Control of the Plasma and the Power Flow in a Reactor

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The present White Paper is the first of three concerning the issue of plasma control, which is taken here to include control of the power flow in addition to the main plasma parameters and profiles. This first paper identifies the individual issues that need to be addressed and does so in a systematic and comprehensive way. The second paper, “Evaluation of Technology Readiness for Physics-Oriented Issues”, addresses the need for quantitative measures of the status of the issues, and the prospects for the presently available techniques to be useable in ITER and a demonstration fusion reactor. It describes these needs in general terms, considering the Technology Readiness Levels, (TRLs) as described in the Theme III White Paper, “Evaluating gaps in fusion energy research using Technology Readiness Levels”, as an example. It then considers some of the general lessons that were learned in constructing the TRL Tables but that have an importance beyond the specific nature of TRLs. The third paper, “Technology Readiness For Control of the Plasma and Power Flow in a Reactor”, develops specific TRL tables and values for each of the control issues identified in the present White Paper. This is intended as an example to show how the TRL process can be applied to more physics oriented issues. The three companion White Papers are designated as WPI, WPII, and WPIII.

A comprehensive approach to plasma control requirements

Control of plasma shape and profiles essentially requires technologies for measuring a quantity and modifying it. This process can be divided into four steps:

(i) Identification of the required parameter value and acceptable range of variance. This is generally defined by the reactor design process and performance requirements.

(ii) Diagnosis of the current state. Generally the diagnostic involves a set of measurements from which the parameters of interest can be derived.

(iii) An actuator to modify the profile. Typically this involves controlling several kinds of input to the plasma that can be related in some quantifiable way to the parameter needing to be controlled.

(iv) An algorithm to translate the required change in the profile to the actuator or actuators controlling the input to the plasma.

The plasma parameters requiring control are strongly interrelated but can be broken down into seven categories where the parameters are more closely related within each category: global parameters; plasma shape; plasma current density profile; plasma rotation profile; plasma DT composition profiles. The latter category, however consists of two main elements: D-T ratios and impurity fractions that need to be considered somewhat separately, since the D-T ratio is critical for a fusion reactor and their diagnostics and actuator requirements are considerably different. Since the ultimate goal of the remaining plasma control issues is essentially to enable control of the power output from the fusion reactor, an additional issue to be considered is power handling control.

The issues are mostly fairly general but their relative importance clearly depends on the ultimate goal envisaged for the required technologies. The following White Paper (WPII) will consider the need for defining such a target as well as some of the consequences of this in more detail. For our purposes we consider the ARIES-AT design as the ultimate target since this has probably the most challenging requirements.

Plasma Control Issues

The following paragraphs are devoted to discussing each of these categories in turn. The discussion is intended to provide a fairly basic initial step toward treating these issues comprehensively and should therefore be expanded upon in the future. Within each category, there are then several specific parameters requiring control. These are listed in each case and a brief description of the current status in terms of the four steps required for adequate control is then provided. For this purpose, the issues are treated as independent. However, it needs to be kept in mind that they are interrelated. Integration is considered briefly separately.

a. Global parameters:

The key global parameters that are required to be controlled are fusion power, plasma beta and confinement quality. Overall, control of these global parameters is well understood from decades of tokamak operation. The required values and range are set by fusion power requirements and Plasma Operation Contour (POPCON) calculations. Measurements of these values are routinely performed in current experiments using diamagnetic loop measurements, and neutron rates and power flows to material surfaces, coupled with equilibrium reconstructions. The parameters can be modified by adjusting fueling, adjusting D-T ratios, and through control of transport barriers by various operational means – especially current ramp rates, and timing of auxiliary heating. Development of the required translation algorithms for converting the desired change in the global parameters to a change in the input fueling or operational details is generally through simple trial and error but more sophisticated time dependent 1 1/2 D transport calculations can be used to support more precise control.

b. Plasma Shape:

Control of the plasma shape includes control of plasma elongation, triangularity, and higher order shaping, especially squareness and divertor balance. The status of control of plasma shape is also well advanced. The required values and ranges are set by the design process. Plasma shape is relatively easily diagnosed in current experiments by measurements using external magnetic loop measurements coupled with equilibrium reconstructions. These parameters can be modified as needed through control of the external poloidal field coils and the translation algorithms required for this are well established since they are routinely applied and automated in all major tokamaks. Elongations up to 3 to 1 and triangularity ~ 1 have been obtained in those machines with the poloidal field coils equipped to reach these extremes. Attainment within the needed tolerances of the shape values specified in the ARIES-AT design, for example, is routine.

c. Plasma Kinetic Profiles:

Plasma kinetic profiles includes the electron and ion pressure, density, and temperature profiles. Control of these profiles is a key feature of all advanced scenarios. The required profiles and ranges are set by the design process, with $T_i \sim T_e$ and n_e set from fusion cross section requirements and the ranges determined from sensitivity calculations. The profiles are currently measured using Thomson scattering and Charge Exchange Recombination (CER) diagnostics and can be modified by pellet injection, gas puffing, and Neutral Beam input, as well as Radio-Frequency (RF) wave heating and divertor pumping. However, there is some level of profile consistency or resilience that presently limits how much these techniques can control the profiles. This will be more true when significant alpha heating is present. Translation of the desired profiles to fueling input typically requires deposition calculations for pellets, RF, beams, and gas. These need to be coupled to equilibrium reconstructions and transport simulations. In addition, for fusion relevant plasmas, alpha particle slowing down and heating calculations will be required but the tools needed to calculate these already exist. These tools, however, will need to be benchmarked against actual data in a relevant environment. Presently, no such environment exists.

