Review of Scientific Instruments

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Cite as: Rev. Sci. Instrum. **89**, 10K107 (2018); https://doi.org/10.1063/1.5037713
Submitted: 26 April 2018 . Accepted: 06 June 2018 . Published Online: 30 August 2018

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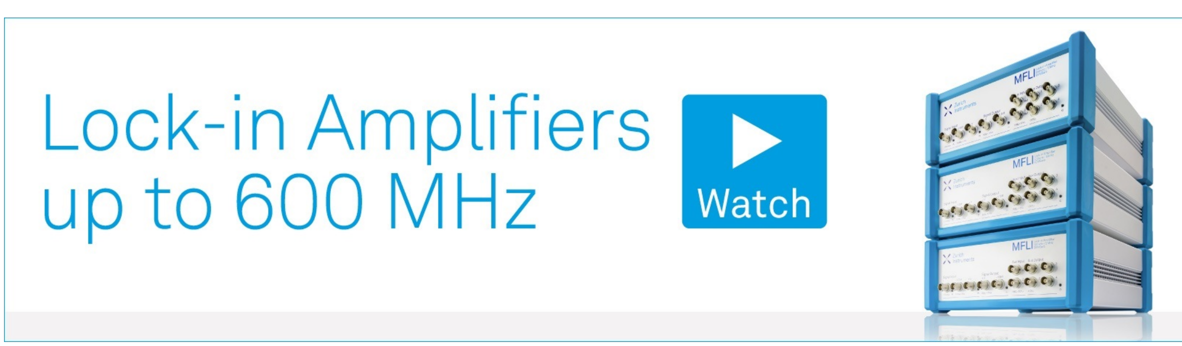
COLLECTIONS

Paper published as part of the special topic on Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics

Note: Paper published as part of the Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics, San Diego, California, April 2018.



REVIEW OF SCIENTIFIC INSTRUMENTS **89**, 10K107 (2018)

Upgrades to the in-vessel calibration light source on JET

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(Presented 18 April 2018; received 26 April 2018; accepted 6 June 2018; published online 30 August 2018)

Since 2010, an in-vessel calibration light source (ICLS) has been used periodically on JET to calibrate a range of diagnostics at UV, visible, and IR wavelengths. During shutdowns, the ICLS (which is essentially an integrating sphere) is positioned within the vacuum vessel by the remote handling (RH) system. Following the 2013 calibration runs, several changes were made to improve the efficiency and quality of the calibrations. Among these was the replacement of a 20 m "umbilical" cable which carried power and other electrical signals through a vessel port to/from a control cubicle. A lightweight 2 m cable now plugs directly into a single connector on the RH manipulator system, greatly reducing the time required for deployment and improving operational flexibility; e.g., the vessel access "floor" no longer needs to be installed. This change also means the system would be compatible with calibrations after a high neutron-fluence period of operation. An on-board micro-spectrometer now allows for real-time verification of the emitted spectrum. Finally, new "baffles" were designed and installed within the integrating sphere itself, greatly improving the spectral radiance uniformity at non-normal viewing angles (necessary due to orientation uncertainties with the RH system). https://doi.org/10.1063/1.5037713

I. INTRODUCTION

The JET in-vessel calibration light source[1] (ICLS) has been successfully used on a number of occasions since 2010 for the absolute calibration of diagnostics from UV to near-infrared (NIR) wavelengths. The calibrations are performed when opportunities arise, which is typically whenever remote-handling (RH) activity takes place inside the vacuum vessel. At the heart of the system is an absolutely calibrated 12″ integrating sphere with a 4″ aperture and 4 internally mounted lamps (2 each of 5 W and 100 W nominal power) which is positioned within the vacuum vessel by the RH manipulator system[2] (see Fig. 1).

Following the 2013 calibration runs, a number of enhancements were initiated. These drew on the experience gained from deploying and operating the ICLS within JET and the particular challenges posed by the RH environment. Chief among them was the goal of dispensing with the original "umbilical" cable, for several reasons—see below. The aim was to be able to simply plug the system into the "chest connector" (an electrical connector block on the main body of the "MASCOT" RH manipulator system) like other in-vessel tooling and inspection equipment. If successful, this would open up new possibilities for upgrades to the system, such as an on-board spectrometer.

