NSTX-U

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# Use of TRANSP for feedback control algorithm development

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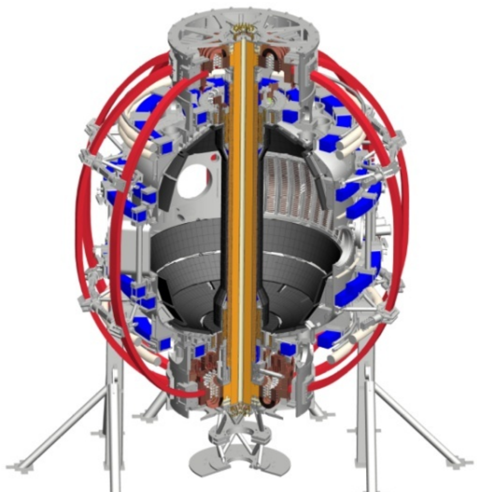
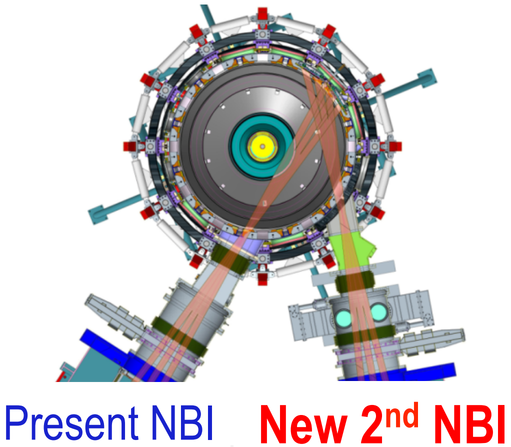
**2015 TRANSP User's Group Meeting**
**3/24/2015**

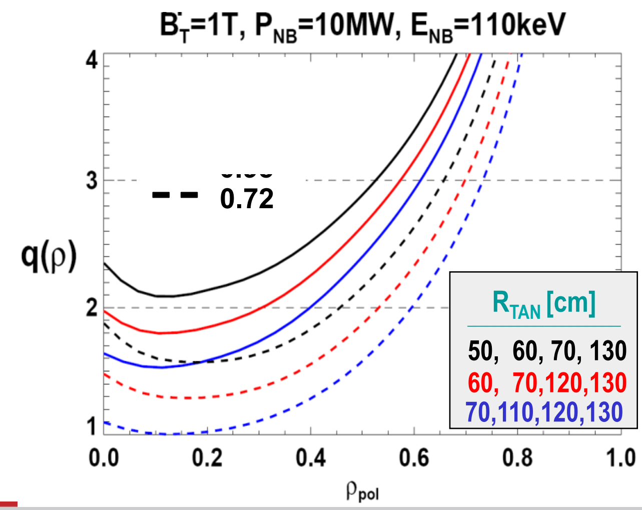


# NSTX-U improves controllability and brings about new control requirements

- **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**




- 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



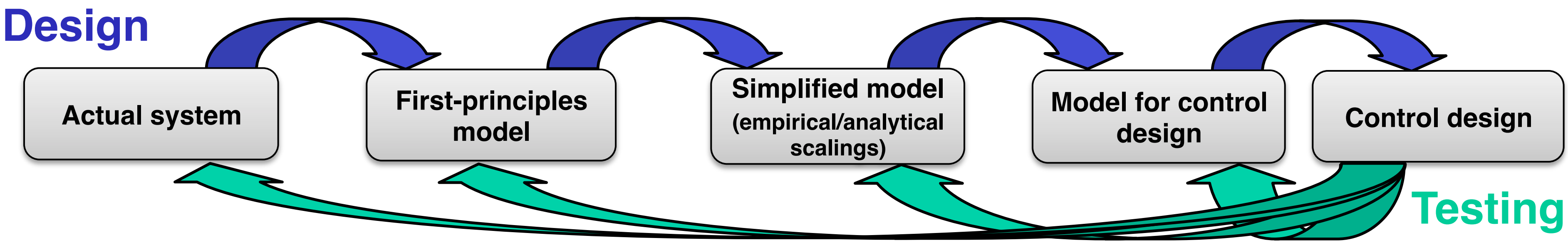
# Complexity of the control problems motivates the use of model-based control design techniques

- **Spatially distributed** systems with **nonlinearities** and **coupling**
  - Multiple actuators and measurements
- Need to balance **competing goals** to achieve optimal performance
  - Need to respect **constraints** to avoid MHD instabilities or machine limits
- Need to consider **actuator limitations**
- **Noisy**, possibly **limited real-time measurements**

- **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
- 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

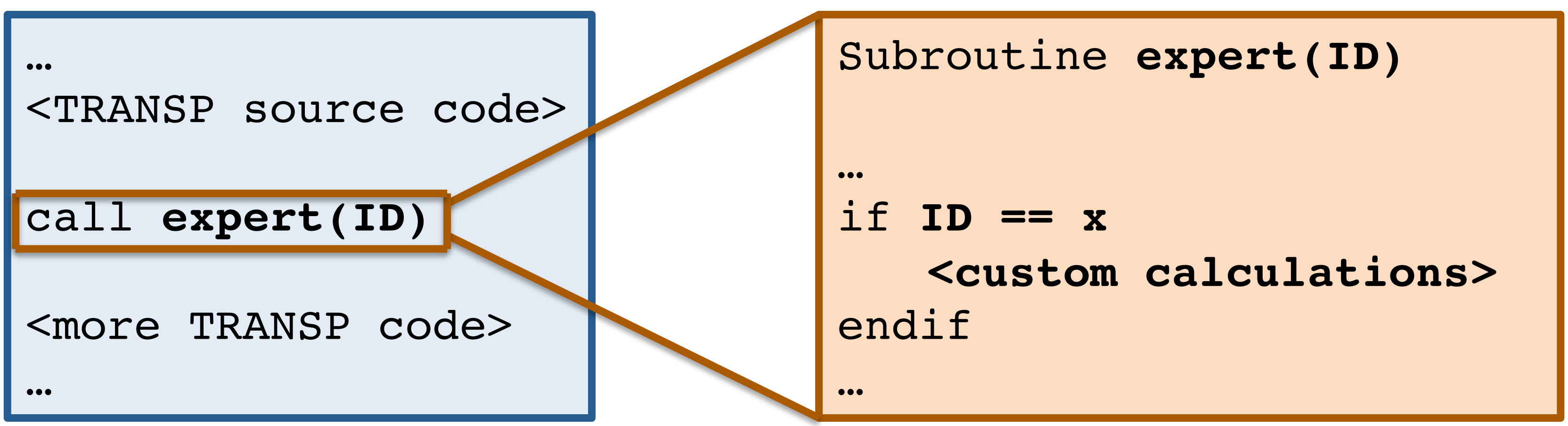
1. Ability to change actuators in `real-time', i.e., based on feedback control

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



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

- Focus has been on actuators used for current/rotation profile control so far, but others will be added in the future

- Hooks added to TRANSP code and appropriate code added to expert file to overwrite U-file data for:
  - Beam powers,
  - Density,
  - Total plasma current,
  - NTV torque (I. Goumiri, Princeton U.),
  - Plasma boundary shape request

# 2. 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

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

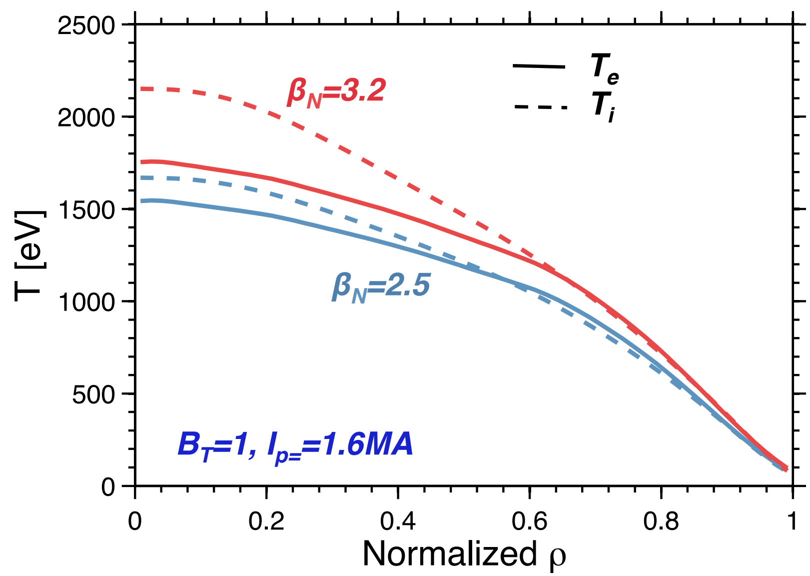
  - Confinement based on scaling (either ITER98 or ST scaling)
  - $P_{net}$ and scaling law parameters from TRANSP internal variables
- Electron temperature assumed to be of the form

