PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3720
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PPPL-3720

Diagnostics for FIRE: a Status Report

by

Kenneth M. Young

July 2002

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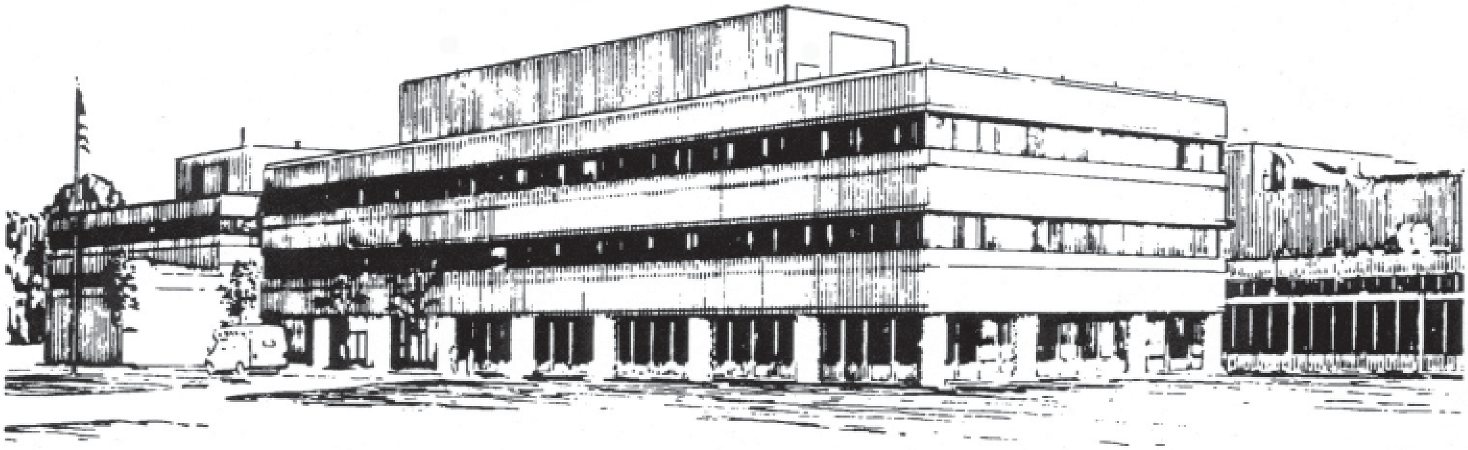

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Diagnostics for FIRE: a Status Report

Kenneth M. Young

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey, 08543

The mission for the proposed FIRE device is to "attain, explore, understand and optimize fusion-dominated plasmas". Operation at $Q \geq 5$, for 20 s. with a fusion power output of ~ 150 MW is the major goal. Attaining this mission sets demands for plasma measurement which are at least as comprehensive as on present tokamaks, with the additional capabilities needed for control of the plasma and for understanding the effects of the alpha-particles. Because of the planned operation in advanced tokamak scenarios, with steep transport barriers, the diagnostic instrumentation must be able to provide fine spatial and temporal resolution. It must also be able to withstand the impact of the intense neutron and gamma irradiation. There are practical engineering issues of minimizing radiation streaming while providing essential diagnostic access to the plasma. Many components will operate close to the first wall, e.g. ceramics and mineral insulated cable for magnetic diagnostics and mirrors for optical diagnostics; these components must be selected and mounted so that they will operate and survive in fluxes which require special material selection. The measurement requirements have been assessed so that the diagnostics for the FIRE device can be defined. Clearly a better set of diagnostics of alpha-particles than that available for TFTR is essential, since the alpha-particles provide the dominant sources of heating and of instability-drive in the plasma.

I. INTRODUCTION

The proposed experimental device, the Fusion Ignition Research Experiment (FIRE)[1], is a relatively compact tokamak with the mission of attaining, exploring, understanding and optimizing fusion-dominated plasmas. An operational goal of operating with deuterium-tritium (D-T) plasmas and achieving $Q \approx 10$ (the fusion power gain, Q, is the ratio of power output from fusion reactions to the power input to the plasma) will permit thorough studies of the behavior of the alpha-particles, generated in the fusion reaction, as they slow down and heat the background plasma. The mission leads to some specific physics goals. In the physics of burning plasmas, high frequency modes of instability will be studied over a range of plasma conditions. The properties of advanced toroidal plasmas with steep internal transport barriers will be examined in the presence of this new intense central heating source. Learning to control the build-up of alpha-ash, the residue of He-ions after they have given up their energy to the main plasma, and the ability to use the measured pressure and current profiles in plasma control while maintaining satisfactory heat and particle fluxes to the divertors will form a significant part of the experimental program.