A. Motivation for replacing the umbilical

The desire to replace the umbilical was mainly driven by efficiency concerns and the wish to permit use of the system after the planned "DTE2" deuterium-tritium campaign on JET (the DT pulses will greatly increase the radio-activation of structures within the JET torus hall and lead to access restrictions for personnel). The original umbilical was very heavy, having a cable mass of ~20 kg or roughly double the mass of the ICLS itself, and this put extra strain on the motors which drive the RH system—pauses were sometimes required to allow the motors to cool down. Furthermore, the cable often became snagged on obstacles, e.g., small gaps in the vessel manned-access floor (MAF), while the ICLS was being moved around the vessel; this caused significant delays. Also, calibrations could only be performed while the MAF was present in the vessel (since the umbilical lay on top of the MAF), reducing the flexibility for scheduling calibrations within a shutdown. Finally, the umbilical had to be fed into the vessel through a port; since there is beryllium and tritium contamination within JET, this necessitated the use of an "isolator"—essentially an *in situ* plastic glove box—for holding and manipulating the umbilical. However, during shutdowns, the vacuum vessel is held below atmospheric pressure (again, to prevent the spread of contamination), and thus isolators collapse onto their contents under the suction from the vessel port. This made the insertion of the cable a difficult job which routinely took hours to complete while in very close proximity to the vacuum vessel. Therefore, this was not an activity which could reasonably have been performed after significant radio-activation of the machine, as will occur in the DTE2 campaign, because the radiation dose to personnel would have been unacceptably high.

B. Other enhancements

The ICLS has an on-board photometer, consisting of a photodiode with a photopic filter. This is used as a cross-check

Note: Paper published as part of the Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics, San Diego, California, April 2018.
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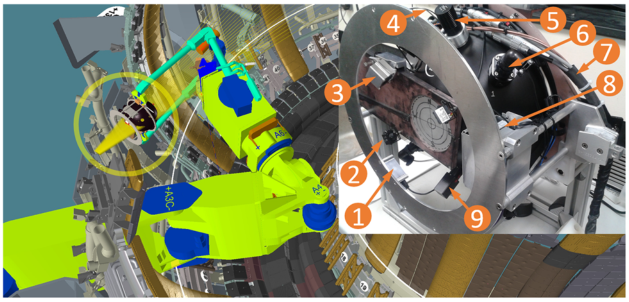

FIG. 1. The ICLS system depicted during a calibration. Inset: photograph of the ICLS, with key features indicated—(1) micro-spectrometer, (2) CCTV camera, (3) webcam, (4) optical fibre, (5) LED torch, (6) lamp, (7) new umbilical, (8) Raspberry Pi, (9) photometer.

that the output is in line with the reference values. If, for example, the sphere aperture is positioned too close to partially reflective surfaces, the photometer reading rises significantly, providing a warning that the spectral radiance will not match the calibrated curve. Equally, if the spectral output of a lamp has varied, the photometer can in principle be used to re-scale the spectral radiance to account for the change, but this is really only valid near the peak of the photopic filter (centred at ∼555 nm and full-width at half-maximum of ∼100 nm) or if there is reason to believe that the colour temperature has not changed. However, as tungsten-halogen lamps age, the spectral radiance curve can change shape. It was therefore considered desirable to fit a compact spectrometer to the ICLS to complement the photometer, provide information on spectral stability, and potentially correct for changes, regardless of the source.

Another improvement was connected with the on-board cameras which view the shutter. The original CCTV units had some issues—e.g., their monochrome images sometimes made it hard to distinguish spurious reflections of in-vessel lights from the light intentionally projected onto the shutter from optical fibres to help position the ICLS. Also, at low light levels, noise could be a limiting factor. Improved cameras were sought which could provide colour images with improved low-light performance.

II. REALISATION

A. Feasibility study

The first step was to assess the feasibility of operating the ICLS via the wiring harness that runs between the MASCOT chest connector and the RH "boom interface cubicle" (BIC), where the connections to the main ICLS power and control cubicle would be made. The main section of articulated boom[2] (see Fig. 1) which supports the remote manipulator is over 12 m long, and the other sections of cable (e.g., boom to BIC) add another ∼20 m to this. The available conductor cross sections are generally smaller than those used in the original umbilical—see below.

One of the key unknowns was whether the electrical current to the lamps could be maintained with adequate precision over a longer and more resistive circuit with many connections along the way, especially given that the connection resistances were believed likely to vary when the boom moved. In fact, the concept of using the chest connector had already been considered during the original development of the ICLS, but it was recognised at that time to be a high-risk option with R&D requirements for which there was inadequate time, and so the lower-risk direct umbilical was selected instead, despite its disadvantages.

