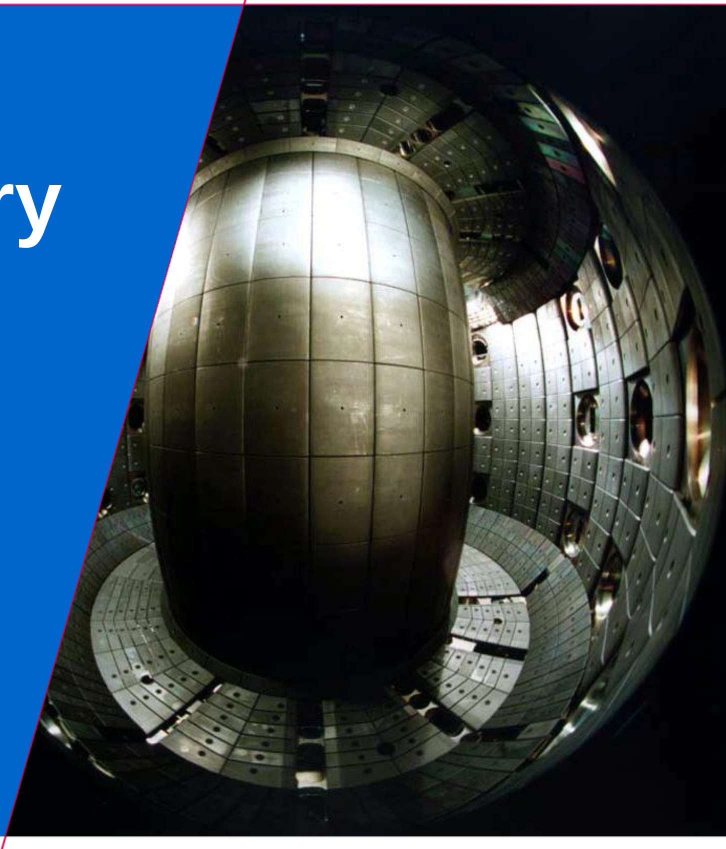
SWISS PLASMA CENTER

Real-time plasma event monitoring and supervisory control on TCV



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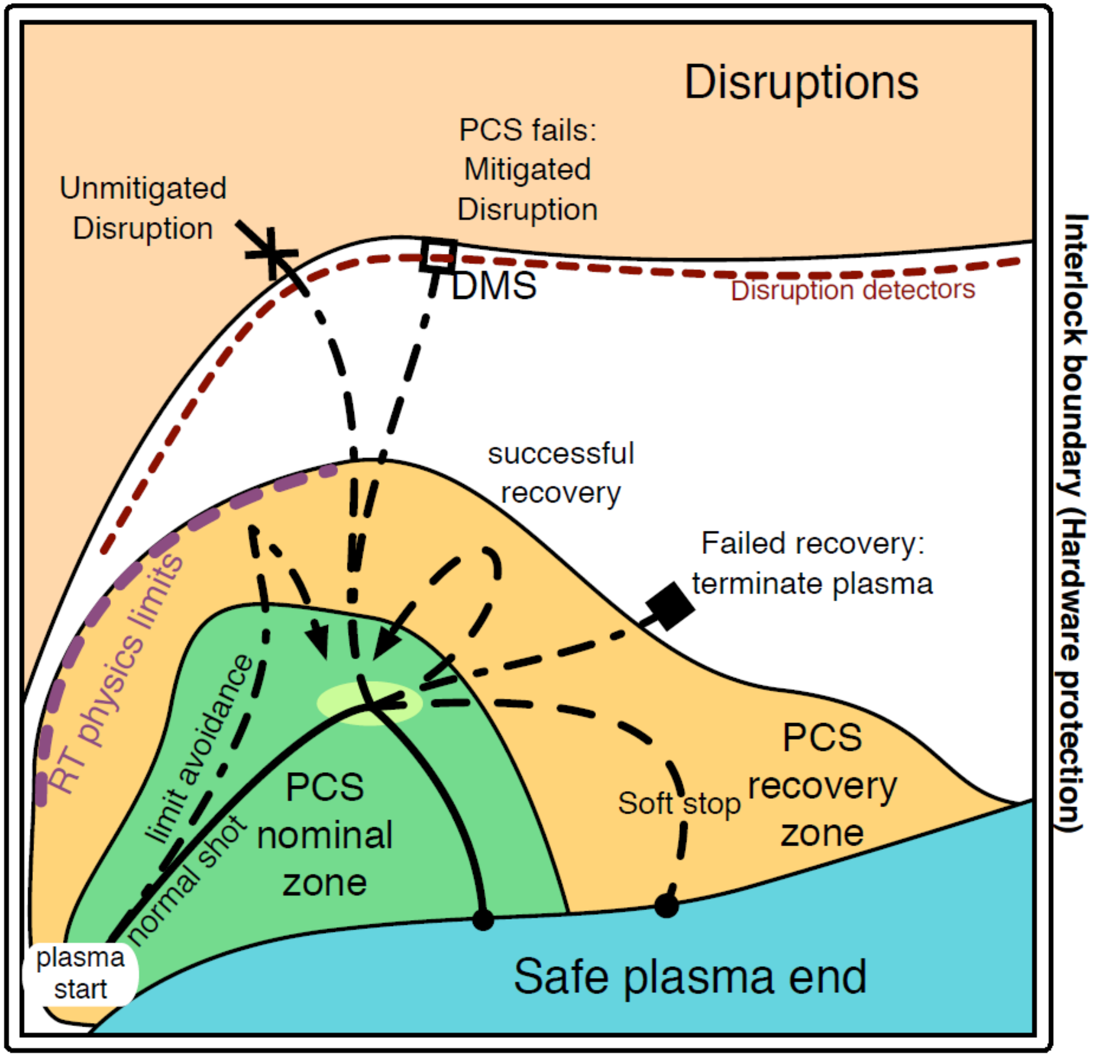
Where innovation starts

Disruption avoidance, prediction and mitigation: integrated scenario monitoring

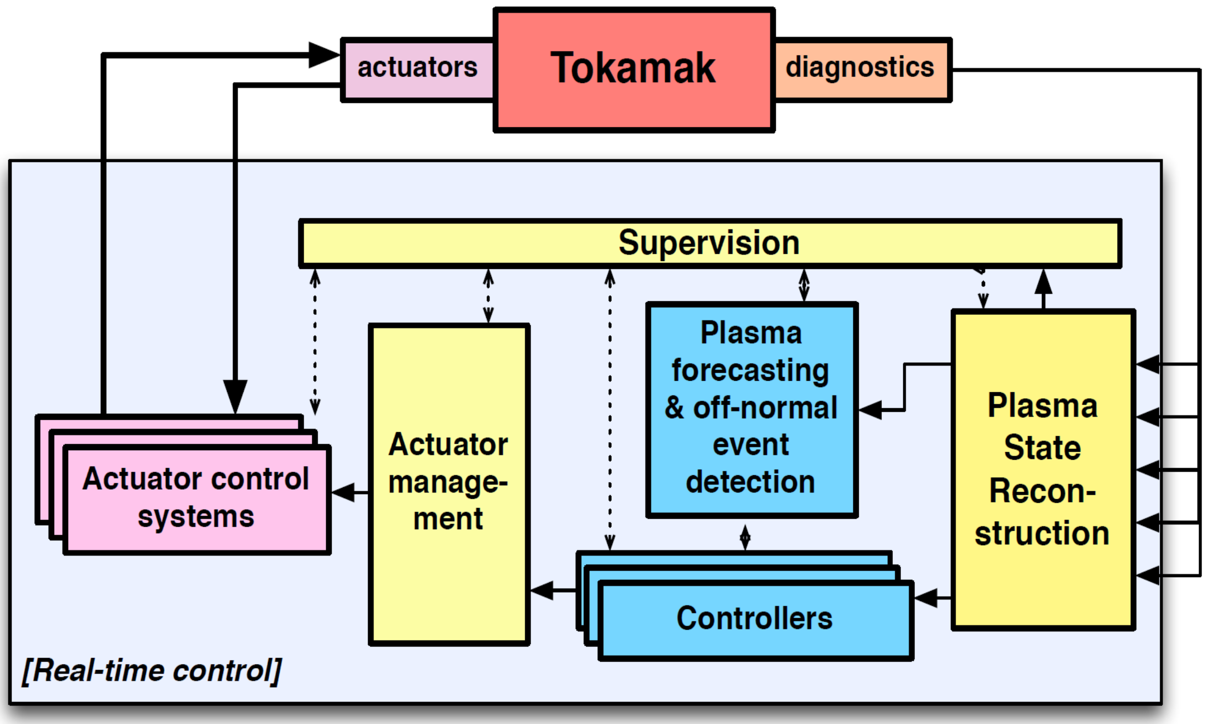


Advanced algorithms in the Plasma Control System should provide a first line of defense, avoiding disruptions when the plasma parameters leave a ‘trusted zone’ in the operating space.

These zones is where PCS is commissioned by simulations and experimental validation.

