# DIAGNOSTICS

# PROCUREMENT PACKAGE # 55.PF

# MICROWAVE DIAGNOSTICS

# ANNEX 1: TECHNICAL SPECIFICATION

# Contents

# LIST OF TABLES

# 1 5.5.F Microwave - System Description and Specification

## 1.1 Summary

The ITER microwave diagnostics considered in this PP are:

| **System** | **WBS 5.5…** | **Described from page** |
|---|---|---|
| Electron Cyclotron Emission (ECE) | F.01 | 11 |
| Main Plasma reflectometer | F.02 | 29 |
| Position reflectometer | F.03 | 41 |
| Divertor reflectometer | F.04 | 45 |
| Divertor ECA | F.05 | |
| Fast wave reflectometry | F.07 | 54 |

The diagnostics require wires, connectors, vacuum feed-throughs and windows. These are part of another PP. However relevant specifications given where known.

## 1.2 Measurement specification

Microwave diagnostics contribute to numerous plasma parameter measurements. Table 1 summarises the measurements and shows which of the sub-systems contribute to the measurement. Table 2 shows the measurement requirements corresponding to the measurements of Table 1.

**Table 1:Links between measurement purpose and measurement technique**

| # | Plasma Parameter to be measured | Purpose | Candidate Diagnostics |
|---|---|---|---|
| 2 | Plasma position and shape | Advanced Control | F.03 |
| 8 | Locked Modes | Basic Control | F.01 / F.02 |
| 9 | Low (m,n) MHD Modes, Sawteeth, Disruption Precursors | Basic Control | F.01 / F.02 |
| 10 | Plasma Rotation | Advanced Control | F.02 |
| 11 | Fuel Ratio in Plasma Core | Basic Control | F.07 |
| 14 | H-mode indicator | Basic Control | F.02 |
| 15 | Runaway electrons | Machine Protection | <F.01> |
| 23 | Electron Temperature Profile | Advanced Control | F.01 |
| 24 | Electron Density Profile | Advanced Control | F.02 |
| 27 | High Frequency micro-instabilities | Physics understanding | F.02 |
| 41 | Divertor electron parameters (ne, Te) | Advanced Control | F.04 |

A “,” links sub-systems working together for a measurement. A “/” separates alternative measurements. A “;” is a link to a backup or calibration system. Systems enclosed in < > provide qualitative information only.

Table 2: Measurement specifications (including target accuracy) for the measurements which depend on information from microwave diagnostics.

| **MEASUREMENT** | **PARAMETER** | **CONDITION** | **RANGE or COVERAGE** | **ΔT or ΔF** | **ΔX or Δk** | **ACCURACY** |
|---|---|---|---|---|---|---|
| Plasma Position and Shape | Main plasma gaps, $\Delta_{sep}$ | $I_p$ > 2 MA, full bore | - | 10 ms | - | 1 cm |
| | | $I_p$ Quench | - | 10 ms | - | 2 cm |
| Locked Modes | $B_r$(mode)/$B_p$ | | $10^{-4} – 10^{-2}$ | 1 ms | (m,n) = (2,1) | 30 % |
| Low (m,n) MHD Modes, Sawteeth, Disruption Precursors | Mode complex amplitude at wall | | TBD | DC – 3 kHz | (0,0) < (m,n) < (10,2) | 10 % |
| | Mode – induced temperature fluctuation | | TBD | DC – 3 kHz | 0,0) < (m,n) < (10,2)<br>Δr = a /30 | 10 % |
| | Other mode parameters TBD | | | | | |
| Plasma Rotation | $V_{TOR}$ | | 1 – 200 km / s | 10 ms | a/30 | 30 % |
| | $V_{POL}$ | | 1 – 50 km / s | 10 ms | a/30 | 30 % |
| Fuel Ratio in Plasma Core | $n_T/n_D$ | r/a < 0.9 | 0.1 – 10 | 100 ms | a /10 | 20 % |
| H-mode: ELMs and L-H Transition Indicator | ELM Dα bursts | Main Plasma | - | 0.1 ms | One site | - |
| | ELM density transient | r/a > 0.9 | TBD | | | |
| | ELM temperature transient | r/a > 0.9 | TBD | | | |
| | L-H Dα step | Main Plasma | | 0.1 ms | One site | - |
| | L-H Pedestal formation (ne, Te) | r/a > 0.9 | - | 0.1 ms | - | TBD |
| Runaway Electrons | $E_{max}$ | | 1 – 100 MeV | 10 ms | - | 20 % |
| | $I_{runaway}$ | After Thermal quench | (0.05 – 0.7) $\cdot I_p$ | 10 ms | | 30 % rel |
| Electron Temperature Profile | Core Te | r/a < 0.9 | 0.5 – 30 keV | 10 ms | a/30 | 10 % |
| | Edge Te | r/a > 0.9 | 0.05 – 10 keV | 10 ms | 0.5 cm | 10 % |
| Electron Density Profile | Core Ne | r/a < 0.9 | 3·1019 – 3·1020 / m3 | 10 ms | a/30 | 5 % |
| | Edge Ne | r/a > 0.9 | 5·1018 – 3·1020 / m3 | 10 ms | 0.5 cm | 5 % |
| High frequency macro instabilities (Fishbones, TAEs) | Fishbone – induced perturbations in B,T,n | | TBD | 0.1 –10 kHz | (m,n) =(1,1) | - |
| | TAE Mode – induced perturbations in B,T,n | | TBD | 30 –300 kHz | n = 10 - 50 | - |
| Divertor electron parameters | $n_e$ | | $10^{19} – 10^{22}$ /m3 | 1 ms | 10 cm along leg, 3 mm across leg | 20 % |
| | $T_e$ | | 0.3 –200 eV | 1 ms | 10 cm along leg, 3 mm across leg | 20 % |

## 1.3 Additional design and costing assumptions

### 1.3.1 General

The system is designed for 100% availability except where explicitly noted otherwise.

### 1.3.2 Vacuum

Sensors, wiring, in-vessel connectors and electrical feedthroughs are compatible with the torus vacuum.

### 1.3.3 Mechanical

In vessel components and attachments to the machine structures shall survive accelerations up to 30 g (20 ms) for >1000 cycles.

### 1.3.4 Electrical / Electronic

The main earthing point is the vacuum vessel. Earth loops are avoided by laying cables radially outward from the machine and providing an optical break in the input circuit. This protects the digital input circuit which has a local earth.

HF Oscillations will normally be observed using amplifiers. The data will be recorded at variable rates (typ. 20 kHz to 1 MHz) for selected times. The selection of the rate will be automatic. The analysed signals, mode numbers and amplitudes, may provide indicators for limits of the plasma stability and may initiate evasive action.

Automatic tests shall be provided for all main functions of the front end electronics and coupled to an alarm system for all sub-systems in "advanced control" category (see table 1.1-1).

Other than for direct tests of the link to the data acquisition system (CODAC), sufficient control (computing , instrumentation, effectors and local data storage and analysis) capability shall be built into each sub-system so that maintenance, fault finding and alignment procedures can be performed in a stand-alone fashion.

### 1.3.5 Thermal

Components mounted on the inner wall of the vacuum vessel will be cooled by conduction and radiation to the surrounding structure. The maximum operating temperature shall be 900 °C. Design is to assure fast thermal relaxation of overheated antennas or other near-first-wall structures to avoid self-sustained chemical reactions between the materials and steam.

### 1.3.6 Radiation

All components and wiring on the inner wall of the vessel are designed to survive the maximum expected neutron fluence at their location.

RF (3 - 300 GHz) leakage from test sources, local oscillators or the plasma at joints where personnel exposure is possible shall be limited to < 10 mW / cm $^2$.

### 1.3.7 Installation

The location of first mirror and antennas w.r.t. the vessel / block axes shall be accurate within 30 / 10 mm except as individually noted. The orientation shall be accurate to 1.5° / 1°.

### 1.3.8 Maintenance

Sources, receivers and instrumentation will be monitored electronically during pulses.

Sources, receivers and instrumentation will be accessible for inspection and maintenance during pulses.

Accessible in-vessel components will be inspected during scheduled maintenance periods.

## 1.4 Common QA

This section specifies tests common to all sub-systems. Additional tests are recorded in the sub-system sections.

### 1.4.1 Factory tests

- Leak test of mechanical feed-throughs
- Vacuum bake of all in vessel and cryostat interspace components

### 1.4.2 Testing during installation

- Optical alignment mirror to mirror.
- Waveguide joint visual inspection by endoscopy techniques.

### 1.4.3 Post-installation Testing

- Installation accuracy
- Continuity and polarity from ex-vessel connector
- Voltage stand-off, resistance to earth

### 1.4.4 Commissioning Tests (without plasma)

- Reflectometry (reflectivity vs. distance by radar technique) of each waveguide run mid-band.
- Cross-talk vs. distance by radar technique for each waveguide pair on the same run.

# 2 F.01 Electron Cyclotron Emission

This sub-system is comprised of

- In-vessel quasi optical antenna system
- Port Interspace waveguide system
- In vessel calibration source
- In vessel shutter / mirror mechanism
- Port interspace mechanical transmission system
- Ex-cryostat waveguide system
- Diagnostic Hall signal distribution system
- Diagnostic Hall spectrometers

## 2.1 Sub-System Description and Specification

### 2.1.1 Functions and Performance Specification

The Electron Cyclotron Emission (ECE) is one of several diagnostic systems proposed for ITER. Its objective to provide the electron temperature with good spatial and temporal resolutions. Secondary objectives are to obtain information on non-thermal electron populations and the power loss due to ECE.

The system divided into three main parts:

- the front end, which collects the radiation from the plasma and transmits it through to the pit;
- the transmission system which transports the ECE emission from the front end to the instrumentation and
- the instrumentation which is housed at a distance from the tokamak in an ITER provided building.

### 2.1.2 Description

The ECE front end uses two collection antennas. A view of the front end from the plasma is shown in Figure 2.1-1. The antennas are staggered vertically to give access to the core for a variety of plasma heights near the nominal plasma centre height. All antennas are Gaussian beam telescopes (Figure 2.1-2). The antennas are subject to surface heat loads of ~50 kW/m$^2$ during plasma operation and therefore are cooled. For each antenna, there are built-in calibration hot sources at the front end. The sources can be intermittently viewed through a shutter (Figure 2.1-3). A schematic of the front end, showing the major components of one sightline, is shown in Fig. 2.1-4.

The radiation from each antenna is transmitted to the pit using wide band corrugated waveguide with suitable assemblies to take up machine movements. There, the signal is split into X and O mode components using a polarising beam splitter, before transmission to the diagnostic hall by a dedicate evacuated corrugated waveguide system. In the diagnostic hall, the signal is divided between two survey spectrometers and two fixed multichannel spectrometers.

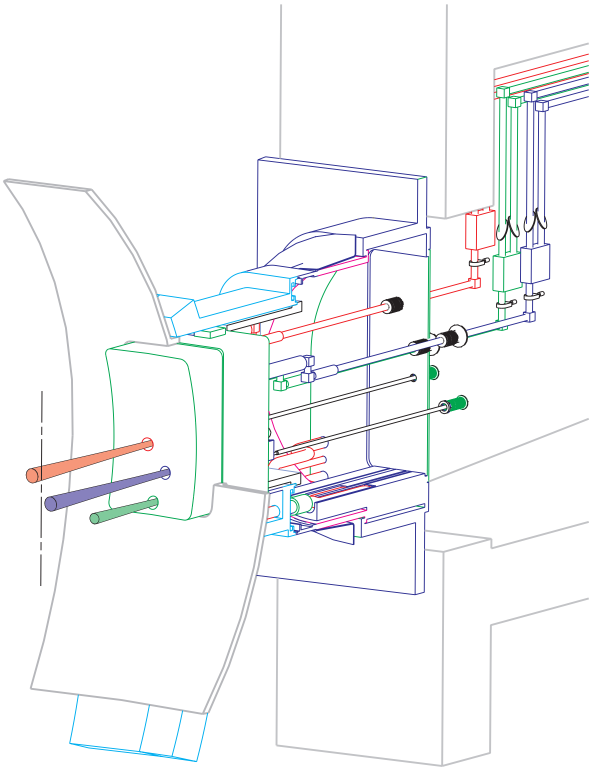


Figure 2.1-1: View of the ECE system from the plasma side. The vacuum vessel port extension has been cut to show interspace equipment. Note that the 3rd sightline (in green) has been eliminated since this picture was created.

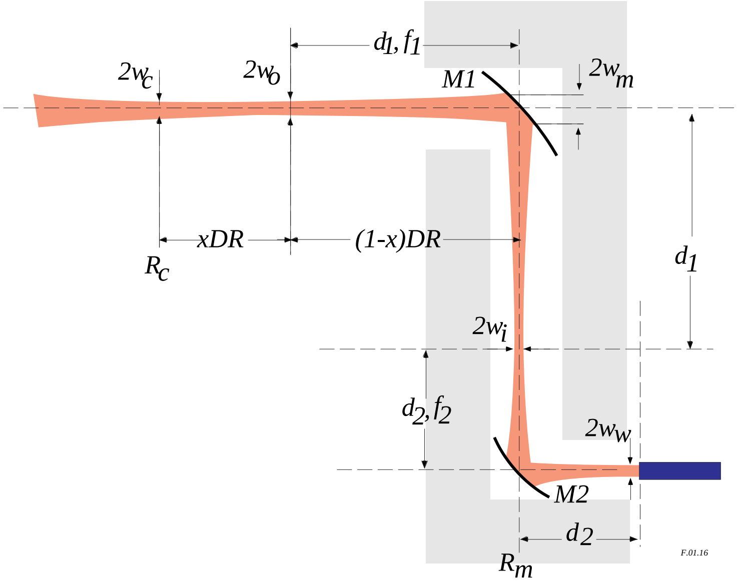


**Figure 2.1-2: Principle of the Gaussian beam telescope (sketched embedded in shielding). Quasi-monomode radiation collected from the plasma (left) is matched onto the HE11 mode at the input of the waveguide (right).**

