Non-Plasma Diagnostic Instrumentation for a Next-Step Tokamak with a Burning Plasma

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Abstract

Any device to succeed ITER and demonstrate successful engineering implementation of a first wall and tritium generation will require very extensive instrumentation of the device components. Measurements of slow and fast movements of components, strains and stresses on them, temperatures and fluid flow parameters will all be necessary. While it is hoped that the physics of the plasma will become fully known during the life of such a device (enabling a major reduction in the complexity of plasma diagnostics) qualification of the engineered components will be the primary output of the operation. Survival of the first wall for long-pulse full-power operational periods, breeding sufficient tritium to maintain operation, reliable behavior of coils and the auxiliary systems of fueling, heating and remote maintenance equipment, must all be demonstrated. This paper puts together a preliminary estimate of the instrumentation that will be necessary to meet this requirement for a specific example of a tokamak design.

Keywords: instrumentation, tokamaks, burning plasmas, radiation impact.

Introduction

A lot of measurement equipment will be mounted on ITER's components to allow determination of the performance of all its sub-systems. Much of that implementation will provide input to the instrumentation required for any next-step tokamak with a burning plasma, because of the similar magnetic fields, in-vessel temperatures, and levels of neutron/gamma radiation in which the instrumentation will operate. The significant differences for its instrumentation will be the much higher neutron fluence and the likely different maintenance concept. The handling and monitoring of the data for such instruments will be a significant challenge, but the potential multitude of instruments may impact the reliability of the overall device and complicate its maintenance by remote handling. Also present-day instrumentation is unlikely to be able to withstand the harsh environment so that very extensive R&D will certainly be necessary to ensure that instruments (and actuators) will be sufficiently radiation-hard. The purpose of this paper is to give some insight into the complexity of the instrumentation.

Hence it behooves us to try to quantify the measurement requirement, assumed to be necessary throughout the life of such a tokamak, particularly those measurements in and close to the tokamak in the high radiation environment. These are the measurements being considered in this document. They clearly will be complemented by other measurements elsewhere in the facility. Judgment on whether the measurements are absolutely necessary will be required: to some extent that will depend on the margins built into the engineering design. Summaries of the instruments already applied on the large superconducting tokamaks are already available[1,2].

This document provides a speculative, and rather conservative, assessment of the total monitoring requirements for a next-step device. For this study we have chosen the specific example of FNSF (Fusion Nuclear Facility Study)[3]. Its conceptual design is shown in fig. 1. While there are presently many different design concepts for next-step devices, it is probable that the quantity of instrumentation required for all of them will not be very different. The definitive requirement for monitoring will only be decided during the full engineering design and analysis of the final device.

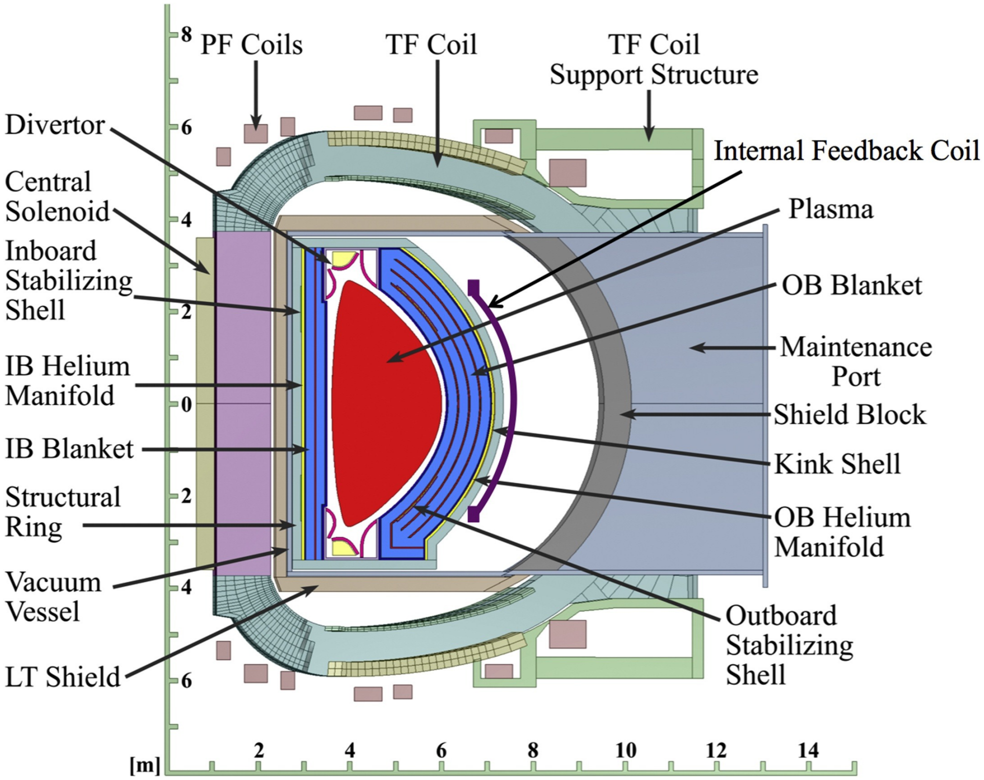

Fig 1. The FNSF concept[3]. The principal parameters of this device are B_T = 7.5 T, I_P ~ 8 MA, R = 4.8 m, neutron wall load ~ 1.75 MW/m^2.

During the design of the tokamak itself, responsibility for satisfactory engineering of the major components is usually divided into the areas listed below.

