Surface temperature measurement of plasma facing components with active pyrometry

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Abstract
In fusion devices like ITER, plasma facing components will be in metal, (Tungsten and Beryllium), with emissivity in the range of 0.1-0.4. Therefore, surface temperature monitoring by infrared system will become more challenging due to low emissivity and consequently non negligible reflected flux. The active pyrometry method proposed in this paper allows surface temperature measurements independently of reflected and parasitic fluxes. A local increase of the surface temperature (ΔT(t)~10 °C) introduced by a transient heating source (pulsed or modulated) results in an additional component of the flux collected by the detector. A filtering of the signal allows extracting a temporal flux proportional only to the variation of the emitted flux. The ratio of simultaneous measurements at two wavelengths allows solving the unknown emissivity (same as for classical bicolour pyrometry). In this paper, it is described how the active pyrometry method is adapted to the surface temperature measurements of metallic PFCs independently of the reflected fluxes. Experimental results for carbon and tungsten samples are reported. Finally, it is shown how, by using the active pyrometry, the overall 2D standard IR perturbed by a reflected flux is corrected to recover the full 2D surface temperature close to the real surface temperature.

1. Introduction
In the existing tokamaks, such as JET, Tore Supra ..., monitoring heat flux deposition on plasma facing components (PFC) is a critical issue for the safety of the devices. Indeed, a reliable surface temperature measurement of PFCs is crucial for a real time control of the PFC safety and also for physics studies of plasma wall interaction. So far, most of the tokamaks were equipped with carbon PFCs with a known and high emissivity (ε >0.8). In these conditions, surface temperatures measured by standard IR camera [1] are reliable since the contribution of the reflected flux in the total flux collected by standard infrared system can be neglected. However in future fusion devices such as WEST project or ITER [2], carbon will be replaced by metallic materials like Tungsten and Beryllium [3]. The PFC surface temperature knowledge is of major importance since the Beryllium melting temperature is about 1250°C and this material is exposed to flux from 0.5 to 5 MW/m² whereas the Tungsten of divertor could receive flux up to 20 MW/m². Since these materials have a low emissivity (0.1-0.4), the contribution of the reflected flux in the total collected flux will not be negligible and this leads to difficulties in signal analysis to determine the true PFC surface temperature.

In this paper, active pyrometry method is proposed to measure the surface temperature T₀ independently of the emissivity and the reflected fluxes [4]. A local increase of the target surface temperature ΔT(t) is introduced by a pulsed laser. This variation induces a temporal increase of the
emitted flux only. The resulting increase of the photon flux from the heated surface does not depend on the reflected fluxes but only on the surface temperature, $T_0$, and the $\Delta T(t)$ introduced. The dynamic part of the signal measured by an IR detector reveals three unknowns: $T_0$, the material emissivity and $\Delta T(t)$. The ratio of two simultaneous measurements at two different wavelengths leads to the temperature variation elimination whilst an emissivity ratio appears. The latter can be calibrated or assumed to be known as for the classical bicolor pyrometry. Finally, the ratio of the two measurements depends only on the surface temperature $T_0$.

The first part of this paper presents the theoretical approach for active pyrometry, and the experimental setup is detailed in the second section. Experimental results and their analysis are reported and discussed in the third section and the last section shows the IR camera correction applied to perform a 2D surface temperature measurement.

2. Theoretical approach

The radiance $L^\lambda_{\beta}$ collected by an IR detector at a wavelength $\lambda$ viewing a surface at temperature $T_0$, following the Kirchoff law with a diffuse reflectivity, in an environment assumed to be a blackbody at a temperature $T_{env}$ can be written:

$$L^\lambda_{\beta}(T) = \varepsilon_{\beta} L^\lambda_{\beta}(T_0) + (1 - \varepsilon_{\beta}') L^\lambda_{\beta}(T_{env})$$  \hspace{1cm} (1)

where $L^\lambda_{\beta}(T)$ is the blackbody radiance at the temperature $T$ and $\varepsilon_{\beta}'$ the spectral directional emissivity.

From this equation it is worth noting that when the emissivity drops, there is not only the issue of its absolute value which occurs but also an additional unknown which is the reflected flux. For a diffuse surface (Lambertian) this additional flux is reflected in all directions and it can be of a modest contribution in the collected flux through a reduced solid angle of collection (classical IR camera). However for specular surface this reflected flux can become dominant as soon as the emissivity becomes low (less than 0.5) and/or when $T_{env}$ is in the range or larger than $T_0$.

