U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Plasma control algorithm development on NSTX-U using TRANSP

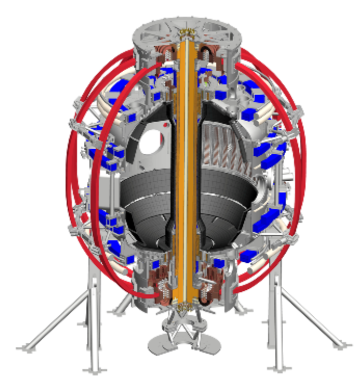
Dan Boyer

for the Integrated Scenarios science group

NSTX-U Program Advisory Committee Meeting (PAC-37)

January 26, 2016

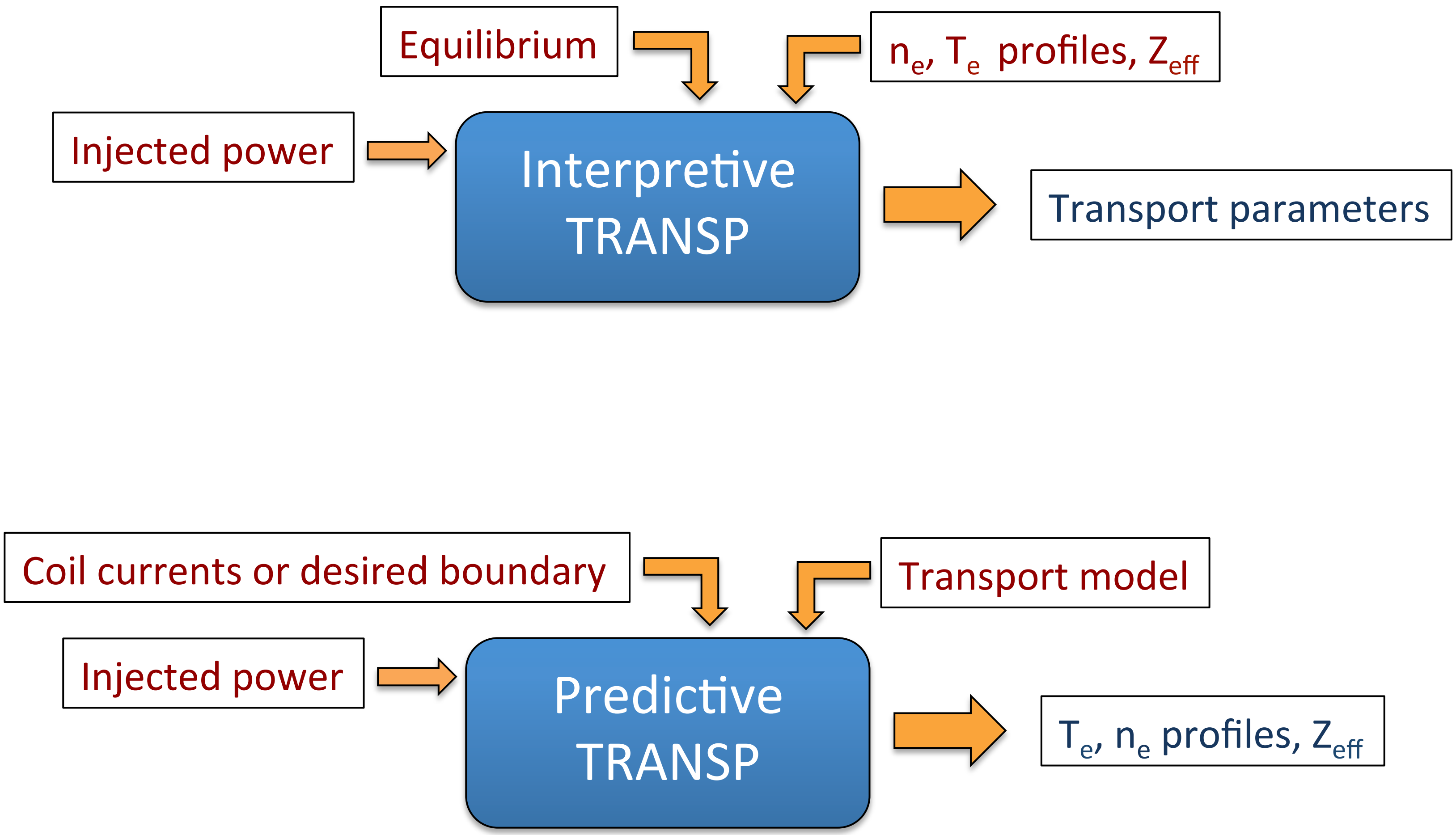
PPPL



NSTX-U Mission Elements
5 Highest Research Priorities

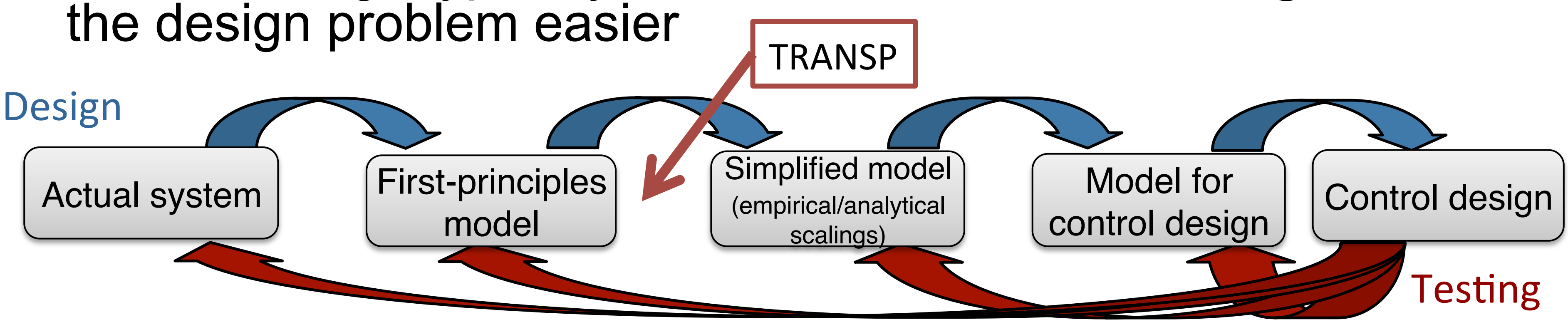
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

TRANSP routinely used in interpretive mode, increasingly in predictive mode



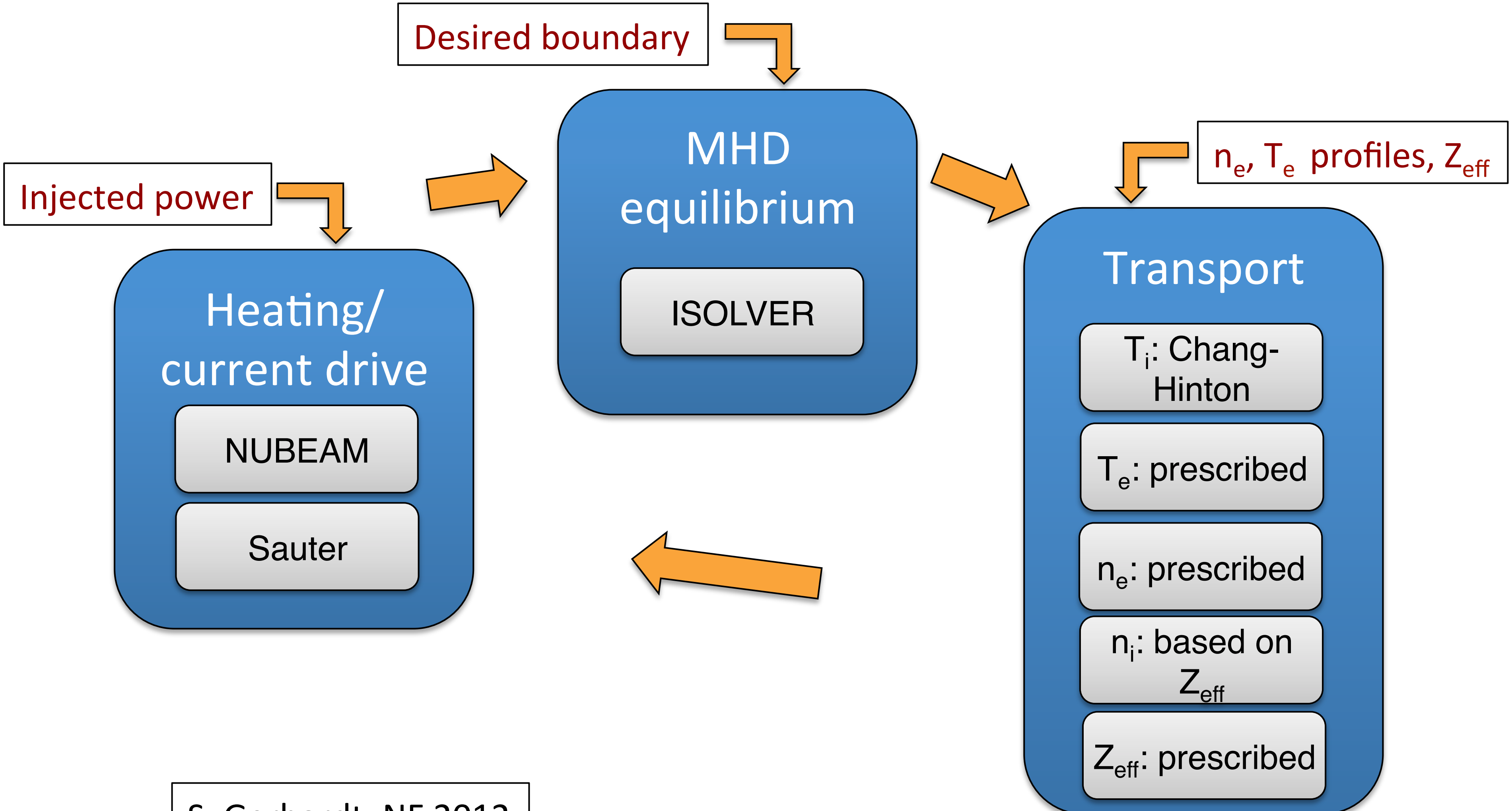
High-fidelity control simulations needed for model-based control design and validation

- Control design typically relies on **reduced modeling** to make the design problem easier



