Effect of wall light reflection in ITER diagnostics

Shin Kajita[1], Marie-Helene Aumeunier[2], Eiichi Yatsuka[3], Andrey Alekseev[4], Evgeny Andreenko[4], Alexander Kukushkin[4,5], Vladislav Neverov[4], Martin Kocan[6], Michele Bassan[6], Evgeny Veshchev[6], Maarten De Bock[6], Robin Barnsley[6], Andrei Kukushkin[4,5], Roger Reichle[6] and Michael Walsh[6]

[1]IMaSS, Nagoya University, Nagoya 464-8603, Japan
[2]CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[3]QST, Ibaraki 801-1, Japan
[4]NRC Kurchatov Institute, Kurchatov sq. 1, 123182 Moscow, Russia
[5]NRNU MEPhI, Kashirskoye sh. 31, 115409 Moscow, Russia
[6]ITER Organization, 13067 St. Paul Lez Durance Cedex, France

Corresponding Author: kajita.shin@nagoya-u.jp

Abstract:
Reflection of light on walls will form parasitic signal on various optical diagnostics and be a serious issue in ITER. In this study, we show recent progress in the assessment of the effects of the wall reflections in ITER based on the simulation results. Four different diagnostics in ITER were chosen for the simulation, i.e., visible spectroscopy, infrared thermography, Thomson scattering, and charge exchange recombination spectroscopy, using ray tracing simulation codes.

1 Introduction

Electromagnetic (EM) waves in wide wavelength range are used for various purposes in nuclear fusion devices, especially for plasma diagnostics. In ITER, the inner wall will be tungsten and beryllium, which have higher optical reflectance than carbon based materials. There is a concern that reflection of the EM waves from the wall perturbs the diagnostics that use emissions from plasmas including passive spectroscopy [1], active spectroscopy [2], laser aided spectroscopy, and infrared (IR) thermography [3].

For example, misinterpretation of the IR measurement could strongly hamper the ITER operations and the scenario development by excessive interruptions of the plasma shots or, on the contrary, by endangering the machine safety in the case of underestimation of the surface temperature. Background light reflection on the first wall would degrade signal to noise ratio of laser aided spectroscopy and active spectroscopy. It is of importance to investigate the influence of the reflection for all the diagnostics using light emissions and deal with them properly before starting the ITER operation.

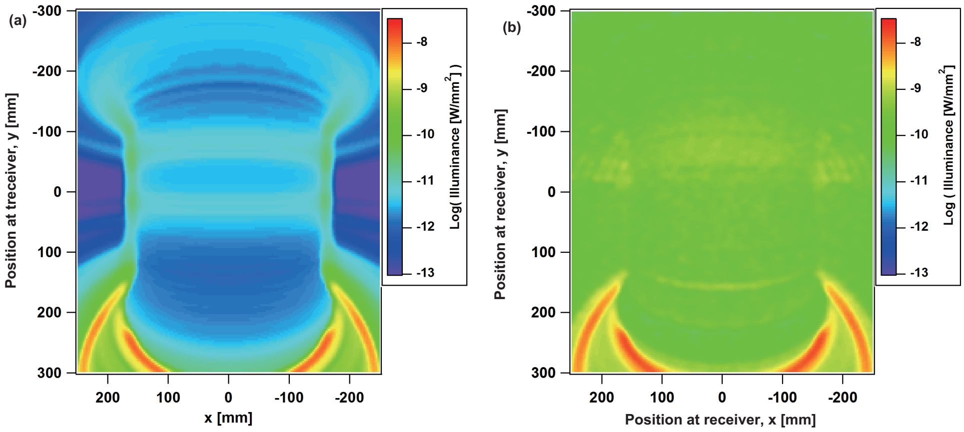

FIG. 1: Simulated illuminance profiles of H_α using LightTools (a) without and (b) with wall reflection.

In this study, we discuss the influence based on the ray tracing simulations. For visible spectroscopy, simulations are conducted using LightTools and Zemax, and practical mitigation methods of stray light are discussed. For IR measurement, a Monte Carlo ray tracing code (SPEOS ® CAA V5 [4]) was used to assess the impact of changing radiative properties of materials (emissivity and reflectivity) on surface temperature measurement. Moreover, the influence of emission from divertor in edge Thomson scattering diagnostics and the influence of the reflection of signal in charge exchange recombination spectroscopy (CXRS) are shown.

