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TRANSP as a control design tool

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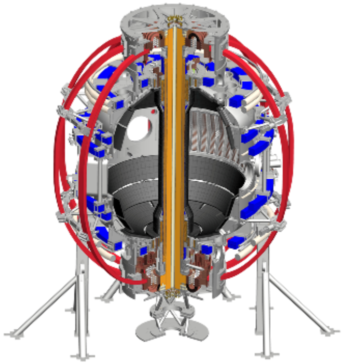
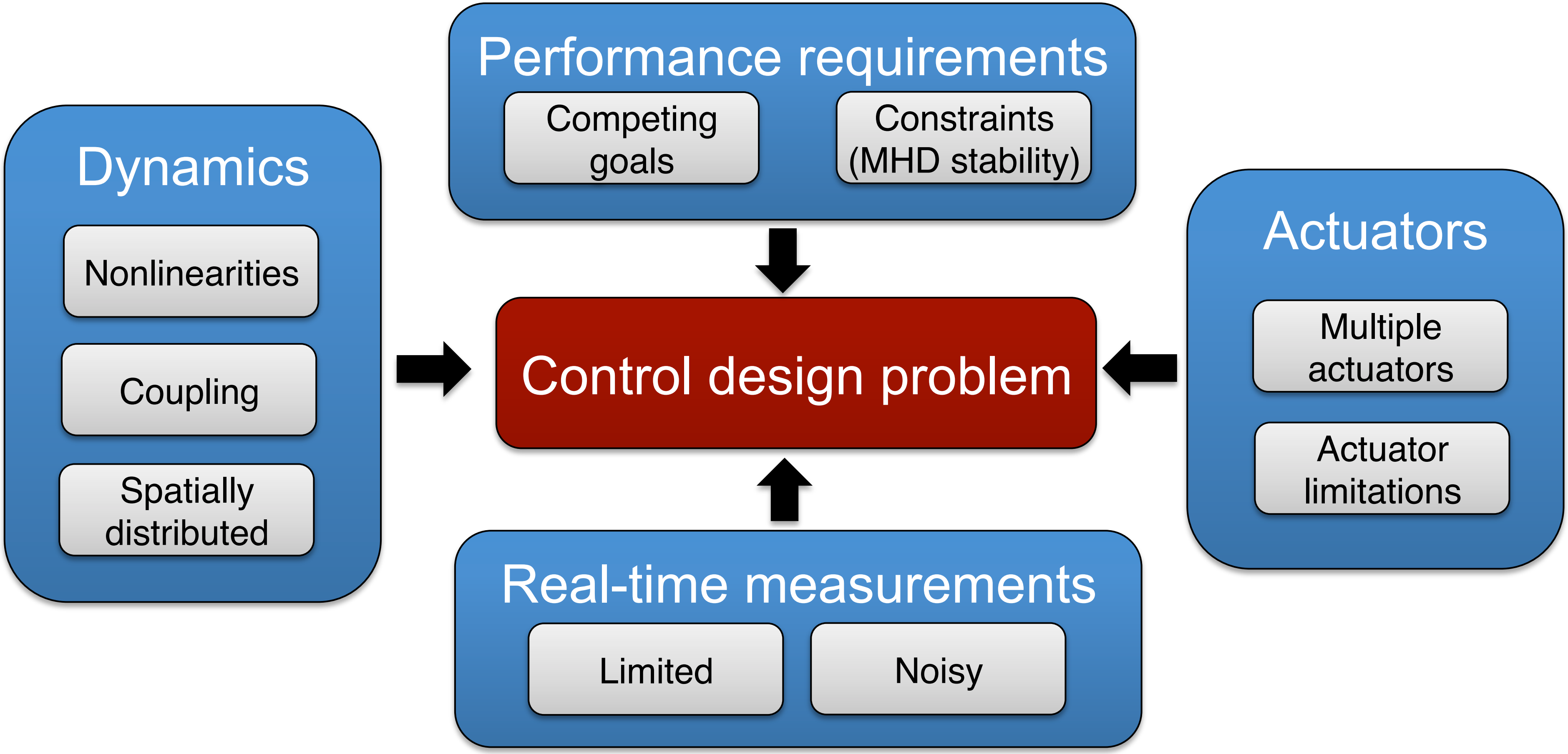
PPPL



TRANSP as a control design tool

- Motivation for model-based control design
- Current implementation of control in TRANSP
- Example applications
- Challenges, plans, and opportunities

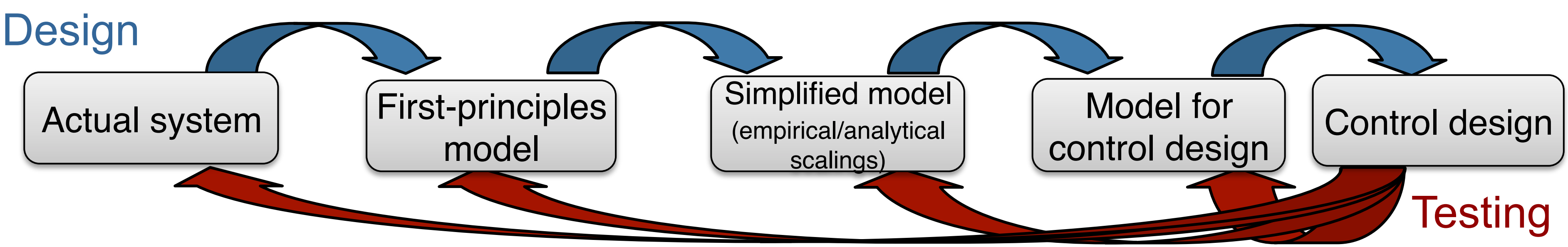
Complexity of control problems motivates use of model-based control design



- **By incorporating dynamic models in the design process, control algorithms can be made to handle all of these issues**

The need for high-fidelity control simulations

- Control design typically relies on **reduced modeling** to make the design problem easier **(TRANSP can contribute to this)**



- When tested experimentally, the **nonlinearities** and **coupling** of the actual system **may degrade performance**
  - Dedicated experimental time needed for commissioning
- Testing controllers using the integrated modeling code **TRANSP** prior to implementation may:
  - Improve controller performance and **reduce time for commissioning and fine tuning**
  - Enable demonstration of **new control techniques** to justify implementation and experimental time

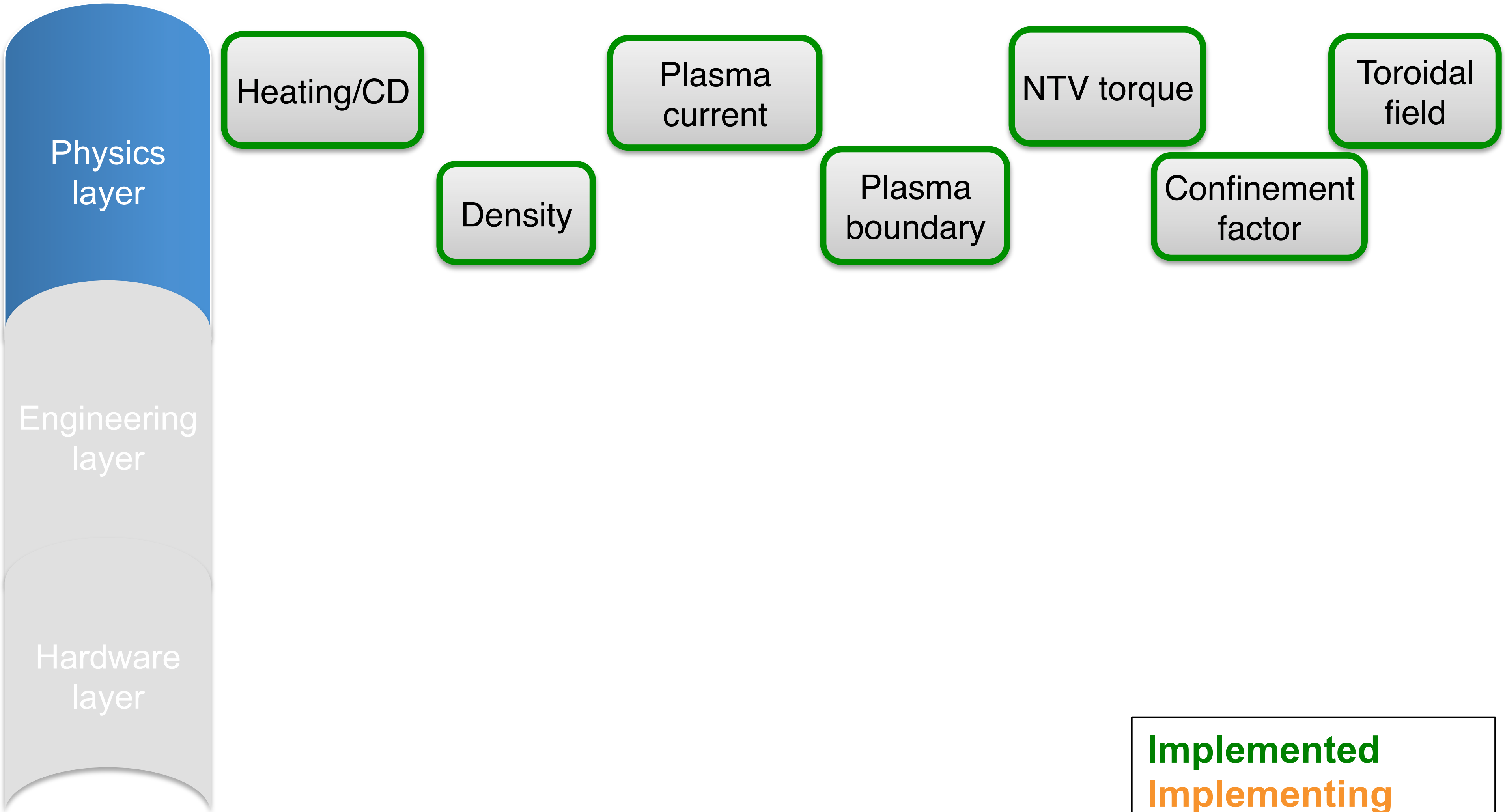
Control has been implemented using external code: the Expert file

