Technology Readiness For Control of the Plasma and Power Flow in a Reactor

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The present White Paper is the last 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. The first paper, "Control of the Plasma and the Power Flow in a Reactor", identifies the individual issues that need to be addressed. 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 present, third paper develops specific TRL tables and values for each of the control issues identified in the first White Paper. This is intended as an example to show how the TRL process can be applied to more physics oriented issues, as opposed to the more engineering issues for which they were designed. The three companion White Papers are designated as WPI, WPII, and WPIII.

Technology Readiness Level Tables

The role of Technology Readiness Levels, (TRLs) in quantifying the status of a given technology with respect to its intended use was described briefly in the accompanying White Paper (WPII) and in detail in the Theme III White Paper "Evaluating gaps in fusion energy research using Technology Readiness Levels". As an example of this applied to a more physics oriented issue, a set of TRLs was constructed for the two issues of control of the plasma and control of the power flow that were described in the accompanying White Paper WPI. The construction follows the procedure summarized in the accompanying White Paper WPII.

All the plasma control issues are similar enough that a single generic TRL table can be constructed that is applicable to them all. The power distribution issue, however, is sufficiently different that it requires its own set of descriptions of the requirements. The respective tables are shown in Tables I and II.

TRL Values for Plasma Control

Using the TRL definitions in Table I, individual TRL values can then be assigned to each of the seven categories for plasma control identified in the accompanying White Paper WPI. The following paragraphs discuss the evaluation for each of these categories in turn. The values given reflect an overall evaluation for the category, mainly driven by the status of the most limiting element. Values are assigned according to the descriptions in the TRL Tables of what is required to reach that level and the evaluation is performed for two possible targets, the modest extrapolation scenario and the more ambitious advanced scenario described in the accompanying White Paper, WPII. However, the philosophy of dynamic control is assumed. With that assumption, diagnostics are considered an integral and necessary component. The confidence levels for scaling up to the final target, as described in the accompanying White Paper (WPII) are also discussed.

a. Global parameters:

The specific global parameters that are required to be controlled are fusion power, plasma beta, confinement quality, and heat and radiation loads. Overall, we can conclude that control of global parameters is unlikely to be an obstacle. Under either the modest extrapolation scenario or the advanced concept scenario, the current TRL can be rated as 5, limited only by the lack of facilities needed to test the scale up to fusion conditions. In addition, one can assign a very high confidence that the diagnostic, actuator, and algorithm techniques currently available will scale if applied in a BPX.

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. Overall, control of plasma shape rates a moderate TRL. For the modest extrapolation scenario, the current TRL can be assigned a value of 5. For the advanced concept scenario, where optimization of the plasma shape is more crucial, the current TRL is naturally lower at a value of 4. There is high confidence that the techniques currently available will scale to a BPX. However, there is a concern that the stringent divertor requirements may limit the higher triangularities needed for the most advanced scenarios.

c. Plasma Kinetic Profiles:

Plasma kinetic profiles includes the electron and ion pressure, density, and temperature profiles. At present, control of kinetic profiles is still an active area of current research being one of the foci of the Advanced Scenario. For the modest extrapolation scenario where active control of the profiles is not a key element, the current TRL is assigned at a value of 4. For the Advanced concept scenario, where profile control is crucial, the current TRL = 3. Direct application of the diagnostic techniques to a BPX is not expected to be an issue. However, extrapolation of the actuator techniques to a BPX is limited to the extent that alpha heating will then dominate the temperature profile evolution.

d. Plasma Current Profile:

Control of the current density profile, or equivalently, the safety factor, is a key element in the Advanced Scenario. Present research is actively focused on current profile control and for the modest extrapolation scenario, the TRL is currently assessed at 4 and for the Advanced concept scenario at TRL = 3. With respect to the extrapolation prospects, the MSE diagnostic scales well to the higher fields expected but current drive techniques have some scaling issues. In particular there are density limitations to each of the current drive schemes. While the efficiency generally scales with temperature, which is favorable, the required driven current also increases. These issues need to be resolved.

e. Plasma Rotation Profile:

