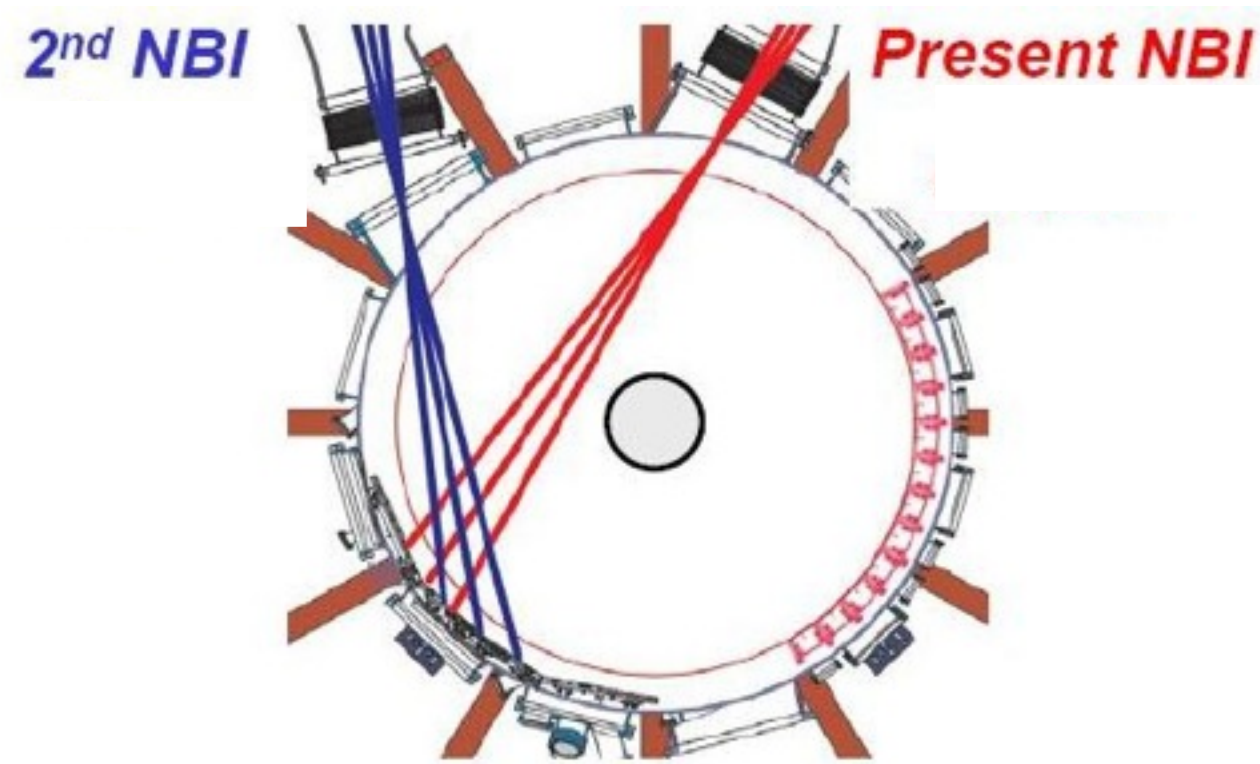
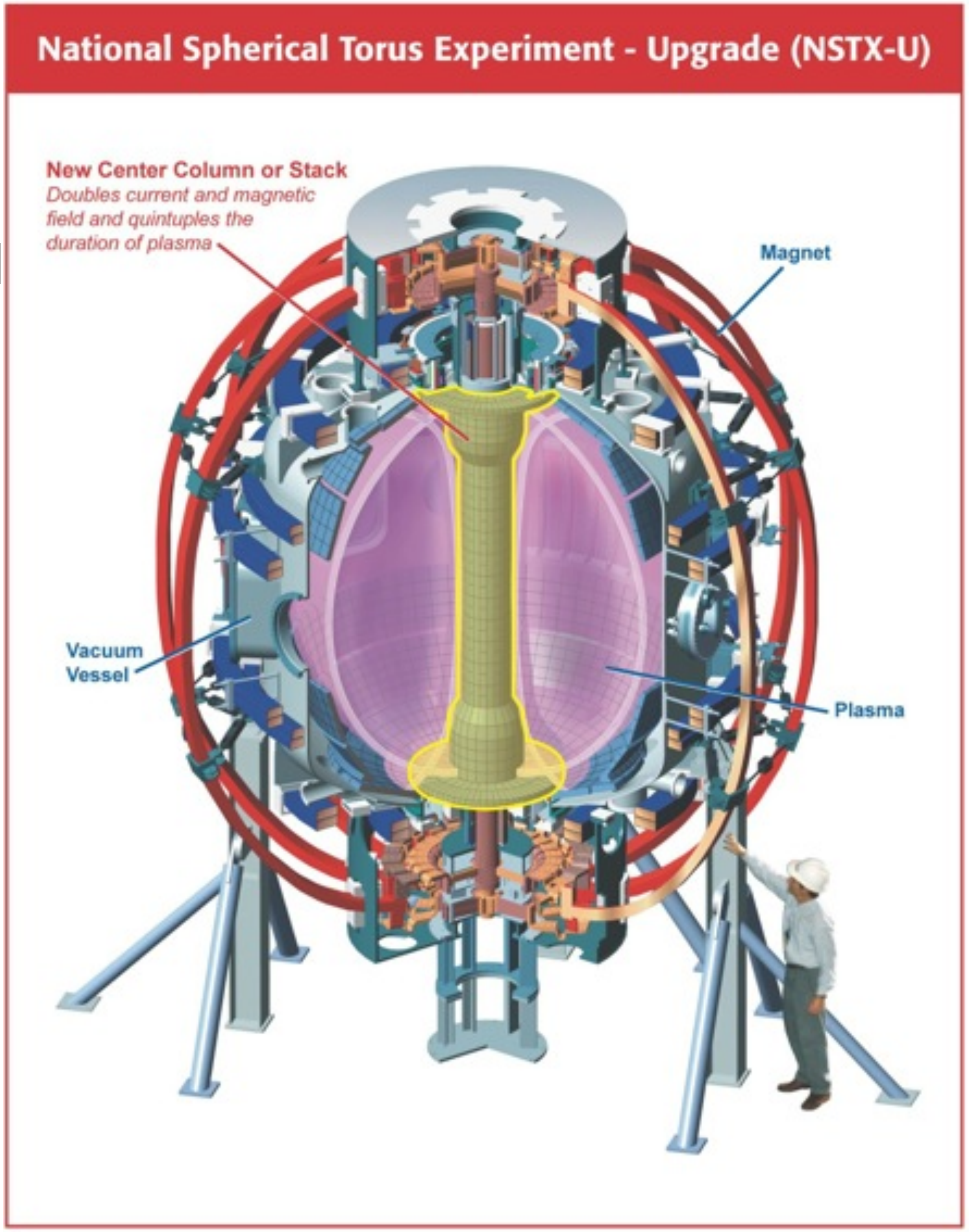
The primary components of the upgrade:

- The complete **replacement** of the center stack (containing the inner-leg of the toroidal field coils, the ohmic heating solenoid…)
- The **addition** of a second neutral beam injector aimed more tangentially.





The upgrade of NSTX machine will:

- Increase the TF (Toroidal field) capability from 0.55T to 1.0T.
- Increase the maximum plasma current from 1.3 MA to 2 MA.
- Increase auxiliary heating power.
- **Increase neutral beam current drive and the ability to tailor their deposition profiles.**

Modified Toroidal Momentum Equation

$$(nm)\left\langle R^2\right\rangle \frac{\partial\omega}{\partial t} = \left(\frac{\partial V}{\partial\rho}\right)^{-1} \frac{\partial}{\partial\rho}\left[\frac{\partial V}{\partial\rho}(nm)\chi_\phi \left\langle R^2(\nabla\rho)^2\right\rangle \frac{\partial\omega}{\partial\rho}\right] + \sum_{i=1}^{4} T_{\mathrm{NBI}i}\left(P_{\mathrm{NBI}}\right) + T_{\mathrm{NTV}}\left(\omega, I^2\right)$$

Energy Equation: β_n control

Energy stored

$$\frac{\partial W}{\partial t} + \frac{W}{\tau_E} = \sum_{i=1}^{4} P_{\mathrm{NBI}i}(t)$$

Empirical Constant coming from H98 code

$$\tau_E = H_{98y,2}\, 0.0562\, I_P^{0.93}\, B_T^{0.15}\, n_e^{0.41}\, P_{Loss(th)}^{-0.69}\, R_0^{1.97}\, \epsilon^{0.58}\, \kappa^{0.78}$$