2 Visible passive spectroscopy

The line emission will be much stronger from the divertor region than from the scrape-off layer (SOL) in ITER. Figure 1(a) and (b) present the illuminance profiles of H_α without and with wall reflection, respectively, simulated using the commercially available ray tracing software LightTools [1]. The emission from the divertor region is so strong that the stray light dominates the illuminance profile when considering the wall reflections. It is shown that the stray light becomes significant even for visible spectroscopy measurement in divertor region if there are regions where original illuminance is much lower than the other parts.

The verification of results in Fig. 1 was made with benchmarking against simulations with “Zemax OpticStudio” software package. For this benchmarking a slightly simplified (smoothed) model of ITER first wall (FW) was used to ease Zemax code operation, while all other parameters were similar to those in [1]. The results are shown in Fig. 2. The higher noise in Zemax results seems to come from the more cumbersome accumulation of ray’s statistics (direct ray tracing from the source to detector in Zemax vs. inverse ray tracing in LightTools).

It is necessary to reduce the stray light level by using various methods. It was assessed

[1] that viewing dumps could reduce the stray light level by an order of magnitude. In addition, it is confirmed that the ray tracing method can mitigate the stray light and reconstruct the original emission profile by considering the reflections on walls [5]. The special measurement scheme [6] which uses the optical dump (OD) along with the line of sight (LoS) targeted at the neighboring area of the FW (so called bifurcated LoS scheme) can address this issue allowing to "subtract" the unknown spectral contribution of the DSL to the total signal on the LoS in the main chamber. The studies, using Zemax simulations of the DSL spectral intensity, of reflection properties of the ODs of various design and location on the FW and the comparative analysis of OD's efficiency were performed in [7], using the principles of the Hα synthetic diagnostics (SD) [8].

This SD estimates the errors of the solution of the inverse problems aimed at recovering the neutral hydrogen parameters in the SOL with allowance for (i) strong divertor stray light (DSL) on the observation chords in the main chamber, (ii) substantial deviation of the neutral atom velocity distribution function from a Maxwellian in the SOL, and (iii) the data from the direct observation of the divertor. The results of recovering the relative contributions of all three sources to the signal along a LoS in the main chamber, namely, the emissions from the plasma at different magnetic field strengths (e.g., on the LFS and HFS sections on the LoS) and the DSL, together with the isotope ratios in the SOL, were presented for the flat-top stage of $Q = 10$ inductive operation of ITER.

An application of this approach to the high-resolution spectroscopy data, without using ODs, of recent JET-ILW experiments enabled [9] to evaluate the spectrum of the DSL and the signal-to-background ratio for Balmer-alpha light emitted from the far SOL and divertor in JET-ILW. The results support the expectation of a strong impact of the DSL upon the ITER main chamber Hα (and Visible Light) spectroscopy diagnostics and the necessity of using the ODs in ITER.

The measurement scheme [6] is effective only if the OD, which suppresses the DSL, does not distort its normalized spectral intensity (the line shape). The accuracy of the separation of the spectral contribution of the SOL plasma emission near the high-field side of the FW to the total measured signal was estimated in [7] as a function of the fraction of the DSL in the total signal for various types of OD in the BM#4.

3 Infrared thermography

Infrared thermography is a key diagnostics for the machine protection, in particular for monitoring of the surface temperature of the Plasma Facing Components (PFCs). Nevertheless, wall light reflections and low and variable emissivity are very damaging for infrared measurement interpretation. This can hamper the experimental programs by triggering a fast termination of plasma, whilst the real hot spots might not be detected.