The electrical signal delivered by a detector cannot be used for separating the emitted flux and reflected flux. Assuming (standard IR pyrometry) that all the collected flux is due to the emission from the sample and the reflected flux due to the temperature environment assumed to be negligible, the effect of the reflected flux is enhanced as the emissivity drops to low values.

For high emissivity (>0.8), the reflected flux can be neglected whereas reflected flux has to be considered for low emissivity. As an example, for a surface at 400 °C in an environment at 600 °C, the measured apparent blackbody temperature is about 550 °C with an emissivity of 0.8 whereas the temperature could be 1000 °C with an emissivity of 0.1.

The active pyrometry is based on a local temperature increase $\Delta T(t)$ introduced by a laser pulse, therefore the previous relation, can be written at the second order, with $\Delta T(t) \ll T_0$:

$$L^\lambda_{\beta}(T_0) = \varepsilon_{\beta} \left[ L^\lambda_{\beta}(T_0) + \Delta T(t) \frac{\partial L^\lambda_{\beta}}{\partial T}(T_0) + \frac{(\Delta T(t))^{2}}{2} \frac{\partial^2 L^\lambda_{\beta}}{\partial T^2}(T_0) \right]$$

$$+ (1 - \varepsilon_{\beta}) \left[ L^\lambda_{\beta}(T_{env}) - L^\lambda_{\beta}(T_0) \right] \frac{\partial L^\lambda_{\beta}}{\partial T} \left[ (\Delta T(t))^{2} \frac{\partial^2 L^\lambda_{\beta}}{\partial T^2}(T_0) \right]$$  \hspace{1cm} (2)

For a temperature increase negligible compared to $T_0$, $(\Delta T(t)$ in the range of $\sim 10^\circ C$, the emissivity variation can be ignored, besides the reflected flux is taken to be constant, so the expression becomes:

$$L^\lambda_{\beta}(T_0) = \varepsilon_{\beta} \left[ L^\lambda_{\beta}(T_0) + \Delta T(t) \frac{\partial L^\lambda_{\beta}}{\partial T}(T_0) + \frac{(\Delta T(t))^{2}}{2} \frac{\partial^2 L^\lambda_{\beta}}{\partial T^2}(T_0) \right] + (1 - \varepsilon_{\beta}) \left[ L^\lambda_{\beta}(T_{env}) \right]$$  \hspace{1cm} (3)
The temporal signal delivered by a detector viewing a heated surface $\Delta S$ through a solid angle $\Delta \Omega$ developed at second order can then be written in the form:

$$S_i = D_i \epsilon_i \Delta \Omega \Delta \lambda \left[ \frac{\partial L_2}{\partial \lambda} (T_0) \int_{\Delta S} \Delta \lambda \Delta T \, dS + \frac{\partial^2 L_2}{\partial T^2} (T_0) \int_{\Delta S} \frac{\Delta T^2}{2} \, dS \right]$$

(4)

where $D_i$ is the detector responsivity, and $\tau_i$ the filter transmittance over the bandwidth $\Delta \lambda$.

There are three unknowns in this expression: $T_0$, $\epsilon / \lambda$ and $\Delta T$. The signal/noise ratio allowing a clear separation of the first and second order behavior of the photothermal signal as a function of $\Delta T$ is in the range of 10%. In these conditions for the shortest detection wavelength, the signal ratio increases by 3%. Therefore the second order part is considered negligible compared to the first order part when $\Delta T$ verifies:

$$\Delta T \leq \frac{1}{5} \frac{\partial L_2}{\partial T^2} (T_0)$$

(5)

The choice of the detection wavelength has consequences on the maximum surface temperature variation induced by the laser in order to satisfy the above condition for $\Delta T$ and remains in the linear part of the signal response as a function of $\Delta T$.

On figure 1, the maximum temperature increase, $\Delta T$, is plotted as a function of the surface temperature of the target sample. It can be seen that the $\Delta T$ allowed for remaining in the linear part of the photothermal response increases with the sample temperature.

Since the surface temperature increase induced by the laser pulse is difficult to evaluate with accuracy (waist, power and pulse duration, material properties like thermal conductivity, absorptivity at the laser wavelength, heat deposition profile, roughness of the material...), it is necessary to eliminate $\Delta T$. Therefore, with two detectors working at $\lambda_1$ and $\lambda_2$, the ratio of the two signals leads to the elimination of $\Delta T$ and also of the geometrical term $\Delta \Omega$.