Figure 1 shows a cut-away drawing of FIRE and table I gives the principal design parameters and some of the anticipated plasma parameters for this device. It is a relatively high field tokamak[2] which will normally operate at high density. The toroidal field coils will be made of copper, cooled by liquid nitrogen so allowing a pulse-length of 20 s, much longer than the plasma time scales of interest. The cold coils require a cryostat, which leads to long necks to the ports for the diagnostics. The operation in DT fuel to produce $Q \sim 10$ to permit physics studies of a burning plasma provides high neutron fluxes. These, in turn, lead to integration of diagnostics with thick radiation shielding and the use of remote handling in the maintenance of components inside the vacuum vessel.

The physics goals of FIRE, and requirements for feed-back control of advanced-tokamak plasmas, set stiff challenges for the measurement capability in the presence of this harsh nuclear radiation environment. In addition to having to provide the same quality of profile information as in present-day devices, a much better set of alpha-particle physics measurements than were available for TFTR[3] are necessary. These operational circumstances are very close to those already encountered and evaluated for the much larger ITER[4,5]. The severe restraints on access and maintenance on diagnostics leads to careful planning of the diagnostic set, starting with defining the measurement requirements and then investigating the capability of various diagnostic techniques to meet these requirements in the real configuration. Table II shows some of the requirements on the quality of measurement set for FIRE diagnostics so that the physics mission can be achieved.

The significant special design features for FIRE diagnostics will be described in Section II. The third section will show those diagnostics presently being considered for installation for the burning plasma studies on FIRE, and expected to be in place by the fourth year of operation.

II. DESIGN FEATURES FOR DIAGNOSTIC MEASUREMENT IN FIRE

There are four main areas which lead to major advances in diagnostics for a device like FIRE, and which make the engineering of diagnostics concurrent with the design and construction of the device itself essential. The first is accessibility to the plasma, with sharing of ports and the availability of sightlines through the high-heat load first wall components. The second is ensuring that the diagnostics will function correctly in the neutron and gamma radiation environment, while, at the same time preserving the necessary shield quality. The third is the measurement of plasma parameters for which the known techniques depend on a neutral beam. The measurement of many of these parameters, such as the ion temperature and plasma rotation profiles and the current density profile, is expected to play a role in the control of the plasma. The last is advancing the state of the art in measurement of the alpha-particles, which are the key particles in the new physics, providing the heating, the sustainment of the plasma and also the impurity build-up through the thermalized helium residue.

a) Accessibility

The FIRE tokamak plasma is relatively accessible through quite large ports as shown in fig. 2. Presently twelve of the large radial ports are assigned to diagnostics and six to auxiliary RF heating. Some of the space will have to be used for shielding and clearly any tangential observation will require a mirror or other component close to the mouth of the port near the plasma. Since the present engineering concept is based on a single integrated unit comprising the components for all the diagnostics and the shielding sharing each port, the limited human access to the vacuum vessel is not considered an issue. In any case, such access would not continue after the first few high-neutron yield pulses and all diagnostic components have to be designed with remote-handling in mind. It does mean, however, that great reliability must be built into moving parts, such as optical shutters, and that calibration techniques must be integrated well into the structure.

Diagnosing the plasmas in the two divertor regions requires many diagnostics making use of the outer ports pointing toward the x-points. Some diagnostics will view into the opposite divertor while others will have to have sightlines through the high heat flux divertor plate components. The divertors are made of a tungsten brush structure and removal of a row of "bristles" is possible giving a 30 mm wide aperture. A 50 mm slot between the divertor hardware and the copper stabilizing shell allows viewing toward the opposite divertor. Only half of these ports can be assigned to diagnostics and in those, the diagnostics will share with water pipes for cooling the divertor. The 50 mm x 150 mm top and bottom ports will require sightlines at some locations through the divertor, but it is presently planned to use these mostly for wiring for magnetics or stationary probes.