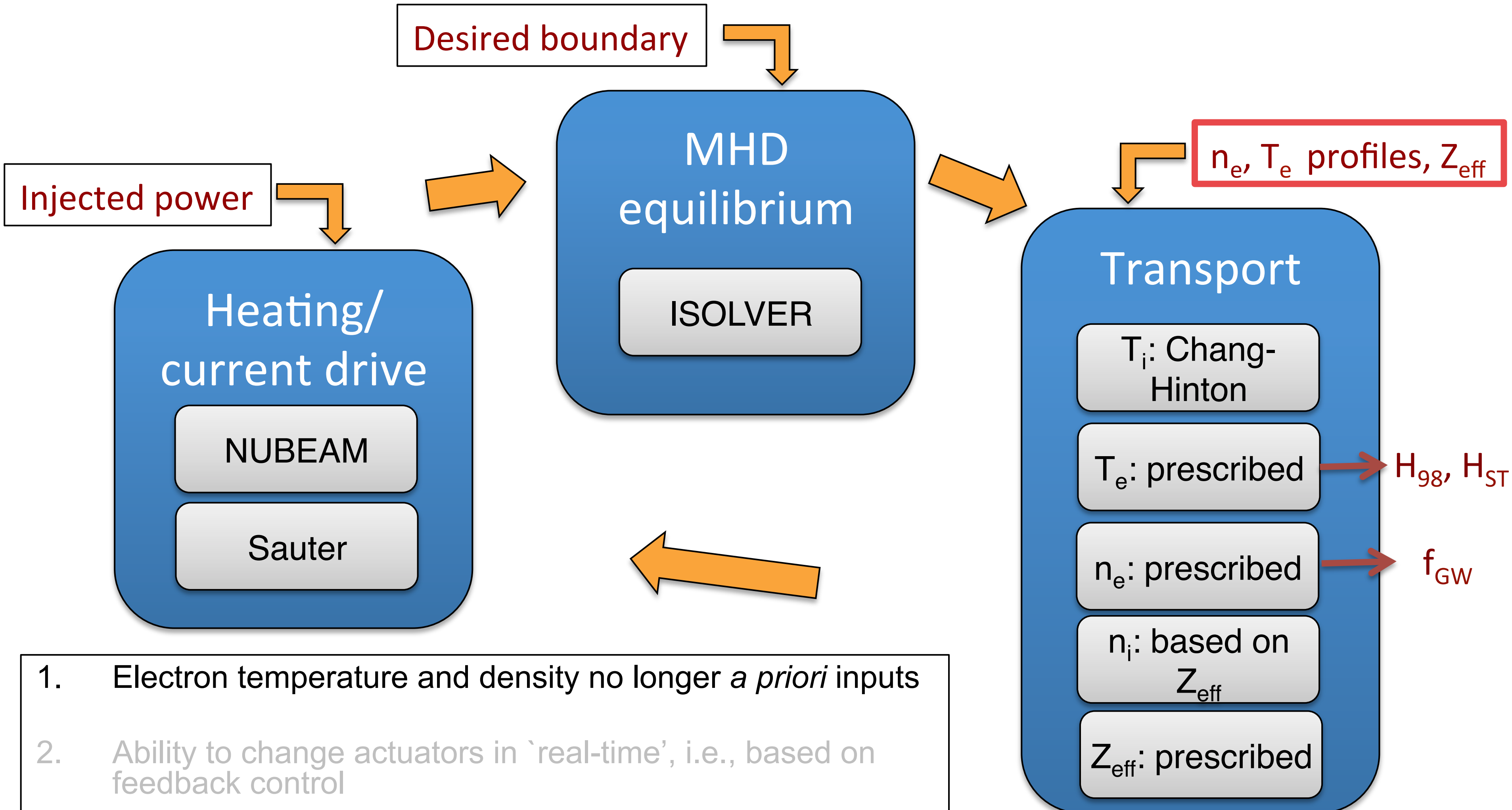
- When tested experimentally, the **nonlinearities** and **coupling** of the actual system **may degrade performance**
  - Dedicated experimental time needed for commissioning
- Testing controllers using the integrated modeling code **TRANSP** prior to implementation may:
  - Improve controller performance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

NSTX-U TRANSP feedback control simulations based on scenario development



S. Gerhardt, NF 2012

Now using TRANSP as a virtual tokamak for control design



1. Electron temperature and density no longer *a priori* inputs
2. Ability to change actuators in `real-time', i.e., based on feedback control
3. An analog to the plasma control system (PCS)

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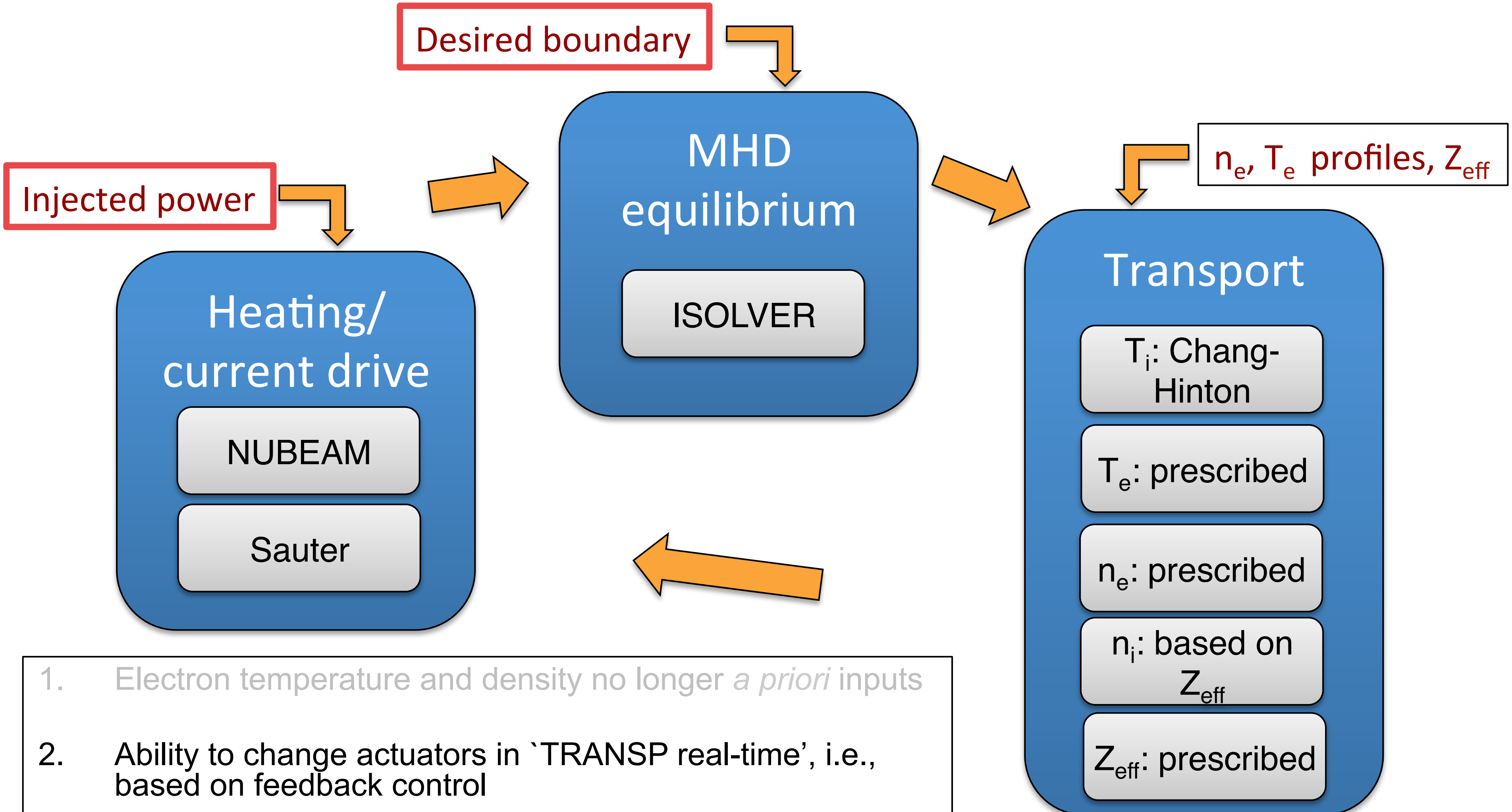

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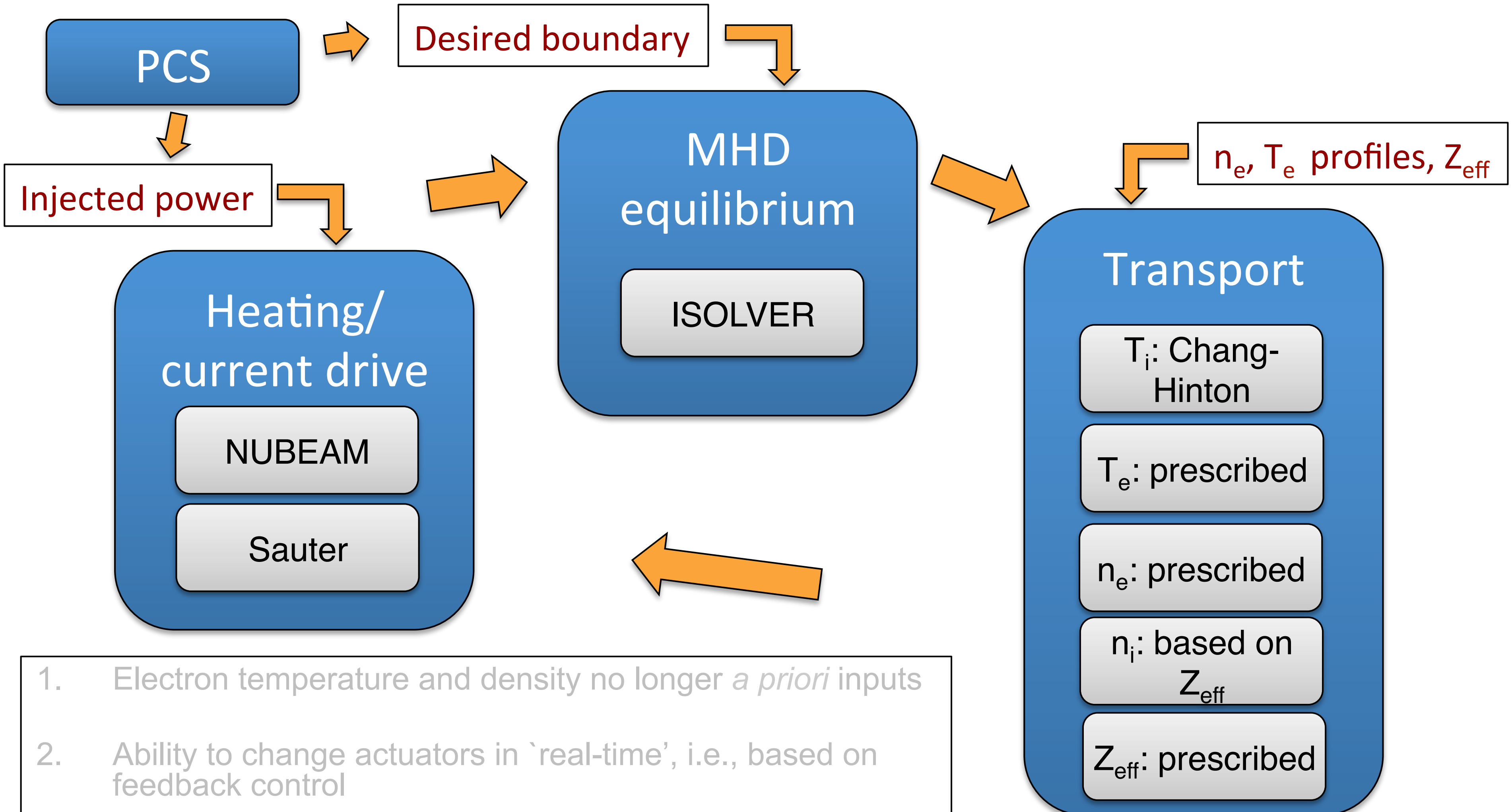