- Expert subroutine called at many places throughout TRANSP production code
- An identifier is passed along with the call
  - different snippets of code can be run at different points during the simulation
- Custom run-specific code can be run at each call to manipulate certain variables (which would typically be input ahead of time) based on the state of the simulation

```
…
<TRANSP source code>

call expert(ID)

<more TRANSP code>
…
```

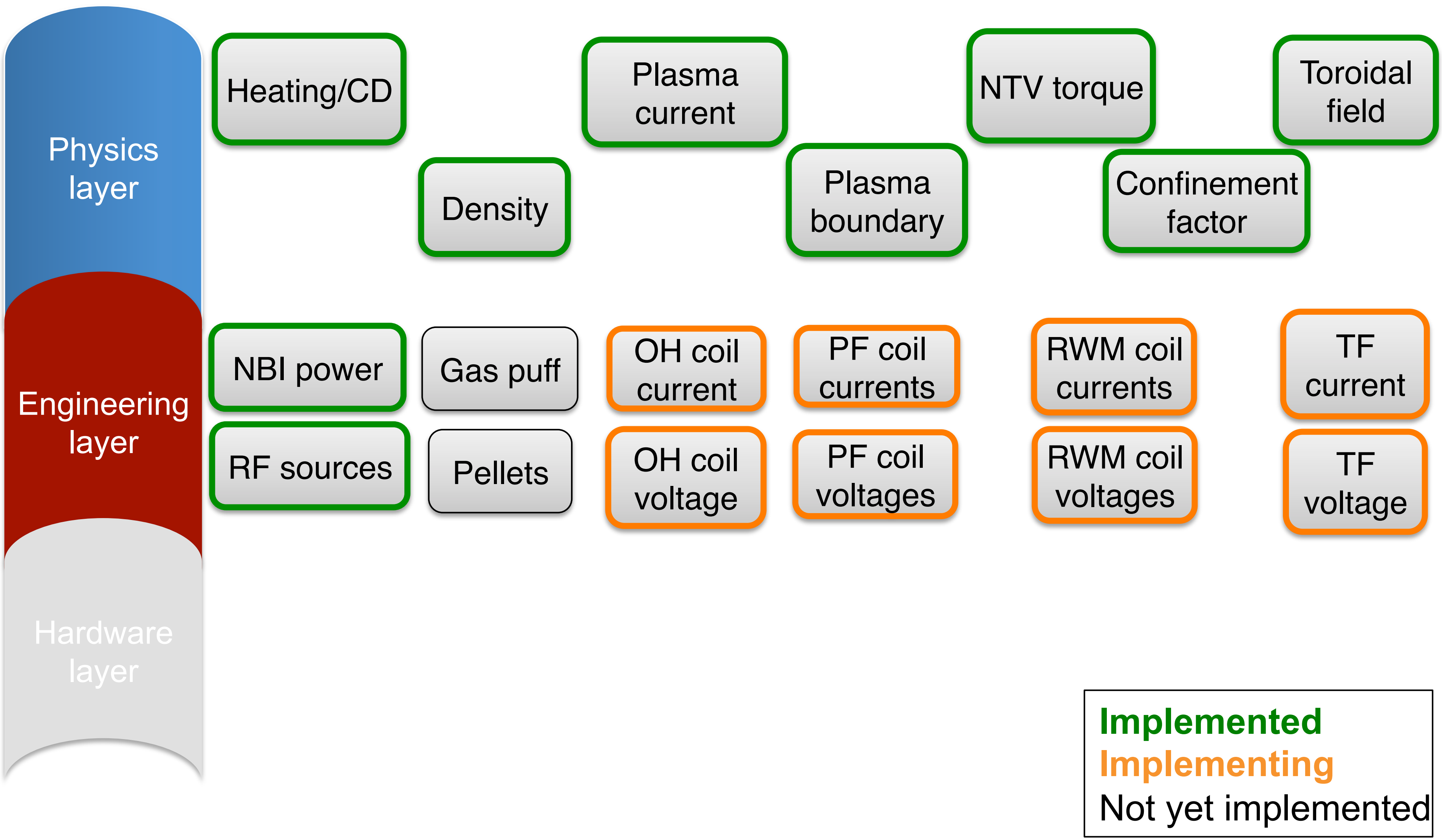
```
Subroutine expert(ID)

…
if ID == x
   <custom calculations>
endif
…
```

Ability to change actuators in `real-time', i.e., based on feedback control



Implemented
Implementing
Not yet implemented

Ability to change actuators in `real-time', i.e., based on feedback control



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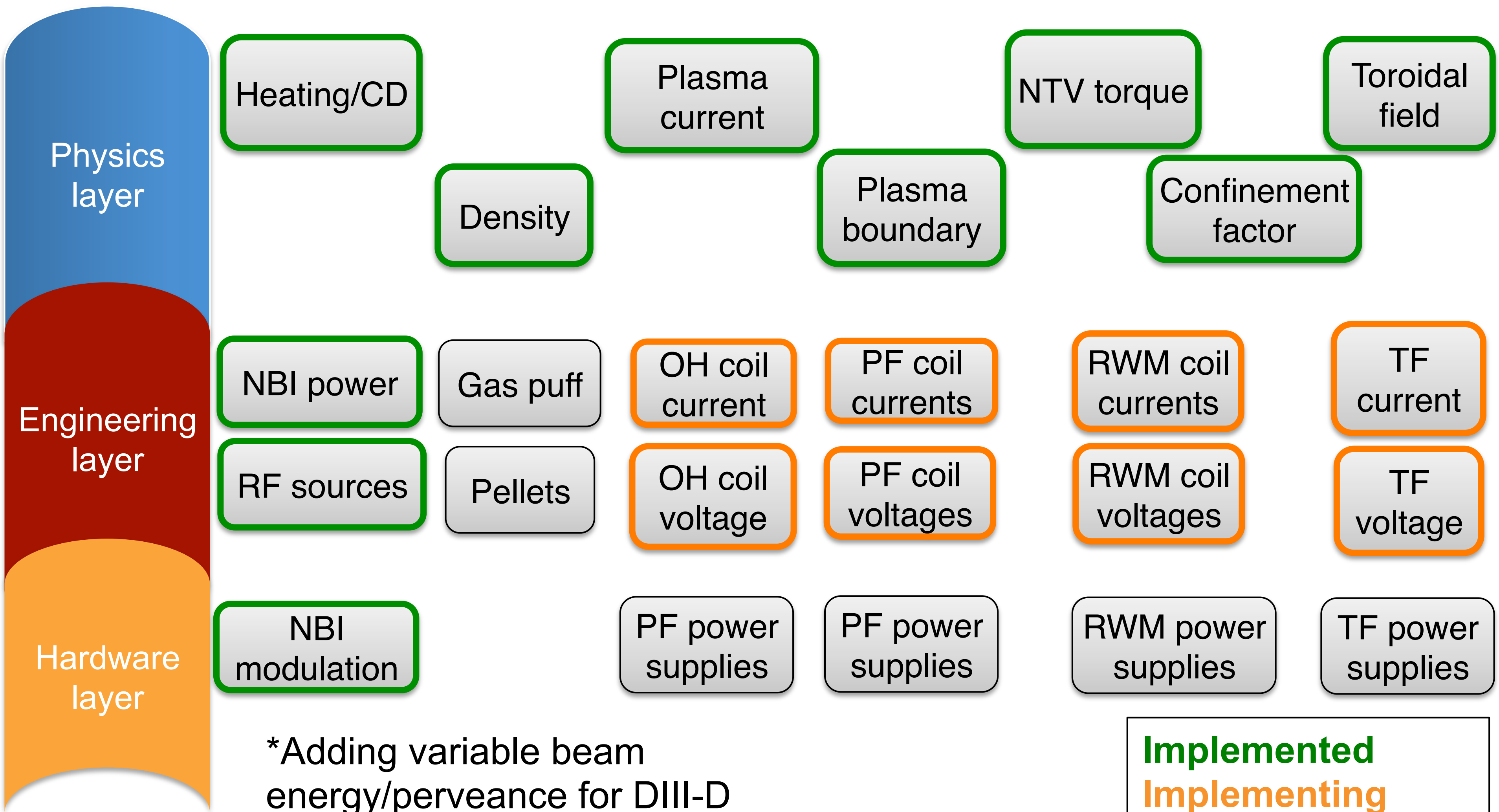


