PLASMA SHAPE, PROFILES AND FLUX CONTROL
FOR
HIGH-BOOTSTRAP STEADY STATE TOKAMAKS

D. Moreau

EFDA-JET CSU, Culham Science Centre, Abingdon, OX14 3DB, U. K.

Euratom-CEA Association, CEA-Cadarache, 13108, St Paul lez Durance, France

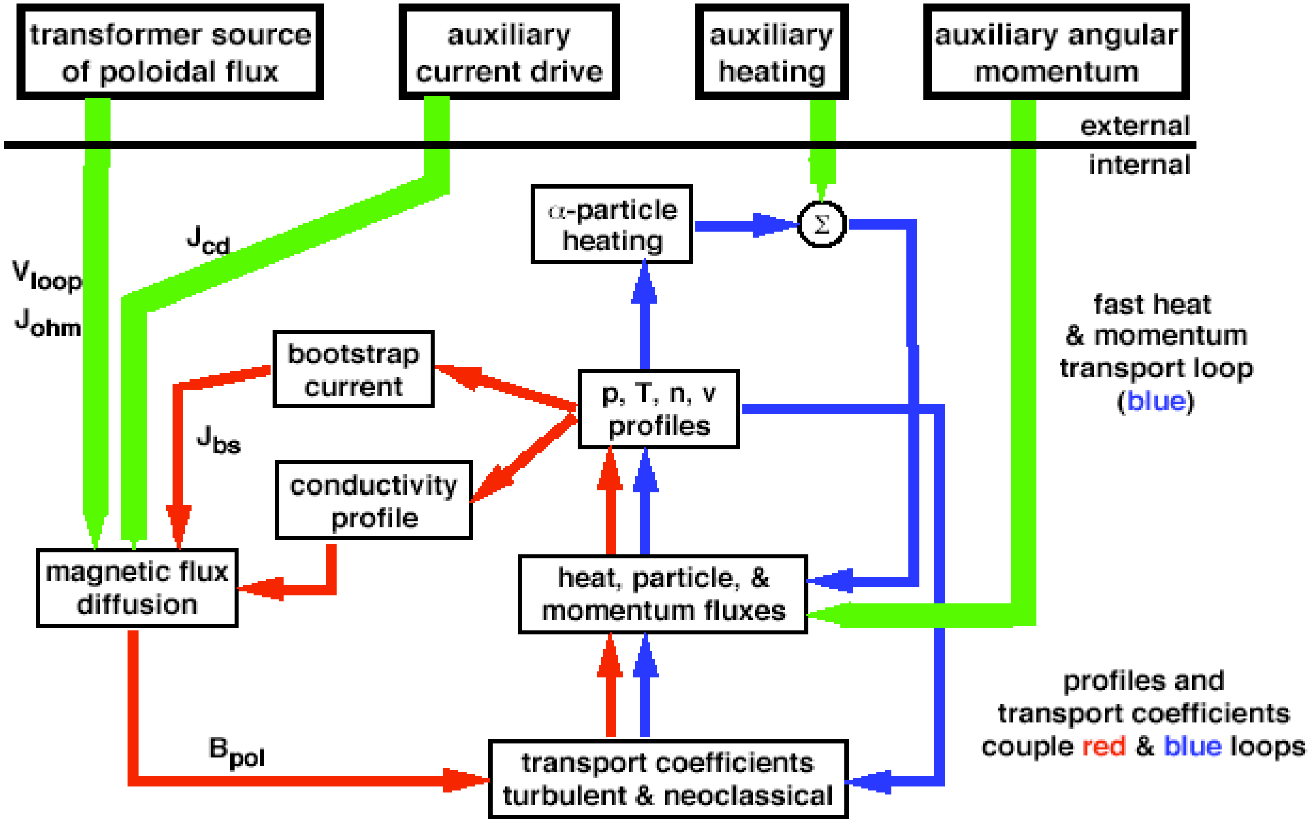
Acknowledgements : L. Laborde, D. Mazon, A. Murari, T. Tala
and many JET-EFDA Contributors

OUTLINE

- Introduction (issues, actuators, sensors, non-linear couplings ...)
- Strategy for an integrated profile control in the AT regime
- Results from initial experiments on JET
- The multiple time scale approach under development
- The JET Extreme Shape Controller
- Integration of shape, profiles and flux control for steady state operation
- Conclusion

Nonlinear transport couplings in present day experiments

TOKAMAK NONLINEAR TRANSPORT COUPLINGS



transformer source of poloidal flux

auxiliary current drive

auxiliary heating

auxiliary angular momentum

external

internal

α-particle heating

Σ

V_{loop}

J_{ohm}

J_{cd}

bootstrap current

p, T, n, v profiles

J_{bs}

conductivity profile

magnetic flux diffusion

heat, particle, & momentum fluxes

fast heat & momentum transport loop (blue)

profiles and transport coefficients couple red & blue loops

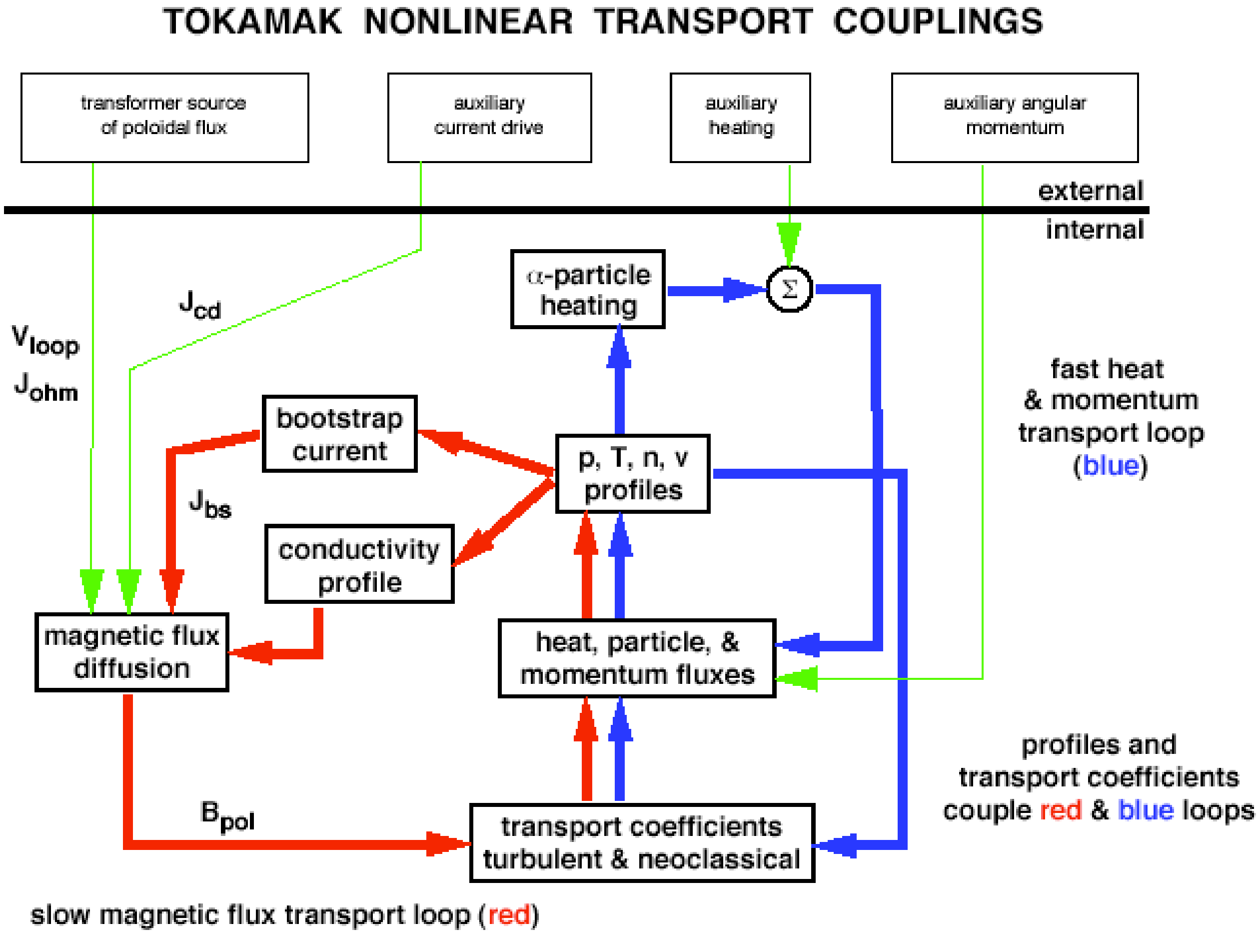
B_{pol}

transport coefficients turbulent & neoclassical

slow magnetic flux transport loop (red)

P. Politzer et al., ITPA meeting Lisbon 2004

Nonlinear transport couplings in a bootstrap-dominated steady state burning plasmas



TOKAMAK NONLINEAR TRANSPORT COUPLINGS

fast heat & momentum transport loop (blue)

profiles and transport coefficients couple red & blue loops

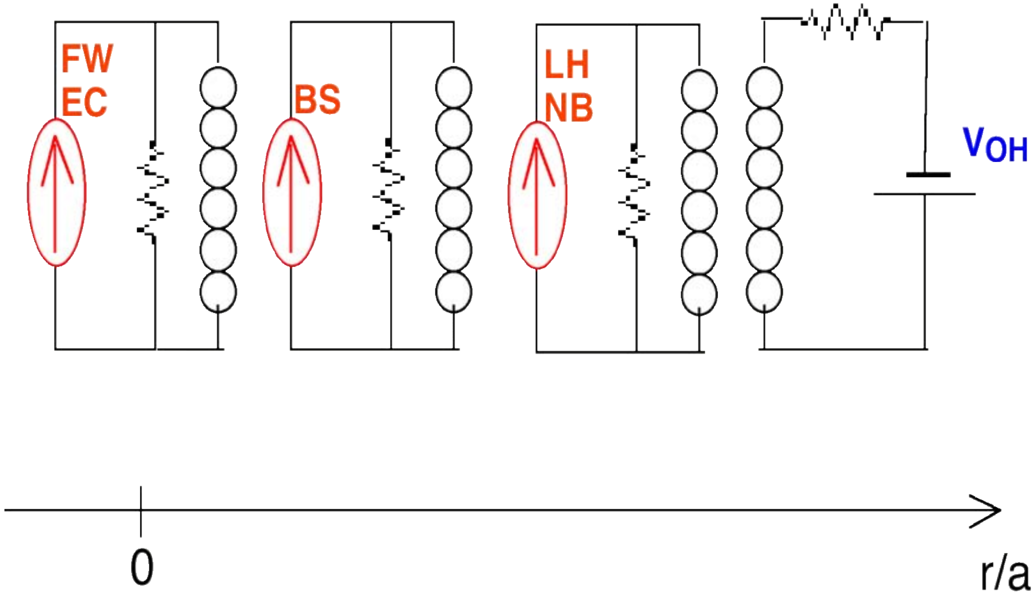
slow magnetic flux transport loop (red)