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χ_ϕ has to be modeled as well as the background variables

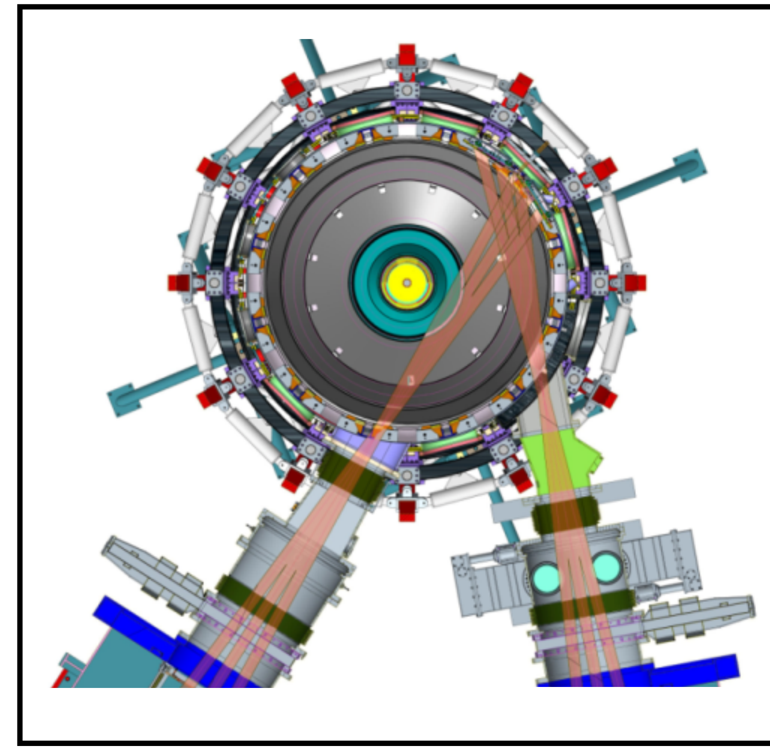
Since experimental data is not yet available for NSTX-U, these models were identified from simulated data generated using predictive TRANSP simulations.

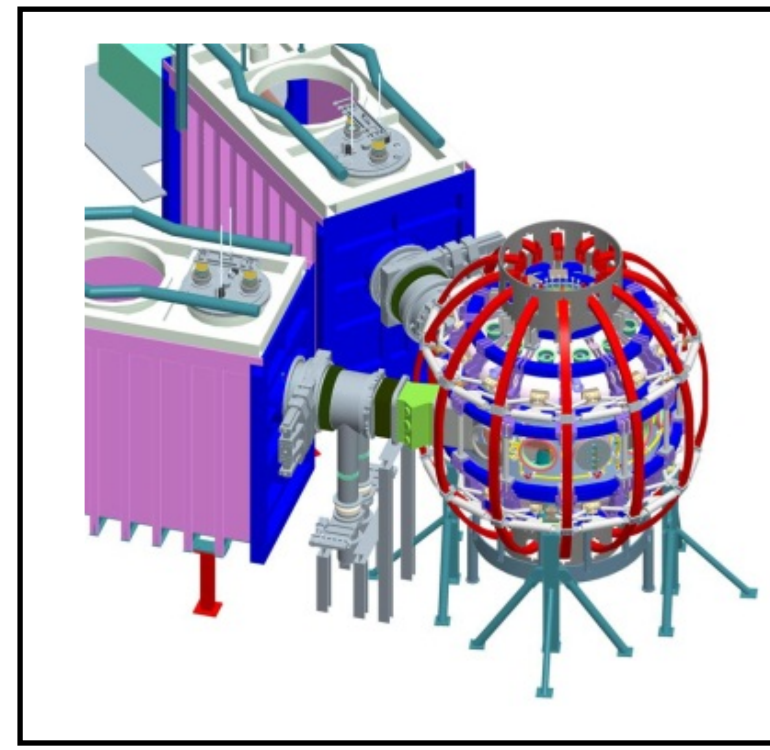
NBI Modeling for NSTX-U:

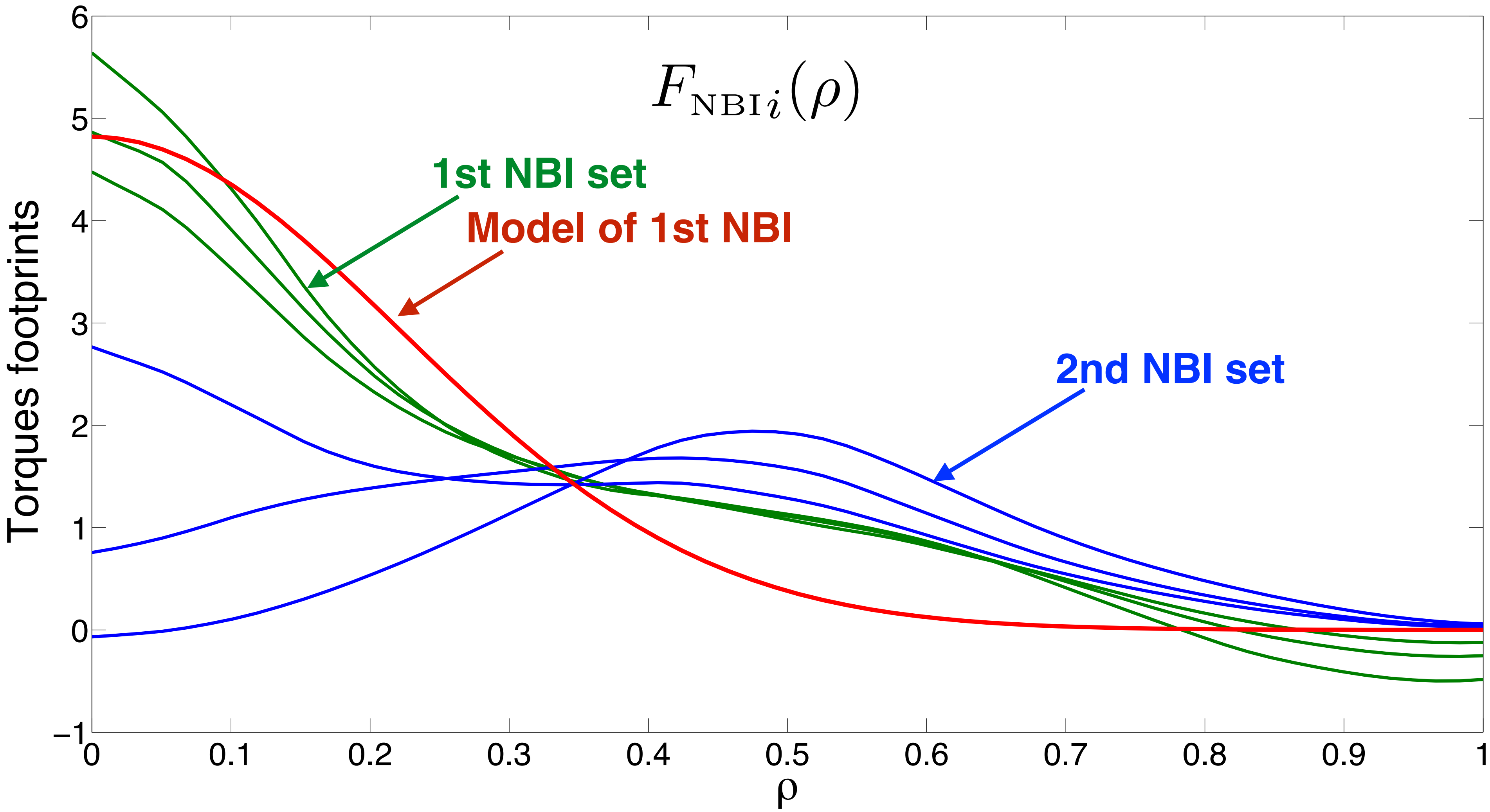
$$T_{\mathrm{NBI}i}(t,\rho) = \overline{T}_{\mathrm{NBI}i}(t) F_{\mathrm{NBI}i}(\rho)$$

$$\frac{\partial \overline{T}_{\mathrm{NBI}i}}{\partial t} + \frac{\overline{T}_{\mathrm{NBI}i}}{\tau_{\mathrm{NBI}i}} = \kappa_{\mathrm{NBI}i} P_{\mathrm{NBI}i}(t)$$

- 6 NBI beams – Power 2MW each: Max **12MW**
- Each beam can be blocked 20 times max.
- Block min duration: 10ms
- Min duration between blocks: 10ms