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

  - Scale factor calculated as

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

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



# 2. 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:***

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

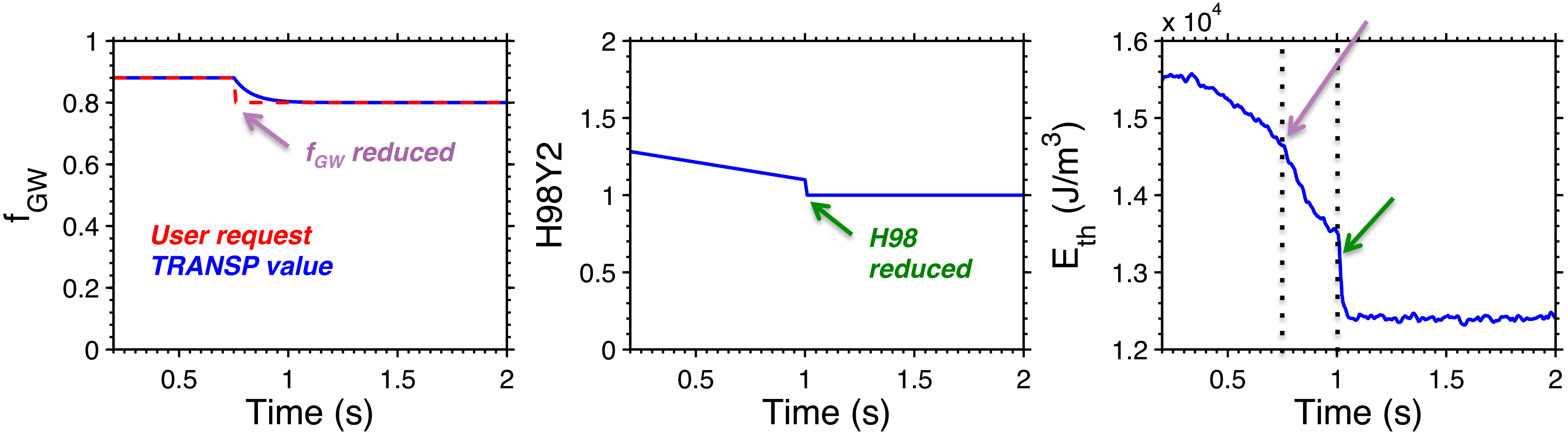
***$y_c$ = $f_{GW}$:***

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

- Profile scale factor calculated from the predicted inventory as

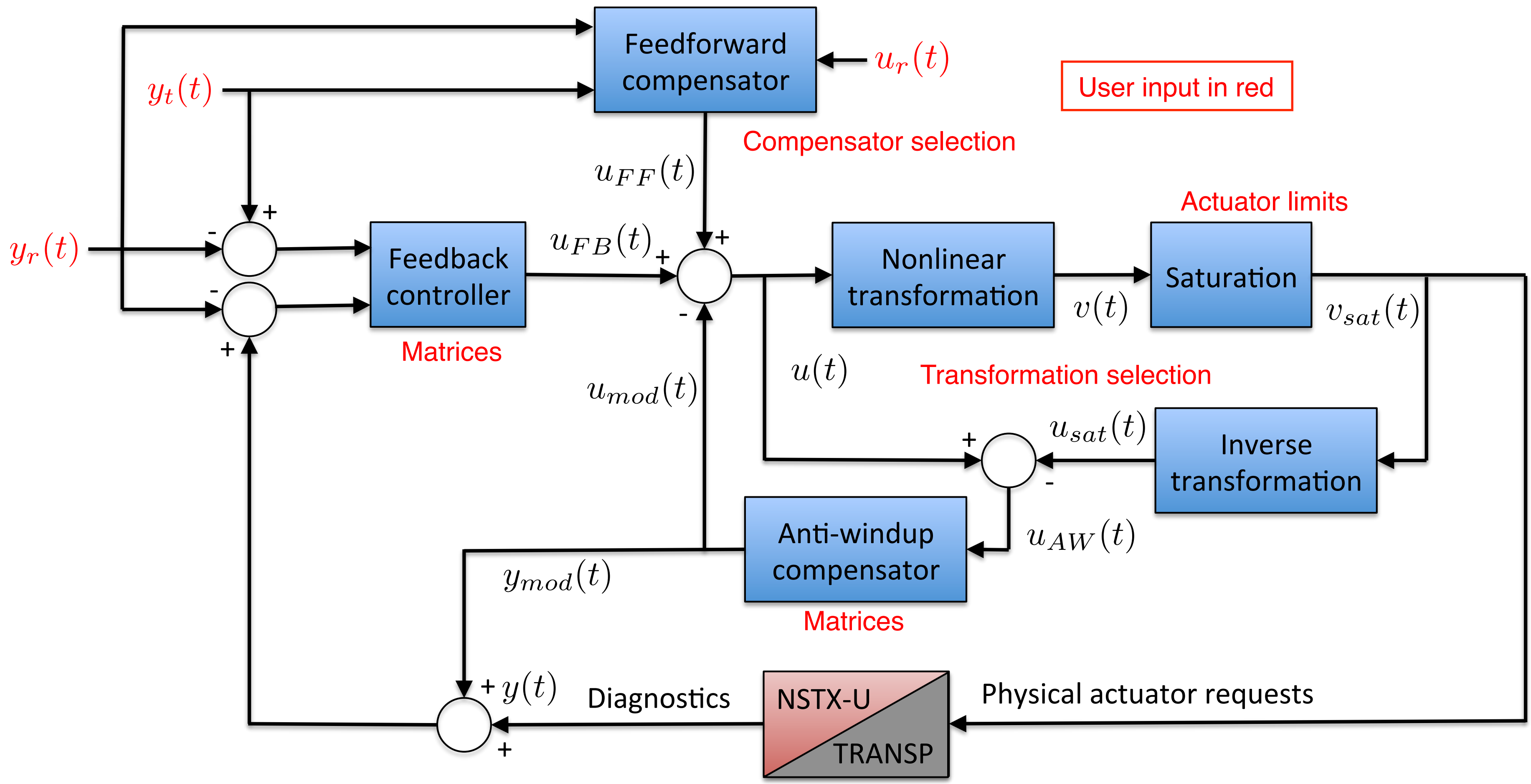
$$n_{e,0} = \frac{N}{\int_0^1 n_e^{ref}\frac{\partial V}{\partial \hat{\rho}}d\hat{\rho}}.$$

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



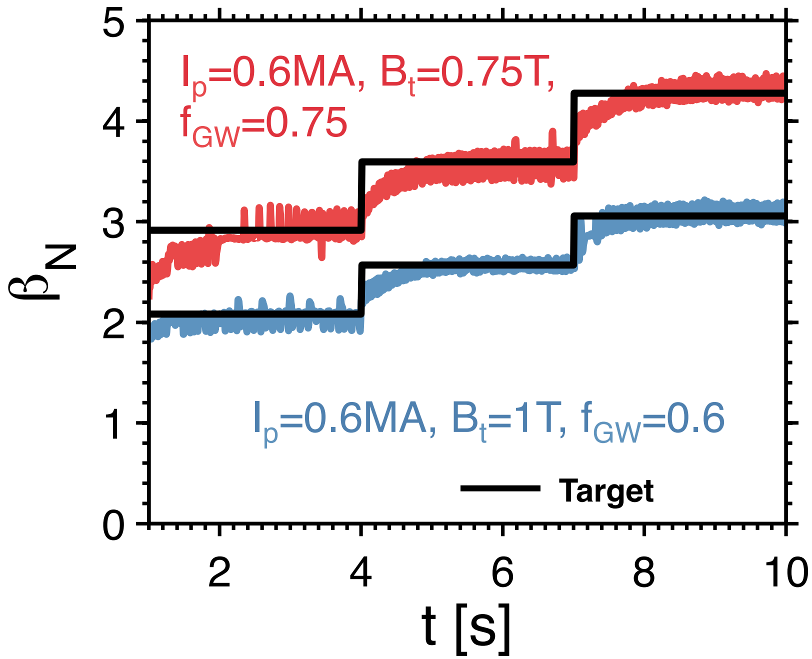

- Greenwald fraction request decreased at 0.75s
  - TRANSP modifies the density (on an appropriate time scale for density changes) to achieve the request
- H98 request ramped down until 1.0s, step at 1.0s
- Stored energy prediction responds to $f_{GW}$ and $h_{98}$
  - drops slowly as $H_{98}$ ramps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

