MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Flight simulators

ASDEX Upgrade

Embedding Integrated Plasma Models into Plant & Control System Models (and/or the other way around)

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EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Plant systems and control systems

Everything required to have a working fusion device

- Coils (toroidal, poloidal, MP-coils…) ⇨ react to plasma evolution
- Vacuum vessel and pumping systems ⇨ stabilize pumping speed (temperature, gas flow…)
- Plasma facing component (first wall, divertor, diagnostic protections…) ⇨ avoid damage
- Fuel cycle and injection systems (pipes, valves, pellets, breeding blanket…) ⇨ Maintain ideal D-T ratios
- Heating systems (NBI, ECRH, ICRH…) ⇨ optimize plasma temperature and ensure best heat deposition
- Cooling systems (cryogenic cooling if supras, heat removal…) ⇨ avoid over-heating
- Diagnostics ⇨ Enable all mentioned actions
- Power supplies for all of the above ⇨ Adapt to the power demand
- Central control system (synchronize and centralize most event generation)

Outline

1. What is control, and why do we need it?

a. Short introduction to control (strengths and challenges)

b. 2 practical examples of plasma controllers

2. Why “close the control loop” in simulations?

a. Limitations of experiment-based control strategies

b. What is a “flight simulator” and how can it be used?

Disclaimer: Not a control theory class!

The fusion plasma:
an dynamic system in a dynamic environment

How a plasma discharge is often pictured:

How a plasma discharge actually happens:

- Transient phases (ramp up/down, LH-transition…)
- Unexpected changes: plasma instabilities (ELMs, NTMs…) and perturbations (system late/failing…)

➢ **Need for control strategies**

What is a controller?

- **Without controller = “feedforward” (FF)**

Example for temperature control:

(= “you are the controller”)

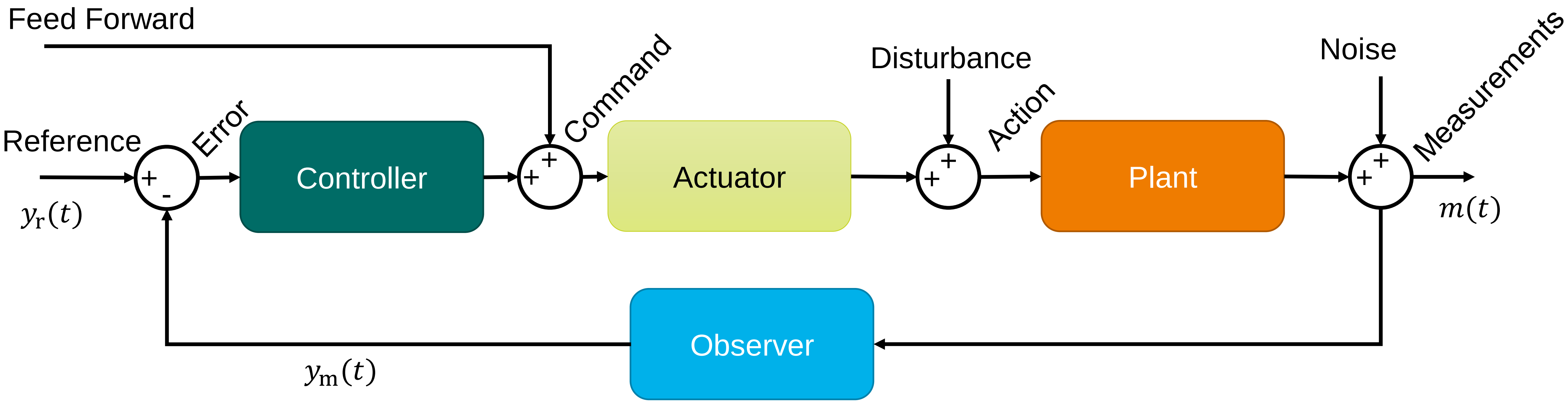
- **With controller = “feedback” (FB)**

Example: regulated temperature control

➢ Controller = follow the command using the available tools

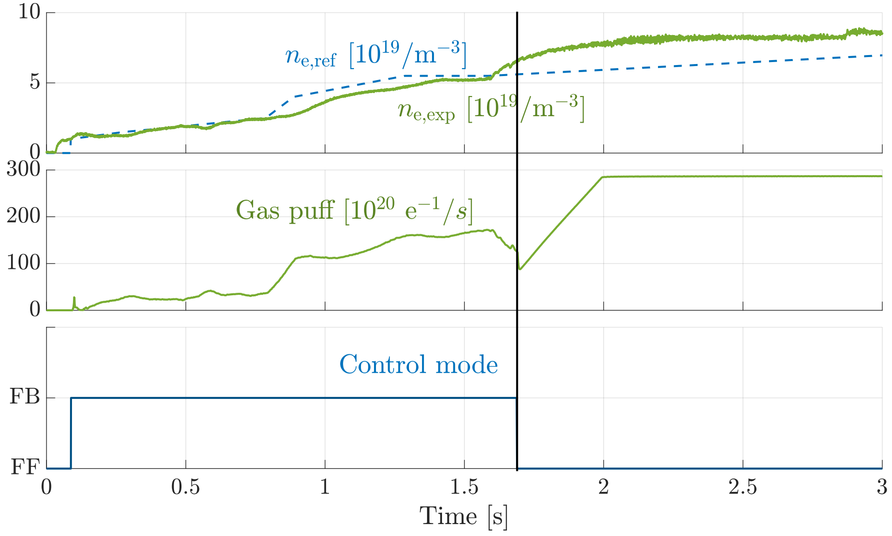
Diagram of a control loop

Example for plasma vertical position control

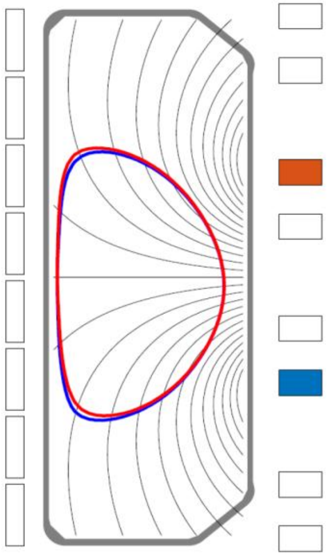


Control more than stationary targets

- **Time varying targets (“trajectories”)**
  - Daily life example: car trajectory
  - Fusion plasma example: density trajectory during ramp-up



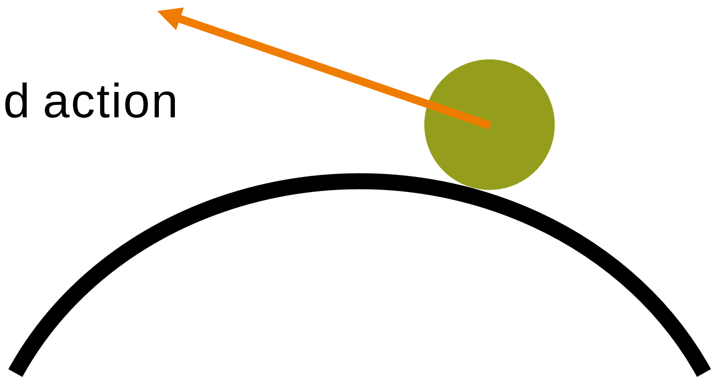
- **Stabilize unstable systems**
  - Daily life example: quadrocopter drones
  - Fusion plasma example: plasma vertical stabilization



