NSTX-U

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A framework for control simulations using the TRANSP code

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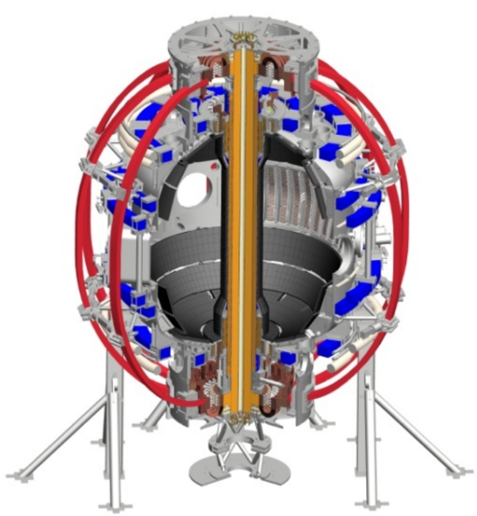

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Overview

- A framework for performing **feedback control simulations** in the **TRANSP** integrated modeling code has been developed
- Control design typically relies on **reduced models** of system dynamics
  - Additional complexity of the actual system could degrade performance when tested experimentally
- Proposed framework enables **testing** of control algorithms on a high-fidelity model **prior to experimental implementation**
- The framework is demonstrated by testing
  - β_N control through modulation of total beam power
  - q_0 and β_N control through modulation of total beam power and the plasma boundary shape

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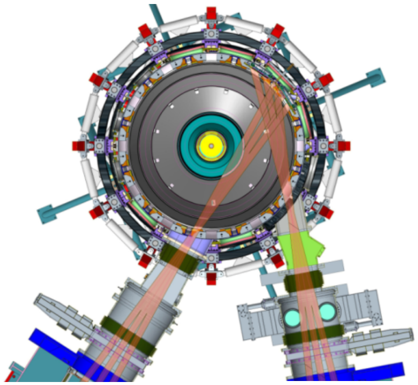
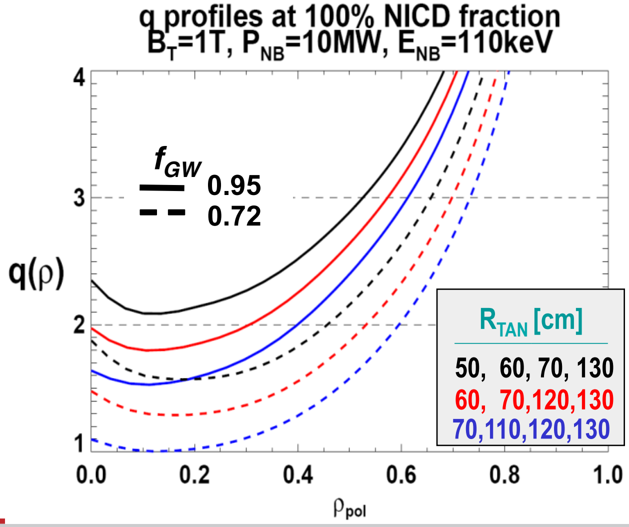
NSTX-U improves controllability and brings about new control requirements

- **New opportunities** to use feedback control to optimize performance as a result of:
  - Longer pulse length, increased toroidal field, increased heating and current drive
- **Advanced control** will be **necessary** for achieving many operational goals, e.g.,
  - **Non-inductive scenarios, snowflake divertor, rotation control, current profile control**



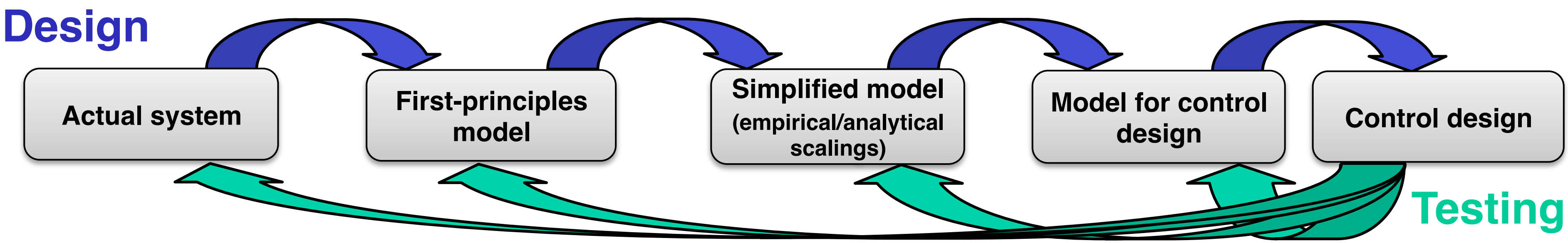
Present NBI   New 2nd NBI

- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position



The need for high-fidelity control simulations

- 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

TRANSP has been used previously for NSTX-U predictive simulations (open loop)

- The computational approach used in this work is based on NSTX-U steady-state **scenario development**
  - **S. Gerhardt (*Nuclear Fusion* 2012)**
  - T_i profile predicted from Chang-Hinton model
  - MHD equilibrium calculated using **free boundary code ISOLVER**
  - Beam heating and current drive profiles calculated using **NUBEAM** with beam shielding calculated by Lin-Liu and Hinton model
  - Sauter model used for bootstrap current
  - T_e, n_e profile shapes and scale factors **prescribed prior to simulation** runs
    - Scale factors **scanned during several runs** to achieve desired H98 and Greenwald fraction
  - Z_{eff} prescribed, used to calculate n_i assuming carbon as the only impurity

Modifications to the previous approach are necessary to perform control simulations

1. Ability to change actuators in `real-time', i.e., feedback
   - Focus has been on actuators used for current/rotation profile control so far, but others will be added in the future
   - Beam powers, density, total plasma current, NTV (see poster by I. Goumiri, Princeton U.), plasma boundary shape
2. Electron temperature and density no longer *a priori* inputs
   - Interested in transient behavior unlike previous scans of steady state
   - Temperature should change based on confinement as beam powers are modified
3. An analog to the plasma control system (PCS) is needed
   - To perform control calculations, allow targets and gain waveforms to be loaded, etc.
   - To mimic the beam modulation algorithms used to modify heating power in the actual experiment

