Profile control in a steady-state advanced tokamak: a white paper for ReNeW

John Ferron, March 17, 2009

Issue

A steady-state tokamak as presently envisioned will operate with 100% of the current driven noninductively and beta near the ideal wall stability limit (e.g. betaN >5). A fundamental assumption for an advanced tokamak is that the current and pressure profiles are optimized so that these requirements for a steady-state tokamak can be achieved. This optimization of the profiles requires some degree of external control. There are large gaps in our present knowledge of how to implement the necessary control.

- In order to minimize the recirculating power in a reactor, the externally applied current drive and heating power should be minimized. This requires that as close to 100% of the current as possible should be self-generated bootstrap current (e.g. 90%) and that any external heating power should be much less than the power absorbed from alphas. Therefore, the actuators for profile control will be very weak. It will only be possible to make subtle changes in the current and pressure profiles. **How can advanced tokamak-type "optimized" profiles be maintained with only weak actuators available?** This includes the control required to both force the profiles away from the "natural" tokamak profiles to the optimum, if necessary, and return the profiles to the optimum after a perturbation. An advanced tokamak reactor design is typically based on an equilibrium with self-consistent current and pressure profiles. These are the natural profiles for an advanced tokamak. If the profiles envisioned by reactor designs actually exist, it may only be necessary to use control to maintain the equilibrium against perturbations.
- Advanced tokamak reactor designs have beta chosen to be within, for instance, 10% of the ideal wall stability limit. The consequence of crossing the stability boundary is a rapidly growing, global instability which will likely cause a disruption. The difficulty is not just in maintaining beta below the maximum stable value for a given set of profiles. If the current or pressure profile were to drift away from the optimum, the stability boundary could move so that the nominal operating beta is in the unstable region. Fluctuations in the discharge operating point could transiently move the discharge across the stability boundary. **How can the current and pressure profiles be controlled robustly enough and the fluctuations in operating point minimized in order to operate reliably near the ideal stability boundary?**
- Presently, the mechanism envisioned for control of the pressure profile is modification of the particle and energy transport profiles. **Is there a practical method available for control of the transport profiles and is this type of control necessary?**
- **If the actuators available to control a discharge with 90% bootstrap current operating within 10% of the ideal stability limit prove to be insufficient, how much must the performance of the discharge be reduced in order to make it controllable?**
- **How can self-consistent current and pressure profiles in a self-heated, steady-state discharge be controlled given the close coupling between the bootstrap current and pressure profiles?**
- Assuming that current drive actuators of sufficient strength are available, robust feedback control algorithms are required. **Robust, model-based current and pressure profile feedback control algorithms are not presently available.**
- **There has yet been no experimental demonstration of a steady-state discharge operating near the ideal wall stability limit with beta and betaN at the large values envisioned for an advanced tokamak reactor.**

- **Control algorithms and actuators must be developed to transition the discharge from the breakdown phase to the optimized profiles required for the steady-state phase.**

Research requirements

To address the issues described above, work on both externally-heated and alpha-heated discharges will be required, in both cases studying both strong and weak actuator configurations.

- The fundamentals of profile control must first be addressed. Model-based control algorithms must be developed and tested experimentally. Development of model-based algorithms includes experimental validation of simplified, control-appropriate plasma response models. This is best done in a strong actuator configuration to begin with, with the work transitioning to a weak actuator configuration.
- Existence proofs for the envisioned discharges are required. A steady-state discharge must be demonstrated in order to establish the requirements for accessing the steady-state configuration and maintaining it. This would first be done in a strong actuator configuration, but the demonstration must also be executed while using only a minimum of actuator power.
- Simulations of the steady-state discharge behavior should be validated against experimental discharges and then used to test profile control algorithms.
- The results from these three steps would then be combined to demonstrate control of a steady-state discharge at high betaN. This might first be attempted in a strong actuator configuration operating safely away from the beta limit. The operating point would then be moved toward the ideal stability limit and 100% bootstrap current fraction as much as possible. This work would establish how closely a controllable discharge exists to the idealized advanced tokamak steady-state discharge.
- The previous four steps will need to be executed first in an externally-heated experiment and then repeated in an alpha-heated discharge. Presumably, the state of knowledge when the alpha-heated discharge is attempted would be sufficient to allow most of the detailed work in the externally-heated case to be skipped.

Research thrusts

Two experimental research facilities will be needed.

1. An externally-heated device with the diagnostic and actuator capability required to demonstrate steady-state tokamak operation over a range of bootstrap current fractions and beta values. This facility requires the following:
    - Sufficient heating power to take the discharge to the ideal stability beta limit.
    - Sufficient external current drive capability to provide up to, for instance, 40% of the total plasma current so that strong actuator experiments will be possible.
    - Capability for discharge pulse length equal to a multiple of the resistive current relaxation time that is large enough to allow demonstration of steady-state operation with fully relaxed profiles.
2. A burning plasma device with capabilities similar to the externally-heated device described in the previous item.
    - The external heating power available would need to be a significant fraction of the alpha heating power anticipated in the full performance discharge in order to allow for steady-state operation at a range a performance levels.

- Similarly, the external current drive capability should allow for more than the weak actuator capability that might be required for the full performance discharge.