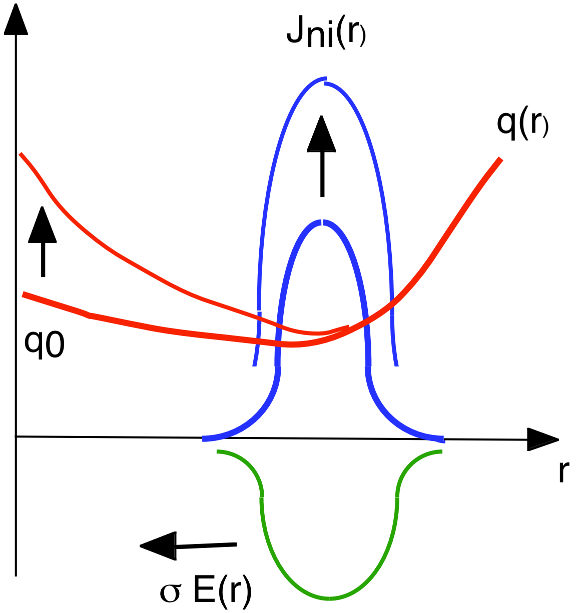
P. Politzer et al., ITPA meeting Lisbon 2004

Towards bootstrap-dominated steady state plasmas

On the way to a bootstrap-dominated burning plasma,
the bootstrap current driven by the fusion power
acts as the primary circuit of a transformer

This can lead to the formation of a current hole
and requires integrated real-time profile control (magnetic/kinetic)





q-PROFILE CONTROL ISSUES IN BURNING ADVANCED TOKAMAK PLASMAS

Alpha-power drives large bootstrap current

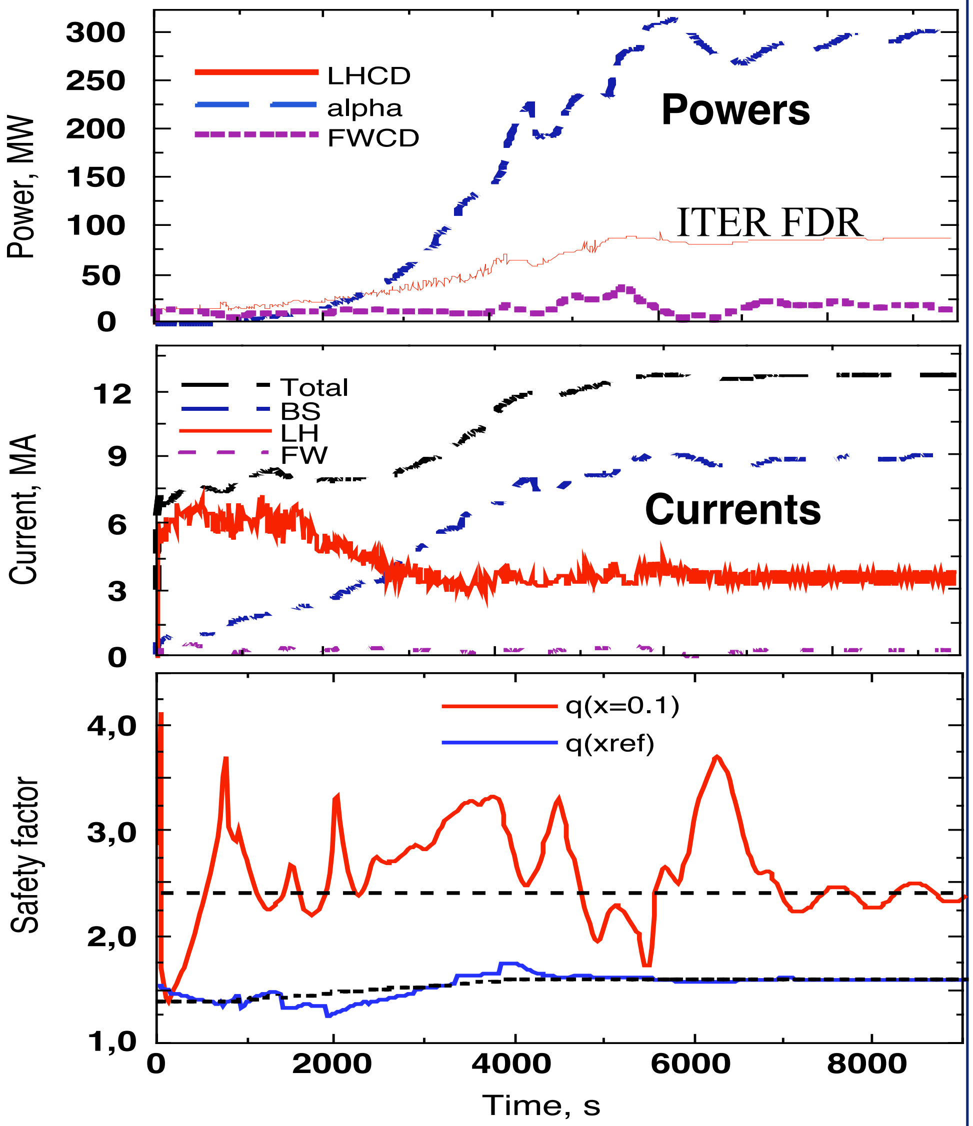
Excessive bootstrap current induces a current hole

Control with additional H&CD is difficult because of the interplay of confinement vs. resistive times

REQUIRES ULTRA-SLOW FUSION POWER RAMP-UP

AND/OR

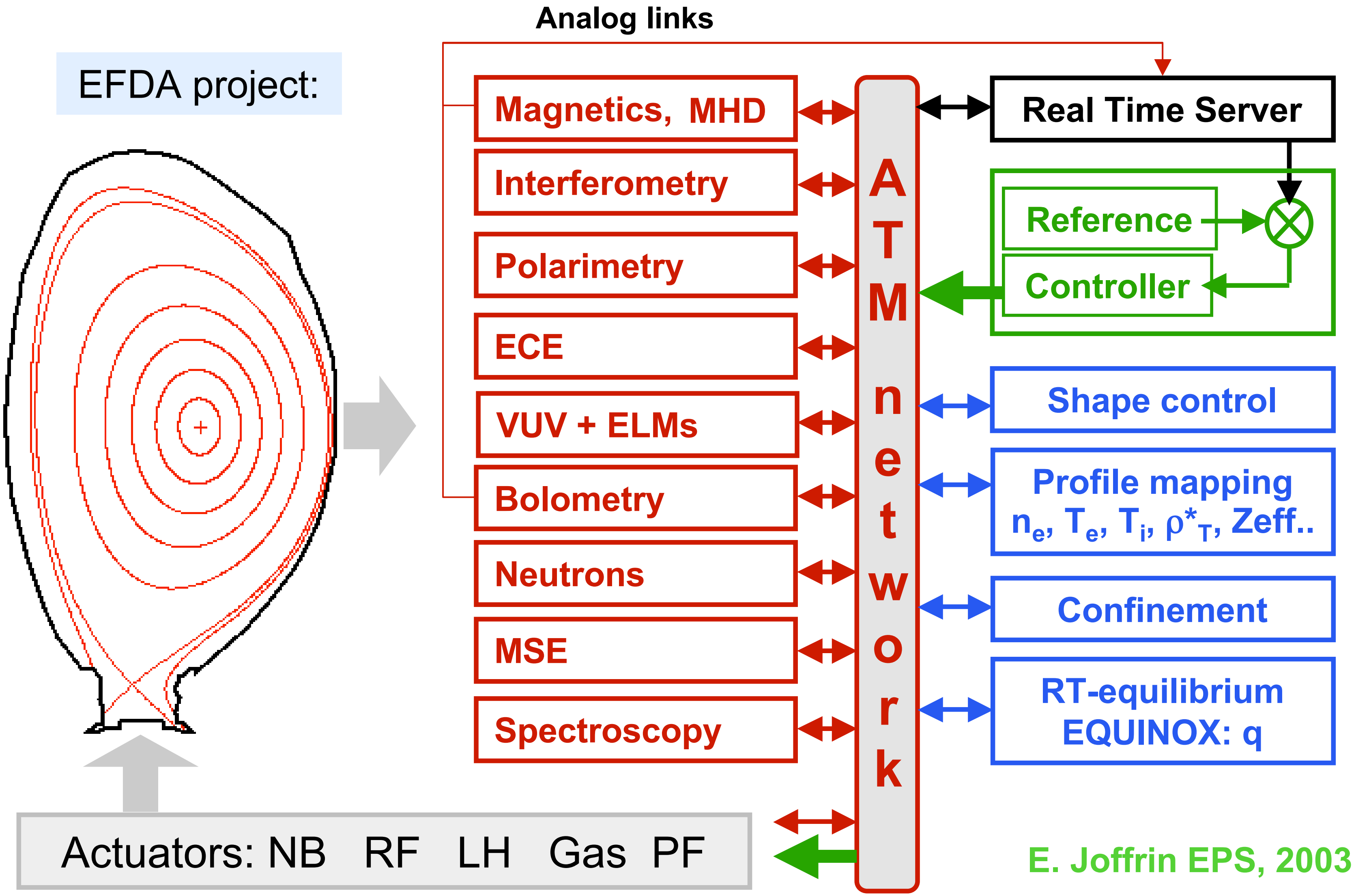
ACCURATE INTEGRATED CONTROL (MULTIPLE TIME SCALE)



D. Moreau et al., Nucl. Fus. 39 (1999) 685

Real Time Measurements and Control network on JET

EFDA project:



Analog links

Magnetics, MHD

Interferometry

Polarimetry

ECE

VUV + ELMs

Bolometry

Neutrons

MSE

Spectroscopy

ATM network

Real Time Server

Reference

Controller

Shape control

Profile mapping
n_e, T_e, T_i, ρ^*_T, Zeff..