F. Felici, IAEA 2016, EX/P8-33

Envisioned future plasma control system



This approach requires:

1. **estimation of the plasma state evolution based on multiple diagnostics.**
2. **control of the plasma state to remain in the desired envelope.**
3. **monitoring of the estimated plasma evolution (1.) w.r.t. the RT predicted evolution.**
4. **monitoring of the plasma state evolution (1. & 3.) w.r.t. physics limits.**

RT plasma monitoring → off-normal event classification → supervised control actions

F. Felici, IAEA 2016, EX/P8-33

Motivation for supervisory control and actuator allocation in reactors

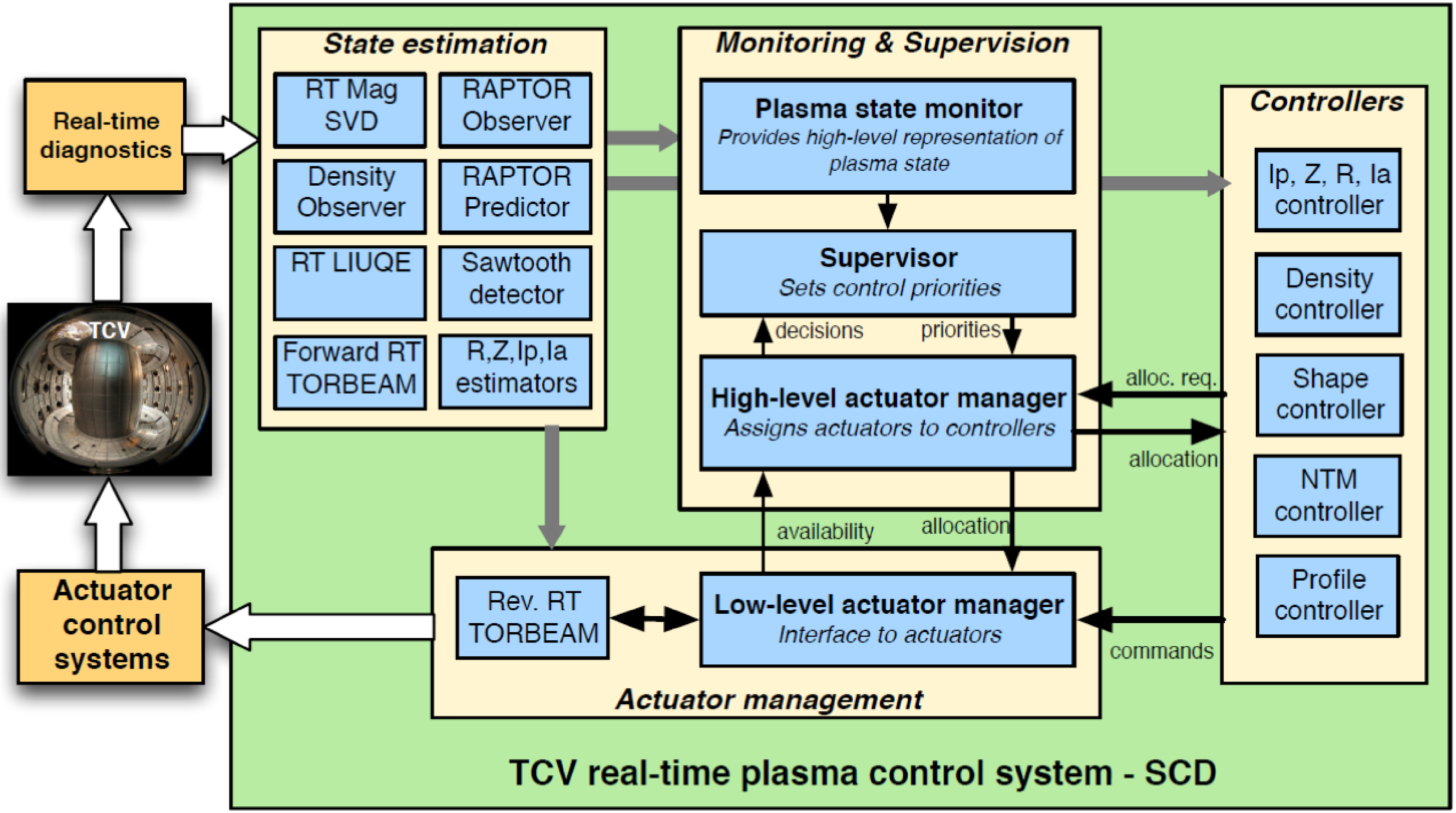
- Multiple control tasks using ECHCD
  - NTM control (suppression and preemption)
  - Profile control (pressure and safety factor)
  - Impurity control (accumulation prevention)
  - ST control
- Limited resources: ECHCD system
  - Constraints on available power, mirror angle range and motion
  - Hardware failure (e.g. EC trips)
- Control task priority depends on plasma state and hardware status
  - Which actuators can each controller use?

Prioritizing tasks and allocating actuators to control tasks is nontrivial in off-normal situations!

Outline

- **Disruption avoidance: a real-time control perspective**
- **Overview of real-time tools on TCV PCS**
- **First results of real-time tools for integrated control**
  - **Plasma state monitor for MHD**
  - **Supervisory control of multiple tasks**
  - **Actuator management for ECHCD system**

Real-time control tools on TCV PCS



Real-time MHD analysis

SVD analysis of Bpol measurement

- Sub-ms cycle time

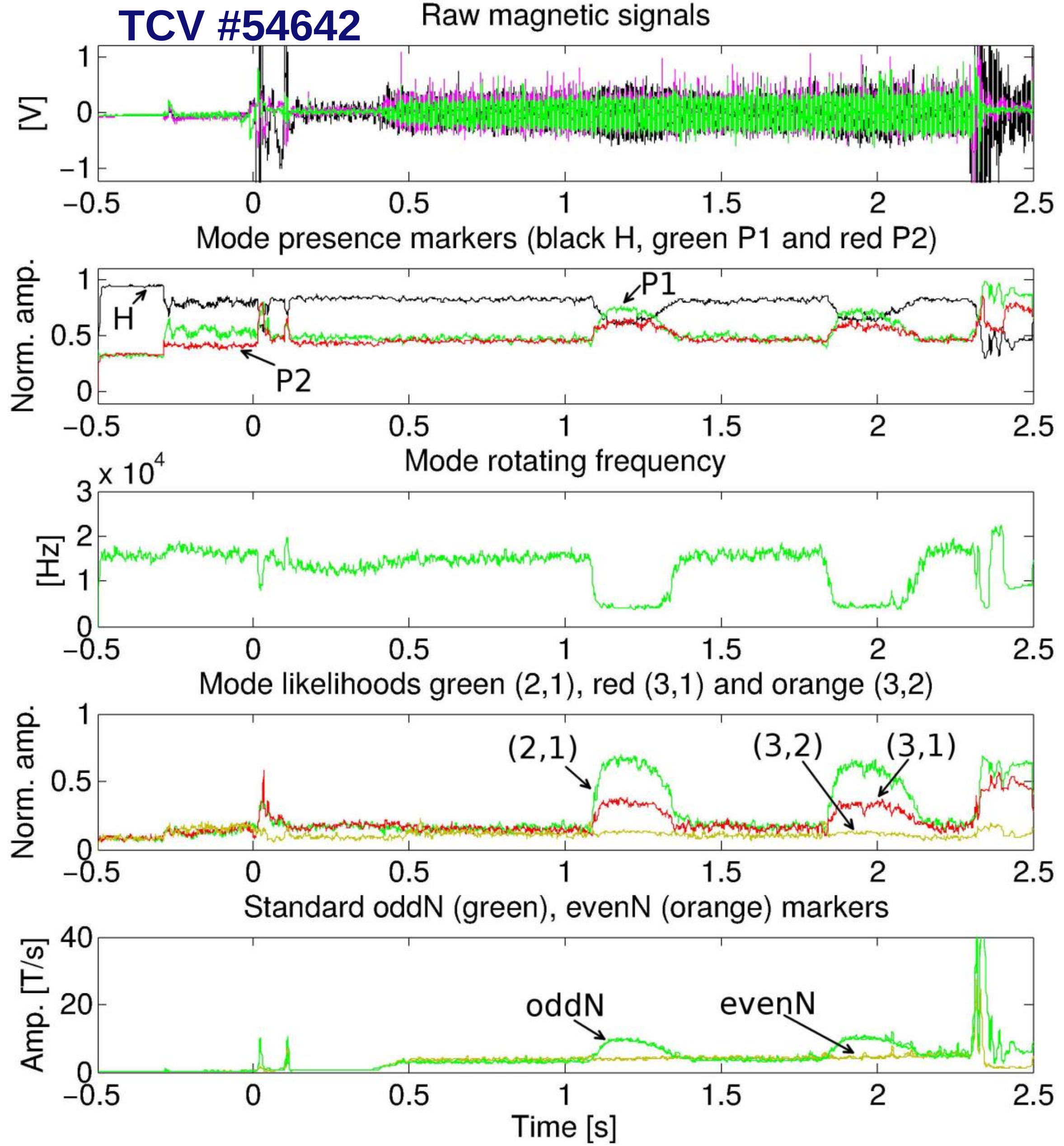


Figure adapted from

C. Galperti *et al*, IEEE Trans. on Nucl. Sci., vol 64, (2017)

Plasma state monitor

Goal: forms a finite-state representation of the plasma

- **Receives plasma current, NTM m/n likelihood+frequency+amplitude, LM amplitude, (to be done) profiles, control references, reconstructed equilibrium**