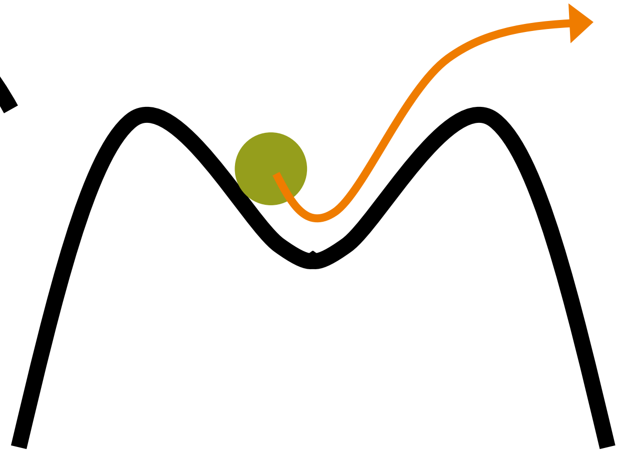
Yet not just a magic tool

A controller can be unstable

Typically by over estimating the required action



Or worse: it can render a stable system unstable



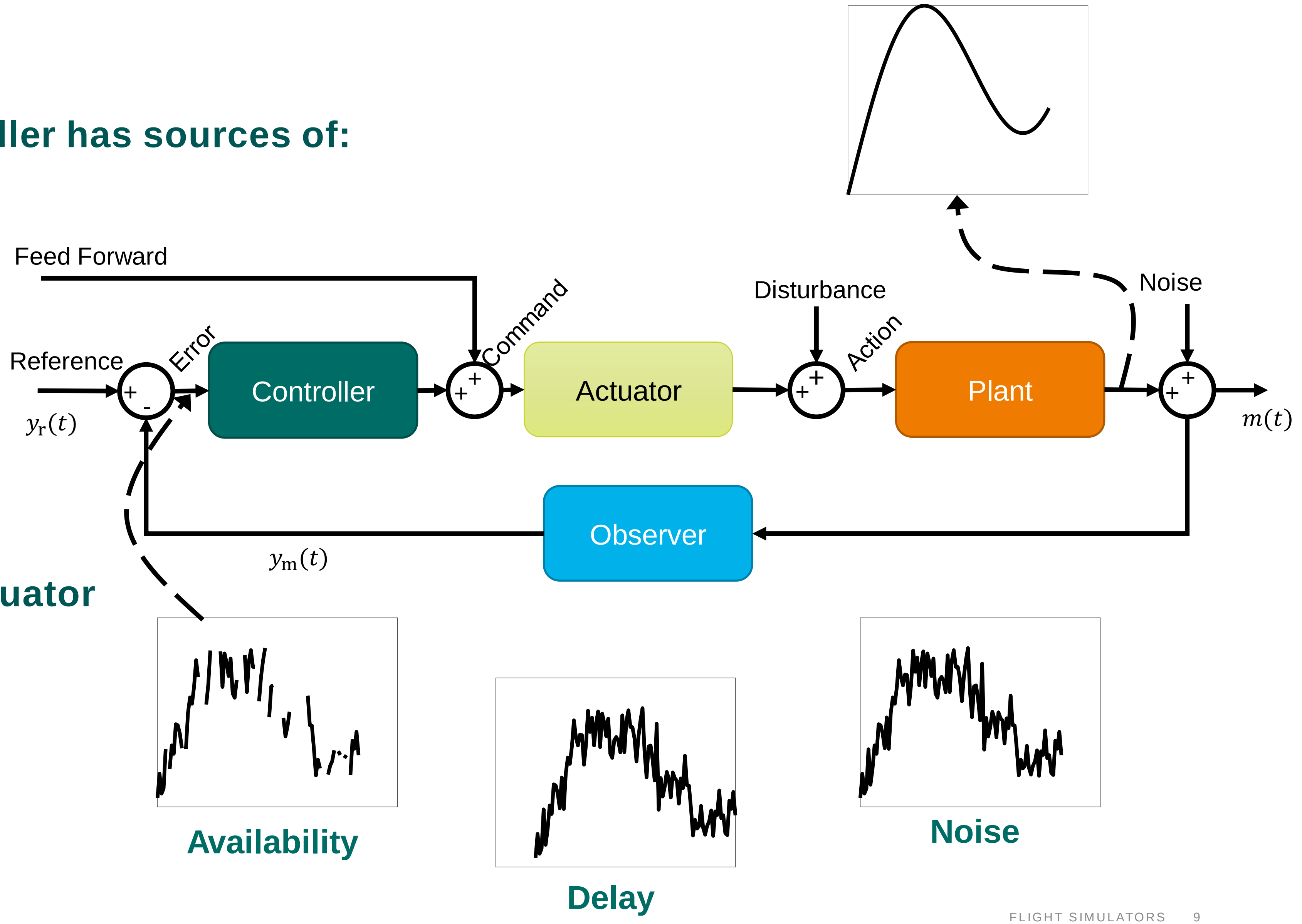
➢ In order to control a system, “sufficient” knowledge about it is required

Real systems are not perfect

The signal used by the controller has sources of:

- Noise
- Delay
- Reduced availability

Bonus: additional delay of actuator



Controllers are not always independent

Controllers can compete with each others

For instance:

Radiation controller (don't burn the divertor)

+

Auxiliary heating control (keep fusion going)

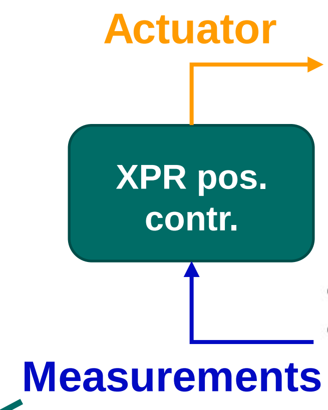
Dissipate Radiate all the power

Most cases are not that "obvious"

Example of control in tokamaks: X-Point Radiator (XPR) position

XPR = small volume in the confined region close to the X-point with high radiated power

- $0{,}985 < \rho_{pol} < 1$
- Local high density and low temperature
- Usually achieve with impurity seeding (but not only)
- ✓ High edge-localized power exhaust
- ✓ Can suppress ELMs

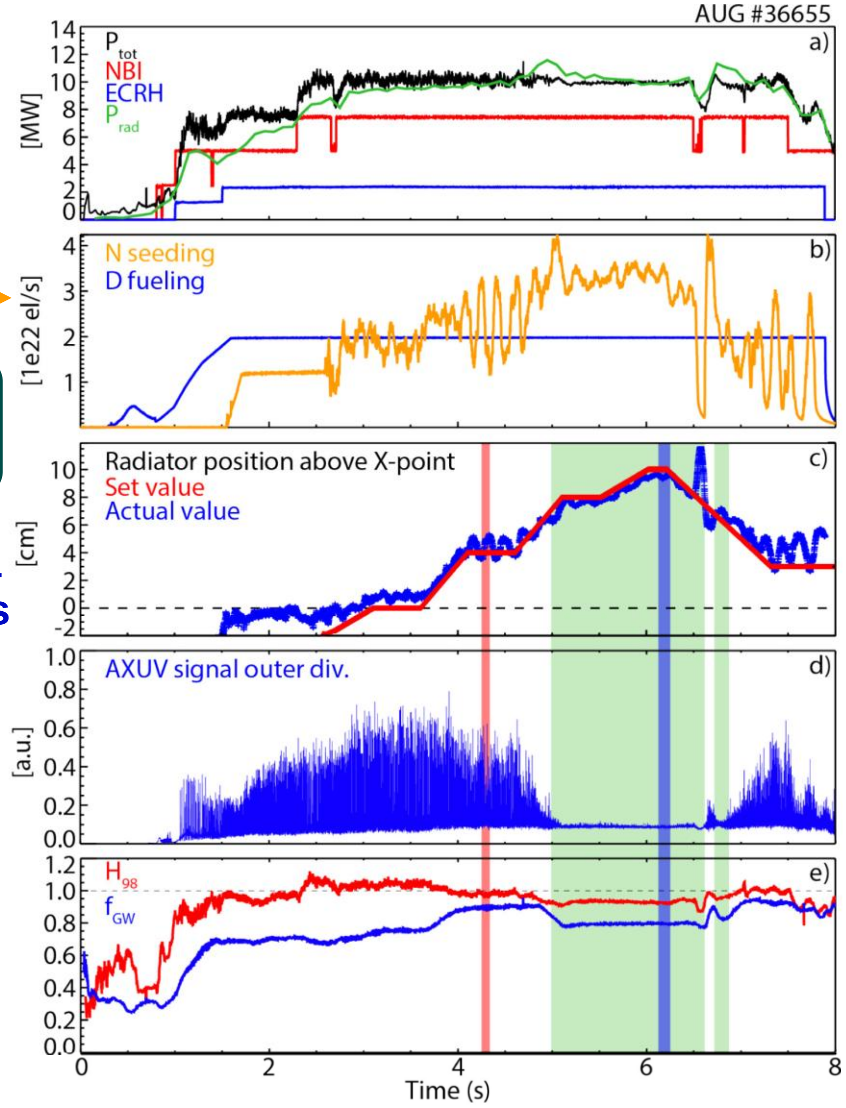


Diagnostic or observer?