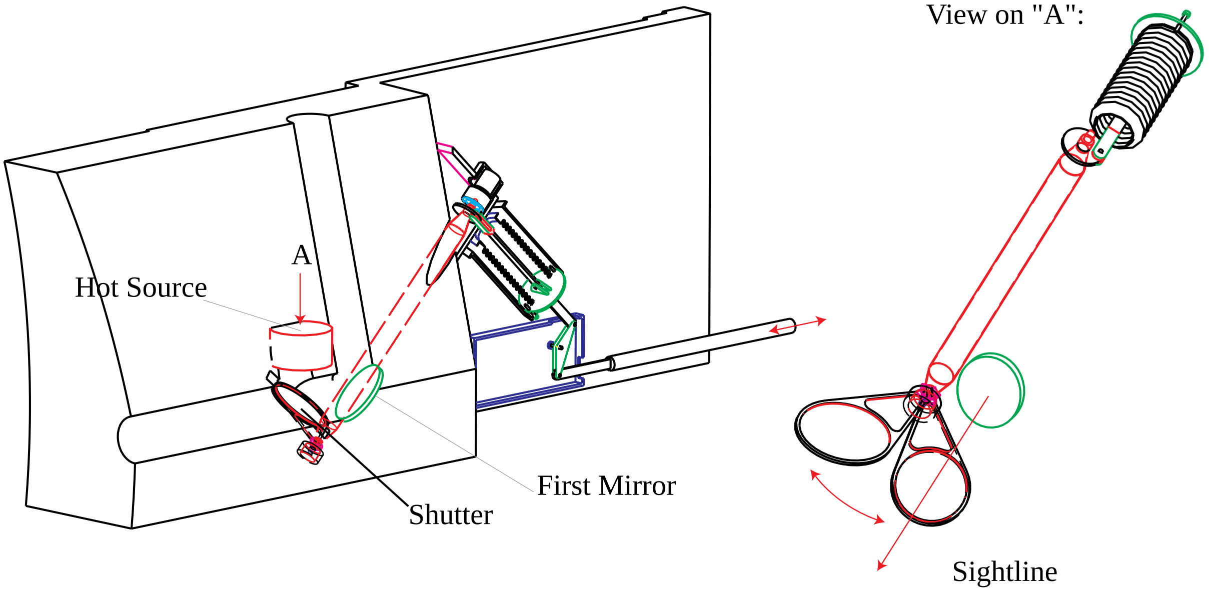


**Figure 2.1-3: Principle of the calibration source / shutter**

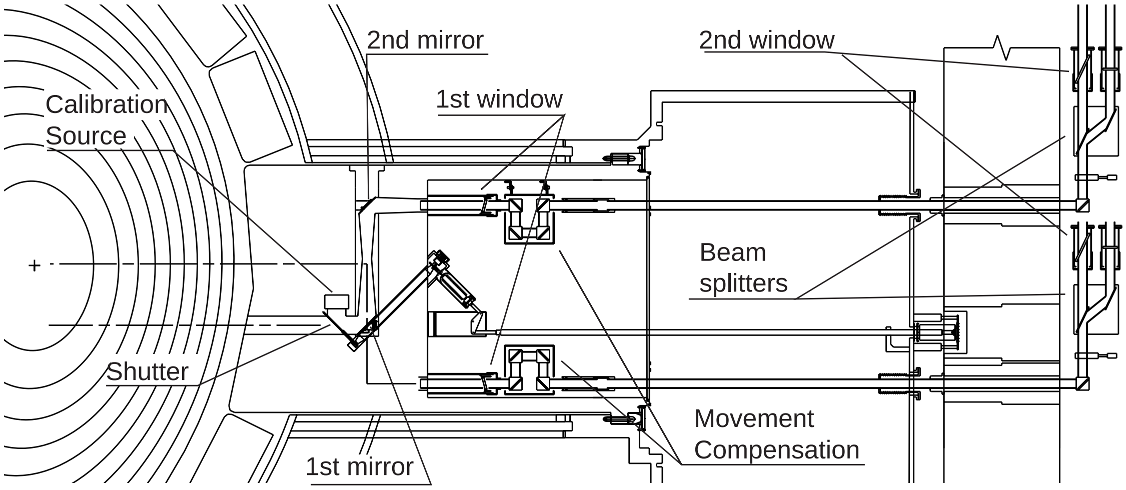


**Figure 2.1-4: Sketch of the system through the port, showing key elements.**

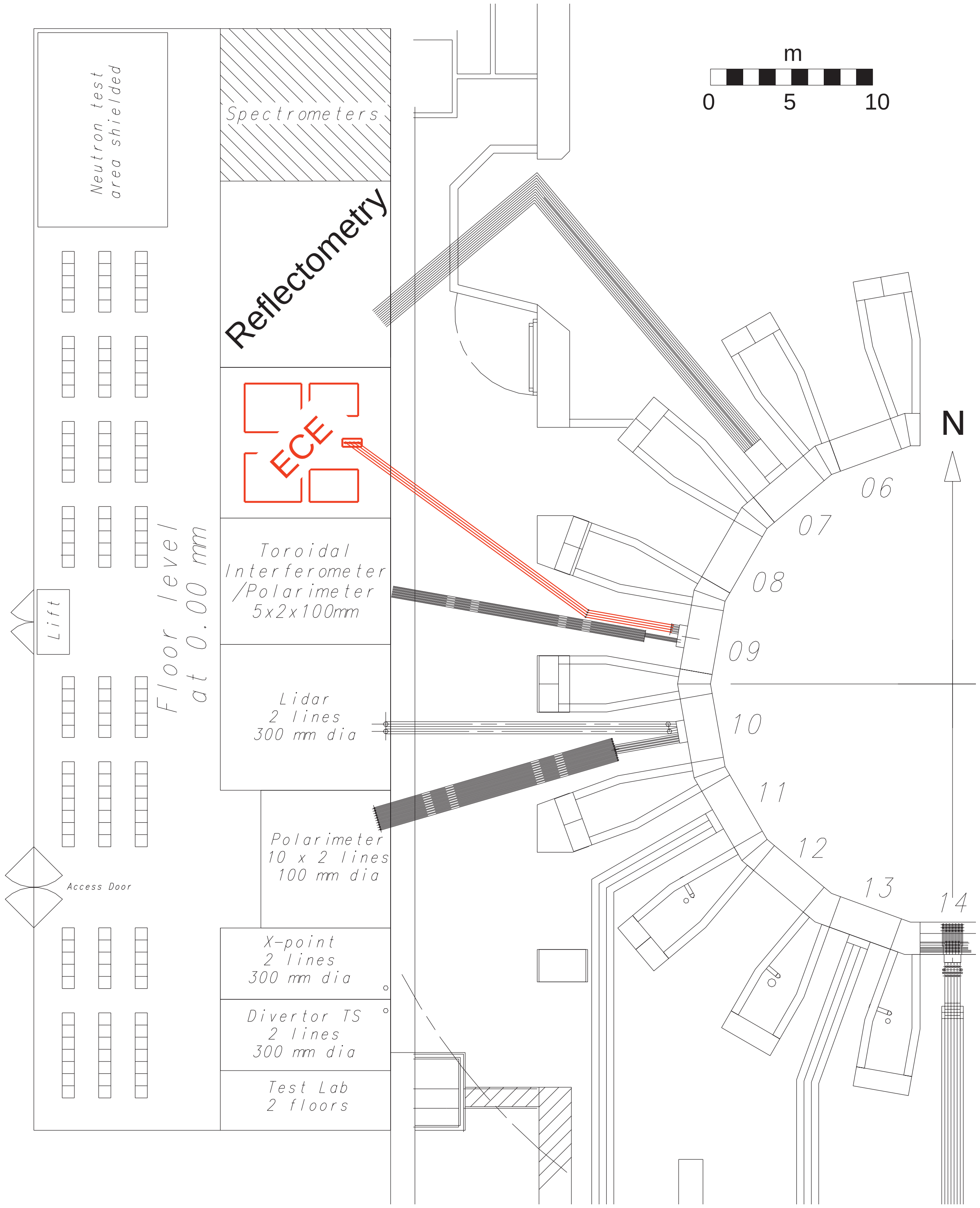


**Figure 2.1.5: Plan view of the ECE waveguide route to the diagnostic hall. There are 5 mitre bends and ~ 30 m of waveguide between the bioshield and the distribution box.**

### 2.1.3 Assembly

The front end is supplied from the factory in modular sub-assemblies. Figure 2.1.-6 shows some of the key modules, including the two telescope units, hot sources, shutter mechanisms, vacuum extensions (bearing the vacuum windows), and movement compensation assemblies.

The modules are attached to units or sub-units of the diagnostic block as part of another PP (55.PN).

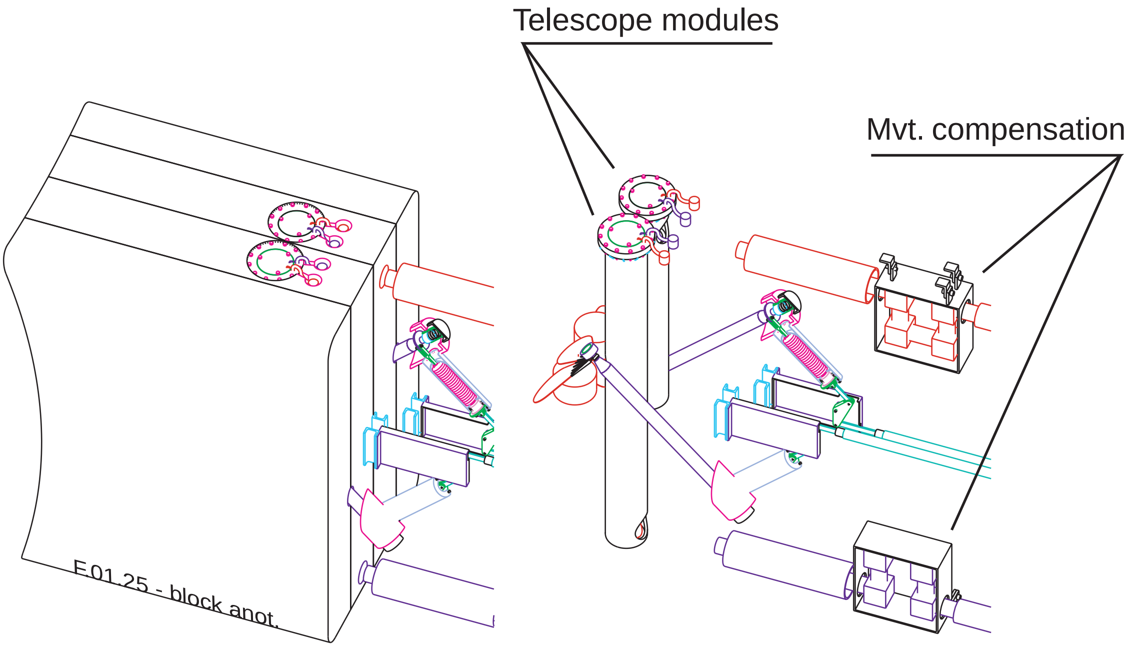


**Figure 2.1-6: Key diagnostic block sub-assemblies in the block (left) and with the shielding removed (right)**

### 2.1.4 Specific Commissioning

A spot comparison (in frequency) of the calibration using the block source with a standard source in-vessel is required once the block is assembled. This requires the use of a spectrometer covering approximately the same wavelength range as the one intended for final use (it can be the same one if available).

## 2.2 Component Description and Specification

### 2.2.1 Microwave components

2.2.1.1 First and Second mirror

The first two mirrors form a Gaussian beam telescope, which can be thought of as projecting the radiation pattern at the mouth of the exit waveguide (in HE11 mode) to the resonance plane in the plasma.

The mirror focal lengths are chosen to minimise the spot size in the core of the plasma for the minimum O-mode frequency, subject to the additional constraint of a first mirror size no larger than 200 mm aperture.

The mirrors are ellipsoidal. Their specifications are summarised in Table 3 and Table 4.

**Table 3: Nominal parameters for the ECE first mirror**

| Parameter | Value | Comment |
|---|---|---|
| Material | St. St. | Polished to optical quality |
| Thickness (max.) | 10 mm | |
| Cooling | External st.st. spiral tube, welded on back | |
| Support | 3-point, fixed | Accurate to ± 1 mm / 0.1° |
| Nominal Aperture | 200 mm | |
| Inclination | 45° | |
| Nominal Focal Length | 1000 | |

**Table 4: Nominal parameters for the ECE second mirror**

| Parameter | Value | Comment |
|---|---|---|
| Material | Copper plated St. St. | Polished to optical quality |
| Thickness (max.) | 10 mm | |
| Cooling | External st.st. spiral tube, welded on back | |
| Support | 3-point, factory adjustable, spot welded for transport / installation | Adjustment Range ±5 mm, 0.5° |
| Nominal Aperture | 200 mm | |
| Inclination | 45° | |
| Nominal Focal Length | 1000 | |

2.2.1.2 Telescope tube

The telescope tube holds the first two mirrors in factory pre-aligned position. It is formed of two concentric stainless steel tubes, with a water cooled cavity interspace, reinforced with ribs. Water from this cavity is tapped off to cool the mirrors. Connections to the block cooling circuit are by two standard welded water connectors, shown at the top of each tube. Shielding blocks are added in each tube as appropriate to allow the top of the tube to rest flush with the top of the diagnostic block, where its flange is bolted to the block. Shims are used during block assembly to adjust the tube in order to align the telescope with the first wall aperture.

### 2.2.1.2 Primary vacuum window

The 1st vacuum barrier is a fused silica window of 150 mm nominal diameter, supported on a plane inclined 15° to the direction of beam propagation to mitigate standing wave effects, and designed for over pressures to 5 bar in the primary vacuum side, and 2.5 bar on the secondary vacuum side.

The vacuum barrier assembly is designed to be remotely welded / cut along a circular lip. The window is bonded on an annular lip, in turn mounted on a relatively thin support of cylindrical cross-section designed to accommodate thermal expansion differentials between the support and the window (see figure 2.2.1-1). The window itself is part of PP 55.PN.07.

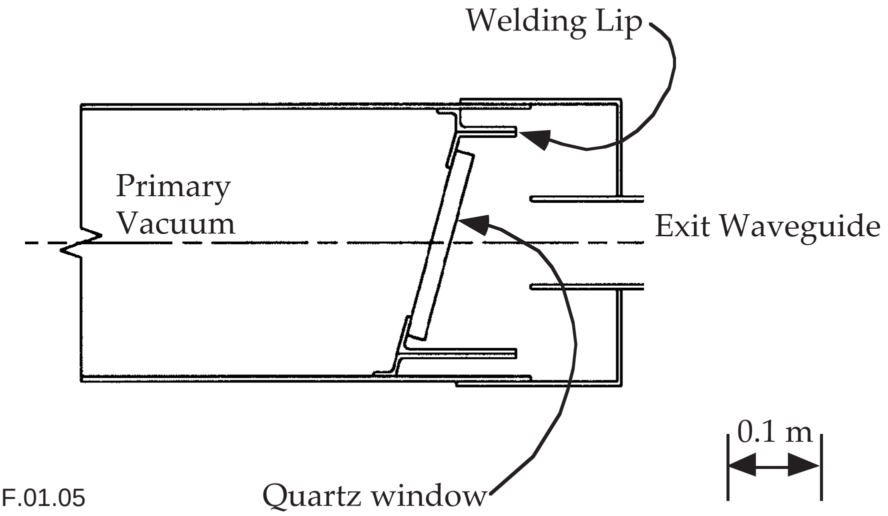


**Figure 2.2.1-1: The first vacuum window at the end of the vacuum extensions attached to the vacuum vessel seal plate. The window clear aperture is 150 mm dia. Note that this is a schematic only, not showing the flexible support necessary to isolate the window from the stiff vacuum extension.**

**Table 5: Critical parameters of the ECE 1$^{st}$ window.**

| Parameter | Value | Comment |
|---|---|---|
| Angle between two faces | .1 mrad | |

### 2.2.1.3 Movement compensation unit (MCU)

The first part of the movement compensation mechanism is attached to the end of the primary vacuum extension, immediately after the window. It is a pair of waveguide dog-legs, which permit swivelling (shift and tilt) in the plane perpendicular to the antenna axis. The vertical sections have sliding joints permitting a variation in height.

The orientation of this waveguide with respect to the last mirror on the diagnostic block (primary vacuum) side, is critical, so a special 1/4 turn bayonet type locating mechanism is used to mount it to the vacuum extension (not shown in Figure 2.2.1-1).

The arm of the dog-legs is vertical because it is primarily designed to alleviate the effect on the waveguide of the frequent (~ twice per pulse) small displacements of the vacuum vessel in the toroidal direction.

The alignment tolerance in the swivel joints is critical because machine movements make any power loss time dependent, so this error will not be compensated for by the calibration.

**Table 6: Critical parameters of the ECE MCU. The ranges include full provision for installation adjustment.**

| Parameter | Value | Comment |
|---|---|---|
| Range – radial | 0 mm | Taken up by the interspace waveguide bearing / coupling joint (below) |
| Range – vertical | 30 mm | |
| Range – poloidal | 20 mm | |
| Range – angular | 3 mrad | Poloidal plane only |
| Alignment tolerance (bend/bend and tube / bend) | 0.3 mrad | |
| Bearings | UHV compatible | |
| Design life | > 10 $^{5}$ cycles | |

2.2.1.5 Interspace waveguide

The interspace waveguide is a straight piece of corrugated waveguide, with an oversize bearing and coupling assembly (Figure 2.2.1-2) forming the second half of the movement compensation mechanism. In addition, it provides a gap in the transmission line which helps attenuate spurious waveguide modes.

