U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

A plasma rotation control scheme for NSTX and NSTX-U

Imene R. Goumiri, *C. W. Rowley, D. A. Gates, S. A. Sabbagh, M. D. Boyer, S. P. Gerhardt, E. Kolemen, J. E. Menard*.

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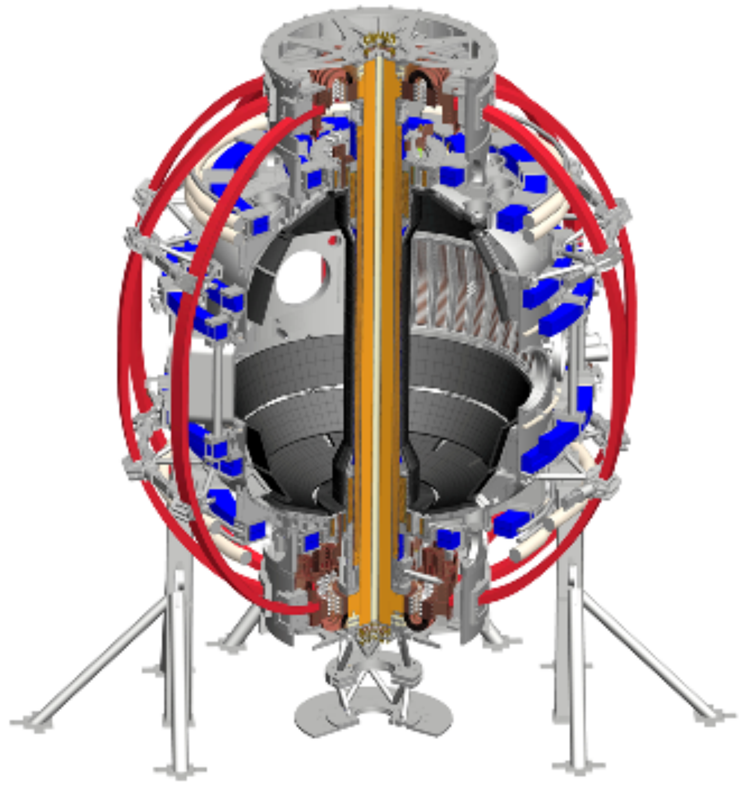

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Controlling toroidal rotation and stored energy helps **avoid disruption**

Issues

- MHD (magnetohydrodynamics) instabilities
- Turbulence

Consequences

- Disruption, plasma termination
- Highly increased transport

NSTX and NSTX-U as laboratory for **Rotation and Stored energy control**

- Plasma has high rotation velocity
- flexible actuators

→ Tracking a reference rotation profile and stored energy value using **feedback control theory**

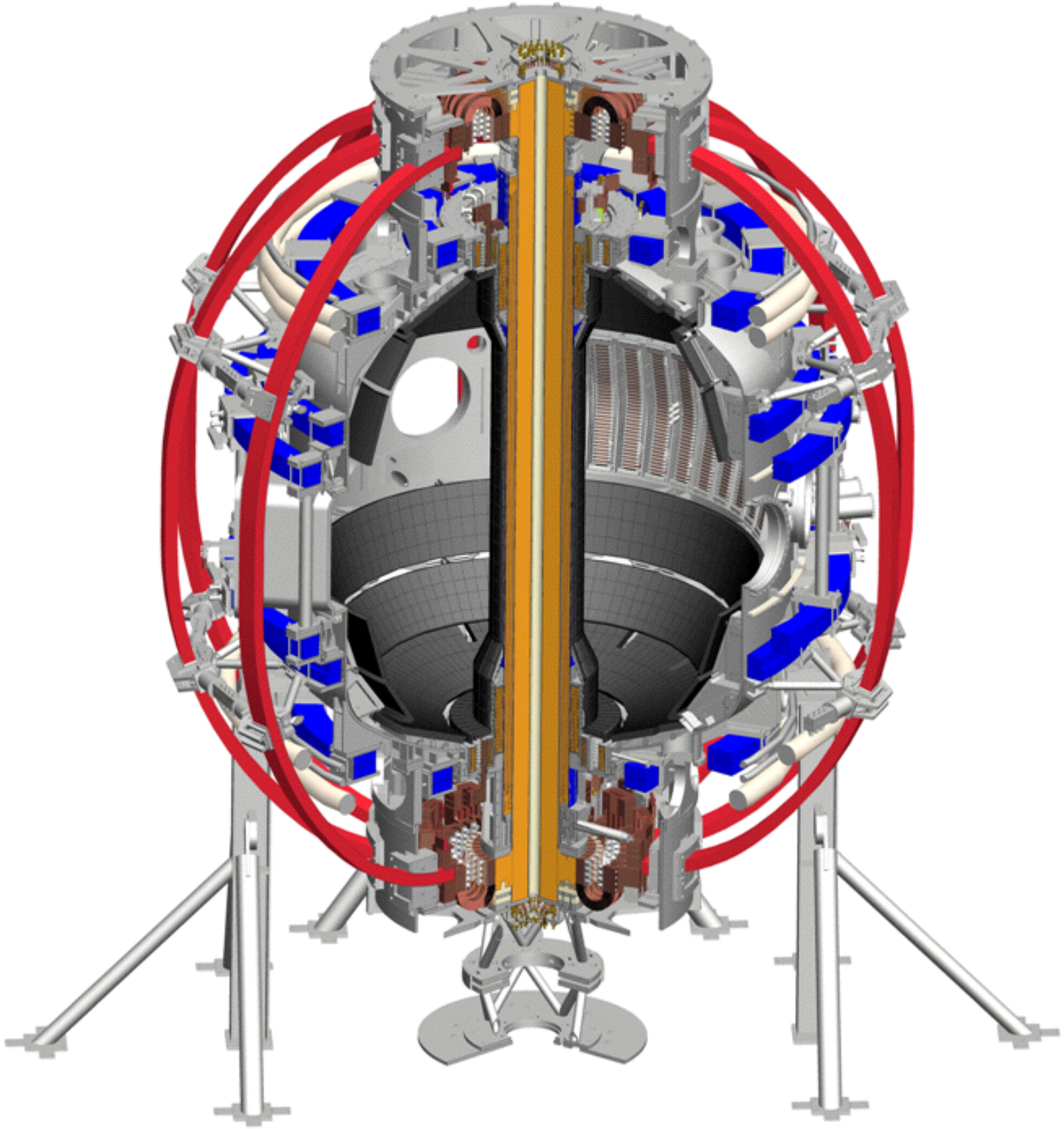
The National Spherical Torus Experiment Upgrade

The primary components of the upgrade:

- **Replacement** of the center stack:
  - inner-leg of the toroidal field coils
  - the ohmic heating solenoid
- **Addition** of a second neutral beam injector at large major radius

The upgrade of NSTX machine increases:

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



Can we drive a state of a system to a desired state and stabilize it there?

Main idea :

Established methods of **reduced order modeling** and **feedback** control for **linear time invariant** systems enable us to build *controllers* to solve some plasma fusion tokamaks issues.

1- **Modeling**
- Start with a model of the dynamics
- Apply model reduction
- Linearization

2- **Controlling**
- Building a *linear controller* for the *linear reduced* order model
- Connect the controller to the original *nonlinear* model

Complexity of the rotation control problem motivates **advanced control**

- Spatially distributed, **multi-input-multi-output** system
  Controlled Variables: rotation profile and stored energy
  Actuators: individual beam powers, Coil current

- **Actuator limitations:** maximum/minimum beam power and coil current

- Handling experimental **noise**, possibly **limited real-time measurements** **(***see* Podesta **NP10.00009** wed. AM**)**

- Some of the **model parameters are uncertain** making planning actuator trajectories offline difficult

- It may be necessary to **balance competing goals** to achieve optimal performance

- Need to respect **constraints** to avoid MHD instabilities or machine limits

TRANSP simulation used as plasma proxy for developing control algorithm

time-dependent transport code

TRANSP

Interpretive mode

Read, smooth (treat), manipulate experimental data

Predictive mode

Model and simulate mechanisms and physics dynamics: Rotation, stored energy

plays a role of a tokamak plasma

- TRANSP can run in two different modes.
- The control algorithm used within TRANSP prediction
- Momentum diffusivity is inferred from NSTX data

1- Toroidal rotation: the modeling

The physics models for the rotation and energy control

Toroidal Momentum Equation

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

Equilibrium property fixed in time

Stored Energy Equation:

