FUSION REACTOR INSTRUMENTATION

At the present stage of development in the worldwide fusion program, the device with the highest promise for providing a power-producing fusion reactor is the tokamak (see FUSION PLASMAS). Significant levels of power and energy have been achieved recently in the Tokamak Fusion Test Reactor (TFTR) (1) and in the Joint European Tokamak (JET) (2) tokamaks, and many critical design studies have been carried out for extrapolation from present-day tokamaks to the ultimate reactor. A major international design program is in progress now for designing a large tokamak, International Thermonuclear Engineering Reactor (ITER), to provide the full capability of a self-sustaining "burning" plasma and testing of necessary technology such as power-generating and tritium-breeding blankets. While the development of other concepts using magnetic confinement techniques are showing good progress, many aspects of their plasma measurements are similar to those used on tokamaks, and extrapolation of these measurements to a reactor will follow a similar path. The requirements of instrumentation for inertially confined plasmas using high-power pulsed lasers or beams of heavy particles, another potential route to a fusion reactor, are quite different because of the very short pulses and very localized reaction volume, and they will not be described here. Our concentration will be on the instrumentation necessary to maintain a steady-state burning plasma at the core of a power-producing reactor (see FUSION REACTORS).

The instrumentation for ITER must fulfill the needs of scientists aiming to achieve the full physics understanding of the plasma behavior while creating very long plasma pulses; the design specifications call for about 20 min. Hence the instrumentation set must be capable of giving very detailed physics information about the plasma behavior, but also much of it must be integrated into the automatic control system for maintaining the performance for these long periods. The expectation must be that the instrumentation required for a final thermonuclear reactor will be much simpler, partially because the developmental physics issues will have been fully explored but also because the plasma parameters key to providing necessary control information will have been identified. Since the optimal mode of operation of the plasmas in the tokamak for long-term stable behavior has not yet been determined, the actual instrumentation cannot be defined too tightly and we will therefore consider here the instrumentation being conceived for the ITER device, and other tokamaks under design now, as being able to illustrate the requirements and implementation of the reactor.

We will first address the requirements for instrumentation for these tokamak devices and, in particular, what role it is expected to play in the control of the plasma performance. Some of the techniques used in these diagnostic measurements will then be described briefly to illustrate some of the design and integration challenges to be overcome for achieving the necessary quality of measurement for an active control system. For a detailed physics understanding of the measurements, the reader is referred to Refs. 3–5. No attempt will be made to address issues of the instrumenting of relatively conventional parts of a fusion reactor such as the electrical generation or of the plasma-surrounding blanket modules for breeding tritium and converting neutron energy into thermal energy, assuming the type of deuterium–tritium (D–T) burning plasma expected to be exploited first. The temperature measurements, neutron measurements, and flow measurements are expected to be conventional, at least in concept. After describing the plasma diagnostic techniques, some of the developments necessary for some techniques and demonstrations of the viability of other techniques will be described. The very serious aspect of achieving industrial-quality instrumentation with its reliability and durability from the set of sophisticated scientific instruments described will not be addressed here but is clearly an essential element in achieving an effective fusion reactor.

MEASUREMENTS FOR CONTROL OF THE PLASMA

In describing the instrumentation for the plasma and plasma-facing first-wall of a next-step tokamak device, one can consider its main requirements under three categories: (1) to provide input for protection of the hardware inside the tokamak vacuum vessel, (2) to provide information for achieving and maintaining operation of the burning plasma at high output power, and (3) to provide the detailed data for physics understanding and optimization of the plasma performance. Some of the plasma diagnostics will participate in all three categories. The priority for providing redundancy, reliability, and maintenance will be highest for those measurements having a protective role.

Table 1 shows the parameters whose measurement is presently considered to play a necessary role in the control of a tokamak reactor. Following from the scheme developed for the ITER design (6–8), the measurements have been divided into (1) a basic control set needed to enable the device to achieve short-pulse good performance and (2) an advanced set which will provide capability for a long-time ignited-plasma operation. The combination should extrapolate fairly effec-

Table 1. Proposed Matrix of Measurements for Control

Basic Control		Advanced Control	
Control Component	Measured Parameter	Control Component	Measured Parameter
Plasma creation, shape and equilibrium control	Plasma current, poloidal flux, toroidal flux, line-averaged density	Kinetic profile control	Electron density, electron temperature, ion temperature, rotational velocity
		Current profile control	Current density distribution
Impurity content and radiated power	Spectroscopic line radiation, total radiation, visible continuum radiation	Impurity content and radiated power	Helium density (ash), total radiation profile, visible continuum profile
		MHD activity (sawteeth, ELMs, high-frequency Alfven modes)	Magnetic fluctuations, electron temperature fluctuations, electron density fluctuations,
Operational issues	First-wall surface temperatures, "halo" currents, $m = 2$ and locked-mode magnetic perturbations, runaway electrons, H-mode transition by H_α spectroscopy, gas pressures and composition	Operational issues	Alpha-particle loss detection, neutral density particle source, neutron fluence
Performance goals	Plasma pressure (beta), neutron flux, triton/deuteron densities in plasma core	Performance goals	Alpha-particle source profile
Divertor and edge control	Surface temperature, currents to tiles, radiated power from divertor and x-point, gas flow, gas pressure	Divertor and edge control	Edge density, radiation in divertor, heat deposition profile in divertor, electron density and temperature in divertor, radiation front position, surface erosion

tively to the required set for an operating tokamak fusion reactor. The basic control set should be considered at this time to be the set providing the protective role for the device, though it is almost certainly a larger set than will finally be required. The set does include all the diagnostics needed to start up the plasma operation. The table might need minor modification in the light of specific design attributes of the reactor.

Two things should be made very clear at this point. First, the implication of the table is that there will be very complex control algorithms required because of the interaction of the different plasma parameters and the actuators, such as disparate heating and fueling systems, which have not been addressed. The second is that while all the parameters shown in the table have been measured on existing tokamaks with very good success, only a few of the basic control parameters have been used so far in a feedback loop. Considerable technical development is necessary to demonstrate control capability on a burning-plasma device. The maintenance of the so-called reversed-shear discharges in the operating devices is leading to application of some of the advanced controls where profiles of some of the parameters are a key to a long-lasting high-performance plasma without disruptions (see FUSION PLASMAS).

