

2.6 Plasma Diagnostic System

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To meet the requirements for plasma and first wall measurements, an extensive diagnostic set of about 40 individual measurement systems is required. In general, very high levels of reliability are necessary, particularly for systems providing measurements for protecting the in-vessel machine components from abnormal events, and/or used in real-time control. Most systems are based on the experience of similar ones on current machines, but in order to fulfil some measurement requirements it has been necessary to use techniques still under development.

2.6.1 Selected Diagnostic Systems and Startup Set

It is neither necessary nor desirable to build all diagnostics during the machine construction phase: some will not be required until later in the operational programme, e.g. those specific to the DT programme, and a phased installation will permit the most advanced techniques and technologies to be used. However, it will be necessary to assess the interface, space and service requirements of each diagnostic that will eventually be used, and make any necessary provisions during machine construction to avoid expensive modification costs later. The subset of diagnostics for initial machine operation is called the ‘startup set’. A provisional selection of the startup set has been made and is included in the list of diagnostic systems and their planned readiness (see Table 2.6-1). For some systems only a limited measurement capability will be available for first plasma. Novel diagnostics still under development are marked with ‘N/C’ (new concept). Some systems require a dedicated diagnostic neutral beam (DNB), which is also shown in the table.

2.6.2 Diagnostic Integration

Individual diagnostic systems are installed on the tokamak taking into account measurement requirements, shielding, vacuum boundaries and activation requirements, length and complexity of transmission lines, and maintenance requirements as well as requirements for confinement of radioactive and toxic materials. For optical and microwave systems, windows and fibre-optic feedthroughs are used to cross the vessel and cryostat flanges; for electrical signals, vacuum feedthroughs are used.

Diagnostic components are installed in four locations – within the vacuum vessel (VV), in divertor ports, and in equatorial and upper ports. The installation issues are different in these locations and so they are discussed separately.

Table 2.6-1 Status of Diagnostic Systems at the Startup of the H Phase and of the DT Phase

Diagnostic	Status at Startup (H phase)	Status at Start of DT Phase
Magnetic Diagnostics		
Vessel Wall Sensors, Divertor Magnetics, Continuous Rogowski Coils, Diamagnetic Loop	Complete	
Neutron Diagnostics		
Radial Neutron Camera, Vertical Neutron Camera	Interfaces complete	Complete
Micro-fission Chambers (In-Vessel) (N/C)	In-vessel components and interfaces complete	Complete
Neutron Flux Monitors (Ex-Vessel)	Interfaces complete	Complete
Gamma-Ray Spectrometer		Complete
Activation System (In-Vessel), Lost Alpha Detectors	In-vessel components and interfaces complete	Complete
Knock-on Tail Neutron Spectrometer (N/C)		Complete
Optical/IR(Infra-Red) Systems		
Core Thomson Scattering	Complete except for two lasers and one power supply system	Complete
Edge Thomson Scattering , X-Point Thomson Scattering	Complete except for some spares	Complete
Divertor Thomson Scattering	Penetrations, in-vessel optics and interfaces complete	Complete
Toroidal Interferometer/ Polarimeter, Polarimeter (Poloidal Field Measurement)	Complete	
Collective Scattering System (N/C)	Penetrations, in-vessel optics and interfaces complete	Complete
Bolometric Systems		
Arrays for Main Plasma, Arrays for Divertor	Complete	
Spectroscopic and Neutral Particle Analyzer Systems		
H Alpha Spectroscopy, Visible Continuum Array	Complete	
Main Plasma and Divertor Impurity Monitors, X- Ray Crystal Spectrometers,	Penetrations, in-vessel optics and interfaces complete. Partial operation	Complete
Charge eXchange Recombination Spectroscopy (CXRS) based on DNB, Motional Stark Effect (MSE) based on heating beam, Soft X-Ray Array, Neutral Particle Analyzers (NPA), Laser Induced Fluorescence (N/C)	Penetrations, in-vessel optics/sensors and interfaces complete	Complete

Table 2.6-1 Status of Diagnostic Systems at the Startup of the H Phase and of the DT Phase (cont'd)

Microwave Diagnostics		
Electron Cyclotron Emission (ECE)	Complete except for one spectrometer	Complete
Main Plasma Reflectometer	One LFS (low field side) X-mode and one LFS O-mode complete	Complete
Plasma Position Reflectometer, Divertor Reflectometer, Divertor EC absorption (ECA), Main Plasma Microwave Scattering, Fast Wave Reflectometry (N/C)	In-vessel components, interfaces	Complete
Plasma-Facing Components and Operational Diagnostics		
IR/Visible Cameras, Thermocouples, Pressure Gauges, Residual Gas Analyzers, IR Thermography (Divertor), Langmuir Probes	Complete	
Diagnostic Neutral Beam		
Diagnostic Neutral Beam (DNB)	Interfaces and main source components complete	Complete

2.6.2.1 In-vessel Installations

The principal diagnostic components mounted in the VV are sensors for the magnetic diagnostics, bolometers, soft X-ray detectors, waveguides for reflectometry, micro-fission chambers, and transmission lines for neutron activation foils. A summary of the diagnostic sensors and their location is shown in Table 2.6-2. The critical design issues for each component are also mentioned. On the inboard side, the sensors are either welded directly on the vessel (e.g. micro-fission chambers, magnetic loops), or are grouped in remote replaceable plugs mounted in bosses on the vacuum vessel. On the outboard side they are mounted on the blanket coolant manifolds. The number and the toroidal and poloidal locations of the diagnostic sensors are defined by the measurement requirements.

Most sensors and cables are shielded by the blanket modules although some sensors, for example bolometers and soft X-ray detectors, would view the plasma through the 20 mm gap between blanket modules.

The principal candidate cable for use in the vessel is mineral insulated (MI) cable, with copper core, alumina insulant and stainless steel sheathing. All wires will be screened or twisted in pairs to cancel inductive pick-up. The sheath of the cable will be grounded. The in-vessel sensor cabling is marshalled in specially constructed cable looms running behind the blanket modules. The cables are brought out along the upper port to feedthroughs.

Table 2.6-2 Summary of Diagnostic Sensors located on the Vacuum Vessel and Blanket

Location	Diagnostic Sensor	Particular Radiation and Environmental Effects ¹	Particular Design Problems
Inner wall	High Frequency Response Coils	Heating	Fragile, exposed insulator, RF pickup
	Equilibrium Coils	RIC, RIEMF	Signal drift integration, thermal stability, connector noise
	Joint-less Equilibrium Coils	Heating, RIC, RIEMF	Lifetime
	Diamagnetic Loop	Heating where exposed	Planarity
	Diamagnetic Loop Compensation	Heating, RIC	Size
	Voltage and Saddle Loops	Heating where exposed	Routing conflicts with in-vessel components
	Halo Current Rogowskis		Quantity
	Micro-fission Chambers		
	Neutron Activation Detector		Through vacuum boundaries
Side of blanket	Lost Alpha Detectors		Fragile and exposed to the plasma
Filler module	Interferometer Retroreflectors	Erosion and/or deposition	Degradation in optical performance
Blanket module	Polarimeter Retroreflectors		
Inner wall	Bolometer	He swelling, radiation	Microphony, large cable, many lines of sight (LOS), ECH
	Soft X-ray		Small signal currents, e-m interference
Inner wall and/or blanket	Reflectometer Antennas	Heating where exposed	Wide temperature range

¹ RIC – Radiation Induced Conductivity; RIEMF – Radiation Induced EMF.

