Short White Paper
Virtual Laboratory for Plasma Diagnostics, Instrumentation and Control for Advanced Fusion Devices

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Introduction:

Thrust 1 of the ReNew Report in 2009 emphasized the need to develop "diagnostics critical to the burning plasma research goals" to enable the understanding and control of burning plasmas[1] for the fusion program. This is one of three issues that must be addressed in preparation of the instrumentation for a Demo device. These issues require specific attention over the next several years to provide input into the design, and hence anticipated performance, of a Demo. The work must be done in parallel with the physics studies being done on current machines to establish the basis for the design of the Demo.

Previous reports have defined the scope of work in preparation of measurement equipment for a Demo[2,3]. The difficulty of implementing the necessary plasma measurement capability on such a device has been shown in ref 4. It is important to note that the demands of plasma profile control set by advanced tokamak scenarios are very high, and it is not clear yet whether those of a stellarator are any less. These issues have been largely ignored in past design studies of Demo-like devices (e.g. Aries-AT[5]) which have oversimplified the integration of blankets and shielding with all auxiliary tokamak systems.

A virtual laboratory is proposed to plan, coordinate and carry out the developments deemed necessary for the instrumentation of a Demo and, beyond that, for a reactor. Some aspects of the development will be applicable to ITER. The development of alpha-particle diagnostics is a definite example. Also the later engineering operational phase of ITER will be critical in the evaluation of plasma diagnostic effectiveness in providing sufficient plasma control and operational safety. The radiation fluxes at the first wall in Demo (~3 – 4 MW/m^2) will be a factor 3 or so higher than for ITER and in Demo, the useful lifetime fluences will be many orders of magnitude greater. All the measurement equipment will have to be robust, reliable and remain calibrated for a large fraction of its operational lifetime.

The three concerns to be addressed are:

1) Develop plasma diagnostics critical to the burning plasma research goals;
2) Define the necessary control data and develop control algorithms to help define the control of a (hopefully limited) variety of plasma scenarios;
3) Develop minimum plasma diagnostic requirements for control of burning plasmas; define the access required relative to blankets and other components surrounding the plasma such as heating and other ancillary equipment, define calibration requirements and engineer reliability into the systems.

These three are very tightly coupled. They must be pursued urgently because it is probable that the measurement requirements will significantly affect the design of the Demo. All of them will require coordination with materials studies and radiation testing being done elsewhere for the fusion program.

Specific Activity Areas:

1) Burning Plasma Diagnostics:

The most obvious gap in measurement capability for a Demo is that of the main source of heating, the α-particles. The excellent measurements on TFTR[6] cannot be easily extrapolated to ITER or a Demo and there is only a European development of collective scattering[7] currently in progress. Measurement of the escaping particles will be very problematic if thought to be necessary. The plasma size and temperature will limit the use of diagnostics dependent on neutral beams for their measurement source and detector sensitivity to neutron damage will affect many diagnostics. Thus new concepts for measurement of ion temperature, plasma rotation, current density distribution and relative fuel densities in the core should be considered.

Even diagnostics, relatively simple in concept, will have to be reappraised. Design of optical diagnostics dependent on mirrors close to the first wall in ITER to give spatial coverage will need to evolve for the very long pulses and the high level of wall-reflected light to be expected. The standard type of magnetic diagnostics, particularly those that have to be close to the plasma to allow for fast time-response for instability identification, may not be possible because of radiation-induced conductivity effects in their insulators and a rethinking of the measurement of plasma localization may be necessary. Sufficiently radiation-hard bolometers and vacuum gauges might have to be developed. Development of measurement of dust and erosion of first wall materials is presently in its infancy[8], and techniques to provide sufficient spatial coverage will have to be studied.

Experience shows that for present-day tokamaks, it takes about 10 years from concept to a fully developed plasma diagnostic with reliable control capability. For instruments to operate in, and provide control information for, a Demo, it could well take longer, since these have to contend with the hostile environment and severe restrictions on accessibility to the plasma.

2) Developments in Plasma Control (Thrust 5, ref. 1):

It is clear that the purpose of plasma diagnostics in a Demo or fusion reactor will be the control of the plasma and for protection of the device (e.g. prevention of disruptions). The plasma measurements will provide all the data needed to control the plasma for all its phases; start-up, development, burning phase and rampdown. Thus the equipment has to operate over a huge dynamic range of plasma properties. The information provided will probably be of lower quality than in present-day tokamaks because of the restricted access and the intense radiation environment.

