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Integrated real-time supervisory control actuator management for handling of off-normal-events and feedback control of tokamak plasmas

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Swiss Plasma Center

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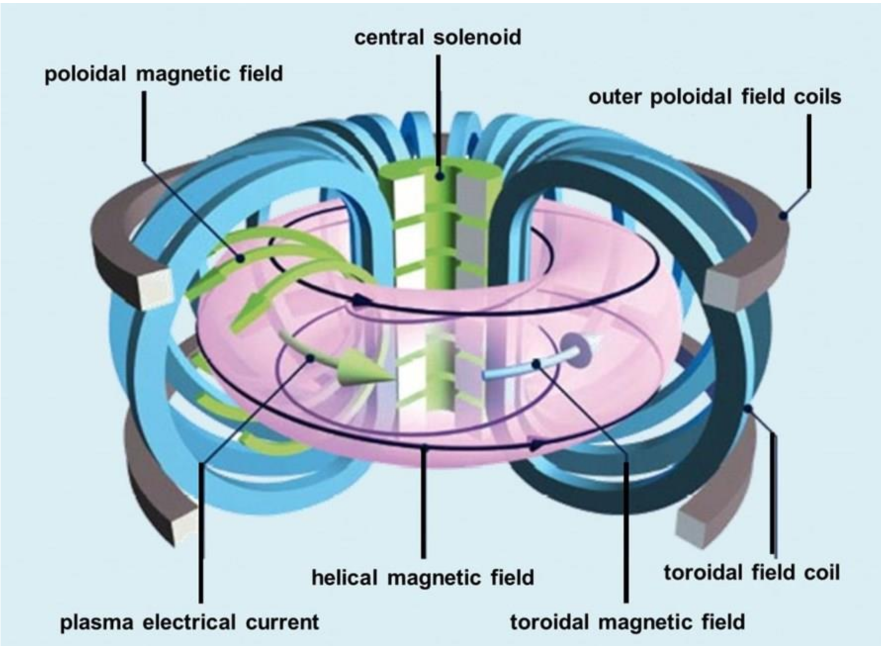
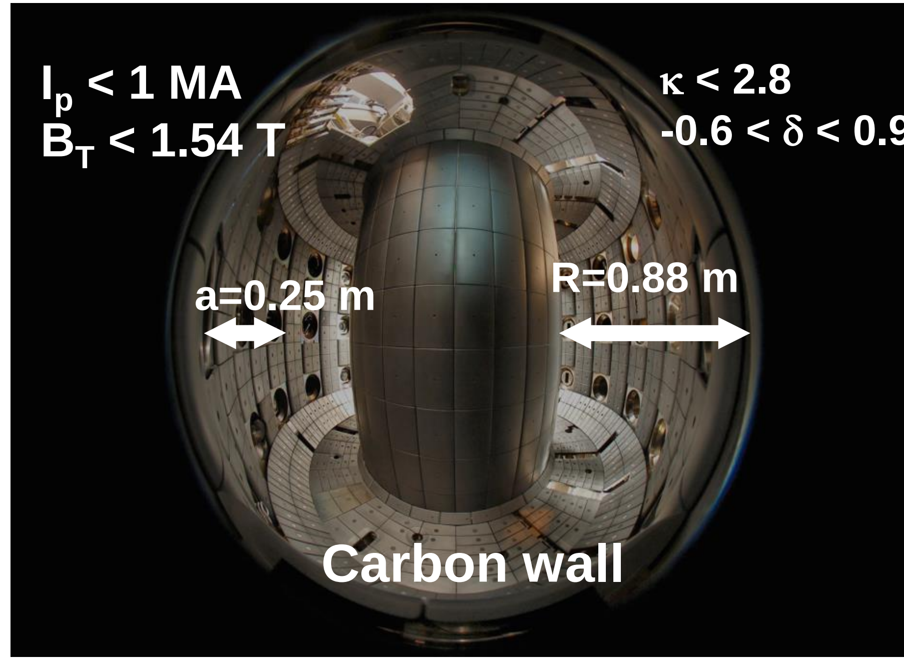
Outline

1. Integrated real-time control issue of tokamaks
2. Generic plasma control system architecture
3. Experimental result
4. Conclusion

TCV (Tokamak à Configuration Variable)
an ideal test-bed for integrated control



Tokamak schematic



TCV inside view

- Located at **Swiss Plasma Center (SPC**), Lausanne, Switzerland
- First plasma in November 1992
- **16 poloidal field coils** & elongated vacuum chamber: **strong shaping capabilities**
- Neutral beam injection (**NBI**) + flexible electron cyclotron (**EC**) systems
- **Flexible real-time digital control system**

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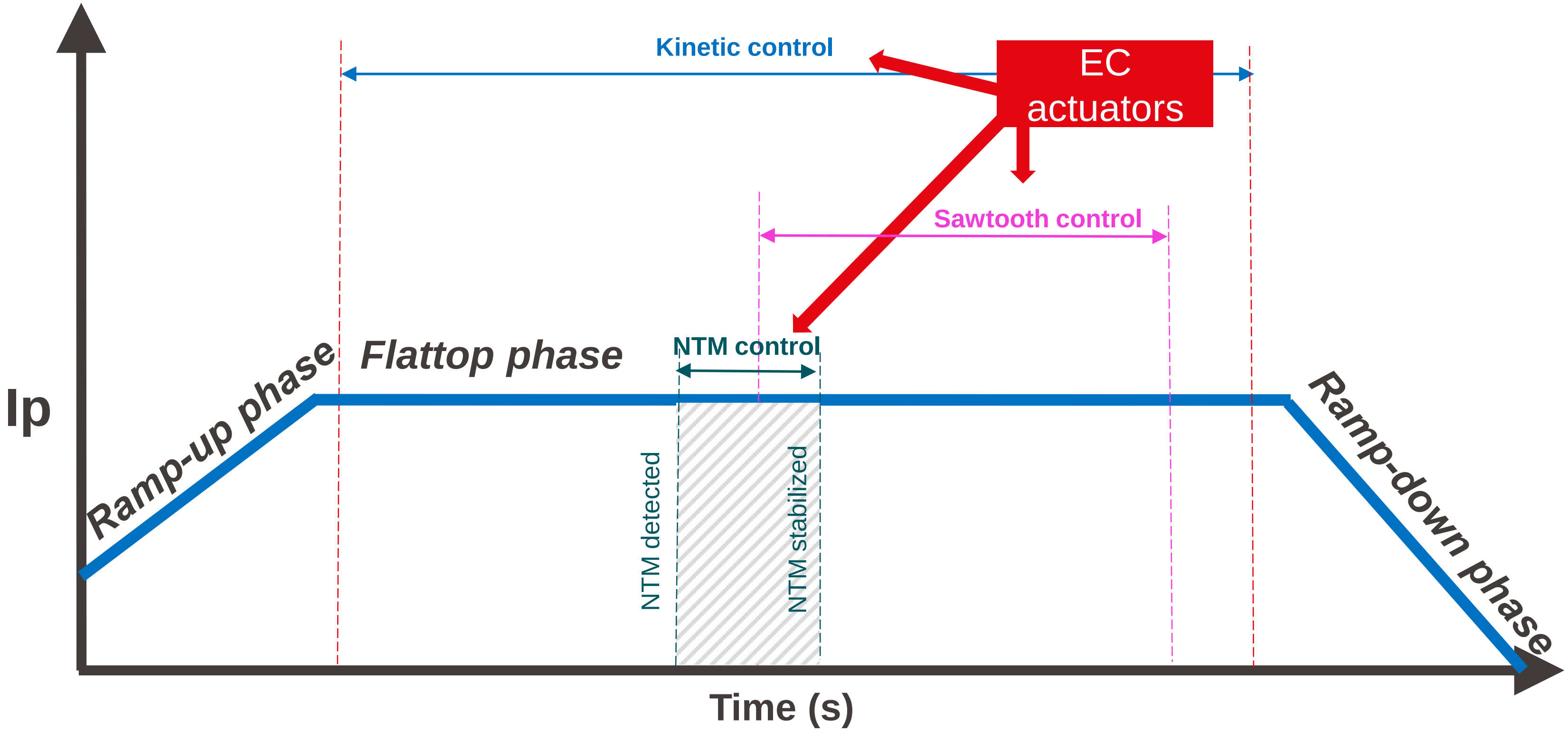
Future long pulse experiment (e.g. ITER) will require real-time task prioritization



Real-time decision:
- multiple control tasks
- actuator sharing
- time varying priority