2.6.2.2 Equatorial and Upper Ports

Four equatorial ports are dedicated to diagnostics. Two more ports, allocated to remote handling, are foreseen to have diagnostics that can be removed easily before the start of a maintenance procedure. Several factors have to be taken into account in optimising the allocation of diagnostics to the available ports: for example, large aperture systems are placed at port centres and tangential viewing systems at the sides of ports, whereas systems which need to view one of the neutral beams, need to use specific ports. Systems which have complicated transmission lines are located in the ports on the west side of the tokamak near

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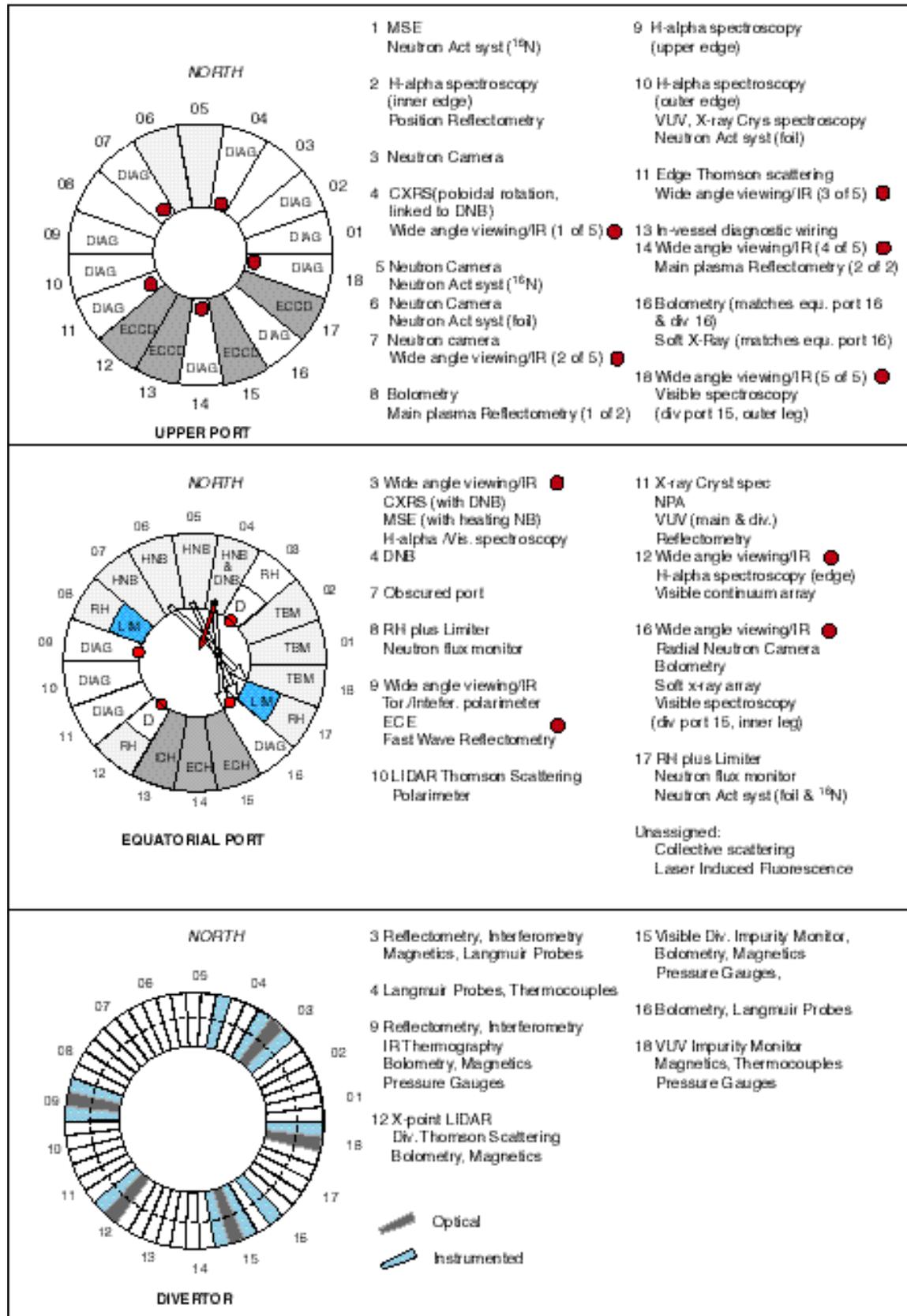


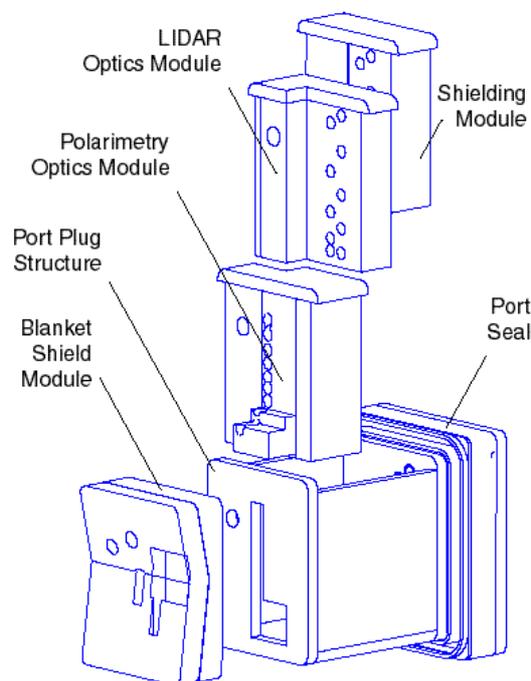
Figure 2.6-1 Provisional Diagnostic Port Allocation at the Upper, Equatorial and Divertor Port Levels

to the diagnostic hall. Some systems, for example the plasma and first wall viewing system, are distributed systems and it is the performance of the combined installation that is important. Figure 2.6-1 shows the provisional port allocation for diagnostics which takes into account these factors.

In most cases, diagnostic equipment in equatorial ports is mounted in a single port plug within the primary vacuum. The principal components of the plug are a special blanket shield module, and a port plug structure incorporating a VV closure plate. The shield module comprises a first wall made from armoured beryllium tiles bonded to seamless stainless steel water cooling pipes and a shielding manifold box, an arrangement similar in design and technology to other equatorial ports, in particular the limiter one. The port plug structure (see Figure 2.6-2) has the dual functions of supporting the diagnostic components and providing the necessary shielding. A single structure similar for all ports is used, containing shielding/diagnostic modules. The common arrangement allows a simple concept for remote maintenance of all the port plugs and the modularity of internal components allows a standardised approach for hot cell maintenance.

Outside the primary vacuum, a structure is located in the connecting duct between the vessel flange and the port interspace closing flange. The connection between vessel and cryostat is relatively simple for the diagnostics which require optical connections, whilst substantial connections are required for waveguides and vacuum extensions.

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**Figure 2.6-2 Assembly of a Typical Diagnostic Equatorial Port Plug Structure with the Diagnostic Systems: LIDAR and Poloidal Field Polarimeter (Port 10).
The apertures in the blanket shield module are also shown.**

The VUV, X-ray crystal spectrometry, and the NPA, have to be directly coupled and require an extension of the primary vacuum outside the bioshield, as shown schematically in Figure 2.6-3. The primary vacuum extension is enclosed in a secondary vacuum chamber, which is able to resist a pressure larger than 0.2 MPa, and which is separated from the cryostat vacuum to avoid cross-contamination.

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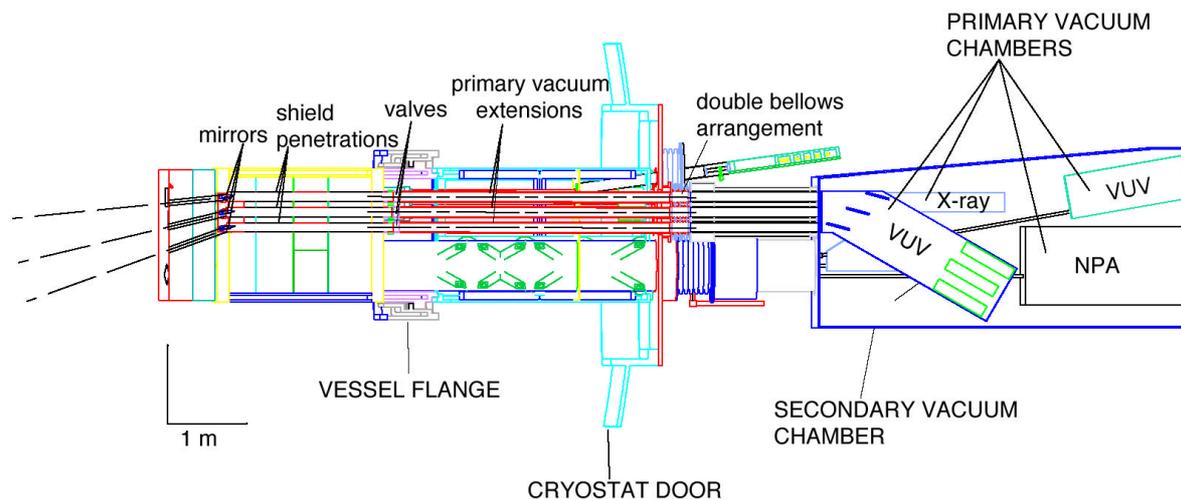


Figure 2.6-3 VUV Vacuum Extension at the Equatorial Port 11

For maintenance operations, the diagnostic port plug will be brought to a dummy port installed in the hot-cell area. While in the dummy port, in-vessel components can be accessed remotely, while the windows and other feedthroughs on the vacuum vessel flange can be replaced hands-on. Tests can be carried out on the port plug and the interspace structure while they are mounted in the dummy port.

