ITPA-IOS Joint Experiment # 6.1

First Integrated Magnetic and Kinetic Control for AT Scenarios on DIII-D

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Outline

- ARTAEMIS model structure and integrated control
- Control of the internal poloidal flux profile, $\psi(x)$
- Integrated control of $\psi(x)$ and β_N
- Lehigh University controller and $\iota(x)$ control
- Proposal for 2012 and beyond

The ARTAEMIS (grey-box) model-based approach

D. Moreau et al., Nucl. Fusion ***48*** *(2008) 106001*

What could a **minimal state space model** look like ?

Are there **natural state variables and input variables** ? How are they coupled ?

Generic structure of linearized flux-averaged plasma transport equations :

$$\frac{\partial \Psi(x,t)}{\partial t} = \mathcal{L}_{\Psi,\Psi}\{x\}\cdot\Psi(x,t) + \mathcal{L}_{\Psi,K}\{x\}\cdot\begin{bmatrix}V_\Phi(x,t)\\ T(x,t)\end{bmatrix} + \mathcal{L}_{\Psi,n}\{x\}\cdot n(x,t) + L_{\Psi,P}(x)\,P(t) + V_{ext}(t)$$

$$\varepsilon\,\frac{\partial n(x,t)}{\partial t} = \mathcal{L}_{n,\Psi}\{x\}\cdot\Psi(x,t) + \mathcal{L}_{n,K}\{x\}\cdot\begin{bmatrix}V_\Phi(x,t)\\ T(x,t)\end{bmatrix} + \mathcal{L}_{n,n}\{x\}\cdot n(x,t) + L_{n,P}(x)\,P(t)$$

$$\varepsilon\,\frac{\partial}{\partial t}\begin{bmatrix}V_\Phi(x,t)\\ T(x,t)\end{bmatrix} = \mathcal{L}_{K,\Psi}\{x\}\cdot\Psi(x,t) + \mathcal{L}_{K,K}\{x\}\cdot\begin{bmatrix}V_\Phi(x,t)\\ T(x,t)\end{bmatrix} + \mathcal{L}_{K,n}\{x\}\cdot n(x,t) + L_{K,P}(x)\,P(t)$$

etc …

ARTAEMIS is a set of algorithms that use ***singular perturbation methods :***

(i) a semi-empirical system identification method

(ii) a model-based, 2-time-scale, control algorithm for magneto-kinetic plasma state

The ARTAEMIS controller design and parameters for combined $\psi(x)$ and β_N control

- Singular perturbation analysis ➔ Near-optimal control = Optimal control up to $O(\varepsilon^2)$

The dynamics minimizes $\int_0^\infty X^+(t)\,Q\,X(t)\,dt + \int_0^\infty u^+(t)\,R\,u(t)\,dt$

given weight matrices, Q and R, with X = controlled variables and u = actuators

- The slow proportional + integral feedback tracks a steady state that

minimizes $\int_{x1}^{x2} \left[\psi(x) - \psi_{\text{target}}(x)\right]^2 dx + \lambda \left[\beta_N - \beta_{N,target}\right]^2$

to control simultaneously $\psi(x)$ and β_N

- The fast proportional feedback loop maintains the kinetic variables, e. g. β_N, on a trajectory which is consistent with the slow magnetic state evolution, $\psi(x, t)$.

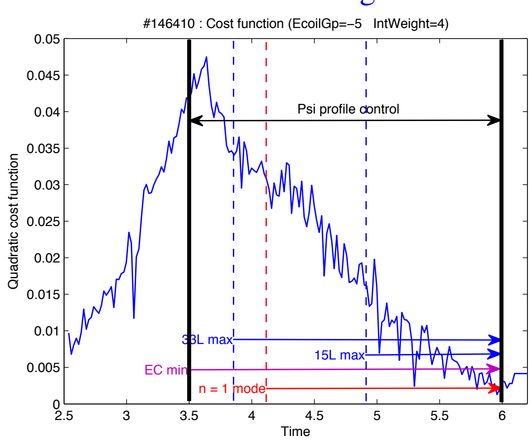
Control of the internal poloidal flux profile : $\psi(x) = \Psi(x) - \Psi_{boundary}$

The controller minimizes $$\int_{x1}^{x2} \left[\psi(x) - \psi_{target}(x) \right]^2 dx$$

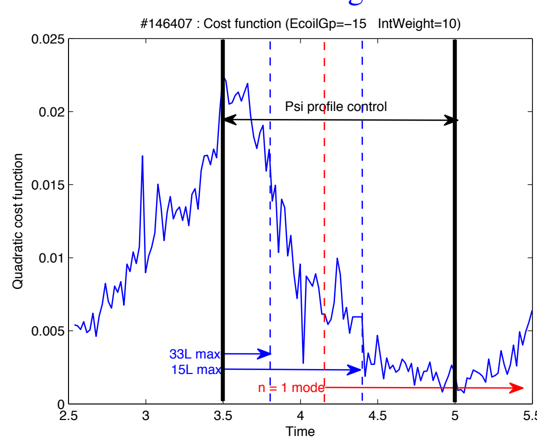
with actuator constraints and optimal gain matrices that depend on controller parameters :

- 4 actuators = NB-Co, NB-Bal, ECCD (5 gyros), Vsurf (NB 210R unavailable on 09/13)
- R-matrix : actuator weight fixed by considering actuator headroom (MW & Volts ?)
- Q-matrix : same weight on 9 different controlled radii (x = 0.1, …, 0.9)
- Controller order = 2 (proportional + integral control)
- Weight on integral control in the Q-matrix = 4, 10, 25, respectively, on the 3 examples below :

