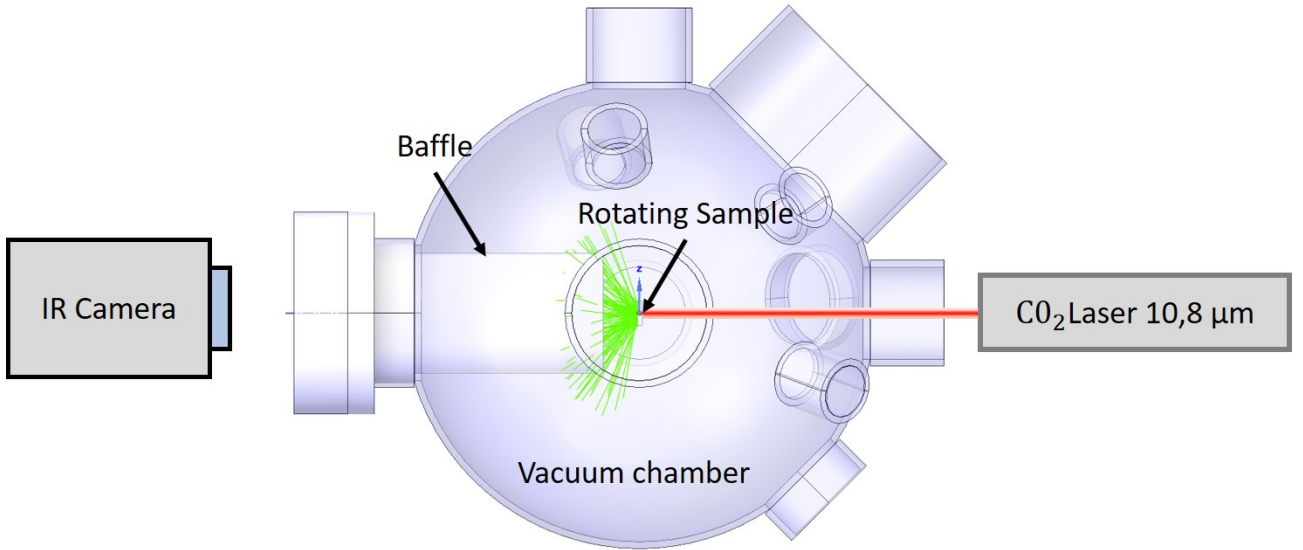


Figure 3: Schematic view of the experimental MAGRYT setup.

up to 1000 °C. As the samples being measured are small and have high thermal conduction, the laser provides a uniform temperature at the front to within 5%. This result was demonstrated by modeling using Ansys Mechanical software. Figure 4 shows the surface temperature calculated for a tungsten sample receiving 50W backside at steady state. The other windows in the vacuum chamber are made of sapphire. As sapphire is opaque beyond 4.75 μm, this ensures the system's laser safety. The temperature of the sample is measured using a K-type thermocouple inserted inside the sample. The IR camera is a “CEDIP” camera with 320 × 256 pixels, InSb detectors sensitive in the 3–5 μm wavelength range and equipped with a filter holder. The IR camera is actively cooled with a cooling bath. A stable temperature reduces thermal noise, improves the sensitivity and ensures an accurate calibration. As the vacuum chamber is very smooth and metallic, we have to handle multiple reflections within the sphere coming from the hot sample. To minimize parasitic light, a tube acting as a diaphragm has been designed, as shown in Fig. 5. With a 20 mm diameter opening, it is placed in front of the sample inside the vacuum chamber. The tube is isolated from the sample to prevent it from heating and becoming another parasitic source. A ray-tracing model of the experiment ensured that no reflected flux reached the infrared camera sensor.

3.2 Principle

The spectral, directional emissivity can be defined as [12]

$$\epsilon'_{\lambda}(T, \lambda, \vec{s}) = \frac{I_{\lambda}(T, \lambda, \vec{s}) \cos \theta_0 d\Omega_0}{I_{b\lambda}(T, \lambda) \cos \theta_0 d\Omega_0} = \frac{I_{\lambda}(T, \lambda, \vec{s})}{I_{b\lambda}(T, \lambda)} \quad (1)$$

which is the ration between directional emissive power with that of a black surface at the same conditions. $I_{\lambda}(T, \lambda, \vec{s})$ the radiative intensity emitted by the sample at temperature T at the wavelength λ in the direction \vec{s} and $I_{b\lambda}(T, \lambda)$ the radiative intensity of a black body under the same conditions. The results presented in this paper have all been obtained for the same wavelength, so in the following we will concentrate only on total directional emissivity:

$$\epsilon'(T, \vec{s}) = \frac{I(T, \vec{s})}{I_b(T)} \quad (2)$$

To determine directional emissivity, we use a direct method which consist in measuring the radiative intensity emitted by a material at a given temperature and compare it with that of a black body at the