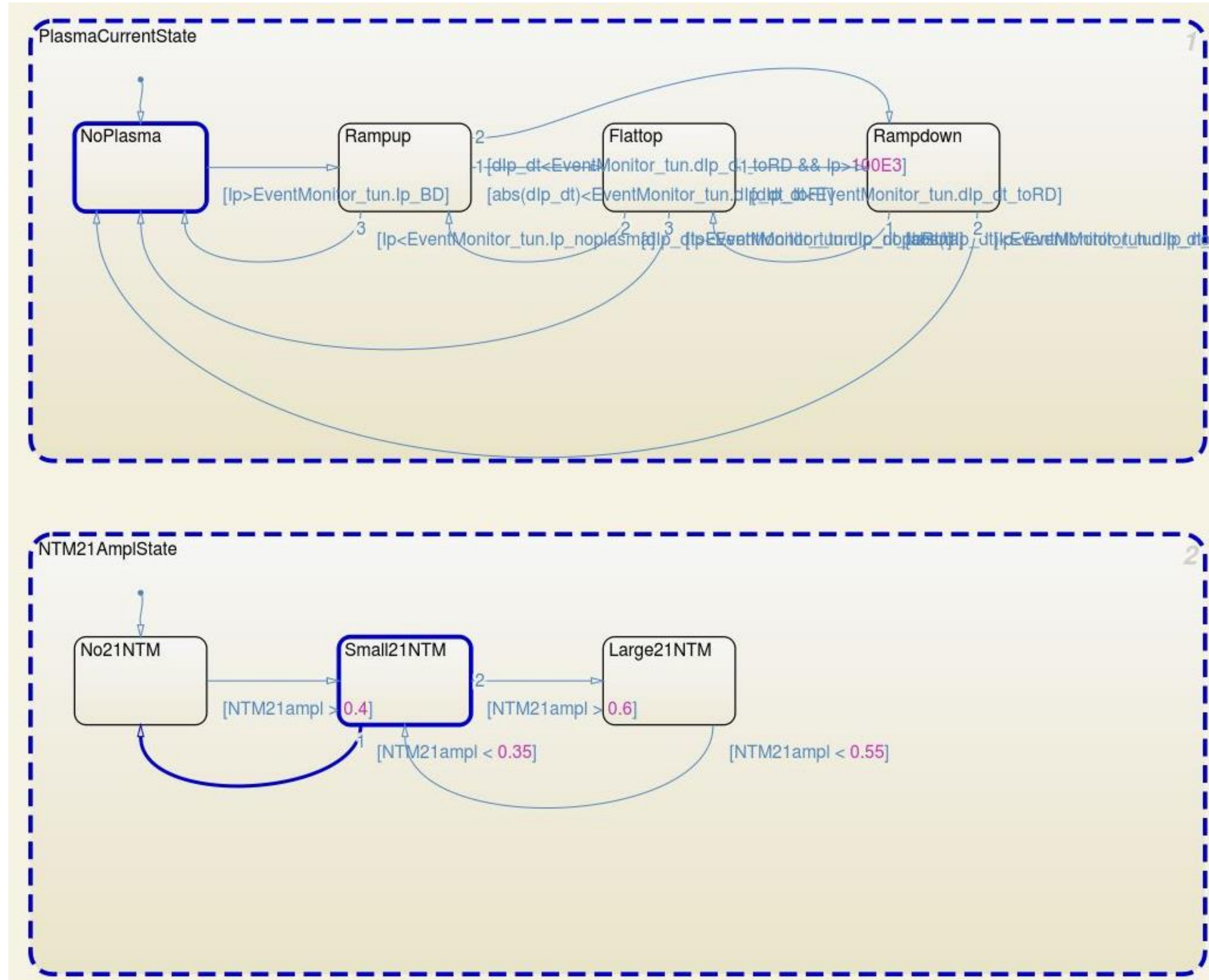
- **Returns active states of finite-state machine**
  - **Plasma current state**
  - **NTM amplitude state (m/n = 2/1, 3/2, 3/1)**
  - **NTM frequency state**
  - **LM amplitude state (n=1, n=2, n=3)**
  - **Observed vs. Reference profile discrepancy**
  - **Observed vs. Prediction profile discrepancy**
  - **Proximity to physics limits**
  - **Vertical control state**

