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Real Time Control of advanced scenarios for steady-state tokamak operation

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Courtesy: J.F Artaud, A. Bécoulet, S. Brémond, D. Campbell, J. Ferron, G. Giruzzi, C. Gormezano, E. Joffrin, S. H Kim, D. Mazon, D. Moreau, P. Politzer, T. Suzuki, T. Tala

OUTLINE

TOWARDS REAL TIME PROFILE CONTROL ?

- **Challenges for continuous operation**
  - continuous tokamak reactor operation
  - real time control requirement
- **Real time control of kinetic & magnetic energy**
  - optimal profile for steady-state & MHD stable profiles
  - approaches to profiles control
- **Real time fusion D-T burn control**
  - burn control with dominant bootstrap and α-heating ?
- **Control of core performance with the plasma facing components constrains**
  - wall scenario compatibility issues
  - simultaneous control of core & edge

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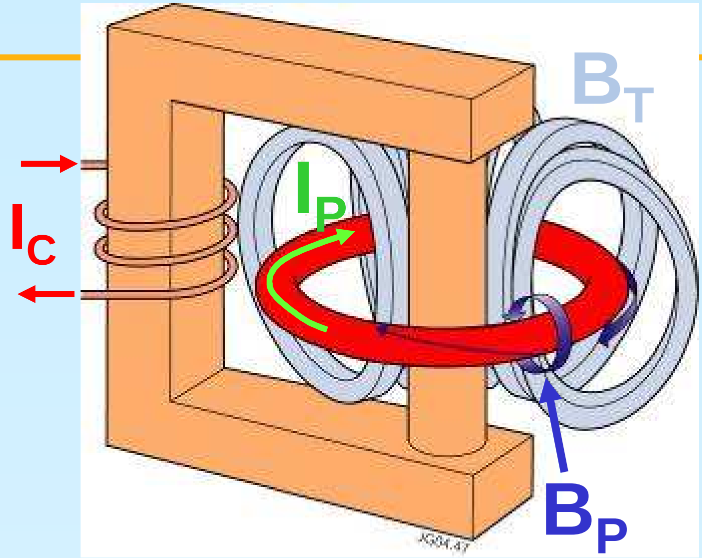
Optimisation of tokamak concept



I_P = $I_{inductive}$ + $I_{Non\text{-}Inductive}$

➤ **Long-Pulse Operation**

→ I_P = $I_{Non\text{-}Inductive}$

➤ Non-Inductive Current Drive

– **Externally driven, e.g. waves injection**

- To drive 15MA on ITER requires 150MW
- 150MW coupled power requires ~ 1GW fusion

– **Internally driven ∝ ∇Pression: bootstrap effect**

➤ **Efficient reactor at high Q =P_{fus}/P_{add} relies on the optimisation of bootstrap current**

[e.g. Kikuchi M Nucl. Fusion 1990, Gormezano C ITER physics basis Nuc Fus 2007]

Challenges of continuous tokamak operation

- **Fully non-inductive regime**
- **High confinement & bootstrap current**
- **Real time control of kinetic & magnetic configuration close to operational limits with a large fraction self α-heating & bootstrap**
- **Technology of Long Pulse Operation**
  - **Coils, Plasma Facing Components, Structure Materials, Heating &Current Drive systems, Diagnostics, data acquisition, fuel cycle…**

Worldwide research activity: physics, modelling, technology

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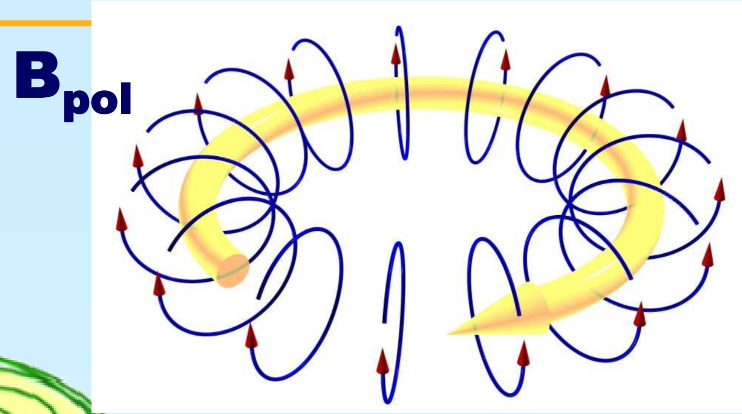
Towards a continuous tokamak reactor

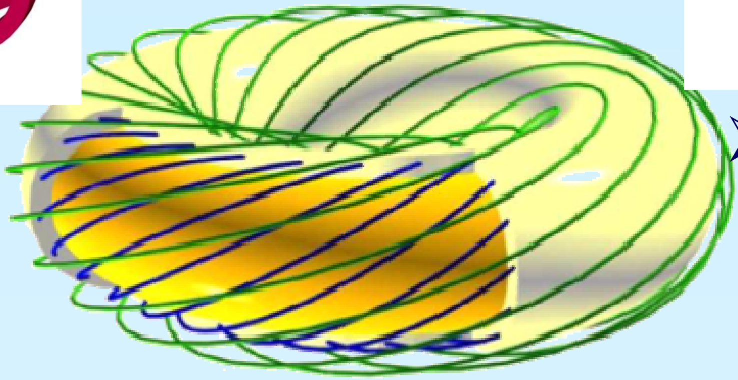
A scientific and technical challenge

	Tore Supra	JET	JT60-SA	ITER	DEMO
P_{fusion}/P_{add}	DD	Q ~ 1	DD	Q ~ 10	Q ~ 30
duration	~400s	2s	~100s	400-3600s	Continuous
self-heating	0%	10%	0%	70%	80 to 90%
bootstrap	20%	20%	>60%	10-50%	60-80%

Existence and control of a self-organised plasma state for continuous tokamak operation ?

Basic standard tokamak parameters





- **Toroidal**
  - $\beta_t = \langle P \rangle / p_{Btor}$
  - $p_{Btor} = B^2_{tor} / 2\mu_0$

- **Poloidal**
  - $\beta_p = \langle P \rangle / p_{Bpol}$
  - $p_{Bpol} = B^2_{pol} / 2\mu_0$

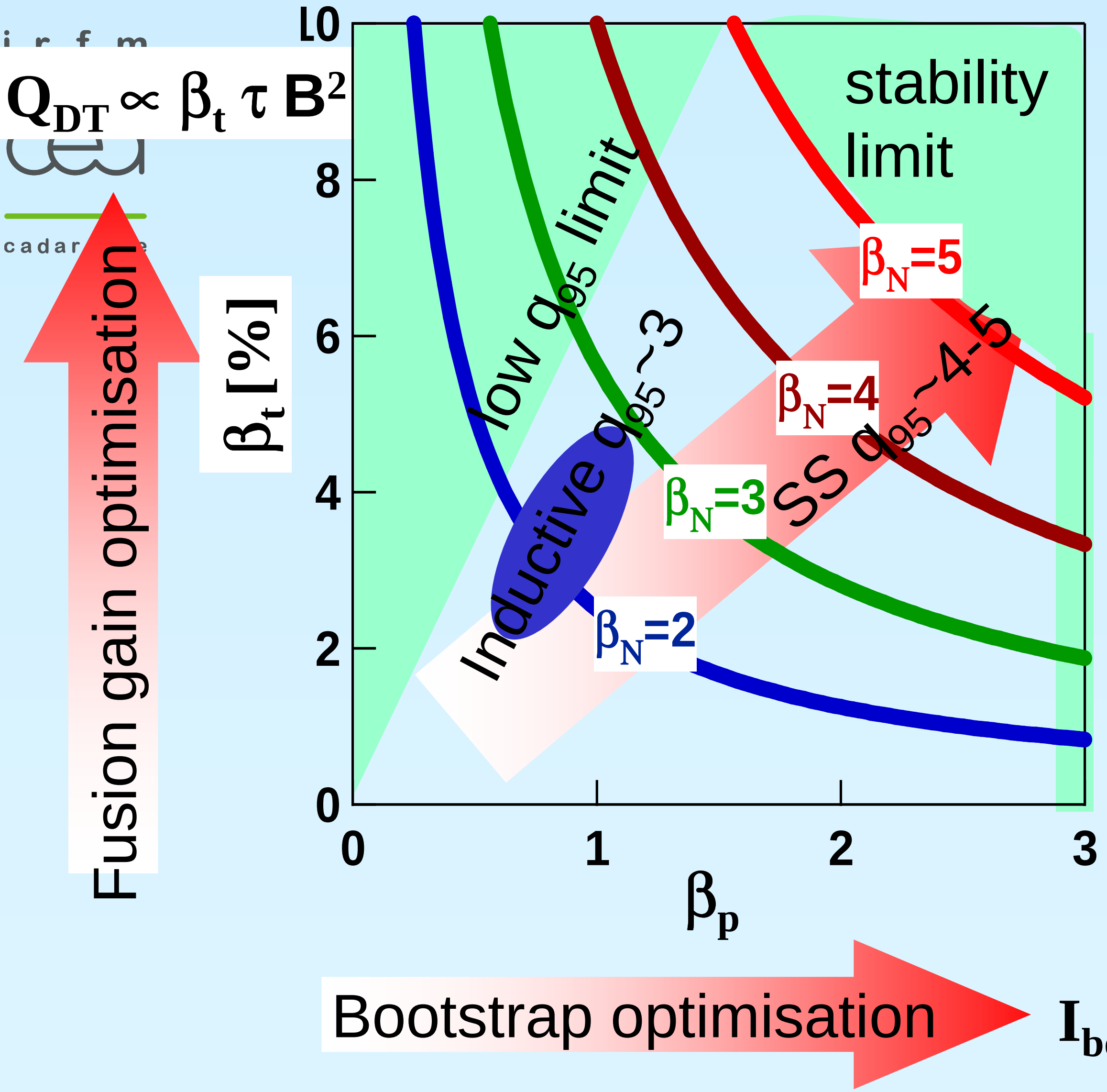
- **Safety factor q**
  - number of toroidal turns for one poloidal turn