In order to anticipate the IR measurements in such a metallic environment, a photonic simulation was performed using a Monte Carlo ray tracing based on SPEOS ® CAA V5 able to propagate the light in a 3-D complex environment and integrating the photon-material interaction. Such a simulation must provide "realistic" synthetic data such as that obtained with the real instrument. The accurate prediction of the measurements will

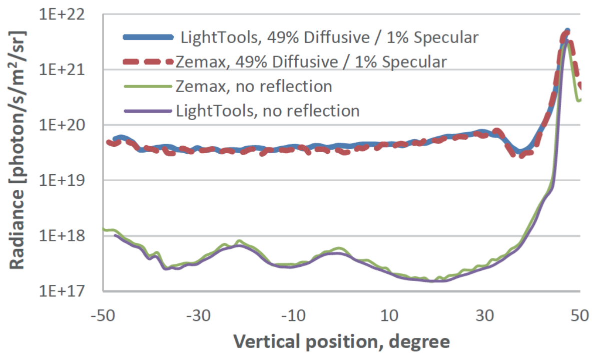

FIG. 2: Comparison of simulations of the H-alpha signal in ITER with the Zemax and LightTools for the conditions of Fig. 1 for a smoothed first wall model. The radiance at a vertical line on the detector in the EPP11 is shown. The cases of no reflection from the wall and 50% reflectivity (49% diffusive and 1% specular) are considered.

depend on the capability of modelling accurately all physical processes involved in the measurements, i.e.: (1) the plasma heat loads deposit and the resulting surface temperature of in-vessel components for different plasma scenario (2) the radiative properties of materials (reflectance and emission models) (3) the infrared wide-angle imaging system.

Figure 3 shows synthetic infrared images of ITER Wide Angle Viewing System (WAVS) of equatorial port plug and for the left tangential view. For the first simulations, a baseline burning plasma equilibrium has been considered. The surface heat loads have been computed with the plasma current $I_p = 15$ MA, edge safety factor $q_{95} = 3$ and the distance between the primary and the secondary separatrix $\Delta_{sep} = 9$ cm at the outboard midplane [10]. The surface emission is modelled using the n-cosines power model as a function of viewing angle with $n = 0.6$ and by considering uniform emissivity independent of the wavelength, of 0.2 and 0.15 respectively for W and Be materials. The reflected light behavior incident on metallic surface is modelled as a combination of Lambertian and specular component. The study aimed to evaluate the impact of reflections by considering extreme values of surface roughness: a diffuse model (100% Lambertian) and a highly specular model (2% Lambertian) following a Gaussian shape with a full-width half maximum of 12° [11]. Last, the optical model aimed to reproduce the camera view taking into account the camera geometrical parameters (field-of-view, image size in the focal plane and wavelength range) without including the possible optical effects on resolution (diffraction, pixel cross-talk).

Such a simulation allows evaluating the part of reflected flux ("parasitic light") within the total flux collected by camera and identifying the main contributor causing reflection features. The results of this study have shown that the contribution of reflections within IR image is larger than 75%. The contribution of reflected flux is slightly higher in a case of diffuse surface (>85%). But materials with specular surfaces cause remarkable light patterns in infrared images which may be confused with enhanced localized heat flux, potentially dangerous. Concerning the surface temperature measurements from infrared images, the measurement error due to reflections depends also on the precise knowledge of

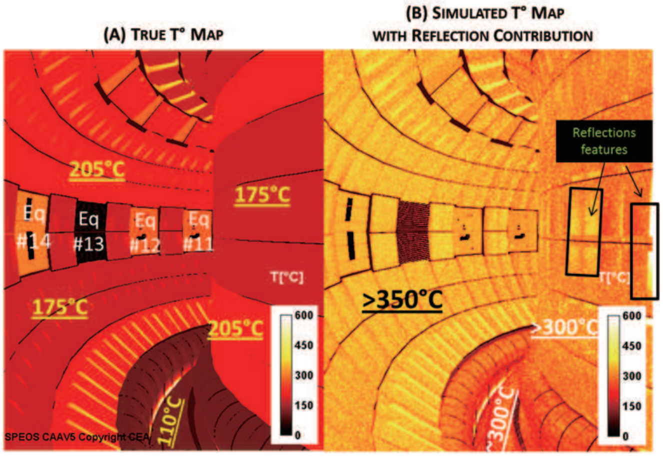

FIG. 3: *Infrared images as seen from the left tangential of WAVS in equatorial port #17, simulated for baseline burning plasma equilibrium: (A) True surface temperature map used a sinput of photonic simulation (B) Equivalent gray body temperature maps (ϵ known and corrected) in a case of specular materials.*