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
…
```

Temperature is set based on stored energy predicted by confinement scaling expressions

- At each TRANSP step (from time t_a to t_b), stored energy predicted by

$$W_{th,b} = W_{th,a} + (t_b - t_a)\left(-\frac{W_{th,a}}{\tau_E} + P_{net}\right),$$

  - Confinement based on scaling (either ITER98 or ST scaling)
  - P_{net} and scaling law parameters from TRANSP internal variables

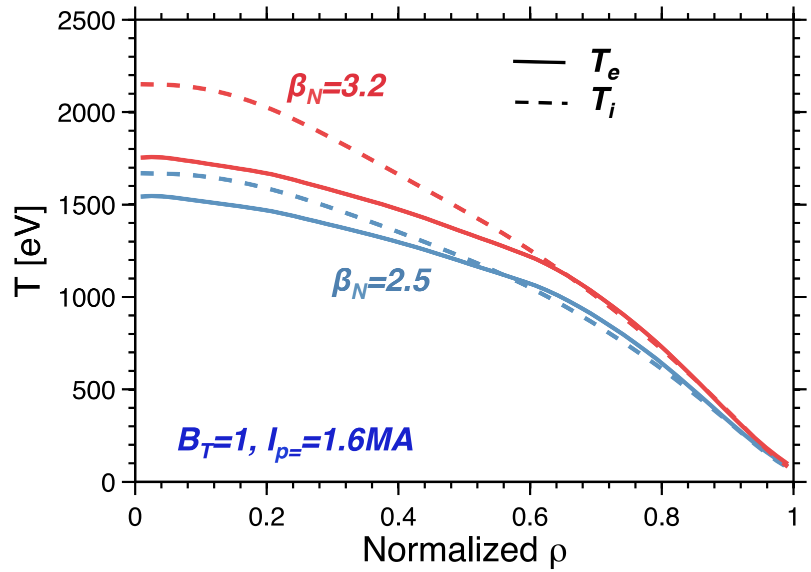
- Electron temperature assumed to be of the form

$$T_e(\hat{\rho}, t) = T_{e,0}(t) T_e^{ref}(\hat{\rho})$$

  - Scale factor calculated as

$$T_{e,0} = \frac{\frac{2}{3}\langle E_{th}\rangle - \langle n_i T_i\rangle}{\langle n_e T_e^{ref}\rangle}$$

$$\langle E_{th}\rangle = \frac{W_{th}}{V} = \frac{3}{2}\left[T_{e,0}\langle n_e T_e^{ref}\rangle + \langle n_i T_i\rangle\right].$$



Line-averaged electron density or Greenwald fraction requests can be tracked

- Density assumed to be of the form

$$n_e(\hat{\rho},t) = n_{e,0}(t)n_e^{ref}(\hat{\rho})$$

- A simple model is used to evolve the electron inventory N at each TRANSP transport time step (from time t_a to t_b)

$$N_b = N_a + (t_b - t_a)(N^{req} - N_a)/\tau_N$$

- N^{req} prescribed by controller or calculated from requested line-averaged density or Greenwald fraction f_{GW}:

Controller output y_c = inventory:

$$N^{req} = y_c$$

y_c = line-averaged density:

$$N^{req} = y_c \frac{N^{ref}}{\bar{n}_e^{ref}}$$