Controllability:

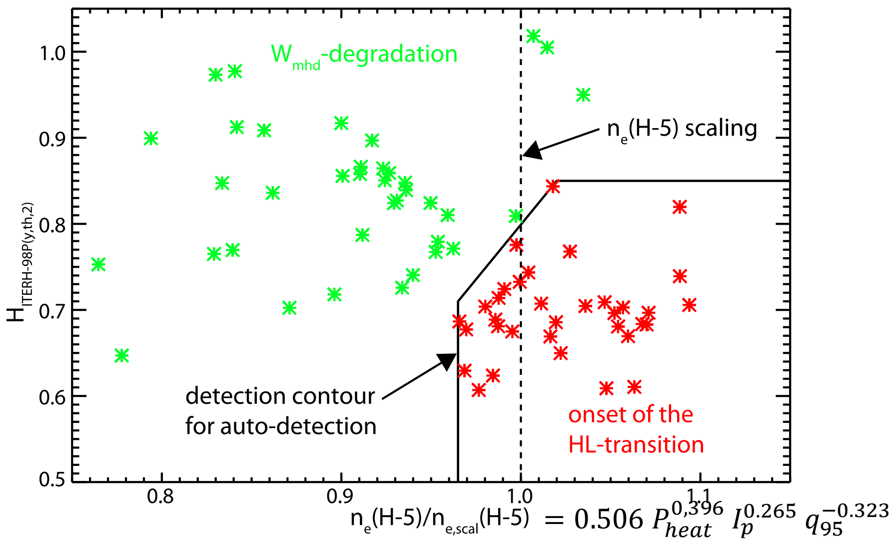
- Moves further inside with more seeding (/less aux. power)
- Moves toward the X-point with less seeding (/more aux. power)

[M. Bernert et al. NME 2025]

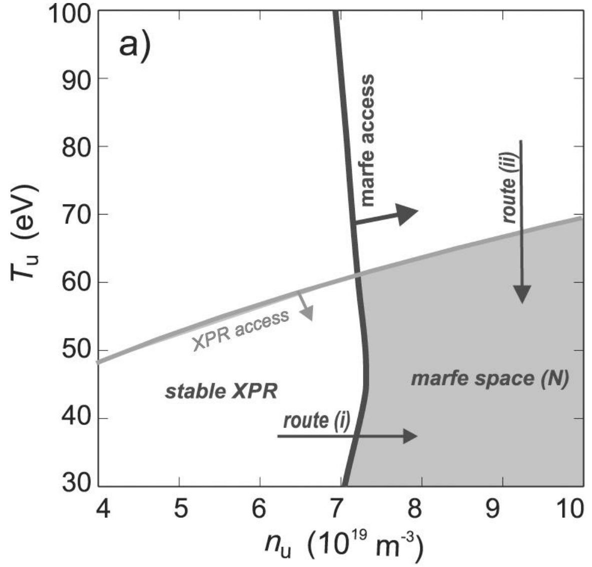


Example of plasma control: disruption avoidance (1/3)

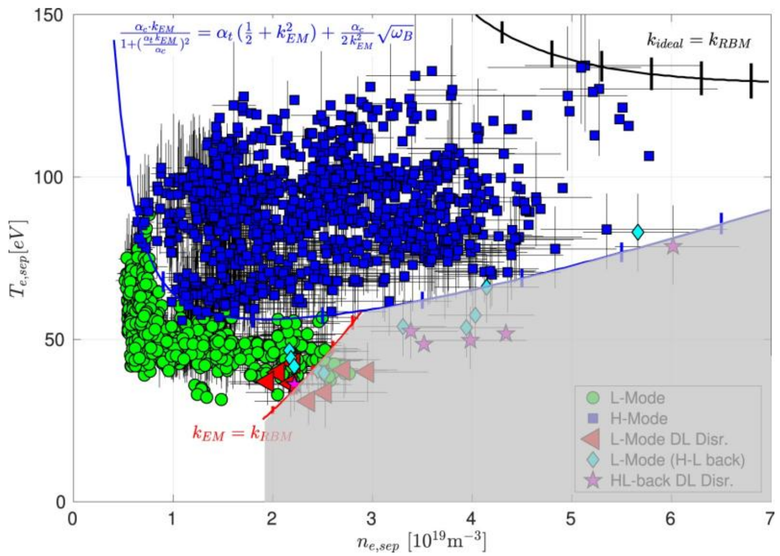
- Context: prevent the plasma to get to close to a ‘disruptive state’
  - ➢ Here: avoid disruptive H-mode Density Limit (HDL)
- Disruption region from models and empirical descriptions: high density and low temperatures



[M. Maraschek et al. PPCF 2018]
[M. Bernert et al. PPCF 2015]



[U. Stroth et al. NF 2022]



[T. Eich et al. NF 2021
M. Giacomin et al. PRL 2022]

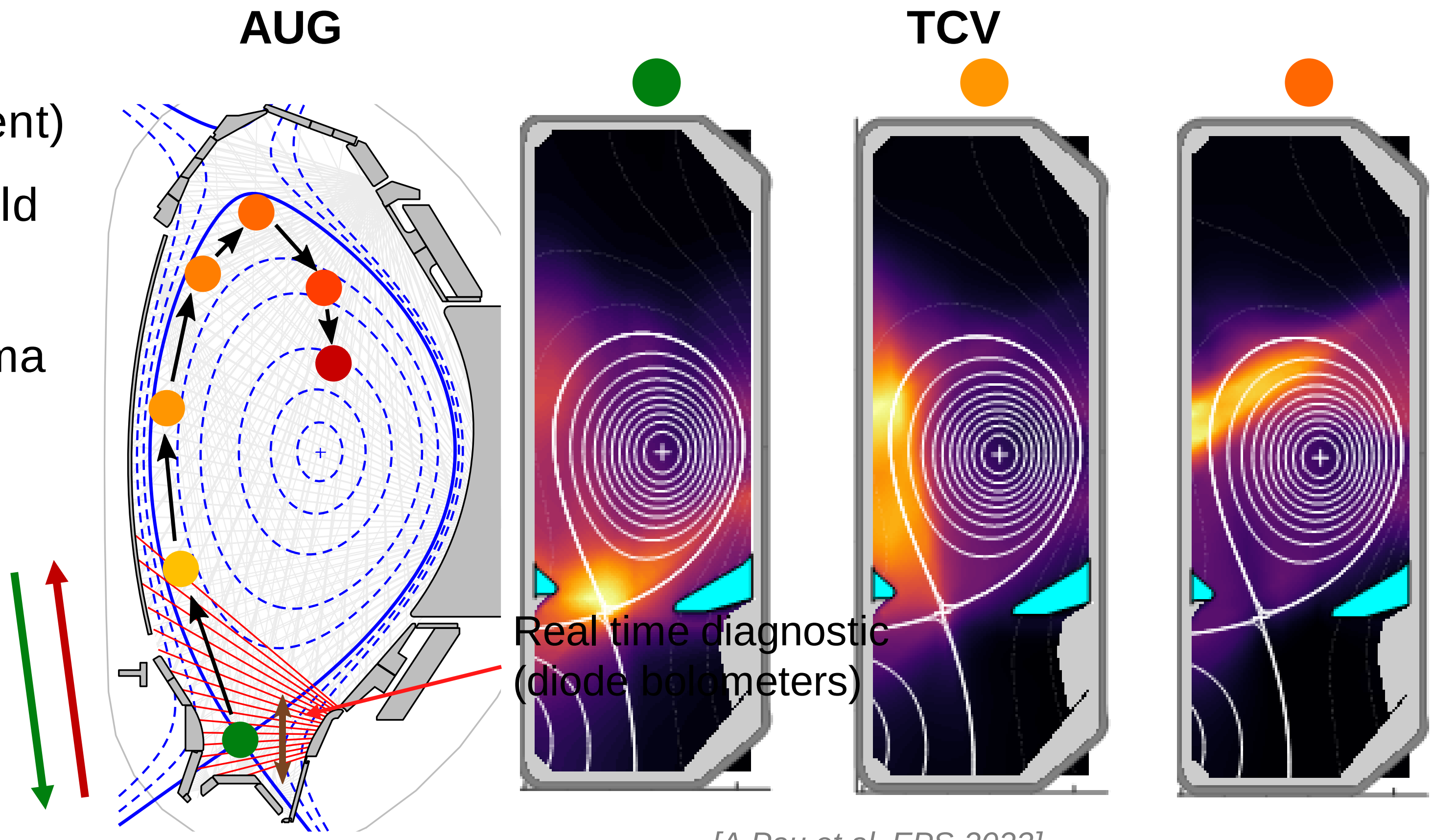
Example of plasma control: disruption avoidance (2/3)

In addition, when approaching the HDL: movement of XPR to upper high field side ("MARFE"), to inside the upper plasma (disruption)

- 🟢 XPR close to X-Point (stable + detachment)
- 🟡 Movement away from X-Point on high field side along field lines
- 🟠 MARFE edge localised up to top of plasma
- 🔴 Radial movement into confined region

✓ observed at AUG, TCV and JET (larger machine = slower movement)

Actuators → Gas fueling + / Aux.. power +



[B. Sieglin et al. SOFT 2024]

[A.Pau et al. EPS 2023]