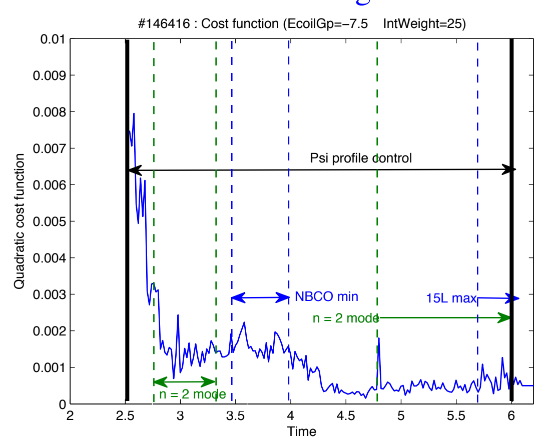
#146410 : IntWeight = 4



#146407 : IntWeight = 10

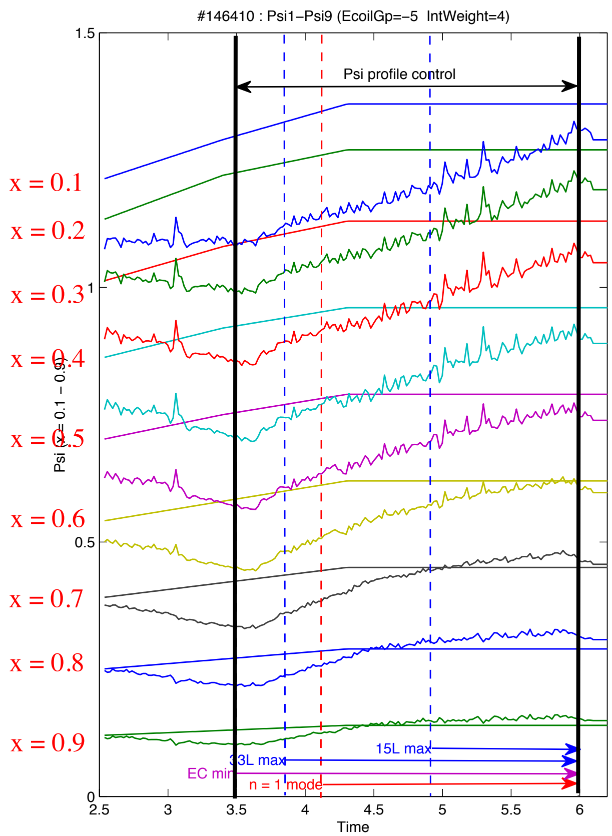


#146416 : IntWeight = 25



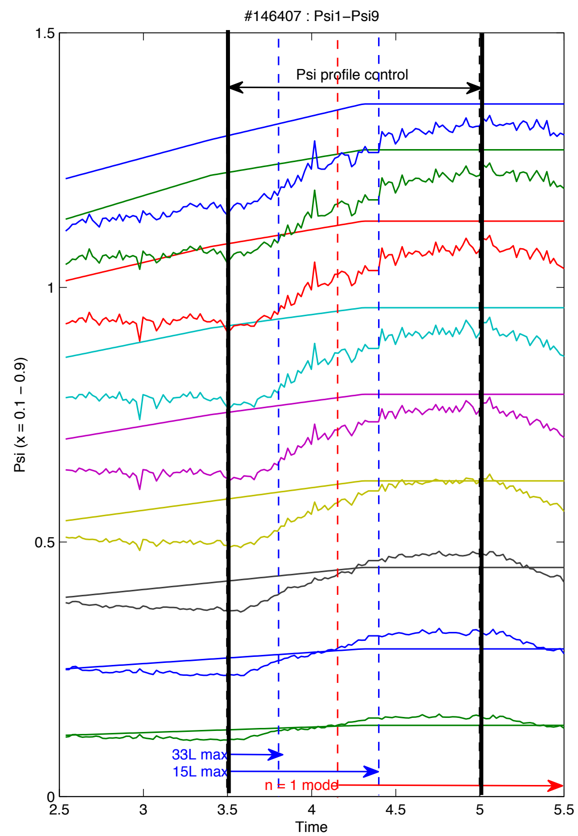
Control of the poloidal flux profile (x = 0.1, 0.2, … 0.9)