1. Vacuum vessel integrity.
2. Thermal shield
3. Magnetic field coils and cryostat:
    - 3.1 TF and PF coils and central solenoid inside the cryostat,
    - 3.2 Feedback coils inside the vacuum vessel.

4. Structural rings supporting the blankets, stabilizing shells, first wall and feedback coils.
5. First wall and divertor.
6. Tritium breeding blankets, incorporating stabilizing and kink shells.
7. Auxiliary heating systems:
    - 7.1 Electron Cyclotron Heating,
    - 7.2 Ion Cyclotron Heating,
    - 7.3 Neutral Beam Heating.
8. Fueling systems:
    - 8.1 Gas feed,
    - 8.2 Pellet injection.
9. Plasma diagnostic systems (non-plasma measurement aspects).
10. In-vessel inspection and preparation for remote maintenance.

The detailed scheme for implementing the required instruments can only be developed around a real engineering design so that this breakdown of the engineered systems is appropriate. The goal of this paper is to draw attention to the scale of the instrumentation that will be necessary so that its implementation can be considered in the early design phase of the tokamak.

Any evaluation of the total number of engineering instruments needed for ITER and for next-step tokamaks depends mostly on two factors: (a) the level of complexity of the tokamak device, and (b) the growing tendency toward more and more complete and accurate instrumentation of any equipment and installations, such as in cars, airplanes, bridges, industrial and power plants, etc. This tendency has, in general, led to a significant reduction in the cost of single instruments. As an example, just one optical fiber can carry tens of FBG strain gauges and can simply join all structural fibers inside the composite wing of an airplane or wind turbine. Hence the number of the engineering instruments in ITER and next generation tokamaks, as suggested in this paper, will be comparable to that in modern industrial plants having a similar number of parts and components.

In an ideal world the necessary measurements of strain, relative motion and absolute accelerations of the device components will continue through the life of the tokamak. But with the very high neutron fluxes and fluences and the high operating temperatures of a lot of the instrumentation of FNSF, survival of currently available measuring sensors is not likely. Under neutron bombardment, optical sensors are susceptible to fluorescence and loss of transmission, insulation of electrical sensors becomes conductive and the mountings lose mechanical strength. It is assumed here that a development program will yield sensors that will be able to detect the impact of a disruption after many days of full-power operation. Experience with fiber optics in the nuclear environment suggests that optical sensors[4] should not be considered, but it may be possible to use them in early operations to act in cross calibration of neighboring sensors before they die. They could also be used in ex-vessel and ex-cryostat locations. (These sensors have not been included in our assessment).

Three types of measurement will be required. Accelerometers providing 3-D information, strain gauges 2-D and displacement sensors which can provide 1-D to 3-D information. Thus there will be a complex mix of sensor counts, wire (and, possibly, fiber) counts and data acquisition channels. Going beyond the instrument count developed here will only become worthwhile with a detailed machine design. An aspect ignored in this paper is that of redundancy of the instruments. The need will only become apparent during the full engineering design of the device where issues such as significant asymmetric or deformation loads have to be considered.

The number of full-power VDE and plasma disruptions will be kept as low as possible. There will potentially be fast discharges of the magnetic energy stored in the coils. These cannot be simply excluded so the tokamak should be designed to withstand a number of such events and instrumented to gather quantitative data on their effects. Such data can be effectively collected by accelerometers measuring parameters of EM-induced vibrations and movements.

Considerations for the Individual Systems

In this section the requirements for the instruments under each of the headings in the list above will be considered in detail.

1. Vacuum vessel component integrity

The instrumentation needed to assure safe, reliable and long-lasting operation of the tokamak will depend very strongly on the final design of the device. For this section, the design shown in fig. 1 has been chosen. It should be clear that measurements of movement, expansion, strain and temperature will be necessary for all configurations with possibly different specifications. Instruments will have to respond on the time scale of disruptions of the plasma[5,6].

The main vacuum vessel consists of a large shell with very large outside ports allowing access for the structural rings carrying the blanket modules, first wall sections and the divertors and the feedback coils. Penetrations in the port covers (doors), and associated shielding and blankets will allow access for plasma diagnostics, fueling and heating for the plasma and remote maintenance actuators. The vessel is a welded structure made up of sixteen sectors. The design of the structural rings is such that under operating conditions there will be minimal gaps between neighboring pieces of the first wall. The sixteen structural rings brought into the vessel through the large access ports will rest on the lower part of the vacuum vessel.

In this section, the operational measurements of the first wall, divertor and blankets are not considered (see in other sections). Only those of the support structures and the vacuum closure are presented.

A great deal of effort has gone into determining the instrumentation for the ITER vacuum vessel[7]. While its design structure is significantly different from that of FNSF, much of the necessary instrumenting of the vessel will be the same. The FNSF design concept makes the need for temperature control and monitoring of the forces on the vacuum vessel less than for ITER so fewer detectors are suggested. Table 1 provides the list of instruments. No concept for leak checking other than at the main port vacuum seal is considered.

The vacuum vessel will certainly be classified as a Safety Important Component.

Some shielding will be required in the neck of the large ports to prevent neutron streaming. Shield blocks will be mounted off the vacuum vessel doors. It is assumed that these blocks are very simple metallic structures, not requiring instrumentation.