- **Stability**
  - $q > 1$
  - $\beta_N = \beta_t / (I_p / aB) \leq 3$

- **Confinement**
  - $H = \tau / \tau_{scaling}$ $H \sim 1$
  - $\tau_{scaling} = I\, R^2\, P^{-2/3}$

STEADY-STATE REACTOR :
Optimisation of Q_{DT} & Bootstrap current

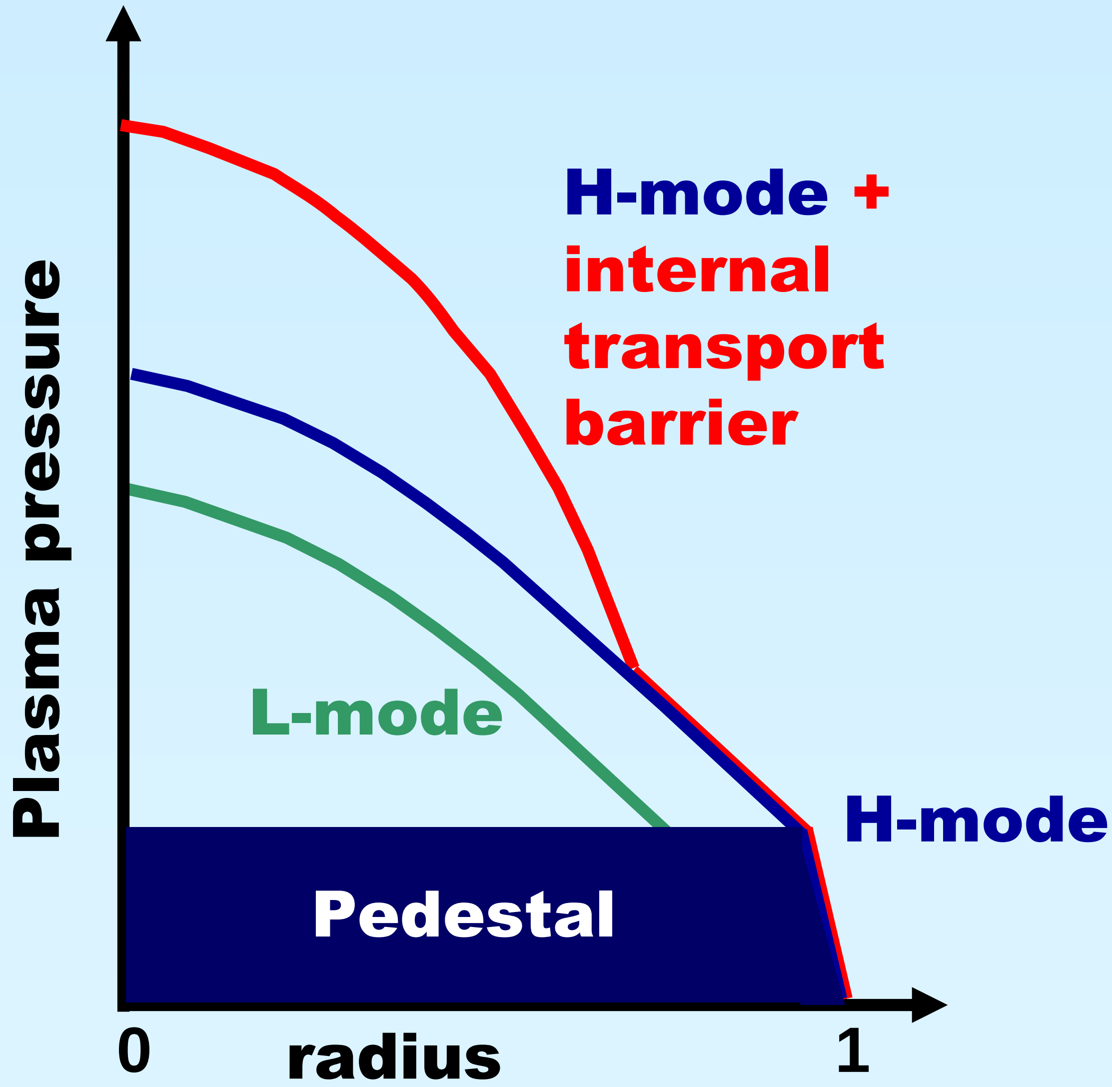
$Q_{DT} \propto \beta_t \tau B^2$



- ↑ **fusion power + bootstrap**
  → **high β_N , τ , B**
  since $\beta_t \beta_p \propto (1+\kappa^2)\, \beta^2_N$
- **Optimise shaping**
- **Stability**
  - -q & pressure
  - -wall stabilisation
- **Confinement**

$I_{boot}/I_p \propto \varepsilon^{1/2} \beta_p = \varepsilon^{-1/2} q \beta_N$

Enhanced performance for non-inductive regimes



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Towards Long Pulse Operation on ITER

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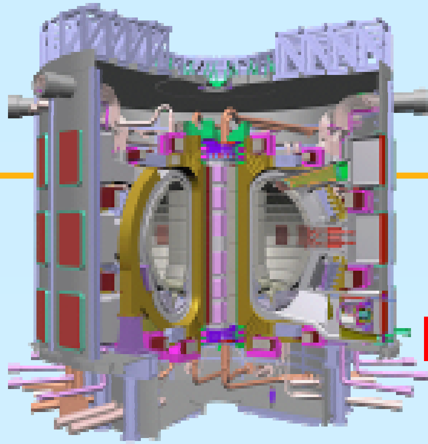


$I_{non\text{-}inductive}/I_p$

20%

50%

100%

$I_{bootstrap}/I_p$

7%

20%

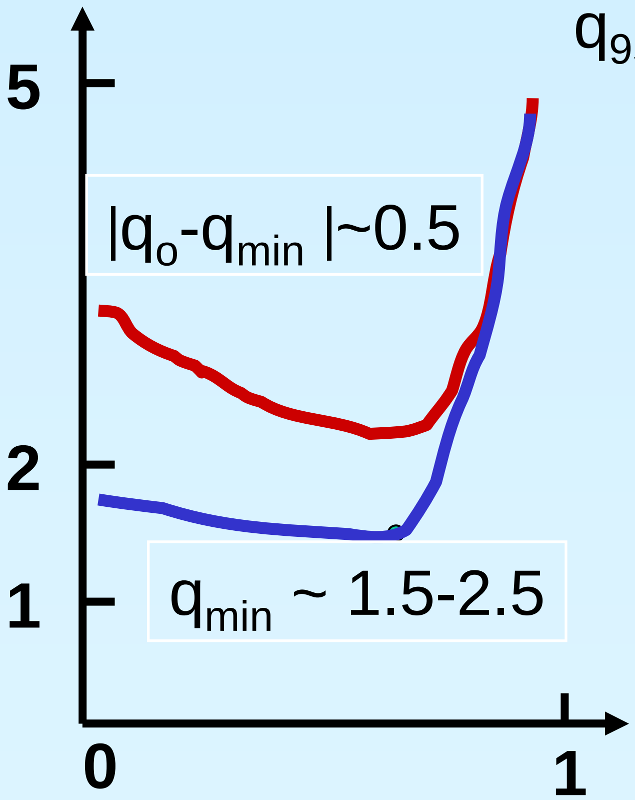
50%

- **Inductive operation**
  - Q ≥ 10 Ip~15MA 400s
- **'Intermediate'**
  - Q ~5-10 Ip~12MA 1000s
- **fully non-inductive**
  - Q~5 Ip~9MA 3000s
  - Active research activity
  - Integration of physics & technology

ITER STEADY-STATE OPERATION

Steady-State operation at Q ~ 5 (P_{α}~P_{add}) with full non-inductive current drive + optimized current & pressure profiles