Another access aspect is the small amount of space provided between the inner vacuum vessel wall and the front face of the PFC tiles. Much of this space is filled by copper providing passive stabilization but also incorporated in the cooling of the vacuum vessel[2]. There are clearly significant design integration issues for the magnetic diagnostics, vital for control and understanding of the plasma, which will be resolved in the next engineering phase.

b) Radiation Environment

The high neutron, and associated gamma, fluxes planned to be achieved by FIRE generating 150 MW of fusion power in a relatively small volume means that remedial steps must be taken for many diagnostics. The prompt radiation dose rates at the first wall are higher than for ITER but, with effective shielding, are similar at the outside of diagnostic ports[6]. Because the pulse lengths are only 20 s long, mechanical damage due to high fluence will not be significant but real-time electrical and optical impacts could strongly effect the diagnostic performance. Magnetic diagnostics could be affected by nuclear heating but good design and mounting should negate this.

The most serious electrical effect is radiation induced conductivity, RIC, which, at the level reached at the first wall in FIRE, the location of the magnetic diagnostics and their connecting cables, can be seven orders of magnitude higher than normal in insulating ceramics like alumina[7], and certainly close to levels which would affect the measurement. Clearly an R&D program and careful material selection and design will be necessary to produce the accuracy and reliability depended upon for magnetic diagnostics. Another potential issue is induced voltage, RIEMF, which may be a problem for mineral insulated cable and is the subject of intensive study for ITER.

A major impact on optical diagnostics is the necessity to use reflecting optics until the components can be well shielded. Hence periscope arrangements through shield labyrinths are necessary for the port inserts. Vacuum windows should be sufficiently shielded so that the transient absorption and luminescence will be insignificant because the windows are relatively thin. But fiberoptics, with much longer lengths potentially exposed to radiation, even outside the vacuum windows, must be carefully chosen, and possibly monitored. Very many diagnostics use fibers for imaging so that it has been very worthwhile for ITER to sponsor finding best-performing fibers and even development of fibers which are less affected by radiation[7]. Even after extensive research on fiber optics at TFTR[8] and carefully shielding the fiber bundle used in the escaping-alpha diagnostic[3], there was a noise pedestal in the image of about 10% of the signal.

A side effect of using a reflecting mirror close to the plasma, as will frequently be necessary in FIRE, is the hazard to it caused by neutral particle bombardment causing erosion or deposition. Mirrors with special metallic surfaces for retaining their reflecting properties useful for quantitative measurements have been studied for some time for the ITER program[9] and such studies will have to be continued to ensure satisfactory operation in FIRE.

c) Diagnostic Neutral Beam

Measurements, such as those of ion temperature and plasma rotation and of the safety factor, q(r), with good spatial resolution, which have contributed strongly to understanding the advanced tokamak plasma configurations, presently use techniques dependent on an enhanced neutral particle density in the plasma. This enhanced density has been available because of heating neutral beams not presently included in the FIRE plan. Even though the plasma has a small plasma radius the high electron density makes penetration difficult in the range of 100 - 150 keV/amu most favorable for optimizing the signal to noise ratio for the temperature and rotation measurements deep in the plasma. A conventional long-pulse beam, which leaves the plasma relatively unaffected, leaves the signal many orders of magnitude less than the bremsstrahlung background[10]. Hence development of a pulsed beam operating with 1 μs pulses of 1 MAm^{-2} in a cross-section of 0.04 m^2 at 30 Hz has been identified as a possible solution. Initial studies of a possible pulsed ion source have been carried out at LANL[11]. This beam would have to enter the plasma nearly radially in FIRE so that observation from above or below will be necessary to get the best spatial resolution. Note that recent modeling has shown that it may be possible to use O-mode and X-mode reflectometry off low-level turbulence as a replacement technique for measuring q(r) in FIRE[12] and this possibility should be actively investigated in a tokamak. It is difficult to see that beam emission spectroscopy could be a viable technique for studying turbulence with such a short-pulse beam.