Finite-state machine implementation using MATLAB Simulink Stateflow

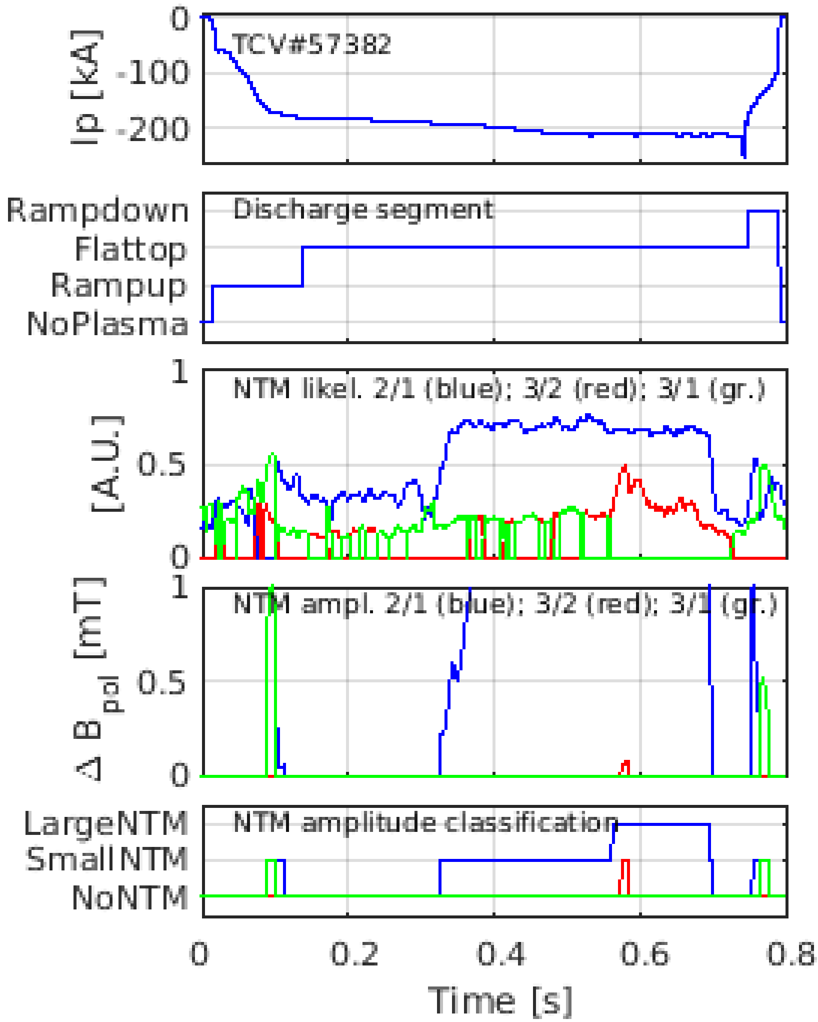
Finite-state machines

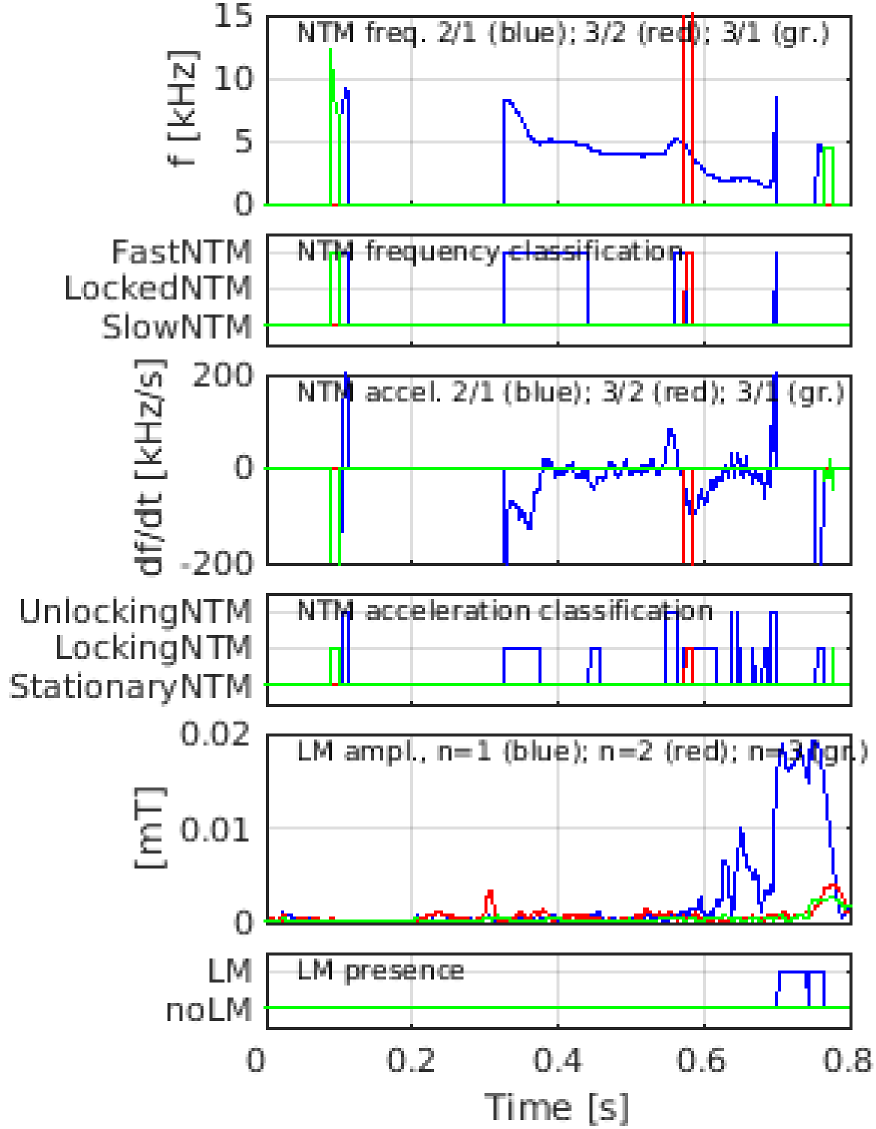
- ‘Clean’ way for high-level system representation

Script-based generation of finite-state machine



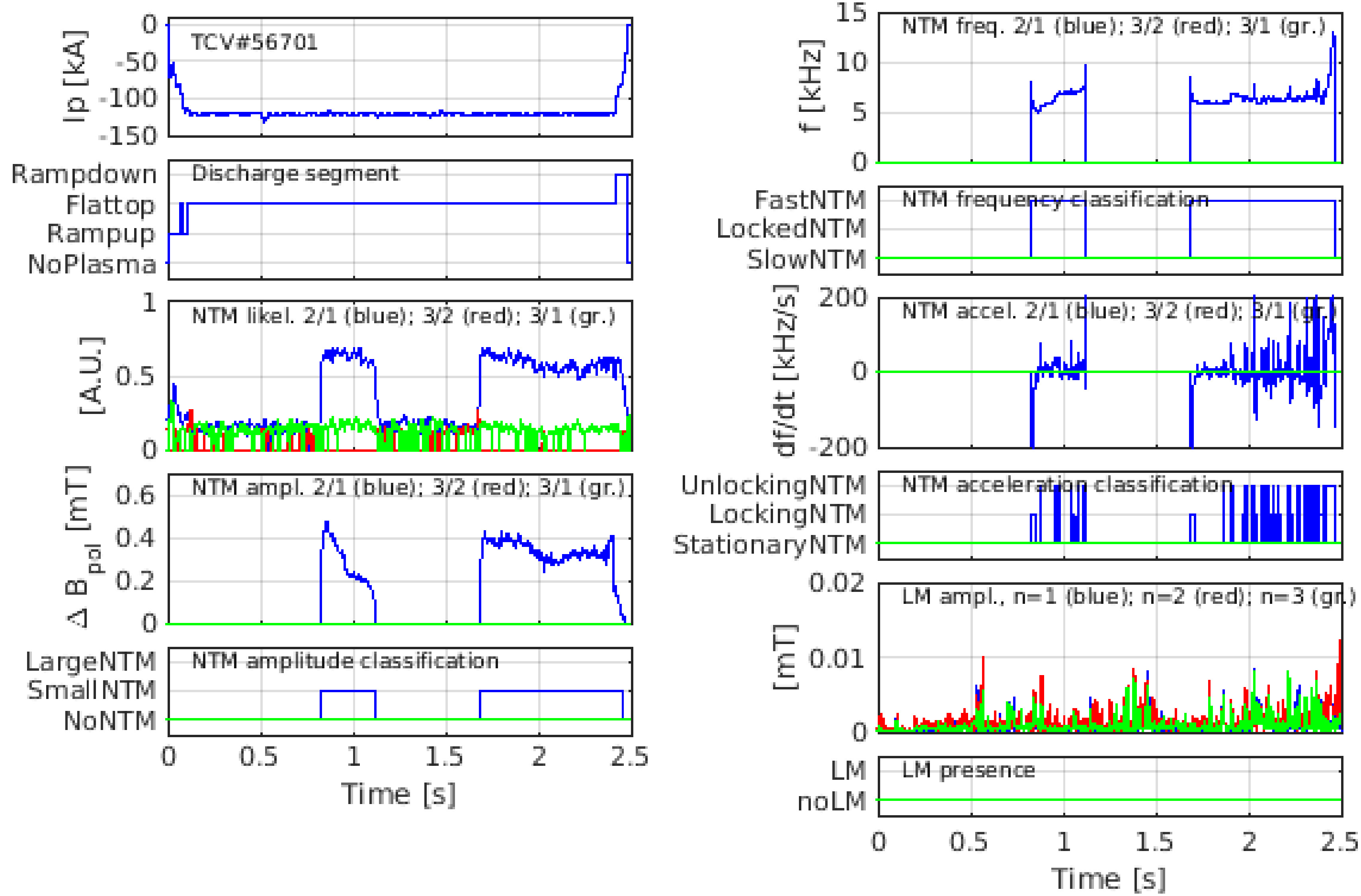
State monitoring on TCV #57382



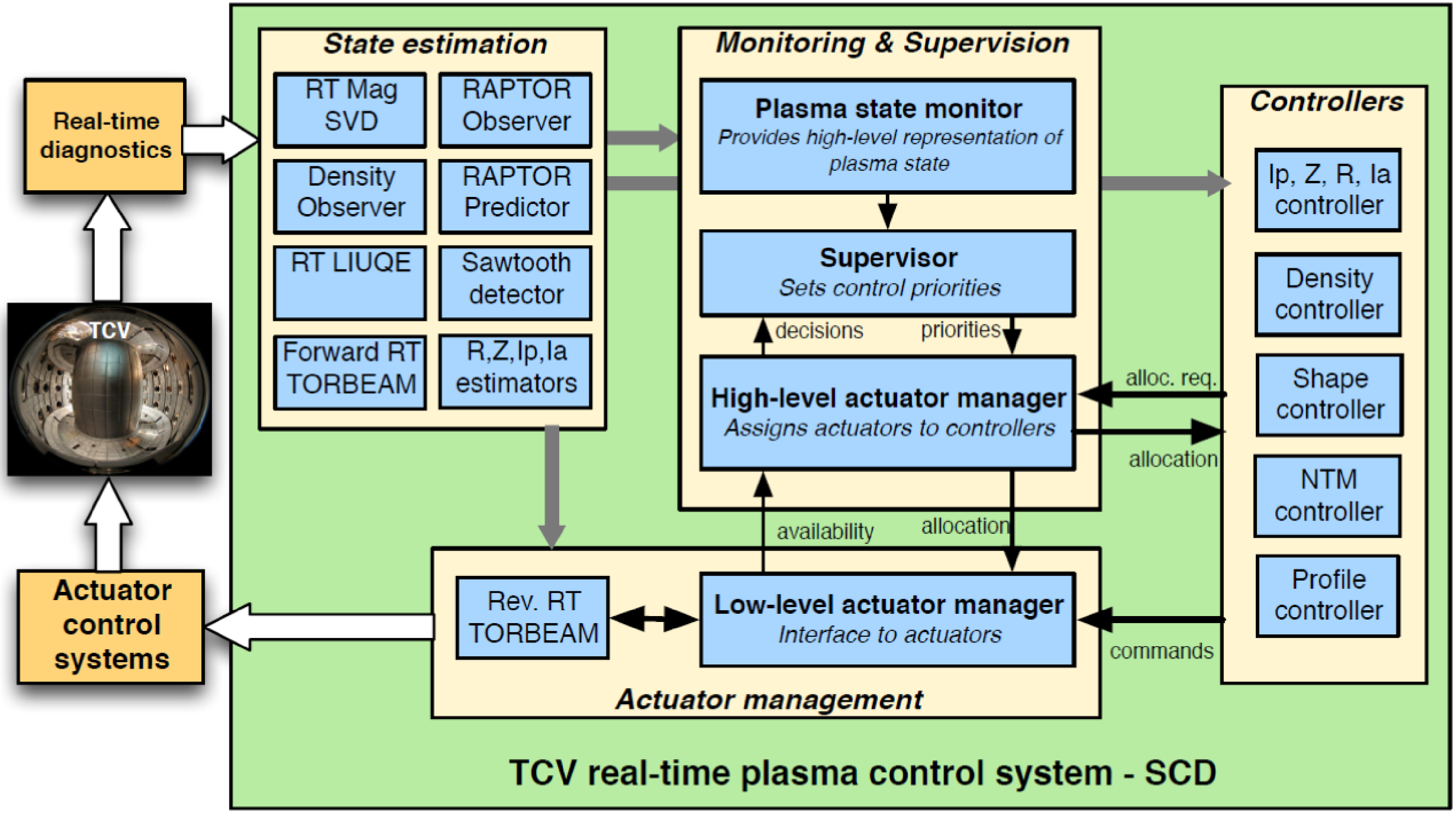


[Blanken *et al*, APS 2017]