Figure 1 shows a cross section of the ITER device; its dimensions should be similar to those of a reactor (9). At full power, with the plasma generating ~1.5 GW of fusion power, the plasma will have both very large stored thermal energies and magnetic energies. The plasma in a tokamak reactor must operate for long times (>1000 s) with a steady confining magnetic field provided by (1) the large toroidal coils, (2) field windings providing vertical and horizontal fields, and (3) the plasma current. In addition to the plasma heating by the current, there will also be additional heating provided by neutral particle beams or by radio-frequency power matching to the plasma particles at one of the resonant frequencies in the magnetic field, and the effectiveness of this heating must be determined. To optimize the heating and minimize energy losses, it is necessary to ensure sufficient plasma density, low impurities (non-fuel ions) so that loss of power by line radiation of impurity ions is as small as possible from the core plasma, and minimal turbulence in the plasma. The plasma must be kept away from the first wall because of very high power flows for which even short contact (≤1 s) could cause local melting of the surface. But it must achieve high power levels, determined from the flux level of neutrons for a deuterium–tritium reactor, and sustain them with control of the plasma temperatures and densities, while avoiding additional plasma losses due to turbulence. An event that can only be tolerated very rarely, because of the potential damage it could cause to first-wall components, is a disruption, a catastrophically fast loss of the plasma current and its energy. Disruptions can arise from a number of causes, such as the plasma pressure rising over a specific value related to the device parameters (Troyon limit), the plasma density exceeding a specific density value (Greenwald limit), or a growth in the magnetic turbulence, either at high plasma velocity or slowing down to "lock" and become purely growing (see, for example, Ref. 8). All these factors have to be taken into account in providing a control system for protecting the device. But there are many other requirements to optimize the performance of the plasma; these are, of course, the subject of much of the research currently in progress to advance the fusion program.

The description of plasma control in terms of measurements of the different plasma or device parameters shown in Table 1 must now be related to instrumentation techniques

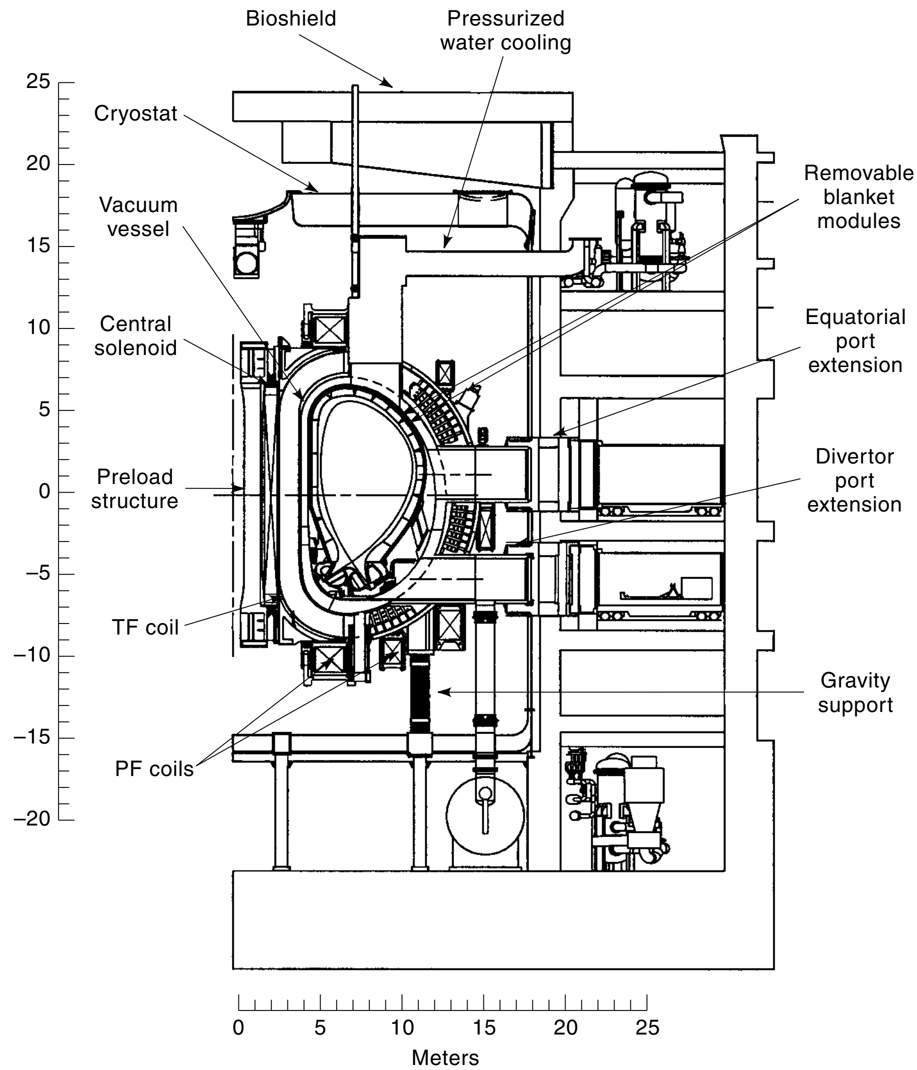

Figure 1. A poloidal cross-sectional view of the ITER device (9).

which can provide this information sufficiently quickly that it can be applied in control. Often significant analysis is required for interpreting a detector's output in terms of the physics parameter being measured. In some cases more than one measurement is needed to be able to interpret a single plasma parameter. Hence considerable fast computing power will be required in such control, but such is the advance in computer capability that this is not considered an issue for devices to be built decades from now. For experimental work on current devices, either simple permissive switching or neural network techniques are being applied, the former mostly in protective roles and the latter in trying to improve the operational performance.

Diagnostic techniques now in use for carrying out these measurements are listed in Table 2. They will be described in a little more detail in the next section. It is also necessary to consider the quality of the measurement required for the plasma control. Important issues will be the dynamic range of the measurement, the spatial resolution within the plasma, the temporal resolution, and the necessary accuracy. It has become the practice to define measurement requirements in such a way for the new tokamaks and some examples of the definitions set for ITER are shown in Table 3 (6). For these tokamaks, there is a major physics mission requiring as good as possible spatial and time resolution as well as accuracy. For some parameters, some relaxation of the requirements for control may be possible, but clearly for others, such as the neutron count rate used in controlling the operational burn of the fusion reactor, it is not.

For an effective control system, most of the time resolutions for measurement shown in Table 3 are much faster than can be applied in control, so that the requirements are dominated by the need for physicists to be able to understand the observations. The time constant for current-driving magnetic field to penetrate the steel structures surrounding the plasma could be longer than 1 s, and the current will take a similar time to penetrate to the core of the plasma. Using neutral beam particles or radio-frequency techniques to drive current, it may be possible to change the current density distribution in the plasma on a faster time-scale, perhaps as short as 100 ms. Providing raw signals directly to the control section of the computer systems, provided with appropriate interpretive and averaging algorithms, will allow the plasma to be controlled, provided also that the software includes knowledge of the response of the plasma to imposed external actuation (10). In parallel the signals will be fed to analysis areas where the physics team can develop understanding of the plasma behavior and be able to make changes to the control responses as the plasma performance develops. Thus for the generation of next-step fusion devices epitomized by ITER, physics understanding and control development will go hand-in-hand to provide the optimum performance. It is hoped that tokamak reactors beyond that stage will be able to have simpler requirements on multiple measurements for determining the necessary control and fault identification. This simpler instrumentation set will be definable after the operation of an ITER-like device.