The concepts and approach developed for the equatorial ports are also used for diagnostics installed in the upper ports. However, some diagnostic equipment in these ports will have permanent features such as wiring and waveguides with as few connections as practical. The neutron camera will have a special arrangement outside these ports (2.6.3.2).

2.6.2.3 Divertor Ports

In the divertor, diagnostic components are installed in the three remote handling ports and on the divertor cassettes at these positions. At each location there are two instrumented cassettes (with Langmuir probes, bolometers, pressure gauges, etc.) on either side of a central, 'optical', cassette. The latter is modified to incorporate optical and microwave diagnostics and includes a mirror on a central mount (Figure 2.6-9). Side plates, up to 20 mm thick, complete with pre-wired sensors and wiring loom, are bolted to the body of the cassette. These permit relatively simple installation and replacement of diagnostic components (Figure 2.6-4).

Signals are marshalled at the electrical connector on the outboard end of the cassette. In the space between the VV closure plate and the divertor cassette, a diagnostic block is installed

which carries waveguides and optical equipment. Remote maintenance inside the machine is performed for the diagnostic cassettes in the same way as for standard cassettes.

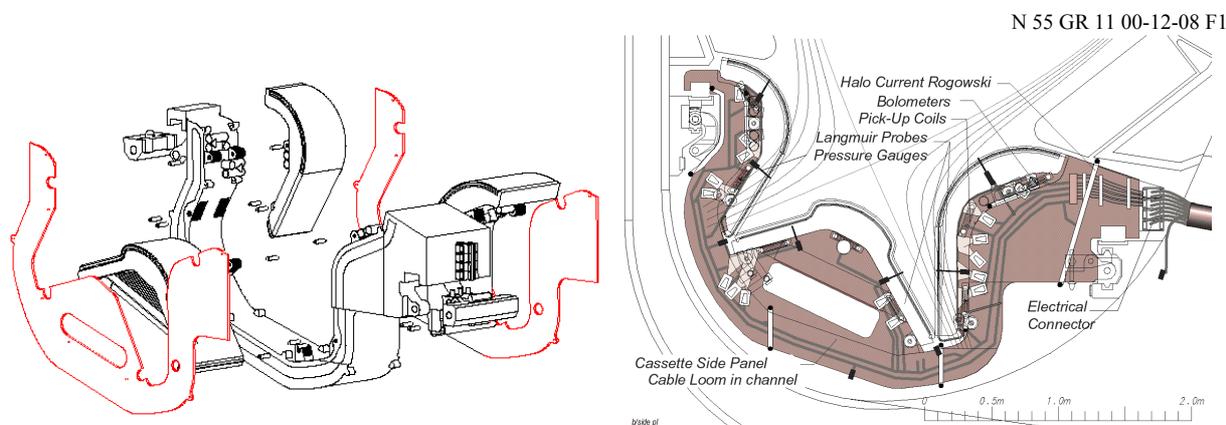


Figure 2.6-4 Side Plate of a Divertor Cassette with Typical Sensor Locations

2.6.3 Diagnostic Systems

The individual diagnostic systems can be grouped into seven generic groups (Table 2.6-1). The different groups of diagnostics have different implementation details and so it is convenient to discuss them separately.

2.6.3.1 Magnetics

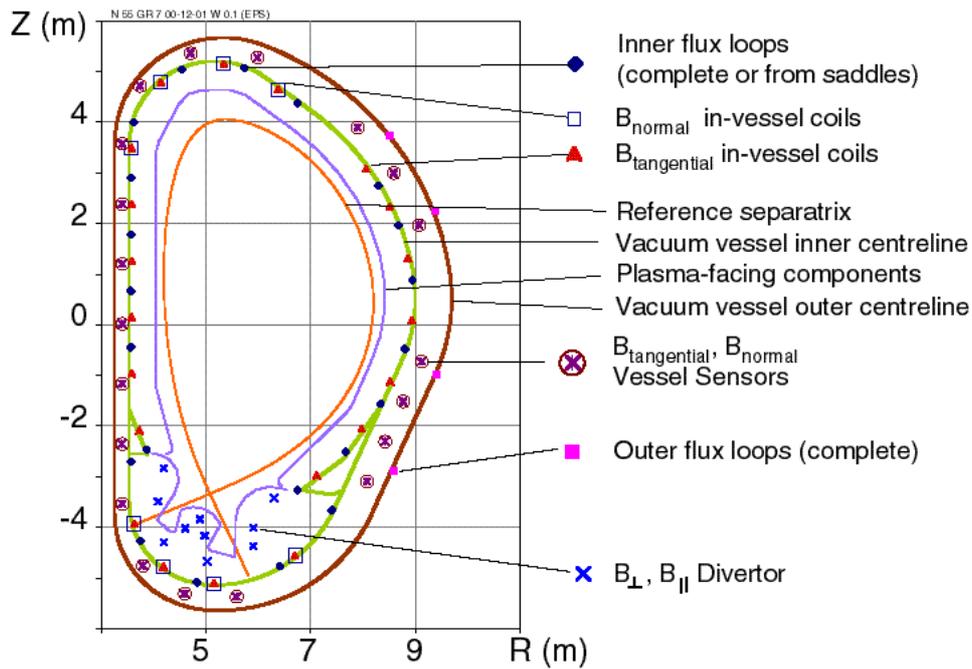
The magnetic diagnostics comprise several subsystems:

- sets of pick-up coils, saddle loops and voltage loops mounted on the inner wall of the vacuum vessel for equilibrium and high frequency measurements (in-vessel system);
- sets of pick-up coils and steady state sensors for back-up measurements, currently proposed to be mounted between the VV shells;
- continuous poloidal (Rogowski) loops mounted on the outside of the vacuum vessel;
- sets of coils mounted in the divertor diagnostic cassettes;
- diamagnetic system comprising poloidal loops on the inner wall of the VV and compensation circuits inside and outside the vessel;
- Rogowski coils mounted around earth straps of the blanket/shield modules for measuring the 'halo' currents.

The in-vessel system comprises:

- tangential, normal and toroidal equilibrium coils mounted on the inner surface of the VV;
- tangential high frequency coils mounted on the inner surface of the VV;
- complete and partial flux loops mounted on the inner surface of the VV;
- dedicated saddle loops mounted on the inner surface of the VV;
- a (temporary) PF and TF error field measurement assembly.

The distribution of the main elements of the system is shown in Figure 2.6-5.



**Figure 2.6-5 Poloidal Distribution of Magnetic Sensors
(The diamagnetic loops and external Rogowski coils are not shown)**

The pick-up coils mounted on the inner surface of the VV are wound on a stainless steel former with a protective cover. The important irradiation effects, radiation induced conductivity and radiation induced EMF, are minimised by a careful choice of materials and sensor location. The voltage loops have a bridge at every sector joint. Special connectors are used to permit reconnection of the voltage loop if replacement of a vessel sector were needed. The coils, the cable and other ceramics (e.g. those used in the HF coils) are sufficiently shielded by the presence of the blanket modules that their lifetime is comparable to or longer than the lifetime of ITER.

The coil set proposed to be mounted between the VV inner and outer shells, and on the VV, would form a back-up system for the in-vessel magnetics for long pulses. By placing coils of large effective area in this relatively low radiation environment, it is expected that the signal to noise ratio at the input of the integrator will be significantly enhanced. In addition, this environment allows the use of steady state sensors of the strain gauge type, which do not suffer from drift. Finally, this set is mechanically and electrically very well protected. There is a drawback: the slow frequency response (of order 1.2 s for 2 % error following a step).