q_{95}~5 (9MA) at high κ, δ

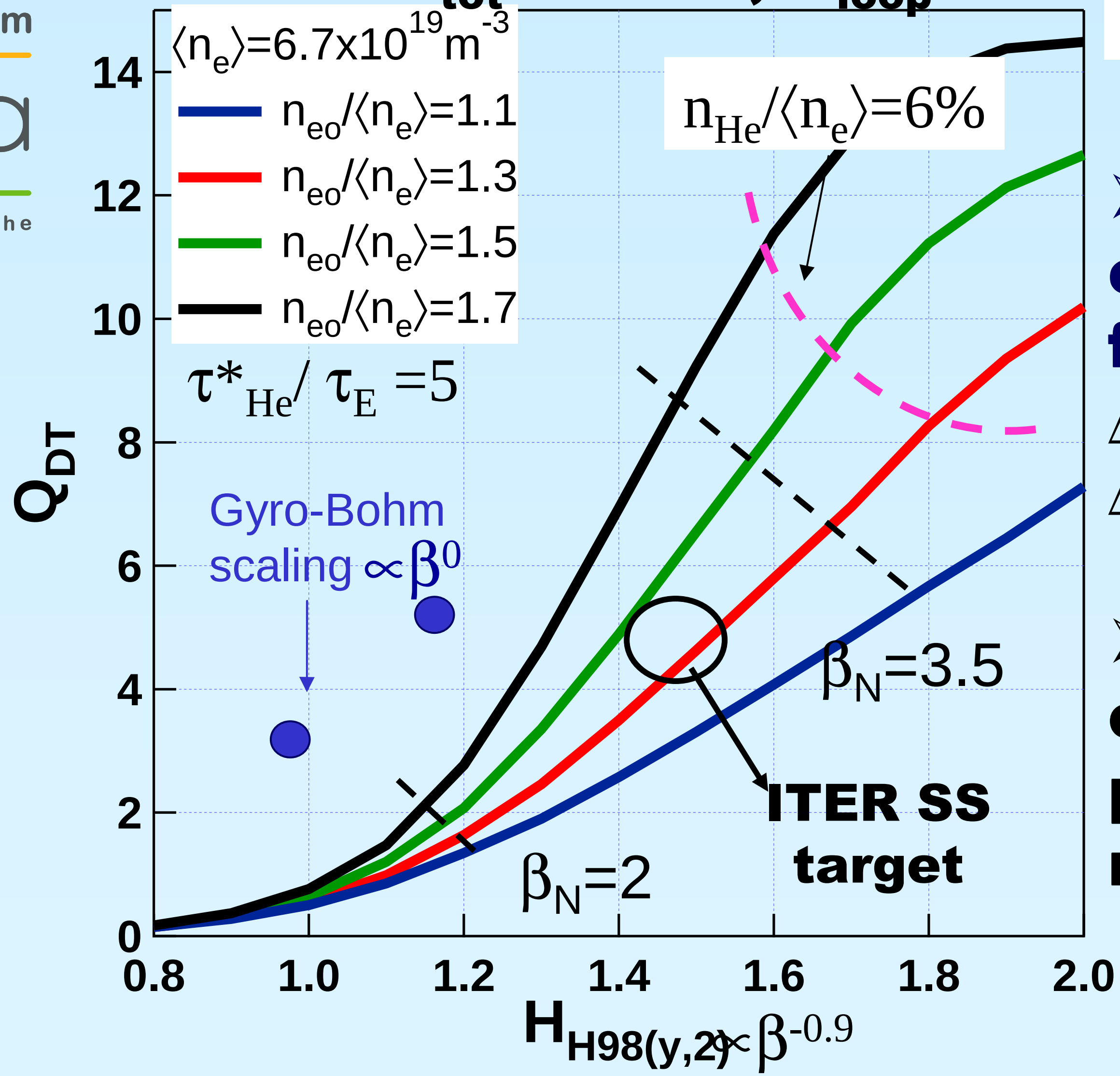


- $I_{boot}/I_p \geq 50\%$
- β_N~3, $H_{98(y,2)}$ ~1.5
- n_l~$7x10^{19}m^{-3}$
- T_i/T_e ~ 1
- τ_D~3000s

[Gormezano Nuc Fus 2007, Campell Pop (2001), Green et al PPCF 2003 & ITPA steady-state group]

CONTROL OF CORE CONFINEMENT IN STEADY-STATE ITER OPERATION

ITER-AT: P_{tot}=73MW, V_{loop}=0



CRONOS-0D

- **Control of high confinement for steady state:**
  ΔH/H~20% → ΔQ/Q~50% (at Q~5)
- **favourable effect of density peaking while $n_{He}/\langle n_e\rangle$< 6%**

[Litaudon PPCF 2006]

The decisive role of real time control

- **Bringing Fusion to its "Reactor Era" requires an innovative programme of "discharge mastering", combining:**
  - **real time control of the magnetic/kinetic configuration (non-linear and time effects)**
  - **real time control of component integrity**
  - **high-level algorithms and control schemes**
  - **a consistent set of simulation tools:**
    - first principles ("PFlops")
    - integrated modelling ("CPU hours")
    - fast simulators ("~ 10 ms")

[A. Becoulet & G.T. Hoang PPCF 2008 and Joffrin et al PPCF 2003]

Control requirement: plasma scenario

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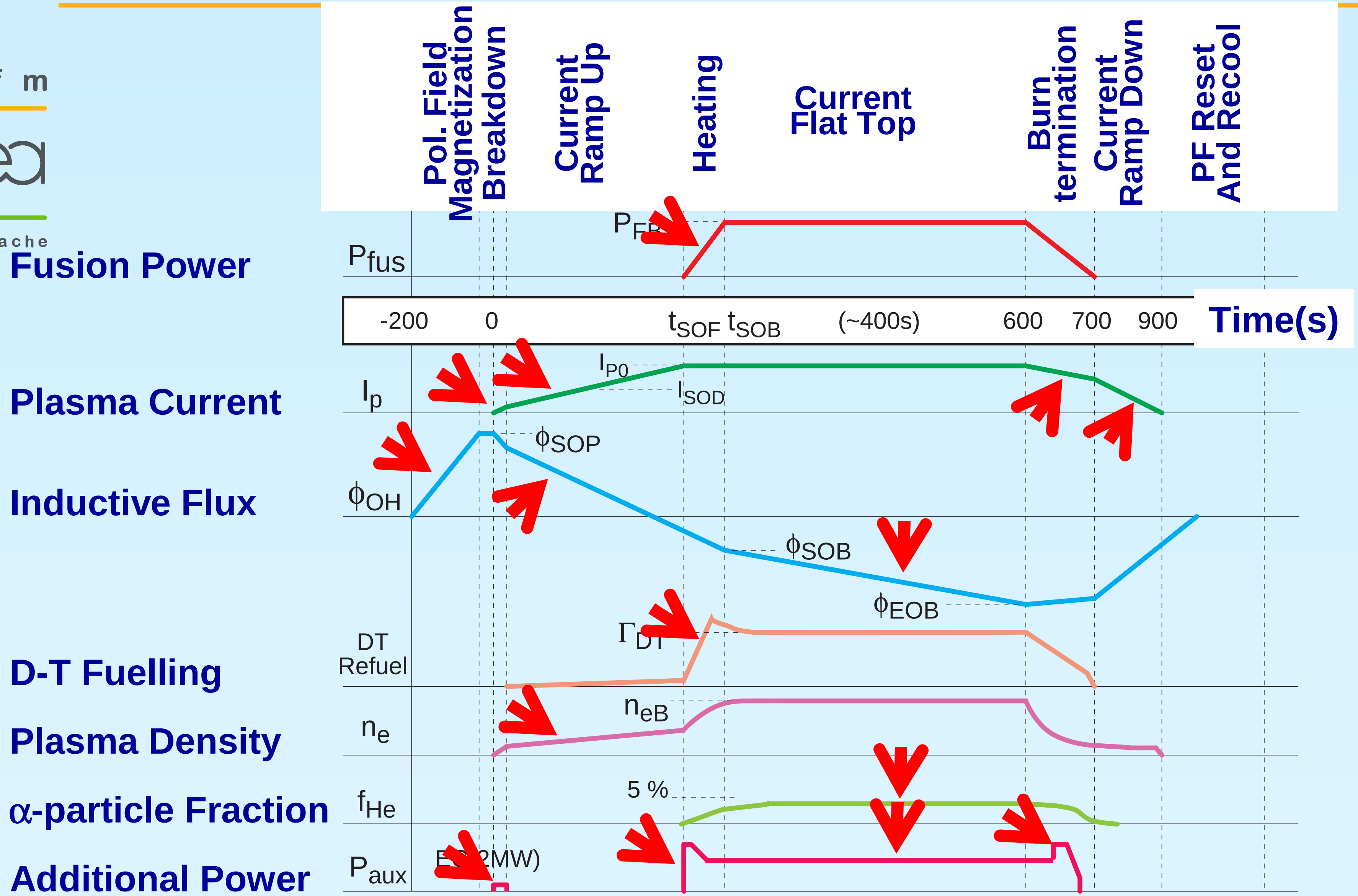

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Example of scenario: JET plasma

JET #67687

Real Time plasma profile reconstruction (EQUINOX code)

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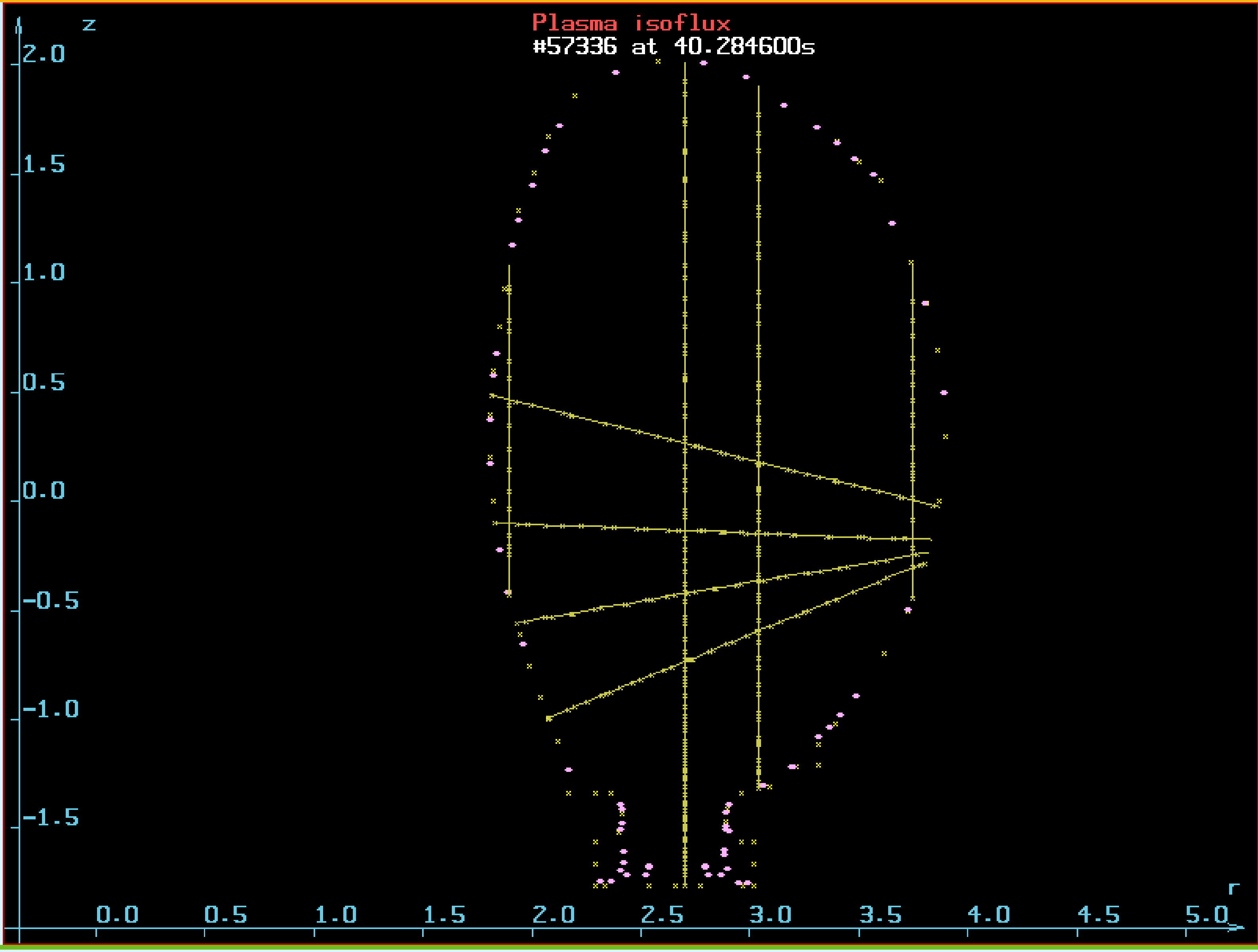
[Joffrin et al PPCF 2003, Joffrin et al PPCF 2007]