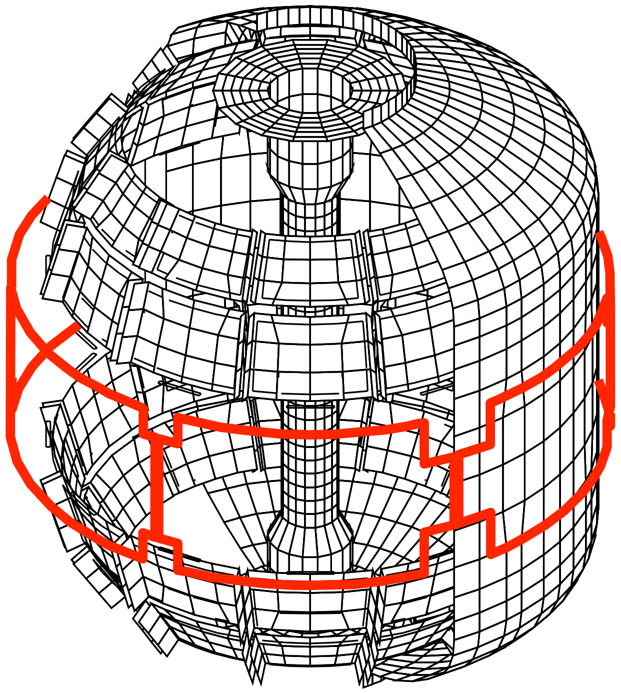




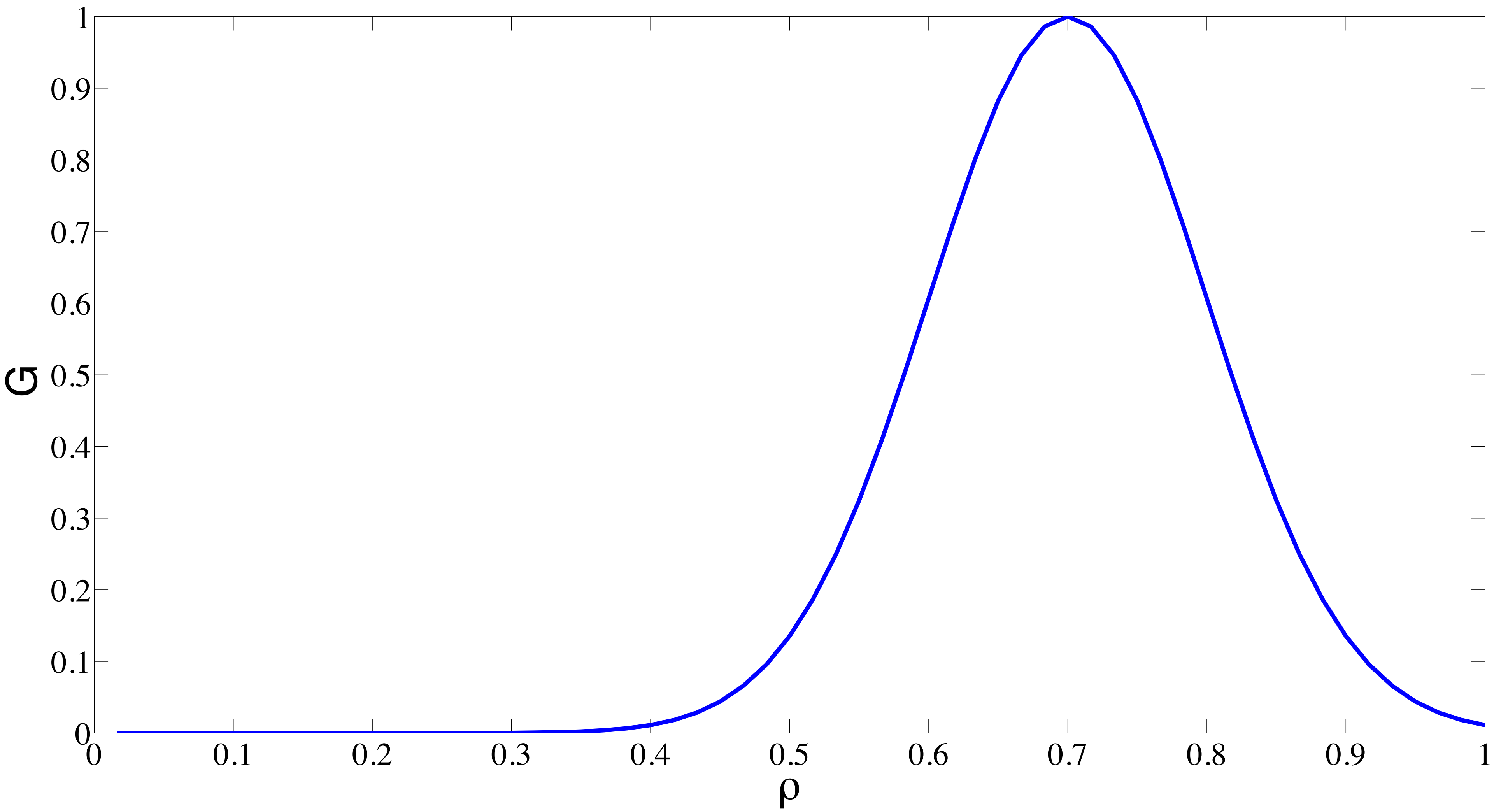


NTV Modeling for NSTX-U:

- Same model used for NSTX: Max. Current = 3kA



$$T_{\mathrm{NTV}}(t,\rho) = K\,G(\rho)\,\langle R^2\rangle\,I^2(t)\,\omega(t,\rho)$$



Model reduction

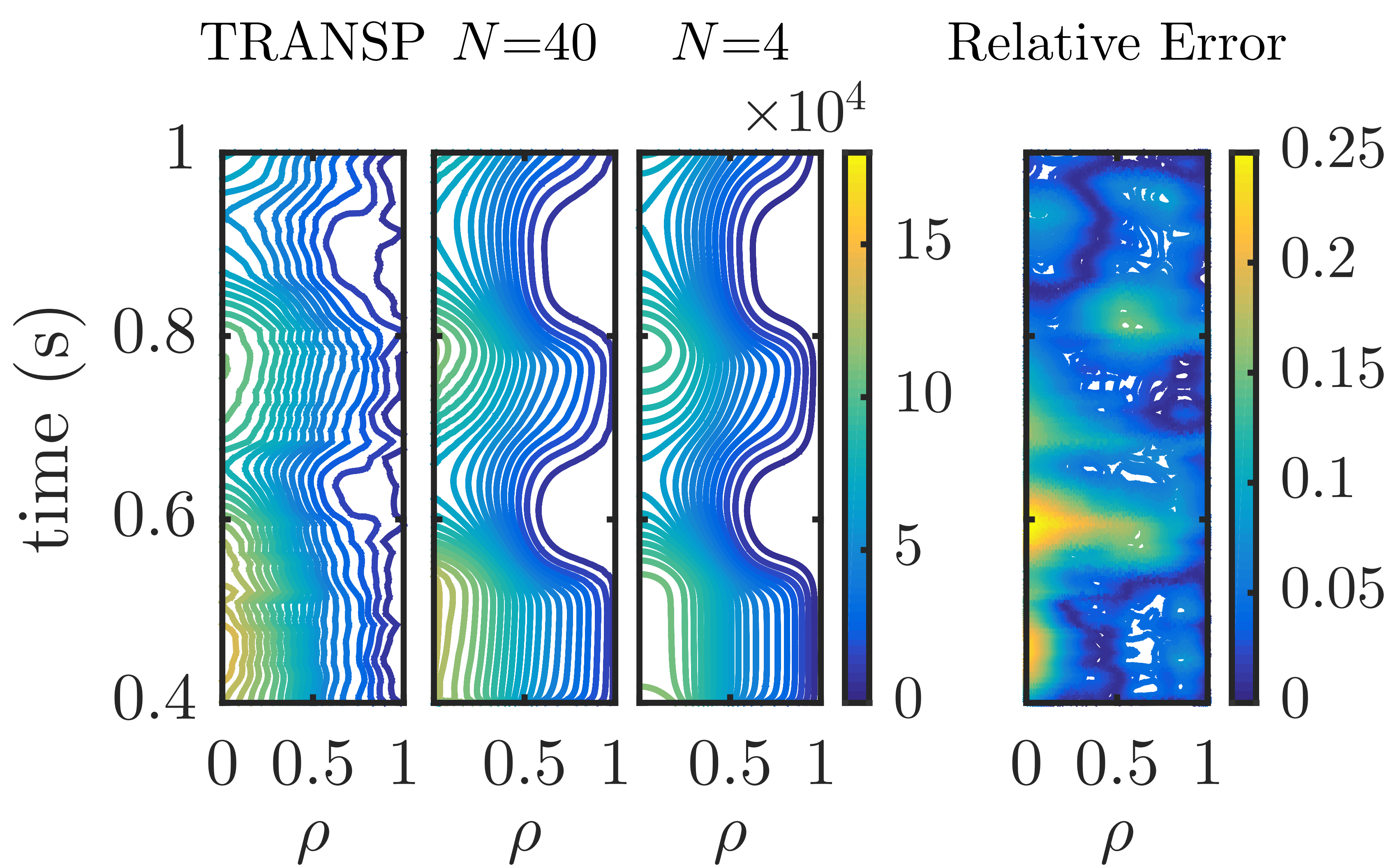
$$\omega(\rho, t) = \sum_{n=1}^{N} a_n(t)\varphi_n(\rho)$$

