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Requirements for calibration & testing of ITER microwave based diagnostic front-end components

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Executive summary

The suite of microwave-based diagnostics proposed for ITER include reflectometry, refractometry, Electron Cyclotron Emission (ECE), and Collective Thomson Scattering (CTS). The common feature is the use of simple metallic antennas and waveguide transmission lines. These *front-end* components (as distinct from the *back-end* diagnostic electronics), which also includes vacuum windows, tapers, mitre-bends, expansion and swivel joints, isolation valves and shutters, voltage breaks, air-gaps and mode filters etc. are relatively insensitive to machine behaviour, eg. radiation damage, nevertheless, each needs careful installation and alignment for the correct operation of the diagnostic. A series of tests and calibrations are required. The microwave performance (losses, reflection, mode-conversion) of each component and sub-system must be measured and documented prior to installation. This is to allow subsequent component degradation to be identified. The antennas require special attention; their radiation patterns, cross-coupling, placement and lines-of-sight need to be measured. The mechanical and electrical continuity of the waveguides, as well as their high-voltage isolation should be checked and corrected during installation. The operation of ECRH protection devices, as well as additional hardware needed for the system calibration, must be ensured. Finally, the overall performance of the antenna / transmission line system, eg. presence of resonances and the power transmission curve is to be documented.

1. Introduction

Microwave diagnostic techniques, such as reflectometry, refractometry, Electron Cyclotron Emission (ECE), and Collective Thomson Scattering (CTS) etc., launch into and/or collect microwave radiation (10 – 300 GHz) from the plasma using local horn (-reflector) antennas and remote sensor electronics connected by waveguide transmission lines. For ITER, the use of metallic *front-end* in-vessel antennas and waveguides make the diagnostics notably robust to neutron and radiation damage. Any radiation sensitive parts of the diagnostics, such as the *back-end* transmitting and receiving electronics, can be positioned behind suitable shielding. In principle, the front-end components – antenna, waveguide and vacuum break – are relatively undemanding and ideally can be designed to exceed the required system performance. In practice, physical constraints, particularly restricted access, the tight waveguide routing in-vessel, large thermal stresses etc. can lead to waveguide distortions and hence compromise the optimal performance. Although the system design can mitigate some of the expected limitations it will be necessary to perform a series of calibrations and tests on individual components after manufacture, sub-systems after assembly, and the complete front-end system during and after installation. This is necessary, not only to check for component failures and installation faults (tests), but to document the system performance (calibration) to permit identification of subsequent system degradation, allow system deficiencies potentially to be compensated via the back-end hardware, and finally to ensure the correct interpretation of the signals.

This report, commissioned by the ITPA (International Tokamak Physics Activity) Topic Group on Diagnostics in April 2009 (Action item 16a312) and prepared by the Microwave Working Group (MWG), assess the requirements necessary for calibration and testing of the ITER microwave based diagnostic front-end components. Here, front-end means from the in-vessel antennas all the way to the ex-vessel waveguide flanges in the diagnostic hall. It does not cover the back-end electronics. The assessment is essentially generic and applies to all the waveguide based diagnostic systems.

2. Background

The ITER microwave diagnostic suite includes ECE, reflectometers and CTS. Together they span the range 10 GHz – 1 THz (see appendix 1).