Stored energy

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

Energy confinement time

Actuators

NBI: Neutral Beam Injection

NTV: Neoclassical Toroidal Viscosity

Important Model parameters

ITER 98 empirical energy confinement scaling

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

χ_ϕ (momentum diffusivity) is inferred from NSTX data

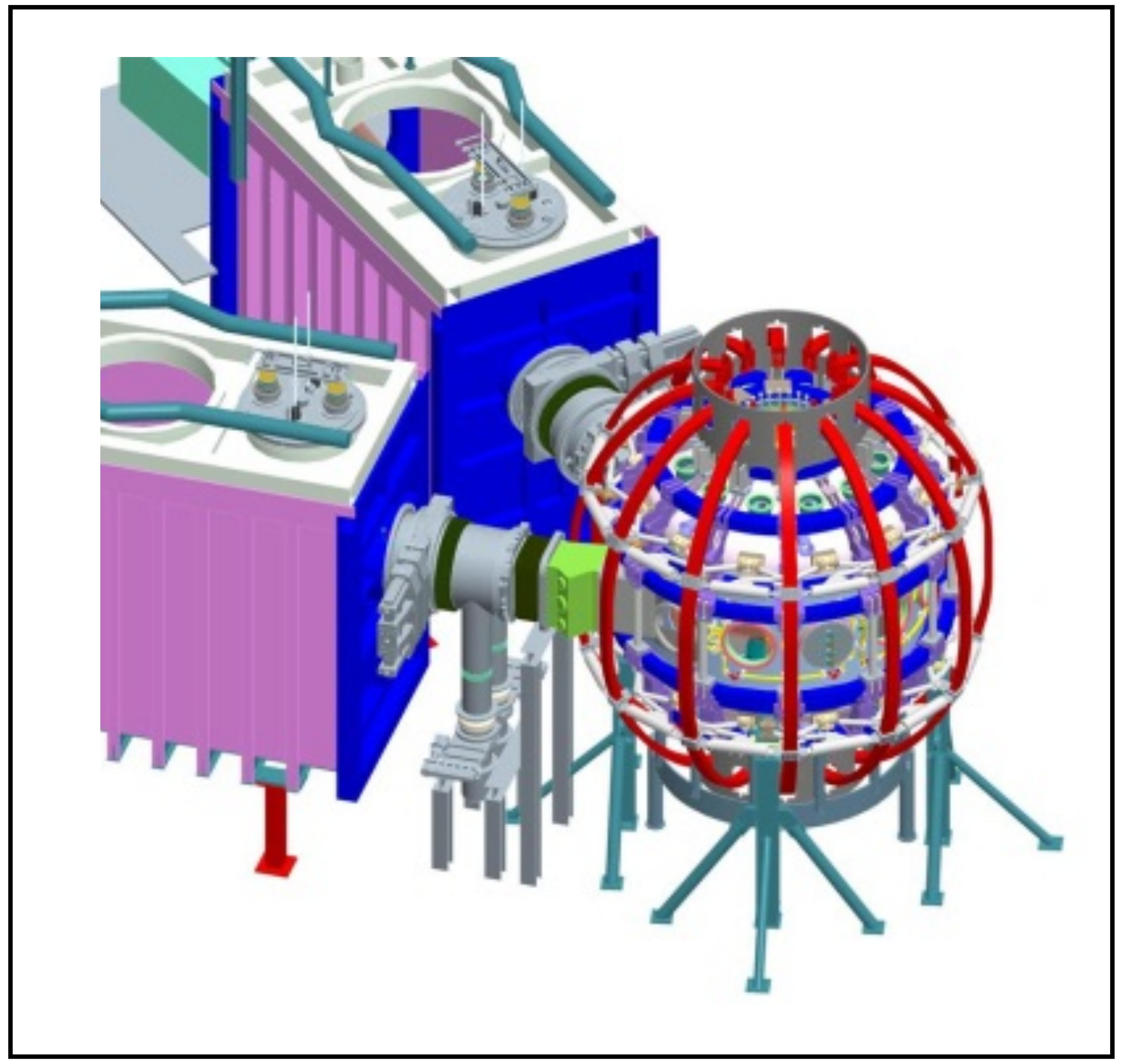
The modeling of the NBI actuator

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

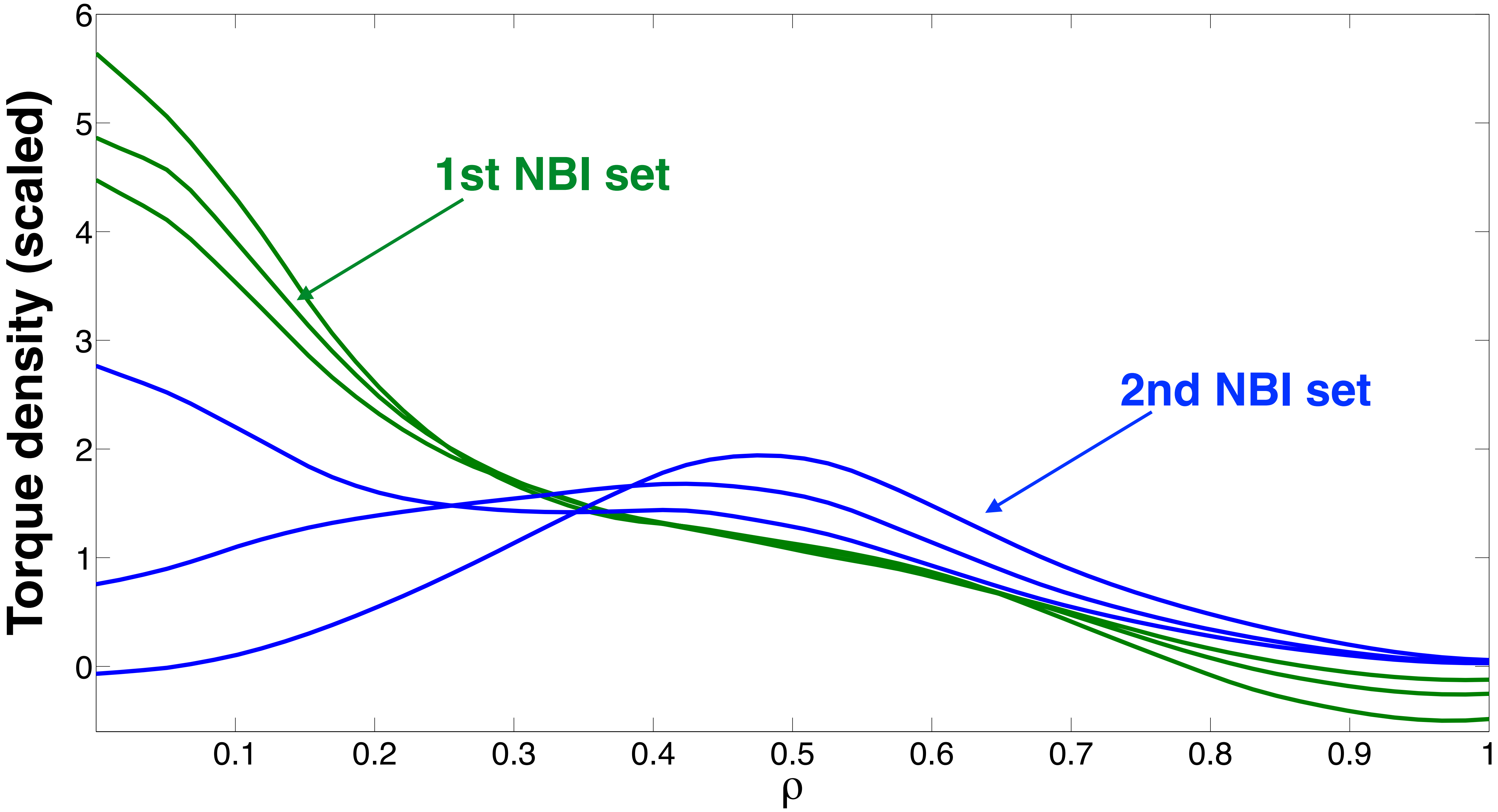
$$\frac{\partial \overline{T}_{\mathrm{NBI}i}}{\partial t} + \frac{\overline{T}_{\mathrm{NBI}i}}{\tau_{\mathrm{NBI}i}} = \kappa_{\mathrm{NBI}i} P_{\mathrm{NBI}i}(t)$$

Slowing down time

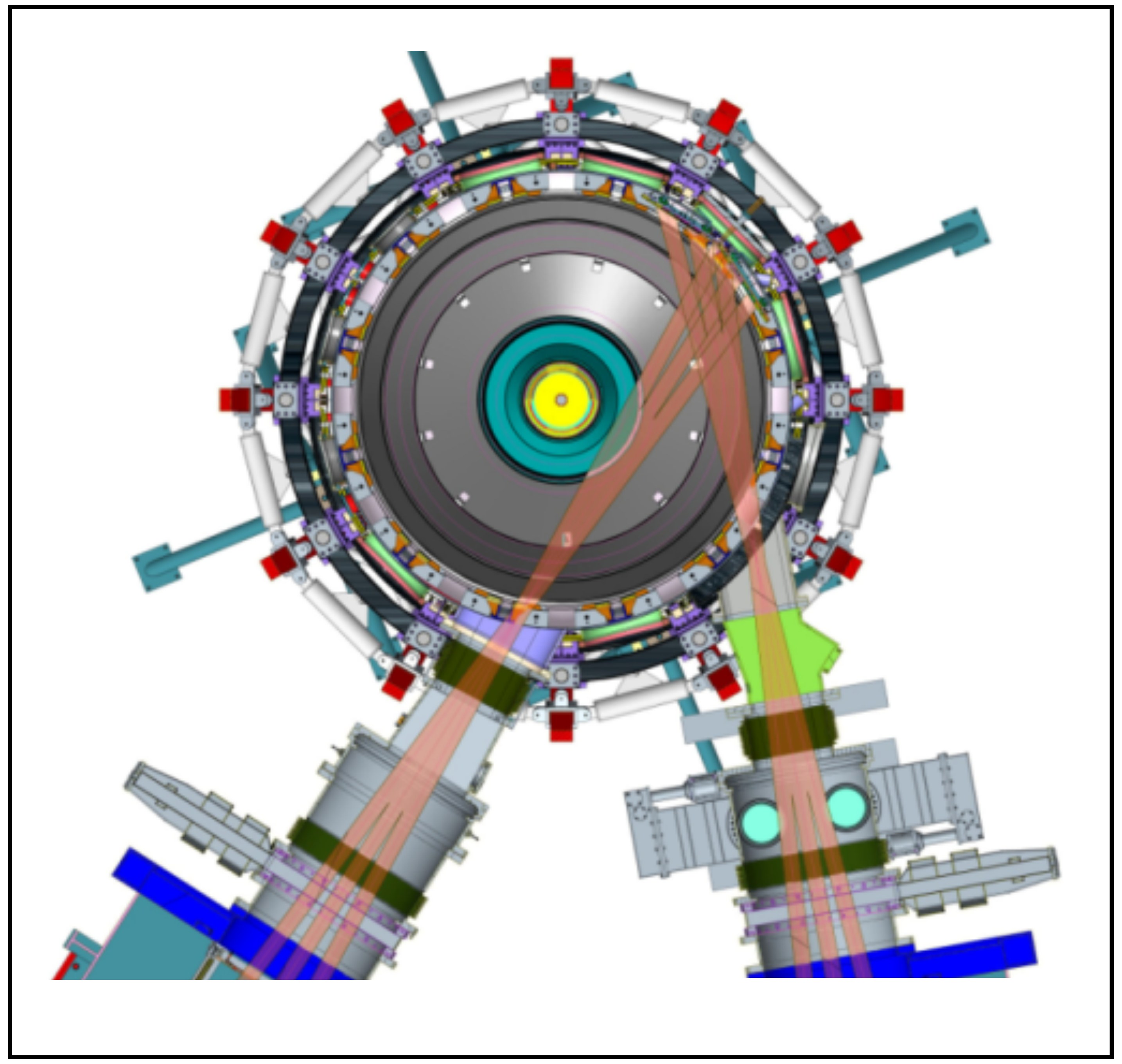
- 6 NBI beams – Power 2MW each: Max 12MW
- Each beam can be blocked 20 times max.
- Block min duration: 10ms
- Min duration between blocks: 10ms



NBI: Neutral Beam Injection



- **First neutral beam sources do not give different torque profiles**
- **Sources of set 2 give more flexibility for the control**