Table 1 Instrumentation for the vacuum vessel components

Location	**Type of instrument**	**Number of detectors/actuators**
Vacuum vessel shell	Strain gauges	64 on bottom flat
		64 on remainder
	Displacement sensors	32
	Accelerometers	16
	Temperature monitors	128
	Helium flow	8
(16) Shield blocks	Displacement sensors	1
	Accelerometer	1
	Temperature monitors	4
(16) Vacuum Vessel Supports	Accelerometer	1
(16) Vacuum vessel “doors”	Leakage in main seal	1
	Accelerometer	1

From table 1, ~ 460 instruments with cabling and feedthroughs in the cryostat are considered to be necessary. There will be many more feedthroughs and vacuum pipes and windows built into the “doors” bringing power, fluids and monitoring to the many systems within the vacuum vessel; their number will be considered later.

2. Low temperature shield

A low temperature shield filled with a gas or liquid coolant is necessary to control the heat reaching the coils both during the plasma operation, bake-out and during the after-heat due to the nuclear products. This shield will be closely attached to the vacuum vessel and therefore only needs monitoring of the coolant flow. The shield is assumed to be made up of four sections. There will also be sections filling unused space in the large ports. The necessary instrumentation is shown in table 2.

Table 2 Instrumentation for the thermal shields.

Location	Type of Instrument	Number of detectors
(4) Main shield sectors	1 coolant flow monitor	4
	1 temperature sensor	4
(16) port shield units	1 coolant flow monitor	16
	1 temperature sensor	16

About 40 instruments will be needed.

3. Magnetic field coils and cryostat

3.1 Toroidal, central solenoid and poloidal field coils and correction coils inside the cryostat

The toroidal, central solenoid and poloidal field coils and the field correction coils will be superconducting and will be housed in a cryostat surrounding the vacuum vessel, similar to the design of ARIES ACT-2[9]. The conductors will probably be high-temperature superconductors but the necessary instrumentation will not be significantly different in concept if low temperature superconductors were to be used. During operation the coils will experience a complex 3-D loading including tension and bending of coil cases, and wedge-compression of TF coil noses. Fast electromagnetic events cause additional pulsed EM loads which may generate some vibrations of all coils (called EM-induced inertial loads). Because of the relatively few temperature cycles in the whole life of FNSF, the fatigue consideration for coil cases will be associated mostly with the cyclic component of the EM loads. Variation of the global EM loads during a plasma pulse is predictable from simulation codes, but strain and displacement sensors are necessary to

Table 3.1 Instrumentation for the magnetic field coils inside the cryostat

Location	Type of instrument	Number of detectors/actuators
(16) Toroidal field coils	Temperature monitors	4
	Displacement sensors	4
	Accelerometer	1
	Resistive strain gauges	8
Neutron monitors	Fission chambers for flux	4
	Activation detectors for fluence	4
Central solenoid	Temperature monitors	16
	Displacement sensors	16
	Resistive strain gauges	8
(14) Poloidal field coils	Temperature monitors	2
	Displacement sensors	4
	Accelerometer	1
	Resistive strain gauges	2
(4) Field correction coils	Displacement sensors	4
	Accelerometer	1

monitor specific uneven redistribution of interface loads associated with realistic tolerances in joints and links between various coils and in the magnet supports. ITER designers have developed a detailed plan of the instrumentation to be installed on its coils and cryostat[10.11]. Table 3.1 indicates the proposed instrumentation for FNSF.

From table 3.1, ~ 470 instruments with cabling and feedthroughs in the cryostat will be necessary.

2.2 Feedback Coils inside the Vacuum Vessel

Presently coils to provide feedback for vertical position control are shown in the design but it is probable that resistive wall mode (RWM) coils and ELM-suppression coils will be required. All these coils will require effectively continuous conductors toroidally but made up of saddle coils mounted identically in every sector. These are likely to be single or several turn insulated copper of fairly large cross-section. They will be instrumented occasionally for temperature and movement. Where the leads penetrate the vacuum port cover there will be an especially engineered double vacuum seal. Table 3.2 suggests the instrumentation for the possible set of coils. The benefits of these coils are the subject of research on present-day devices so that the need for all the coils is not yet fully determined.

The number of these coils is not yet known but the total of in-vessel coils is not likely to be much different from that shown in table 3.2.

Table 3.2 Instrumentation for the vertical position control coils

Location	Type of Instrument	Number of detectors/actuators
(16) Position saddle coils	Temperature monitors	4
	Strain gauge	4
	Accelerometer	1
(16) RWM coils	Temperature monitors	4
	Strain gauge	4
	Accelerometer	1
(16) ELM-suppression coils	Temperature monitors	4
	Strain gauge	4
	Accelerometer	1

From table 3.2, ~ 430 instruments will probably be required with ~96 multiwire cable feedthroughs in the vacuum vessel "doors".

4.Structural rings supporting the blankets, first wall and control coils

The materials surrounding the plasma - blankets, first wall, divertor(s) and control coils - will be supported by sixteen structural rings. These rings will be mounted on the vacuum vessel held in place by an, as yet, undefined method. Each ring supports two blanket sectors with their first-wall attachments and the control coils. Since occasional fast EM events cannot be excluded, the rings will be instrumented for detection of resultant EM torques and associated vibrations. The combined effects of these two can be monitored by a combination of accelerometers, strain gauges and displacement sensors shown in table 4.

In this section, the operational measurements of the first wall, divertor and blankets are not considered (see in other sections). Only those of the supporting ring structures are considered. The rings should have no direct mutual electrical contacts and hence there should be no toroidally closed eddy currents in them. However for fast EM events and discharges of coil magnetic energy there will be eddy current loops within each ring creating EM torques.

