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ABSTRACT
InfraRed (IR) thermography systems are mandatory to ensure safe plasma operation in fusion devices. Developed systems so far consist in monitoring and controlling in real time the power load on the Plasma Facing Components (PFCs) through their surface temperature measurements. However IR measurements are made much more complicated in metallic environment because of the spurious contributions of the reflected fluxes. This paper presents a full predictive photonic simulation able to assess accurately the surface temperature measurement with classical IR thermography from a given plasma scenario and by taking into account the optical properties of PFCs materials. This simulation has been carried out the ITER-like wide angle infrared camera view of JET in comparing with experimental data. The consequences and the effects of the low emissivity and the Bidirectional Reflectivity Distribution Function (BRDF) used in the model for the metallic PFCs on the contribution of the reflected flux in the analysis are discussed.

1. INTRODUCTION

In nuclear fusion experiments, infrared (IR) thermography systems are routinely used to minimize operational risks in Tokamaks. Developed systems so far consist in monitoring and controlling in real time the power load on the Plasma Facing Components (PFCs) through the surface temperature measurements. However, with metallic components as in JET and ITER, the evaluation of the surface temperature of PFCs is made much more complicated. Indeed, due to their low and variable emissivity (ranging from 0.1 to 0.4), the total IR flux collected by the imaging systems includes both an emissive part coming directly from the target surface and a so-called reflective part coming from the hot surrounding areas and reflected by the observed targets. A predictive photonic simulation has been first performed to assess the contribution of the reflected flux in the collected photon flux of the Upper Port VIS/IR System of ITER [1]. It is shown that due to the low emissivity, the contribution of the reflected flux can lead to overestimation of surface temperature of up to 20% for the hottest targets and up to 90% for the coldest surfaces. In both cases, it is demonstrated that in a highly reflective environment, these overestimations can lead to false alarm and limitations on the plasma scenario operations and thus developments towards high performances.

In this paper, the photonic simulation has been improved by using as input the predicted power deposition on PFCs computed by an additional code developed also at CEA (PFCFLUX3). Moreover, the new configuration of JET PFCs, with its ITER-like wall (tungsten divertor and beryllium first wall), in addition to its ITER-like wide angle IR camera [2], is a good opportunity to go one step further in the understanding of IR signals in a fully reflective environment by comparing the simulated and the experimental data.

2. MODELING METHOD

The objective of this "end-to-end" simulation is to predict accurately the IR thermography measurements from a given a plasma scenario. The present approach is based on a 3-D CAD

(Computed Aided Design) of PFCs, with a simplified tessellation representation, used as input both in the heat flux computations and in the photonic computations. The simulation process described in Fig.1 is composed of three main stages. The first stage consists in simulating the 3D distribution of the heat flux on PFCs. For a given magnetic equilibrium reconstruction and a given physic model of the plasma power (plasma decay length, total power in the SOL), the particle deposition power is first computed by including the shadowing effect through PFCFLUX code3. The contribution of the plasma radiation power is also taken into account and added separately. The second stage is to evaluate the PFCs' surface temperature Tsurf resulting from the deposited heat flux Φ. In a first approximation, a linear semi infinite model described in (1) is used.

$$T_{surf} = T_O + \frac{\Delta\varphi\sqrt{at}}{\lambda} \tag{1}$$

with T_O is the initial surface temperature, ΔΦ the deposited heat flux assumed to be constant during the time t, λ the thermal conductivity in $W.m^{-1}.K^{-1}$, a the thermal diffusivity in $m^2.s^{-1}$.

In a third stage, the 3-D temperature field is used as an input in the simulation of the IR thermography. The photonic simulation code is based on a Monte Carlo ray tracing (SPEOS®CAA V5 Based) able to propagate the ray through the complex geometry of our lighting scene and taking into account the multiple inter-reflections of the ray in the vacuum vessel. The interaction between a photon and the surface is included in the model through the properties of a material knowing its Bidirectional Reflectance Distribution Function (BRDF). Finally, the measured surface temperature is evaluated from the resulting simulated radiance maps of the IR thermography and compared with the actual surface temperature. Finally, the temperature measurement error is qualified.

