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

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This work is related to ITPA-IOS Joint Experiment # 6.1

Outline

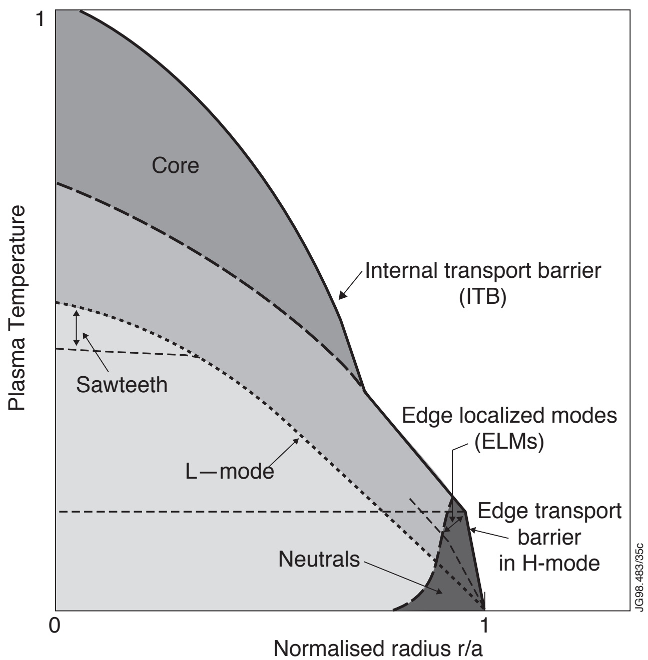
- Motivation for integrated profile control
- Control-oriented models and system identification
- Control of the poloidal flux profile on DIII-D
- Control of the poloidal flux profile and β_N on DIII-D
- Summary and future prospects

Motivation for integrated profile control (magnetic-kinetic)

«Advanced Tokamak» approach (T. S. Taylor 1997 *Plasma Phys. Control Fusion* ***39*** *B47)*

Self-consistent plasma state with high confinement + high-β_N + high-bootstrap

Plasma shape + ExB shear flow	→	Reduced microturbulence
Current density profile ≠≠ σ.E	↺	Unstiff pressure profile
Non-monotonic safety factor profile		Large bootstrap component



Confinement $H = \tau_E / \tau_{ITER\text{-}89P}$

MHD stability $\beta_N = \beta_T / (I_p/aB)$

Bootstrap $I_{BS} / I_p \propto \beta_p \propto q \cdot \beta_N$

Fusion figure of merit $\propto H \cdot \beta_N / q^2$

and

$$\beta_T \cdot \beta_p \propto \{ (1 + k^2) / 2 \} \beta_N^2$$

Shape control + MHD control + profile control

The ARTAEMIS (grey-box) model-based approach

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 :

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

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

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

etc …

ARTAEMIS is a set of algorithms that use singular perturbation methods for control

(i) a semi-empirical system identification method

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

Singular perturbation expansion and 2-time-scale models

$\varepsilon << 1$ t = slow time scale $\tau = t / \varepsilon$ (fast time scale)

Slow model : $\varepsilon \rightarrow 0$ (resistive time scale)

$$\frac{d\Psi}{dt} = \mathcal{A}_{slow} \cdot \Psi(t) + \mathcal{B}_{slow} \, U_{slow}(t)$$

$$\begin{bmatrix} V_\Phi(t) \\ T_i(t) \end{bmatrix}_{slow} = \mathcal{C}_{slow} \cdot \Psi(t) + \mathcal{D}_{slow} \, U_{slow}(t)$$

Slow controller : $U_{slow}(t)$

opt. PI feedback

Fast model ($\tau = t / \varepsilon$)

magnetic / kinetic time scale):

$$\frac{d}{d\tau}\begin{bmatrix} V_\Phi(\tau) \\ T_i(\tau) \end{bmatrix}_{fast} = \mathcal{A}_{fast} \cdot \begin{bmatrix} V_\Phi(\tau) \\ T_i(\tau) \end{bmatrix}_{fast} + \mathcal{B}_{fast} \, U_{fast}(\tau)$$

$$\begin{bmatrix} V_\Phi(t) \\ T_i(t) \end{bmatrix} = \begin{bmatrix} V_\Phi(t) \\ T_i(t) \end{bmatrix}_{slow} + \begin{bmatrix} V_\Phi(\varepsilon t) \\ T_i(\varepsilon t) \end{bmatrix}_{fast}$$

Fast controller :

$$U(t) = U_{slow}(t) + U_{fast}(t/\varepsilon)$$

opt. Prop. feedback

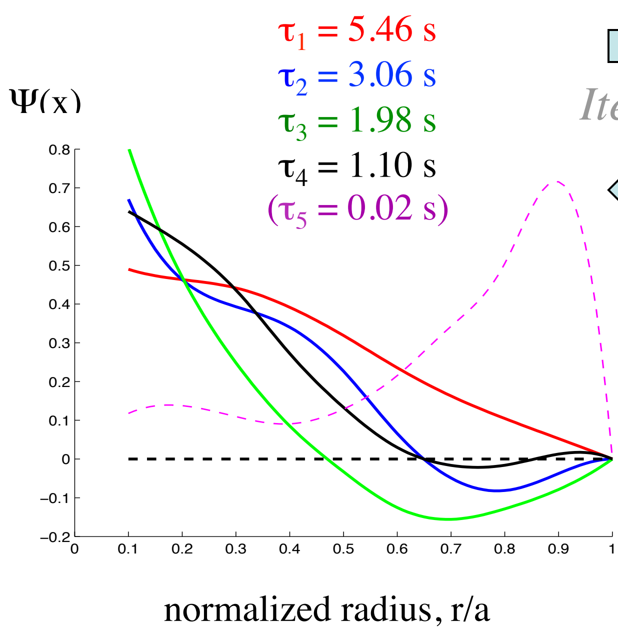
Identification of a state space model for Ψ(x) on DIII-D

(D. Moreau et al., Nucl. Fusion 2011)

Each identification iteration maximizes a global fit parameter

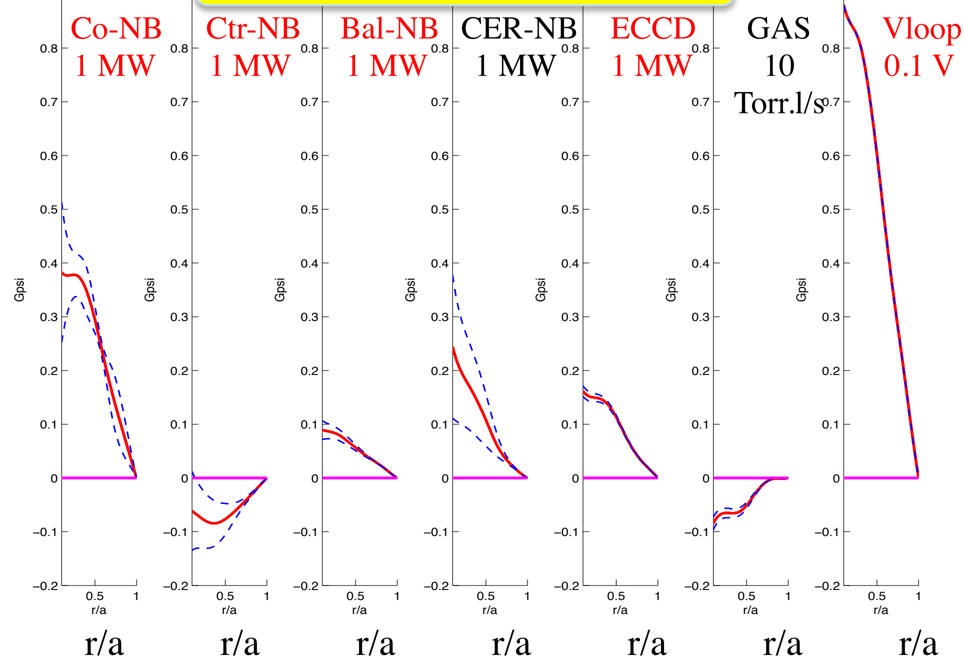
$$f = 1 - \left[\sum_{samples} \int_{0.1}^{0.9} \left(\Psi(x) - \Psi_{model}(x)\right)^2 dx \Big/ \sum_{samples} \int_{0.1}^{0.9} \left(\Psi(x) - \langle \Psi(x) \rangle_{samples}\right)^2 dx \right]^{1/2}$$