Table 4 Instrumentation/cabling for the structural rings

Location	Type of Instrument	Number of detectors/actuators
(16) Stuctural rings	Resistive strain gauges	4
	Temperature monitors	4
	Displacement sensors	4
	Accelerometer	1
	Rogowski loops	1

Table 4 indicates a need for ~ 220 instruments with their necessary cabling and vacuum feedthroughs.

5. First Wall and Divertor Measurement and Monitoring

The components of the plasma-facing first wall and upper and lower divertors are key elements in the FNSF program. Demonstration of materials to withstand the concurrent temperatures, magnetic forces, neutron bombardment, and hydrogenic species deposition is one of the goals of the device. Their environment will be significantly harsher than that which has been available in present-day devices or in ITER. The materials, and to some extent the detailed design, of the first wall and divertors might be changed a few times in the life of the device.

The concept of the sector design is that under the operational temperatures the first wall and the divertor will be almost continuous. This will require that the sectors are very closely aligned: it is assumed that the alignments are assured by very detailed pre-installation preparation of each sector. Necessary instrumentation for the installed components is shown in table 5.

Erosion (and, to some extent, redeposition) of the first wall and divertor material will be a major concern. Presently this measurement is covered by plasma diagnostics where a speculative holographic or interferometric technique will be incorporated into the viewing systems. But note that it will not be possible to provide observation of more than a fraction of the surfaces.

Mirnov coils, probably mounted on the back of first wall tiles are included in the plasma diagnostic scope. The risk associated with mounting of Langmuir probes and their expected very short life preclude their use for measuring plasma edge densities, temperatures and flows close to the first wall. Thermocouples will almost certainly be used for temperature measurement though an optical system has recently been used on WEST[12].

The gas pressure and helium content of the gas in the divertor as well as the assessment of dust gathered behind the divertors are addressed under plasma diagnostics.

Table 5 Instrumentation for the first wall and divertor measurement and monitoring

Location	Type of Instrument	Number of detectors/actuators
(16) first-wall halo current monitors per sector	Rogowski coils	8
(16) first-wall temperature monitors per sector	Temperature monitors	8
(16) Outer and inner cooling gas flows	Flow gauges outside sector	2
	Input/output temperature gauges	2
(16) upper and lower divertor halo current monitors	Rogowski coils	2
(16) upper and lower divertor temperature monitors	Temperature monitors	16
(16) Upper & lower divertor gas flows	Flow gauges outside sector	2
	Input/output temperature gauges	2

A total of 672 instruments is suggested.

6. Tritium Blanket Instrumentation

A next-step device, such as FNSF, must be self-sufficient in tritium and will also be the principal experiment to demonstrate breeding performance. Hence precise measurement of the blanket performance will be essential. But also tests of different blanket configurations will be expected during the life of the device.

It has been assumed that every module of the tritium blanket system mounted on the tokamak will have the full complement of instrumentation required to determine exactly how they perform. For the earlier part of the FNSF operation, initial performance will be demonstrated, problems can be identified and resolved and new design criteria created. For the latter part of the operation, many of the modules will be identical, confidence in the results will be assured and, to some extent, there will be redundancy for failed instruments. Table 6 identifies instrumentation required within, or close to, the tokamak boundary. As for the other systems, only a fraction of each instrument will be in the high-radiation environment; it will be connected by cable to the final data-handling component in a facility outside the biological shield. The instrumentation in the tritium processing facility is not included in this assessment.

Three types of measurement are to be expected to control and monitor the blankets' performance.

a) Time-dependent neutron measurements at a few locations within the instrumented blanket modules.

b) Temperature monitoring at several locations within the blankets (measurements in the first wall have already been considered).

c) Fluid flow velocity of the two tritium breeding fluids and the helium coolant at several locations in the blankets including at the inlet and outlet manifolds.

There will be 16 sectors each carrying two blanket modules, an inboard (IB) and an outboard (OB) one. The 16 inboard modules should be identical but there will be some differences in the outboard modules to accommodate a variety of penetrations. There will also be a capability for small test blankets to go inside penetrations. The latters' internal structures, and materials may be significantly different from those in the main blankets but the same basic measurement needs have been assumed. Some measurements, such as the internal flow velocities, may be reduced in number by detailed experimental testing of module prototypes in the laboratory. Table 6 gathers the proposed instrumentation. The proposed FNSF blankets are described in reference 13 and the instrumentation for ITER blankets is discussed in references 14. 15 and 16.

Table 6 Instrumentation for the tritium blankets

Location	Type of Instrument	Number of detectors/actuators
(16) Inboard blankets	Neutron flux	8
	Temperature monitors	8
	(2) Fluids flow	8
	Helium cooling flow	1
(16) Outboard blankets	Neutron flux	8
	Temperature monitors	8
	(2) Fluids flow	8
	Helium cooling flow	1
(3) Test blanket modules	Neutron flux	4
	Temperature monitors	4
	(2) Fluids flow	4
(35) 2 input, 2 output pipes from tritium facility to blanket modules	Heaters and temperature monitors	4

From the table, 1232 instruments, plus the necessary monitoring of the vacuum seals at the fluid pipes and electrical feedthroughs, are required around the tokamak for the instruments to control and monitor the behavior of the blanket modules. These cables will pass through the shield wall to electronics to register and control the blanket performance.

It has been assumed that real-time measurements of corrosion products are not necessary for each blanket module, but they will be monitored for the overall system in the tritium processing facility.

