DIAGNOSTICS FOR BURNING PLASMA EXPERIMENTS

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OUTLINE

Requirements for Plasma and First Wall Measurements on a BPX

Environment of a BPX: Impact on Diagnostic Selection and Design

- Key radiation effects and impact on materials used in diagnostic component construction

- Other necessary developments
  specific components and new techniques

Comments on Design (ITER Diagnostics)

Brief Assessment of Measurement Capability

Conclusions

REQUIREMENTS FOR PLASMA AND FIRST WALL MEASUREMENTS ON A BPX

Measurements of key plasma and first wall parameters are required for

- Machine protection
- Plasma control
- Physics evaluation

The measurements of some parameters may contribute to all three roles although the specifications may be different depending on the role.

Machine protection

Need to protect against even short contact (< 1 s) of plasma with first wall. Need measurement of

- ⇨ separatrix/wall gap, first wall temperature

Uncontrolled rise of the fusion power

- ⇨ fusion power

Excessive thermal load on the divertor plates

- ⇨ divertor plate surface temperature

Need to avoid disruptions.

- ⇨ disruption precursors (particularly detection of locked modes)

High mechanical stresses duee to halp currents

- ⇨ halo currents in key components
- ⇨ etc

Plasma control

The parameters that should be employed for plasma control will include those used for control in the present generation of tokamak plasmas

⇨ plasma shape and position, plasma current and electron density, etc

Operation with a burning DT plasma results in additional plasma control requirements

⇨ fusion power, divertor heat load and helium-ash

A substantial fraction (~ 75%) of the total power must be radiated to keep the power deposited on the divertor plates to acceptable levels.

It may be necessary to inject a controlled amount of a specific impurity (eg Ne, Ar), but bremsstrahlung power loss and plasma dilution in the core must be maintained at levels acceptable for the plasma burn.

The kinetic control must also keep the plasma away from the β and density limits and provide sufficient power flow through the separatrix to ensure H-mode plasma operation. It is clear that a sophisticated multi-input, multi-actuator feedback control scheme is required for the successful operation of a BPX in a driven burn regime.

This leads to requirements for a wide range of additional plasma measurements for control, including:

⇨ radiative power loss from the plasma core, SOL, X-point region and from the divertor, plasma density profile, β, n_T/n_D ratio, rotating MHD modes and a degree of divertor detachment, ie 'ionization front' position and/or T_e and n_e at the divertor plate.

Sustained operation in high confinement modes, for example reverse shear, is likely to be required.

⇨ spatial profile of key parameters such as q, pressure and rotation.

For sustained operation near the β-limit, it is expected that suppression of neoclassical tearing modes (NTMs) will be required. Similarly, for steady-state operation at high β levels stabilization of the resistive wall modes (RWMs) will be required.

⇨ location and amplitude of NTMs and RWMs.

Physics Evaluation

The BPX plasma will be the first in which there is significant α-heating, so the experimental programme will have an extensive explorative physics component. Key topics to be investigated include

confinement physics
operational limits
high-current plasma disruptions
physics of high power radiative divertor
α-particle effects
steady-state burn.

An extensive set of plasma measurements is required to support these programmes, for example

⇨ confined alpha particles, location and TAE modes,fishbones, n_e and T_e fluctuations, and radial electric field and field fluctuations.

Plasma and First Wall Measurements required for a BPX

GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Measurements for Advanced Control	GROUP 2 Additional Measurements for Performance Eval. and Physics
Plasma shape and position, separatrix- wall gaps, gap between separatrixes	Neutron and α-source profile	Confined α-particles
Plasma current, q(a), q(95%)	Helium density profile (core)	TAE Modes, fishbones
Loop voltage	Plasma rotation (toroidal and poloidal)	T_e profile (edge)
Fusion power	Current density profile (q-profile)	n_e, T_e profiles (X-point)
$\beta_N = \beta_{tor}(aB/I)$	Electron temperature profile (core)	T_i in divertor
Line-averaged electron density	Electron density profile (core and edge)	Plasma flow (divertor)
Impurity and D,T influx (divertor, & main plasma)	Ion temperature profile (core)	$n_T/n_D/n_H$ (edge)
Surface temp. (div. & upper plates)	Radiation power profile (core, X-point & divertor)	$n_T/n_D/n_H$ (divertor)
Surface temperature (first wall)	Z_{eff} profile	T_e fluctuations
Runaway electrons	Helium density (divertor)	n_e fluctuations
'Halo' currents	Heat deposition profile (divertor)	Radial electric field and field fluctuations
Radiated power (main pla, X-pt & div).	Ionization front position in divertor	Edge turbulence
Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate)	Impurity density profiles	MHD activity in plasma core
Disruption precursors (locked modes, m=2 mode)	Neutral density between plasma and first wall	Pellet ablation
H/L mode indicator	n_e, T_e of divertor plasma	
Z_{eff} (line-averaged)	Alpha-particle loss	
n_T/n_D in plasma core	Low m/n MHD activity	
ELMs	Sawteeth	
Gas pressure (divertor & duct)	Net erosion (divertor plate)	
Gas composition (divertor & duct)	Neutron fluence	

For ITER very detailed specifications have been developed: eg for Radiated Power

MEASUREMENT	PARAM.	COND.	RANGE	ΔT or ΔF	ΔX or Δk	ACCURACY
Radiated Power	Main Plasma Prad	Default	TBD – 0.3 GW	10 ms	Integral	10 %
	X-point / MARFE region Prad	Default	TBD – 0.3 GW	10 ms	Integral	10 %
	Divertor Prad	Default	TBD – 0.3 GW	10 ms	Integral	10 %
	Total Prad	Disruption	TBD – 50 GW	3 ms	Integral	20 %
Radiation Profile	Main plasma Prad		0.01 – 1 MW/m^3	10 ms	a/15	20 %
	X-point / MARFE region Prad		TBD – 300 MW/m^3	10 ms	a/15	20 %
	Divertor Prad		TBD – 100 MW/m^3	10 ms	5 cm	30 %

Summary on Requirements

Requirements for first wall and plasma measurements will be similar to those employed on existing machines exploring advanced mode operation. In terms of reliability and some other specifications such as relative spatial resolution, accuracy etc, they may be even more demanding.

ENVIRONMENT OF A BPX: IMPACT ON DIAGNOSTIC SELECTION AND DESIGN

In a BPX there will be

- high neutron and gamma radiation fluxes
- substantial heat loads from plasma radiation
- high neutral particle fluxes from charge exchange processes
- material evaporated from the divertor and first wall
- Time varying magnetic fields

It is not just the inetnsity of these conditions but also the duration (hundreds of seconds per pulse) that is important.

