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Plasma diagnostics for INTER-FEAT

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A comprehensive set of diagnostics is planned for ITER-FEAT. The design of the systems is a substantial technical challenge because of the combination of the harsh environment with the demanding measurement requirements. Through a combination of careful choice of technique, materials, and design, supported by dedicated research and development, an extensive diagnostic set has been developed. The designs are based on existing techniques as much as possible but in some cases novel approaches have to be adopted. In the article the requirements for measurements are outlined and representative diagnostic designs are presented. Key issues in the design are identified and areas requiring further development are highlighted. *© 2001 American Institute of Physics.* [DOI: 10.1063/1.1310588]

I. INTRODUCTION

Following the successful conclusion of the design of the International Thermonuclear Experimental Reactor (ITER) in 1998, ITER-FEAT has been outlined.[1] The principal physics goals of the new device are:

(i) to achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power Q of at least 10; and

(ii) to aim at demonstrating steady-state operation using noninductive current drive with a ratio of fusion power to auxiliary heating power for current drive of at least 5. Moreover, the design should not preclude ignition, that is, the chosen main machine parameters must not exclude operation at high Q (>30) according to the established physics rules.[2]

To support the goal, an extensive range of plasma and first wall measurements is required. These will be made with a diagnostic system comprising about 40 individual measurements systems. The designs are based on existing techniques as much as possible, but in some cases novel approaches have had to be adopted. The design of the systems is a substantial technical challenge because of a combination of the harsh environment (Table I) with the demanding measurement requirements. The conditions are most severe for systems mounted inside the vacuum chamber where there are high neutron and γ radiation fluxes, substantial heat loads from plasma radiation, and high neutral particle fluxes from charge exchange processes in the edge regions of the plasma. Systems with complicated transmission lines which interface with the vacuum vessel have to be compatible with stringent vacuum integrity, tritium containment, and maintainability requirements.

In this article the requirements for measurements are outlined and representative diagnostic systems are briefly described. Key issues in the design are identified and areas requiring further development are highlighted. The designs are based on those developed for the earlier version of ITER[3–5] but have appropriate modifications for ITER-FEAT.

II. REQUIREMENTS FOR PLASMA MEASUREMENTS AND DIAGNOSTICS

The measurements will have different roles in the ITER-FEAT program. Some of the measurements will be used in

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TABLE I. Radiation environment for the diagnostic components.

Location Typical diag. component	Neutrons		Heating rate (SS) (W/cm^3)	Fluence $>$0.1 MeV (n/m^2)	Particle flux (atoms/m^2 s)	Plasma radiation (peak) (kW/m^2)
	$>$0.1 MeV (n/m^2 s)	14 MeV (n/m^2 s)				
First Wall	3×10^{18}	8×10^{17}	8	3×10^{25}	$\sim5\times10^{19}$	500
Blanket gap (on vacuum vessel) Mag. coils Bolometers Retroreflectors	3×10^{16}	2×10^{16}	0.4	3×10^{23}	$\sim10^{18}$	10
Vacuum vessel (Behind blanket) Mag. loops	2×10^{16}	3×10^{14}	0.3	2×10^{23}	~0	~0
Diagnostic block First mirrors	1×10^{16}	9×10^{15}	0.1	1×10^{20}	$\sim10^{17}$	~1.5
Labyrinth Second mirrors, windows	2×10^{13}	3×10^{13}	3×10^{-4}	2×10^{20}	~0	~0
Vacuum vessel (Inboard TFC side) Mag. loops	1×10^{14}	1×10^{12}	10^{-4}	$\sim10^{21}$	~0	~0
Divertor cassette First mirrors	1×10^{18}	3×10^{17}	~3	$\sim10^{25}$	$10^{17}-10^{19}$	1–100
Divertor port Second mirrors	$10^{13}-10^{15}$	$10^{12}-10^{14}$	$\sim10^{-3}$	$10^{19}-10^{21}$	TBD	TBD

real time to prevent the onset of conditions that could potentially damage the first wall and other in-vessel components (machine protection). Others will be used in real-time feedback control loops to control the magnitude of key parameters at values required for specific plasma performance (plasma control); while yet others will be used to evaluate the plasma performance and to provide information on key phenomena fundamental to ITER performance (physics studies). Since resources such as manpower, budget, port space, etc. are limited, it is necessary to be selective and to set priorities. Naturally, the highest priority must be given to measurements for machine protection and basic plasma control. This leads to a convenient classification of the measurements: those that are required for machine protection and basic plasma control (group 1a); those that are required for advanced plasma control (group1b); and those that are required for evaluation and physics studies (group 2). The selected measurements and the principal diagnostics in each case are shown in Table II.

