EFDA JET

Implementation of an In-Vessel Calibration Light Source on JET

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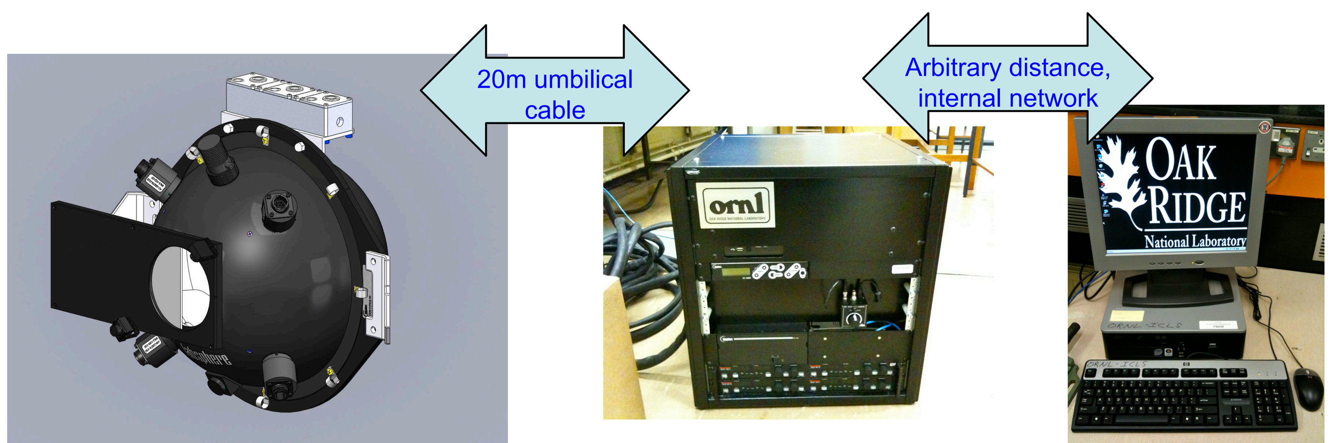
** See the Appendix of F. Romanelli et al., Fusion Energy 2010 (Proc. 23rd Int. FEC Daejeon, 2010) IAEA, (2010)*

ABSTRACT

The absolute intensity calibration of visible light diagnostics is an integral link in the scientific chain that connects ADC counts on a detector to plasma physics parameters. These calibrations are routinely accomplished on high temperature plasma devices through the use of integrating spheres coupled to a stable, broad spectrum, "white" light source of known radiance. These spheres are typically manually inserted (in-vessel) into the optical line-of-sight of a diagnostic during vacuum openings, e.g. on machines like ASDEX or NSTX. Such an operation is problematic for JET (and ITER and DEMO) due to in-vessel environmental hazards, e.g. radiation and contamination. An in-vessel calibration light source (ICLS) has been implemented for remote use during extended shutdown periods of JET. The ICLS is a 12 inch integrating sphere (4 inch opening) with 4 lamps, which can be positioned inside the JET vacuum vessel via the Remote-Handling Arm (RHA). The ICLS facilitated the *in-situ* calibration of optical diagnostics, which previously were performed when the diagnostics were removed from JET. Use of the ICLS has reduced the mechanical stresses associated with the repositioning of diagnostics for calibration purposes. Since the ICLS is used to calibrate diagnostics over the entire, exact optical path as used when plasma discharge data is measured, the ICLS calibration implicitly accounts for any vignetting losses in the JET vessel viewports in addition to the vacuum window transmission. The window transmission is included in the ICLS calibrations across all visible wavelengths relevant to each diagnostic, and can be compared to off-line, 2-color laser transmission measurements using a retroreflector. The ICLS for JET is a demonstration technology for how such calibrations could be accomplished remotely on ITER. At least 10 diagnostic systems have benefited from the ICLS during the extended ITER-like wall shutdown of 2009-2011. Examples of the use of the ICLS in JET will be given.