Table 2. Plasma Measurements and Diagnostic Techniques for Plasma Control

Measured Plasma Parameter	Diagnostic Technique
Plasma current	Magnetic Rogowski coil
Plasma position and shape	Magnetic flux loops
Line-averaged electron density	Interferometer
Spectroscopic line radiation	Spectroscpic impurity monitors
Radiated power	Bolometers
Visible continuum radiation, H-mode transition	Filter spectroscopy
First-wall/divertor surface temperatures	Infrared imaging cameras
"Halo" currents, currents to tiles	Current monitors in first-wall/ divertor structure
MHD activity and locked modes	High-frequency magnetic probes
Runaway electrons	Synchrotron radiation detectors
Neutral gas pressure, gas composition	Pressure gauges, residual gas analyzers
Plasma pressure (beta)	Diamagnetic loop
Neutron flux	Neutron flux monitors
Triton/deuteron densities	Neutral particle analysis, spectroscopy
Electron temperature profile	Thomson scattering, electron cyclotron emission
Electron density profile	Thomson scattering, interferometry, reflectometry
Ion temperature and rotational velocity	Spectroscopy, enhanced by a neutral beam
Current density profile	Motional Stark effect spectroscopy, polarimetry
Helium density (ash)	Spectroscopy, enhanced by a neutral beam
Radiated power profile (core and divertor)	Array of bolometers
Visible continuum profile	Array of filter spectroscopy
Electron temperature fluctuations	High-frequency electron cyclotron emission
Electron density fluctuations	Correlation reflectrometry
Alpha-particle loss detection	Faraday cups at wall, infrared camera
Neutral density particle source	Fast ion gauges
Neutron fluence	Activation foils
Alpha-particle source profile	Neutron camera
Edge electron density	Reflectometry
Electron density in divertor	Interferometry, Thomson scattering
Electron temperature in divertor	Thomson scattering, Langmuir probes
Radiation front position	Visible imaging, filter spectroscopy array
Surface erosion	To be determined

PLASMA MEASUREMENT TECHNIQUES CURRENTLY IN USE

In the last 10 years, there have been major advances in the quality of measurement of plasma parameters, both in number of spatial locations and in time resolution. The advances were largely the result of improvements in technology, but the need for them was largely driven by the discovery of new high-performance operating modes, the computer codes developed for modeling and predicting the plasma performance and the associated theoretical studies. This improvement in theoretical prediction of the plasma behavior and the capability for simulating the plasmas also led to the requirement to measure some additional parameters, most notably the current density distribution and fine-spatial dependent ion temperature. Some of the diagnostic methods closely related to the needs of plasma control will be described here; more detailed information, both about these techniques and about the wide range of methods used on tokamaks can be found in Refs. 4 and 11.

Magnetic Measurements

Magnetic measurements have provided most of the fundamental information for plasma control until now, giving information on the plasma current, its shape and position, and the total plasma pressure, as well as about magnetic turbulence inside the plasma (12,13). All of these measurements, except the last, require time integrals of the changing magnetic field so that for very long pulse or steady state operation some alternative technique is required.

Plasma Current. The plasma current is measured by a coil wound in a small diameter solenoid looped around the plasma in a plane normal to the current. This looped solenoid is called a Rogowski coil. The voltage measured in the solenoid is proportional to the rate of change of the magnetic flux through the solenoid. This magnetic flux is proportional to the current passing through the loop. For a fusion reactor this solenoid must be mounted inside the vacuum vessel, to provide sensitivity for rapidly changing currents. It must be made with relatively radiation-resistant ceramic insulation and it must operate into electronics capable of integrating relatively small signals for times up to 1000 s.

Plasma Position and Shape. The plasma position and shape are measured using small discrete coils distributed in the plane of the plasma minor cross section. The concept proposed for ITER is shown in Fig. 2. The coils are normally oriented with their axes nearly parallel to, or nearly perpendicular to, the field provided by the plasma current, and the external coils are provided to control the plasma current position and shape. These discrete coils are mounted on structure inside the vacuum vessel. Reconstruction magnetic codes are used to optimize the number and location of these coils with respect to the main plasma, the x-point in the flux surfaces induced in the field shaping for the divertor and in the divertor itself. The insulating materials for the coils, including that in the cabling to carry signals out to long-time integrating electronics, must operate within a radiation environment. For steady-state operation, Hall probes could be used if they can be made to withstand the radiation environment. Some new ideas in which mechanical movements induced by the mag-

Table 3. Examples of Assessment of the Target Plasma Measurement Capability for ITER (6)

Parameter	Parameter Range	Spatial Resolution	Time Resolution	Accuracy
Plasma current	0.1–28 MA	Not applicable	1 ms	1% ($I_p > 1$ MA)
Total neutron flux	10^{14}–10^{21} ns^{-1}	Integral	1 ms	10%
Neutron and α-particle source	10^{14}–4×10^{18} $ns^{-1} \cdot m^{-3}$	30 cm	1 ms	10%
Divertor surface temperature	200–2500°C	1 cm	1 ms	10%
Core electron temperature profile	0.5–30 keV[a]	10 cm	10 ms	10%
Edge electron density profile	$(0.05–3) \times 10^{20}$ m^{-3}	0.5 cm	10 ms	5%
Radiation profile in main plasma	0.01–1 $MW \cdot m^{-3}$	20 cm	10 ms	20%
Radiation profile in divertor	$\leq$100 $MW \cdot m^{-3}$	5 cm	10 ms	20%

[a] 1 keV = 1.1×10^4 K.

netic field might be coupled with the electrical measurement described above are being developed. Measurement of the density by microwave reflectometry to determine the vacuum-plasma boundary is also being considered for the position and shape measurement in ITER.

Magnetic Turbulence Measurement. Similar small coils designed for measurement of plasma-induced fluctuating magnetic fields are needed. Magnetohydrodynamic (MHD) instabilities are always observed at some level in all tokamak plasmas, with their amplitude and structure providing significant clues about the plasma performance. They are usually in the frequency range of a few tens of kilohertz; but in the presence of fast ions, such as the alpha particles created in the D–T fusion reaction, the range can be several hundred kilohertz so that the design must be suitable for high frequencies. They must be mounted close to the plasma so that eddy currents created in close-by conducting material do not reduce the high-frequency response. Because the structure of the instabilities inside the plasma must be determined, there must be many measurement locations and there are normally many coils distributed in more than one plane around the torus. The fluctuations observed by the coils are caused by the rapid movement of the instabilities inside the plasma. The instabilities should align with the magnetic field lines passing around the toroidal plasma; and their frequency, phase, and amplitude at localized measurement locations can identify specific kinds of MHD modes. The strongest impact on plasma performance is caused by low m (number of nodes in the waves measured around the minor circumference) close to the axis of the plasma. $m = 2$ modes or $m = 1$ sawteeth (so-called because of shape of the time-dependent signals observed at the coils) are of most concern, so that their presence is an indicator for a control response. Sometimes the MHD modes slow down and "lock" in position, a condition which frequently results in a catastrophic termination of the plasma, known as a disruption.