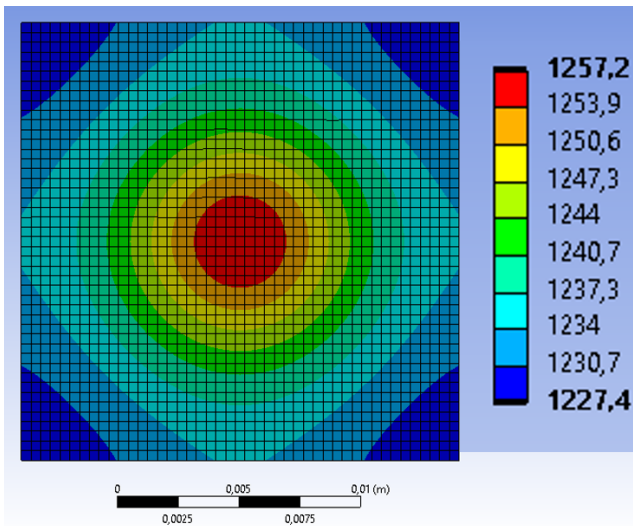


Figure 4: Modeling the temperature of the front face of a tungsten sample (18×18×2 mm) receiving a 50W flux on the back face.

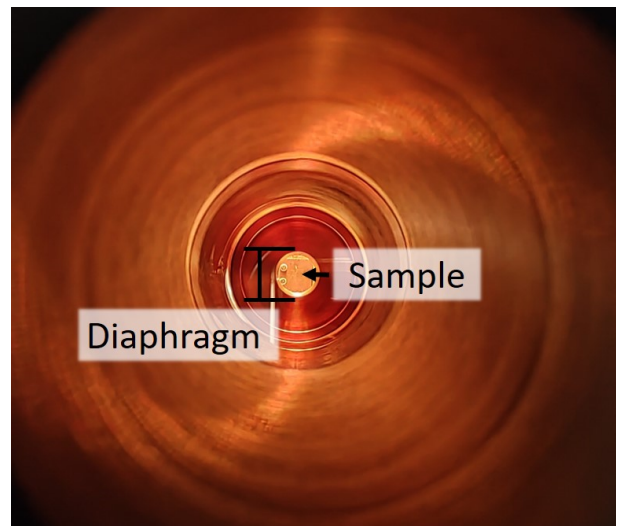


Figure 5: Photo of the diaphragm in front of the sample.

same temperature. The direct method for measuring emissivity is based on reference measurement using blackbody source as shown in equation (1). A reference measurement on a black body were carried out before the measurements on the samples. A blackbody with an extended emissive surface (Optris BR400) up to 450°C was used to obtain reference data for different IR camera integration times.

4. RESULTS

4.1 Samples

This study focuses on 3 samples with interesting and different surface properties. The samples are shown in Fig. 6. Sample 1 is made of tungsten with an un-machined surface. Sample 2 is also made of tungsten but with a polished surface. Sample 3 is tungsten with a silver coating. These samples are representative of the materials present inside tokamaks [14]. In order to better characterize the surface of the samples, they were analyzed using a confocal microscope. The measured surface area is 800×800 μm. Figure 6 shows the topography of the surfaces of the three samples and highlights the diversity of the three samples. Sample 1 has a very chaotic surface with significant variations in height. Sample 2 has a much more uniform and smoother surface. Sample 3 has a more exotic surface with areas of varying heights. This is due to the spray coating process. As the confocal measures the height of the surface, it enables to calculate different roughness parameters. Surface roughness parameters were extracted from the confocal topography measurements for the three tungsten-based samples. The arithmetic mean roughness (R_a), the root mean square roughness (R_q), and the ten-point mean roughness (R_z) were computed to characterize the overall height amplitude, while the skewness and kurtosis provided information on the asymmetry and sharpness of the surface height distribution, respectively. The results are gathered in Table 1. Although Samples 1 and 3 exhibit comparable roughness parameters, the confocal topography clearly reveals distinct surface morphologies. This observation highlights that conventional roughness metrics, while useful for quantifying amplitude variations, are insufficient to fully describe the complexity of surface textures. A more complete description therefore requires considering the spatial organization and topographical features beyond the standard roughness parameters.