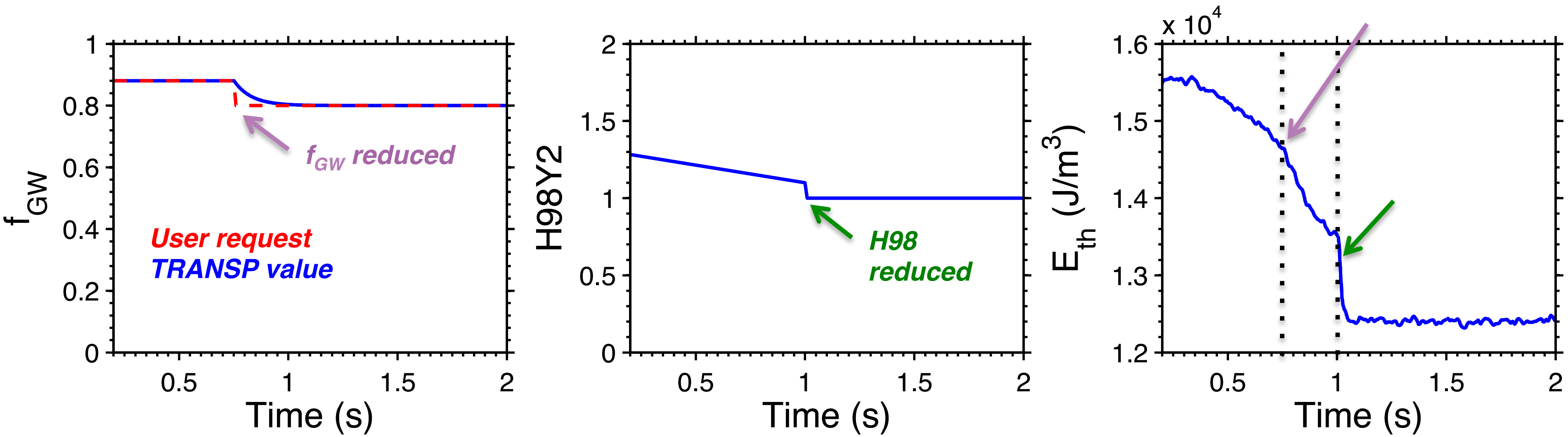
$y_c = f_{GW}$:

$$N^{req} = \frac{y_c I_p}{10\pi a^2} \frac{N^{ref}}{\bar{n}_e^{ref}}$$

- Profile scale factor calculated from the predicted inventory as

$$n_{e,0} = \frac{N}{\int_0^1 n_e^{ref} \frac{\partial V}{\partial \hat{\rho}} d\hat{\rho}}.$$

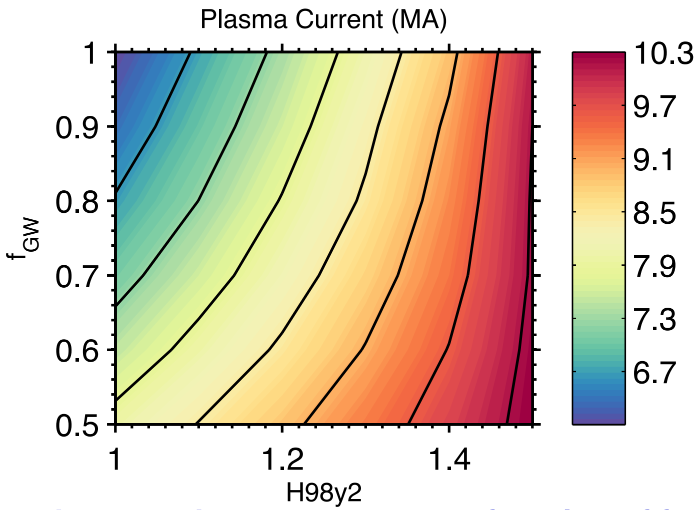
The added capabilities can be used to constrain simulations to match a desired time-varying f_{GW} and H_{98}



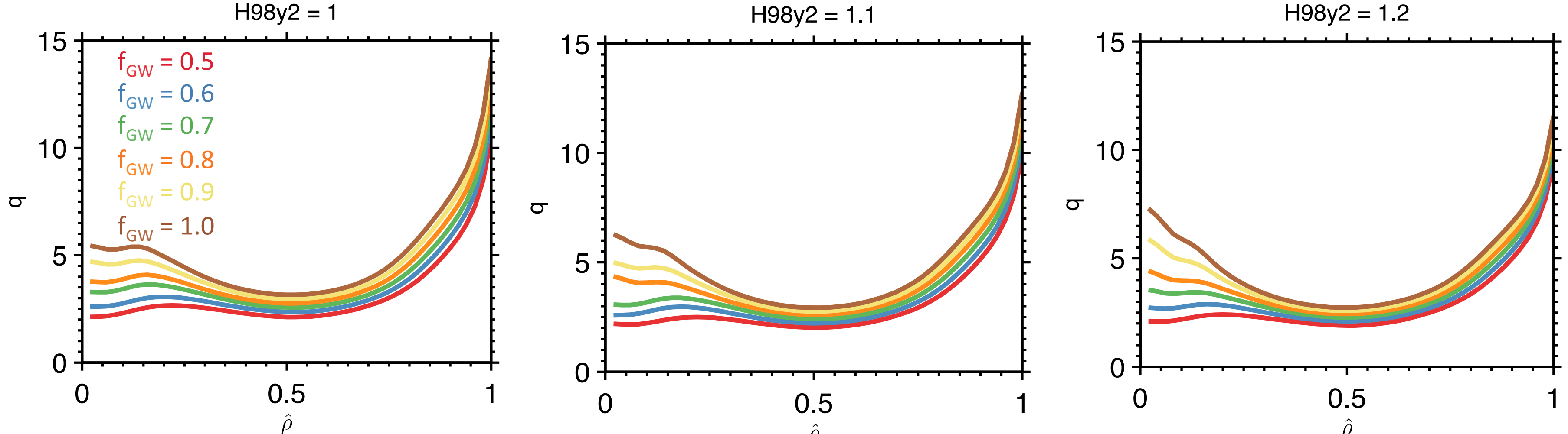
- Greenwald fraction request decreased at 0.75s
  - TRANSP modifies the density (on an appropriate time scale for density changes) to achieve the request
- H98 request ramped down until 1.0s, step at 1.0s
- Stored energy prediction responds to f_{GW} and h_{98}
  - drops slowly as H_{98} ramps down (0.0-0.75s), and faster as the density is decreased
  - Step change in H_{98} causes a large drop in stored energy

Implemented density and energy constraints are necessary for control testing, but also useful for scenario development

- Ongoing work, scanning f_{GW} and H_{98} values for FNSF-ST
  - Assess effect of assumptions on fully non-inductive operating points
  - Determine optimal neutral beam tangency radii
  - Study controllability
- To be used in non-inductive ramp-up simulations for NSTX-U
  - see poster by F. Poli



Steady-state plasma current as a function of f_{GW} and H_{98} for a particular beam configuration on FNSF-ST.

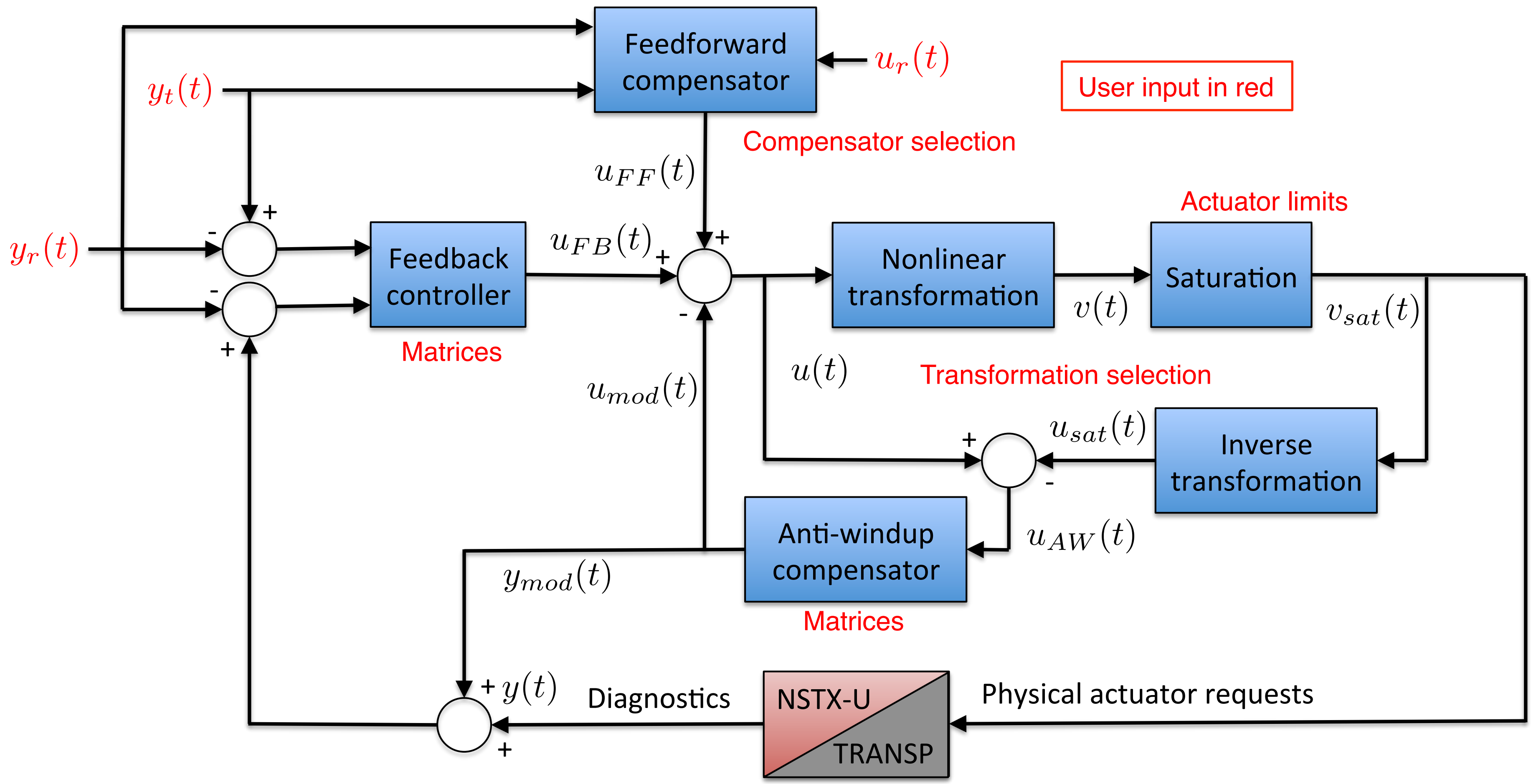


