5.16 Diagnostics

5.16.1 Introduction

The success of FIRE's physics mission is dependent on there being a comprehensive set of plasma diagnostics. This set must be capable of providing the same quality of data available in present-day devices, in addition to providing new information about the alpha-particles, the new feature of a burning plasma experiment. The set must provide high quality, reliable information on many plasma parameters, including data on profiles, to be used as input to plasma control. The set must operate with good space and time resolutions in an extreme radiation environment.

At this point in the design process, it has only been possible to begin to consider some conceptual aspects of the integration of diagnostics with the tokamak, its internal hardware and the necessary radiation shielding. There are many diagnostics requiring optical sightlines to the core plasma and to the divertor, which will require labyrinthine paths through thick shielding "plugs" in the access ducts. Magnetic diagnostics, for measuring parameters such as the plasma current and position and high-frequency instabilities, will necessarily be mounted immediately behind first-wall tiles and must be integrated with the structures planned for these areas. For access to the divertor, and to gain sightlines for the x-points and separatrix legs into the divertor and their contact points, significant design integration with the divertor and first wall components is required.

FIRE diagnostic design, at least at the concept stage, can benefit from the much, much greater design effort put into conceiving access routes for diagnostics for ITER [1]. Very similar measurement requirements apply for FIRE and ITER with similar spatial resolution requirements (as a fraction of minor radius) and temporal resolutions. The higher toroidal magnetic field and higher expected plasma density may affect the diagnostic technique chosen to make the measurement. Also since FIRE's mission is more exploratory in terms of plasma scenarios and in investigating alpha-particle physics than ITER's, higher priority for some particular measurements may be found. So far, the measurements have only been considered in terms of full-scale operation in deuterium-tritium (D-T), and little consideration has been given to optimizing the timing of instrumentation to different phases of the operational program.

5.16.2 Aspects of Diagnostic Design

The measurements required and the diagnostic techniques proposed to carry them out are shown in table 5.16.2-1. In this table, there is indication, by a tick, of which measurements would provide data to the control systems. During the construction phase of FIRE, it is likely that some of these systems will be dropped while new techniques will be adopted as the physics and diagnostic technology evolve. Twelve large radial ports are presently available for diagnostics, one of which may be shared with vacuum pumping of the vessel. There are also upper and lower outer ports aligned with the x-points which provide access to the divertor plasma regions. Of these half of each of the upper and lower ports are available for diagnostic use, but the access is shared with water cooling to the internal divertor hardware. There are sixteen small vertical ports, at the top and bottom of the vacuum vessel. All of these ports have been provisionally allocated to different diagnostics and this plan is shown in fig. 5.16.2-1.

Detailed design of all of the components to be installed in the ports, including the necessary shielding to limit radiation doses to the coils and the facility, will be necessary before it can be shown that the planned installation is possible. Hence, while a relatively simple set of diagnostics will be installed initially for start-up and early device demonstration, planning of the final set is required *ab initio.* Rather detailed designs of individual diagnostic, with the necessary first labyrinths and first mirrors - refractive optical components will not survive the first wall flux levels - will be required to determine whether the required spatial resolutions are achievable. In some cases, such as techniques using measurement of plasma x-rays, it may not be possible to implement the diagnostic because of the radiation environment.

The magnetic diagnostics have to be mounted in the high-radiation (~ 1.2 Gy/s) and high temperature environment experienced near the first wall. There are design issues with their size and the ability to integrate them with the copper stabililzer and tiles so that they can function and be sufficiently cooled. Their design and placing should limit the detrimental effect caused by radiation-induced conductivity (RIC) in the ceramic insulation, but the small size and mineral insulated (MI) cable connections make this challenging. Success in this implementation is critical to the tokamak's operation, because of the role magnetic signals play in plasma control and physics understanding.