Note that it has been assumed that the stabilizing shells and kink shells are mounted securely to the walls of the shield modules and so do not require independent monitoring.

7. Auxiliary Heating Systems

Three types of auxiliary heating and current drive. at the level of a few hundred megawatts are being considered for FNSF. Electron cyclotron heating (ECH) will be useful for heating electrons, controlling the temperature profile and possibly instability modes in the plasma. Ion cyclotron and lower hybrid range frequency heating (ICRF) will be used for heating the ions. Neutral beams are proposed for heating, and driving current in, the plasma. While unattractive because of the large aperture sizes necessary for their access to the plasma which reduces the space for blankets and eases escape of neutrons, and are difficult to implement within the FNSF concept, neutral beams have been proven to provide the most effective heating in present-day devices. Hence all three systems must be considered.

7.1 Instrumentation for the ECH System in the Torus Hall

High frequency electron cyclotron heating will be used for heating the electrons and controlling instabilities in FNSF. Physics studies in precursor devices should better determine how the ECH system will be used, but it will involve steerable antennae inside the vacuum vessel and long transmission lines. Because of the high power required for considerable lengths of time and inevitable power losses the transmission lines will require extensive cooling and temperature control[17].

The heating system will not be fully defined until the tokamak is in design, so it has been assumed that the system will be similar to the ITER system[18,19], though it may be even

Table 7.1: Instrumentation on and close to the tokamak in support of the ECH heating system.

	Component	Number of Detectors/actuators
(6) ECH launchers	Temperature monitor	1†
	Angular actuator	1
	Angular measurement	1
	Vacuum window monitor	1
(6) Isolation valves	2 per line, each with pumping	4
(12) Transmission line vacuum control	Vacuum pumping for each line	2
	Pumps/pressure monitors	2
	Vacuum window monitor	4
(12) Transmission line temperature control	Heater systems	3*
	Temperature controller	3*

† It is assumed that the temperatures of the plasma-facing launcher components are monitored by the plasma diagnostics' infra-red monitoring systems.

* Includes 2 miter-bends per line.

more complex. The present high number of transmission lines is dictated by the limited power of the sources and matching issues into the lines. However, one must expect needs for a) control and monitoring of actuators of all variable-direction ECH launchers, b) double vacuum windows, c) ECH transmission line vacuum control, d) temperature control of transmission line precision and mode purity.

Some 216 measurements are required. For the transmission lines the locations of some of the "front-end" detectors may be in a reduced radiation environment.

7.2 Instrumentation for the ICRF Heating System in the Torus Hall

ICRF Heating is considered to be the preferred plasma heating technique for FNSF. Unfortunately very little effort has gone into the design of antennas for such a tokamak so that the required number of connections and measurements is not at all certain. Also the full definition of the heating systems and their power requirements awaits the final machine design. Hence it has been assumed that the system will be similar to the ITER system[19] with enhanced operational times, and the potential instrumentation is shown in table 7.2.

Table 7.2: Instrumentation on and close to the tokamak in support of the ICRF heating system.

	Component	Number of Detectors/actuators
(2) RF launchers	Temperature distribution	12†
	Voltage measurements	12
	Current measurements	12
	Arc detection in the antennae	1
	Location and movement control	1
(4)Transmission line vacuum control	Pumps/pressure monitors	4
(2) Reflectometer for edge plasma density	Reflectometers*	2

† It is assumed the temperature measurement of the plasma-facing antenna components by infra-red optics is covered by the plasma diagnostics.
* May be part of plasma diagnostics.

Approximately 96 measurements and actuators are required. Some of the transmission-line instruments may be outside the high-radiation zones.

7.3 Neutral Beam Heating and Current Drive System

Because of the large aperture in the shield wall required for access of a neutral beam to the plasma, the beamlines will have to be enclosed in thick shielding for protection of the coils in the cryostat and, to some extent, of their own internal components from the neutron radiation. This shielding will be integrated with the main shield wall of the facility. For a power level of 100 MW or so two negative-ion beamlines are likely. All vacuum, electrical and cooling interfaces will be within the beamline enclosures.

The measurements required for controlling the heating and current drive are assumed to be similar to those planned for ITER[20]. They are shown in table 7.3. Many fewer thermocouples are proposed here than for ITER because of the experience gained by operating the more experimental beamlines on ITER. The actual number will depend on the final design and number of swirl tubes involved in the cooling. It has been assumed that no aligning of the beamline will be required to change current drive properties. Also it has been assumed that the source and accelerator grids will be installed as a unit and will be checked for alignment before installation. With the negative ion beam there is no

Table 7.3: Instrumentation in the Neutral Beam Boxes.

	Component	Number of Detectors/actuators
(2) Cs Oven	Temperature monitor	4
	Cs vapor pressure gauge	1
(2) RF Source	Filament current monitor	4
	Plasma grid temperature monitor	4
	Gas pressure	1
	D & T fueling lines	2
	Water flow monitor	2
	Local magnetic field monitor	2
(2) Source/neutralizer interface region	Local magnetic field monitor	2
(2) Electron dump	Temperature monitor	2
	Water flow monitor	1
(2) Neutralizer	D fueling line	1
	Gas pressure monitor	1
	Temperature monitor	8
(2) Residual ion dump (RID)	Temperature monitor	2
	Water flow monitor	1
	Local magnetic field monitors	2
(2) Before baffle	Gas pressure monitor	1
(2) After baffle	Gas pressure monitor	1
(2) Calorimeter	Temperature monitor	8
	Water flows	8
(2) Exit scraper	Temperature monitor	4
	Water flow monitor	4
(2) Fast shutter	Position monitor	1
	Water flows	2
	Temperature monitor	2
(2) Vacuum box	Residual gas analyzer	1
(2) Drift duct liners	Water flow monito	4
	Temperature monitors	4

requirement for monitoring the beam content and velocity by an optical technique so no windows are provided.