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Ability to change actuators in `TRANSP real-time', i.e., based on feedback control

Physics layer

Engineering layer

Hardware layer

Heating/CD

Density

Plasma current

Plasma boundary

NTV torque

Confinement factor

Toroidal field

Implemented
Implementing
Not yet implemented

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

Physics layer

- Heating/CD
- Density
- Plasma current
- Plasma boundary
- NTV torque
- Confinement factor
- Toroidal field

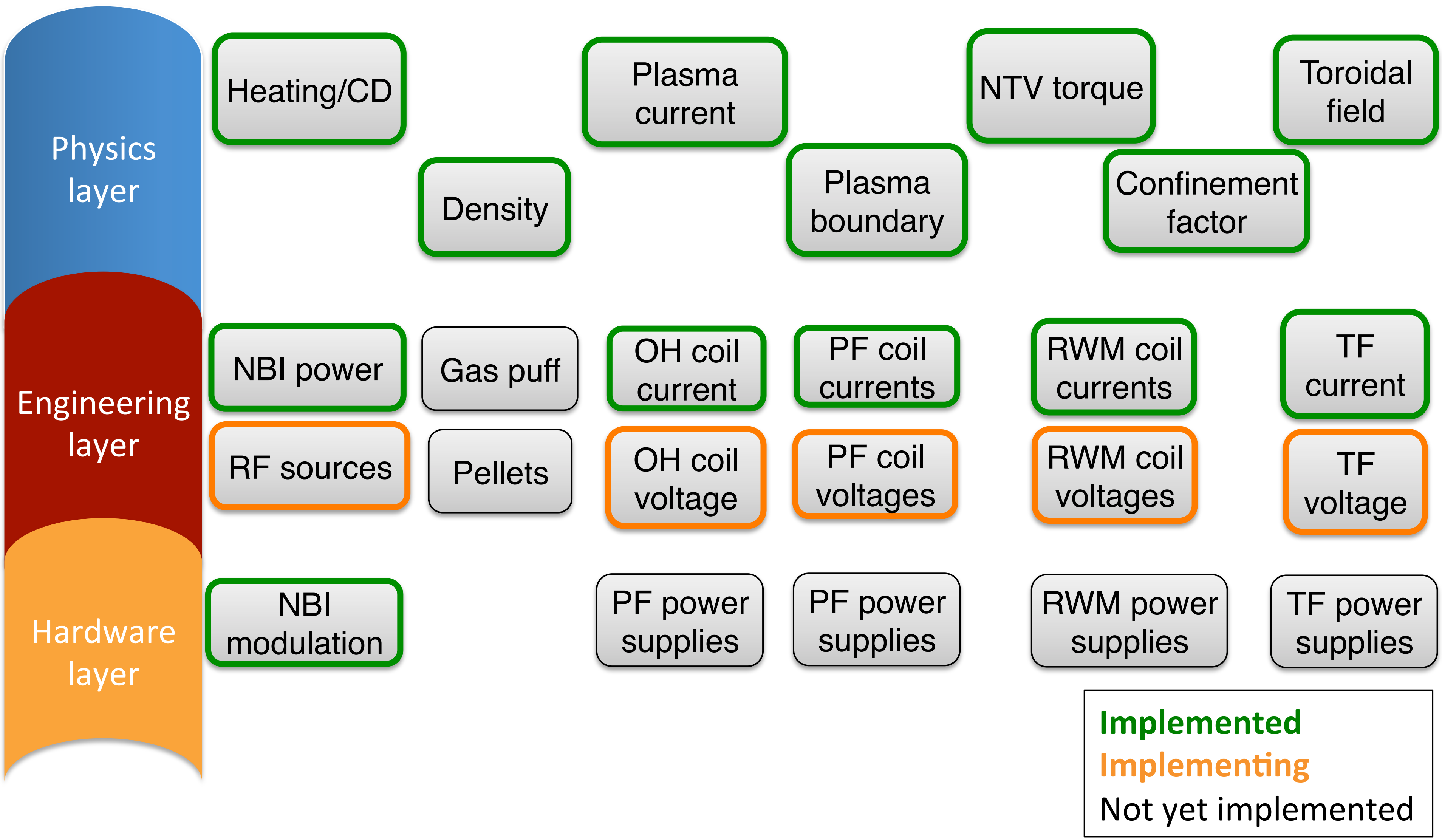
Engineering layer

- NBI power
- RF sources
- Gas puff
- Pellets
- OH coil current
- OH coil voltage
- PF coil currents
- PF coil voltages
- RWM coil currents
- RWM coil voltages
- TF current
- TF voltage

Hardware layer

Implemented
Implementing
Not yet implemented

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



Several on-going projects using TRANSP feedback control framework

- Stored energy and q_0 control on NSTX-U
  - M. D. Boyer, PPPL, Experiment: XP-1509
- Stored energy, q_0, and I_p control on NSTX-U (non-inductive scenarios)
  - M. D. Boyer, PPPL, Experiment: future XP, possibly XP-1507
- Rotation profile control on NSTX-U
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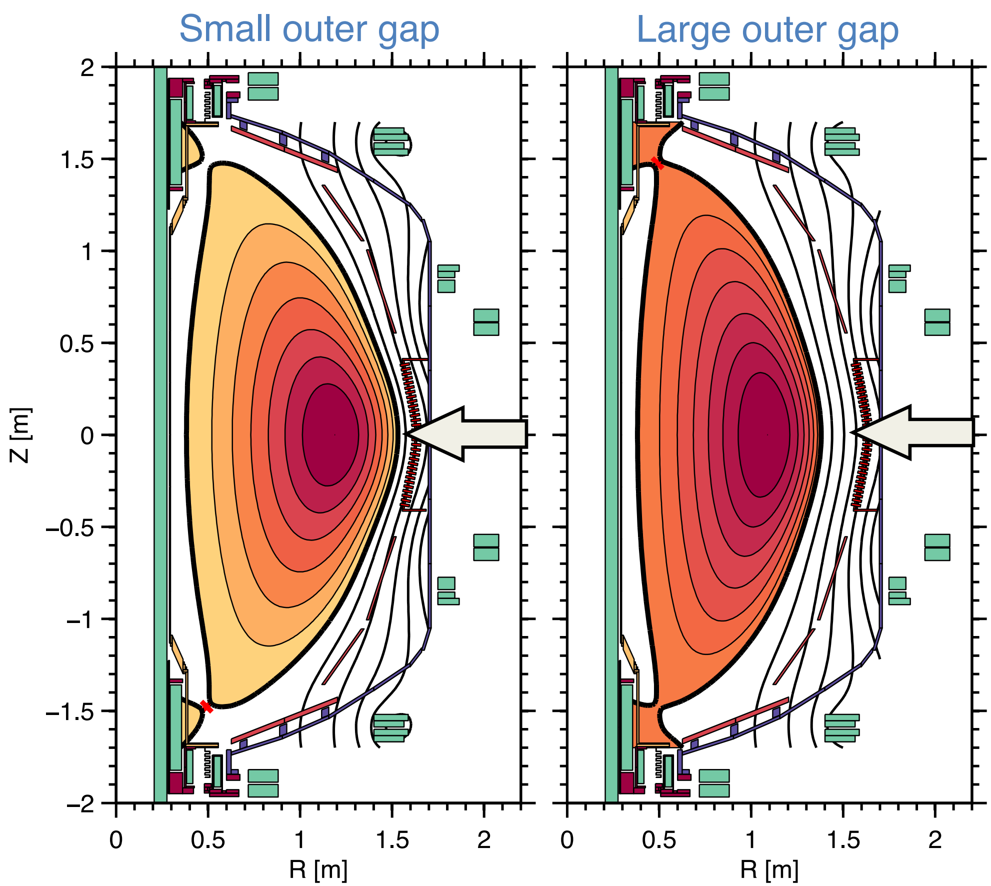
Using TRANSP to test q_0 and β_N control via beam power and outer gap size actuation