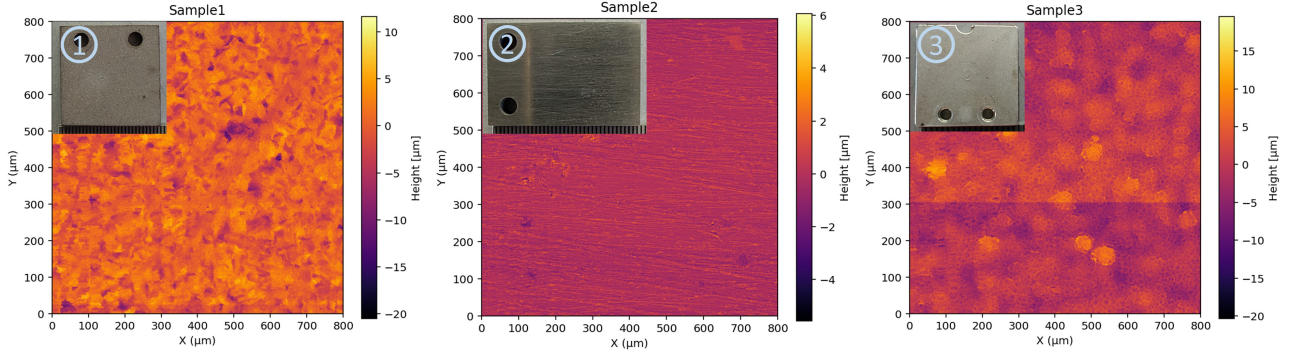


Figure 6: Photos of the three studied samples with a confocal image of their surface.

Table 1: Surface roughness parameters of the studied samples.

Sample number	1	2	3
Surface	Sand-blasted tungsten	Polished tungsten	Silver coated tungsten
R_a [μm]	2.96	1.12	2.90
R_q [μm]	3.62	1.33	3.53
R_z [μm]	34.29	10.61	35.41
Skewness	-0.155	-0.133	-0.158
Kurtosis	2.709	2.254	2.730

4.2 Radiative measurements

Radiative measurements were carried out for the three samples between 300 and 500°C between 3 and 5 μm . For this study, the camera was not filtered to maximize the flux received by the sensor and therefore the accuracy of the measurements. This has little influence on the results, given that the samples studied are quasi gray between 3 and 5 μm , as shown by the Drude and Hagen-Rubens models [15, 16] and the experimental results [17]. At each temperature step, measurements were taken at nine angles of incidence: 0, 15, 30, 45, 60, 75, 80 and 83°. Figure 7 shows the different acquisitions made by the infrared camera for sample 3 at 450 °C at nine angles of incidence.

In Figure 7, the colorbar indicates the digital level (DL) of the camera's sensor, and is identical for different angles of incidence. Below the sample, the thermocouple can be seen, measuring the sample temperature. The two points of strong flux to the left of the sample are the screws that hold it to the sample holder. These screws are less hot than the sample, but emit a higher flux due to their high emissivity. In the image for $\theta_i=0$, the reflection of the back of the sample on the vacuum chamber can be seen in the background. When the picture was taken, the diaphragm was not as closed as the one shown in section 2.2 but this phenomenon is now invisible during measurement. We can already qualitatively note that the DL of the measured zone (blue square) increases as the angle of incidence increases, suggesting an increase in emissivity for grazing angle. Based on these measurements and those taken on the blackbody, equation 1 can be used to determine the directional emissivity of the three samples as a function of temperature and angle of incidence.

4.3 Emissivity measurements

In order to validate the measurement bench, we performed a directional emissivity measurement on a standard sample. This standard is a sample painted with thermographic paint (LabIRPaints ©). The measurements obtained using MAGRYT were quantitatively compared with the spectral and directional emissivity data provided by the supplier. Figure 8 shows the directional emissivity at

