IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

INTRO TO FLIGHT SIMULATORS
AND ITS DEVELOPMENT FOR COMPASS-U

Jan Hečko and the CU FS team

Seminář FPTF @ Mariánská, 16.-20.1.2023

Outline

1. Use cases of a flight simulator
2. Less abstraction, more examples
3. The Flight simulator (for COMPASS-U)
4. Conclusion

Key topics

Plasma control, feedback control

Equilibrium simulation code

Transport simulation code

IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

Flight simulator

use cases

ANALOGY TIME

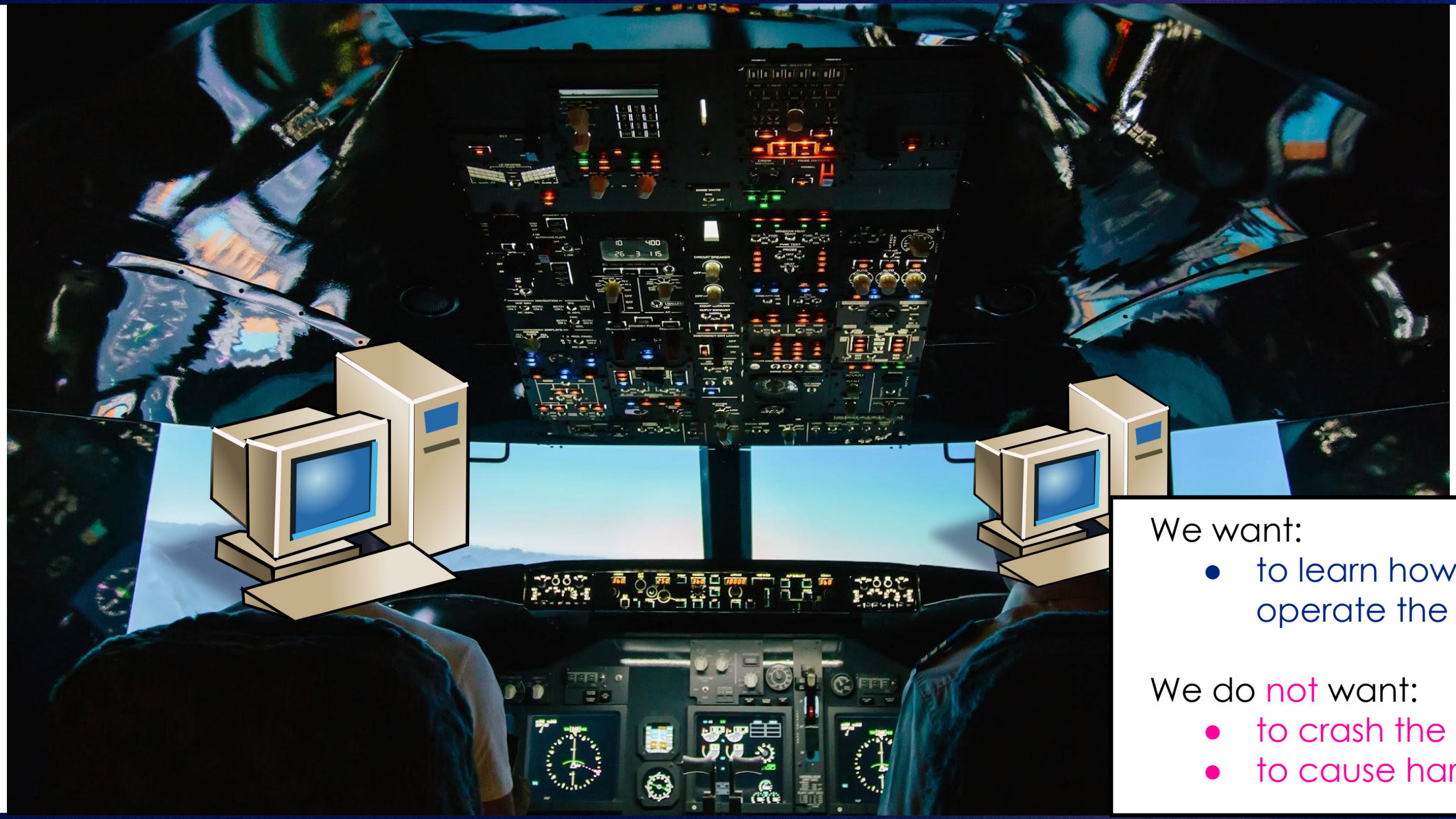
We want:

- to learn how to operate the plane

We do not want:

- to crash the plane
- to cause harm

ANALOGY TIME



We want:

- to learn how to operate the plane

We do not want:

- to crash the plane
- to cause harm

A side note on the correct terminology

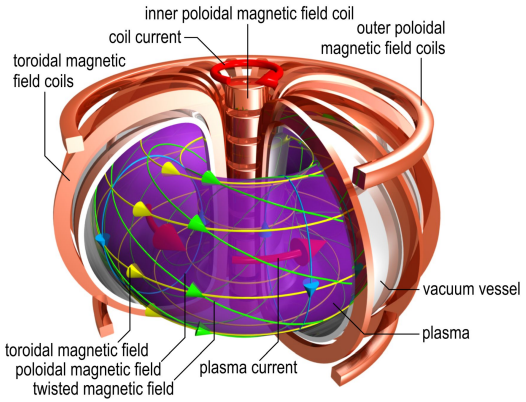
- Plasma simulator (no feedback loop)