For example on ITER, relative to the harshest conditions experienced on existing machines

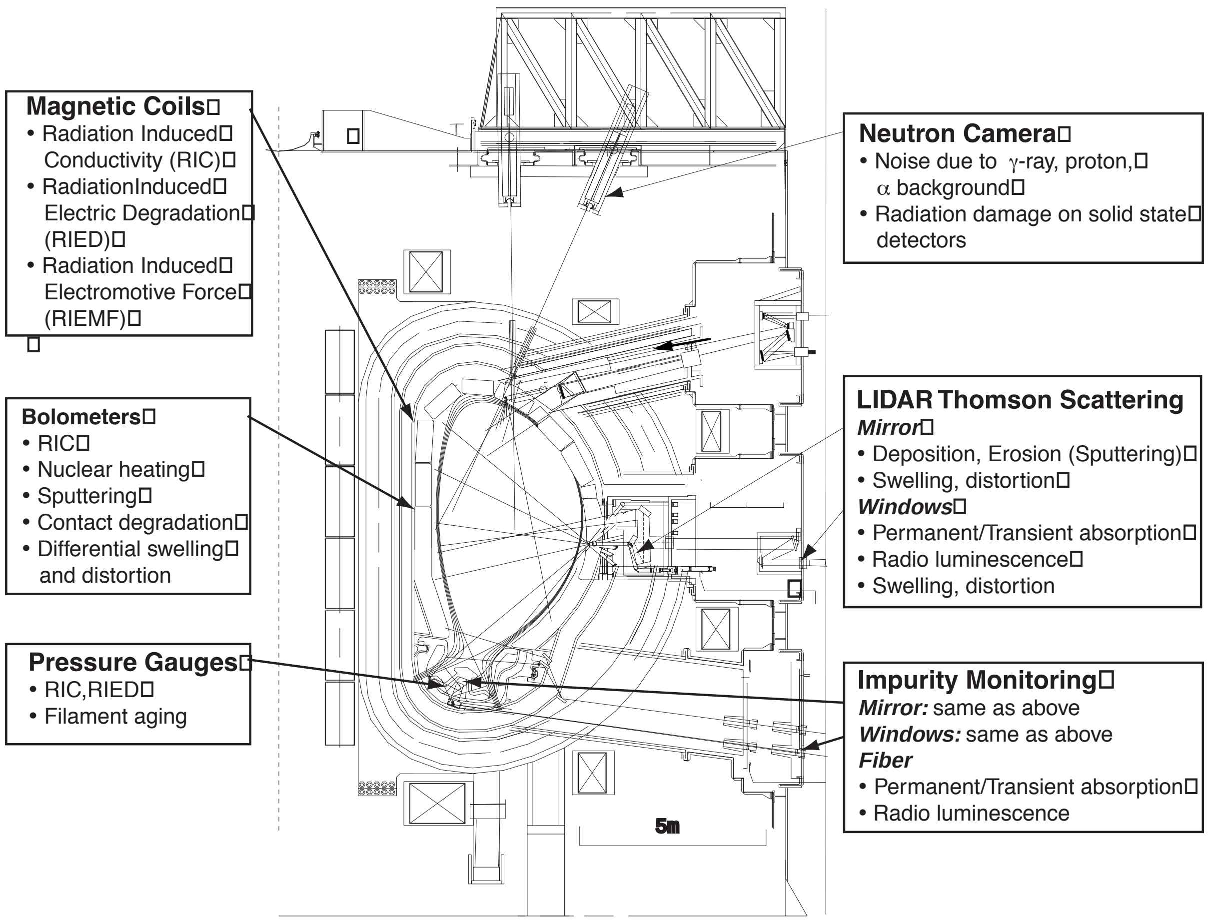
- neutral particle fluxes are about 5 times higher
- neutron flux levels are about 10 times higher
- neutron fluence is about 10,000 times higher
- pulse lengths are about 100 times longer.

Taken together with the measurement requirements this represents a major challenge in diagnostic development, arguably the most substantial challenge ever undertaken.

Radiation Environment for the Diagnostic Components on ITER

Location Typical diag. component	Neutrons > 0.1 MeV n/m^2s	Neutrons 14 MeV n/m^2s	Dose Rate Gy/s	Fluence > 0.1 MeV n/m^2	Particle flux atoms $/m^2s$	Plasma radiation (peak) kW/m^2
First Wall [1]	$3x10^{18}$	$8x10^{17}$	$2x10^{3}$	$3x10^{25}$	$\sim 5x10^{19}$	500
Near Blanket Gap (on VacuumVessel) Mag. coils Bolometers Retroreflectors	$0.2 - 1x10^{17}$	$0.8 - 4x10^{16}$	20 - 100	$0.4 - 2.0 x10^{24}$	$\sim 10^{18}$	10
Vacuum Vessel (Behind Blanket) Mag. loops	$2x10^{16}$	$3x10^{14}$	≤ 20	$2x10^{23}$	~ 0	~ 0
Diagnostic block First mirrors	$1x10^{16}$	$9x10^{15}$	20	$1x10^{23}$	$\sim 10^{17}$	~ 1.5
Labyrinth Second mirrors,Windows	$2x10^{13}$	$3x10^{13}$	10^{-2}	$2x10^{20}$	~ 0	~ 0
Vacuum Vessel (Inboard TFC side) Mag. loops	$1x10^{14}$	$1x10^{12}$	0.1	$\sim 10^{21}$	~ 0	~ 0
Divertor Cassette First mirrors	$1x10^{18}$	$3x10^{17}$	$1x10^{-3}$	$\sim 10^{25}$	$10^{17} – 10^{19}$	1 - 100
Divertor Port Second mirrors	$10^{13} \sim 10^{15}$	$10^{12} \sim 10^{14}$	10^{-2} - 1	$10^{19} \sim 10^{21}$	TBD	TBD

[1] **Corresponding to a possible maximum fusion power of 700 MW.**



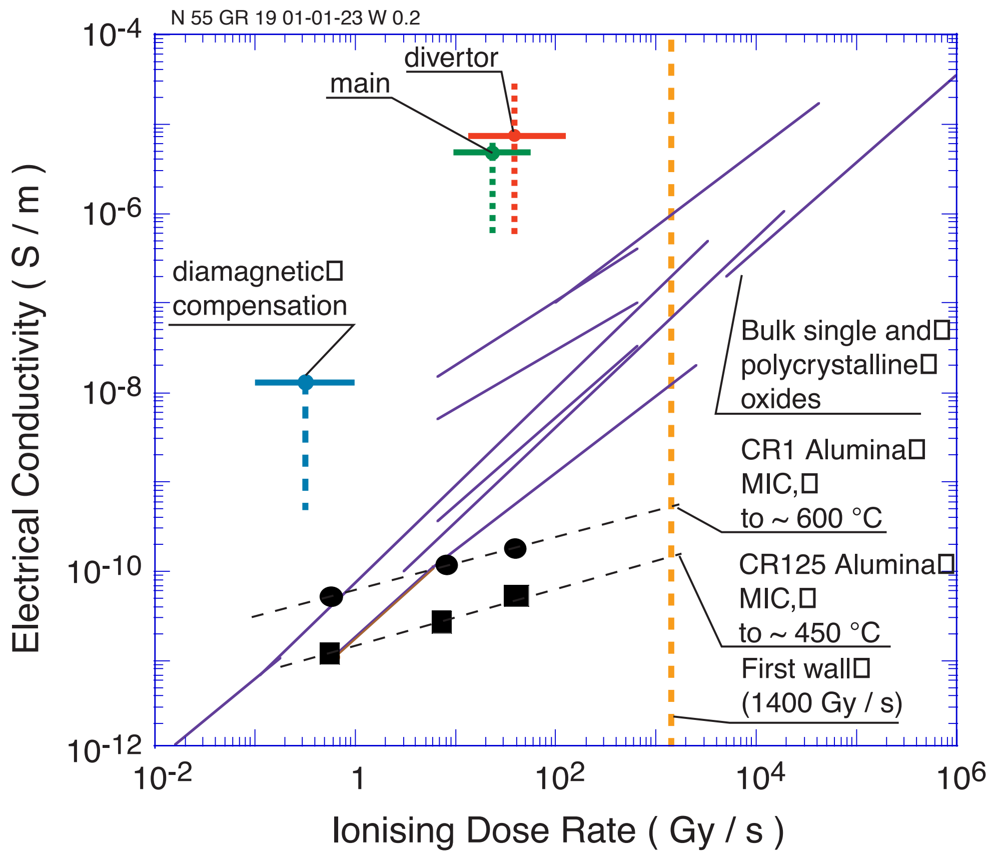
ITER: Location of some representative diagnostic components and the principal, radiation induced, physical effects of interest.