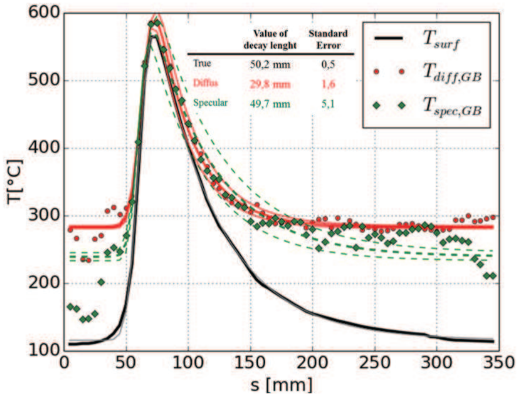

FIG. 4: *Predicted Gray Body (GB) Temperature profiles on inner vertical targets and their fits (solid and dashed lines) in the case of diffuse and specular materials. The exponential decay length is fitted from temperature profile.*

emissivity value ϵ. Without knowing the emissivity value, blackbody is assumed with $\epsilon = 1$, which leads to underestimate the temperature of the hottest region, higher than 275°C. For intermediate temperatures between 175-200°C, emissivity and reflection compensate each other and T_{surf} is estimated within 20% of accuracy. By correcting only emissivity, the surface temperature of colder target is always overestimated between 50-100% due to the reflections. This impacts especially the decay length measurement from peak target profile in diffuse case as shown in Fig. 4. The diffuse case is more unfavorable with an error of 40% on decay length but the fit in specular case is more difficult due to the non-uniformity of reflections contribution along the peak profile.

Such synthetic diagnostic provides an indispensable tool for helping the infrared image interpretation and getting more confident the surface temperature measurement. Now the next challenge is to strengthen the confidence in the method by consolidating the different physical models involved this end-to-end simulation, from the model of the thermal environment to the radiative properties of in-vessel components and instrumental model. To do that, WEST [12] upgrade and ASDEX-Upgrade will be used as the benchmark to compare and adjust simulated infrared images with experimental data. In parallel, laboratory experiments will be performed to characterize the materials features (emissivity and reflectivity) and this as a function of surface roughness to take into account the possible change during the machine life.

4 Laser Thomson scattering

Ray-tracing simulations on the level of background light were carried out to improve both performance and availability of diagnostics at the same time. Because of low electron density, effect of background light may be relatively significant for lines of sight for edge region. In edge Thomson scattering system (ETS) of ITER, there is the intermediate image of the laser beam between fourth and fifth mirrors (M4 and M5) [13]. As shown in Fig. 5(a), the collection optics of ETS was modelled precisely up to M4 and intensity of the background light was evaluated along the intermediate image. There is one-to-one relationship between the positions on the laser beam and the intermediate image. The aperture of the first wall was also modelled precisely to restrict direction of lights coming from plasma side.

Profiles of emissivity were referred from simulations on the carbon-free ITER divertor with Ne seeding evaluated from SOLPS4.3 modeling. Figure 5(b-d) shows expected intensity of background light on each line of sight within the wavelength of (b) 450-600 nm, (c) 700-800 nm and (d) 900-1000 nm, respectively. It was assumed that the peak thermal flux on the divertor target was 10 MW/m^2 and total radiated power was 43 MW. The solid lines and the dotted lines correspond that the first wall is assumed to be reflective and absorptive, respectively. Since the bremsstrahlung from core plasma directly comes to the detector along the lines of sight, total amount of bremsstrahlung from core plasma increases slightly, i.e. by factor of ~50%. On the other hand, line emission coming from divertor plasma increase drastically due to multiple reflections on the first wall. The accuracy of measurement was evaluated in the same manner as Reference [13]. It was confirmed that the laser pulse energy injected into plasma of approximately 4 J and the laser pulse duration as short as 4 ns would be needed to satisfy the requirements on electron temperature and density measurements of edge plasma in ITER.