#146410 : IntWeight = 4



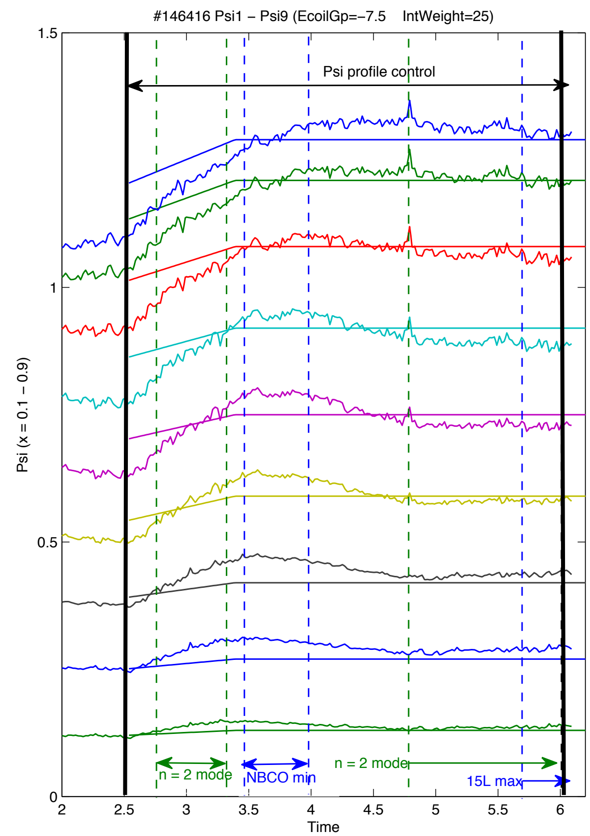
Control : 3.5 s - 6 s

#146407 : IntWeight = 10



Control : 3.5 s - 5 s

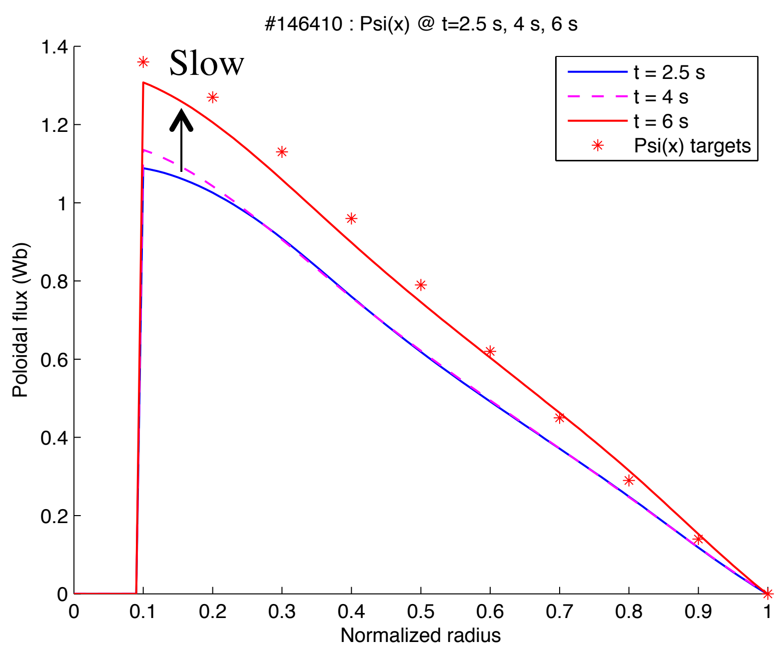
#146416 : IntWeight = 25



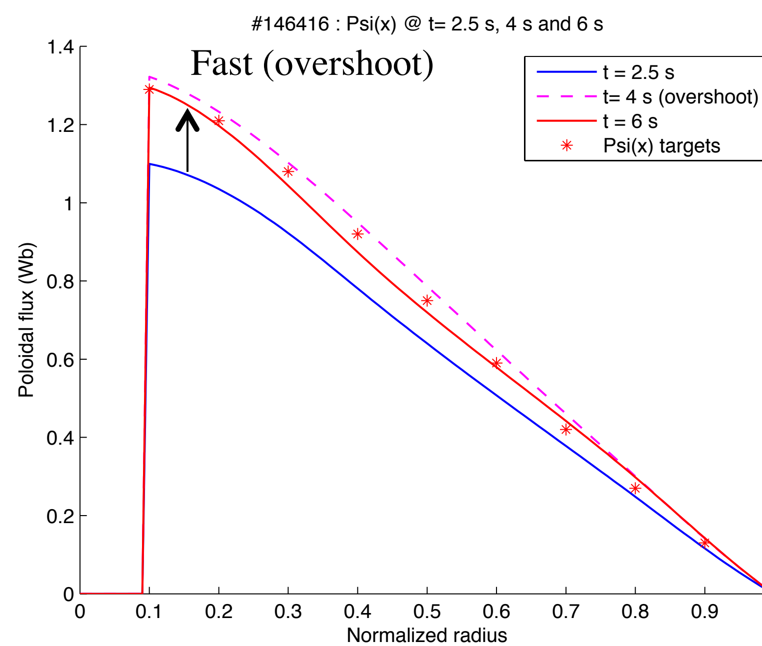
Control : 2.5 s - 6 s

Control of the poloidal flux profile
$\psi(x)$ @ t = 2.5 s, 4 s, 6 s

#146410 : IntWeight = 4



#146416 : IntWeight = 25



Simultaneous control of the ψ(x) profile and β_N

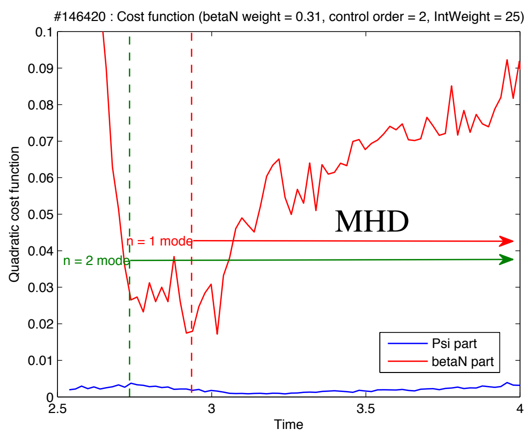
5 actuators : NB-co, NB-bal, NB-cnt, ECCD, Vsurf

The controller minimizes $$\int_{x1}^{x2} \left[\psi(x) - \psi_{\text{target}}(x) \right]^2 dx + \lambda \left[\beta_N - \beta_{N,\text{target}} \right]^2$$

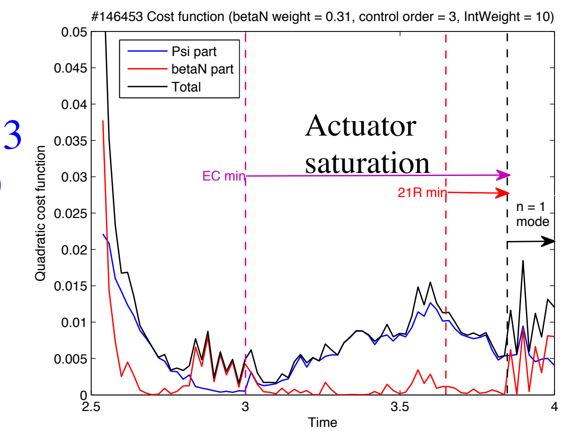
with actuator constraints and optimal gain matrices that depend on controller parameters :

- 5 actuators = NB-Co, NB-Bal, NB-Cnt, ECCD (6 gyros), Vsurf
- R-matrix : actuator weights fixed by considering actuator headroom (MW & Volts ?)
- Q-matrix : same weight on 9 controlled radii for ψ(x), x=0.1, 0.2, … 0.9
- Weight on β_N control : $\lambda = 0.3$
- Controller order = 2 or 3 (proportional + integral control)
- Weight on integral control in the Q-matrix = 25 and 10, respectively, in the 2 examples below :