The external, continuous, Rogowski coils are located on poloidal contours outside the vacuum vessel and supported by the TF coils, and measure all current passing through their cross-sections, that is, the sum of plasma current, and vessel current. An independent measurement of the vacuum vessel current is needed to derive the plasma current. This is provided by the vessel and in-vessel sensors.

The diamagnetic loop system measures the magnetic flux expelled by the plasma. From this measurement, the perpendicular energy content can be derived. This in turn gives the confinement time. The method is based on a pair of poloidal loops on the inner wall of the vessel, and compensation circuits. The poloidal loop measures the flux change inside its

contour. The compensation circuits measure the vacuum flux inside and outside the vessel, and the local vertical field. The exit wires are twisted and routed out of the vessel through the nearest divertor port, with already existing wiring, feed-throughs and connectors. Multi-turn compensation coils of the same surface area as the diamagnetic loop are placed inside the vacuum vessel below the triangular support frames (see section 2.2), and outside the vacuum vessel, for the same sectors as the diamagnetic loop. In addition, the TF current (including casing) change during the pulse is measured by Rogowski coils around the TF coil cases on the low field side.

Distinct sensors are used to measure halo currents. Since current enters the wall through the blanket/shield modules and these are electrically connected to the VV by means of earth straps, one way of measuring halo currents is to measure the current in the earth straps using Rogowski coils. In addition, the blanket/shield modules provide an opportunity of obtaining higher spatial resolution, required since halo current density varies poloidally and toroidally. However because of the large number of modules, it is impractical to obtain full coverage using this method. The present design attempts to obtain reasonable coverage of the important areas. The inner top and bottom of the vessel have dense coverage. The halo-sensing Rogowski coil is wound on a ceramic body with grooves with a bare wire or within a thin metal case using sheathed cable. Approximately 300 turns are required to give signals of order 1 V during disruptions. Separate sensors are used to deduce the current flowing through selected divertor cassettes.

2.6.3.2 Neutron Systems

The principal neutron systems are a radial neutron camera, a vertical neutron camera, neutron spectrometers, neutron flux monitors, and a neutron activation system.

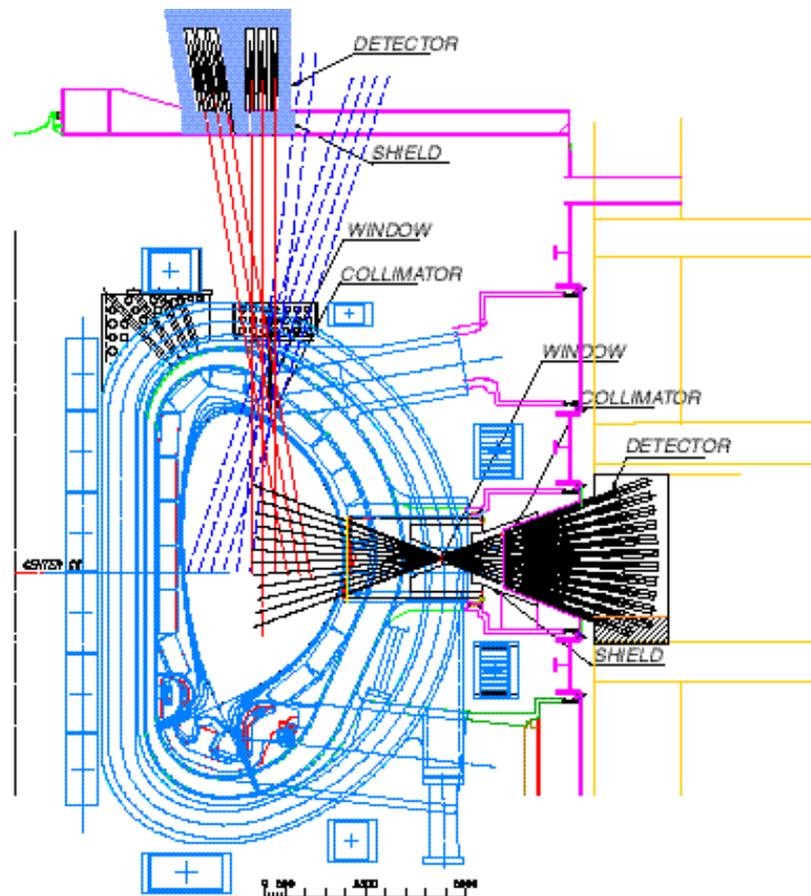
The radial neutron camera consists of a fan-shaped array of flight tubes, viewing the plasma through a vertical slot in the blanket shield module of an equatorial port plug. The sight lines intersect at a common aperture defined by the port plug and penetrate the vacuum vessel, cryostat, and biological shield through stainless steel windows (Figure 2.6-6). Each flight tube culminates in a set of detectors chosen to provide the required range of sensitivity, and temporal and spectral resolution. Some of the viewing chords will be equipped with high resolution neutron spectrometers, enabling the system to provide emissivity-weighted, chord-averaged measurements of ion temperature. Appropriate spectrometers have not yet been selected but there are several that could meet the measurement requirements with development.

The proposed vertical neutron camera measures the line-integral neutron emissivity along chords viewing downward through the upper ports. Each sight-line views the plasma through long narrow tubes in the upper port plug and vacuum vessel, cryostat and the second collimator in the shield. The first collimators are integrated into the plug of the upper port. For each sight-line, a 45 mm inner diameter flight-tube passes through the vacuum vessel and contains a thin stainless steel 'window'. The detectors and the second collimators are in the space between the cryostat lid and the top bioshield. Shielding on the cryostat lid, around the detectors, provides a beam dump and will allow hands-on maintenance.

Summation of the chordal signals, together with knowledge of the plasma vertical position, gives the global neutron source strength, hence the total fusion power. Combined with data from the radial neutron camera, these measurements allow reconstruction of the spatial

distribution of neutron emissivity, which determines the alpha particle source profile and fusion power density, and serves as a constraint on inferred values of fuel concentrations and effective ion temperature.

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**Figure 2.6-6 Schematic of Proposed Radial and Vertical Neutron Cameras
(The sight-lines for the vertical camera would be distributed at four different toroidal locations)**

The neutron flux is measured by fission chambers containing ^{235}U or other isotopes, situated at different locations in the diagnostic ports and outside the VV. In addition, micro-fission chambers are deployed behind the blanket modules in poloidal arrays at two toroidal locations. These are miniature fission detectors of the type commonly used for in-core neutron flux measurements in fission reactors. The use of multiple locations allows compensation of effects due to changes in plasma position or shape, and provides redundancy in case of detector failure. Together these systems give the global neutron source strength from which the total fusion power is obtained, and the measurement should be insensitive to plasma position.

Two activation systems are planned. One uses pneumatic transfer to place a sample of material close to the plasma for irradiation. This will give an accurate but relatively slow measurement. The second system measures the gamma rays from the decay of ^{16}N produced

in a flowing fluid. This system will be faster (typically several seconds) but less accurate. Taken together these systems will provide a robust, independently calibrated, measure of fusion power.

2.6.3.3 Optical/Infrared Systems

The principal optical systems are two multi-pulse Thomson scattering (TS) systems (core and edge), an equatorial plane interferometer, and a poloidal interferometer/polarimeter.

The core TS system operates on the time-of-flight (LIDAR) principle. Light from a high power laser is transmitted to the plasma using a folded mirror arrangement inside a shielded labyrinth at an equatorial port. The plasma-facing mirror is metallic and actively cooled. Scattered radiation returns along the same labyrinth to remote spectrometers. An active alignment system is employed to compensate for movements of different parts of the system.

The key element in the system is the plasma-facing mirror. The mirror will be located at the bottom of a duct about 2 m in length and view the plasma through a 0.2 m diameter aperture in the blanket shield module. It will be actively cooled. In this location, it can potentially be damaged by two processes. The mirror surface can be eroded due to bombardment from energetic neutrals arising from charge exchange processes occurring in the plasma edge region, and/or it can be covered by a thin layer of first wall or duct material due to erosion of these components. Extensive R&D¹ has shown that mirrors made from low sputtering coefficient materials deposited on a high thermal conductivity substrate are robust against erosion. The chosen mirror for the LIDAR system is Rh on a V substrate. Baffles, cleaning techniques, and/or shutters are possible mitigating methods against deposition.