  X
- Flight simulator

  X
- Tokamak simulator (accounts for machine limits, e.g. coil current)

Flight simulator use cases

1 Virtual tokamak (with limitations).
= for development of a feedback control

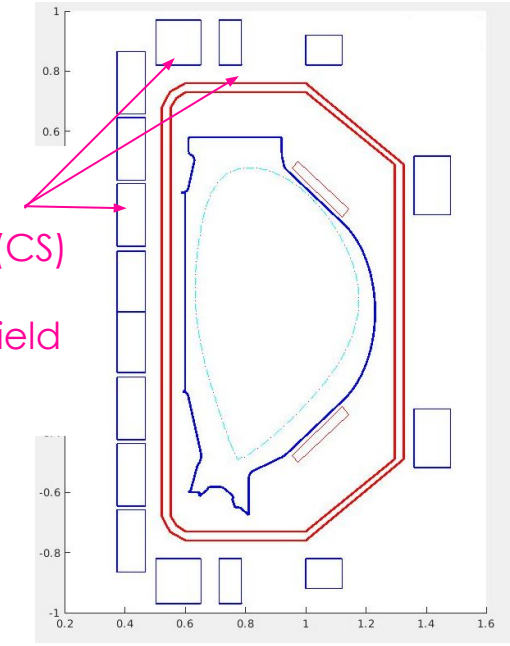


[Proll, J. H. E., 2014, *PhD thesis*]

Controlled plasma parameters:

- current Ip
- position (magnetic axis)
- shape (□, ε)
- density
- …

Central solenoid (CS) + Poloidal field coils (PF)



The simplest means of (passive) control is to prescribe fixed setpoints and "hope for the best".

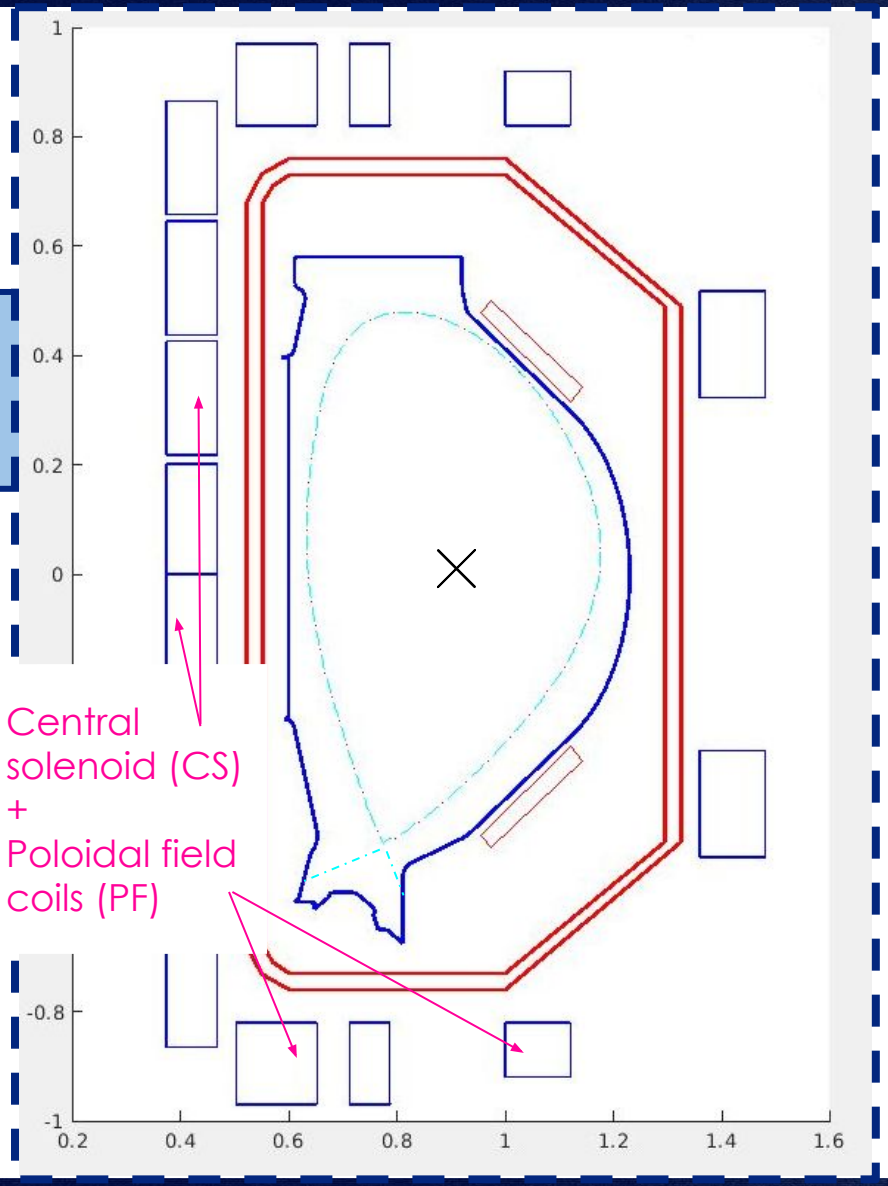
Feedback control is an active approach, it takes into account the actual state of the plasma.