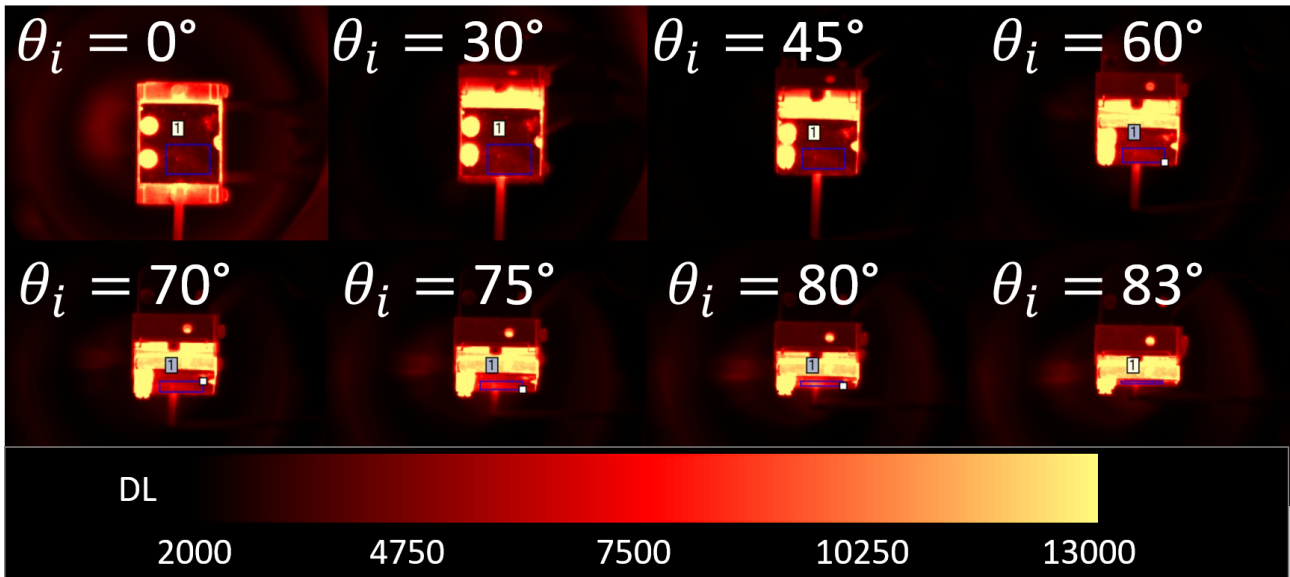


Figure 7: Digital level (DL) of the sample 3 at 450 °C at different incident angles acquired by the IR camera.

4.9 μm measured with the Magryt bench and the supplier data. The measurements align with the supplier data, exhibiting a mean error of 2.3%. This close agreement validates the reliability of the measurement bench.

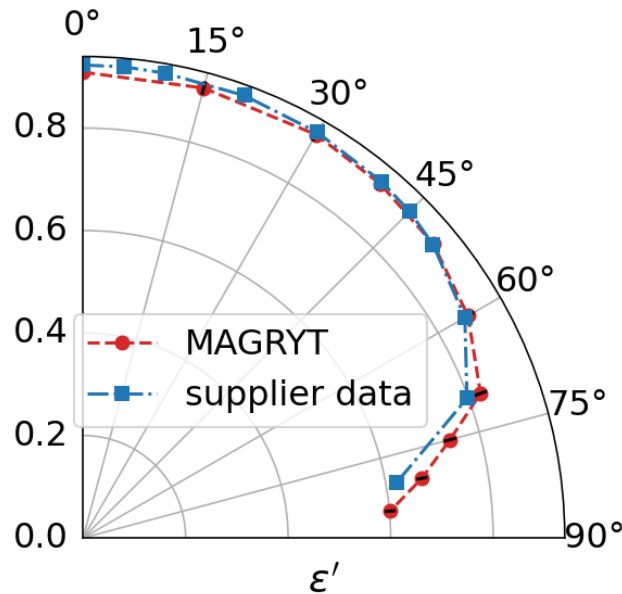


Figure 8: Comparison between the directional emissivity at 4.9 μm of a standard sample measured with MAGRYT and provided by the manufacturer (LabIRPaints ©).

Figure 9 shows the directional emissivity obtained for the three samples for different incident angles between 300 and 500 °C. For this initial demonstration, the paper focuses on the angular dependence of emissivity within a limited temperature range of 300-500°C. Previous work [17] has demonstrated the low temperature dependence of normal emissivity values. However, the conservation of this behavior for directional emissivity at higher temperatures (up to 1000°C) will be verified. Error bars are determined with the standard deviation of the digital level measured in the region of interest used during the measurements and the thermocouple accuracy given by the manufacturer.