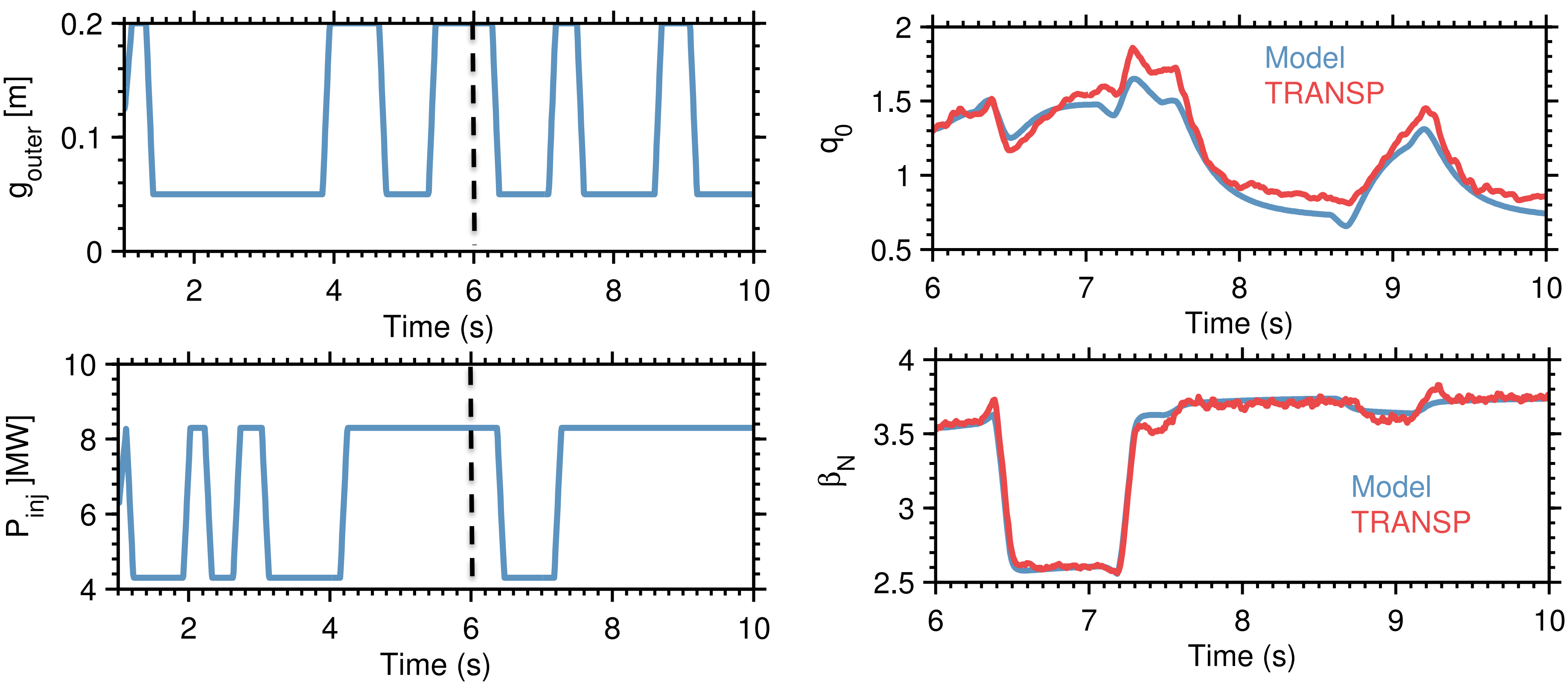
- Boundary can have strong effect on q profile through
  - Effect on **beam deposition** profile
  - Effect on **bootstrap current** through change in elongation
- Two **reference boundaries** with different outer gap sizes were chosen, and **interpolated between** based on the feedback controller request



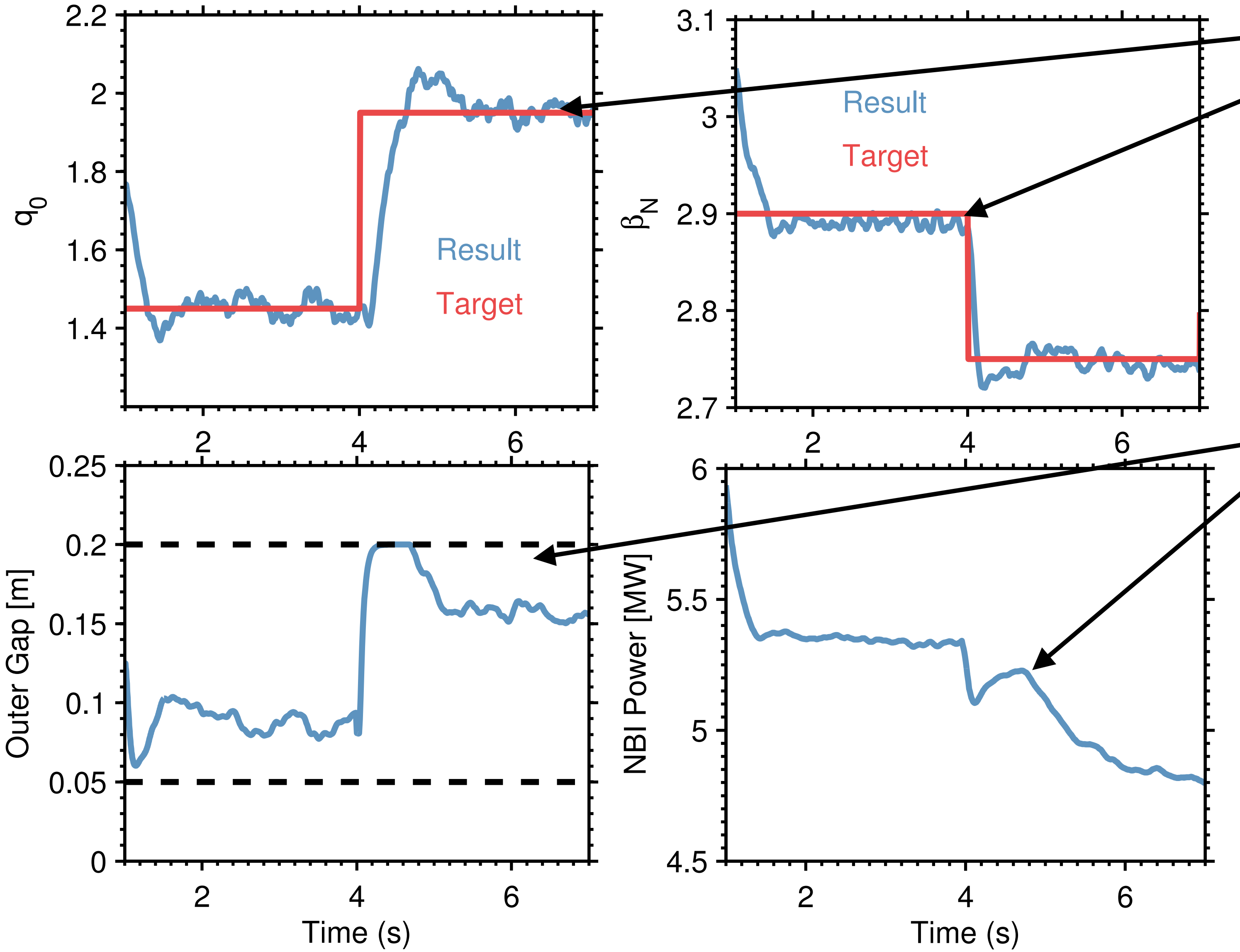
M.D. Boyer, NF 2015

State-space system identification used for designing simultaneous q_0 and β_N controller

- Open loop signals applied to each actuator in several TRANSP runs
- Linear dynamic model optimized to predict outputs



Optimal controller achieves good target tracking in TRANSP simulations



Evolution tracks step change in requested values

Controller increases outer gap and decreases beam power to track change in request

Controller has important implications for MHD stability – ability to avoid q=1, or to move radius of the q=2 surface to avoid 2/1 NTMs.

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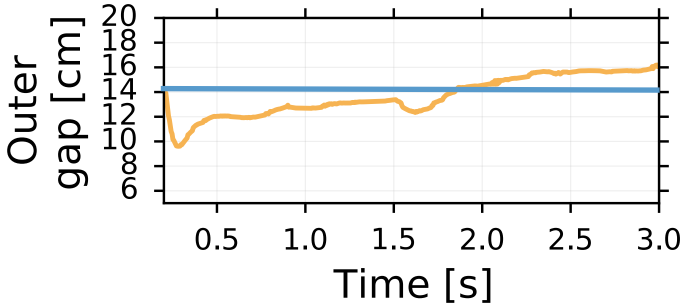
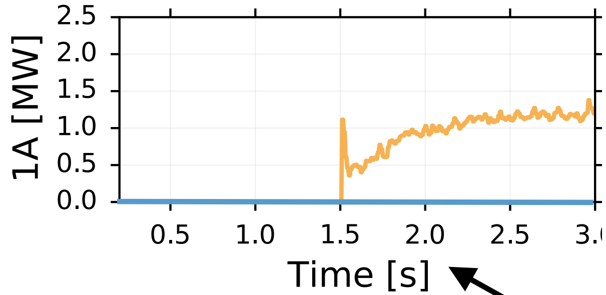
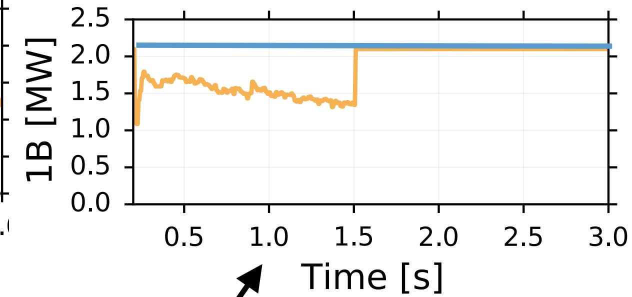
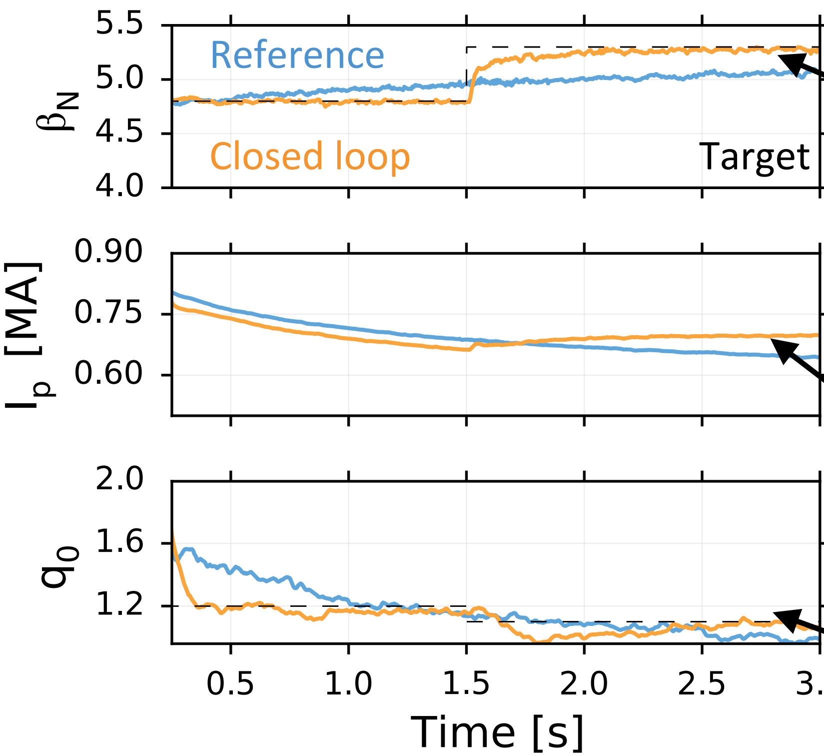
β_N and q_0 control with beam line 1 and outer gap improves response and tracks targets