State monitoring on TCV #56969

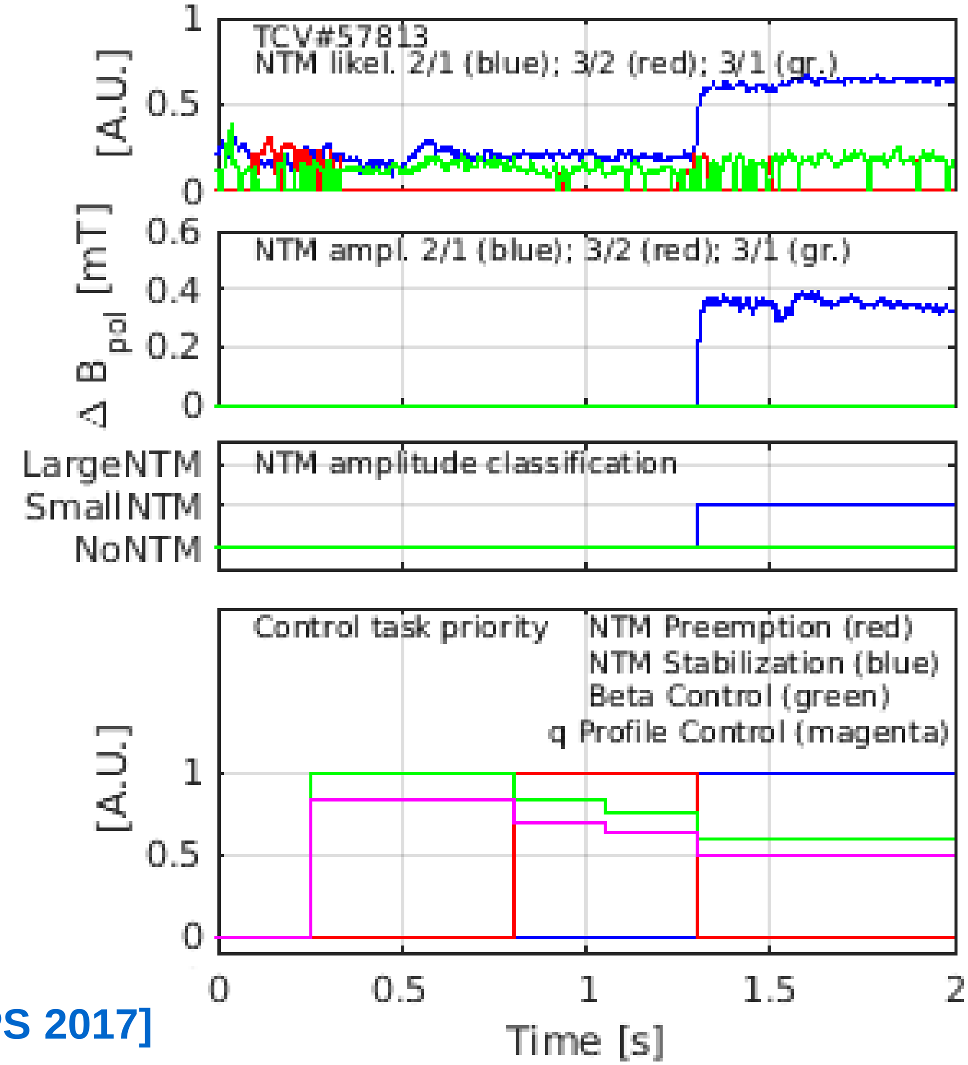


Real-time control tools on TCV PCS



Supervisory control of control tasks

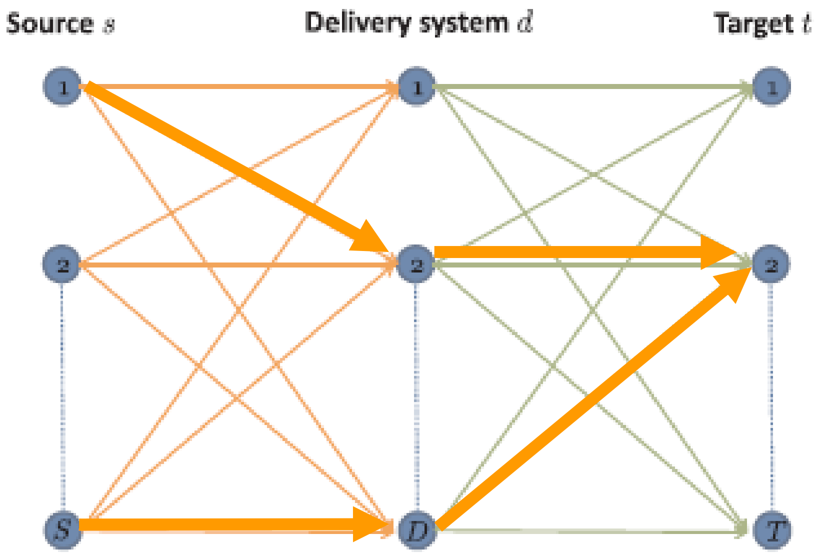
- **Goal: assign priorities to all control tasks**
- **Method: program decision logic based on timed triggers and plasma events**



[Blanken *et al*, APS 2017]

Actuator management and allocation

- **Goal: assign actuators to control tasks**
  - **Satisfy requests of power, current drive and deposition location**
  - **Minimize requests vs. allocation mismatch, weighted by priority**
  - **Minimize launcher movement**
  - **Constrained to actuator availability and capabilities**



[E. Maljaars *et al*, Fus. Eng. Des. (2017)]