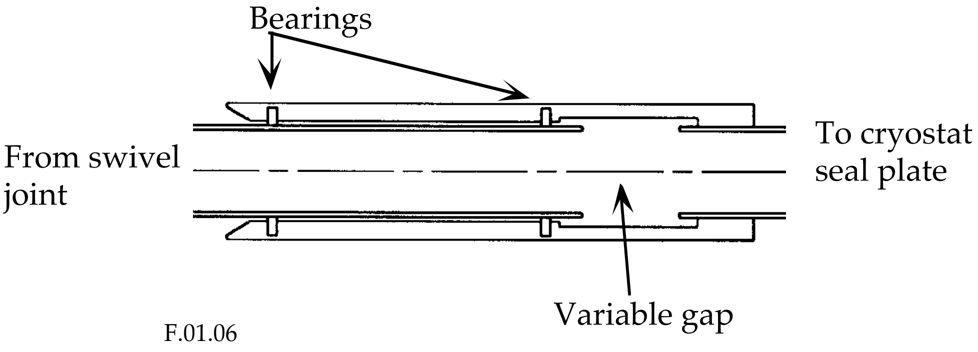


**Figure 2.2.1-2: Detail of the bearing / coupling joint**

During operation, the waveguide extension is sealed to the cryostat seal plate using a bellows. This bellows de-couples the cryostat movement from the transmission line. The part of the waveguide extension outside the cryostat seal plate forms a secondary vacuum boundary extension.

The bearing assembly engages onto the swivel joint when the cryostat seal plate is placed into position. It compensates for the radial expansion of the vacuum vessel

To allow for the easy removal of the bioshield subsidiary plug with the waveguide flanged outside the bioshield, the ex-cryostat part of the vacuum extension has a metal sleeve. This sleeve can also be used to lock the waveguide onto the cryostat seal plate, if removal of the complete assembly is needed.

The waveguide / vacuum extension penetrates the bioshield through a subsidiary shield plug.

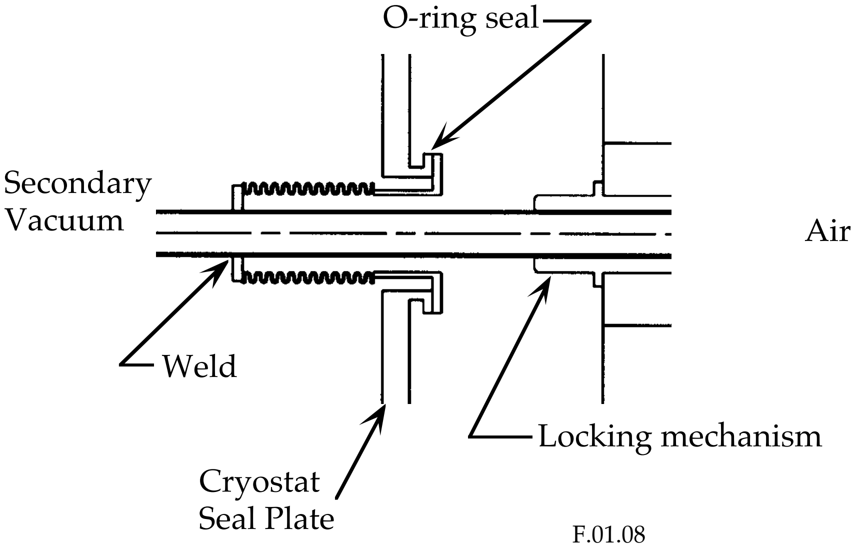


**Figure 2.2.1-3: Detail of the region around the cryostat seal plate**

The bellows / seal assembly is designed to accommodate the cryostat movement and some tolerance with respect to the bioshield. The movement range it can accommodate is ± 3.0 cm (TBC) in the vertical and toroidal directions and ± 2.5 cm (TBC) in the radial direction. The bellows / seal assembly is welded to the waveguide extension. The bellows / seal assembly is bolted onto the cryostat seal plate
The vacuum boundary between the main horizontal port secondary vacuum and atmosphere is an elastic O-ring, clamped in place by the bellows /seal assembly.

The sleeve mentioned in above (“locking mechanism” in Figure 2.2.1-3) locks the waveguide extension to the bellows / seal assembly when the waveguide is removed or installed. It becomes part of the bioshield during operation.

#### 2.2.1.6 Isolator valve

An isolator valve is fitted on the exit waveguide to allow for easy isolation of transmission line components. This is a standard high vacuum valve with special adapter flanges to the waveguide. The required clear bore is 100 mm.

#### 2.2.1.7 Beam splitter & box

For each waveguide, outside the cryostat and bioshield there is a QO beam splitter, using a conductive grid printed onto a fused quartz substrate and inclined at the Brewster angle. This beam splitter separates the O and X polarisations with low power loss.

A vacuum extension box contains the polarisation beam splitter described above. The combined beam splitter / second vacuum boundary box is shown in Figure 2.0.3-5.

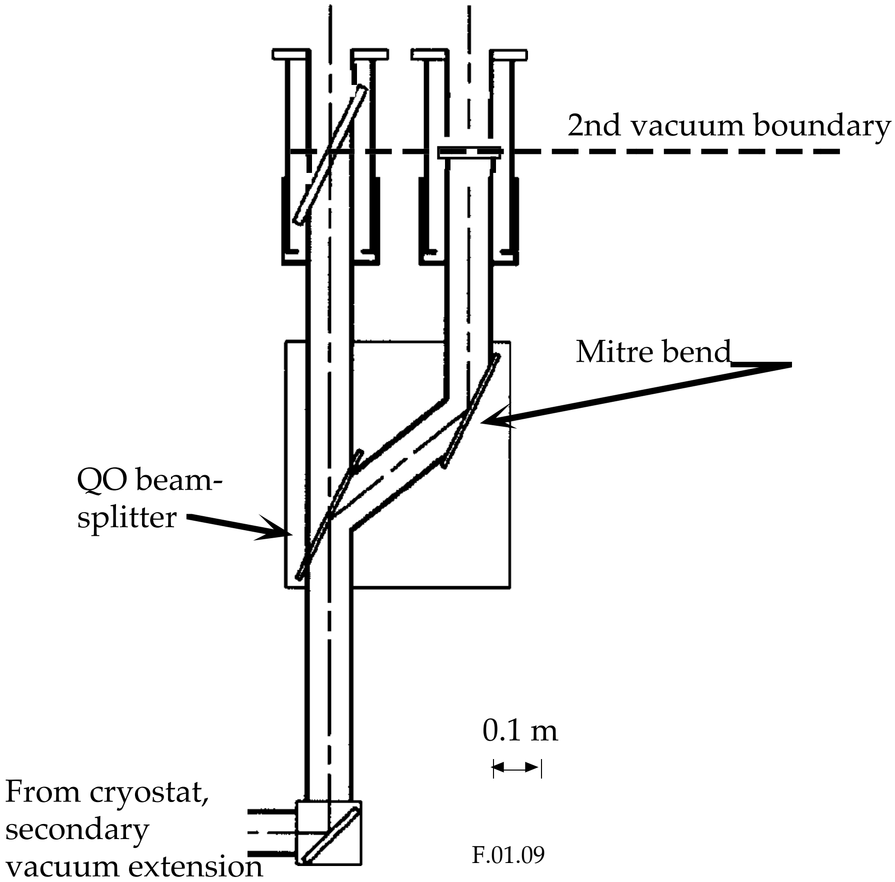


**Fig 2.2.1-4: Beam splitter and second vacuum boundary. Note that the vacuum valve is not shown.**

The box is mounted on the waveguide extension, and supports the second vacuum boundary window assemblies. The pressure boundary is maintained by means of an O-ring seal at the connection with the waveguide extension and the second vacuum boundary window assembly flanges.

2.2.1.4 Secondary vacuum window

This is an in-waveguide SiN Brewster angle window (71° inclination). This window forms part of PP 55.PN.07.

2.2.1.5 Pit waveguide

The radiation from each antenna is split in O and X-mode. Thus there are 4 waveguides transporting the radiation to the diagnostic hall, where the instrumentation is located. The waveguide is of the oversize circular corrugated type, with a diameter of 89.5 mm.

The waveguide is evacuated to reduce calibration uncertainties due to water absorption. Rough vacuum is sufficient for this purpose. The waveguide is fitted with pressure relief mechanisms (burst disks) for the unlikely event of a double window failure. These vent into the pit. The pumping station for the waveguides (not shown) is also in the pit.

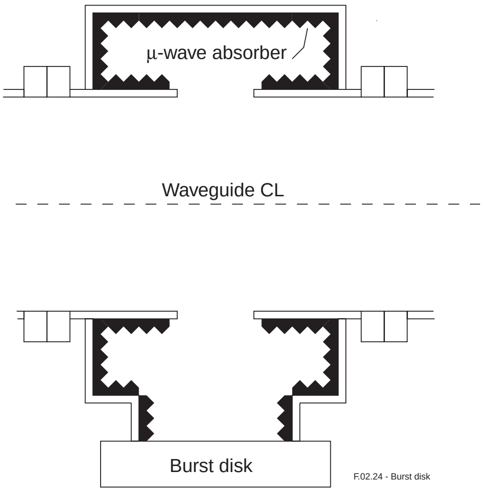


**Figure 2.2.1-5 Waveguide burst disk**

The total length of waveguide required is ~ 30 m. for each line. Figure 2.1.-5 shows the nominal waveguide path through the ITER building.

### 2.2.1.6 Splitter unit

An automated system of switches and selectable beam-splitters is to be provided to allow for the selection of transmission lines in real-time, with a switch-over delay of 0.25s or less. Figure 2.2.1-5 shows a schematic of the switching arrangement. The splitter unit is at atmospheric pressure. At each input to this unit, a thin mylar window is used. For each input line, a polarisation rotator is also fitted.

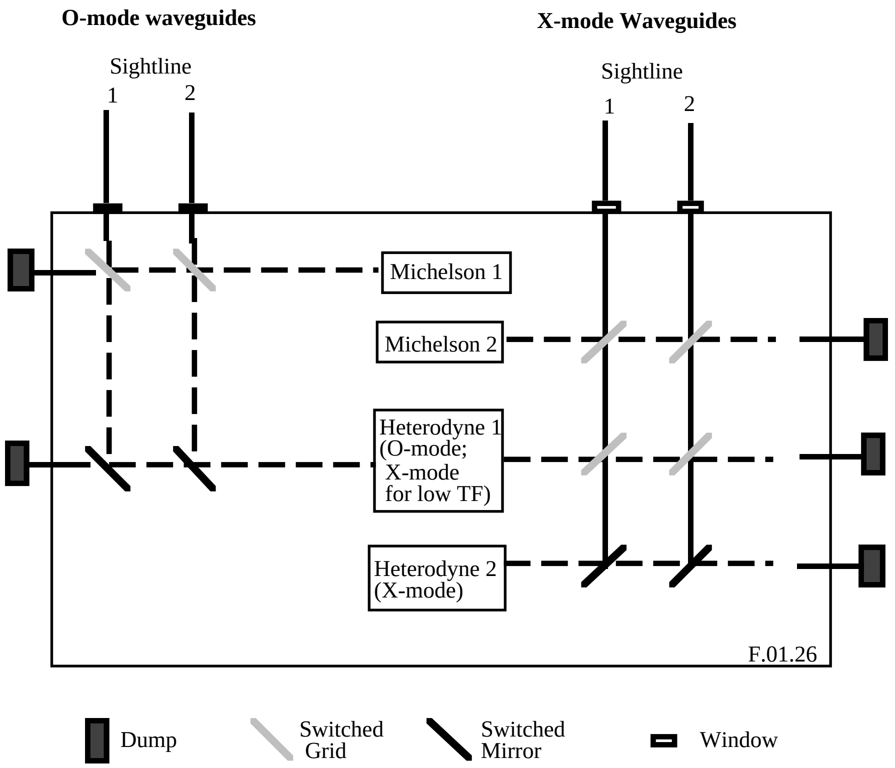


**Figure 2.2.1-6 Connection diagram for the sightline switch-over unit for costing purposes. The unit (not depicted) is at atmopspheric pressure; thin mylar windows**

### 2.2.1.7 Michelson Spectrometers

The characteristics of these spectrometer are shown in Table 7. A schematic of the assumed operating principle is shown in Figure 2.2.1-7

**Table 7 Nominal specification for the O and X-mode Michelson spectrometers**

| Parameter | Value | Comment |
|---|---|---|
| Type | Reciprocating mirror Martin-Puplett type Michelson interferometer. | |
| Spectral range | 70 GHz – 1 THz | |
| Resolution | 10 GHz | |
| Scan rep. rate | 20 ms | |
| Duty cycle | continuous | |
| Detector | Indium Antimonide Hot Electron Bolometer | |
| Noise Equivalent Temperature at input | 10 eV | |
| Dimensions (L x W x H) | 3 x 2 x 2 m | Excludes detector, PSUs and Liquid He Supply equipment. |

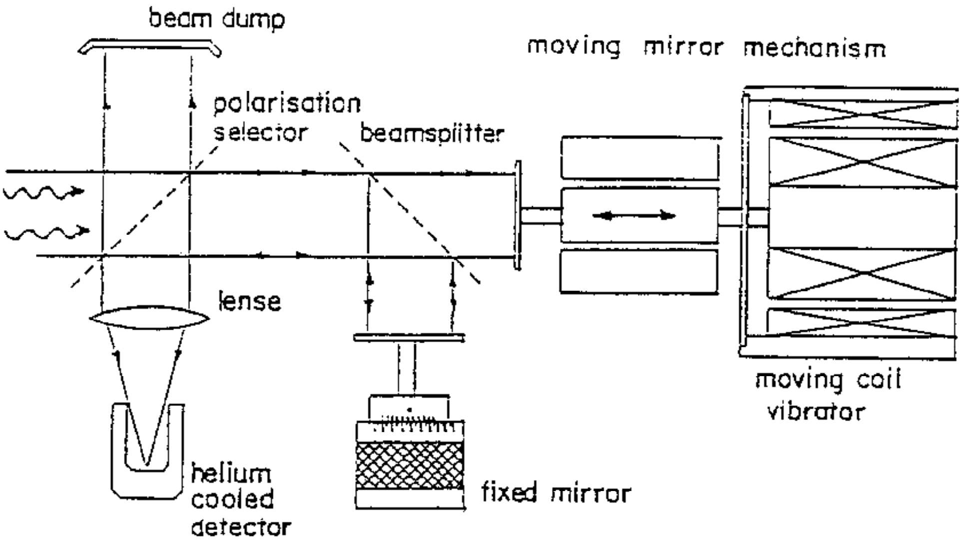


**Figure 2.2.1-7: Principle of operation of a simplified Martin-Puplett type Michelson interferometer. The throw of the moving mirror is inversely related to the required resolution.**

### 2.2.1.8 Heterodyne (O-mode)

**Table 8 Nominal specification for the O-mode heterodyne radiometer**

| Parameter | Value | Comment |
|---|---|---|
| Type | Multi-band, Broadband multichannel receiver | |
| Frequency range | 122 GHz – 230 GHz | |
| Channel separation (122-139 GHz) | 1 GHz (18 Chan.) | F-band waveguide (edge);<br>1 mixer |
| Channel separation (141-169 GHz) | 2 GHz (15 Chan.) | D-Band waveguide;<br>2 mixers |
| Channel separation (172-218 GHz) | 3 GHz (16 Chan.) | G-Band waveguide;<br>2 mixers |
| Channel Separation (222-230 GHz) | 4 GHz (3 Chan) | 1 mixer |
| Duty cycle | continuous | |
| Detector | Mixer / IF Amp/ Detector | |
| Video BW | 1 us – 100 us | Further integration to be performed digitally |
| Dimensions (L x W x H) | 3 x 3 x 2 m | Excludes PSUs and electronics |
| | | |

2.2.1.9 Heterodyne (X-mode)

**Table 9 Nominal specification for the X-mode heterodyne radiometer**

| Parameter | Value | Comment |
|---|---|---|
| Type | Multi-band, Broadband multi-channel / single channel receiver | |
| Frequency range | 244 GHz – 355 GHz | |
| Channel separation (244-278 GHz) | 2 GHz (18 Chan.) | edge; 2 mixers |
| Channel separation (282-298 GHz) | 4 GHz (5 Chan.) | 1 mixer; limit of multi-channel capability |
| Channel separation 302-338 GHz | 4 GHz (10 Chan.) | 10 mixers |
| Channel separation (343-353 GHz) | 6 GHz (3 Chan.) | 3 mixers |
| Duty cycle | continuous | |
| Detector | Mixer / IF Amp/ Detector | |
| Video BW | 1 us – 100 us | Further integration to be performed digitally |
| Dimensions (L x W x H) | 3 x 3 x 2 m | Excludes PSUs and electronics |
| | | |

### 2.2.2 Mechanical components

2.2.2.1 Vacuum extension

The purpose of the vacuum extension is to bring the first window components out of the re-entrant cavity of the port, to a place where they can be easily accessed for maintenance. It forms part of PP 55.PN.