Steady-state q profile as a function of f_{GW} and H_{98} for a particular beam configuration on FNSF-ST.

A general controller structure has been implemented

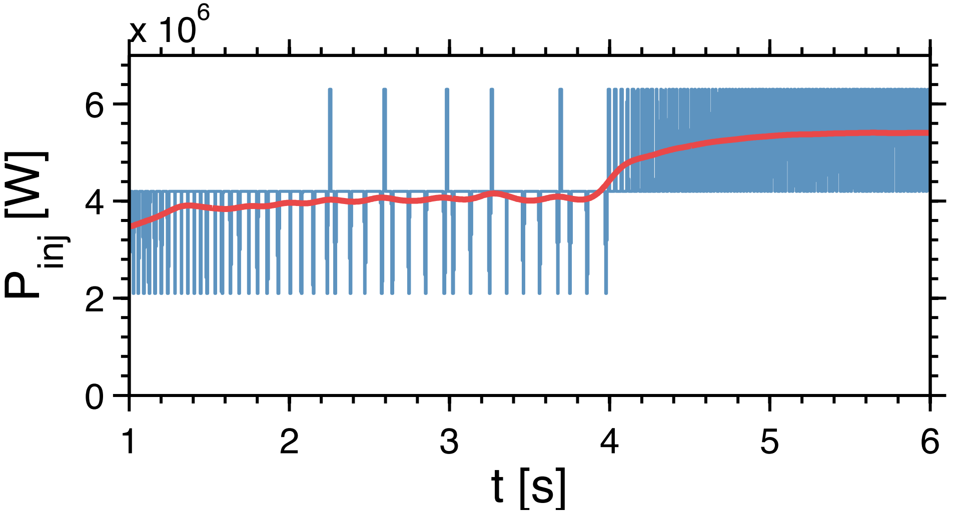
- General **feedback controller** implemented as a **state-space system**
  - Additional run-specific **nonlinear transformation** of the outputs
- **Saturation** included to respect **physical actuator constraints**
- **Anti-windup** system calculates an adjustment to the controller input/output
  - Helps ensures closed-loop system is well-behaved in presence of actuator saturation
- **Feedforward compensator** can be used to predict the actuator response
  - Helps handle changes in target waveforms and measured disturbances
- Input text file used to load gain matrices, targets, and references
  - Allows different designs to be tested without altering code

Controller implementation diagram



Beam power modulation algorithms planned for NSTX-U have been implemented in TRANSP simulations

- Enables assessment of modulation's effect on performance
  - Results can help determine optimal modulation parameters (minimum on/off times) and control gains to achieve desired levels of performance
- Alg. #1: Individual power control
  - **Duty cycle** of each beam is determined from the power of each beam and the **individual power requests from the controller**
  - **Modulation status** (on/off) of each beam chosen to achieve duty cycle while respecting **minimum on/off times** and **maximum number of modulations per shot**