Finally, in the case of the Wien approximation, the surface temperature can be expressed:

$$T_0 = \frac{C_i \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right)}{\ln \left[ \frac{S_{\lambda_1} \epsilon_{\lambda_1} \tau_{\lambda_1} D_{\lambda_1} \Delta \lambda_1}{S_{\lambda_2} \epsilon_{\lambda_2} \tau_{\lambda_2} D_{\lambda_2} \Delta \lambda_2} \right]}$$

(6)

where $S_{\lambda_1}/S_{\lambda_2}$ is signal ratio from the two detectors, $\Delta \lambda$ is the bandwidth of the filters used for the detection and $\tau_i$ is the transmission of the acquisition chain at the detection wavelength.

**Figure 1.** Acceptable temperature increase vs sample temperature for $\lambda_1=2.35 \mu m$ and $\lambda_2=3.42 \mu m$.

**Figure 2.** Measured temperature vs sample temperature for signal considered at $1^{st}$ and $2^{nd}$ order.
To obtain the true temperature, the emissivities ratio \( \epsilon_2/\epsilon_1 \) has also to be determined. For low temperatures, the weight of this ratio on the accuracy resulting \( T_0 \) increases as the signal/noise ratio drops. However for high temperatures (larger than 450-500°C in the reported experiments), the ratio can be considered constant. Like bicolour pyrometry, the two emissivities can be taken to be equal. Results presented in section 4 follow this assumption. In order to assess the effect of temperature increase over the signal, we plot the measured temperature considering detector signal at the first and second order, with calculated reliable temperature increase (see figure 2). For the temperature range (400 °C-600 °C), the difference between temperature calculated with signal at first order and second order is about 3%. For high temperatures, the gap between measured temperature and the sample temperature results from the Wien approximation limit. For our experiment the two allow to satisfy the Wien approximation.

3. Experimental Setup

The experimental setup presented on figure 3 is composed of a sample heated on the back side by an IR lamp. The sample is equipped with two Chromel-Alumel thermocouples to monitor its temperature. Thermocouples are settled at 5 mm of depth in each sample lateral side (in front view of the sample, TC1 is on the right side and TC2 on the left side) at 2 mm from monitored the surface. A YAG laser (1064 nm) beam of 8 mm is used to create a photothermal effect on the sample. Its pulse duration is 160 μs and its energy is about 650 mJ. The detection system is composed of ZnS lens collecting the flux from a 12 mm spot on the sample and focusing it on the two InSb detectors (Judson J10D, preamplifier with bandwidth from DC to 750 kHz) cooled by a “Stirling” engine. A beam splitter (transmittivity of 50%), divides the flux to each detector. The detector perpendicular to the optical axe is equipped with an interference filter of \( \lambda_1=2.35 \mu m \) (bandwidth of 335 nm). The detector in direct aim is equipped with an interference filter of \( \lambda_2=3.42 \mu m \) (bandwidth of 128.7 nm).

Electrical signals from detectors are preamplified and are acquired by a digital “Wavesurfer” scope. To simulate a parasitic flux effect over the signal, a ZnS lens focuses the flux from a hot furnace (~800 °C) onto the sample. An IR camera (Cedip JADE) views the sample for surface temperature monitoring and for evaluating the emissivity effect on the collected flux by the camera.

4. Experimental results and analysis

1. Parasitic flux effects

The first experiment step has been a validation of the experimental set up and particularly an evaluation of the contribution of the parasitic flux on the signal delivered by the detector. A medium emissivity (about 0.75) carbon sample is heated at 428 °C and the parasitic source temperature is heated up to 812 °C. The parasitic source introduces an increase of the signal amplitude of 17% (see figure 4). With the tungsten sample at 430 °C (emissivity~0.6) an increase of 23% of the signal is observed.
2. Measurement process
Since, the status of the viewed surface is not known and can change over time and also due to the effects of hot spots and possibly burning dust, a series of 20 pulses is performed. An average of these signals is carried out and an example is shown on figure 5. This variation represents the temperature variation created by the laser pulse. For long observing time compared to pulse duration, the time evolution of temperature variation can be written [5]:

\[ \Delta T(t) = \frac{\alpha_{\lambda_0} P t_e}{\sqrt{\pi t e S}} \]  

(7)

where \( \alpha_{\lambda_0} \) is the material absorptivity at laser wavelength \( \lambda_0 \), \( P t_e \) the pulse laser energy, \( e \) the material effusivity and \( S \) the surface heated by laser beam.

As soon as the \( \Delta T \) behaves as \( t^{-1/2} \), the ratio of the signals at \( \lambda_1 \) and \( \lambda_2 \) can be performed without any assumption on the optical properties of the viewed area at the laser wavelength and particularly at the two detection wavelengths. This signal ratio can be performed at a given time ("one point") or integrated over a short duration in order to increase the signal accuracy. Therefore, for the reported experiments, the integral signal ratio is carried out over the period when both of signals behave as \( t^{-1/2} \) [6].