2.2.2.2 Shutter, Shutter Shaft, Shutter Cap, Shutter feedthrough

A shutter/mirror is introduced in front of the first antenna element allowing it to view the hot source located above the beam line. The design of the shutter is constrained by the cycling requirement of $>10^5$ cycles between maintenance operations, the operation in vacuum, the thermal management and the requirement to preserve the double vacuum boundary.

To conserve space within the block, and allow the shutter to rest in a position normally protected from the plasma, it is brought into the sightline by rotation about an axis at 45° to the vertical, slightly behind the first element of the antenna. The rotation extent is 50° between resting positions.

The mirror on the shutter is made out of a thin sheet of tungsten, with a polished side facing the hot source. The other side is roughened to form an efficient radiator.

The mirror and frame are designed to withstand indefinite exposure to the plasma during operation (typical heat load 50 kW/m2), so they can act as a protective shutter, and survive accidental exposure. In normal machine operation they are shielded from the plasma in a recess within the diagnostic block.

Transmission of the mirror movement to the intermediate vacuum is by means of an axle, a connecting rod and of a guided bellows assembly, designed to withstand overpressure events of up to 5 bar. The movement of the bellows is 42 mm.

The components inside the primary vacuum are cooled by radiation. Thus, the mirror, and the thin hollow axle rotating the shutter, are designed to form effective radiation heat sinks to the surrounding shielding, for the frame assembly and the moving part of the bearing, respectively.

The axle incorporates an insulating break. It is coupled to the shutter by a relatively loose plug and socket arrangement. Thus the axle can be inserted and extracted from the rear of the block.

The mechanism is designed to be serviced in the hot cell (see section 4). Nevertheless the mechanism is simple enough for maintenance to be possible in situ, for parts from the axle outwards.

The lower bearing is a UHV compatible all-metal sliding bearing, rated at $10^6$ reversals. The upper bearing is a dry lubricated (UHV compatible) all metal single row angular contact rolling bearing, sliding within a sleeve and pre-loaded by a spring. The spring is designed to take up tolerances in normal operation. The lower bearing supports the weight of the shaft (~3 kg, resulting in 15 N side load and 15 N axial load) and the spring load thrust (50 N; axial) .

The axle lug (disk) is connected to a clevis using a single pin joint, incorporating a self-aligning, all-metal, plain spherical bearing, dry lubricated (UHV compatible). The clevis connects to the bellows flange using a sliding single pin joint, and a similar bearing.

#### 2.2.2.3 Actuator extension

Transmission to the second vacuum boundary at the cryostat seal plate done by a lever and an ~5 m long connecting rod connected to a simple lever mechanism.

The connecting rod is designed to be inserted from the air side after the installation of the seal plate, and locks to the lever assembly with a bayonet coupling. It is made of CFC.

Single pin joints incorporating self aligning plain spherical bearings are used throughout.

#### 2.2.2.4 Secondary Mechanical feedthrough

At the cryostat seal plate, there is a guided bellows assembly, designed to accommodate both the shutter movement and the thermal expansion effects between the vacuum vessel and the cryostat (~ 3 cm), a total of 7 cm radially. An edge-welded bellows is used to reduce the overall length. The displacements and rotations due to movement of the vessel in the toroidal and vertical direction are taken up in the connections at either end of the rod.

#### 2.2.2.5 Actuator

The shutter is moved by a balanced pair of compressed air driven pistons acting on the Actuator Bellows assembly . The pistons are attached to the cryostat seal plate

### 2.2.3 Electrical Components

#### 2.2.3.1 Calibration Source

The calibration source is a cylindrical st. st. container containing heating elements, internal radiation reflecting elements and a main radiating element directing thermal radiation to the shutter / mirror. Its parameters are shown in Table 10.

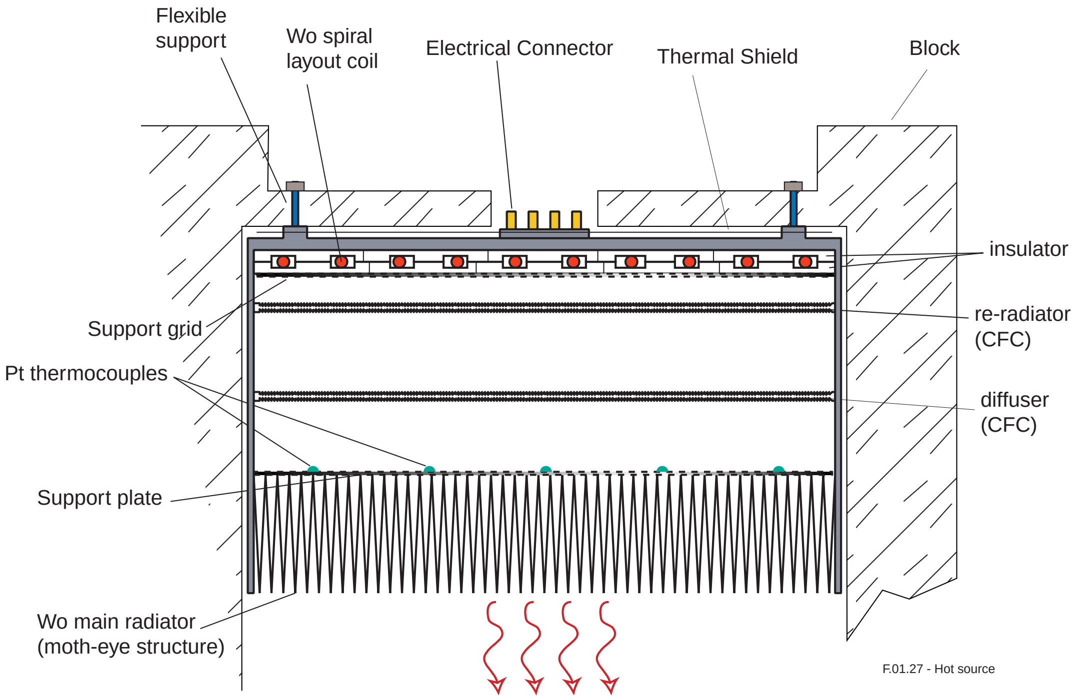


**Figure 2.2.2-1: Sketch of the hot source cross-section (to scale) for costing purposes. The overall diameter of the source is 200 mm**

**Table 10: Critical parameters of the ECE hot source**

| Parameter | Value | Comment |
|---|---|---|
| Temperature, max | 1000 °C | Any external surface; heater left on; in the plug. |
| Temperature, max | 1200 °C | Minimum rating of all components |
| Nominal radiation temperature | 700 °C | |
| Radiation temperature accuracy | 10 K | Long term stability included |
| Radiation temperature stability | 3 K | 24 hr period |
| Radiation temperature uniformity over surface | 10 % | |
| Absolute emissivity | > 0.7 | 122 GHz – 366 GHz |
| Absolute emissivity | > 0.5 | 70 GHz – 1THz |
| Lifetime | > 5000 hrs | > 100 calibrations |
| Efficiency | > 0.7 | power radiated through front aperture / total power input |
| Filament supply | 220 V / 20 A | Maximum |

#### 2.2.3.2 Calibration power supply

Each calibration source is designed to be powered by a triac-controlled 220 V AC 50/60 Hz supply rated at 5 kW. Regulation of the power supply is made using the Pt thermocouples as sensors.

### 2.2.4 Control and Data Acquisition

Approximately 105 channels of variable gain, variable rate (1 – 100 us) data acquisition channels are required for the ECE system, distributed as follows:

**Table 11:** Fast data channels for the ECE system

| System | Number of channels |
|---|---|
| O-mode radiometer | 61 |
| X-mode radiometer | 36 |
| O-mode Michelson | 4 |
| X-mode Michelson | 4 |

In addition, slow data acquisition is required to check the settings of mm-wave switches etc., and to monitor the calibration process (including thermocouple). The number of these channels is estimated to be ~ 100.

Refer to Annex 7 for details of the coupling of this sub-system to CODAC.

# 3 F.02 Reflectometry for the main plasma

This sub-system is comprised of

(i) **LFS X** : an extraordinary mode (X-mode) launch system, reflecting off the upper cutoff is used on the low-field side to provide measurements of the scrape-off layer (SOL) profile;
(ii) an ordinary (O-mode) system is used to provide the inboard (**HFS O**) and outboard (**LFS O**) density profile in the gradient region; and
(iii) **HFS X-l**: an X-mode system reflecting of the lower cutoff and launched from the high field side is used to provide the core profile.

## 3.1 Sub-System Description and Specification

### 3.1.1 Functions and Performance Specification

The Reflectometer for the Main Plasma provides essential information on the density profile and density perturbations due to plasma modes, to be used for machine protection, optimisation of plasma operation and for establishing performance characteristics. In addition, it supplies valuable information on plasma turbulence in all regions of the plasma. In order to provide coverage of the full profile, three sub-systems are necessary: (i) an extraordinary mode (X-mode) launch system, reflecting off the upper cutoff is used on the low-field side to provide measurements of the scrape-off layer (SOL) profile; (ii) an ordinary (O-mode) system is used to provide the inboard and outboard density profile in the gradient region; and (iii) an X-mode system reflecting of the lower cutoff and launched from the high field side is used to provide the core profile. A combination of these three systems matches or exceeds the performance target set for the ITER density profile measurement with respect to time and space resolution.

In addition to profile measurements, the system is designed to contribute to various other measurements in the manner summarised in Table 12. The requirements for each numbered measurement can be found in Table 2.

**Table 12: Link between measurement and sub-system capability for the main reflectometer.**

| Measurement | Region of interest | Unique aspects of reflectometry measurement | Minimum required launch set | Category |
|---|---|---|---|---|
| 24. Electron Density Profile | All | continuous sub-ms & sub-cm edge/gradient region density profiles | LFS O, X | 1b |
| | | continuous sub-ms core profiles | HFS X-l | |
| 8. Locked modes | Core /Gradient | Island size, $n_e$ amplitude | LFS O,<br>HFS X-l | 1b |
| 14. H-mode: ELMs and L-H Transition Indicator | Gradient/ Edge | Unambiguous $\Delta n_e$ | LFS O, X | 1b |
| | | Inboard-outboard comparisons | HFS O | 2 |
| 9. Low (m,n) MHD Modes, Sawteeth, Disruption Precursors | Core /Gradient | Radial structure | LFS O<br>HFS X-l | 1b |
| 27. High frequency macro instabilities (Fishbones, TAEs) | Core | radial structure | LFS O,<br>HFS X-l | 2 |
| Density fluctuations | All | | LFS O, X<br>HFS X-l | 2 |

1b: Advanced control 2: Physics understanding

### 3.1.2 Description

3.1.2.1 Low field side (equatorial port) systems

The LFS X system employs an array of 2 pairs of broad-band antennas of typical diameter 90 mm, mounted on a diagnostic block in an equatorial port and view the plasma through apertures in the blanket/shield. The antennas do not protrude in front of the diagnostic block. As a result, the front ends of the antennas are at least 0.8 m away from the plasma during operation, with the first mirror at least 1 m away from the first wall. Broad-band overmoded corrugated circular transmission lines (63.5 mm dia) couple the front ends to the system electronics. Components such as swivelling mitre bends, expansion joints and long elastic sections are used to accommodate vessel movement with respect to the bioshield whilst preserving mm-wave performance. The LFS O system is implemented in the same way, and employs 4 antenna pairs. Figure 3.1.1-1 shows the topology of the antenna layout within a port.

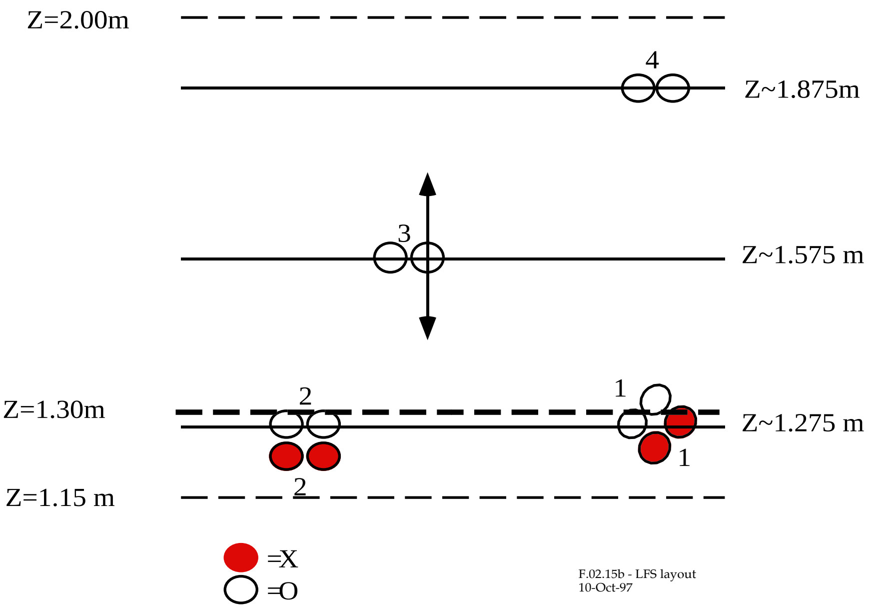


**Figure 3.1.1-1: Idealised LFS antenna arrangement. The view is from the plasma towards a main horizontal port. (Horizontal axis in the toroidal direction) The thin dashed lines denote the range of plasmas expected; the thick dashed line shows the position of a reference scenario. The arrowed line shows the extent assumed to be covered by a single antenna pair in O-mode. All distances are approximate.**

The LFS X system is designed to operate with central magnetic fields in the range 3.7 - 5.3 T, and for densities up to 3 $10^{20}$ / m $^{3}$ at the edge (~ 2 $10^{20}$ / m $^{3}$ near the centre; limited by absorption). This corresponds (approximately) to the frequency range of 76 – 220 GHz. The LFS O is designed to operate in the density range 0.03 - 3 $10^{20}$ / m $^{3}$, corresponding to the frequency range 15 - 155 GHz.

Each waveguide / antenna pair for the low field side systems is capable of the full frequency range for that system. Each system is fed by multiple sets of electronics covering appropriate full or partial waveguide bands, and arranged in groups for each waveguide pair. There are a total of 6 waveguide pairs, leading to six groups of electronics. Figure 3.1.1-2 shows the layout.