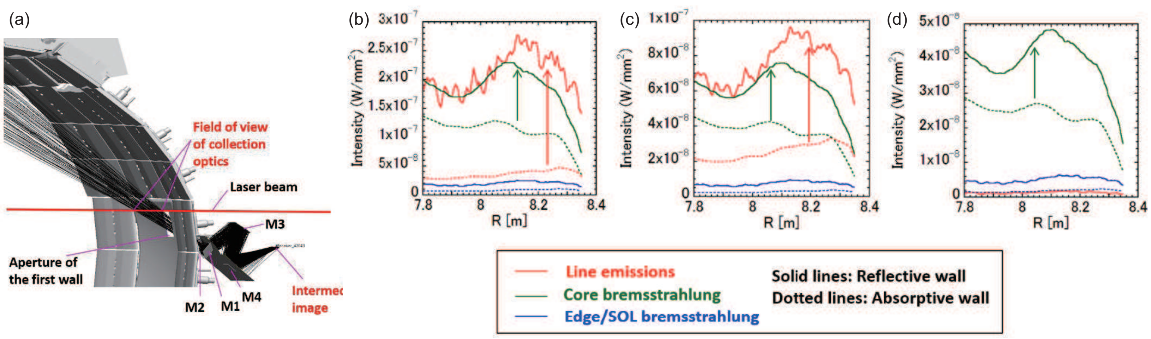

FIG. 5: (a) Model for evaluating intensity of background light on ETS, and expected intensity of background light on each line of sight within the wavelength of (a) 450-600 nm, (b) 700-800 nm and (c) 900-1000 nm

5 Charge exchange recombination spectroscopy

There are various error sources originated from the reflection in active spectroscopy. Concerning CXRS, there are three issues taken care of: (i) influence of the reflected active CXRS that could overlap with the active CXRS, (ii) disturbance of the CXRS spectrum by the emission from the divertor region (cold component), and (iii) increase in the noise by the reflected continuum radiation. The above three effects were investigated using a ray tracing simulation in ITER case [2]. It was found that the cold component can be significantly, say more than five orders of magnitude, greater than the real signal in the worst case for the He II line at 468 nm, leading to saturation of the detector. The results indicated that special care will be necessary when designing the spectrometer and choosing the detector. Also, it was also found that the background bremsstrahlung noise level would be double by the reflection. Concerning the above item (i), it was found that the stray light level is sensitive to the reflection property. Here, detail investigation is provided.

Figure 6(a) and (b) shows the ratio of the stray light to the signal in low density and high density scenarios, respectively, as a function of the ratio of the diffusive reflectance, R_d, to the specular reflectance, R_s. It is seen that the stray light significantly increased in the range 0< $R_\mathrm{d}/R_\mathrm{s} < 20$ %. When $R_\mathrm{d}/R_\mathrm{s} \sim 20\%$, the stray light can be ∼20% in the core. The result suggested that the bidirectional reflectance distribution function (BRDF) is important to know to assess the influence of the active signal.

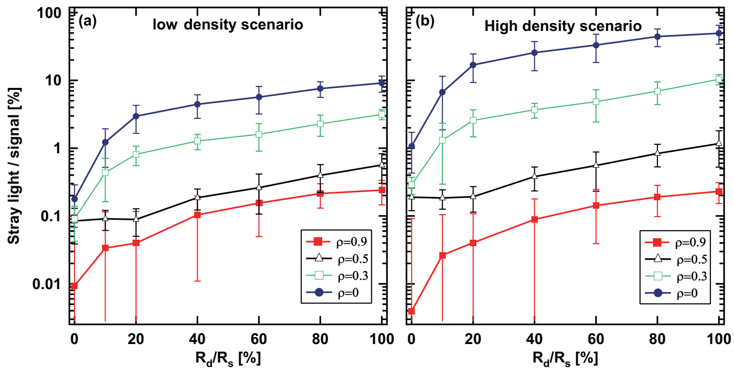

FIG. 6: The ratio of the stray light to the signal in (a) low density and (a) high density scenarios as a function of $R_\mathrm{d}/R_\mathrm{s}$.

6 Conclusions

The reflection of visible and infrared radiation was investigated using ray tracing simulation and the effects on Hα spectroscopy, infrared thermometer, edge laser Thomson scattering, and CXRS were discussed based on the simulation results. On Hα spectroscopy, it was shown that the stray light could be up to three orders of magnitude greater than the actual signal level, and the mitigation methods were discussed. In addition to arrange viewing dumps, which can reduce the stray light by an order of magnitude, ray tracing and spectral shape analysis will be inevitable. In the edge Thomson scattering diagnostics, reflected line emission from the divertor may increase the noise level. The infrared thermography and CXRS simulation results suggested that the characterization of optical property such as optical emissivity and ratio of specular to diffusive reflection is important to determine the influence of stray light.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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