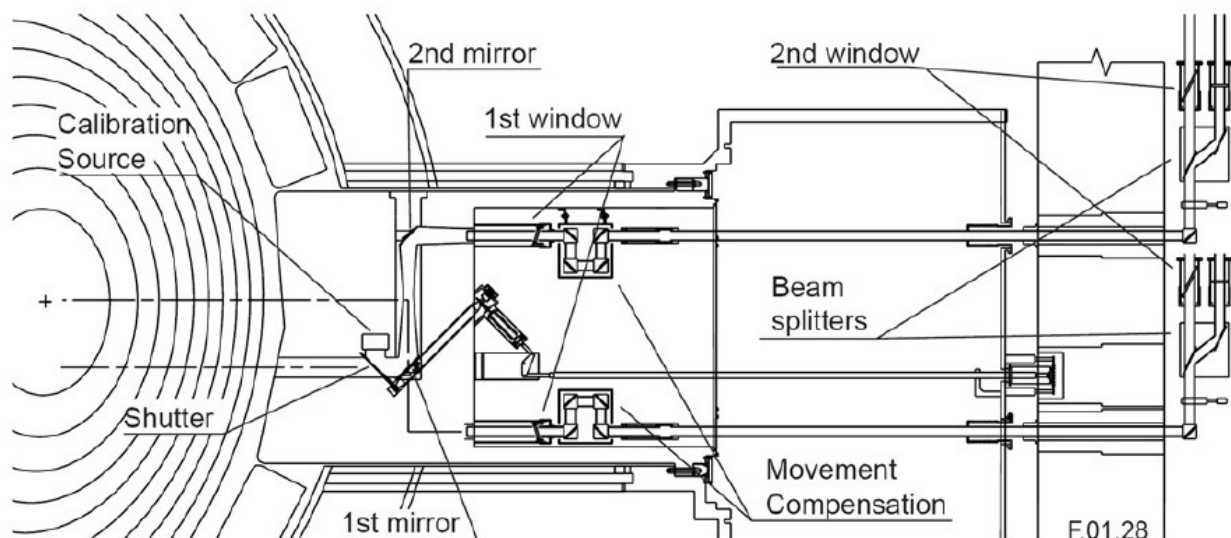


Figure 1: Schematic of the ECE diagnostic front-end [DDD].

The ECE system has a broad-band (60 GHz – 1 THz) front-end, shown in figure 1, and employs

circular corrugated waveguides (typ. 89 mm ID) and metallic mirrors. These feed polarising beam splitters and long, conditioned-atmosphere transmission lines that cross several pressure barriers before distribution to a suite of instruments. These include broad-band Michelson interferometers and heterodyne radiometers operating in narrower bands (122-230 GHz). Calibration sources will be incorporated in the port plug and additional sources can be coupled into the transmission line at suitable locations - still to be identified in the detailed system design phase recently started in IN and US. The ECE measurement mission arising out of the ITER measurement requirements in the PR as allocated in the SRD is summarised in appendix 2.