→ **Solution: controller cross-talk**

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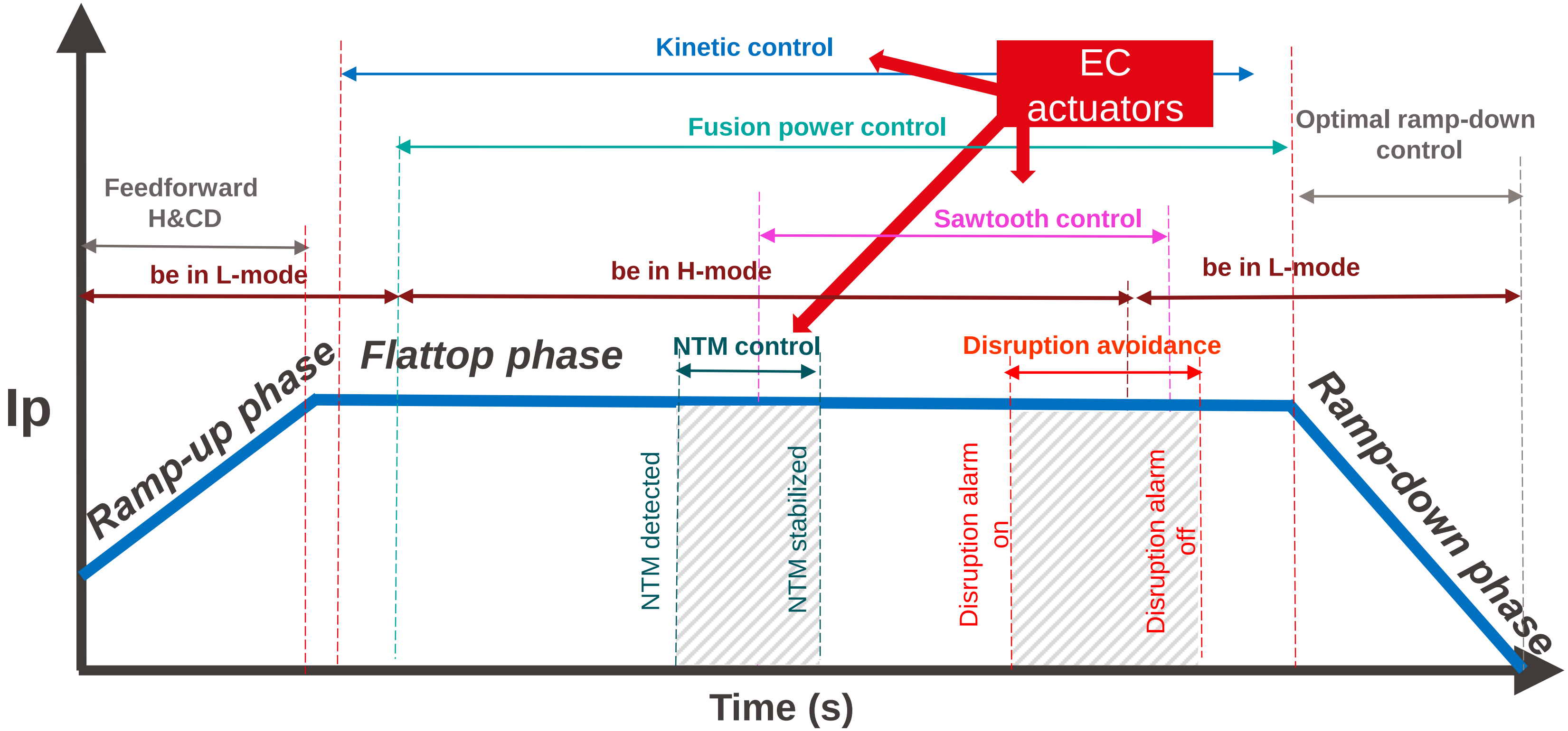

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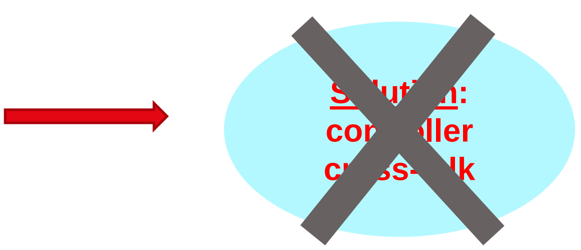

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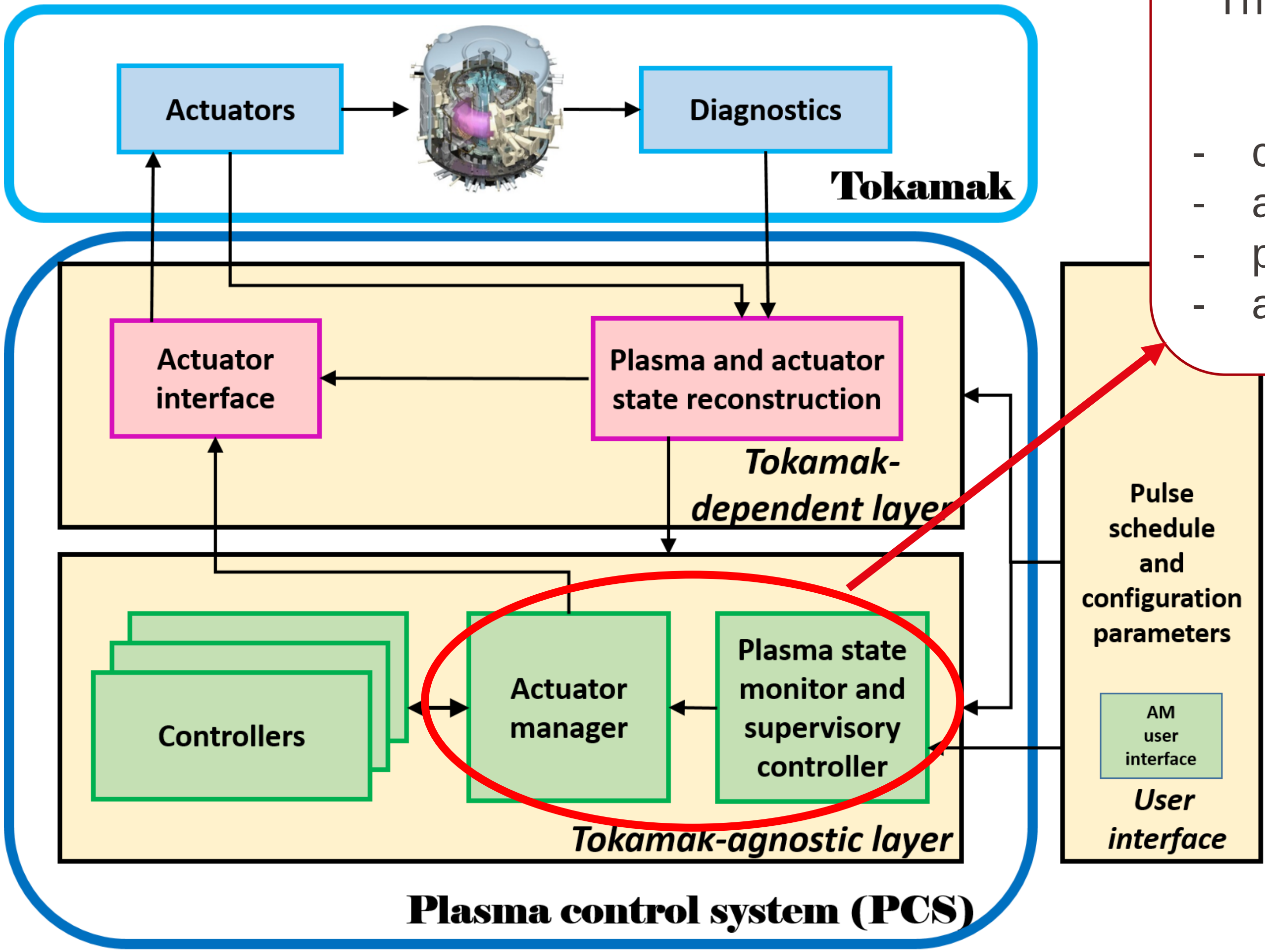
Generic PCS architecture: solution with a supervisory layer

Separates clearly responsibility/decision making in various components of PCS



The **supervisory layer** makes high level decisions:
- choose scenario
- activate control tasks
- prioritize control tasks
- assign actuators