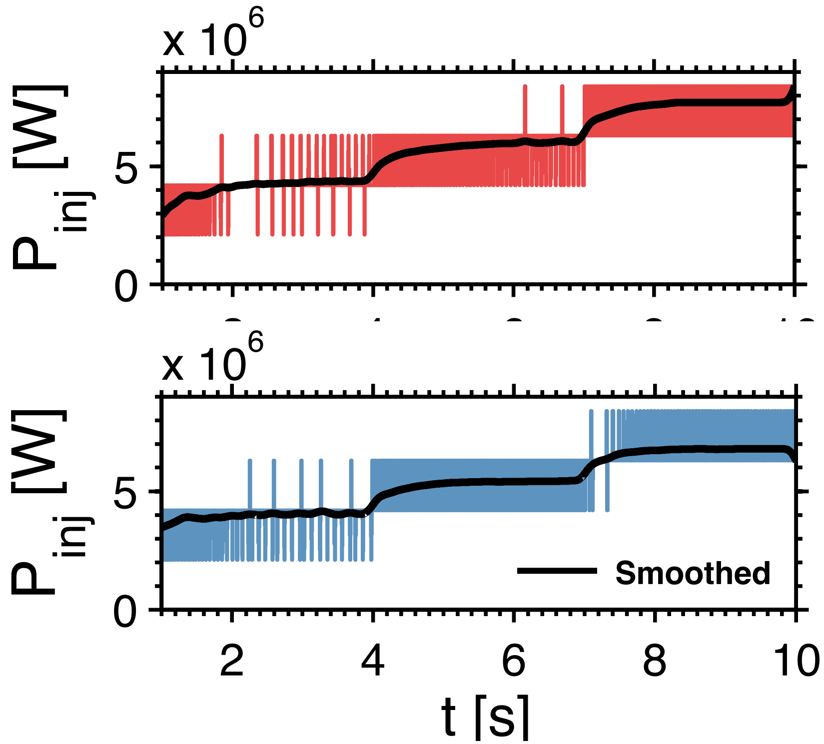
# 3. A general controller structure has been implemented within the Expert file



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

- Enables assessment of modulation's effect on performance
  - Beams modulated to achieve requested average power, respecting minimum on/off times and maximum modulations per shot.
  - Results can help determine optimal modulation parameters (minimum on/off times) and control gains to achieve desired levels of performance



# Several on-going projects using TRANSP feedback control framework

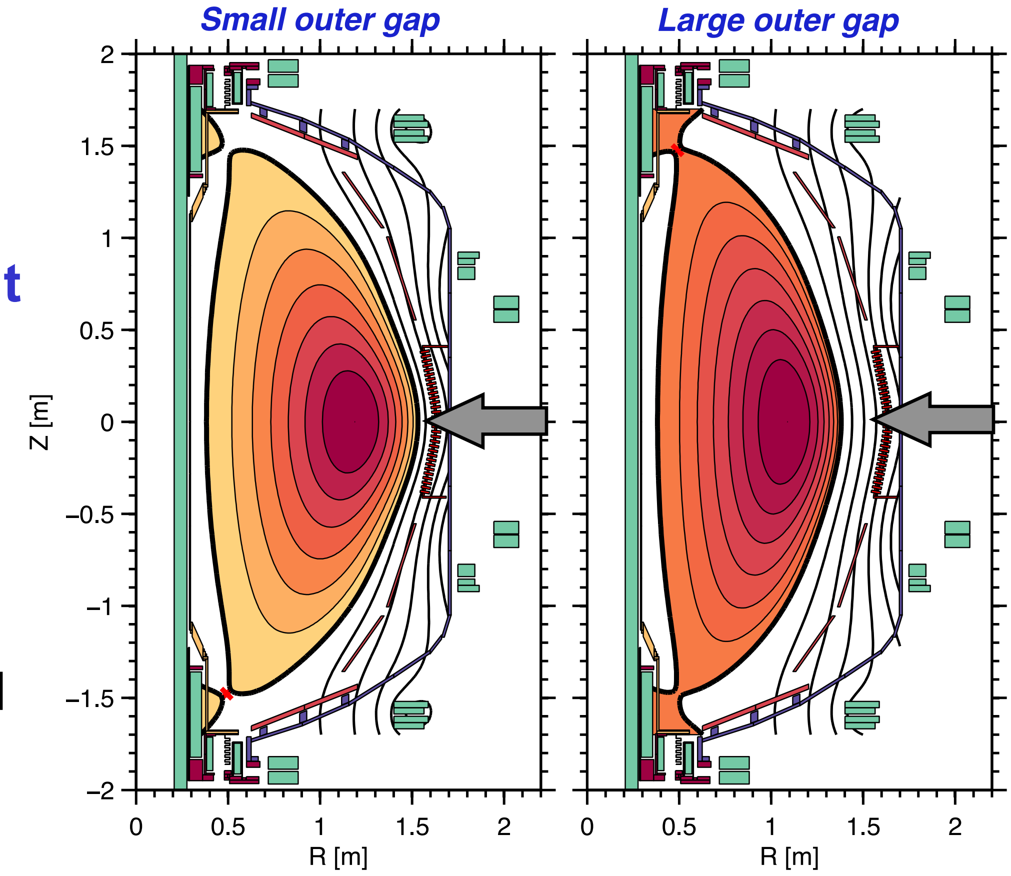
- **Stored energy, $q_0$/li control on NSTX-U**
  - M. D. Boyer, PPPL
- **Rotation profile control on NSTX-U**
  - I. Goumiri, Princeton U.
- Current profile control on NSTX-U
  - Z. Ilhan, Lehigh U.
- Rotation profile control on DIII-D
  - W. Wehner, Lehigh U.
- Shape control on NSTX-U
  - M. D. Boyer, PPPL

# TRANSP testing of simultaneous $q_0$ and $\beta_N$ control via beam power and outer gap size

- 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

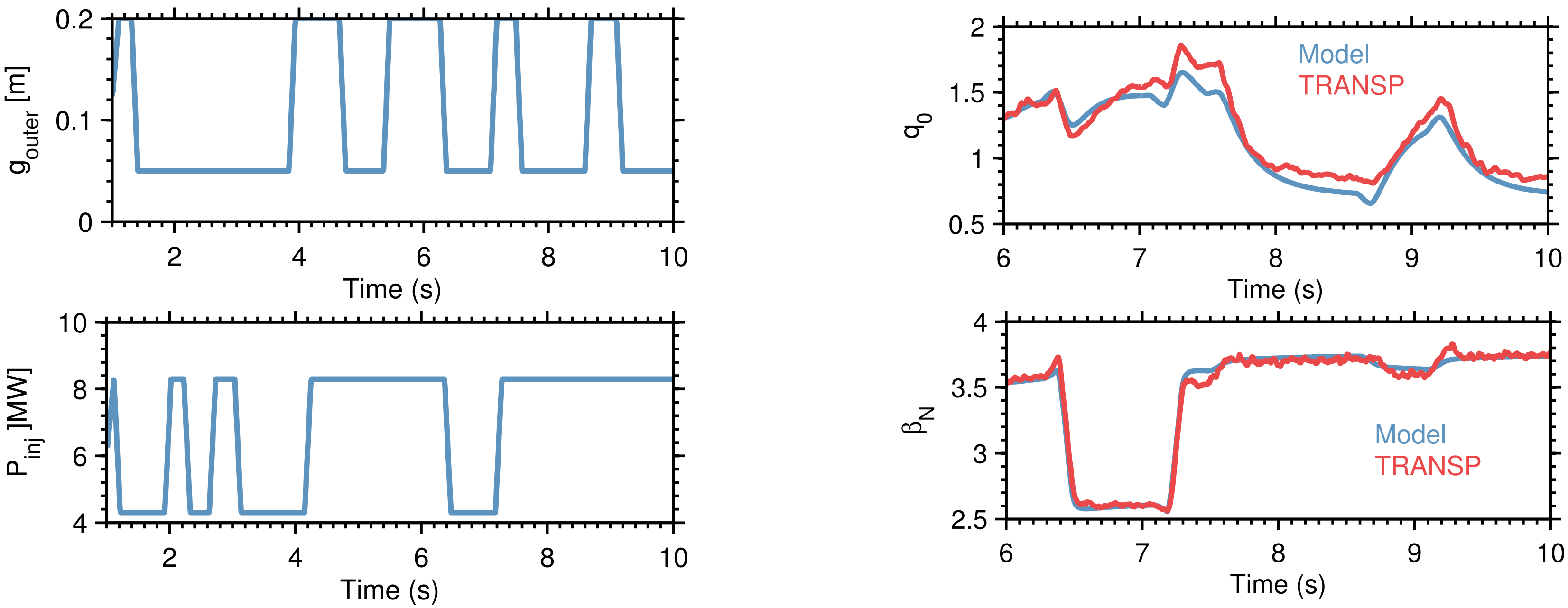
*Reference plasma boundaries:*




***M.D. Boyer, NF 2015***

# State-space system identification for simultaneous $q_0$ and $\beta_N$ 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