Some Key Radiation Effects

Ceramic insulators, and wires/cables.

Key effects:

- Radiation Radiation-induced conductivity (RIC)
- Radiation induced electrical degradation (RIED)
- Radiation-induced electromotive force (RIEMF)



Measured Radiation-Induced Conductivity in bulk single and polycrystalline oxides, and MI Cables as a function of Ionising Dose Rate combined with magnetic diagnostic requirements at selected locations. The vertical bars represent the range of design values of RIC that can be tolerated for each coil; the horizontal bars represent the uncertainty on the flux.

Radiation-induced electrical degradation (RIED)

Not understood but an extensive database has been established. The effect has been found to occur only with electric fields > 50 kV/m applied when the temperature of the ceramic is between about 150 °C and 650 °C and so can be avoided by design.

Radiation Induced EMF (RIEMF)

Observed in experiments in which mineral insulated (MI) cable and prototype magnetic coils have been irradiated in test reactors. In general observed RIEMF is current driven, and the generated current is ~ a microampere or less.

In the experiments with magnetic coils the asymmetric component of the induced electromotive force ~ microvolts, which could lead to serious long-term integration drifts in the measurement of magnetic flux.

Since the magnitude of the effect is small it is difficult to ensure that other effects - for example, thermoelectric effects and grounding problems - are not causing systematic errors in the measurements and further tests are needed.

Mirrors and reflectors.

For many diagnostic systems the plasma facing optical element will be a mirror. The lifetime of these first mirrors (FMs) is therefore a key parameter.

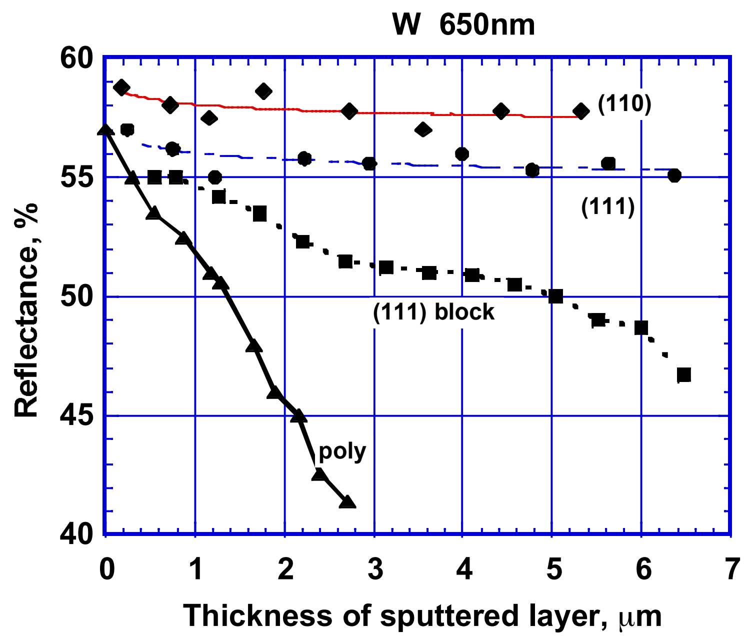
The mirrors will be subject to intense neutron, gamma and uv radiation, neutron heating, particle fluxes arising from charge exchange atoms (typically 2×10^{19} particles/m^2/s with energies up to several keV), and will be subjected to the deposition of material eroded from the divertor, first wall and shield structure.

Extensive tests in which candidate mirror materials have been subject to different types and levels of radiation have been carried out.

For diagnostic first mirrors, probably the most important effects are the CXA fluxes, which can lead to erosion, and deposition. Mirrors of several metals (Be, Cu, SS, Mo, Ta, W) with different microstructure (polycrystal, single crystal, film) have been bombarded for long periods (many hours) by deuterium ions of wide energy (0.07 to 1.5 keV) and the optical properties of the mirrors have been measured.

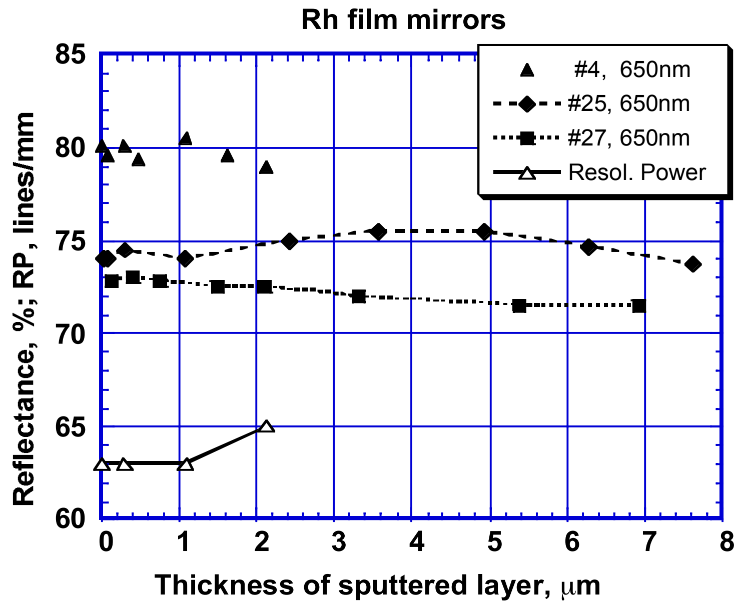
Due to different sputtering rates of grains with different crystallographic plane orientations, the polycrystal mirrors develop a step structure soon after bombardment starts.

Single crystal mirrors (Mo, W) do not demonstrate the step structure: their surfaces have a high mirror quality after erosion by sputtering of a layer several μms thick.