Resistive diffusion eigenmodes



Iterations

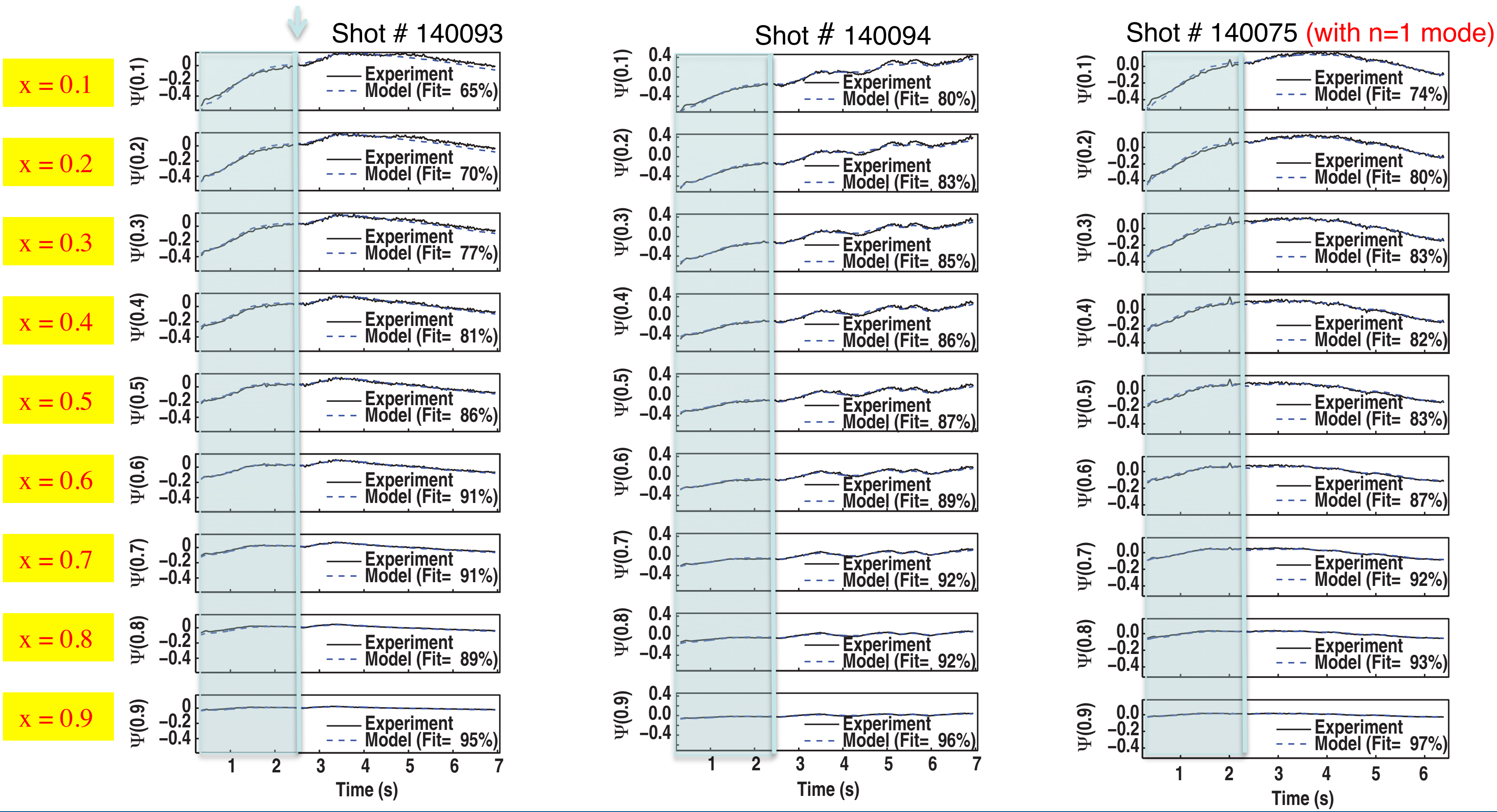
Steady state Ψ(x) response



Comparison between measured and model-simulated
Ψ(x, t) data (Wb) at x = 0.1 , 0.2, ... 0.9

Identification t > 2.6 s

Validation from t = 0.3 s (ramp-up) to the end

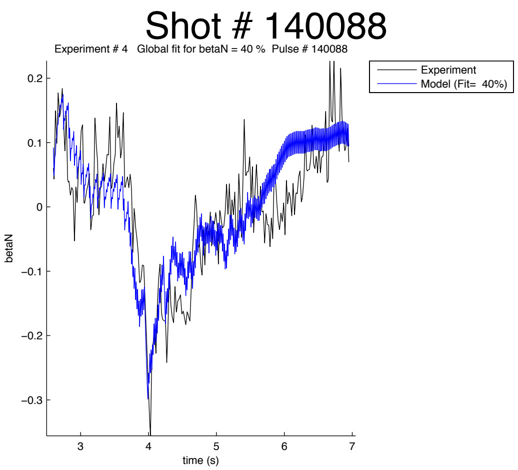


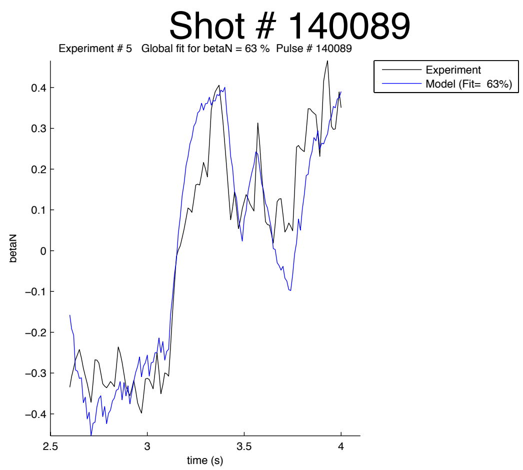
Two-time-scale model for coupled Ψ(x, t) and β_N (t)

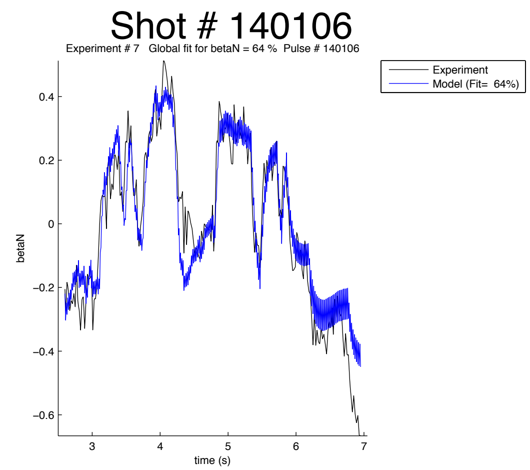
Measured and model-simulated β_N

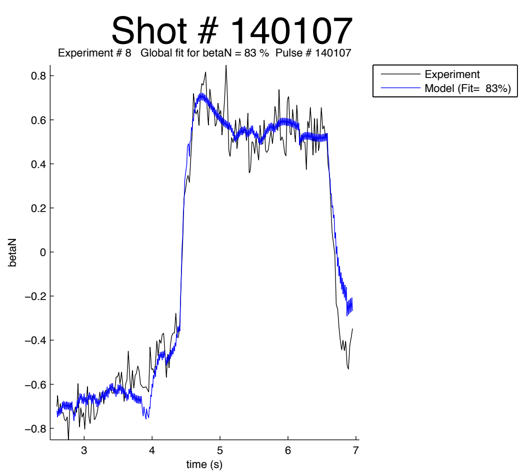
Identification t > 2.6 s

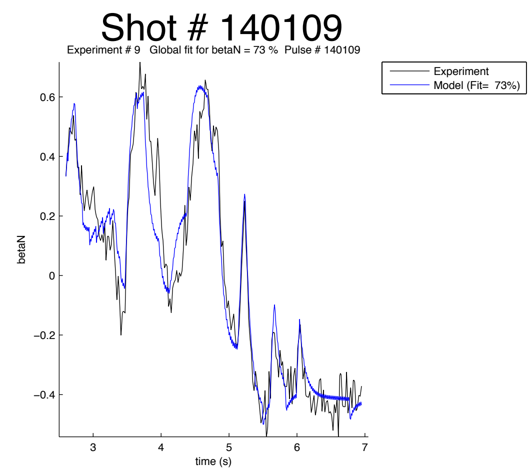
Validation from t = 2.6 s to the end











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

- Singular perturbation analysis ➔ Near-optimal control *(D. Moreau et al., Nucl. Fusion 2008)*

(amounts to conventional optimal control when $\varepsilon \to 0$)

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, $\psi(x, t)$.