3. Carbon sample
The carbon sample with two emissivities is heated with the IR lamp at three different temperatures 400, 500 and 600 °C. For the medium emissivity part, estimated to 0.75, for each temperature, four series of 20 pulses are carried out. The ratio of signal integral leads to the temperature (see Table 1).

| Target Temperature | 400°C | | Target Temperature | 500°C | | Target Temperature | 600°C |
|-------------------|-------|---|-------------------|-------|---|-------------------|-------|---|
| Serial Number     | TC1   | TC2 | Temperature       | Serial Number | TC1 | TC2 | Temperature       | Serial Number | TC1 | TC2 | Temperature       |
| 1                  | 413   | 422 | 503 ± 37         | 1                  | 499 | 512 | 584 ± 45         | 1                  | 583 | 601 | 639 ± 51         |
| 2                  | 413   | 422 | 520 ± 38         | 2                  | 503 | 517 | 594 ± 46         | 2                  | 583 | 602 | 630 ± 50         |
| 3                  | 414   | 423 | 517 ± 38         | 3                  | 500 | 512 | 583 ± 44         | 3                  | 583 | 602 | 629 ± 50         |
| 4                  | 414   | 423 | 518 ± 38         | 4                  | 501 | 513 | 593 ± 46         | 4                  | 583 | 602 | 610 ± 48         |

| Table 1. Experimental temperature measurements for low emissivity (ε=0.75) part of carbon sample. |
The temperature calculation follows the hypothesis of emissivity ratio equal to one. The error over the measured temperature is calculated assuming an emissivity ratio error about 10%. These results show that an emissivity ratio of 1.1 gives temperatures close to the temperature measured by thermocouples. Assuming that the temperature delivered by the thermocouple is the reference, a very good reproducibility of the experiments is obtained. The measured temperatures become close to theoretical temperature when the sample temperature increases.

The high emissivity which is estimated to be equal to 0.85 is tested at same temperatures as the medium emissivity part. In this case, only two series of experiment pulses are carried out (see Table 2). Previous hypothesis are still considered.

| Target Temperature | 400°C | Target Temperature | 500°C | Target Temperature | 600°C |
|--------------------|-------|--------------------|-------|--------------------|-------|
| Serial Number      | TC1   | TC2    | Temperature     | Serial Number | TC1   | TC2    | Temperature     | Serial Number | TC1   | TC2    | Temperature     |
| 1                   | 438   | 421    | 450 ± 32        | 1           | 521   | 498    | 573 ± 44        | 1           | 642   | 606    | 599 ± 48        |
| 2                   | 438   | 421    | 448 ± 32        | 2           | 521   | 498    | 563 ± 43        | 2           | 642   | 606    | 639 ± 52        |

Table 2. Experimental temperature measurements for high emissivity (\(\varepsilon\approx0.85\)) part of carbon sample.

For this experiment, the calculated temperature appears closer to thermocouple temperature than previous experiment with low emissivity part, however an emissivity ratio of 1.1 gives better results compared to temperature delivered by thermocouple. Besides, results obtained for 400 °C and 500 °C confirm an efficient reproducibility. For the carbon sample active pyrometry allows getting a temperature valuation without considering parasitic flux effects.

4. Tungsten sample

The next experiment concerns a copper sample with a thin tungsten layer, with an estimated emissivity of 0.6. The experiments consist again in two series of 20 measurements with a temperature of 400 °C (see Table 3). For each series, the temperature is determined with and without parasitic flux created by a furnace with a temperature of 800 °C. The assumption of emissivities ratio equal to one is still considered for the tungsten sample. The results show that the temperature calculated by the active pyrometry method is higher than the temperature measured by thermocouple. In order to find a temperature close to the thermocouple temperature, the emissivity ratio has to be equal to 1.3, it could be the consequence of sample oxidation at such temperature. However, we can notice that the temperature obtained does not depend on the parasitic flux. Indeed, the maximum determined temperature with active pyrometry is only 3 °C above an average temperature of 556 °C with or without parasitic flux, demonstrating that active pyrometry allows surface temperature measurements independently of reflected flux. These series of result demonstrate that the experiment is reproducible. Indeed, 12 series of 20 averaged pulses were performed for the low emissivity part of the carbon sample and 6 series for the high emissivity part. For the tungsten sample the results show that active pyrometry is very efficient in high reflective environment.