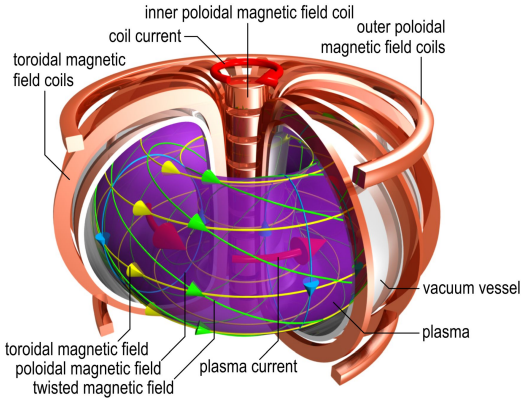
FS use cases

1 Virtual tokamak.
= dev. of feedback

Controlled plasma parameters:

- current Ip
- position (magnetic axis)
- shape (□, ε)
- density
- …





[Proll, J. H. E., 2014, *PhD thesis*]

The simplest means of (passive) control is to prescribe fixed setpoints and "hope for the best".

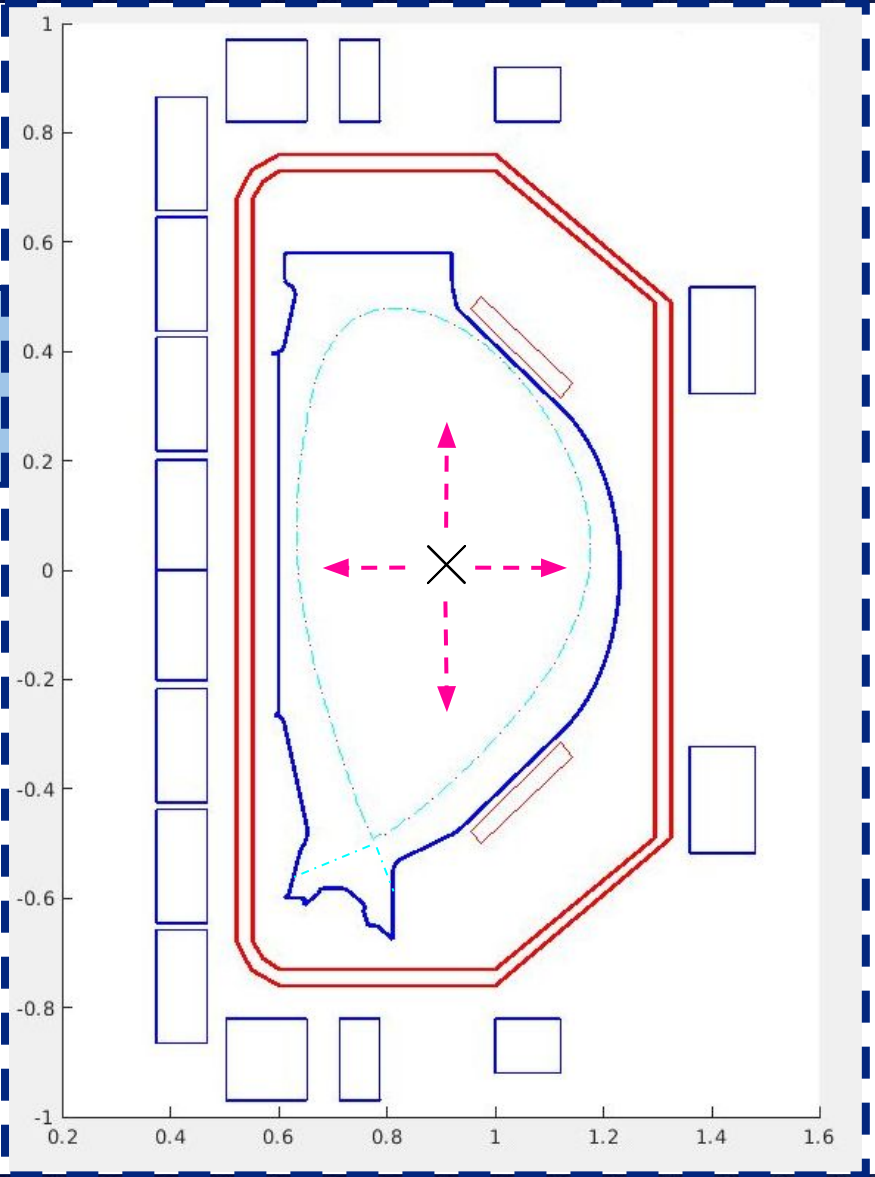
Feedback control is an active approach, it takes into account the actual state of the plasma.

