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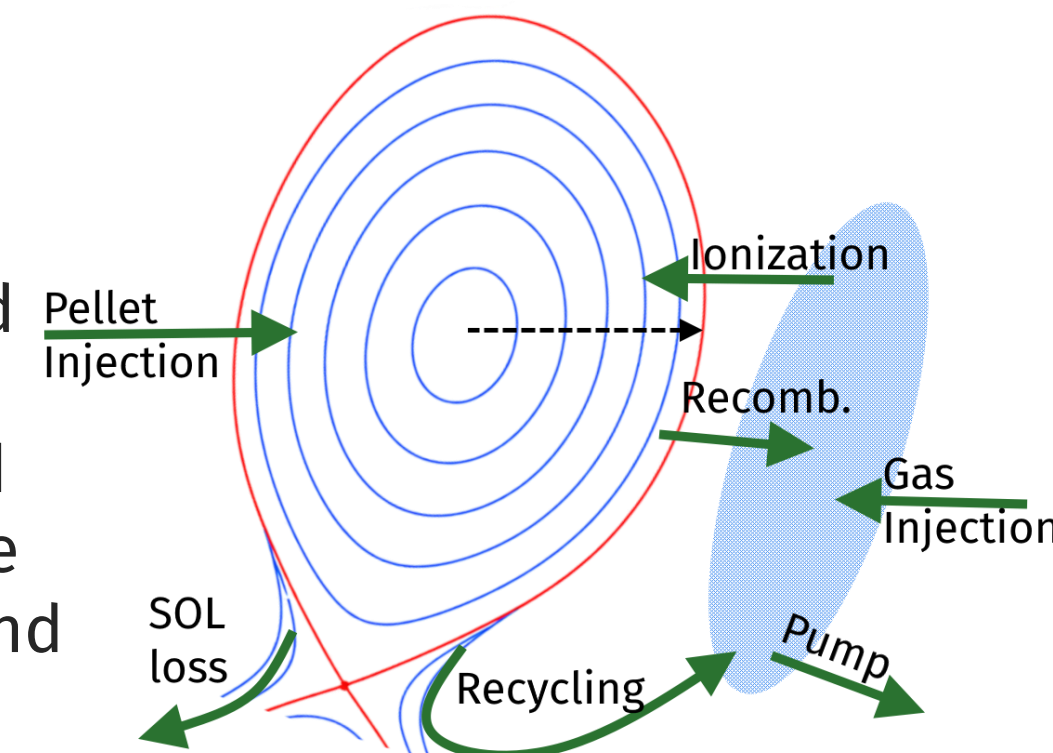
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# Integrated modeling and assessment of ITER fueling control for real-time implementation

## Introduction & Background

ITER fueling control regulates the plasma particle inventory by coordinating gas & pellet injection. From a control perspective, the objective is to maintain the plasma density required for safe and effective operation while respecting actuator & operation limits. The fueling problem is also multiscale: gas injection is slower and mainly influences the edge density and neutral-particle behavior, while pellet injection provides a faster and deeper particle flux. The integrated controller therefore has to distribute the fueling demand across many actuators and account for the plasma response, wall recycling, and limit-monitoring logic.



The Figure (left) illustrates the main particle fluxes in a plasma. The nested blue curves are magnetic flux surfaces; the plasma core is at the center, the plasma scrape-off layer (SOL) is the red curve. Fueling particles are injected as by gas and ice pellets. Particles can also leave the confined region into SOL, interact with plasma-facing components, and return through recycling. These coupled pathways are why ITER fueling control requires an integrated model of actuators, plasma response, operation limits, and edge / wall interactions.