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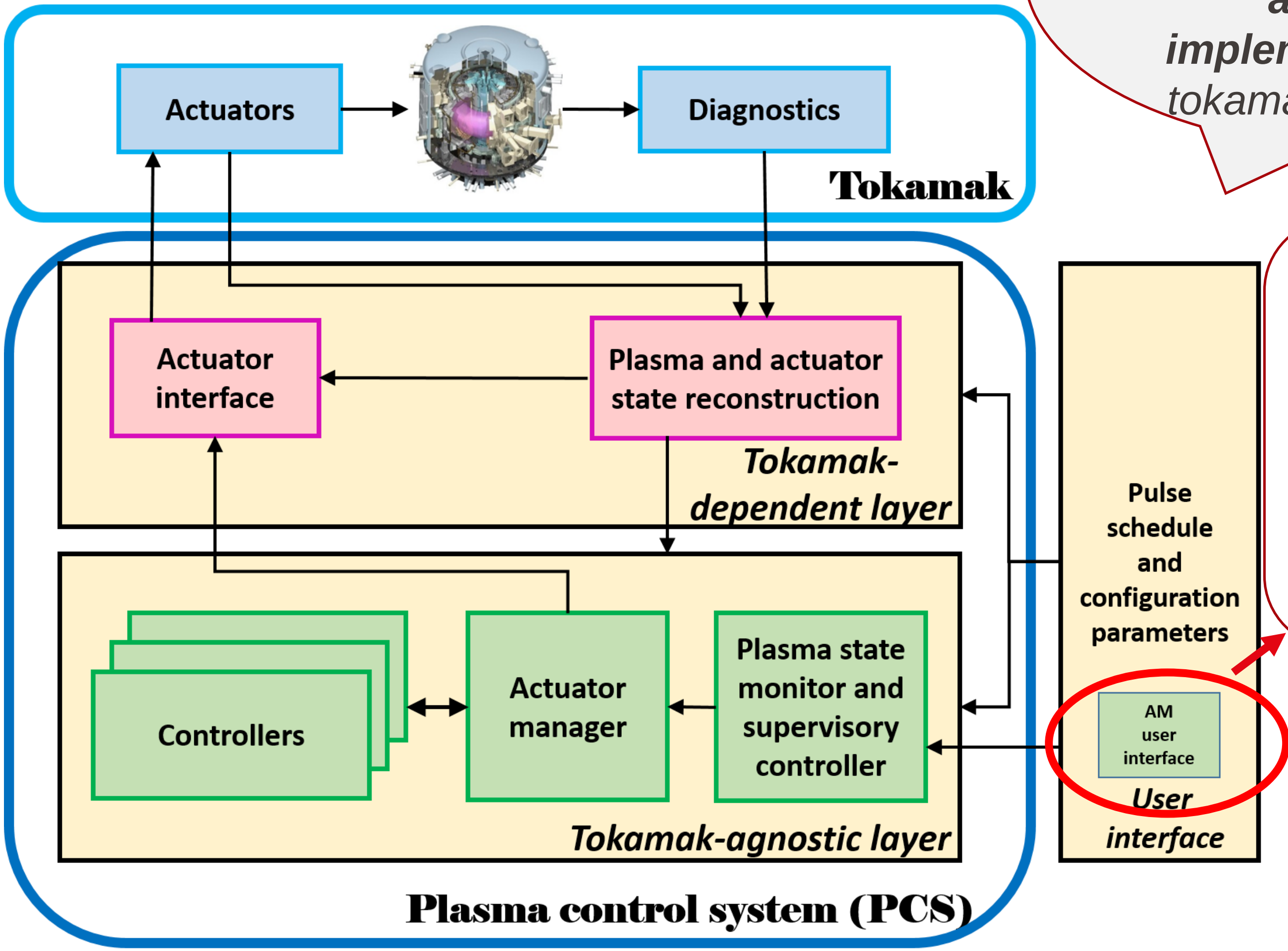
[1] T. Vu et al., Fusion Eng. Des. **147** 111260 (2019)
[2] T. Blanken et al, Nucl. Fusion **59(2)** 026017 (2019)

Generic PCS architecture: solution with a supervisory layer

Separates clearly responsibility/decision making in various components of PCS

"Tokamak-agnostic" in the sense that the ***functionality, algorithm, implementations*** are *tokamak-independent*



Specific *pulse-schedule & tunable parameters for all components are configured in the* ***user interface***

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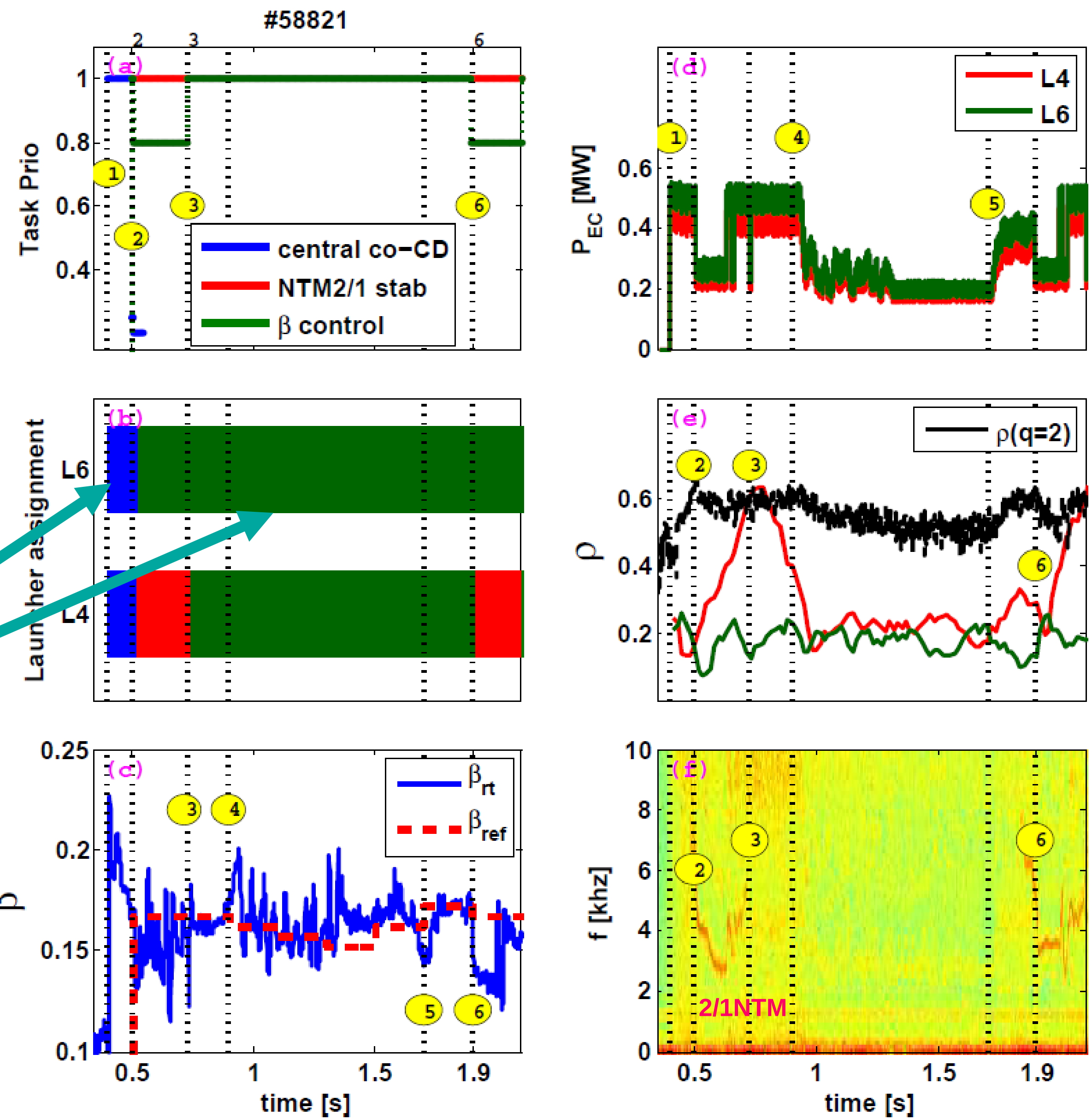
Example: β, NTM, feedforward controls

(3 control tasks & 2 actuators)