For the premier operating tokamaks, a number of measurements of key plasma parameters, and obviously their profiles, have been made using spectroscopic techniques dependent on a relatively high neutral particle density at the plasma core provided by heating neutral beams. Such beams will not be available on FIRE with its narrow radial ports. Unfortunately, there are not good alternative methods, in terms of spatial resolution, to the spectroscopic techniques so that a diagnostic neutral beam is necessary. The beam energy is optimal for most measurement at ~125 keV/ amu (atomic mass unit), but very high current density is required to provide a sufficient density at the center of the plasma despite the beam attenuation. This beam should operate in short pulses so as not to affect the plasma and will require special development.

The measurement of the alpha-particles, the internal energy source for the burning plasma, and determination of their behavior under different plasma operational scenarios, is a major goal of this program. While some success was achieved on TFTR [2], and hopefully more will be attained during the upcoming JET-EP program, significant improvements are necessary to provide reliable measurement throughout the high-yield neutron part of the discharges. Radiation-hard detectors are needed for determining the energy and source region of the escaping high-energy alpha-particles. Reduction of radiation-induced fluorescence and absorption in optical components, full testing of collective scattering techniques with lasers or microwaves, and developing methods for measuring the high-energy neutron tail created by collisions of the alpha-particles with the fuel ions, are all necessary elements in developing an understanding of the confined alpha-particles. A high-energy lithium-impurity pellet is desirable to provide a source of particles with which the alpha-particles can interact so that their spatial distribution can be determined. At the same time a full complement of measurements of high-frequency instabilities is essential for understanding the impact of this new component of high-energy ions in the plasma.

5.16.3 Research and Development Necessary for Diagnostic Implementation

There are three main areas in which research and development (R&D) of diagnostic systems is necessary. Much of the work parallels the requirements of ITER diagnostics [3], so that hopefully there can be some sharing of the expense of this effort. Some examples of scope in the three areas are:

i) Irradiation Tests of Materials;

Studies of RIC in selected ceramics and MI cable to define the materials to be used;

Investigations of the cause of radiation-induced electromotive force (RIEMF) with MI cables to prevent signal pollution;

Evaluation of electrical connection techniques for MI cable for remote-handling and insulation properties;

Testing of selected optical fibers for performance in realistic radiation environments at relatively low light-signal levels.

ii) Development of New or Improved Diagnostic Techniques:

Development of an intense pulsed diagnostic neutral beam with ~125 keV/amu, $1x10^6$ A/m^2 for 1 μsec at 30 Hz repetition rate;

Demonstration of fast-wave reflectometry for measuring hydrogen isotope ratios in the plasma core;

Extension of the range of Faraday-cup based and scintillator-based detectors for lost alpha-particles to the higher temperatures and radiation levels at FIRE conditions.

iii) Development of New Components and Techniques:

Continuation of development of small radiation-hard high-temperature magnetic probes;

Development of a prototype shielding "plug" containing diagnostic components for a radial port to incorporate required tolerances, alignments, assurance of ground isolation, actuation of shutters, etc., while maintaining sufficient shielding.

Evaluation of metallic mirror performance and the effects on reflectivity of neutral particle bombardments and nearby erosion sources.

This R&D program is critical to demonstrating performance of the measurements and should be carried out in parallel with the design.

5.16.4 Summary

The determination of the capability for measuring the necessary plasma parameters both for understanding the behavior and for feeding back control signals is in its infancy. Some of the key issues have been indicated and the initial design efforts must be applied to these. The supporting R&D must move ahead in parallel with the design. Fortunately there has been a strong ongoing effort on diagnostic implementation on ITER and this effort is leading the way to a number of solutions.

[1] ITER Physics Basis, chapter 7, Nucl. Fusion, **39**, 2541 (1999) and the ITER Final Design Report.
[2} S.J. Zweben et al., Nucl. Fusion, **40**, 91 (2000).
[3] A.E. Costley et al., Fus. Engg. & Des., **55**, 331 (2001).

