A Proposed In-Vessel Calibration Light Source for the Joint European Torus[*]

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An in-vessel calibration light source (ICLS) is proposed for use during extended shutdown periods of the Joint European Torus (JET). The ICLS is primarily a 12 inch integrating sphere (4 inch opening) with 4 lamps (of known radiance), which can be positioned inside the JET vacuum vessel via the Remote-Handling Arm (RHA) during interventions in the JET operating schedule. This will facilitate the *in-situ* calibration of optical diagnostics, which rely on absolute light intensity measurements currently made when the diagnostics are removed from JET. The ICLS could ultimately reduce/remove the mechanical stresses associated with the repositioning of diagnostics for calibration purposes. At least 10 diagnostic systems ($\sim$ 20 diagnostic sub-systems) could benefit from the ICLS; in some instances the ICLS provides the only viable absolute-calibration strategy. Moreover, the ICLS will be a broad-spectrum white light source, enabling intensity calibrations at all visible wavelengths. A secondary benefit of the ICLS is in its use as an illumination source for making measurements of the reflectance (over a broad spectral range, and at multiple angles) from the tiles lining the JET vacuum vessel. During the ITER-like wall (ILW) intervention new Be, C, and W tiles will be installed in JET and their reflectance measured. Measurements made in subsequent JET interventions will provide data on the effect of high-temperature plasma operation on the reflectance of these tiles.

INTRODUCTION

High temperature plasma discharges, produced in the Joint European Torus (JET)[1], a large tokamak operating at the Culham Science Center in Oxfordshire, England, emit light that is observed by a variety of diagnostic systems. The translation of “emitted photons” into “plasma parameters” is a multi-layered process. The top layer involves a developed physical model, which relates detected photons to plasma parameters. But on a more fundamental layer is the relationship between detected photons at the diagnostic and emitted photons from the plasma. Meaningful physical results about the plasma dynamics can only be attained through attentive calibration of the diagnostic systems.

Essential to the calibration process of visible light observing diagnostics on JET and elsewhere[2, 3] is the use of calibration sources of known radiance. These calibration sources consist of an integrating sphere with a fixed opening, which has been calibrated with a lamp at a fixed brightness to give a known radiance at the exit port[4]. Ideally, the calibration source is placed in the diagnostic line-of-sight, providing an *in-situ* calibration of the diagnostic. This is not always practical, due to spatial or radiological constraints, as has been the case on JET. Instead the diagnostics are removed from the machine (risking mechanical damage) and calibrated “on the bench.” The fiber optics could consequently be bent at different radii compared to their usual state. And the optical window (at the tokamak vacuum-air interface) transmission must be measured separately. Alternatively, diagnostics may be left in place, and schemes of “transfer calibrations” are used, from one diagnostics to another via inferred plasma parameters. This introduces uncertainties from both the diagnostic perspective and the physics perspective, which are not present from a direct calibration of a given diagnostic. While these uncertainties are quantifiable and manageable, it is preferable to avoid them if possible.

An in-vessel calibration light source (ICLS) has been proposed for JET. Its implementation will be described in this paper, as well as potential further applications.

THE IN-VESSEL CALIBRATION LIGHT SOURCE

There are a number of factors which influence the selection of hardware for an integrating sphere calibration source. The average radiance at the exit port of an integrating sphere is given by the relation:

$$L_s = (\rho\phi_i)/(\pi A_s(1 - \rho(1 - fj))). \quad (1)$$

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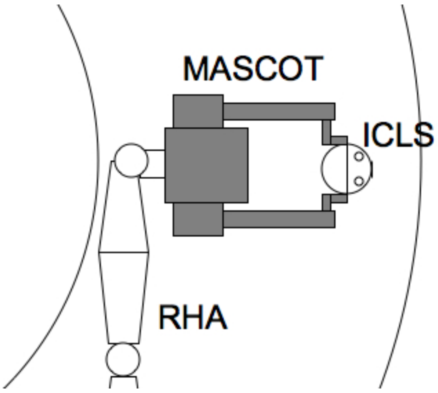

FIG. 1: Schematic view looking down on a toroidal section of the JET vacuum vessel with the in-vessel calibration light source (ICLS) deployed, held by the MASCOT device (in grey) on the end of the remote handling arm (RHA).