At ①: central co-CD is the only active task

At ③: β is the only active task

AM reacts: assign both *L4* and *L6*

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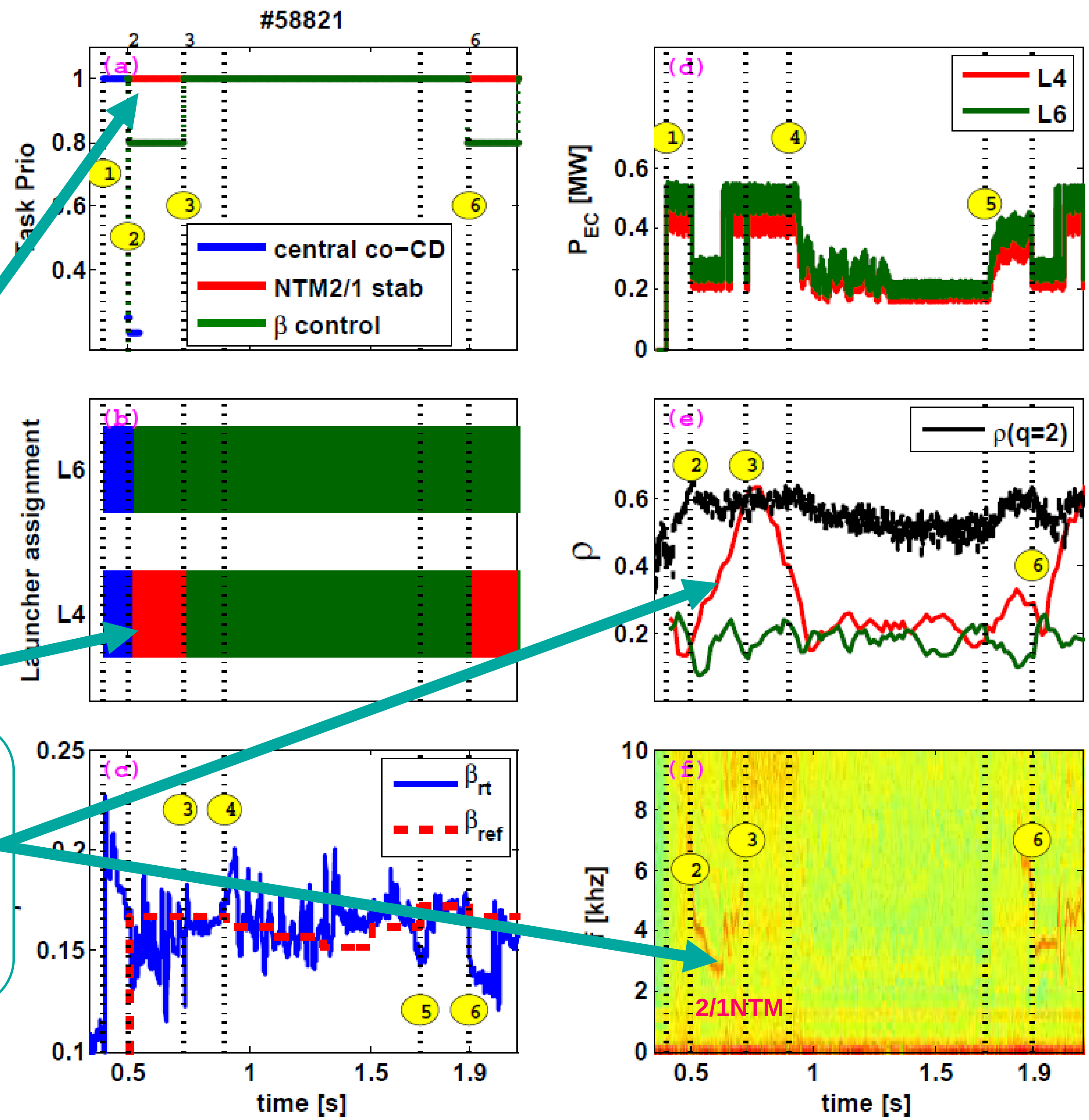
Example: β, NTM, feedforward controls
(2 NTM stabilizations)



At ② & ⑥ : NTM detection & β ctrl activation

AM reacts: change task priorities, assign *L4* for NTM task and *L6* for β ctrl task

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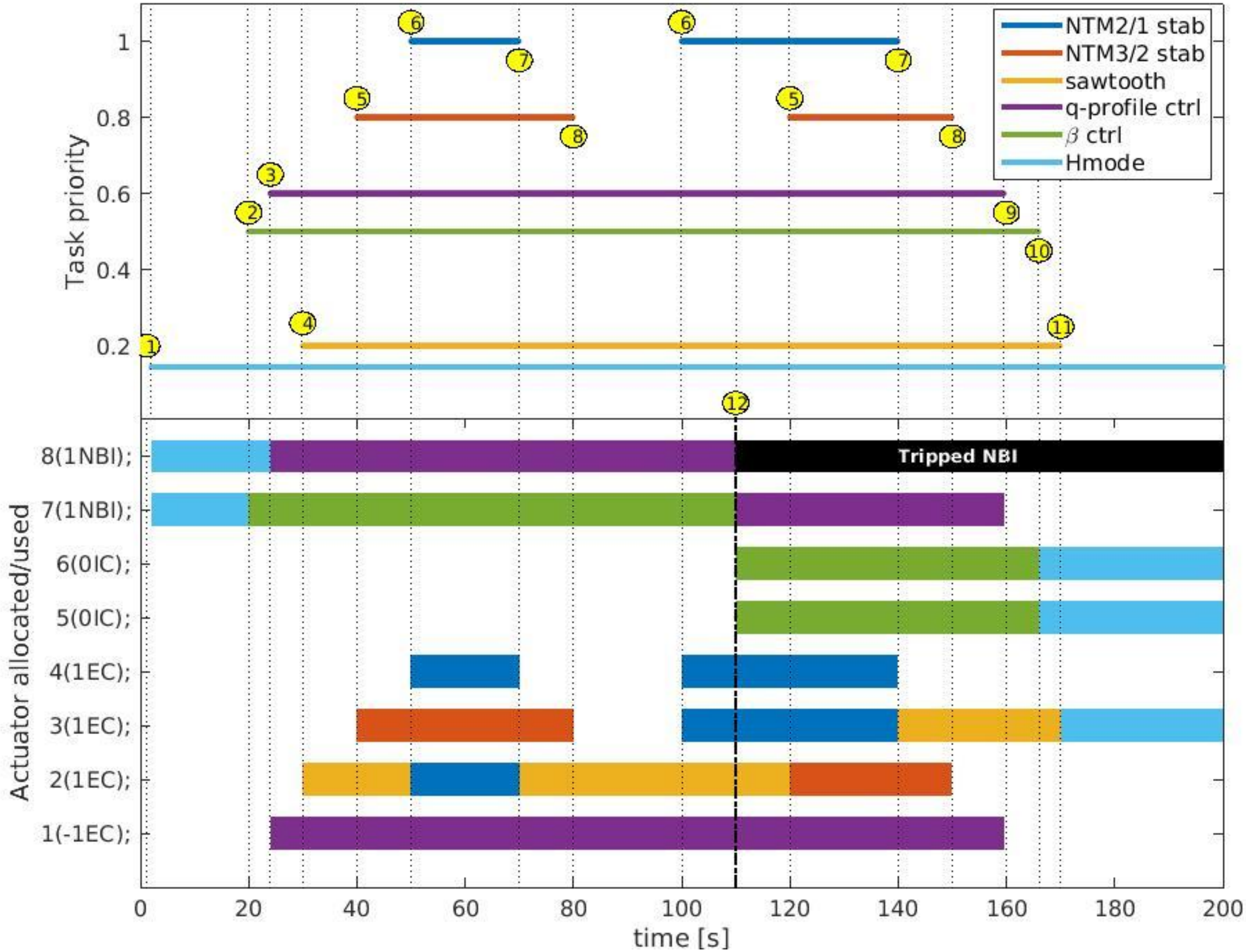
ITER example: multi-control tasks and actuators



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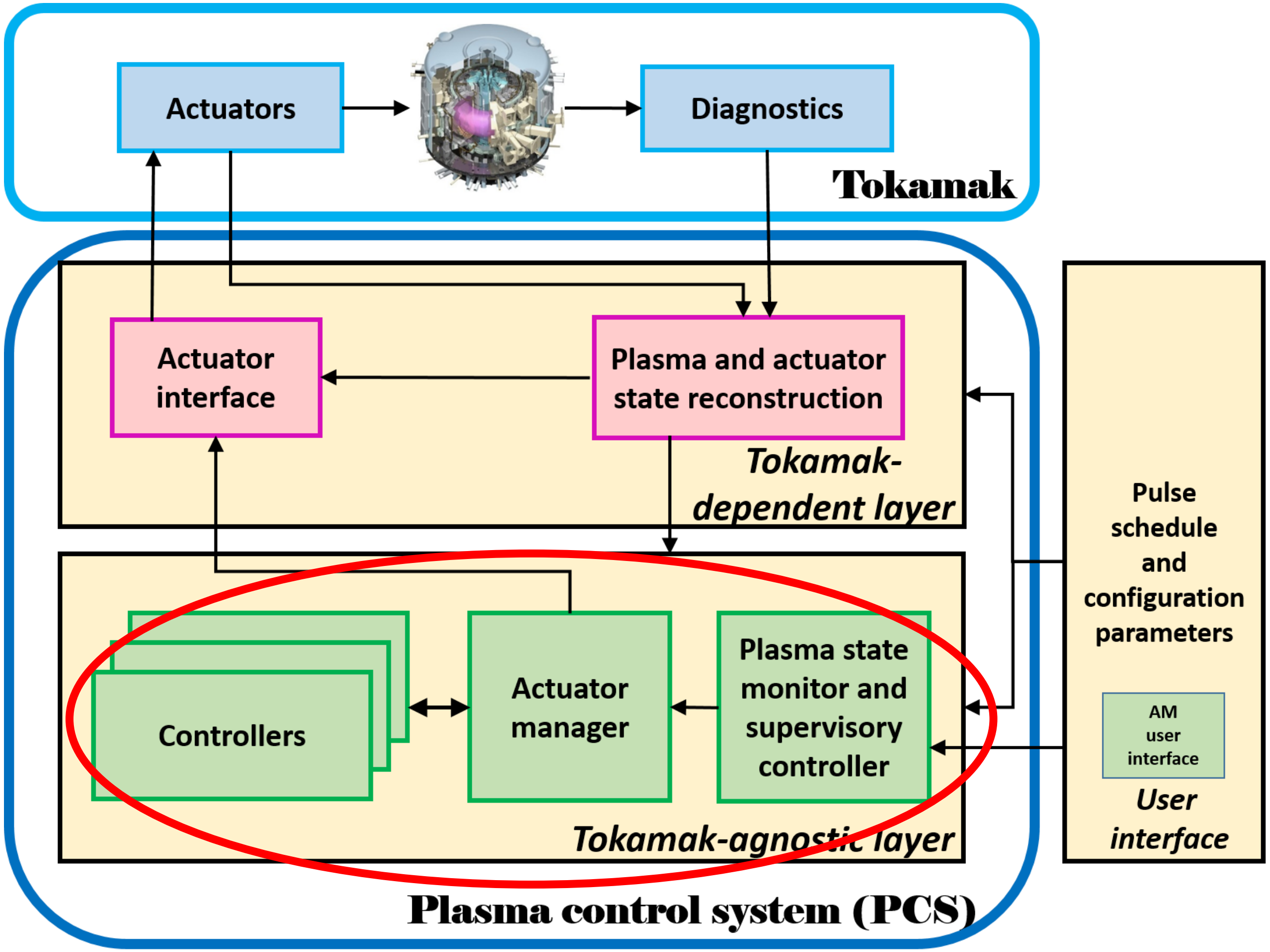
Generic PCS architecture