In order to meet the requirements for high-resolution measurements in the edge region, a conventional Thomson scattering system is employed. The large upper ports permit the installation of separate input and collection lines in the same port (Figure 2.6-7). Moreover, implementation at this level allows advantage to be taken of the flux expansion in this region. The collection line is transmitted beyond the secondary confinement barrier using heated optical fibres (although space is allowed for a conventional optical relay with discrete elements if required).

A vibration-compensated interferometer employing Faraday rotation techniques will be used to measure line-integrated density for use in feedback control. The plasma is probed along lines of sight in the equatorial plane. Each beam path has collinear 10.6 μm (CO_2) and 5.3 μm (CO) laser probe beams. The laser beams paths are generated from one 10.6 μm (CO_2) laser and one 5.3 μm (CO) laser and are spatially separated by a mirror system. They enter and exit the plasma chamber from a single port and are reflected back down the same beam path (with an offset) by retroreflectors. There are several possible locations for the installation of the retroreflectors, including the filler modules between the blanket shield modules and in the special shield modules on other ports.

¹ 'Diagnostic First Mirrors for Burning Plasma Experiments', V Voitsenya et al, Rev. of Sci. Instrum, 72, number 1 (2001) 475.

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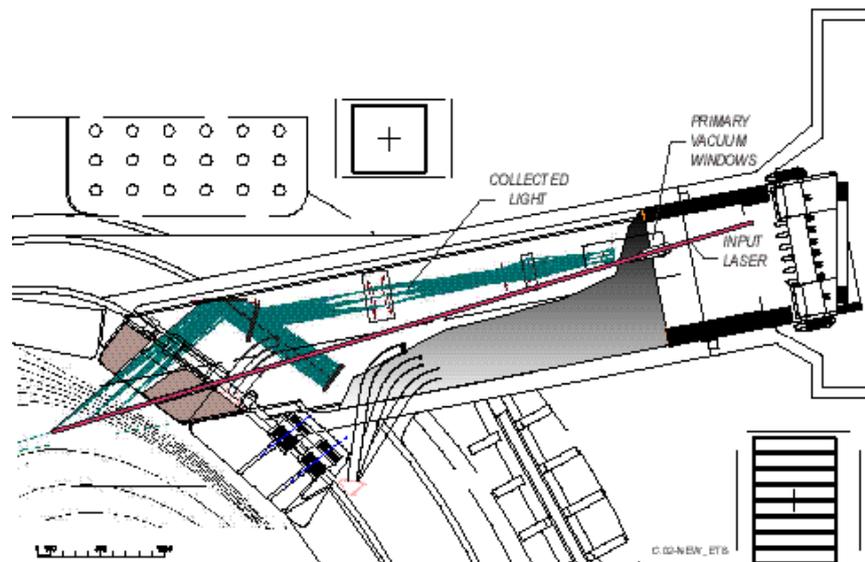


Figure 2.6-7 Schematic of the Thomson Scattering System installed in an Upper Port

The phase change due to the plasma is measured at both $10.6 \mu\text{m}$ and $5.3 \mu\text{m}$. Also, the Faraday rotation is measured at $10.6 \mu\text{m}$. Analysis of the data gives the line-integral of the electron density along each line of sight which, when inverted and combined with other measurements, gives the profile of the electron density. Vibration compensation is obtained by taking the difference between the results at $10.6 \mu\text{m}$ and $5.3 \mu\text{m}$. High reliability and high sensitivity are obtained from the Faraday rotation and phase measurements respectively.

A plan view of the beam paths through the port shield plug is shown in Figure 2.6-8.

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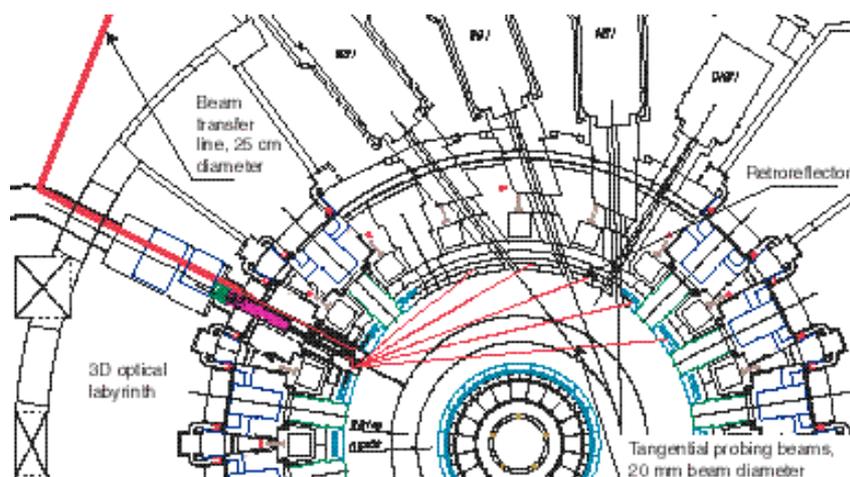


Figure 2.6-8 Schematic of the Layout of the Interferometer/Polarimeter showing the Five Lines of Sight through an Equatorial Port

Multi-chord polarimetry in the poloidal plane will be used to provide measurements of the q profile and/or to anchor reconstructions of the magnetic equilibrium. As for the interferometer, in-vessel retroreflectors have to be used, but in this case it is proposed to mount them in the remote handling vertical slots in the blanket modules.

Additional planned optical systems under investigation are Thomson scattering systems for the X-point and divertor regions, and a collective scattering system to provide measurements of the confined alpha particle population.

2.6.3.4 Bolometry

The bolometric systems aim to provide the spatial distribution of the radiated power in the main plasma and in the divertor region with spatial resolutions of 20 cm and 5 cm, respectively. The proposed method, used on many tokamaks, is sparse-data tomography. This would require a large number of lines of sight (approximately 340).

The bolometer arrays will be installed in the equatorial and upper ports, in the specially instrumented diagnostic divertor cassettes (and possibly at selected locations on the VV). From each of these locations several arrays of lines of sight observe the plasma in a fan-shaped geometry. From the equatorial port, the inner divertor leg and the main plasma are viewed. From the upper port, the main plasma, the area of the X-point, and the largest part of the divertor legs, can be seen. This last view provides the total radiated power. Bolometers mounted on the VV would view the plasma through the poloidal gaps between adjacent blanket/shield modules. This provides some shielding from the nuclear radiation.

In the equatorial and upper ports, the bolometer arrays are integrated rigid units with all wiring attached, mounted in a diagnostic shield plug. In the divertor, there are multiple small heads assembled in a rigid conduit with the wiring attached to the side wall of the instrumented divertor cassette. The wiring runs to an automatic remote handling connector near the exit port. The plasma is viewed through the gap between cassettes, nominally 1 cm. The bolometers, if present on the vacuum vessel, are proposed to be housed in removable carriers that are plugged into permanent bosses. There are remote handling connectors between the bolometers and the wiring runs which are in conduits behind the blanket/shield module.

2.6.3.5 Spectroscopic and Neutral Particle Analyzer (NPA) Systems

An extensive array of spectroscopic instrumentation will be installed covering the visible to X-ray wavelength range. Both passive and active measurement techniques will be employed. The four main regions of the plasma - the core, the edge, the scrape-off layer (SOL), and the divertor - will be probed. The principal diagnostic systems employed are listed in Table 2.6-3. In addition there will be an NPA system which shares access with the X-ray and VUV systems and so is included in this group. A wide range of plasma parameters are determined including impurity species, impurity density and input flux, ion temperature, He density, fueling ratio, n_T/n_D and n_H/n_D , plasma rotation, Z_{eff} , current density, and q profile.

The H-alpha spectroscopy system measures the emission in the Balmer hydrogen lines. Several wide-angular optical systems located in the upper and equatorial ports view the upper, inner, and outer regions of the main plasma and the part of the divertor inner region visible from above. Collected light is transmitted by mirror optics through the labyrinths in

port plugs and then focused onto the fibre light guides leading to the spectrometer installed behind the biological shield. The divertor region is also probed with the divertor impurity monitoring system which views the plasma through the divertor ports and can measure the emission in the Balmer hydrogen lines.