- Alg. #2: Total power control
  - A `**batting order**' is used to determine which beams should be on, which should be off, and which one should be modulated



TRANSP testing of β_N feedback control design

β_N dynamics can be written as

$$\dot{\beta}_N = \frac{400a\mu_0}{3I_pB_TV}\left(-\frac{W}{\tau_E}+P_{net}\right)+\frac{400\mu_0 W}{3I_pB_TV}\dot{a} - \frac{400a\mu_0 W}{3I_pB_TV^2}\dot{V} - \frac{400a\mu_0 W}{3I_pB_T^2V}\dot{B}_T - \frac{400a\mu_0 W}{3I_p^2B_TV}\dot{I}_p$$

Assume $P_{net} \approx P_{inj}$ and define $u = \frac{400a\mu_0}{3I_pB_TV}P_{inj}$

to write $$\dot{\beta}_N = -\frac{\beta_N}{\tau_E} + u + d.$$

Considering a desired reference evolution:

$$\dot{\beta}_{N,ff} = -\frac{\beta_{N,ff}}{\tau_{E,ff}} + u_{ff} + d_{ff}$$

dynamics of deviations can be written as

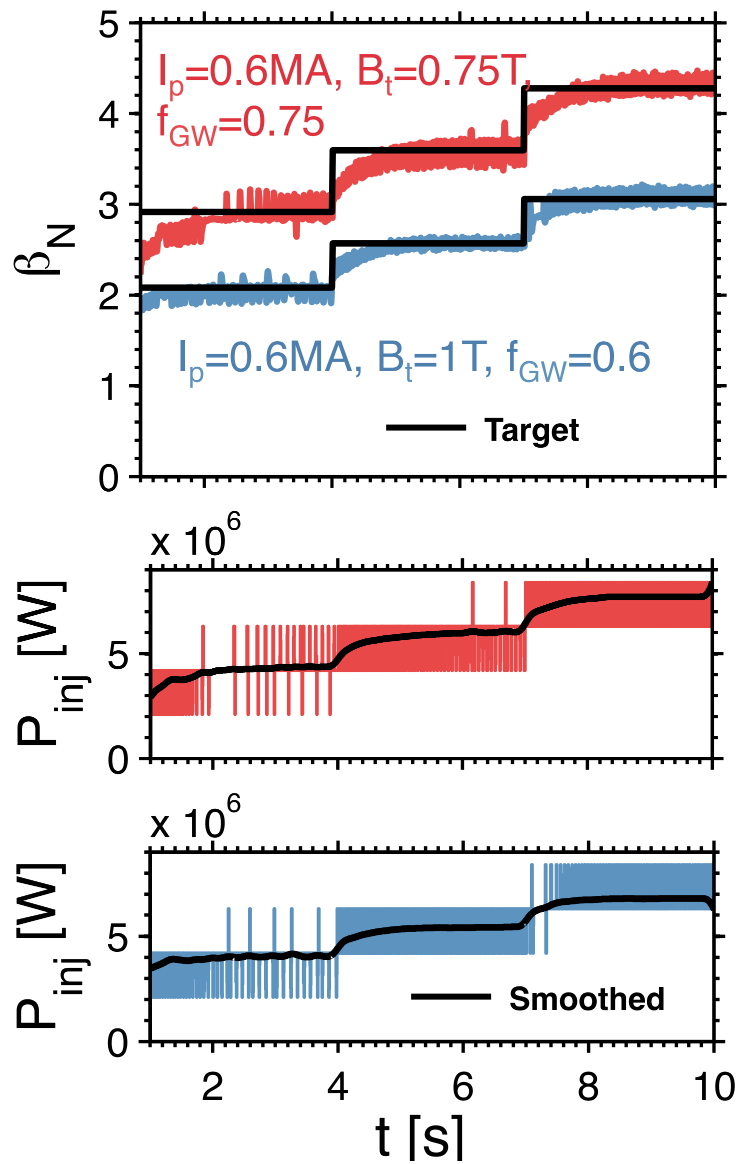
$$\begin{aligned}\dot{\tilde{\beta}}_N &= -\theta\beta_N + u + d + \theta_{ff}\beta_{N,ff} - u_{ff} - d_{ff} \\ &= -\theta\tilde{\beta}_N - \tilde{\theta}\beta_{N,ff} + \tilde{u} + \tilde{d},\end{aligned}$$ where $\theta = \frac{1}{\tau_E}$

Stabilizing controller can be chosen as

$$\tilde{u} = -\tilde{d} + \tilde{\theta}\beta_{N,ff} - K_{P,\beta}\tilde{\beta}_N - K_{I,\beta}\int_0^t \tilde{\beta}_N d\tau$$

Reject measured disturbances ($-\tilde{d} + \tilde{\theta}\beta_{N,ff}$)

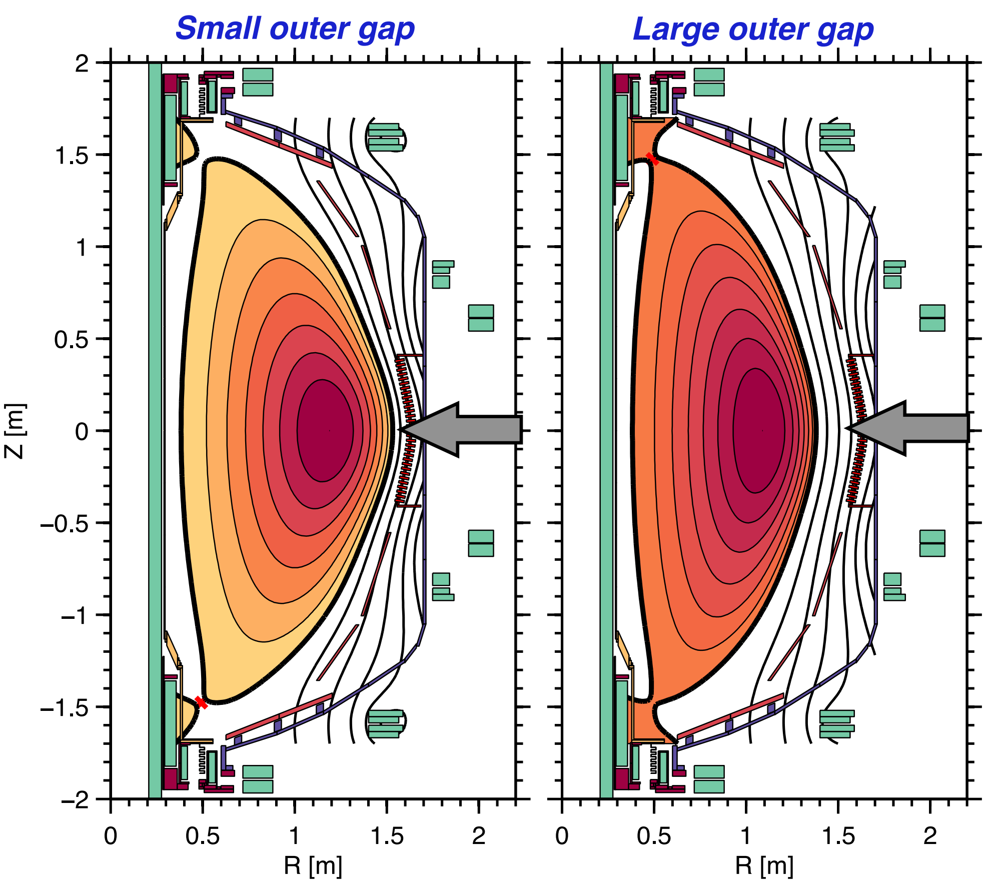
PI controller ($- K_{P,\beta}\tilde{\beta}_N - K_{I,\beta}\int_0^t \tilde{\beta}_N d\tau$)