| Target Temperature | 400°C |
|--------------------|-------|
| Serial Number      | TC1   | TC2    | Temperature     |
| 1                   | 448   | 445    | 556 ± 42        |
| 1*                  | 448   | 444    | 555 ± 41        |
| 2                   | 447   | 444    | 559 ± 42        |
| 2*                  | 448   | 444    | 555 ± 41        |

Table 3. Experimental temperature measurements for tungsten sample with(*) and without parasitic flux.
The calculated temperature by this method is quite higher than the true sample temperature (see figure 6). Considering a variation of 0.05 on the emissivity at one of the two studied wavelengths, if the original emissivity is about 0.2, the emissivities ratio becomes 1.33 instead of 1, whereas for an original emissivity of 0.85 the ratio becomes 1.06. On figure 6, we can notice that the carbon and tungsten samples get the same behaviour for low emissivity, the high temperature evolvement could be the consequence of sample oxidation.

5. Infrared system correction

1. Image evolvements

For this experiment, the worst case has been assessed, with a very specular aluminium sample (observed face polished) which emissivity is estimated at 0.16. The target gets a temperature of 366 °C and the integration time of camera is increased to 1050 µs to collect more flux. The image shows that the signal from camera increases by 50% with the parasitic flux (see figure 7).

| Thermocouple temperature | 366°C |
|----------------------------|-------|
| Estimated emissivity       | 0.16  |
| DL (without parasite)      | 6265  |
| DL (with parasite)         | 9650  |
| Temperature (without parasitic flux) | 362°C |
| Temperature (with parasitic flux) | 721°C |

Table 4. Table of measure results for aluminium sample assuming environment temperature at 20 °C.

On this image it can be confirmed that the aluminium is a true specular surface. Therefore, the orientation of the sample is adjusted to enable the camera [3-5 µm, 50 Hz, 320x240] to receive the maximal flux from the target. Indeed, the digital level (DL) measured increases from 6265 DL to 9650 DL with the parasitic flux (see Table 4). Assuming that the aluminium emissivity is equal to 0.16, the evaluated temperature rises from 362 °C to 721 °C. This result demonstrates that a high reflective environment could highly modify a temperature measured by an IR camera if reflected flux is not taken into account. At lower environment temperature, the reflected flux on the sample is lower for diffuse surface (and constant for any viewing direction) whereas for specular surface the reflected flux part can increase significantly when the incident angle is equal to the viewing angle (reflected angle). At higher temperature the contribution of the reflected flux collected by the camera is much higher and less dependant of the surface properties. Besides, an error on emissivity could distort a measure because an error of 0.1 on low emissivity could represent an error of 50% whereas such error represents less than 15% of error for a high emissivity material.
2. Image corrections
In this section, it is shown how the determination of the surface temperature measurement of one small area (size of the laser spot) through active pyrometry can contribute to the correction of the 2D view obtained with a classical IR camera. Considering that the true surface temperature \( T_0 \) is measured by active pyrometry and \( L' \) is measured by camera, there are two unknowns in equation (1) : \( \varepsilon \) and \( L(T_{env}) \). In the worst case, if the emissivity of the target is not known at all, infinity of solution couple result. However, and as usual for classical IR measurement, the surface emissivity has to be mentioned in the IR camera.

Figure 8. Original IR image (a) and corrected IR image (b) from Aluminium sample (emissivity about 0.16).

In these conditions, knowing the temperature \( T_0 \) of one pixel and assuming the emissivity range of the material viewed, it is possible to determine the environment temperature of this pixel. Therefore, assuming the same emissivity for entire sample and the same environment temperature, we calculate the true temperature of each pixel which of the 2D view from the IR camera (see figure 8). These assumptions could lead to aberrant temperature for some pixel due to emissivity change or different parasitic flux but this method provides a better evaluation of the sample temperature.

Conclusion
In this paper, it has been demonstrated that using active pyrometry, surface temperature can be measured independently of the reflected flux in a high reflective environment for 400-600 °C temperature range. It has been shown that a parasitic flux does not modify the temperature value determined by this method. It appeared that the main parameter in this calculation is the emissivity ratio which could modify the result significantly. However, from a reference known temperature, this ratio can be evaluated leading to a better accuracy of this method and allows a correction on 2D viewing. Also, from the local surface temperature measurement delivered by active pyrometry within duration less than 1 ms, it has been shown that a global correction can be used on standard IR surface temperature monitoring. Extending the local measurement to many points of the 2D view would therefore allow for a correction of the 2D picture with the pulsed pyrometry method. If the emissivity is unknown, it is necessary to get a range of emissivity value.

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