Improved feedforward command on Ecoil for better Vsurf control ?

First tests were not quite satisfactory in producing a given Vsurf reference requested by the profile controller :

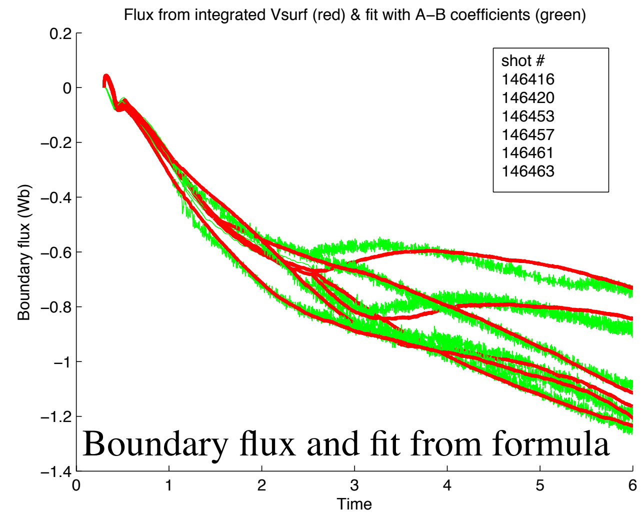
Low feedback gain ➔ large offset
High feedback gain ➔ large oscillations

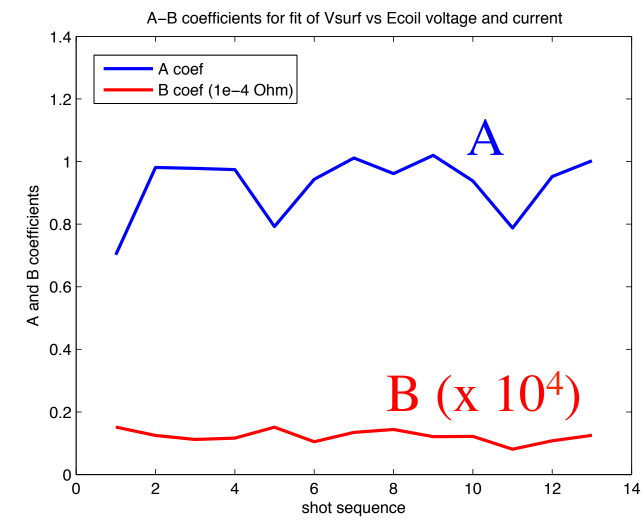
An estimate of the surface voltage could be found empirically as a function of the Ecoil voltage and current through a fit of the form:

Vsurf ≈ A*V_ecoil + B*I_ecoil

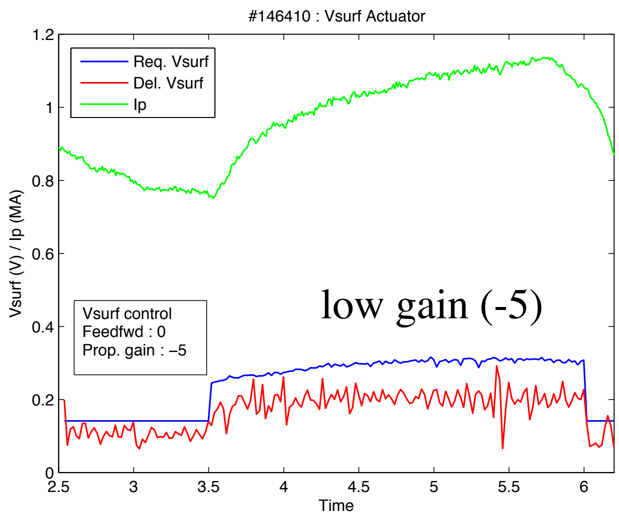
⇩

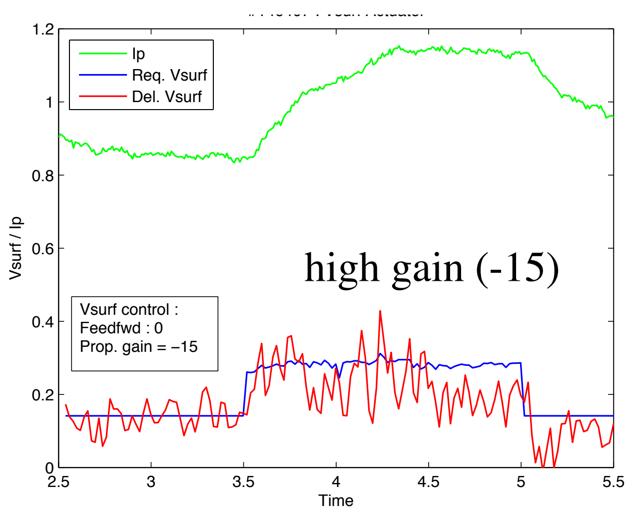
Suggests a feedforward command :
V_ecoil = (Vsurf – B*I_ecoil)/A



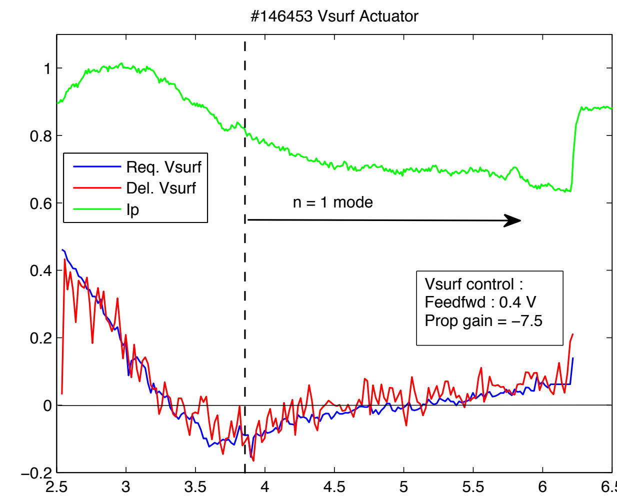


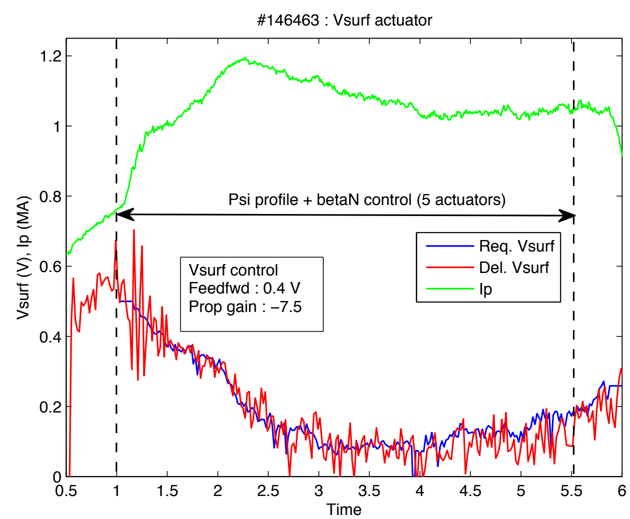
Control of the Vsurf actuator
feedback ➔ feedforward + feedback