III. DIAGNOSTIC INTEGRATION AND MAINTENANCE

The individual diagnostic systems have to be installed on the tokamak taking into account the measurement goals, the shielding, activation and tritium containment requirements, and maintenance requirements. The systems are installed in four locations: within the vacuum vessel, in divertor ports, and in equatorial and upper ports (Fig. 1). Many machine systems require ports so the use of the ports has to be efficient. Multiple diagnostic systems are installed in each port. The allocation of port space is guided by the priorities in Table II.

In the vacuum vessel, the components are installed on the plasma side of the wall of the vacuum vessel. Preassembled double sectors of vacuum vessel allow many diagnostic components to be installed prior to the assembly of the vacuum vessel, thereby achieving easier installation and increased reliability. The components have to survive the full ITER lifetime and this is achieved by a careful choice of materials. However, some replacement will be possible because all the diagnostic sensors, except some magnetic loops and microwave antennas, are mounted in small removable sockets integrated into the vacuum vessel wall.

In the equatorial ports, diagnostic components are mounted in a single port plug assembly within the primary vacuum, and interspace diagnostic block. This modularity allows a single concept for remote maintenance of all the port plugs and a standardized approach for hot cell maintenance.[6] A similar approach is adopted at the upper level. Here, the inclined ports enable systems such as edge Thomson scattering, vacuum ultraviolet (VUV), and x-ray spectroscopy to view the plasma edge in the expanded flux region, thereby achieving a relatively high spatial resolution, with no background from the core.

At the divertor level, diagnostic components are mounted on specially modified divertor cassettes at five different toroidal locations. Some of the cassettes accommodate diagnostic sensors such as probes, bolometers, and pressure gauges, while others have mirror relay systems for optical and spectroscopic diagnostics. Microwave waveguides are installed in three toroidal locations for the reflectometer and interferometer measurements.

TABLE II. Priorities for control measurements.

Group 1a Mach. protect. and basic control		Group 1b Advanced control		Group 2 Evaluation and physics	
Parameter	Diagnostic	Parameter	Diagnostic	Parameter	Diagnostic
Shape/position Vertical speed Locked modes Ip, $q(a)$, $q(95\%)$,β $m=2$ Mode, I_{halo}, V_{loop}	Magnetics	Magnetohydrodynamics (MHD) activity	Magnetics, ECE, Reflectometry	Fishbones, TAE modes	Magnetics, reflectometry, ECE
Impurity and DT influx (main plasma and div.)	Impurity monirors	Shape/position (very long pulse)	Reflectometry (plasma posit.)	Confined α particles	Collect. scatt., Knock-on tail neut. spec., NPA
Runaway electrons	Hard x rays, Synchotron radiation	Neutron profile, α source profile	Rad. neut. camera, Vert. neut. camera	$n_T/n_D/n_H$ (edge)	NPA, H_α Spectr., Laser induced flouresce
Line-averaged density	Interferometer/ polarimeter	n_{He} Profile	Active CXRS	$n_T/n_D/n_H$ (div.)	H_α spectroscopy
Div. detachment (J_{sat} (divertor))	Tile shuts	Plasma rotation, T_i profile, Impurity profile	Active CXRS, X-ray crystal spectroscopy VUV spectroscopy	T_e profile (edge)	TS (edge)
Surf. temp. (divertor plates and FW)	IR cameras	T_e profile (core), n_e profile (core)	LIDAR (main), ECE	n_e, T_e Profiles (X point)	TS (x point)
Rad. power from Core, x-pt and Div.	Bolom. array (main pl. and div.)	T_i profile (core)	Radial neutron spectrometer	n_e, T_e (plate)	Langmuir probes
Fusion power	Neutron flux monitors	n_e profile (edge)	Refl.(main)	T_i in Divertor	Imp. monitors (div.)
n_T/n_D in plasma core	NPA, Fast wave reflectometry	q profile	MSE, polarim. system	Plasma flow (div.)	Imp. monitors (div.)
Z_{eff} line-aver.	Vis. continuum (single channel)	P_{rad} profile	Bolom. arrays (main pl. and div.)	Pellet ablation	H_α spectroscopy
H/L mode indicator	H_α spectr. (typ. channel)	Z_{eff} profile	Visible continuum array	T_e fluctuations	ECE, Soft x-ray array
ELMs (typ)	ECE, Refl. (main) H_α spectroscopy	n_{He} (divertor)	RGA imp. monitor	n_e fluctuations	Reflectometry, Microw. scatt.
Gas pressure (div. and duct)	Pressure gauges	Heat deposition profile in div.	IR camera	Radial E field and E fluctuat.	CXRS (plasma rot.)
Gas composit. (div. and duct)	Residual gas analyzers (RGAs)	Div. ionization front position	Visib. spectrom., bolometry	Edge turbulen	Reflectometry
Toroidal magnetic field	Current shunts	Neutral density (near wall, Particle source	H_α spectroscopy (many channels), Pressure gauges	MHD activity in plasma core	ECE, soft x-ray array
		n_e, T_e (divertor)	Refl. (div.), ECA (div.), TS (div.)		
		Impurity and D, T influxes in Div. with spat. res.	Imp. monitors, H_α spectroscopy		
		α loss	α-loss Det., IR camera		
		Neut. fluence	Neutr. act. syst.		
		ELMs	ECE, Refl.(main), Magnetics		
		Sawteeth	ECE, Soft x-ray array		
		NTMs	Magnetics, ECE		
		RWMs	Magnetics		
		Erosion (plate)	Imp. monitors, Reflectometry		