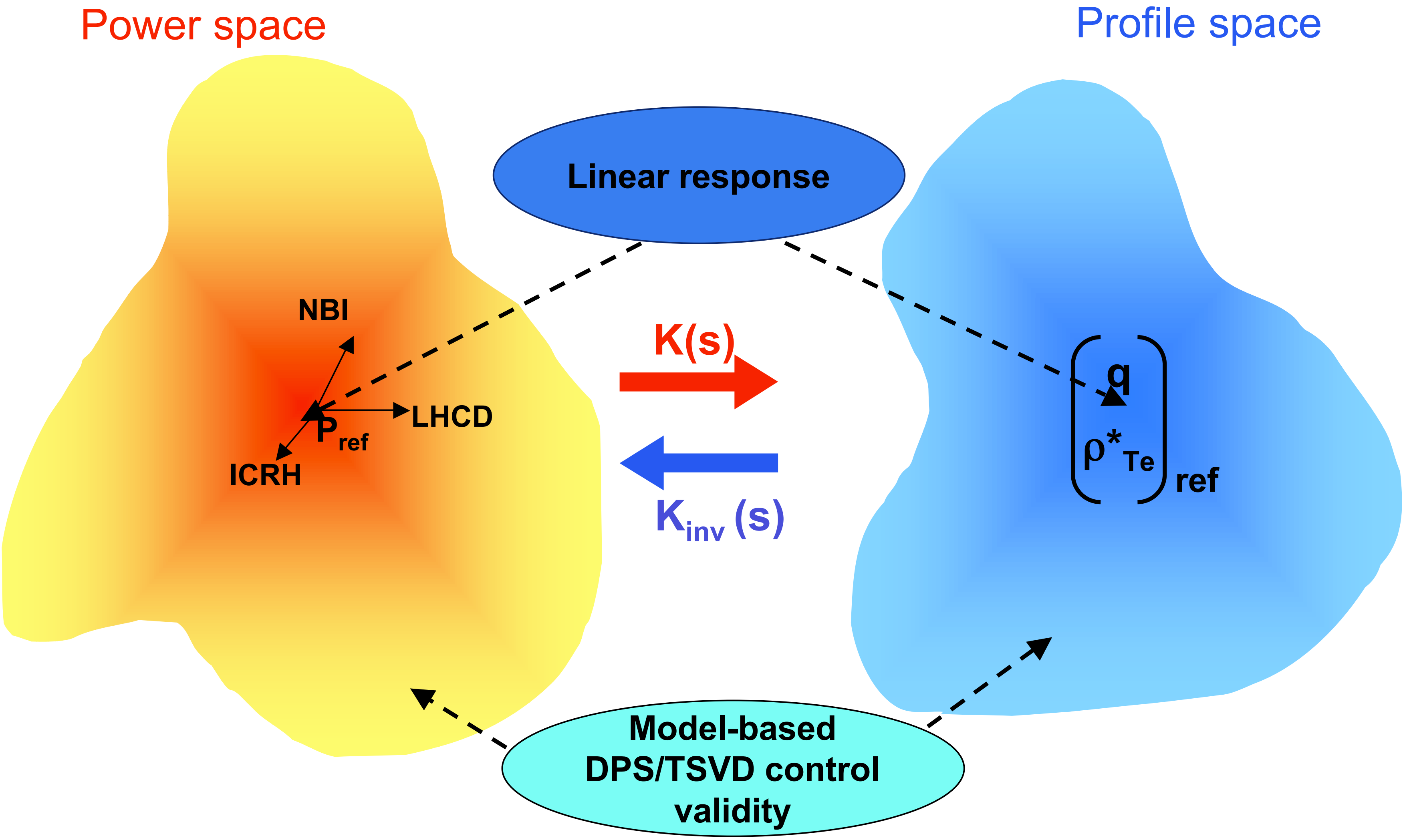
Confinement

RT-equilibrium
EQUINOX: q

Actuators: NB RF LH Gas PF

E. Joffrin EPS, 2003

PI feedback control validity > linear response domain



Power space

Profile space

Linear response

NBI

LHCD

ICRH

$\mathbf{P_{ref}}$

$K(s)$

$K_{inv}\,(s)$

$\begin{pmatrix} q \\ \rho^*_{Te} \end{pmatrix}_{ref}$

Model-based DPS/TSVD control validity

Linear response around an equilibrium state and singular value decomposition

$\mathcal{K}$ = Linear response function ($\mathcal{Y}$ = [current, pressure] ; $\mathcal{P}$ = heating/CD power)

$$\mathcal{Y}(x,t)=\int_0^t dt'\int_0^1 dx'\,\mathcal{K}(x,x',t-t')\,\mathcal{P}(x',t')$$

Laplace transform :

$$\mathcal{Y}(x,s)=\int_0^1 dx'\,\mathcal{K}(x,x',s)\,\mathcal{P}(x',s)$$

Kernel singular value expansion in terms of orthonormal right and left singular functions + System reduction through Truncated SVD (best least square approximation) :

$$\mathcal{K}(x,x',s)=\sum_{i=1}^{\infty}\mathcal{W}_i(x,s)\,\sigma_i(s)\,\overline{\mathcal{V}}_i(x',s)$$

Set of output trial function basis

Output profiles :

and

Output singular functions :

$$\mathcal{Y}(x,s)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\mathbf{Q}_j(s)+\text{residual}$$

$$\mathcal{W}_k(x,s)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\Omega_{kj}(s)+\text{residual}$$

With 2 profiles (current, pressure) :

$$\mathcal{D}_j(x)=\begin{bmatrix} a_j(x) & 0 \\ 0 & b_j(x) \end{bmatrix}$$

Identification of the operator $\mathcal{K}$

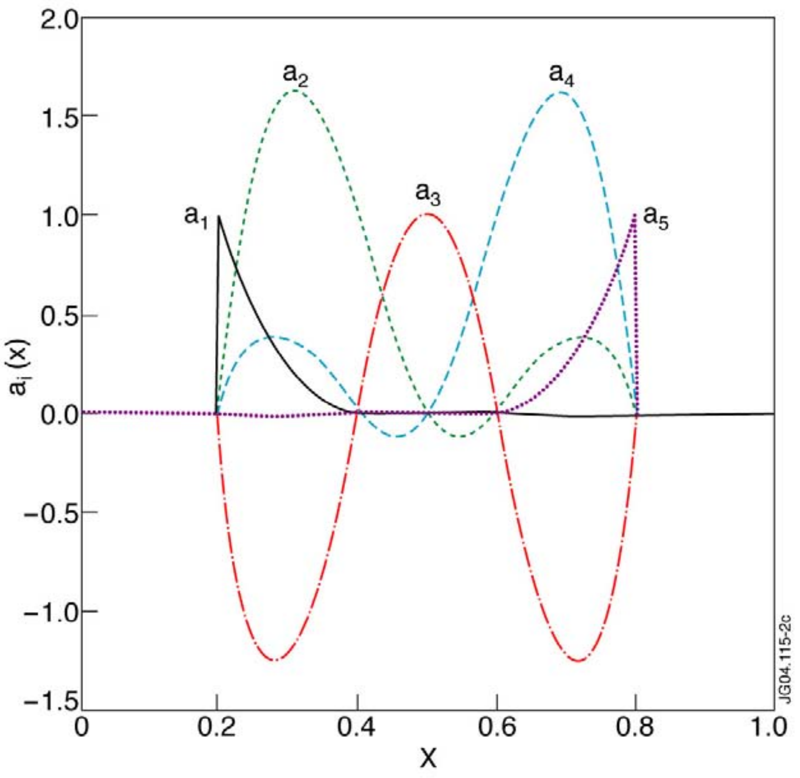
Galerkin's method : residuals spatially orthogonal to each basis function

$$\mathcal{Y}(x,s)=\int_0^1 dx'\,\mathcal{K}(x,x',s)\,\mathcal{P}(x',s)$$

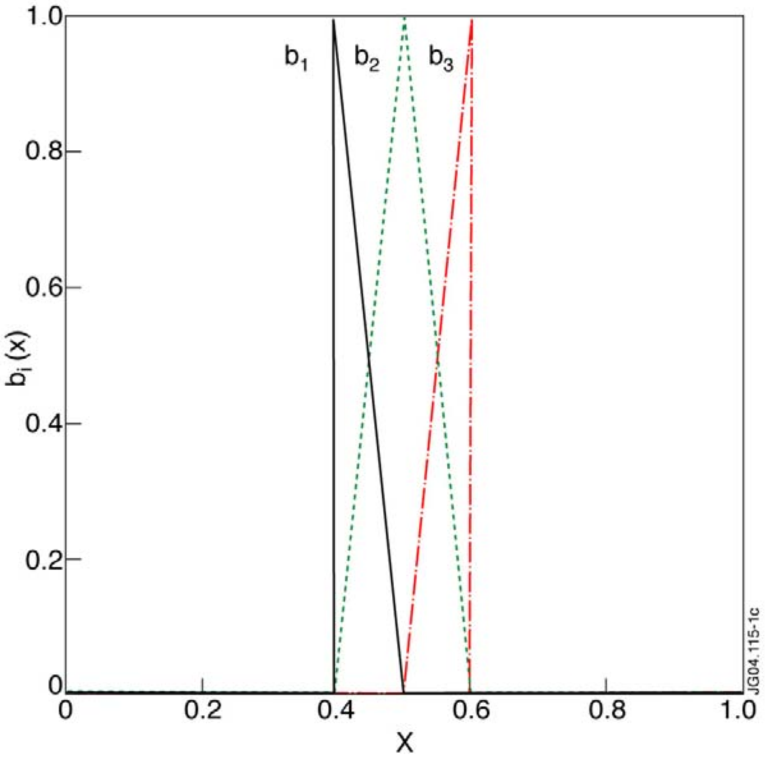
$$\int \text{residual}\,.\,\mathcal{D}_i(x)\,dx=0$$

➡ **Q(s) = K$_{\text{Galerkin}}$(s) . P(s)**

Set of output trial function basis



q-profile



ρ_{Te}*-profile

What should the controller achieve ?

Output profiles : $\mathcal{Y}(x,s)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\mathbf{Q}_j(s)+\text{residual}$

Setpoint profiles : $\mathcal{Y}_{\text{setpoint}}(x)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\mathbf{Q}_{j,\text{setpoint}}+\text{residual}$

Define scalar product to **minimize a least square quadratic form** :

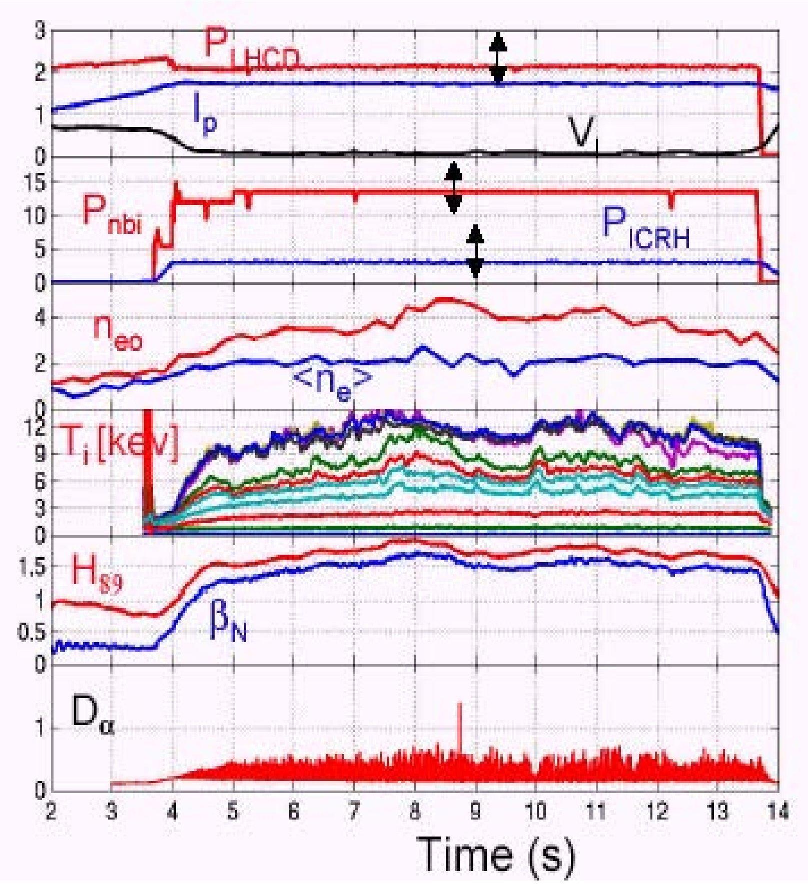
$$\int_0^1 \mu_1(x)\left[q(x)-q_{\text{setpoint}}(x)\right]^2 dx+\int_0^1 \mu_2(x)\left[\rho_T^*(x)-\rho_{T,\text{setpoint}}^*(x)\right]^2 dx$$

GOAL = minimize $[\mathcal{Y}(s=0)-\mathcal{Y}_{\text{setpoint}}]\bullet[\mathcal{Y}(s=0)-\mathcal{Y}_{\text{setpoint}}]$