IN-VESSEL CALIBRATION LIGHT SOURCE (ICLS) [1,2]

- Specifications of the In-Vessel Calibration Light Source (ICLS)
  - 12-inch integrating sphere with 4-inch exit port
  - Internally coated with Spectraflect (high reflectance, Lambertian)
  - Externally black-annodized, Aluminum shells (not painted)
  - 4 ports for calibrated lamps
    - 2x internally mounted 100 W Tungsten-Halogen bulb
      - ~40 mW/cm^2/sr/μm at 600 nm (similar to divertor intensity)
    - 2x internally mounted 5 W Tungsten-Halogen bulb
      - ~1 mW/cm^2/sr/μm at 600 nm (similar to plasma limb intensity)
    - 2000 hour lamp lifetime (recommended recalibration after 10% of lifetime)
      - Cross calibration between lamp sets to extend operating lifetime
  - Radiometer sensor to monitor lamp radiance at arbitrary orientation
  - LED (80 cd) for illumination of the JET vessel when positioning the ICLS
  - 2 cameras (0.0003 lux, 600 TV lines, auto-exposure, 70 degree F.o.V.)
    - Forward facing camera to assist in proximity reckoning while positioning
    - Shutter viewing camera to assist in alignment of backlit lines of sight
  - Shutter mechanism
    - Protection to ICLS internal surfaces during transport
    - "Target" landmarks to assist in alignment of backlit lines of sight with ICLS opening
- 20 m cabling so that only ICLS "head" is brought inside JET vacuum vessel



ICLS head: JET in-vessel

Electronics half-rack: JET midplane, torus hall ex-vessel

Control PC: RH control room

Figure 1: (a) CADD model of the ICLS head, which is connect by a 20 m long "umbilical" to (b) the external half-rack of electronics, which is connected over the JETnet internal network to (c) a control PC in the RH control room at essentially arbitrary distance.

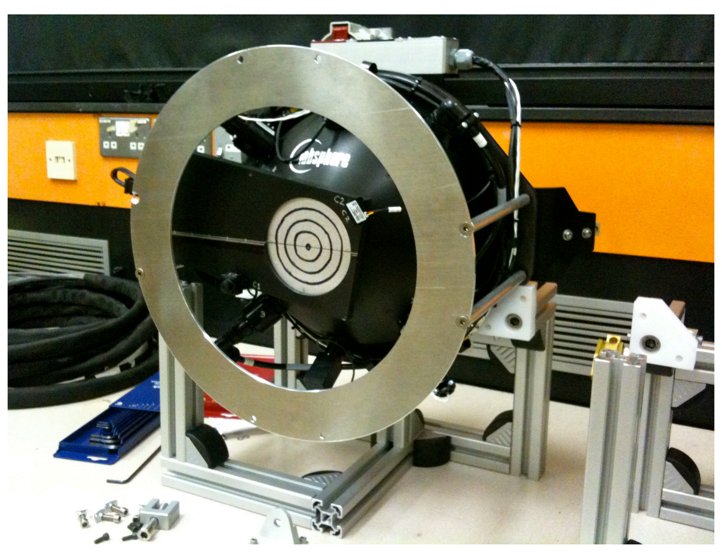


Figure 2: Photograph of the ICLS resting on its transport cradle. An Aluminum "bumper" was added for mechanical protection.

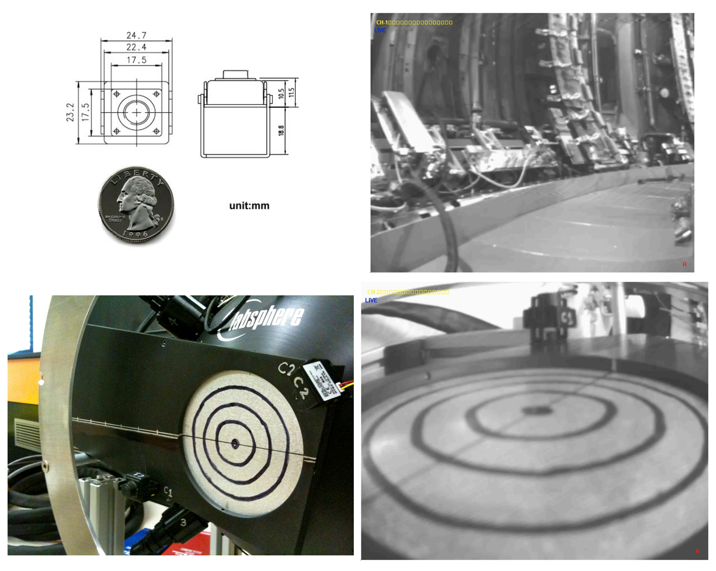


Figure 3: The ICLS is fitted with 2 compact cameras (a), which are oriented to be1) forward facing, here showing (a) the "first light" view inside JET, and 2) directed across the face of the ICLS opening (c), which shows (d) the target and landmarks that are present on the ICLS.