The visible continuum array measures the emission at $\lambda = 523$ nm along multiple lines of sight in the equatorial plane. By using many sight lines (~ 35), an accurate unfolding of the Z_{eff} profile can be obtained. The emission is multiplexed into one transmission line and an optical labyrinth provides the required shielding.

The VUV main plasma impurity monitor has two subsystems: one consists of two spectrometers located at an upper port viewing from the flux expansion region up to 1 m into the plasma, and the other consists of a single spectrometer located at an equatorial port with a radial view through the plasma centre. Both systems measure the emission in the wavelength range 10 – 100 nm. Grazing collecting optics ($5^\circ - 7^\circ$) and spectrometers are employed, and thereby some shielding of the detectors is achieved. In this wavelength range, it is not possible to use windows, and so direct coupling of the instruments is required.

Table 2.6-3 Summary of Spectroscopy and NPA Diagnostics

Instrument	Wavelength Range	Regions Probed/ Viewing Directions	Function
H system	Visible region	Main plasma: inner, outer and upper regions Divertor: inboard and outboard regions	ELMs, L/H mode indicator, n_T/n_D and n_H/n_D at edge and in divertor.
Visible continuum array	$\lambda = 523$ nm	Core plasma. Multiple LOS in the equatorial plane	Z_{eff} , line averaged electron density.
VUV (main plasma)	10 – 100 nm	Upper and equatorial regions	Impurity species identification.
X-ray (survey and high resolution)	0.1 – 10 nm	Core region: five LOS in the poloidal plane	Impurity species identification, plasma rotation, T_i .
Divertor impurity monitor	200 – 1000 nm	Divertor and X – point regions	Impurity and influx, divertor He density, ionisation front position.
CXRS	$\lambda = 468.5$ nm	Core and edge	$T_i(r)$, He ash density, impurity density profile, plasma rotation.
MSE	Visible region	Core	$q(r)$, $E_r(r)$.
NPA	N/A	Core and edge	n_T/n_D and n_H/n_D at edge and core. Fast alphas.

Abbreviations see Table 2.6-1. LOS = Line(s) of sight

For the X-ray region, there will also be two subsystems: a medium resolution spectral survey instrument providing full coverage in the wavelength range 0.1 – 10 nm, combined with a high resolution, multi-channel instrument, with narrow spectral coverage in the range between about 0.1 - 1 nm and multiple radial sight-lines. These will be mounted in an equatorial port along with the VUV system and the NPA in an integrated instrument package.

In addition, there will be a survey instrument mounted in an upper port. This will share access with the upper port VUV system.

The divertor impurity monitoring system measures the emission in a wide spectral range along multiple lines of sight in the divertor region. The plasma is viewed at the divertor level and also from the equatorial and upper ports.

At the divertor level, the light emitted from different chords is collected by mirror optics mounted beneath the dome and on the side, of the special (central) optical divertor cassettes (Figure 2.6-9). It is transmitted through an optical penetration in the divertor remote handling port, the VV shielding plug and the cryostat. A labyrinth in the biological shield provides the necessary shielding. The beams are guided to the collecting and focusing optics where they are focused on to an optical fibre array. The light entering the optical fibre bundles is separated into two wavelength regions: 200 - 500 nm, and over 500 nm. The former enters the spectrometers positioned on a transport cask in the pit. Optical fibre bundles guide light in the wavelength region over 500 nm to spectrometers installed in the remote diagnostic hall, where accessibility for maintenance is better.

The plasma in the upper part of the divertor region to the X-point is observed through the gap between the divertor cassettes. An optical transmission line transmits the emission to the spectrometers and detectors located in the pit, or in the diagnostic hall, depending on the wavelength region.

Additional views of the divertor region are needed in order to meet the measurement requirements for two-dimensional information. These are achieved by viewing the plasma with two separated viewing lines with multi-chords, one from the upper port and the other from the equatorial port.

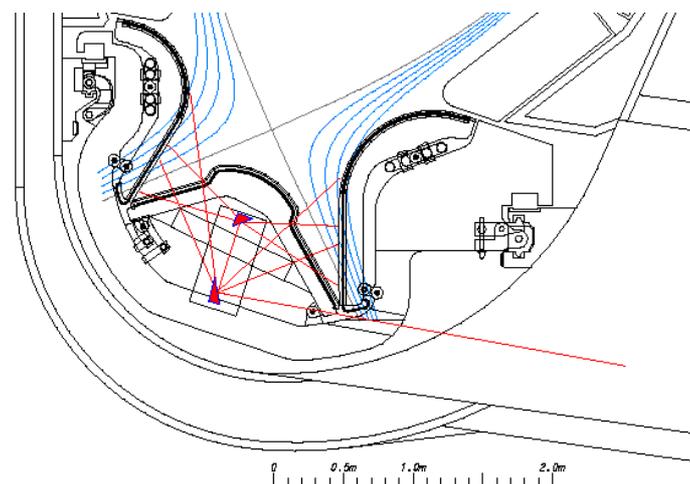


Figure 2.6-9 Viewing Fans in the Divertor Region

Passive spectral measurements in the visible wavelength range are of limited value for probing the core, because of the high temperatures. However, active measurements, employing charge exchange recombination spectroscopy (CXRS) with beams of energetic neutrals, are a rich source of information. For several of the important measurements, the optimum beam energy is ~ 100 keV/amu, well below the energy of the heating beams

(1 MeV). This generates a requirement for a dedicated diagnostic neutral beam (DNB). The beam is viewed through optical labyrinths embedded in shielding blocks in the upper port above the DNB and in an equatorial port. The most important measurement is that of the He ash density. Calculations for standard conditions show that a good signal-to-noise ratio can be achieved in the core region (Figure 2.6-10).

In order to achieve sufficient beam penetration for motional Stark effect (MSE) measurements, a beam energy > 500 keV/amu is necessary. One of the heating beams is therefore utilised for this measurement. The radial electrical field (E_r) can affect the interpretation of the MSE measurements. By using two viewing directions both the E_r and the q profiles can be obtained.

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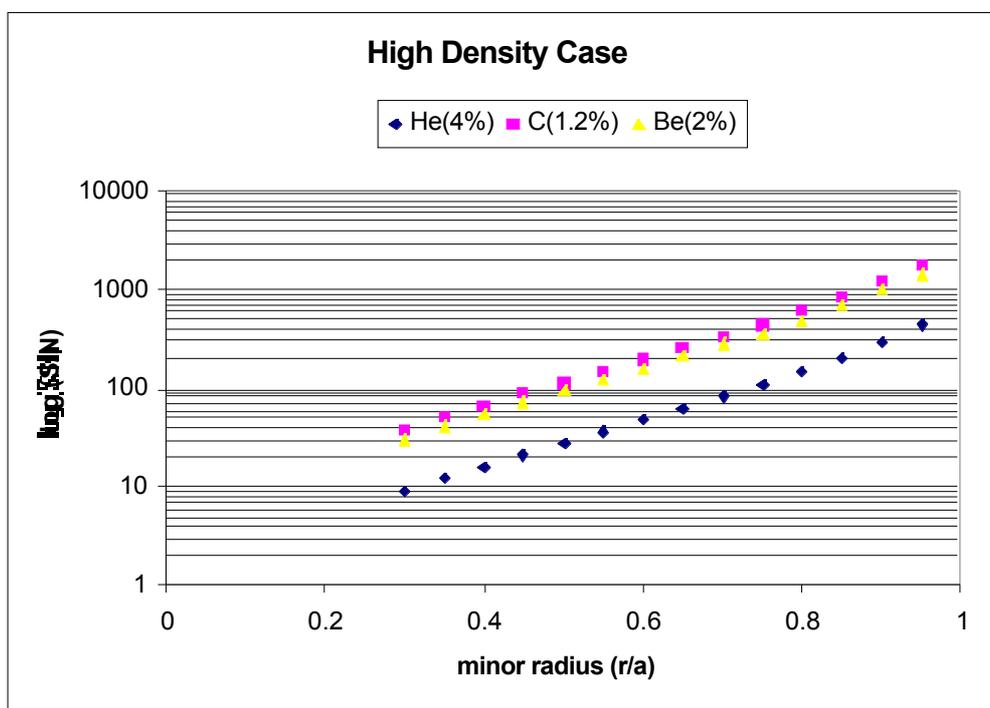


Figure 2.6-10 Signal-to-Noise Ratio at Spectral Half Maximum for the Measurement of 4% Helium, 1.2% C and 2% Be respectively versus Minor Radius for Standard ELMy H-mode Plasma Conditions.