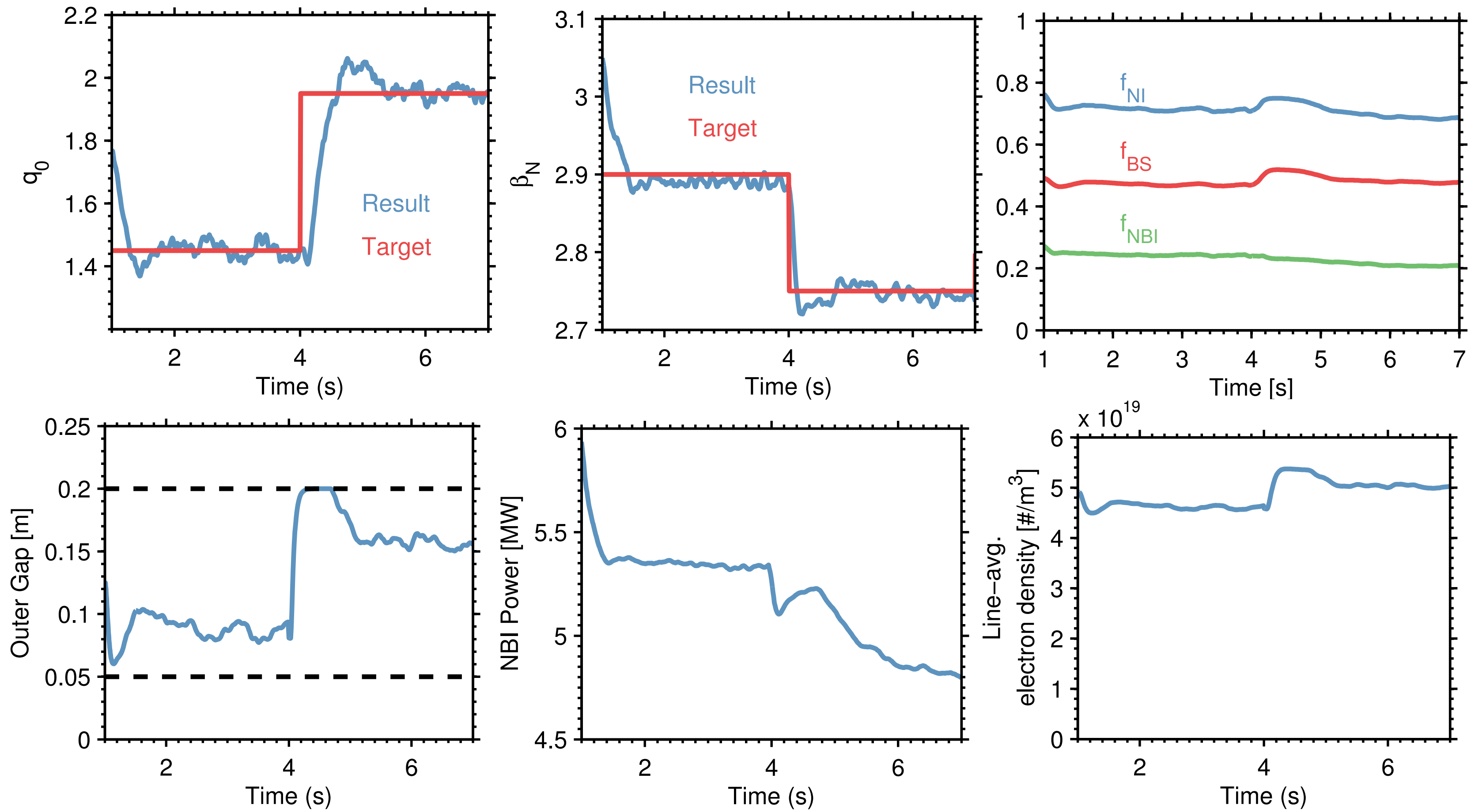
$$\dot{\tilde{x}} = A\tilde{x} + Bu_{fb} + w,$$
$$\tilde{y} = C\tilde{x} + Du_{fb} + v,$$

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

  and $Q_i$ weights the integral of the output tracking error $x_i$

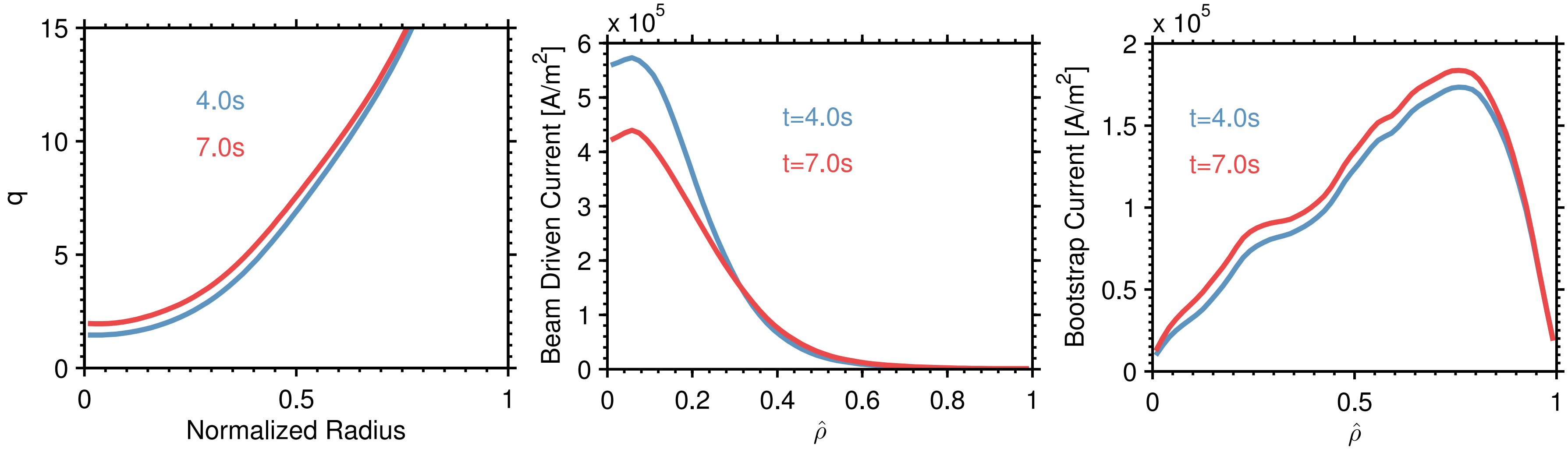
- Since the states of the identified model are not measured, they are estimated by a **Kalman filter**
  - Tuned based on expected process and measurement noise $(w, v)$
- **Integral action** ensures steady-state error is driven to zero in the presence of disturbances or target tracking

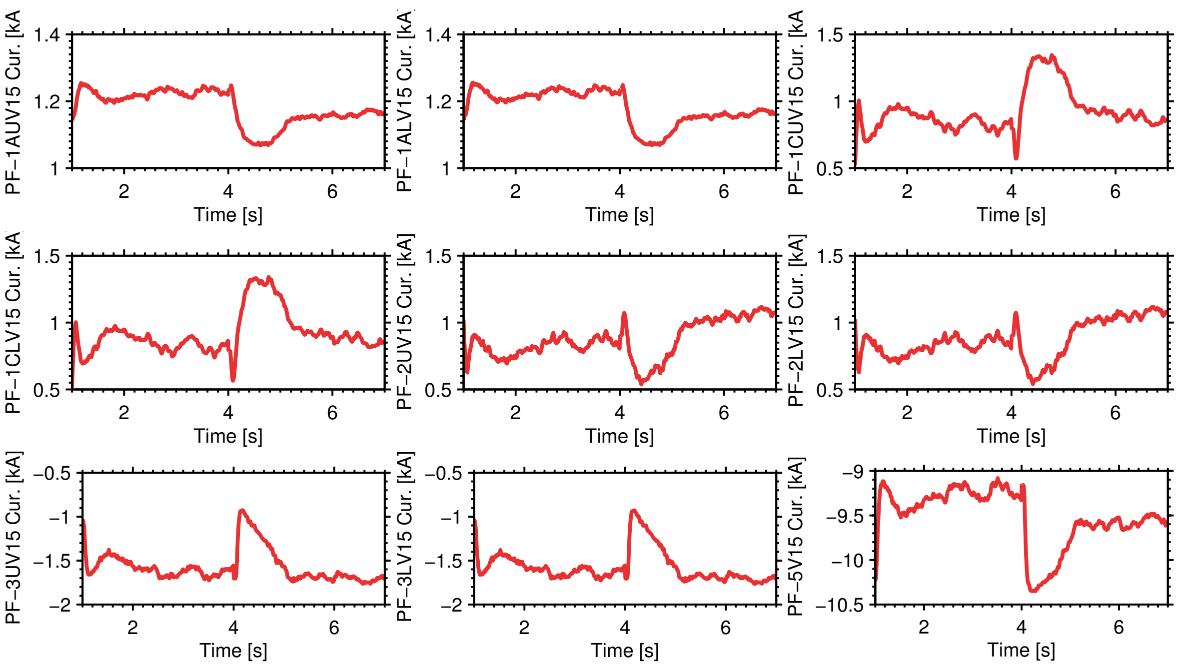
# Optimal controller achieves good target tracking performance in TRANSP simulation testing