Plasma rotation profile control is a key issue for advanced but not for modest extrapolation scenarios. For the modest extrapolation scenario with limited need for rotation control, the current TRL = 4. For the Advanced concept scenario, however, the current TRL should be assigned a value 2 or lower, limited mostly by the lack of actuators that can control the profile details in a predictable way. In a BPX, while the rotation profile can be diagnosed, few methods to modify it appear to exist without large high voltage neutral beam input. It may also be possible to modify the edge rotation using external rotating nonaxisymmetric fields and this is an active area of research.

f. DT fuelling Profile:

With the Tritium neutral beam input and pellet fuelling options envisaged, for both the modest extrapolation and advanced concept scenarios a current TRL value of 4 can be assigned. There is a high confidence that present techniques will scale to BPX conditions.

g. Plasma Impurity Composition Profile:

In contrast, impurity and alpha ash are not easily controlled. Current TRL values assigned for the modest extrapolation scenario and advanced concept scenario are 3 and 2 respectively. It is not clear how any of the control techniques will scale to a BPX. In particular, use of even moderate sawteeth and ELMs to control impurities and ash is problematical in a large fusion experiment. There seem to be few other tools available for modifying the particle and energy confinement balance.

TRL Values for Plasma Control of the Power Flow

TRL values can be assigned to the issue of power handling using the TRL definitions in Table II. In this case, the requirements for two possible targets are essentially the same and a single value is assigned.

For this issue, the present state of understanding is that the radiative divertor solution works in present devices but scale up to a reactor such as ITER or DEMO is highly problematic for the reasons detailed in WPI, namely the poorly understood scaling of runaway amplification, the projections for the volume required to obtain divertor detachment, and the fluctuations from ELMs and sawteeth may be intolerable. Given these considerations, a TRL value of 4 is assigned for the present status but the confidence for scale up to a reactor is low.

TRL Values Assuming ITER is Successful and Resulting Gaps

All of the TRL values assigned are limited to below level 5 and 6 simply by the lack of appropriate facilities available. A useful exercise in identifying gaps is to assign TRL values taking the assumption that ITER successfully completes its mission. For most of the plasma control issues this results in a moderate increase from the current status value. In this evaluation, ITER is considered for plasma control purposes as a 'relevant environment', making a TRL = 5 and 6 accessible, consistent with the specific descriptions in the TRL tables I and II. The result is that in each category, the TRL value is raised to 6 for the modest extrapolation scenario and to 5 or 6 for the advanced scenario.

The assumption that ITER is a relevant environment is arguable, but the argument for it is that the plasma conditions in ITER should not be significantly different from those in DEMO in terms of field strengths, temperatures, densities, alpha particle, and radiation environments. This includes having 14 MeV neutrons. Hence, in a rough sense, the plasma control issues are expected to be not that much different. The transition from long pulse to steady state is reserved in the TRL descriptions for level 8 and the key differences are time scale, robustness, and total fluence. For the time scale, in a plasma physics sense, ITER should run for many times the longest relevant plasma physics time scales since it was designed to do that – this determined the minimum pulse length for ITER. There may be additional longer term time scales that come into play mostly probably related to materials science. But ITER should at least discover those issues. For the basic plasma control issues, the long pulse is effectively infinite.

ITER cannot be considered in any sense as an 'operational environment', however. The key differences between ITER and a target DEMO reactor are the steady state conditions and the consequent much larger total neutron fluence. The control systems need to operate robustly over essentially the lifetime of the reactor and subject to a much larger neutron fluence than in ITER. Most worrying, many of the diagnostics planned in ITER may survive in ITER but not in the far higher fluence in a DEMO and will need to be reconsidered.

Three major problems need to be solved between ITER and DEMO and these must be addressed in achieving levels 8 and 9. Two of the issues are related to the difference between long pulse and steady state – the total fluence and robustness. The third is related to the more commercial aspect of DEMO and is the issue of limited diagnostic access available. While ITER is designed to contribute to a maturation of the physics issues, it also should contribute at least to a maturation of the more technologically oriented issues, including those of the diagnostic capabilities.

(i) The flux in DEMO is not much different from ITER but there this is a very large difference in the fluence from DEMO and this is the key problem DEMO must face. The effect of high fluence on diagnostics is the most serious problem. There are some ideas around now but it is not being addressed in any systematic way. Apparently, this is tentatively planned to be addressed in ITER Phase II but it is not the priority for ITER.