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Plasma scenario :
15MA H-mode ITER scenario

Tokamak simulation: free-boundary equilibrium (DINA-CH) & transport evolution (CRONOS)

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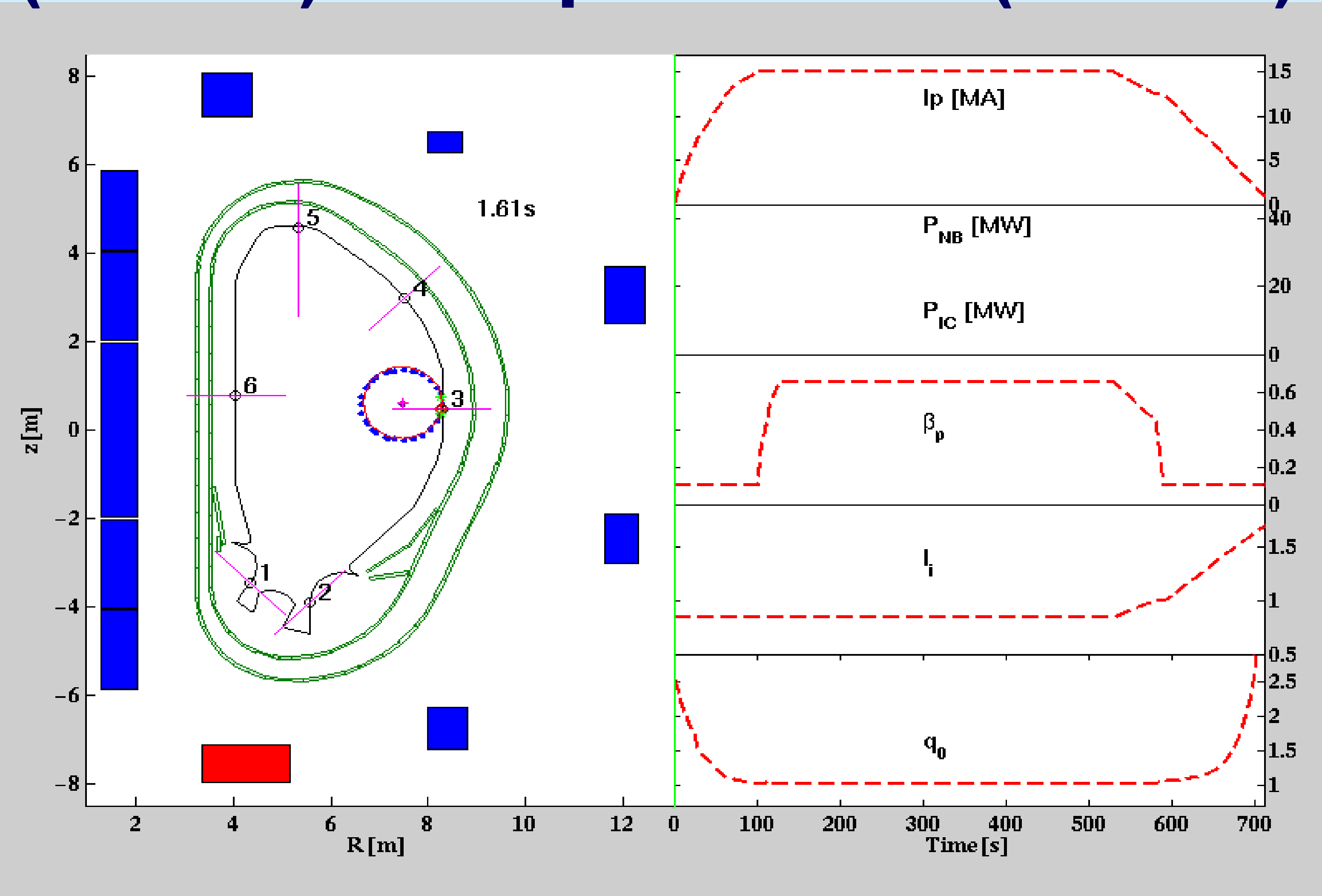
ITER

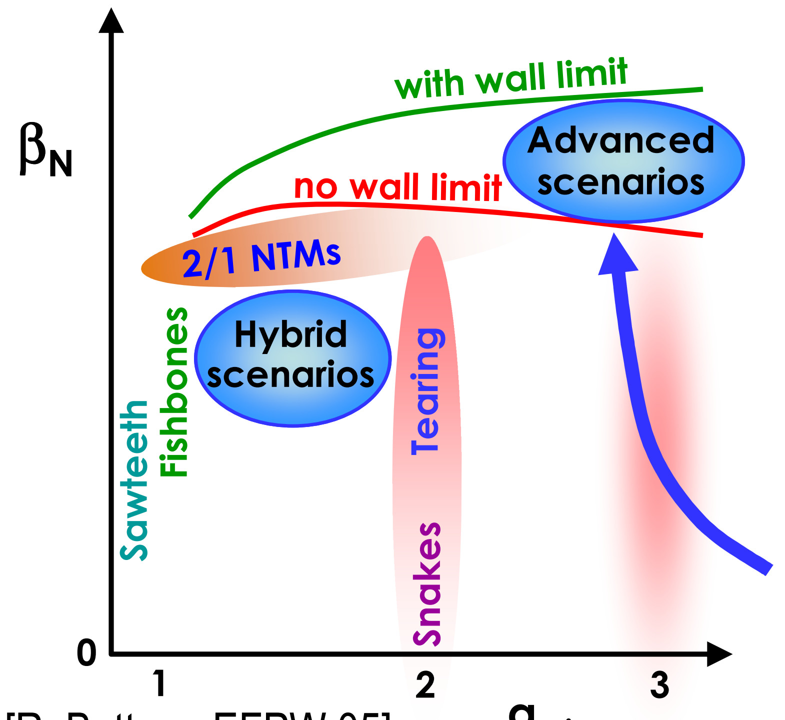


S.H. Kim *et al*, *PPCF* 2009

MHD Stability issues & real time control

- **Edge Localized Modes**
  - Damage to Plasma Facing Components
- **Neo-classical tearing modes**
  - Limiting pressure, risk of disruption
- **Resistive wall modes**
  - Limiting pressure
- **Disruptions**
  - Device safety
- **Fast particle modes**
  - Limiting α-heating, CD

Necessity for Real Time feedback control & localized CD



[R. Buttery, EFPW 05]

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PROFILE CONTROL REQUIREMENTS FOR STEADY-STATE OPERATION

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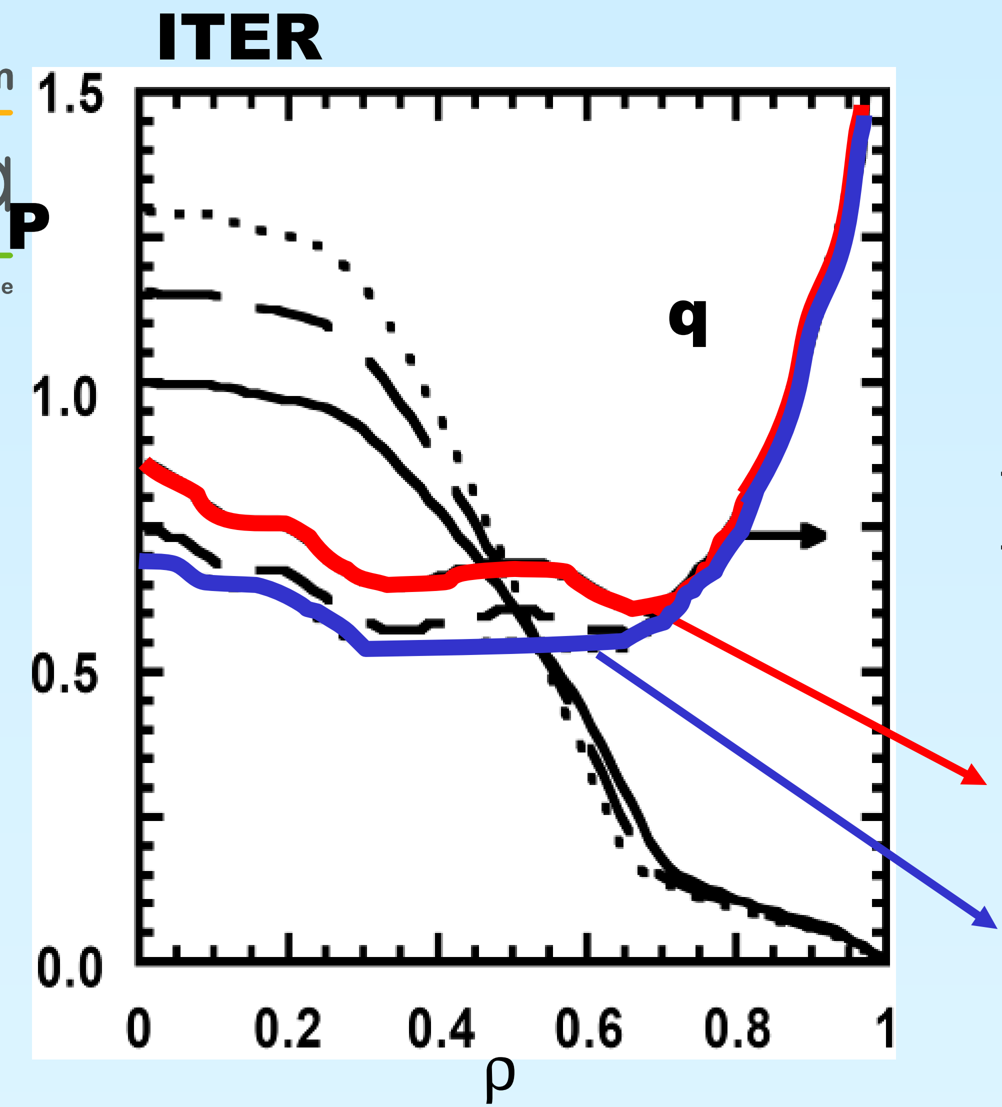