d. Plasma Current Profile:

Control of the current density profile, or equivalently, the safety factor, is a key element in Advanced Scenarios. Current profile control techniques are fairly well developed and present experiments are moving to closed loop. The required current profile and allowable range are set by the design process and coupled with sensitivity studies. The current profile in present devices is usually measured using the Motional Stark Effect (MSE) to find the magnetic field pitch angle and which requires at least a diagnostic Neutral Beam. The local current density is then found from the pitch angle using an equilibrium reconstruction. Polarimetry has also been used to diagnose the current density but has generally not been particularly successful. Modification of the current profile is achieved by noninductive current drive from various waves but the efficiencies attainable are generally low and most schemes are expensive. These include electron cyclotron (EC), Lower Hybrid (LH), and ion cyclotron radio frequency (ICRF) waves. The Advanced Scenarios typically compensate by attempting to maintain a large fraction of the current using the bootstrap current generated from the pressure gradient profile so that only a small part of the current is driven by the waves. However this provides additional strong constraints on the stable profiles that are allowed and that are not easily reconciled. The algorithm to translate the desired current profile to input current drive requires ray tracing and current drive deposition calculations, which are well known.

e. Plasma Rotation Profile:

Plasma rotation profile control is a key issue for advanced but not for conventional scenarios. In the advanced scenarios, the required rotation values and profile are set by resistive wall mode stability and possibly confinement requirements. The minimum generally needs to be satisfied only and extremely fast rotation is theoretically destabilizing. The key physics involves the main ion rotation but this is not well diagnosed; impurity rotation profile measurements are typically done using CER and the main ion rotation is inferred from it. The main ion rotation profile can be modified by momentum input from Neutral Beams. This is the main actuator in current experiments but the momentum input may be insufficient in a large burning plasma environment. Drag from non-axisymmetric error fields can also slow the edge rotation but this can introduce additional undesirable effects. Translation of the desired rotation to beam input requires beam deposition, angular momentum transport, particle loss, and magnetic drag calculations. Of these, the physics of angular momentum transport and magnetic drag is an ongoing area of research but significant progress has been made in the past few years.

f. DT fuelling Profile:

The D-T ratio is relatively easily controlled by fueling and the required values are set by fusion yield calculations with the allowable range adjustable during operation. Diagnostics for the D-T mix are obtained from global measurements of neutron rates and fusion power, which are easily diagnosed. D-T ratio profile measurements can also be obtained; this was done, for example, in TFTR. The global mix and profile are fairly easily modified by a combination of Tritium neutral beam input, and pellet fuelling, and some additional control can be obtained through controlling the isotopic differential transport rates. Translation of the desired D-T ratios to fueling input requires deposition calculations for beams and alpha particle slowing down and heating calculations. One can expect to be able to empirically determine needed adjustments in D-T fueling in an actual reactor during initial operation.

g. Plasma Impurity Composition Profile:

In contrast, impurity and alpha ash are not easily controlled. This requires control over the relative particle and heat transport rates. The values and allowable range are set by the desired fusion yield. The impurity profile density and temperature can be diagnosed using CER. The profile can be modified by altering the balance between the particle and energy confinement. MHD fluctuations from sawteeth and edge localized modes (ELMs) appear to be the main tool that can be used to control ash accumulation. Translation of the desired ash and impurity concentration to MHD fluctuation size and frequencies requires detailed impurity transport calculations as well as some advances in the physics understanding of these processes. ELM and sawtooth frequency and size control will also be needed. These are currently active areas of research. Some techniques such as temperature and density transport barriers exist for selectively transporting impurities but are not yet reactor relevant. Some ELM-free regimes hold promise. However, even moderate sawteeth and ELMs are problematical in a large fusion experiment and there are few other tools available for modifying the particle and energy confinement balance.

Control of the Power Flow

For the issue of control of the power flow, we begin from the premise that all the power flow channels need to be controlled simultaneously; the energy release pathways from multiple channels need to be controlled adequately so that power levels, peaking factors and safety factors, both volumetrically and on surfaces, can be regulated and the energy extracted reasonably and efficiently. The energy release pathways are identified as radiation, including neutrons, heat and thermal particle flows, and high energy, superthermal particle fluxes. Radiation is volumetric, the heat and thermal power fluxes originate at the plasma surface and are directed to a specific area such as a target divertor plate. The superthermal particle fluxes tend to be highly directed and localized but unpredictable. The present H-mode plasma solution envisages a detached radiative divertor in which the thermal fluxes are cooled via enhanced radiation in the divertor region before reaching material divertor surfaces.