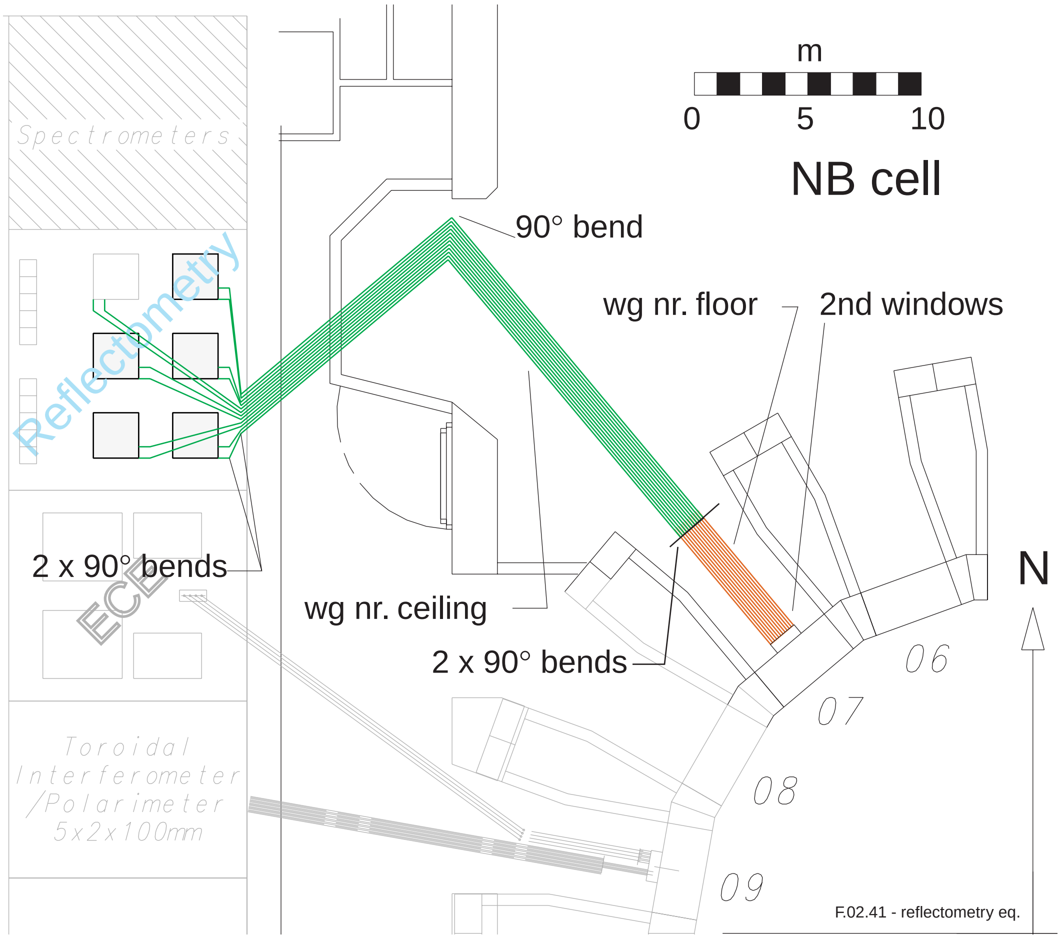


**Figure 3.1.1-1: The low field side system waveguide layout from the equatorial port (#7) exit to the diagnostic hall. There are a total of 7 mitre bends and ~40m of waveguide per line.**

3.1.2.2 High field side (vessel) systems

The HFS X-l system consists of two antenna pairs, mounted on the backplate and viewing the plasma between blanket modules. Radiation is routed to these using small bore ( <35 mm typ.) rectangular or circular corrugated waveguide depending on the frequency range. This waveguide is routed in the diagnostic conduit paths on the vacuum vessel. The waveguides are brought out through an upper horizontal port and the cryostat to electronics located in the pit on a removable trolley, or in the diagnostic hall depending on the frequency range. The HFS - O system is implemented in the same way.

The HFS O is designed to operate in the density range 0.03 - 3 $10^{20}$ / $m^{3}$, corresponding to the frequency range 15 - 155 GHz. It is split into two sub bands, 15 – 60 GHz (whose electronics and waveguide are included in detail in section [ 4 F.03 Reflectometry for plasma position ], and 60 – 155 GHz, described here.

The HFS X-l system is designed to operate with central magnetic fields in the range 3.7 - 5.3 T, and in the density range 0.03 - 3 $10^{20}$ / $m^{3}$. This corresponds to a frequency range of 10 – 98 GHz. This range is split into sub-bands to allow for different bends to be used: 10 – 60 GHz (tapered gradual bends) and 60 – 98 GHz (mitre bends).

The systems are located on two upper ports (8 and 14). Port 8 houses the high frequency sub-bands for HFS O and HFS X-l. Port 14 has the low frequency components. Figure 3.1.2-1 shows the layout.

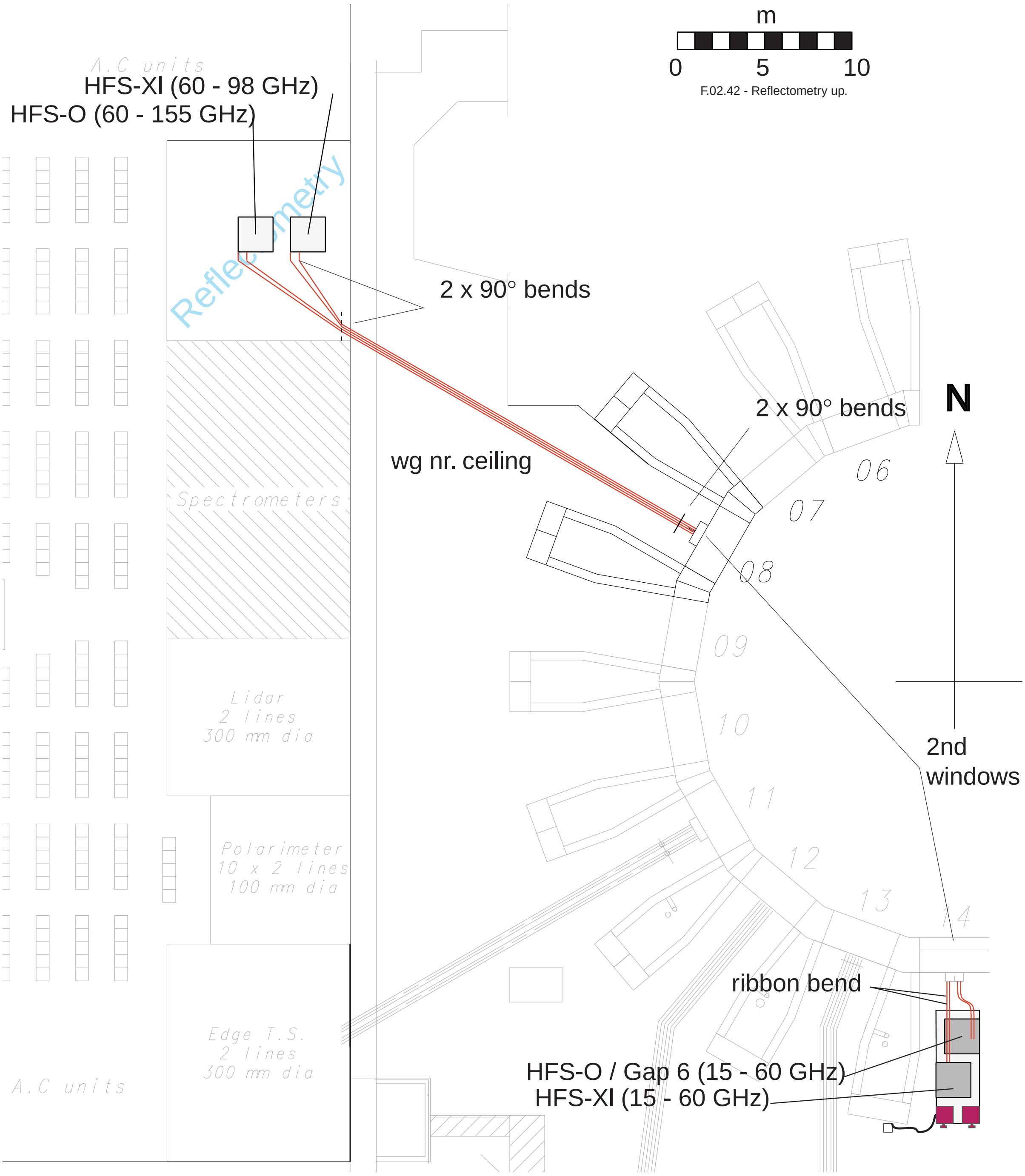


**Figure 3.1.2-1: Layout of the main reflectometer HFS sub-systems. The high frequency band electronics are housed in the diagnostic hall (6 mitre bends and 40 m per line) ; the low frequency components are mounted outside port 14 (2 taper / ribbon bends and < 5 m /line).**

### 3.1.3 Assembly

#### 3.1.3.2 Low field side systems

The front end is supplied from the factory in modular sub-assemblies. The modules are attached to units or sub-units of the diagnostic block as part of another PP (55.PN). Ex-bioshield waveguide runs and electronics installation and testing is part of this PP.

#### 3.1.3.3 High field side systems

The antennas, waveguides and windows are installed within the vacuum vessel by the machine assembly group and thus form part of another PP. Ex-bioshield waveguide runs and electronics installation and testing is part of this PP.

Electronics (transmit receive units, local control and data acquisition) are supplied as modular sub-assemblies. Electronics for the pit area are supplied mounted on removable trolleys.

### 3.1.4 Specific Commissioning

None

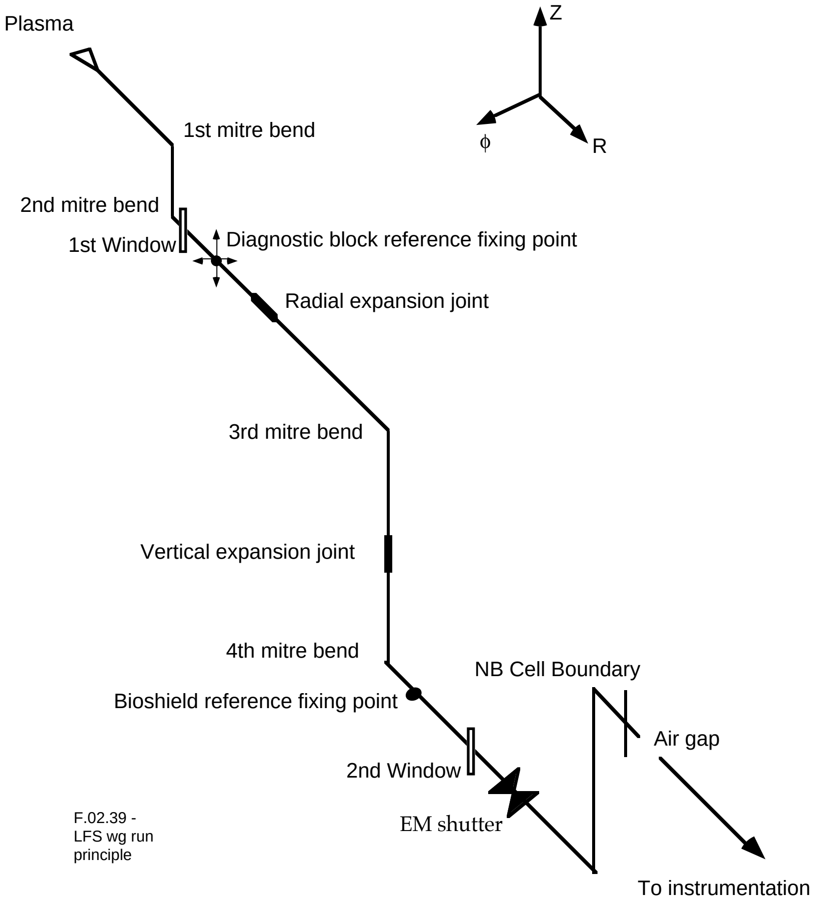


**Figure 3.2.1-1: Schematic of the microwave transmission line, from the plasma to the instrumentation, applicable to all the LFS sightlines.**

## 3.2 Component Description and Specification

### 3.2.1 Microwave components

3.2.1.1 Low field side systems

Figure 3.1.1-1 shows a schematic of the microwave transmission line for a low field side system, with individual components marked. A short description of each component follows.

*Horn antenna/taper*

This is a corrugated, precision machined, copper plated stainless steel element, matching the 90 mm ID antenna aperture to the 63.5 mm dia standard corrugated waveguide components. this component is conduction cooled to the diagnostic block and located with dowels and bolted to the 1st mitre bend

*1st mitre bend*

These is stainless steel component, made by inserting a polished mirror element into a milled-out cubical holder, tapped and doweled to accept 63.5 mm ID corrugated waveguide elements. The mirror element is cooled by conduction and radiation to the antenna and holder. The plasma facing side is polished to optical quality; the reverse is roughened to increase the emissivity.

*2nd mitre bend*

This is identical to the first bend except that the mirror element is finely grooved to provide a reference reflection point for calibration of the line length.

*1st Window*

This is a fused silica window at the Brewster angle (see PP 55.PN.07). It is placed near the VV seal plate.

*Radial expansion joint*

This takes up vessel thermal expansion, provides electrical insulation and allows for the installation and removal of the waveguide. It is similar to the ECE slide joint shown on page 18.

3rd and 4th mitre bend; vertical expansion joint.

These elements together form a mechanism to compensate for vertical shift and toroidal rotation of the vacuum vessel. They also allow for installation misalignment. The vertical expansion joint also allows for rotation along the waveguide axis. The angular change due to toroidal rotation of the vessel is not fully compensated.

*2nd Window*

This is a SiN window at the Brewster angle (see PP 55.PN.07). It is placed at the cryostat boundary.

*EM shutter*

This shutter is based on a standard vacuum valve with appropriate flanges. It is included to allow easy maintenance of components outside its location (including the diagnostic hall electronics), even in the presence of large amounts of EM radiation (from ECH or LH) in the torus.

*NB cell boundary*

At this boundary, sections of standard transmission line with enlarged flanges are bolted onto a common metal flange from the NB cell side, with rubber O-ring seals to maintain NB cell isolation. The line between the 2nd Window and this flange is leak tight to 5 bar or better.

*Air gap*

An air gap is included so that, in the event of double window failure, pressure is released in the pit rather than the diagnostic hall.

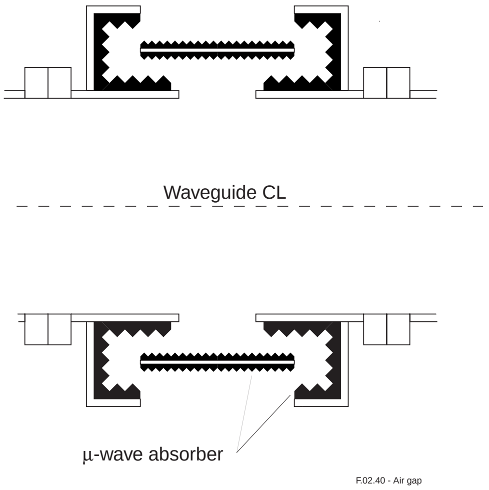


**Figure 3.2.1-1: Illustration of an in-line air gap of total aperture approximately equal to the cross-sectional area of the waveguide. Microwave absorbing material is used to mitigate cross talk; additional absorbing baffles and / or staggering of the air gaps may be required.**

*Pit / Diagnostic Hall Boundary*

At this boundary, sections of standard transmission line with enlarged flanges are bolted onto a common metal flange from the pit cell side. The line between this boundary and the equipment is leak-tight to 2 bar or better.

*Standard transmission line element*

This is a section of stainless steel corrugated waveguide, copper plated. The corrugations can be spiral. It is supplied in 2 m lengths or less, with integral flanges incorporating dowels and guaranteed assembly accuracy suitable for the frequency range (up to 230 GHz). The clear ID is 63.5 mm, the OD is 75 mm or less. The waveguide has to be supported every 2 m.

*Transmit / Receive unit*

Both O and X-mode profile systems will need to divide the signal into appropriate sub-bands (waveguide bands). Each waveguide band will operate independently, and the full profile will reconstructed by merging the information from each sub-band. For example, the reference O-mode electronics split the signal into 5 sub-bands. Well established Quasi-Optical (QO) techniques will be used to perform this split. The X-mode system will be designed on similar principles.