[Shimada et al NF 2004, Polevoi et al IAEA 2002]

- **ITER SS operation above the no-wall limit**

- at ITER wall position, the marginal β is sensitive to **details in q and pressure profiles**

q_{min}~2.4, β_N <3.85

q_{min}~2.1, β_N<2.6

ITER Heating & Current Drive actuators: FLEXIBILITY for profile Control

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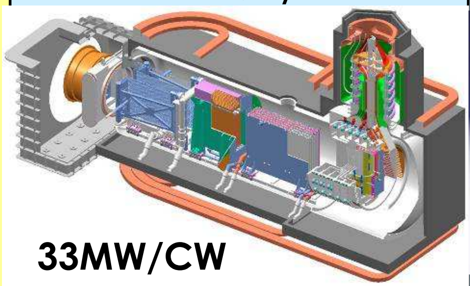
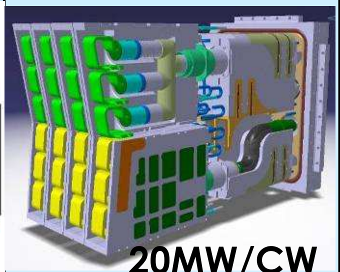
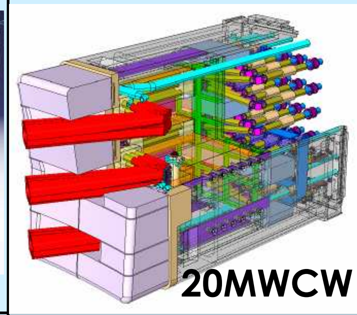
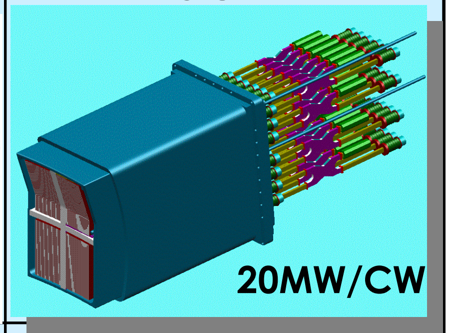
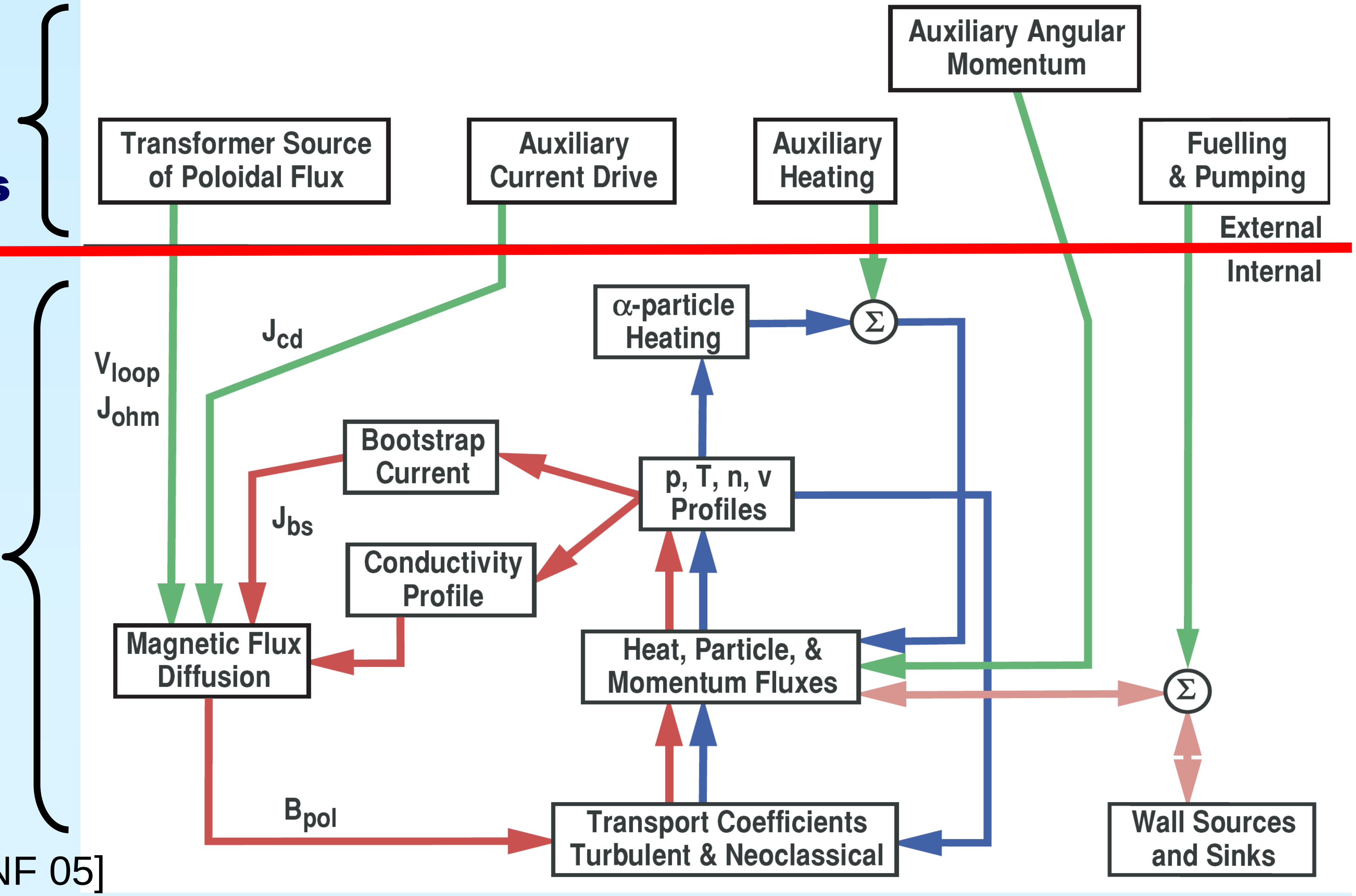
ITER	NNBI 1MeV/D-	ICRH 40-55 MHz	ECRH 170 GHz	LHCD 5 GHz
	 33MW/CW	 20MW/CW	 20MWCW	 20MW/CW
Heating	- electrons - broad deposition	-70% ions -central heating	-electrons -localised -start-up	-electrons -localised -off axis
CD	- yes - broad deposition	-no global CD - Central (MHD)	-yes -localised (MHD)	-yes -off-axis $\rho>0.7$
Torque	yes	no	no	no
Fuelling	small	no	no	no

Control of a self-organised state ?

- two time scale: fast (blue) & Slow (red)
- α-heating dominant in burning reactor



[Politzer et al NF 05]

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Magnetic/Kinetic configuration RT control

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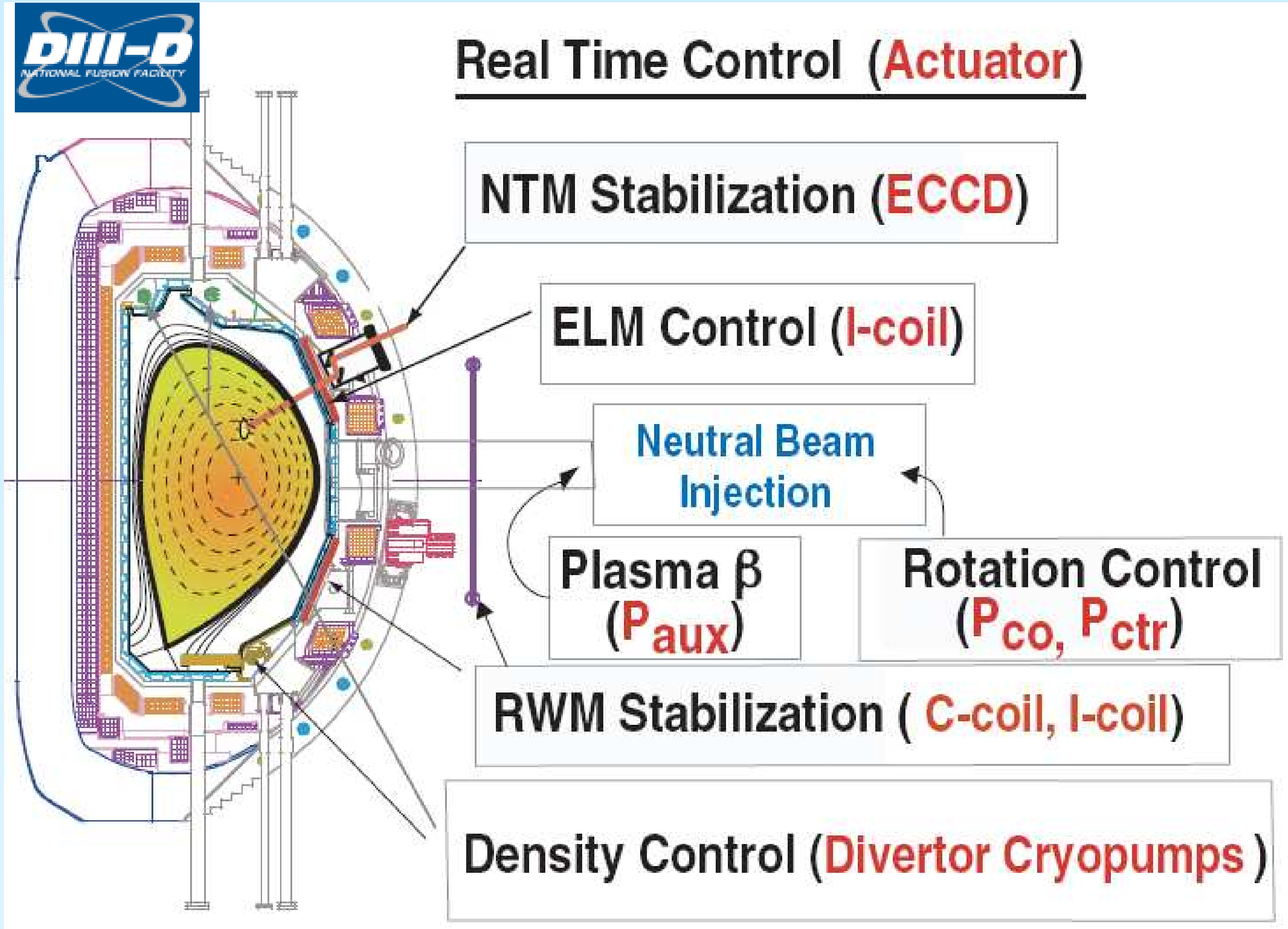