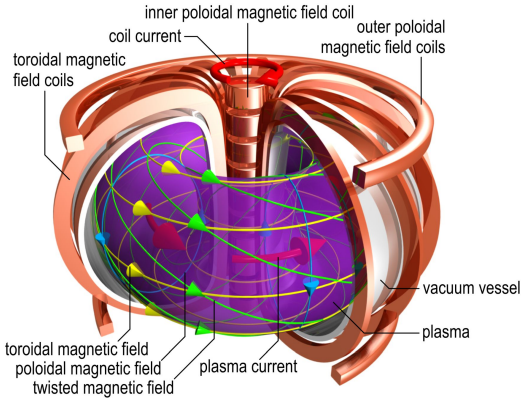
FS use cases

1 Virtual tokamak.
= dev. of feedback

Controlled plasma parameters:

- current Ip
- position (magnetic axis)
- shape (□, ε)
- density
- …





[Proll, J. H. E., 2014, *PhD thesis*]

The simplest means of (passive) control is to prescribe fixed setpoints and "hope for the best".

Feedback control is an active approach, it takes into account the actual state of the plasma.

Flight simulator use cases

1 Virtual tokamak.
= for development of a feedback control

2 Scenario development tool.
= design experimental campaigns

The planning phase

Prepare and validate experimental scenarios.

Ensure efficient utilization of the real machine time.

Flight simulator use cases

1 Virtual tokamak.
= for development of a feedback control

2 Scenario development tool.
= design experimental campaigns

3 Pre-discharge simulation and checks.
= avoiding disruptions, HW failures, damage, …

The operational phase

Help prevent human error and protect the investment.

Flight simulator use cases

1 Virtual tokamak.
= for development of a feedback control

2 Scenario development tool.
= design experimental campaigns

3 Pre-discharge simulation and checks.
= avoiding disruptions, HW failures, damage, …

4 Post-discharge analysis.
= in-depth postprocessing

The data analysis phase

Flight simulator use cases

1 Virtual tokamak.
= for development of a feedback control

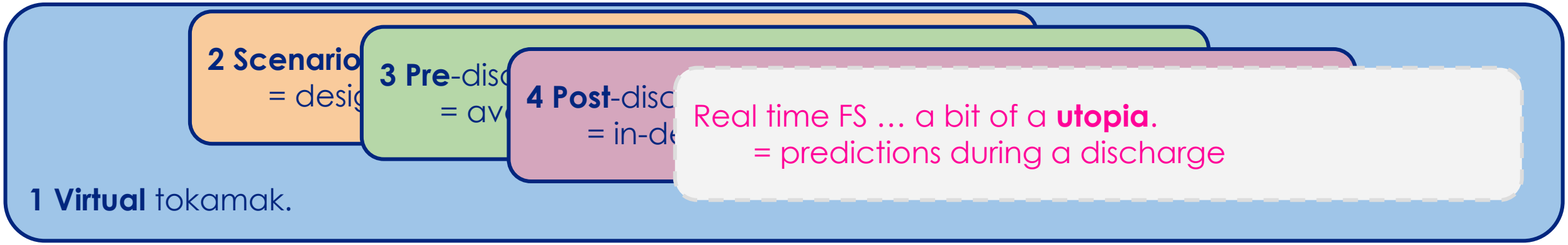
2 Scenario development tool.
= design experimental campaigns

3 Pre-discharge simulation and checks.
= avoiding disruptions, HW failures, damage, …

4 Post-discharge analysis.
= in-depth postprocessing

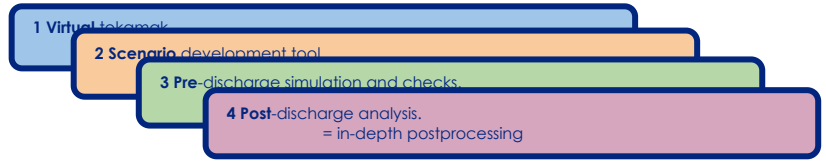
Real time FS … a bit of a **utopia**.
= predictions during a discharge

Flight simulator use cases



The difference is mostly in the *time scale*.
(i.e. simulation time)

Sorted by priority in development



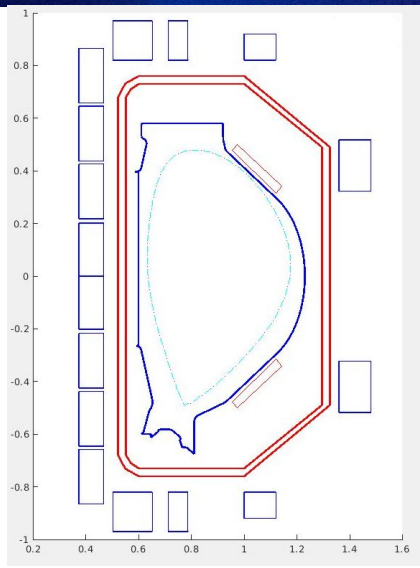
IPP INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Less abstraction, more examples

Describe it in one sentence

Flight simulator

Suite of (simulation) codes working together **in a loop** to re/produce a discharge from ramp-up to ramp-down.