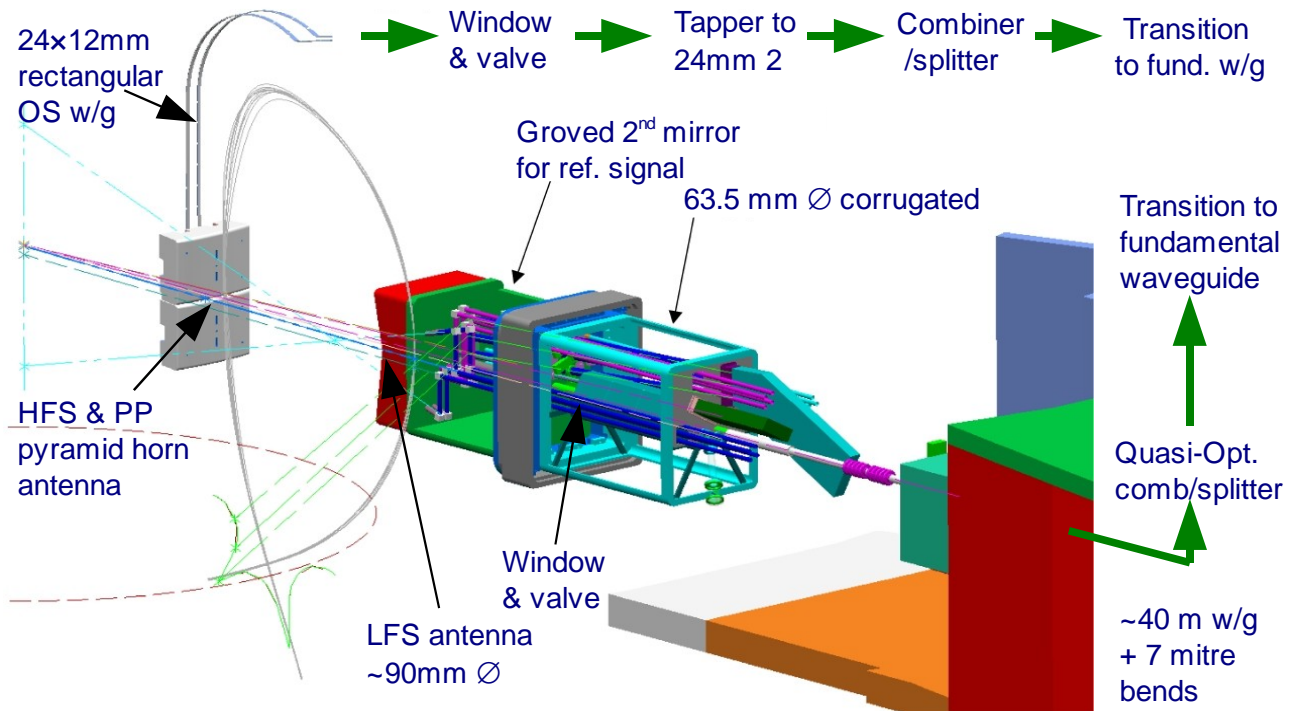


Figure 2: Reflectometry diagnostics F.02 in Equatorial Port plug overview and F.09 in VV fed from Upper Port [PD]

Reflectometry on ITER will use a variety of transmission lines, from smooth rectangular waveguide for the in-vessel systems and circular corrugated waveguide for the port-based systems and the long transmission lines in the building. The overall frequency coverage is in the range 10 – 160 GHz, varying system by system.

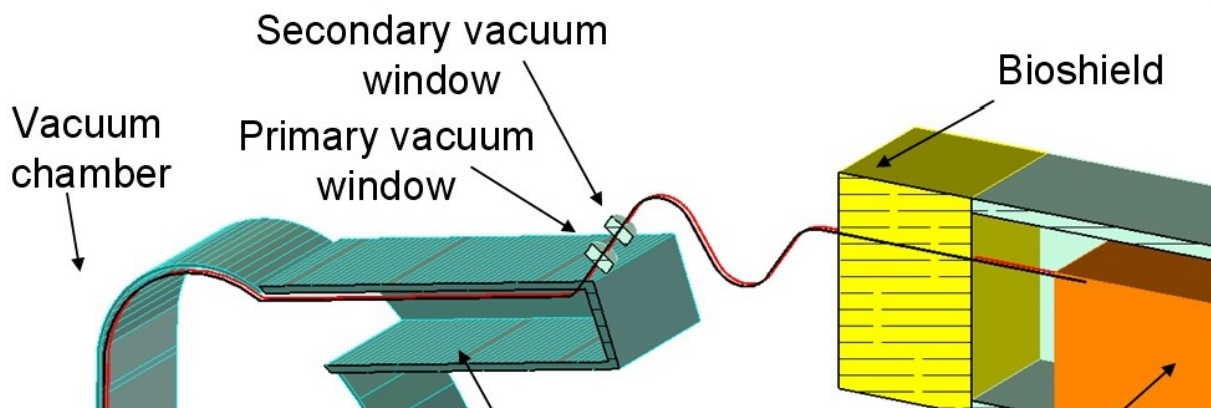


Figure 3: Transmission line layout for a high-field-side rectangular waveguide system [PD]

Features such as gratings and controlled leaks are intended for incorporation into the transmission line to provide reference points for the transmission delay at different frequencies. Figures 2-4 show features of the reflectometer transmission lines. Appendix 3 lists the expected contribution of reflectometry to the ITER targets. Different sub-systems are being designed in the US, EU and RF.