Add Feedforward Voltage on Ecoil (0.4 V)
+
Gain = -7.5





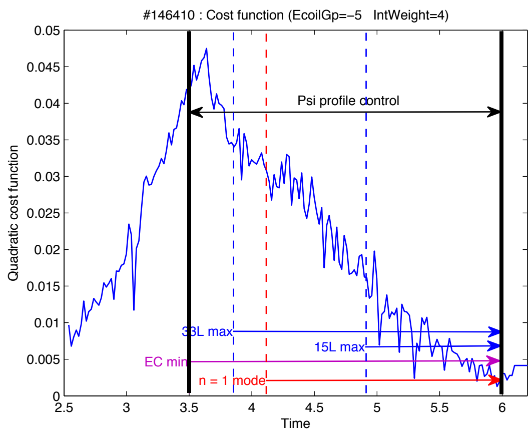
Control of the poloidal flux profile

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

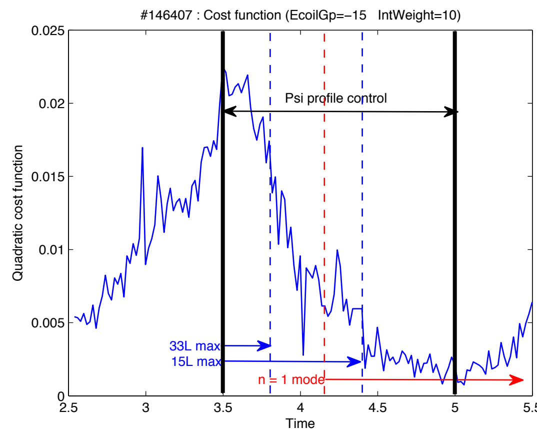
with actuator constraints and optimal gain matrices that depend on controller parameters :

- 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, see singular values of static gain matrix)
- Weight on integral control in the Q-matrix = 4, 10, 25, respectively, on the 3 examples below :

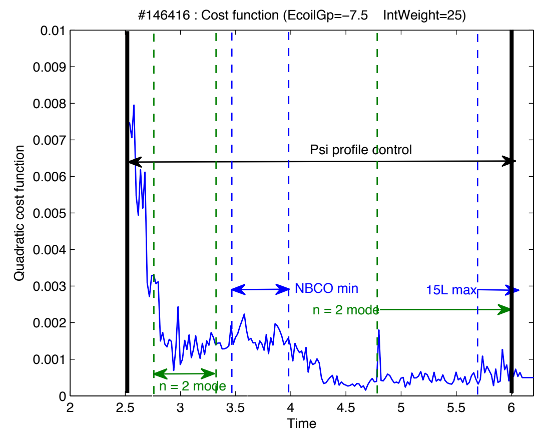
#146410 : IntWeight = 4



#146407 : IntWeight = 10



#146416 : IntWeight = 25

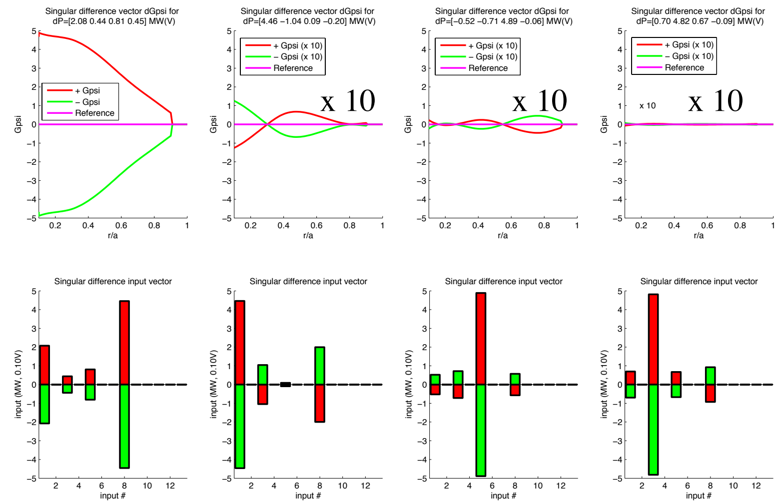


Control of the poloidal flux profile

4 actuators : NB-co, NB-bal, ECCD, Vsurf

Singular Value Decomposition
of the steady state gain matrix

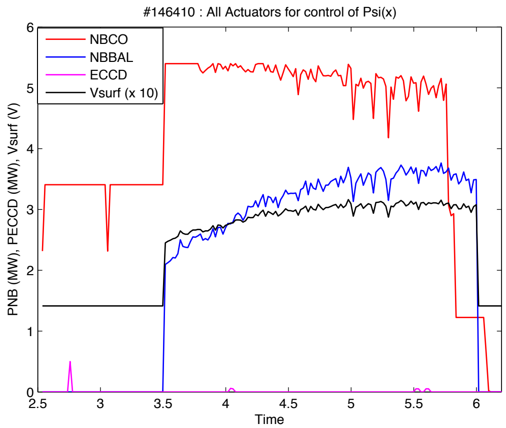
σ = [0.689   0.011   0.005   0.0004]

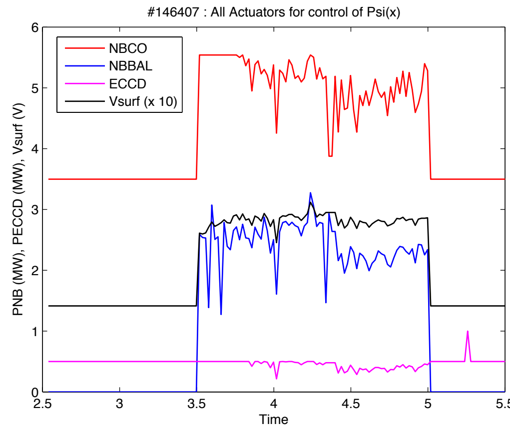


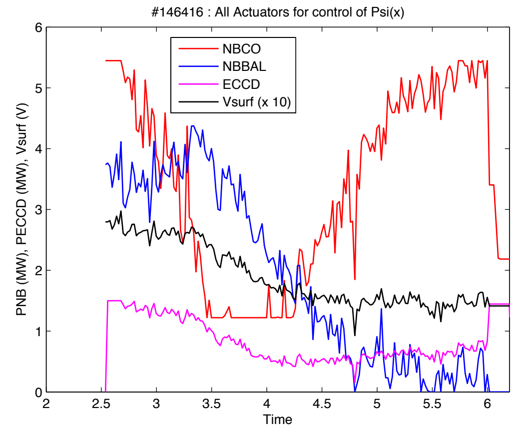
Controller order > 0 ➔ prop.+integral control