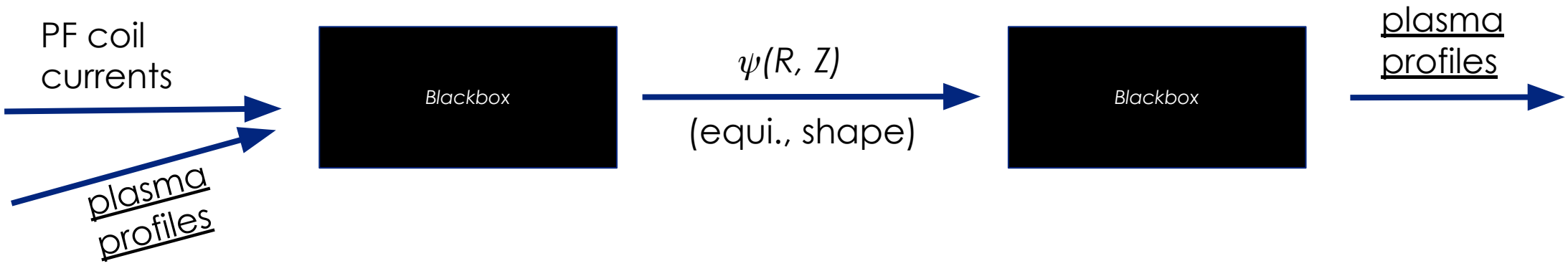
Recipe (1/3)

Equilibrium code

- Grad-Šafranov equation solver
- Used in "Direct mode"
  = in: PF coils currents | out: $\psi(R, Z)$

Transport code

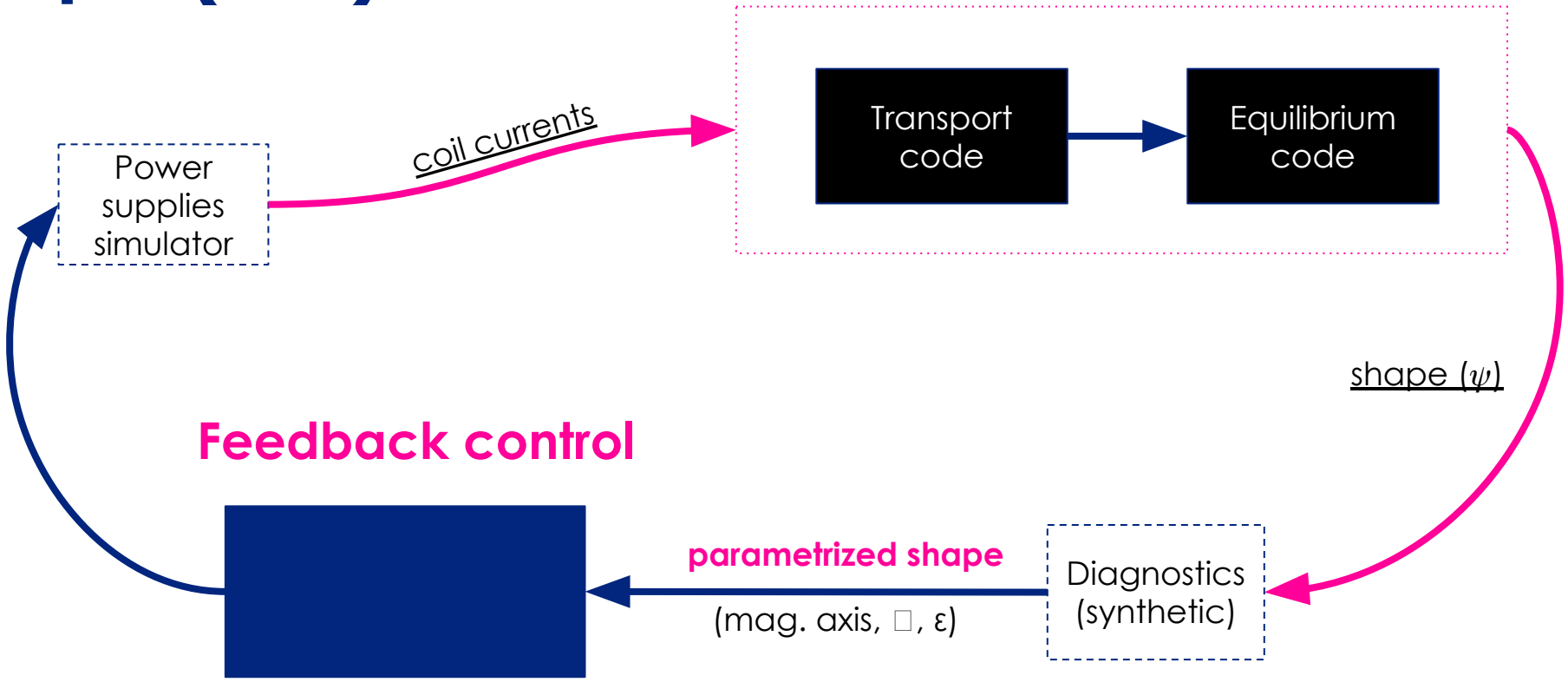
- Simulates core plasma profiles
- …



A side note on the correct terminology

- Plasma simulator = Equilibrium + Transport codes
  X
- Flight simulator
  X
- Tokamak simulator