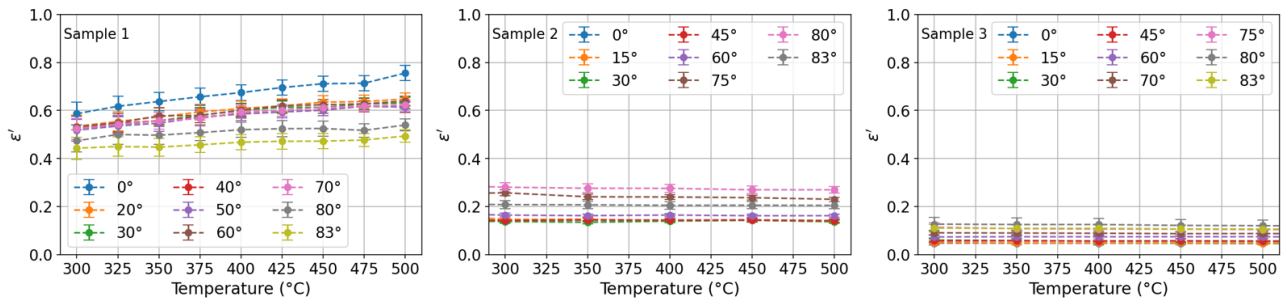


Figure 9: Directional emissivity of the three samples at different incident angles according to temperature between 3 and 5 μm .

Firstly, there is a significant difference in emissivity between sample 1, samples 2 and sample 3. Emissivity is highly dependent on the surface condition of the sample, and not only on the material itself [12]. Due to its high roughness, sample 1 has an emissivity three times higher than sample 2, even though both samples are made of tungsten. As expected, silver-coated sample 3 has the lowest emissivity. The evolution of the temperature has little impact on the emissivity of the samples as predicted by theoretical model such as Hagen-Rubens relations [18] and reported by experimental studies [17]. Conversely, emissivity is found to be dependent on the angle of incidence of the sample, underlining the importance of considering directional emissivity rather than hemispherical emissivity. Figure 10 shows the directional emissivity measured at 450°C for the three samples in polar coordinates, in order to give a better idea of its evolution as a function of angle.

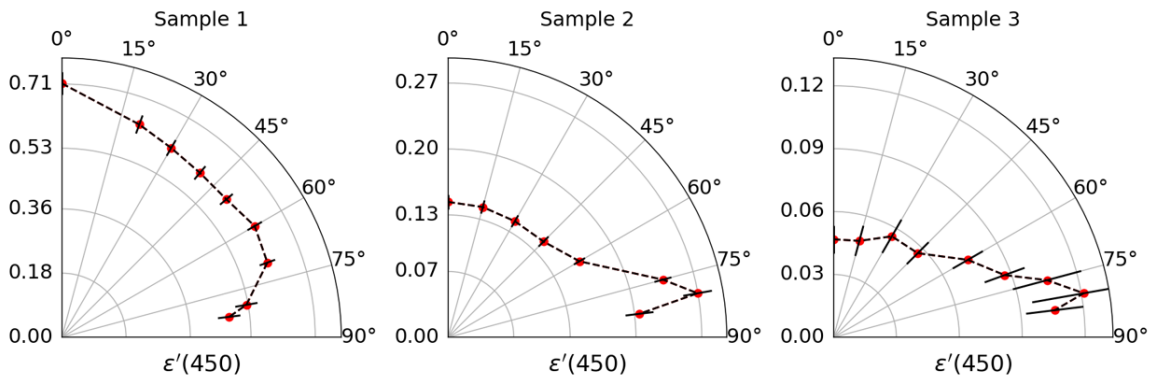


Figure 10: Directional emissivity of the three samples at 450 °C between 3 and 5 μm .

The directional emissivity of sample 1 has a quasi-Lambertian behavior. The directional emissivity varies little over a large range of polar angles but decreases rapidly at grazing angles. This behavior is consistent with the literature for rough metal materials [19, 20]. Samples 2 and 3 show similar behavior except that, at grazing angles, emissivity increases sharply before decreasing. These results are also consistent with the literature [7, 21].

5. CONCLUSION

A new experimental setup, MAGRYT, has been built to measure the directional emissivity of metal samples in a controlled environment up to 1000 °C. Measurements were carried out on representative samples of the materials present inside tokamaks in the temperature range of [300-500°C] between 3 and 5 μm . Highly emissive samples have quasi-Lambertian directional emissivity, while low-emissivity samples behave differently. Their directional emissivity increases sharply at grazing angles ($\sim 80^\circ$) before decreasing. This can lead to major errors in the interpretation of the temperature in fusion machines. This highlights the importance of characterizing the thermal radiative properties

of surface materials under various conditions, such as roughness, layer deposition, and before and after exposure. This knowledge is crucial for advanced processing methods that utilize detailed simulations to invert infrared measurements, thereby estimating surface temperatures. Subsequently, measurements at higher temperatures will be conducted on samples with varying surface properties to verify whether the directional emissivity model changes.

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