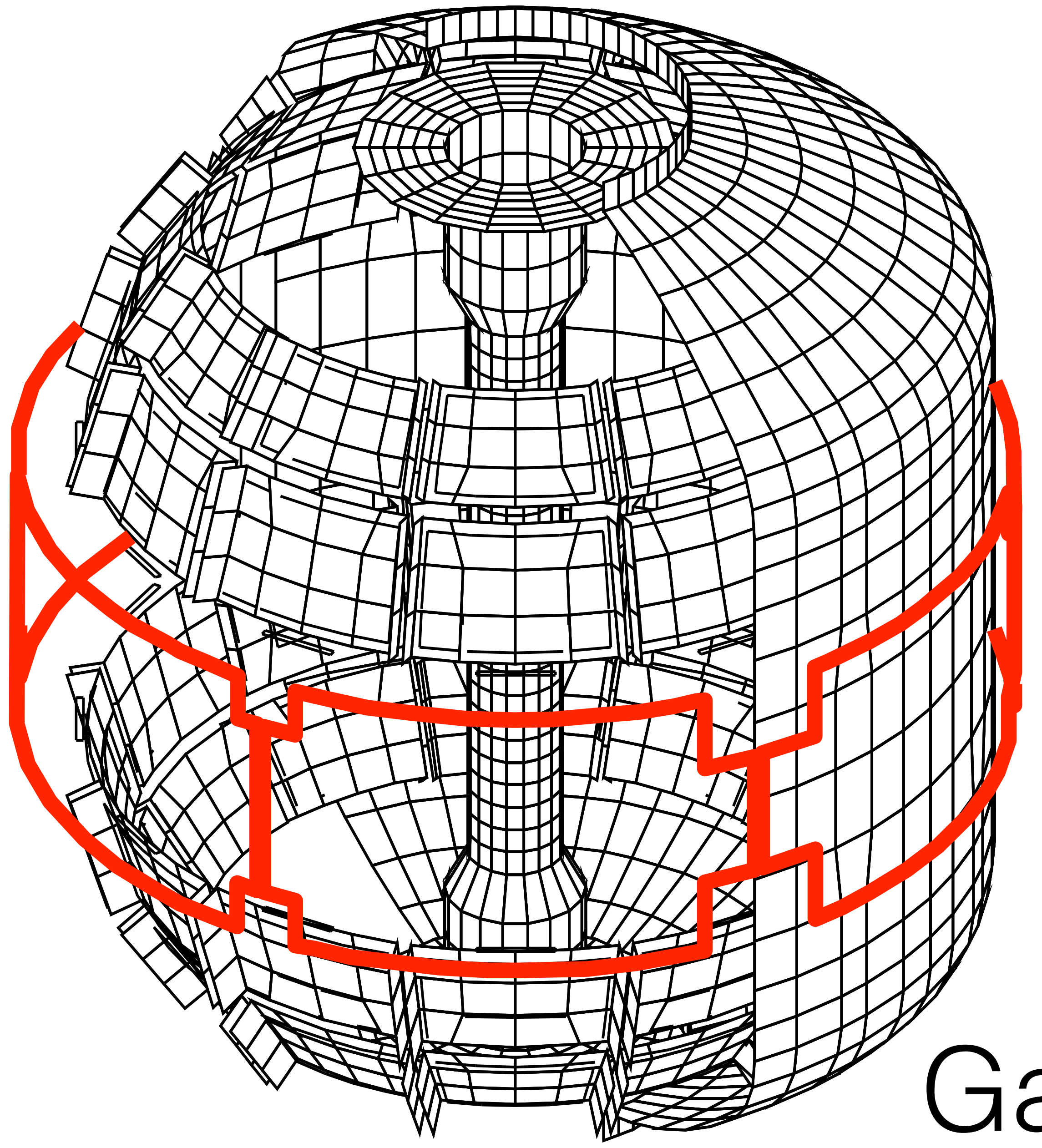
NBI set 1 **NBI set 2**

The modeling of the NTV actuator

NTV: Neoclassical Toroidal Viscosity

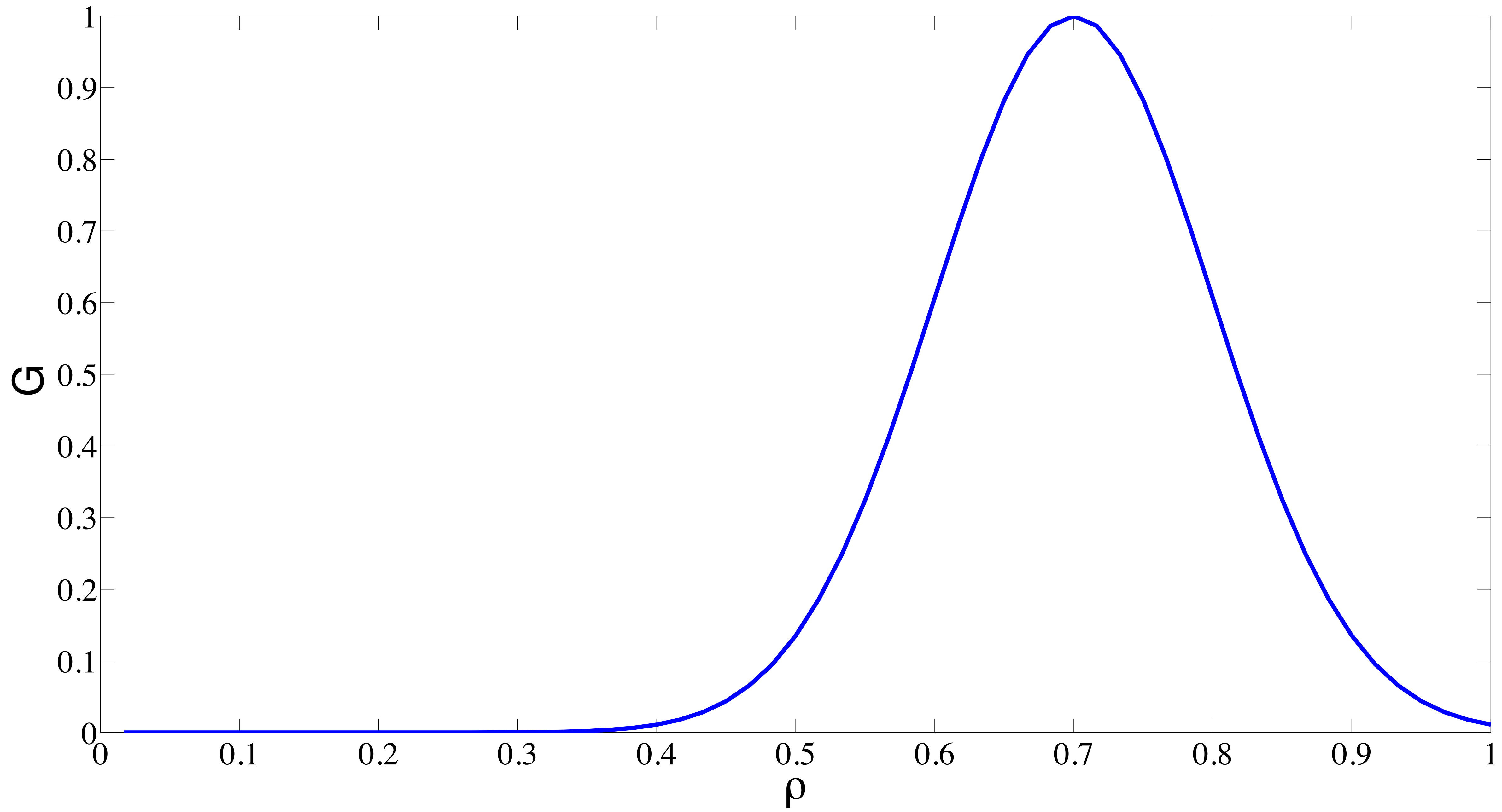
- 3D magnetic field → non-ambipolar diffusion → drag
- Same model used for NSTX & NSTX-U: Max. Current = 3kA

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

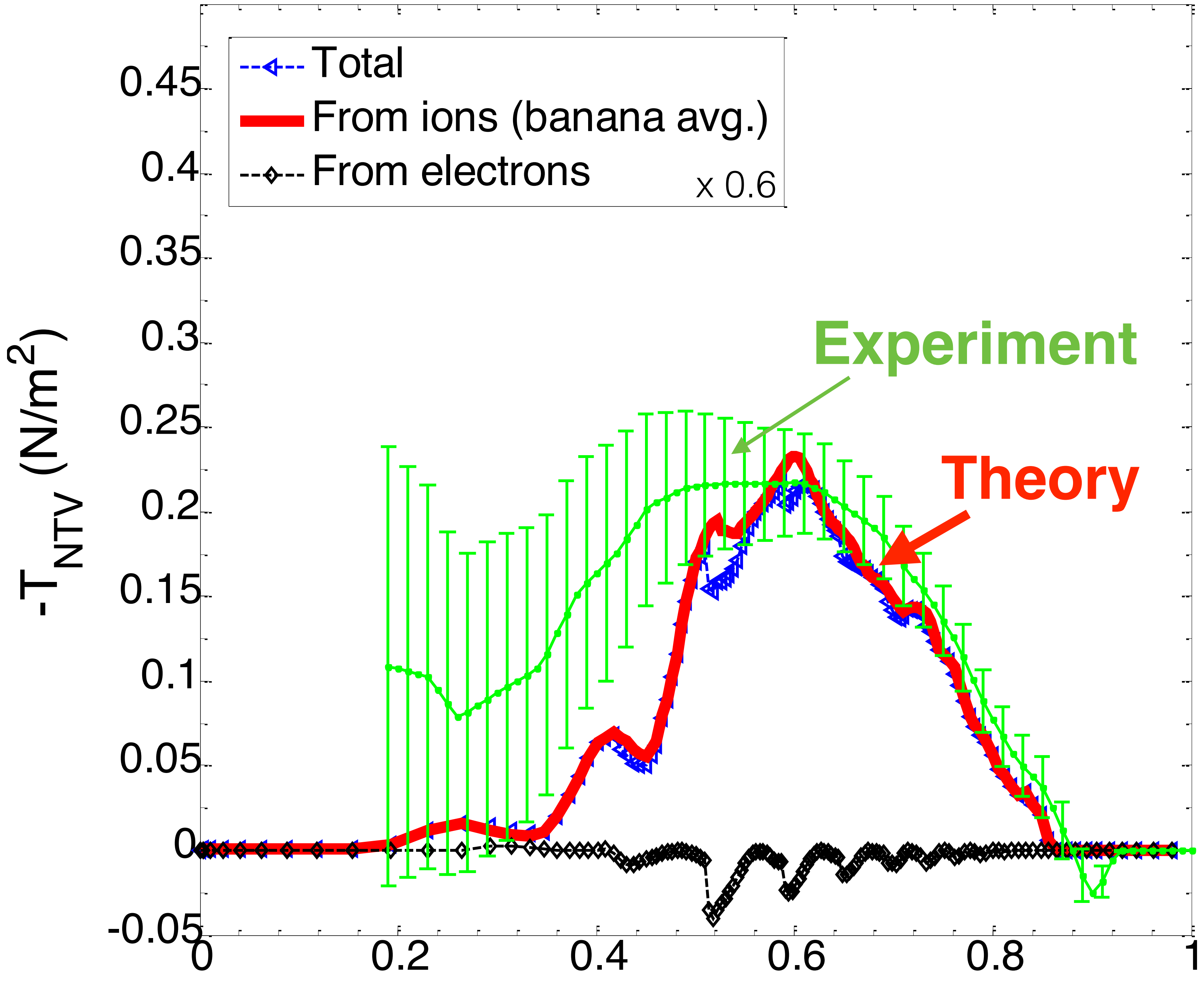


3D magnetic field coils

Gaussian approximation



Experimental NTV profile



W. Zhu, et al., PRL 96 (2006) 225002

S.A. Sabbagh, et al. IAEA FEC (2014) paper EX/1-4

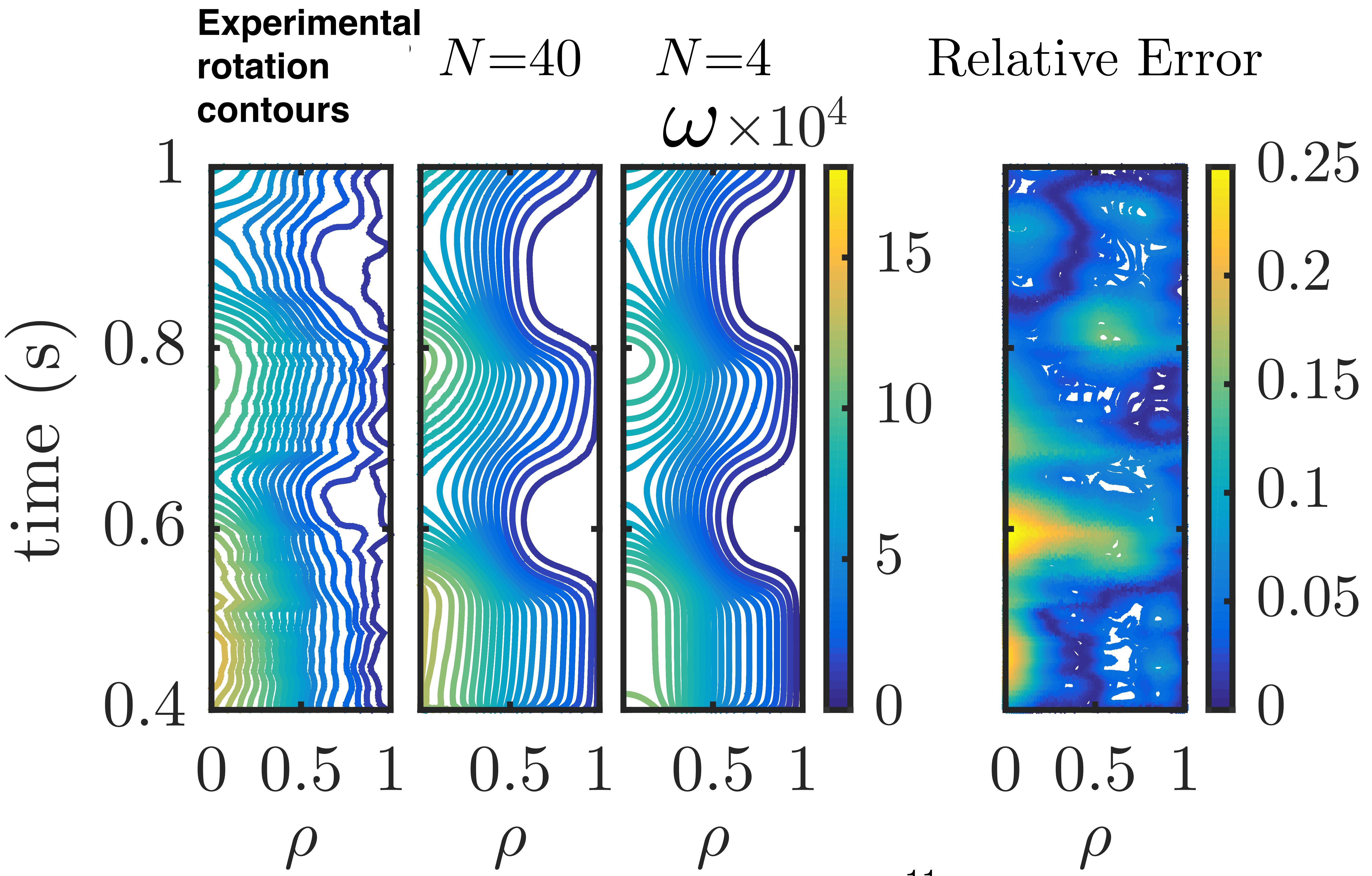
Comparison of the rotational frequency between Reduced order **Models** and **TRANSP**