PROFILE CONTROL REQUIREMENTS

- **Oscillation in confinement observed in steady-state tokamak plasmas**

  $\Rightarrow$ **limiting the fusion perfomance**

- **Tore Supra* & DIII-D****

  (i) non-linear coupling between j & T — **j_{LH}(j,T), j_{boot} (j,T), χ (j,T)**

  (ii) non-linear interplay of heating, CD & MHD — **s<0, double tearing, ideal MHD limits …**

- **ITER SS → extra coupling via α-heating**

  (i) non-linear coupling between j & T — **j_{boot}(j,T), χ (j,T), P_α(T)**

  (ii) non-linear interplay of heating, momentum, CD & MHD — **P_α(T), β limits, TAE (α-particles), …**

*Giruzzi et al PRL 03
**Politzer et al NF 05

Non-linear behaviour in non-inductive regime

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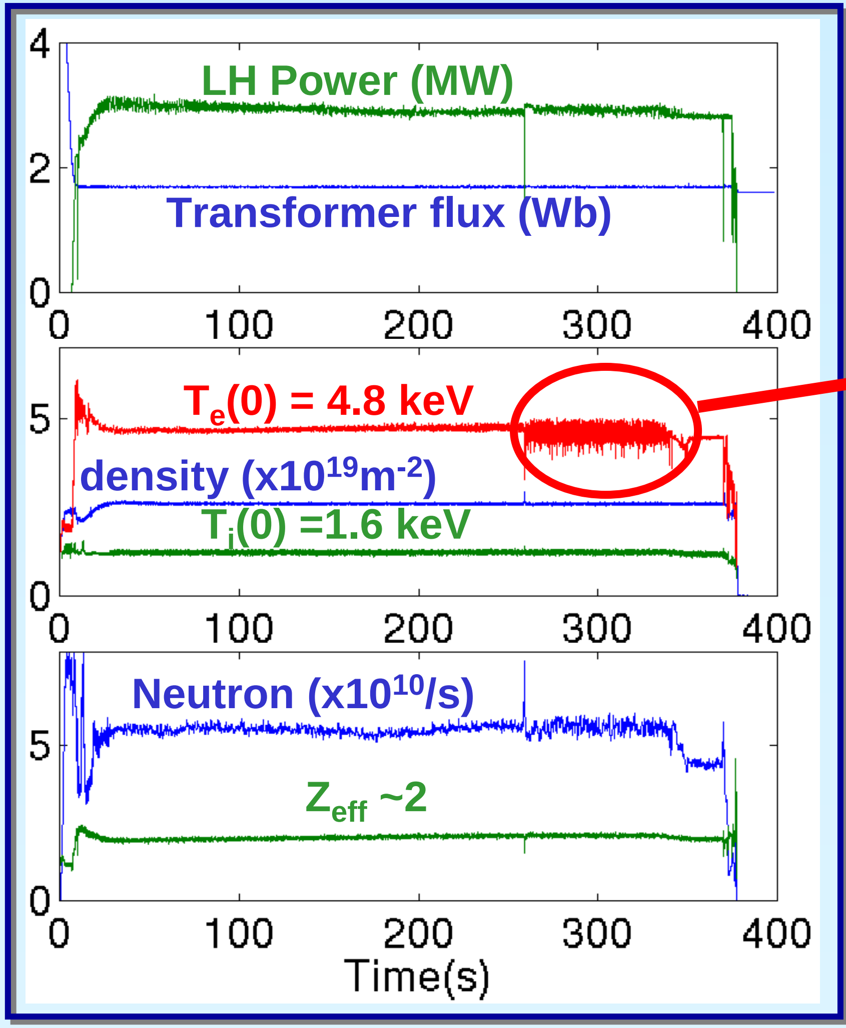
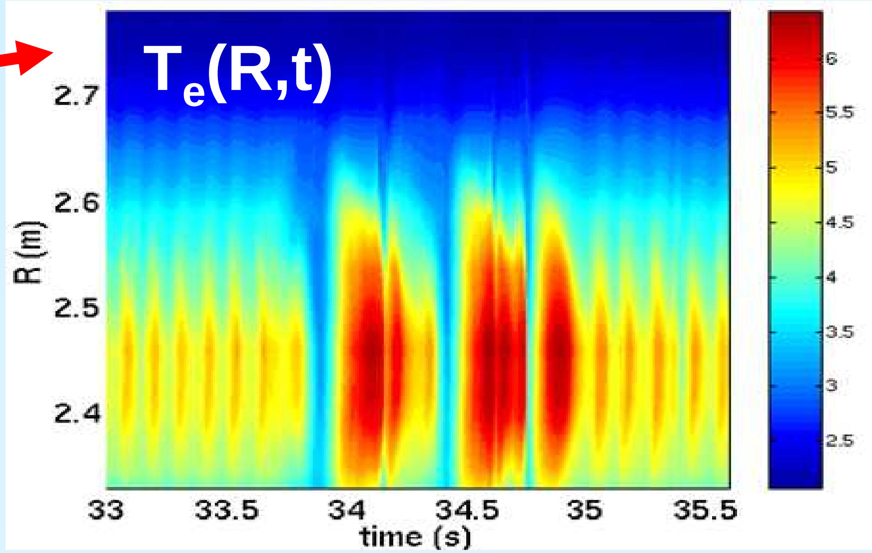
2003

V_{loop}=0 for 6 min, 1 GJ



- **oscillations of core electron temperature**
  - non-linear interplay between q-profile, transport and heat sources (and MHD)



[Giruzzi PRL 03; Imbeaux PRL 06; Maget Nuc Fus 06]