*Adding variable beam energy/perveance for DIII-D

Implemented
Implementing
Not yet implemented

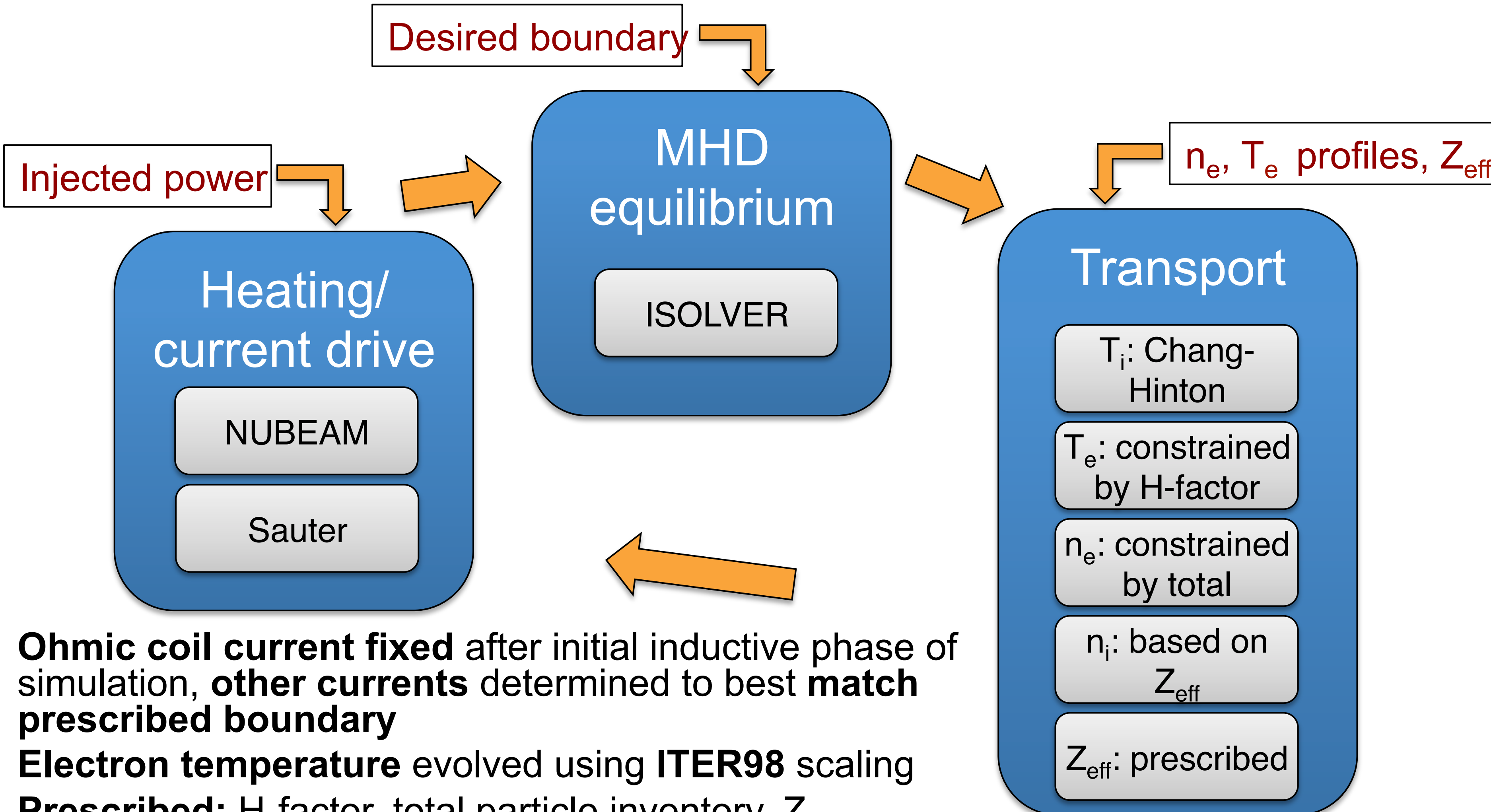
Some recent applications/publications

- Stored energy and q_0 control for NSTX-U [Boyer, et al., Nuclear Fusion 2015]
- Rotation profile control for NSTX [Goumiri, et al., Nuclear Fusion 2016]
- Control of the safety factor profile on NSTX-U [Ilhan, Ph.D. thesis 2016]
- Rotation profile and stored energy control for NSTX-U [Goumiri, et al., Physics of Plasmas 2017]
- **Control of non-inductive scenarios on NSTX-U** [Boyer, et al., Nuclear Fusion 2017]

A major goal of NSTX-U is to study non-inductive operation

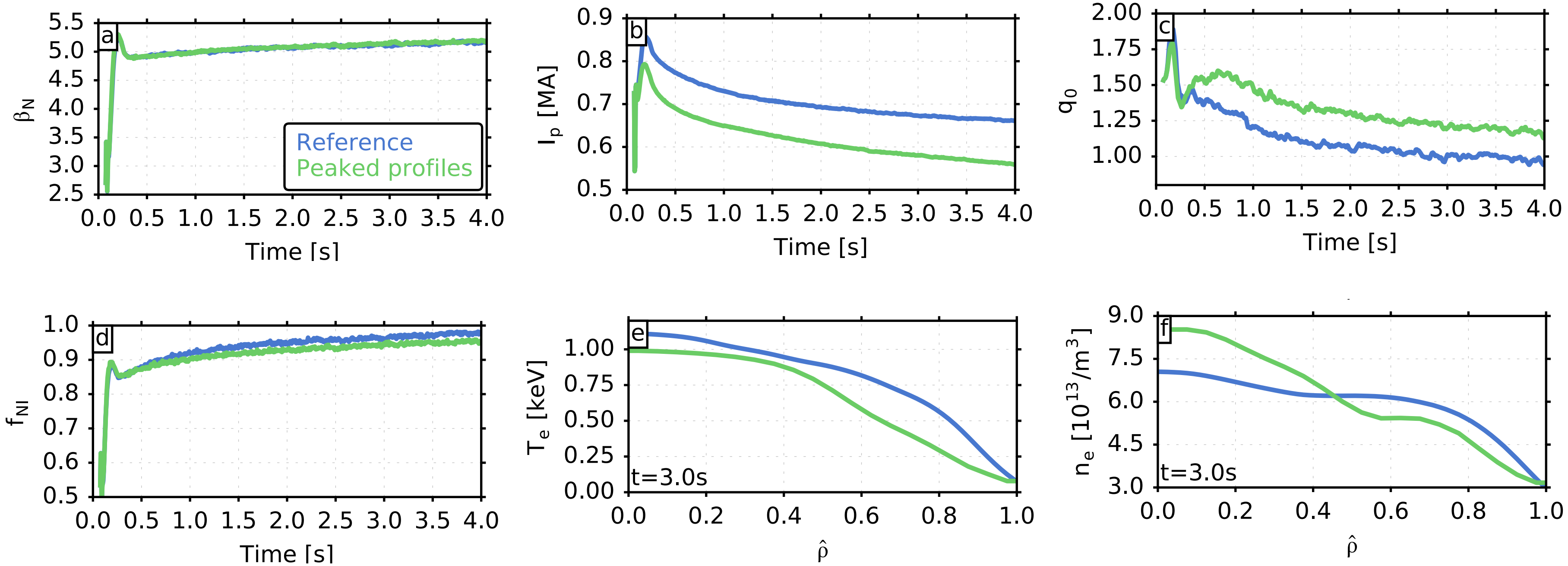
- A spherical torus based design may be an economical option for a **fusion nuclear science facility (FNSF)**
- However, designs have little to **no room for a central solenoid**
  - Plasma current would need to be **generated non-inductively**
- The upgrades to the device in the **NSTX-U** project will enable the **study of non-inductive scenarios**
  - Start-up, ramp-up, and flattop current sustainment
- Early experiments will look at **non-inductive current sustainment** after inductive start-up/ramp-up
  - Solenoid current will be `frozen' to **mimic solenoid-free operation**
  - Plasma current evolution determined by **coupling between kinetic and magnetic profiles**
  - Resulting dynamics may be **intolerably slow** and highly **sensitive to perturbations** in profiles, confinement, etc.
- Can **feedback control** with the available actuators be used to **improve response** and achieve desired conditions?