3. RESULTS

3.1. SIMULATION SETTINGS

We have been interested in reproducing the JET ITER-like wide angle infrared thermography view in the conditions of a steady-state plasma scenario based on JET Pulse No: 82631 with 11MW of total power and without auxiliary RF heating. The first heat flux computations have been applied on the PFCs in the field-of-view of the ITER-like wide angle camera as shown in the simplified 3D model in Fig.2. The simplification of the rest of components (dump plate, saddle coils) is on going work. The 3D distribution of the deposition power is evaluated with the PFCFLUX code using as input the EFIT magnetic equilibrium reconstruction in Fig.3. The plasma power decay length is different for the chamber and for the divertor to take into account the flux expansion. It is worth noting that the tile 5 of the divertor is composed itself of four independent stacks (A,B,C and D) for which the deposited energy is not the same. The contribution of the plasma radiation is assumed to be low and uniform over the whole chamber except for the tile 7 of the divertor where the plasma radiation power has been observed higher by visible cameras. The resulting 3D temperature field is characterized by a mean temperature on the vessel lower than 200°C and a peak temperature of

530°C on the divertor tile 5D. The column 2 of the table 1 summarizes the mean surface temperatures used as input in the simulation photonic for a few main PFCs.

The optical properties of materials are defined with two physical models: a radiative model that describes how the heated surface emits in the 3D space and a reflective model that describes how an incident photon is reflected on the metallic surface (BRDF). The spectral hemispherical emissivity of JET components has been defined in the simulation as 0.2 for Inconel and Tungsten (W) (bulk and coating) and 0.15 for Beryllium (Be). The models of emissivity and reflectivity are based on experimental measurements. For the non-lambertian emitters (Be, W), the sources intensity diagram has been modeled with a cosinus n-power model as cos0.6(θ) for roughly matching with experimental data of [4]. Their BRDF is also modeled with a high specular component (98%) following a Gaussian shape with a full-width half maximum of 12 degree in order to be adjusted to the experimental data in [5].

In order to reproduce the JET-ITER like wide angle IR view, the parameters of the optical model are a field-of-view of 70°, a detector of 512×640 pixels of 25Mm covering the wavelength range [3-5Mm] and a filter with a narrow band-pass of 40nm centered on 3990nm.

3.2. SIMULATION VERSUS EXPERIMENTAL IR IMAGE

As a first qualitative comparison, Fig.4 shows the experimental IR image in digital levels of Pulse No: 82631 and the simulated IR image giving the total radiance flux collected by the IL wide angle camera. The remarkable features in the divertor area are well-reproduced with the simulation: the particles deposition power causes regular local heat patterns on the stack D of the tile 5 whereas the plasma radiation power causes a rise in the surface temperature of the tile 7.

3.3. SIMULATION ANALYSIS FOR THE SURFACE TEMPERATURE MEASUREMENTS

Two kinds of images are simulated: (1) the “reflectionfree” images including only the thermal emission of targets and (2) the “realistic” images reproducing the infrared camera view also taking into account the contribution of the reflected flux. The “reflection-free” simulated IR images are used for evaluating the surface temperatures of the PFCs (column 2 of Table 1) and for comparison with the surface temperatures obtained through the wide angle IR camera (columns 3 and 4 of Table 1). The measured surface temperatures of the PFCs are deduced from the simulated radiance maps using preliminary calibration tables. Two cases have been considered: 1) the PFCs’ emissivity is unknown and assumed to be equal to one as a blackbody (BB) 2) the emissivity of materials is supposed to be well known and is used to weigh the total radiance picked by the camera. The calibration tables establish then a correspondence between the surface temperature and the total radiance of a grey body resulting of the integration of Planck’s function over the filter spectral range, and this for a given emissivity, if it is known.