TRANSP testing of simultaneous q_0 and β_N control via beam power and outer gap size

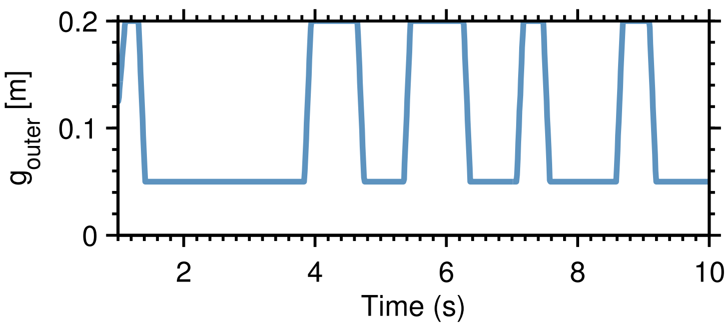
- Most approaches to current profile control **assume the plasma boundary to be held fixed** by a shape controller
- Boundary can have strong effect on q profile through
  - Effect on **beam deposition** profile
  - Effect on **bootstrap current** through change in elongation
- Here we explore **using the plasma outer gap** and **total beam power** as manipulated variables **to control q0 and β_N** simultaneously
- Two **reference boundaries** with different outer gap sizes were chosen, and **interpolated between** based on the feedback controller request

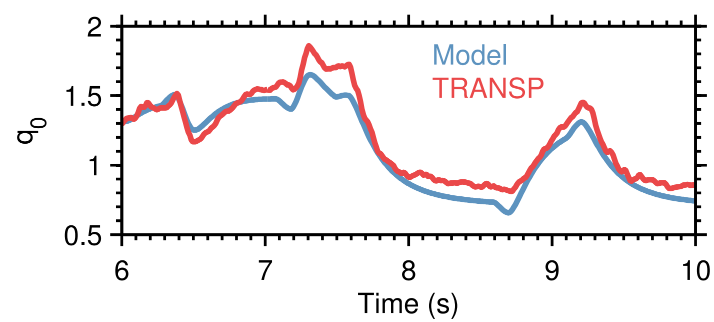
Reference plasma boundaries:

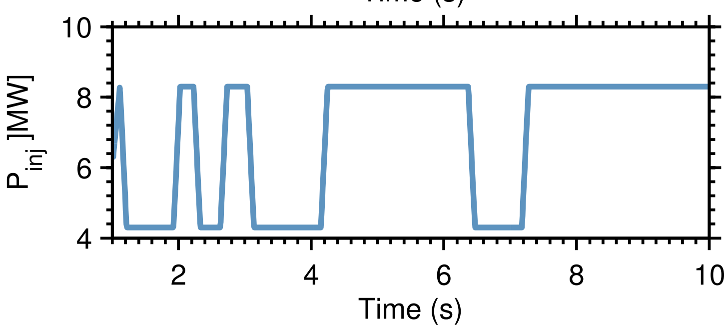


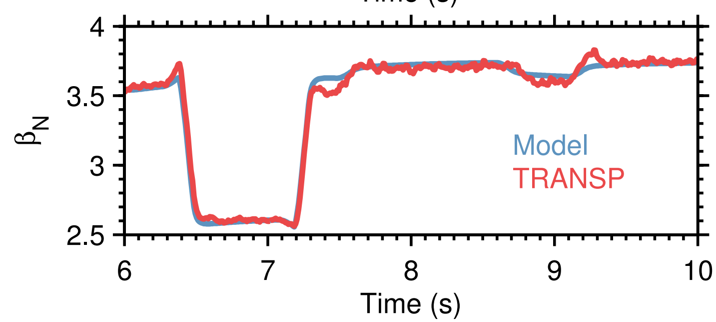
State-space system identification for simultaneous q_0 and β_N control

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









LQG servo controller designed for identified system

- Solves the **optimal control problem** of minimizing the cost function

$$J = E\left\{ \lim_{\tau\to\infty} \int_0^\tau \left(\left[\tilde{x}^T, u_{fb}^T\right] Q_{xu} \begin{bmatrix} \tilde{x} \\ u_{fb} \end{bmatrix} + x_i^T Q_i x_i \right) dt \right\},$$

  for the system

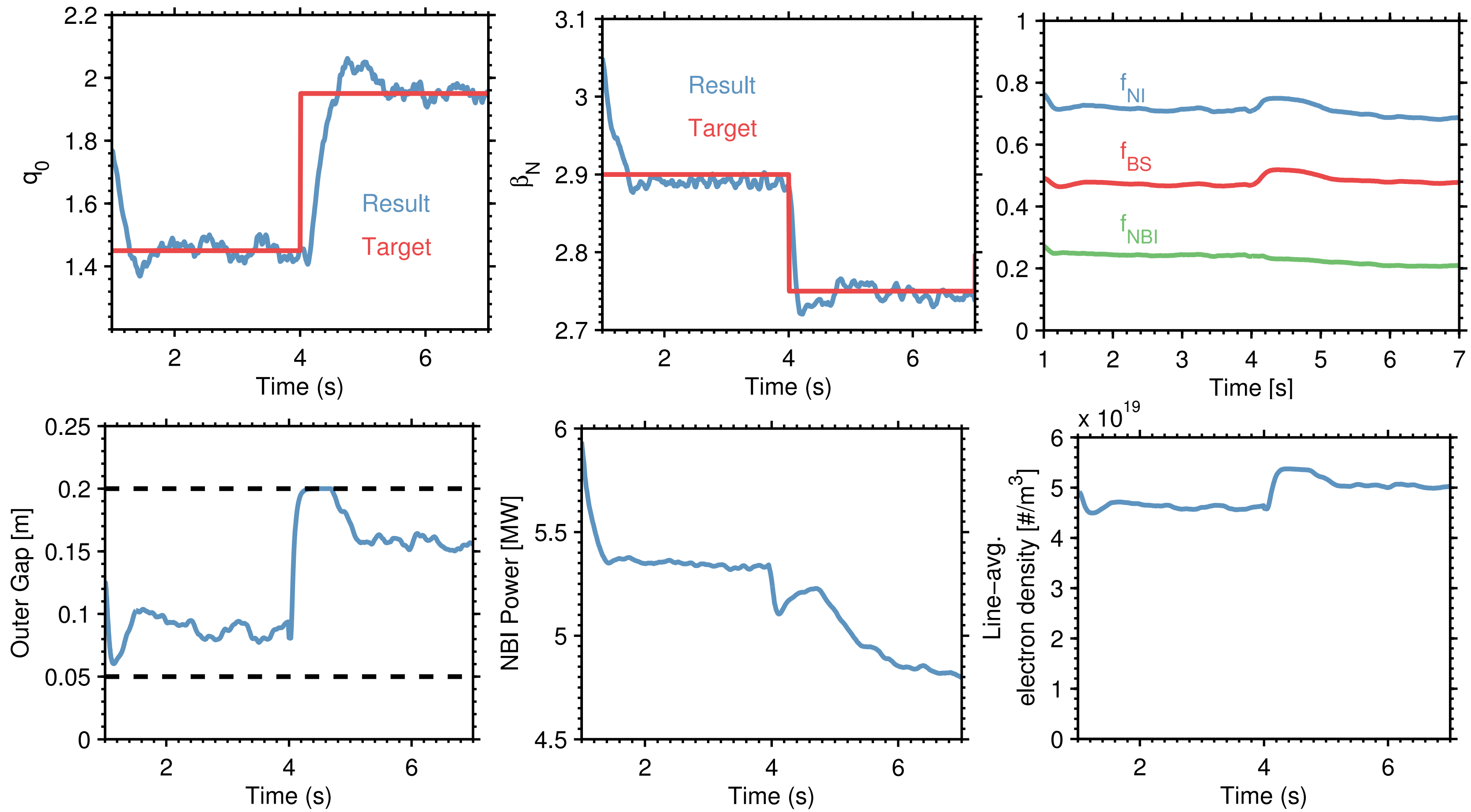
$$\dot{\tilde{x}} = A\tilde{x} + Bu_{fb} + w,$$
$$\tilde{y} = C\tilde{x} + Du_{fb} + v,$$