D. Moreau et al., Nucl. Fusion 43 (2003) 870 **L. Laborde et al., PPCF 47 (2005) 155**

Experimental "linear response" model identification

Reference non-inductive pulse #62146, 3T/1.7MA



D. Mazon et al., EPS 2004

- Power modulations around a target steady state

- Identification of a linear model relating injected power modulations and profiles variations of q and ρ_{Te}^*

Dynamic model : K(s) . **P**(s) = **Q**(s)

or

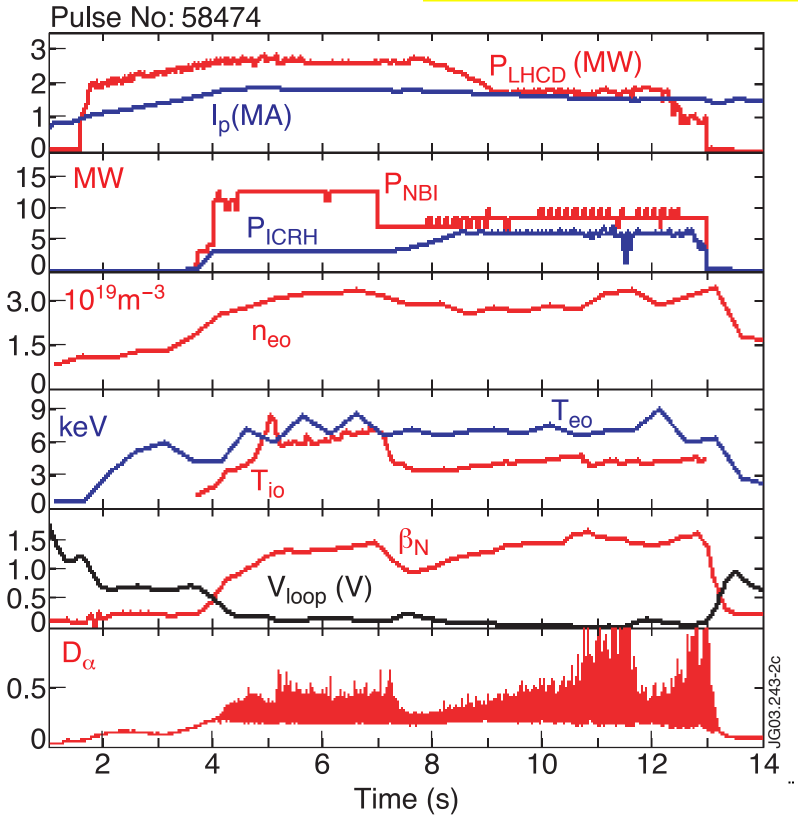
Static model : K(0) . **P**(0) = **Q**(0)

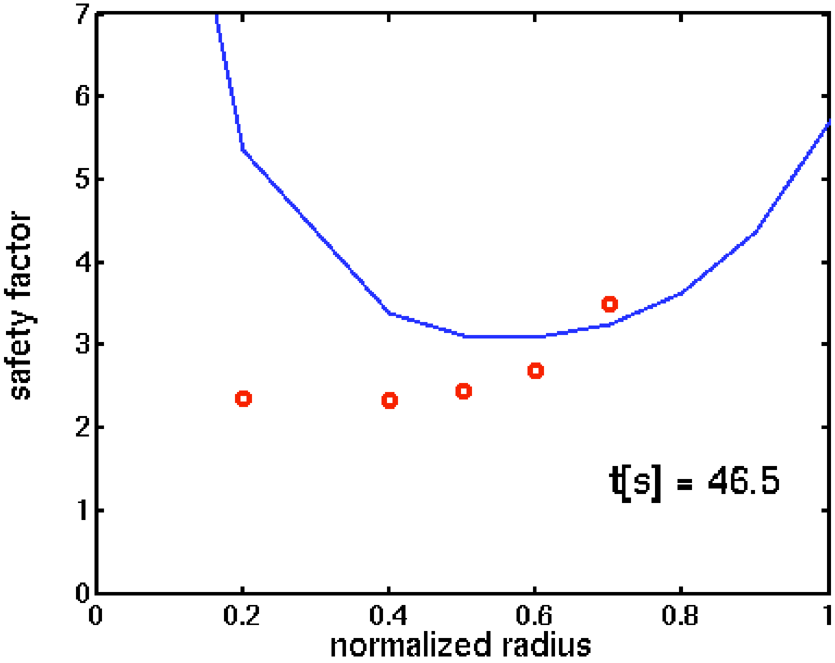
- 5 pulses with power variations

P_{ICRH}	3MW	5MW	
P_{LHCD}	1.5MW	2MW	2.5MW
P_{NBI}	13.5MW	10.5MW	

Initial experiments with the lumped-parameter version of the algorithm with 3 actuators
2-mode TSVD for 5-point q-profile control

$$K_T = \sigma_1 W_1.V_1^+ + \sigma_2 W_2.V_2^+$$





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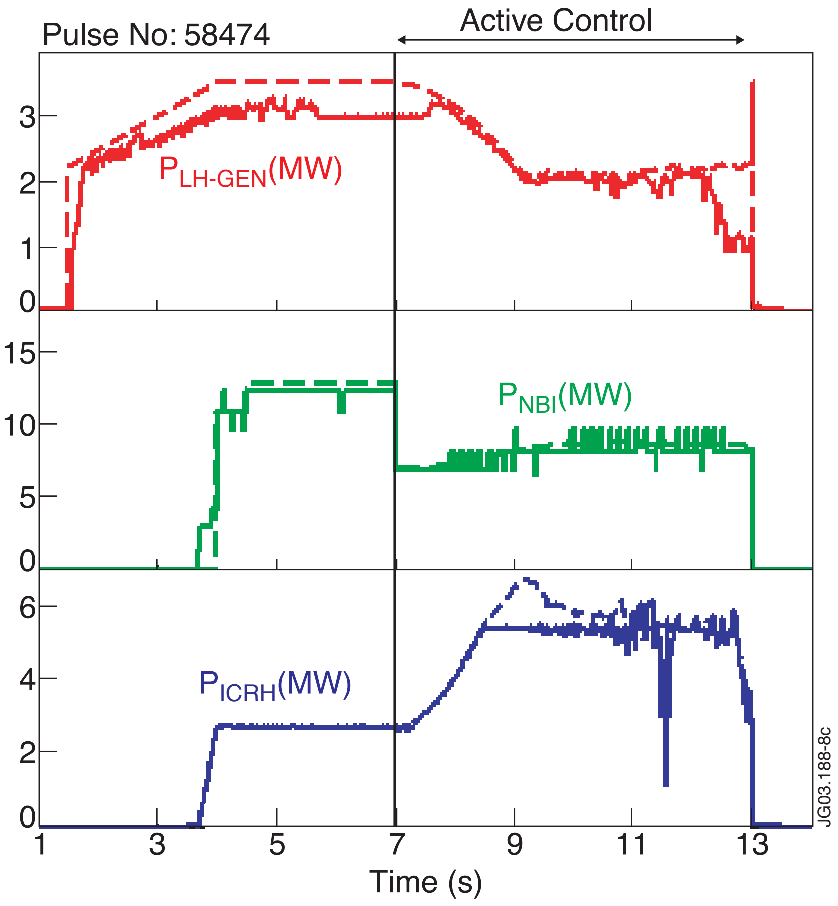
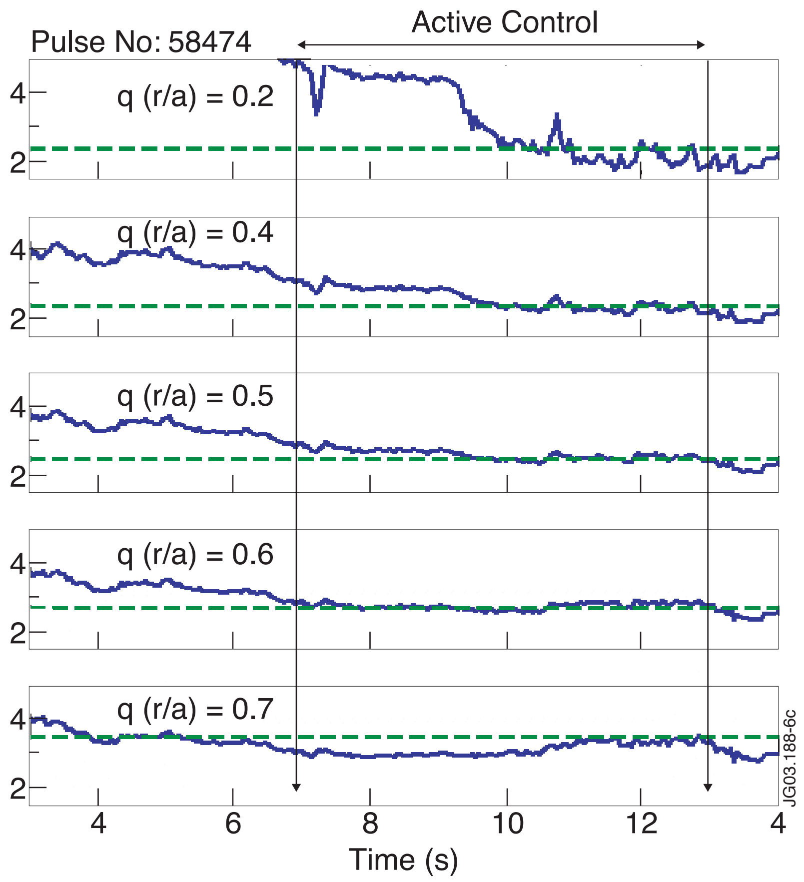