Table 5.16.2-1: Diagnostics Proposed for FIRE

Physics Parameter	ontrol	Diagnostic Set
Magnetic Measurements		
Plasma current	√	Rogowski Coils
Plasma shape and	√	Flux/voltage loops
Shape, position & MHD	√	Saddle coils (inc. locked-mode)
	√	Discrete Br, Bz coils
Plasma pressure	√	Diamagnetic loops
Disrupt.-induced currents	√	Halo current sensors
Current Density		
Current density for most of profile	√	Motional Stark effect
		FIR polarimetry
Current density in edge		Li-beam polarimetry
Electron Density		
Core elect. density	√	Thomson scattering
		FIR multichannel interferometer/polarimeter
X-point/div. dens.		Thomson scattering
Edge, transp. boundary profile		mm-wave reflectometer
Edge density profile		Li-polarimetry
		Fast-moving probe
Divertor density variation along		Multichannel interferometer
Divertor plate density		Fixed probes
Electron Temperature		
Core electron temperature profile	√	Thomson scattering
		ECE heterodyne radiometer
		ECE Michelson interferometer
X-point/divertor		Thomson scattering
Edge elect. temp. profile		Fast-moving probe
Div. plate elect. temp.		Fixed probes
Ion Temperature		
Core ion temperature	√	Charge exchange spect.
		Imaging x-ray crystal
		Neutron camera spect.
Divertor ion temperature		UV spectroscopy
Plasma Rotation		
Core rotation profile	√	Charge exchange spect.
		Imaging x-ray crystal
Relative Isotope Concentration		
Density of D and T	√	Charge-exchange spect.
		Neutron spectroscopy
Radiation		
Zeff,visible bremsstrahlung	√	Visible bremsstrahlung array
Core hydrogen isotopes, low-Z impurities		Visible filterscopes
Divertor isotopes and low-Z impurities	√	Divertor filterscopes
Core low-Z impurities		Visible survey spectrometer
		UV survey spectrometer
Radiation (continued)		
Divertor low-Z imps. and detachment	√	Multichord visible spectrometer
High-Z impurities		X-ray pulse height
Divertor impurities		UV spectrometer
Total radiation profile		Bolometer arrays
Total light image		Visible TV imaging
MHD and Fluctuations		
Low-frequency MHD	√	Discrete Br, Bz coils
		Saddle coil for locked-mode
		Neutron fluctuation dets.
High-frequency MHD, TAE, etc.	√	High-frequency Mirnov coils
Core density fluctuations		Mm-wave reflectometers
		Beam emission spectr.
Core electron temperature fluctuations.		ECE grating polychromators
Neutron Measurements		
Calibrated neutron flux	√	Epithermal neutron dets.
Neutron energy spectra		Neutron camera spect.
Alpha-particle Measurements		
Escaping α-particles/fast-ions		Faraday cups/scintillators at first wall
		IR TV imaging
Confined thermalizing alphas/spatial		α-CHERS
Confined α-particles' energy distribution		Collective scattering
Spatial distribution of alphas		Li-Pellet charge exchange
Volume-average α-particle energy spectrum		Knock-on bubble-chamber neutron detectors
		Neutron spectrometer
Runaway Electrons		
Start-up runaways	√	Hard x-ray detectors
Disruption-induced runaways	√	Synchrotron radiation detection
Divertor Pumping		
Pressure in div. gas-box		ASDEX-type press. gauges
Helium removed to div.		Penning spectroscopy
Machine Operation Support		
Vacuum base pressure	√	Torus ion gauges
Vacuum quality		Residual gas analyzer
Vac. vessel illumination		Insertable lamps
Surface Temperature		
First-wall/RF antenna	√	IR TV imaging
Divertor plate temps. and detachment	√	IR TV imaging
		Thermocouples
Neutral Particle Sources		
Neutral particle source for core spectroscopy	indirect	Diagnostic neutral beam
Lithium source for polarimetry		High current lithium beam
Li-pellet target for confined-α spatial dist.		High velocity lithium pellet injector