  where Q_{xu} is a weight matrix for the states and inputs,

  and Q_i weights the integral of the output tracking error x_i

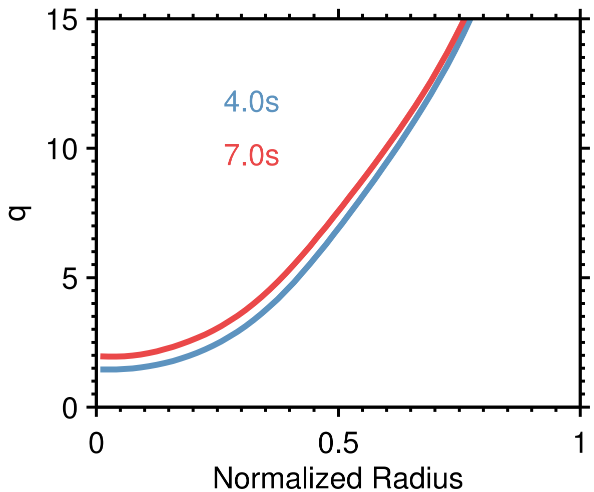
- Since the states of the identified model are not measured, they are estimated by a **Kalman filter**
  - Tuned based on expected process and measurement noise (w, v)
- **Integral action** ensures steady-state error is driven to zero in the presence of disturbances or target tracking

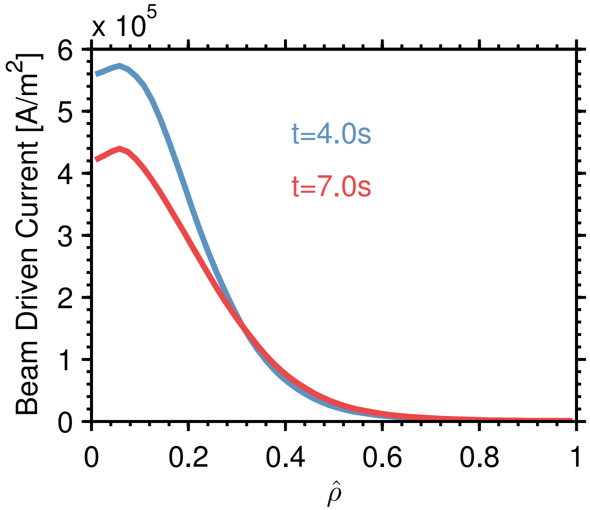
Optimal controller achieves good target tracking performance in TRANSP simulation testing

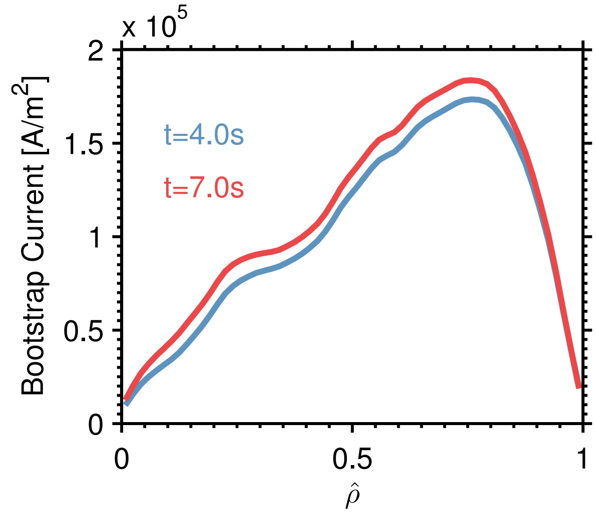


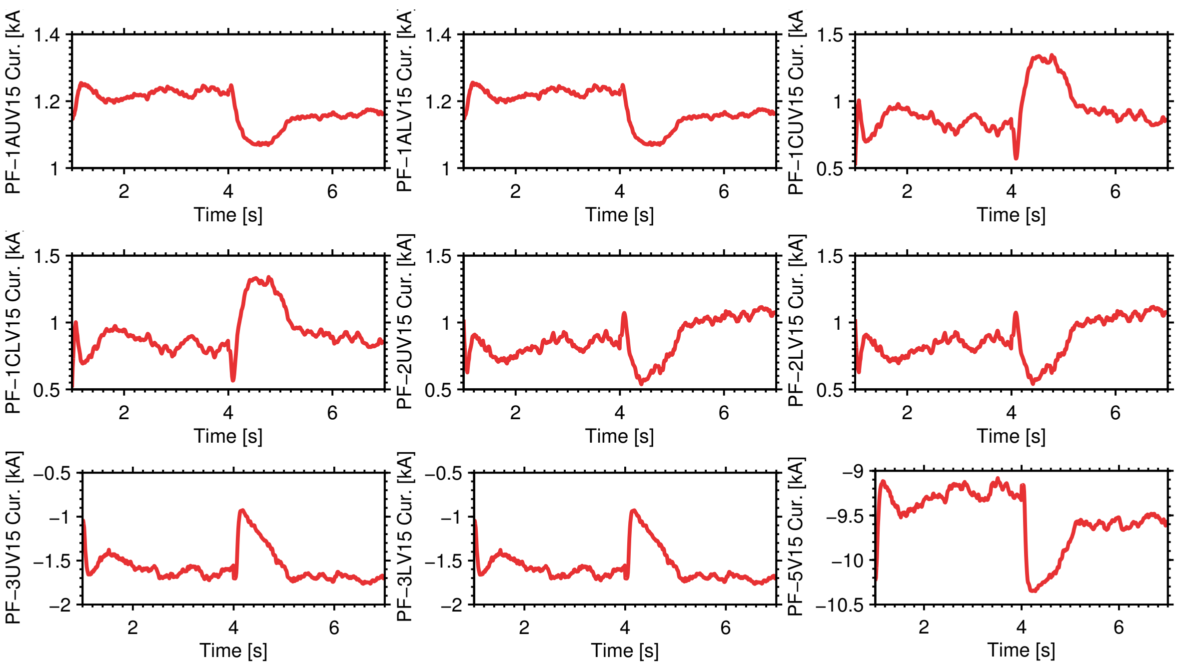
- Outer gap saturated at 4s, but performance is still good
- Small change in non-inductive fraction, line-average density increased due to decrease in volume at fixed particle inventory

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

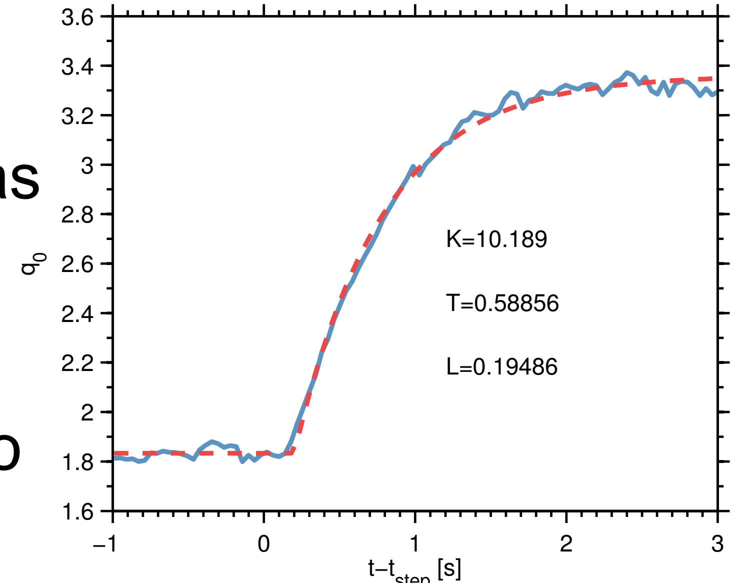
Difference in time scales and weak coupling motivates testing a two loop control structure

- Two PID loops: beam control of β_N, outer gap control of q_0
  - Intuitive, easier to retune during operation
  - β_N controller described earlier (p. 15)
- To tune q_0 gains, dynamics modeled as

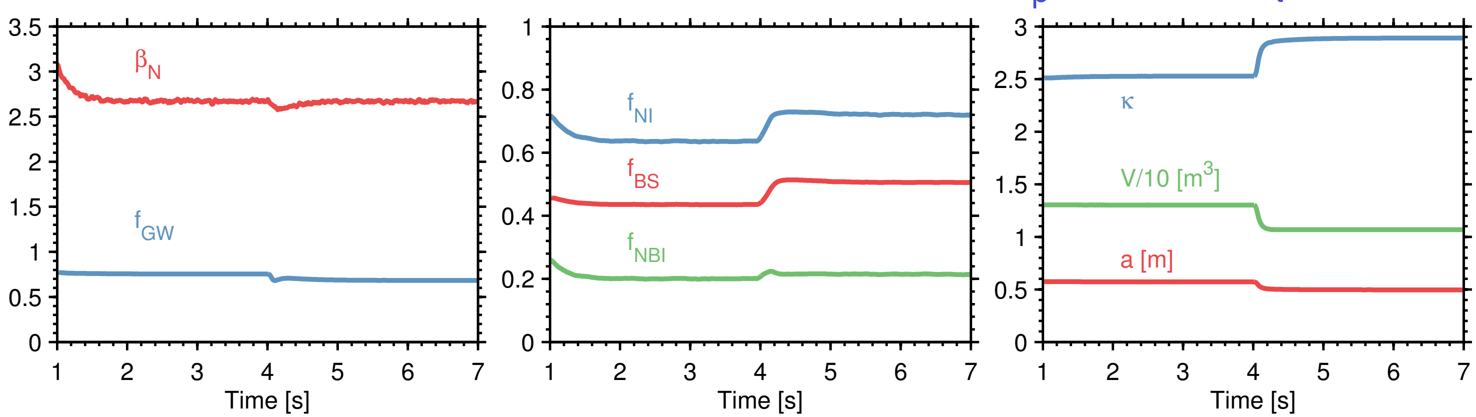
$$\dot{y}(t) = -\frac{y(t) + Ku(t-L)}{T}$$

K - static gain, *T* - time constant, *L* - dead time

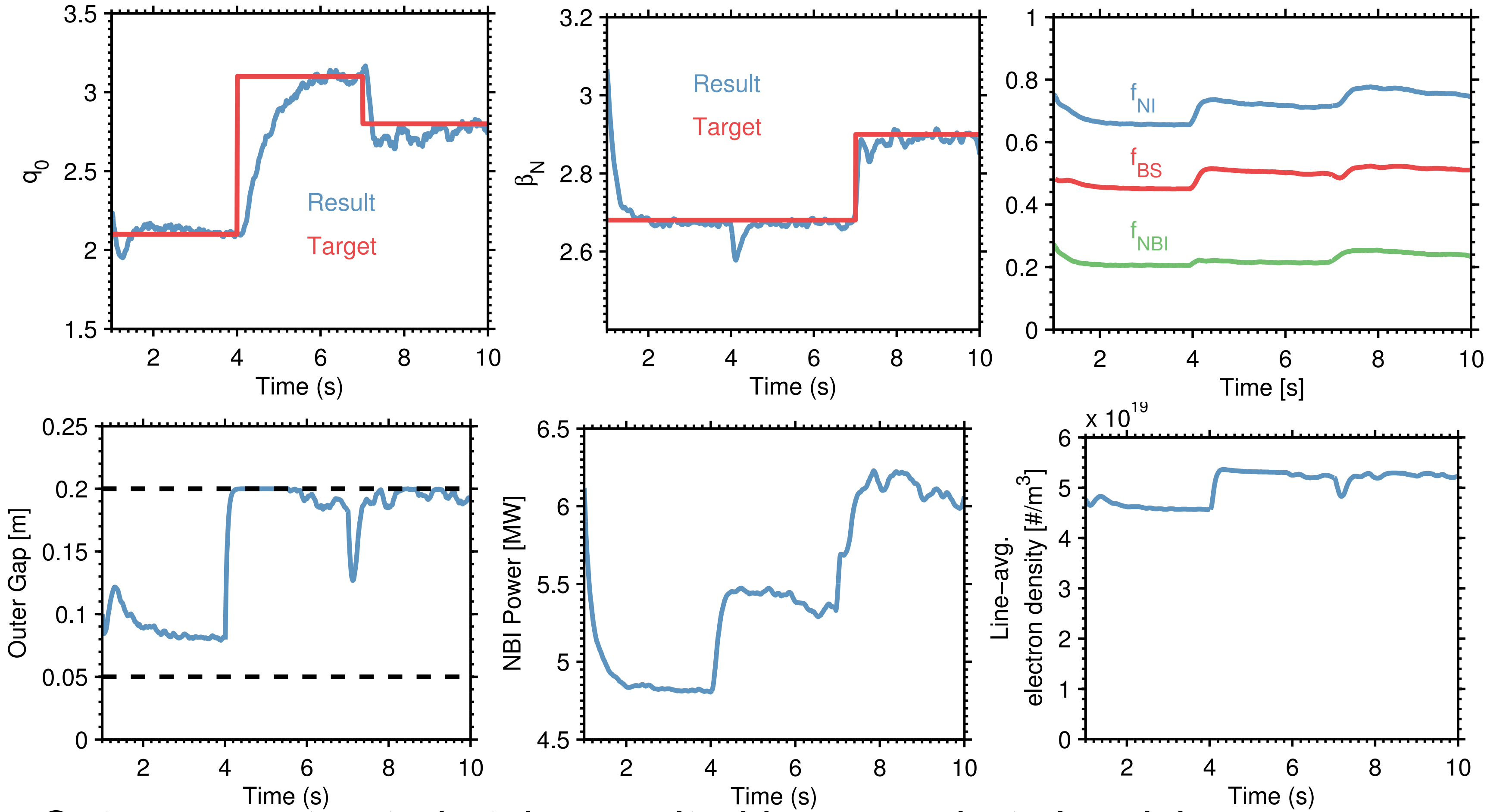
- Model identified from response of q_0 to step change in outer gap in TRANSP