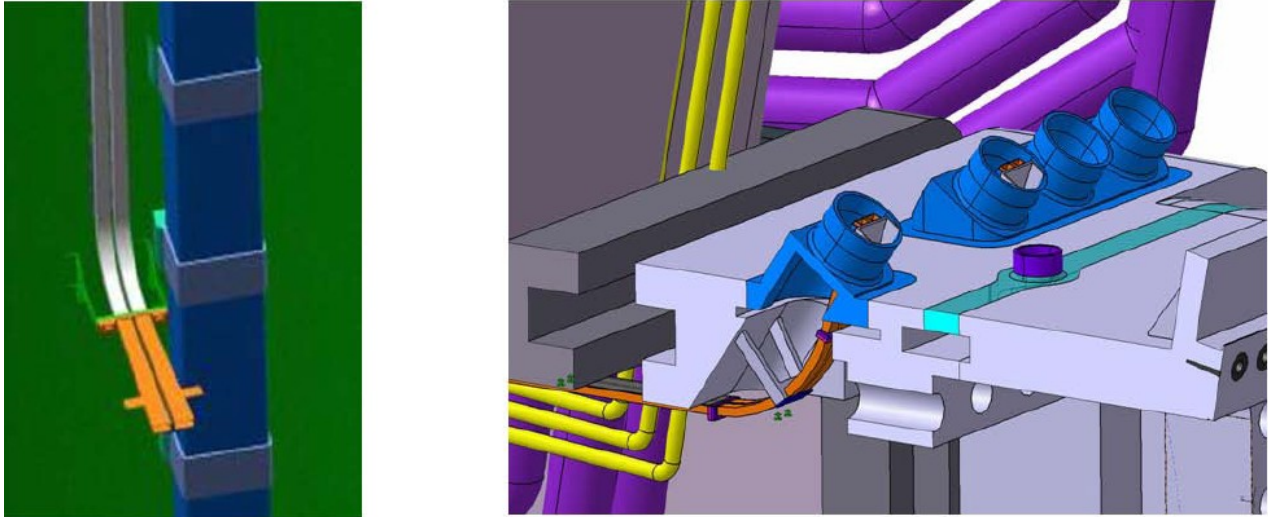


Figure 4: Reflectometry waveguide details [PR]. (a): antenna facing the plasma between blanket modules (b) waveguide exit above the upper port.

CTS in ITER is designed to measure key properties of the confined alpha and other fast particle populations (appendix 4). It employs a pair of gyrotron sources and detectors in the same port and within the vessel (figure 5). The detection hardware and waveguide access are similar to those for the reflectometer for plasma position. The EU will undertake the design study to enable this system.

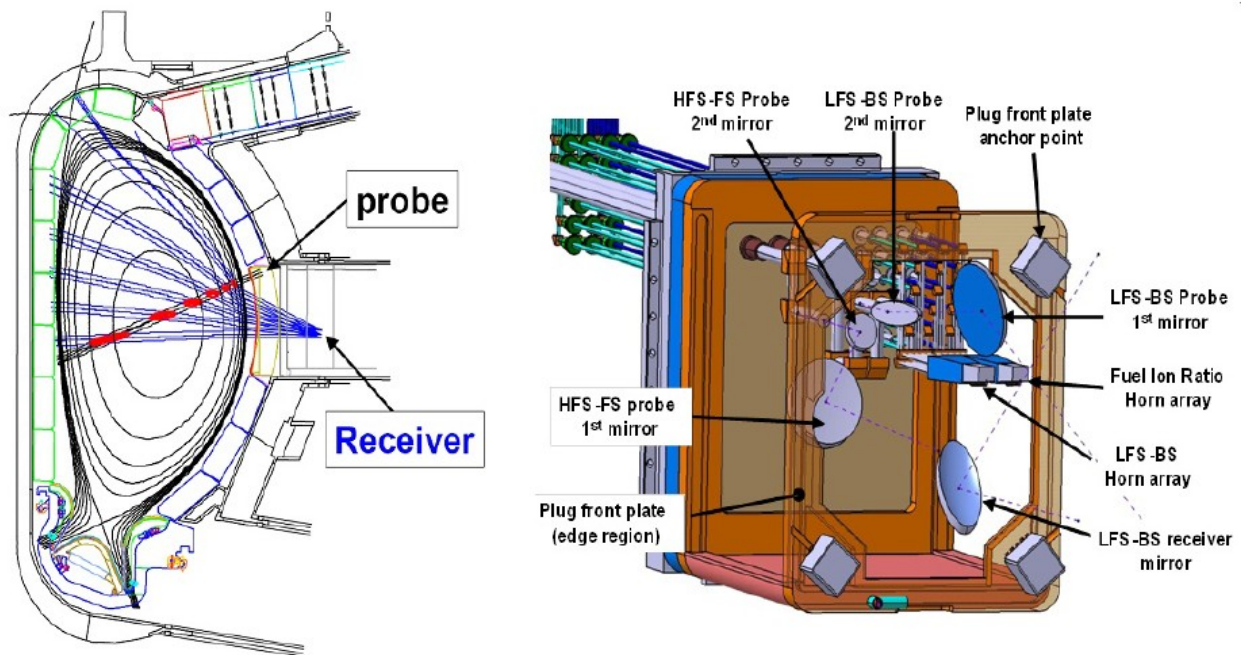


Figure 5: CTS overview [PR]. Only the low field side system is in the present baseline.

3. Test requirements

3.1 Test measurement categories

The following set of test measurements and calibrations are intended to be generic and universally applicable to all of the microwave diagnostic systems proposed for ITER that involve some form of waveguide transmission lines and launch/receive antennas. The tests begin at the individual component and sub-system level and move towards the diagnostic systems as a whole. Some specific functional tests may be particularly appropriate, and even crucial, for certain diagnostics, while others are somewhat less important, and perhaps may even be considered optional, for others.