D. Moreau et al., Nucl. Fusion 43 (2003) 870

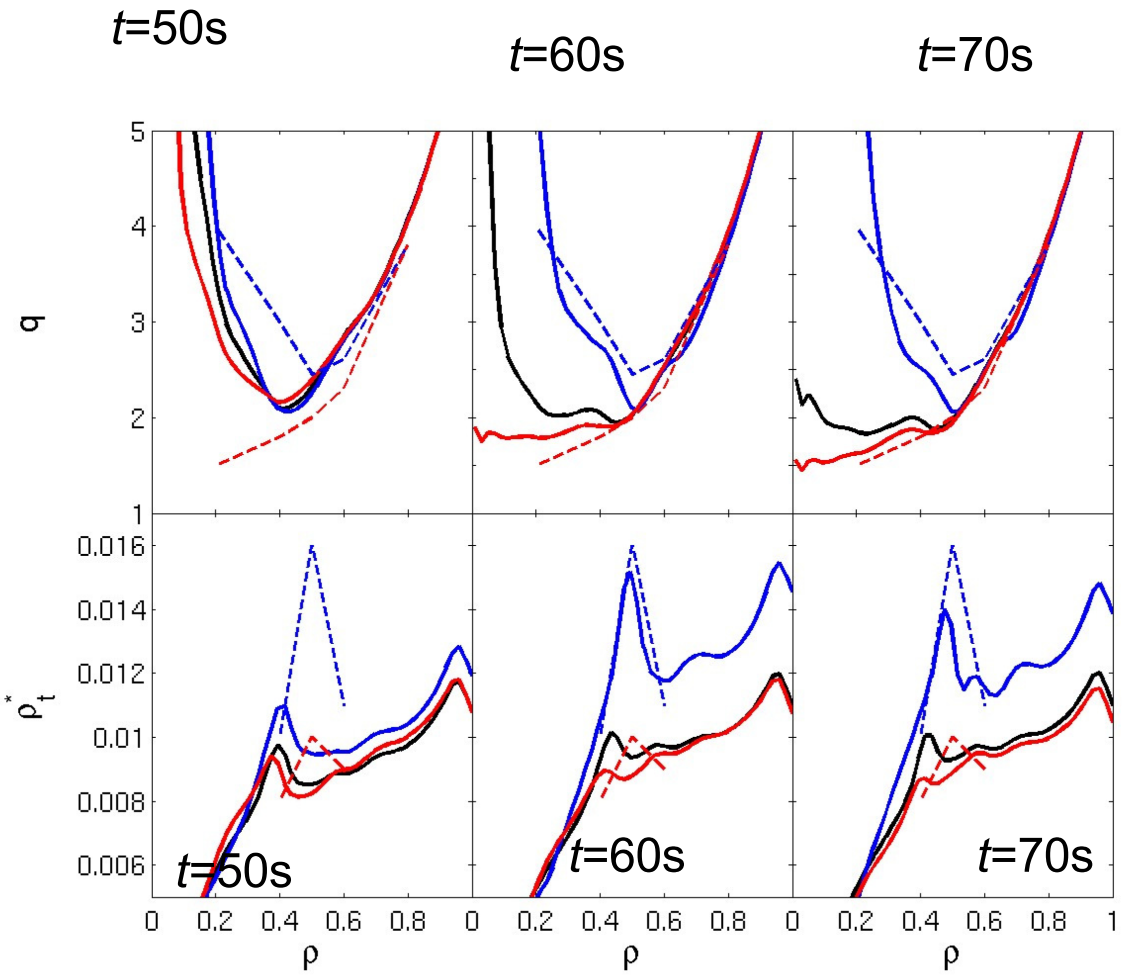
Closed-Loop JETTO Simulations with Combined Control of *q* and ρ_{Te}^*

Predictive JETTO Simulations

Open-Loop Reference
Reversed *q*, ITB
Monotonic *q*, no ITB

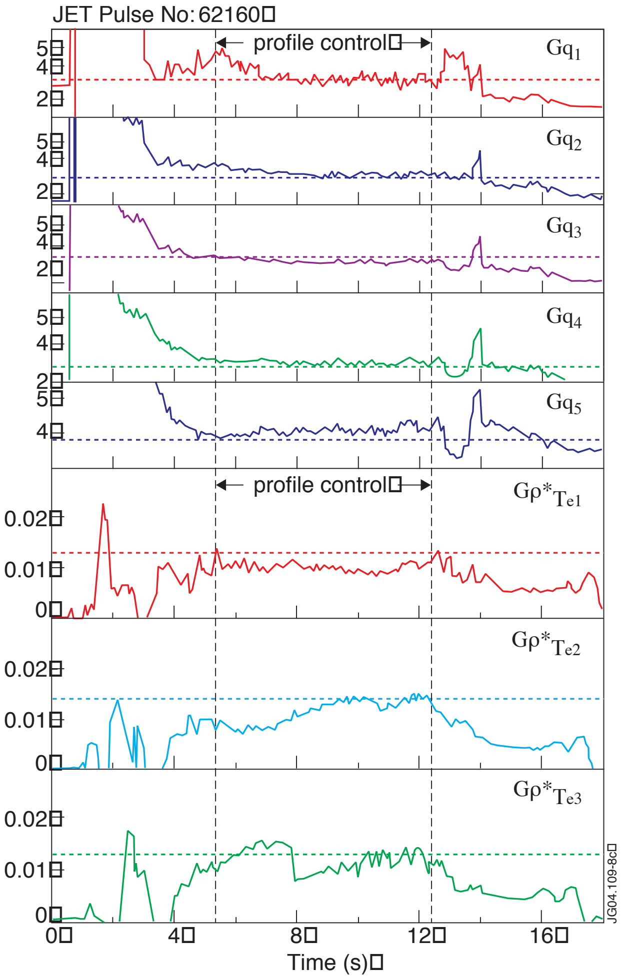
Set-point profiles

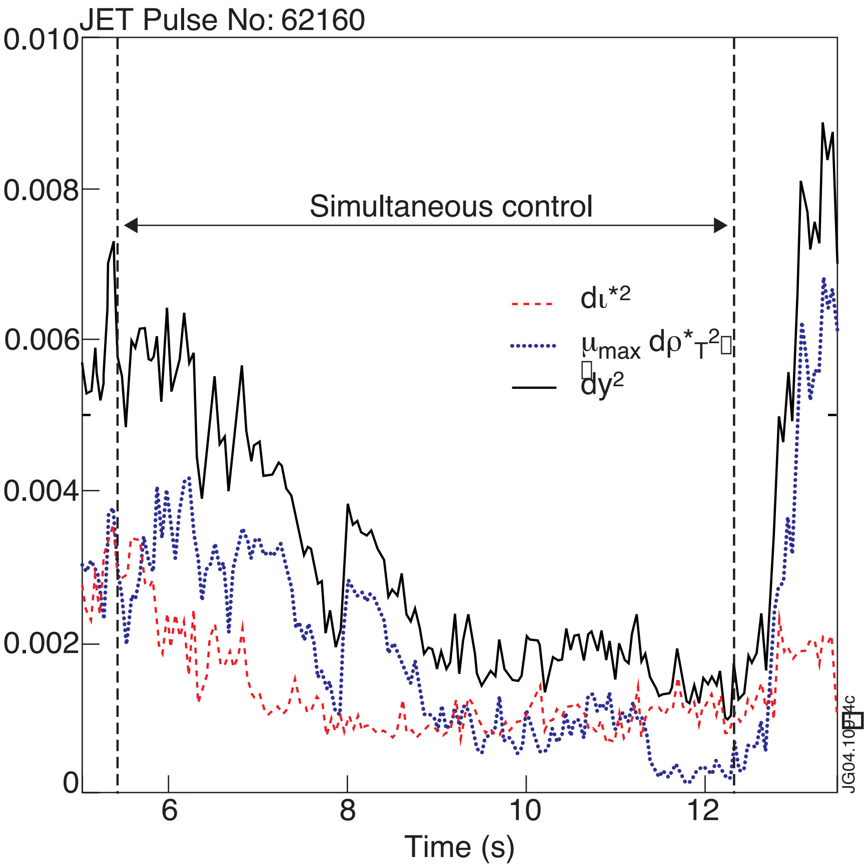
Reversed *q*, ITB
Monotonic *q*, no ITB



T. Tala et al. IAEA 2004

Distributed-parameter control of q and ρ_{Te}* (Galerkin)



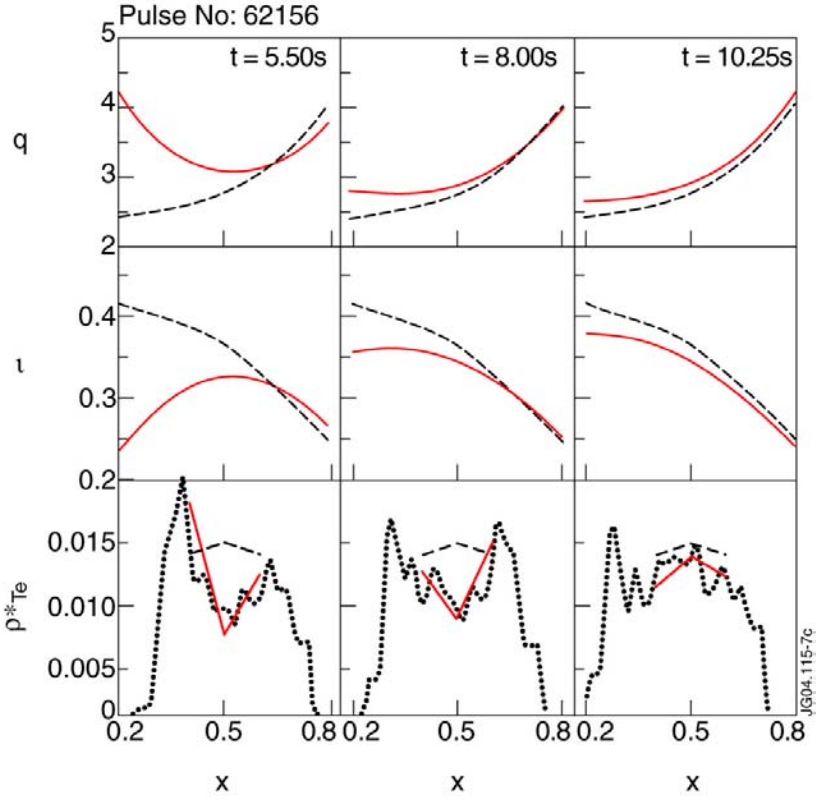


Quadratic minimization

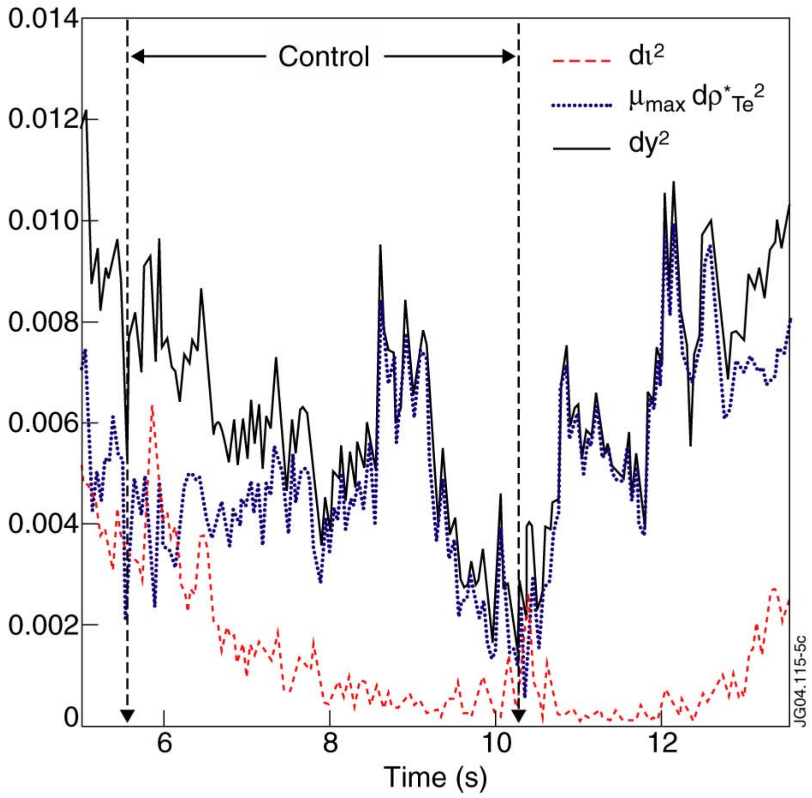
L. Laborde et al., PPCF 47 (2005) 155 **D. Mazon et al., EPS 2004** **D. Moreau et al. IAEA 2004**