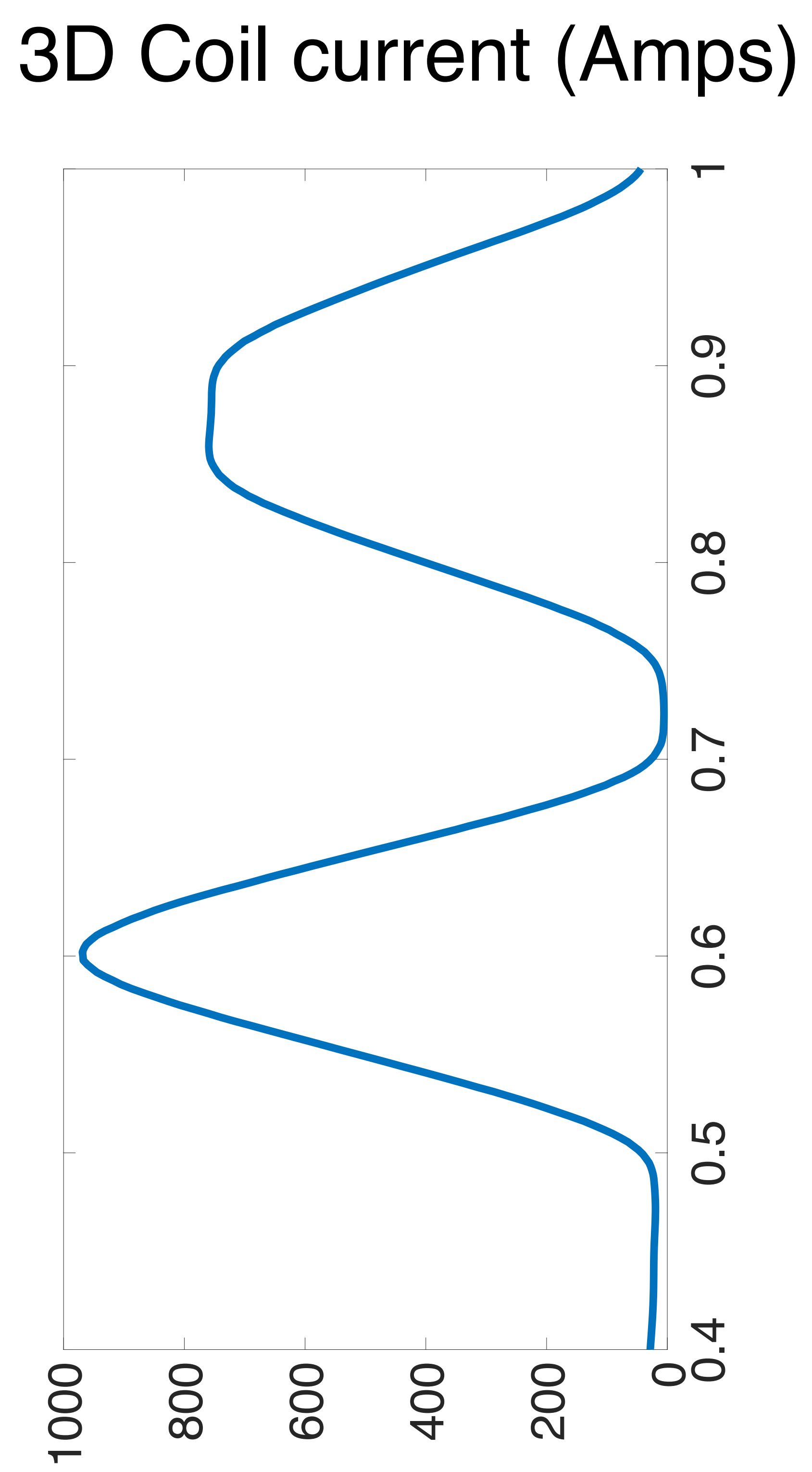
$$\omega(\rho, t) = \sum_{n=1}^{N} a_n(t)\varphi_n(\rho)$$

where

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

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





Summary of the governing equations for **rotation control**

1- Simplified Toroidal Momentum Equation

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

2- Energy Equation

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

3- NBI torque modeling

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

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

4- NTV torque modeling

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

2- Toroidal rotation: the control

Control theory can help us design the feedback control law

Model-based control

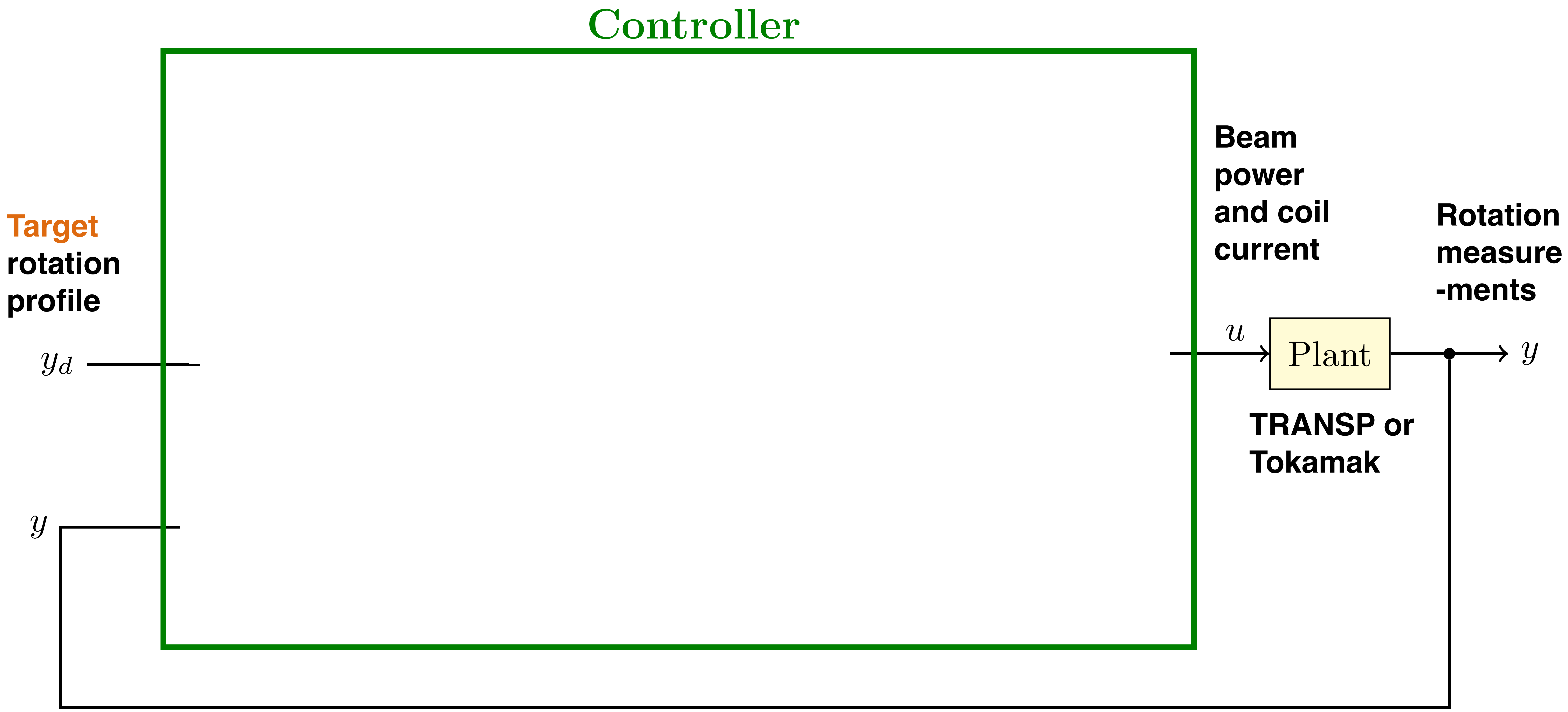
- Embeds (simplified) models of the known **physics in the design**
- Provides **constructive** tools for structuring and tuning control laws

  Saves experimental time*! (compared to empirical tuning)*

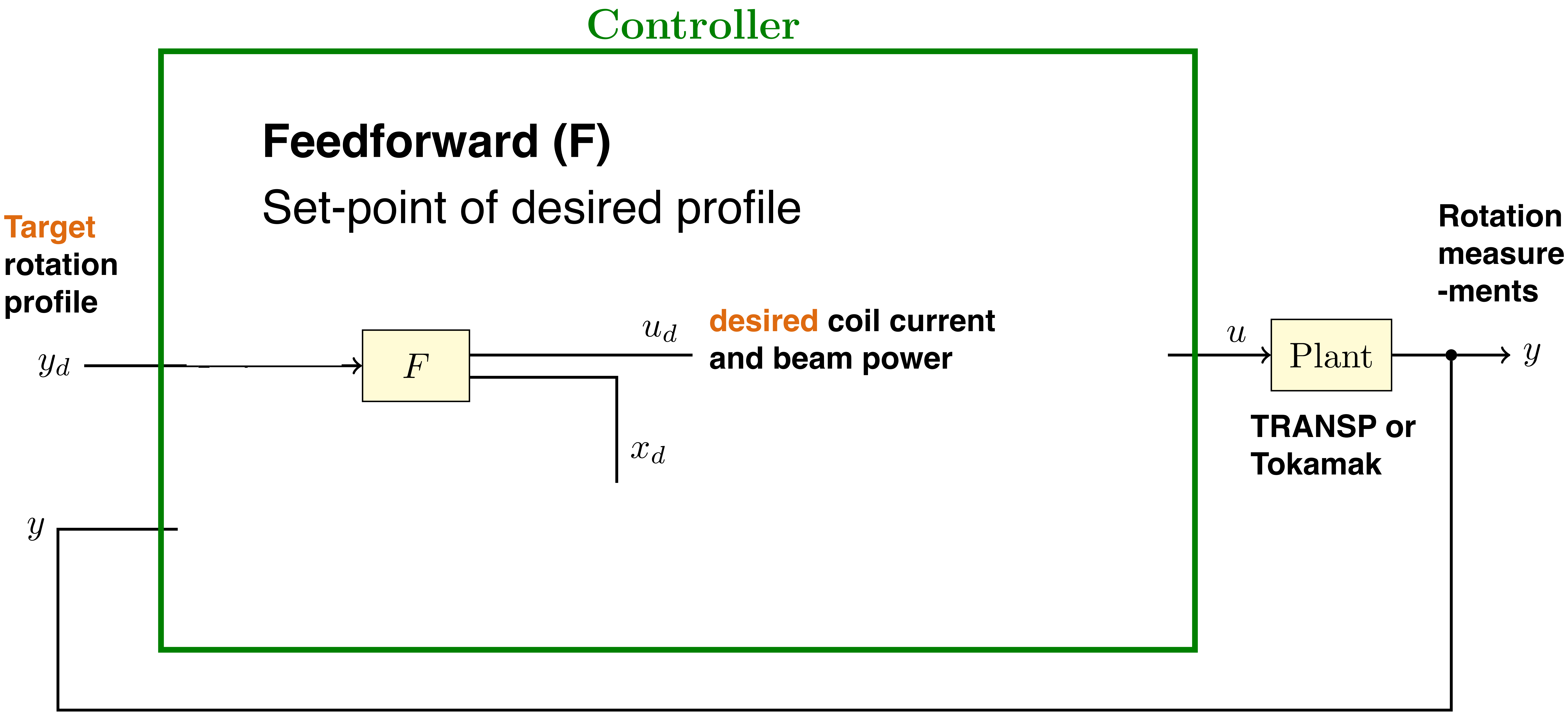
Linear-Quadratic-Regulator with Integral Action **(LQI)**