In the reference design, each band employs a fast (< 10 ms sweep time) linearly swept source, and a tracking local oscillator to produce a local oscillator (LO) signal. Both fast homodyne and heterodyne detection will be employed in the intermediate frequency (IF). The group delay vs. frequency curve will be reconstructed for each band, and inverted to produce a density profile.

The unit associated with each transmission line is self contained in a volume less than 2(W) x 2(D) x 3(H) m.

The power requirements for each system are ( effective at the input to the waveguide after the combiner / splitter; above 60 GHz)

For the LFS O-mode system, > 40 mW
For the LFS X-mode system, > 40 mW
For the HFS O-mode system, > 50 mW
For the HFS X-l mode system, > 500 mW

### 3.2.1.2 High field side systems

*In vessel antennas*

The construction of these antennas is shown in Figures 3.2.1-1,2 for the low frequency band and 3.2.1-3 for the high frequency band. The low frequency band antenna is a pair of tungsten pyramidal horns, supported flexibly by a stainless structure mounted on the vessel, and (loosely) by lugs spot welded to the side of the nearby blanket module.

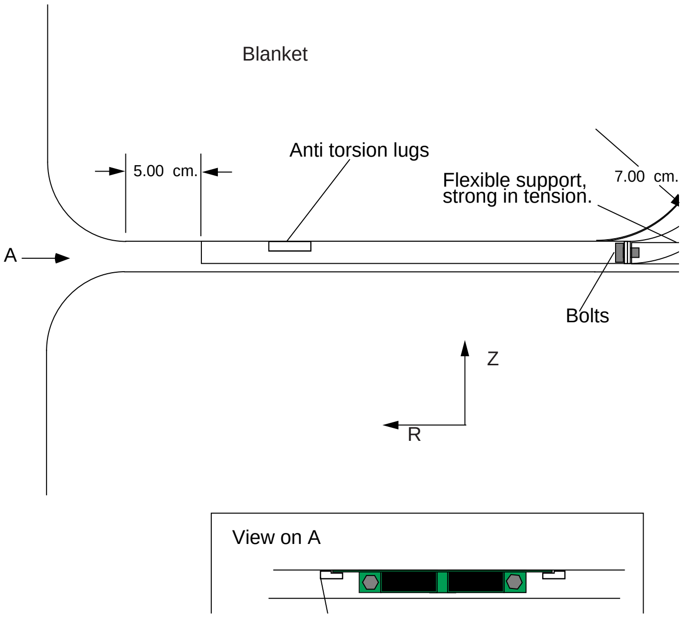


Figure 3.2.1- 2: Low frequency antenna assembly viewed from the toroidal direction.

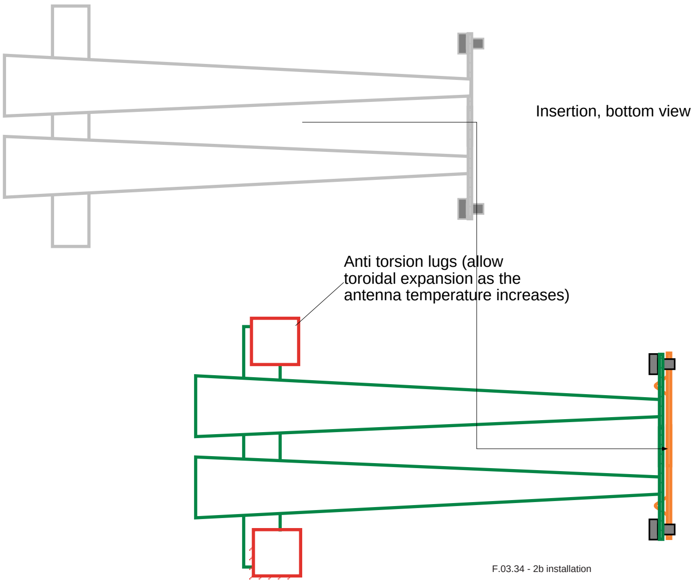


Figure 3.2.1-1: Low frequency antenna assembly in plan view, showing the installation sequence.

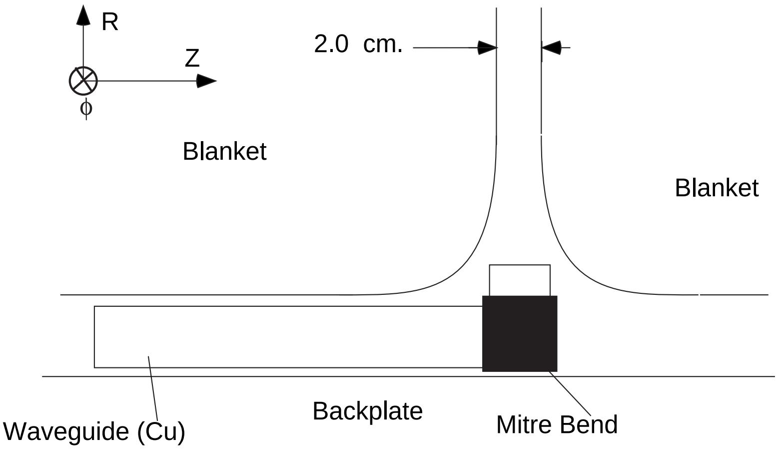


**Figure 3.2.1-3: High frequency antenna assembly. For “backplate” read vacuum vessel.**

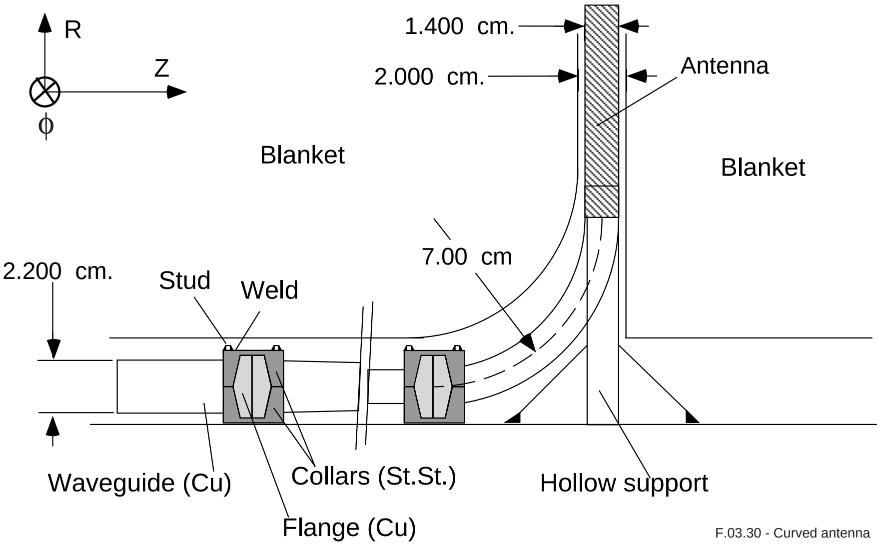


**Figure 3.2.1-4: Illustration of the waveguide joint structure in-vessel (antenna details not up –to-date).**

*In-vessel transmission line*

For the low frequency range (10 – 60 and 15 – 60 GHz), 20 x 10 mm smooth-walled copper waveguide is used. The first bend coupling the waveguide to the antenna is a hyperbolic secant bend extending over approximately 0.15 m. This transmission line is similar to that used for the reflectometer for plasma position (F.03).

For the high frequency range, 25 mm OD circular corrugated waveguide is employed. The first bend coupling the waveguide to the antenna is a mitre bend.

Except near the antenna, the waveguides follow the contours of the vacuum vessel, and are routed in the space reserved for the diagnostic conduit between the vacuum vessel and blanket module. They are held loosely by clamps at suitable intervals, with the minimum number of joints. Figure 3.2.1-4 illustrates the joint structure.

*1st Window and associated structure*

The first vacuum barrier for each waveguide is mounted on the vacuum vessel seal flange. It is a fused quartz window mounted at 15° to the waveguide axis (see PP 55.PN.07).

Electrical breaks for the waveguide are incorporated on both sides of the window structure. An expansion sliding joint is incorporated on the vacuum side of the window assembly. A taper from 20 x 10 to 20 x 20 mm waveguide is also included.

Movement between the blanket backplate and the vacuum vessel is taken up by the elastic bending of the waveguide and /or an expansion joint.

*Ex-vessel (interspace) transmission line*

For the low frequency range (15 – 60 GHz), 20 x 20 mm smooth-walled copper waveguide is used for both polarisations. This transmission line is similar to that used for the reflectometer for plasma position (F.03). For the high frequency range, 25 mm OD circular corrugated waveguide is employed.

*2nd Window and associated structure*

This is a SiN window inclined at the Brewster angle for the appropriate polarisation. It is mounted on a bellows structure to accommodate cryostat movement.

*Pit waveguide*

For the low frequency range (15 – 60 GHz), 20 x 20 mm smooth-walled copper waveguide is used. Tapers and ribbon bends are used to guide the radiation to and from the electronics, which are placed on a trolley in the pit. This transmission line is similar to that used for the reflectometer for plasma position (F.03).

For the high frequency range, the signal is coupled quasi-optically to 63.5 mm transmission line and taken to the upper level of the diagnostic hall.

*Electronics*

For the low frequency range, the electronics are identical (O-mode) or similar to those proposed for the reflectometer for plasma position (F.03) on page 42.

### 3.2.2 Control and Data Acquisition

**Table 13:** Fast data channels for the reflectometer for plasma position

| System | Number of channels |
|---|---|
| LFS-O | 48 |
| LFS-X | 48 |
| HFS-O | 24 |
| HFS-Xl | 24 |

In addition, slow data acquisition is required to check the settings of mm-wave switches etc. The number of these channels is estimated to be ~ 100.

Refer to Annex 7 for details of the coupling of this sub-system to CODAC.

# 4 F.03 Reflectometry for plasma position

## 4.1 Sub-System Description and Specification

### 4.1.1 Functions and Performance Specification

This diagnostic is designed to act as a stand-by gap measurement, in order to correct or supplement the magnetics for plasma position control, during very long (>1000 s) pulse operation, where the position deduced from the magnetic diagnostics could be subject to substantial error due to drifts. To meet the ITER requirements for accuracy of the location of the gaps, density profile recovery to a density comparable to, or exceeding the separatrix density is necessary.

### 4.1.2 Description

An ordinary mode reflectometer operating in the frequency range 15 to 60 GHz is being proposed, which can measure the location of a plasma density surface near the separatrix with sufficient accuracy to be used to supplement the magnetics for position control. A swept frequency (FM-CW) is used (Figure 4.1.2-1). Such a system can be implemented using the same frequency range at each poloidal control location, and it is possible to consider many common components. A bistatic (separate transmit and receive units) antenna arrangement his used.

As for the HFS of the main reflectometer with which it shares one antenna pair, the antenna pairs are mounted on the vacuum vessel and view the plasma between blanket modules. Radiation is routed to them using small bore waveguide. The waveguide resides in the space allocated within the VV and blanket structure for the diagnostic conduit. The waveguides are brought out through two of the upper ports to electronics residing in the pit. Expansion joints and elastic sections are used to accommodate the vacuum vessel movement.

Labyrinths in the transmission lines reduce neutron streaming outside the vacuum vessel and bioshield. Vacuum windows of fused quartz directly bonded to metal structures and inclined at the Brewster angle for the appropriate polarisation provide robust, low mm-wave loss, pressure boundaries.

In total there are 4 pairs of antennas. One pair is accounted for in F.02 (Main plasma) and is mounted on port 14 to measure Gap 6 (Figure 4.1.2-2). The remaining 3 are introduced from port 2 to measure gaps 3,4 and 5.

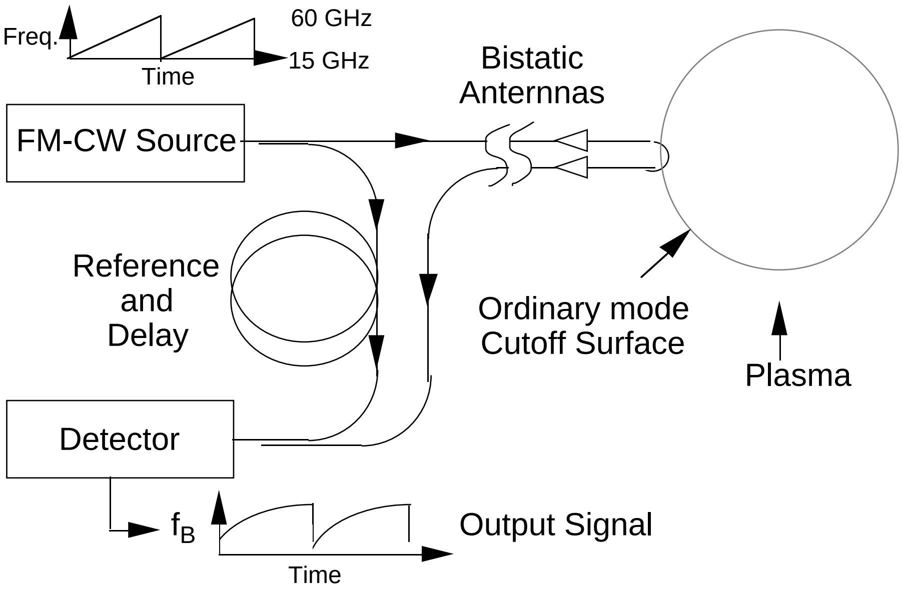


**Figure 4.1.2-1 A block diagram of an FM-CW reflectometer is shown. The source sweeps repetitively between the upper and lower frequency limits, 15 and 60 GHz. The detector samples the beat frequency, $f_B$, between the delayed source and reflected signal from the plasma cutoff.**

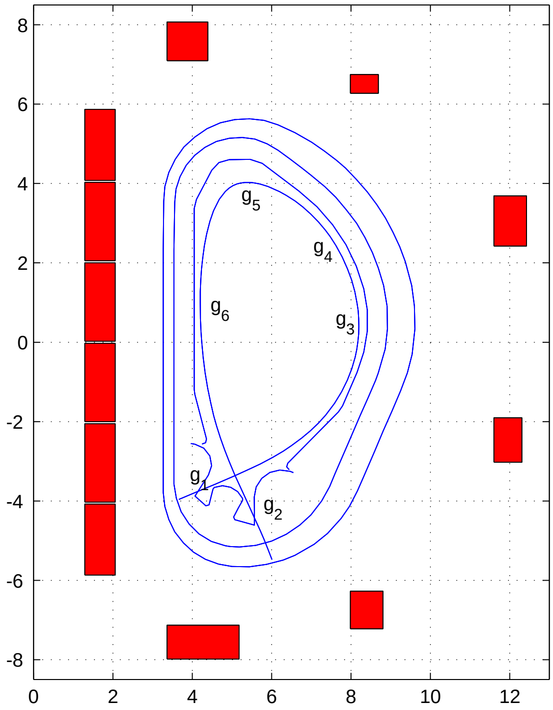


**Figure 4.1.2-2: Location of the gaps for position control on ITER. Gaps 1 and 2 are measure by IR thermography techniques.**

### 4.1.3 Assembly

The antennas, waveguides and windows are installed within the vacuum vessel by the machine assembly group and thus form part of another PP. Ex-bioshield waveguide runs and electronics installation and testing is part of this PP.

Electronics (transmit receive units, local control and data acquisition) are supplied as modular sub-assemblies. Electronics for the pit area are supplied mounted on removable trolleys.

#### 4.1.4 Specific Commissioning

None

## 4.2 Component Description and Specification

### 4.2.1 Microwave components

See 3.2.1 (HFS-O) except for *electronics*, described above.

### 3.2.2 Control and Data Acquisition

Approximately 36 channels of variable gain, variable rate (1 – 100 us) data acquisition channels are required for the this system. In addition, slow data acquisition is required to check the settings of mm-wave switches etc. The number of these channels is estimated to be 30. Refer to Annex 7 for details of the coupling of this sub-system to CODAC.