- 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

# Rotation profile control in NSTX [I. Goumiri]

- For design, a simplified form of toroidal momentum equation is assumed, with model profiles derived from TRANSP

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

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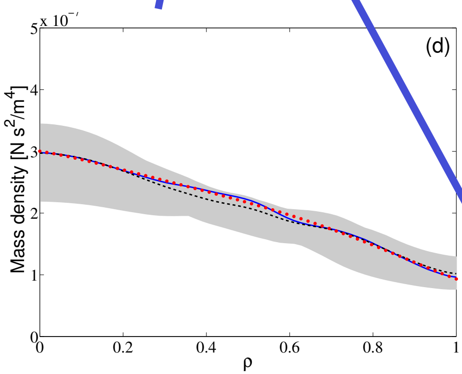
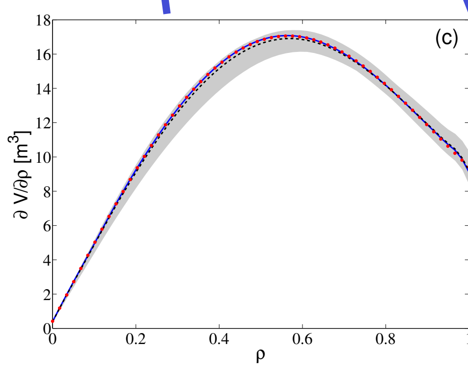
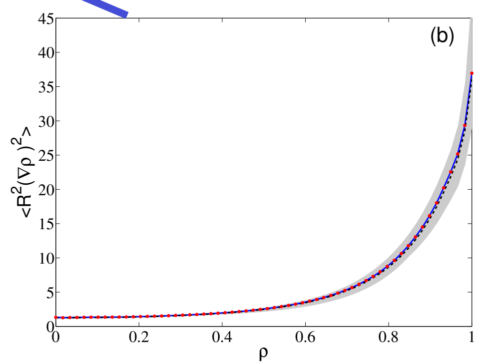
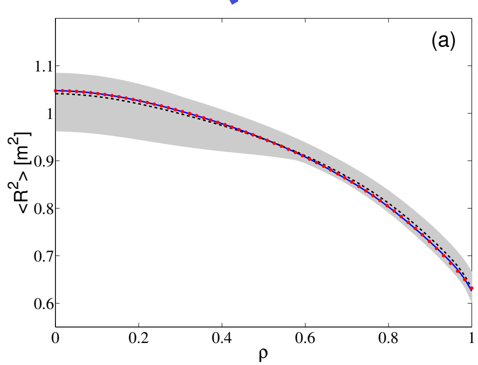
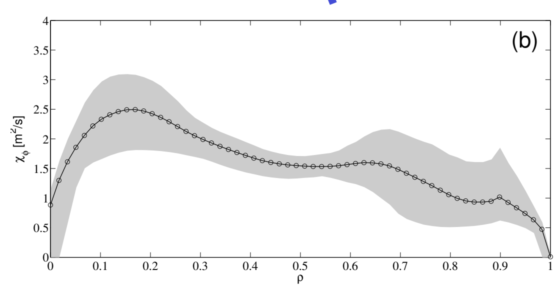


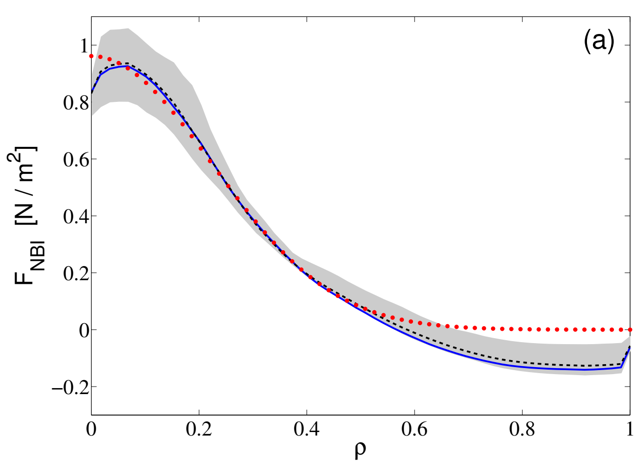



# Simplified models assumed for NBI and NTV torque [I. Goumiri]

## NBI Torque

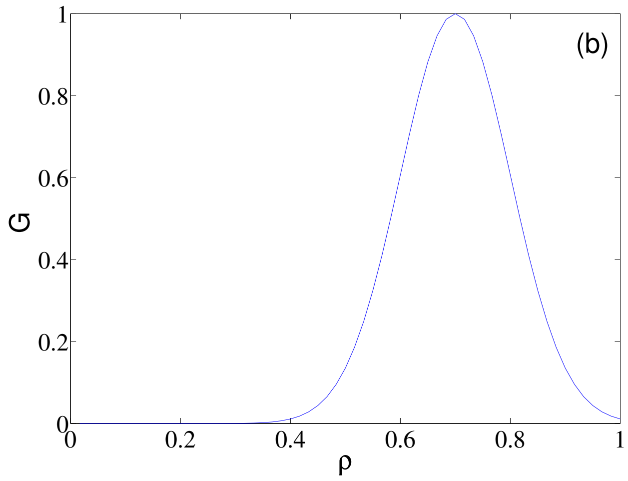
$$T_{NBI}(t,\rho) = \bar{T}_{NBI}(t)F_{NBI}(\rho)$$

$$\frac{d\bar{T}_{NBI}}{dt} + \frac{\bar{T}}{\tau_{NBI}} = \kappa_{NBI}P_{NBI}(t)$$




## NTV Torque

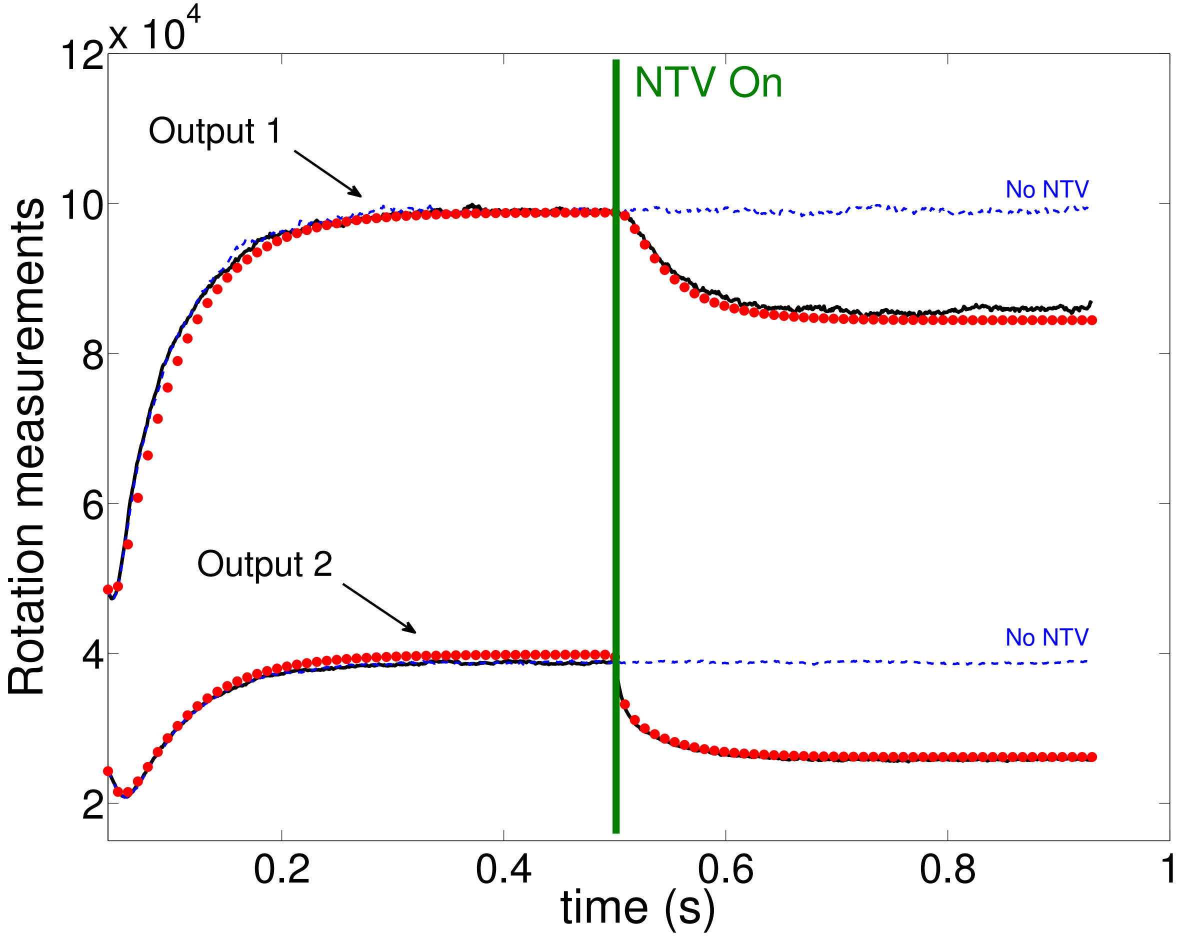
$$T_{NTV}(t,\rho) = -KG(\rho)\langle R^2\rangle I^2(t)\omega(t,\rho)$$



