Integrated Modeling and Assessment of ITER Fueling Control for Real-Time Implementation

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***Abstract*—ITER fueling control must regulate plasma particle inventory over multiple time scales while coordinating gas injection and pellet injection actuators, respecting operational limits, and accounting for plasma and vessel response. This paper presents an integrated real-time-oriented fueling-control testbench for the ITER Start of Research Operation scope, built in MATLAB/Simulink and deployed in a Plasma Control System Simulation Platform compatible workflow. The integrated model combines the prefill and density controller, Gas Injection System and Pellet Injection System plant models, the fueling actuator manager, support functions for limits and fueling-efficiency monitoring, and a control-oriented plasma-density response model. The emphasis is on integrated assessment and traceable verification of the closed-loop fueling architecture rather than on standalone model development. The test framework executes representative scenarios in a single model, links the results to documented testcase definitions in the Plasma Control System Design Book, and produces plots and machine-readable summaries for engineering review. Representative results show coordinated gas and pellet requests during density transients, correct reference limitation against Greenwald and error-field bounds, and successful execution of the limits-monitoring logic in the full integrated loop. The remaining identified gap is the detachment-monitoring scalar path, which is still under development, while the main integrated fueling-control workflow is now in place.**

***Index Terms*—Actuator management, density control, ITER, plasma control, real-time systems, Simulink, tokamak fueling.**

I. Introduction

ITER fueling control regulates the plasma particle inventory by coordinating gas injection and pellet injection in order to maintain the density required for safe and effective operation. For the ITER Start of Research Operation (SRO) scope, this problem is particularly demanding because the fueling system spans more than 60 gas-valve and pellet-injector actuators, combines slow and fast actuation channels, and interacts with plasma response, vessel and scrape-off-layer dynamics, and operational monitoring logic.

Earlier integrated fueling-control work established the main modeling ingredients needed for ITER fueling-control studies: the Gas Injection System (GIS), the Pellet Injection System (PIS), an actuator manager (AM), and the RAPid DENsity Simulation (RAPDENS, used as a simplified plasma-density response model) [1]. The present paper extends that work with a different emphasis. The main contribution is an integrated assessment framework in which the controller, AM, support functions (SFs), GIS/PIS plant models, and RAPDENS are executed in a single Plasma Control System Simulation Platform (PCSSP)-compatible MATLAB/Simulink workflow. The resulting environment is used not only to demonstrate closed-loop behavior, but also to verify timing, logic consistency, limit handling, and requirement traceability for the ITER fueling-control architecture.

From a control point of view, the integrated fueling problem is multiscale. Gas injection mainly influences edge density and neutral-particle behavior on a slower time scale, while pellet injection provides a faster and deeper particle source. The controller must therefore split the fueling demand across heterogeneous actuators while accounting for wall recycling, changing fueling efficiency, and reference limitation. These interactions motivate a unified architecture-level verification environment rather than isolated module tests.

This paper presents the implemented architecture, the integrated test workflow, and representative verification results. The focus is intentionally limited to the fueling-control modules directly involved in integrated fueling closed-loop behavior and automated assessment.

II. Integrated Fueling-Control Scope

The integrated model used in this work contains the following main elements:

- GIS and PIS plant models that supply particles to the vessel;
- a prefill/density controller that generates fueling demand through feedforward and feedback pressure and density control;
- a GIS/PIS AM that converts particle-flow requests into actuator commands;
- a limits monitor that supervises pressure, density, and detachment estimate (μ-factor) related constraints;
- a fueling-efficiency estimator that evaluates GIS and PIS fueling efficiency and associated confidence;
- RAPDENS for plasma-density calculation and plasma response modeling.

These modules are integrated in a single Simulink model that can be executed within the broader PCSSP workflow [2],