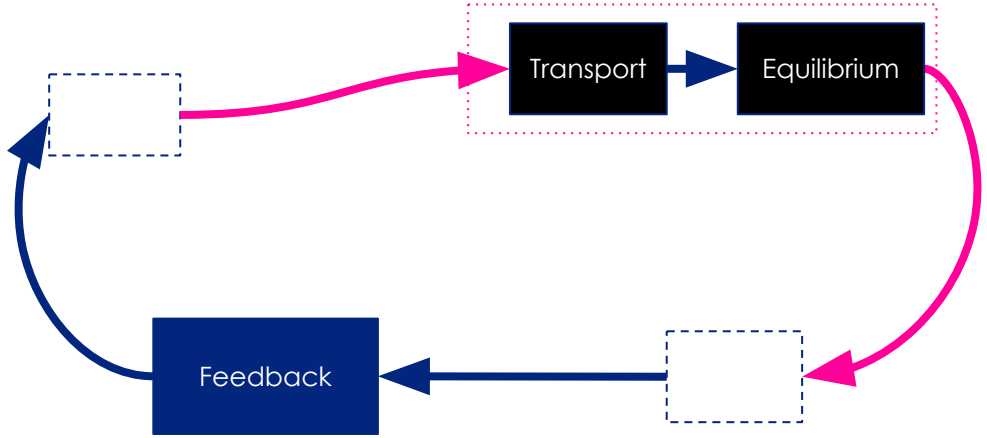
Recipe (2/3)


Power supplies simulator
coil currents
Transport code
Equilibrium code
shape (ψ)
Feedback control
parametrized shape
(mag. axis, □, ε)
Diagnostics (synthetic)

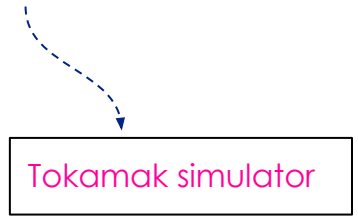
Recipe (3/3)

Complicate things

= i.e. optimize for accuracy and efficiency



- Accuracy (more components)
  - Add more components
  - Accurate synthetic diagnostics
  - Physical limitations of power supplies
  - Physical limitations of coils



- Efficiency (run time)
  - Loop shortcuts, fast&slow iterations
  - Select correct codes
  - Parallelization

FS “simulates a tokamak”, however, limitations…

Primarily, it offers

- Testing & assessment of feedback control
- Insight into core plasma
- Insight into plasma shaping, parametrization
- General machine operational limits
- Discharge “from the operator’s point of view”

Potentially, it could offer

- Insight into edge plasma
- Heat load predictions (first wall, divertor)
- Operator training

Not expected to offer

- New physics, new observations
- Limited by the underlying simulation codes

IPP INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

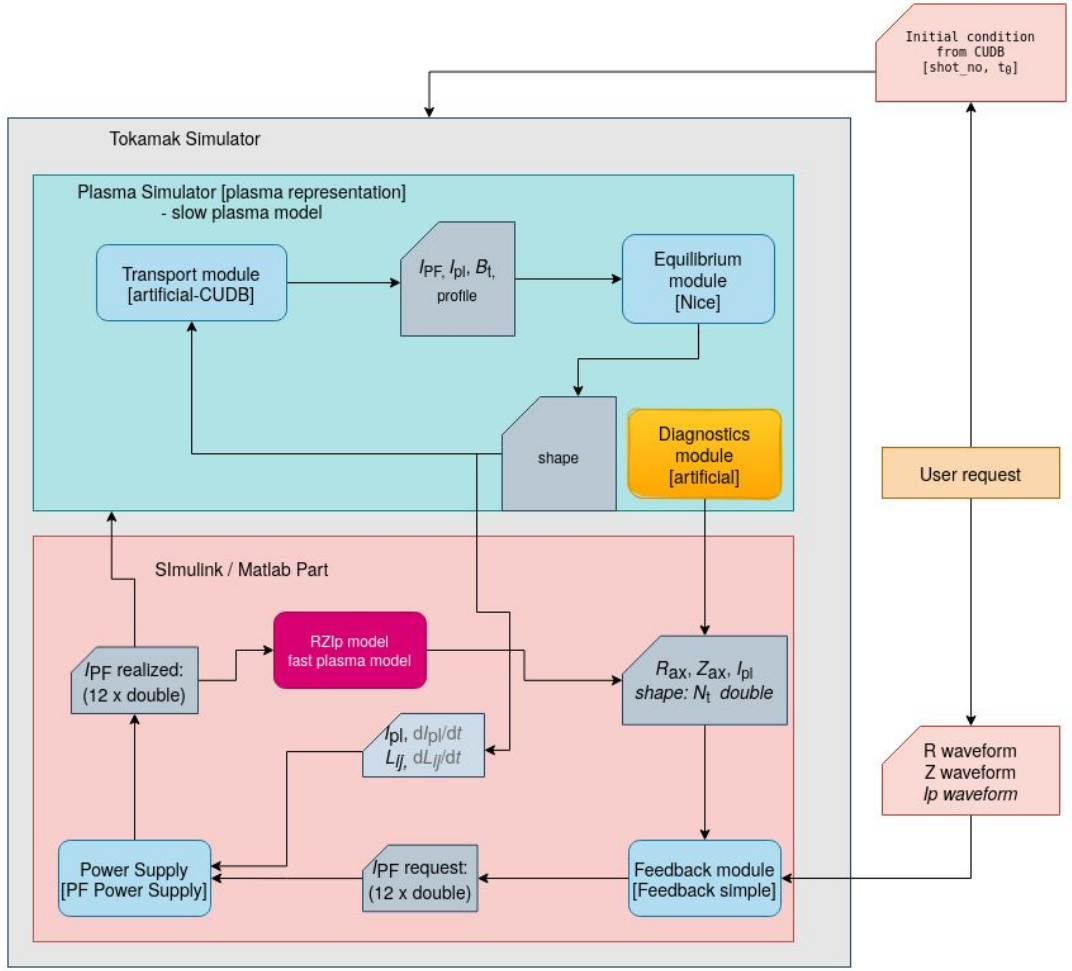
The Flight simulator for COMPASS Upgrade

