Integrated Modeling Needs for Plasma Control Design

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A substantial theoretical and experimental physics effort has been going on for decades to develop predictive models for plasma evolution in toroidal plasmas. Unfortunately, plasma control design has not fully benefited from these developments since most of these physics-oriented models are not tractable from a control-design point of view. There is an urgent need for generation of control-oriented models, or conversion of detailed physics models to forms useful for control design. This represents at the same time an immense opportunity for plasma theorists to strongly impact tokamak operation by enabling model-based plasma control design.

There are basically two stages in control design, namely control synthesis and control simulation. During control synthesis, control-oriented models can be embedded in the synthesized controller or estimator in order to incorporate the physics of the plasma and to cope more effectively with the complexity of its dynamics. Moreover, these models are absolutely crucial for the *study of controllability and stability boundaries*, and for the *design of actuator sharing and control integration strategies*. Applications of control-oriented models in control synthesis include:

- *Feeforward controllers*: Computed off-line, implemented in open loop, designed to achieve desired plasma state by optimizing control laws for the different actuators. Potential systematic model-based approach to scenario planning (predictive model coupled with optimizer).
- *Feedback controllers*: Computed on-line, implemented in closed loop, and designed to add robustness to the control scheme by rejecting plasma variability, external disturbances and initial-conditions perturbations, and by accounting for model uncertainties. Model capturing plasma response to available actuators is embedded in controller to increase performance.
- *State estimators (observers)*: Computed on-line, implemented in closed loop, and designed to reconstruct plasma internal states from a limited number of noisy diagnostics by filtering measurement noise not consistent with physics (model) and regulating tradeoff between real-time model prediction and diagnostic data. Potential use for fault detection and isolation.
- *Real-time optimizers*: Computed on-line, implemented in closed-loop, and designed to adapt control laws to future plasma conditions predicted by faster-than-real-time simulations in order to keep the plasma operating point within changing controllability and stability boundaries, which are also computed in real time based on available models, and to avoid disruptions.

During control simulation, control-oriented models are used to test in closed-loop the controllers developed during the control-synthesis stage in order to evaluate their performance and to assess the readiness for experimental implementation.

These technologies are critical to operation of future devices beginning with ITER, and so are the prerequisite control-oriented models for both synthesis and simulation. Modeling needs for control synthesis and control simulation are indeed significantly different, and they are at the same time extremely different from modeling needs for physics-oriented simulations. To be tractable from a control-design point of view, the complexity of models used for the synthesis of feedback controllers, state observers and real-time optimizers usually needs to be lower than that of models used for the synthesis of feedforward controllers or for the performance evaluation of controllers in closed-loop simulations. Feedforward control synthesis, which is a combination of an optimization scheme with repetitive open-loop simulations, and closed-loop simulations are carried out off-line, which allows for higher model complexity and accuracy at the expense of a larger simulation time. Feedback controllers and state observers must run in real time, while models used for real-time optimization must be simulated faster than real time, which can only be achieved at the expense of lower model complexity and accuracy. Fortunately, all these control solutions are implemented in closed-loop, which is tolerant of lower model complexity and accuracy since one of the main characteristics of feedback is its ability to deal with model uncertainties. Therefore, the control-oriented models used for control simulation (and for feedforward control synthesis as a special case of control simulation) must be reduced further in complexity before being used for feedback control synthesis. The control-oriented models used for control simulation need however to be much less sophisticated than those powering predictive codes such as TRANSP, CORSICA or ONETWO, which are used for physics studies. A control-oriented predictive simulation code must be capable of running full-discharge closed-loop simulations in at most a matter of minutes to be an effective tool for iterative control design.

Physics-oriented predictive codes such as TRANSP, CORSICA or ONETWO were never designed for closed-loop simulations. Although extraordinary progress has been made recently to provide them with this capability, several limitations remain and prevent them from being systematically used for plasma control design by control scientists. First, control scientists must go through a very steep learning curve to be able to run these predictive simulation codes. Even when this is achieved, the capability of dealing with runtime errors is usually outside their domain of expertise. Overcoming these common runtime errors, which are often generated by the tested controller, requires the intervention of code experts outside the home institution, which hampers the control design process. Second, control scientists may not be familiar with the programming language used. Moreover, this programming environment does not provide the versatility of other control-oriented programming tools such as MATLAB/SIMULINK (world-wide-accepted software standard for control design and simulation), which makes the implementation of a controller in these physics codes cumbersome. Finally, and probably most importantly, the time required by these predictive codes to simulate a full discharge is prohibitive for control design, which requires an iterative process based on simulation and redesign. Therefore, the development of a fast, control-design-friendly, closed-loop simulation capability is at the core of present model-based control design needs for disruption-free tokamak operation.

As ITER's construction progresses, it is essential that funding agencies and the fusion community leadership direct efforts on integrated modeling not only at increasing our plasma physics understanding but also at *enabling model-based control design for tokamak operation*. As discussed above, the development of plasma response models capturing only the dynamics that is relevant for control design will enable the design of critical plasma control components by providing *fast off-line*, *real-time*, and *faster-than-real-time* simulation capabilities. The level of model reduction that physics-oriented models must undergo before being suitable for control design depends heavily on the intended application (simulation vs synthesis, off-line vs on-line, open-loop vs closed-loop). While control scientists are capable of carrying out this model reduction using standard techniques (e.g., spatial discretization, volume averaging, linearization), the approach is risky because they may inadvertently neglect valuable physics. It is far more effective for plasma theorists to develop these control-oriented models, while still capturing the nonlinear spatially-distributed nature of the fusion plasma, by directly tailoring their complexity and accuracy to the intended control-design application. This creates new research opportunities for plasma theorists with huge potential benefits for tokamak operation, and will attract many more talented control scientists to fusion research.