1. Wiring scheme

To make the upgrade as simple and cost-effective as possible, the intention was to re-use the existing power and control scheme if possible. This approach required at least as many conductors as had been used by the original umbilical.

The four lamps used one pair of conductors each, so as to preserve independence of the lamp circuits and prevent a fault on one lamp's power supply from damaging multiple lamps. Three coaxial signal cables were used: one for the on-board photometer, to carry the sub-nA currents from its photodiode, and two more for the CCTV cameras, to carry the MHz-bandwidth video signals. The power to the cameras (12 V DC, ∼200 mA) and the LED torch (∼1.5 A at 3.5 V) used another pair each. Finally the shutter system's stepper motor and limit switches needed 9 conductors. The grand total for the original umbilical is 27 conductors. The 100 W lamps (nominally 12 V, 8 A) were connected to 12 AWG wires, and everything else apart from the coaxial cables used 22 AWG wiring, including the 5 W lamps (nominally 12 V, 400 mA).

The RH chest connector (Fig. 2) meets the ARINC 404 standard (designed for aerospace applications) and has a 106-way shell; roughly 40 pins of the connector are actually populated, 32 of which can be linked to the BIC. The current rating of the individual connector pins is only 5 A, but fortunately five of the conductors within the cable harness were each linked to a pair of such pins, and only four 8 A conductors were actually required—two per 100 W lamp. The harness also included three co-ax cables—exactly the number required for the ICLS.

The 12 AWG wiring used for the 100 W lamps in the original umbilical has an effective cross-sectional area of ∼3.3 mm^2. The heaviest-gauge wiring available in the boom was only 1 mm^2 (8 such conductors) and thus much more resistive, but at 8 A, the power dissipation in each conductor pair is only ∼2 W/m, so overheating was not a concern. The other available boom wiring consisted of shielded twisted-pair (24 AWG, 4 pairs) and 0.25 mm^2 single wires (10 conductors).

In summary, the wiring harness had sufficient capacity to duplicate the original connection scheme.

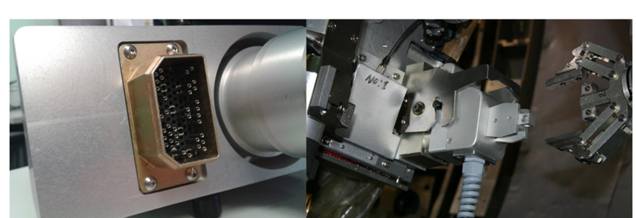

FIG. 2. The ICLS RH chest connector assembly in close-up (showing the high pin-density) and installed in the mating connector on the MASCOT chest (the gripper jaws are visible on the far right).

2. Initial testing

The ICLS lamp power supplies are digitally programmable units, configured for constant-current mode. Careful tests were performed to assess the impact of having a more resistive cable and of sudden changes in circuit resistance—first on dummy resistors and then on the actual ICLS lamp circuits. The tests demonstrated that the power supplies reacted very quickly to step changes in resistance, returning to the nominal current value in well under a second. When the ICLS lamps were tested, the photometer readings showed that the system luminance was identical to much better than 1% with low and high resistance cables. The modified wiring dramatically increased the total voltage required for the 100 W lamps (from ~13 V to ~29 V), but this was well within the capacity of the power supplies.

The other elements of the system were also tested with full length dummy cables of the types used in the RH boom to ensure they would still function: shutter system, video cameras, and photometer. All of these tests were successful.

3. On-board enhancements

With 32 conductors available for use, and only 27 needed to duplicate the original connection scheme, there was some spare capacity. It was decided to use two of the twisted-pair cables to attempt to provide the ICLS with a Fast Ethernet (100 Mbps) network link. This was to be connected to a compact on-board computer which would interface to other peripherals, such as a spectrometer and additional cameras.