JET REMOTE HANDLING ARM CONSIDERATIONS [3]

- JET in-vessel environment posses a danger due to radiation and Be contamination.
- Long in-vessel dwell times of the ICLS require the use of the JET RHA and MASCOT.
- ~20 pound ICLS "head" can be easily grasped and stably held with standard RHA handles.
- 2 sets of handles for "on the fly" re-gripping of ICLS if maneuvers require
- Winch point to prevent excessive drop-height in the event of power loss to MASCOT grippers
- Aluminum "bumper" to prevent damage to lamp mounts, etc., from collisions
- RH compatible connectors for umbilical cable connections in-vessel
- Transport cradle for bringing ICLS in-vessel and to rest ICLS on during other RH tasks
- Full Virtual Reality mock-up of all movements and positioning scenarios.
- Final positioning done with "Man-in-the-loop" manipulation of the ICLS while observing backlighting
- ICLS is remotely operated via PC over the JET intranet.

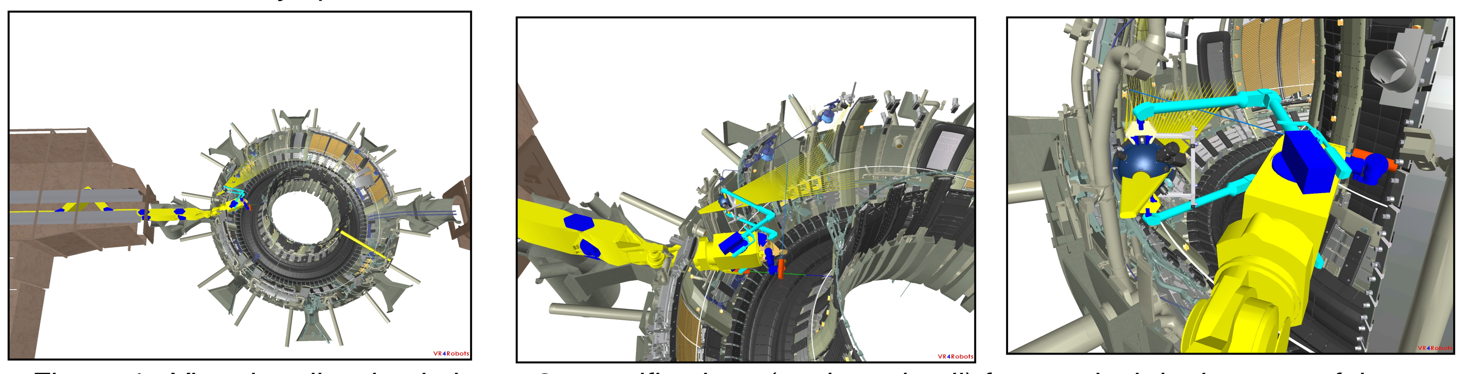


Figure 4: Virtual reality simulation at 3 magnifications (to show detail) for a typical deployment of the ICLS via the RH arm and MASCOT manipulator in JET.

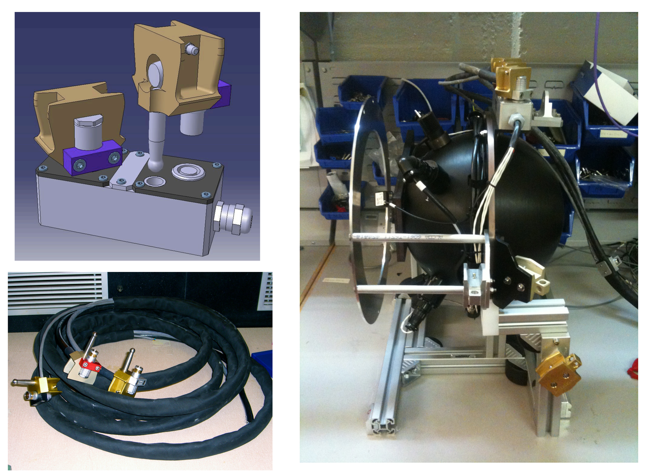


Figure 5: (a) CADD detail of the RH compatible, multi-pin connectors, which attach the umbilical cable (b) to the ICLS. Detail of the ICLS and transport cradle can be seen in (c).