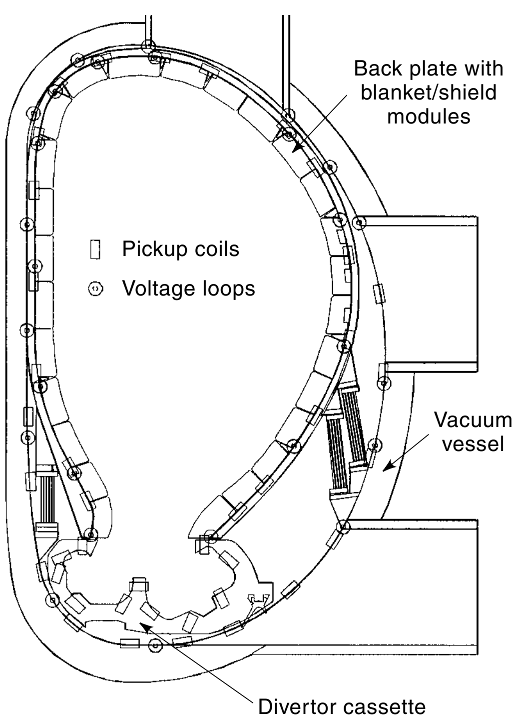

Figure 2. The distribution of magnetic detectors planned for the ITER device (8).

Plasma Pressure. The total plasma pressure can be measured from the diamagnetic effect it has in reducing the toroidal vacuum magnetic field. This effect is, at best, only a few percent even for an effective tokamak reactor, so the measurement is not easy though the concept for magnetic measurement is very simple. A complete loop of wire surrounding the plasma in the plane of the minor cross section will give a measurement of the field change. But possible misalignment or moving the coil out of this plane can give changes larger than the one being sought, so that normally ingenious compensating loops are included in the design. The measurement is crucial, because exceeding a defined value is known to cause the plasma to terminate in a disruption. While this measurement is so conceptually straightforward, it may well have to be replaced by a complex set of kinetic measurements of density and temperature combined together and integrated over space to provide the key information. In current experiments, such data are routinely compared with the "diamagnetic" pressure, but only a long time after the relevant plasma discharge.

Measurement of "Halo" Currents (14). When a discharge terminates in a disruption, the current in the plasma decreases dramatically (at a rate as great as 1×10^9 A/s) and the pressure collapses. In so doing, currents pass into the structure in the first wall which are found to be potentially large, (hundreds of kiloamps) and nonuniform. There is considerable concern that these short-lived currents, in the presence of the large steady toroidal magnetic field, will cause forces in the structure that could cause serious damage to it. The disruption process and the formation of these halo currents are subjects of urgent study and development of instrumentation to measure them. So far, small "Rogowski" coils have been placed around structural members. It is assumed for the moment that such measurement will be provided on a reactor device. No control response will be possible in the timescale of the disruption, if it should happen, but the data will enable engineers to compare the calculated forces with those used in their design.

Electron Density and Temperature

The electron density has three significant roles to play in the control system. Fueling of the plasma is clearly going to be controlled to match the required plasma densities. The sum of the electron and ion pressures, the pressure being the product of density and temperature, can be used to replace the measurement by the diamagnetic loop, particularly for long times. Minimum density levels are often necessary before noninductive power can be applied effectively, and high densities can also lead to a rapid termination of the plasma in a disruption. In the most recent successful experiments on plasma confinement in tokamaks, very low levels of energy transport have been found inside radii with very steep density gradients. There is thus a possible need for very good spatial resolution in the density measurement, though it is not presently clear how the data could be used in plasma control.

The most straightforward measurement of the density is interferometry, since the refractive index of the plasma is linearly proportional to the density over a wide range, provided that the probing wavelength is selected appropriately. For large plasmas ($r \geq 1$ m), densities in the range $\sim 10^{20}$ m^{-3}, and wavelengths from ~ 100 μm to ~ 4 mm, the far-infrared to microwave region are used. The interferometer is usually in the Michelson or Mach–Zender configuration, the former being usually favored since it does not require a long compensation leg. Several sightlines vertically through the plasma are very desirable, and unfolding techniques have been developed to arrive at density profiles of the toroidal plasma. A dual wavelength system is used so that defects due to movements of the mirrors can be corrected (15). The presence of divertors in the reactor-grade devices with intense heat loads tend to prevent many vertical lines of sight, so sightlines tangential to the minor axis of the plasma are being considered. The probing beams pass through the plasma, are reflected from conical retroreflectors mounted off the wall of the tokamak with as much protection from the plasma as possible, and return along the same path. The geometry does not allow for very accurate unfolding and requires additional information from the magnetic diagnostics about the position of the plasma axis. Because of the longer pathlength in the plasma, a shorter wavelength (e.g. 10.6 μm of a CO_2 laser) is preferred. However, there is the advantage that the density can be obtained from the Faraday rotation of the polarization of the light. The rotation is proportional to $\int nB_l dl$, where n is the density and B_l is the component of magnetic field along the line of sight and dl is the distance along the line of sight. For a tangential sightline arrangement, the magnetic field strength, B_l, is dominated by the large toroidal field strength so that it is nearly constant and the rotation angle is therefore primarily related to the density.

The density and electron temperature can also be measured by the scattering of intense laser light off the electrons, Thomson scattering. Because of the very small cross section for this scattering, very high power pulsed lasers are generally used. Nowadays, Nd:YAG laser with energies of several joules are used. The intensity of the scattered light is a measure of the plasma density,and the broadening of the spectral line is a measure of the electron temperature. The spatial localization of the light emission to provide profile information is obtained by one of two techniques. In the first, an imaging technique, light is imaged onto a fan of fiber optics, each fiber identifying a potential spot in the plasma along the line of the laser light (16). The second technique, more effective for large plasmas with difficult access for imaging sightlines, is to use very short laser pulses (<1 ns) and viewing along the laser beam and measure the scattered signal for different short time delays (17). The discrete pulses of the laser limit the time-dependent nature of the measurement, but now lasers of sufficient quality capable of firing at ~ 30 Hz for many minutes are available commercially. A combination of the two types of system may be necessary to achieve the necessary spatial resolutions for the core, edge, and divertor plasmas (13).

A continuous measurement of the electron temperature is highly desirable for following turbulent plasma behavior and is available by observing the radiation by the plasma electrons in the microwave spectral region. The electrons accelerating in the magnetic field radiate at their fundamental resonant frequency in the magnetic field, $f \sim eB/m_e$, where B is the field strength, e the electron change, and m_e its mass. The intensity of the emission is, to first approximation for a wide range of density and temperature, proportional to the electron temperature. By selecting a frequency value, the position of the source of the emission can be determined since for a toroidal plasma the toroidal magnetic field is inversely proportional to the major radius. Various instruments can be used; a grating instrument with say 20 detectors gives the time behavior at 20 locations simultaneously, or an instrument sweeping in frequency provides a spatial scan of the temperature (18). There may be significant difficulty for devices with large plasma dimensions due to overlap in signal from the higher harmonic emission from a different location but at the same frequency.