# 5 F.04 / F05 Reflectometry and ECA for the divertor

This sub-system is comprised of front end antennas, waveguides and mm-wave transition pieces mounted on specific divertor cassettes, a removable in-vessel transmission line set, a permanent interspace transmission line set, a short ex-cryostat transmission line set and self-contained electronic transmit/receive assemblies mounted on trolleys in the pit.

## 5.1 Sub-System Description and Specification

### 5.1.1 Functions and Performance Specification

The divertor reflectometer is a density profile measurement system for the divertor. It is the only divertor system potentially able to provide good (sub-cm) resolution across the divertor legs for selected sightlines. The waveguide set for this system will also be used for electron cyclotron absorption (ECA) and interferometric measurements.

The wide density operating space forces the use of two distinct types of measurement. In the mm-wave domain, it is reasonable based on present technology to plan for continuously swept reflection measurements of the density profile. In the sub-mm domain, spot measurements at a number of frequencies are planned (see figure 5.1.1-1). By combining transmission and reflection measurements it is expected that the first few moments of the density profile (peak density, width) can be estimated. For costing purposes, only O-mode reflectometry systems are to be assumed.

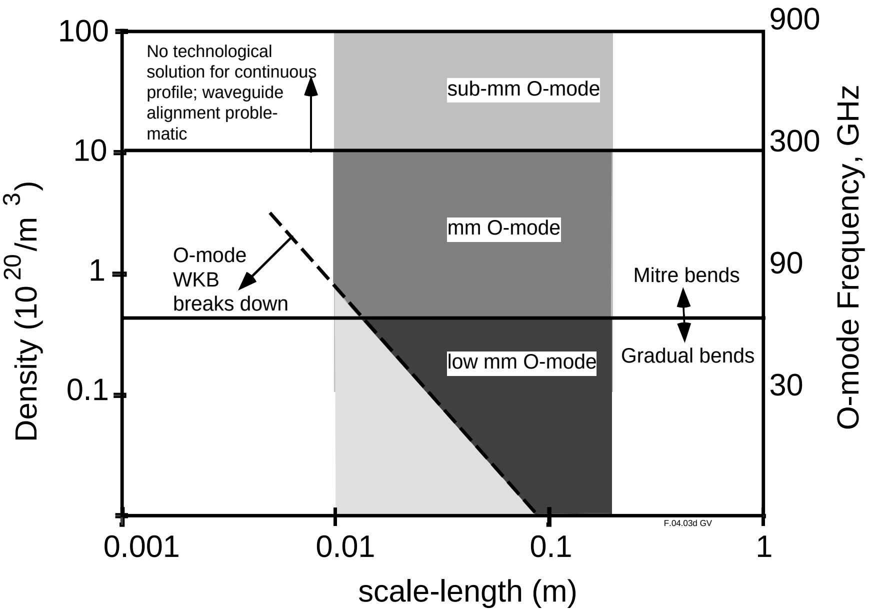


**Figure 5.1.1-1: Divertor operating space. The required density measurement range is $10^{19}$-$10^{22}$/m$^3$. The x-axis represents the local density scale length. To cover the density range in O-mode with good accuracy requires frequency coverage from ~9 to 900 GHz. This is to allow for initialisation of the profile reconstruction for the lowest density in this range. In the region where the WKB approximation is violated, it appears that the resultant errors in the reconstruction are small (~ 1 mm). X-mode can be used to improve accuracy in this area.**

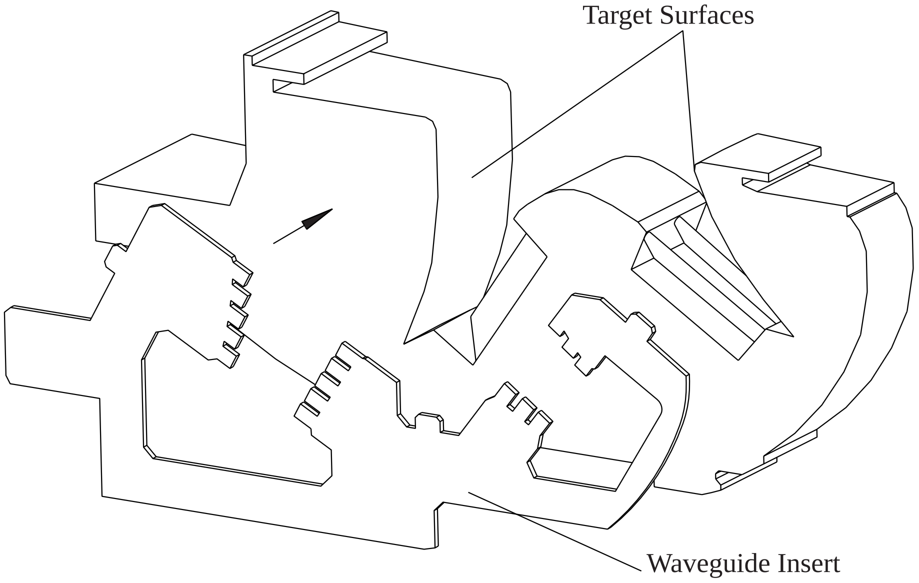


**Figure 5.1.2-1: The principle of attaching a pre-assembled waveguide insert onto a divertor cassette. This design allows for considerable freedom within the insert envelope. Outside the cassette the waveguides are coupled to circular corrugated waveguide, then transmitted to the machine pit via a removable set of waveguides that allows maintenance of the cassette and the rest of the divertor.**

### 5.1.2 Description

The design is for multiple sightline, low transmission line diversity system. Once the limitation on the total number of sightlines is taken into account, it is possible to accommodate 5 sightlines on the outer leg, and 3 sightlines on the inner leg by making full use of two ports (40 waveguides).

A concept of using a semi-independent insert to house and cool the front end waveguides and antennas is adopted (Figure 5.1.2-1). The frequency operating space requirements, combined with the space constraints combine to define the waveguide that can be used in each frequency band within the inserts.

The antennas view the plasma between divertor modules. The waveguides in the insert are brought out through conversion boxes to a size suitable for long distance transmission to electronics residing in pit. Expansion joints and elastic sections are used to accommodate the vacuum vessel movement. Labyrinths in the transmission lines reduce neutron streaming outside the vacuum vessel and bioshield. Vacuum windows of fused quartz directly bonded to metal structures and inclined at the Brewster angle for the appropriate polarisation (where possible) provide robust pressure boundaries. Figure 5.1.2-2 shows an outline of the system.

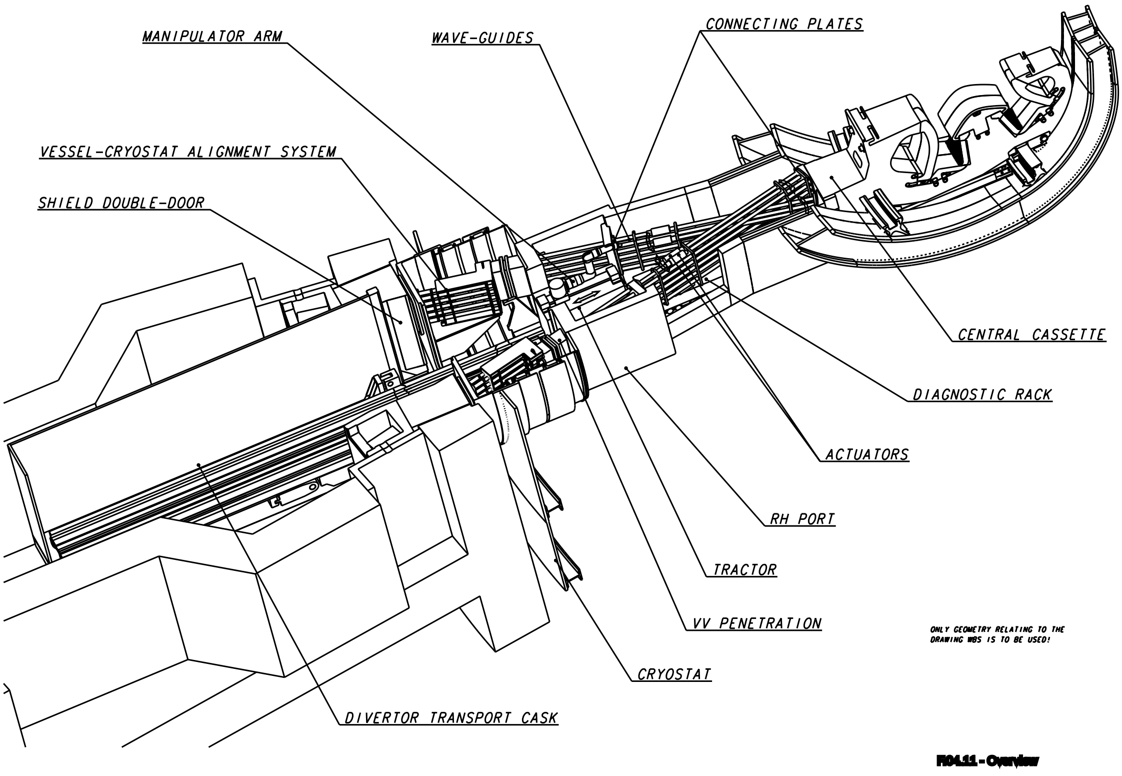


**Figure 5.1.2-1: Overview of the reflectometry hardware in one of the RH ports, showing the key elements of the transmission line.**

### 5.1.3 Assembly

In vessel components are assembled by the machine assembly group and do not form part of the PP. Ex-vessel components are delivered as modular subassemblies and installed as part of this PP.

### 5.1.4 Specific Commissioning

None

## 5.2 Component Description and Specification

In this section, please refer to figure 5.2-1 to locate each component

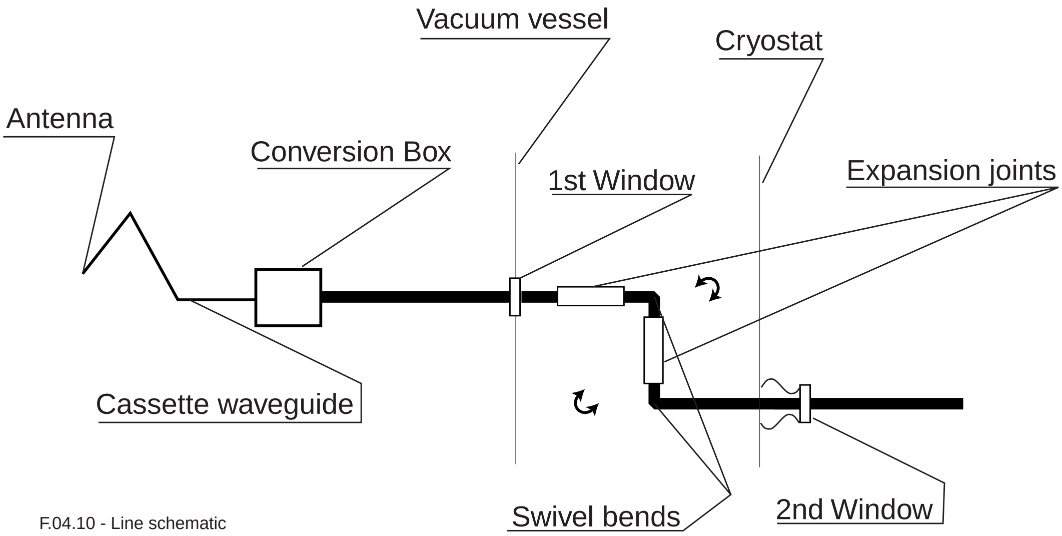


**Figure 5.2.-1: Schematic of a single divertor transmission line.**

### 5.2.1 Microwave components

5.2.1.1 Antenna

The antennas couple the waveguides embedded in the sideplate to the plasma. They extend the transmission lien to 80 mm behind the divertor plasma facing components. Their typical length is 100 mm; other dimensions correspond to the appropriate waveguide (see Table 15 below).

### 5.2.1.2 Cassette waveguides

**Table 14: Measurements and corresponding waveguide under the assumption that 10% loss per bend is tolerable.**

| Measurement | Band and Polarisation | Suggested Waveguide size (mm), toroidal x poloidal | Bend type in poloidal plane | Bend type in toroidal plane |
|---|---|---|---|---|
| Profile reflectometry, low density | low mm O | ~10 x 10 | Optimised non-linear bends (e.g. hyperbolic secant) | |
| Profile reflectometry, medium density | mm O | ~10 x 20 | Mitre | None |
| ECA | mm/<br>sub mm X | ~10 x 20 | Mitre | None |
| Interferometry, Plasma Dispersion Measurements (including peak density and profile width) | sub-mm O | ~10 x 20 * | Mitre | Mitre |

**Table 15: Nominal waveguide dimensions for each sightline, and number of waveguides.**

| Waveguide Channel | Position of Diagnostic Cassettes | | | |
|---|---|---|---|---|
| | Port-A | | Port-B | |
| | Right* | Left* | Right* | Left* |
| I1 | | 20 mm x3 | | 10 mm x2 |
| I2 | 10 mm x2 | | 20 mm x3 | |
| I3 | | 20 mm x3 | | 10 mm x2 |
| O1 | | 10 mm x2 | | 20 mm x3 |
| O2 | | | 10 mm x2 | 20 mm x3 |
| O3 | 10 mm x2 | | 20 mm x3 | |
| O4 | 20 mm x3 | | 10 mm x2 | |
| O5 | 20 mm x3 | 10 mm x2 | | |
| Total Number | 10 | 10 | 10 | 10 |

### 5.2.1.3 Conversion box

The waveguides are provided with a connector on the radially outboard side of the central cassette, where a set of microwave converters are placed. In the converter, microwaves are transmitted from rectangular waveguides to circular corrugated pipes with an inner diameter of 63.5 mm. Figure 5.2.1-1, shows the schematic of such a converter, with approximate dimensions.

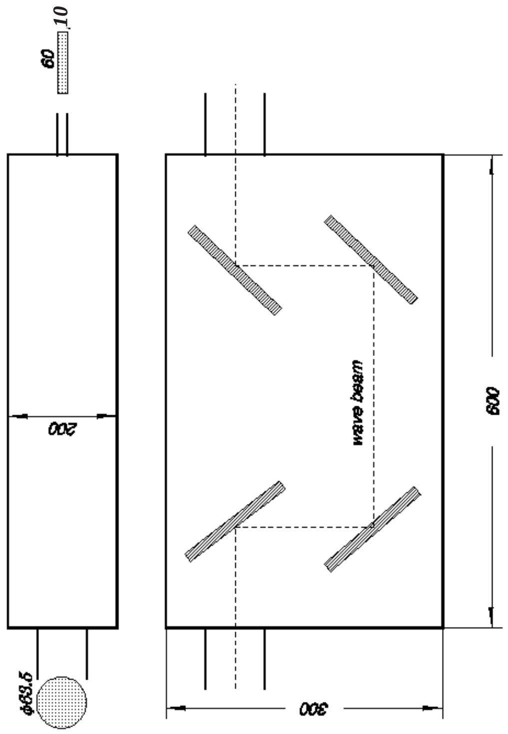


**Figure 5.2.1-: Schematic of a broad-band quasi-optical converter from 10 x 60 mm waveguide to circular corrugated waveguide (Courtesy D. Wagner).**

### 5.2.1.4 Microwave rack

Inside the divertor ports, a demountable waveguide assembly is installed to connect the cassette-mounted waveguides to an in-vessel permanent waveguide assembly. The demountable waveguides are mounted on a RH microwave diagnostic rack. The in-vessel permanent waveguides are routed along the side wall of the RH port and penetrate the end wall of the port.

The microwave rack is installed and removed using the RH A set of actuator rods locks the rack to the diagnostic cassette, and to the in-vessel permanent waveguides. The rack is insulated at numerous points to prevent off-normal currents from damaging the waveguides.