TRANSP predictive simulation approach



- **Ohmic coil current fixed** after initial inductive phase of simulation, **other currents** determined to best **match prescribed boundary**
- **Electron temperature** evolved using **ITER98** scaling
- **Prescribed:** H-factor, total particle inventory, Z_{eff}, electron density/temperature profile shapes, beam power, plasma boundary

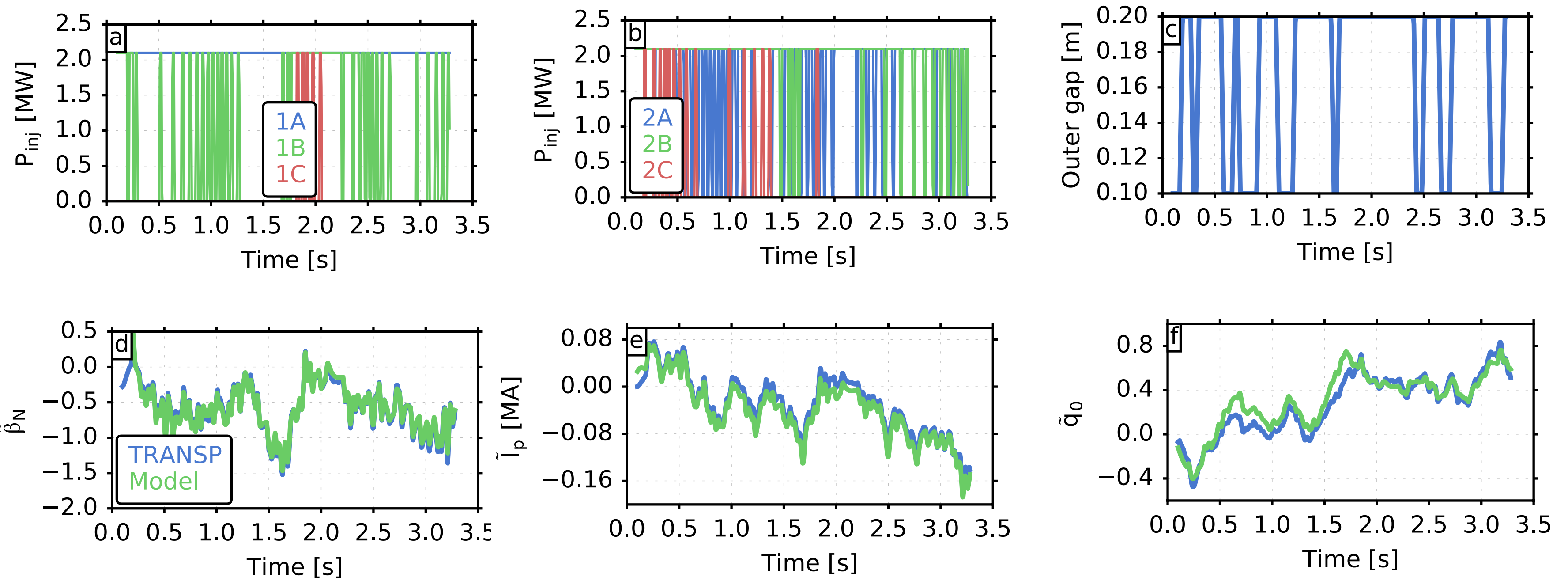
Reference simulation evolves slowly toward steady-state, is sensitive to profile shapes



- **NB sources**: 1B, 1C, 2A, and 2B
- **Outer gap**: 14cm
- Broad **n_e, T_e profiles** from NSTX 142301
- **Particle inventory** held fixed during simulation

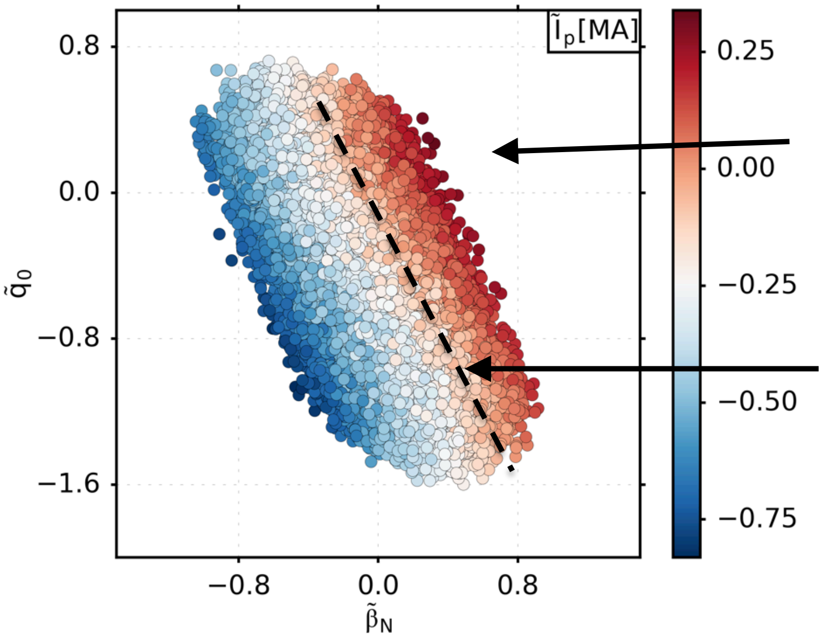
- Slow evolution to 100% non-inductive in both reference (broad) and peaked profile case
  - Using peaked profiles results in similar β_N, lower current and higher q0

Dynamic system ID based on modulation of beams and outer gap in TRANSP



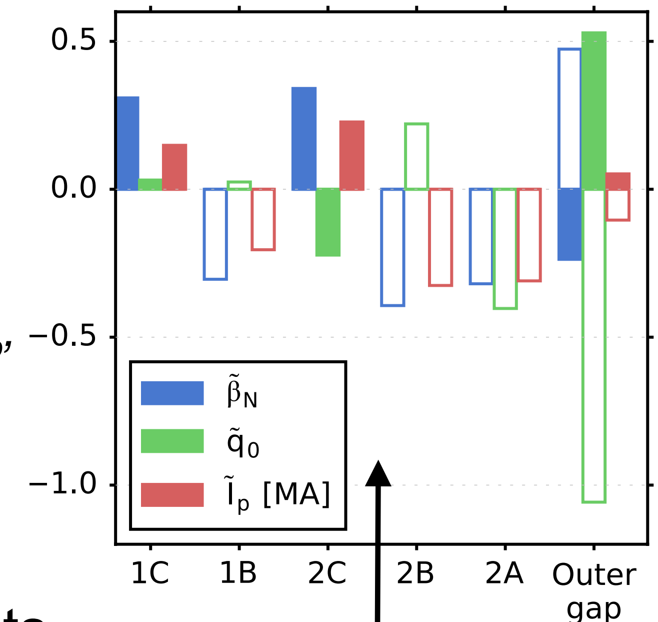
- Open loop signals applied to each actuator
- Prediction-error method used to determine optimal model parameters for a chosen model order using part of data set (estimation set)
- Remainder of data (validation set) used to determine best model order (number of states)

Actuator constraints and strong coupling limit the controllability of the scenario



Maximum q_0, β_N cannot be achieved simultaneously

For a particular I_p, the values of q_0, β_N are roughly constrained around a line

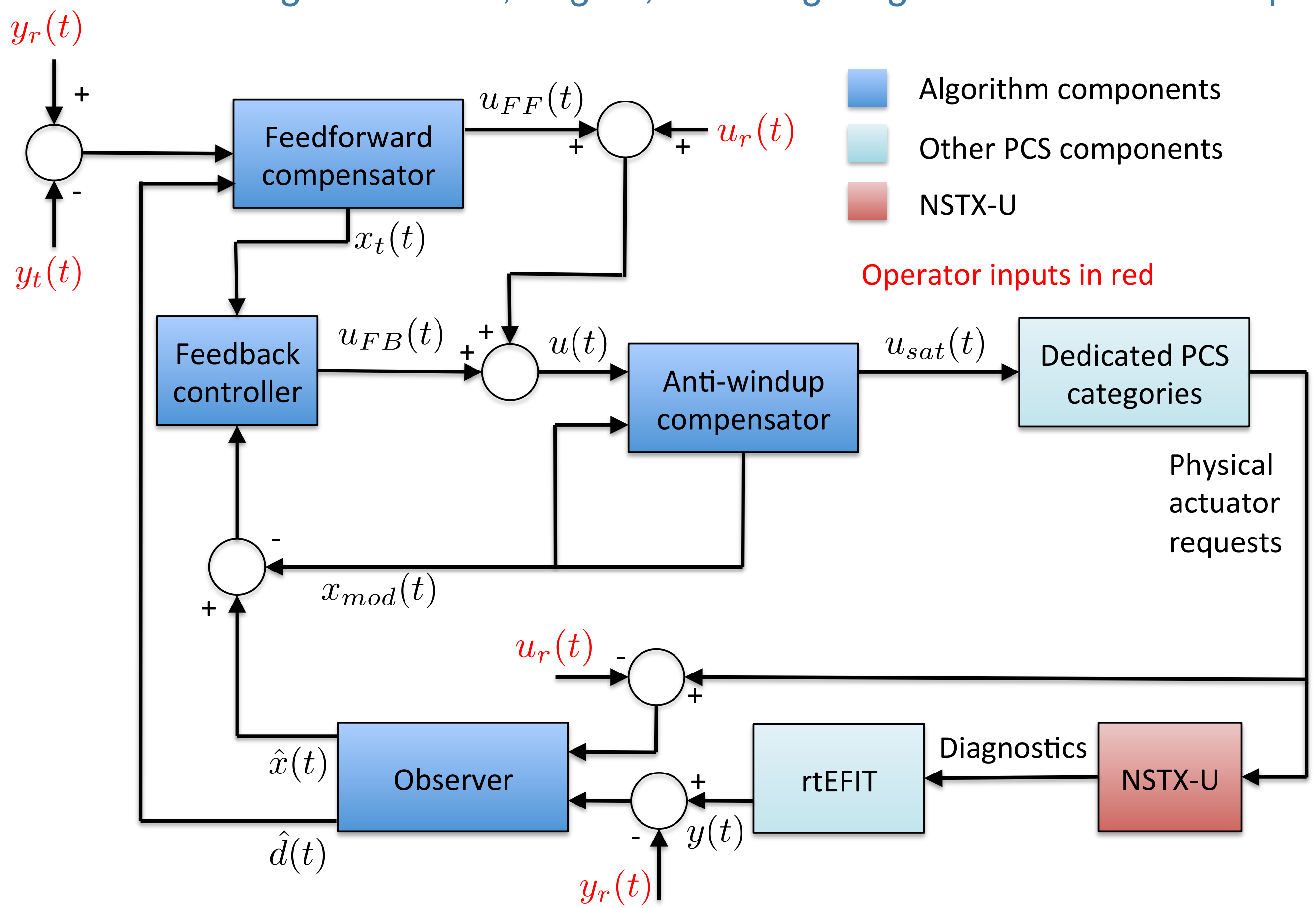


Effect of maximum positive change in actuator shown with solid bar, maximum negative change shown with empty bar.
1A considered fixed on to enable MSE measurements.