Ion Temperature

Measurement of the temperature of the ions is much more problematic. The hydrogenic ions at the plasma center are fully stripped of their electrons and do not radiate for plasmas of interest here. Hence, spectroscopy cannot be used to find the temperature by determining the Doppler broadening of spectral lines. The measurement must therefore be done making use of ionized states of impurity atoms. Impurities like carbon and iron are normally naturally present, but often noble gases are introduced into the plasma. Spectral line-width measurements are often adequate in the outer regions of the plasma or in the divertor region. But even atoms as heavy as iron will be fully stripped of electrons in ITER. Potentially, krypton would not be fully stripped and spectroscopy of the

He-like or Li-like ions in the X-ray region could provide information on the ion temperature or plasma motion, from the Doppler-shift (19). A curved-crystal spectrometer with a multiwire proportional counter detector could be applied for each line of sight through the plasma with high-energy resolution. Most of the signal will come from the region for which the ionization state of the impurity ion is determined by the local electron temperature so that the measurement can be relatively local. A significant disadvantage of X-ray instruments, which require significant radiation shielding for a reactor, is that they cannot provide very good spatial resolution.

Hence, a preferred technique is visible spectroscopy, making use of an artificially enhanced population of low-mass (e.g., carbon) ions with one electron in the plasma core. Some of the neutral particles from a neutral heating beam, or occasionally a beam specifically provided for diagnostic purposes, penetrate to the center of the plasma (20,21). There they can exchange an electron with the fully stripped ions, enabling them to emit light in characteristic line radiation. The optimum beam energy for this process is about 100 keV for hydrogen atoms. The Doppler-broadened spectral line provides the temperature of the impurity ions; the value can be corrected to infer the temperature of the fuel ions. An optical arrangement focusing the plasma source light on to an array of optical fibers provides for many sightlines and hence the possibility of unfolding to provide a profile of the ion temperature. At the plasma edge, it is possible to measure the ion temperature making use of the emission from the partially ionized ions in this cooler region.

A practical deficiency of requiring a significant density of neutral hydrogen atoms in the core of the plasma is that their penetration to the center of the plasma without ionization by electrons or charge exchange with ions further out becomes increasingly difficult as the plasmas become larger and hotter, as, for example, in ITER. The energy of the heating and current-drive beams being developed for ITER is 1.2 MeV, very good for penetration and for producing plasma rotation. Unfortunately the charge-exchange process for creating a singly charged ion to radiate to meet the spectroscopic needs is optimum at $\sim$100 keV and falls off very rapidly to higher energies. Thus development of a neutral beam designed with very high current for a short time is extremely desirable (22); this is discussed later.

Current Density Distribution

Two techniques that are relevant to reacto-grade plasmas have been used for measuring the spatial dependence of the magnetic field within the plasma and hence the current density distribution and the pitch of the magnetic field lines. The first is to measure the Faraday rotation of probing laser beams, but this time with the beams aligned in the plane of the plasma minor radius where the magnetic field variation is dominated by the field of the plasma current (23). The technique is rather limited in spatial resolution, and the accuracy is affected by having to unfold an integral measurement of the product of two rapidly varying quantities. The second is to measure the polarization of one component of the light emitted by neutral beam atoms excited by electron collisions as the beam enters the plasma. The motion of the atoms in the local magnetic field creates an electric field which leads to Stark splitting on the spectral lines. The polarization of one of the lines identifies the direction of the magnetic field locally where the line of sight of the detector intersects with the beam. This technique has been named motional Stark effect (MSE) and has been used successfully in important plasma confinement studies on TFTR (24) and DIII-D (25), and it is planned to be used on ITER. The heating neutral beam provided for driving current and inducing toroidal rotation of the plasma has an energy of 1.2 MeV. It will penetrate readily to the axis of the large plasma and provides a strong electric field. The major challenge for its use is the ability to provide a viewing mirror to collect sufficient light and provide sightlines to the outer edge of the plasma while maintaining its optical quality.

Impurity Concentration

Impurity ions dilute the fuel ions in the plasma because of their higher charge and the requirement for approximate charge neutrality with the electrons in a plasma. Because the heavier ions do not become fully ionized until the electron temperature is much higher, they emit a lot of energy in impurity line radiation characteristic of the particular ion and its charge state. Hence, spectrometers viewing in the visible and ultraviolet spectral regions with fairly wide spectral coverage will provide spectra of the fuel particles and the impurities (26). In the visible region, an array of fiber optics can again provide spatial dependence of the emission. This array can also be used with narrow-band spectral filters in front of photodetectors to identify one line from selected fuel or impurity ions to give a very precise time behavior. Such a technique is used to identify good performance patterns of the plasma edge or to give quantitative information about the plasma's impact in the divertor where an impurity gas may be used to radiate over a broad area to reduce the power load impinging to a small surface area of the divertor plates. In present-day devices, fiber optics can be used close to the plasma with a vacuum window and simple optical lenses. Unfortunately, the reactor radiation environment will provide so much absorption and prompt fluorescence in transmission optics (27) during the measurement that this preferred equipment will have to be removed beyond the main shielding of the tokamak. Mirrors in shielded labyrinths will be necessary to bring the light out to the vacuum windows and then on to the lenses and fiber optics of the main transmission system. As for all the plasma diagnostics, it is desirable to keep all the sensitive detectors and their associated electronic packages in areas well shielded from the tokamak to allow as much commercial equipment to be used as possible.

In addition to line radiation, free–free electron, or bremsstrahlung, emission is always present and radiates a significant fraction of the power radiated. This emission can be quantified and is normally observed using a narrow-band-pass filter centered at a wavelength where there is no line radiation (28). The ratio of this observed intensity to that calculated for a pure hydrogen plasma provides information on an averaged impurity level. It can be a very valuable control value, particularly when the dominant impurity atoms are relatively light—for example, carbon, which is expected to be used as the material in parts of the first wall facing the plasma. A similar measurement can be made in the soft-X-ray region with a pulse height analysis system which can also identify lines of heavier ions like iron which are present in structural elements inside the vacuum vessel.

Total Radiation by Bolometry

To measure the total power radiated from the plasma, bolometric techniques can be used. Emission of radiation from the plasma covers a very wide spectral range. It is therefore important to measure this radiation with detectors with very flat spectral response over as wide a spectral range as possible. Much of the radiation comes from near the plasma edges where the incoming particles are only partially ionized; but as we have seen, much comes from the center of the plasma in free–free radiation and from highly ionized states of impurities. It is necessary to view the plasma with arrays of bolometer detectors to be able to carry out tomographic analysis of the source of the radiation both for control and for physics assessments of the energy transport in the plasma (29). The control requirements range from seeking to reduce the impurity concentration to trying to increase the radiation close to the divertor plates to reduce the heat load conducted onto the plates by radiating the energy over a greater fraction of the wall. Introduction of a noble gas such as krypton onto the divertor is proposed for producing this "radiating" divertor.

The arrays of bolometers will be mounted at many locations on the first-wall support structure. Because of the asymmetric shape anticipated for the plasma of the reactor, detectors numbered in the hundreds, mounted in groups of tens or so, will be needed to provide a sufficiently good base for the tomographic analysis. To meet the requirement for control, at least initially, a few lines of sight encompassing key regions may be sufficient for developing basic control data. The groups of detectors will be mounted behind pinholes delimiting the size of the viewed volume. They will be mounted in boxes with well-designed temperature control. The detectors themselves will probably be gold-blackened etched platinum resistance thermometers, typically about 1 cm^2 (30). The platinum is mounted on one side of a ceramic with a matching platinum resistor on its back, facing away from the plasma. The second resistor has the necessary role of measuring other transient sources of heat, particularly the nuclear heating caused by the neutrons and gammas coming from the plasma and the surrounding structure. These two resistors make up one pair in a Wheatstone's bridge, the other pair being in the electronics boards away from the tokamak environment. Such bolometer arrays are providing very valuable information in the present-day tokamaks, but there is significant concern for their operation and survival in a reactor environment. Development and testing of a bolometer with a better ceramic interspace is an urgent requirement.