(ii) Robustness, cannot be dismissed. The techniques used in ITER for the diagnostics and actuators may be insufficiently robust for DEMO. The key concern in DEMO is that there should be no windows having a direct line of sight between the main plasma volume and the outside world. This means diagnostics relying on collecting or emitting photons (or other particles or radiation) must rely on reflections. This is not an insurmountable problem unless the diagnostic relies on measuring the polarization.

    For most AT solutions the key issue limiting operational robustness is the possible formation of steep internal transport barriers leading to runaway pressure peaking and fusion rate and a disruption. This is a bifurcation event so in the neighborhood of this parameter choice the system is inherently non-robust. ITBs can apparently be avoided if the minimum of q is far enough out but the physics is still not fully understood so it is not clear if this is just due to the operational constraints needed to keep the minimum of q far enough out.

(iii) ITER should reveal how much of its diagnostic capability is really necessary. This can also be done using the other machines expected to be available before ITER, namely KSTAR and EAST. But the real answer probably will not be fully known even after ITER unless ITER itself designates real time to looking at it.

Discussion

It is worth noting that it is not surprising to get a high TRL value for plasma control after ITER since ITER is a physics experiment designed to demonstrate that a thermonuclear plasma can be controlled in long pulse and we already have 20 years of experience with plasma control research. On the other hand, the step to TRL = 9 is large and problematical and the confidence levels for attaining that using the presently available solutions are quite low.

Note that, in the TRL for plasma control, the levels 3-5 address the transition from open to closed loop and this is an active and progressing research area. This makes a difference for the two different philosophical views of the AT: the dynamic view would take closed loop control as an integral part of the AT. The assumption of a dynamic view also means that diagnostics turn out to be the most limiting in terms of confidence estimates. It needs to be stressed that ARIES-AT effectively designed a system where the actuators – according to current knowledge – were adequate to control the plasma profiles. There is a disconnect, however, in that the ARIES-AT design did not include the diagnostics needed to measure what the profiles were. In that sense it was not dynamic control. It should be noted that all the new control systems in existing and planned experiments (especially DIII-D, ASDEX-U, KSTAR, and EAST) are designed to respond to diagnostic signals. As was pointed out in the accompanying White Paper WPII, it is not entirely clear that the passive view of control in either of the target reactor visions, where the actuators are set at predefined levels, and only very limited diagnostics are provided for, is feasible. It is difficult to imagine that the plasma will behave in the way designed with no excursions that need to be measured. Some compromise will need to be reached in providing diagnostics that still maintains the overall high level goals for the reactor.

Summary

The TRL values assigned are summarized in table III below. A confidence level for scaling up to the final target, TRL = 9, is also given as one of five levels – very low, low, medium, high very high – based on the discussion for each category. In addition, TRL values assuming ITER successfully completes its mission are given in brackets.

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.

Table I: Technology Readiness Levels for plasma control

High Level Requirement: Maintenance and Control of Stable Reactor Conditions			
Issue: Reliable Control of the plasma			
TRL		Generic Definition	Issue-Specific Definition
1	Concept Development	Basic principles observed and formulated.	Development of basic concepts for diagnostics and actuators for controlling plasma shape and profiles.
2	Concept Development	Technology concepts and/or applications formulated.	+Design of systems and hardware to diagnose profiles and systems to modify profiles in open loop in a moderate β plasma. Development of robust algorithms for translating diagnostic measurements to actuator signals.
3	Concept Development	Analytical and experimental demonstration of critical function and/or proof of concept.	+Demonstration of techniques for controlled plasma shape and profiles within approximate limits in closed loop in a moderate β laboratory plasma.
4	Proof of Principle	Component and/or bench-scale validation in a laboratory environment.	#Demonstration of controlled plasma shape and profiles within approximate limits in closed loop in a current high temperature plasma confinement experiment.
5	Proof of Principle	Component and/or breadboard validation in a relevant environment.	#Self-consistent integration of multiple techniques to control each of the required plasma parameters in closed loop in a current high temperature plasma confinement experiment.
6	Proof of Principle	System/subsystem model or prototype demonstration in relevant environment.	¶ Scale-up of diagnostic and actuator technologies to realistic fusion conditions. Demonstration that excursions from transient phenomena can be kept to a tolerable level.
7	Proof of Performance	System prototype demonstration in an operational environment	†Demonstration of the integrated plasma shape and profile control system with control of excursions from transient phenomena in a high performance reactor grade plasma in long pulse, essentially steady state operation.
8	Proof of Performance	Actual system completed and qualified through test and demonstration	§Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration.
9	Proof of Performance	Actual system proven through successful mission operations	Demonstration of the integrated plasma shape and profile control system in a steady state burning plasma configuration for lifetime conditions.