$$\varphi_n(\rho) = J_0(k_n \rho), \qquad n = 1, \ldots, N$$

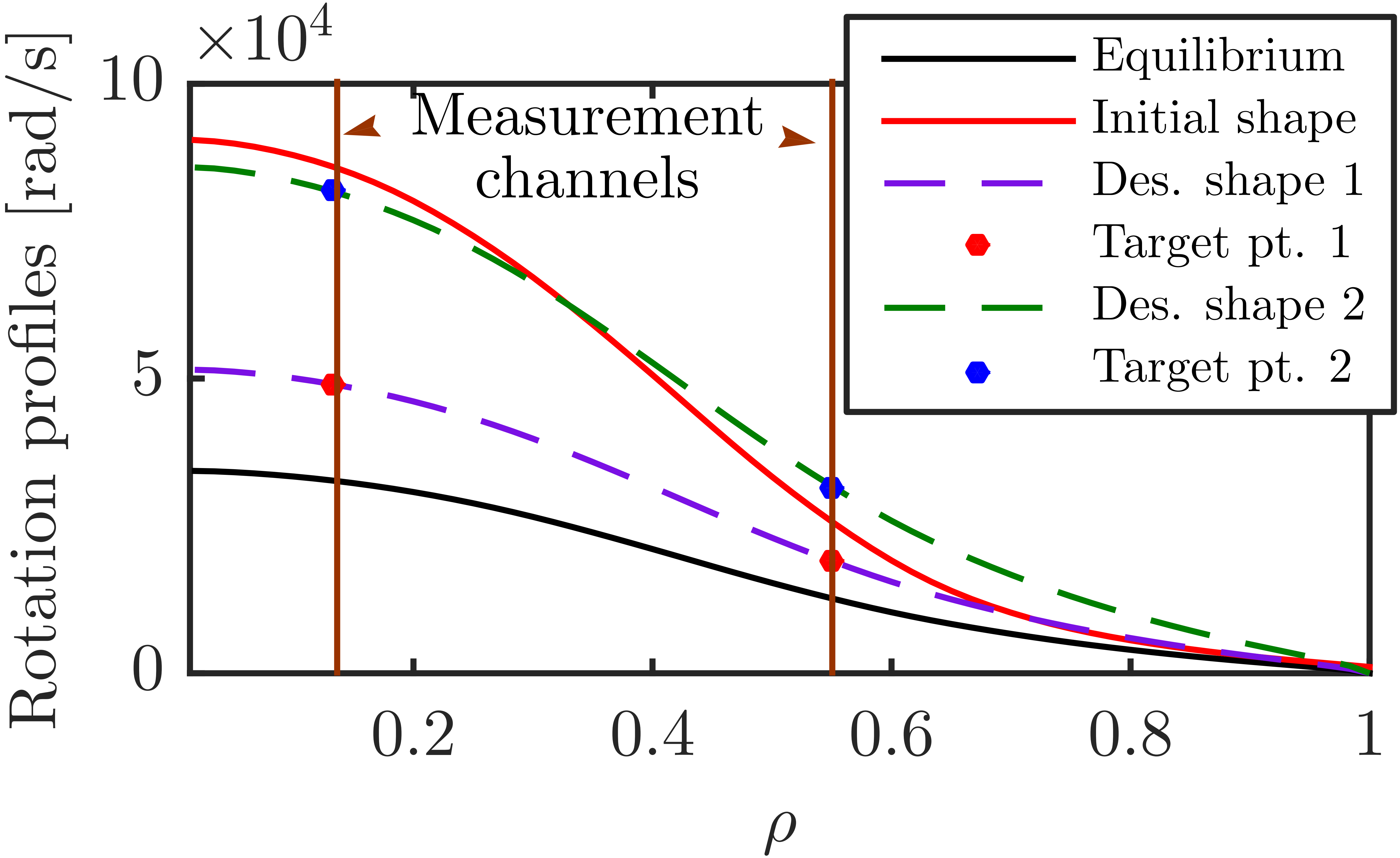
J_0 denotes the Bessel function of the first kind and k_n denotes the n-th root of J_0

$$\langle \varphi_n, \varphi_m \rangle = 0, \qquad \text{for } m \neq n$$

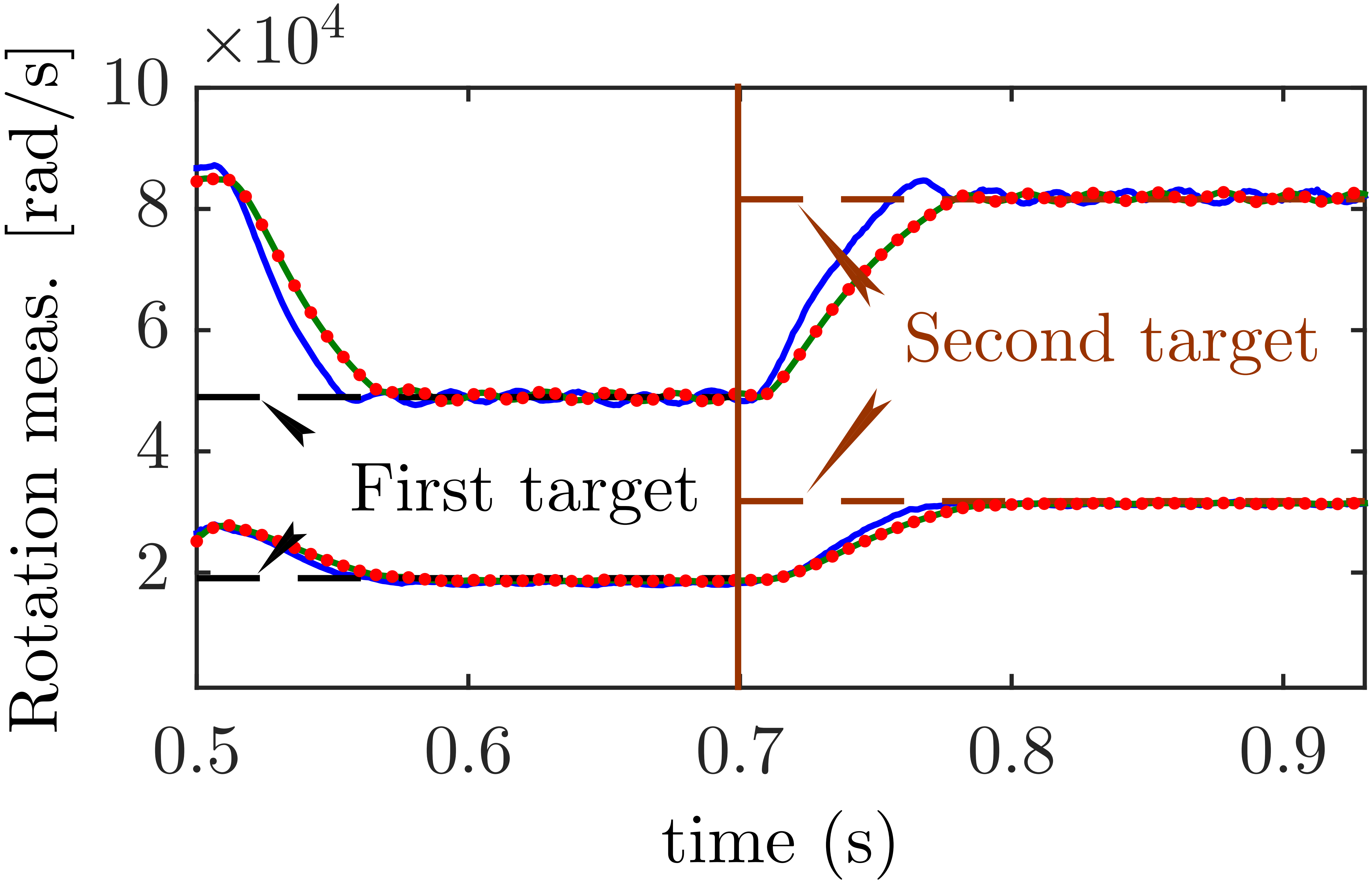
$$\langle f, g \rangle = \int_0^1 \rho\, f(\rho)\, g(\rho)\, d\rho$$