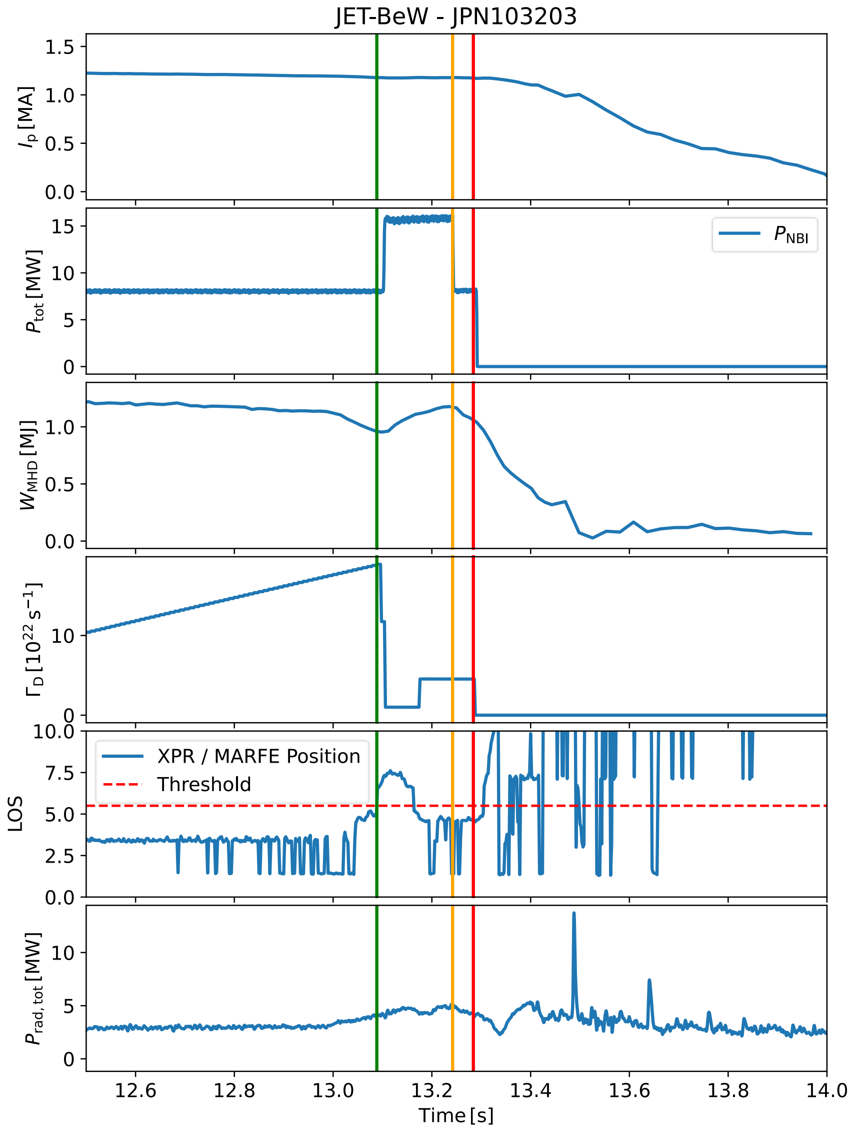
Example of plasma control: disruption avoidance (3/3)

Application at JET:

1. XPR at threshold (green line)
   - ➢ NBI increased & gas decreased
2. XPR moves back down
3. After a delay, fueling is increased again
   - ➢ The discharge can resume, all is well!

   Except…

4. Each NBI turn off by safety system (orange then red)
5. XPR moves back up and NBI still not available
   - ➢ Disruption



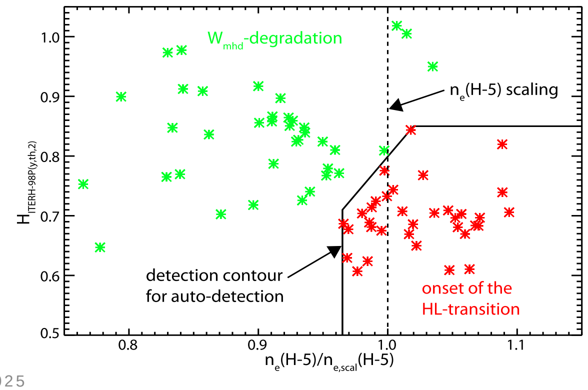
[B. Sieglin et al. FED 2025]

Takeaways from example on disruption mitigation

1. Robust control method: can save experimental time

2. HDL state space use empirical critical area

3. Although replaced by machine-agnostic radiator position, experimental validation can be dangerous for the machine



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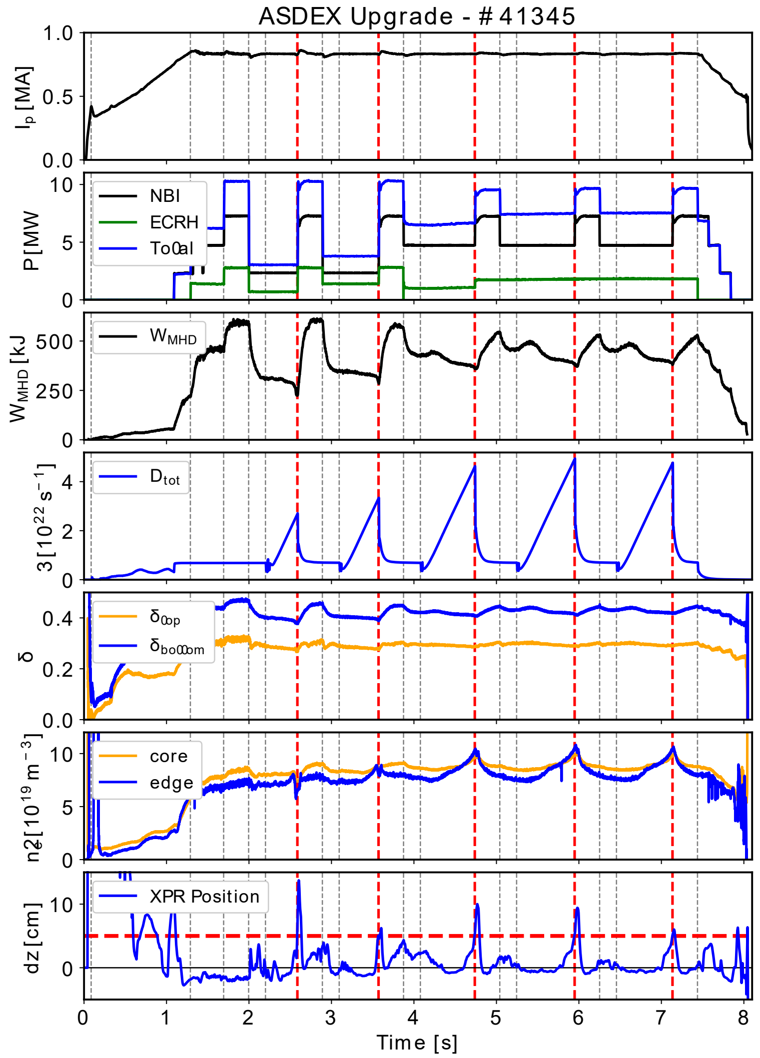

[B. Sieglin et al. FED 2025]

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Summary so far

- Plasma control required
- Controller development requires models for the involved systems
- Many interactions between control(led) quantities not solvable by control theory alone
- Experimental signals can be noisy, corrupted, delayed, missing…
- Experimental development limited/risky
- FB works best close to FF reference, if it can even be estimated