After exploring various options for the on-board computer and peripherals, the most promising candidates were selected and tested. The Raspberry Pi Model B+ was the chosen computer, primarily because it had very low power requirements (~5 W) plus built-in Ethernet and universal serial bus (USB) capabilities. The STS-VIS micro-spectrometer from Ocean Optics was selected based on its compact size (40 × 42 × 24 mm, 60 g) and the availability of software to permit the Pi to serve spectra directly to a web browser in addition to local storage for later analysis. It was coupled to a short optical fibre viewing the interior of the sphere. (Typical setup: one spectrum recorded every 10 s, by averaging 150 spectra, each of 15 ms exposure time; specifications: 350–800 nm range and 6 nm FWHM with 100 μm slit.) A number of webcams were tested with the Pi, and their low-light performance was generally very good, partly owing to their ability to use a long exposure time when required, unlike the CCTV cameras which were limited to 1/60 s exposure. A camera with a hardware-MJPEG capability was chosen (Microsoft LifeCam HD 6000) because the MJPEG output minimised the CPU load on the Pi during video streaming. Power to all of these systems was provided at 5.1 V (~2 A) by an on-board DC-DC convertor fed by an uprated 12 V supply shared with the CCTV cameras.

If the ICLS is used after a high neutron-yield campaign, the gamma radiation levels within the vacuum vessel may be as high as 10 mSv/h (mainly from cobalt isotopes). This level is unsafe for humans but is not expected to pose any problems for the on-board electronics; the total dose over an entire calibration run should be well under 2 Gy (200 rad).

B. Implementation

With the feasibility proved, the next steps were the manufacture of a new umbilical cable to link the chest connector to the ICLS, plus an equivalent cable to link the ICLS cubicle to the BIC, followed by full testing with the RH system in JET's in-vessel test facility (IVTF)—this would become the first test of the ICLS on the actual RH boom wiring harness. The IVTF is a full-scale mock-up of three-quarters of the JET vessel, within which the RH booms and MASCOT are deployed so that tasks can be rehearsed and new operatives can be trained between shutdowns.

1. New umbilical

After discussions with RH personnel about the requirements (including maintainability) for the new umbilical, it was decided to make it readily dismountable from the ICLS for rapid replacement (via a manned entry to the boom enclosure). This was achieved by using a combination of LEMO and BNC connectors for the various wiring. Two cable assemblies were manufactured so that a spare was always available. The length for the cable was set at 2 m—long enough to let MASCOT position the ICLS in any required position and orientation but not so long as to drag on the vessel floor. The wire types used were identical to those within the boom harness.

2. Testing in the IVTF

With the new umbilical and on-board electronics ready, the complete system was tested in the IVTF in August 2014, prior to the February 2015 calibration run.

All of the lamps functioned as expected, and the luminance measurements from the on-board photometer indicated that the lamps were operating at the correct currents. The shutter drive and on-board CCTV cameras also worked well. One issue was found: the wired Ethernet did not work over the boom cabling. However, the on-board electronics were still successfully tested through the use of a USB WiFi adaptor plugged into the Pi.

Despite WiFi working well in the IVTF, there was little confidence that it would be usable in the much more enclosed JET vessel itself as reflections of the radio signal were expected to be a problem. An alternative networking solution was therefore required, and a promising candidate was found: VDSL2 "Ethernet extender" units, which use a high-frequency carrier over a single twisted-pair cable—technology created for domestic broadband data provision. A second IVTF test of the full system was carried out using off-the-shelf VDSL2 units, and data rates of over 40 Mbps were achieved with good stability and low latency. This bandwidth was more than sufficient for transferring spectra and streaming video data.

III. SPHERE UNIFORMITY IMPROVEMENTS

When results from the 2010 calibration run were analyzed, it was noticed that for one diagnostic (the "KT3" divertor spectroscopy system), the data for three overlapping sections of the radial profile showed a mismatch of ~5%–10%; this was subsequently investigated. These particular calibrations were of very long duration (several hours per position), so the inboard and outboard sections had been calibrated first, with the central section being calibrated around 24 h later. Between the two sessions, the RH system had performed other work, including calibrations of other diagnostics. This created the possibility that the sphere had not been oriented in quite the same way for both sessions. The internal uniformity of the integrating sphere was believed to be very good, so the orientation was not expected to have made a difference, but checks were performed to rule this out. However, an off-axis non-uniformity was found (which *may* have caused the issues for KT3), originating from a shadow cast on the internal surface of the sphere by the baffle beside the active lamp.

The role of the baffles in an integrating sphere is to prevent light from reaching certain parts of the sphere, e.g., the exit port, without scattering at least once from a diffusely reflecting surface. The original baffles in the ICLS were configured to prevent the lamps from directly illuminating the "central zone" of the sphere, i.e., the portion seen through the aperture when looking along the axis. The uniformity within this region of the sphere was good, but when viewing off-axis, it was possible to observe a brighter region which was directly illuminated by the lamp (see Fig. 3). The radiance in this zone beyond the shadow line was found to be 5%–20% higher than that of the central zone.