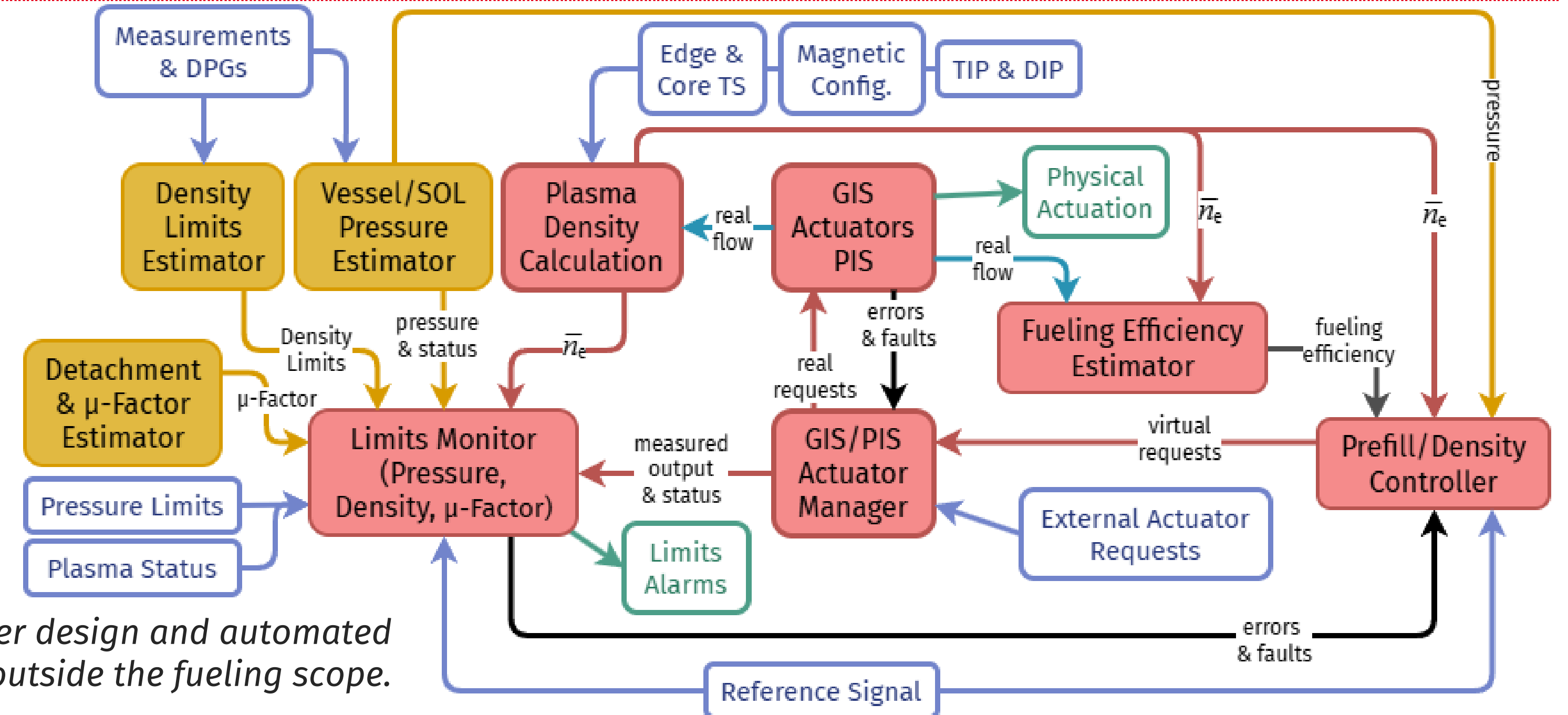
## Architectural Design

The ITER SRO fueling system will have more than 60 actuators. Coordinating them requires an Actuator Manager (AM), multiple Support Functions (SFs), and an integrated plasma-density model. This poster presents the implemented MATLAB/Simulink + Plasma Control System Simulation Platform (PCSSP) framework used to design and verify the fueling control system.

\*Note: Only the red modules in the Figure (right) are part of this work and are detailed below.