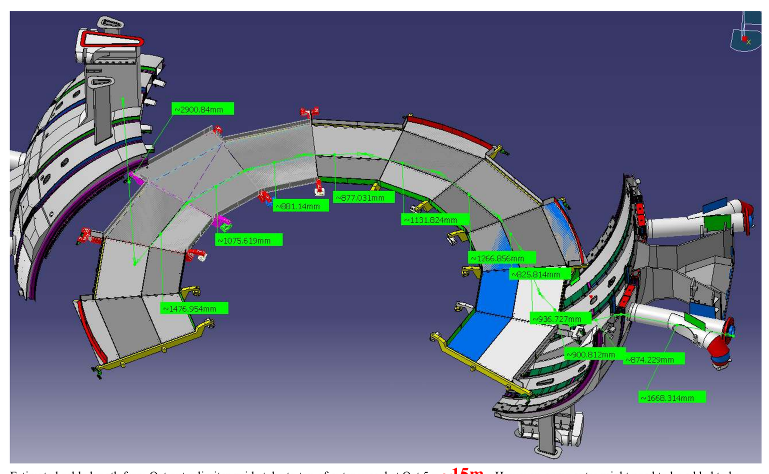


Figure 6: Virtual reality layout of a typical umbilical deployment used to estimate the total cable length from trans-vessel feed at the midplane to the opposite side of JET.

DIAGNOSTIC CALIBRATION RESULTS

- More than 10 diagnostic systems on JET have benefited from *in-situ* calibration using the ICLS
  - Visible spectroscopy and imaging diagnostics
  - Charge-Exchange Recombination spectroscopy diagnostics
  - High Resolution Thomson Scattering
  - Divertor spectroscopy diagnostics
  - VUV spectroscopy diagnostics
  - IR imaging diagnostics
- Initial calibrations required ~200 hours of wall-time, and ~90 hours of lamp-time
- Future calibrations will benefit from recorded RHA fine-position locations of initial calibrations
- Next opportunity for deployment of the ICLS is during the 2012 intervention
- Video of use of the ICLS can be found at: http://www.youtube.com/watch?v=LqKxD9ui4as

SUMMARY

- An in-vessel calibration light source (ICLS) has been successfully deployed on JET to facilitate the *in-situ* calibration of visible spectroscopy diagnostics via Remote Handling.
- This is a demonstration technology of how such calibrations could be accomplished on ITER and DEMO.

REPRINTS

Electronic copy available at: http://sprott.physics.wisc.edu/biewer/HTPD12poster.pdf

ACKNOWLEDGEMENTS

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[3] D. Locke, "JET Remote Handling Requirements - Remote Handling Equipment," CD/S/J408, U.K.A.E.A. Culham Science Center, Abingdon, UK OX14 3DB (2007).

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Implementation of an In-Vessel Calibration Light Source on JET (Supplemental Material)

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INTEGRATING SPHERE CALIBRATED LIGHT SOURCES [4]

- Specifying the integrating sphere: L_s = average radiance at exit port
  - ϕ_i = total radiant input flux (from lamp)
  - $A_s = 4\pi r^2$ = sphere surface area
  - ρ = sphere wall reflectance
  - f_j = port fraction
- Desire large port opening for ease of diagnostic calibration
  - Exit port area should not exceed ~5% of the sphere surface area
- Overall sphere size limited by torus entry/exit constraints and stable lifting restrictions
- Lamp arrangement
  - "Externally mounted" lamps couple ~40% of light from a similar "internally mounted" lamp
  - A variable attenuator has an additional ~72% coupling efficiency