Distributed-parameter control of q and ρ_{Te}^*

monotonic q-profile



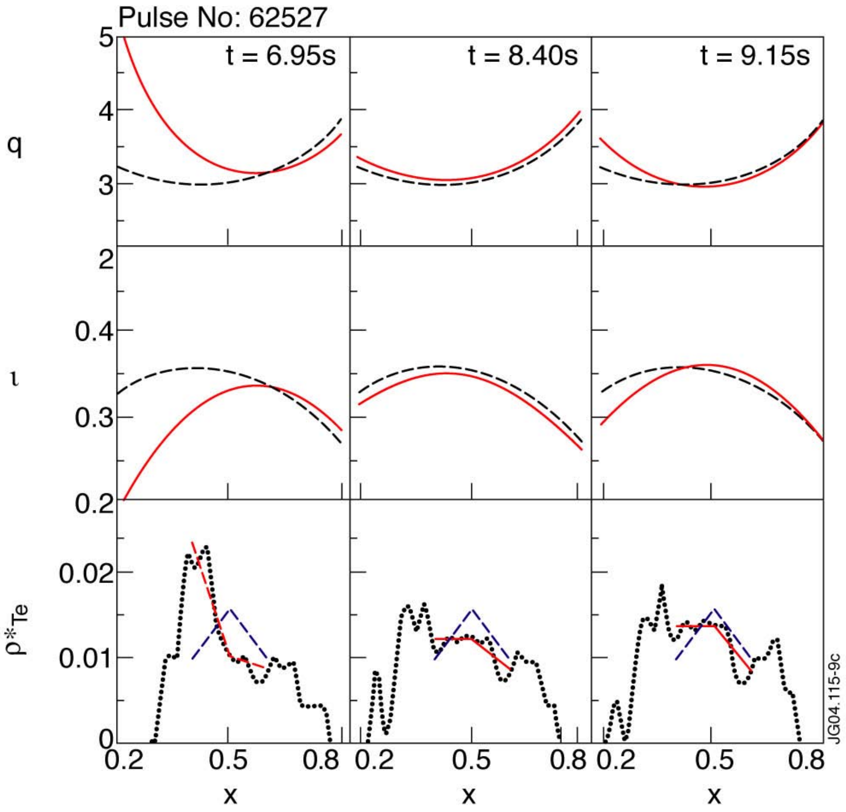
Profiles



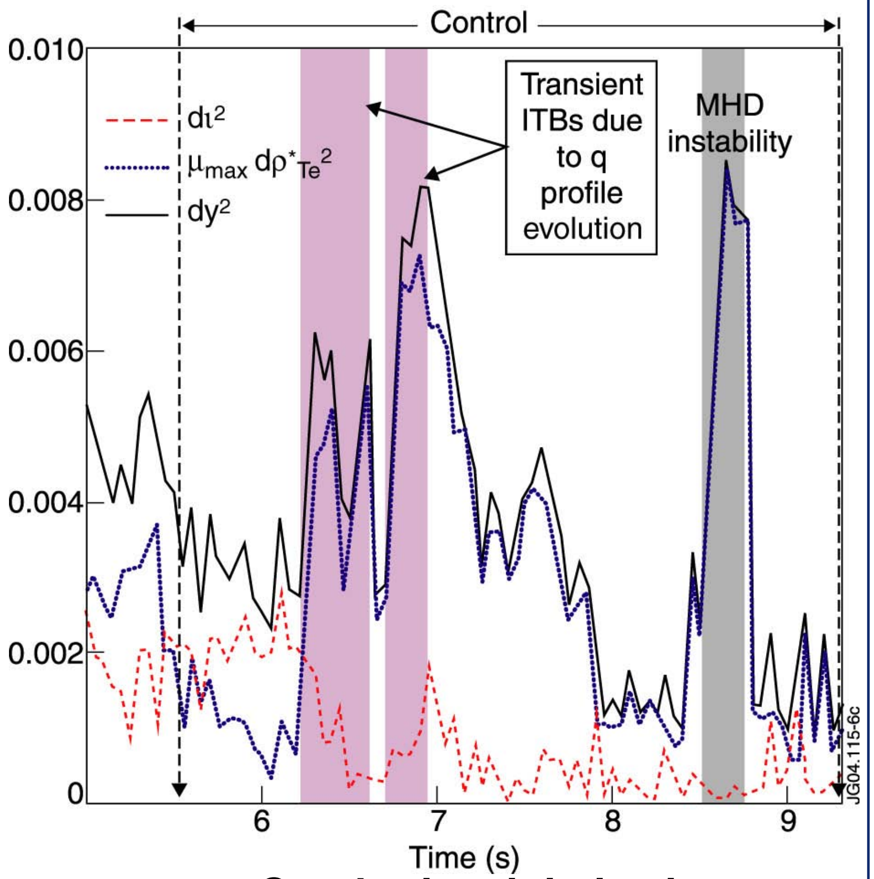
Quadratic minimization

Distributed-parameter control of q and ρ_{Te}^*

reversed-shear q-profile



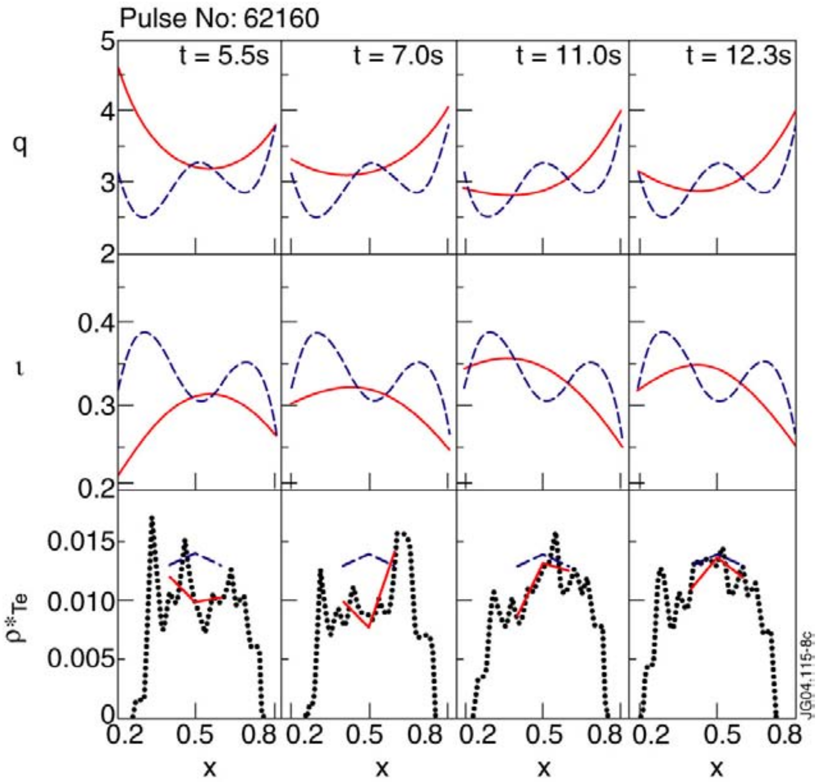
Profiles



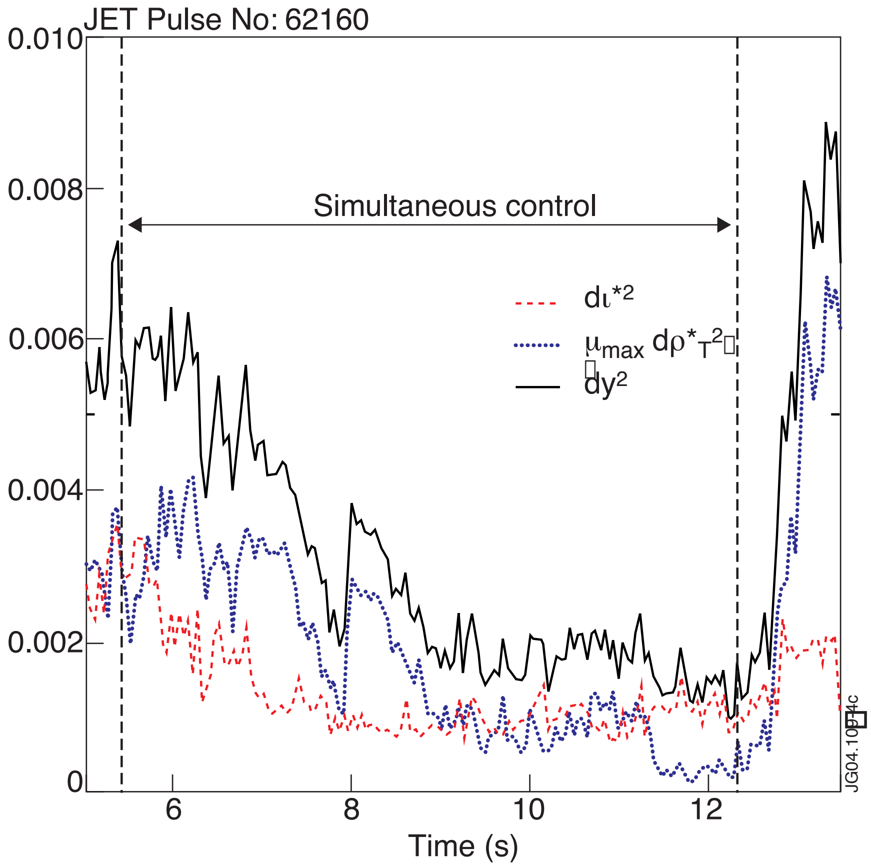
Quadratic minimization

Distributed-parameter control of q and $\rho_{Te}{}^{*}$

least square approach to unaccessible q-profile



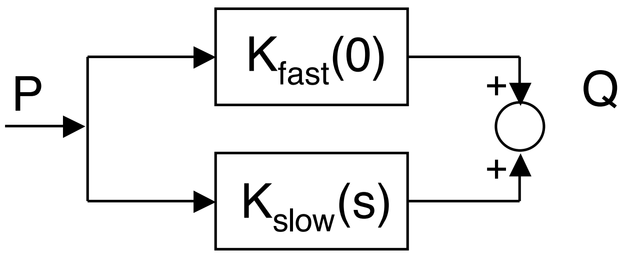
Profiles



Quadratic minimization

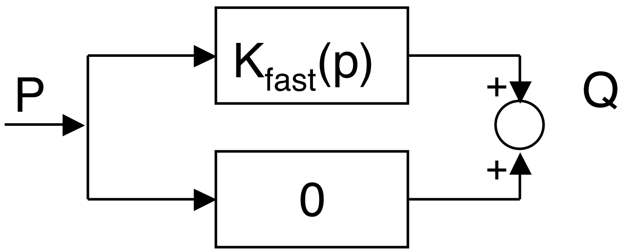
Multiple-time-scale control

- Selection of N appropriate state variables (magnetic + kinetic)
- Choice of M controlled output variables
- Identification of a state-space dynamic model ($N_{order} \leq N$)
- Separation of slow and fast modes ($N_{slow} + N_{fast} = N_{order}$)
- 2-time-scale controller design ($P = P_{slow} + P_{fast}$)