First, it is worth noting that the surface temperature measurement is always under-estimated with blackbody assumption. Indeed, without correcting the low emissivity of PFCs and in a case of a low contribution of the reflected flux, the measured photon flux directly used in the inverse Planck's function is almost always under-evaluated, which leads to measure a surface temperature up to half as much of the true temperature. With the known emissivity assumption, the surface temperature is obtained with an accuracy of about 10% for the tiles 1, 3 and 7 with a mean temperature about of 235-265°C. For the other colder targets (<150°C), the surface temperature is slightly over-estimated with a maximum error value of 40%. These surface temperature errors seem to be smaller than the ones predicted for the ITER wide angle imaging system in [1]. Indeed, for this plasma scenario at low regime and without transient events (ELMs), the part of the reflected part picked up by the JET wide angle camera is evaluated lower than 50% for almost all the PFCs. This is mostly explained by the low plasma power used as input of the JET simulation with a maximum temperature peak of 530°C. Moreover, the reflection contribution is minimized because of the geometry of the JET divertor coupled to the 3D distribution of the deposition power, focused very locally on the stack D of the tile 5, as shown in Fig.3.

CONCLUSION

A full predictive photonic simulation of the JET ITER-like wide angle view has been achieved from a given a plasma scenario. This simulation allows predicting accurately the thermography measurements from a complex 3D temperature field and by taking into account the optical properties of the PFCs.

As a first qualitative comparison, the parameters used as input of the simulation are based on a JET experimental (steadystate) plasma scenario. A good agreement with IR images has been found proving the impact of the particles deposition power and of the plasma radiation power in the divertor. The simulation has shown that, because of the JET divertor configuration and for low plasma power (10MW, i.e 530°C of maximum temperature), the reflection contribution is not dominant and it is possible to get a surface temperature for the colder targets with a maximum error of 40% if the materials' emissivity is known and without compensating the reflected flux.

To go further, this first full simulation has shown that additional efforts (theoretical and experimental) will be necessary to improve the knowledge and the understanding of some key physical parameters used as input in the simulation: especially the plasma power decay length variation along the magnetic field and the distribution of the plasma power radiation. This has also shown the need to investigate a non linear modeling for the surface temperature evaluation of peaked heat flux loads. At last, we need to investigate the variation of the materials optical properties (emissivity and reflectivity models) during a campaign and the consequences on the reflection contribution.

Finally this simulation could be extended to other plasma scenario with high plasma power (30MW) with auxiliary heating and particularly during transient events. The simulation could be then an interesting help to get reliable surface temperature in such a plasma scenario by predicting accurately the spurious contributions of the reflected fluxes in the total signal collected by the camera.

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PFCs	Input T	Eq. BB T (ε=1)	T with emissivity correction ($\varepsilon_{W/Be}$=0.2/0.15)	Reflected flux
JET ILW				
Inner Guard Limiter [Be]	190°C	110°C	215°C	34%
Inner cladding	170°C	110°C	200°C	34%
Outer Poloidal Limiter [Be]	190°C	115°C	225°C	51%
Antennas Protection [Be]	160°C	100°C	200°C	50%
DIVERTOR				
Tile 1	235°C	150°C	250°C	16%
Tile 3	270°C	165°C	280°C	9%
Tile 4	150°C	95°C	175°C	33%
Tile 5A/B	**110°C**	**90°C**	**170°C**	**70%**
Tile 5D	**515°C**	**300°C**	**495°C**	**0.5 %**
Tile 7	265°C	165°C	275°C	15%
Tile 8	160°C	110°C	200°C	45%
Tile 9	150°C	110°C	200°C	55%

TABLE 1:Predicted mean surface temperature measurement T and reflection contribution.