- Many more actuators than controlled outputs
  - However, only two outputs independently controllable
- Several actuators have similar effects on the outputs
- Beams are only uni-directional since they are either at there minimum or maximum in the reference scenario

Multi-component model-based controller proposed to handle complexity of problem

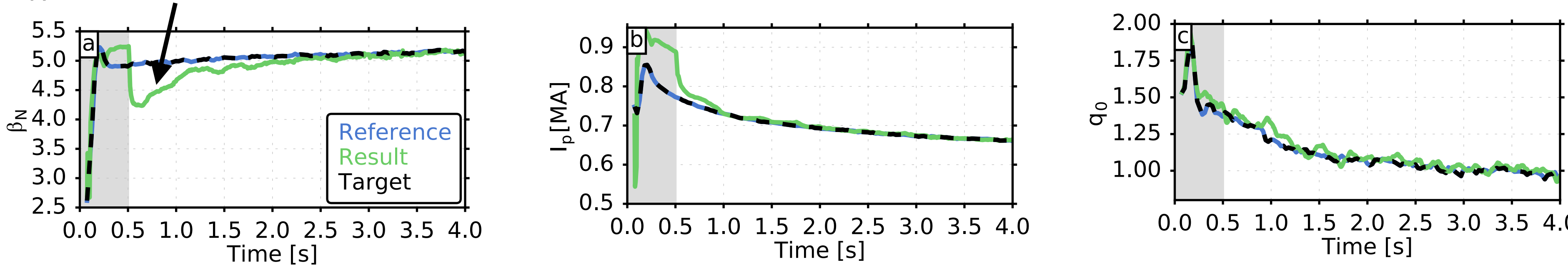
- Each component uses an optimal control approach to minimize a cost function weighting outputs and actuator effort
  - More complex design than PID, but makes tuning more intuitive for operators
  - Each block has some 'expert' settings that would be set up during commissioning
  - Operators can then change reference, targets, and weighting of actuators and outputs



Closed-loop TRANSP simulations used to test effect of disturbances on performance

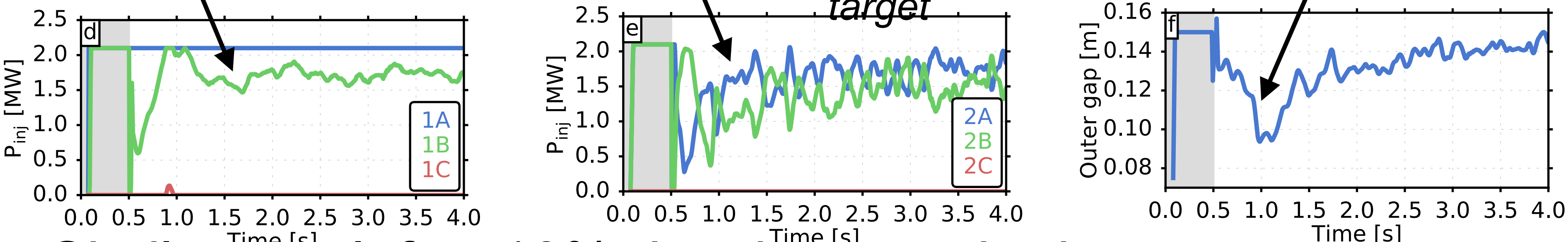
- Reference evolution can be recovered with +10% confinement

β_N weighted less than other outputs in this example

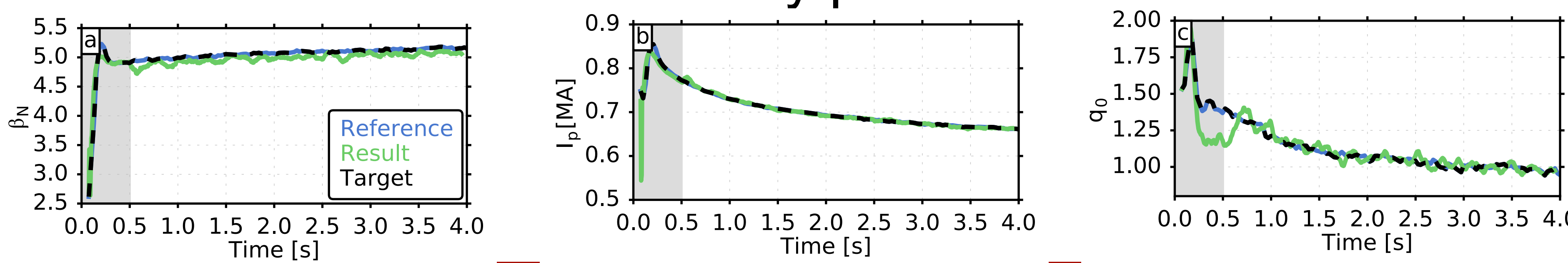


Beam power reduced to reduce plasma current to target

Gap transiently reduced



- Similar result for -10% density perturbation



Challenges to using TRANSP for control

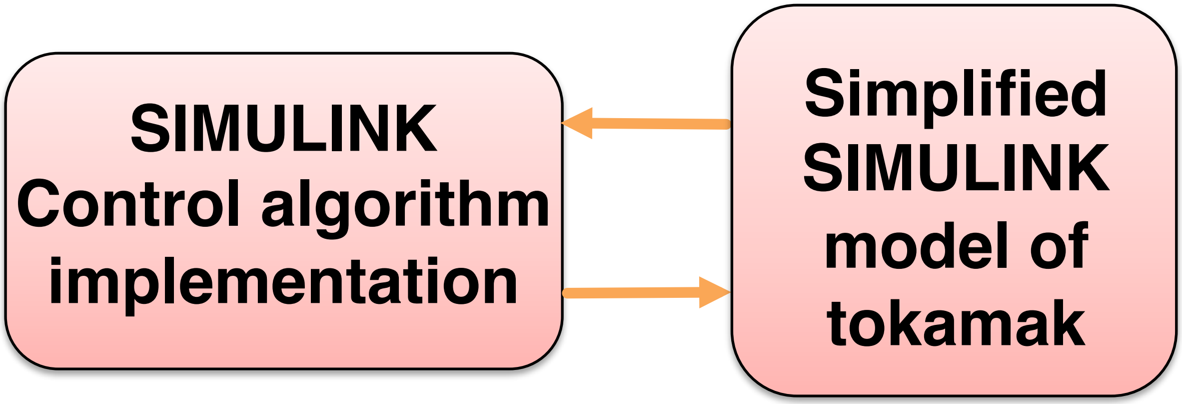
- **Simplified models** (like confinement scaling) are currently implemented in the Expert file
  - Hard to maintain, share with others
- Expert file has to handle gathering **'measurements'** and sending **actuator requests**
  - Need to develop **synthetic diagnostics**, add **noise**, etc.
  - **Time stepping** in TRANSP makes actuator requests **complex**
- **Mimicking the PCS in Expert file** is not easy
  - PCS has ~20 different algorithms running at any given time (each of which may be 100s-1000s of lines of code), with hundreds of set-up parameters
  - PCS can switch between algorithms based on operator set up or changes to plasma conditions (e.g., disruption detection)

Potential solutions

- Implement **simplified models within TRANSP**
  - Enable replacing transport module with confinement scaling or neural network model for faster preliminary simulations
- Implement modules to generate **synthetic diagnostics**
  - Magnetics, profile diagnostics, etc.
    - Include noise, latency
- Implement modules for **simplified (or detailed) actuator models**
  - Power supply switching, gas puff delays, etc.
  - Handle the time stepping issues automatically
- Implement an **interface to external control algorithms**

Socket connection with Matlab would improve control development workflow

- **MATLAB** has numerous control design toolboxes as well as a graphical design and simulation tool **SIMULINK**