The line-averaged electron density is $1.4 \times 10^{20} \text{ m}^{-2}$. The viewing geometry is a poloidal periscope with a typical path length through the plasma of about 6 m.

The integration time is 0.1 s.

The NPA is designed to measure the tritium-to-deuterium ion density ratio n_T/n_D in the plasma and to provide information on the distribution function of alpha particles in the MeV energy range. The system is directly coupled with a 200 mm tapering to 70 mm conical tube, approximately 6 m long, enveloped in a stainless steel shield in an equatorial port. The incoming neutral particles are ionized in a stripping target foil and then pass the magnetic and electric fields of the analyzing magnet and electrostatic condenser before detection. The NPA primary vacuum chamber (located outside the equatorial port 11, is enveloped in a secondary vacuum chamber together with the X-ray and VUV diagnostics.

An enhanced version of the NPA is under development. This will measure the neutral particles emitted at high energy (> 100 keV) and with this detector it is expected that under typical conditions (peaked T_i) measurements of n_T/n_D will be possible in the plasma core region (Figure 2.6.11).

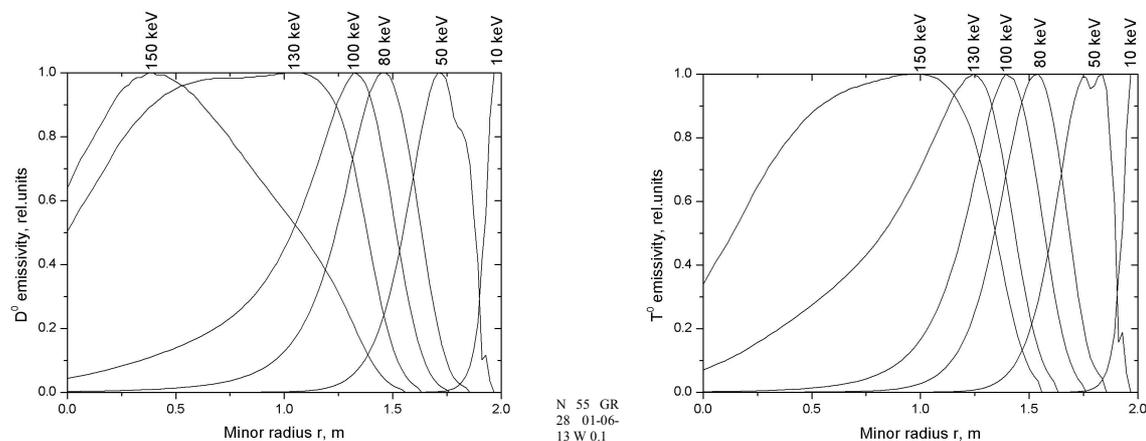


Figure 2.6-11 Calculated Emissivity Functions for D and T under Typical ITER Conditions (Peaked T_i) showing that with the Upgraded NPA Detector Measurements of n_T/n_D should be Possible in the Plasma Core Region

2.6.3.6 Microwave Systems

The principal microwave diagnostics will be a system to measure the electron cyclotron emission (ECE) from the main plasma, and three reflectometry systems for probing the main plasma, the divertor plasma, and for measuring the plasma position. Additional systems under study are an electron cyclotron absorption (ECA) system for use in the divertor region, a fast wave reflectometry system, and a microwave scattering system.

The ECE system consists of two collection antennas in an equatorial port plug, a transmission line set, and spectrometers for analyzing the emission. The antennas are staggered vertically to give access to the core for a variety of plasma heights near the nominal plasma centre height. The antennas are Gaussian beam telescopes. They are subject to surface heat loads of ~ 50 kW/m² 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.

The radiation from each antenna is transmitted to the pit using wide-band corrugated waveguide with suitable mechanisms to take up machine movements. There, the signal is split into X and O mode components using a polarising beam splitter contained in a box which is an extension of the secondary vacuum. The signals are transmitted to the diagnostic hall through a secondary vacuum window and via a dedicated corrugated waveguide which is open to the pit pressure (see scheme in Figure 2.6-12). In the diagnostic hall, the signal is divided between two survey spectrometers (Michelson interferometers) and two fixed multichannel spectrometers (heterodyne radiometers).

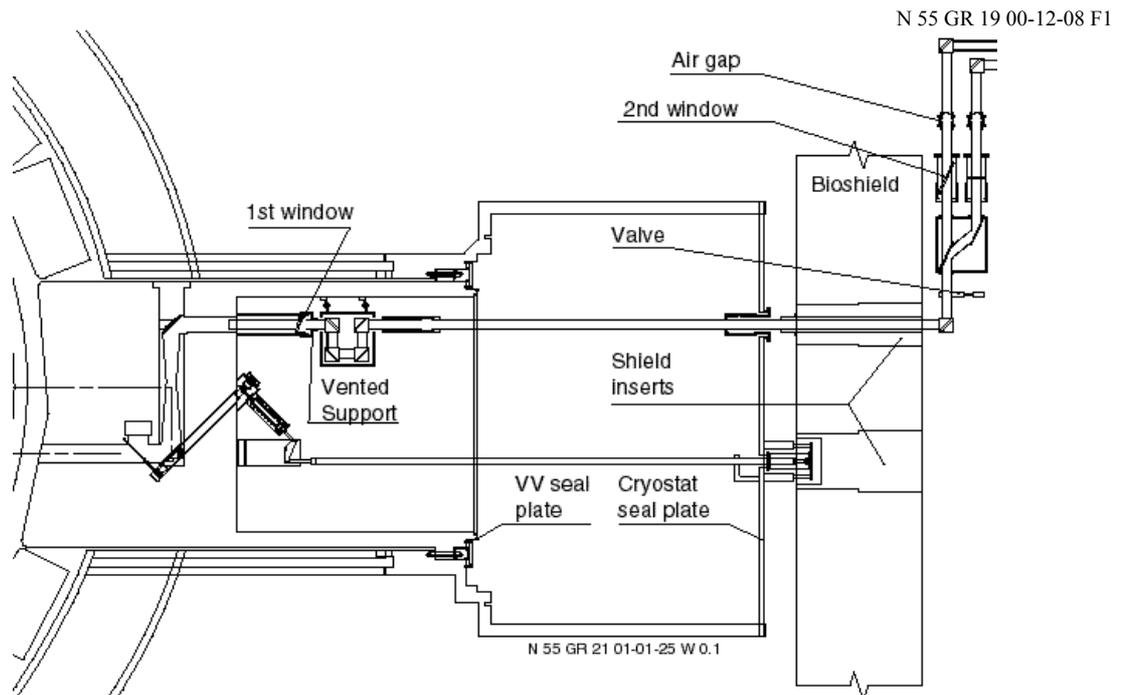


Figure 2.6-12 Schematic View of the Vacuum Boundary and Window Locations in the ECE System

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 on the low-field side which provides measurements of the SOL profile, (ii) an ordinary (O-mode) system to provide the inboard and outboard density profile in the gradient region, and (iii) an X-mode system reflecting off the lower cutoff and launched from the high field side to provide the core profile.

The plasma position reflectometer 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 (>1,000 s) pulse operation, where the position deduced from the magnetic diagnostics could be subject to substantial error due to drifts. To meet the requirements for accuracy of the location of the gaps, it is necessary to measure the density profile to a density comparable to, or exceeding, the separatrix density. As for the high field side of the main reflectometer with which it shares one antenna pair, the antenna pairs (about 1.4 cm tall) are mounted in the 2 cm gap between blanket modules on the vacuum vessel and view the plasma between blanket modules. Radiation is routed to them using small bore waveguides. The waveguides are brought out through two of the upper ports to the sources and detectors installed in the pit.

The divertor reflectometer measures the profile of the electron density in the divertor region. 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. By combining transmission and reflection measurements, it is expected that the first few moments of the density profile (peak density, width) can be estimated.

Labyrinths in all 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.

2.6.3.7 Plasma-Facing and Operational Diagnostics

A range of diagnostics will be installed to aid the protection and operation of the tokamak. Several diagnostics will be dedicated to monitoring the condition of the high heat flux components in the main chamber and the divertor. Other systems include Langmuir probes, pressure gauges, residual gas analyzers, and runaway monitors (hard X-ray detectors and tangential view IR systems).