Fusion Products

The nuclear reaction products from the fusion reaction of deuterium and tritium fuel ions are neutrons and fast helium ions, called alpha particles. The neutrons escape from the plasma and provide the source of energy for generating electrical energy. The alpha particles, originating with an energy of ~3.5 MeV, stay inside the plasma and slow down, giving up their energy to heat the plasma and sustain the burning plasma. Integral measurement of the neutrons gives information about the overall performance of the discharge. It will play a key role in keeping a stable plasma burn at the center of the fusion reactor. Additional information on the spatial distribution of the ion temperature and the source region of the alpha particles can also be obtained (31). For present-day devices and the next-step fusion devices, the measurement of alpha particles will be very important to find out how they diffuse in space, how they respond to instabilities in the plasma and how the "ash" of alpha particles that have slowed down is accumulating in the core of the plasma, reducing the performance (32). For the fusion reactor it is probable that only the ash measurement and the prompt loss of alpha particles causing local hot spots on the first wall will be considered necessary because much simpler measurements of other plasma parameters will provide sufficient control information. It is possible that external measurement of the partial pressure of helium beyond the divertor region may provide an adequate control parameter.

Neutron Diagnostics

The simplest neutron measurement, very suitable for feeding into a control system, is a total flux measurement using a standard proportional counter (33). A fission-chamber proportional counter, surrounded by a moderator, can be placed outside the tokamak so that it can measure the flux of neutrons reaching it with relatively good time resolution. No spectral information is required because the neutrons have been scattered many times on their route to the detector. There is a very significant requirement that the neutrons need to be measured over a very wide dynamic range (as much as seven or eight orders of magnitude) to allow full control. The most difficult aspect of this measurement is relating the flux at the detector quantitatively to the source of neutrons originating in the plasma. The massive structures of the tokamak and its shielding must be taken into account. The geometry is such that nuclear codes are not adequate for providing this calibration, so that a calibration source must be used inside the tokamak (34). This calibration requirement may extend the dynamic range even further because available point sources are relatively very weak compared to any relevant plasmas. This time-dependent measurement can be enhanced by using neutron activation foil techniques whereby an elemental foil can be exposed close to the plasma and then the activation can be measured later at a remote location (35). The mechanical response is too slow to allow use of the foil technique for control purposes but it does provide the opportunity for checking on the instrumental reliability and calibration of the time-dependent measurements, in addition to providing a record of the total fluence.

Neutron cameras consisting of arrays of collimated tubes between the plasma and a variety of detectors or spectrometers can provide information about the spatial distribution of the neutron source and the temperature of the ions (36). The different sightlines across the plasma cannot be very close since massive shielding is needed to prevent crosstalk between different observation channels. Thus their usefulness is of some value for physics studies where the information is not otherwise available, but is not likely to be useful for the burn control.

Alpha-Particle Measurements

The measurement of the alpha particles confined inside the plasma is very important for the next-step device from the point of view of physics understanding and hence performance improvement. But for a reactor the essential measurements are those to ensure that the reactor can sustain operation. An urgent question to be resolved is how rapidly the helium ash (the residue left of the alpha particles after they have passed all their energy over to the background plasma, thereby creating and sustaining the burning plasma) diffuses out of the core plasma and away through the divertor. Recent experiments (37) suggest that it is sufficiently fast, but more experiments are needed. Techniques using radio-frequency waves have been suggested for accelerating its removal, but these await demonstration now. This ash, if it accumulates, has the effect of reducing the densities of the fuel particles significantly for a given controlled electron density. Only one technique for measurement has so far been suggested. The technique makes use of the same active spectroscopic method with an incoming neutral beam discussed above for ion temperature measurement, but in this case the intensity of a visible spectral line of singly ionized helium will be measured (21).

Some alpha particles will be lost continuously from the plasma, though most are relatively well confined despite their very high energy. But in some circumstances, such as certain kinds of MHD instabilities, there will be enhanced loss to the first wall in relatively localized regions. Since it is conceivable that the total energy deposited will be sufficient to cause damage if the loss is allowed to continue, it is desirable to measure the loss directly for the control system. The first technique suggested is to provide infrared imaging of as much of the first wall as possible. Such a system has already been proposed for detection of hot spots arising from misalignments of the first wall and for monitoring the heat load on the divertor plates. The data used for control would be selected from a few of the pixels of the camera image. Conceptual designs of the imaging system indicate the use of periscopes using reflective optics to take the light outside the radiation environment to a fiber-optic/camera imaging system. The benefit of this technique is that it is not dependent on any theoretical projection of where the escaping particles should go; its deficiencies are that it cannot discriminate between particles of different energies and that it may not be sufficiently sensitive until damage is close at hand because the camera is already viewing a very hot wall. A second technique makes use of discrete detectors placed at strategically chosen locations in the first wall. The detectors could consist of small scintillators mounted in small cameras to provide information about the energy and origin of the alpha particles as in the TFTR tokamak (38). A scintillator with better radiation survivability than that presently used and an optical system insensitive to radiation will have to be defined. Alternatively, small Faraday cup detectors measuring the total number of alpha -particles entering them could be used, as in the JET device. In this case, there is a much simpler electrical connection but a significant loss of information, which, nevertheless, is probably sufficient for control needs.

DEVELOPMENT ISSUES TO BE PURSUED

In the preceding section, many of the measurement techniques likely to be used in control of a fusion reactor have been discussed very briefly. Nearly all of these techniques will be evolutions from the techniques used in the physics studies being carried out on currently operating tokamaks. However, the radiation environment causes many compromises to be made. Many of these should be demonstrated during the operation of the next-step device where the neutron fluxes to the first wall and the main components of the tokamak should be approximately the same as for a reactor. For most of the plasma diagnostic equipment, the prompt noise induced in the signals is the most severe concern so that this will provide a good demonstration of the capability. However, the total fluences in which the equipment will have to function and maintain calibration in a reactor may be considerably higher, and this should be taken into account in its design. Such possibilities as ensuring replaceability will have to be considered. But at this moment, the development issues that have to be addressed are those needed for measurements on a next-step ignited-plasma device. Some of the studies are in progress.