#146420
Control order = 2
IntWeight = 25



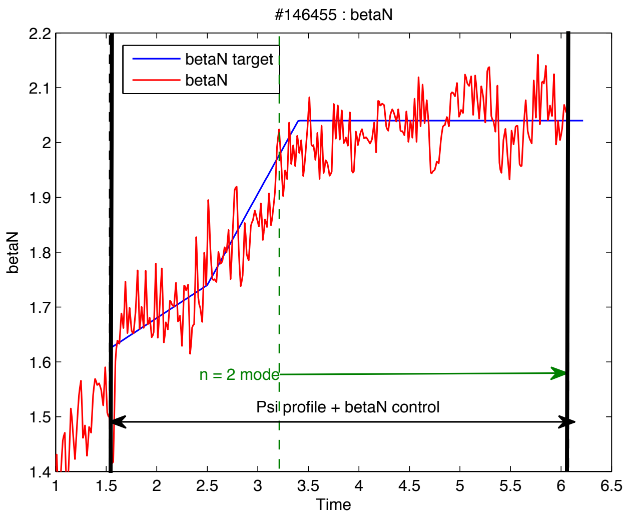
#146453
Control order = 3
IntWeight = 10



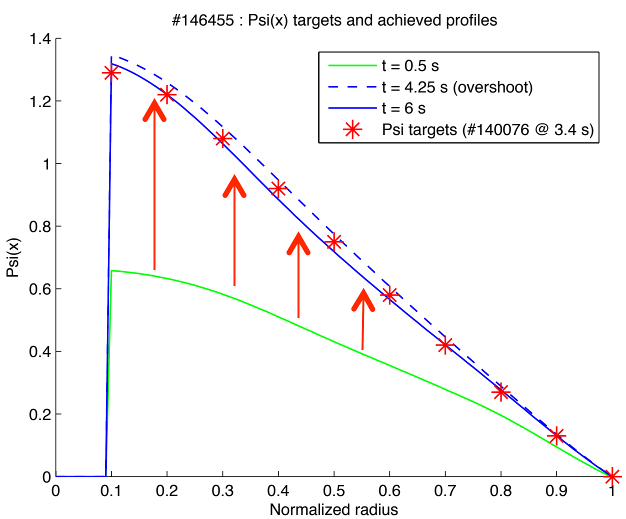
Simultaneous control of the ψ(x) profile and β_N

(shot # 146455 : control starting @ t = 1.5 s)

β_N control



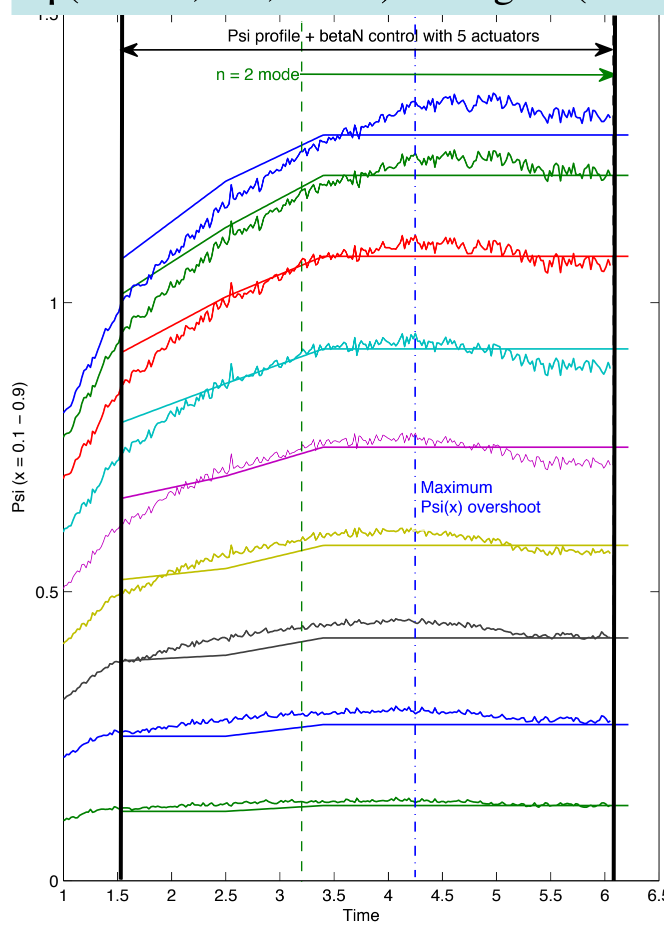
ψ-profile control



ψ(x= 0.1, 0.2, …0.9) & targets (lines)

radii

x = 0.1
x = 0.2
x = 0.3
x = 0.4
x = 0.5
x = 0.6
x = 0.7
x = 0.8
x = 0.9

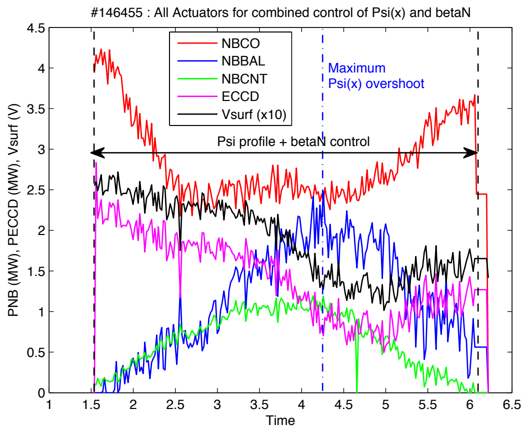


Time

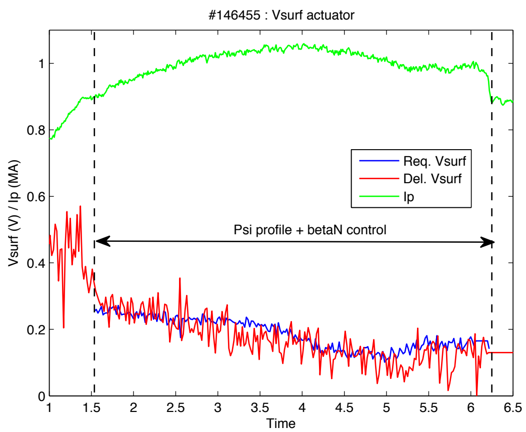
Simultaneous control of the $\psi(x)$ profile and β_N