➢ Need for simulation with control loop

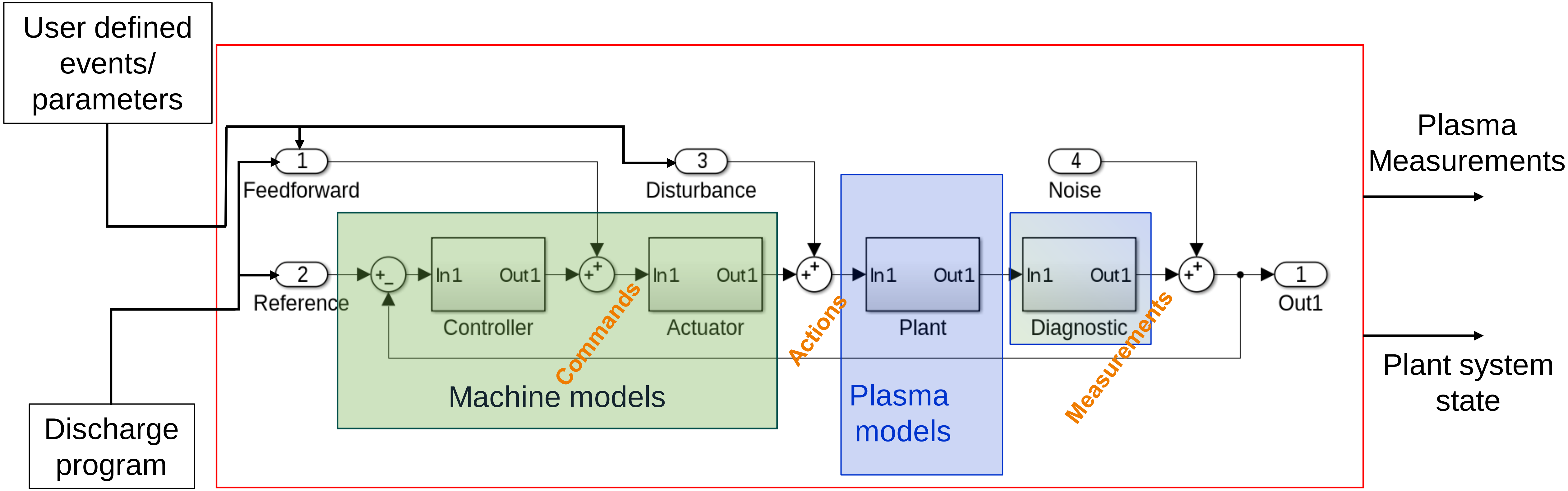
List of requirements for the simulations

- ✓ Span “macroscopic” time scale (not instability, but stabilization)
- ✓ Large spatial coverage (relevant for actuators and controlled quantities)
- ✓ Wide range of models (for multiple/MIMO controllers)
- ✓ Can be iterated (tests and optimization with different conditions)

Best candidates: (simplified) integrated models with a control loop

What is a flight simulator

What is a flight simulator



Why “flight simulator”

They are to be used like the actual system they model

- ✓ Use same inputs as in the experiment (discharge program)
- ✓ Can directly compare the output to the experiment
- ✓ Safer than experimental tests

- ❖ Can be as complex as the experiment to use
- ❖ Identifying issues

What are the goals of a flight simulator?

- **Simulate a full discharge (~~plane~~ plasma + environment) in order to…**

… prepare and test experimental scenarios by checking if:

- the discharge operates within the machine limits
- all the parameters and reference waveforms are consistent with the experimental program
- the discharge program meets experimental goals

… develop, test and validate:

- control system modules (controllers, strategies, observers, optimization...)
- benchmark physical models against experiments

Common integrated tools

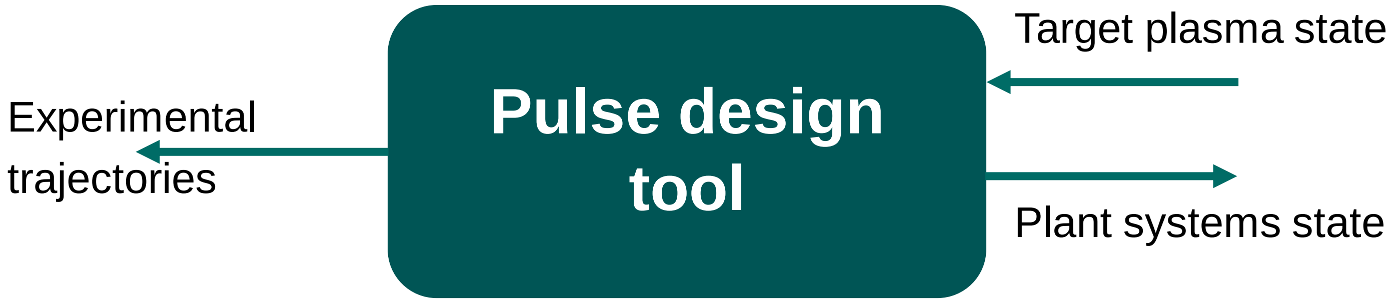
1. Flight simulators

2. Pulse design tools

3. Digital twins

- ➢ Shown here: one interpretation. Exact definitions are flexible, more so that they are still mostly emerging topics in fusion.

Pulse design tool



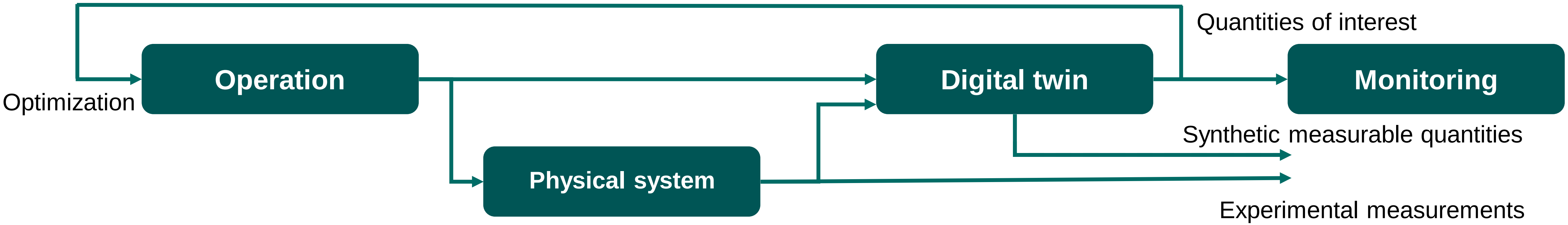
- Find how to safely reach a desired operation point
- Mostly uses (automatic or manual) iterations
- Needs to have even simple system model
- Typ.: control loop can be omitted

Digital twin

- **DTs are more commonly used in industry, and therefore more specifically defined.**
- Model of any physical system
- Can evolve in parallel to its physical twin

Example of uses:

- Prototyping: model behaviour of the future physical system
- Monitoring: estimate non-measurable quantities of a system

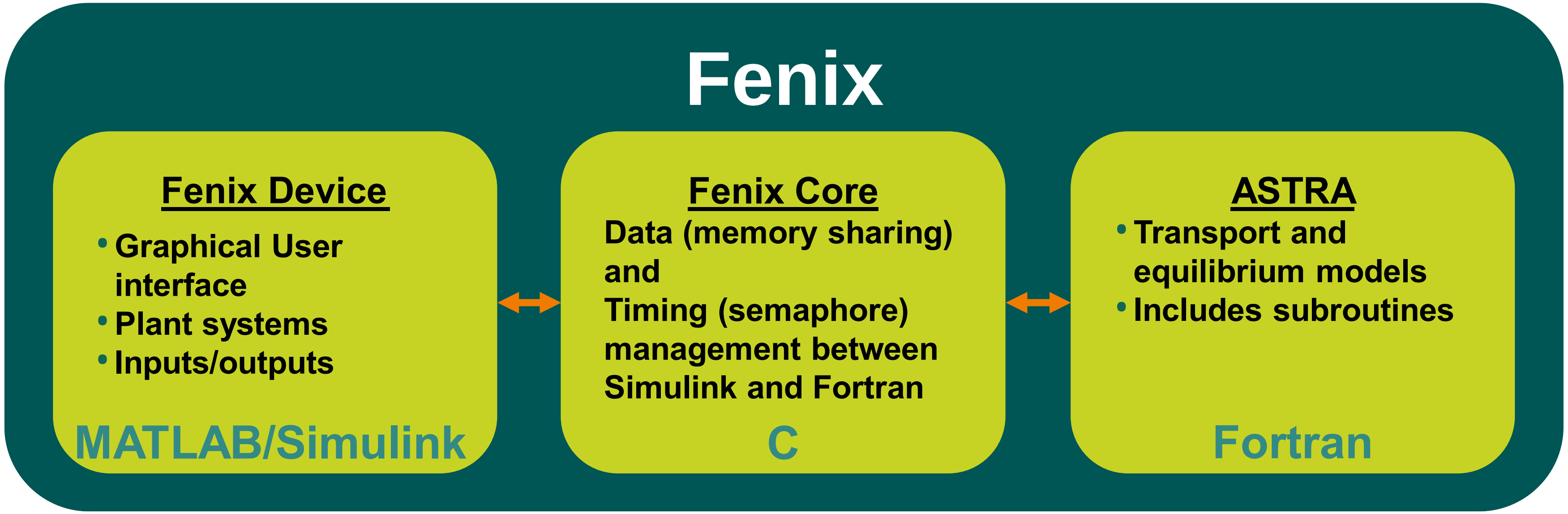


- **Flight simulators can be seen as a subset of digital twins**

Example of flight simulator: Fenix

- Deployed for: AUG[1], DEMO[2], ITER and TCV[3]