Separates clearly responsibility/decision making in various components of PCS



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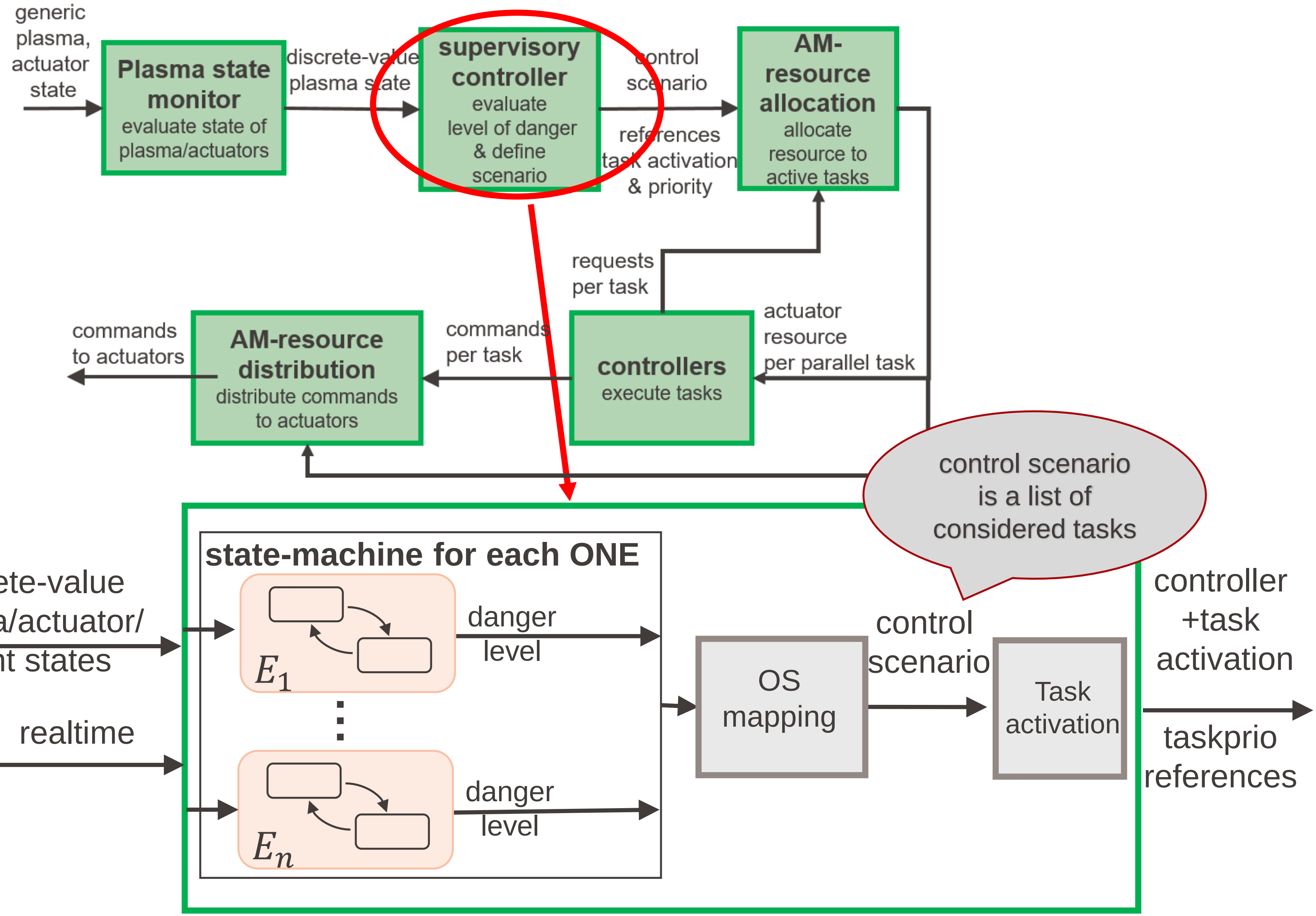
Tokamak-agnostic layer



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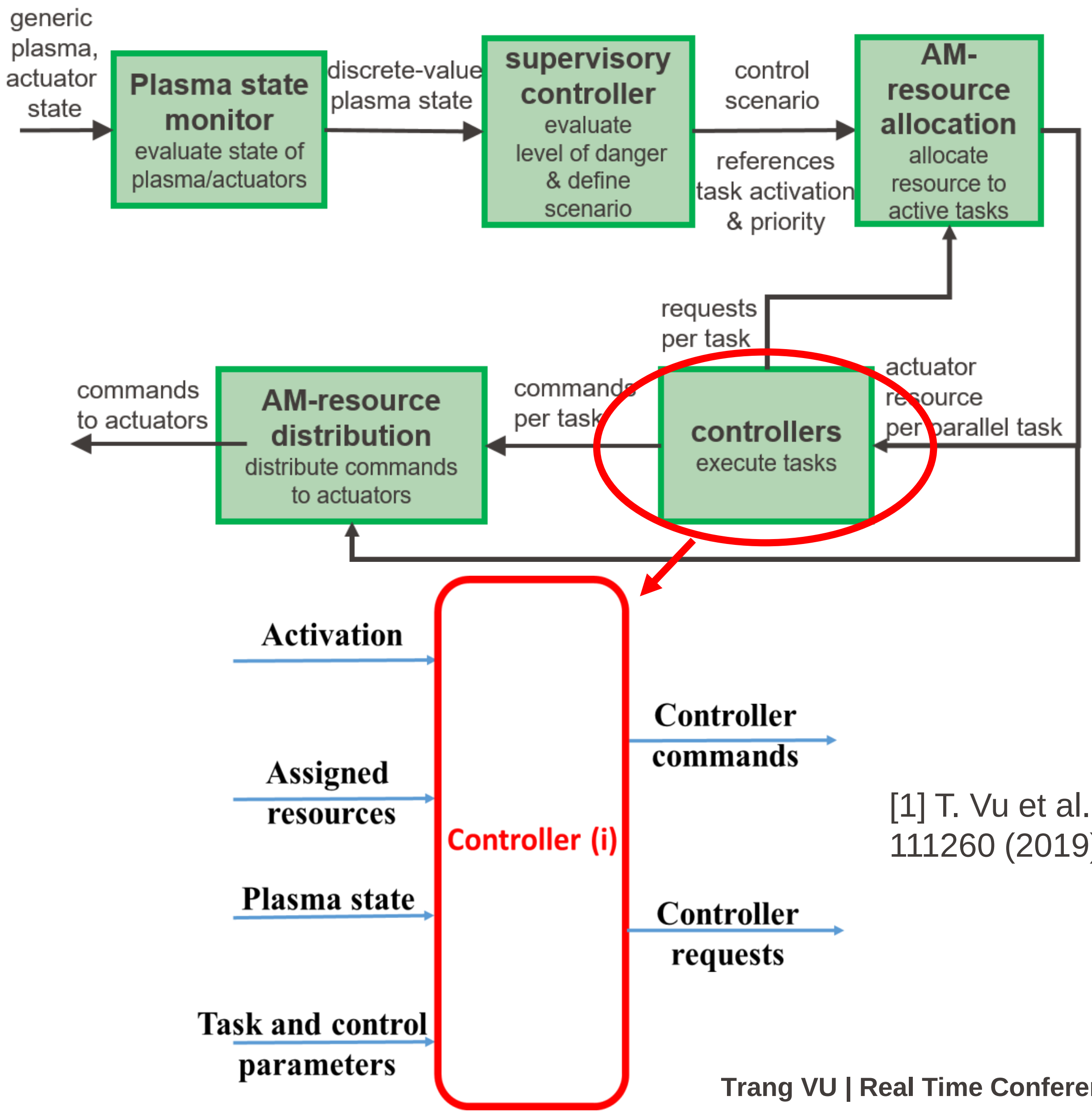
Generic controllers: with standardized interfaces, key for rapid development and maintenance