This non-uniformity would not cause issues for normal laboratory usage of the sphere because there would be minimal risk of accidentally viewing sufficiently off-axis, but in the RH environment, calibrations were susceptible to errors arising from it because of the way the ICLS is positioned. This is done by moving the sphere's aperture into the view of the diagnostic; e.g., for fibre-optic based diagnostics, the shutter is typically closed and one or more fibres are back-illuminated; the sphere is moved until the light spots from the fibres are appropriately positioned on the target pattern on the shutter itself. However, this is only guaranteed to put the *centre* of the sphere aperture in the correct place; it does not ensure that the sphere orientation is correct, i.e., that the sphere axis is aligned with the diagnostic line of sight.

In the RH environment, movements of MASCOT and its tooling are monitored by using a range of cameras and by the use of a real-time virtual-reality/CAD system. In discussion with the RH team, it became clear that due to mechanical issues, such as stretching of drive cables to the MASCOT "wrists," discrepancies as large as 20° could exist between the true orientation of the ICLS and its indicated orientation, which could be enough to allow diagnostics to view the brighter regions of the sphere. In any case, before the non-uniformity was discovered, there was little scrutiny of the orientation during calibrations. It should be noted that the KT3 diagnostic is not especially sensitive to the problem; the symptoms are simply more readily noticed with it than with most other diagnostics.

There are two ways to address this issue: avoiding "bad" orientations when positioning the sphere or reducing the non-uniformity. For the 2013 and 2015 runs, care was taken to reduce the risk of viewing the brighter region, including intentionally biasing the ICLS orientation slightly off-axis—away from the brighter zone. A number of schemes to permit more precise orientation were then considered, but by the time of the 2017 runs, the non-uniformity itself had been addressed, as described below.

When the non-uniformity was first observed, inspection of the CAD model and non-sequential ray-tracing (using Zemax) provided a clear understanding of the root cause. A new baffle shape was required. Using a simple Python code, calculations were made of the baffle shape required on any chosen plane to block light from reaching a chosen locus on the sphere surface—typically a circle, e.g., the exit port or an enlarged region around the central zone. In the end, after assessing a number of designs and some discussion with Labsphere (the original manufacturers of the ICLS), an extremely small and simple baffle design was chosen (see Fig. 4). The new design permits the lamps to directly illuminate the central zone—its only role is to prevent light from directly reaching the exit port—with the beneficial side-effect of giving a slight increase in spectral radiance. In Fig. 5, Zemax uniformity modeling

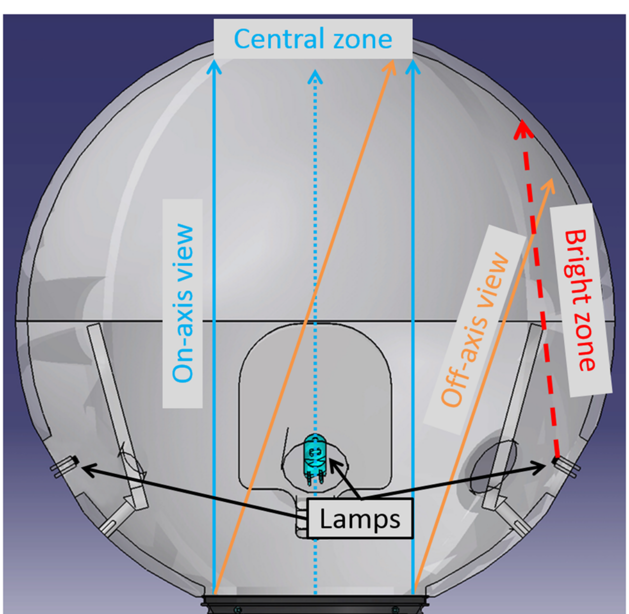

FIG. 3. Cross section of ICLS depicting lamp and baffle locations, and the origin of the brighter region away from the axis.

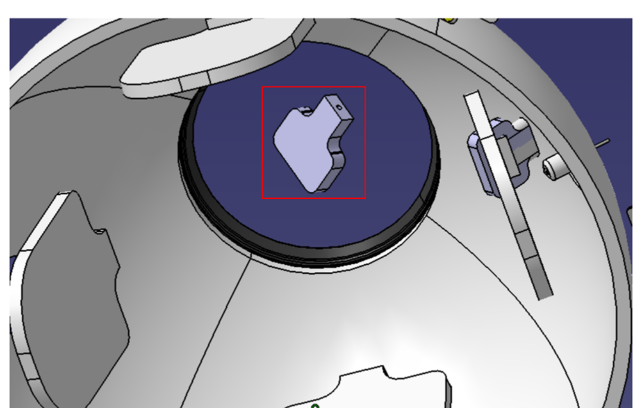

FIG. 4. CAD model depicting both baffle designs. The new smaller baffle is shown both in the inset and *in situ* in the right-most position, overlaid with the original baffle.