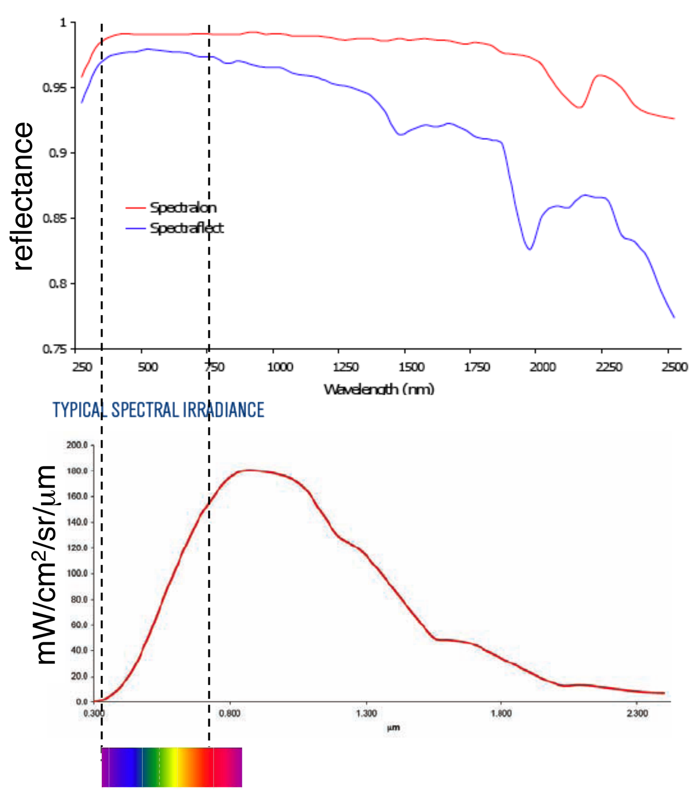

Figure 7: (a) The spectral reflectance of commercially available integrating sphere coatings, and (b) a typical spectral irradiance curve for a Tungsten-Halogen lamp. The visible range of light is shown for comparison.

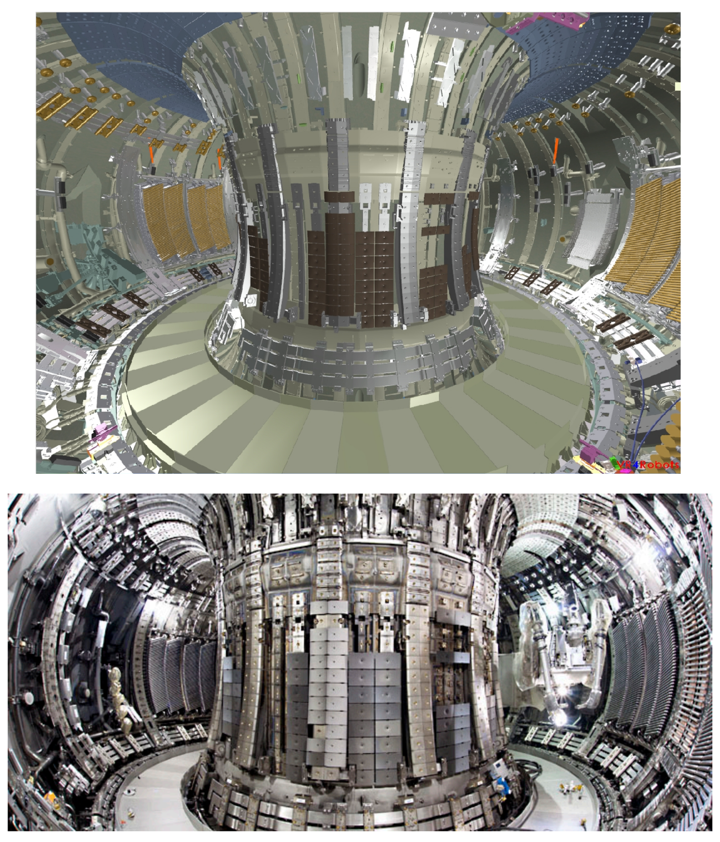

Figure 8: (a) Virtual Reality model of the in-vessel JET configuration on Sept 7, 2010, and (b) an in-vessel photograph of JET from Sept 20, 2010, showing the accuracy that is kept daily in the model to assist in positioning of the Remote Handling arm and MASCOT.