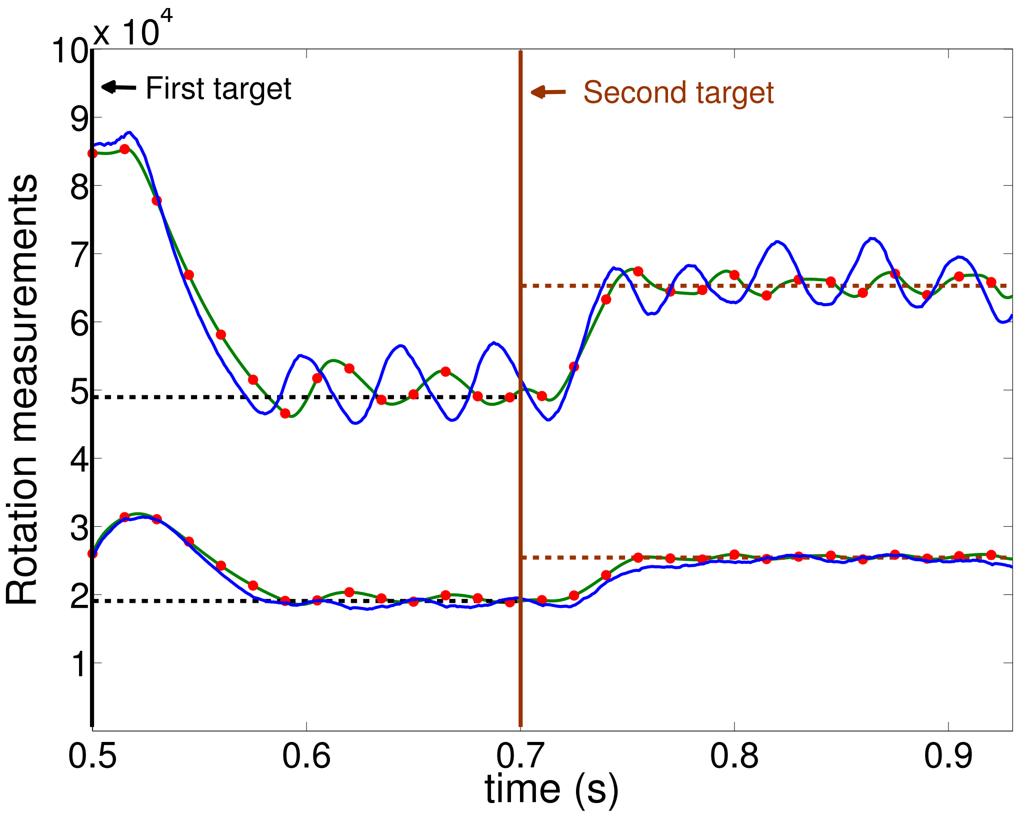

## Actuators:

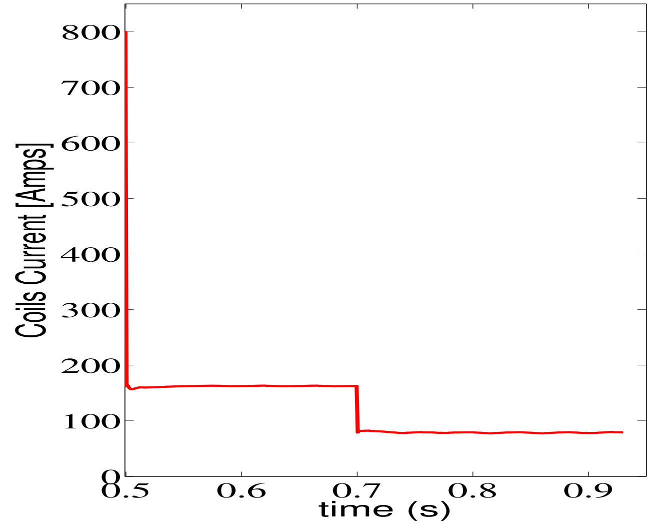
| | |
|---|---|
| $P_{NBI}$ | ***Total neutral beam power*** |
| $I$ | ***3D coil current*** |

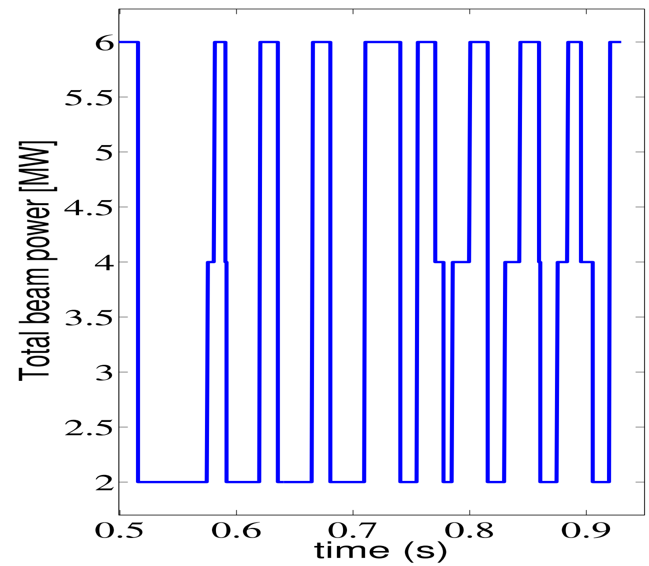
# Simplified model predictions compare very well to TRANSP simulations [I. Goumiri]



# TRANSP simulation of rotation profile controller [I. Goumiri]



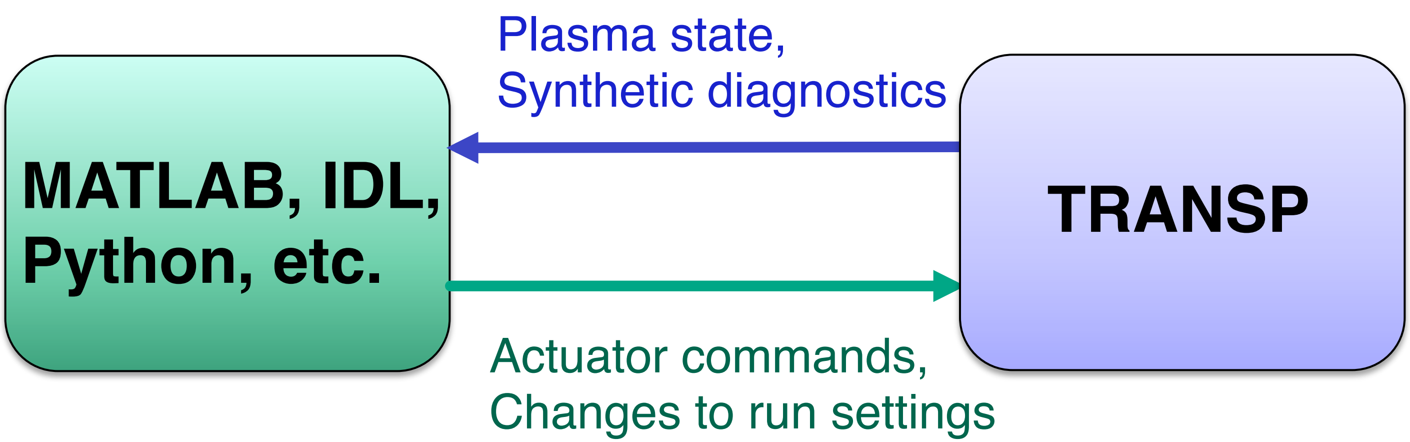
# Future plans for feedback control simulations in TRANSP