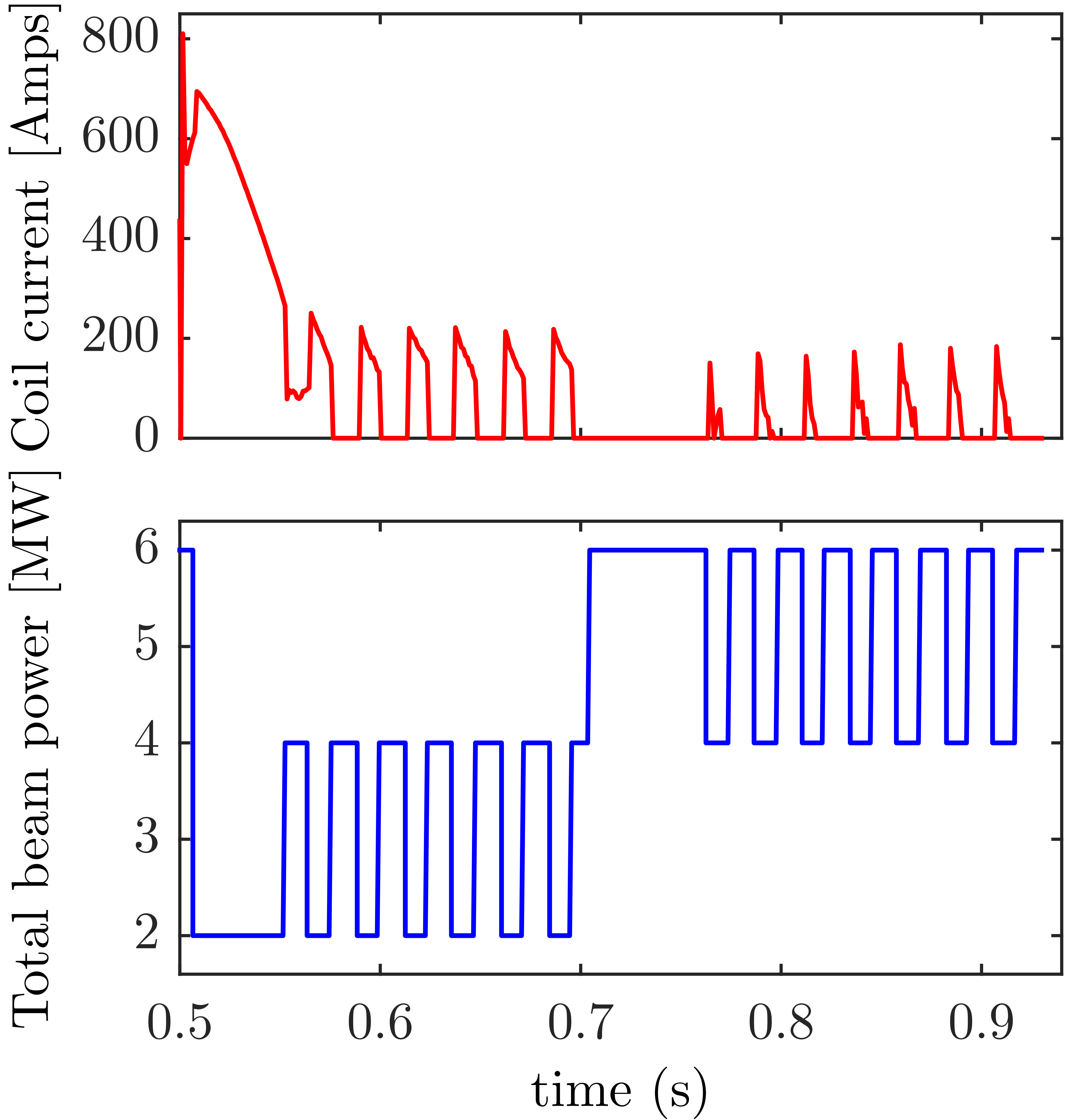
Previous results for NSTX



Previous results for NSTX



Inputs needed for NSTX



Building the state space realization

$$\omega(t,\rho) = \omega_0(\rho) + \omega_1(t,\rho)$$
$$P_{\mathrm{NBI}i}(t) = P_{0i} + P_{1i}(t)$$
$$I(t) = I_0 + I_1(t)$$
$$W = W_0 + W_1$$

$$\frac{\partial}{\partial t}\begin{bmatrix}\omega_1\\ \overline{T}_1\\ \overline{T}_2\\ \overline{T}_3\\ \overline{T}_4\\ W\end{bmatrix} = \overbrace{\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & 0\\ 0 & a_{22} & 0 & 0 & 0 & 0\\ 0 & 0 & a_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & a_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & a_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & a_{66}\end{pmatrix}}^{\mathbf{A}}\begin{bmatrix}\omega_1\\ \overline{T}_1\\ \overline{T}_2\\ \overline{T}_3\\ \overline{T}_4\\ W\end{bmatrix} + \underbrace{\begin{pmatrix} b_{11} & 0 & 0 & 0 & 0\\ 0 & b_{22} & 0 & 0 & 0\\ 0 & 0 & b_{33} & 0 & 0\\ 0 & 0 & 0 & b_{44} & 0\\ 0 & 0 & 0 & 0 & b_{55}\\ 0 & 1 & 1 & 1 & 1\end{pmatrix}}_{\mathbf{B}}\begin{bmatrix}I_1^2\\ P_1\\ P_2\\ P_3\\ P_4\end{bmatrix}$$

$$\dot{x}_1 = Ax_1 + Bu_1$$
$$y_1 = Cx_1$$

$$a_{11} = \frac{1}{nm\langle R^2\rangle}\left[\left(\frac{\partial V}{\partial \rho}\right)^{-1}\frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho}(nm)\chi_\phi\langle R^2(\nabla\rho)^2\rangle\frac{\partial}{\partial\rho}\right] - KG(\rho)\langle R^2\rangle I_0^2\right]$$

$$a_{1,i+1} = \frac{F_{NBI_i}(\rho)}{nm\langle R^2\rangle}$$

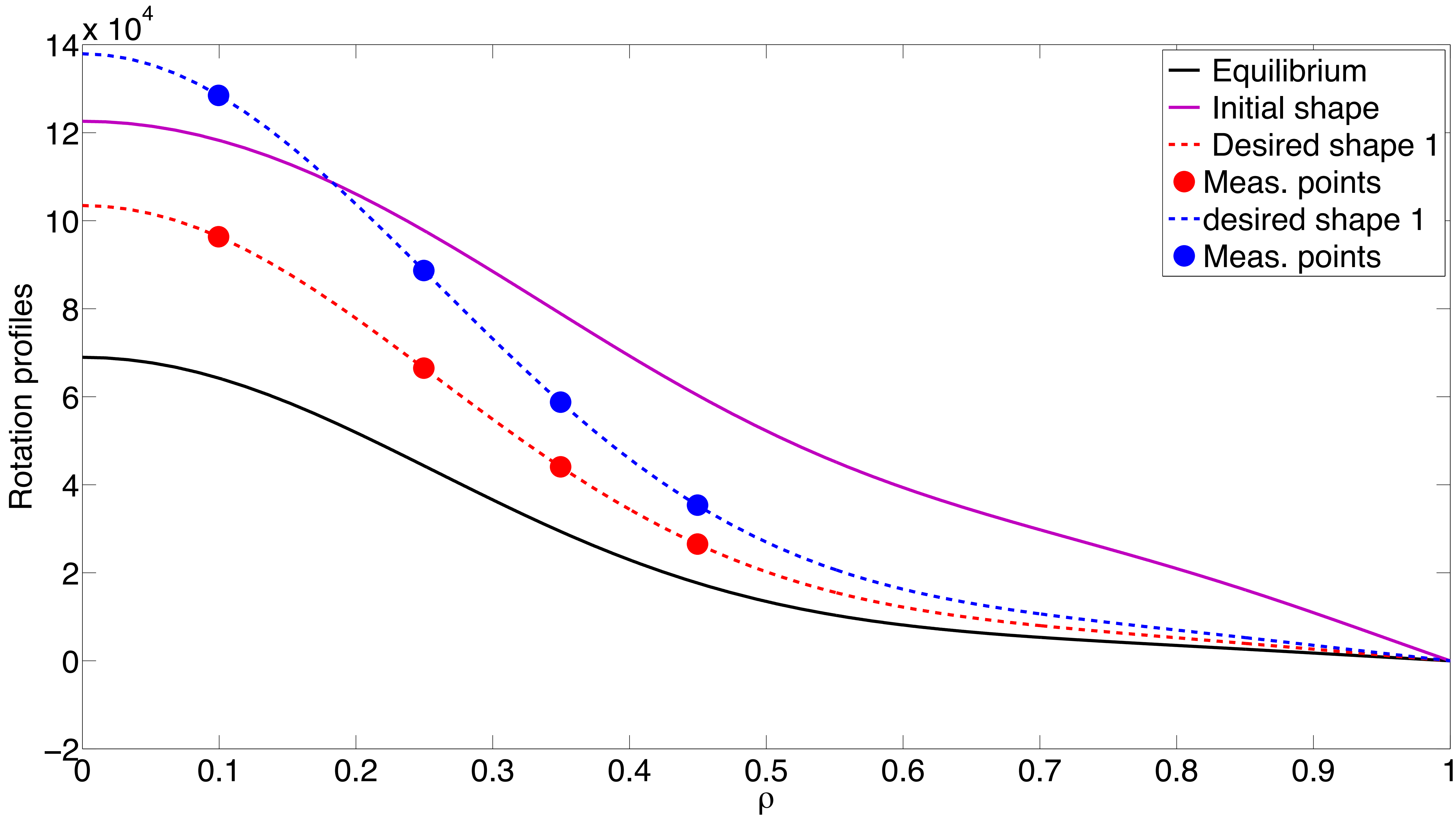
$$a_{i+1,i+1} = -\frac{1}{\tau_{NBI_i}}$$