- The **optimal** control law given a **linear system** and a **quadratic cost function**
- Achieves **tracking** and **disturbance rejection**
- Typically **robust** (can tolerate modeling uncertainties due to linearization to a reasonable degree)

Overview of the designed control system



Overview of the designed control system



Controller

Feedforward (F)

Set-point of desired profile

Target rotation profile

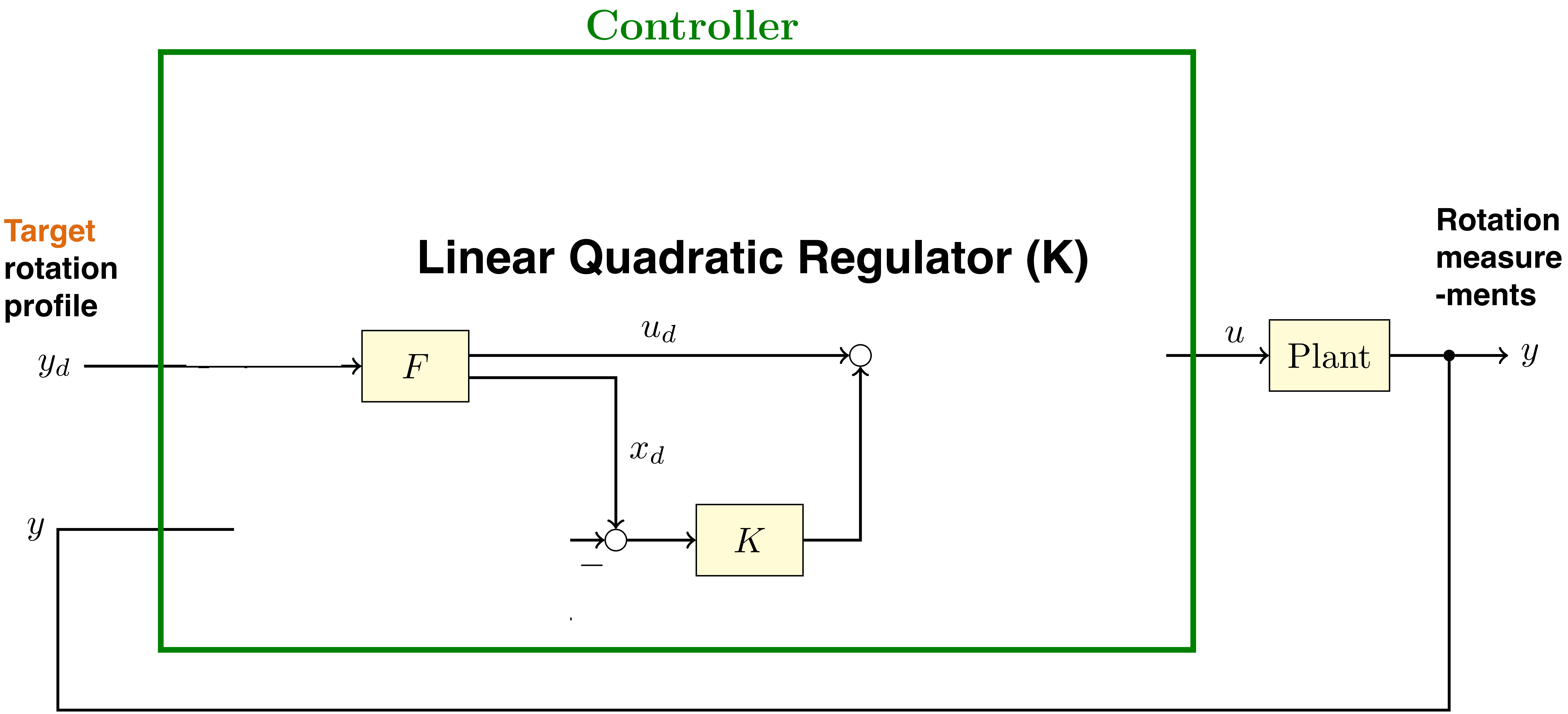
desired coil current and beam power

Rotation measure -ments

TRANSP or Tokamak

- A **pre-defined** way without responding to how the system reacts
- This control action is **independent** of the "plant output” (Open loop control)

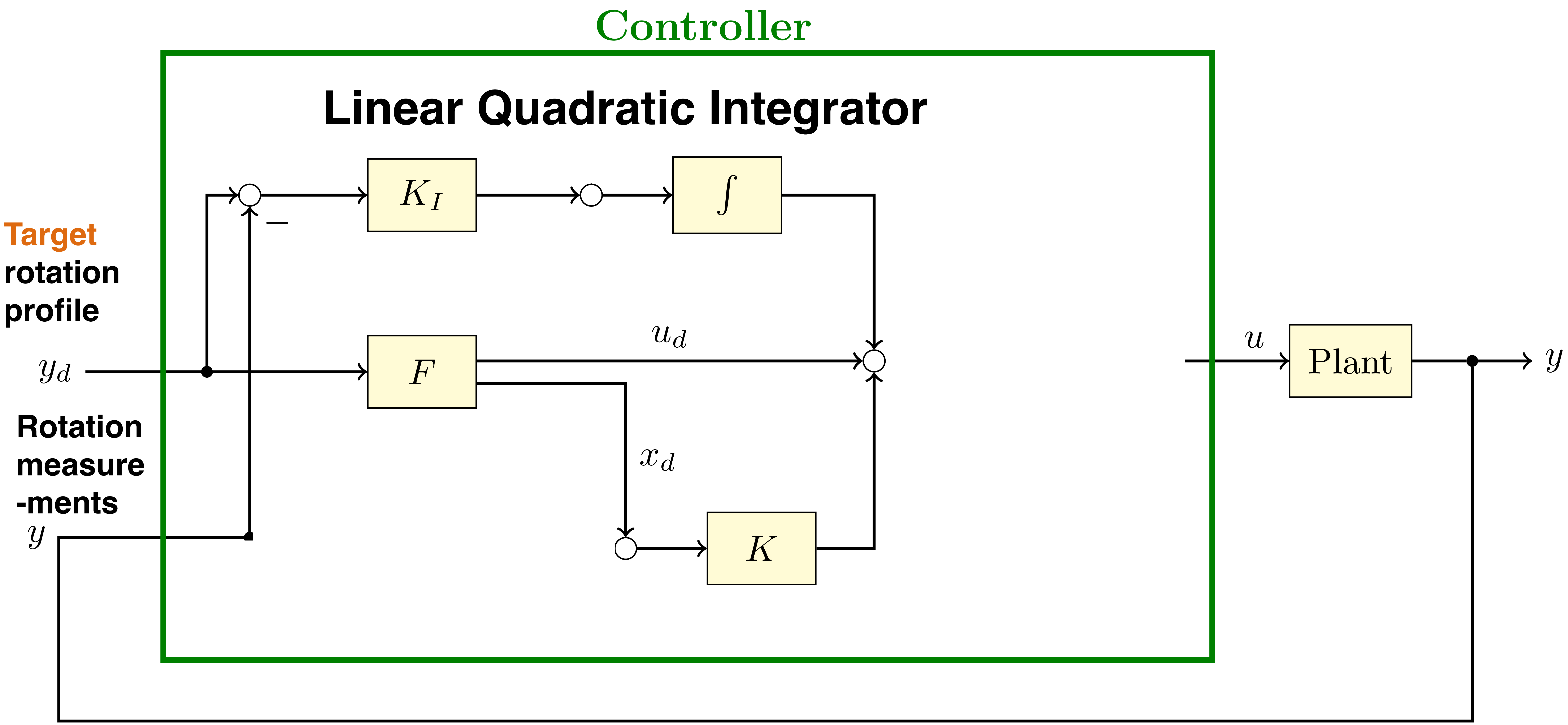
The **LQR** algorithm reduces the amount of work done by the control systems engineer to optimize the controller



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

with weighting factors supplied by an engineer or physicist

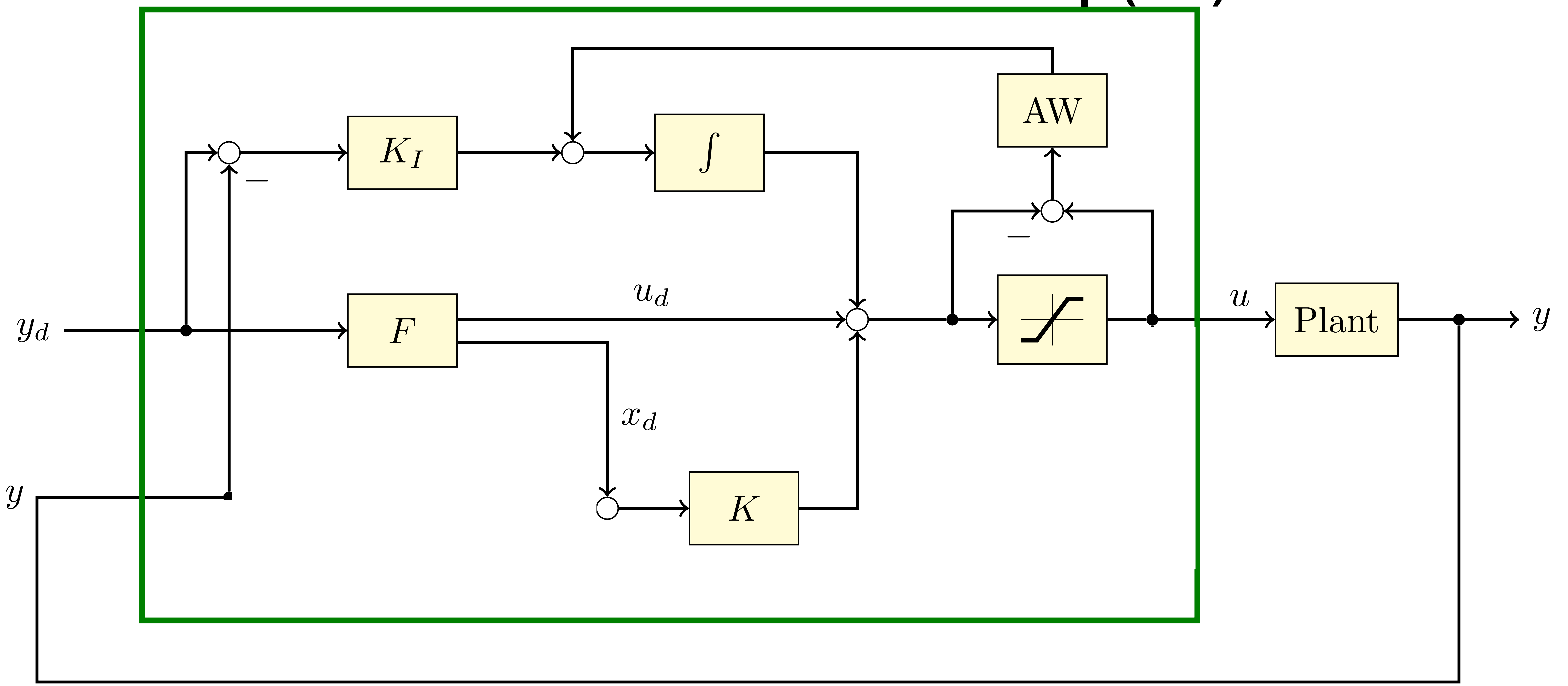
LQI *compensate* whatever difference or error remains between the set points and the system response to the open loop control (*Feedforward*)



- **Integrate** error to remove steady-state error
- The integral action is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously → create overshoot