d) Alpha Particle Measurements

The DT campaigns in TFTR were notable because of the very effective physics studies made using new and evolving alpha-particle diagnostics[3]. Many of the best measurements were made in the period immediately following the turning off of the heat source, an impossibility in worthwhile studies of a burning plasma. The escaping alpha diagnostic[3] worked well apart from noise background caused by scintillation in its fiberoptics, but developments in high temperature scintillators or in Faraday cups[13] will be necessary for application to FIRE, or for a test in JET. Such detectors will be important on FIRE, even though the ripple-losses will be low and there is little room for an array of detectors. The pellet charge exchange technique which provided the only profiles of the high energy confined particles[3] was limited in penetration of the impurity pellets while beam heating was on and by the number of available pellets so that a major development of an injector would be necessary for FIRE. The alpha-CHERS technique[3] for measuring slowing-down alphas makes use of the high-energy tail of the 468.6 nm helium spectral line in charge exchange spectroscopy with a neutral beam. Because the signal is very small, the background level is critical and neutron-induced effects in the fiberoptics were very difficult to subtract in TFTR. This technique would benefit greatly from a high current pulsed beam.

There are two promising developments in collective scattering and knock-on neutron detection which both provide information on the confined alpha-particles. Collective scattering did not work well on either TFTR or JET, but is currently under prototype testing on TEXTOR, in studies of a fast-ion component driven by ICRF heating[14]. The microwave frequency used in TEXTOR has proven the principle of the technique, but it is important to test its effectiveness on the more spread-out energy range of the slowing-down alpha-particles. A change in wavelength to the far infra-red would be necessary for measurement in FIRE with its high field and density. There is a high energy tail to the neutron spectrum due to the alpha-particles accelerating the colliding deuterons and tritons and two techniques for observing this tail are proposed. One uses magnetic proton recoil neutron spectroscopy as applied in a pioneering experiment at JET[15], while the other depends on a set of bubble chanbers with narrowly separated sharp energy thresholds[16], currently under development.

There are good grounds for optimism in improving the measurement of alpha-particles, but intense development is needed, with tokamak testing a real necessity prior to the burning plasma experiments. Note that the studies of alpha-particle physics will not be effective without good plasma turbulence measurements and good profile measurements of the core plasma properties.

III DIAGNOSTICS PROPOSED FOR USE ON FIRE

An extensive set of plasma diagnostics is planned for FIRE to fulfill its physics mission. This set, with the main measurement purposes, is shown in table III. Although multiple listings of techniques are shown for many parameters there is not duplication because of the different aspects of the measurement involved. A battery of alpha-particle diagnostics is proposed, but this is necessitated by the different relevant physics feature which each measures. Assignment of the diagnostics to ports on FIRE has been made, but without extensive engineering design of the interfacing of diagnostic components with other diagnostics sharing the same port and the necessary thick shielding, their performance cannot be fully assessed. For some diagnostics it is clear that extensive developments are necessary before they can be assured of working; examples are radiation testing of ceramics for use in diagnostics near the plasma surface like the array of magnetic sensors and the development of a pulsed neutral beam.

IV. ACKNOWLEDGEMENTS

This work has been carried out in collaboration with Dale M. Meade and the FIRE design team. It has been supported by DOE Contract # DE-AC02-76CHO.

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Table II. Examples of Target Plasma Measurement Capability for FIRE.

Table III. Measurements and diagnostic techniques to fulfill the FIRE mission.

FIGURE CAPTIONS

Fig. 1. Cutaway drawing showing the main features of the FIRE device.

Fig. 2. The vacuum vessel ports for FIRE, showing the dimensions in mm. The top and bottom ports are 50 mm x 150 mm.

Table I. FIRE's Design Features and Projected Plasma Parameters.

Design Parameter	**Value**
Major Radius (m)	2.14
Minor Radius (m)	0.595
Elongation (X-point)	2.0
Triangularity (X-point)	0.7
Toroidal Magnetic Field (T)	10
Plasma Current (MA)	7.7
ICRF Heating Power (MW)	20
Double Null Divertor	
Target Plasma Parameters	
Central Plasma Density (10^{20} m^{-3})	5.5
Central Plasma Temperature (keV)	11
Fusion Power (MW)	150
Fusion Power Gain (Q)	10
Pulse Length (inductive) (s)	20

Table II. Examples of Target Plasma Measurement Capability for FIRE.