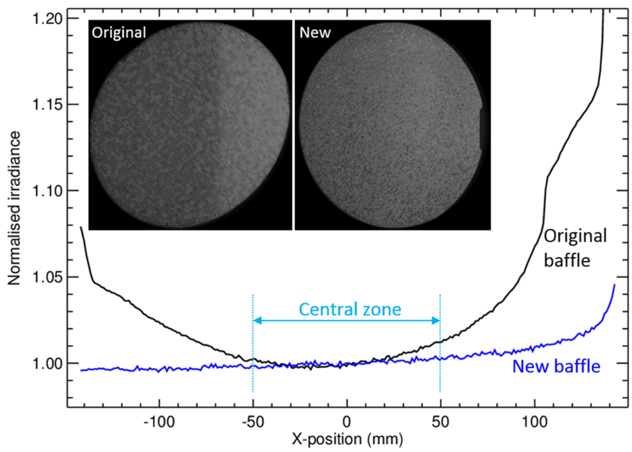

FIG. 5. Zemax modeling of uniformity with both original and new baffle designs. The inset photographs (taken from off-axis) show that the shadow line in the original system has been eliminated.

results for old and new designs are compared. It can be seen that the new design has removed the off-axis step increase and improved the uniformity within the central zone. A full set of four baffles was subsequently manufactured and installed; tests were made which confirmed the improved uniformity performance (see the inset photographs in Fig. 5).

IV. OPERATIONS

A. New operating protocols

When the ICLS was first used in 2010, a cautious approach was taken so as to avoid perturbing the calibration. For example, after turning on a lamp, a warm-up period of 15 min was adopted prior to taking data; after turning off, the sphere was not moved until a cool-down period of 10 min had elapsed. For long calibrations, these delays were of no consequence, but in other cases, they could dominate the duration of the process. Testing was therefore carried out to assess how short the delays could be made. Time-resolved spectroscopy during warm-up showed that the spectral output stabilised to within 1% in well under 100 s and to within 0.5% in well under 200 s. There were also some indications that repeatedly power-cycling a lamp had a noticeable effect on the spectral radiance—of order of a few parts per thousand. With spare lamps at the ready, aggressive testing was then carried out to see if a cool-down period was required: the sphere was simply picked up and shaken as hard as possible *while a lamp was running*, with no detectable effect on the spectral radiance curve. Based on these tests, new guidance was adopted: short warm-ups (~3 min) and no cool-down period before moves; additionally, small movements became permissible with a lamp running, with this actually being the preferred approach when the alternative would be many short runs for a lamp interspersed with movements. For a number of diagnostics, these changes dramatically improved the useful fraction of the calibration sessions.

B. Post-upgrade calibrations

The new umbilical and on-board systems were used in the 2015 and 2017 calibration runs, both of which were very successful. The number of diagnostics being calibrated has increased with each new run, and several of these take full advantage of the new protocols to reduce the down-time at each movement. In the 2017 calibration run, more than 20 separate diagnostic calibrations were carried out, most of which required multiple positions. The ability to deploy the ICLS without the MAF in the vessel has also been exploited, most recently in 2017 when an extra run (for repaired diagnostics) was performed very late in the shutdown, after the MAF had been removed for the final time.

The on-board spectrometer provides live readout of spectra from the sphere, including a normalised mode which shows the variation from the nominal spectrum for the lamp in use; this immediately highlights issues and is also useful for verifying that warm-up is complete.

Before and after each set of runs, an on-site cross-calibration system is used to generate updated spectral radiance curves for each lamp in the ICLS by comparison with a reference sphere (calibrated at the UK's National Physical Laboratory) over the range 300–1650 nm.

ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance from the entire RH team at JET, our colleague Simon Dorling for suggesting the use of VDSL2 technology, and various members of the team at Labsphere, Inc.

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The work was also supported, in part, by the U.S. DOE under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. The views and opinions expressed herein do not necessarily reflect those of the European Commission or the U.S. DOE.

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