Order 2 controller for ψ(x) control

#146410 : IntWeight = 4 ➔ #146407 : IntWeight = 10 ➔ #146416 : IntWeight = 25

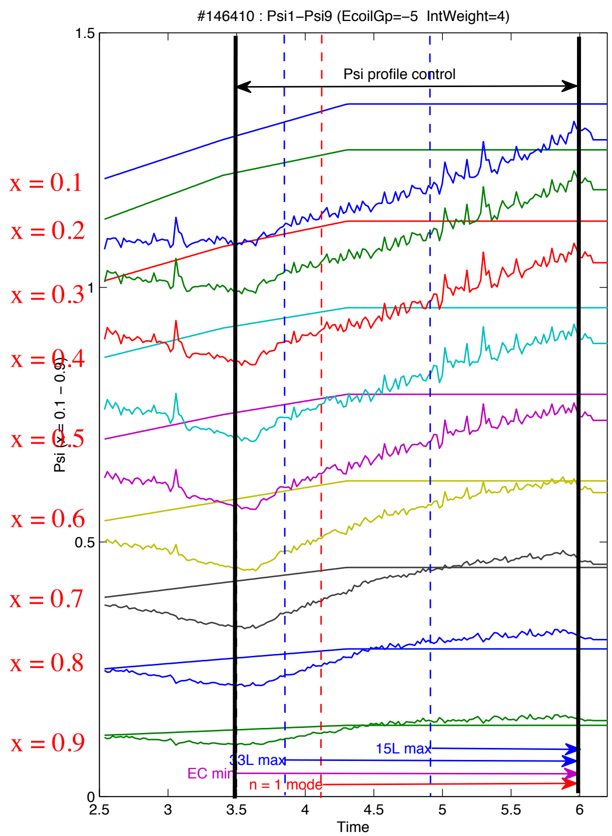






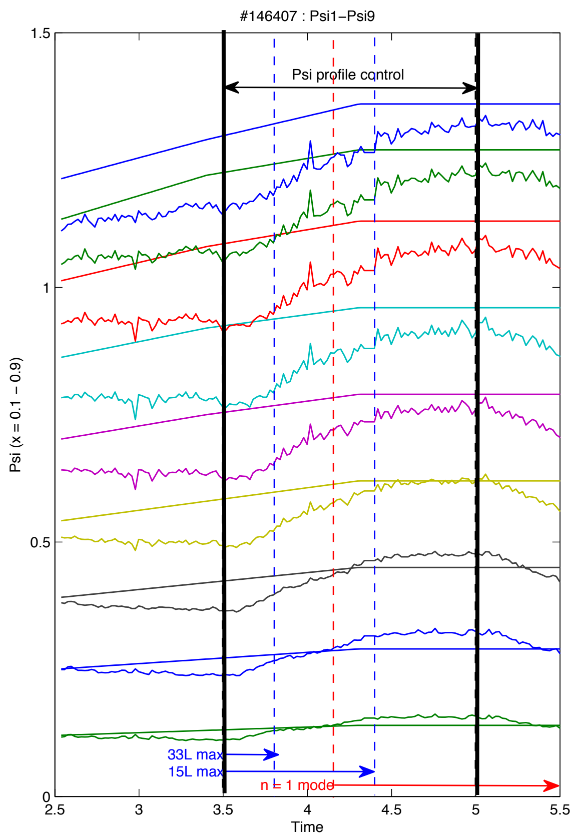
Control of the poloidal flux profile (x = 0.1, 0.2, … 0.9)

#146410 : IntWeight = 4



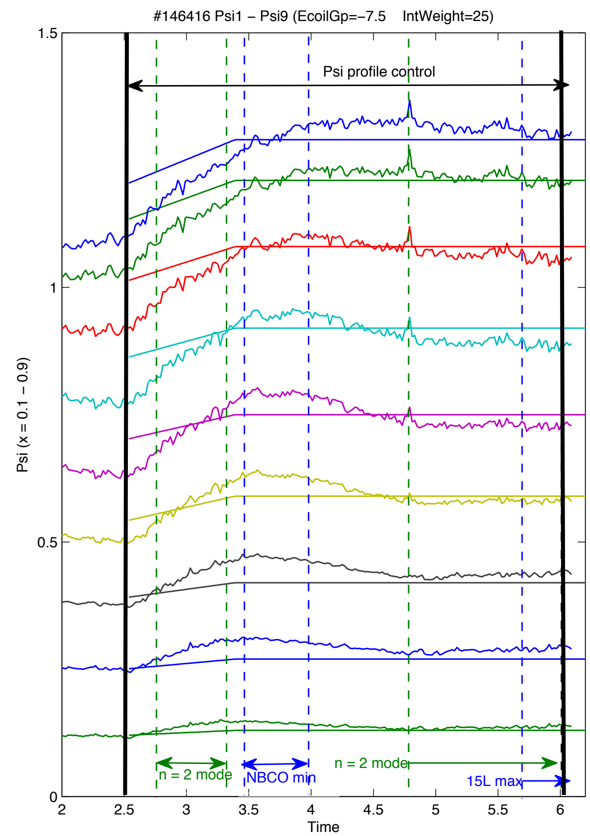
Control : 3.5 s - 6 s

#146407 : IntWeight = 10



Control : 3.5 s - 5 s

#146416 : IntWeight = 25

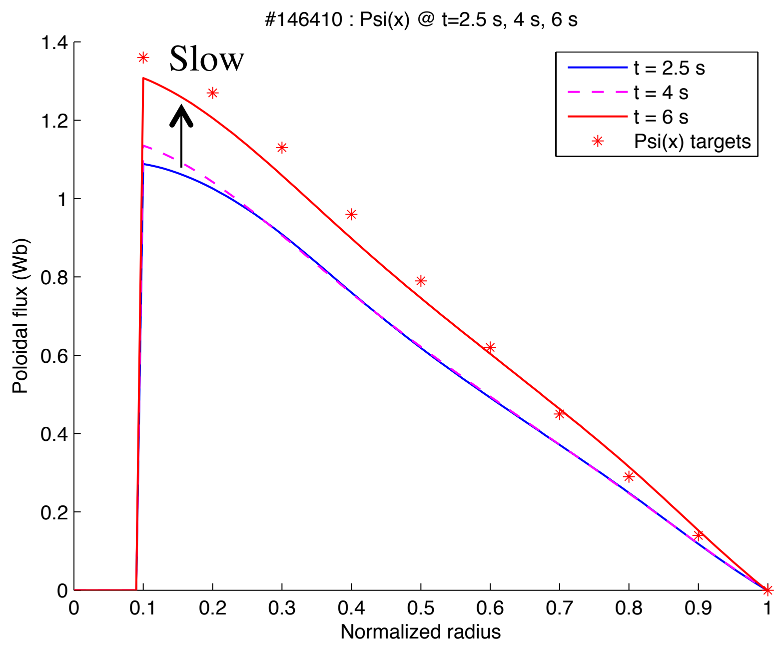


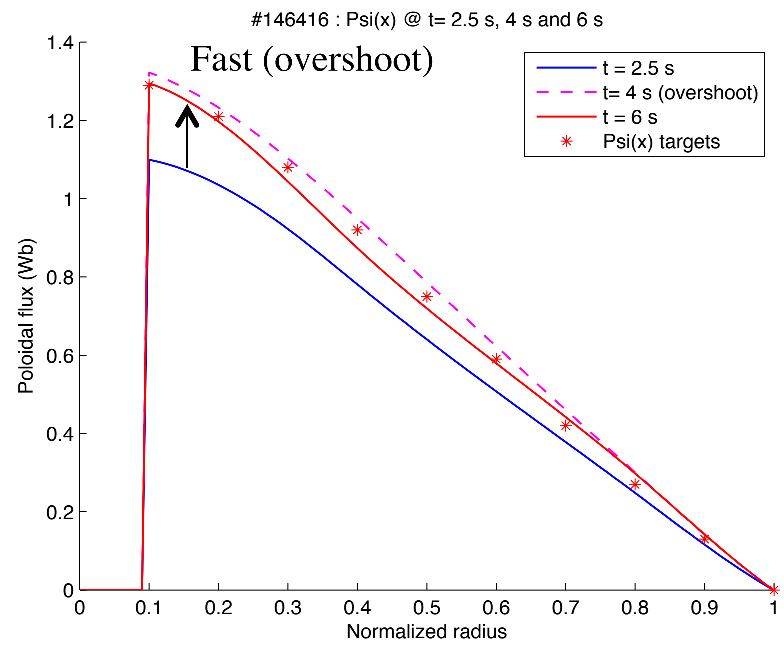
Control : 2.5 s - 6 s

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

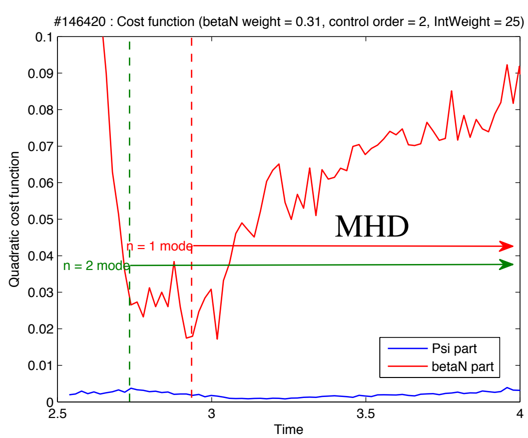
5 actuators : NB-co, NB-bal, NB-cnt, ECCD, Vsurf

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

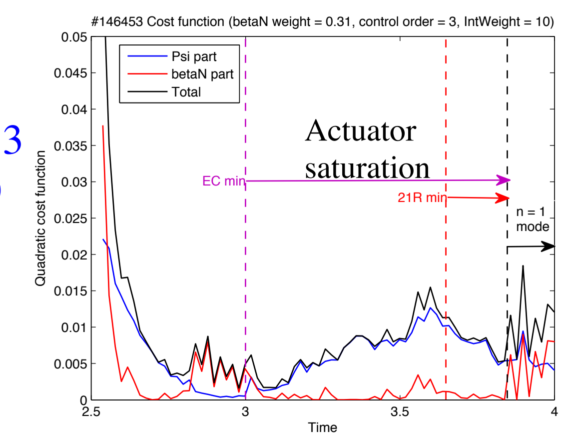
with actuator constraints and optimal gain matrices that depend on controller parameters :