(shot # 146455 : control starting @ t = 1.5 s)

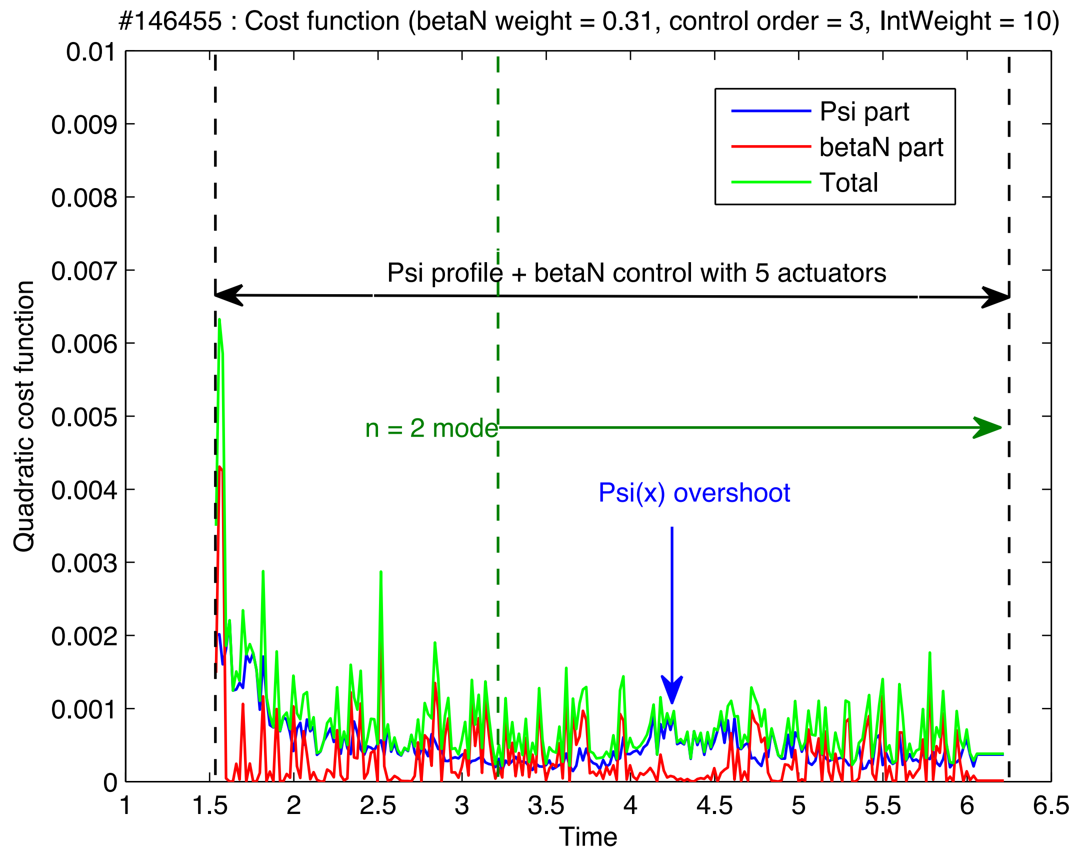
5 actuators (no saturation)



Vsurf actuator control & Ip



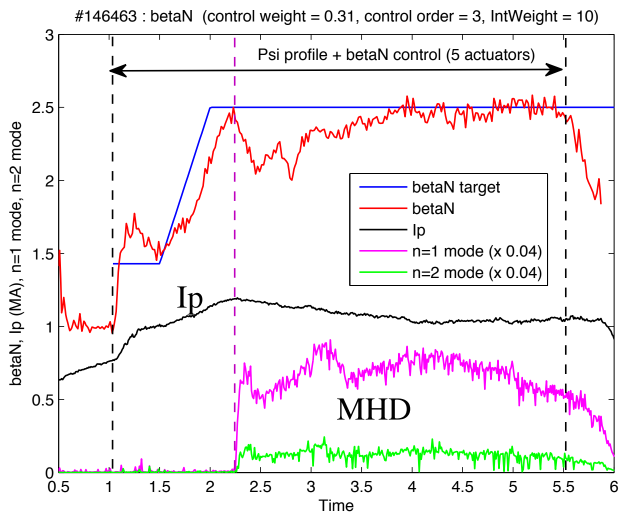
Cost function minimization



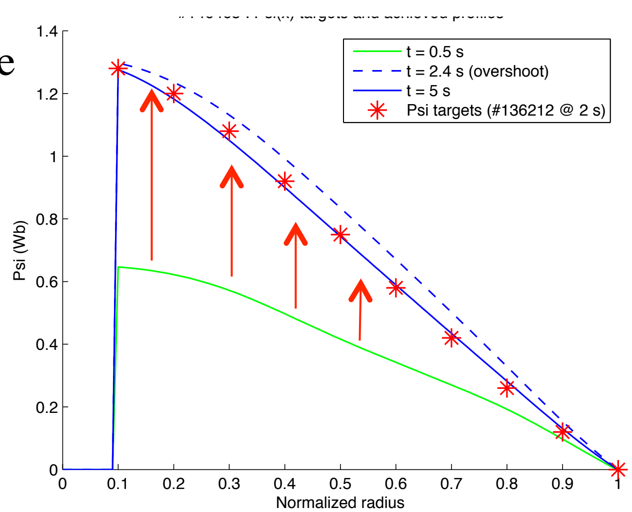
Simultaneous control of the ψ(x) profile and β_N

shot # 146463 : control starting @ t = 1 s (ramp-up)