### 5.2.1.5 1st window

The first vacuum boundary consists of a window assembly, mounted on the port extension and incorporating 10 windows. The assembly (figure 5.2.1-2) is removed complete if maintenance is required. the windows form part of another PP (55.PN.07). However the window assembly including waveguide aligning components are included in this PP.

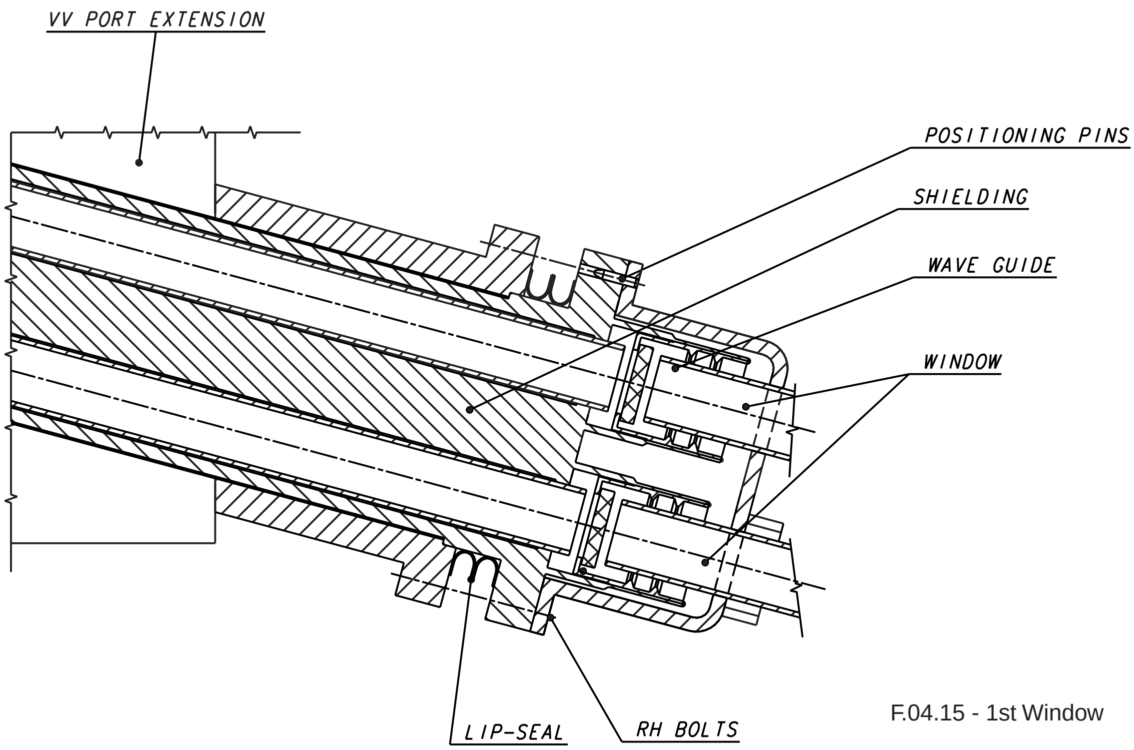
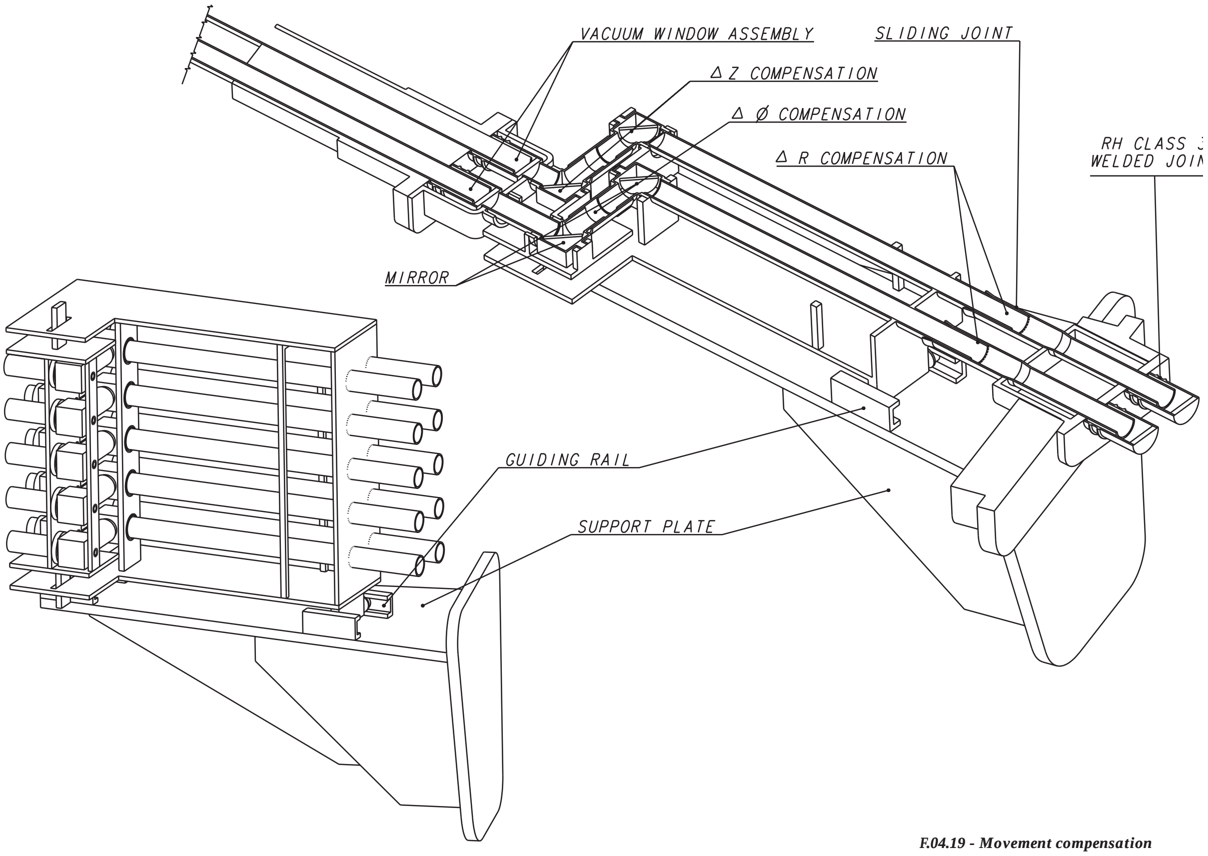


**Figure 5.2.1-2: Schematic horizontal section through one pair of waveguides at the second vacuum boundary.**

### 5.2.1.6 Interspace transmission

The interspace transmission line is 63.5 mm corrugated waveguide. Movement compensation between the vacuum vessel and the cryostat is accomplished by means of an array of waveguide dog-legs incorporating sliding joints and rotating mitre bends. The arrangement is shown in figure 5.2.1-3.



F.04.19 - Movement compensation

**Figure 5.2.1-3: Illustration of the movement compensation mechanism enclosed within the secondary vacuum for costing purposes.**

### 5.2.1.7 2nd Window

This is an array of SiN windows mounted at the Brewster angle. The is removed complete if maintenance is required. the windows form part of another PP (55.PN.07). However the window assembly including waveguide aligning components are included in this PP.

### 5.2.1.8 Ex-cryostat transmission

The ex-cryostat transmission line is 63.5 mm corrugated waveguide. Movement compensation between the cryostat and the building is accomplished by means of an array of waveguide dog-legs incorporating sliding joints and rotating mitre bends.

### 5.2.1.9 Transmit / Receive units

A number of these modular assemblies will be required. They are shown, sorted by frequency band, in Table 16.

**Table 16: Transmit / receive units for the divertor reflectometry / ECA**

| Unit type | Number | Specification |
|---|---|---|
| Sub – mm O-mode | 8 | 10 – 60 GHz |
| mm O-mode | 8 | 60 – 300 GHz |
| Comb – reflectometer / interferometer | 8 | 300 GHz – 1 THz |
| ECA | 8 | |

The units are mounted on trolleys and placed in the pit close to the cryostat seal plate. Quick-release links are required for the waveguides.

### 5.2.2 Control and Data Acquisition

Approximately 500 channels of fast data acquisition are required for the full system, with an equivalent number of channels for switching purposes. Refer to Annex 7 for details of the coupling of this sub-system to CODAC.

# 6 F.07 Fast wave reflectometer

This sub-system is comprised of a wide-band RF generator unit, RF transmission lines, in-vessel transmit and receive antennas and RF heterodyne receivers phase locked to the transmitter unit.

## 6.1 Sub-System Description and Specification

### 6.1.1 Functions and Performance Specification

This system is aimed the measurement of the fuel ratio in the core ($n_D/n_T$). It can also supply an estimate of the line integral density. Both measurements are performed by launching and receiving RF radiation in the ion cyclotron range, and measuring the return phase and amplitude. The measurement specification are given in Table 2.

### 6.1.2 Description

A simplified schematic of the system is shown in Figure 6.1.2-1 (only one receiver channel shown). A broad-band RF system, operating in the range 20 – 60 MHz is required. The transmission antenna is a single strap mounted on a diagnostic port. The receive antennas are coils mounted in filler and blanket module gaps. There are 8 receive antennas in the same sector as the transmitter, and an additional 9 antennas at toroidal intervals of 40°. 120 dB of isolation between the amplifier and receiver front end electronics is required.

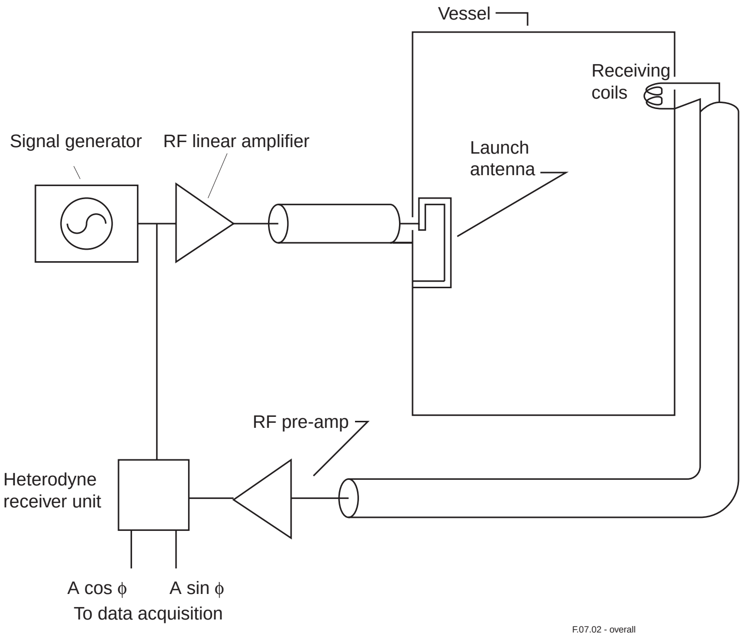


**Figure 6.1.2-1 Simplified block diagram of the fast wave reflectometer with one receiver channel. The source sweeps repetitively between the upper and lower frequency limits. The detector samples the beat frequency, $f_B$, between the delayed source and reflected or transmitted signal from the plasma.**

### 6.1.3 Assembly

#### 6.1.3.1 In-bioshield

Receiver antenna components are confined within one machine assembly sector are mounted, wired, tested, surveyed and delivered with the machine sector.

Wiring in-vessel is brought through appropriate conduits to the top or divertor level ports. Wiring to the first connector or feedthrough is within the scope of this package. All other wiring, and all feedthroughs, is included in 55.PN.

Descriptions of the mounting of components can be found in section 6.2.

#### 6.1.3.2 Ex-bioshield

Wiring and cubicles external to the bioshield are outside the scope of this package. They are included in 55.PN.

Electronics will be installed in the diagnostic hall, in supplied cubicles (55.PN

### 6.1.4 Specific Commissioning

RF reflectometry of each transmission line should be performed after installation.

## 6.2 Component Description and Specification

### 6.2.1 Transmitter

**Table 17: Nominal parameters for the RF generator of the fast wave reflectometer**

| Parameter | Value | Comment |
|---|---|---|
| Type | Arbitrary Waveform Generator | |
| Frequency range (sine) | 10 – 70 MHz | |

**Table 18: Nominal parameters for the RF power amplifier of the fast wave reflectometer**

| Parameter | Value | Comment |
|---|---|---|
| Pass-band (-1 dB) | 20 – 60 MHz | |
| Power | 1 kW | |

### 6.2.2 Transmit antenna

**Table 19: Nominal parameters for the transmit antenna of the fast wave reflectometer**

| Parameter | Value | Comment |
|---|---|---|
| Type | Single strap in poloidal plane | |
| RF Power handling (continuous) | 2 kW | |
| RF Power handling (peak) | 5 kW | |
| Construction | Be on Cu on single hollow stainless tube | MgO insulation at live end |
| Cooling | Water; loop through end grounded in the block. | |
| Dimensions | < 500 mm (poloidal) x 50 mm (toroidal) x 100 mm (radial) | Space allocation in port. |

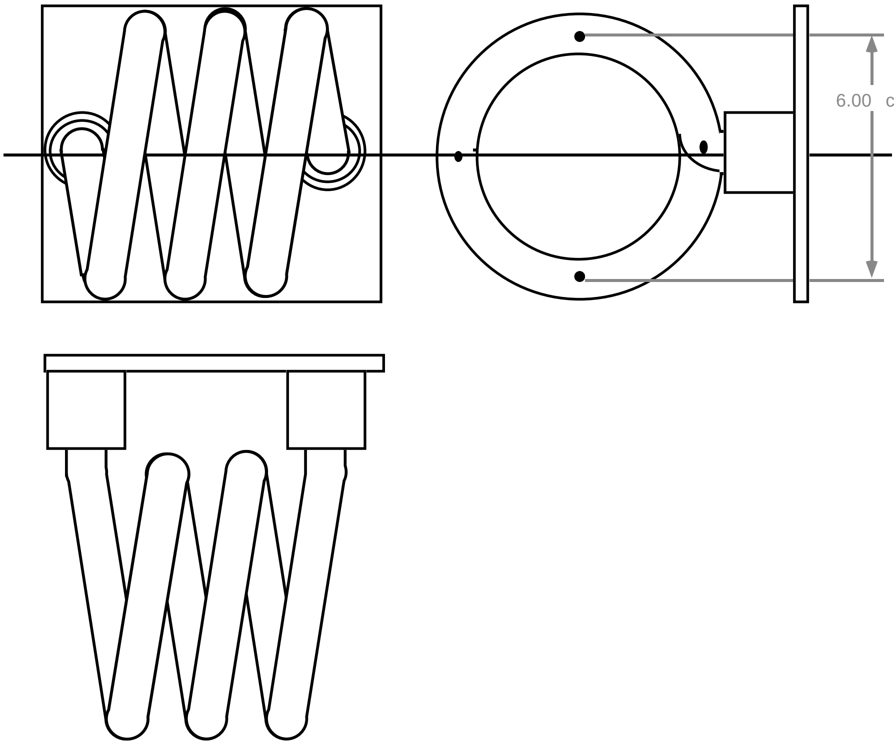


**Figure 6.2-1: Sketches of the fast wave reflectometer receiver coil and mount plate for costing purposes. The coil is formed from hollow tungsten tube (0.5 mm thick).**

### 6.2.3 Receiver antennas

**Table 20: Nominal parameters for the receive antenna of the fast wave reflectometer**

| Parameter | Value | Comment |
|---|---|---|
| Type | Multi-turn RF coil; toroidal axis | |
| RF Power handling | > 50 W | |
| Construction | Hollow tungsten spiral (see figure) | MgO insulation at live end |
| Cooling | passive | |

### 6.2.4 Control and Data Acquisition

Approximately 50 channels of fast data acquisition are required for the full system, with an equivalent number of channels for switching purposes. Refer to Annex 7 for details of the coupling of this sub-system to CODAC.

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