The principal high heat flux protection diagnostic will be a wide-angle camera system which will give views of the in-vessel components (including parts of the divertor) in the IR and visible wavelength ranges. Combining several cameras can achieve high coverage (~ 80%) of the area of the first wall. The first element of the system is a metal mirror and the image is transmitted through a rigid labyrinth to a flattening array immediately before the vacuum window. From here the image is transmitted by lenses to ccd cameras mounted on the shielded side of the biological shield.

Dedicated divertor diagnostics include an IR thermography system for measuring the profile of the power deposition on the target plates, Langmuir probes for local measurements of plasma parameters and as attachment/detachment indicators, and fast pressure gauges, all to be installed in diagnostic divertor cassettes. These have special provisions for diagnostic sensors and provide access for optical and microwave transmission lines. IR thermography provides surface temperature measurements of both divertor target plates in a poloidal plane with good spatial and temporal resolution. Two different methods of implementation are being considered – a conventional optical periscope or a novel multiplexing scheme. In the latter case, the thermal radiation collected at different wavelengths from different points on the target plates is merged into a single beam using a shielded low-frequency grating close to the front mirror. Using this “inverse spectrometer” set-up, the number of optical elements inside the vacuum vessel is drastically reduced and only a small diameter optical window is needed.

2.6.3.8 Diagnostic Neutral Beam and CXRS

The optimum beam energy for the diagnostic neutral beam is ~ 100 keV/amu. This is considerably below the energy of the heating beams (1 MeV), so a dedicated beam is required (see section 2.5.1). To minimise the cost with high reliability, a conservative approach is proposed, i.e. to use the same negative ion source and the same maintenance tools as in the main ITER injectors. The beam would have a beam current of 15 A (H^0

atoms), a footprint of 30 x 30 cm and pulse duration 1 – 3 s every 10 – 20 s. The beam can be modulated at 5 Hz.

2.6.4 Conclusions – System Performance Assessment and Key Issues

Feasible concepts have been developed for the installation and maintenance of diagnostic sensors and components in the upper and equatorial ports, and in the divertor region. In the VV ports, diagnostic components installation faces integration issues: suitable cabling and hardware for the necessary penetrations through the VV and the cryostat have been identified. Detailed analyses are in progress to confirm the compatibility of the in-vessel diagnostics with the vessel fabrication, in-vessel cooling manifolds, blanket support system, and neutron streaming but this work is not yet complete.

At the equatorial and upper levels, promising design concepts for the special blanket shield modules are well developed and it is expected that the required viewing apertures can be provided. The effectiveness of the shielding, the stresses in the structure, and the cooling of the modules, are all being analysed. Margins have been left for design iteration when this is completed.

Guidelines have been developed for optimizing the distribution of diagnostics in the available ports. Application of the guidelines has led to a distribution of diagnostics which, it is believed, enables most of the selected systems to be accommodated. However, detailed neutron calculations have been done on only a few representative ports. It is possible that, when these have been done on all ports, further optimisation of the selection and distribution of the diagnostics will be necessary.

At the divertor level, the concept of installing diagnostic components on, and in, the divertor cassettes allows for relatively easy installation and maintenance. No insurmountable engineering problems are foreseen, but the details have yet to be developed. The major issue at this level is the survivability of the diagnostic components.

The ability of the diagnostic systems to meet their individual measurement requirements depends on factors which are in general different for each generic group of diagnostics, and so these are assessed separately.

For the magnetic diagnostics, it is expected that it will be possible to install a configuration of sensors which will meet the measurement requirements. A key issue is the lifetime of the in-vessel coils and loops. Although it is believed that necessary lifetimes can be achieved using materials examined in the supporting radiation effects R&D programme, at least one backup system should be included for key control measurements. The most vulnerable sensors are in the divertor cassette and have been designed for quick replacement. A particularly difficult area is the repair and maintenance of the in-vessel diagnostic components.

Tests with prototype coils and integrator have shown an unexplained high asymmetric voltage apparently due to the phenomenon of radiation induced electromotive force. However, a recent reexamination of the results suggests that there were problems with the long pulse integrator used in the tests, and/or other sources of voltage, for example thermoelectric effects. Latest tests with a gamma source suggest that the phenomenon will be negligible, as was expected from simple models. Further tests are planned.

No insurmountable difficulties are expected for the implementation of the neutron flux monitors and activation systems. However, the ability of the neutron cameras to provide the measurements for which they are intended, for example the total fusion power and the alpha particle source profile, is directly linked to the available access. A wide angle of view is necessary in both the radial and vertical directions. This is difficult to achieve in the vertical direction due to the limited height of the equatorial port. The view through the upper ports for the vertical camera is a new concept and some key interfaces are not yet developed.

All optical/IR, spectroscopic and microwave systems view the plasma with a mirror and a critical issue is the lifetime of this component. It is believed that solutions for the first mirrors exist for those systems that operate in situations where the dominant potentially damaging mechanism is erosion due to the bombardment of high energy neutral particles. This is likely to be the case for most systems installed in the equatorial and upper ports. However, it is possible that deposition of eroded first wall material or viewing duct material will also occur leading to a degradation of optical performance. Mitigating methods in this case would be baffles in the duct, cleaning techniques, and/or shutters in front of the mirror.

For diagnostic components in the divertor, it is probable that deposition of eroded material will be the dominant potentially damaging mechanism. At this stage, only limited information is available on this process. More investigations and developments are required before the extent of the problem is really known and the most effective countermeasures can be selected. Alternative views from the equatorial and upper ports are also under consideration.

A bolometer which is believed to be sufficiently radiation-hard for use during the initial DT operation exists, but a device with enhanced radiation hardness may be required for the anticipated end-of-life fluence level of the machine. Potentially suitable devices are being investigated in a supporting R&D programme. Dedicated development is likely to be necessary.

A design for the implementation of the spectroscopic systems which require direct coupling to the vessel vacuum (X-ray crystal, VUV spectrometers and NPA systems) has been developed for the measurements on the main plasma and it is believed that good performance will be achieved. In the divertor the VUV measurements are more difficult, and the visible and near UV capability needs to be exploited.

For the microwave measurements (ECE and reflectometry) which are made from the low-field side, no insurmountable problems are foreseen. A conceptual design exists for the installation of the antennas and waveguides for the reflectometry measurements on the high-field side and at various locations in the poloidal cross-section for the plasma position reflectometer. The details of these designs need to be developed.

The integration of waveguides through the divertor ports and in the divertor cassettes has been studied and appears feasible. However, the R&D on the associated diagnostics - electron cyclotron absorption (ECA) and divertor reflectometry - is still in an early stage, and so the information that can be obtained from these measurements is not certain.

A promising design has been developed for the wide angle visible/IR viewing diagnostic and it is expected that it will meet its measurements specifications. A key issue is the extent of surface coverage that is necessary. Presently, sufficient cameras are envisaged to give a coverage of about 80%. Measurement of the surface temperature of the divertor plates is important for operation and conventional imaging systems are difficult to implement in the restricted divertor space. The novel IR multiplexing technique has the potential to provide the required measurements but there is no experience with using such a technique on existing machines. No insurmountable difficulties are foreseen with the basic operational diagnostics such as pressure gauges and gas analyzers.

Substantial progress has been made with design of the diagnostic neutral beam and its integration onto the tokamak (see 2.5.1). However the performance of the active CXRS remains marginal in the core for reference plasma conditions, although it is much better in the edge region and at reduced densities.

In terms of the overall measurement capability, it is expected that all the measurements necessary for machine protection and basic plasma control can be made although the detailed performance has yet to be determined in many cases. There are difficulties with some of the measurements necessary for advanced control, for example the q profile measurement, but it is too early in the design process to determine what limits, if any, there will ultimately be to the operation of the tokamak. Some of the measurements which are intended solely for physics purposes also have implementation difficulties. Current design and R&D work is focussed in these areas.

Considerable further design work is required to permit the implementation of specific diagnostics on ITER. This work requires special skills and knowledge. These are, in particular, available in the fusion laboratories of the home teams, and it is expected that they will take the lead in developing individual diagnostics for ITER.