# Establishing the Basis for Reliable Steady-State Fusion Power

E.J. Strait, D.L. Humphreys, J.R. Ferron, R.J. La Haye, and M.L. Walker, General Atomics
March 13, 2009

The operational requirements of ITER for pulse duration and stable operation are significantly more stringent than those of any present tokamak. However, the requirements of a Fusion Development Facility or DEMO power plant represent an even greater leap beyond those of ITER. As the first facilities to require fusion production runs for high-fluence materials testing and power production, they must operate reliably, with high availability, for pulse durations measured not in seconds or minutes, but in weeks and months. These requirements imply:

1. Robust equilibrium control to maintain the desired operating state
2. Active control of plasma stability, to maintain high availability
3. Prompt recovery of normal operation after off-normal events

Many of the plasma control tools to achieve these goals are now being developed. Concepts exist for others. In the next 10 to 20 years, these building blocks must be developed, and integrated into a control system that will ensure reliable, steady state operation of magnetically confined plasmas for fusion power. ***Development of integrated and reliable fusion plasma control is a potential research thrust that could allow the U.S. to play a leading role in the world fusion program.***

**1. <u>Robust equilibrium control</u>** is necessary in order to maintain the desired operating state. The plasma shape must be controlled accurately to ensure high performance while avoiding undesired contact with the wall. Equally important, maintaining the optimum energy confinement and plasma stability requires control of the internal profiles of pressure and current density, and perhaps also of rotation. New challenges will arise in the burning plasma environment due to strong self-heating of the plasma, a regime with which we have no experience yet. Areas in which research is needed include:

- Multivariable shape control algorithms, to maintain the plasma shape in a way that is consistent with power supply limits, even as the plasma pressure, current and internal profiles change.
- Actuators for modification of the pressure, current density, and rotation profiles, while using a minimum of circulating power.
- Actuators for burn control, to maintain full fusion power without excursions that could lead to MHD instabilities or other off-normal events.
- Reliable diagnostics for measurement of plasma shape and internal profiles, capable of steady state operation in a high neutron flux environment.
- Predictive understanding of the potential benefits of non-axisymmetric fields, e.g. in applying torque to the plasma, and controlling edge pressure gradient and edge stability.

- Well-tested control algorithms that will use these diagnostics and actuators to robustly maintain and vary the desired operating state as needed

Much development is needed in all of these areas. Although plasma shape control has grown increasingly sophisticated, true multivariable control is not yet in routine use. Feedback control of pressure, current density, and rotation profiles has been demonstrated in certain limited conditions, but is far from routine. Understanding of three-dimensional effects in tokamak equilibria is still in its infancy. Integration of these various aspects of plasma control will also require a significant effort.

Much of the development of these tools can be done in existing facilities, with increased operating time and additional diagnostics, actuators, and control systems. However, plasma control in a burning plasma environment, with large neutron flux and strong self-heating of the plasma, and diagnostics suitable for this environment, cannot be fully tested until ITER operates. Therefore, development of plasma equilibrium control will necessarily continue in ITER, toward ultimate use in FDF and DEMO.

**2. Active control of plasma stability** is necessary for sustained, full-performance operation. Fusion power depends strongly on plasma pressure, so power output is maximized by operating near stability limits. The rapid growth rate of most ideal MHD instabilities means that their stability limits must be detected and avoided. On the other hand, normal operation may lie beyond passive stability limits such as those for the neoclassical tearing mode or the resistive wall kink mode; these cases require active stabilization of the plasma. Research needs include:

- Real-time prediction of stability limits, through real-time MHD stability calculations.
- Real-time measurement of plasma stability, e.g. measurements of MHD damping rates with "active MHD spectroscopy"
- Actuators for modification of the pressure, current density, and rotation profile to avoid stability limits (closely related to the equilibrium control described above).
- Well-tested control algorithms that can steer the operating point away from an impending instability, without approaching any other operating limits.
- Actuators for localized current drive to stabilize neoclassical tearing modes or other magnetic islands.
- Coils for direct feedback stabilization of resistive wall modes or other slowly growing instabilities, consistent with operation in a nuclear environment.
- Sensors and actuators to detect and correct intrinsic error fields generated by asymmetries of the magnet coils, ferromagnetic components, and induced currents.

There has been significant progress in this area in the last 5 to 10 years, but much development is still needed. Feedback-controlled stabilization of neoclassical tearing modes and resistive wall modes, and feedback-controlled correction of error fields, have been successfully demonstrated, but are not yet in routine use. MHD spectroscopy has been successfully used in off-line analysis of specialized experiments, but development toward its routine use in real time is needed. Similarly, development of real-time MHD stability analysis is needed. Control algorithms to take appropriate action based on calculated or measured approach to stability limits also are needed. High bandwidth coils for feedback control and MHD spectroscopy may present a significant engineering challenge in a nuclear environment.

Virtually all of the development needed here can be done in existing short-pulse facilities, with suitable upgrades to diagnostics, actuators, and control systems. In the future, the emerging generation of medium-size superconducting tokamaks (EAST, KSTAR, SST-1, JT-60A) may eventually be able to demonstrate stability control in high-performance plasma for very long pulses. However, robust control of plasma stability for very long pulses, in a burning plasma environment, can only be demonstrated in devices such as ITER, FDF, and DEMO.