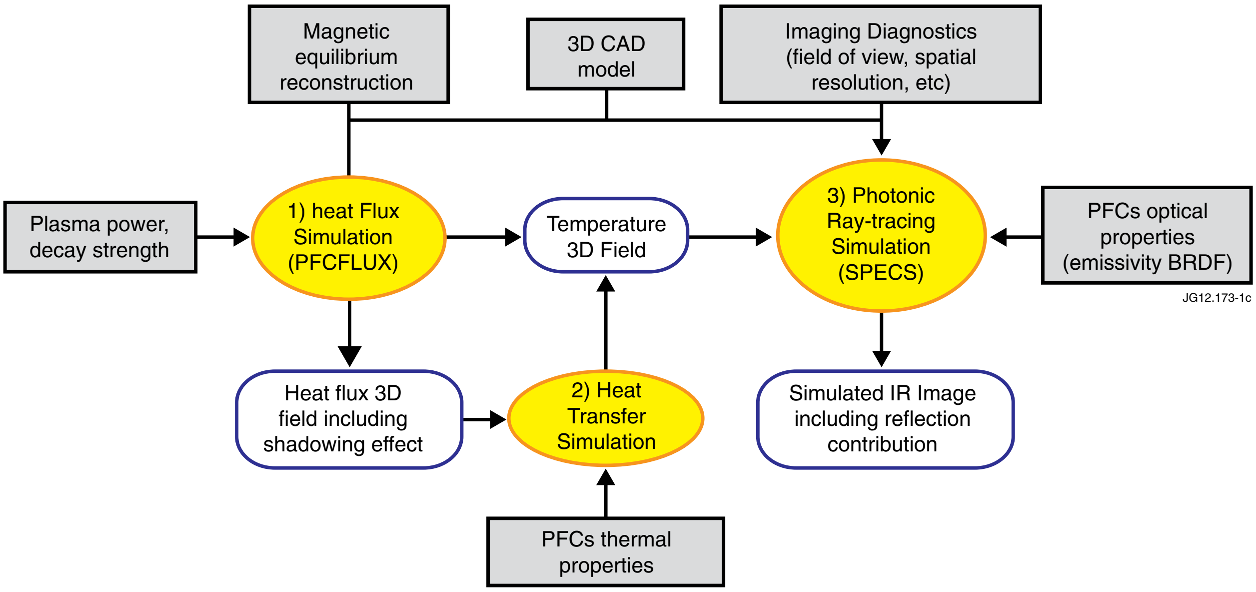

Figure 1: An end-to-end simulation: from a given plasma scenario to infrared temperature image.

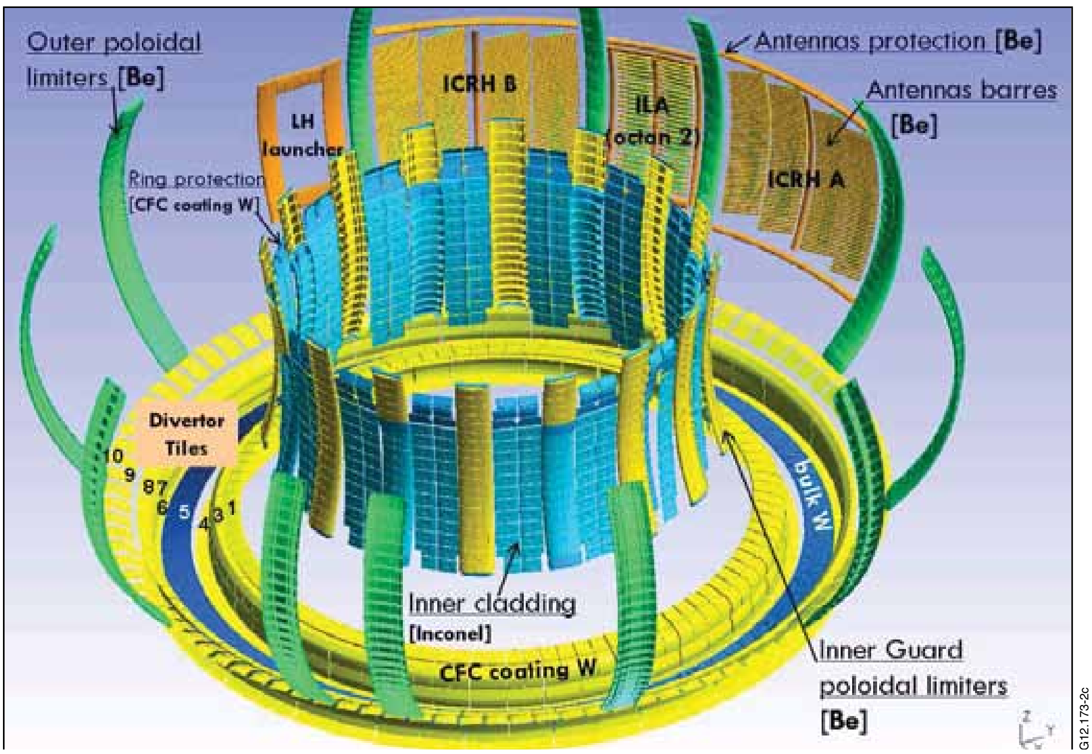

Figure 2: JET PFCs 3D mesh.