Overview of the designed control system

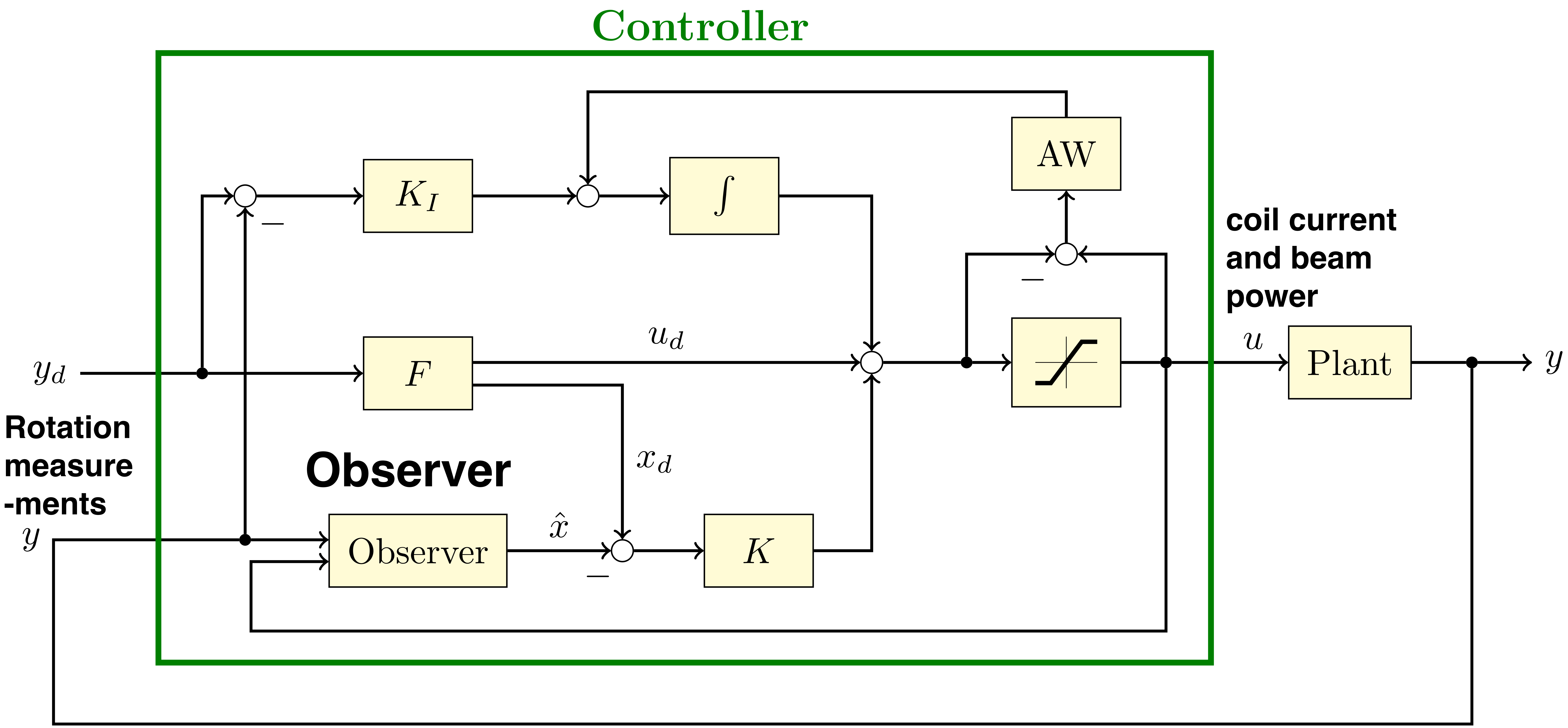
Controller **Anti-windup (AW)**



- **Accumulates a significant error during the rise (windup), thus overshooting and continuing to increase as this accumulated error is unwound:** *windup due to saturation*

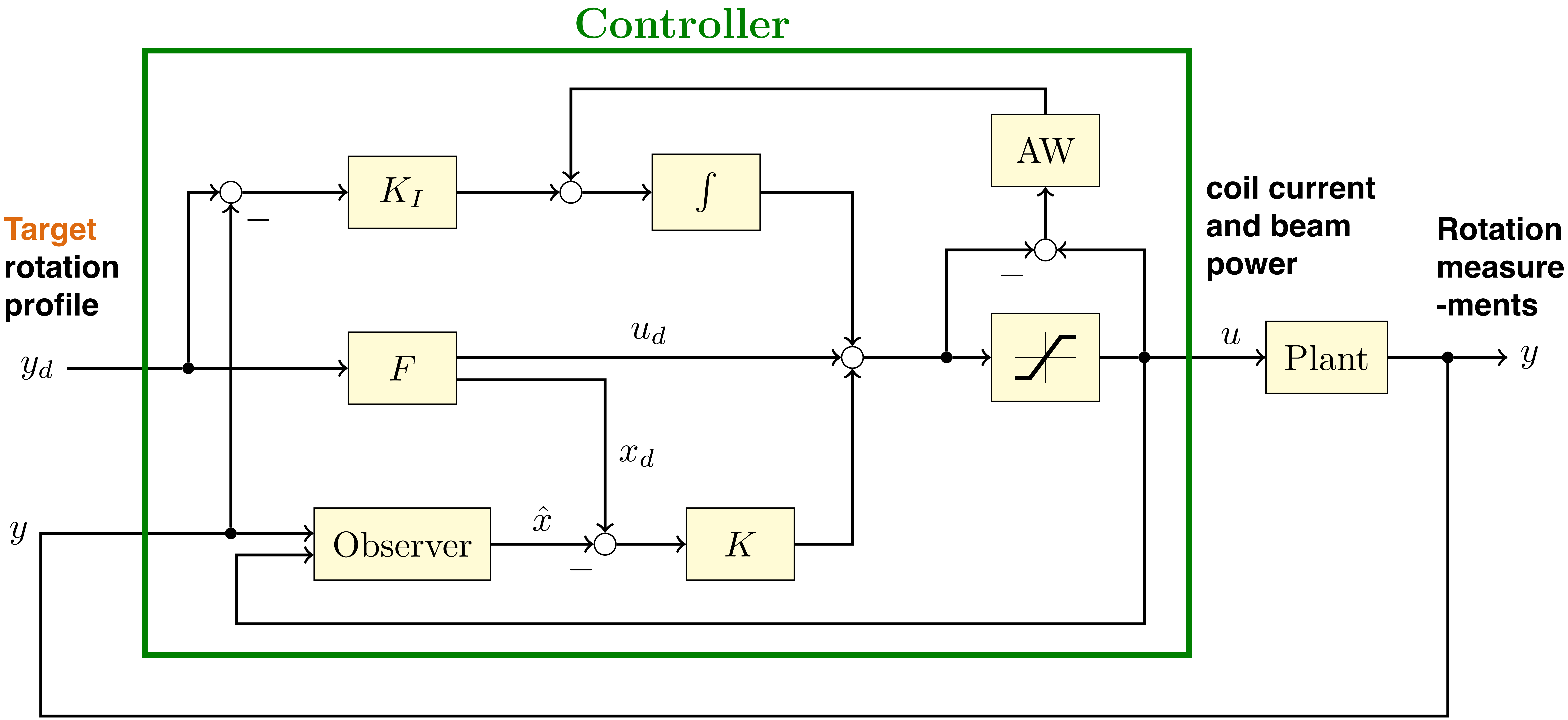
- **Anti-windup : integrator being turned off for periods of time**

Overview of the designed control system

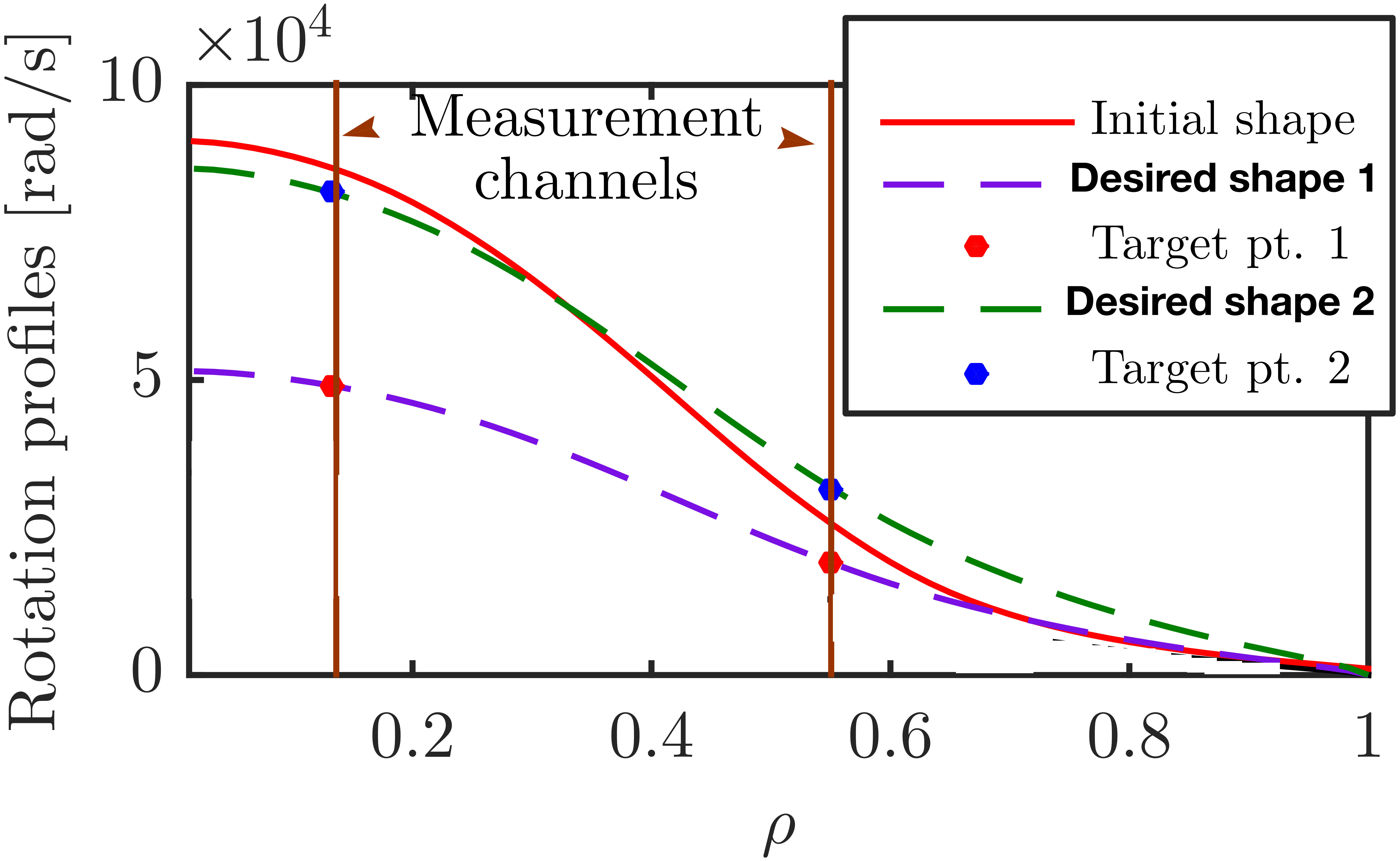


- **Estimate** the internal state *(full rotation profile)* of a given real system (*Tokamak*), from measurements of the input (*Beam power, coil current*) and output (*point-wise measurements of rotation*) of the real system.
- It is typically computer-implemented: **Kalman filter**