- Extend framework to other machines
- Extend to include additional actuators and control loops
  - Coil voltages for shape control in TRANSP (mostly finished)
    - For testing control laws
    - Or for ensuring that predictive simulations mimic experiments
  - RF for heating, current profile control, NTM control, etc.
    - Will need hooks for modifying RF input parameters in `real-time’
- Use transport models for $T_e$, density
  - Add puffing/pellets/pumping as feedback actuators
  - May want a simplified transport model to speed of simulations
    - Neural networks? O. Meneghini

# Suggested upgrades

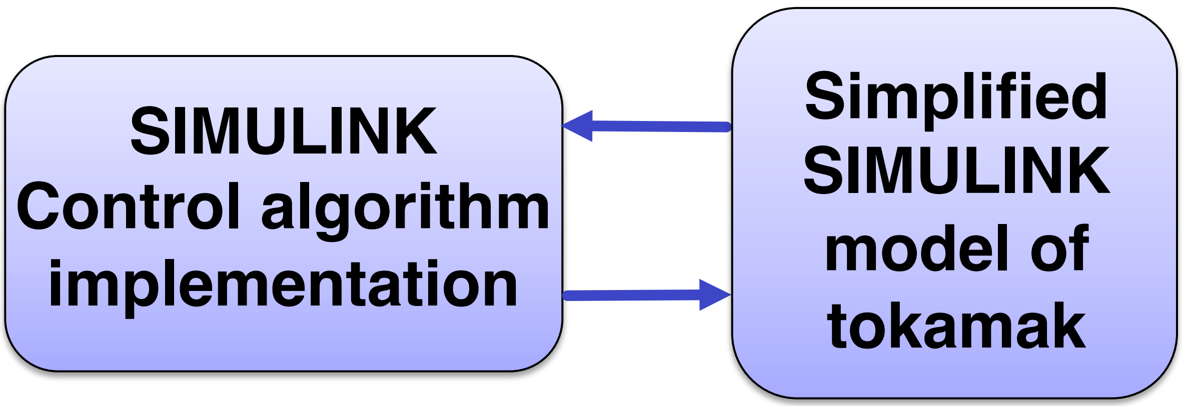
1. Add confinement and Greenwald fraction constraints to production code
   – These have been useful for several users already

2. Enable external programs to `steer' TRANSP through a socket connection:



# 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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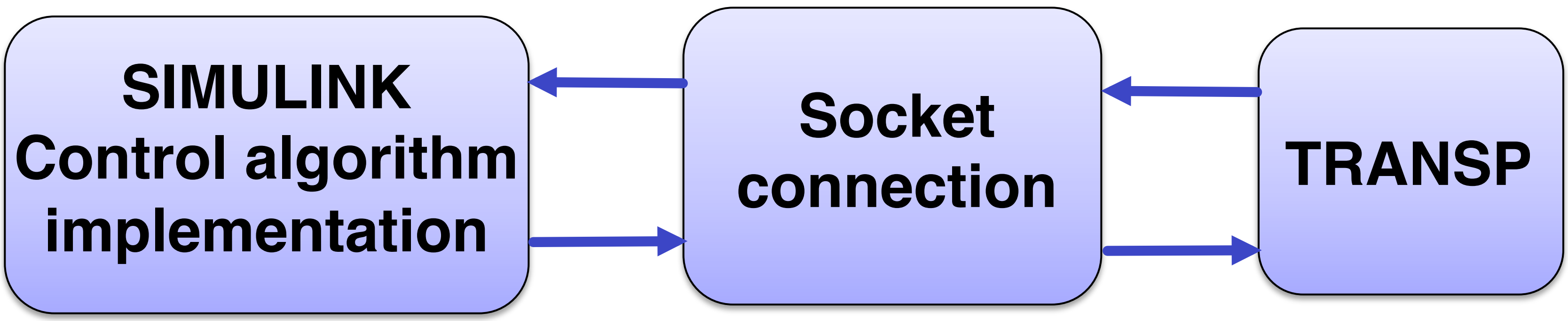

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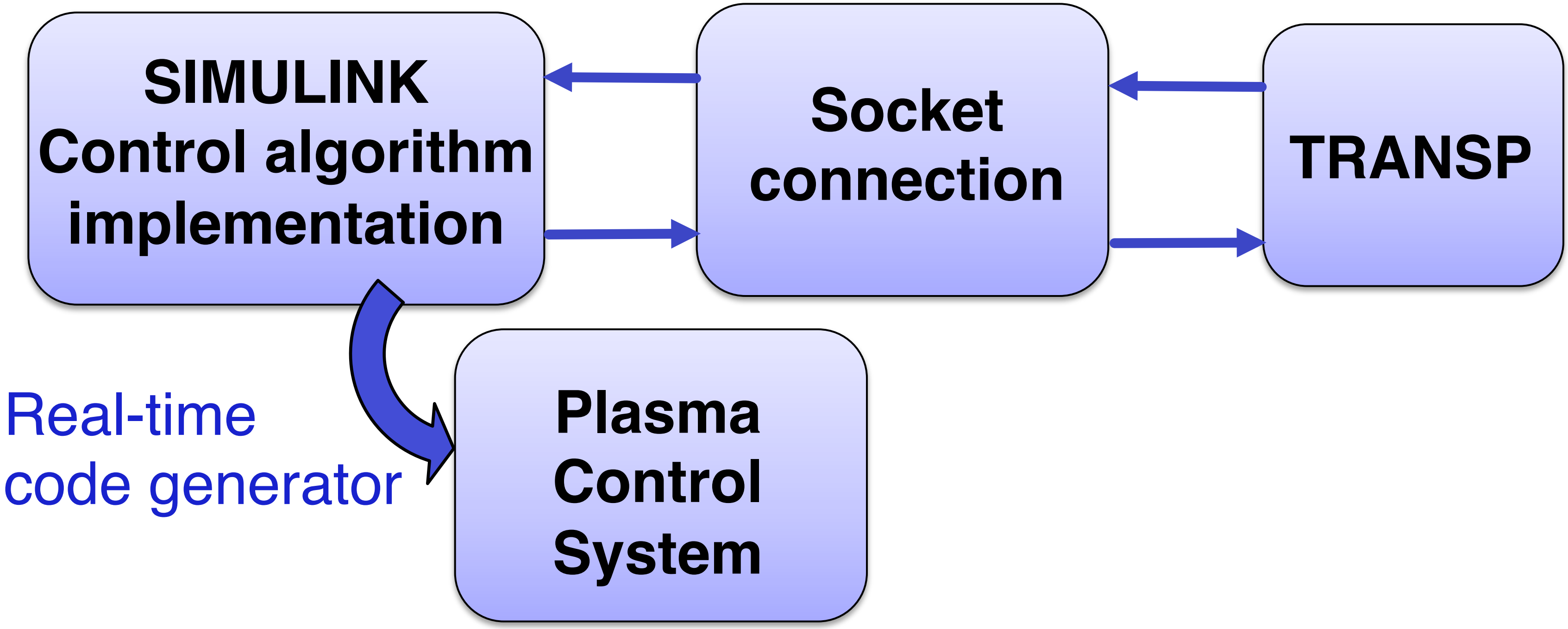