Low frequency : $s = o(1)$

$K_{slow}(s) = K(s) - K_{fast}(0)$



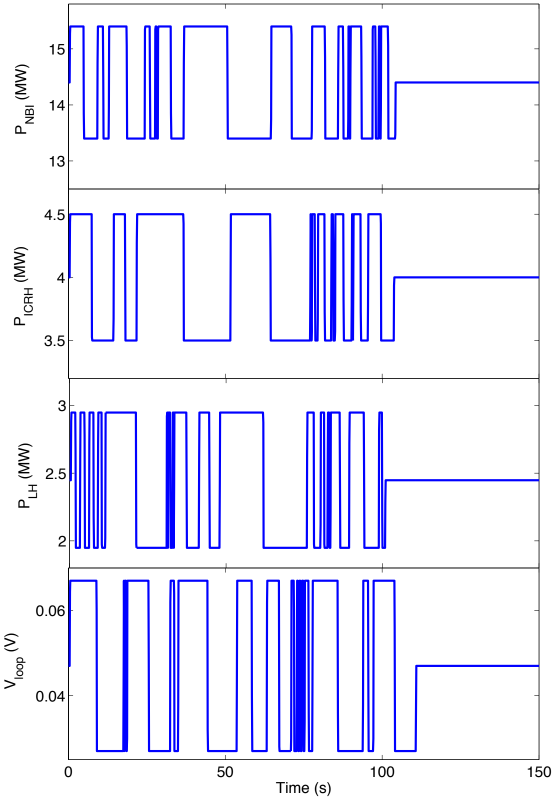
High frequency : $p = o(1)$

$K_{fast}(p=\varepsilon s)$

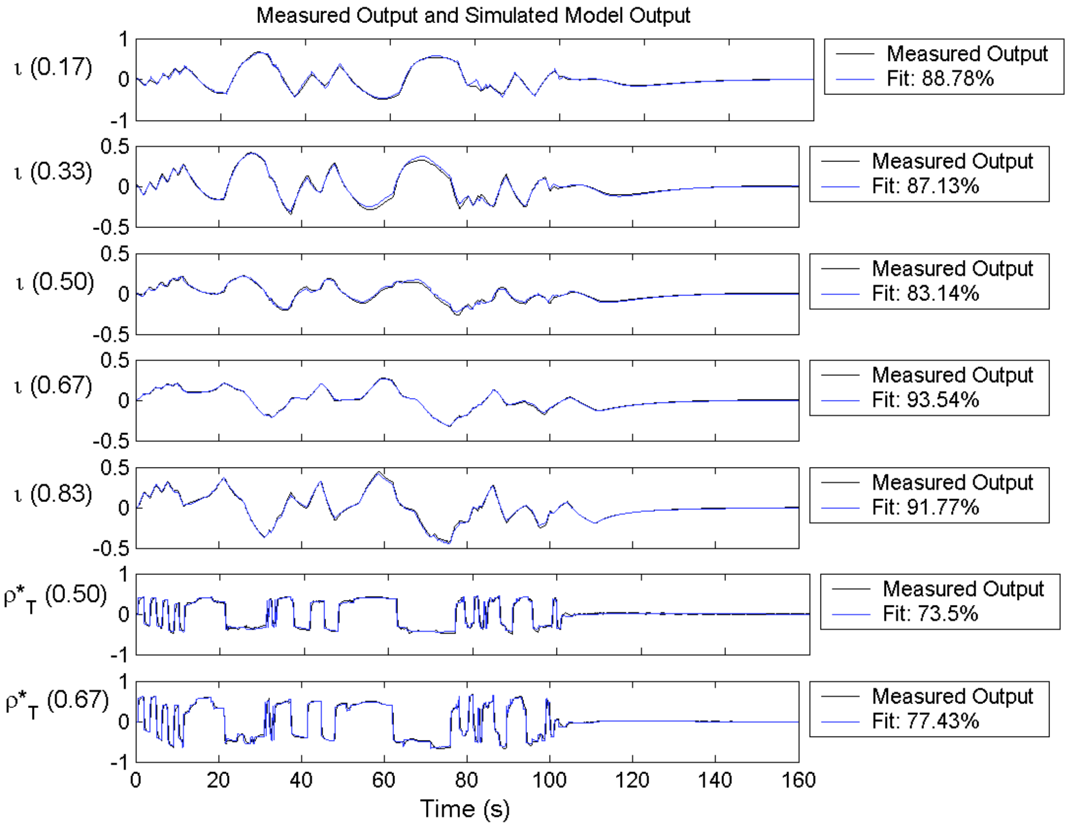
$\varepsilon = \tau_E / (\mu_0 \sigma_0 a^2)$ ⇒ Singular perturbation methods and composite feedback

Profiles ($\iota = 1/q$ and ρ_T^*) and flux control Linear response model identification (simulations)

Powers and loop voltage



5 ι and 2 ρ_T^* traces

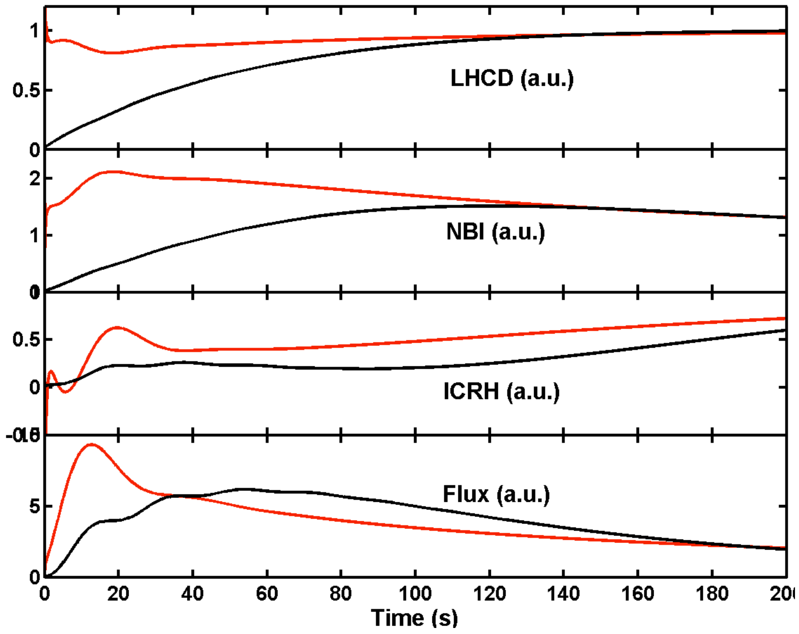


Simulated closed-loop evolution of powers, flux, $\iota=1/q$ and ρ_T^*

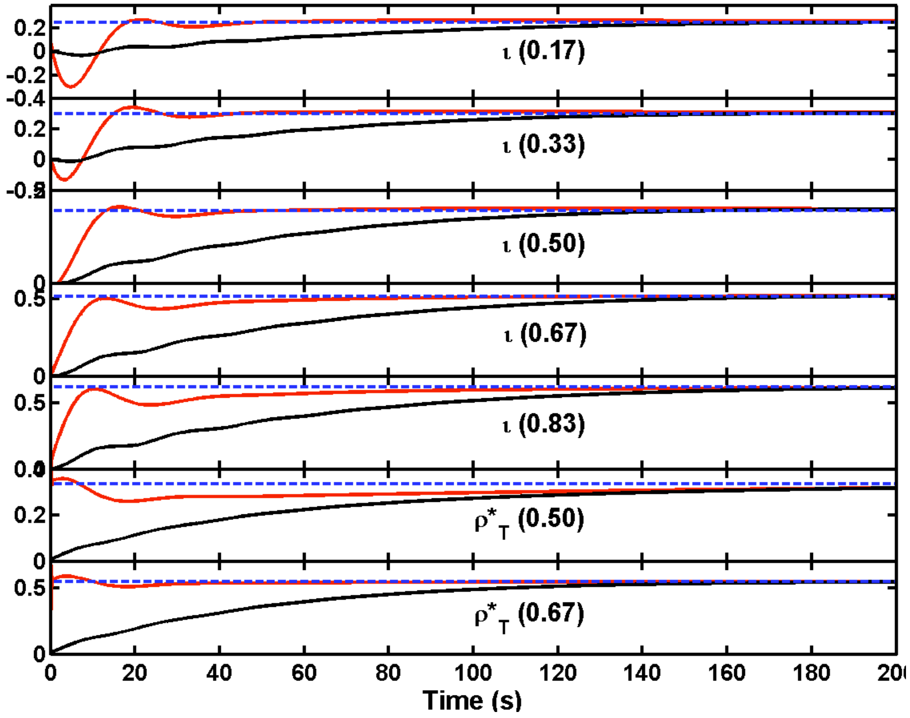
— simple PI control

— 2-time-scale control

Powers and surface flux



5 ι and 2 ρ_T^* traces



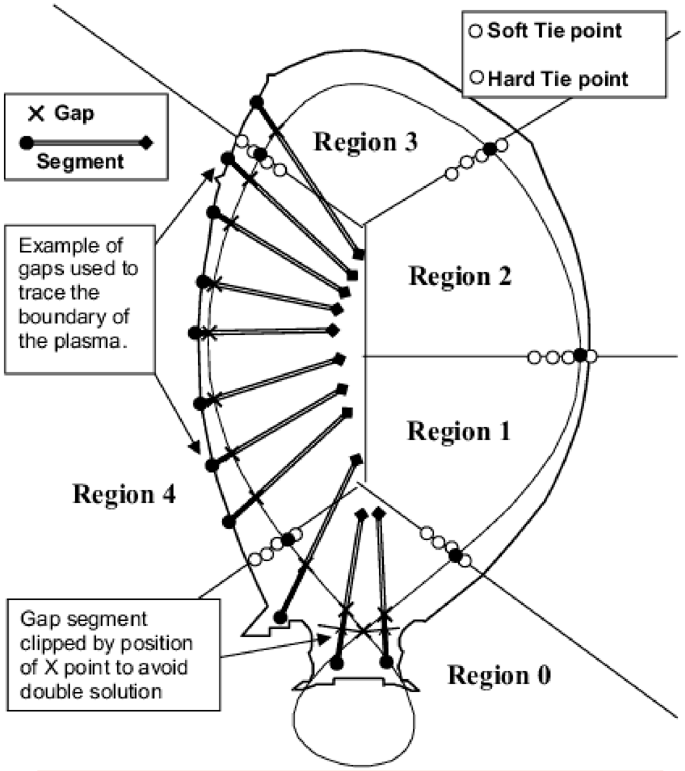
New eXtreme Shape Controller (XSC) on JET

G. Ambrosino, M. Ariola, A. Pironti, Report CREATE/JET 2002

ITER reference scenario requires high quality H mode plasmas at a volume density close to the Greenwald limit, achievable with high triangularity and elongation .