Radiation Effects in Materials

The sensitivity of components of diagnostic systems to the neutron and gamma radiation environment close to the plasma is a very serious concern for diagnostics which have to provide reliable, quantitative information with good accuracy throughout the plasma discharge. Ceramic insulating material must retain sufficiently good insulation levels despite the induced effects, radiation-induced conductivity (RIC), radiation-induced electrical degradation (RIED), and radiation-induced electromotive force (RIEMF) (39). In the flux level at the first wall in ITER, $\sim 6 \times 10^3$ Gy/s for ceramics, the conductivity can be increased by as much as six orders of magnitude relative to the radiation-free environment, with some ceramics being more affected than others. The design criterion of an induced conductivity $<1 \times 10^{-7}$ S/m necessary for small electrical stand-off pieces and cable insulation has been measured in *in situ* fission reactor neutron/gamma exposure for some alumina samples. Adequate insulation has also been seen in some samples of mineral-insulated cable, but much more detailed development and testing is needed to ensure qualified components. There is concern that the cables are severely affected by the quality of their termination so that they are suitable for use in vacuum, and also by the configuration of the wiring, so that extensive further testing in the radiation environment is necessary. In addition to this prompt property of the ceramics in a radiation field, a new concern is that of an RIEMF which is observed in reactor testing of magnetic coils made from mineral-insulated cable. The effect is not yet understood, but it has the effect of providing slow drifting of the integrated signal of, for example, a magnetic coil used in position measurement. In addition some ceramics show a cumulative damage effect (RIED) when irradiated with applied voltage, particularly in electron-radiation testing, which could lead to catastrophic failures. This behavior does not seem to be as significant in reactor irradiations. Again definitive qualification tests are required before application of the materials for making components to be used in the next-step device. Once those tests are completed, testing of the components integrated into a complete instrument will be highly desirable.

Nuclear radiation also drastically affects the transmission of transparent optical components such as windows, lenses, and fiber optics as well as causing fluorescence (27,39). The latter tends to be a more serious issue in fiberoptics because of the much greater length of transmission medium. The fluorescence occurs only during the radiation period—that is, the plasma discharge. The absorption is transient during the discharge, varying with the intensity of the neutron emission, but is also cumulative. Many quantitative in situ radiation studies at high flux levels have been carried out, but perhaps the most informative have been in relatively low flux examinations of behavior of fibers on the TFTR tokamak. The light signals from the plasmas, from spectroscopy, or from scintillators near the plasma are relatively low intensity (for the escaping alpha-particle diagnostic, the background radiation-induced pedestal in the fibers was about 20% of the maximum signal produced in the scintillator by the alpha particles) so that the background generated by neutrons should be both small and relatively well quantified.

Since the use of fiber optics can open up the possibility of using imaging techniques and because of their flexibility, they are very desirable for interweaving optical paths through the shielding material surrounding the plasma. Hence, the development of new quartz fiber materials which are relatively radiation-hard to allow the fibers to be placed closer to the neutron source is highly desirable, and such development of low-OH and F-doped fibers are in progress. This development is at an early stage; meanwhile the use of quartz fibers with low defects, very careful handling, and a metallic cladding to permit hot operation at ~300°C to minimize the absorption buildup is the best plan. Unfortunately, there do appear to be significant differences in the performance of fibers from apparently the same source, so that each fiber will have to be characterized very carefully for its specific use.

It is very unlikely that the development of fibers for use in a radiation environment will ever achieve a quality to allow their use close to the first wall. Thus periscopes with mirrors reflecting light through shielding labyrinths are expected to form the first elements in the light paths from the plasma. The first mirror necessarily will be required to look through a wide aperture into the plasma to see a wide field of view and to collect sufficient light, particularly for spectroscopic measurement. This mirror is likely to be bombarded by a flux of order 10^{19} $m^{-2} \cdot s^{-1}$ of high energy neutral atoms from charge-exchange reactions between hot ions and cold neutral gas atoms in the outer regions of the plasma, in addition to the impact of neutrons and gammas. The design of these front mirrors, most of which have to maintain high optical quality, is a major challenge. Research in support of this design effort has recently started (40). From the point of view of minimal sputtering, a reflecting surface of rhodium appears most desirable, but major development is needed to first create the mirrors of sufficient optical and mechanical quality and then to test them thoroughly in high-energy neutral particle sources.

Other aspects of the reactor plasma relative to the plasmas in today's most advanced devices, such as the much larger size and higher electron temperatures arising from the heating by alpha particles, lead to concern about the viability of some measurement techniques. For example, the spectroscopic techniques based on atomic interactions with ~100 keV hydrogenic neutral particles will only operate with a beam intensity more than three orders of magnitude higher than in today's conventional heating neutral beams applied to tokamaks. A development program for a 5 GW, 1 ms beam has been started (22). With the short pulse length, the total energy requirement and the impact on the plasma of this probe beam will be constrained.

No techniques for measurement of the erosion of first wall surfaces and redeposition onto them in real time have been used on tokamaks. Some concepts such as some range-finding methods may be applicable, but development will be needed to apply any technique to provide sufficient spatial coverage. But it is not only in technology that research and development is required to make some of the measurement requirements credible (8). Quantitative evaluation of the concentrations of impurity elements in the divertor will be very difficult because of the strong spatial variation, partial self-absorption of spectral lines because of high local plasma densities, and the fact that most of the radiated power will be in spectral lines emitted in the vacuum ultraviolet spectral range. Because of accessibility issues, it is extremely difficult to get good spatial resolution in this range. Hence, some atomic-physics analysis to identify potentially good ways of getting the quantitative information from visible lines and more detailed spectroscopy of cold, high-density plasmas in operating divertors are clear areas for more research. New techniques should be found for measuring the core helium ash and the ratios of the hydrogenic fueling particles, not dependent on a very powerful diagnostic neutral beam. A direct measurement of the electric field inside the plasma, rather than from inference from measured plasma motions, could provide more direct information for the control system.

SUMMARY

It is clear that the instrumentation required for a fusion reactor will be rather complex, particularly if it is based on the tokamak concept as appears likely at the moment. Many plasma parameters have to be measured, often with demanding requirements on resolution and accuracy, to provide the necessary information for control. While it is difficult to predict now exactly which of the measurements so important for the physics understanding and which are used in improving the performance of the plasma will remain important for maintaining an ignited plasma for long times, many of those shown in Table 1 will be necessary to fulfill the proper fueling, external heating, current drive, equilibrium, and stability properties.

The instruments used in the many measurements carried out for physics reasons now are commercially available with proven reliability. It seems likely that similar instruments will be used for the reactor, with the advances in computer power making feasible the use of large quantities of interpreted data in its feedback controls. The difficult step for providing a full instrumentation capability for a fusion reactor will be in the interfacing with the plasma and the high-radiation environment. The demands for good spatial information about many plasma parameters set requirements for many penetrations in the shielding (to be compensated by labyrinths in shielding and additional shields) and for components to be located in severe environmental conditions, not only of nuclear radiation but also of high temperatures and high vacuum. Integration of operating systems with sufficiently good signal to noise, resistance to damage, and reliable calibration integrity is the major engineering demand for the plasma diagnostics.

Meanwhile, the physics program in magnetic fusion must continue to move forward to achieve an ignited plasma which is sustained for sufficiently long times to interest utilities in fusion as a power source. Part of that program will include improving the measurement capability through new techniques, better understanding of the physics interpretation of some measurement techniques, and adding better spatial and temporal resolutions. It is hoped that with better understanding of the details of the plasma behavior, it will be possible to greatly reduce the instrumentation demands for fusion reactor operation.