$$a_{6,6} = -\frac{1}{\tau_E}$$

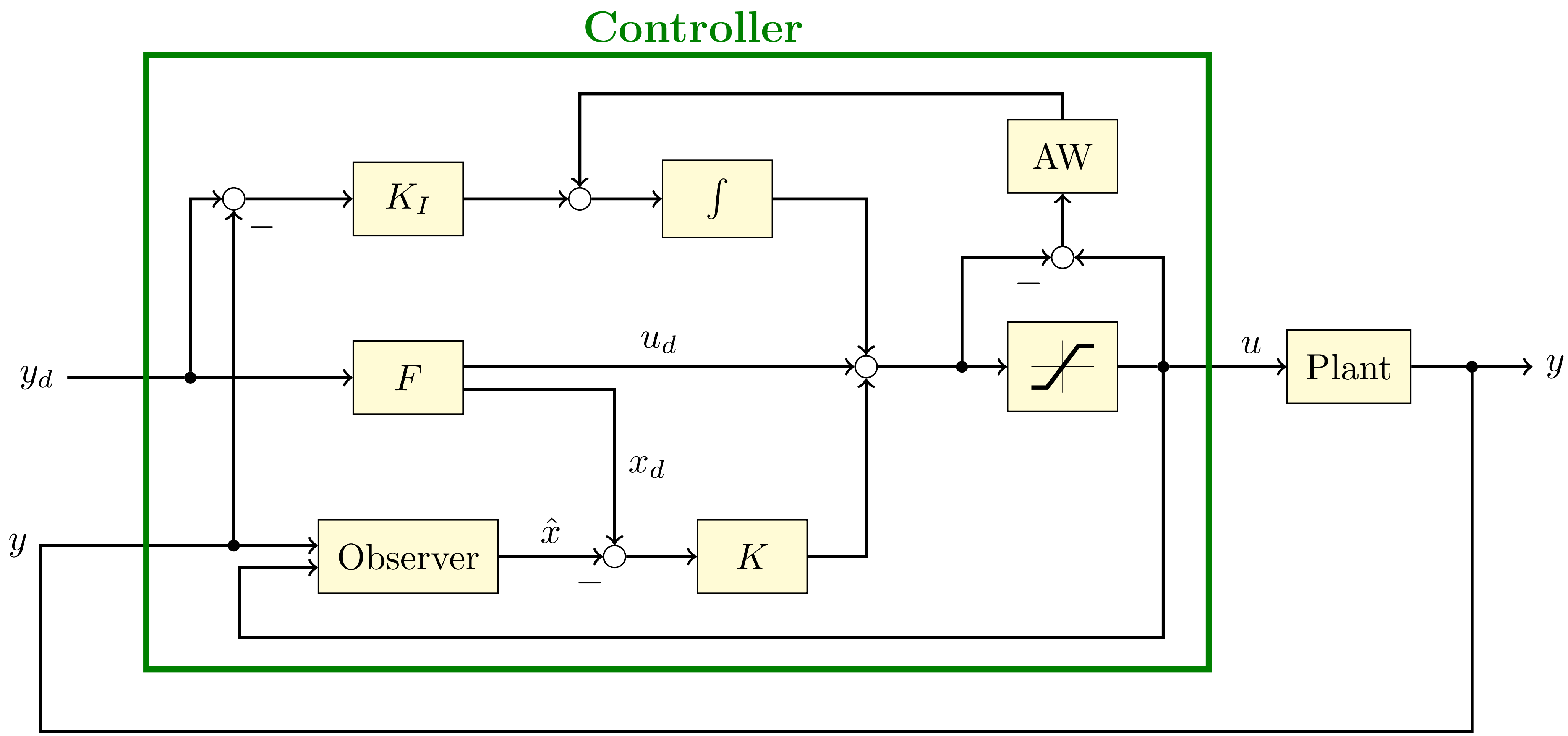
$$b_{11} = -\frac{1}{nm\langle R^2\rangle}KG(\rho)\langle R^2\rangle\omega_0$$

$$b_{i+1,i+1} = \kappa_{NBI_i}$$

Initiation states for NSTX-U:



Controller design (LQG) for NSTX-U:



•Feedforward (F)
Set-point of desired profile

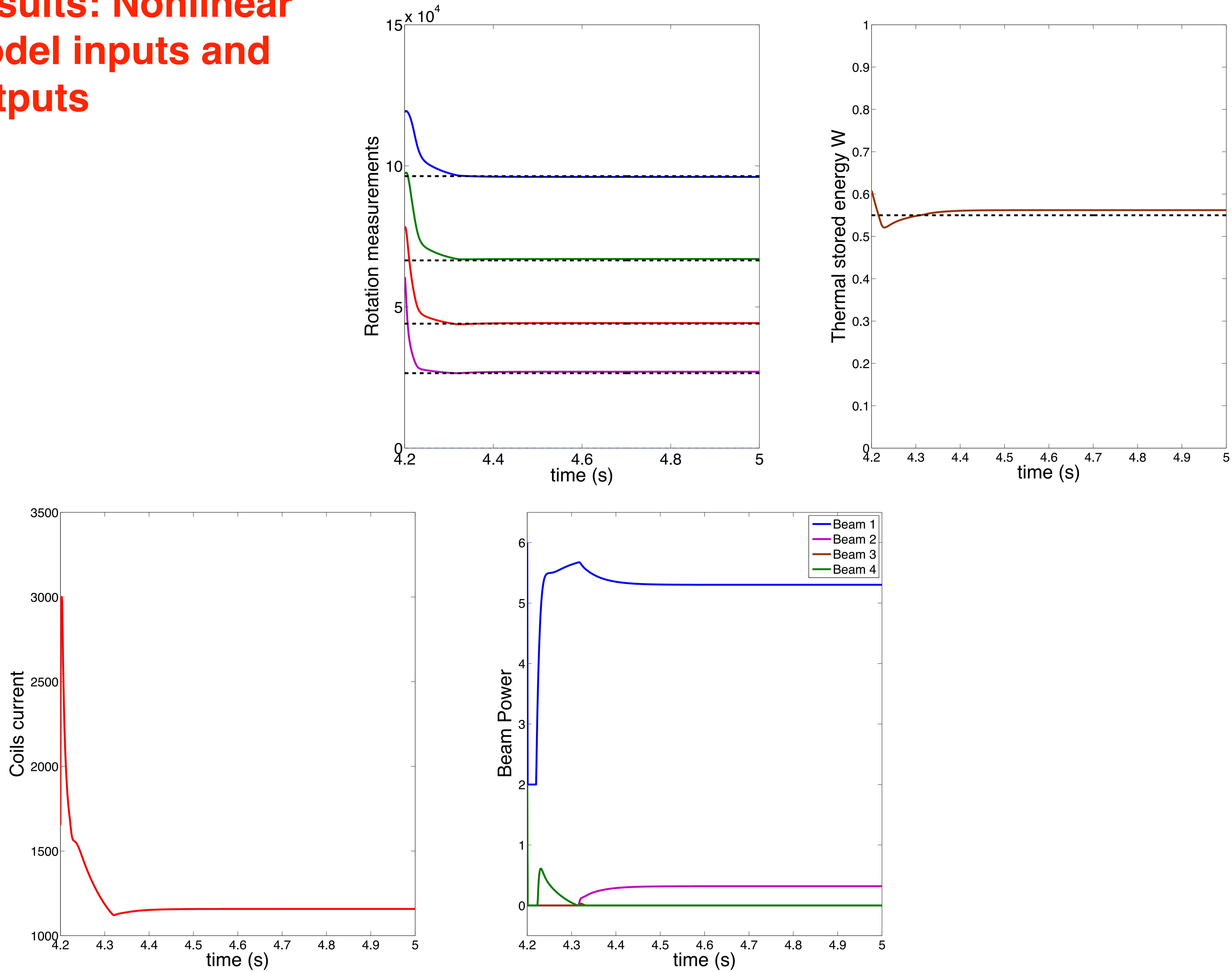
•Linear Quadratic Regulator (K)
Minimize cost function: $\mathcal{J} = \int_{t_0}^{\infty} \left(x^T Q x + u^T R u\right) dt$