- Power reduced for first β_N target, increased for second
- Outer gap decreased to speed q_0 response, increased to maintain elevated target
- Plasma current (not controlled) response varies from reference
- q_0 approaches 1 after target change (could adjust target trajectories or control gains)

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Simplified model used for rotation profile control design in NSTX-U [I. Goumiri]

- Using simplified form of toroidal momentum equation for design, profiles derived from TRANSP

Rotation

$$\sum_i n_i m_i \langle R^2 \rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \langle R^2 (\nabla \rho)^2 \rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}$$

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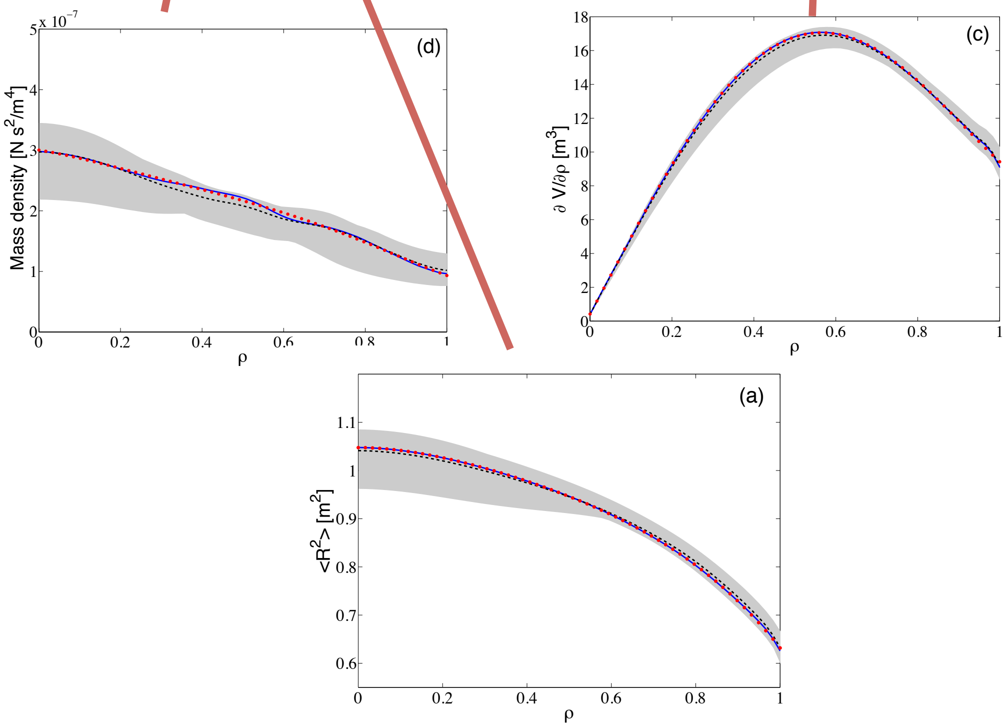

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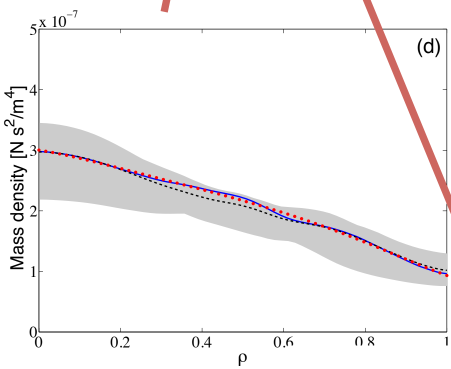
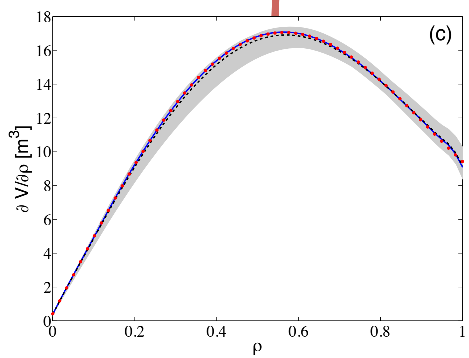
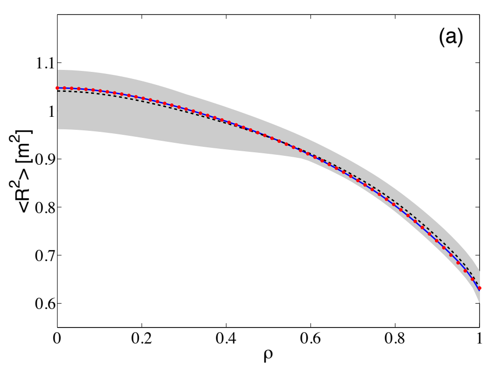
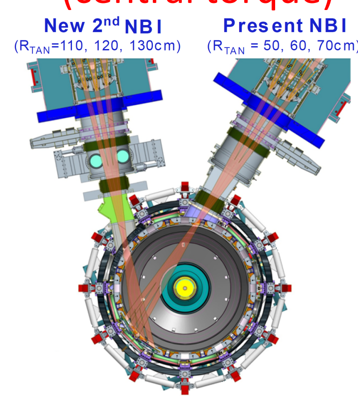






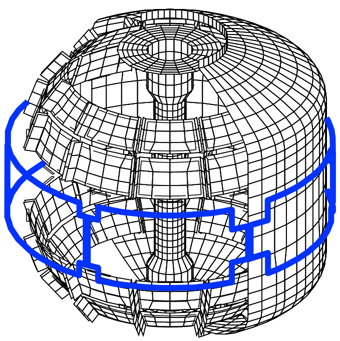
New NBI

(central torque)

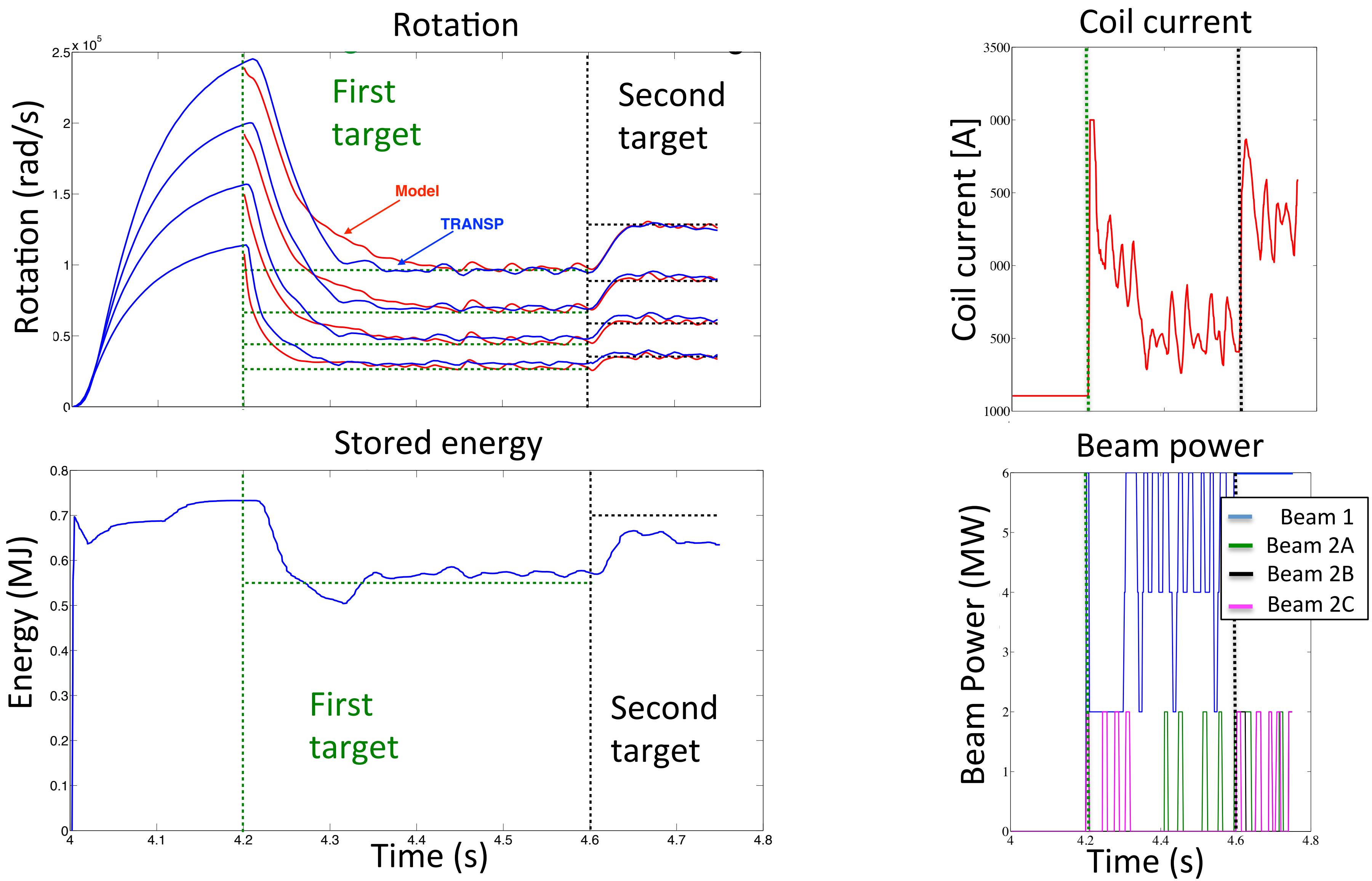


3D Field Coil

(edge torque)



State-space controller achieves good tracking in TRANSP simulations [I. Goumiri]



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Simplified current profile model used for feedback and feedforward control design

- Magnetic diffusion equation
  - Similar form to momentum diffusion equation
  - Enables similar modeling approach

$$\boxed{\frac{\partial\psi}{\partial t} = \frac{\eta(T_e)}{\mu_0\rho_b^2\hat{F}^2}\frac{1}{\hat{\rho}}\frac{\partial}{\partial\hat{\rho}}\left(\hat{\rho}D_\psi\frac{\partial\psi}{\partial\hat{\rho}}\right) + R_0\hat{H}\eta(T_e)\frac{<\bar{j}_{NI}\cdot\bar{B}>}{B_{\phi,0}},}$$

