Report on the "Workshop on Measurement Needs in Magnetic Fusion Plasmas"

Preamble

A Workshop on Measurement Needs in Magnetic Fusion Plasmas was convened on February 25, 1998 at the Department of Energy, Germantown Building. The people attending the Workshop were D. Colchin (ORNL), C. Forest (U. Wisconsin), M. Greenwald (MIT), P. Guzdar (U. Maryland), A. Hoffman (U. Washington), S. Kaye (PPPL), J. Manickam (PPPL), D. Markevich (DOE), R. Stambaugh (GA), R. Taylor (UCLA), J. Van Dam (U. Texas), A. Wootton (U. Texas), and K. Young (PPPL). The purpose of the Workshop was twofold: 1.) to identify fusion measurement needs and problems and the input required for the modeling codes and 2.) to consider the development of new, first-of-a-kind magnetic fusion diagnostics applicable to tokamaks, innovative concepts, and/or burning plasma devices. This report summarizes the discussions at the Workshop.

Introduction

Improvements in measurement methods have contributed enormously to the understanding of the plasma behavior in tokamaks, providing the information necessary for analysis codes and theoretical interpretation. Two DOE initiatives in transport diagnostics and alpha-particle diagnostics provided impetus for these advances, which have been further improved by the operators of the tokamaks. Measurements on tokamaks must still be improved to be able to validate theoretical predictions. New devices are being proposed based on innovative concepts. In order to demonstrate their scientific feasibility, the newly funded and proposed non-tokamak devices require comparable measurements, often in a very different range of engineering and plasma parameters.

The Workshop participants reviewed requirements for the full spectrum of devices: tokamaks - including needs for burning-plasma measurements, spherical tori (STs), stellarators, reversed-field pinches (RFPs), and field-reversed configurations (FRCs). The plasma parameters in such devices cover a wide range of magnetic field strengths, plasma densities, and plasma temperatures. Plasmas in the core, edge, and divertor regions have very different measurement demands, which are becoming more severe as the theoretical and modeling capabilities are advancing. It will soon be possible to compare measured data with sophisticated and detailed simulations of the plasma, so that very detailed information on profiles and fluctuations will be required.

At the Workshop, there was considerable discussion of measurement needs, with a particular concentration on the voids in the current measurement capabilities. Cheaper and more efficient alternatives for existing diagnostic tools were also thought to be important. Each participant identified needs relative to his experience. Then the group summarized the requirements under a few specific headings relating to physics measurement needs for the fusion program. There were many other suggestions that were more device specific. Information for some of the significant U.S. devices can be

found on the relevant device Web pages, whose addresses are given in the Appendix.

It was felt that the developers of diagnostics should aim to be cost effective, and should target their diagnostic to specific devices and collaborate with the staff at these devices as early as possible in the planning stages of the diagnostic. Because innovation is involved, it is recognized that the design effort may require an analysis phase prior to entering into the development phase.

Diagnostic Needs

The perceived needs for diagnostic development have been grouped into seven main areas given below. These areas define major physics issues and gaps in measurement capability and are shown in alphabetical order. There is necessarily some overlap among the areas. No priority is being defined. This listing is not intended to preclude other innovative suggestions.

- **Disruptions**

  Operation of tokamaks close to their best performance frequently results in a disruption with resultant rapid energy dissipation from the plasma. Potentially the same will happen for STs and compact stellarators with large bootstrap currents. It is extremely desirable to understand the mechanisms involved in order to be able to compare experimental results with current theoretical projections. For a large ignition device, disruptions may severely limit the operational life. Measurements of the spatial distribution of the runaway electrons (with energies of up to ~100 MeV) created in the disruption will be needed. Measurement of the rapid electron temperature profile decay is also necessary. Pellets have been proposed as a mechanism for stopping the runaway process, and the rapid ablation of these pellets should be measured quantitatively.

- **Divertor and Edge Measurements**

  The edge-plasma interface, with its surrounding wall or connected divertor region, is difficult to study with non-intrusive techniques. The divertor normally has a huge range of densities and temperatures to be measured with high precision to match the modeling. Very complex plasma-wall interactions and the atomic physics involving many molecules and atoms through multiple ionization states are involved. In some regions, the plasma is spectroscopically optically thick, and this limits interpretation. Techniques for measuring steep edge pedestals in density and temperature and providing 2-dimensional profile information on the densities and temperatures in the divertors need to be developed. Sufficiently fast measurements of quite fundamental parameters, such as neutral density in the edge, do not exist, and techniques for assessing molecular concentration have not been developed. Erosion and redeposition of material onto, and hydrogenic gas entrainment in, the local first wall surfaces during the plasma pulse have only been measured in a preliminary way using insertable probes. These measurements are key to predicting the performance of next-step tokamaks.