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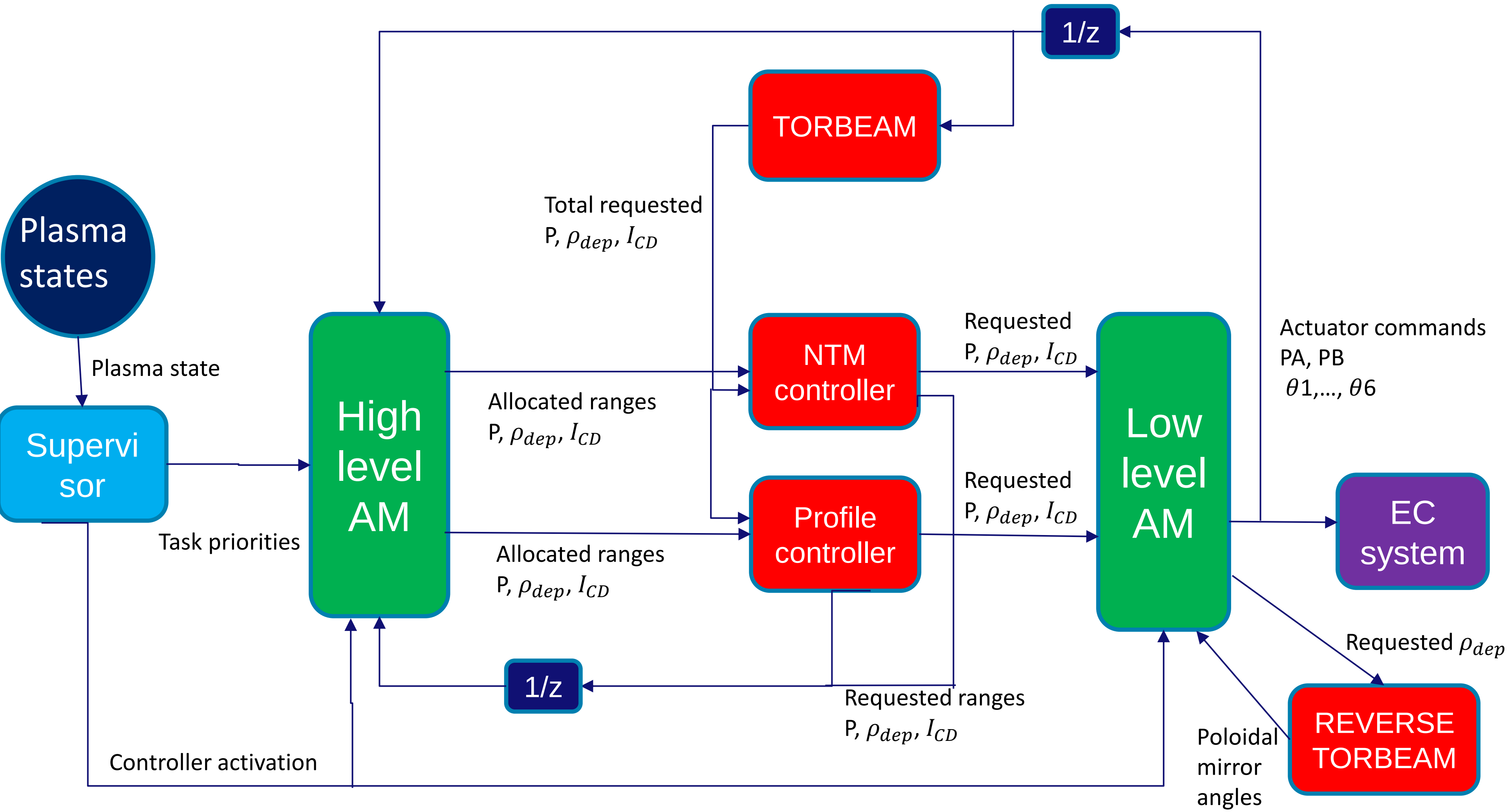
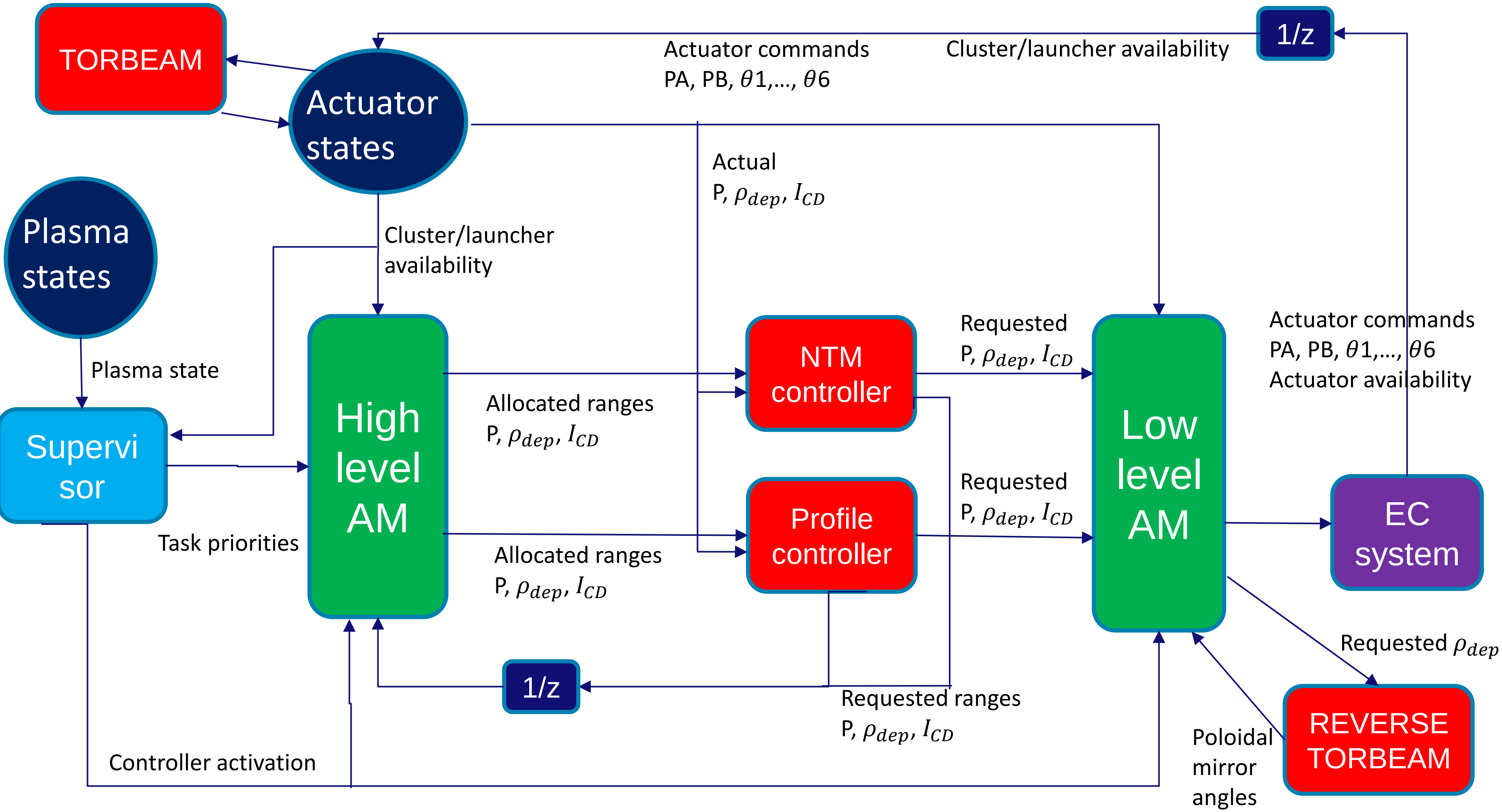
- Various possible architectures [E. Maljaars *et al*, Fus. Eng. Des. (2017)]
  - Pre or post allocation

- Actuator allocation as constrained optimization
  - Brute force optimization for AUG [C. Rapson *et al*, Fus. Eng. Des. 96-97 (2015)]
  - Mixed-integer programming for ITER [E. Maljaars *et al*, Fus. Eng. Des. (2017)]

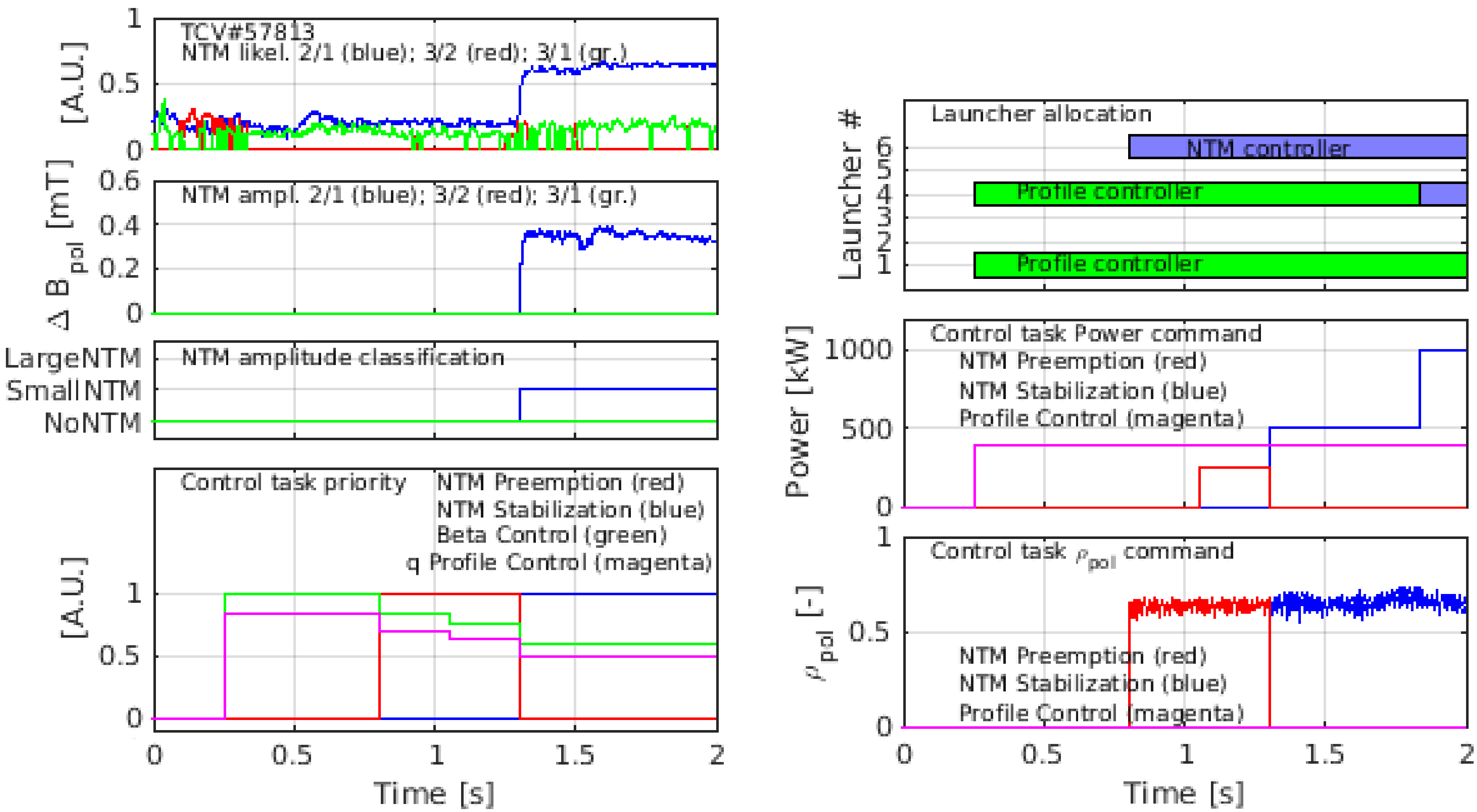
Hybrid AM on TCV: present



Hybrid AM on TCV: more complete



State monitoring, control supervision and actuator allocation on TCV #57813



[Blanken *et al*, APS 2017]