CALIBRATION SEQUENCE

- The umbilical is threaded through a port at the midplane from ex-vessel to in-vessel using a bridging tool.
- The umbilical is grasped by the RHA MASCOT and drawn into JET, stretched out on the "manned entry floor", while connections are made to the electronics half rack ex-vessel.
- The ICLS head is transported into JET on a cradle. The RHA sets the ICLS and cradle on the floor.
- The umbilical connections to the ICLS are made and operability of lamps, etc., is confirmed.
- Winch cable is connected to the ICLS and the ICLS is lifted out of the cradle by the RHA.
- Gross positioning of the RHA and ICLS is accomplished by pre-programed movement sequence as established in the Virtual Reality model.
- Typical diagnostic sightlines are back-lit by the diagnostic responsible officer.
- Fine positioning of the ICLS is accomplished by man-in-the-loop manipulation of MASCOT, while back-lit spots are observed on the ICLS shutter and monuments.
- When proper alignment is achieved, the RH MASCOT servo joints are "locked" in position.
- The diagnostic lines of sight are configured for absolute intensity measurements, while the calibration lamps are turned on and allowed to thermally stabelize with the shutter open.
- The diagnostics is absolute intensity calibrated at the discretion of the RO.
  - If multiple wavelength settings of the diagnostic are required, the measurement sequence can be "scripted" by JET CODAS.
- The ICLS lamp is turned off for background light meaurement sequence.
- Lamp is allowed to cool for a minimum of 10 minutes before movement of the ICLS to next diagnostic position.
- The ICLS can be returned to the transport cradle if the RHA is required to perform other tasks during an operational shift. This allows, eg. ICLS calibrations to be conducted overnight (for long exposures not requiring movement of the ICLS), while the RHA is utilized during regular work hours eg. For tile installation.

JET REMOTE HANDLING ARM [3]

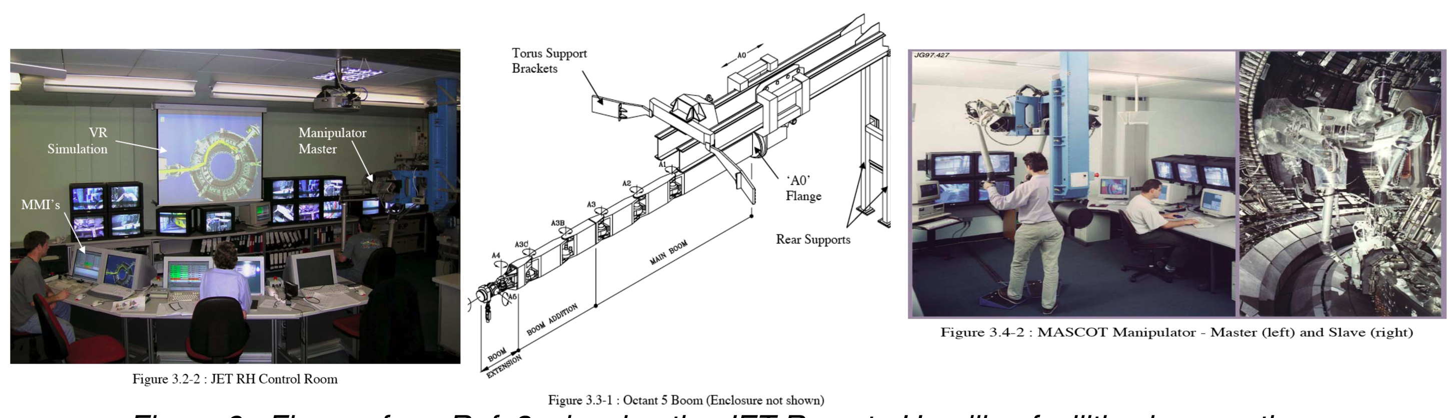

Figure 9: Figures from Ref. 3, showing the JET Remote Handling facilities in operation.

DIAGNOSTIC CALIBRATIONS DURING ITER-LIKE WALL INTERVENTION [5]

- An in-vessel calibration light source (ICLS) has been deployed in JET to facilitate the *in-situ* calibration of visible spectroscopy diagnostics.
- Video of use of the ICLS can be found at: http://www.youtube.com/watch?v=LgKxD9ui4as