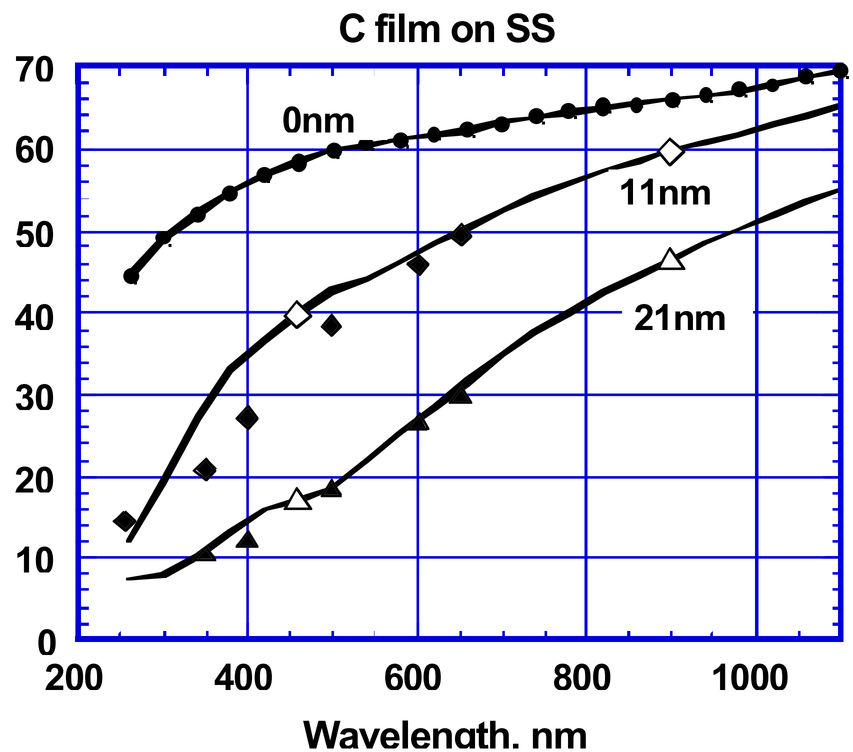
Reflectance of W mirrors (polycrystal, block monocrystal and real monocrystals with two planes of orientation) at λ = 650 nm depending on the sputtered layer thickness. [V S Voitsenya et al, Rev. Sci. Instrum, vol. 72 No 1, 475, (2001)]

Suitably chosen metal film mirrors mounted on a metal substrate can have a good resistance to the CXA flux. For example, Rh film mirrors of thickness ~10 μm mounted on Cu can be used in locations where the CXA flux onto the mirror surface will not exceed 2×10^{18} atom/m^2s (~1/10 of the CXA flux to the first wall)



Dependences on sputtered layer thickness of reflectance at λ = 650 nm and resolving power versus thickness of sputtered layer for Rh film on copper substrate mirrors. [V S Voitsenya et al, Rev. Sci. Instrum, vol. 72 No 1, 475, (2001)]

On the other hand, even very thin layers (h ≥ 10 nm) of a contaminating film can seriously reduce the reflectivity.



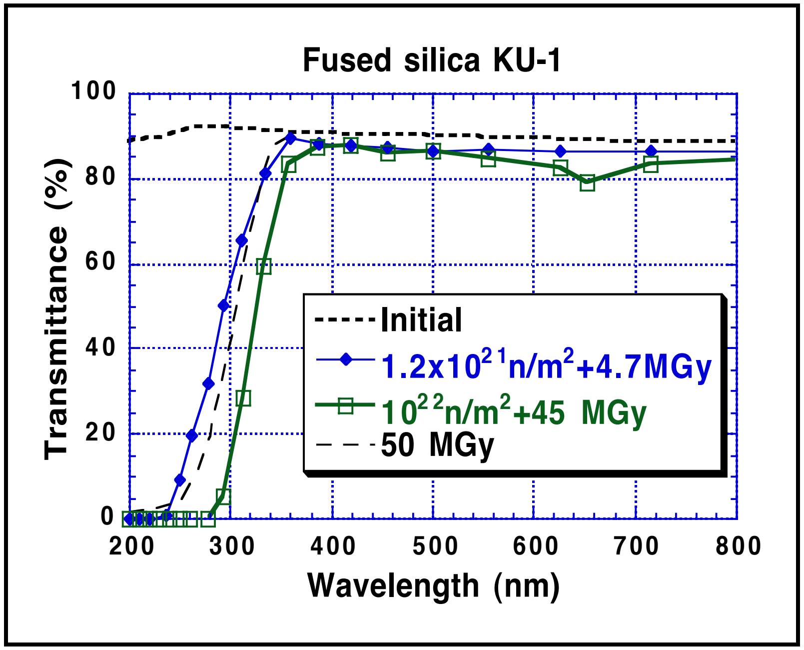
Experimentally measured (solid points) and calculated (lines with corresponding open markers) spectral dependencies of effective reflectance for clean SS and for SS with carbon coating of thickness indicated near every curve. [V S Voitsenya et al, Rev. Sci. Instrum, vol. 72 No 1, 475, (2001)].

Mitigating methods (baffles and shutters) as well as potential cleaning methods (e.g. low energy discharge cleaning, laser cleaning) are therefore under development.

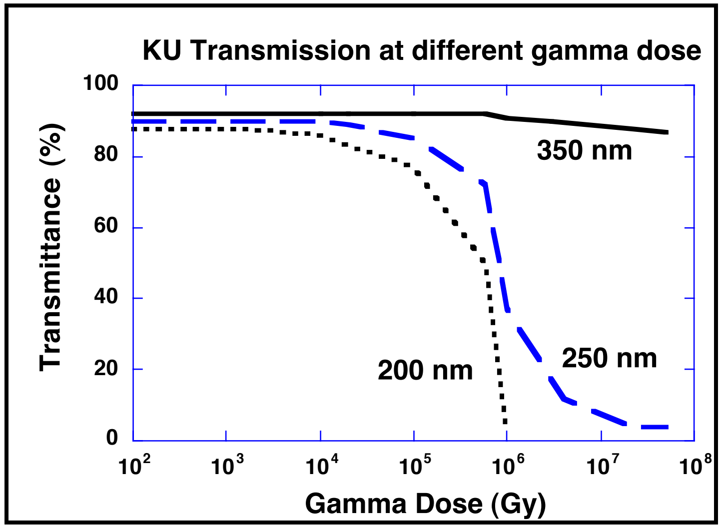
Windows

The principal properties of concern for diagnostic windows are the radiation induced absorption, which has an instantaneous and a permanent component, and radioluminescence.

The impact of radiation on the optical properties of several materials, including sapphire, and crystalline and amorphous quartz, has been investigated. The result show that suitable window materials are available for passive diagnostic systems operating in the wavelength ranges ~ 400 nm to 5 μm.



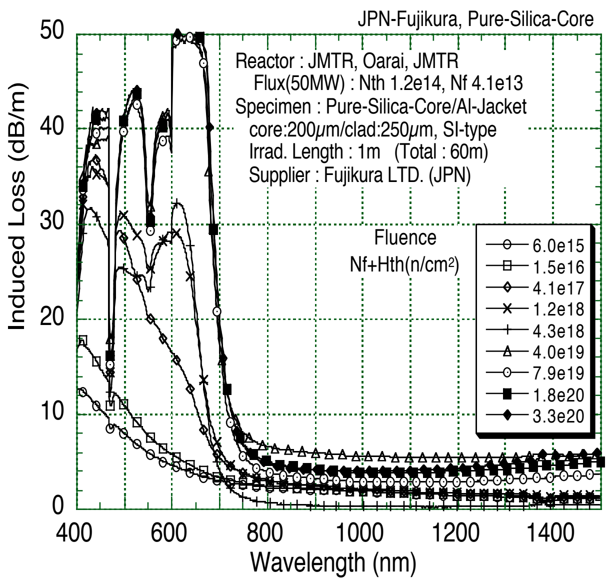
Measured transparency of KU1 fused silica (8 mm thick): as a function of wavelength for different neutron and gamma fluxes after irradiation in a nuclear reactor at T = 180°C and with a Co^{60} gamma source at a room temperature [D.V.Orlinski. in J. Problems of Atomic Science and Engineering (in Russian), series – Nuclear fusion, v.2, 2000, p.21 – 39].