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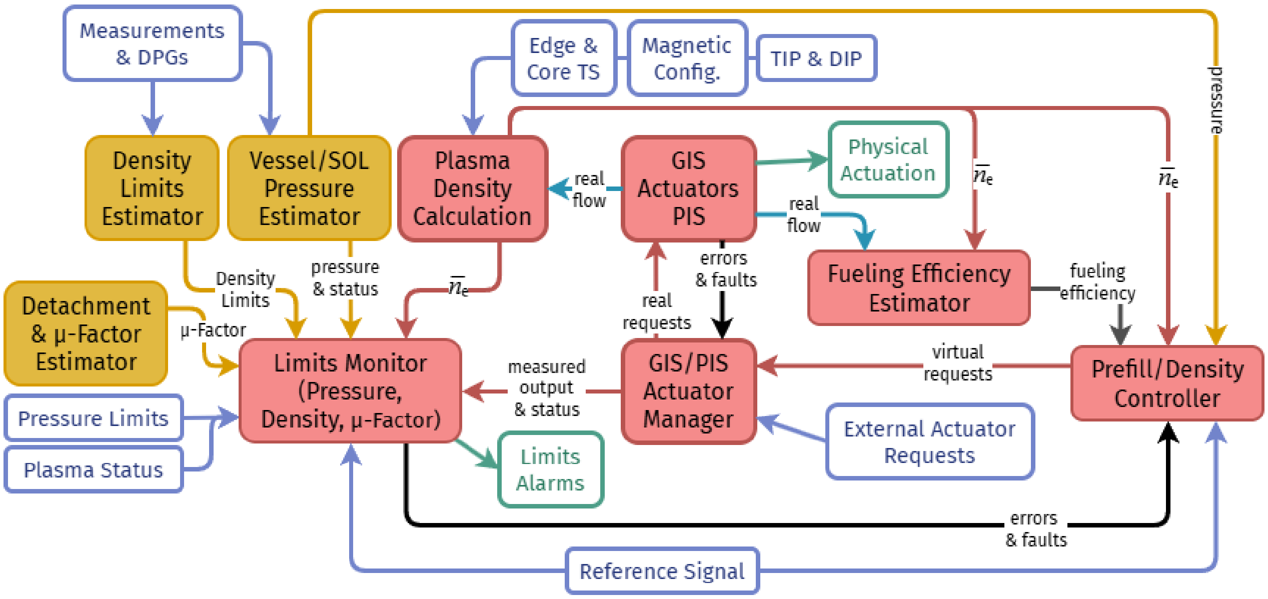

Fig. 1. Implemented integrated fueling-control architecture used for controller design and automated assessment. The red (dark) blocks are the principal scope of this work. Blue and green blocks (no fill) represent external I/O signals, and the yellow (light) blocks represent SFs that interface with the fueling loop.

[3]. The testbench is aimed at the ITER SRO fueling scope and is structured so that individual assessment cases remain directly connected to documented requirements and functional blocks in the Plasma Control System Design Book (PCSDB).

The architecture also reflects the physical and operational structure of fueling in ITER. Gas and pellet particles are injected through distinct plant paths, traverse different transport dynamics, and deposit particles into the plasma with different effectiveness. In addition, density control cannot be considered independently from vessel pressure estimation, density limits, error-field constraints, and edge-related monitoring. The resulting architecture is therefore broader than a single density controller and instead resembles a coordinated supervisory control structure.

III. Architecture and Modeling Approach

Figure 1 summarizes the implemented integrated fueling-control architecture. The prefill/density controller generates fueling requests based on density-related objectives and feedback. Those requests are distributed by the GIS/PIS AM, which translates high-level particle-flow demands into actuator-level commands while also handling status, errors, faults, and actuator trips [4]. The plant side is represented by GIS and PIS models, which in turn feed the plasma-density calculation through effective particle sources. RAPDENS closes the loop by providing the plasma response needed for density control and assessment [5], [6].

A. Actuation and Plasma Response

The GIS and PIS models represent the two dominant fueling pathways available in the ITER fueling-control strategy. The GIS model captures slower gas-line and vessel-coupling dynamics. The PIS model captures the faster pellet-related actuation path. In the integrated loop, these channels are sufficiently orthogonal to support coordinated multivariable control action: rapid response is primarily delivered through pellets, whereas slower compensation and sustainment are delivered through gas. This division of roles is visible in the representative transient discussed in Section V-B.

RAPDENS provides the plasma response model required to connect actuator particle delivery with density evolution. In the present context, RAPDENS is used as a simplified control-oriented plasma model whose fidelity is selected to support real-time design, closed-loop assessment, and deployment-oriented testing rather than full transport simulation [5]. The edge-facing part of the density-response workflow is consistent with the RAPDENS scrape-off-layer particle-balance extension discussed in [7]. In the present workflow, RAPDENS is treated as the integrated plasma-density calculation block inside the fueling loop.

B. Support Functions and Monitoring

The fueling-control architecture relies on several SFs beyond the basic closed-loop controller. The limits monitor supervises pressure, density, and μ-factor related signals and raises status or alarm information when hard or soft limits are approached or violated. Here, the μ-factor denotes the internal scalar used by the detachment-monitoring path to indicate proximity to detached operating conditions. The fueling-efficiency estimator provides a dynamic estimate of GIS and PIS fueling efficiency and associated confidence. Vessel and scrape-off-layer pressure estimation and density-limit estimation provide further supervisory information to the controller and monitors.