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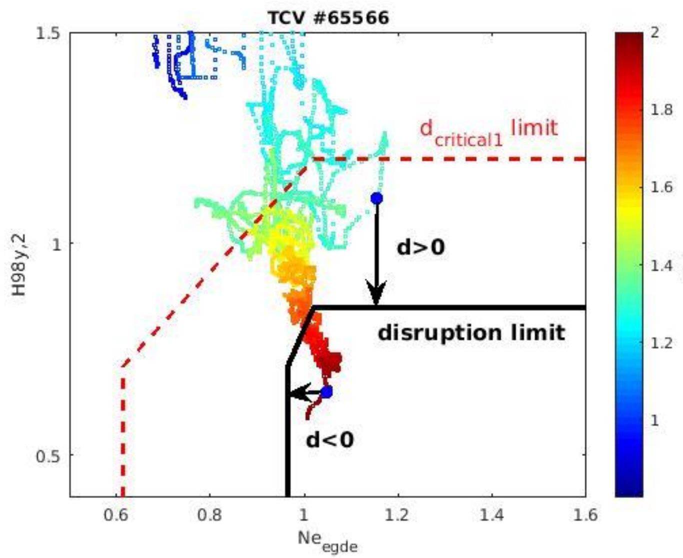
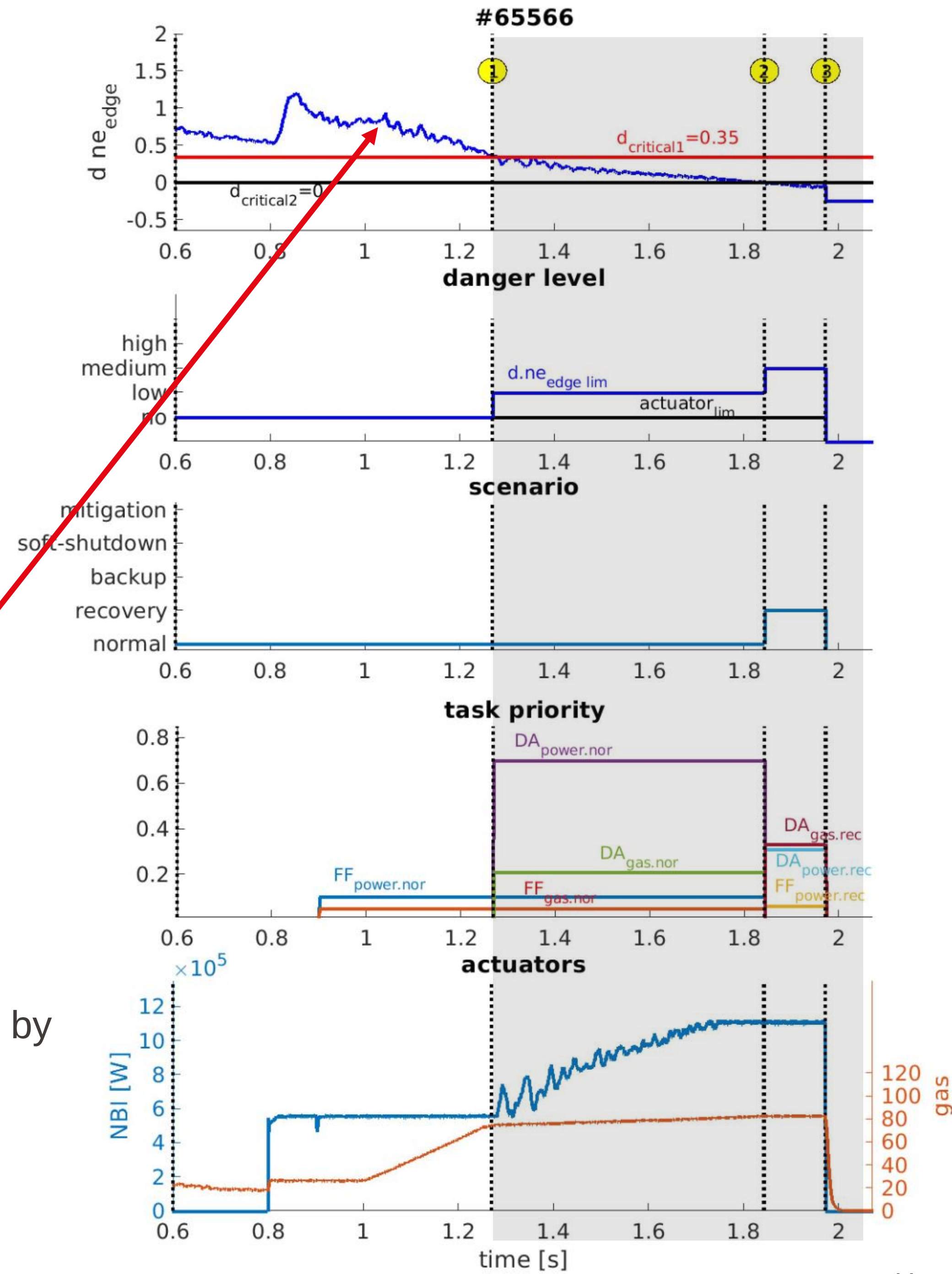
Disruption avoidance discharge with density limit



$$d_{ne\_lim} > d_{critical1}$$

- *no* danger for event « density limit»
- *normal* scenario:
  - NBI and gas valve are controlled by the feedforward tasks