Outlook: further development of real-time plasma monitoring

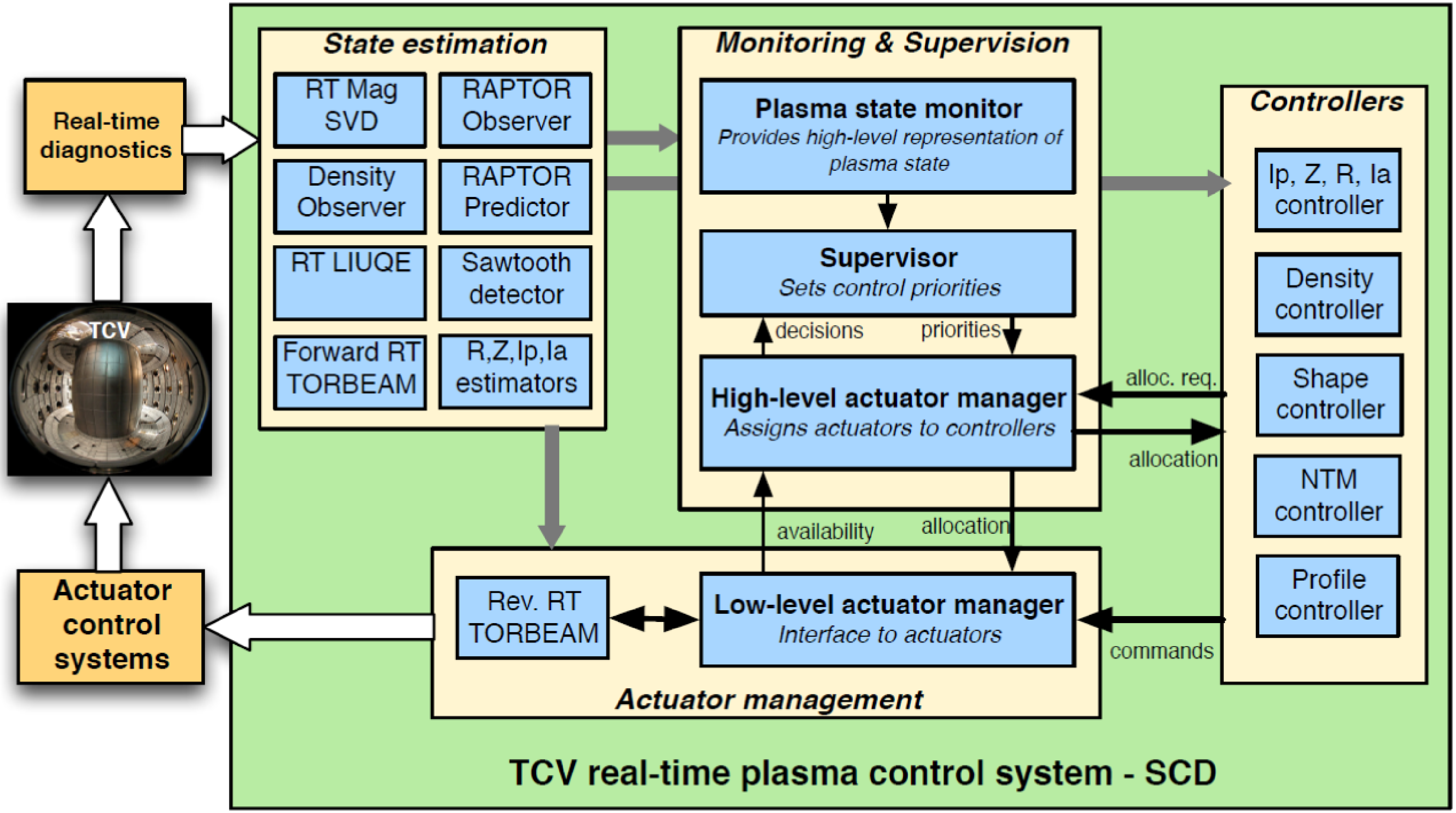
- **Add more states in Plasma State Monitor:**
  - **VDE and vertical position control faults/oscillations**
  - **Elongation and internal inductance limits**
  - **Density limits**
  - **Expected LM time from NTM frequency extrapolation**
  - **Confinement mode and ELM frequency**
  - **Discrepancies between observed (RAPTOR-observer) and predicted (RAPTOR-predictive) profiles**

- **Parametrization of physics limits for RT evaluation**
- **Faster than RT prediction with hazard assessment**
- **Test in conjunction with disruption avoidance strategies**

Conclusions

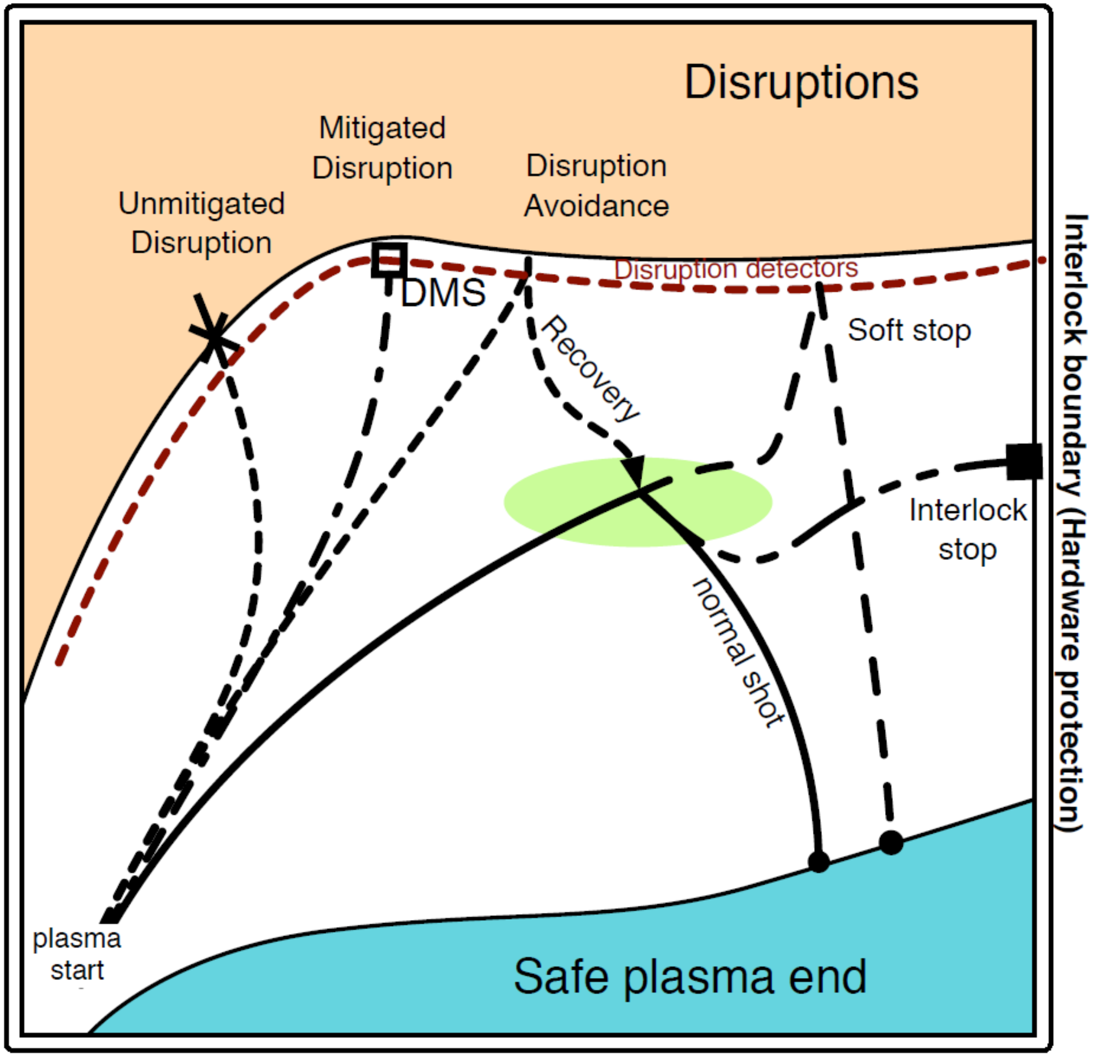
- We present a first implementation of the integration of high-level plasma supervision, control and actuator management on TCV.
- Conflicting requirements of low detection delay and avoiding false detection may cause problems in the presence of signal noise.
- Systematic definitions of component interfaces is challenging, both conceptually and in a real-time implementation!