In the context of this document *Tests* are essentially functionality checks for component failures, faults and installation flaws. ie. performance behaviour outside of design specifications. *Calibrations* on the other hand detail the actual performance of the complete installed system as per design.

The various tests can be categorized as follows:

- (a) Pre-installation component specification checking and documentation.
- (b) Installation checks and performance documentation.
- (c) Post-installation system/assembly testing and documentation.
- (d) Periodic operational performance checks and calibrations.

Category (a) may mostly be performed during system sub-assembly and laboratory testing, while categories (b) & (c) are essentially tests to be performed on-site during and after antenna/waveguide installation and before vessel closure. Category (d) are tests that should be performed periodically during the lifetime of each diagnostic to assess the continuing correct operation of components and the system as a whole. Such tests may also include in-line system calibrations during machine operation and/or during suitable in-vessel interventions.

The successful completion of these tests should form an integral part of the full documentation and qualification of the system performance for each diagnostic.

3.2 System calibrations

System calibrations encompasses any measurements or procedures necessary for the determination of correction and/or conversion factors required for the translation of the microwave signals into the measurement parameters. For example, correcting the reflectometer propagation group delay for transmission line distortions/dilations, or converting the ECE radiation signal to electron temperature. These calibration factors are likely to vary slowly (although hopefully not too dramatically) over the machine operation period, thus regular re-calibration checks need to be performed using non-invasive procedures. These system calibration issues are reasonably well established and are addressed in the respective diagnostic DDDs. These issues and the proposed system calibration procedures are listed in section 5 below for completeness. Nevertheless, it is within the scope of this document to highlight the requirement for testing the effectiveness and correct operation of the system calibration procedures and hardware.

3.3 Manufacturing compliance checks

Not discussed in this document are the necessary compliance checks which need to be made on all external manufactured components, and the presumption that all such items and components meet the specified manufacturing tolerances before installation.

4. Test measurements

4.1 Microwave component performance

- Measure and document microwave performance (e.g. losses, reflection coefficients, mode conversion etc.) of individual transmission line components such as vacuum windows, mitre-bends, splitters, combiners, polarizers etc.

Justification: The documentation of the microwave performance (as distinct from manufacturing tolerances) of all individual components at the time of installation is a primary requirement which is necessarily, not only for identifying and compensating for poor components, but to facilitate the subsequent identification and monitoring of causes of system performance degradation (eg. due to neutron radiation or arcing damage etc.).

Requirement: Various component tests in the laboratory. Applicable to all diagnostic systems.

Note that over-moded waveguide components, which includes tapers, mitre-bends, expansion joints, isolation valves and shutters, vacuum windows, voltage breaks, air-gaps and mode filters etc. require particular attention for compliance with mode-conversion design specifications.

4.2 Antenna radiation pattern

- Measure antenna radiation patterns in the far-field (or actual measurement) location (to be specified for each diagnostic), in the required polarization (O-mode or X-mode orientation or both):
 - at 3 representative frequencies, around bottom, middle and top end of measurement band;
 - in both poloidal and toroidal planes.
- Measure antenna 3 dB half-width (or 10 dB power width) vs distance from antenna face (i.e. from near-field to far-field) at one or more selected (typical) frequencies.

Justification: The antenna radiation pattern is a fundamental parameter (or set of parameters) which determines the basic measurement performance of the diagnostic as a whole. All the proposed systems use antennas (Gaussian beam or pyramidal horn) fed by oversized waveguide, hence there is a strong potential for the presence of unwanted higher order modes to distort the ideal antenna pattern. In any case, a full antenna qualification is necessary for the correct interpretation of the data and subsequent modelling.

Requirement: The base-line antenna specifications outlined in the procurement package (PP) for each system and application should be validated against laboratory measurements.

There is debate whether a full testing of each production antenna is required or whether it is sufficient to make representative measurements from pre-production prototypes of each antenna type and size using a laboratory test-rig of the vessel mock-up, which includes the blanket module recesses etc. As a minimum, visual and mechanical inspections of each production antenna must be performed and supported with selected representative far-field pattern (distance to be specified) 3 dB half-width measurements. For the CTS antennas, which involve quasi-optical mirror elements, it is highly desirable to characterize each separate antenna pattern after installation.

