Measurement Requirements and Diagnostic System Designs for ITER - FEAT

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Abstract The requirements for plasma measurements necessary to support the different planned operating scenarios of ITER-FEAT are presented. It is found that as the plasma performance becomes more enhanced the requirements for plasma measurements become more demanding. The measurements will be made with a comprehensive diagnostic system and this is briefly described.

1. Introduction

ITER-FEAT is a flexible machine capable of operating in a range of scenarios: standard inductive ELMy H mode, hybrid (extended pulse) and ultimately steady state [1]. It will require an extensive range of plasma measurements to support these operation scenarios. The precise measurement requirements will vary according to the scenario and the principal goals of the experimental programme. In this paper we examine the measurement requirements and outline how they change for the different scenarios. An extensive diagnostic system has been designed for ITER-FEAT to meet these requirements and key representative diagnostics are briefly described.

2. Measurement Requirements and Relation to Operating Scenario

The first phase of ITER operation will be a Hydrogen, non-nuclear phase, mainly intended for full commissioning of the tokamak systems in a non-nuclear environment. The main elements of the full DT phase reference operation, such as plasma current initiation, current ramp-up, formation of a divertor configuration and current ramp-down will be developed in this phase. Plasma operation will be inductive, mainly L mode with some limited operation in H mode, probably at reduced toroidal magnetic field, B_{tor}. Plasma measurements will be required to support the control and operation of the plasma and to evaluate the performance achieved. The principal measurements required for control are the plasma shape and position, plasma current, I_p, loop voltage, V_{loop}, vertical speed, and line-average density. Identification of MHD modes, particularly modes that may lock, will be necessary to minimise the number of disruptions. Measurement of the surface temperature of the divertor plates and first wall will be required and used in the protection of these components. Key measurements for performance evaluation will include the core electron density and temperature profiles, $n_e(r)$ and $T_e(r)$, the core ion temperature: T_i, and the radiated power from the core, P_{rad}. A full list of the required measurements is shown in Table I.

TAB. I: Required Plasma Measurements According to Operating Scenario

Operating Scenario	Special Features	Required Measurements
H phase. Inductive. Ohmic L mode. Limited H Mode		Plasma shape and position, vertical speed, B_{tor}, I_p, V_{loop}, locked modes, m = 2 modes, low m/n MHD modes, q(a), halo current, line-averaged density, runaway electrons, impurity identification and influx, $n_e(r)$ and $T_e(r)$ in core, T_i in core, surface temperature of divertor plates and first wall, P_{rad} from core, line-averaged Z_{eff}, H/L mode indicator, gas pressure and composition (divertor and duct)
D phase. Inductive. ELMY H mode	Exploration of H mode and initial fusion operation	As above plus: β, q(95%), ELM occurrence and type, $n_e(r)$ and $T_e(r)$ at edge, P_{fus}, $P_{rad}(r)$, heat deposition profile in divertor, divertor detachment,
High power D/T phase. Inductive. ELMY H Mode	Full exploration of H mode and fusion performance	As above plus: shape and position (500 s), neutron and alpha source profiles, $v_{tor}(r)$ and $v_{pol}(r)$, impurity profile, $T_i(r)$ in core, $Z_{eff}(r)$, $n_{He}(r)$, n_{He} in divertor, n_T/n_D in core, D and T influx, divertor ionisation front position, neutral density (near wall), n_e and T_e in divertor, impurity and DT influxes in divertor with spatial resolution, alpha loss, neutron fluence, erosion of divertor tiles.
D/T Phase. Inductive ELMY H mode. High β	Extension to high β including stabilisation of NTMs	As above plus: localisation of q = 1.5 and q = 2 surfaces, high sensitivity measurements of n_e and T_e, detection and measurement of NTMs.
Hybrid operation	Extension to long pulse using current drive	As above plus: shape and position (for 1000 s)
Steady state operation	Extension to steady state using current drive, stabilisation of NTMs and RWMs, and possibly ITBs.	As above: plus q(r) (in particular location and value of q_{min}), high resolution measurements of the gradient of T_e and T_i, measurement of RWMs.

The next operational phase will be a deuterium phase in which fusion reactions will occur for the first time. The operating mode will be the standard, inductive, ELMy H mode. The additional control measurements will be the ELM type and occurrence, and indicators of divertor detachment. The fusion power, P_{fus}, will be low but measurements of it will be required for evaluation purposes. Additional evaluation measurements include $n_e(r)$ and $T_e(r)$ at the edge, and $P_{rad}(r)$ (Table I).

The high power D/T phase will follow the deuterium phase. The primary operating scenario will be the standard inductive ELMy H mode. Fusion burn times of ≥ 300 s, β_N values of 1.5 - 2 and fusion powers of 400 MW are expected. Some of the measurements required in the H and D phases for evaluation will be brought into the control loops, for example measurements of P_{rad} and P_{fus}. Some additional measurements will be required for control, in particular measurements of the core T_e and T_i, the helium density profile, $n_{He}(r)$, the tritium/deuterium density ratio, n_T/n_D, the rotation velocities in toroidal and poloidal direction, v_{tor} and v_{pol}, and the position of the divertor ionisation front.