  - β_N held at 2.7 by beam power loop



I_p=0.6MA, B_t=1T, N=5.05x10^{20}

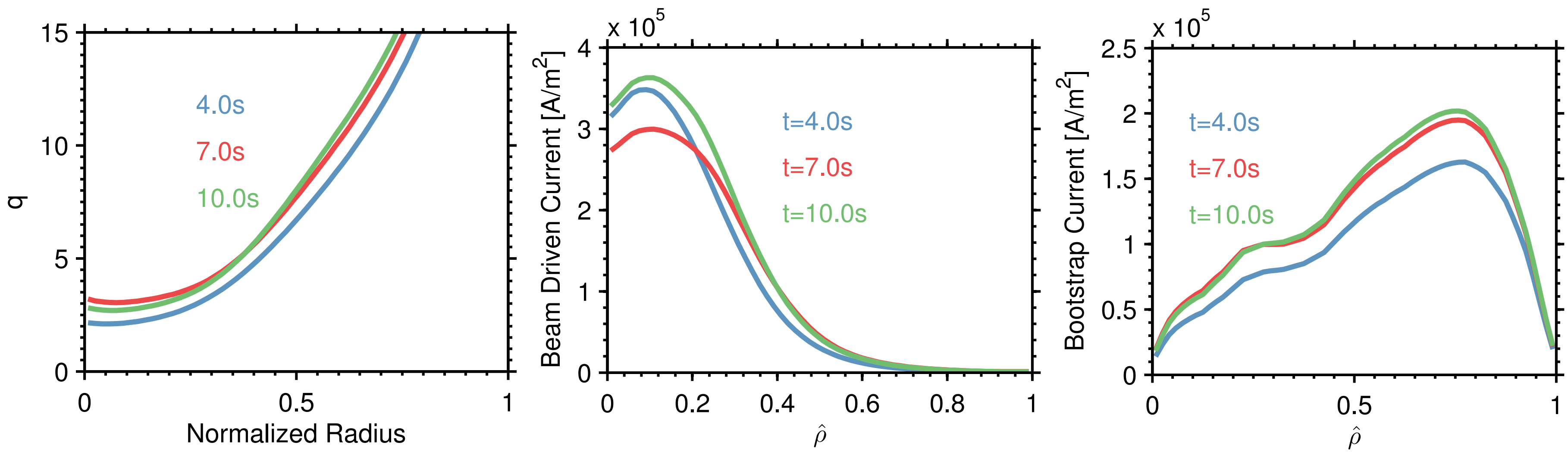


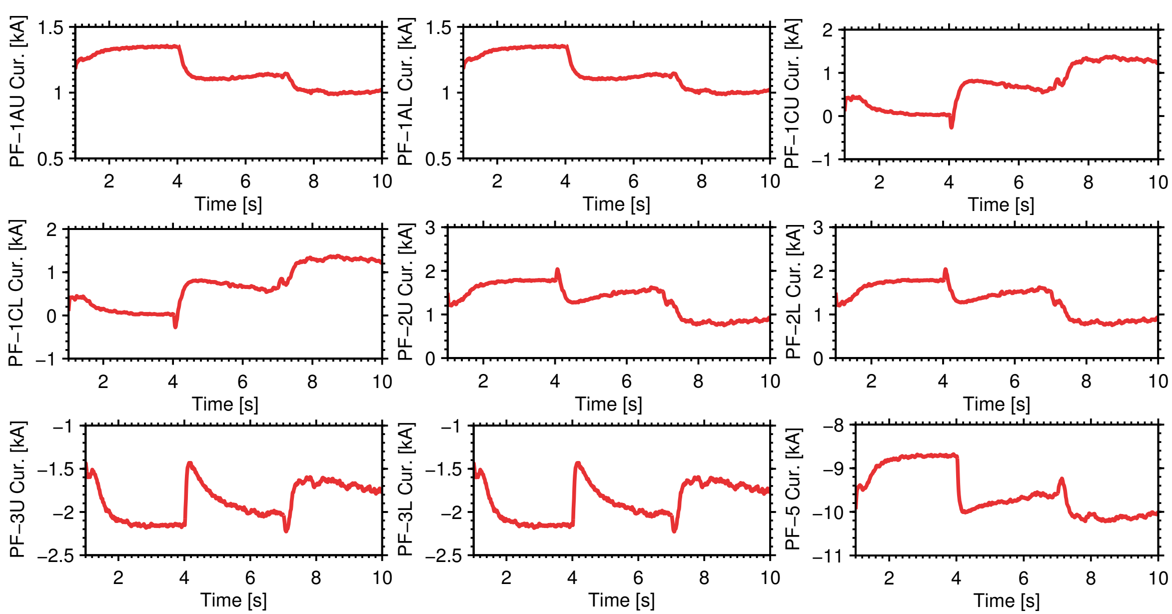
Two loop design achieves tracking performance comparable to the optimal controller



- Outer gap saturated at 4s, resulted in somewhat sluggish response
  - Otherwise, performance comparable to optimal controller
- Non-inductive fraction increased due to increased beam power and bootstrap current, line-averaged density increased due to decrease in volume

Profiles and coil currents during the two loop controller simulation





- 7s: change in outer gap shifts q profile up
  - Less peaked NBCD
  - Increased bootstrap cur.
- 10s: Decrease in outer gap and increase in β_N keeps q elevated
  - Profile shape is altered
- Coil currents appear physically achievable

Discussion and future work

- A framework for control simulations in TRANSP has been developed
  - demonstrated through simulations of β_N control and a novel algorithm for simultaneous control of q0 and β_N
- Framework will be used as a `virtual experiment' to explore new control approaches for NSTX-U, tune gains, and study robustness
  - See posters on NSTX-U current profile control (Z. Ilhan, Lehigh U) and rotation profile control (I. Goumiri, Princeton U)
- Additional actuators will be added, including coil currents/ voltages and ECCD
- Will be applied to control problems on other devices
  - Studies of FNSF underway