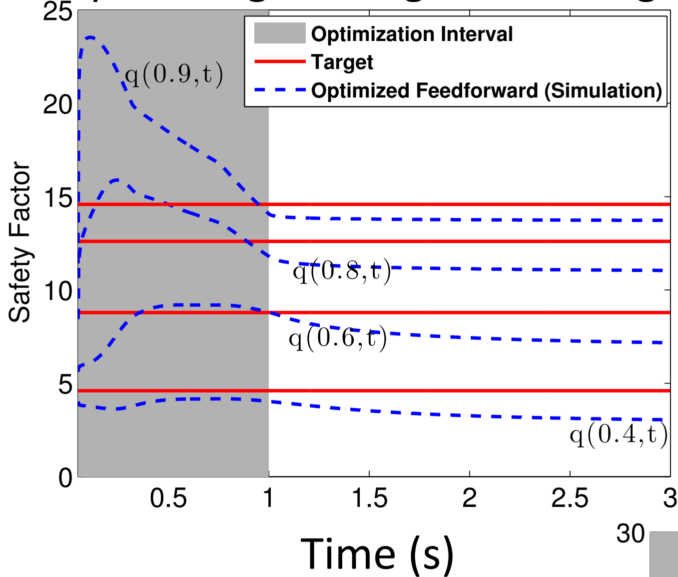
- Multiple actuators considered:
  - Loop voltage
  - Individual beam heating
  - Density
- Feedback controller for tracking and disturbance rejection designed and tested in TRANSP
- Feedforward control optimization based on reduced model

LEHIGH UNIVERSITY

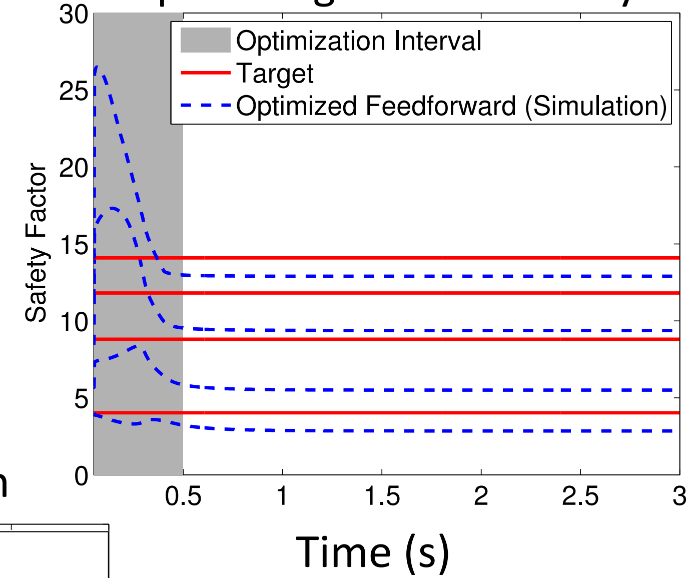
Z. Ilhan, W. Wehner, E. Schuster

Feedforward actuator trajectory optimization to match target q profile

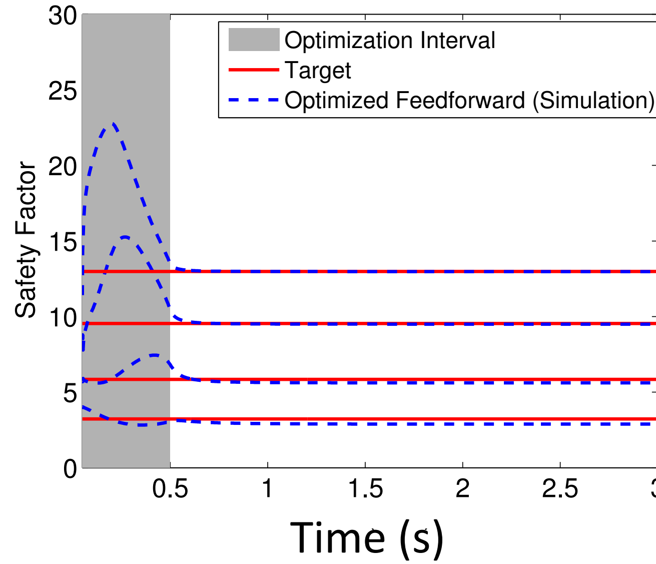
Optimizing for target matching



Optimizing for stationarity



Optimizing for both



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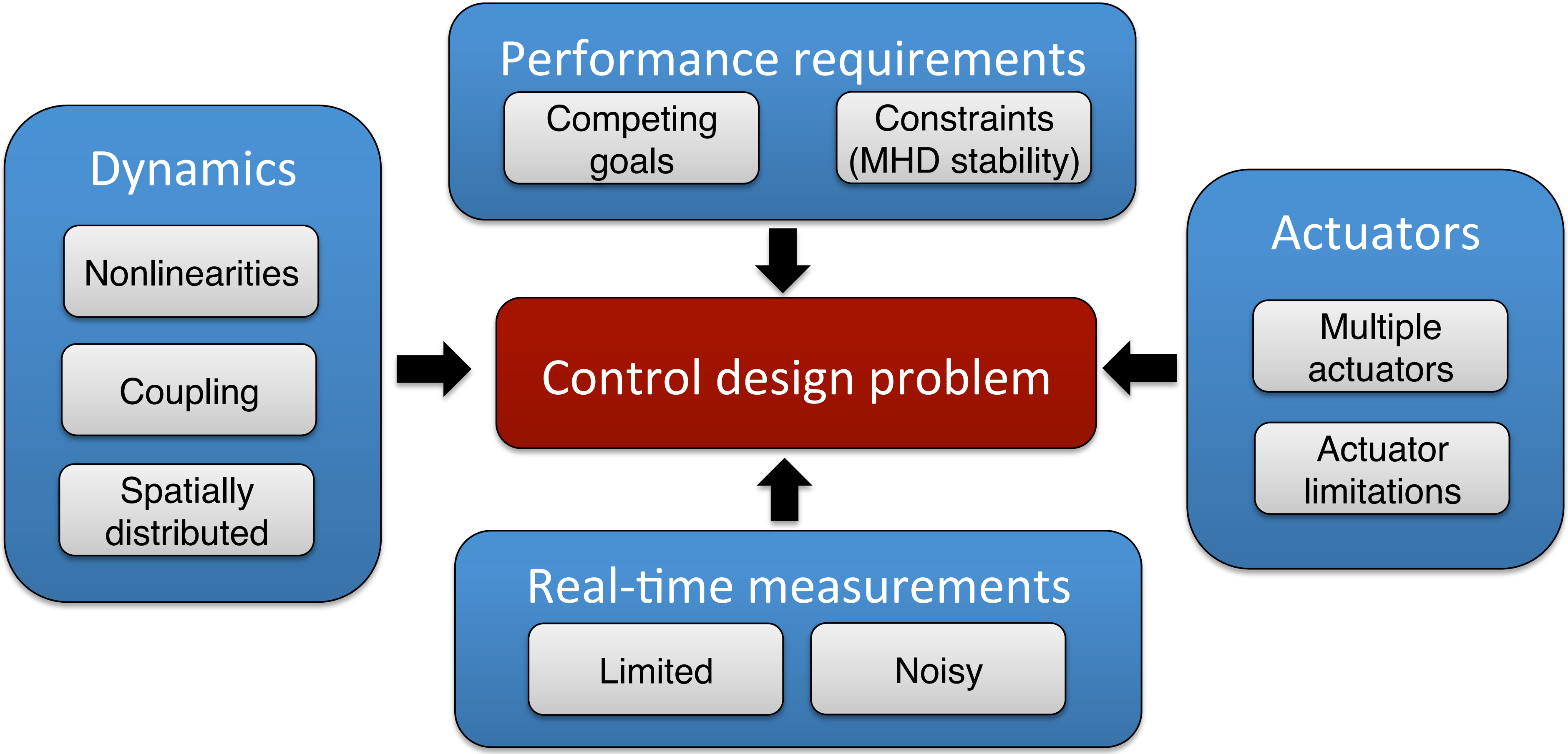
Z. Ilhan, W. Wehner, E. Schuster

Summary and future work

- Complexity of the control requirements for NSTX-U motivates use of model-based control
- A TRANSP framework for testing feedback controllers prior to experiments has been developed:
  - Generate and test control-oriented models
  - Test/tune feedback control algorithms
  - Test new algorithms, demonstrate new control approaches
- Future work
  - Test on NSTX-U!

Backup Slides

Feedback control of NSTX-U is a complex task but model-based design can help



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

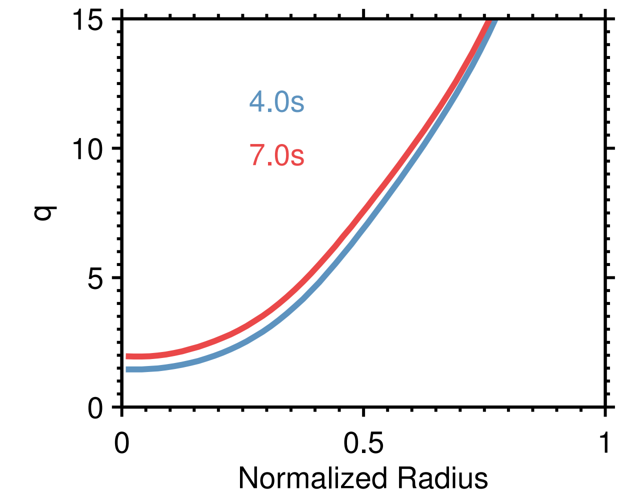
Modifications have been implemented using external code: the Expert file

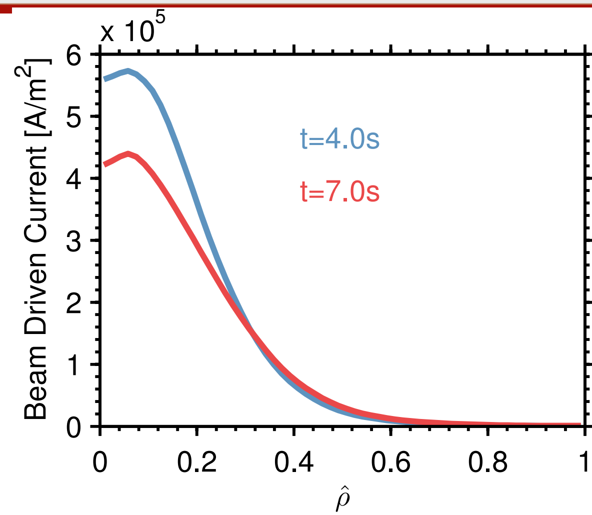
- Expert subroutine called at many places throughout TRANSP production code
- An identifier is passed along with the call
  - different snippets of code can be run at different points during the simulation
- Custom run-specific code can be run at each call to manipulate certain variables (which would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