At high values of β_N (≥ 2) active stabilisation of Neoclassical Tearing Modes (NTMs) may be necessary to avoid deterioration of the plasma confinement or the occurrence of disruptions. NTMs occur around the rational q-surfaces $q = 1.5$ and $q = 2$ and they are usually observed as periodic perturbations on T_e and n_e (and also on the related soft X-ray emission) measured around these positions. They can also be clearly observed with magnetic pick-up coils. Experiments have shown that they can be stabilised by current drive at rational q surfaces, but to have ample time to stabilize the modes it is necessary to detect them when they are still at low amplitude. Measurements of the perturbations are required along with the location of the rational q surfaces.

By driving a substantial fraction of the plasma current by non-inductive current drive at reduced current the pulse duration can be significantly extended. This 'hybrid operation' offers a promising route towards true steady-state operation. In this case, no new measurements are required but measurements are required for relatively long times (~ 1000 s).

A complete scenario for steady-state operation at high values of Q (the ratio of fusion power from plasma to auxiliary heating power to plasma) has not yet been developed but there are a variety of candidate scenarios. Two possibilities are: weak central magnetic shear and strong reversed shear operation. Both would employ reduced minor radius, reduced current (10 MA), increased elongation ($\kappa_x = 2$) and both need improved confinement ($H_H \geq 1.5$) and high β_N ($\geq$ 3). Since this is still a rapidly developing area it is not possible to be definitive about the requirements for measurements in these cases. However, it will be necessary for both to have accurate measurements of the profiles of current density and pressure. In particular, for strong reversed shear it will be important to know the location and the value of q_{min}.

Recent experiments have shown that internal transport barriers (ITBs) can be stimulated by active profile control and can lead to enhanced performance, albeit so far only for relatively short duration. One method of stimulating an ITB is to create a region of low (or reversed) magnetic shear in the vicinity of a rational q surface by local current drive. ITBs can usually be observed as strong gradients in the electron and ion temperature profiles as well as strong shear in the poloidal and toroidal rotation profiles. Active control of ITBs is, however, not straightforward since very minute changes in the value of q (smaller than the typical measurement accuracy of present diagnostics) may lead to the creation or destruction of ITBs. More pronounced and rapid changes are observed on the electron and ion temperature profiles and on the rotation profile and so control on the gradient of these parameters may be more successful.

Another class of modes, Resistive Wall Modes (RWMs), can also occur under high β conditions and are observed as low frequency, low m- and n-number modes on magnetic signals as well as periodic perturbations in T_e and n_e. They can be stabilised by inducing plasma rotation. For indefinite stabilisation it will be necessary to drive appropriate fields using an external coil set.

3. Diagnostic Systems

In order to meet the requirements for plasma measurements, a comprehensive diagnostic system will be provided which will include magnetic, neutronic, optical/IR, spectroscopic and microwave systems [2]. The magnetic diagnostics will include high frequency and equilibrium pick-up coils, flux loops and Rogowski coils (*see Fig. 1*). The basic equilibrium set will be inductively operated and, it is expected, will operate satisfactorily for the standard operation, but for extended pulses and true steady-state a capability to measure static fields is required. Potentially suitable sensors are currently being developed in the supporting R&D programme. In addition, direct measurement of the plasma-wall gaps is being considered using plasma position reflectometry.