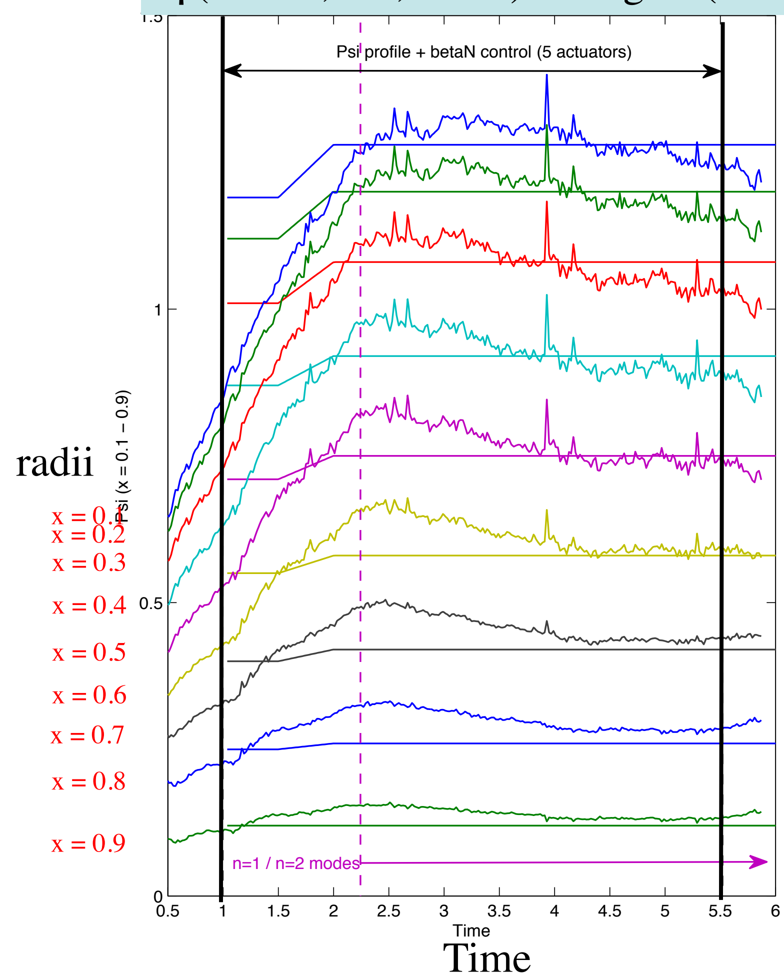
β_N control



ψ-profile control



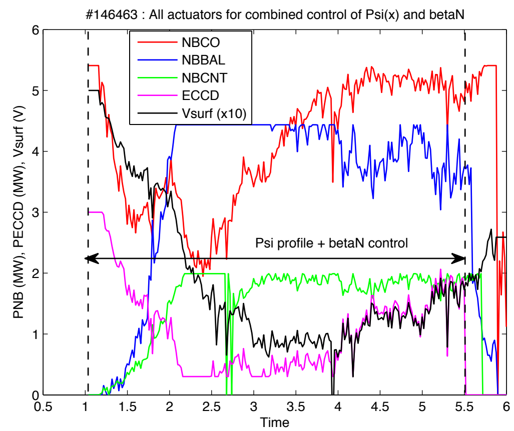
ψ(x= 0.1, 0.2, …0.9) & targets (lines)



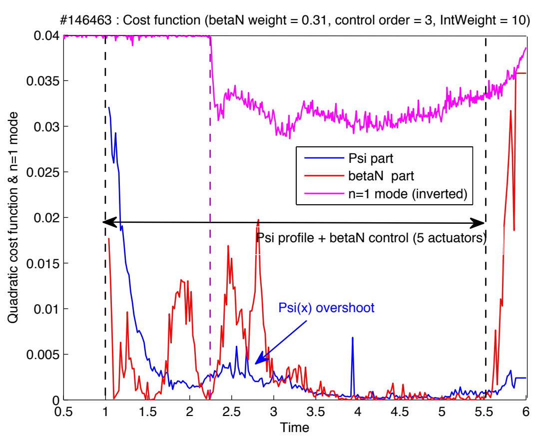
Simultaneous control of the ψ(x) profile and β_N

shot # 146463 : control starting @ t = 1 s (ramp-up)

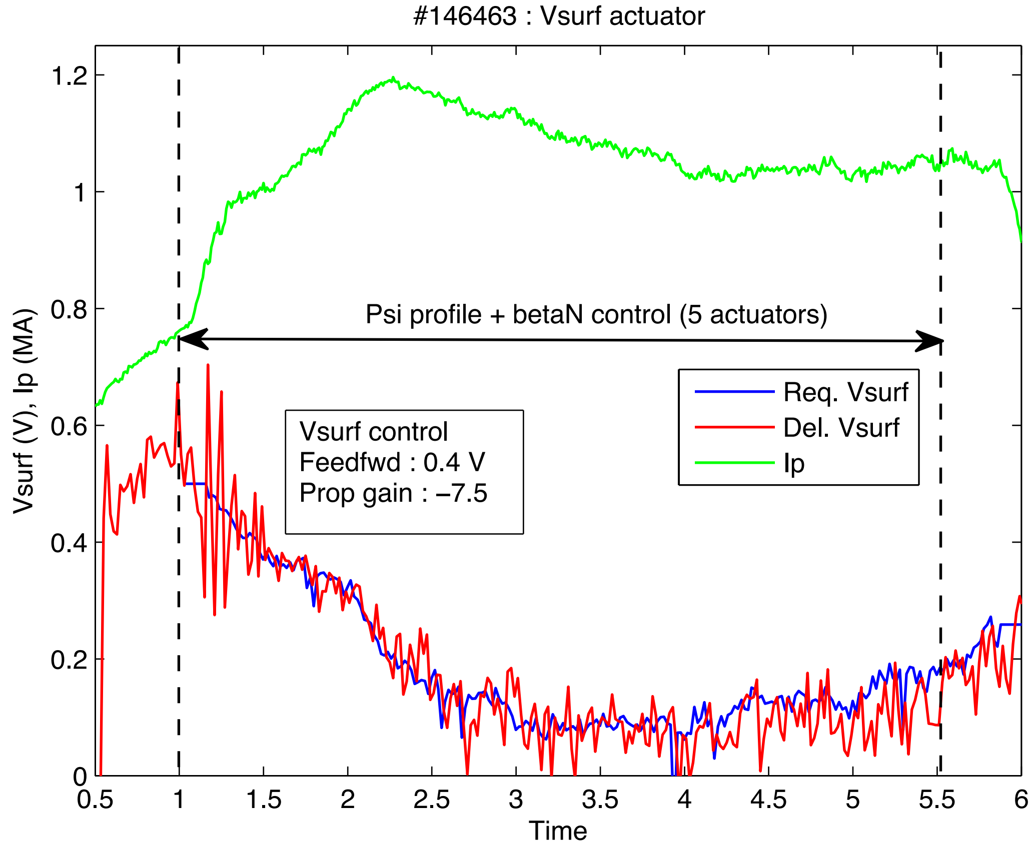
5 actuators (MHD ➔ NB-Bal saturation)