- **Fast-Ion and Alpha-Particle Measurements**

The performance of STs, stellarators, and next-step tokamaks may be critically dependent on the confinement of the fast ions and alpha particles. The energetic particles originate from neutral beam injection, RF-wave acceleration of ions, or fusion reactions. Because of the range of passing and trapped orbits available to these ions, it is necessary to have good two-dimensional spatial, energy, and pitch-angle information about the confined and the escaping fast particles. Because their orbits depend sensitively on the magnetic configuration, precise measurements of q(r) and dq(r)/dr are needed. The anisotropic contribution of the fast ions to the pressure profile should be taken into account in MHD stability evaluations. Measurements of the radial profiles of the electric field and magnetic field fluctuations would also be useful for comparison with theoretical calculations.

- **Fluctuations as They Relate to Transport**

  Perturbations in the density, temperature, and magnetic fields are frequently observed. Theories used in the modeling of the plasma transport, and particularly used in extrapolation to next-step devices, have predicted certain fluctuation behavior. Thus direct measurements will be able to validate specific models. Two-dimensional measurements can lead to definitive mode identification. For turbulence correlation functions, three-dimensional measurements of electrostatic and electromagnetic fluctuations are needed in addition to density fluctuations. In the same way as for the profile measurements, some present fluctuation measurements are impacted by poor neutral beam penetration. Therefore, alternate or enhanced techniques are desirable.

- **Magnetic Structures**

  Many alternate concepts have a magnetic structure that is largely determined by the plasma current. There is no large superimposed background field, as there is in a tokamak or stellarator, so that both magnetic field magnitudes and gross directions can have large variations. It is important to determine this structure for even the most basic understanding of equilibrium, stability, and transport. Internal probes have been used for diagnosing low density, low temperature plasmas, but this technique is inappropriate for energetic plasmas of current interest. Non-perturbative measurements of the internal magnetic fields are required for a wide range of plasmas where the first-order field is unknown. The magnetic structures can range from perturbations that are quasi-stationary, islands, or stationary magnetic perturbations, to fluctuations that can be as high in frequency as a few megahertz in FRCs. The MHD mode structure in STs is expected to be predominantly on the high-field side due to the high shear of field lines on the low-field side. The performance of a compact stellarator depends on large bootstrap currents, whose spatial distribution should therefore be measured. In devices utilizing helicity injection, magnetic disturbances are key to understanding current sustainment processes and their effect on confinement. In extremely high-ß devices like the FRC, internal magnetic field strengths will vary over several orders of magnitude and have strong influences on both MHD and kinetic contributions to stability. In other devices, high-ß can induce island

formation while internal currents will strongly affect the local magnetic shear. The influence of magnetic field fluctuations on electron thermal transport is potentially important in all devices and this measurement is therefore highly desirable.

- **Profile Measurements**

  a) *Replacing NB-based diagnostics*: Very successful measurements of ion temperature profiles, plasma rotation profiles, impurity density profiles, safety factor profiles, and electron density fluctuations have been made in tokamaks with the use of a hydrogen-isotope neutral beam, typically with energies between 50 and 100 keV. But there are limitations in penetration of the beam for plasmas with high densities and/or large size, devices without beams, and others with low magnetic field that can have high losses. Alternative techniques for these measurements are necessary. The measurement of plasma rotation should be associated with direct measurement of the electric field.

  b) *Lack of electron-cyclotron emission*: Time- and space-dependent electron temperature data have been provided by electron-cyclotron emission in the microwave region. This measurement is not available for low-field ($B < 2$ T) devices and some supplemental techniques for pulsed Thomson scattering are required to provide temporal information.

  c) *Spatial requirements for transport barriers in tokamaks*: Discharges with internal and edge transport barriers are exhibiting very steep transport barrier features, which demand fine spatial resolution in the radial direction. Such gradients are predicted by modeling. Density, temperature, $q(r)$, and rotation profiles with improved spatial resolution are required.

- **Wave Propagation and Deposition**

  Many devices make use of radio frequency techniques for heating and current drive. There is little direct measurement of the wave propagation and deposition, information normally being derived indirectly from measurements of plasma density or temperature. From the point of view of relating experiments to RF or transport-code predictions, information on the wave fields in the plasma, mode conversion, and deposition are needed. Quantitative evaluation of the accelerated high-energy ions and the behavior of the minority fractions would provide a much better understanding of the physical processes. ICRF heating also requires good control of the isotopic mix. For hydrogen species there is no good method for measuring minority concentrations in the plasma core. Helium concentrations can be measured via charge-exchange recombination, but only if beam diagnostics are available and only when these are not viewing other species. Routine measurement of hydrogen and helium fractions would allow optimization of heating and better comparisons with codes.

Appendix

Information available at Web sites

Alcator C-Mod (MIT)
http://www.pfc.mit.edu/cmod/cmod_diag_needs.html

DIII-D (GA)
http://fusion.gat.com/diag/diag-opp.html

NSTX (PPPL)
http://www-local.pppl.gov/nstxhome

UCLA Program (UCLA)
http://tokamak.seas.ucla.edu