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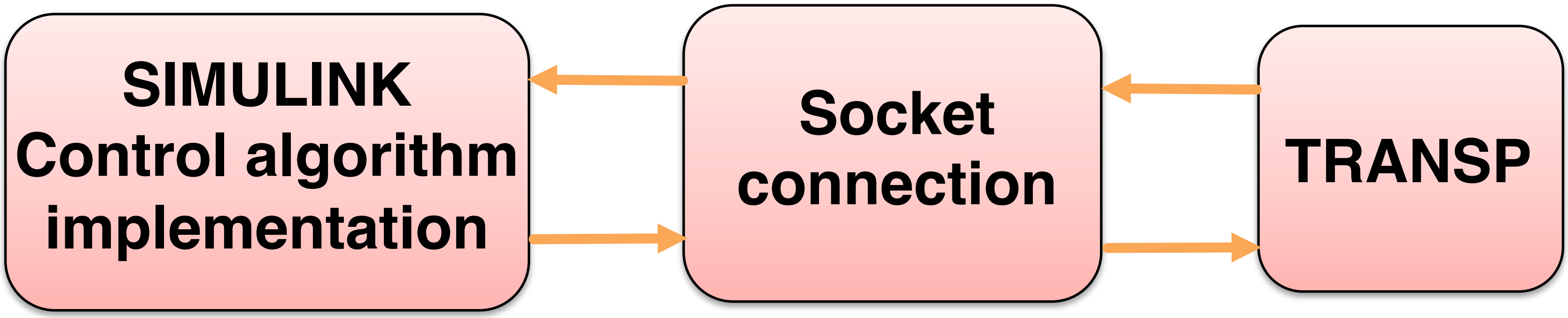

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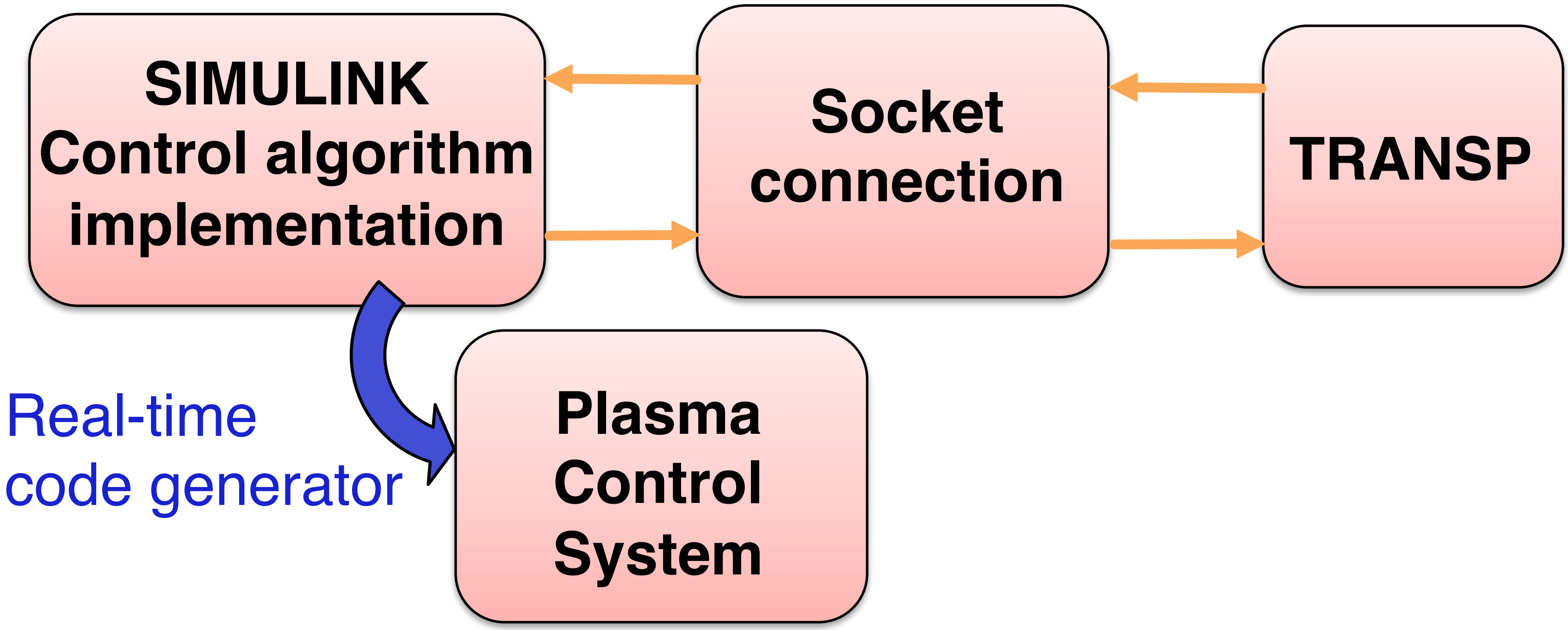

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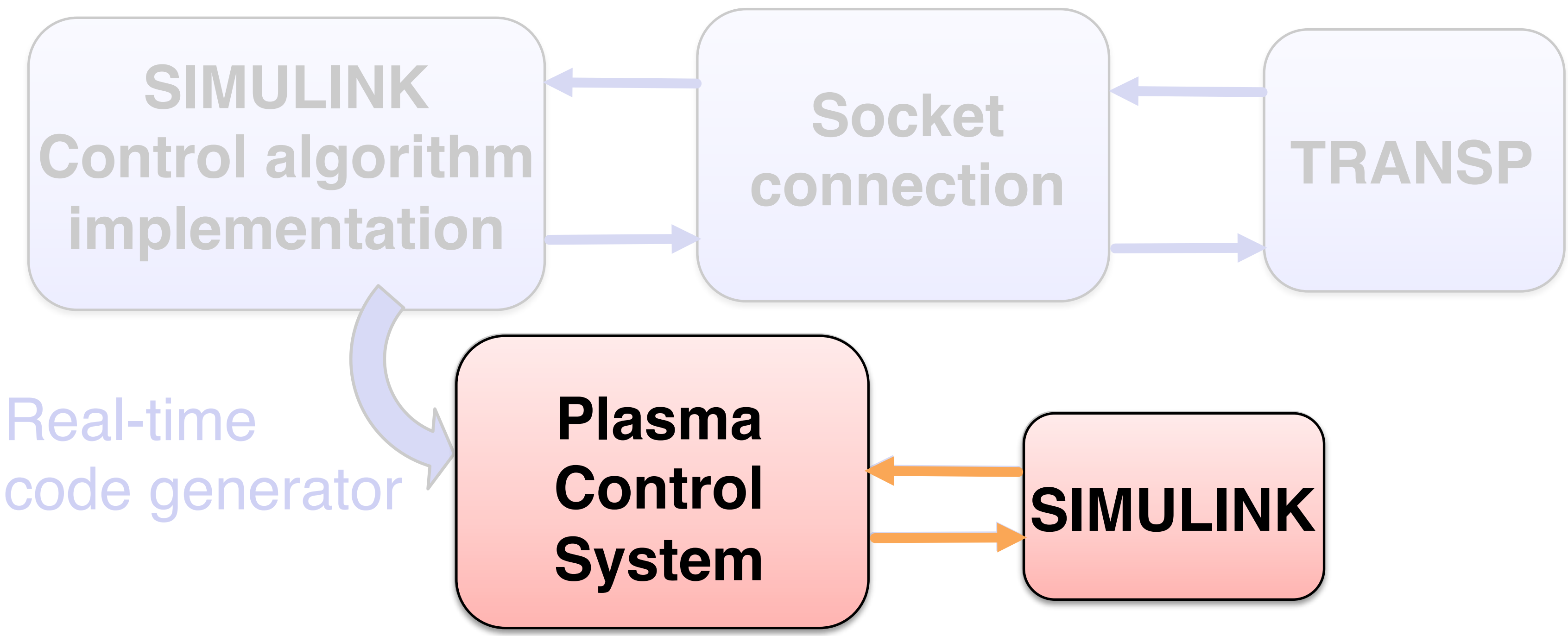

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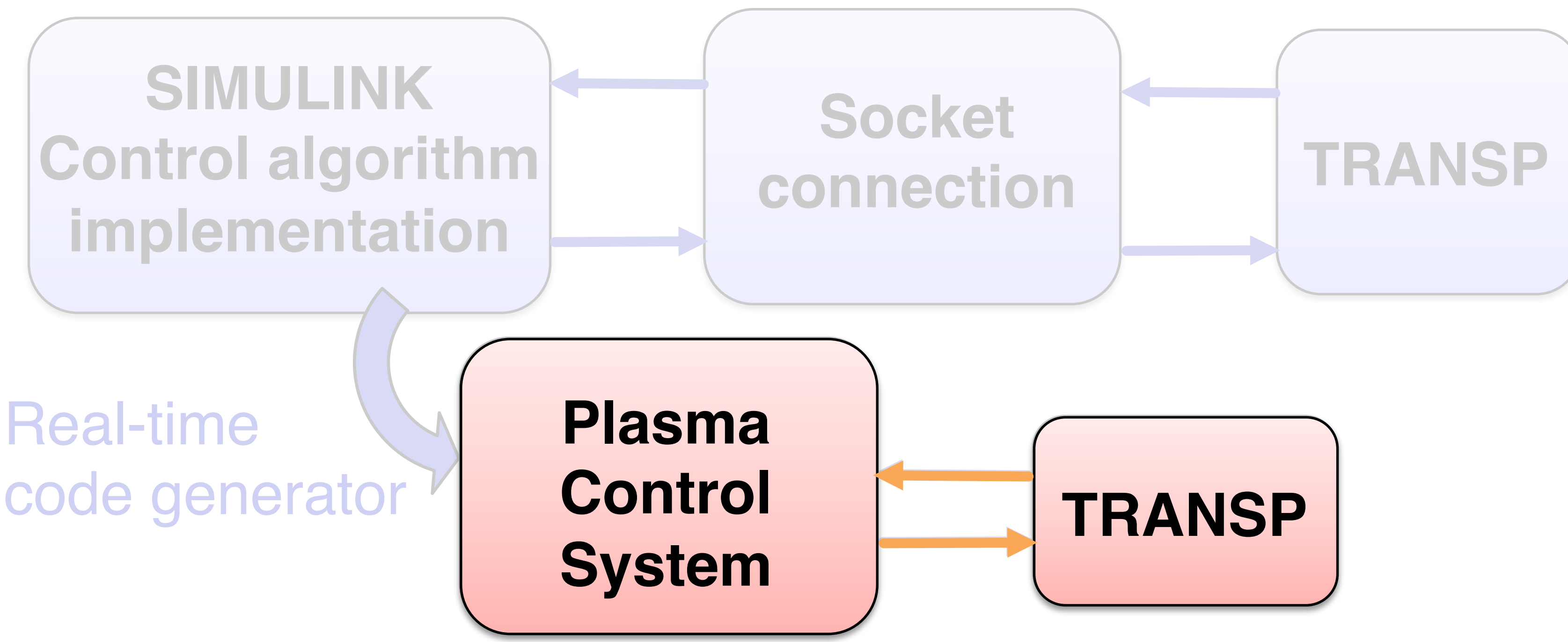