Hence there is a definite need for the development and validation of interpretive and predictive modeling tools to be incorporated into the control systems. These will have to be tested on operating tokamaks, and also on ITER where the plasmas will be more representative of those to be expected in Demo. It has to be assumed that the principle operational regimes for Demo will have been demonstrated on ITER. It is felt that the computation capability will be easily able to handle a transport code such as TRANSP to allow profile fitting to a limited set of positional information within the necessary control time interval. The implementation of synthetic diagnostics to validate limited spatial data sets will also be necessary.

3) Evolutions required for Plasma Measurement Equipment:

An urgent task is to define what plasma diagnostics will be required for the control mission and to what quality, in spatial and temporal resolution, they will have to perform. This definition will obviously evolve as the proposed operational plasma scenarios become better defined. Presently more and more diagnostic information is being fed into the control of tokamak plasmas but this growth will have to be reversed prior to the Demo. The access to the tokamak will be severely constrained by the need to generate tritium (and electrical power generation ability) in the blankets. Both diagnostic and blanket designers prefer to occupy the outer equatorial region (the neutron flux is highest there), and the possibility of putting diagnostic access off the midplane has to be considered. This type of consideration could strongly impact the design of the tokamak, as well as the performance of the diagnostics.

Another significant issue is the robustness of the measurement equipment. Relative to the instrumentation in a fission reactor, the instrumentation (which has to be within the tokamak environment) is much more complex. A strong engineering effort must be set up to consider the issues of radiation effects on operation and lifetime of components, control and operation of movable components such as shutters, capability for maintaining calibration and redundancy. Obviously all systems will have to be maintained and replaced using remote-handling equipment, though this aspect will should have been prototyped on ITER.

There is a fourth area of instrumental development which is much less well defined. Up to now, measurement of the performance of the engineering systems in operating tokamaks has mostly made use of commercial equipment with some care necessary because of the high magnetic fields. An initial attempt to assess the needs for evolutions of the instrumentation toward Demo was shown in ref. 2, section 9.3, but a much better assessment is necessary. A few examples of areas where design studies and developments may be necessary are given below. The design studies would consider where the instrumentation would have to be placed relative to the very hostile radiation and temperature environment. They will also be affected by the particular solutions for heating, current-drive, and fuelling chosen for the plasma. Since the plasma in a Demo must survive through any transient "off-normal" events, such as disruptions, mitigation techniques will have to be considered, though the instrumentation will probably only require faster response times of injection and heating systems than would be necessary for the normal plasma control. Some potential examples of instrumentation for engineering systems are:
i) Gas injectors and their monitors;
ii) Temperature sensors of the first wall and vacuum vessel;
iii) Temperature sensors and neutron flux monitors for superconducting coils;
iv) Temperature distributions in RF launchers;
v) Internal measurements in neutral beam boxes, if NB heating is employed;
vi) Speed measurement and mass measurement at exit of pellet injectors;
vii) Neutron measurements, fluid temperatures and flow velocities in blanket modules;
viii) In-vessel inspection components (in a highly activated vacuum vessel);
ix) Instrumentation of versatile robotic equipment for remote maintenance.

Recommendation for the Virtual Laboratory:

An organized approach for developing the instrumentation necessary for Demo and fusion reactor operation is proposed. An advantage of the structure of a Virtual Laboratory is that it will allow for participation in the development programs of people from many institutions, particularly the Universities. These institutions will then be able to nurture new participants for the fusion program. The developed equipment will require prototyping and testing on operating fusion devices and radiation testing facilities, so providing excellent experience for these new experimentalists.

Such a facility would add to the U.S. Fusion Program's strong record of diagnostic leadership. This facility could be initiated immediately.

Costing:

An approximate costing of the necessary development over a ten-year period was suggested in reference 2, section 9.8 Appendix 2. After an exploratory period in the first year at ~$1M reaching to ~$5M in the fifth year (total for five year period ~$16M) a constant level of funding at ~$5M per annum should be provided thereafter. Note that these costs do not include the final implementation of an instrument on a Demo. A significant activity in the first year would be to develop a much more accurate cost assessment.

References:

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