These SFs are necessary because the fueling problem is not only about tracking a density reference. It is also about ensuring that the reference used for control remains compatible with operational limits and that actuator behavior remains consistent with plant and monitoring assumptions. The integrated model therefore treats monitoring and assessment as part of the control architecture rather than as an external post-processing layer.

IV. Integrated Assessment Workflow

One of the main advances beyond the SOFT 2024 work is the move from integrated model development to integrated, traceable verification. The full fueling-control simulation is executed in a single PCSSP-compatible MATLAB/Simulink model containing the controller, AM, SFs, GIS/PIS plant models, and RAPDENS.

The workflow is driven by test-case (TC) files and associated setup files. The TC files select the scenario, for example representative $I_p = 3.5$ MA and $I_p = 7.0$ MA operating cases, and call setup functions that:

- generate signals used in place of real-time plant or PCS signals;
- modify parameters for the selected evaluation case, such as deposition location or control mode;
- run the simulation;
- perform post-processing needed for plots and automated assertions.

The TC layer then applies assertions through the standard Simulink testing framework. This organization keeps the integrated model reusable while allowing individual assessment cases to remain explicit and reviewable. The approach also supports direct linkage to Plasma Control System DataBase (PCSDB)-oriented requirement, functional-block, and testcase definitions through the assessment framework, allowing the results to be consumed both as engineering evidence and as structured verification artefacts.

Each run produces multiple outputs, including logged figures, testcase reports, XML summaries, other machine-readable continuous-integration outputs, and documentation inputs for PCSDB updates. This is important for ITER because controller design is not sufficient on its own; the development process must also demonstrate structured traceability across model behavior, tests, requirements, and review evidence [8], [9].

V. Representative Results

This paper focuses on two representative integrated assessments that are already used in the current verification workflow: density-limit verification and integrated density-control response. Together they show that the main fueling loop now operates in a unified assessment environment with meaningful supervisory logic and coordinated actuation.

A. Density-Limit Verification

Figure 2 shows a representative verification case in which the density reference is driven through low, medium, and high operating points while the limits-monitor logic constrains the reference used for control. The figure contains both the continuous density-related signals and the corresponding hard/soft limit-status outputs, which is essential because the verification objective is not only numerical tracking but also correct monitor behavior.

Several observations follow directly from this test. First, the integrated control loop keeps the average density within the Greenwald and error-field related supervisory bounds during the evaluation interval. Second, the reference limiter correctly modifies the reference seen by the controller when the unconstrained density request would exceed permitted operating conditions. Third, the monitor outputs remain synchronized with the integrated model state, which verifies the coupling among controller, AM, and limits-monitor logic during full-model execution.

In practical terms, this test demonstrates that the integrated architecture can evaluate bounded density evolution and no hard-limit violations over the assessment window. This is an important step from isolated module development toward deployable supervisory behavior for ITER fueling control.

B. Integrated Density Control and Actuator Coordination

Figure 3 presents a representative rapid-response density-rise case. The figure shows the density reference, the average density response, rise metrics, and the corresponding pellet and gas flow commands. The integrated model reproduces the expected multichannel control behavior: pellet requests provide the initial rapid response, while gas requests evolve on a slower time scale in support of the sustained control objective.

This test is useful because it simultaneously exercises the controller, the AM, the GIS/PIS plant models, and RAPDENS. The density response tracks the reference within the intended transient behavior, while the actuator requests remain consistent with the known roles of the two fueling channels. The rise metrics shown in the figure are also automatically evaluated by the assessment framework, which means that the same run provides both engineering plots and machine-checkable pass/fail evidence.

The key result is not merely that density tracking is possible, but that the full integrated testbench can reproduce the closed-loop dynamics in a way that is compatible with systematic assessment. The test therefore supports two claims: first, that coordinated gas and pellet flow commands follow the control objective, and second, that the integrated fueling testbench is now suitable for automated, traceable verification.

VI. Discussion

The results above indicate that the integrated fueling-control framework has reached a useful engineering maturity. The primary modules of the fueling loop are now connected in one executable assessment environment, and representative tests verify both continuous dynamic behavior and supervisory logic. This closes an important gap between model development and design verification.