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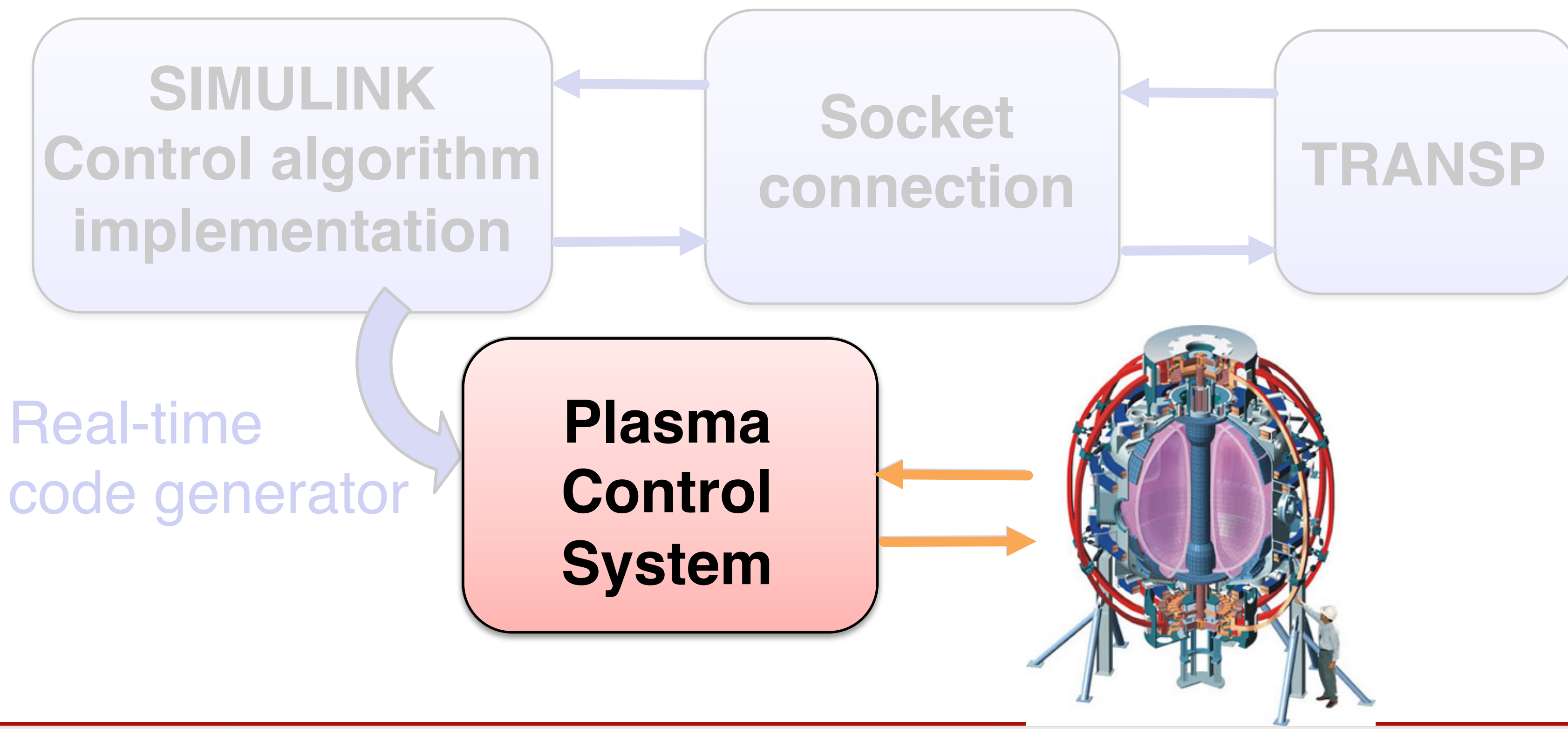


Additional benefits of suggested features

- Predictive simulations with feedback
  - Control stored energy, profiles, density etc. in self-consistent and realistic ways during scans
- Include TRANSP in ITER Plasma Control System Simulation Platform (Simulink based)
- Set up predictive runs using the PCS GUI
  - Flight simulator for physics operators, easy to view changes, restore previous shots or parts of shots
- Adding simplified modules for different physics could enable faster preliminary predictive simulations
  - Confinement scaling, neural networks, etc.
  - Use for optimization and scans, use more complex models once broader studies are complete

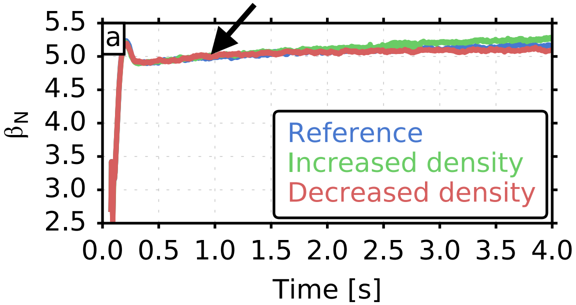
Thank you!

Back up

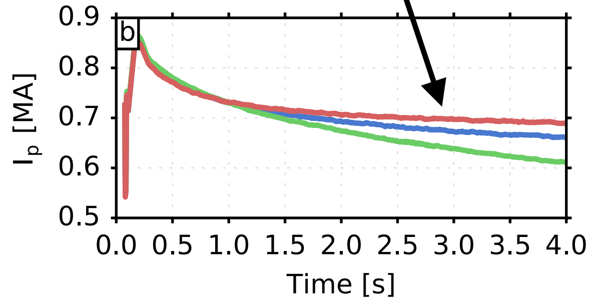
Scenario is also sensitive to disturbances in density and confinement

Density disturbances (+15%, -10%)

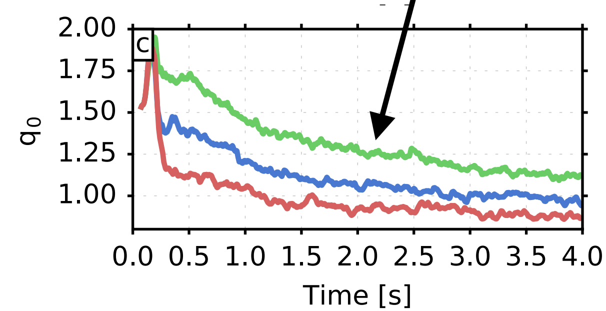
Small effect on β_N



Current inversely proportional to density

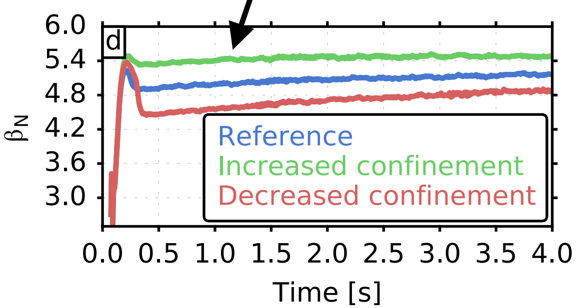


q_0 proportional to density

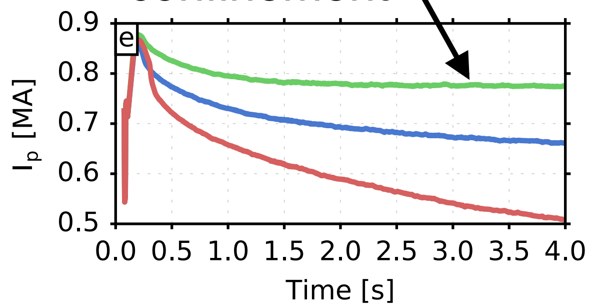


Confinement disturbances (+10%, -10%)