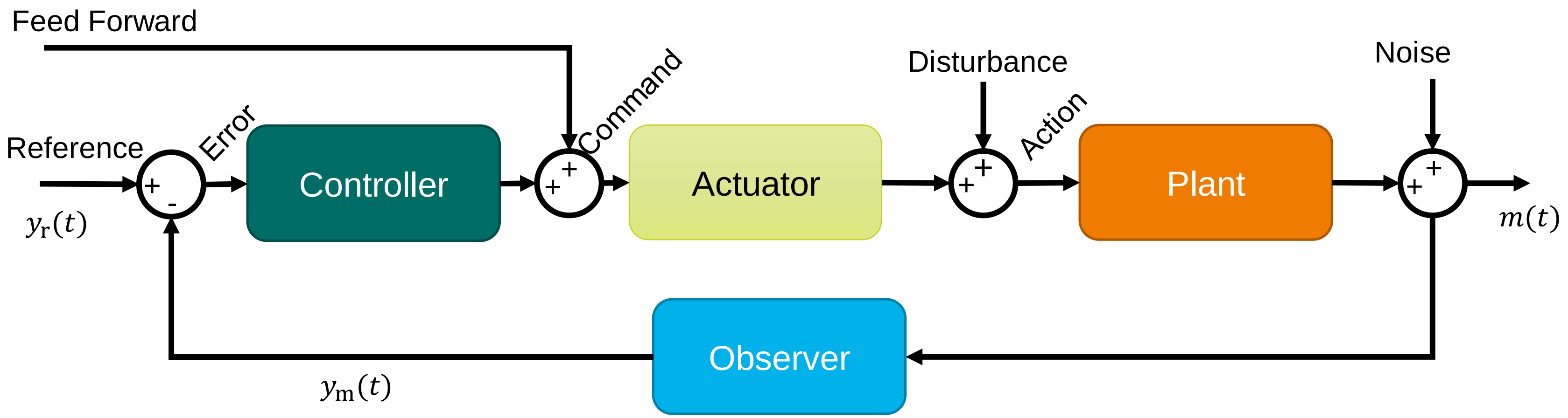
- General architecture:

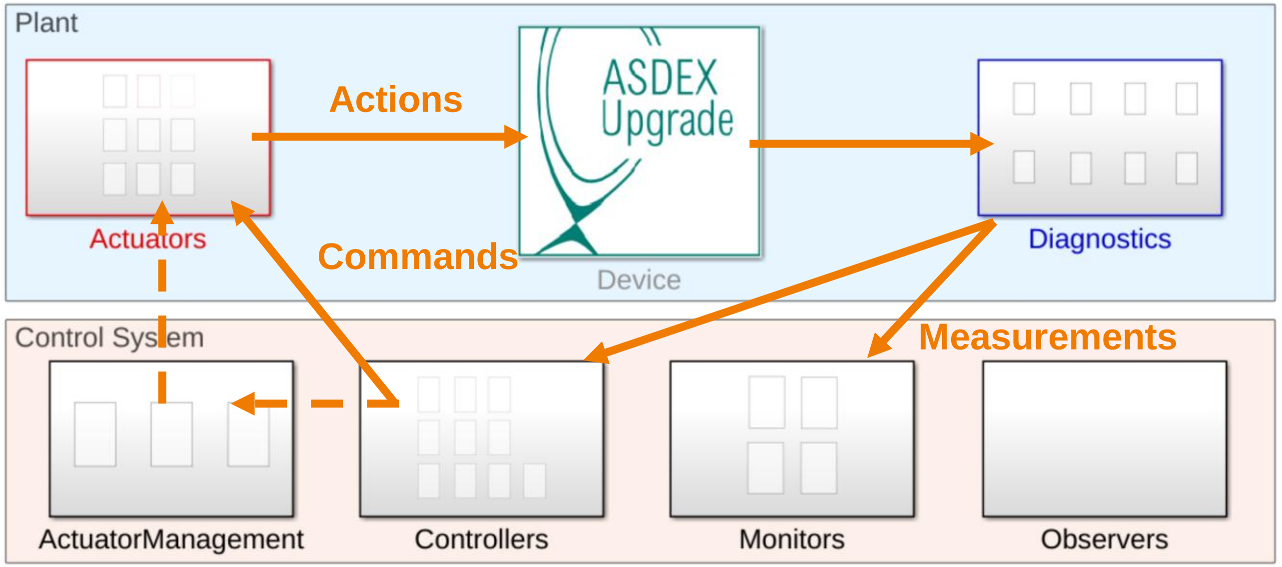


[1] P. David et al. OPS 2025
[2] L. Di Grazia et al. FED 2025
[3] R. Coosemans et al. EPS 2025

Description of Fenix AUG

GUI in Simulink

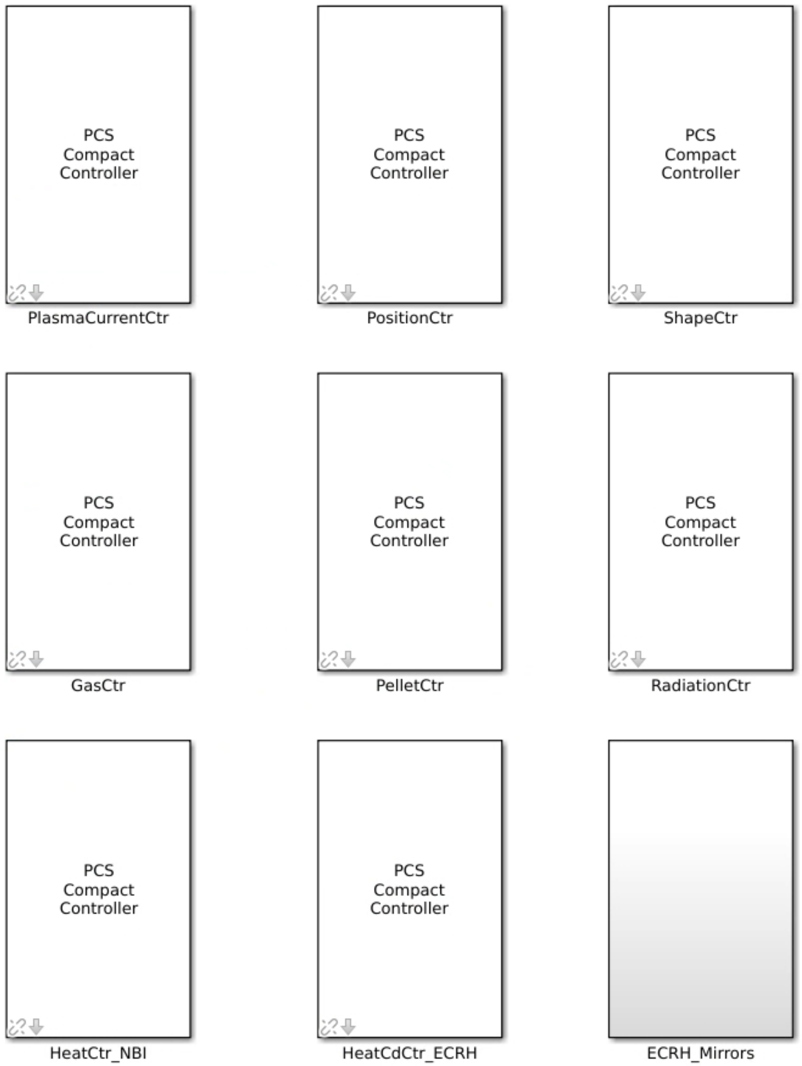




Configurations can be imported from AUG:

- Discharge program
- Controllers
- Monitors
- Actuators setup

List of controllers of AUG/Fenix AUG



- Plasma current
- Plasma position
- Plasma shape
- Gas fueling
- Pellet injection
- Plasma radiation
- Heating systems (NBI, ECRH and ICRH)

➢ They can all interfere with each other's tasks

Use case of a flight simulator: P_{sep} controller (1/2)

- **Question:**

Can P_{sep} be controlled using $P_{\mathrm{rad,sep}}$ computed from real time gaussian process tomography?

$$= P_{\mathrm{in,tot}} - P_{\mathrm{rad,sep}} - \frac{\mathrm{d}W_{\mathrm{MHD}}}{\mathrm{d}t}$$

Actuator: heavy impurity seeding (core radiation, typ. Kr)