Parameter	**Parameter Range**	**Spatial Resolution**	**Time Resolution**	**Accuracy**
Plasma current	0.1 - 8.0 MA	Not applicable	1 ms	1% (I_p> 1MA)
Total neutron flux	$1x10^{14}$-$1x10^{20}$ ns^{-1}	Integral	1 ms	10%
Neutron & α-particle source	$1x10^{14}$-$5x10^{18}$ $ns^{-1}m^{-3}$	a/10	1 ms	10%
Divertor surface temperature	200-2500°C	10 mm	2 ms	10%
Core electron temperature	0.5 - 30 keV	a/30	10ms	10%
Edge electron density	$(0.05-10)x10^{20}$ m^{-3}	5 mm	10 ms	5%
Confined-α's energy spectrum	0.1-3.5 MeV	a/10	100 ms	20%
Radiation profile in main plasma	0.01-1 MWm^{-3}	a/15	10 ms	20%
Radiation profile in divertor	≤100 MWm^{-3}	50 mm	10 ms	30%

Table III. Measurements and diagnostic techniques to fulfill the FIRE mission.

Physics Parameter	Diagnostic Set
Magnetic Measurements	
Plasma current	Rogowski Coils
Plasma shape and position	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 profile	Thomson scattering
	FIR multichannel interferometer/polarimeter
X-point/div. dens. profiles	Thomson scattering
Edge, transp. boundary profile	mm-wave reflectometer
Edge density profile	Li-polarimetry
	Fast-moving probe
Divertor density variation along separatrix	Multichannel interferometer
Divertor plate density	Fixed probes
Electron Temperature	
Core electron temperature profile	Thomson scattering
	ECE heterodyne radiometer
	ECE Michelson interferometer
X-point/div. Temp. profiles	Thomson scattering
Edge elect. temp. profile	Fast-moving probe
Div. plate elect. temp.	Fixed probes
Ion Temperature	
Core ion temperature profile	Charge exchange spect.
	Imaging x-ray crystal spect.
	Neutron camera spect.
Divertor ion temperature	UV spectroscopy
Plasma Rotation	
Core rotation profile	Charge exchange spect.
	Imaging x-ray crystal spect.
Relative Isotope Concentration	
Density of D and T concentrations in core	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 analysis
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 Activation
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 distribution	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 Performance	
Pressure behind divertor	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 temp.	IR TV imaging
Divertor plate temps. and detachment	IR TV imaging
	Thermocouples
Neutral Particle Sources	
Neutral particle source for core spectroscopy	Diagnostic neutral beam
Li-beam source for polarimetry	High current lithium beam
Li-pellet target for confined-α spatial dist.	High velocity lithium pellet injector

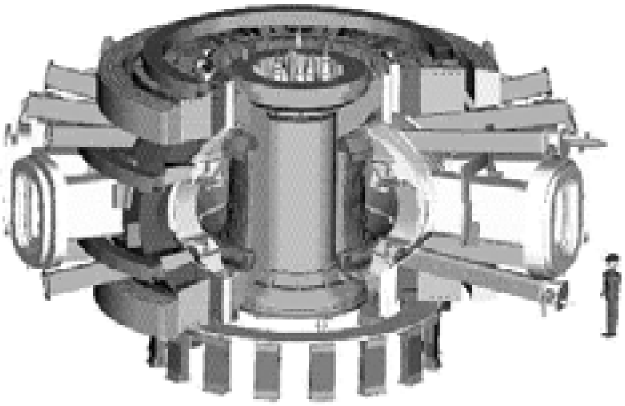

Figure 1
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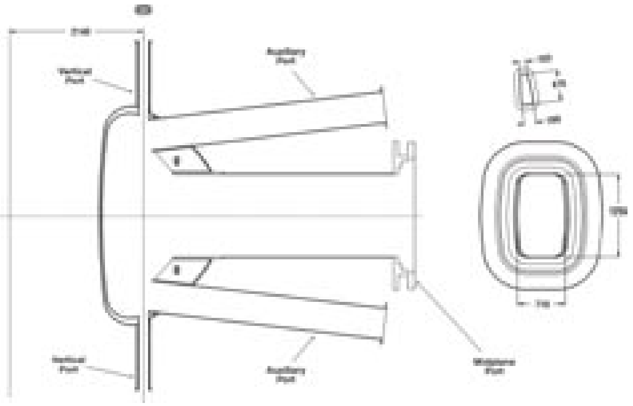

Figure 2
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