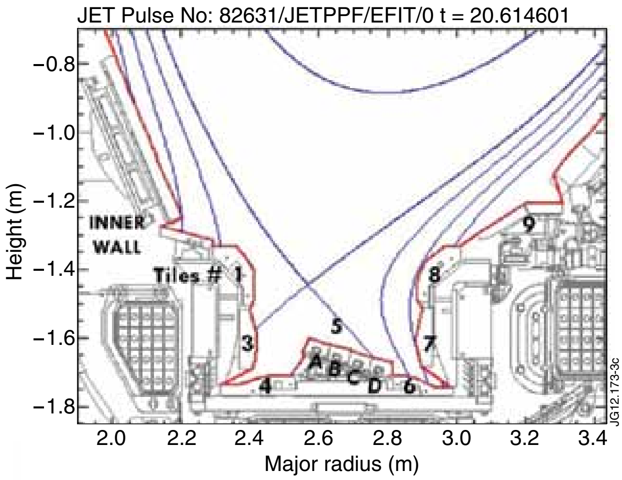

Figure 3:EFIT magnetic equilibrium reconstruction of JET Pulse No: 82631.

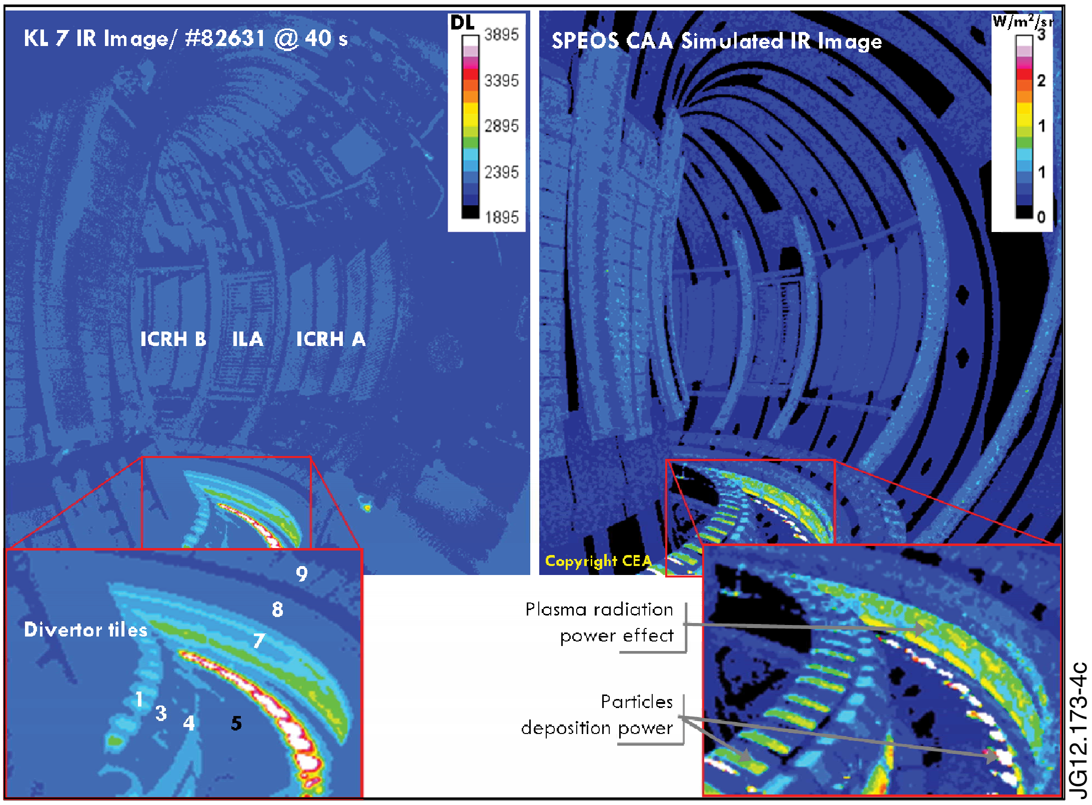

Figure 4: (Left) IR Image of the JET ITER-like wide angle thermography (digital level unit), (Right) IR image simulated with SPEOS CAA V5 based (radiometric unit).