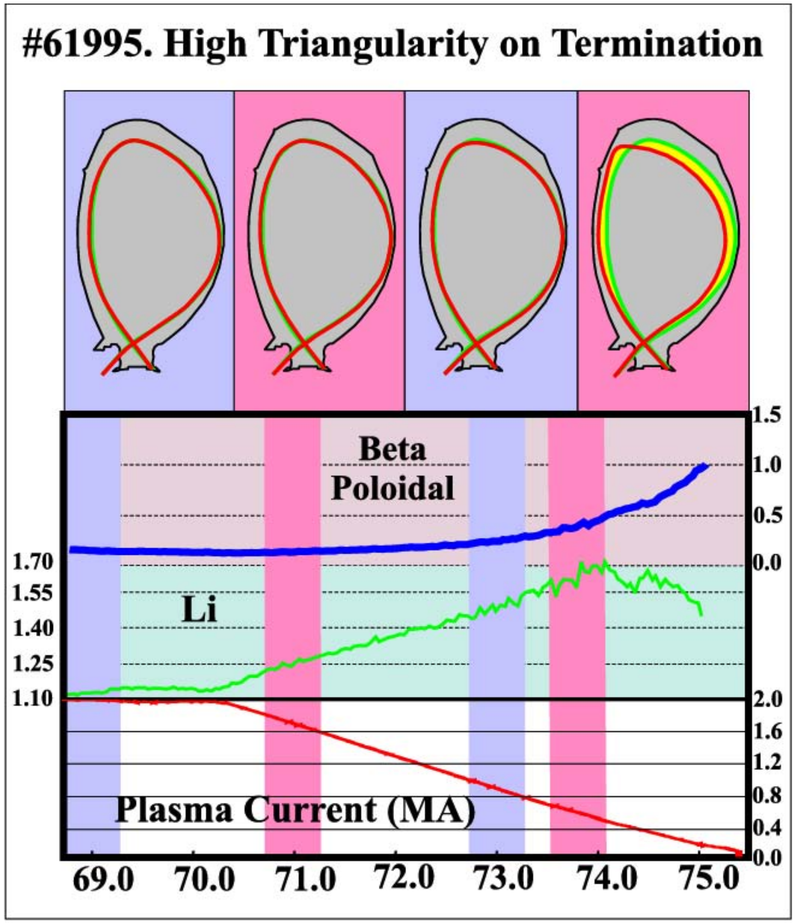
A control system that is able to maintain the plasma shape in presence of large disturbances (e.g giant edge localised mode ELMs) and large variations of βp and/or l_i is essential.

Shape Controller	eXtreme Shape Controller
Only few geometrical parameters were controlled, usually ROG and two strike points	Uses the errors on 38 descriptors of the plasma shape minimizes the error on the "overall" shape in a least square sense
Shape modifications due to variations of β_p and l_i cannot be counteracted	The controller manages to keep the shape more or less constant even in the presence of large variations of β_p and l_i
Good performance fixed points but the shape cannot be guaranteed precisely	The shape is usually achieved with an average error of about 1 cm



Descriptors: 32 GAPS plus coordinates of X point and strike points

G. Ambrosino et al., Fus. Eng. and Design 2003
R. Albanese SOFT 2004 F. Sartori SOFT 2004


#61995. High Triangularity on Termination

Diagnostics and algorithms

Real time magnetics and determination of the boundary (XLOC)

Good control with centimetre precision on a wide range of plasma parameters (Δl_i up to 0.5, $\Delta \beta_{pol}$ up to 1.5)

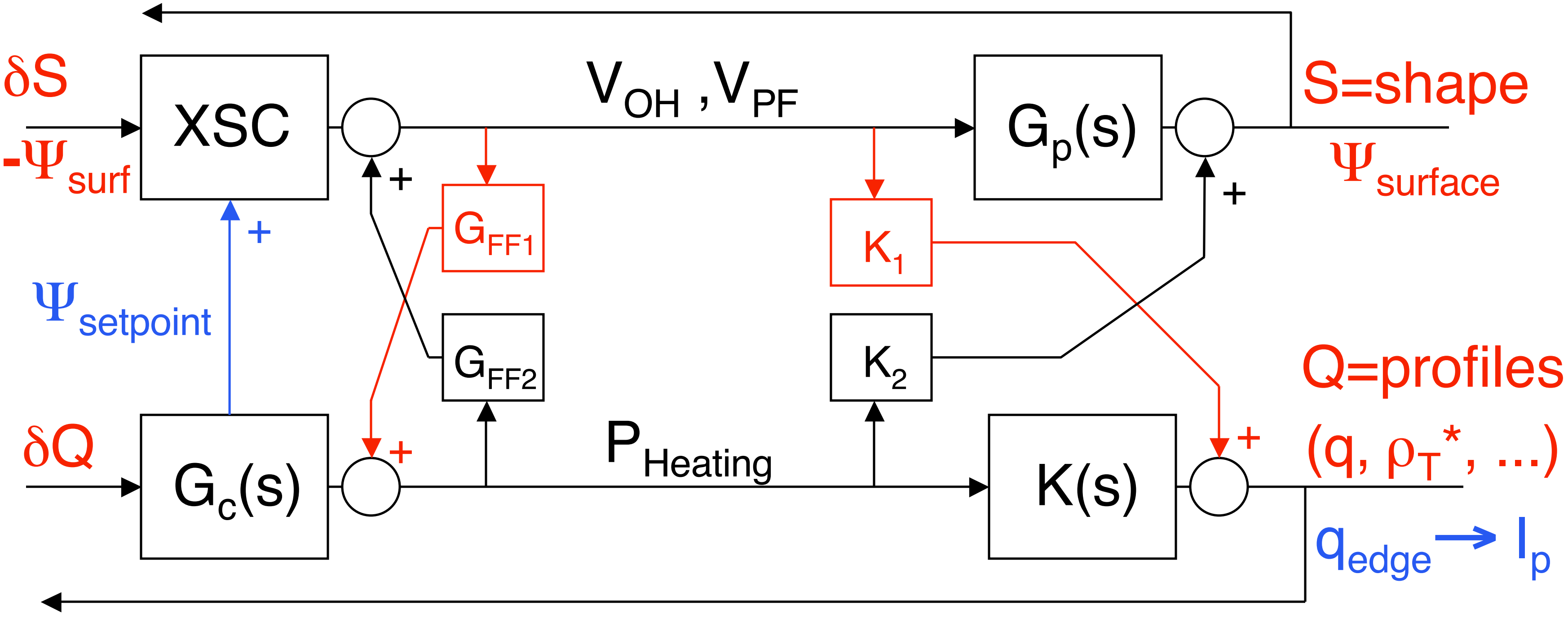
PRELIMINARY

Shape, profile and flux control for steady state operation

(CEA-CREATE-ENEA collaboration in the framework of the XSC2 project)

Development of high-bootstrap steady state scenarios for ITER

Since the total current is controlled through the edge safety factor the primary controller can be used to control the flux in the transformer or at the plasma surface, as shown on the **example (schematic) control diagram below**, and insure continuous operation.



Towards controlled advanced scenarios on JET

1. 1999-2000 : Conceptual and modelling studies for controlling strongly coupled plasma profiles with a limited number of actuators :

   Safety factor profile (q)

   ITB :Dimensionless temperature or pressure gradient ($\rho_{Te}{}^{*}$, $\rho_{Ti}{}^{*}$, $\rho_{P}{}^{*}$)

   Density, rotation ...

2. 2001-2002 : Control of the current profile :

   One actuator in the preheat phase : LHCD

   Three actuators in the performance phase : LHCD, NBI, ICRH

3. 2002-2004 : Extreme Shape Controller (XSC)

4. 2003-2004 : Simultaneous control of q(r) and $\rho_{Te}{}^{*}(r)$ with 3 actuators

   Modelling with JETTO and first experiments in JET

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5. 2005-20... : Integrate shape, flux and 2-time-scale profile control in high-bootstrap non-inductive plasmas (profile control + XSC2 project).

   Simulate burning plasma conditions with ICRH. DT Experiment.

Conclusions

The **potential extrapolability** of the proposed techniques to **strongly coupled distributed-parameter systems** with a large number of output parameters but a limited number of actuators (perhaps with more flexibility in the deposition profiles), is an attractive feature for an **INTEGRATED CONTROL FOR ADVANCED STEADY STATE OPERATION IN JET and ITER :**

- **control of the plasma shape (eXtreme Shape Controller)**
- **of the safety factor profile, including q_{edge} (H&CD)**
- **of the temperature, density and rotation profiles (H&CD)**
- **of the primary flux consumption (XSC2 JET project)**

... ITER perspective ...

Extend to an ICRH-simulated burn and to a D-T burning plasma

Real time control system in JET (preparation for ITER)

Parameter to control

Equilibrium

Profiles T_e, T_i, q, V_{rot}

neutrons, n_D, n_T

Actuators

PF coils & saddles coils

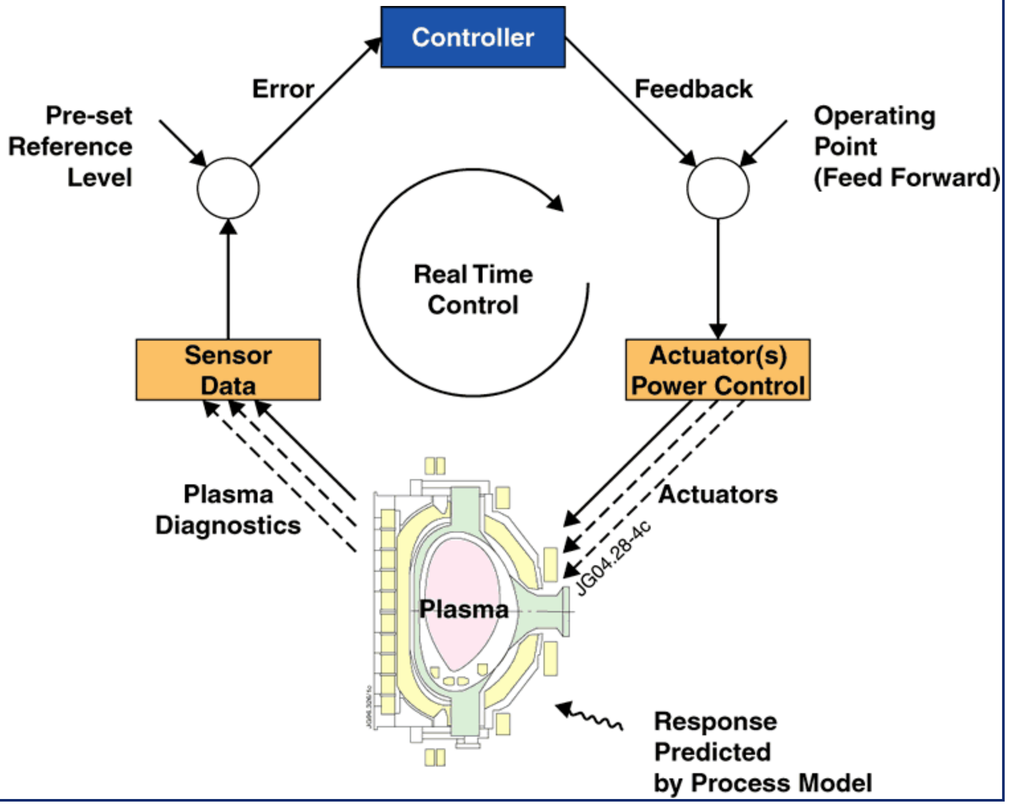
Heating: LHCD, ICRH, NBI

Fuelling

Distributed system
Parallel computing
Multiplatform
(VME, PCI)

Good candidate for ITER architecture:

Flexible, efficient and even more important "Adaptive"



R. Felton, et al., SOFT 2004

Pseudo-modal controller design

SVD provides decoupled open loop relation between modal inputs $\alpha(s) = \mathbf{V^{+}P}$ and modal outputs $\beta(s) = \mathbf{W^{+}BQ}$

Truncated diagonal system (≈ 2 or 3 modes) : $\beta(s) = \Sigma(s) \,.\, \alpha(s)$

STEADY STATE DECOUPLING

Use steady state SVD (s=0) to design a Proportional-Integral controller

$$\alpha(s) = G(s).\delta\beta(s) = g_c\,[1+1/(\tau_i.s)] \,.\, \Sigma_0^{-1} .\, \delta\beta(s)$$