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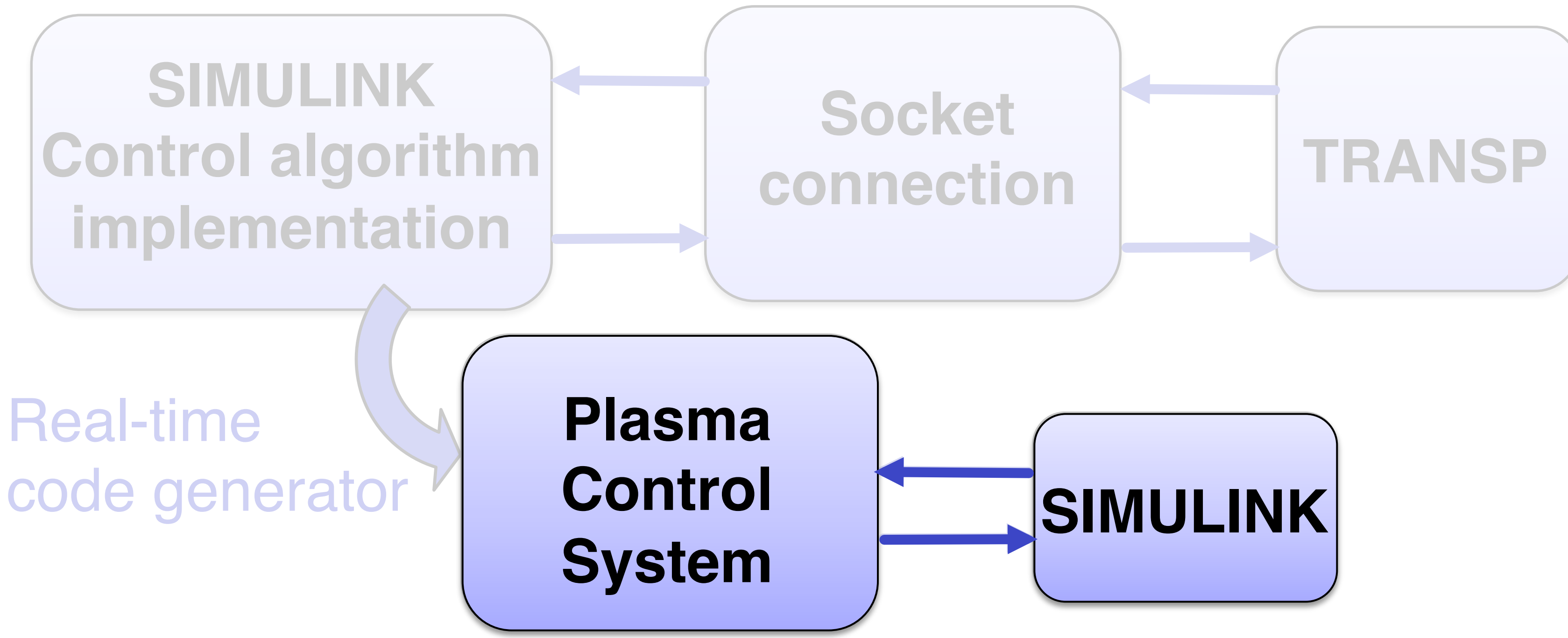

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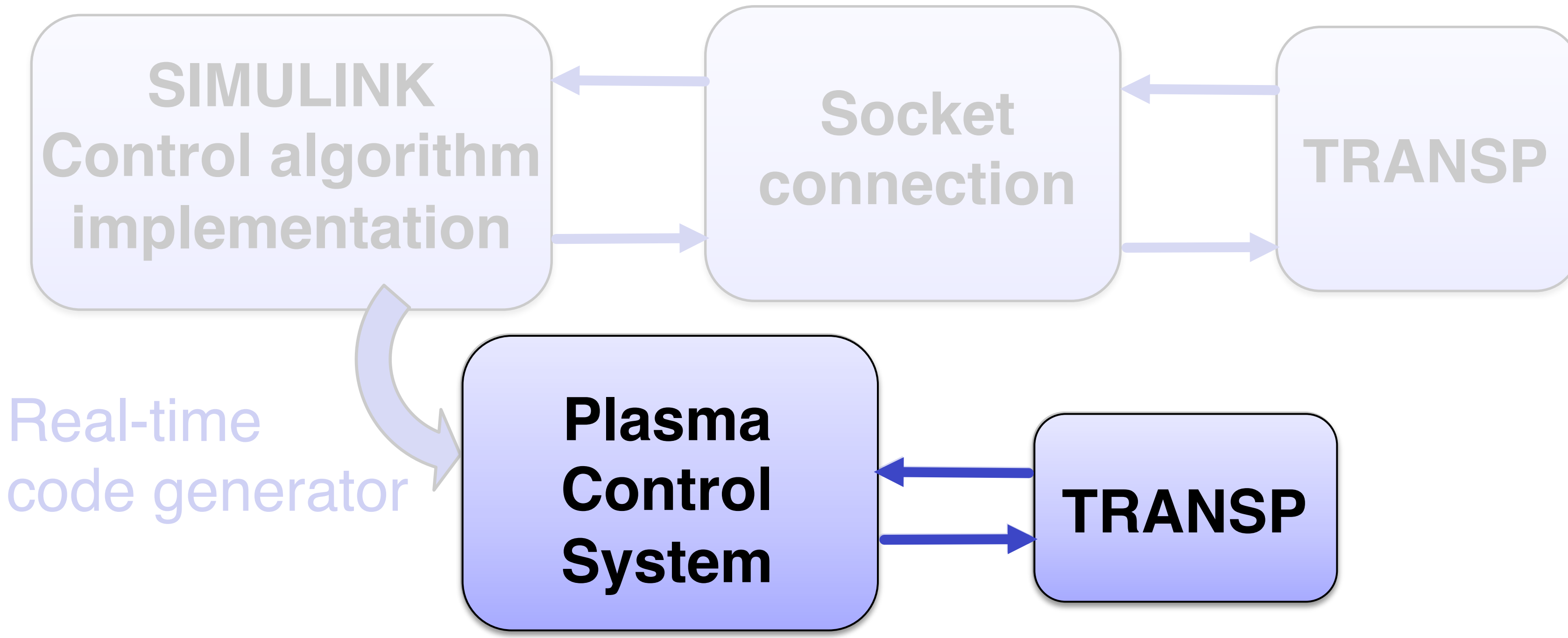

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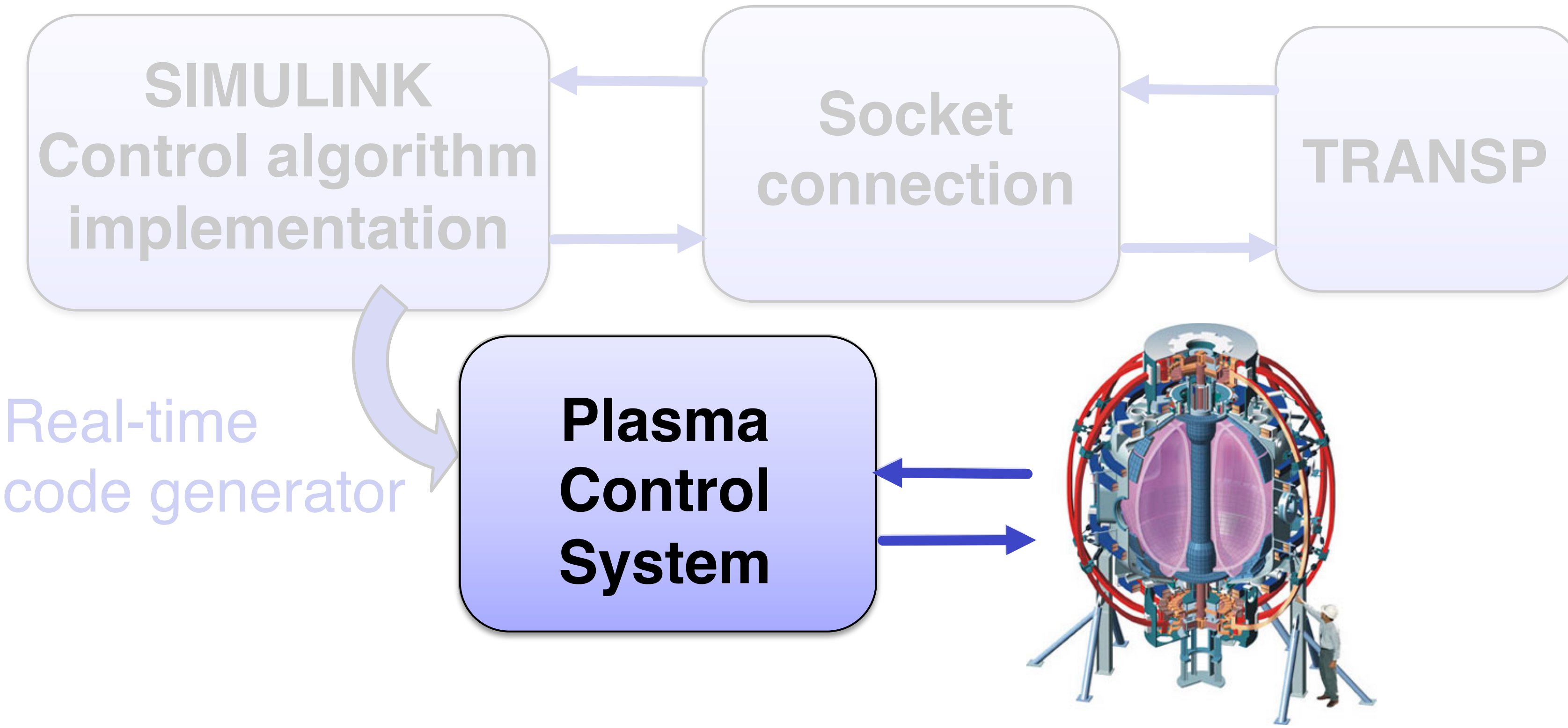

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