4.3 Antenna cross-coupling

- For antenna clusters measure and document antenna cross coupling leakage between adjacent antennas. Measure cross coupling for both polarizations as necessary.
- Measure reflectometer *transmit/receive* antenna coupling vs distance using reflecting plate.

Justification: The clustering of antennas, particularly the close positioning of adjacent paired transmit and receive reflectometer antennas, can lead to unwanted signal cross talk. The cross-talk should be low enough to allow a minimum of 40 dB measurement signal to noise ratio, possibly more.

Requirement: The measurement could be performed in either a laboratory mock-up, prior to installation, or after antenna installation in the blanket module prior to port-plug installation, or even in-vessel after final installation.

Tx/Rx antenna cross-coupling is likely to be less of an issue for the CTS system as the antennas are widely displaced. The receiver antenna array (>10 circular horn antennas), however, are very closely spaced.

For the cross-coupling vs distance measurements the HFS cutoff layers will be notably flat (in the poloidal plane), however, significant curvature will be present (together with toroidal tilting due to the magnetic field ripple) on the LFS so it may in some case be appropriate to model the plasma surface with convex/concave shaped plates.

4.4 Antenna alignment

- Measure absolute position of antenna centres (reference point).
- Measure direction/orientation of antenna lines-of-sight (LoS).

Justification: Precise knowledge of the antenna lines-of-sight are required for correct data interpretation; the antenna orientation is particularly important for Doppler reflectometry purposes as this will define the probed turbulence wave-number. The CAD drawings will specify the desired position and alignment of each antenna, however, these must be checked during antenna installation and again re-measured after.

Requirement: A reference point for each antenna will need to be specified. For the rectangular horn antennas of the plasma position reflectometer this could be a corner of the antenna mouth, while for the circular aperture / horn antennas either a point on the lower lip, or the antenna centre (defined using an insert plug in the antenna mouth).

The antenna line-of-sight is a vector and hence requires a two point measurement. There are several possible methods, one of which is to insert a special purpose plug in the antenna mouth which contains a laser aligned with the antenna axis for sighting. Intersection points along the laser path are then measured in-vessel after antenna installation using a Coordinate Measuring Machine (CMM), such as the FARO ® arm and/or laser sighting arm/tracker. Alternately, two reference points are marked on each antenna during manufacture which can define the antenna axis. These are then measured directly with the CMM / laser sighting head.

ITER proposes two in-vessel transport systems, an equatorial rail and arm (IVT) and an articulated boom (MPD) which should facilitate antenna LoS and system calibration requirements [Cho09].

4.5 Electrical isolation / DC breaks

- Perform high voltage testing of waveguide isolation to vessel wall and blanket modules etc.

Justification: The presence of vessel halo currents and changing magnetic fields can induce large currents and $j \times B$ forces in the waveguides, which can lead to waveguide distortion, dislocation of flanges and damage to support elements. Ground loops between waveguides, the vessel/blanket and waveguide clamps are mitigated using DC breaks. Sufficient electrical isolation is also required to prevent arcing during disruptive events.

Requirement: Functionality of the waveguide electrical isolation should be checked and corrected as necessary during waveguide installation, and further rechecked after installation.

4.6 Waveguide continuity

- Check mechanical and electrical continuity of waveguides during installation and after.
- Measure waveguide flange microwave leakages and inter guide isolation performance.
- Check for misalignment in waveguide joints and flanges; rectify/optimize as necessary.
- Check for misalignment/straightness in corrugated waveguide sections.

Justification: Breaks in the waveguide wall, and in particular discontinuities at waveguide flanges due to poor installation, can lead to unwanted reflections and signal leakage. Excessive bending of the corrugated waveguide sections will lead to unwanted mode-conversion; this must be minimized by careful installation.

Requirement: Identify any spurious reflections from misaligned joints and windows etc. using a frequency swept microwave vector analyser. Correct or mitigate reflections where possible. During installation check the straightness of the o/s waveguide runs (possibly using laser alignment) and adjust hangers to correct excessive curvature/sagging due to gravity.

4.7 Waveguide microwave performance

- Measure waveguide losses – document holes and resonances, plus polarization effects and mode-conversion.
- Check operation of passive waveguide components such as splitters, tapers, QO couplers.