Here ϕ_i is the total radiant flux incident on the sphere wall from a given lamp, $A_s = 4\pi r^2$ is the surface area of the sphere (of radius r), ρ is the sphere wall reflectance ($0 < \rho < 1$), and f_j is the port fraction (sum of all port areas divided by the surface area of the sphere). Over the visible range of wavelengths, commercially available integrating spheres[4] made of Spectralon have $\rho \sim 98.5\%$, or coated with Spectraflect have $\rho \sim 97\%$.[5] For ease of diagnostic calibration a large exit port aperture is desired, particularly when attempting to calibrate multiple lines-of-sight simultaneously. But, the exit port area should not exceed $\sim 5\%$ of the sphere surface area, otherwise the radiance uniformity over the exit port can be comprimised. Moreover, the overall size and weight of the sphere must be practicable for entry/exit through the tokamak access port, along with in-vessel handling and support limitations. These considerations effectively determine the size of integrating sphere and exit port that can be utilized for a given application. The desired radiance can then be achieved by careful selection of the calibrated lamp configuration.

The ICLS will consist of a 12 inch integrating sphere with a 4 inch opening, coupled to 4 calibrated lamps of known radiance. The lamp set will consist of two externally mounted 100 W bulbs and two internally mounted 5 W bulbs. The estimated radiance at the exit port for a 5 W bulb at 600 nm is ~ 3 mW/cm^2/sr/μm, which is roughly equivalent to the light intensity of the plasma limb at this wavelength. The corresponding radiance at the exit port for a 100 W bulb is ~ 75 mW/cm^2/sr/μm, which is on the order of light emitted from the divertor region during plasma discharges. The manufacturer estimates that an externally (to the main sphere cavity) mounted lamp couples $\sim 40\%$ of the illuminated flux of a similar internally mounted lamp. Adding a variable aperture further reduces the coupling efficiency to $\sim 72\%$ of the external lamp, when fully open.

Having two sets of tungsten-halogen bulbs (1 each of 5 W and 100 W) allows for a longer operating life of the ICLS. The bulb lifetime is rated to be $\sim$ 2000 hours. But the manufacturer recommends that the integrating sphere/lamp system be returned for re-calibration after 10% of its lifetime has been consumed ($\sim$ 200 hours). It is estimated that a complete calibration of all the relevant JET diagnostics for a single intervention will require $\sim$ 120 hours of lamp-time. Manufacturer re-calibration is not an option for the ICLS, since hardware which has been inside JET for extended periods is regarded as contaminated with beryllium and tritium, and by regulation cannot leave the JET Be-handling area. Hence, it is intended that the calibration of one set of (duty) bulbs will be periodically cross-checked against the other set of (reserve) bulbs, effectively extending the lifetime of the system beyond 400 hours ($= 2 \times 200$ hours). The ICLS will have manufacturer-installed radiance feedback monitoring. Operational data from the radiance monitoring can be used to ensure the duty lamps remain within calibration tolerance, especially as their use is extended past their nominal 200-hour calibration lifetime. Moreover, the "color temperature" of the duty lamps can be periodically checked against the color temperature of the reserve lamps (whose calibration is certified), since the ICLS will often be illuminating spectroscopic instruments sensitive to segments of the visible range of wavelengths. When the manufacturer supplied calibration of the duty lamps becomes out-of-tolerance, then the reserve lamps can be put into service as duty lamps. Ultimately, the ICLS head (consisting of the integrating sphere, lamps, and mounting hardware) will have to be replaced (after about 3-4 JET interventions, which is $\sim$ 3-5 calendar years), however the power supplies, control hardware, and cabling can be re-used with a replacement head.