Notes:

+ This can be performed in either a dedicated laboratory plasma physics experiment or one of the current national facilities.

This should be performed in one of the current national facilities.

¶ This step should be performed in a dedicated planned experiment such as KSTAR.

† This step can be performed in KSTAR or in ITER running in high power mode.

§ ITER might be able to satisfactorily complete this step but it may require a burning plasma experiment. This may be a dedicated experiment or DEMO.

Table II: Technology Readiness Levels for control of power distribution

High Level Requirement: Economic power management			
Issue: Control of the plasma power flux distribution			
TRL		**Generic Definition**	**Issue-Specific Definition**
1	Concept Development	Basic principles observed and formulated.	Development of basic concepts for extracting and handling outward power flows from a hot plasma (radiation, heat, and particle fluxes).
2	Concept Development	Technology concepts and/or applications formulated.	Design of systems to handle radiation and energy and particle outflux from a moderate beta core plasma.
3	Concept Development	Analytical and experimental demonstration of critical function and/or proof of concept.	Demonstration of a controlled plasma core at moderate beta, with outward radiation, heat, and particles power fluxes to walls and material surfaces, and technologies capable of handling those fluxes.
4	Proof of Principle	Component and/or bench-scale validation in a laboratory environment.	*Self-consistent integration of techniques to control outward power fluxes and technologies for handling those fluxes in a current high temperature plasma confinement experiment.
5	Proof of Principle	Component and/or breadboard validation in a relevant environment.	#Scale-up of techniques and technologies to realistic fusion conditions and improvements in modeling to enable a more realistic estimate of the uncertainties.
6	Proof of Principle	System/subsystem model or prototype demonstration in relevant environment.	¶Integration of systems for control and handling of base level outward power flows in a high performance reactor grade plasma with schemes to moderate or ameliorate fluctuations and focused, highly energetic particle fluxes. Demonstration that fluctuations can be kept to a tolerable level and that energetic particle fluxes, if not avoided, at least do not cause damage to external structures.
7	Proof of Performance	System prototype demonstration in an operational environment	†Demonstration of the integrated power handling techniques in a high performance reactor grade plasma in long pulse, essentially steady state operation with simultaneous control of the power fluctuations from transient phenomena.
8	Proof of Performance	Actual system completed and qualified through test and demonstration	§Demonstration of the integrated power handling system with simultaneous control of transient phenomena and the power fluctuations in a steady state burning plasma configuration.
9	Proof of Performance	Actual system proven through successful mission operations	Demonstration of the integrated power handling system in a steady state burning plasma configuration for lifetime conditions.

Notes:

* This can be performed in current experiments. The detached radiative divertor concept is sufficient to satisfy this requirement.

This step may require an intermediate experiment between current devices and ITER, or an upgrade of a current device. As described in the background above, the detached radiative divertor may or may not scale up.

¶ This step is envisaged to be performed in ITER running in basic experimental mode.

† This step is envisaged to be performed in ITER running in high power mode.

§ This step will require a burning plasma experiment. This may be a dedicated experiment or DEMO.

Table III: ***Summary of current state and future prospects of key issues for plasma control***

Issue	Modest Extrapolation Scenario TRL	Advanced Extrapolation Scenario TRL	Scale up Confidence Level for TRL = 9
Global parameters	5 (After ITER: 6)	5 (After ITER: 6)	Very High
Plasma Shape	5 (After ITER: 6)	4 (After ITER: 6)	High
Kinetic Profiles	4 (After ITER: 6)	3 (After ITER: 6)	Moderate
Current Profile	4 (After ITER: 6)	3 (After ITER: 5)	Moderate
Plasma Rotation	4 (After ITER: 6)	2 (After ITER: 4)	Low
D-T Ratio	4 (After ITER: 6)	4 (After ITER: 6)	High
Impurities	3 (After ITER: 6)	2 (After ITER: 6)	Low
Power Flow	4 (After ITER: 6)	4 (After ITER: 6)	Very Low