Real-time control tools on TCV PCS



Back-up slides

Disruption avoidance, prediction and mitigation: signal/detection-based

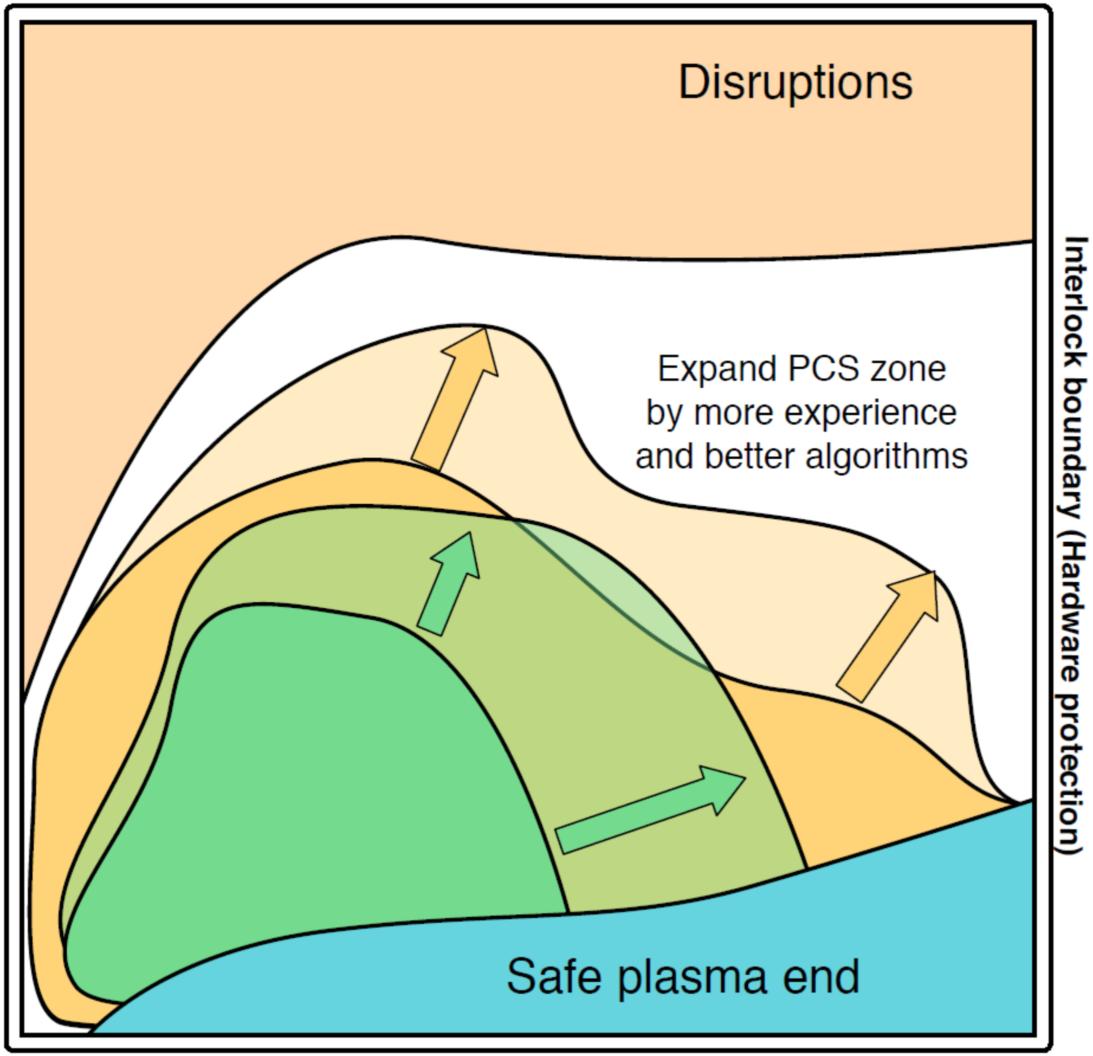


Most tokamaks employ disruption prediction and mitigation only as a last line of defense.

This approach is not advised for ITER and other large tokamaks, where use of DMS should be minimized.

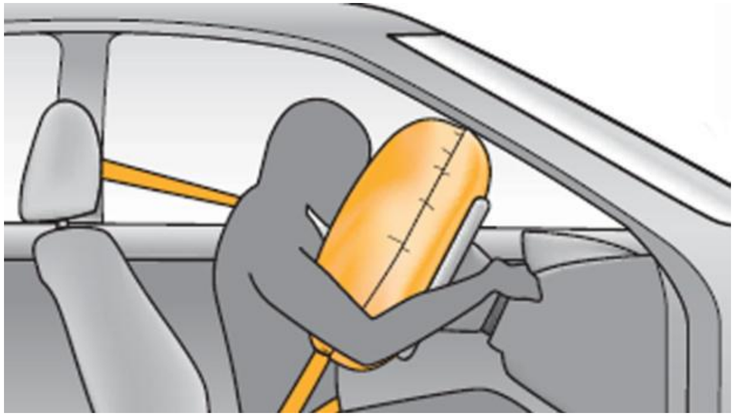
F. Felici, IAEA 2016, EX/P8-33

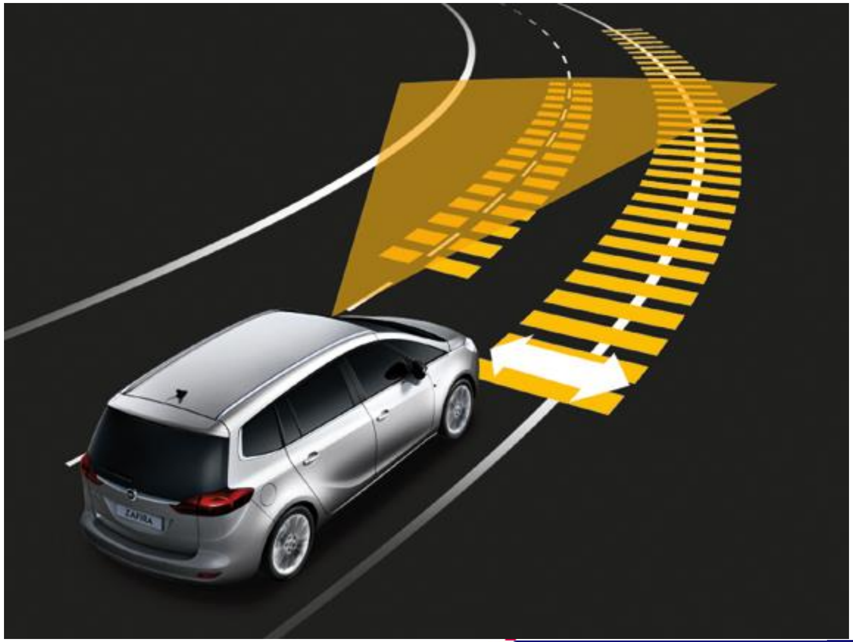
PCS functions for disruption avoidance



F. Felici, IAEA 2016, EX/P8-33

Disruption avoidance, prediction and mitigation: integrated scenario monitoring

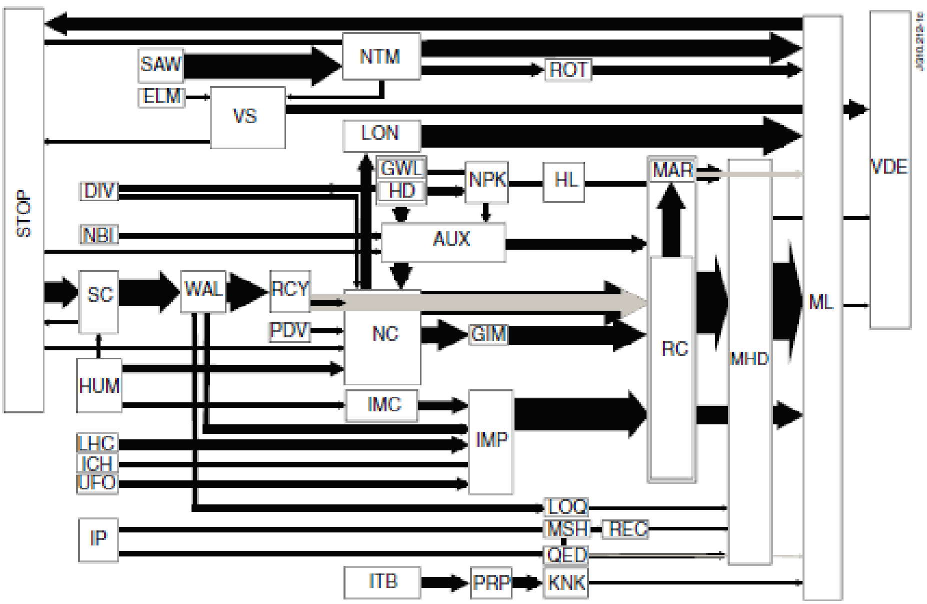




TCV

- **X2 ECHCD system**
  - **Presently 3 gyrotrons/launchers on 2 power supplies**
  - **RT control over power supplies and poloidal mirror angles**

Handling with disruption causes



P.C. de Vries *et al,* Nuclear Fusion 51 (2011) 053018

- **Physics origins**
- **Technology origins**