Overview of the designed control system

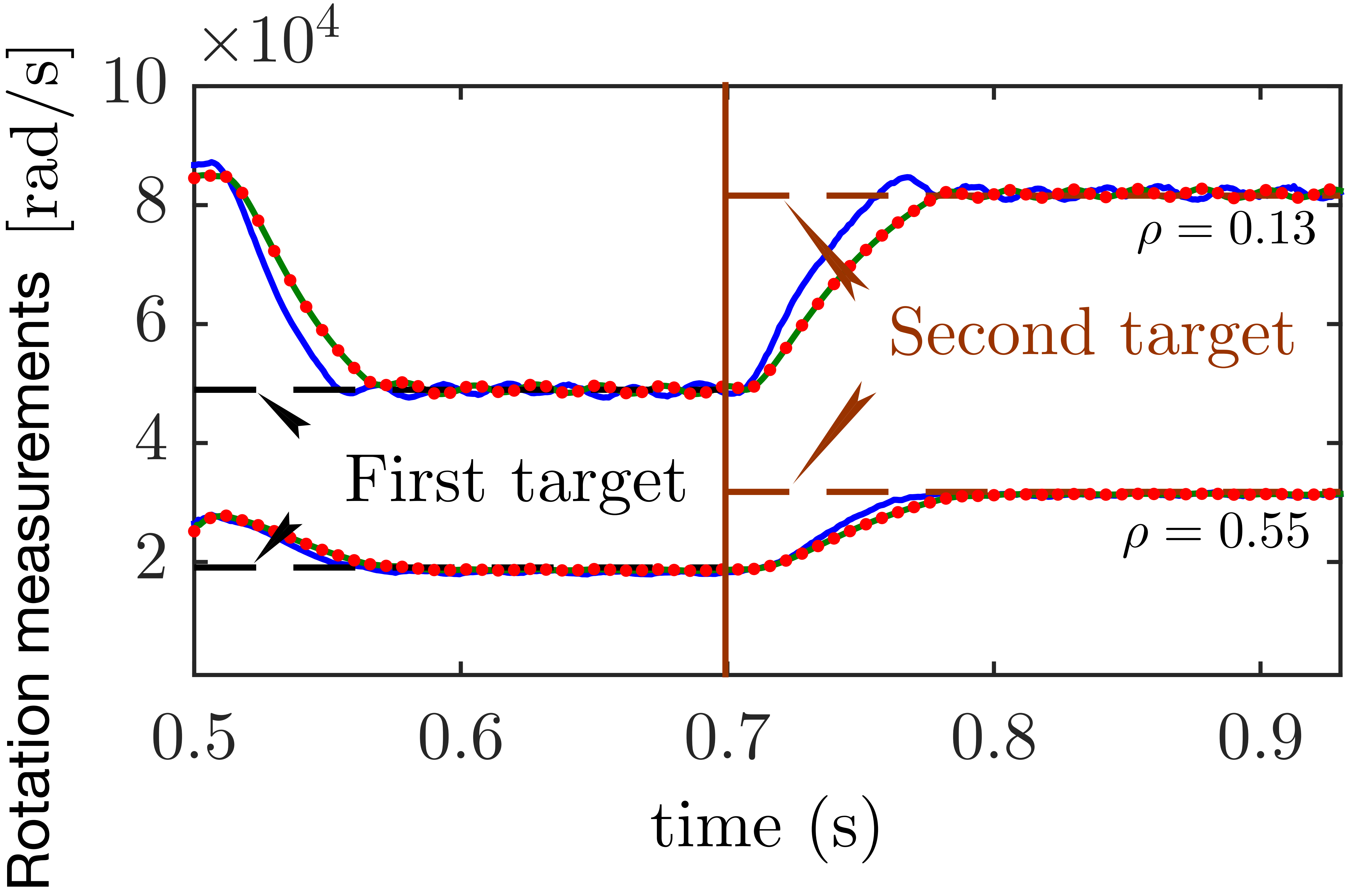


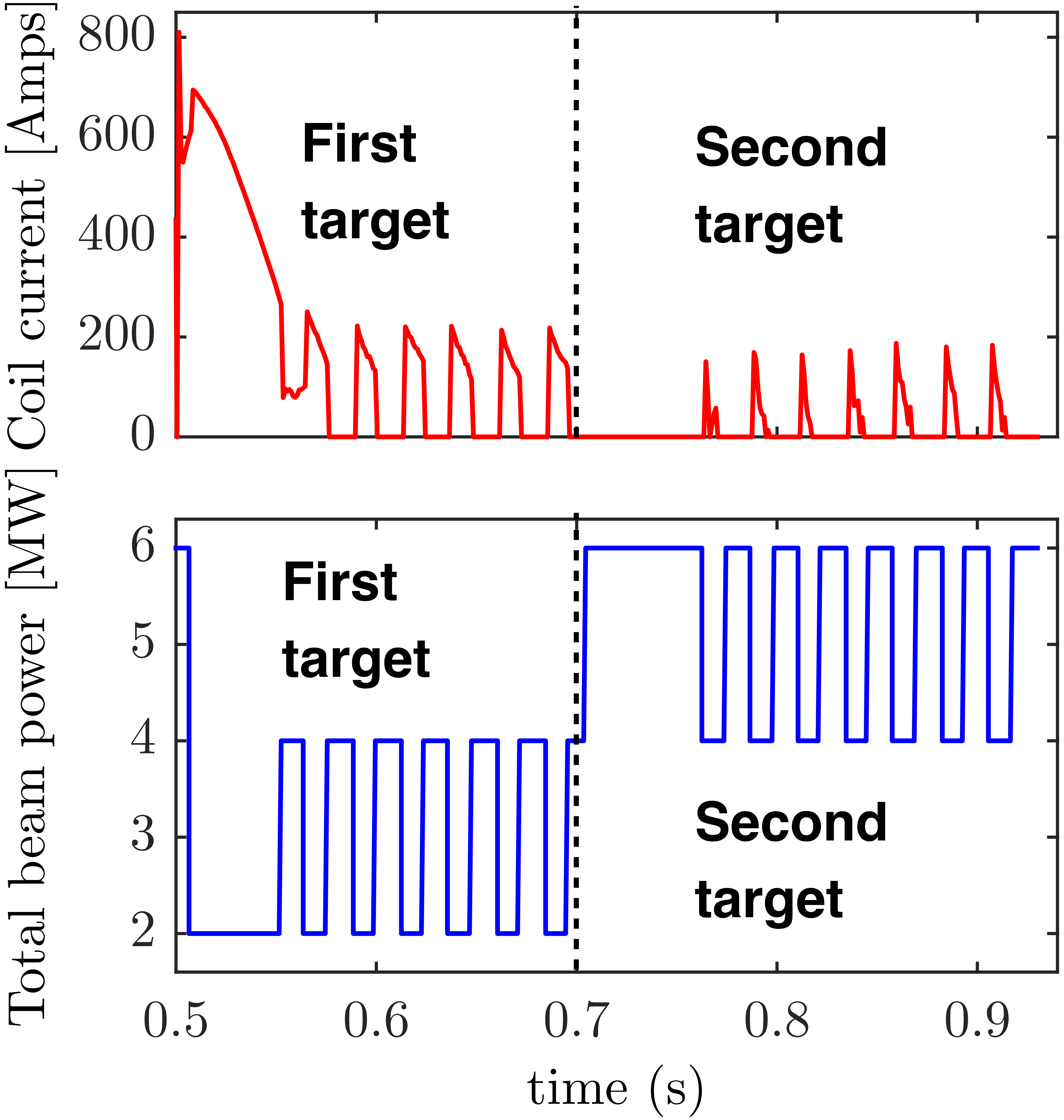
We have defined target profiles and the initial profile for **NSTX**



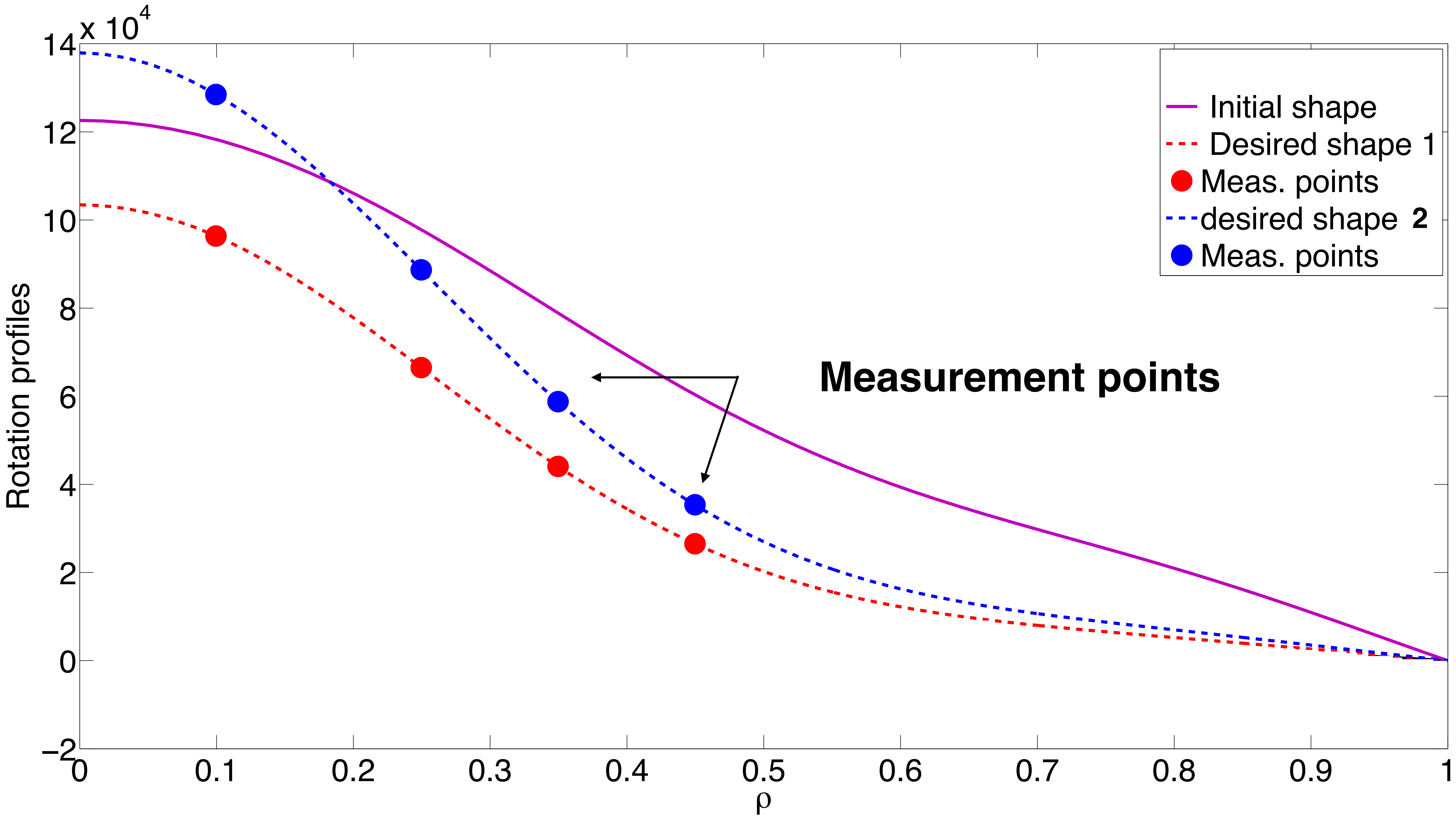
The controller enables the rotation to reach its target for **NSTX**

- **Comparison of the rotation measurements between the reduced-order model and the TRANSP predictive model.**
- ***Feedback control*** **applied at 0.5 and 0.7 seconds**