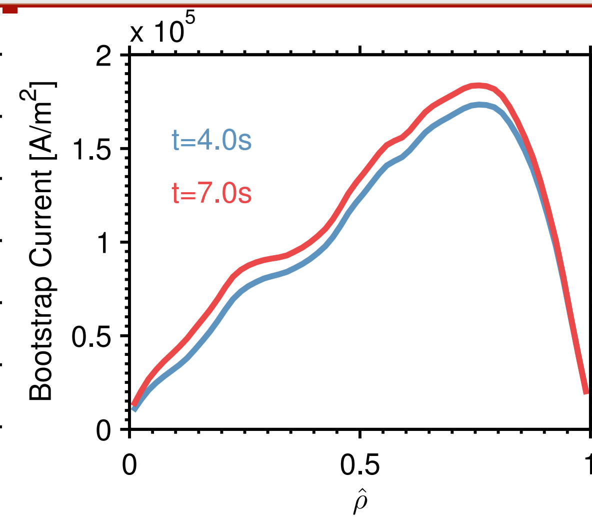
```
…
<TRANSP source code>

call expert(ID)

<more TRANSP code>
…
```

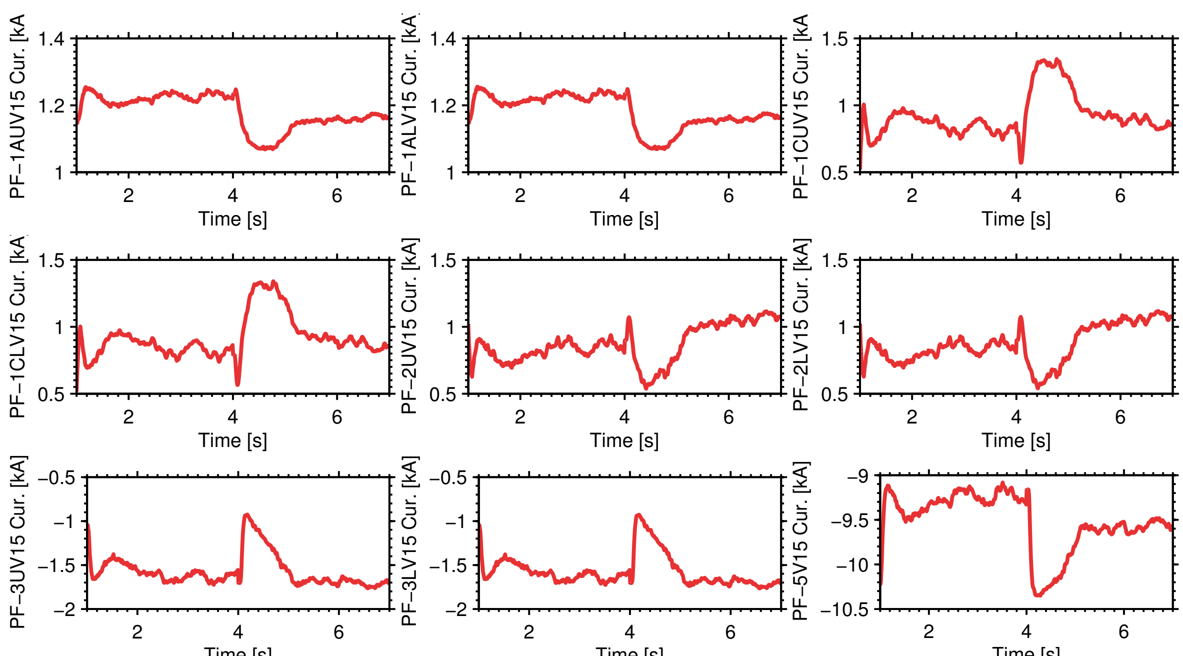
```
Subroutine expert(ID)

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

Profiles and coil currents during optimal controller simulation





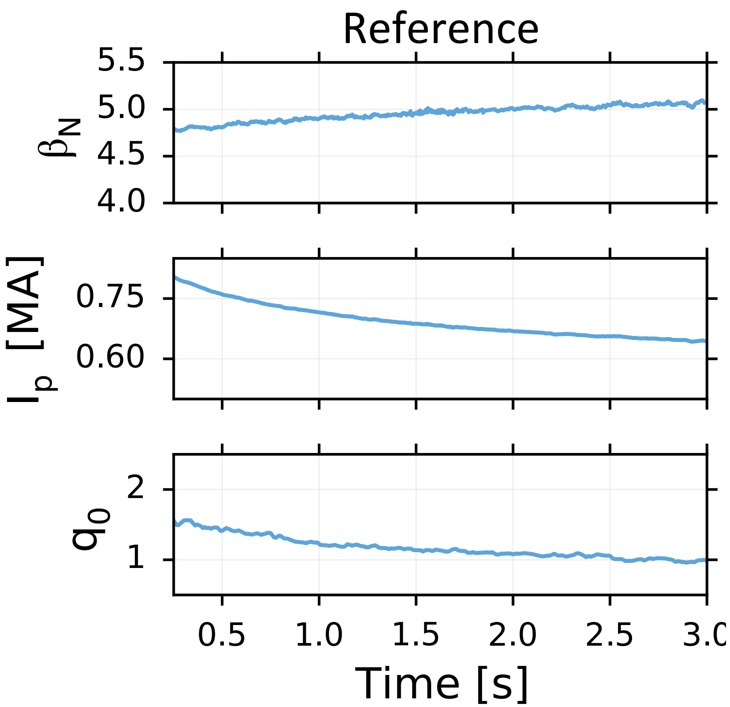


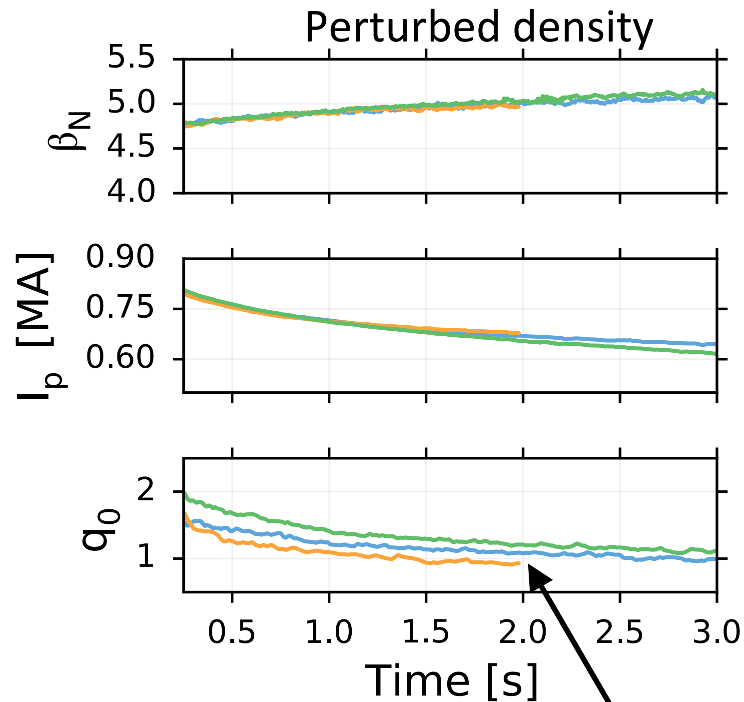


- 7s: change in outer gap shifts q_0 up
  - Less peaked NBCD
  - Increased bootstrap cur.
- Coil currents appear physically achievable

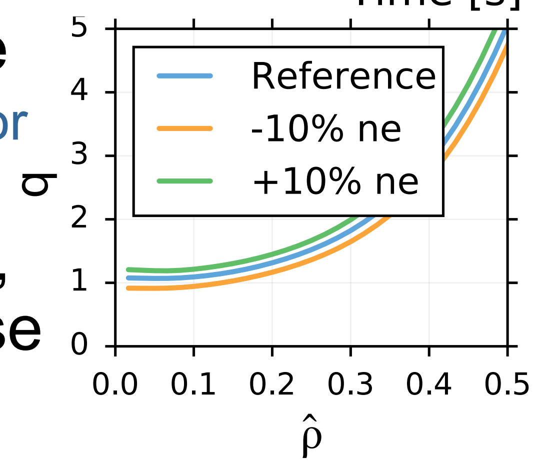
Reference simulation w/ fixed OH current: slow response, sensitivity to disturbances

- **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



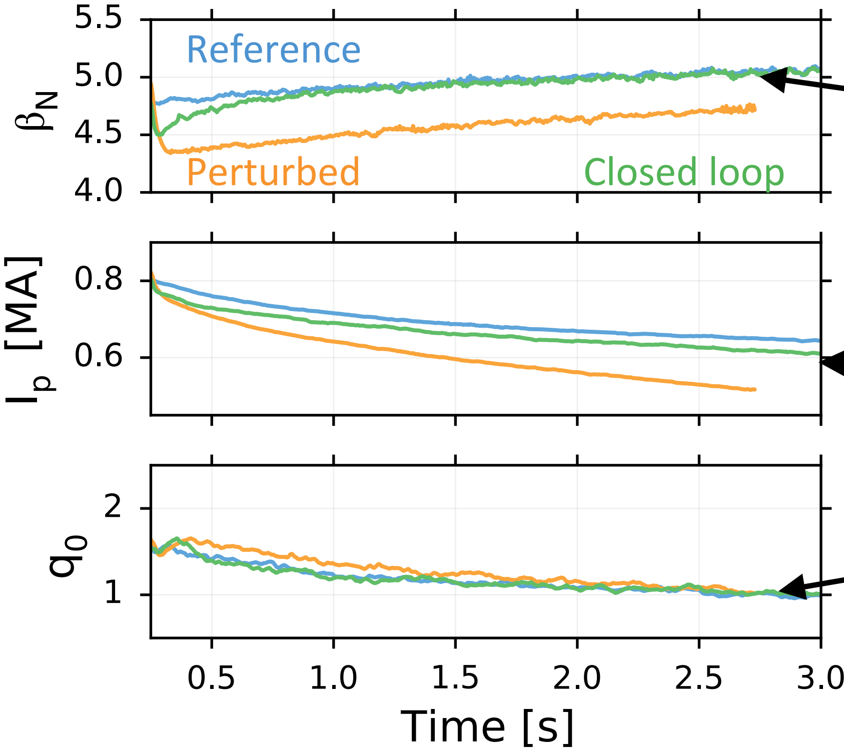


- Slow evolution to 100% non-inductive
  - Can feedback control speed up response or track different targets?
- Perturbations in density, confinement, and profile shapes can affect response
  - Can feedback recover performance?

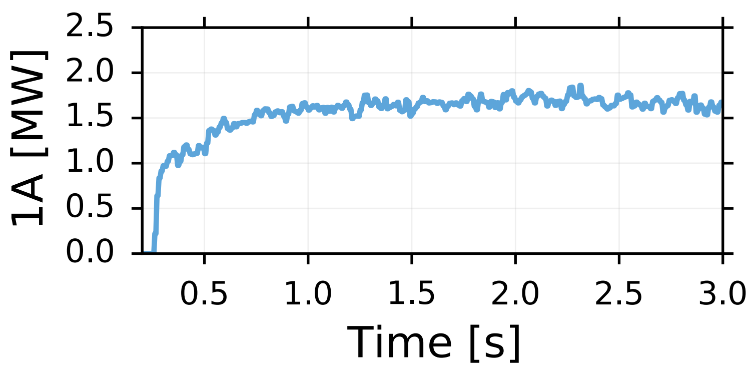


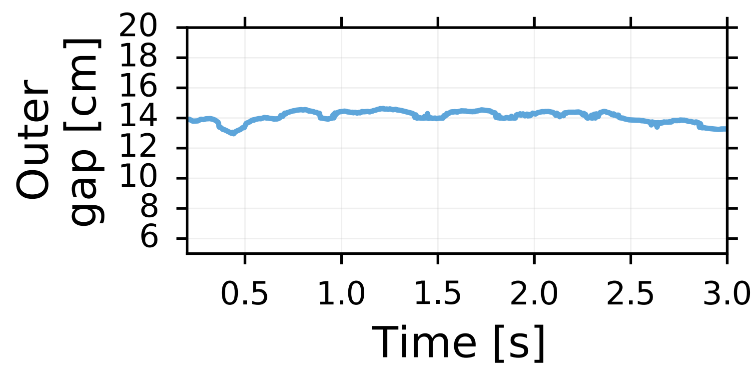
$q_0 < 1$ earlier with lower density

β_N and q_0 feedback using beam line 1 and outer gap control during confinement pert.



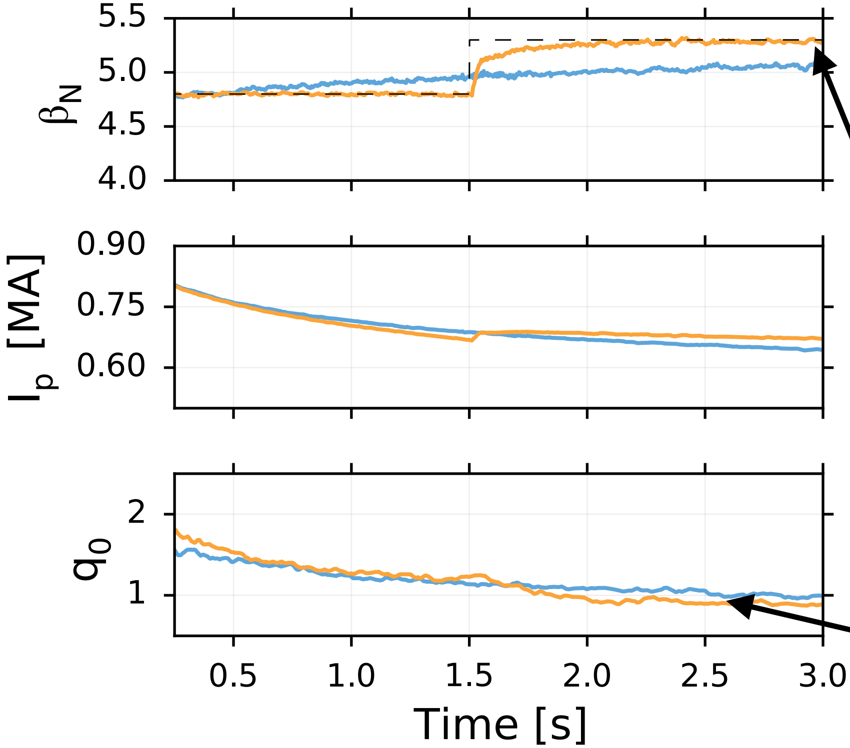
- Beam line 1 power increased to track reference β_N
- Increasing beam power and β_N leads to increased current
  - Reference current nearly recovered despite no feedback control on current
- Outer gap adjusted to maintain q_0



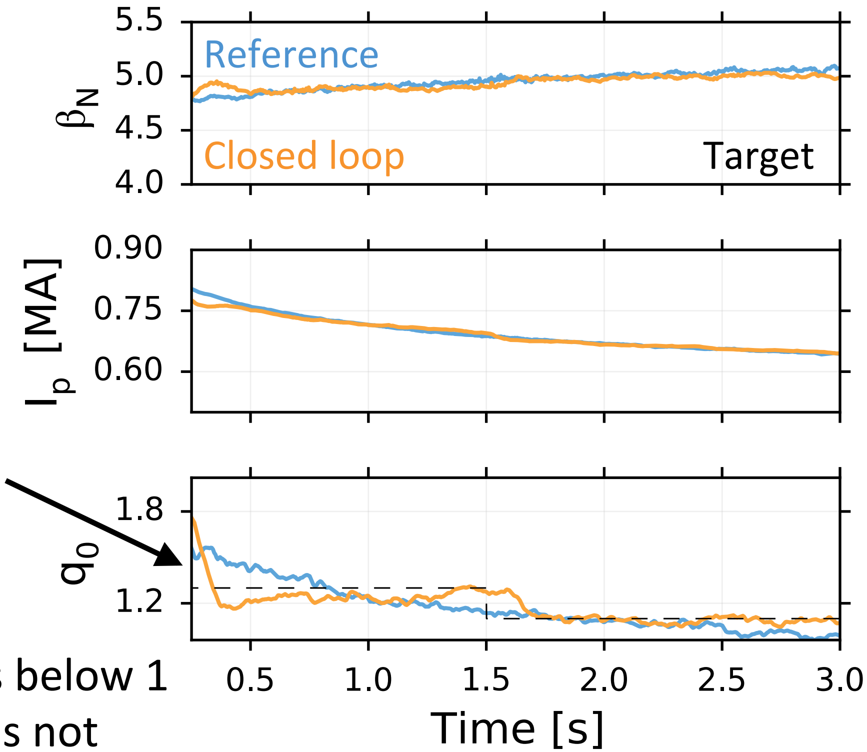