- **Actuators:** GIS and PIS plant models supplying particles to the vessel
- **Prefill/Density Controller:** FF/FB density and pressure control
- **GIS/PIS Actuator Manager (AM):** Converts particle flow into actuator commands
- **Limits Monitor:** Raise flag when pressure/density/ $\mu$ -Factor exceeds limits
- **Fueling efficiency estimator:** GIS/PIS effectiveness + confidence
- **Plasma Density Calculation:** RAPDENS – plasma response model

Implemented architecture of the ITER SRO fueling system used for controller design and automated assessment. Blue and green signals come from or go to functions outside the fueling scope.



## Representative Verified Results

### Integrated Density Control & Actuator Response

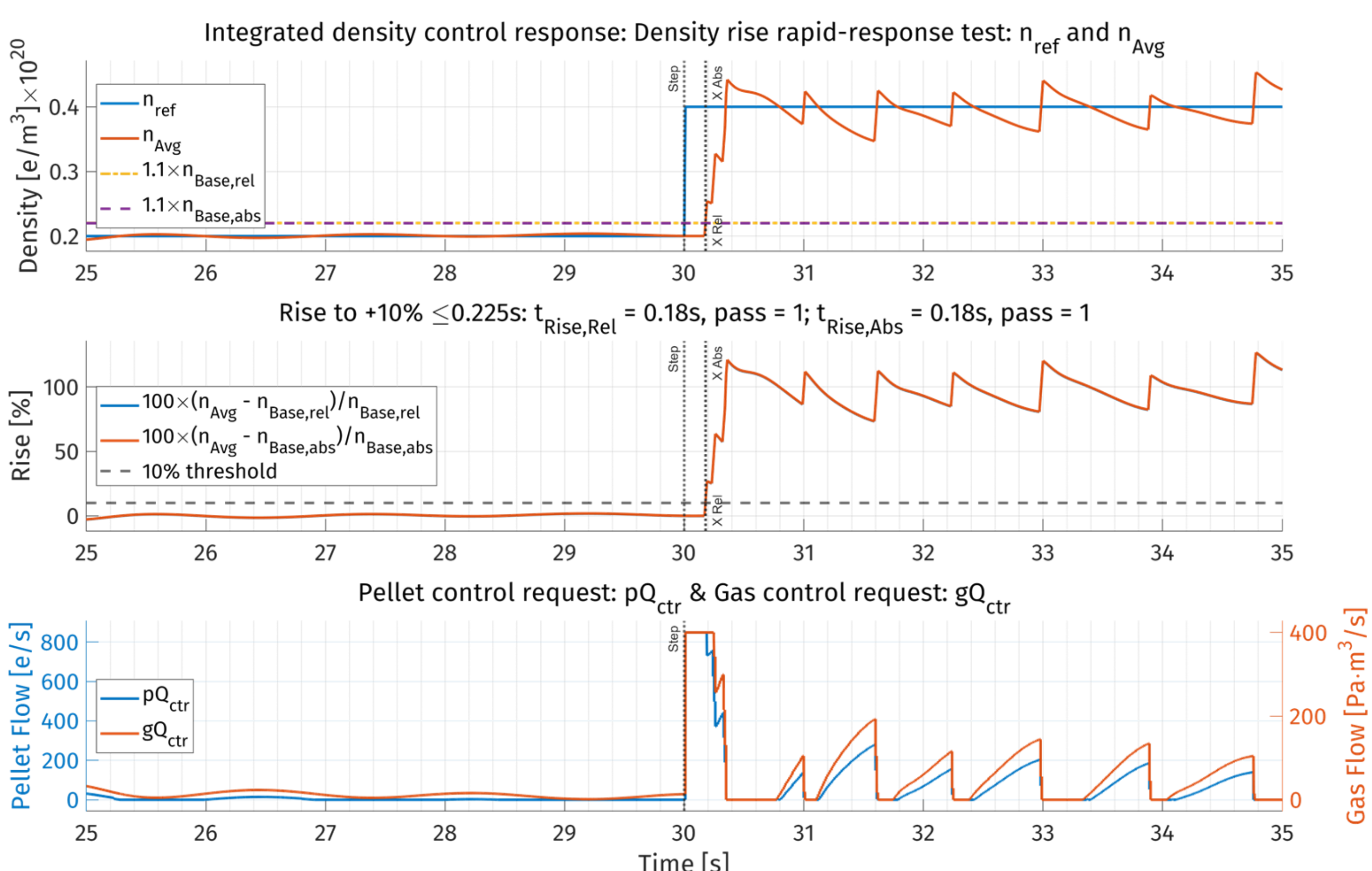
The integrated fueling testbench reproduces closed-loop density control using: Controller, AM, GIS/PIS plant models, and RAPDENS