Oscillation in bootstrap-dominated regime

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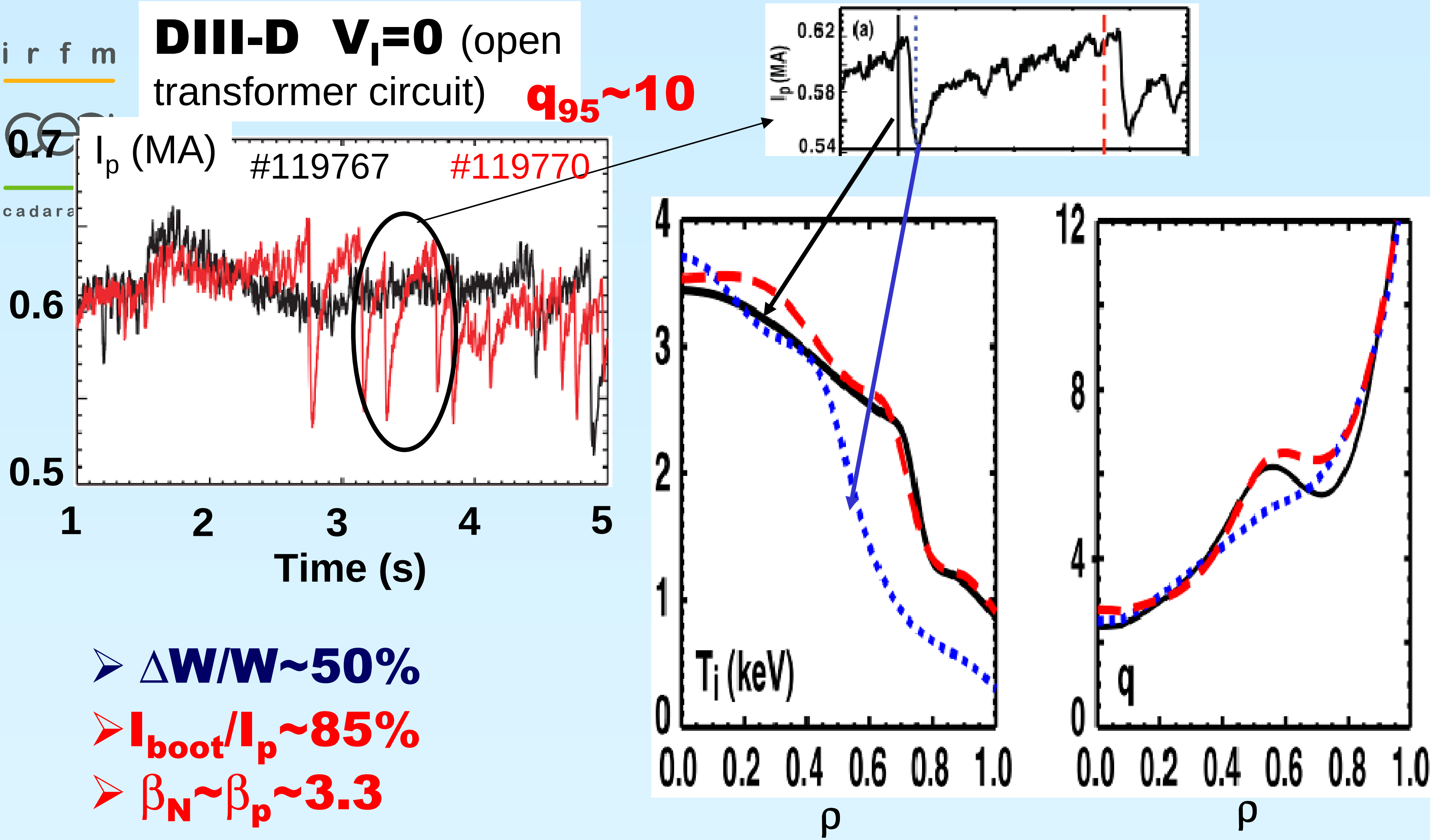
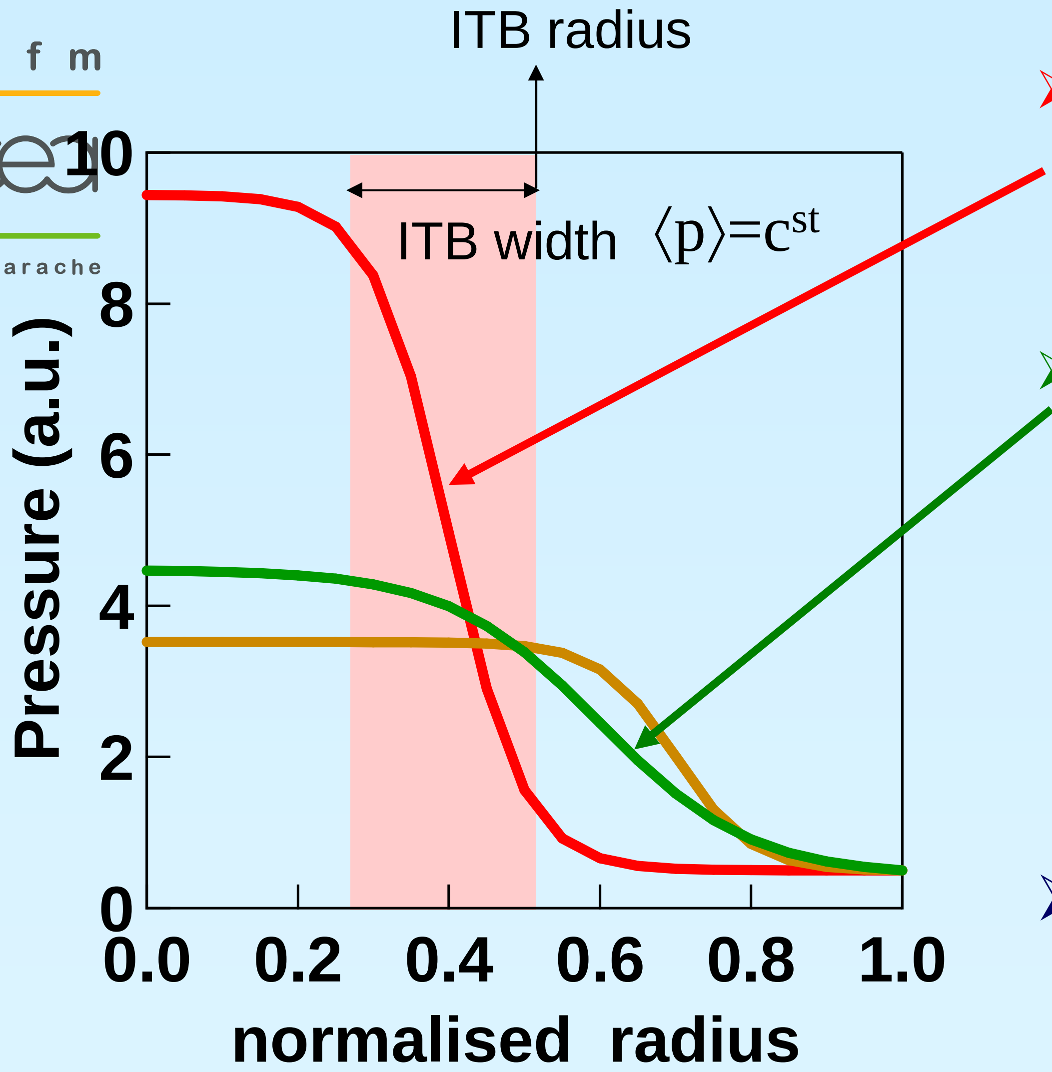
DIII-D V_l=0 (open transformer circuit) **q_{95}~10**



- $\Delta W/W$~50%
- I_{boot}/I_p~85%
- $\beta_N \sim \beta_p$~3.3

[Politzer et al NF 2005]

ACCESS TO HIGH β_N OPTIMAL PROFILES ?



- **Non-optimal : narrow profiles and steep gradients**
- **Optimal ITB : broad profiles with moderate gradients**
  - MHD stability
  - broad J_{boot} and J_{tot}
  - broad n_e for reduced impurity accumulation
- **control of ITB radius, strength & width**

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High β_N requires broad pressure profiles

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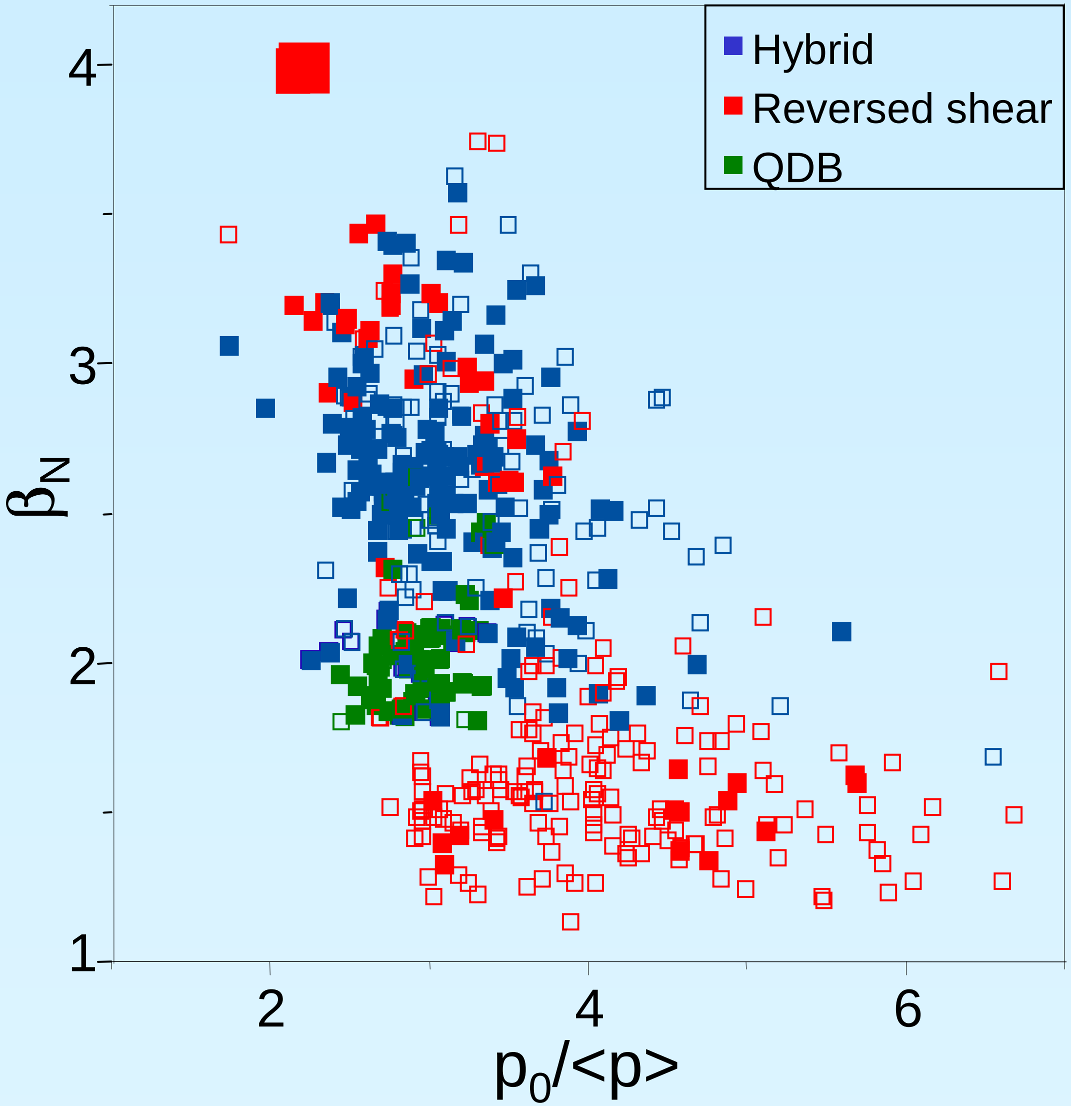