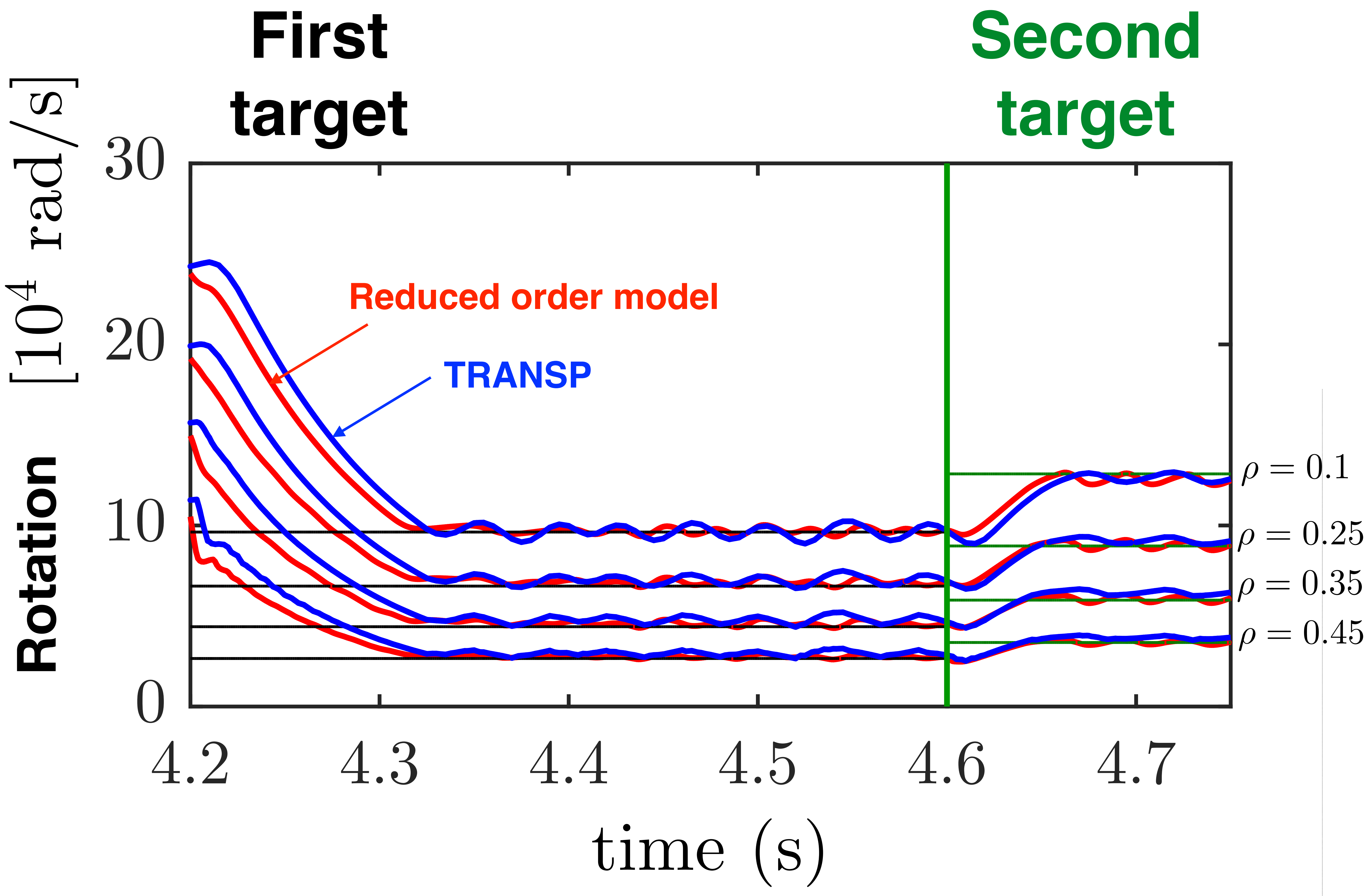


Definition of the initial profile, equilibrium profile used for the linearization and the desired profiles to reach for **NSTX-U**

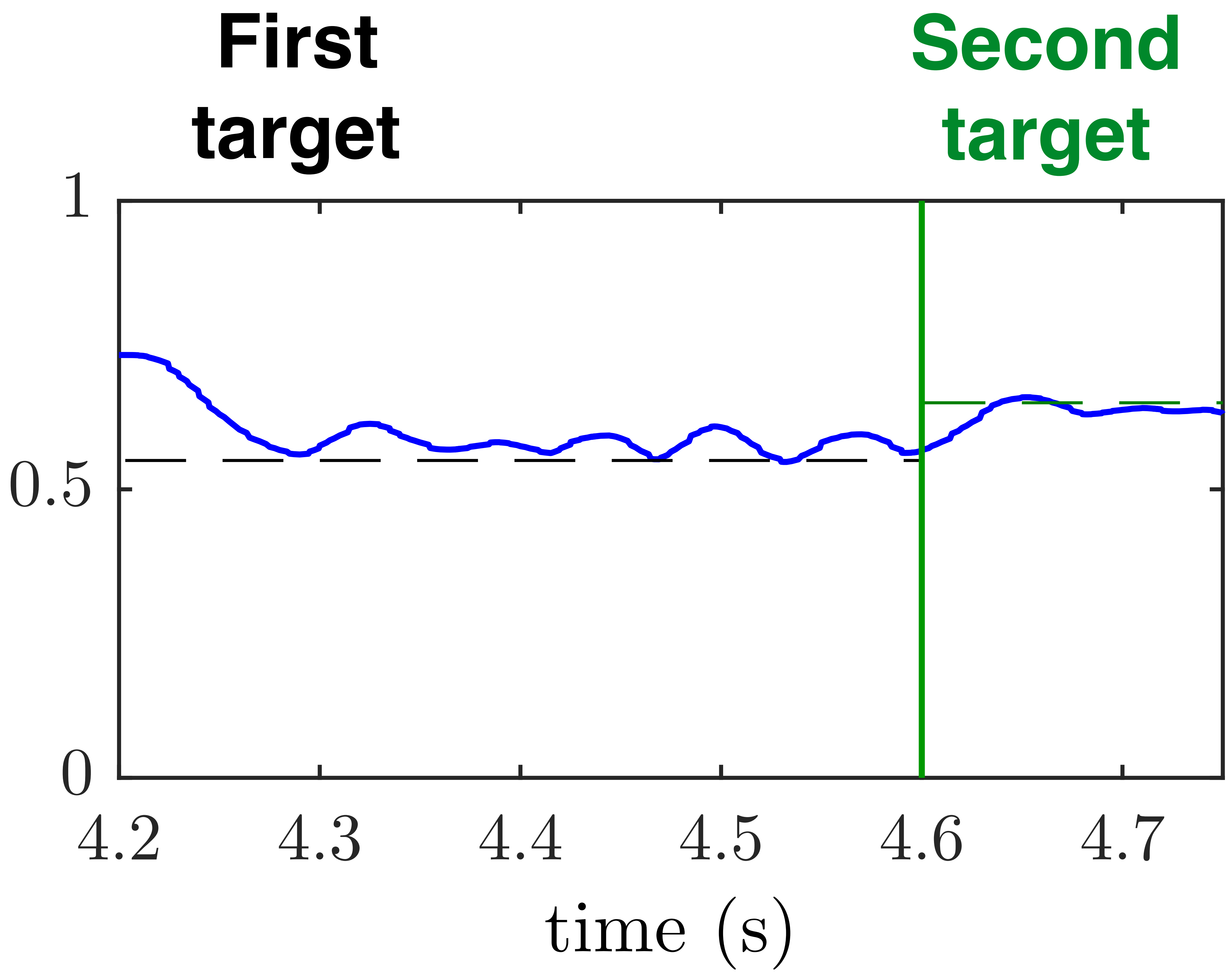


- 4 rotation measurement points + 1 measured stored energy = **5 sensors** (*Outputs*)
- 4 Beams powers + 1 coils current = **5 actuators** (*Inputs*)

The controller enable the rotation and the stored energy to reach its target for **NSTX-U**

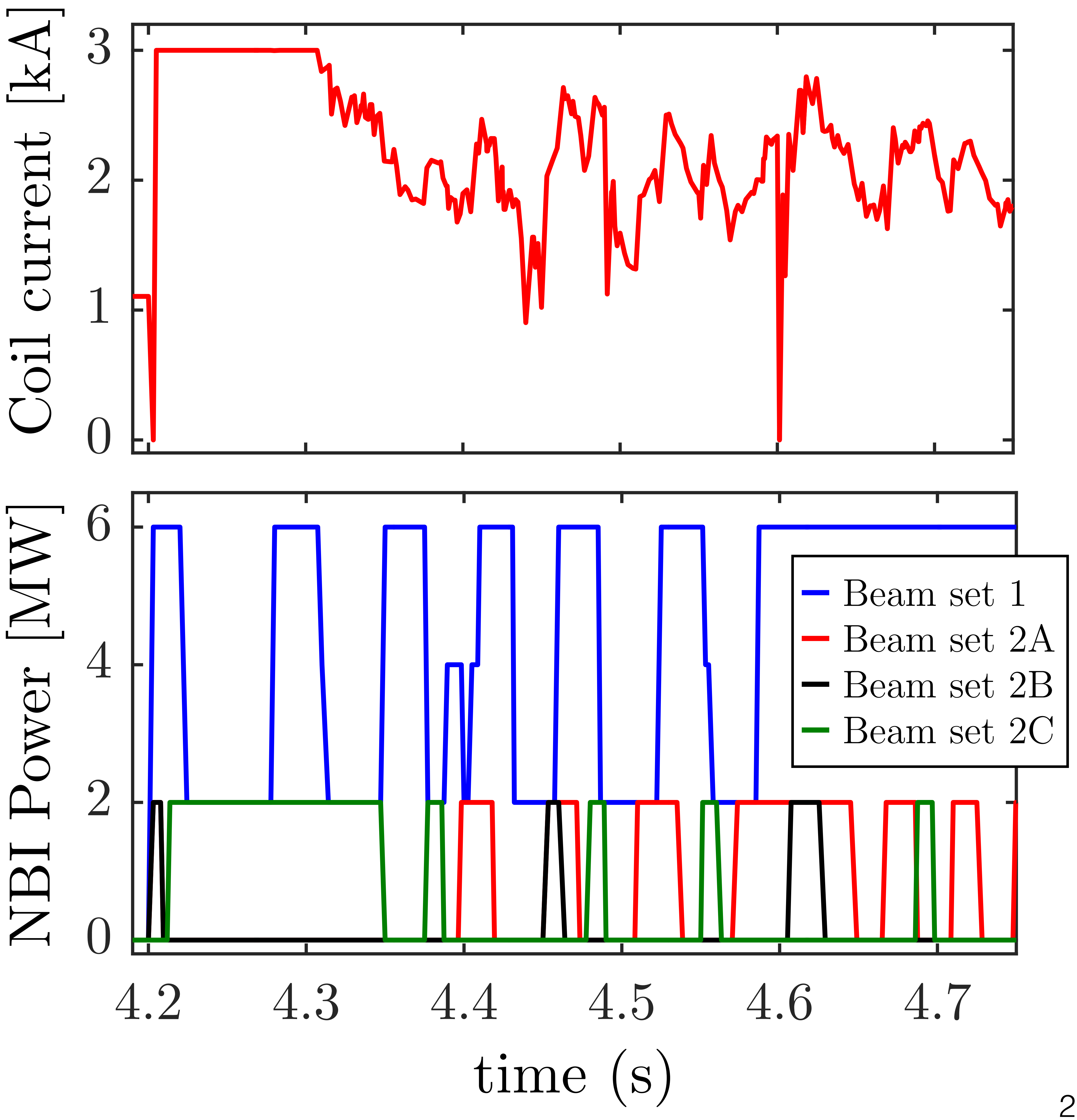


Stored energy



- **Comparison of the rotation measurements between the reduced-order model and the TRANSP predictive model**
- ***Feedback control*** **applied at 4.2 and 4.6 seconds**

Rotation controller handles more complex actuators for **NSTX-U**



- Controlling both Rotation and Stored energy introduces a higher level of complexity

Rotation and energy control has been developed and tested **successfully** in **NSTX** and **NSTX-U** simulations

- Used only linear control tools
- Based on reduced order model
- Only few measurement points
- Strict constraints on the actuators (beams and coils)
- *Model based* approach (**NSTX-U**) or *Data based* approach (**NSTX**)
- Control implemented in TRANSP for the first time

Future directions

- Implementing rotation and stored energy control on NSTX-U spherical torus through PCS (Plasma Control System)

- Study interaction between different controllers: rotation control, current profile control, ELMs…

- Optimize choice of actuators and positioning for design of future reactors