**3. Recovery from off-normal events** must be possible with minimal impact on availability. The equilibrium and stability control described above should, in principle, predict and avoid or actively suppress instabilities. However, some events cannot be predicted, such as failure of an actuator or a piece of foreign material falling into the plasma. These can lead to "off-normal" events such as ELMs, tearing modes, bursts of alpha particle loss, radiative instability, transition to L-mode, plasma contact with the wall, runaway electron generation, or disruption. In these cases, the consequences must be minimized. Control systems must be available that will recover normal operation if possible, or shut down the discharge with minimum impact in order to allow a prompt restart. A shutdown will have an impact on availability, and the previously described elements of normal operation must be robust enough that the shutdown response is seldom needed. Research needs include:

- Well-tested algorithms that can "repair" the damage to the discharge and recover a normal operating state, including re-establishment of specific pressure and current density profiles.
- Well-tested algorithms that recognize when recovery is not possible, necessitating a shutdown and restart.
- Actuators and procedures for a soft shutdown that can be accomplished quickly and with minimal consequences for the facility.
- Well-tested algorithms that recognize when soft shutdown is not possible, necessitating a rapid shutdown.
- Actuators (e.g. injection of a large quantity of radiating impurity) for a rapid shutdown that will avoid or mitigate possible damage to plasma-facing components.
- Validated modeling to provide predictive understanding of the possible consequences of various possible off-normal events, and of the intended means of responding to them.

Isolated elements of these systems to address off-normal events have been developed. For example, many facilities routinely apply a soft shutdown or retreat from high performance in case of loss of the desired operating state or onset of a tearing mode. However, return to full operation within the same pulse is rarely attempted. Methods for detecting the loss of actuators or sensors (of which there are many possible combinations) and shutting down the discharge are rarely applied on existing devices. Methods for recovering nominal operation after such a loss are almost nonexistent. Rapid shutdown by means of gas or pellet injection has received significant attention, motivated by disruption mitigation for ITER, but techniques to suppress runaway electrons during a disruption have not yet been assured. Algorithms to determine when and how to initiate a soft shutdown or a rapid shutdown – reliably but without a high rate of "false positives" – need to be developed.

Much of the development needed here can be done in existing facilities. The plasma energy, heat fluxes, and potential for runaway electron generation become much greater as the device size and toroidal field increase. Therefore, techniques for response to and recovery from off-normal events must be tested to the fullest possible extent in existing facilities, and then in ITER for the benefit of subsequent burning plasma facilities.

**4. <u>A U.S. research thrust to establish the basis for reliable steady state operation</u>** could make a major contribution to the world fusion program. The detailed research elements of such a thrust include the "bullet" items in sections 1-3 above. The high-level elements of this research thrust can be characterized as:

- Focused experimental effort to develop and demonstrate the individual control solutions outlined above, including appropriate diagnostics and actuators
- Focused modeling effort to develop and use both detailed, physics-based models of control solutions, and models suitable for real-time execution
- Focused experimental effort to integrate the control solutions and demonstrate their use to sustain high performance plasmas in near steady-state
- Focused research effort to incorporate individual models into simulations suitable for prediction of control for ITER, FDF, and DEMO, and to validate the simulations experimentally

Such a thrust is very well suited to the U.S. fusion program. <u>Key features of the existing U.S. facilities</u> include

- Extensive and mature diagnostic systems for equilibrium and stability measurements, some already interfaced to real-time control systems
- Actuators for equilibrium profile control, including heating, current drive, and torque from neutral beams, and RF systems for heating and current drive (electron cyclotron, fast wave, and lower hybrid).
- Versatile sets of non-axisymmetric coils (internal and external) for
  - Three-dimensional equilibrium modification
  - Active MHD spectroscopy
  - Direct feedback control of instabilities
- Other actuators for direct suppression of instabilities, including localized current drive
- Gas injectors and pellet injectors for rapid shutdown
- Sophisticated, extensible digital control systems

Present U.S. effort in the areas discussed here is broad, but thin. To address a significant fraction of these elements, on the time scale needed for ITER and DEMO, would require a significant commitment of resources, including:

- Modest facility upgrades, mainly in actuator power and diagnostics
- Moderate upgrades to the digital control systems, to allow more diagnostic inputs and greater real-time computing power
- Significant increase in operating time for
    - Development and testing of individual control elements
    - Demonstration of integrated controls under a wide range of operating conditions
- Significant increase in manpower for
    - Modeling and design of control techniques
    - Experimental testing and analysis of individual control elements
    - Integration and extensive further testing
    - Validation of models suitable to design controls for ITER and DEMO

---

**Related white papers submitted to ReNeW:**

"Active Realtime Control Issues and Role of a Fusion Development Facility" by D. L. Humphreys

"Off-Normal Events in a Fusion Development Facility" by E. J. Strait, J.C. Wesley, M. J. Schaffer, and M. A. Van Zeeland

"Holistic approach against performance-limiting instabilities in steady state plasmas" by Y. In, M. Okabayashi, E.J. Strait, H. Reimerdes, and R.J. La Haye

"Disruptions - A Personal View, by J.C. Wesley"

"Issue: Tearing Mode Avoidance and Stabilization" by R.J. La Haye

"Edge Localized Mode and pedestal control using resonant magnetic perturbation coils" by T.E. Evans Mar 3, 2009