BURN CONTROL IN ITER BY MAXIMIZATION OF ION CYCLOTRON POWER ABSORPTION THROUGH REGULATION OF HELIUM-3 CONCENTRATION

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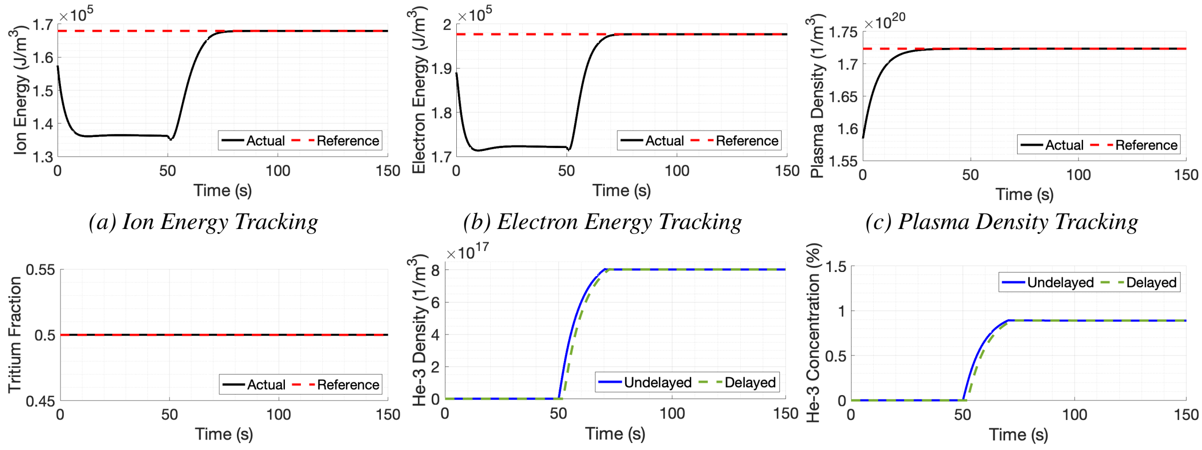
With the aim of regulating the burning plasma's temperature and density, a nonlinear burn control algorithm that takes advantage of the coupling between the plasma's He-3 impurity concentration and the Ion Cyclotron Resonance Heating (ICRH) power absorption is presented along with closed-loop simulations. This controller is synthesized from a plasma model that includes highly nonlinear and coupled differential equations that capture the response of the ion energy, the electron energy, the deuterium density, the tritium density, the fusion-born alpha-particle density, the controlled He-3 density, and the intrinsic impurity density. When taking this model-based approach to control design, ITER-specific actuator and diagnostic systems can be taken into account. Therefore, the proposed controller utilizes a specific diagnostic tool planned for ITER: the Diagnostic Residual Gas Analyzer (DRGA). The DRGA is capable of measuring the concentrations of hydrogen and helium isotopes, including He-3, in the sub-divertor region [1]. The plasma's ICRH power absorption is coupled to the He-3 concentration in the plasma's core region [2], which is assumed to match the DRGA's measurement in the sub-divertor region with a two-second delay. Therefore, the DRGA enables burn control solutions that use He-3 gas injection as an actuator to regulate the external plasma heating by tailoring the ICRH power absorption.

The proposed burn control algorithm tracks references for the plasma's ion energy, electron energy, total density, and tritium fraction by making control requests for auxiliary ion power, auxiliary electron power, external deuterium fueling, external tritium fueling, and He-3 injection. In order to successfully track the references, these control requests must be satisfied using the following actuators: the ICRH and Neutral Beam Injection (NBI) systems that provide auxiliary power to the plasma's ion and electron populations, the D-T pellet injectors that fuel the plasma, and the He-3 gas valve that controls the ICRH power absorption. As shown in prior work [3], burn controllers can be augmented with actuator allocation algorithms that optimally map the aforementioned control requests to these actuators. These "actuator allocators" can manage actuator dynamics, constraints, and time delays. Furthermore, a reference governor can also be included to ensure divertor-safe operation [4].

To avoid unnecessarily diluting the plasma, the proposed burn controller is designed to only inject He-3 gas if the ICRH power or the NBI power saturates at its maximum value. When these actuators saturate, the controller is unable to deliver the necessary amount of auxiliary power to drive the plasma's ion energy and electron energy to their reference values. Therefore, these auxiliary power actuators must be desaturated before burn control can be achieved. The control algorithm overcomes this issue by automatically injecting He-3 gas when actuator power saturation is detected. It uses He-3 gas injection to regulate the He-3 concentration in order to improve the ICRH power absorption. If the ICRH power absorption is improved enough, then the actuator power will desaturate, and the controller will be able to drive the plasma states to their references.