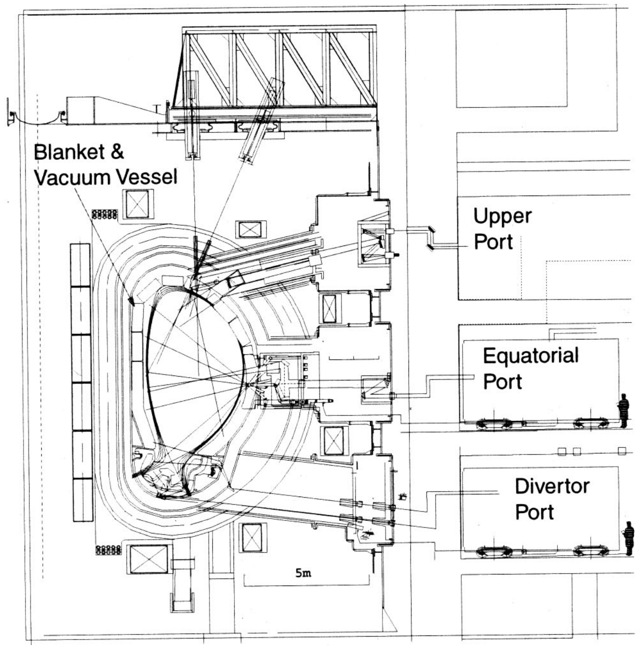

FIG. 1. ITER-FEAT cross section showing the main access routes for diagnostic transmission lines.

IV. DIAGNOSTIC SYSTEMS

A. Magnetics

Magnetic diagnostics will measure the plasma shape and position, plasma current, loop voltage, plasma energy, and the magnitude of the ''halo'' currents in some key support structures. The system consists of several individual subsystems:

(i) sets of pickup coils, saddle loops and voltage loops mounted on the inner wall of the vacuum vessel for equilibrium and high frequency measurements;
(ii) continuous poloidal (Rogowski) loops mounted on the outside of the vacuum vessel and poloidal diamagnetic loops mounted inside the vessel;
(iii) sets of coils mounted in the divertor diagnostic cassettes; and
(iv) Rogowski coils mounted around earth straps of the blanket/shield modules for measuring the halo currents.

The pickup coils and loops are made of mineral insulated (MI) cable wound on a stainless steel former with a protective cover and are cooled by conduction. The coils and loops are located behind the blanket shield modules where they are shielded and have a lifetime comparable to or longer than the lifetime of the machine. While the lifetime is not thought to be an issue, a key outstanding issue is radiation induced electromotive force. This has been observed to occur in experiments in which MI cable and prototype magnetic coils have been irradiated in test reactors. It is a potential threat to long-pulsed operation, and is being studied in a dedicated research and development program.