Fridrich, D., Havránek, A., Hečko, J., Imríšek, M., Jaulmes, F. Kripner, L., Mendonca, J. R., Tskhakaya, D.

Recent design iteration

Usage goals

1. Feedback control development
2. Scenario development / validation
3. Pre-discharge checks
4. Post-processing



Fridrich, D., Havránek, A., Hečko, J., Imríšek, M., Jaulmes, F. Kripner, L., Mendonca, J. R., Tskhakaya, D.

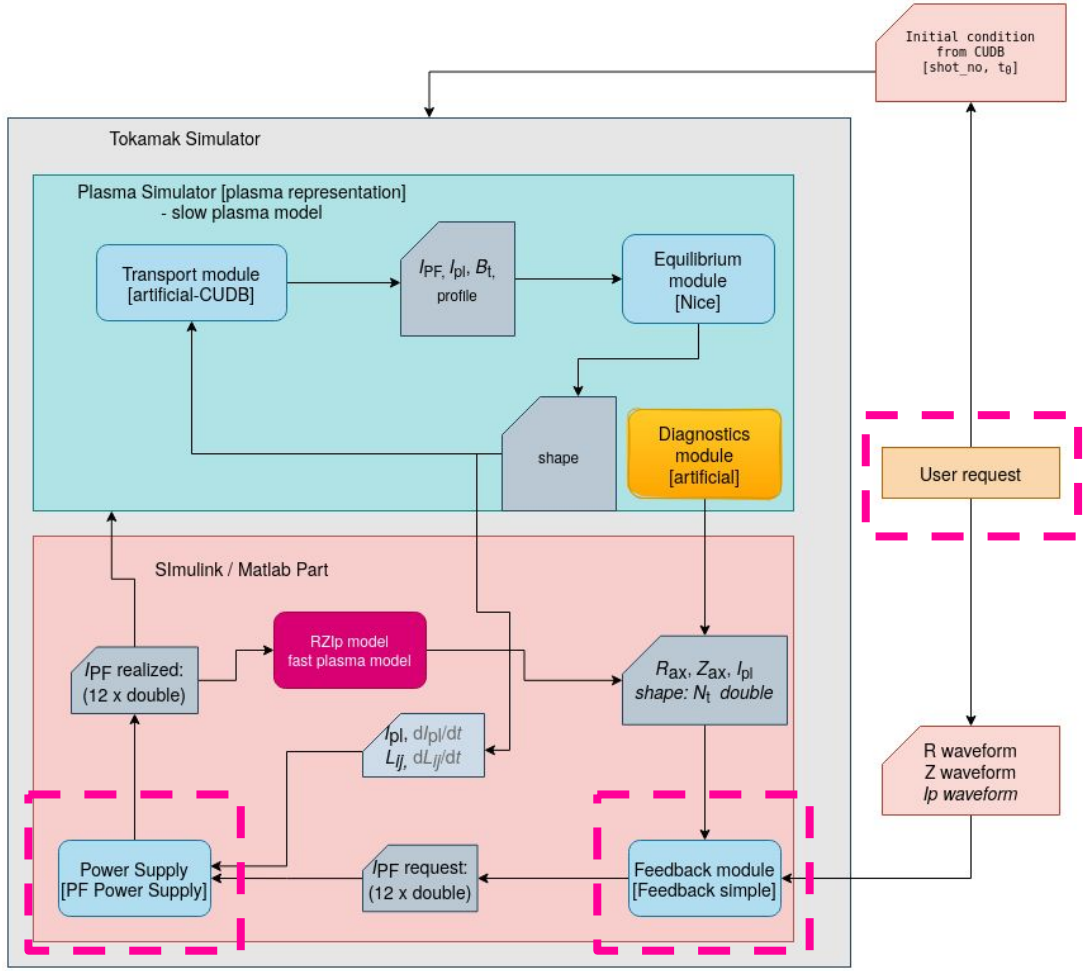
Recent design iteration

Equilibrium code: NICE

[Faugeras, B. 2020 *Fusion Engineering and Design* **160** 112020]
https://doi.org/10.1016/j.fusengdes.2020.112020