About 154 instruments and 6 gas-feeding lines are necessary. While all of these are inside the neutral beam box shielded area they must be provided with vacuum feedthroughs with the necessary monitoring for vacuum/tritium leaks to protect the tokamak vacuum integrity.

8. Fueling systems

Two different fueling techniques will be used, gas injection and pellet injection.

8.1 Instrumentation for the Gas Feed Systems

There are three very different requirements for injecting gases into the tokamak:

a) Control of injection of main fueling gases.
b) Control of injection of impurity gases in the divertor regions.
c) Control of massive gas injection for disruption mitigation.

There will be independent supply lines for deuterium and tritium to permit variable fueling of each during a plasma pulse. The gas quantity requirements may be very different for a device with liquid metal walls or divertor but the control instrumentation will be little different. There will be two supply lines into each divertor to permit different gases to provide the detachment capability for plasma operation (and also possibly for plasma diagnostic purposes). The supply line for massive gas injections to mitigate disruptions will need very fast response provided by a valve very close to the plasma. An assessment of the instrumentation needs is given in table 8.1.

The number of valves shown is the minimum possible but gas conduction issues around the tokamak, particularly behind the divertor, may require injection at more locations. For good control of the gas flows the 7 monitored valves, and the necessary pressure gauges, will have to be relatively close, immediately outside the cryostat.

Table 8.1: Instrumentation on and close to the tokamak in support of the gas injection system

	Component	Number of Detectors/actuators
D & T fueling lines	2 valved pipes	2
(2) 2 Divertor gas lines	2 valved pipes	4
Massive gas injection lines	Pipe with fast valve	1

8.2 Instrumentation for the Pellet Injection System (PIS)

The pellet injection system (PIS) has three principal functions:

a) Fueling of the plasma,
b) Fueling of the plasma edge to control ELMs,

c) Providing impurities for controlling radiation or in support of plasma diagnostics.

It is expected that all these functions will be contained in one injector system inside its own shielded container close outside the cryostat. Its precise location can only be determined after full design of the tokamak but it cannot be too far from the device because of timing concerns. The nearest approximation to a system for FNSF is contained in the concept proposed for ITER[21].

Three gas inlet lines (for D, T and impurity gases) and one exhaust line to the main FNSF pumping system are required in addition to the injection lines going to the tokamak. The built-in microwave units for measuring the mass and velocity of the pellets, switchers for the pellet lines, refrigerator units and pellet preparation with all the electronic interfacing will all be contained in a single containment chamber.

Table 8.2: Instrumentation close to the tokamak in support of the pellet injection system.

	Component	Number of Detectors/actuators
D pellet-fueling line	2* Gate valve	1 at tokamak, 1 in PIS
T pellet-fueling line	2* Gate valve	1 at tokamak, 1 in PIS
(3) Impurity fueling lines	2 Gate valves	1 at tokamak, 1 in PIS
Exhaust vacuum line	Gate valve	In PIS
(5) Refrigerator units	Temperature monitor	1 in PIS
	Coolant pump	1 in PIS
(5) Switchers for injector lines	Position drive and monitor	2 in PIS
(5) Pellet preparation controls	Temperature monitor, cutter monitor	2 in PIS
(5) Microwave units	Microwave power control and monitor	2 in PIS

* Assumes that both inboard and outboard pellet fueling injection are not required.

9. Operational Instrumentation of Plasma Diagnostics

A very complex array of instrumentation is required for the understanding and control of the plasma in FNSF. Its interfacing with the tokamak involves many different requirements. Capability for signal penetration without compromising shielding, capability for calibration, capability for changing sightlines, ability to tolerate bake-out temperatures, ability to tolerate high neutron fluxes are examples. The operational history of FNSF[3] requires that initially there is a full scope of plasma diagnostics, comparable to the most instrumented of currently operating devices and ITER, to enable extrapolation of the physics from predecessor devices to full control of the burning plasma in the engineering phase of operation of FNSF. A very reduced set will be used for the last-named phase to permit the necessary wall coverage of tritium-generating blankets and demonstrate the likely complement for a reactor.

Ensuring the operation of the diagnostics requires a lot of instrumentation on or close to the tokamak and that will be described here, noting that it will be at a maximum for the first day of operation of FNSF and after a few years it will be greatly reduced.

Many diagnostic detectors, notably the magnetic diagnostics, will be inside the vacuum vessel. Four types of infrastructure are to be expected for the other plasma diagnostics:

a) Many shutters and actuators and their monitors necessary for operating and protecting components and for performing calibrations.
b) Many double vacuum windows requiring pumping and monitoring.
c) Capability for controlling the temperature of some diagnostic components, particularly during bakeout of the tokamak.
d) At least one technique for cleaning mirrors, possibly by RF.

These in-vessel components will obviously be connected to the outside world through complex vacuum feedthroughs.

