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Integrated control on TCV including real-time monitoring, supervision and actuator management

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For long-pulse scenarios in large tokamaks like ITER, supervising the plasma discharge evolution and sharing a limited set of actuators for multiple purposes are increasingly important [1]. This requires reliable real-time (RT) plasma state reconstruction, monitoring and supervision, actuator management (AM) and controllers. Following a generalized integrated control framework, all the above mentioned components have been implemented and RT control of neoclassical tearing modes (NTMs), of beta and of model-estimated safety factor (q) profiles have been achieved experimentally and simultaneously on TCV for the first time [2-4].

In the new framework, the plasma control system is separated into an interface and a tokamak-agnostic layer. The interface layer translates tokamak-specific signals from actuators and diagnostics into generic ones to be used by the tokamak-agnostic layer, and vice versa. For example, a *plasma and actuator state reconstruction* block uses RT diagnostics as well as RT simulations to generate a generic continuous valued state of the plasma and actuators. Specifically, we will show that RT analyses of magnetic perturbations have been used to provide estimations of mode amplitude and frequency [5], the RAPTOR observer [6] to reconstruct electron temperature and q profiles, the RAPDENS-observer [7] to estimate density profiles and RT-TORBEAM [8] to calculate electron cyclotron (EC) beam depositions.

The continuous valued state is then translated by a generic *plasma state monitor* into a discrete finite-state representation of the plasma state, with state transitions triggered on user-defined thresholds [4, 9]. In many present-day examples, control goals are achieved with tokamak-specific controllers, based on specific diagnostics and actuators. We propose an alternative task-based approach, wherein generic (tokamak-agnostic) *controllers* with standardized interfaces are used to carry out tasks using generic actuator resources. This allows a clear separation of the tokamak-agnostic layer from the tokamak-specific systems, and provides a layer of abstraction for operators as they only have to specify control tasks, without needing to consider the functionality of each controller. Based on the defined tasks, the discrete state and the pulse schedule, a generic *supervisory controller* [4] prioritizes various tasks, activates relevant tasks/controllers, and communicates the parameters specific to each control task. A task-based *AM* [3] is also implemented, which optimizes the actuator allocation for each task based on the plasma state, the actuator state and limits, the task priority and the resource requests per task from the *controllers*.

An example of the integrated control of NTMs, beta and model-estimated q profiles on TCV is shown in Fig.1. EC power is switched on at 0.5s and deposits near the plasma center. The RT profile control starts at 0.7s and both beta and q profile references are followed very well with two launchers (L4 and L6). A 2/1 NTM is detected at 0.85s and NTM control is given the highest priority. L6 is allocated to the NTM stabilization task and moved toward the mode location with full power; once the mode duration exceeds a set time, L4 is also assigned and moved to the mode location; the 2/1 NTM is fully stabilized with two launchers.

The NTM control scheme has also been further explored through dedicated NTM experiments on TCV [2,10] with its flexible EC heating/current drive system. For example, with a novel sinusoidal sweeping technique, the comparison between NTM preemption and stabilization shows that NTM preemption can be more than twice as efficient as stabilization in terms of the necessary power. More details about the NTM control scheme and its standardized interface will also be discussed.

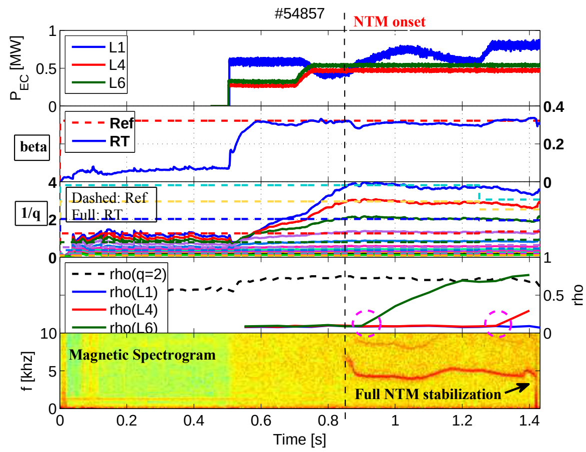

Fig.1 An example of the integrated control test on TCV

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