Transport code: Metis

[Artaud, J.F. *et al* 2018 *Nuclear Fusion* **58** 105001]
https://doi.org/10.1088/1741-4326/aad5b1

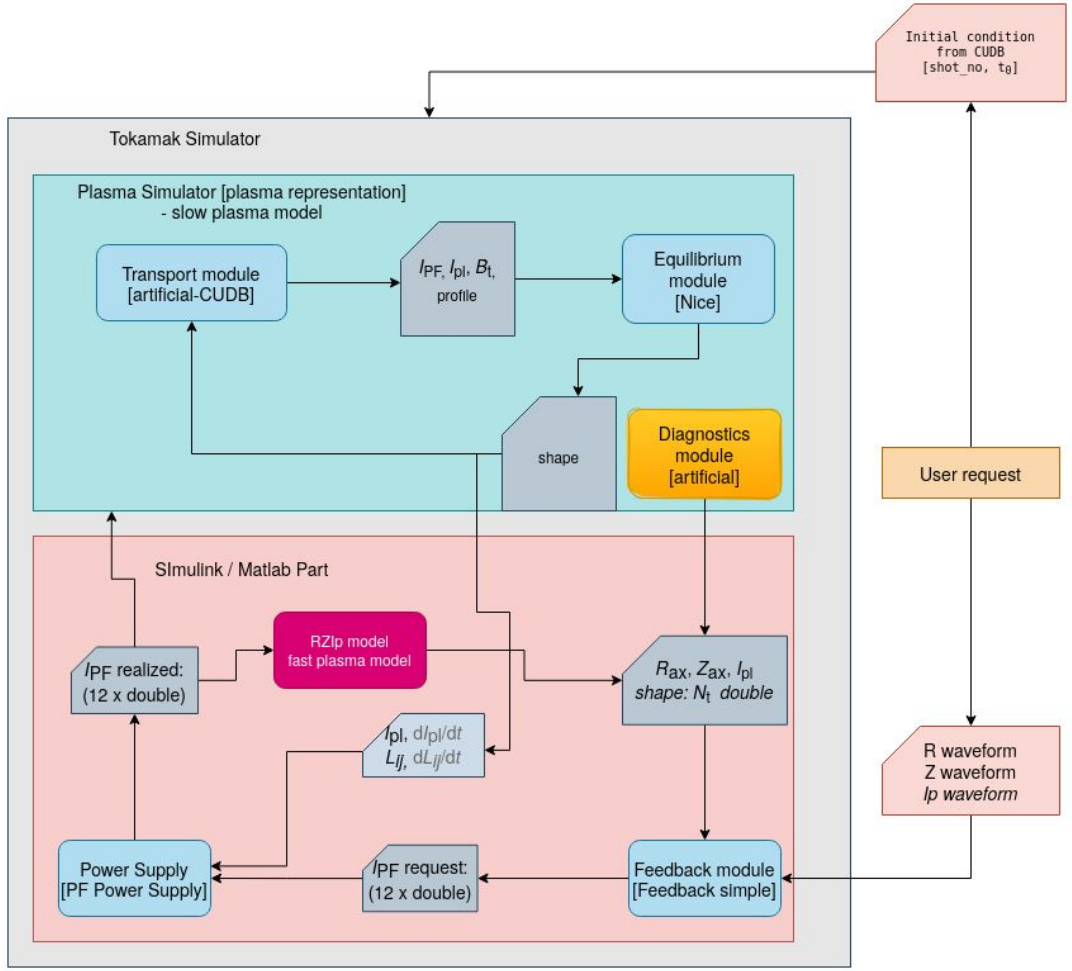


Fridrich, D., Havránek, A., Hečko, J., Imríšek, M., Jaulmes, F. Kripner, L., Mendonca, J. R., Tskhakaya, D.

Recent design iteration

Milestones

- Loop with a placeholder feedback module
- Coupling of transport code
- Loop optimizations (shortcut loops)
- Feedback development
- "Tokamak simulator" features



Fridrich, D., Havránek, A., Hečko, J., Imríšek, M., Jaulmes, F. Kripner, L., Mendonca, J. R., Tskhakaya, D.

IPP INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Summary

Summary

- Flight simulator is
  - a suite of simulation codes working together to re/produce a discharge
  - a very useful component of modern tokamaks
  - usually uniquely tailored to each machine
- Serving multiple roles
  - in tokamak development (feedback control, scenario development)
  - in tokamak operation (pre-discharge checks, post-d. analysis)
- The main challenges of FS development include
  - selecting a good combination of existing codes
  - coupling them correctly
  - optimizing it for different use cases
- The COMPASS Upgrade Flight simulator is in the works!

IPP INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Q?