- **Process**

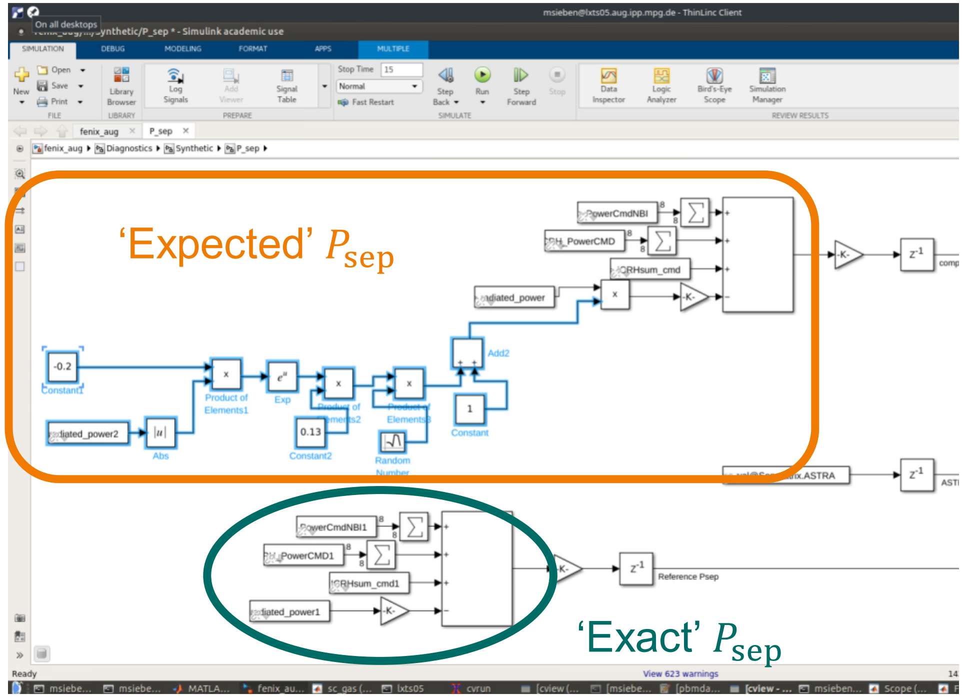
✓ Estimate observer error from synthetic measurements

✓ Implement computed error (mean and std) in Fenix AUG

✓ Implement P_{sep} controller in FS ⇒ identical to AUG

✓ Replace FF signal by FB command ⇒ in discharge program

✓ Compare exp. FF vs sim. FF with sim. FB



Results of Feedback on expected noisy signal

- Only Feedforward (AUG #39061):

  Almost, but not quite:

  Required Kr seeding underestimated

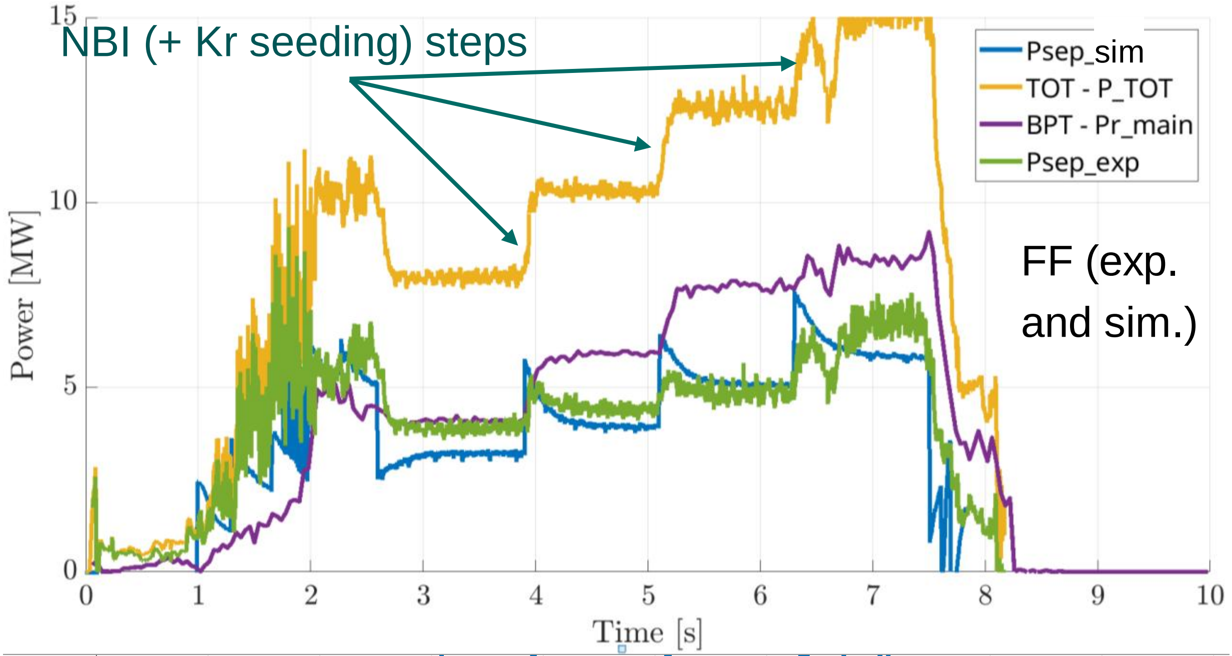
  (first and only try)

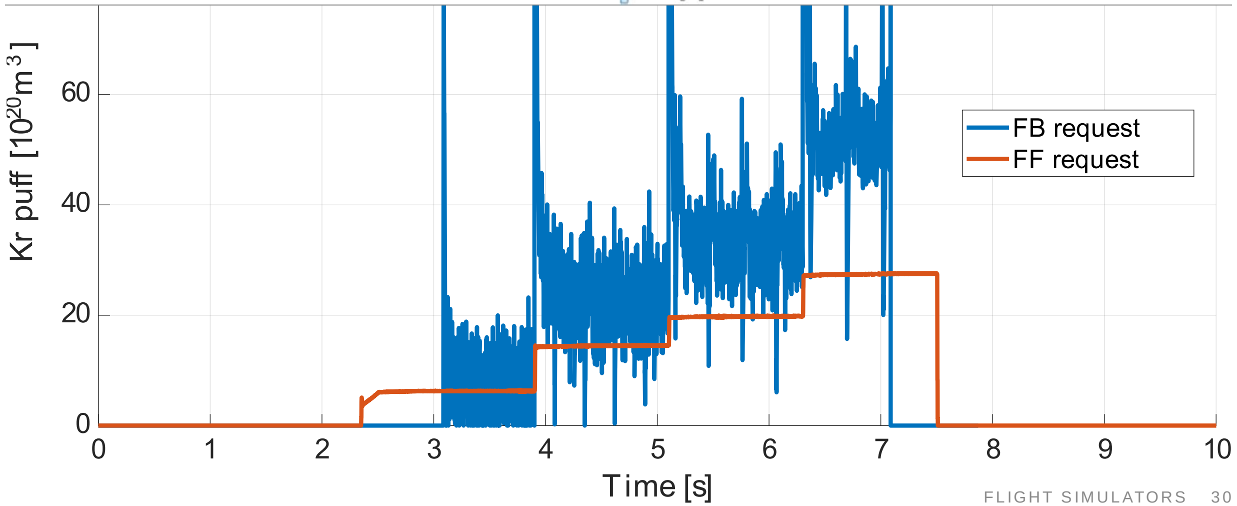
- With Feedback:

  (after iteration on the controller)

  ✓ Constant P_{sep} (apart from spikes)