B. Neutron systems

The principal neutron systems are a radial neutron camera, a vertical neutron camera, 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 slots in the blanket/shield, intersecting at a common aperture defined by a specialized shielding plug in an equatorial port. The vertical neutron camera has a different configuration. Each sightline views the plasma through long narrow tubes in the upper port plug, vacuum vessel, and through an annular shield located adjacent to the intercoil structure. The first collimator is in the port plug and small areas of the vacuum vessel of reduced thickness form neutron ''windows.'' The second collimator, detector, and beam dump are located on the upper cryostat. Typical sight lines are shown in Fig. 1. In total there are 12–14 sight lines distributed over 4–5 upper ports. The cameras provide the fusion power density and the α particle source profile.

The neutron flux is measured by fission chambers poloidally distributed inside the vacuum vessel, and with flux monitors located at the equatorial ports. These devices measure the global neutron source strength. The neutron activation systems use a pneumatic transferring foil. A recent development of a flowing fluid method appears promising and may be applied.[7] These systems will provide robust relative measures of fusion power.

A key design requirement for the neutron systems is the need for accurate and reliable calibrations over a wide dynamic range (approximately 7 orders of magnitude). This is achieved by using detectors of different sensitivity with an overlap in the linear range.

C. Optical/infrared systems

The principal optical systems are two multipulse Thomson scattering (TS) systems (core and edge), an equatorial plane interferometer, and a poloidal interferometer/polarimeter. In addition, TS systems are under study for the divertor and X-point regions.

The core TS system operates on the time-of-flight light detecting and ranging (LIDAR) principle. A high power laser beam is transmitted to the plasma using a folded mirror arrangement inside a shielded labyrinth at an equatorial port.[8] Scattered radiation returns along the same labyrinth to remote spectrometers. The system is integrated with the wide-angle viewing camera, which is used for viewing the first wall. The high-gradient edge region is probed from the upper port with a conventional TS arrangement covering the entire edge region ($r/a > 0.9$) as seen in Fig. 2.

A vibration-compensated interferometer employing Faraday rotation techniques will be used to measure line-integrated density with wavelengths of 10.6 and 5.3 μm.[9] Small retroreflectors viewing the beams will be mounted in the vacuum vessel in the horizontal gaps between blanket modules, or embedded inside the heating neutral beam injection ports at several toroidal locations. The multichord polarimetry in the poloidal plane will provide measurements of the q profile and/or anchor reconstructions of the magnetic equilibrium. The system requires retroreflectors for returning

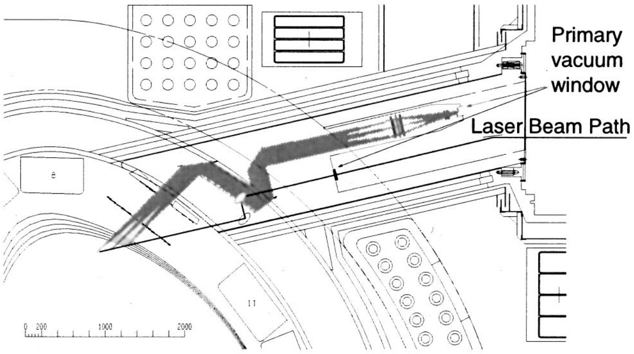

FIG. 2. Schematic of the TS system installed in the upper radial port. (Ray tracing by courtesy of P Nielsen, Consorzio RFX, Padova.)

the probing beam and these will be mounted on the vacuum vessel in the gaps between inner wall blanket modules at several poloidal locations.

The most critical design issue for the optical diagnostics is the survivability of the first mirrors: these must maintain a good optical quality in the presence of the plasma radiation, neutral particle bombardment, and nuclear heating. Study of the first mirror problem and development of candidate mirrors are being pursued in the diagnostic research and development program.[10]

D. Bolometry

Bolometry will be used to provide the spatial distribution of the radiated power in the main plasma and in the divertor region with spatial resolutions of 20 and 5 cm, respectively. The total number of lines of sight will be ~ 200. Bolometer arrays installed in the equatorial and upper radial ports, and on the specially instrumented divertor cassettes in the same poloidal plane will provide sparse-data tomography. The key issue is the lifetime of the bolometer head in the harsh radiation environment. The development of a radiation-hard bolometer is being pursued in the supporting research and development program.

E. Spectroscopic and neutral particle analyzer 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 radiation mantle, the scrape-off layer, and the divertor will be probed.

The VUV and x-ray regions will be surveyed with two systems providing medium resolution coverage in the wavelength range 0.1–10 nm, and with a multichannel high resolution instrument in the range between about 0.1 and 0.2 nm. These instruments will be directly coupled to the tokamak.