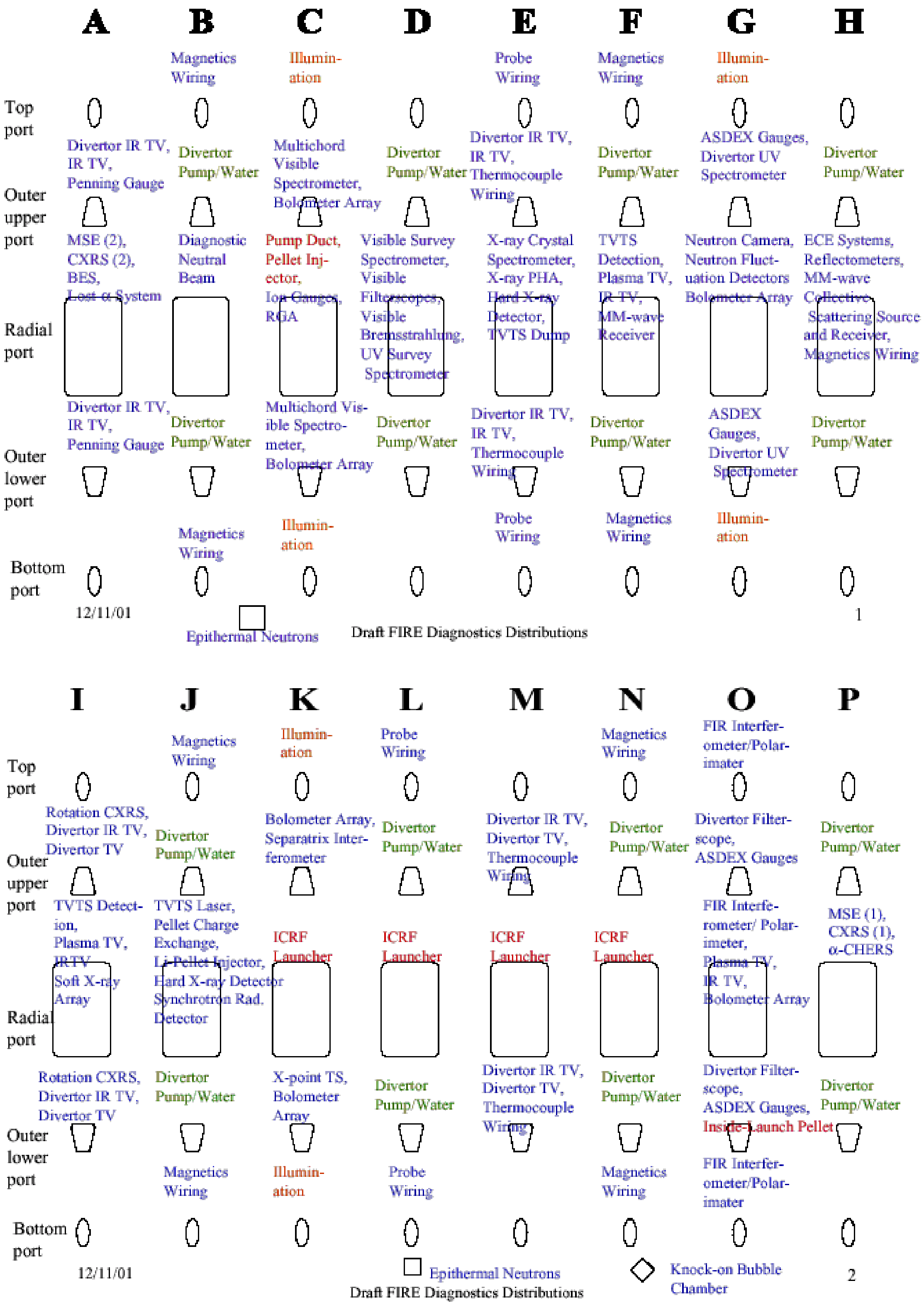

Figure 5.16.2-1 Provisional FIRE Diagnostic Port Occupancy