Cost function minimization

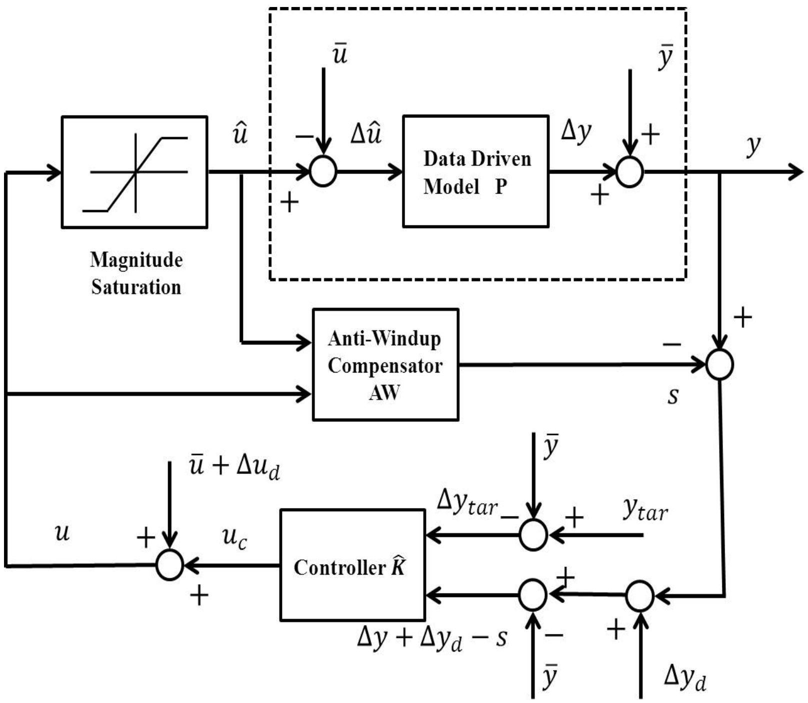


Vsurf actuator control & Ip



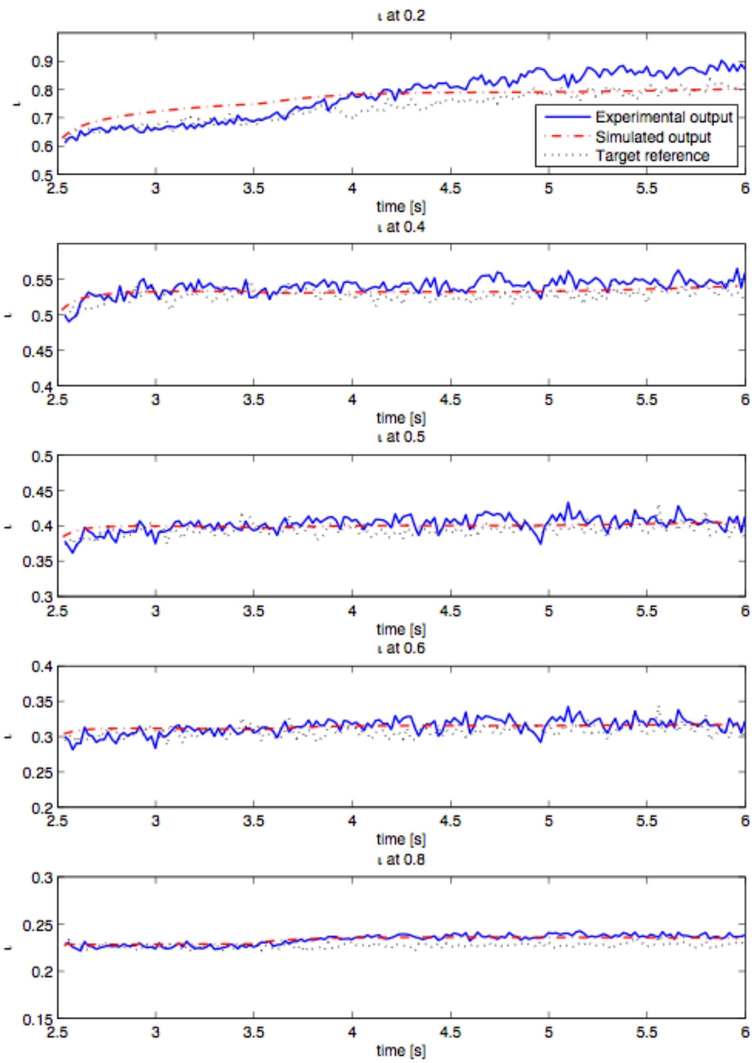
Data-driven Model-based Current Profile Control

