High Reliability Operation and Disruption Control in Tokamaks

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An attractive power plant candidate must provide power more than 70% of the time in a given operational year, typically implying that the frequency of key component failures resulting in unplanned loss of plant availability must be reduced to below 0.001/year [1]. Present fusion devices typically have little motivation to operate with such high reliability, and allow relatively frequent instability-driven plasma-terminating events known as disruptions. The vision of an operational fusion reactor therefore requires a level of reliable control performance and confidence well beyond that of presently operating devices. Maximizing use of the limited number of discharges planned for ITER also implies a major advance in control reliability. Fortunately, the mature field of control theory offers methods that routinely provide such levels of performance in many fields from aerospace to process control.

This lecture discusses the control design methods and issues involved in providing high reliability control for tokamaks, including control to minimize the frequency of disruptions and minimize the damaging effects of faults in general. Providing this level of control requires model-based design of algorithms, a systematic approach to verifying and validating performance, and a detailed mapping of operational control space to ensure this performance across a wide range of real-world conditions. Our consideration of reliable control will take us to the next steps in design beyond nominal stability assurance and satisfaction of performance requirements under ideal conditions. These next steps include designing for robustness to noise and disturbances, as well as for tolerance to variability in plasma, auxiliary system, and diagnostic responses. We also consider how control methods can be used to minimize the incidence of certain faults, and to respond to faults so as to provide high plant availability. Examples are drawn from plasma control and other areas of control.

Systematic design for high reliability implies control choices in both machine design and in the design of operating scenarios. For example, one must decide whether to design a device to provide a high degree of passive stabilization, or to make extensive use of active stabilization systems for key instabilities. One must choose whether various operating scenarios will remain well within stable regimes or will operate near or beyond instability boundaries. We introduce a Control Operating Space (COS) to describe the degree and robustness of closed loop control used in different physics regimes, and consider the design options and control consequences of various choices.

Although the goal of high reliability control is to reduce the frequency of control failure and catastrophic faults to an acceptably low level, a properly designed control system must also include a comprehensive and provable response to faults. The fault response design must be comprehensive in order to sufficiently account for likely fault modes and assess their probabilities, and provable in order to reliably calculate the probability of various response scenarios being effective. We discuss methods of detecting and responding to faults so as to recover and continue operation if possible, or execute algorithms and scenarios for soft rapid shutdown, or in extreme (and extremely unlikely) events, to execute a hard rapid shutdown along with application of damage mitigation tools. We draw analogies between fault responses in high performance aircraft and tokamaks, and argue that the same methods that yield 1 fatality per billion airline passenger miles [2] can also produce a highly reliable tokamak power reactor.

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[1] N.P. Taylor, “A Model of Availability of a Fusion Power Plant,” ISFNT-5, Rome, 1999
[2] A.T. Wells, C.C. Rodriguez, Commercial Aviation Safety, McG raw-Hill (2004)