- 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 : λ = 0.3
- Controller order = 3 (prop. + integral control, singular values σ = 0.929 0.085 0.016 0.006 0.0001)
- Weight on integral control in the Q-matrix = 25 and 10, respectively, in the 2 examples below :

#146420
Control order = 2
IntWeight = 25



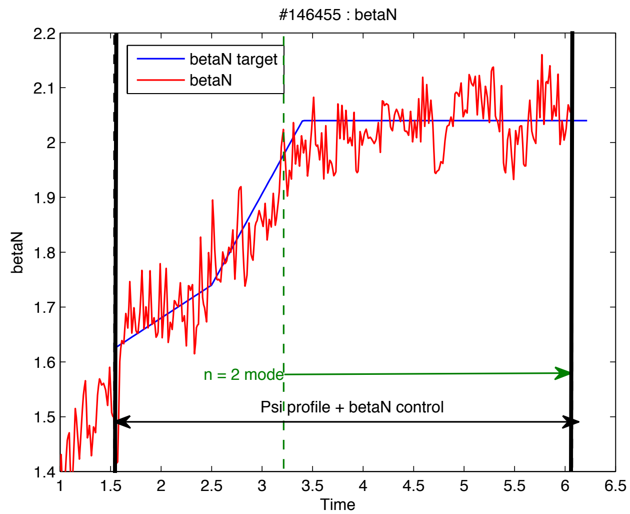
#146453
Control order = 3
IntWeight = 10



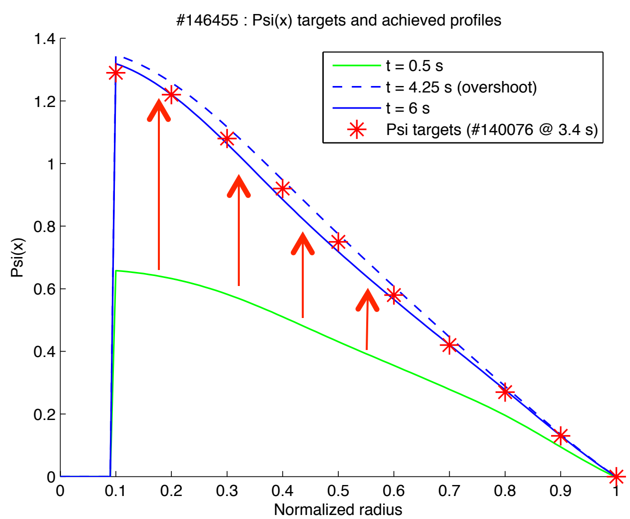
Simultaneous control of the ψ(x) profile and β_N

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

β_N control



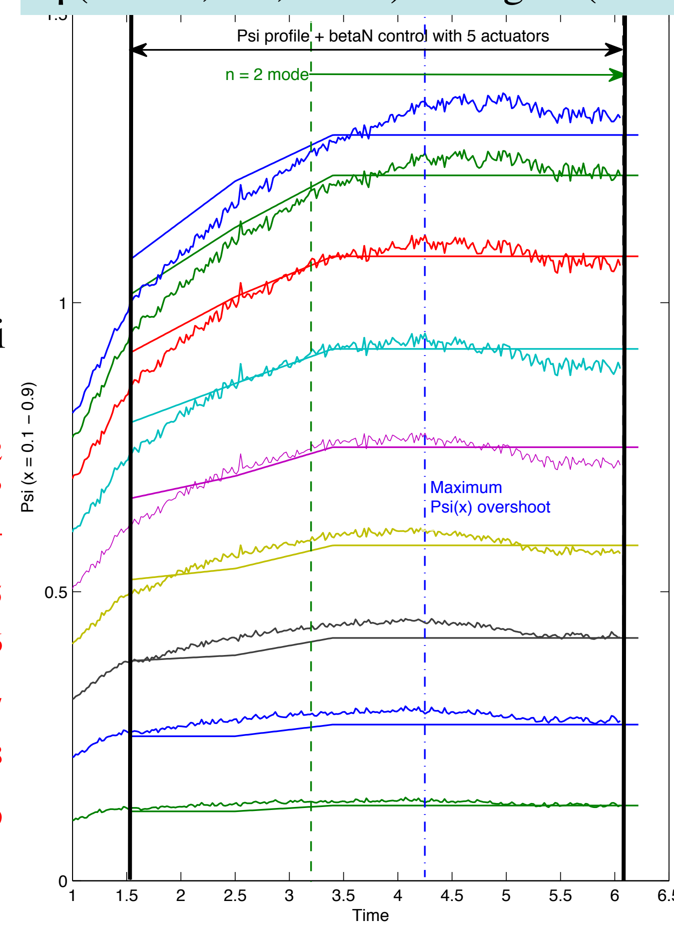
ψ-profile control



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

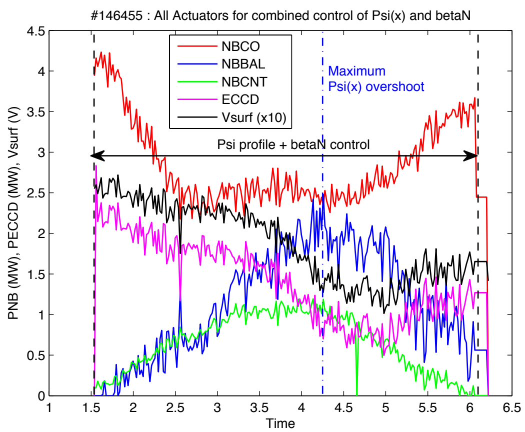


Time

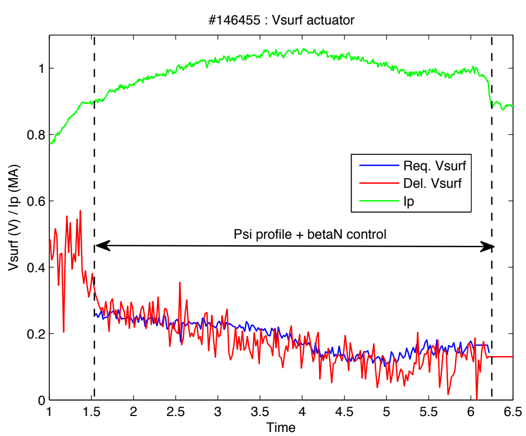
Simultaneous control of the $\psi(x)$ profile and β_N