- **Lehigh University Approach to Feedback Control Design:**



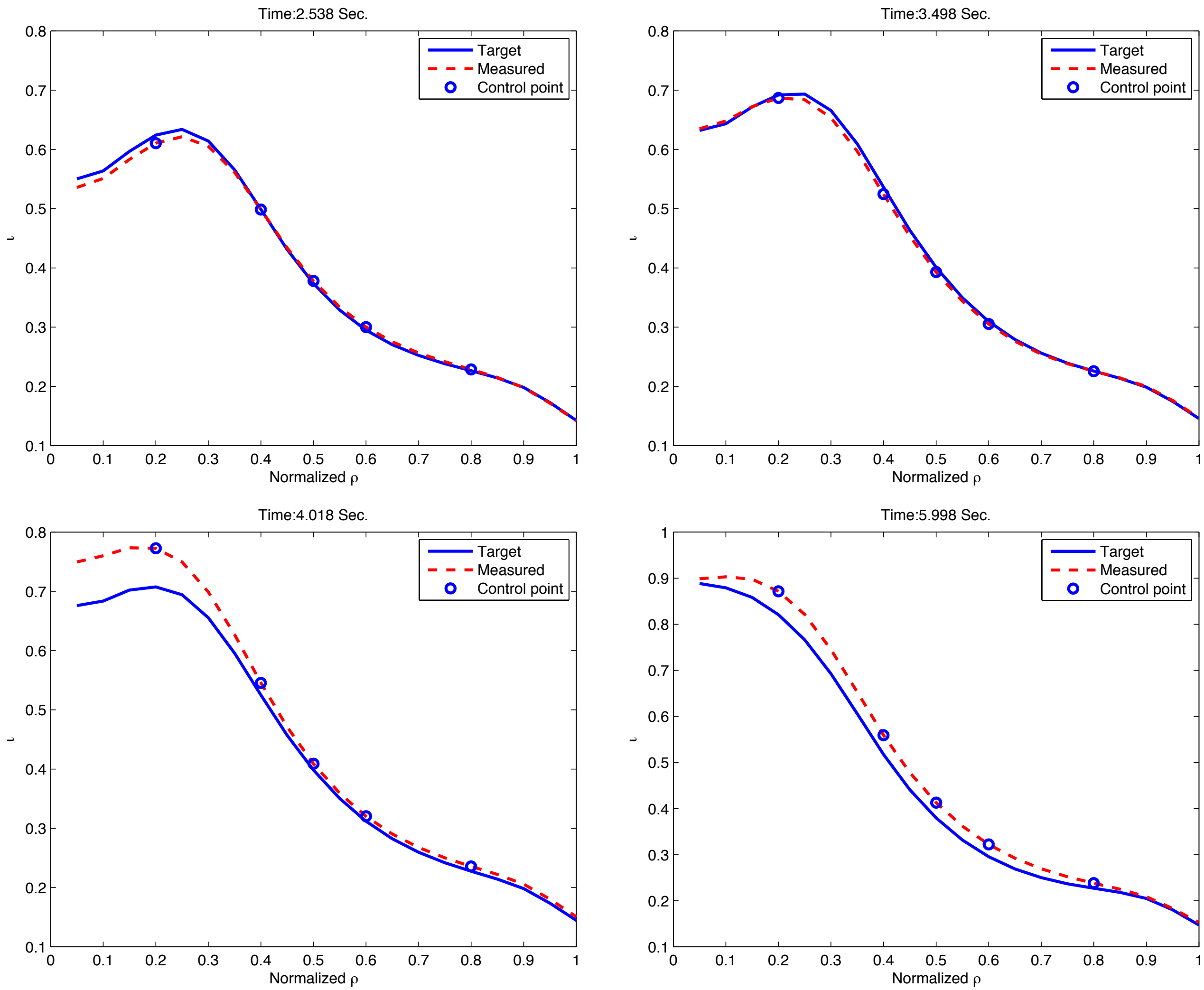
  - Both static and dynamic control-oriented plasma response models are embedded in the control synthesis.
  - A cost functional is defined to quantify the control objectives:
    - Tracking error minimization
    - Disturbance rejection
    - Control power minimization
  - Stabilizing controllers, which are robust against model uncertainties, are synthesized by minimizing different norms (H_∞ and H_2 norms) of the cost functional subject to the control-oriented model.
  - These controllers do not need PID-like empirical tuning.
  - The controllers are augmented with model-based anti-windup compensators to overcome detriments effects due to actuator saturation.

Data-driven Model-based Control of ι(x) =1/q(x)



- In the DIII-D PCS different magnetic profiles ($\psi(\rho)$, $\iota(\rho)$, $q(\rho)$ or $\theta(\rho)=\partial\psi/\partial\rho$) can now be obtained in real time from a complete equilibrium reconstruction using data from the MSE diagnostic.
- Figure on the left illustrates both simulated and experimental evolutions for the rotational transform $\iota(\rho)$ *at normalized radii* $\rho=0.2, 0.4, 0.5, 0.6, 0.8$ for *shot146419*.
- Tracking of the $\iota(\rho)$ target profile was achieved by regulating:
  - Total plasma current
  - Co-injection and balanced beam powers (counter-injection beam not available)
  - Total ECH/ECCD power
- Artificial input disturbances were introduced at $t=3.5$ sec.

Data-driven Model-based Control of ι(x) =1/q(x)



Tight regulation is achieved before t=3.5 sec.

A significant tracking error in the inner part of the profile is noted after the artificial disturbance is introduced at t=3.5 sec.

The controller reacts by decreasing the tracking error at the inner point and slightly increasing the error at the outer points with the ultimate goal of improving the overall profile tracking.

Ip regulation was poor due to setup problem.

More control authority is expected with stronger Ip regulation and counter injection beam.

Summary and proposal for 2012 …

- Control of $\psi(x)$, $\iota(x) = 1/q(x)$ and combined control of $\psi(x)$ and β_N have been achieved for the first time on DIII-D using either 4 or 5 actuators :

  Co-NBI, (Cnt-NBI), Bal-NBI, ECCD, Vsurf

- New PCS with profile control algorithm was qualified and worked perfectly
- $\psi(x)$ and β_N control was switched on during current ramp-up.
- Combined feedback control of $\psi(x)$ and β_N was successful up to [1s-6s]

Proposal for ITPA-IOS 2012 :

Integrated magnetic and kinetic plasma control

- More experiments on DIII-D with different target current profiles and β_N.
- Add control of the rotation and/or Ti profiles (real-time CER)
- Start profile control experiments on other devices (Tore Supra, TCV …?)