Gas & pellet control are sufficiently orthogonal that parallel PIDs can be used effectively:

- rapid response  $\rightarrow$  pellets, slow response  $\rightarrow$  gas

Representative tests show:

- $\bar{n}$  tracks density reference
- gas & pellet control requests evolve consistently with control objective



Integrated density tracking with coordinated gas and pellet control requests following a density-reference step.

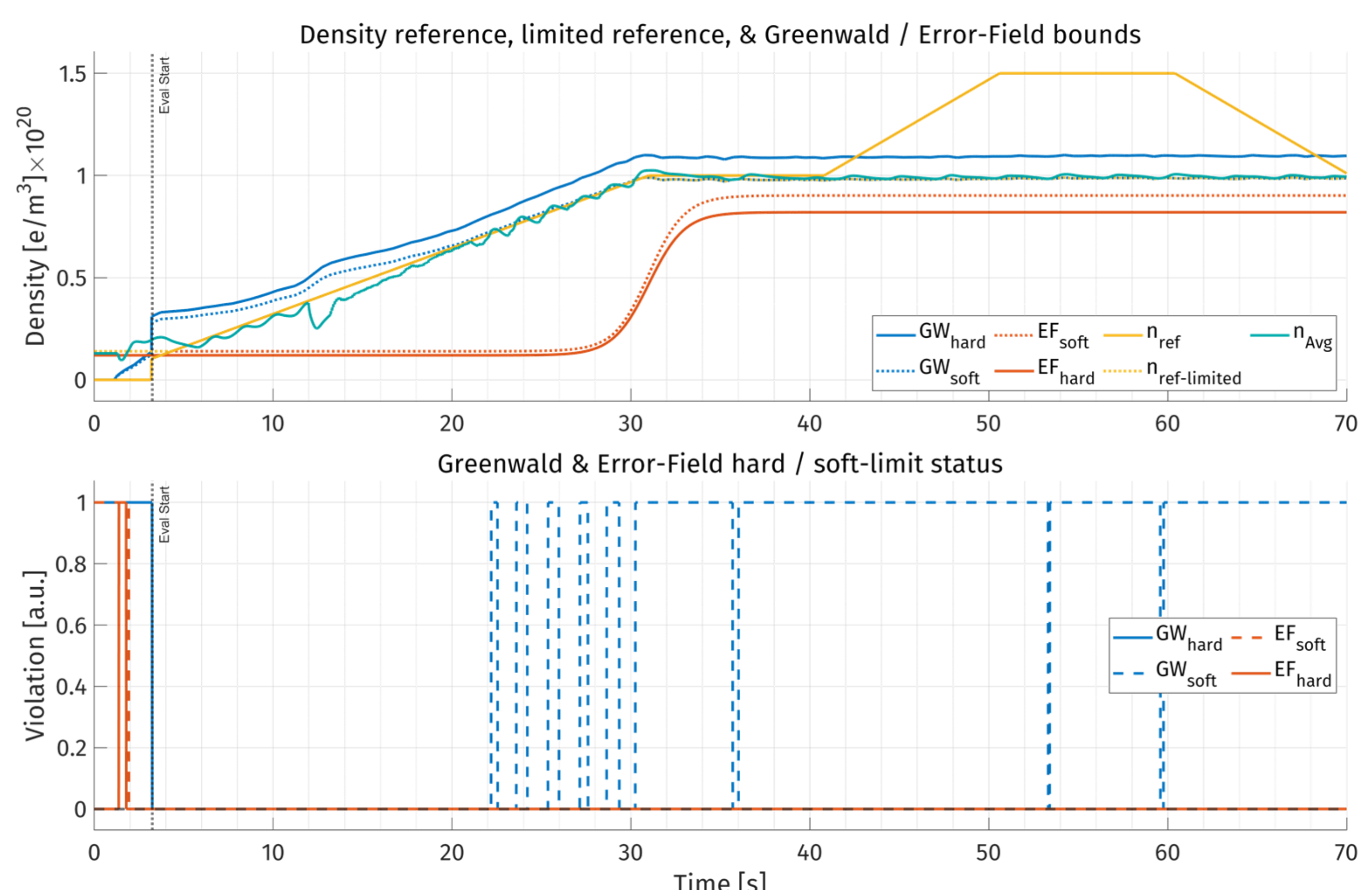
### Density-Limit Verification in the Integrated Fueling Model

