Control of Tokamak Plasmas

Controlled thermonuclear fusion has the potential to address the global need for sustainable energy. Energy can be generated by the fusion of deuterium and tritium (isotopes of hydrogen extracted from water and the Earth's crust) in a harmless way (no direct radioactive waste is generated and the radioactivity of the structure decays rapidly). Fusion devices using magnetic confinement of the plasma, such as tokamaks, can thus be envisaged as a major carbon-free energy resource for the future. Significant research challenges still need to be addressed, however, before tokamaks can be reliably operated and commercially viable. The controls community will play a crucial role in resolving these challenges.

Tokamaks

Tokamaks use a magnetic field to confine a plasma in the shape of a torus. The charged particles follow a helicoidal trajectory according to the field created by controlled magnets, which thus set the position and shape of the plasma. Radio-frequency antennas allow selective action on electrons or ions and modify internal plasma properties such as current and temperature. The plasma is fueled by pellets shot at high speed toward the plasma center, and neutral particles are injected to increase the plasma momentum and energy.

The ITER Tokamak, an international project involving seven members (the European Union, Russia, the U.S., Japan, China, Korea, and India), plans to start operation during the next decade. It is expected to produce 500 MW from 50 MW of input power.

Tokamak control is becoming increasingly important to the success of magnetic fusion research and will be crucial for ITER. Feedback control of the main plasma macroscopic parameters, such as plasma position and shape, total current, and density, is now reasonably well mastered in the various worldwide tokamaks. However, control of internal plasma dynamics and radial profiles (1-D distributions) is still in its infancy. This control is likely to be crucial for robust stability and to maintain high-efficiency tokamak operation.

Challenges in Plasma Physics for ITER

New control methods will be required for meeting five important objectives for tokamak operation.

C1 – Magnetohydrodynamics (MHD) stabilization: Nonaxisymmetric electric currents cause perturbed magnetic fields inside (e.g., magnetic islands) or outside (e.g., resistive wall modes) of the plasma, as well as central plasma relaxations (e.g., sawteeth). MHD instabilities evolve at a fast time scale (~ 10^{-6} – 10^{-3} sec) and need to be addressed in both the poloidal and toroidal directions.

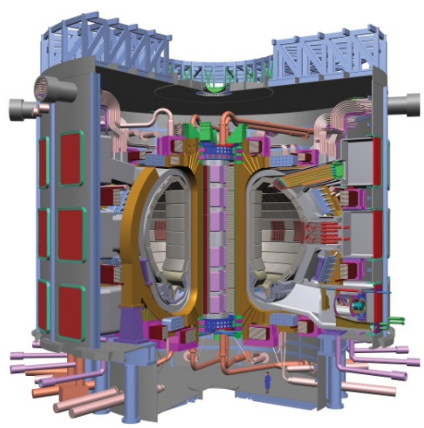
C2 – Heat confinement: The plasma core must be at very high temperatures (up to 150 x 10^6 K, 10 times the central temperature of the sun) while having an edge temperature that can be sustained by the plasma-facing components. Maintaining large temperature gradients is thus essential to achieving an efficient "burn" control while preserving the plasma shell.

C3 – Steady-state operation: "Steady-state" dynamics evolve more slowly than the current density diffusion time (~1 – 100 sec) and relate to the ability to continue the tokamak operation indefinitely; that is, the plasma pulse is terminated by the operator's choice. The so-called "safety-factor" q (calculated as the ratio between the toroidal and the poloidal magnetic flux gradients) and the pressure profiles provide indicators on the potential avoidance of MHD instabilities.

C4 – Control of plasma purity: An impurity flux is driven by different transport phenomena (e.g., ash transport, gas puffing at the plasma boundary, and impurity removal) as well as plasma-wall interactions. This problem is related to both design aspects (e.g., optimal diverter and plasma-facing components) and real-time feedback.

C5 – Plasma self-heating with α-particles: The α-particles (He^{2+}) produced by the fusion reaction are charged and are trapped by the magnetic field, transferring their energy to the plasma. They thus provide an extra heat source and induce a local nonlinear feedback. Anisotropic transport analysis and burn control must be combined to control this phenomenon.