Justification: Oversized waveguides are prone to the formation of high-order modes which can be trapped between mitre-bends and other discontinuities leading to resonances and power drop outs at certain frequencies. Even after all (extensive) mitigation efforts a degree of unevenness in the power transmission curve is inevitable. This needs to be documented.

Requirement: After complete antenna & waveguide installation measure and document the "end-to-end" microwave performance of each transmission line, including transmission and reflection power vs frequency plus any rotation of the polarization vector. Check and document performance of any passive components such as combiners and splitters, tapers and/or quasi-optical coupling to the fundamental waveguides.

4.8 System protection

- Check operation of ECRH protection items, such as w/g filters, arc detectors etc.
- Check operation of active waveguide components such as shutters & isolators etc.

Justification: The diagnostic electronics and sensitive in-vessel waveguide components must be protected from excessive stray radiation due to non-absorbed ECRH/CTS gyrotron beams or fast electron generated Bremsstrahlung. This issue, together with various protection techniques (including fast acting shutters, filters and arc detectors) were addressed in a previous report [Con09].

Requirement: Check correct operation of protection items - in laboratory and after installation.

5. System calibration procedures

System calibration procedures are normally diagnostic specific and generally require some additional components or hardware to be (temporally) introduced into the transmission line system which generate a known or calibrated reference signal - the measurement of which then allows the correction and/or conversion factors to be determined. Slow variations in the calibration factors due to thermal expansion, mechanical dislocations, component degradation/aging or replacement etc. are expected, hence periodic re-calibration should be anticipated and facilitated.

5.1 ECE calibration

The standard approach for the absolute calibration of an ECE radiation signal (as opposed to relative calibration against another diagnostic) is the hot and cold blackbody radiating source technique. The receiver is re-directed via a rotatable mirror flips in and out of the waveguide (preferably close to the antenna) to two alternate (permanently installed) reference sources, one heated (hot source HC typically ~600C) and one at room temperature or even cooled with liquid nitrogen (cold source CS) [Vay97]. For ITER the CS will most likely be the vessel wall. As the difference signal is rather small, lock-in techniques with optical choppers are often employed and many hours of signal integration time are required. It is anticipated that a calibration may be necessary as often as once a month. For more frequent checks on the system stability an additional *stability source* has been proposed.

- Check operation of hot/cold sources and waveguide mirror actuator etc.

Requirement: Check correct operation of calibration sources, monitoring thermocouples and all mechanical waveguide components before and after installation.

5.2 Reflectometry calibration

Before inverting the reflectometer group delay it is necessary to remove the transmission line/antenna propagation. Since the waveguides and antennas will dilate and distort with thermal expansion and cm movement of the vessel (even during the pulse) a calibration procedure is required which can be interlaced with the measurements. Calibration typically involves a reflection from a known position. This can be achieved using either a controlled leak signal, for example the cross-coupling between the transmit and receive antennas, or using a localized reflection near the

antenna [Vay98]. One option is to incorporate a ruled grating on the second in-vessel mitre-bend to produce an out-of-band reflection (>230 GHz). Additional reflectometer electronics can be installed to monitor the reflection continuously during a plasma pulse. Additional static cross-calibrations should be performed using metallic reflectors positioned in-front of the antennas using the ITER in-vessel transport system.

- Perform initial line-length measurement.

Requirement: Install in-vessel reflectors after waveguide/antenna installation but before vessel closure and perform line-length measurements.

5.3 CTS calibration

The CTS receivers will require a similar calibration as for the ECE systems. Similar hot/cold sources are also proposed, with consequently identical functionality tests [Meo03].

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Appendix 1. ITER microwave diagnostics in question [ref. DDD]

1. Electron Cyclotron Emission ECE		
O & X-mode Michelson	70 GHz – 1 THz	Quasi-optic
O-mode Radiometer	122 – 230 GHz	4 bands: F, D, G +
X-mode Radiometer	244 – 355 GHz	4 bands. QO?
2. Reflectometers		
O-mode plasma position	15 – 60 GHz	3 bands: K, Ka, U
LFS O-mode profile	15 – 60 GHz +	3 bands as above
LFS O-mode profile	40 – 160 GHz	4 bands: U, E, F or W, D
LFS Xu-mode profile	76 – 180GHz	2(or 3) bands: W, D, (G)
HFS XI-mode profile	8 – 78 GHz	3-5 bands: (X), K, Ka, U, (V or E)
HFS O-mode profile	15 – 127 GHz	5-6 bands: K, Ka, U, E, F
3. ICRF antenna Reflectometers (proposed)		
LFS O/Xu-mode profile	10 – 60 GHz	3 bands: K, Ka, U
4. Collective Thomson Scattering CTS (proposed)		
LFS Xu-mode	55 – 65 GHz	1 band: V
HFS Xu-mode		Not currently enabled