Measured transparency of KU1 fused silica (8 mm thick): as a function of gamma dose at three wavelengths after irradiation with a Co^{60} gamma source at a room temperature [D.V.Orlinski. in J. Problems of Atomic Science and Engineering (in Russian), series – Nuclear fusion, v.2, 2000, p.21 – 39].

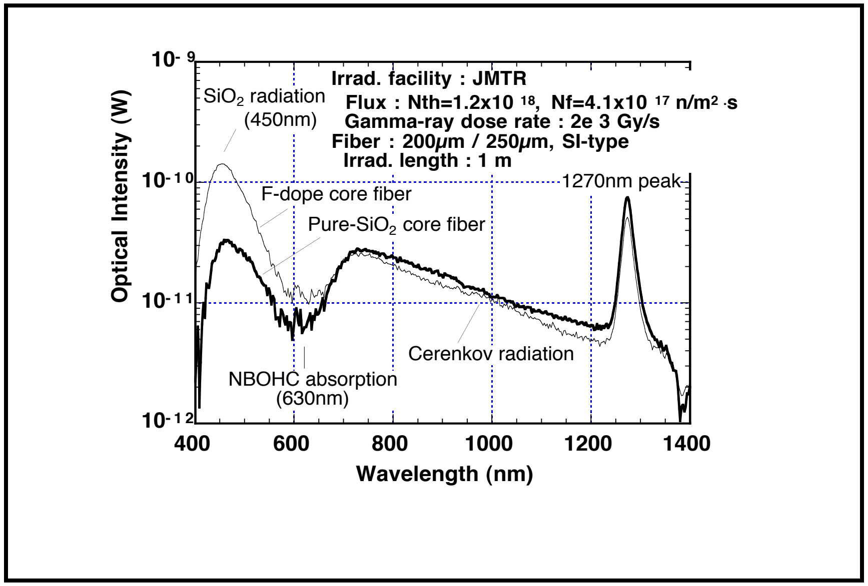
Optical fibres.

Because the optical path in the material is much longer, radiation induced absorption and radioluminescence are even more significant in optical fibres. At high levels of irradiation mechanical damage (embrittlement) can also occur.



Dose dependence of absorption of pure silica core fibre under fission neutron irradiation.

ITER

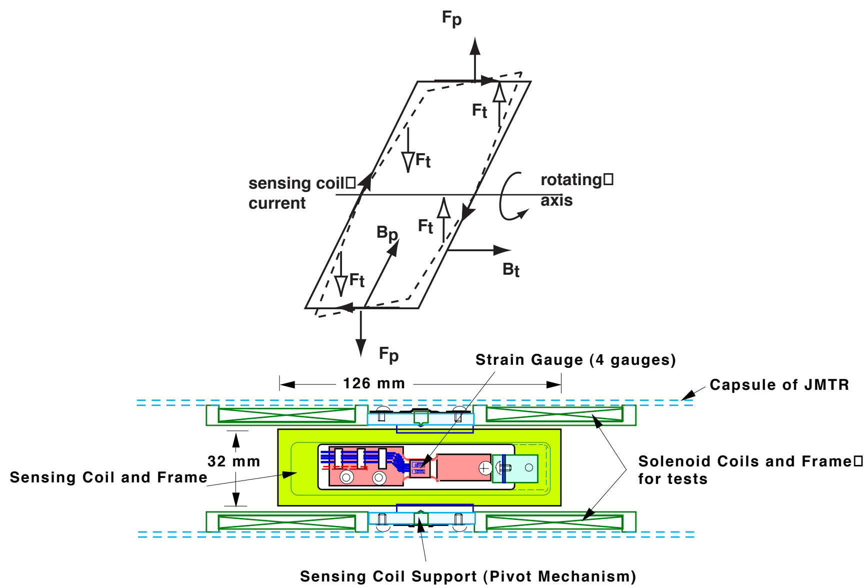


Cerenkov radiation from optical fibre under fission neutron irradiation.

The results show that substantial radiation induced absorption and luminescence occur especially at short wavelengths (< 800 nm). In general, this means that optical fibres cannot be used inside the vacuum vessel.

Other Necessary Developments: Specific Components

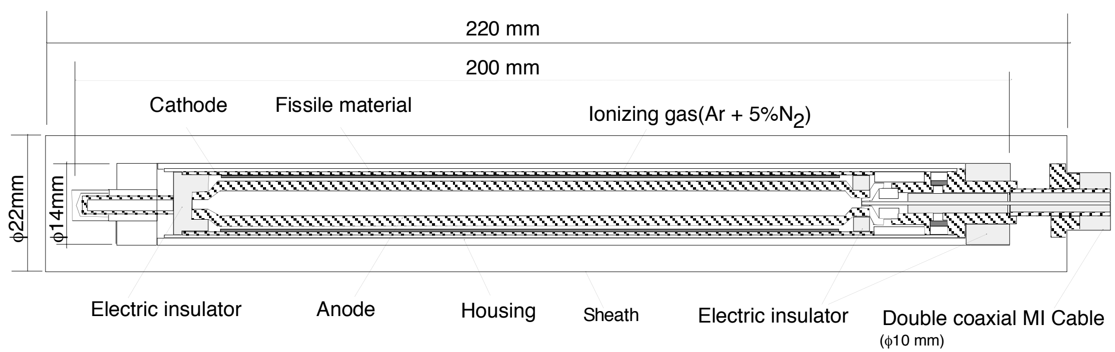
Steady state magnetic sensors eg, Load cell type



Principle of Operation and Prototype Implementation of the Load Cell Type Steady State Magnetic Sensor [S Hara, et al., Rev Sci Instrum 70 No 1 (1999) 435.].

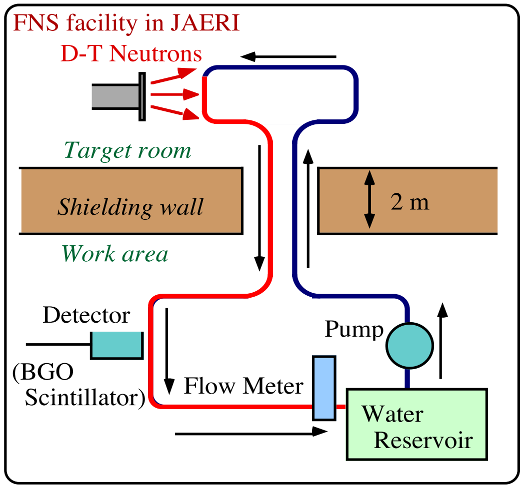
Neutron Flux Monitors (wide dynamic range, energy sensitive)

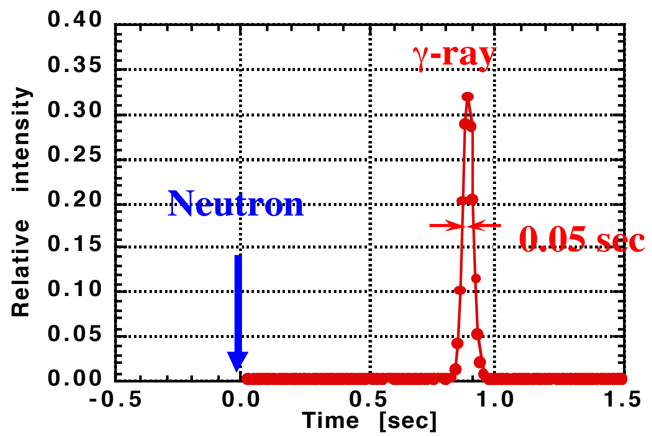
eg, Microfission chambers ^{235}U or ^{238}U threshold type (> 1.1 MeV)



Schematic diagram of typical microfission chamber. Fissile material, such as ^{235}U, is coated on the cylindrical electrode. The ionizing gas between the electrodes is Ar + 5% N_2 (14.6 atm) [T Nishitani et al, Rev Sci Instrum 70 No 1 (1999) 1141]

eg, Neutron activation with fluid flow.