Diagnostic	Description	R.O.	Ports	Factors	Est. Shifts	Est. Lamp hours	Act. Lamp hours
KS3	Vis. Spec.	M. Stamp	3	4-6 lamp pos.	12-16	12-16	5.7
KS4	Vert. CXS	A. Meigs	1	Post, var λ,pre.	4	16	10.6
KS5	Tor. CXS	C. Giroud	2	Post, var λ,pre.	4	24	6.5
KS7	Pol. CXS	Y. Andrew	3	post, pre.	6	18	13
KS8	Zmn. Spec.	M. Stamp	1	post, pre.	2	4	1.8
KS9	MSE Spec.	N. Hawkes	1	Rotary polarizer	2	4	4.8
KT1	Scan. VUV	K. Lawson	2	3-5 rot. mir. pos.	12-20	12-20	10
KE11	HRTS	M. Beurskens	1	post, pre.	2	4	9.8
KT3	Div. Spec.	A. Meigs	1	var λ	4	16	17.5
KT4	VUV Spec.	I. Coffey	1	post, pre.	2	2	0
KT7	VUV Spec.	I. Coffey	1	post, pre.	2	2	0.7
KL1	Wide Angle Camera	G. Arnoux	1				1.1
KL7	Wide Angle IR Camera	G. Arnoux	1				1.4

Table 1: Summary of JET diagnostic proposed/actual usage of the ICLS.

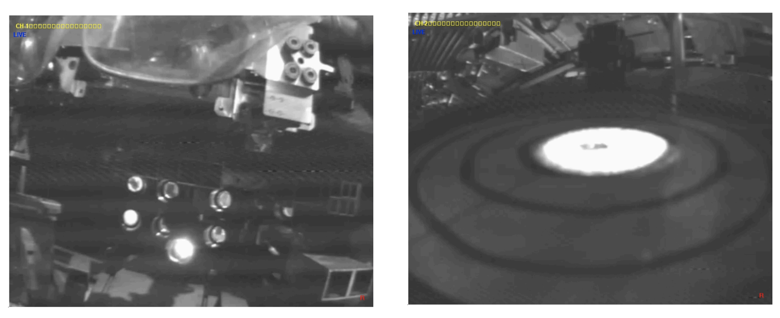

Figure 10: ICLS forward facing camera view (a) of KL7 port in-vessel, and the shutter facing camera view (b) with a back-lit line-of-sight aligned for calibration.

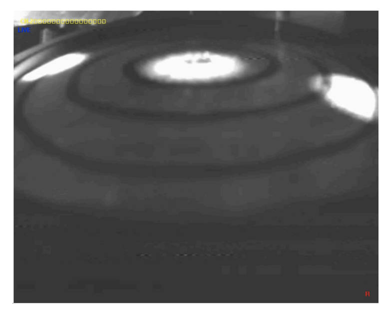

Figure 11: ICLS shutter facing camera view for the KS5 diagnostic showing the outer-most and center lines-of-sight, back-lit and aligned for calibration.

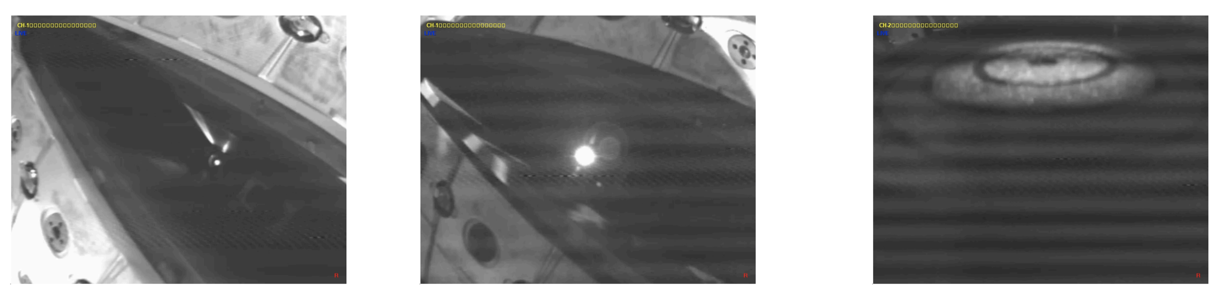

Figure 12: ICLS forward facing camera view of KT7 port showing (a) that the back-lit line of sight is mis-aligned and hitting the side of the port. The same view (b) after the KT7 mirror has been adjusted to steer the line-of-sight through the port, and (c) onto the ICLS shutter target for calibration, as shown in the shutter-viewing camera.

REPRINTS

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[4] R.J. Yeo, "Light Measurement and the Application of Integrating Spheres and CCD Spectrometers," Pro-Lite Technology, http://www.pro-lite.co.uk (2007).
[5] See the JET Data Handbook for more information on individual systems: http://users.jet.efda.org/pages/data-dmsd/jetdatahandbook/web/php/ViewEntry.php?type=0&order=0&view=0