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

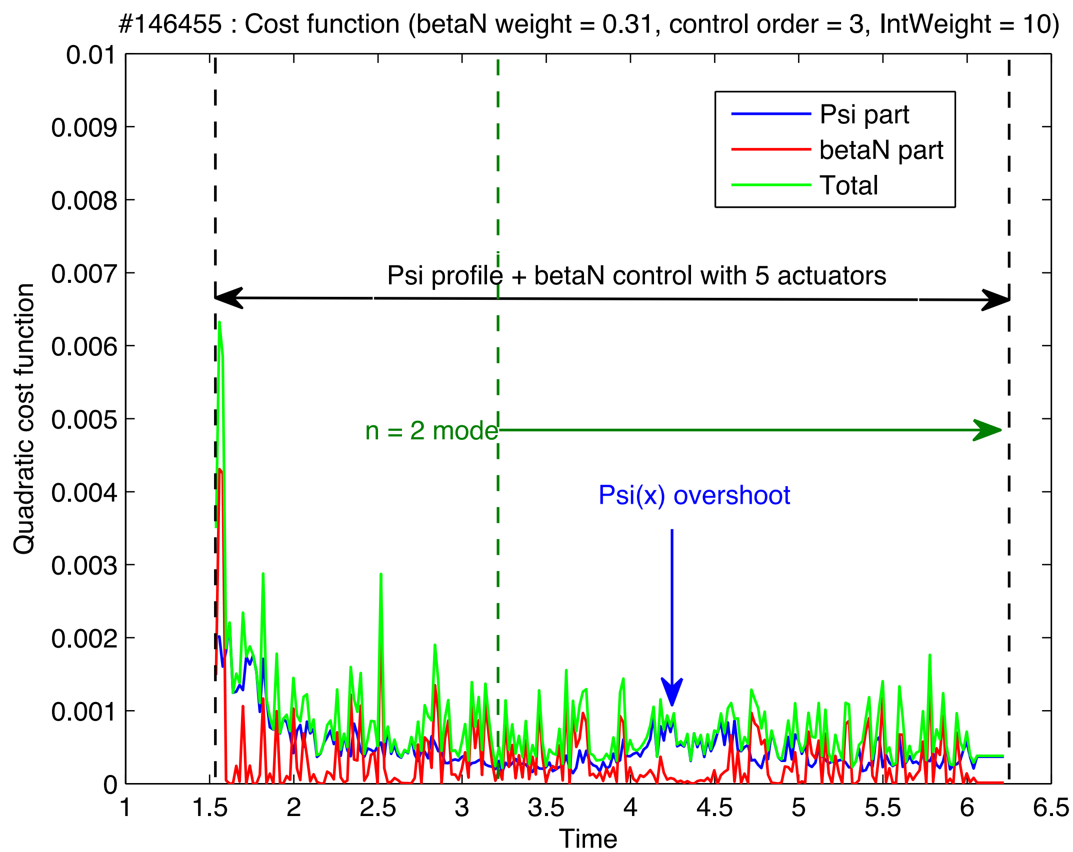
5 actuators (no saturation)



Vsurf actuator control & Ip



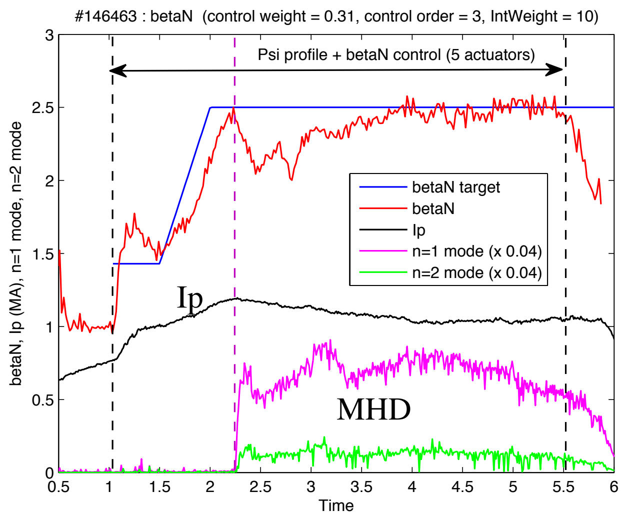
Cost function minimization



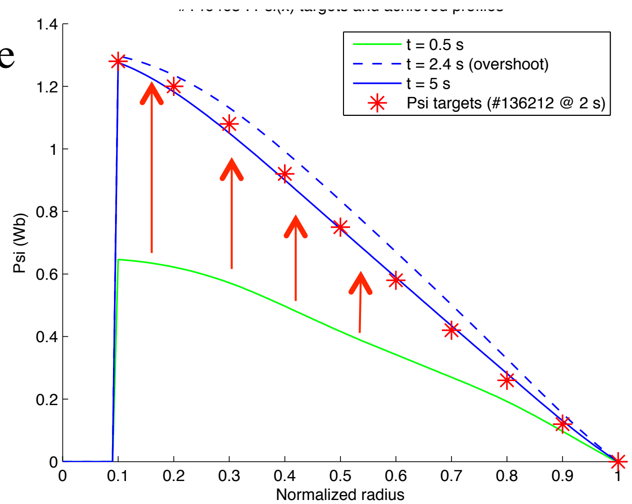
Simultaneous control of the $\psi(x)$ profile and β_N

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

β_N control

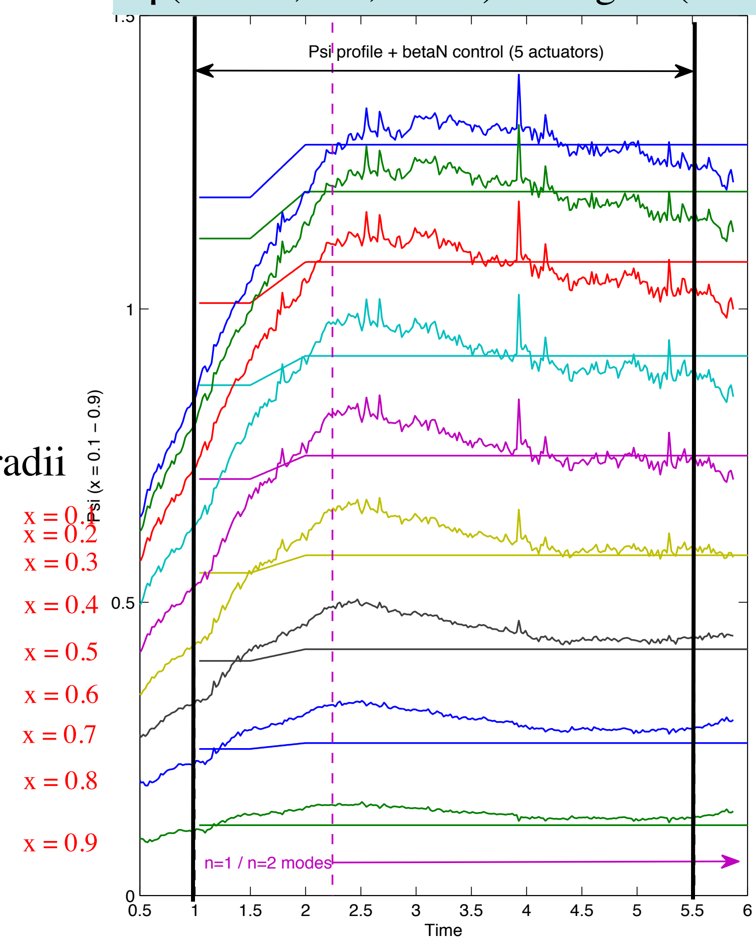


ψ-profile control



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

radii

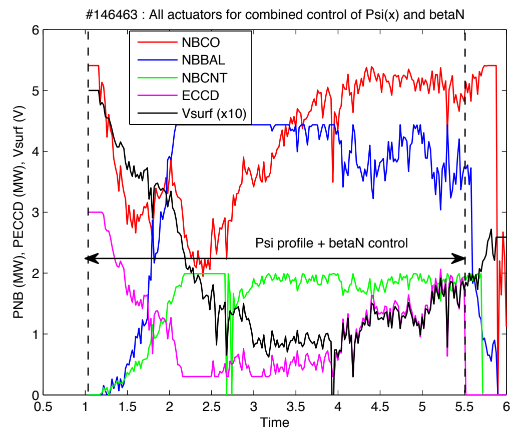


Time

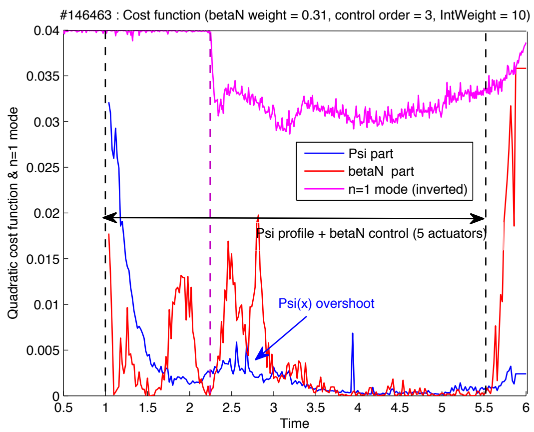
Simultaneous control of the ψ(x) profile and β_N