Schematic of the experimental test of the Fluid Flow Activation technique and some initial results [Y. Uno, et al., to be published in Fusion Eng. Design]

eg, Compact Neutron Spectrometers.

High efficiency, good energy resolution, wide dynamic range

- Natural Diamond Detectors
- Scintillating fibre detector, etc

Radiation Hard Bolometers.

The JET type bolometer (Au absorber on mica substrate) offers promise and is currently under test in JMTR.

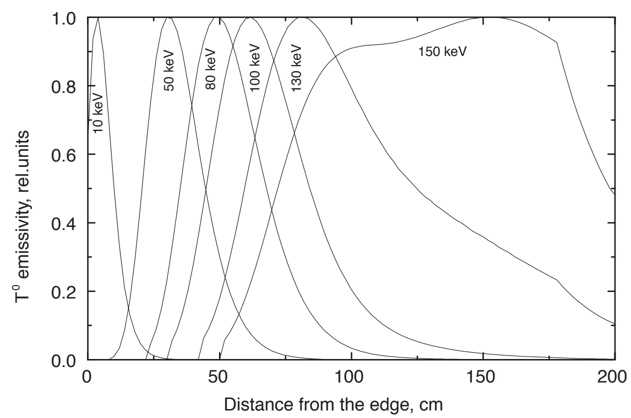
It has been observed that the resistance of the bolometer increases during the irradiation. The most probable cause is a nuclear transmutation from Au to Hg (at a few % per cycle). There have been difficulties with contacts.

The response time of the bolometers did not change significantly. It is thought that with some small improvements (Pt instead of Au, and better contacts and maintaining mica as the substrate) radiation-hard bolometers can be developed.

Other possibilities exist: eg remote measurement of the temperature rise of a foil (G Wurden).

Enhanced NPA

For measurements of nT/nD in plasma core. Need to make measurements of particles emitted with energies up to about 100 keV



Calculated emissivity functions for T and typical ITER-FEAT conditions showing that with the upgraded NPA detector measurements of n_T/n_D should be possible into the central region [A.I.Kislyakov et al, in 'Diagnostics for Experimental Thermonuclear Fusion Reactors 2', ed. P.E. Stott, G. Gorini, and E. Sindoni, Plenum Press, New York, p.353 (1998).

Other Necessary Developments: New Techniques

Plasma Position Reflectometry

An alternative approach to magnetics for providing plasma position control of long pulses

Collective Scattering

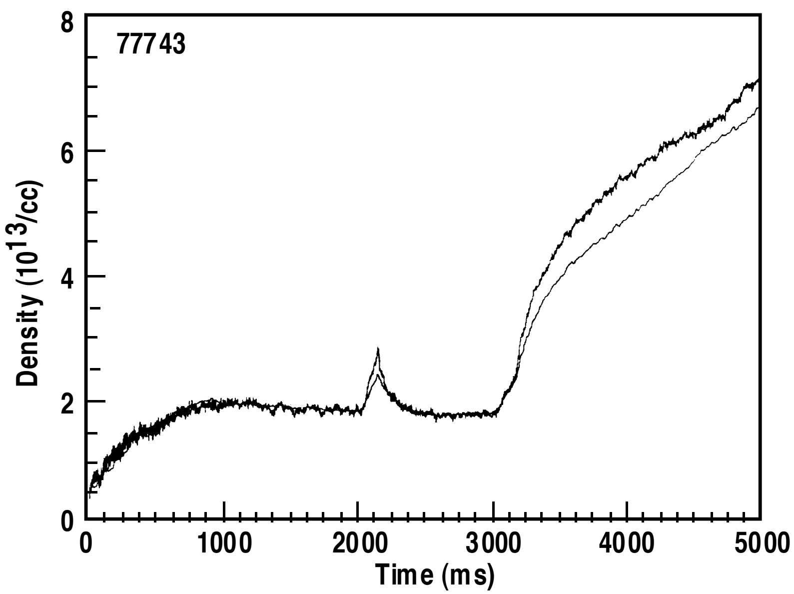
For the measurement of confined fast ions including alpha particles

Measurement of Escaping Alphas

eg, Faraday cup, scinitillators

Fast Wave Reflectometry.

For the measurement of the n_T/n_D in the core with simple reactor relevant hardware.



The electron density measured with a conventional interferometer (noisier curve) and the ion mass density measured from the Alfvén speed curve (quieter curve) on DIIID [H. Ikezi, et al, Rev. Sci. Instrum. 68, 478 (1997)].

Intense Diagnostic Neutral Beam.

A short pulse, intense, ion beam has several advantages for CXRS: increased signal-to-noise because the relatively high-intensity, coupled with very short gating times on the detectors, reduces the bremsstrahlung background. Smaller beam, lower average power requirement (~ 500 kW).

COMMENTS ON DESIGN (ITER DIAGNOSTICS)