Appendix 2. Target contributions for ITER ECE systems [SRD]

Category	Measurement Parameter Title	Plasma Conditions.Title	Coverage	Type	TimeResolution	SpatialResolution	Accuracy
04. Plasma	006: beta p	Ip > 3 MA	.01 - 5	3.S	100 us	Integral	5% @ bp=1
05. Radiated power	008: Main plasma Prad	Default	0.1 MW - 1 GW		1 ms		10%
14. H-mode, ELMs and L-H mode transition	032: ELM temperature transient	r/a > 0.85	0.05 - 10keV	2.B	0.1 ms	5 mm	5 %
15. Runaway electrons	034: Emax	(blank)	1 - 100 MeV	3.S	10 ms	-	20%
	035: I runaway	After thermal	(0.05 - 0.7) x Ip			(blank)	30 % rel.
		Failed breakdown	0 - 1 MA				50 kA
23. Electron temperature profile	052: Core Te	r/a < 0.85	0.5 - 40 keV	1.P	100Hz - 10kHz	a/30	0.1
	053: Edge Te	r/a > 0.85	0.05 - 10 keV	3.S		5 mm	0.1
27. High frequency instabilities (MHD, NTMs, AEs, turbulence)	061: NTM dT / Te. (complex; 100ms integration time)	Te > 1 keV,	(0.1 - 5) x 1E-2	1.P		(m,n) < (2,1),(3,2). dr=50mm	1 x 10-3
				3.S			1 x 10-3
	063: TAE DN / n, dT/T	(blank)	5E-6 - 5E-4		30 kHz - 2 MHz	n = 10 - 50	0.3

Appendix 3. Target contributions for the ITER reflectometer systems [after SRD]

Category	Measurement Parameter Title	Plasma Conditions.Title	Coverage	Type	TimeRes olution	SpatialResolution	Accuracy
02. Plasma position and	004: Main plasma gaps,	$p > 2$ MA, full bore	-	3.S	10 ms	-	10 mm
		lp quench					20 mm
06. Line- averaged electron	011: $[n_e dl / \int dl]$	Default	1E18 - 4E20 m-3		1 ms	Integral	1%
10. Plasma rotation	018: vPOL	(blank)	vPOL = 1 - 50 km/s		10 ms	a/30	0.3
14. H-mode, ELMs and L-H mode transition indicator	031: ELM density transient	$r/a > 0.85$	5E18 - 3E20/m3	1.P	0.1 ms	5 mm	10 %
				2.B			10 %
24. Electron density profile	054: Core n_e	$r/a < 0.85$	3E19 - 3E20 m-3	1.P	10 ms	a/30	0.05
				2.B			0.05
	055: Edge n_e	$r/a > 0.85$	5E18 - 3E20 m-3	1.P		5 mm	0.05
				2.B			0.05
27. High frequency instabilities (MHD, NTMs, AEs, turbulence)	063: TAE DN / n, dT/T	(blank)	5E-6 - 5E-4	1.P	30 kHz 2 MHz	$n = 10 - 50$	0.3

Appendix 4. Target contributions for the ITER CTS

Category	Measurement Parameter Title	Plasma Conditions.Title	Coverage	Type	TimeRes olution	SpatialResolution	Accuracy
11. Fuel ratio	020: nT/nD,	$r/a < 0.85$	0.01 - 10	3.S	100 ms	a/10	0.2
28. Ion temperature profile	064: Core Ti		0.5 - 40 keV			a/30	0.1
	065: Edge Ti		0.05 - 10 keV			5 mm	0.1
30. Confined alphas and fast ions	068: Alpha Density profile	(blank)	(0.1 - 2) E18 m-3	1.P	100ms	a/10	20 %
	069: Alpha Energy	Energy resolution 10 %	0.1 - 3.5 MeV,				20 %
	070: p, D, T He3 energy		0.1 - 1 MeV			a/20	20 %
44. nH/nD ratio in	094: nH/nD, core	(blank)	0.01 - 100	3.S	100 ms	a/10	0.2