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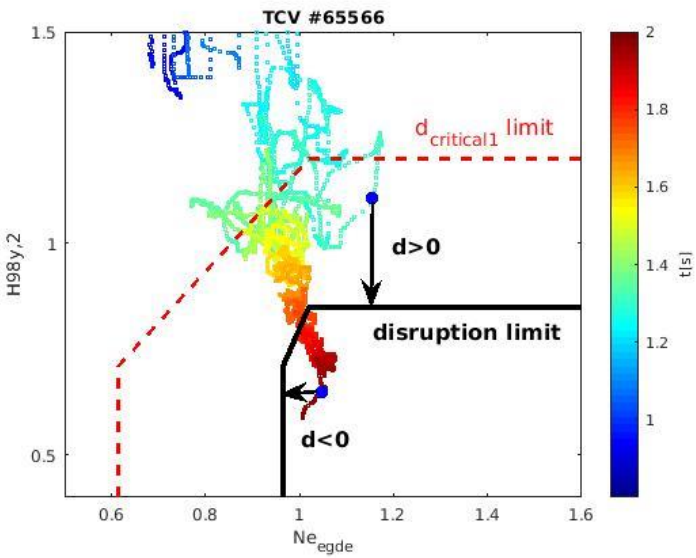
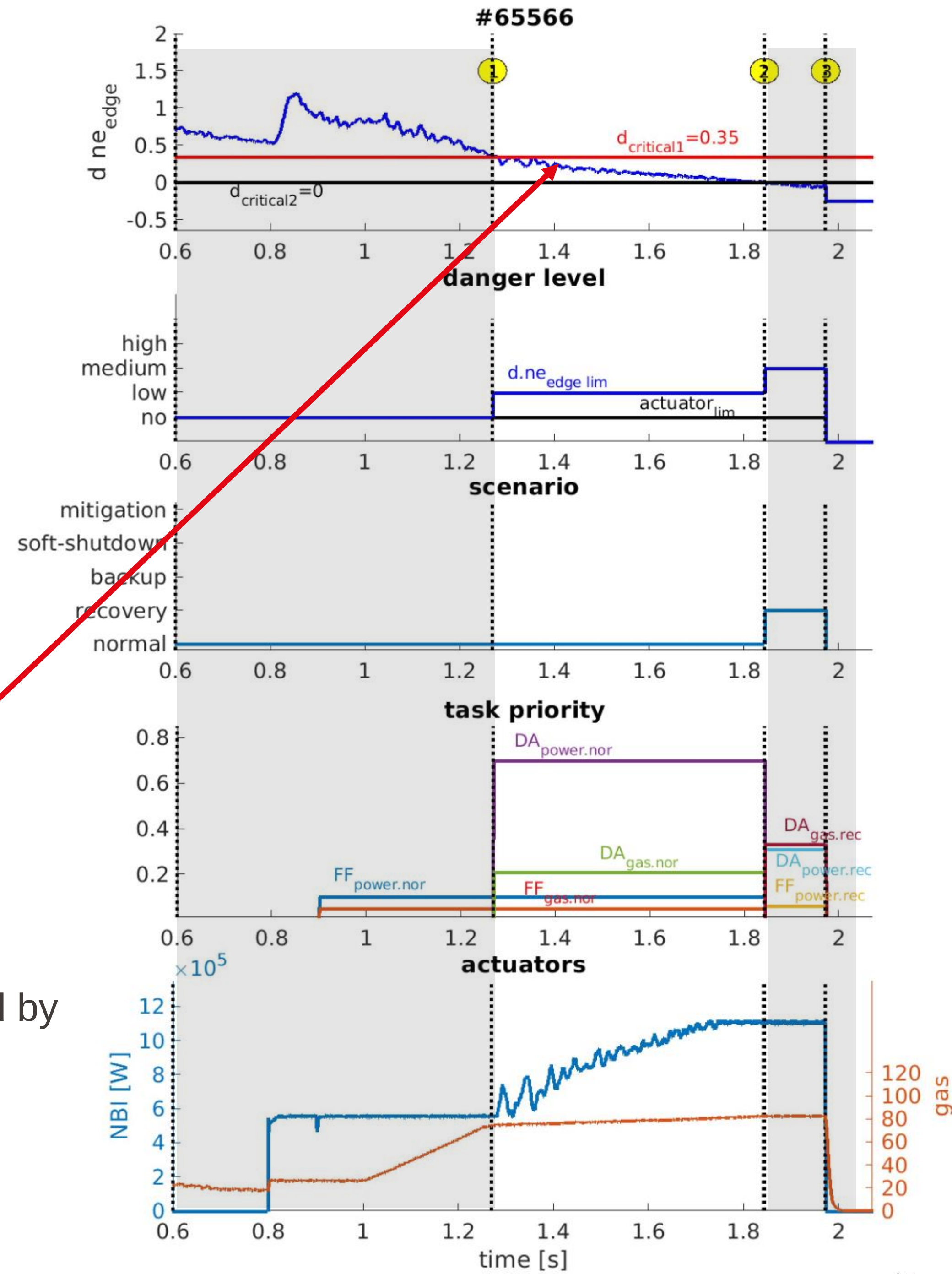
Disruption avoidance discharge with density limit



$$d_{critical2} < d_{ne\_lim} < d_{critical1}$$

- *low* danger for event « density limit»
- *normal* scenario:
  - NBI and gas valve are controlled by the feedforward tasks

  + the modifications of DA tasks



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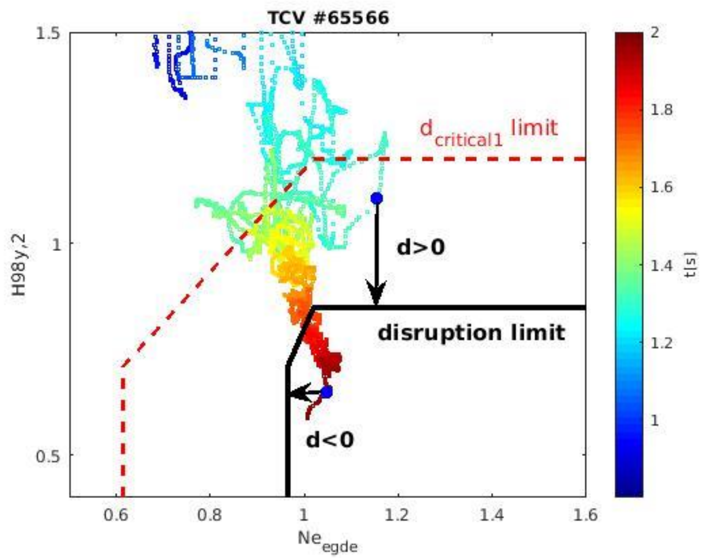
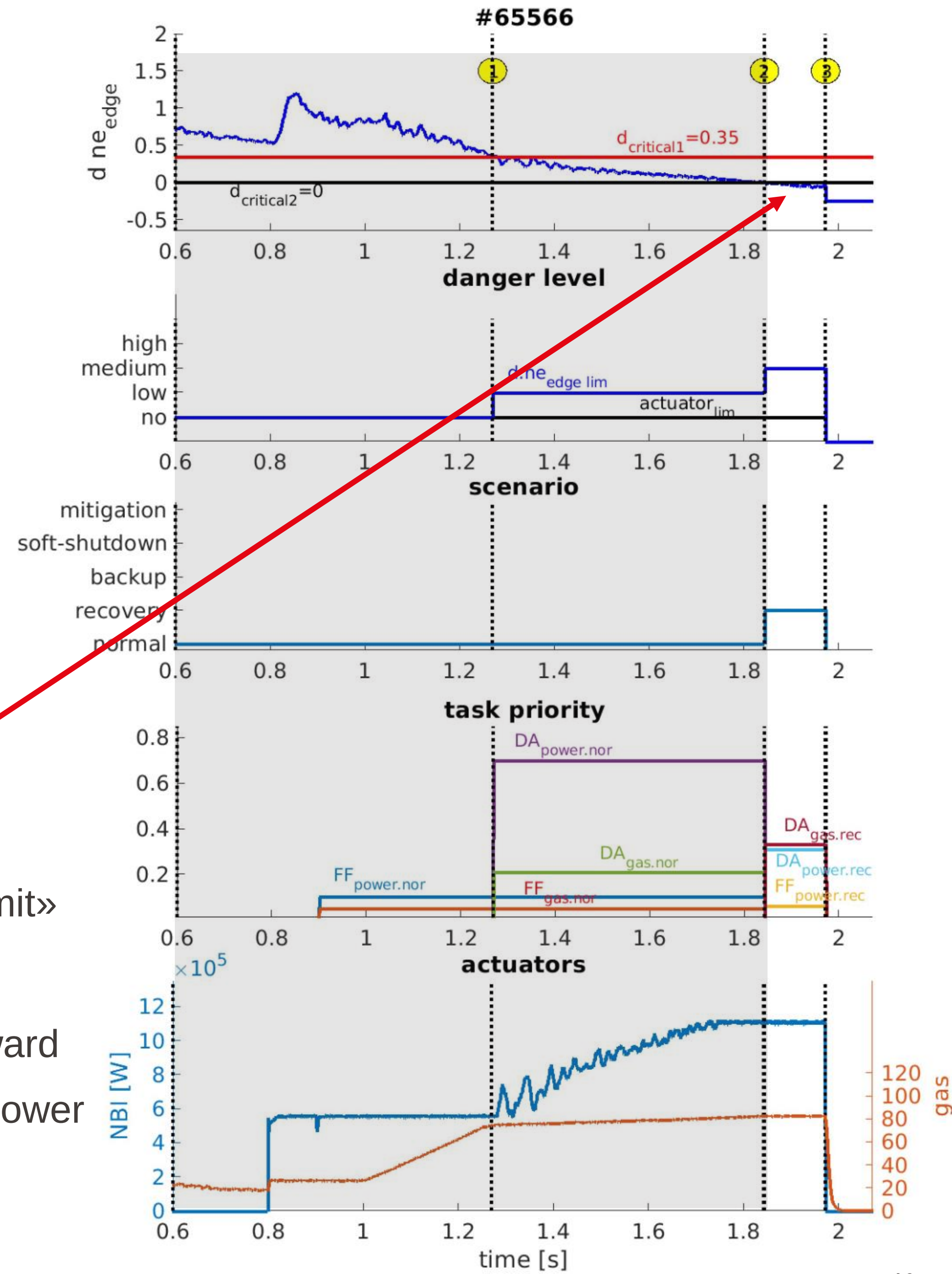
Disruption avoidance discharge with density limit



$$d_{ne\_lim} < d_{critical2}$$

- *medium* danger for event « density limit»
- *recovery* scenario:
  - NBI is controlled by the feedforward
    - + $DA_{power.rec}$ asks for maximum power
    - + $DA_{gas.rec}$ freezes the gas flux



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Conclusion

- A generic PCS architecture is proposed with **a tokamak-agnostic layer**, device-independent

- The supervisor and actuator manager can simultaneously **handle off-normal-events** and **multiple control objectives**

- The **standardized interfaces** between the components facilitate development and implementation (add/remove off-normal-events, controllers,…)