The present work also clarifies the practical division of responsibilities inside the fueling architecture. The prefill/density controller alone is not sufficient to assess deployable ITER behavior; correct behavior depends on the AM translation layer, actuator models, plasma response, effectiveness estimation, and limits logic. The integrated framework therefore provides

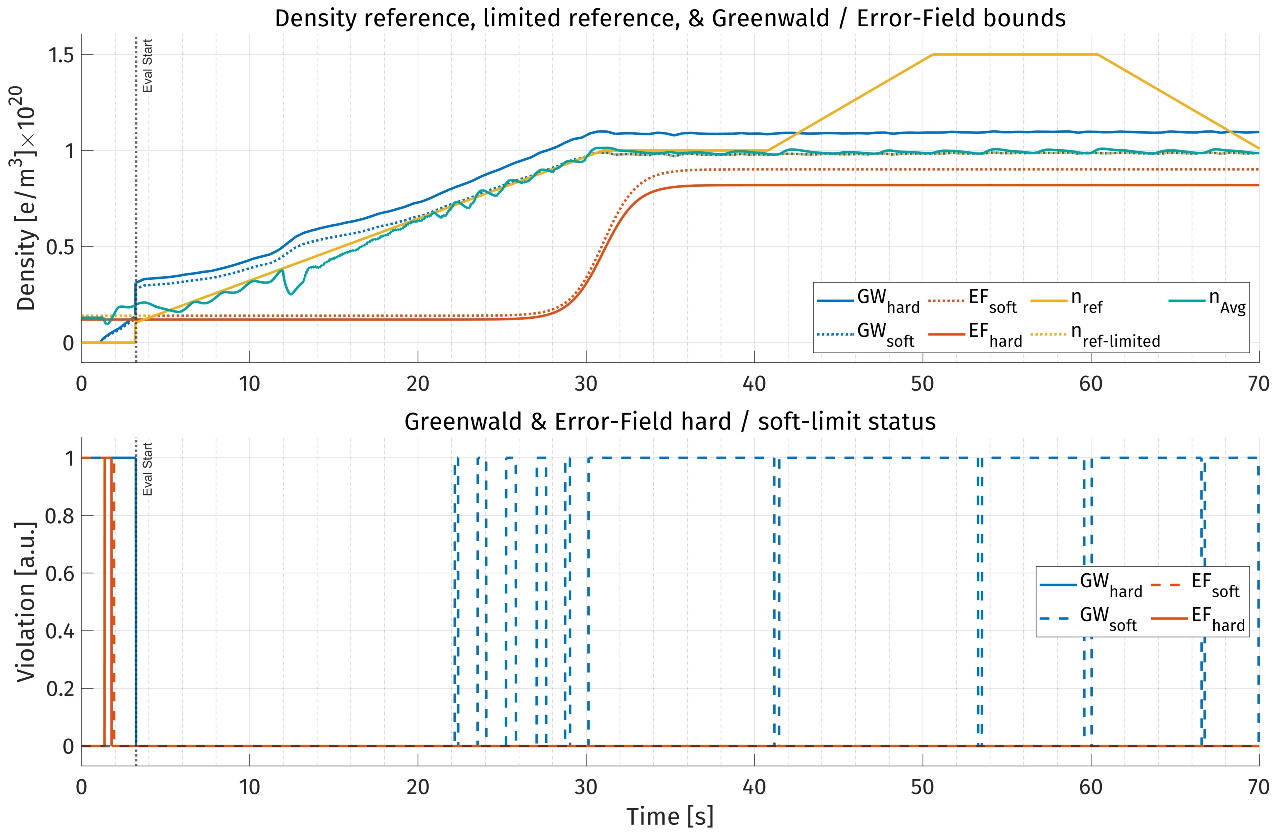

Fig. 2. Representative density-limit verification. The integrated model evaluates the density-reference trajectory, the limited reference, Greenwald-related bounds, error-field bounds, and the resulting hard/soft limit-status signals within one closed-loop execution.