Table 9.1: Instrumentation on the tokamak in support of the plasma diagnostics for the first phase of operation of FNSF

Plasma Diagnostic	Component	Number of detectors/actuators
Magnetic Diagnostics	Various coils	90 (29 feedthroughs)
Optical, UV, IR & X-ray diagnostics (including labyrinths with mirrors)	In-vessel detectors	43 (13 feedthroughs)
	Vacuum windows	51
	Mirror location control	48 (19 feedthroughs)
	Mirror heating/cooling	36 (7 feedthroughs)
	Temperature monitor/control	24 (14 feedthroughs)
	RF mirror cleaning	34 (26 feedthroughs)
	Shutters/modulators	20 (8 feedthroughs)
	Calibration source controls	8 (8 feedthroughs)
Microwave diagnostics	Vacuum windows	26
	Mirror/alignment control	5 (3 feedthroughs)
	Mirror heating/cooling	3 (1 feedthrough)
	Hot source drive and control	2 (2 feedthroughs)
Fusion product diagnostics	In-vessel detectors	4 (4 feedthroughs)
	Inside-bioshield detectors	20 (20 feedthroughs)
	Calibration source control	2 (2 feedthroughs)
	Activation sample pipes	6
	Location monitors	6 (6 feedthroughs)
Particle diagnostics	Dust collectors	4 (4 feedthroughs)
	Penning gauges	4 (4 feedthroughs)
	Ion gauges	4 (4 feedthroughs)
	Residual gas analyzers	2 (2 feedthroughs)
To be determined	J-profile diagnostic	4 (4 feedthroughs)
	He-in-core diagnostic	4 (4 feedthroughs)

It is not yet possible to allocate diagnostics to specific locations on the tokamak. They will be mounted on the 16 sectors, most at the midplane but some near the two divertors. The proposed list of diagnostics at the start of operation of FNSF is taken from Appendix 1 of the FNSF Pathways Assessment[22] for the measurement techniques specified in reference 23. The necessary plasma diagnostics and the challenges in their implementation on ITER and future devices are described in references 24 – 26. Table 9.1 is a first cut at showing a very simplified assessment of the supporting components for the plasma measurements inside the tokamak shield wall. For the table it has been assumed that there will be heating neutral beams installed on the device enabling such diagnostics as the charge exchange recombination spectroscopy and motional Stark effect to function. If these beams are not available, new techniques for carrying out the measurements will have to be developed.

Since none of the plasma diagnostics, nor the tokamak itself, have been designed yet, there is a lot of informed guesswork in assessing the number of windows and feedthroughs that will be involved. However it is believed that the sum totals will be a reasonable assessment for the interfacing to be considered for operational and remote handling requirements. Some might argue that the complex double windows and electrical feedthroughs necessary for full tritium operation might not be necessary for the earliest operational phases, but it is likely that most of this inventory of diagnostics will be necessary for the first burning plasma operation.

Table 9.2; Instrumentation on the tokamak in support of the plasma diagnostics during D-T operation.

Plasma Diagnostic	Component	Number of detectors/actuators
Magnetic Diagnostics	Various coils	90 (29 feedthroughs)
Optical, UV, IR & X-ray diagnostics (including labyrinths with mirrors)	In-vessel detectors	4 (4 feedthroughs)
	Vacuum windows	17
	Mirror location control	7 (3 feedthroughs)
	Mirror heating/cooling	5 (1 feedthrough)
	Temperature monitor/control	9 (4 feedthroughs)
	RF mirror cleaning	9 (4 feedthroughs)
	Shutters/modulators	1 (1 feedthrough)
Microwave diagnostics	Vacuum windows	5
	Mirror/alignment control	3 (1 feedthrough)
	Hot source drive and control	2 (2 feedthroughs)
Fusion product diagnostics	Detectors	8 (4 feedthroughs)
	5 sightlines	5 (5 feedthroughs)
	Vacuum windows	5
Particle diagnostics	Ion gauges	4 (4 feedthroughs)
	Residual gas analyzers	2 (4 feedthroughs)
	Penning gauges	4 (4 feedthroughs)
To be determined	J-profile diagnostic	4 (4 feedthroughs)
	He-in-core diagnostic	4 (4 feedthroughs)

A total number of instruments ~340 (including magnetics because of the necessary vacuum feedthroughs) will be used. About 20 shutters and actuators and about 16 temperature control monitors will all be necessary. Cleaning of mirror surfaces will probably be needed for 8 mirrors; these might require local microwave discharges. By integrating wiring from many different diagnostics into one electrical feedthrough the number of electrical feedthroughs, of a wide variety of specifications, can be reduced to about 160. About 100 vacuum windows and plumbing connections, again with a wide range of specifications, will be necessary.

Note that some allowance has been made for trial and implementation of new plasma diagnostic techniques thought to be necessary to replace diagnostics that cannot work under FNSF burning plasma conditions. The possibility of techniques for measuring current density distribution and for quantifying the helium ash in the core plasma are included.

Because it will be essential to reduce the amount of space allocated to plasma diagnostics to enhance the wall space available for tritium breeding, a major aspect of the early operational phases of FNSF will be the reduction of the diagnostics inventory to the minimum necessary for controlling the plasma and for protecting the device. Hopefully the detector inventory can be reduced to the minimum suggested by Young[27]. In that case the required instrumentation requirements can be shown in table 9.2. It is anticipated that the reduction in diagnostics from the set shown in table 9.1 to that shown in table 9.2 will occur gradually during the first years of FNSF operation as knowledge of the plasmas' properties, the detailed definition of its operational modes and the requirements for plasma control improves.

All the components of the instrumentation are reduced to ~ 188 in number. The very much reduced number of feedthroughs (~60) and vacuum windows (~30) is clear. Resolution of the complexities of their integration with the new connections from new blanket modules has to await the detailed design of the systems.

