KSTAR as a Testbed for Reactor-Grade Density Regulation: Coordinated Gas and Pellet Fueling While Avoiding Density Limits*

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Precise regulation of plasma density is a fundamental requirement for achieving and sustaining active burn control in future reactor-grade tokamaks. To optimize fusion power output and maintain stable burning plasmas, these future machines will rely heavily on the simultaneous use of gas puffing and pellet injection. The effectiveness of fueling by gas puffing is expected to be limited in future reactors due to the increased difficulty for neutral gas particles to penetrate the hot plasma core. To overcome this limitation, fusion reactors will rely on the injection of frozen fuel pellets, which can penetrate deeper into the plasma core, as the main fueling mechanism. However, this fueling approach, largely unexplored in present devices, presents unique challenges, such as size and velocity effects on the spatiotemporal plasma dynamics, the discrete-time nature of the actuation, and the ablation and penetration dependence on plasma conditions. Moreover, integrating these disparate fueling mechanisms into a unified feedback control scheme remains a significant challenge due to inherent actuation time delays and uncertain fueling efficiencies. Existing superconducting devices must serve as proving grounds to develop and validate these critical control strategies. Consequently, KSTAR is being leveraged as a key experimental testbed to demonstrate reactor-grade density regulation. Because the expected actuation challenges require advanced model-based techniques beyond traditional Proportional-Integral-Derivative (PID) controllers, Model Reference Adaptive Control (MRAC) has been employed as the feedback control technique in recent experiments carried out on KSTAR (Figure 1). The MRAC has been augmented with Smith-Predictor solutions to cope with reactor-like lags and delays emulated by the recently implemented NERF-mode algorithm in KSTAR. By actively coordinating both gas and pellet actuators, the MRAC+Smith-Predictor controller adapts model and controller in real time and manages actuator constraints while regulating plasma density around the targets required for efficient operation. Furthermore, to ensure safe and sustained operation, the baseline controller was augmented with a reference governor (Figure 2). This advanced integration enables robust plasma regulation alongside strict density-limit avoidance in KSTAR. As an alternative approach integrating both active regulation and limit avoidance, Safe Reinforcement Learning (Figure 3) was also leveraged in recent experiments. The performance of these comprehensive control solutions has been thoroughly examined in simulations, demonstrating robust target tracking despite actuation delays and plasma variability, and later confirmed in KSTAR experiments. Both modeling and control-design efforts will be presented, while remaining actuation, control, and estimation challenges will be discussed.

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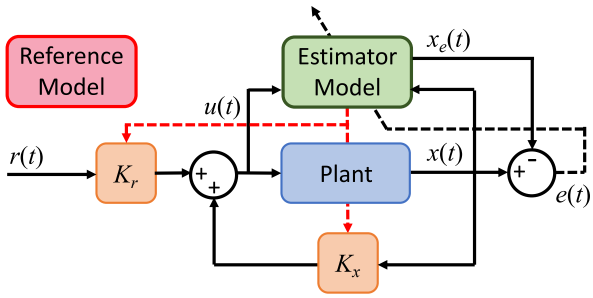

Figure 1: Within the “Indirect” MRAC scheme, the response model embedded into the controller is updated in real time to ensure convergence to the desired target.

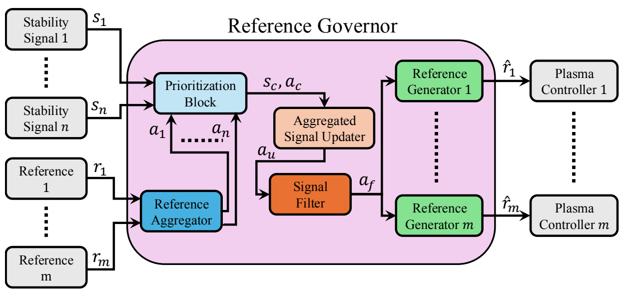

Figure 2: The Reference Governor modifies controller’s targets to satisfy plasma limits (e.g., stability, safety).

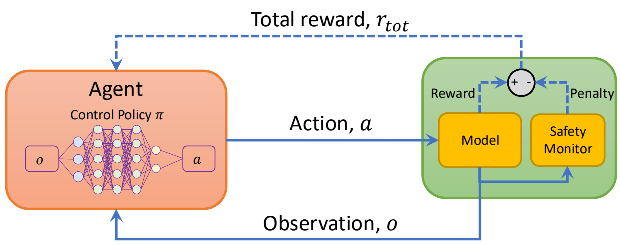

Figure 3: The alternative Safe Reinforcement Learning framework enables regulation of electron density while actively avoiding the density limit.