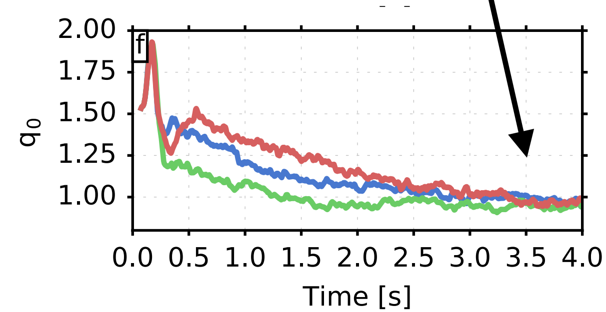
β_N proportional to confinement



Current varies significantly with confinement



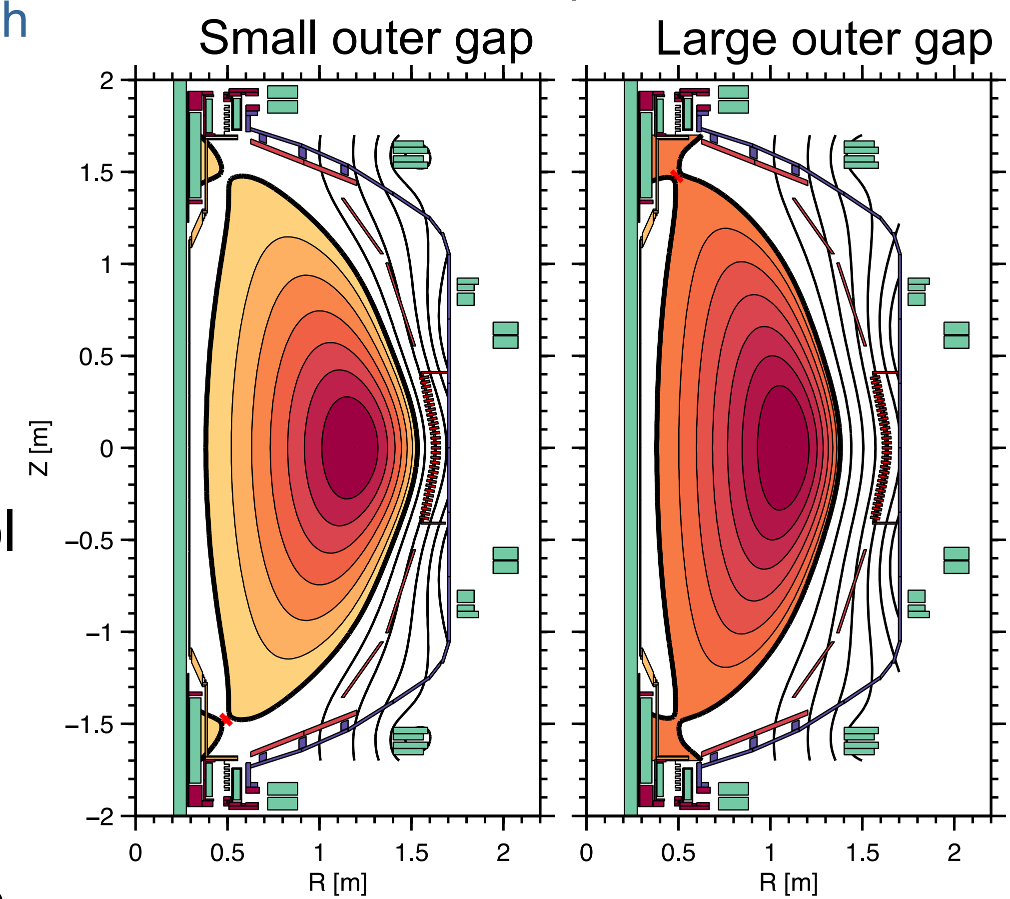
Final q_0 unchanged but evolution is faster with higher confinement



Design goal: Improve response, reject disturbances, + enable tracking w/ feedback

- Control q_0, β_N, and I_p by varying beam sources, outer gap
  - Outer gap affects outputs through **beam deposition** profile and **bootstrap current**
- Initially tried simple PI (proportional-integral) controllers
  - Difficult to tune due to actuator constraints and coupling
- Developed a model-based multi-input-multi-output control approach to explicitly handle:
  - Coupling
  - Actuator constraints
  - Disturbances, tracking
  - Noisy measurements
- Resulting control law tested in feedback TRANSP simulations

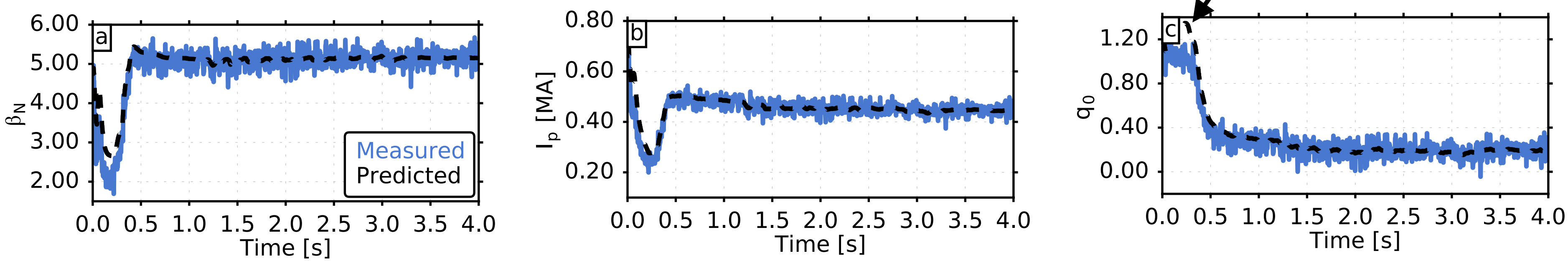
Reference plasma boundaries:



Observer estimates states and disturbances, feedforward compensator tracks targets.

- **Observer** mitigates the effect of **noisy measurements** and input **disturbances**, ensuring **smooth estimates with no steady-state error**
  - Provides **estimate of disturbances** to feedforward compensator
  - Provides **state estimates** for feedback control

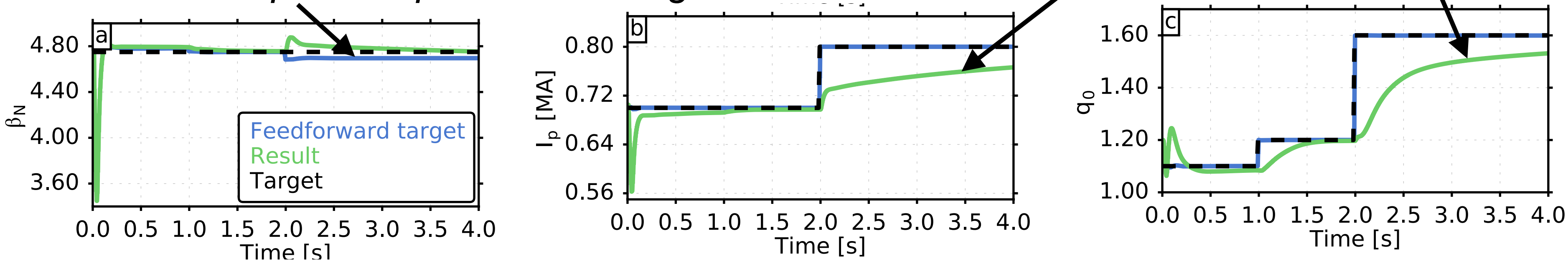
Online estimate of disturbance provides integral action



- **Feedforward compensator** determines actuator values to **optimize a cost function** weighting **steady-state error** and **actuator effort**
  - Uses **model**, estimates of **disturbances**, and actuator **constraints**

β_N weighted less heavily, actuator constraints prevent perfect tracking

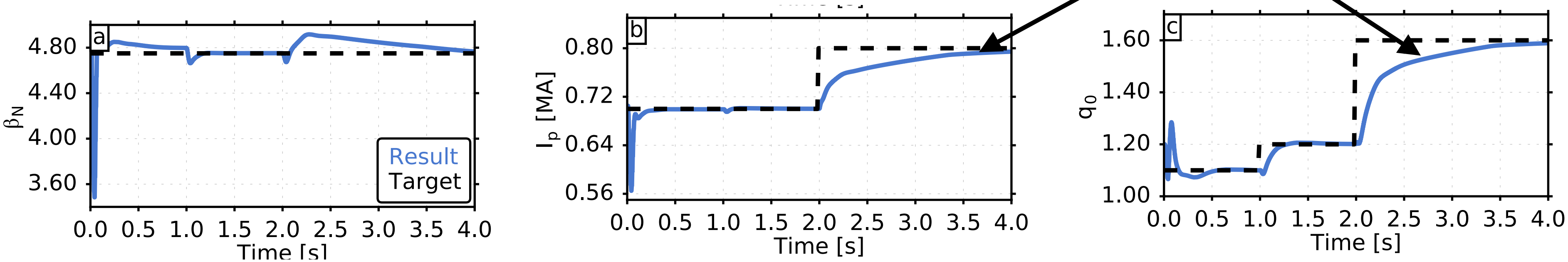
System responds to feedforward command on a slow time scale



Feedback improves system response, anti-windup mitigates actuator limit effects.

- **Feedback controller** acts on difference between **feedforward target states** and **observer estimated states**
  - Allows response time of system to be improved

Faster response compared to feedforward only



- **Actuator saturation** changes the 'direction' of applied feedback
  - Can cause **degraded tracking** of constrained targets
  - **Anti-windup redistributes actuator request** to reduce effect of saturation, **hides effect of saturation** from feedback law

Target tracked more closely with anti-windup active