Representative integrated assessments verify that (figure below):

- plasma-density control remains within Greenwald and Error-Field limits
- density reference driven through low, mid, & high operating points
- monitor and limit logic constrain the reference used for control
- $\bar{n}$  response is evaluated from Eval-Start onward

Limits Monitor reports all hard and soft limit violations:

- assessment verifies no hard-limit violations within eval window
- validates integration of Controller, AM, & Limits Monitor during full-model execution.



Density-limit verification showing bounded density evolution and no hard-limit violations over the evaluation interval.

## Integrated Modeling & Assessment

## Status & Takeaways

Assessment Coverage Summary		
33 automated fueling test cases in the integrated testbench		
Functional Area	Automated TCs	Representative Result
GIS	4	Lag + consistency
PIS	4	Lag + trigger consistency
GPIS / AM	6	Routing + pacing
Density control	7	Closed-loop control
Pressure control	2	VV pressure control
Effectiveness estimator	1	Estimator validity
Monitor / EEA	8	Expected vs actual flags

Note: All TCs use the full model simulation & are included in the Plasma Control System Database (PCSDB) performance coverage.

### Integrated Model Testing Workflow

The full fueling control simulation is executed in one PCSSP-compatible MATLAB/Simulink model, including the Controller, AM, SFs, GIS & PIS plant models, & RAPDENS.

- a single Simulink model was used for all tests.
- TestCase (TC) files set the scenario(s) ( $I_p = 3.5/7.0$  MA) and call their respective setup files.
- setup files:
  - generate the signals that are used in lieu of RT signals,
  - change parameters for the particular test (e.g., deposition location, control mode, etc.),
  - run the simulation,
  - perform post-processing of results for plotting and for TC assertions
- TC files then perform the assertions using standard Simulink TC framework and methods

### PCSDB Traceability & Outputs

- The assessment tests are mapped to the PCSDB system requirements, performance requirements, SFs, functional blocks, and testcase definitions. This keeps the verification results directly connected to the documented ITER fueling-control architecture.
- Each run produces logged figures, testcase reports, XML/Bamboo summaries, and documentation inputs for PCSDB updates. This supports both engineering review of dynamic behavior and structured traceability of verification status.

### Current Status

Integrated fueling control modeling and automated assessment are now in place for the ITER PFP01 scope. The current MATLAB/Simulink testbench executes the Controller, AM, SFs, GIS/PIS plant models, and RAPDENS in a single PCSSP-compatible workflow.

### Key Result

The assessment suite now verifies AM timing and consistency, density and pressure control behavior, fueling-effectiveness estimation, and representative monitor / EEA logic with direct PCSDB-linked traceability.

### Remaining Limitation

The remaining gaps are limited and explicit. In particular, the  $\mu$ -factor path is still under development, while the main integrated fueling-control functions and their supporting assessments are now established.

**Fueling control has moved from model development to integrated, traceable verification.**

### References:

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