- The proposed PCS is **successfully implemented and tested** on TCV

- This PCS architecture is **proposed to AUG and ITER** as well

Backup

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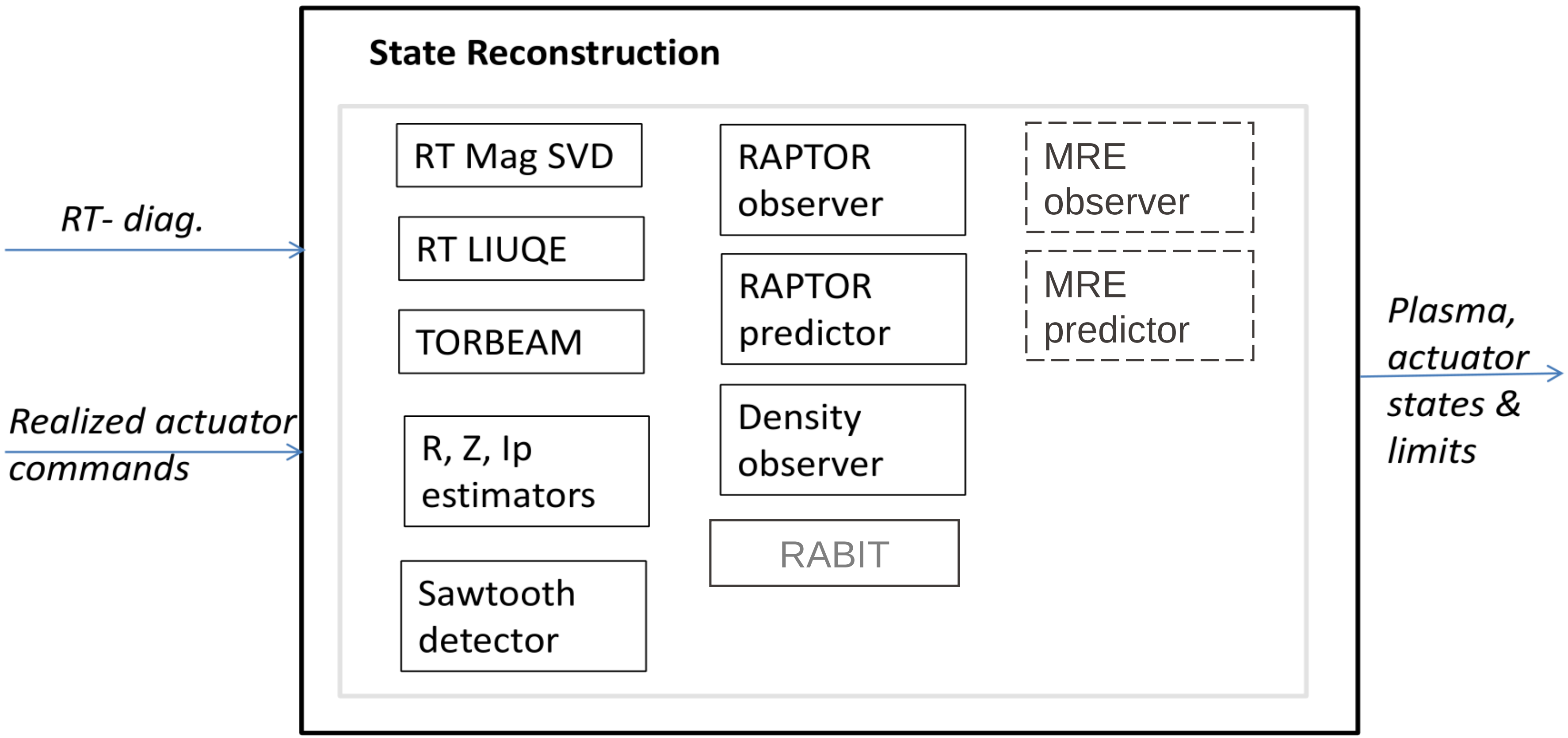
Plasma and actuator state reconstruction: actual developed modules on TCV



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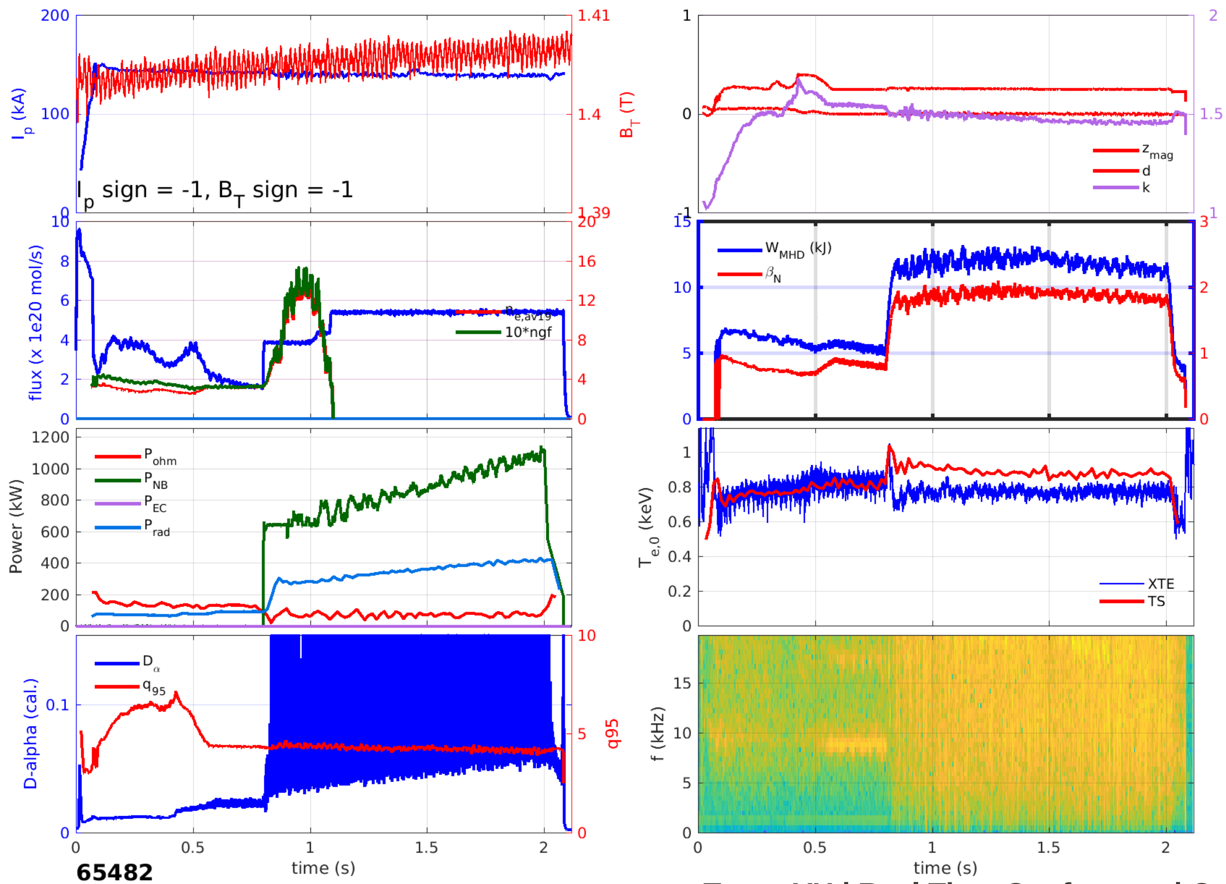
Real-time control and other applications

- Using real-time control for **physics based studies**
  - control of limit approach rate
    (from the example, always approach the density limit at slow rate w.r.t the distance)

- Using real-time distance for better **H-mode control** through **pedestal control**
  - control of distance to stay at «good H and ELMy phase»
    (from the example, very nice regular ELMy H-mode, ~constant β_N~1.9)



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Supervisor for disruption avoidance

The **supervisor** selects the **appropriate scenario based on** Off-Normal-Events**:**

- $\boldsymbol{E_{d\_ne\_lim}}$**: distance** between the (H_{98y2}, edge density) and the disruption limit
- $\boldsymbol{E_{act\_lim}}$: **actuator saturation** from actuator state (e.g energy_max)

Three control scenarios with the corresponding control tasks:

scenario	task	controller
normal $E_{d\_ne\_lim}$ danger= {no, low}	feedforward_power (constant $P_{heat} = 0.65MW$) feedforward_gas (constant then fast-ramp gas flux)	feedforward
	DA_power ($\Delta P_{heat}(d_{nelim})$) DA_gas (slow-ramp gas flux)	disruption-avoidance (DA) controller
recovery $E_{d\_ne\_lim}$ danger={medium}	feedforward_power (constant P_{heat})	feedforward
	DA_power (maximum P_{heat}) DA_gas (freeze gas flux)	DA controller
soft-shutdown $E_{d\_ne\_lim}$ danger = {high} or E_{act_lim} danger = {high}	DA_power (decrease P_{heat} to 0) DA_gas (decrease gas flux to 0)	DA controller

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