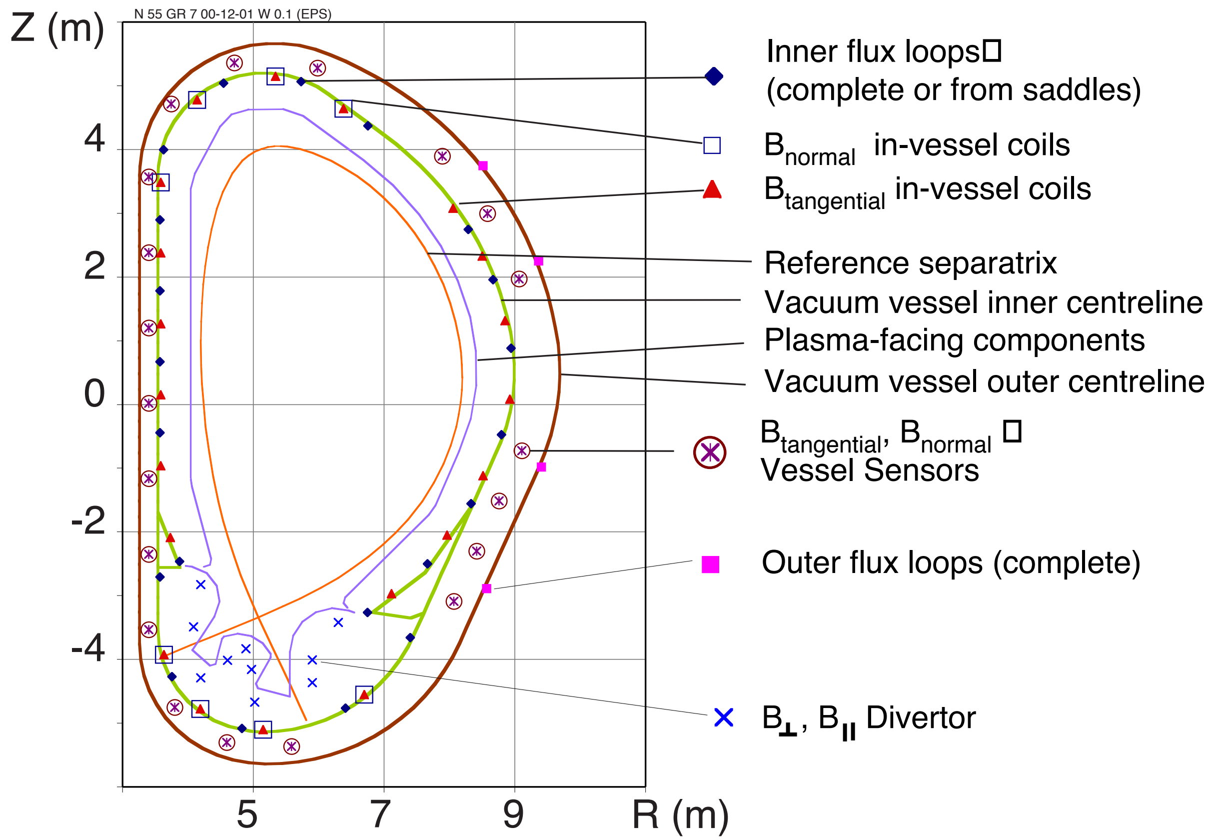
Design of most diagnostics necessary for basic protection and control measurements is well advanced. The diagnostic techniques have been selected and the conceptual design completed and feasibility established.

In many cases detailed design level is being approached on the critical components.

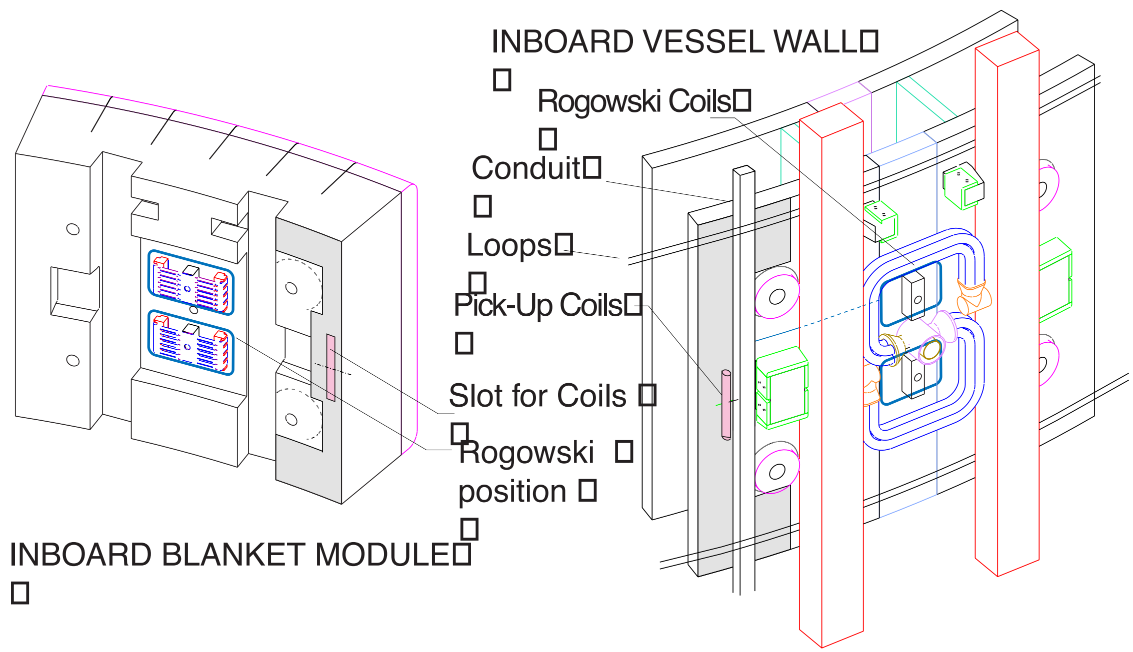
Several key interfaces are outstanding, for example the interface of some in-vessel retroreflectors with the blanket modules and are the subject of current work.

Integration with other diagnostic systems and other tokamak systems is advanced. Key issues such as tritium containment, vacuum integrity, neutron streaming, remote handeling and maintenance have been addressed and solved.

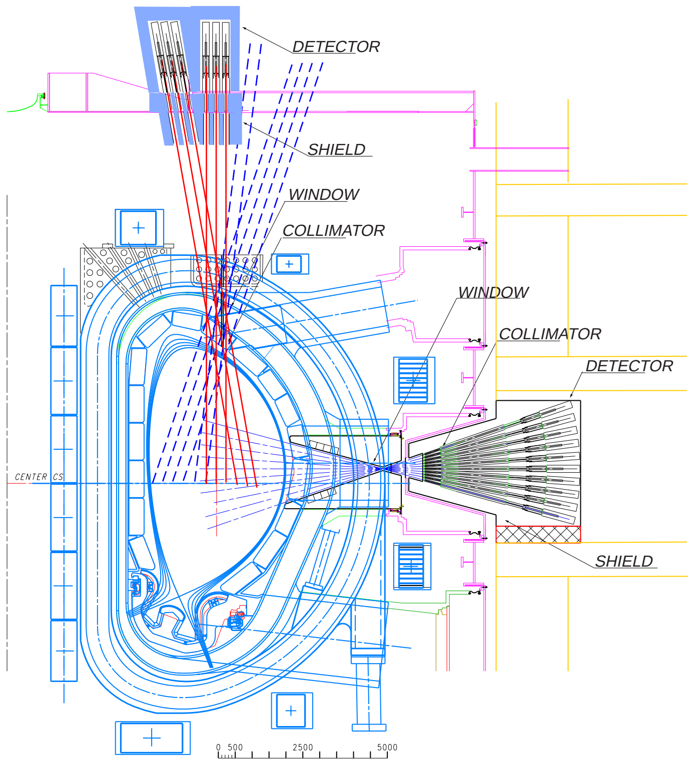
Some Examples of Design



Poloidal Distribution of Magnetic Sensors.
The diamagnetic loops and external Rogowski coils are not shown.
[K Ebisawa et al, Rev. Sci. Instrum, vol. 72 No 1, 545, (2001)].