•Linear Quadratic Integrator (K_I)
Integrate error to remove steady-state error

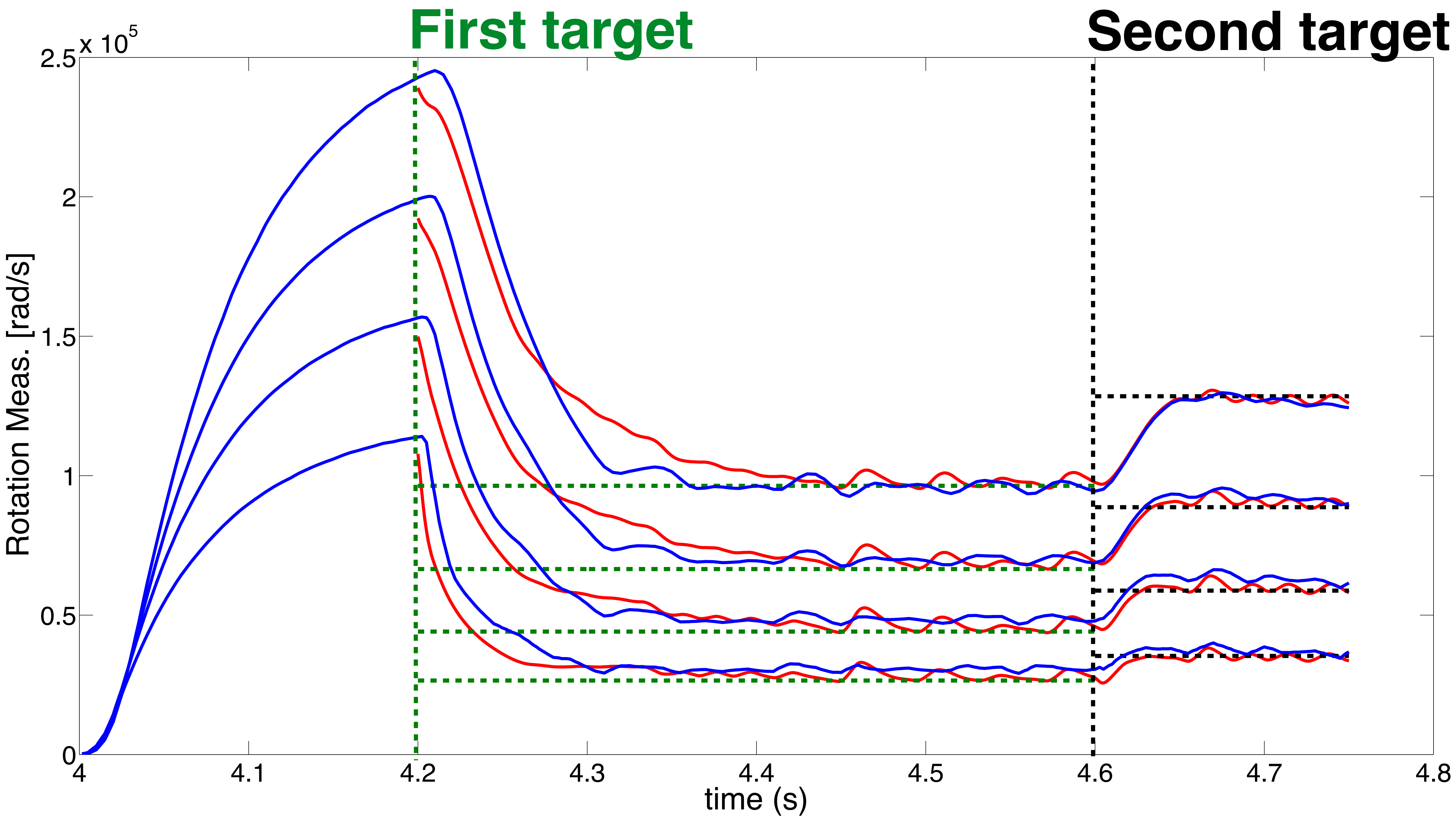
•Anti-windup (AW)
Prevent actuator windup due to saturation

•Observer
Predict full state based on point-wise measurements

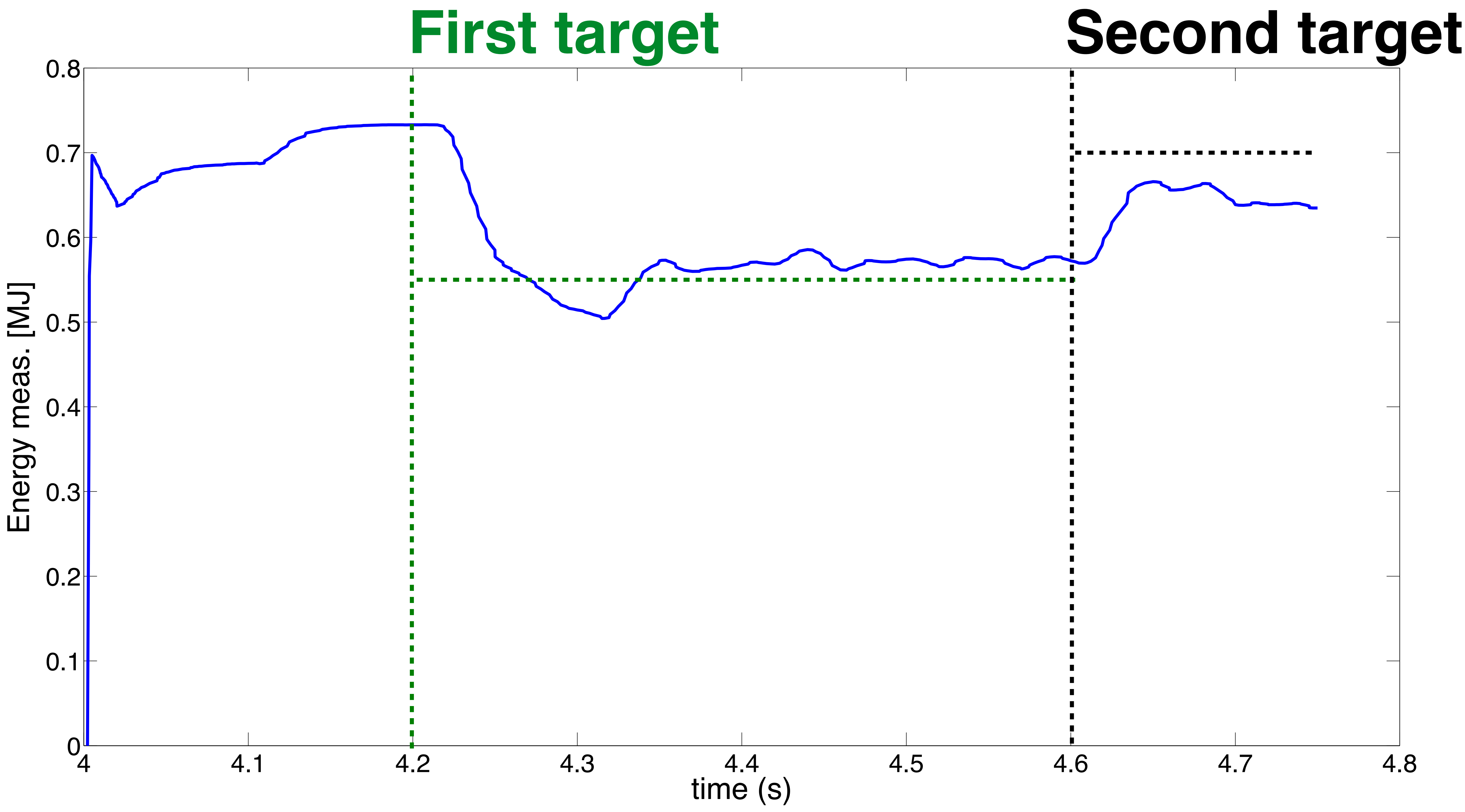
Results: Nonlinear model inputs and outputs