Active measurements employing charge exchange recombination spectroscopy (CXRS), combined with a dedicated diagnostic neutral beam of optimum beam energy ~100 keV/amu, are necessary for probing the plasma core. Motional Stark effect (MSE) measurements using one of the 1 MeV heating beams are also planned.

Measurements in the divertor region will be made through folded optical paths in special cassette modules, however only a limited number of sight lines can be accommodated due to the divertor cassette size. Additional sight lines viewing the divertor region will be provided from the upper ports. A direct coupled system for making VUV measurements is also being designed. Neutral particle analyzers (NPAs) will be used for monitoring the n_T/n_D ratio into r/a ~0.5, and the fast particle and H ion distribution in the energy range 0.5–4 MeV.

As in the case of the optical systems, a key issue is the survivability of the first mirror. This is particularly severe in the divertor region where erosion and deposition are expected to be substantial.

F. 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.

The ECE system consists of an antenna array, a transmission line set, and spectrometers for analyzing the emission. The antennas are mounted in an equatorial port plug. The transmission system carries the radiation through the vacuum vessel, cryostat, and shield and onto the spectrometers in the diagnostic hall.

The reflectometer for the main plasma has three subsystems: (i) a system using the upper cutoff (extraordinary mode) from the low-field side of the plasma to provide measurements of the density profile in the scrape-off, (ii) a system using the plasma frequency cutoff (ordinary mode) from the low-field and high-field sides of the plasma to give the inboard and outboard density profile in the gradient region, and (iii) a system using the lower cutoff (extraordinary mode) from the high-field side of the plasma to provide the core profile.

The divertor reflectometer is intended to provide density profiles across the divertor legs. Multiple sight lines are employed for each leg, and profile information is synthesized from several bands due to the extremely wide density range, as shown in Fig. 3.

The key design issue is the installation of the antennas and waveguides for the reflectometer on the high field side where the optimization of transmission is sensitive to the details of the vacuum vessel and plasma facing components.

G. Plasma facing and operational diagnostics

An important role for diagnostics is to provide signals for the protection of the in-vessel components. To this end, wide-angle viewing camera system will observe the first wall and parts of the divertor in the infrared (IR) and visible wavelength ranges for high heat protection. By combining several cameras it is possible to achieve high coverage (~80%) of the area of the first wall.

In the divertor region it is planned to use IR thermography for surface temperature measurements of both target

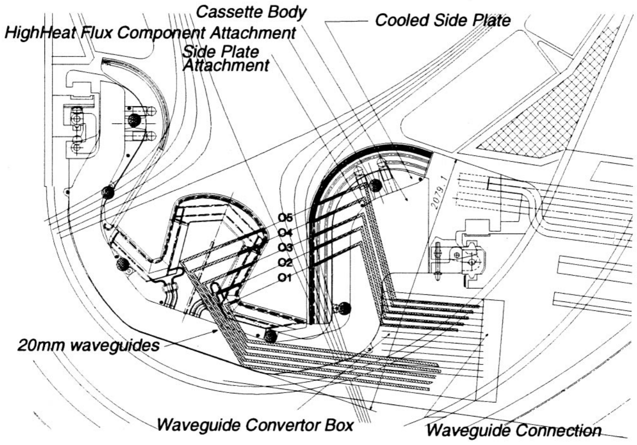

FIG. 3. Waveguides installed on the side plate of the divertor cassettes for reflectometer measurements in the outer leg region.

plates in a poloidal plane with good spatial and temporal resolution.

Other systems, which will be installed to aid the operation of the tokamak, include: Langmuir probes, pressure gauges, residual gas analyzers, and runaway monitors (hard x-ray detectors and tangential view IR systems).

V. CONCLUSIONS: SYSTEM PERFORMANCE ASSESSMENT

While there are still many details to be developed, it is believed that most measurements required for machine protection and basic plasma control can be made using the chosen techniques. However, there are difficulties with some of the measurements necessary for advanced control, in particular the q profile measurement. Both of the methods being pursued, polarimetry and MSE, have implementation difficulties under ITER-FEAT conditions and require dedicated design work. Additional issues, such as the survivability of key in-vessel diagnostic components, for example, first mirrors and bolometers, radiation-induced electromotive force, and steady-state magnetic sensors[11] remain important and are being investigated in the supporting research and development program.

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