  ✓ Validation at different error levels





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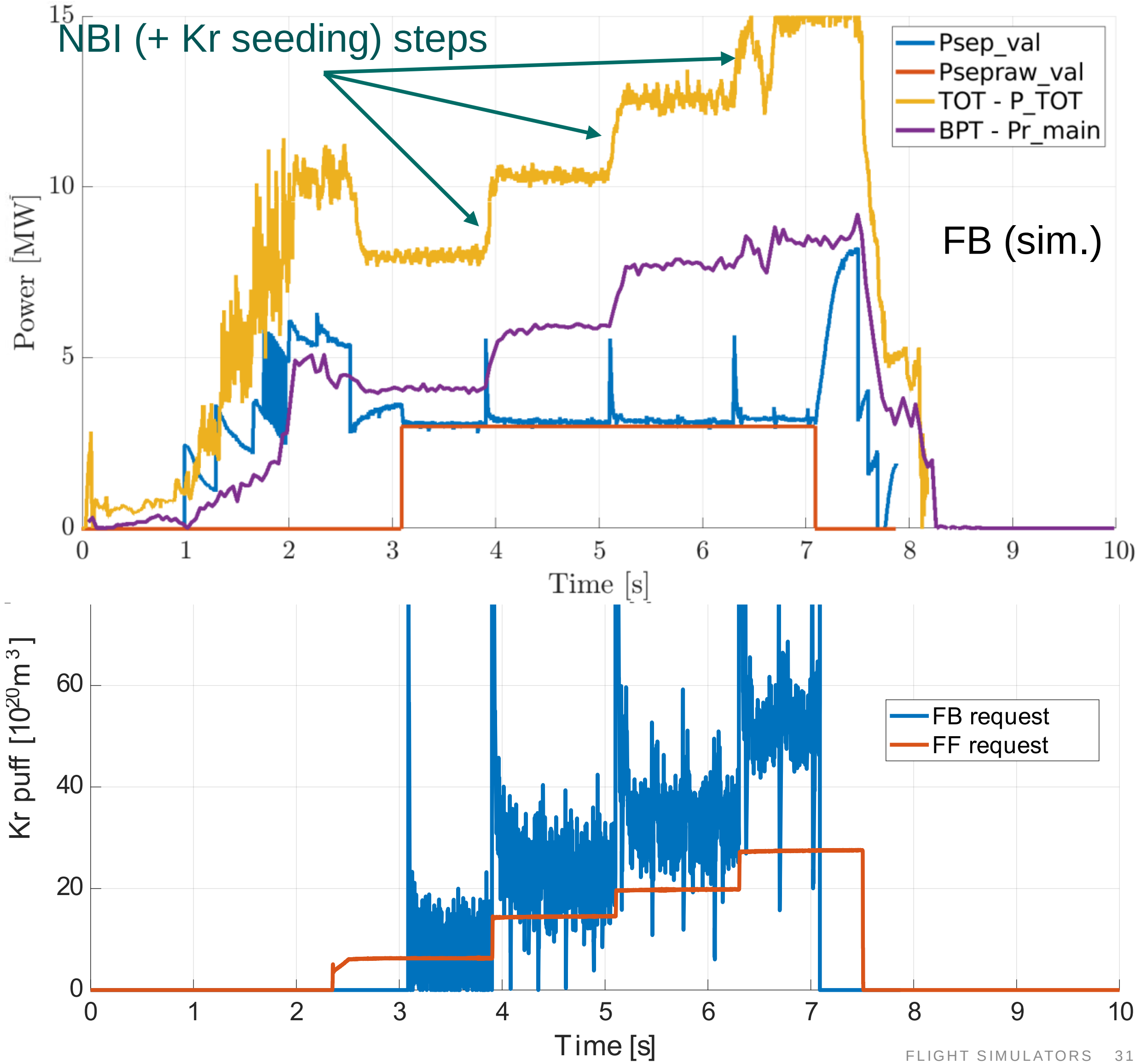


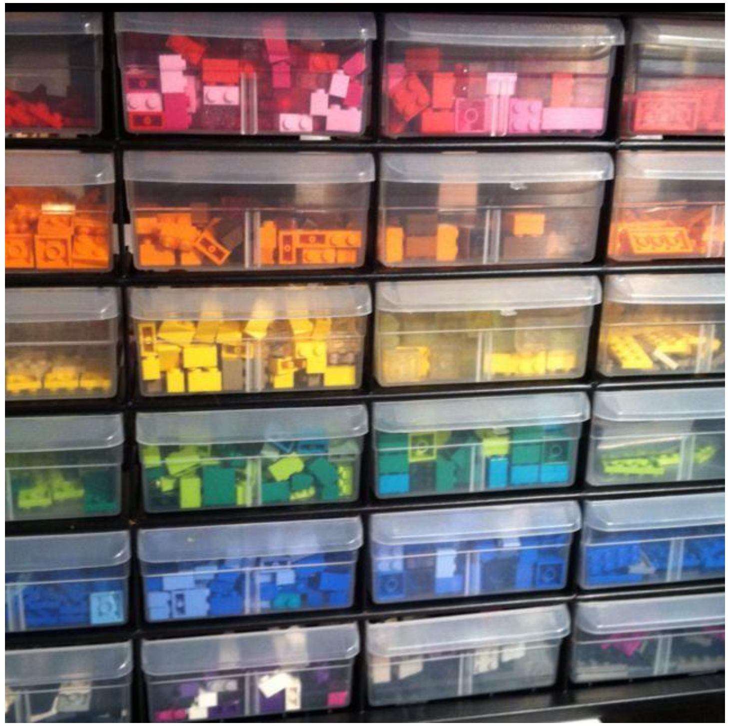
Dynamic ecosystem of models

Integrated models with flexible components can enable interoperability and reusability

- Use of standardized tools like IMAS (ITER Integrated Modelling & Analysis Suite)

  (Recently released in open-source)

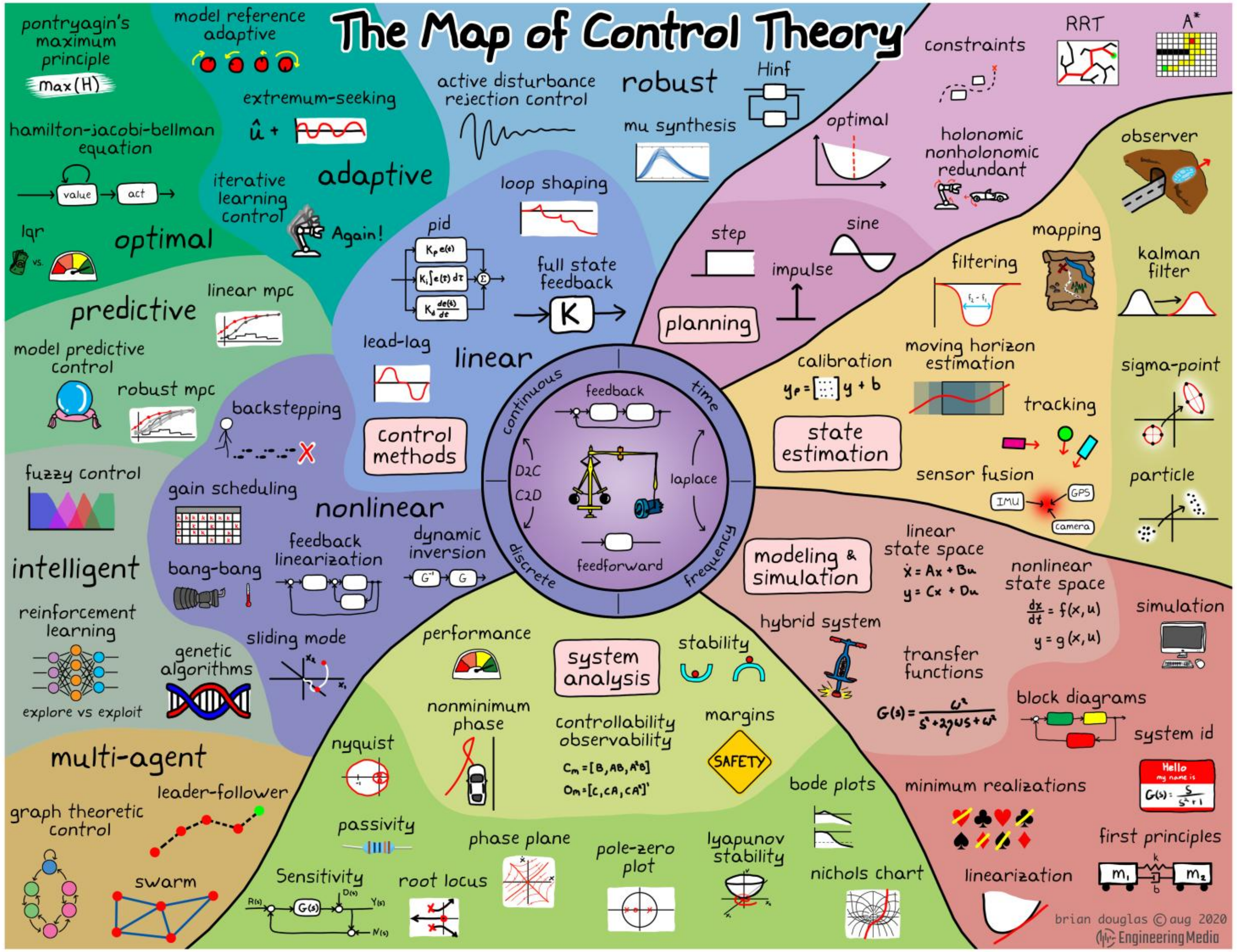
In an ideal world, building blocks for flight simulators:



Control theory: a (yet) mostly unexplored domain in fusion devices

Most of the map unused in fusion

Flight simulators with improving integrated modelling to enable the use of more tools



Key Takeaways

- Closing the control loop is critical for stabilizing complex, nonlinear plasma systems
- Flight simulators brings plasma physics and control engineering together
- Control strategies and requirements evolve from present-day experiments (more flexibility but also more diagnostics) to reactors (more strictly defined operation point, but much fewer diagnostics and errors more critical), so do simulation requirements
- [Not presented here] Reduced models to support real-time control
- Still young topic in fusion