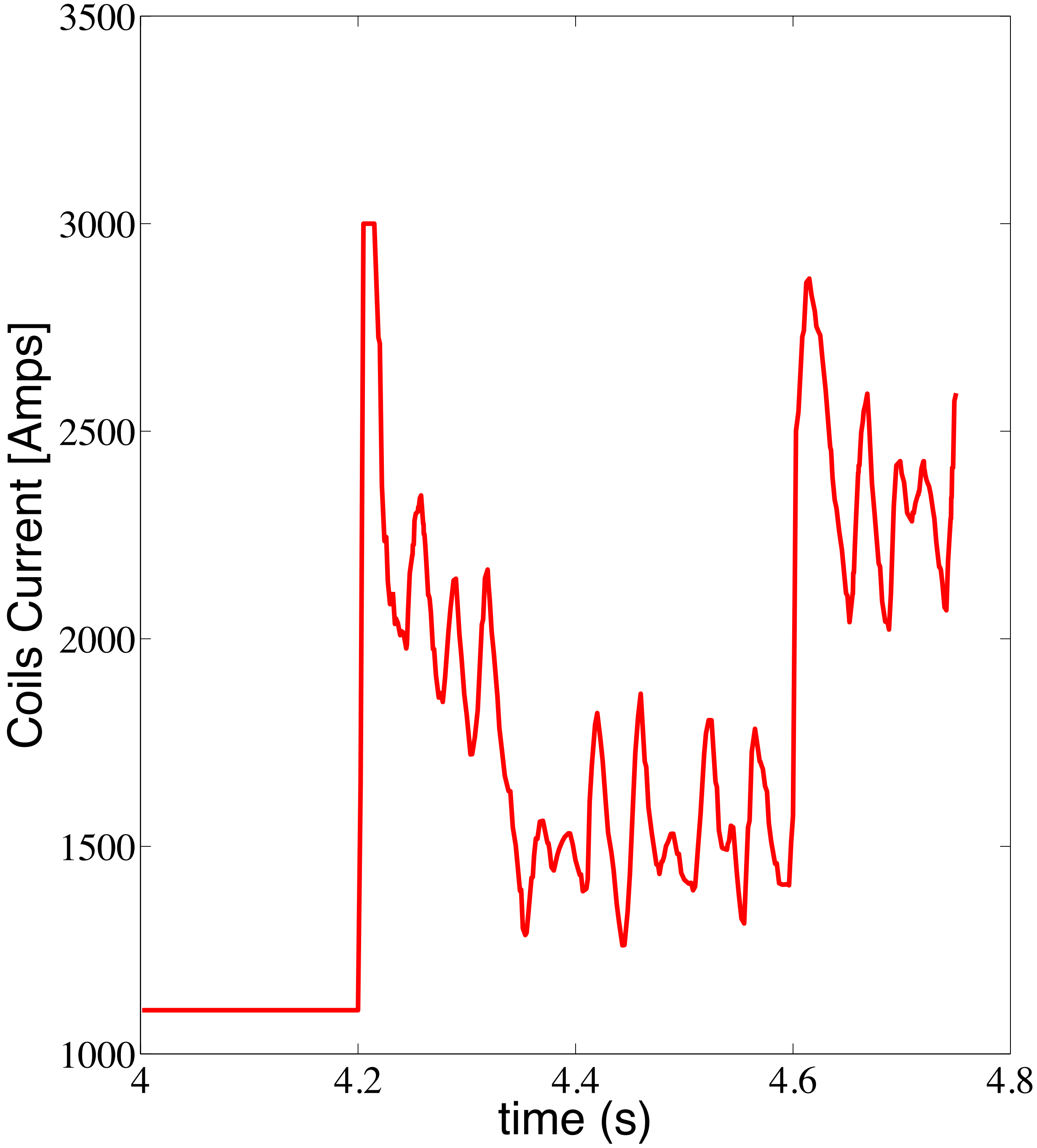
Results: TRANSP model - Measured toroidal rotation

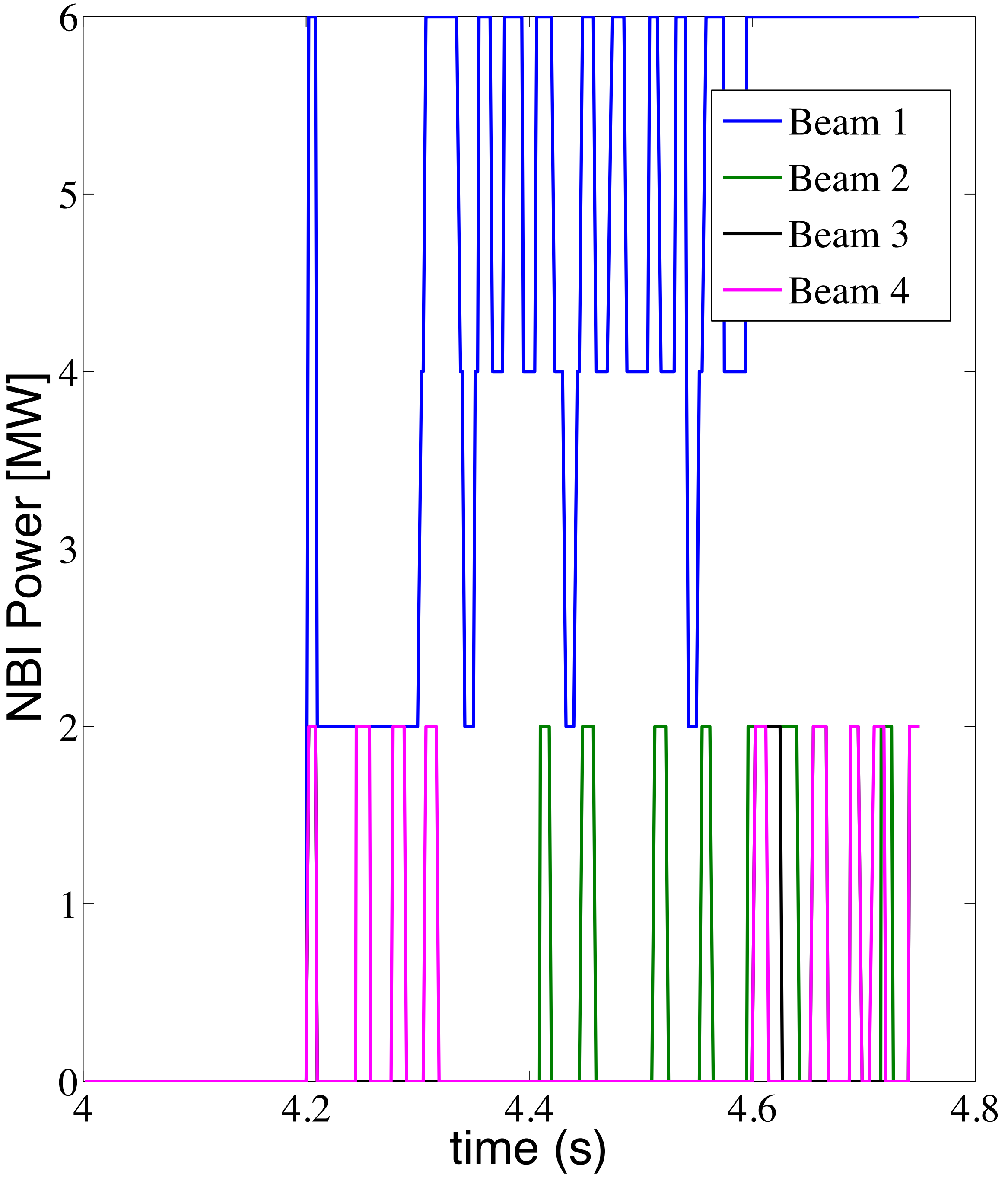


Results: TRANSP model - Measured Stored thermal energy W



Results: TRANSP model - Coil current and Beams power needed





Summary

- NSTX Upgrade device
- Linear control tools
- Based on reduced order model
- Only 4 measurement points
- Strict constraints on the actuators
- Second line of three neutral beams, spatially more extended
- No data available, 100% model based approach
- Satisfactory Control
- Implemented in TRANSP

Work to do

- Study robustness in stability and performance
- Implementing in real machine through PCS