The ICLS will be deployed during JET "interventions," when the vacuum vessel is vented for entry of personnel and the JET remote handling arm (RHA)[6]. Because of beryllium health concerns to humans and radiological concerns from long in-vessel residency, the ICLS would be positioned in diagnostic lines-of-sight via the RHA. The RHA extends roughly 20 m around the inside of the JET tokamak, entering through one of two designated ports. At the end of the RHA is a tool/device called MASCOT. The range of motion accessible with the RHA and MASCOT is extremely large, due to the high number of articulated joints in both devices. A detailed description is given in reference [6]. The ICLS will be fitted with standard handles, which can be gripped by MASCOT. Once positioned in a given diagnostic line-of-sight, the articulated joints on the RHA and MASCOT can be "locked," allowing for long (over night) exposures in a stable position. The ICLS lamp power supplies and radiance feed-back control hardware, will reside outside the JET vacuum vessel, minimizing the Be contaminated (eventual) waste and reducing strain on the RHA joints.

The ICLS "head" will weigh less than 20 lbs, which is well within the stable lifting capacity of the RHA and MASCOT.

INTENSITY CALIBRATIONS

Having a light source of known radiance inside the JET vacuum vessel will facilitate the *in-situ* calibration of many visible-light spectroscopy diagnostics on JET. In particular, the diagnostic systems which would utilize the ICLS include: visible spectroscopy diagnostics, charge-exchange recombination spectroscopy diagnostics[7–10], Zeeman spectroscopy diagnostics, VUV spectroscopy diagnostics, divertor spectroscopy diagnostics, and the high-resolution Thomson scattering diagnostic. In total, it is estimated that a "full calibration" of these diagnostics, with regard to the ICLS tasks, would require ~ 120 hours of lamp-time. This includes a post-calibration (following the end of the previous JET experimental campaign), intervening diagnostic maintenance and/or upgrades, and a pre-calibration (preceding the forthcoming JET experimental campaign.)

As an example, consider the utility of the ICLS for the JET charge-exchange recombination spectroscopy (CXRS) suite of diagnostics. Currently, the CXRS plasma viewing periscopes (of which there are 5) are removed from JET during calibration. Personnel are required to physically manipulate each periscope, to conduct radiological testing, and to erect control barriers. A calibrated light source illuminates the viewing optics at the entrance of the periscope to derive the absolute-intensity calibration. The transmission of the torus vacuum-to-air window is measured separately at two wavelengths with lasers. Alternatively, the ICLS could be placed inside the JET vacuum vessel, in the near-field of each CXRS periscope sequentially, yielding the absolute-intensity calibration of the instruments in the precise optical arrangement that is used during data collection.

WALL TILE REFLECTANCE

Another potential application of the ICLS is to make measurements of the reflectance from the tiles lining the JET vacuum vessel. The reflectance from tiles is a fundamental parameter in the modeling of light reflection from in-vessel components[11], which is important for wide-angle visible and infra-red imaging of JET during plasma operations. During the ILW intervention, new protective tiles will be placed inside the JET vacuum vessel in a configuration similar to the planned tile locations in ITER. Beryllium tiles will be used to line the main-chamber walls. Tungsten tiles will be used to line the majority of the divertor, while carbon and carbon-fiber composite (CFC) tiles will be used at the strike-point locations. The ICLS can be positioned at various angles relative to the new tiles, while the reflected light is measured via multiple diagnostic lines-of-sight. This will give fundamental data on the specular and diffuse reflectance of various material types and geometries. Moreover, if the steps are repeated in subsequent JET interventions, then the change in reflectance due to plasma operation can be ascertained.

SUMMARY

An in-vessel calibration light source (ICLS) has been proposed for JET, as described in this paper. The next opportunity for deployment of the ICLS will be during the ITER-like wall intervention on JET, currently scheduled for summer/fall of 2009. The ICLS would facilitate the absolute-intensity calibration of a large number of optical diagnostics on JET. Additionally, the ICLS could be used to measure the reflectance of protective tiles installed on JET, and monitor the change in reflectance at subsequent interventions after exposure to plasma operation.

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