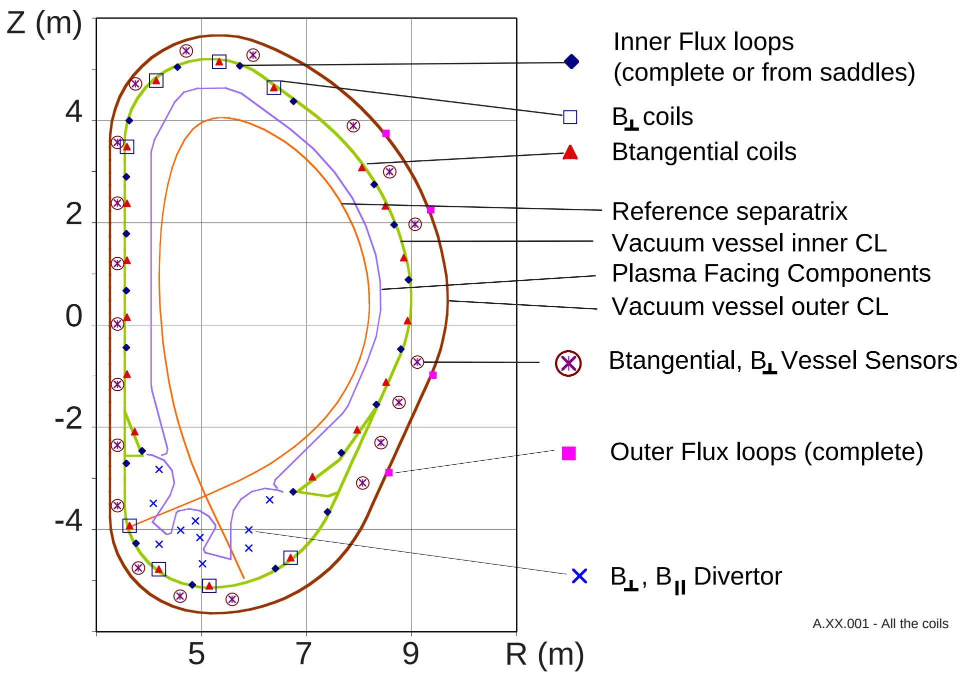

Fig. 1. Poloidal distribution of magnetic sensors. The diamagnetic loops and external Rogowski coils are not shown.

A full set of neutronic diagnostics including in-vessel and ex-vessel flux monitors, neutron cameras (radial and vertical viewing), spectrometers and activation systems, is planned.

The optical systems include a LIDAR Thomson scattering system for core plasma measurements and a conventional Thomson scattering system aimed specifically at making measurements in the edge region (*see Fig. 2*). Additional optical systems include a multi-channel vibration compensated interferometer for measuring $n_e(r)$, and Thomson scattering systems for probing the X-point region and divertor regions. Infrared systems include systems for measuring the temperature of the first wall and divertor plates.

The ionic populations will be probed by passive and active spectroscopy. For the latter a dedicated diagnostic neutral beam (DNB) will be installed. The DNB will have an energy ~ 100 keV and an injected current ~ 15 A [3]. The radiated power will be measured by multi-chord bolometry. A particularly difficult measurement under ITER conditions is the q profile. Systems based on multi-chord polarimetry and Motional Stark Effect using one of the heating beams are being designed. The n_T/n_D ratio will be measured with a neutral particle analyser. A range of techniques including wide-angle viewing and IR thermography are in preparation for viewing the first wall and the divertor.

The principal microwave systems will be a system to measure the electron cyclotron emission and three reflectometry systems for measuring the electron density in the main plasma and in the divertor plasma (*see Fig. 3*), and for measuring the plasma position. Finally several diagnostics will be installed to aid the protection and operation of the tokamak: for example, pressure gauges, residual gas analysers and 'halo' current monitors.

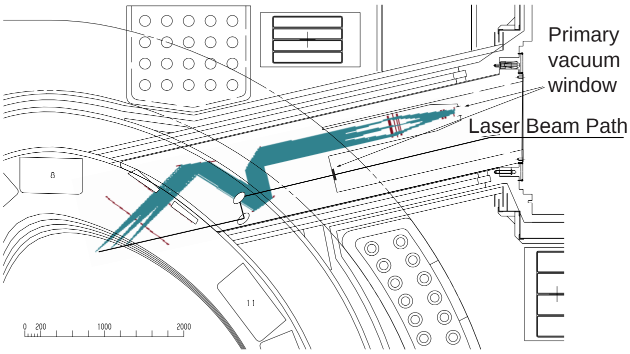

Fig. 2. Schematic of the Thomson Scattering system installed in the upper radial port.

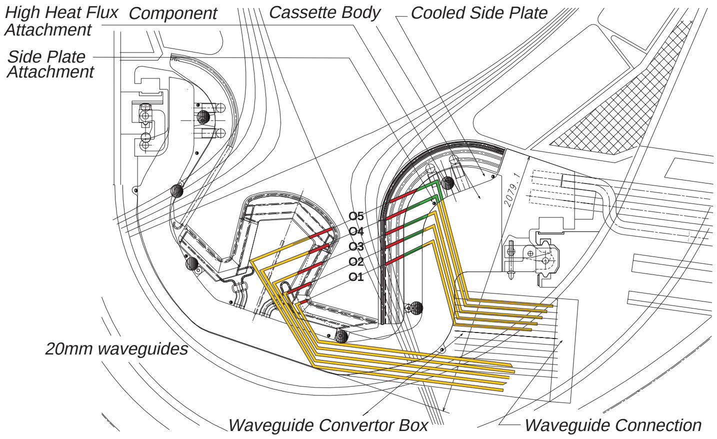

Fig. 3. Waveguides installed in the divertor region for measurements of the plasma density by interferometry and reflectometry.

4. Conclusions

The plasma measurements required to support the operation of ITER in the different operating scenarios have been determined and the detailed measurement specifications have been developed. In general the trend is that as the operating scenario becomes more 'advanced' and the range of plasma performance increases the measurement requirements become more demanding and more measurements are used in plasma control. A comprehensive diagnostic system which includes magnetic, neutronic, optical/IR, spectroscopic and microwave systems is under design to provide the required measurements.

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