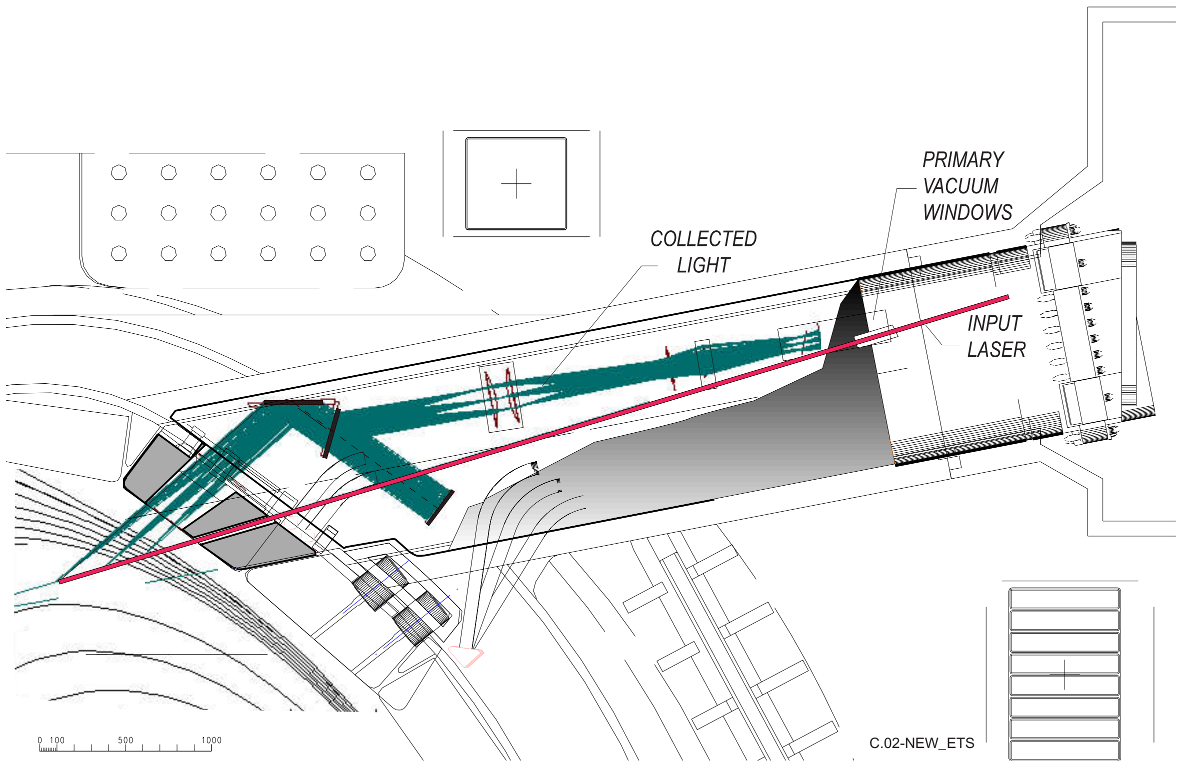

INBOARD VESSEL WALL
Rogowski Coils
Conduit
Loops
Pick-Up Coils
Slot for Coils
Rogowski
position
INBOARD BLANKET MODULE

Radial and Vertical Neutron Cameras



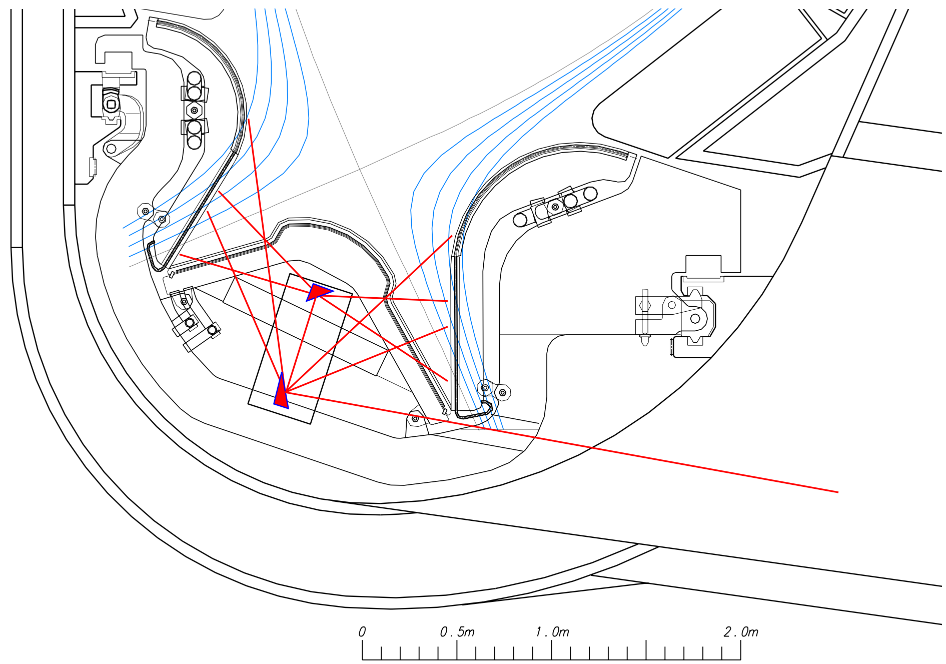
Schematic of Radial and Vertical Neutron Cameras. The Sight-lines for the Vertical Camera will be distributed at Four Different Toroidal Locations [K Ebisawa et al, Rev. Sci. Instrum, vol. 72 No 1, 545, (2001)].

Edge Thomson Scattering System



Schematic of the Thomson Scattering System installed in an Upper Port

Divertor Impurity Monitor



Viewing fans in the divertor cassette

BRIEF ASSESSMENT OF MEASUREMENT CAPABILITY

Magnetics

The measurement of the plasma current, shape and position appears feasible. Similarly we expect to meet the target specifications for the other parameters:

- Loop Voltage
- Plasma Energy
- Locked Modes
- 'Halo' currents
- Toroidal magnetic field
- Low m/n MHD activity

There maybe a pulse length limitation due to possible parasitic signal (RIEMF).

Fusion Power and Related Parameters

It is expected that it will be possible to measure the Global Neutron Source Strength (hence Fusion Power) to the required accuracy, although calibration will be time consuming. Other parameters, such as the alpha source profile, will have some limitations and the measurement may not meet target specifications. It appears as though it will be very difficult/impossible to measure the escaping alphas.

Electron Density and Temperature

Measurements appear feasible in the plasma core and edge regions but difficult in the divertor region. It is probable that target specifications will not be met in the divertor region. There will be an impact on operation that has not yet been determined.

Ion Density and Temperature

Same comment as for n_e and T_e with measurements in the divertor being even more difficult.

Zeff (line-averaged), Impurities and D,T influx (divertor, & main plasma), n_T/n_D

Again, measurements in core and edge look feasible but difficulties exist in the divertor.

Radiated Power

Measurement of total radiated power from the main plasma looks feasible but large numbers of lines of sight for tomography look difficult to achieve. Similarly measurements in divertor look difficult.

q profile

No fundamenatl difficulties but the implementation of the established techniques (Polarimetry and MSE) both have difficulties which may be so severe that the measurement is seriously limited.

First Wall Visible Image & Wall Temperature

It is expected that typically measurements can be made to a resolution ~ 3 mm at 10 m in the visible range and probably about 10 mm in the IR with a coverage ~ 80%. Is this good enough?

CONCLUSIONS

- With expected results in present design and R&D it is anticipated that most measurements required for machine protection and basic plasma control can be made and the target specifications can be met.

- Many of the measurements required for advanced control can also be made at the specified level but in a few cases (especially q profile) it may not be possible to meet target requirements and there might be a consequential limitation in the control capability.

- The divertor appears to be an especially difficult region: the measurement requirements are demanding, the access is limited and much erosion and deposition are expected to occur.

- It is essential that design and R&D are continued in the areas where difficulties have already been identified.