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

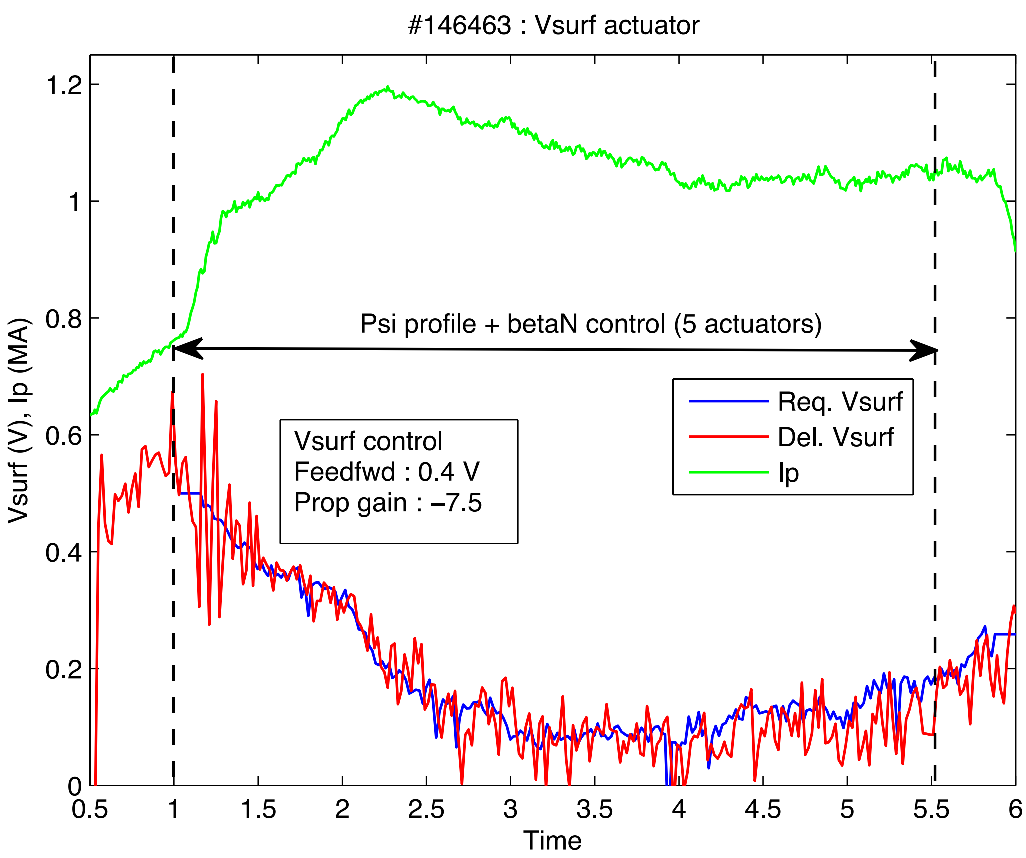
5 actuators (MHD ➔ NB-Bal saturation)



Cost function minimization



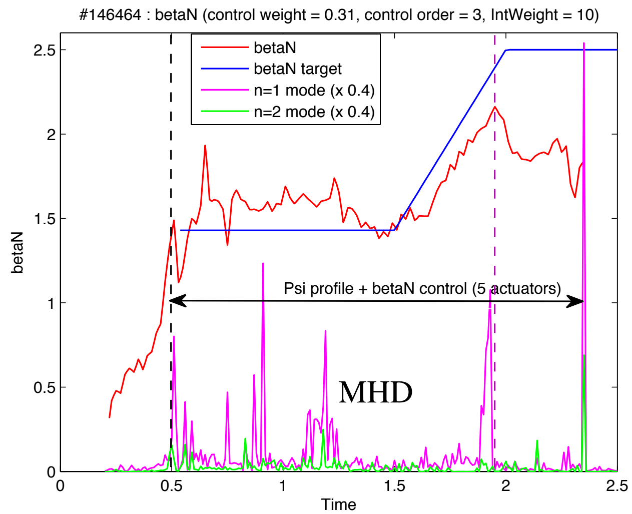
Vsurf actuator control & Ip



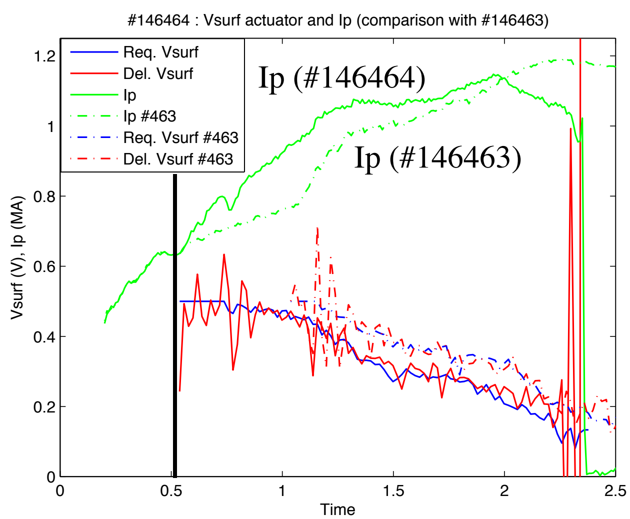
Simultaneous control of the ψ(x) profile and β_N

shot # 146464 : control starting at t = 0.5 s (ramp-up)

β_N control

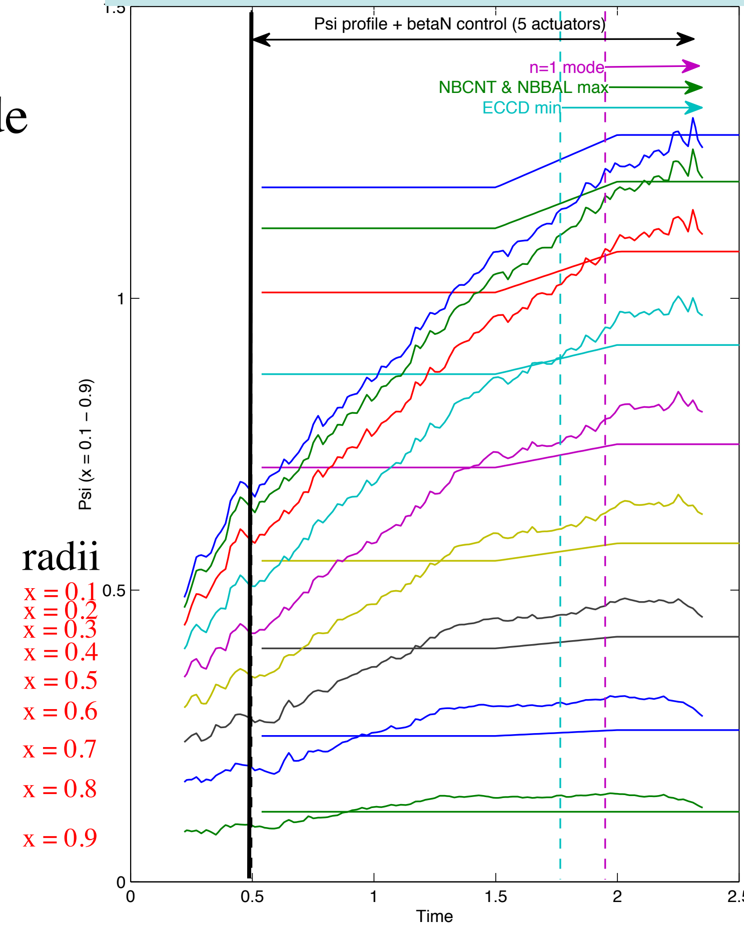


Ip & Vsurf



Locked mode @ t =2.4 s

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



Time

Summary and plans

- Combined control of the current profile and β_N has been attempted for the first time using either 4 actuators (210R beam not available on 09/13) or 5 actuators (09/14) simultaneously :

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

- PCS control of Vsurf was tuned with feedforward + feedback control to produce the real-time waveform requests
- PCS profile control algorithm was qualified and worked perfectly
- Main profile control parameters (controller order, proportional + integral gain matrices, cost function weights) were varied.
- Time window for combined feedback control of poloidal flux profile and β_N was increased successfully up to [1s-6s]
- Next : A couple of shots with full ramp-up control (i.e. starting @ 0.3 s) and 2 significantly different targets (monotonic-q / reversed-q) would demonstrate controlled current profile formation on D3D.
- Next : Combine with control of rotation profile (using real-time CER data)