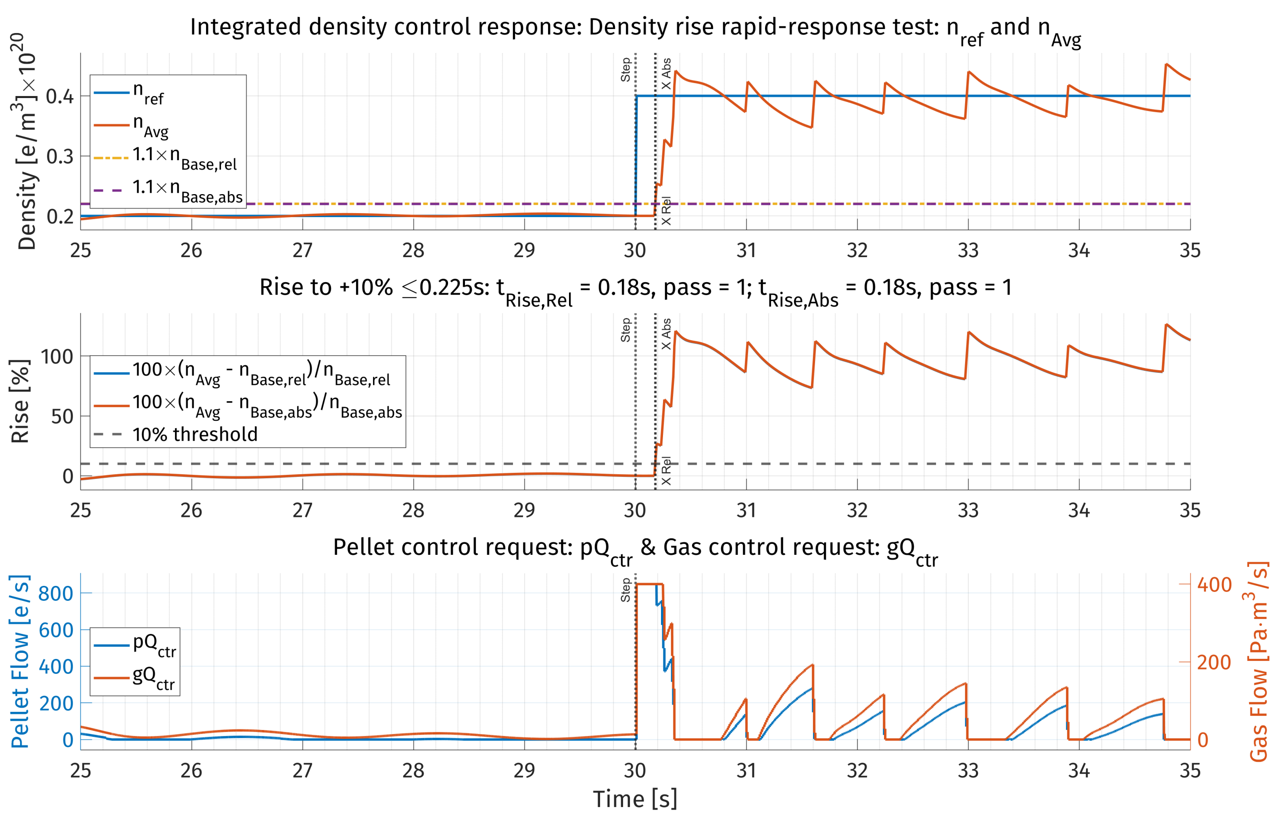

Fig. 3. Representative integrated density-control response for a density-rise rapid-response test. The top panel shows density tracking, the middle panel shows the rise-metric evaluation, and the bottom panel shows coordinated pellet and gas flow commands.

a more realistic basis for controller tuning and verification than isolated subsystem simulations.

At the same time, the current limitations are explicit. The remaining main gap is the μ-factor path, which is still under development. This means the architecture is not yet complete for every supervisory pathway originally envisioned. Nevertheless, the major integrated fueling-control functions and their assessment workflow are already established, which justifies using the present framework as the baseline for further verification and refinement.

The next technical step should be to extend the same assessment discipline to the remaining supervisory paths and to broaden the campaign of integrated scenarios, especially as the current integrated framework is applied to a wider set of fueling-control operating cases and supervisory functions.

VII. Conclusion

This paper presented an integrated modeling and assessment framework for ITER fueling control aimed at real-time implementation. Building on earlier integrated fueling-control work, the main advance is the transition to a unified verification-oriented MATLAB/Simulink and PCSSP-compatible workflow that combines the controller, GIS/PIS AM, SFs, GIS/PIS plant models, and RAPDENS.

Representative results showed that the integrated framework can verify bounded density-control behavior under Greenwald and error-field related supervision, and can reproduce coordinated gas and pellet control action during density transients. The workflow also produces automated testcase evidence linked to PCSDB-oriented verification artefacts, which is essential for structured ITER control development.

The remaining identified gap is the μ-factor path, but the principal integrated fueling-control assessment chain is now in place. The overall conclusion is that ITER fueling control has progressed from module-level model development to integrated, traceable verification in a form that supports real-time control engineering and future deployment preparation.

Note

AI was used to check the document for grammar errors and compare it against the submission criteria.

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