10. In-vessel inspection and preparation for remote maintenance

The pulse length in FNSF will be much longer at higher power than in any predecessor device. The activation of the materials inside the vacuum vessel will be very high so that there will be an intense flux of gammas present at any time after operation. Nevertheless it will be essential to be able to monitor the state of the full coverage of plasma facing components occasionally in support of the plasma diagnostics' monitoring cameras. These diagnostics' cameras will detect optical events in the plasma and provide visual monitoring of a fraction (~50%?) of the first wall between discharges but will not provide visual inspection of all first wall components without vacuum intrusion into the vessel. Long arms or robots carrying remote inspection technology will have to be introduced into the vessel and deployed around the tokamak. The present design concept of FNSF precludes their being permanently mounted on the ports so that their installation and replacement will extend maintenance periods significantly, so markedly affecting the up-time for operation of the device.

The inspection arms will require a) high quality lighting and optics to operate in high γ-radiation background to give precise location information, and b) robotic motors and transducers to operate in the high γ-radiation background. Some impact studies have already been started in Europe[28]. Table 10 indicates some requirements of their instrumentation. About 40 instrument components are required.

Table 10. Instrumentation for remote inspection of the first wall components.

	Component	Number of Detectors/actuators
(2) Remote inspection arms	Optical focusing motors	2
	Lights	4
	Arm-angle motors	3
	Arm-angle monitors	3
	Main motor drive	1
	Elbow locators	6
	Gamma radiation monitor	1

Number of penetrations in the vacuum vessel doors

Without definitive designs of all the systems and how they are integrated into the structure of the tokamak, it is impossible to assess the exact number of penetrations in the vacuum vessel doors and the shield blocks. Of the order of 500 is suggested from the tables in the previous section. They will all require vacuum seal monitoring for the vacuum vessel integrity and for tritium leakage. There will also be holes in the cryostat walls to provide for the monitoring of the coils' performance and of the vacuum vessel.

Concerns and Conclusions

If one simply adds up the number of instruments required (~4250), with all their interfaces with the vacuum vessel or the cryostat, it is clear that this somewhat neglected requirement has a significant impact on the engineering of the next-step device and requires urgent attention. This number was assessed for a specific tokamak concept but it is unlikely to be very different for a similar relevant device where the final engineering qualifications are to be made for a fusion reactor. The number is comparable to that of the instruments currently being planned and implemented for ITER. In addition to the implementation at the tokamak, handling the data to make it available quickly for control purposes will require very extensive manipulation in the computer system[29].

While this number appears to be very large, the authors consider it to be consistent with monitoring such a complex device with its necessarily strong forces and extreme environmental conditions, and the need to obtain accurate engineering data in preparation for a fusion reactor.

One must consider the impact that such a large number of instruments could have on the device. At the least, the operational integrity of the device will be threatened through the necessary additional penetrations and possibility of vacuum leaks or electrical shorting or grounding associated with so many instruments. The engineering operational phase on ITER will help to quantify the need for the instrumentation but that may not be timely for the FNSF completion.

Reducing the number of instruments is obviously desirable. Those involved in the engineering tests of the first-wall, blanket, fueling and heating systems, and in the monitoring and operation of the coils and plasma diagnostics will be essential. But some of the measurements of the structures, the vacuum vessel, cryostat and coil casings could be reduced. But to be able to do so would require that sufficient engineering margins were built into the design, probably requiring greater material thicknesses. It is even possible that a very different design concept for the device could be chosen to minimize the number of intrusive measurements.

But note that we have left aside the issue of the requirement for redundant instrumentation. For example it is almost certain that asymmetric forces on the vacuum vessel and the inevitable lack of symmetries will require significant duplication, thus adding significantly to the count of instruments. Space must therefore be assigned for access for potential additional measurements in the design of the device.

It is also true that little of the present-day instrumentation will survive for very long in the tokamak's environment or will operate satisfactorily in the radiation fluxes. The radiation and thermal environment will be such that extensive development programs should soon be under way because of the length of time required for development and qualification of instruments. There is also the challenge for these instruments of maintaining calibration or being recalibrated. Built-in recalibration techniques will add complexity. Some deterioration of instruments under irradiation should be expected. The very long operational periods without any maintenance periods set very high demands on durability and reliability for all the equipment.

Successful demonstration of the instrumentation, and the knowledge gained about the different forces and loads on this device, will enable a considerable reduction in the number of instruments required in a fusion reactor. The operational experience of the device, learning to avoid hazardous events, will also help to reduce the need for a lot of monitoring. The reactor will still require many instruments but their impact on the security of the device will be much smaller.

There will be significant overlap of the type of instrumentation needed for the different tokamak components. The complexity and special properties required for the environment demand a strong oversight of developments and implementation into the final design of the tokamak. There will be a need for understanding the role of redundant instruments and applying them suitably. Hence there should be a single management group for the whole scope rather than distributing it among the engineers of the major systems. Such an organization should also ensure that sufficient access is allowed for this instrumentation during the design phase of the device. Past experience suggests that the instrumentation has been treated as an afterthought rather than as a key component in the device operation.

This assessment arose from concerns raised during the preparation of the FNSF Pathways Assessment in 2012[22] when it was clear that the engineers working on different components of the tokamak had not considered any aspects of monitoring their performance. This has been a very preliminary study and a much deeper evaluation is required when the real device is in design.

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