Although each of the above challenges is mostly considered as an independent control problem, the automation system will ultimately have to deal with the strong couplings that exist between the various plasma dynamics and the multiple roles of each actuator. For example, the q-profile is a key parameter for both the global stability of plasma discharges and an enhanced confinement of the plasma energy (C1 and C3). Other examples include the couplings between the temperature and the safety-factor dynamics (C2 and C3), and the multiple effects of using an RF antenna at electron cyclotron frequency (C1, C3, and C5).



The ITER Tokamak (www.iter.org)

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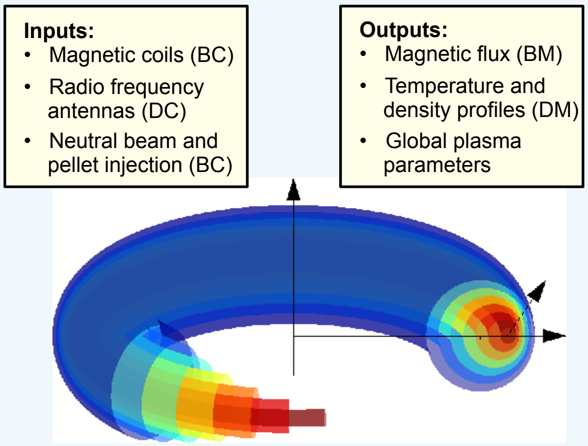
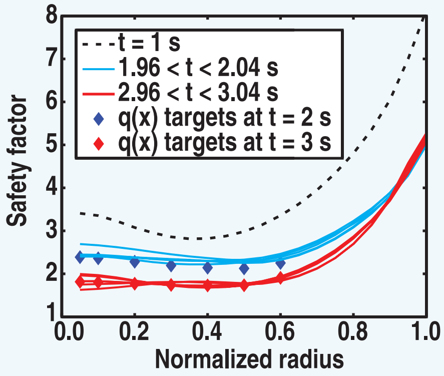
Tokamak Automation

The plasma in a tokamak is actuated with magnetic coils of various sizes and positions, with antennas emitting at different radio frequencies, and with the injection of pellets and neutral particles. In terms of sensing capabilities, distributed measurements of the temperature and density are available, along with the boundary values of the magnetic flux. Real-time equilibrium reconstruction codes provide virtual sensors for the magnetic flux inside the plasma. The resulting integration and sensor fusion of complex diagnostics, combined with the assignment of the actuators to specific regulation tasks, pose control-engineering challenges.

Example: Safety-Factor Profile Control

For "steady-state" operation, the state-space variables can be averaged on surfaces of identical magnetic flux (identified with different colors on the left figure below), and the radial profile is regulated in the 1-D space. Both boundary and distributed controls (BC and DC) and measurements (BM and DM) are available. The first experimental results (right figure below) of integrated control of the safety-factor and pressure profiles were published in May 2013 (Moreau et al., *Nuclear Fusion* 53, 2013).





Experimental results of controller capability to track changes in the target safety-factor profile q(x) (at t = 2 and 3 sec), from an arbitrary value (at t = 1 sec)

Control Challenges for Distributed-Parameter Systems

The control issues associated with tokamaks involve the spatiotemporal dynamics of transport phenomena (magnetic flux, heat, densities, etc.) in the anisotropic plasma medium. The physical models typically involve inhomogeneous partial differential equations (PDEs, mostly of parabolic or hyperbolic type) with transport coefficients that differ by several orders of magnitude, depending on their location, and involve nonlinear couplings between the physical variables. New results are thus sought on the following topics.

Identification and estimation, possibly with unknown inputs, of time- and space-varying transport parameters. The wide range of tokamak instrumentation provides an exceptionally rich database for evaluating new estimation strategies in the PDE framework.

Stabilization with computation constraints for high-order linear systems with multiple time-varying delays. Such models can be used to describe convective transport and MHD instabilities based on modal analysis.

Robust PDE control for the regulation of 1-D transport equations (e.g., safety factor, temperature, and density), which results in a profile control in the radial direction.

Optimal reference design to provide scenarios that integrate the multiple coupling constraints for the feedback strategies. These scenarios can be computed offline and use advanced physical models that include the complexity of plasma interconnected dynamics.

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