Target tracking

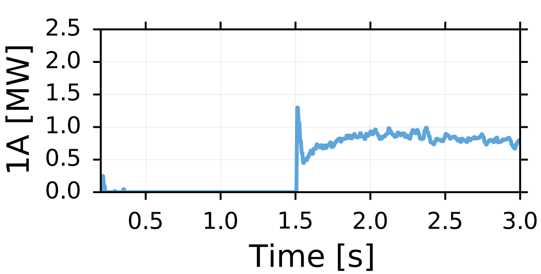
Left: β_N control w/ beam line 1
Right: q_0 control w/ outer gap

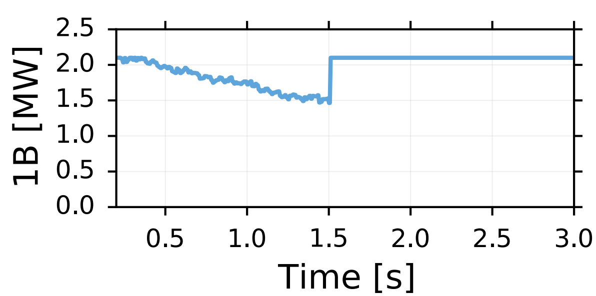


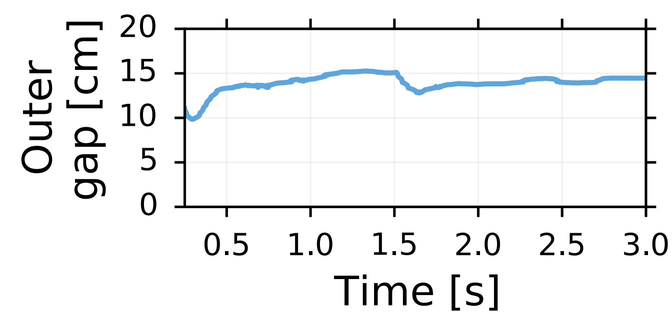
Targets tracked in both cases



q_0 drops below 1 since it is not controlled







Feedforward actuatory trajectory optimization

- **Objective:** Design the actuator trajectories that can steer the plasma to a target state characterized by the safety factor profile $q^{tar}(\hat{\rho}, t_f)$ or rotational transform profile $\iota^{tar}(\hat{\rho}, t_f)$ at a specified time t_f during the discharge such that the achieved plasma state is as stationary in time as possible.
- **Cost functional** defined as:

$$\boxed{J(t_f) = k_q J_q(t_f) + k_{ss} J_{ss}(t_f)}$$

where k_{ss} and k_q are the weight factors representing the relative importance of the plasma state characteristics and

$$J_q(t_f) = \int_0^1 W_q(\hat{\rho}) \left[q^{tar}(\hat{\rho}) - q(\hat{\rho}, t_f)\right]^2 d\hat{\rho} \quad (7)$$

$$J_{ss}(t_f) = \int_0^1 W_{ss}(\hat{\rho}) \left[g_{ss}(\hat{\rho}, t_f)\right]^2 d\hat{\rho}, \quad (8)$$

where $W_q(\hat{\rho})$ and $W_{ss}(\hat{\rho})$ are positive weight functions and

$$g_{ss}(\hat{\rho}, t) = \frac{\partial U_p}{\partial \hat{\rho}} = -\frac{\partial \Psi}{\partial t} = -2\pi \frac{\partial \psi}{\partial t}, \quad (9)$$

where U_p is the loop-voltage profile which can be related to the temporal derivative of the poloidal magnetic flux.