In terms of the four components of a control system identified earlier, values and allowed ranges are set by the reactor design and material limits. Diagnostics may be required in a reactor to know in real time what the power flows really are. Actuators are essentially through the control of the plasma parameters and profiles, as discussed above, especially the shaping and edge profiles. Algorithms will require a simulation capability coupling the edge and core plasma transport and radiation processes as well as ELM and sawtooth stability models. There is currently a lack of a working comprehensive coupled simulation capability but efforts are underway in various places to address this in various simulation initiatives. Presently, the most serious gap is in the predictive capabilities of simulations of the divertor and the plasma edge particle and energy flows. Codes such as UEDGE, for example, can reproduce experimentally measured data but only with considerable additional experimental input. A true predictive capability is currently wanting. The present situation, where additional experimental input is needed, may be sufficient for forming the basis of an algorithm that can translate the required power flow balance adjustments changes into the required plasma and divertor parameter changes. But it is not clear that this can yet be done in real time, or that it could be in future, let alone as part of a full coupled plasma simulation.

Integration Issues

There are serious questions concerning simultaneous control of all the required control elements. The temperature and density profile also contribute to the current density through the bootstrap and Pfirsch-Schluter currents. Fuelling and impurity profiles are also strongly coupled to the main ion kinetic profiles and using transport barriers to control one affects the other, as well as the rotation profile. There is also a synergism between shaping and profiles. Integration issues are mainly incorporated into the algorithm development. Most of the envisaged algorithms incorporate equilibrium calculations and even full 1 1/2D transport simulations. This seems likely to be a necessary element for the integrated control system. These integration and simulation issues are currently an active research area at multiple sites.

Applicability of Presently Available Solutions to ITER and DEMO

The solutions described above for present experiments may or may not be applicable in either ITER or DEMO. Following are some of the more problematic issues:

Ultimately, the diagnostic and actuator technologies need to survive in a BPX environment. This is a serious requirement and it is important to gauge the confidence level that the current state of research can be extrapolated to a final reactor. The most import change in moving to ITER is, of course, the thermonuclear environment. The key difference between ITER and a DEMO reactor, however, is the total neutron fluence. In general, most of the plasma control parameters and profiles appear to be applicable to ITER with only modest changes for the nuclear environment. Most of the actuators and algorithms should be directly applicable. The most important exception here is in the rotation, as the only well studied actuator, neutral beam input, may be inadequate. For Advanced Scenarios, more control over the actual rotation profile may be needed. This is also true for the extrapolation to a DEMO reactor.

For the diagnostics, however, there are serious issues. Many of the diagnostics planned in ITER may survive there but not in the far higher fluence in a DEMO and will need to be reconsidered. Direct line of sight windows will be disallowed and diagnostics will need to rely on reflected beams. Sensitive collectors and surfaces will need to be protected.

Control of the power flow is even more problematic. The present state of understanding is that the present H-mode radiative divertor solution works in present devices but scale up to a reactor such as ITER or DEMO is highly uncertain for several reasons. First, the basic scalings for runaways are poorly known. In present experiments runaways are not a serious problem and amplification factors (amplification of the number of runaway particles from an initial seed) are of order one to five. Projections obtained by scaling between smaller and larger tokamaks suggest much larger amplification factors for ITER and DEMO; in ITER it is expected to be at least an order of magnitude larger and, in DEMO, even larger. Neither the actual factor, nor the consequences of large amplification are well understood but it is generally anticipated that the resultant, highly directed, high intensity electron beams exiting the plasma could cause serious damage to the vessel and surrounding structures. Second, projections suggest the parameter window in power flux to the plasma edge may become too small or non-existent for obtaining proper detachment of the radiative region; the scaling indicates that the volume needed for the radiative divertor in a reactor may be so large as to seriously degrade the plasma performance. Third, additional fluctuations in the power flux from ELMs and sawteeth above the baseline level may be too large to handle. The best present estimates suggest only very small fluctuations may be tolerable. Most measures aimed at minimizing fluctuations also reduce plasma performance or add new technical issues; for example, the most promising technique is to use nonaxisymmetric coils inside the vacuum vessel, which degrades performance and is technically undesirable. Other possibilities involve degrading the high quality edge confinement by impurity seeding or other means.

Recommendation

Any thrust in plasma control must:

(i) Focus on all three aspects of the problem, and specifically on the diagnostics side which has traditionally been ignored

(ii) Demonstrate that conflicting control requirements can be resolved in an integrated system

(iii) Take account of the large difference in neutron fluence between current experiments and ITER and a true DEMO. Some current well developed techniques may never be appropriate in DEMO and new techniques will have to be developed

Particular areas of concern in this regard are:

(i) A solution to the divertor problem is the most glaring gap.

(ii) Diagnostics are generally left out of consideration in a reactor but will be needed. This is a serious issue in DEMO due to the far larger fluences than have been encountered so far.

(iii) A full comprehensive real time modeling capability is needed to provide a sufficient level of detail to be able to translate desired changes in key fusion output parameters into control signals for the plasma control actuators

Acknowledgement

The author wishes to acknowledge many enlightening discussions with many colleagues at DIII-D and the ARIES Group. Nonetheless, the views expressed here are solely those of the author.