There are many challenges associated with creating a fusion reactor. Among them is the provision of a capable set of instrumentation. There is every reason to think that this instrumentation will evolve with the fusion program, and many of the detailed problems apparent now will be resolved with further research and development.

ACKNOWLEDGMENTS

The author is grateful to the very many people who have been involved with him in the pursuit of the best possible plasma measurements. This work has been supported by DOE Contract DE-AC02-76-CHO-3073.

BIBLIOGRAPHY

1. R. J. Hawryluk, Results from deuterium–tritium tokamak confinement experiments, *Rev. Mod. Phys.,* **70**: 537–587, 1998.
2. M. Keilhacker et al., *Nucl. Fusion,* 1998.
3. P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1996.
4. I. Hutchinson, *Plasma Diagnostics,* Cambridge, UK: Cambridge Univ. Press, 1987.
5. A. Miyahara, Y. Hamada, and K. Ida (eds.), *Fusion Plasma Diagnostics, Fusion. Eng. Des.,* **34–35**, 1997.
6. A. E. Costley et al., Requirements for ITER Diagnostics, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1996, pp. 23–37.
7. V. S. Mukhovatov et al., and the ITER Joint Central Team and Home Teams, Overview of the ITER Diagnostic System, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1998, pp. 25–40.
8. *ITER Physics Basis Document, Nucl. Fusion,* to be published 1998.
9. K. M. Young and A. E. Costley, Members of the ITER-JCT, ITER Home Teams and the ITER Diagnostics Expert Group, An overview of ITER diagnostics, *Rev. Sci. Instrum.,* **68**: 862–867, 1997.
10. J. Wesley et al., Plasma control requirements and concepts for ITER, *Fusion Tech.,* **32**: 495–524, 1997.
11. K. M. Young, Advanced tokamak diagnostics, *Fusion Eng. Des.,* **34–35**: 3–10, 1997.
12. A. J. Wootton, Magnetic Diagnostics for Tokamaks, in P. E. Stott, D. K. Akulina, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Contemporary Fusion Experiments,* Bologna: Editrice Compositori, 1991, pp. 17–36.
13. *ITER Physics Basis Document, Nucl. Fusion,* to be published 1998, Chap. 7.
14. E. J. Strait et al., Observation of poloidal current flow in the vacuum vessel wall during vertical instabilities in the DIII-D tokamak, *Nucl. Fusion,* **31**: 527–534, 1991.
15. R. T. Snider et al., Applications of interferometry and Faraday rotation techniques for density measurements on the next generation of tokamaks, *Rev. Sci. Instrum.,* **68**: 728–731, 1997.
16. D. Johnson et al., TFTR Thomson scattering system, *Rev. Sci. Instrum.,* **56**: 1015–1017, 1985.
17. H. Salzmann et al., The LIDAR Thomson scattering diagnostic on JET, *Rev. Sci. Instrum.,* **59**: 1451–1456, 1988.
18. D. V. Bartlett, Physics Issues of ECE and ECA for ITER, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1996, pp. 183–192.
19. K. W. Hill, M. Bitter, and S. von Goeler, Concepts and Requirements of ITER X-Ray Diagnostics, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1996, pp. 341–352.
20. R. J. Fonck, Charge exchange recombination spectroscopy as a plasma diagnostic tool, *Rev. Sci. Instrum.,* **56**: 885–890, 1985.
21. E. S. Marmar, Active Spectroscopy Diagnostics for ITER Utilizing Neutral Beams, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1996, pp. 281–290.
22. H. A. Davis et al., Progress toward a microsecond duration, repetitively pulsed, intense-ion beam for active spectroscopic measurements on ITER, *Rev. Sci. Instrum.,* **68**: 332–335, 1997.
23. H. Soltwisch, Current distribution in a tokamak by FIR, *Rev. Sci. Instrum.,* **57**: 1939–1950, 1986.
24. F. M. Levinton et al., Magnetic field pitch angle diagnostic using the motional Stark effect, *Rev. Sci. Instrum.,* **61**: 2914–2919, 1990.
25. B. W. Rice et al., Direct measurement of the radial electric field in tokamak plasmas using the Stark effect, *Phys. Rev. Lett.,* **79**: 2694–2697, 1997.
26. N. J. Peacock et al., Spectroscopy for Impurity Control in ITER, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1996, pp. 291–306.
27. A. T. Ramsey et al., Radiation effects on heated optical fibers, *Rev. Sci. Instrum.,* **68**: 632–635, 1997.
28. A. T. Ramsey and S. L. Turner, HAIFA: A modular fiber-optic coupled, spectroscopic diagnostic for plasmas, *Rev. Sci. Instrum.,* **58**: 1211–1220, 1987.
29. R. Reichle, M. DiMaio, and L. C. Ingesson, Progress for the Reference Design for ITER Bolometers and Development of a High Performance Alternative, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1998, pp. 389–398.
30. K. F. Mast et al., A low noise highly integrated bolometer array for absolute measurement of VUV and soft X-radiation, *Rev. Sci. Instrum.,* **62**: 744–750, 1991.
31. L. C. Johnson et al., and the ITER Joint Central Teams and Home Teams, Overview of Fusion Product Diagnostics for ITER, in P. E. Stott, G. Gorini and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum Press, 1998, pp. 409–418.
32. K. M. Young, Alpha-Particle Diagnostics, in P. E. Stott et al. (eds.), *Diagnostics for Contemporary Fusion Experiments,* Bologna: Editrice Compositori, 1991, pp. 573–594.

33. E. B. Nieschmidt et al., Effects of neutron energy spectrum on the efficiency calibration of epithermal neutron detectors, *Rev. Sci. Instrum.,* **56**: 1084–1086, 1985.
34. J. D. Strachan et al., Neutron calibration techniques for comparison of tokamak results, *Rev. Sci. Instrum.,* **61**: 3501–3504, 1990.
35. C. W. Barnes et al., Measurements of DT and DD neutron yields by neutron activation on the Tokamak Fusion Test Reactor, *Rev. Sci. Instrum.,* **66**: 888–890, 1995.
36. F. B. Marcus et al., A Neutron Camera for ITER: Conceptual Design, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1996, pp. 385–396.
37. E. J. Synakowski et al., *Phys. Rev. Lett.,* **75**: 3689–3692, 1995.
38. D. S. Darrow, S. J. Zweben, and H. W. Herrmann, Alpha particle loss diagnostics in TFTR and tokamak reactors, *Fusion Eng. Des.,* **34–35**: 53–58, 1997.
39. E. R. Hodgson, Radiation Problems and Testing of ITER Diagnostic Components, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1998, pp. 261–268.
40. V. S. Voitsenya et al., Imitation of Fusion Reactor Environment Effects on the Inner Elements of Spectroscopical, mm and Submm Diagnostics, in P. E. Stott, G. Gorini, and E. Sindoni (eds.), *Diagnostics for Experimental Thermonuclear Fusion Reactors,* New York: Plenum, 1996, pp. 61–70.

KENNETH M. YOUNG
Princeton Plasma Physics
Laboratory