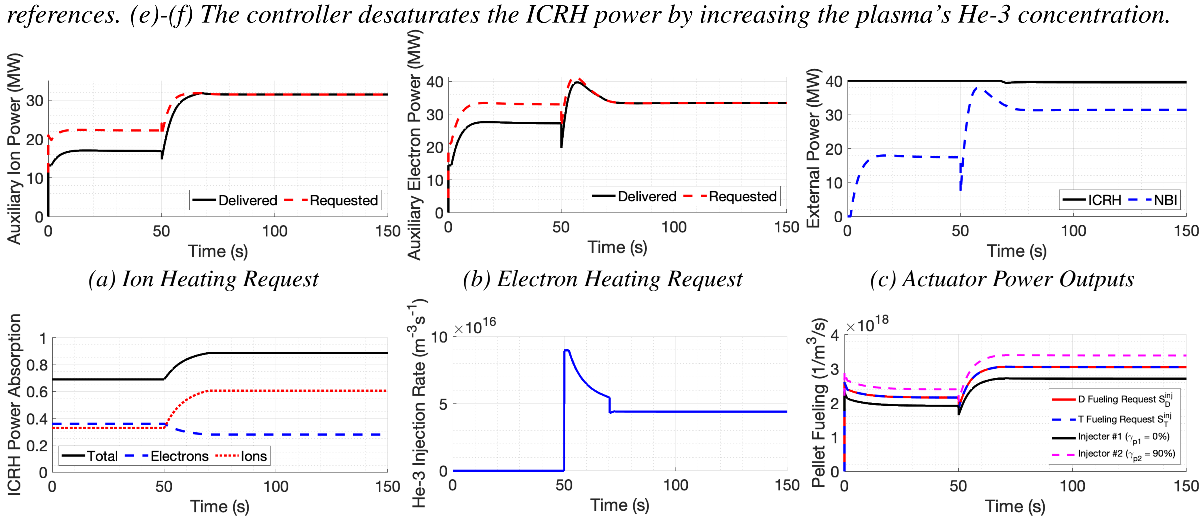
To illustrate the controller's capabilities, closed-loop simulation results are shown in Fig. 1 and Fig. 2. In this simulation, the ICRH and NBI actuators are assumed to saturate at 40 MW, the initial condition for the He-3 density is zero (Fig. 1(e)), and the DRGA measurements for the ion densities suffer from a two-second delay. To demonstrate the necessity of He-3 injection, the He-3 gas valve is forced to be closed during the first 50 seconds. After 50 seconds, the controller can use the He-3 gas valve. Fig. 1(a)-(b) shows that for $t < 50$ s, the ion and electron energies cannot reach their reference values. This is caused by the saturation of the ICRH power (Fig. 2(c)), which results in a deviation between the auxiliary power requested by the controller and the power delivered by the actuators (Fig. 2(a)-(b)). To overcome this obstacle, the He-3 gas injection is activated after 50 seconds (Fig. 2(e)). This gas injection increases the He-3 concentration (Fig. 1(f)) from 0% to 0.89%. As shown in Fig. 2(d), this causes the total ICRH power absorption to increase from 69% to 89%. Because the controller injects just enough He-3 gas to stabilize the energy subsystem, the ICRH power remains near its saturation point of 40 MW (Fig. 2(c)). This is advantageous because it avoids the excessive injection of impurities into the plasma.With the minimal increase in the He-3 concentration, the actuators can satisfy the control requests for auxiliary ion and electron power (Fig. 2(a)-(b)), and the ion and electron energies are brought to their reference values (Fig. 1(a)-(b)). Finally, the controller quickly tracks the references for the plasma density and the tritium fraction (Fig. 1(c)-(d)) using pellet injection (Fig. 2(f)) despite the delay in the density measurements.



(a) Ion Energy Tracking *(b) Electron Energy Tracking* *(c) Plasma Density Tracking*

(d) Tritium Fraction Tracking *(e) He-3 Density Measurement* *(f) He-3 Concentration Measurement*

Fig. 1: (a)-(d) The reference tracking for the plasma states. Because of the saturation of the ICRH power, the reference tracking is unsuccessful for $t < 50$ s. After $t = 50$ s, the valve for He-3 gas injection is turned on. Using He-3 gas injection, the controller is able to desaturate the ICRH power, allowing it to drive the states to their references. (e)-(f) The controller desaturates the ICRH power by increasing the plasma's He-3 concentration.



(a) Ion Heating Request *(b) Electron Heating Request* *(c) Actuator Power Outputs*

(d) ICRH Power Absorption *(e) He-3 Gas Injection* *(f) D-T Pellet Injection*

Fig. 2: (a)-(b) Comparison between the control requests for auxiliary power versus the auxiliary power delivered by the actuators. (c) The power output of the actuators: ICRH and NBI. (d) The ICRH actuator's power absorption efficiency, which depends on the He-3 concentration. (e) The controlled injection rate for He-3 gas. (f) Comparison between the control requests for D-T fueling versus the output of the pellet injectors.

The proposed model-based, nonlinear, burn controller employs a He-3 injection strategy that enables the maximal utilization of ICRH power by relying on the DRGA's measurements in the sub-divertor region. As shown in the simulation study, the control objective is achieved despite the measurement delays and the saturation of the ICRH actuator. Burn control solutions that can take advantage of ITER's diagnostic tools (e.g., the DRGA) despite their limitations (e.g., measurement delays) have the potential to strongly benefit ITER operation.

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