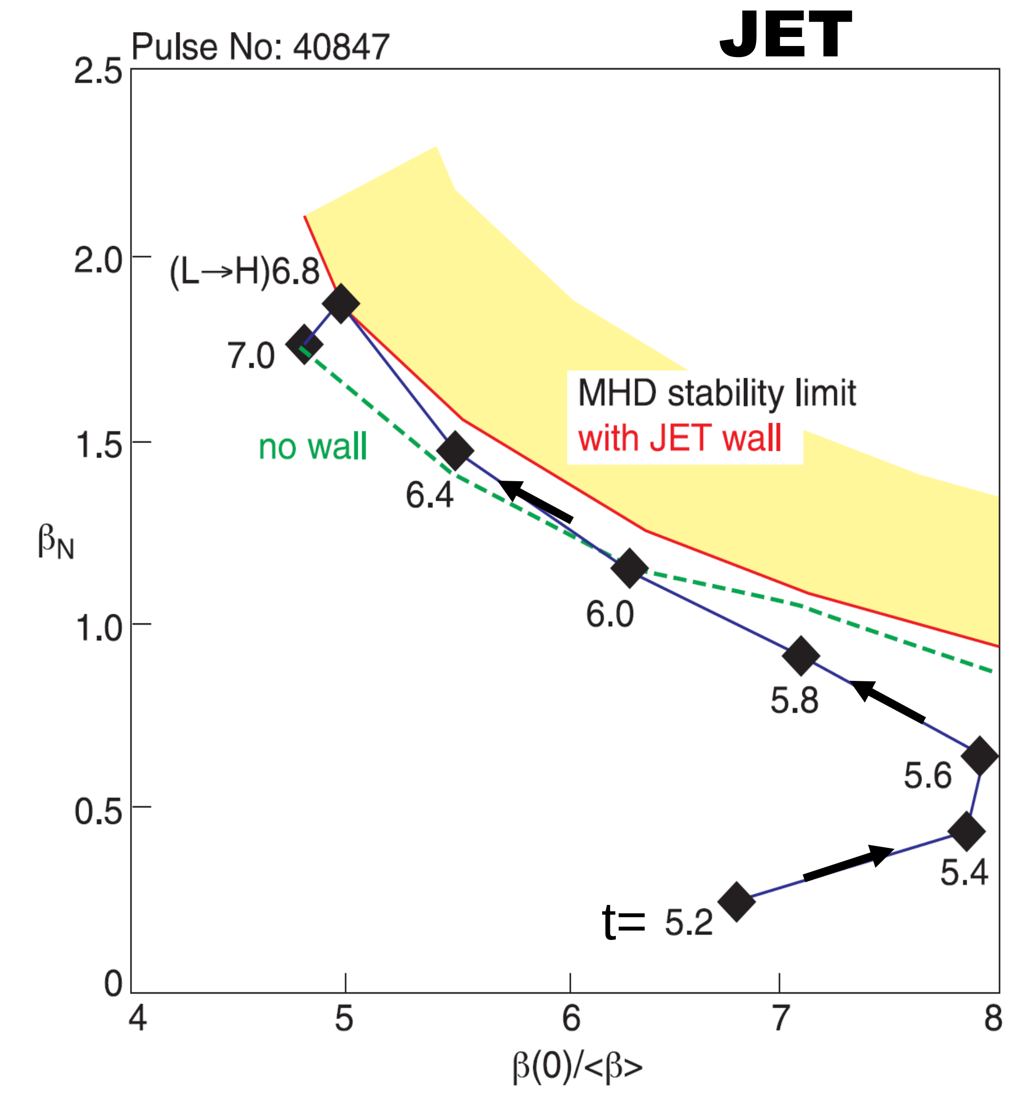
ITPA database

➢ **Stability limit improves with ITB radius and width*→ control of confinement & q-profile ?**

[Sips IAEA 2004 , Litaudon et al PPCF 2004]

*Lao et al APS 99

REAL TIME CONTROL OF KINETIC ENERGY



- **Operation close to the no-wall stability limit while avoiding disruptions**
- **Real time control of neutral beam heating to match a neutron yield production**
- **Similar results obtained on DIII-D, JT-60U**

[G. Huysmans et al., Nucl. Fusion, 1999, C. Gormezano et al FST 2008]

Control of electron temperature gradient

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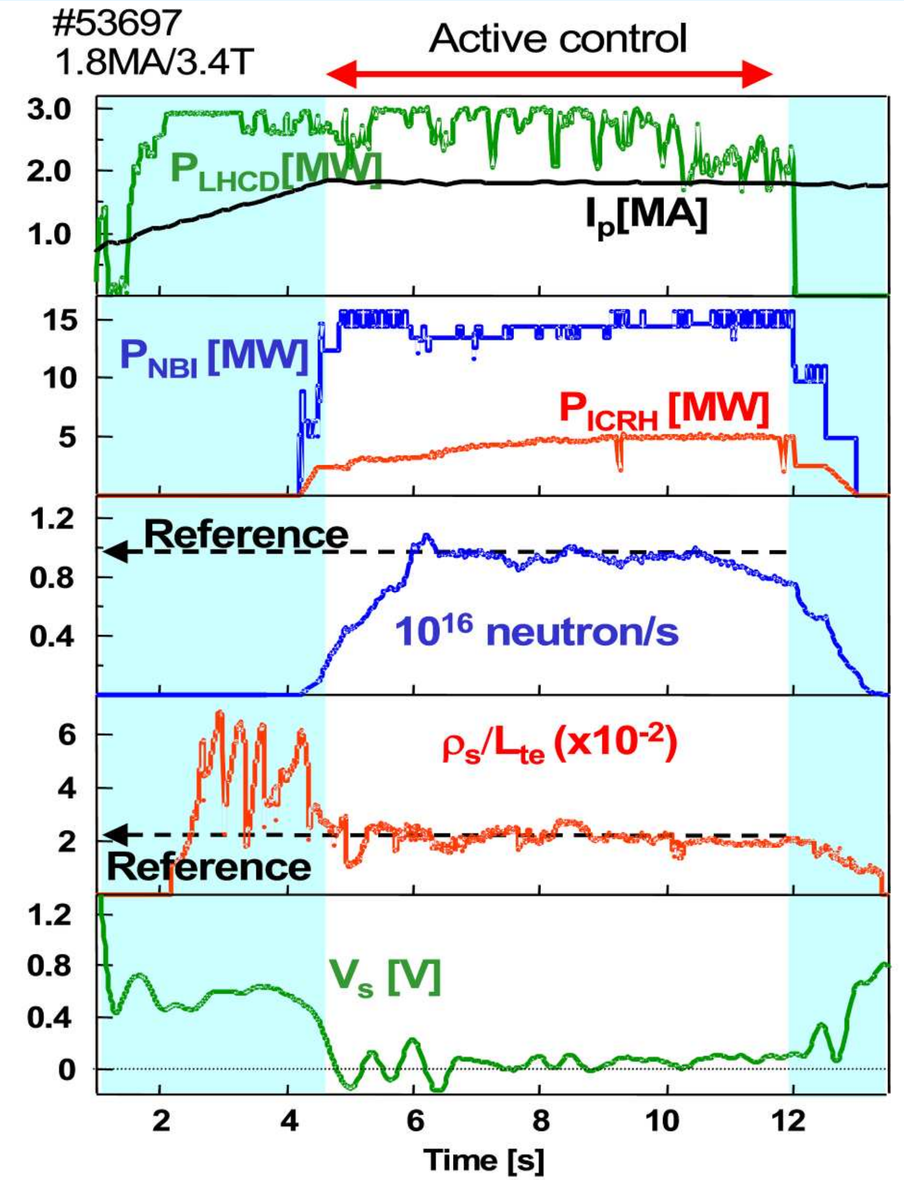
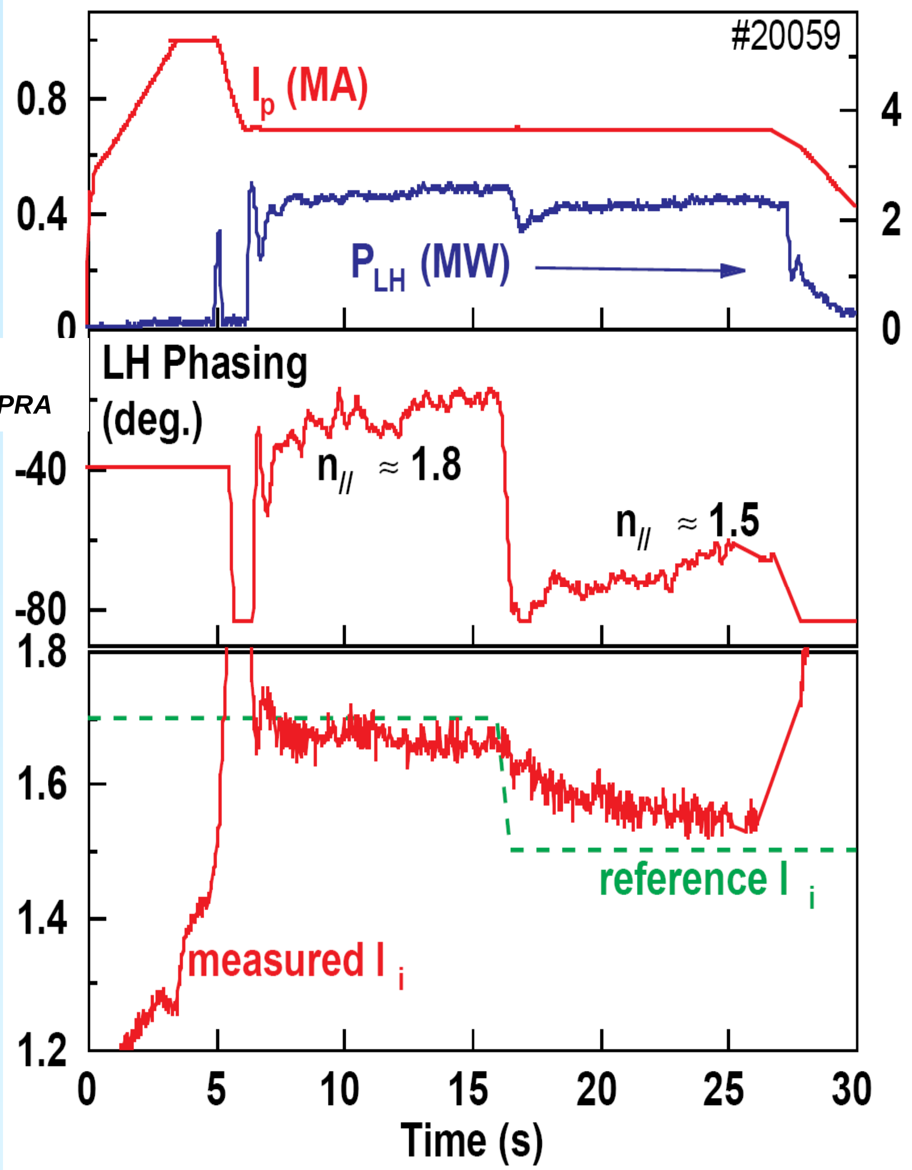


- P_{LHCD} to slow down q(r,t)
- P_{NBI} RT controlled by neutron
- P_{ICRH} RT controlled by ρ_s/L_{Te} where $L_T = \nabla T/T$
- proportional-integral

$$P(t)[\mathrm{MW}] = P(t_0) + G_p \Delta X(t) + G_I \int_{t_0}^{t} \Delta X(u)\,du,$$

[Mazon, Litaudon, Moreau et al PPCF 02]

RT control of magnetic energy



- **feedback control for non-inductive operation:**

1. **Primary voltage ∝ V_{loop}- $V_{loop,\ ref}$**
2. **P_{LHCD} ∝ $I_{p\ ref}$ - I_p**
3. **$n_{//\text{-}LHCD}$ ∝ L_{iref}- L_i**

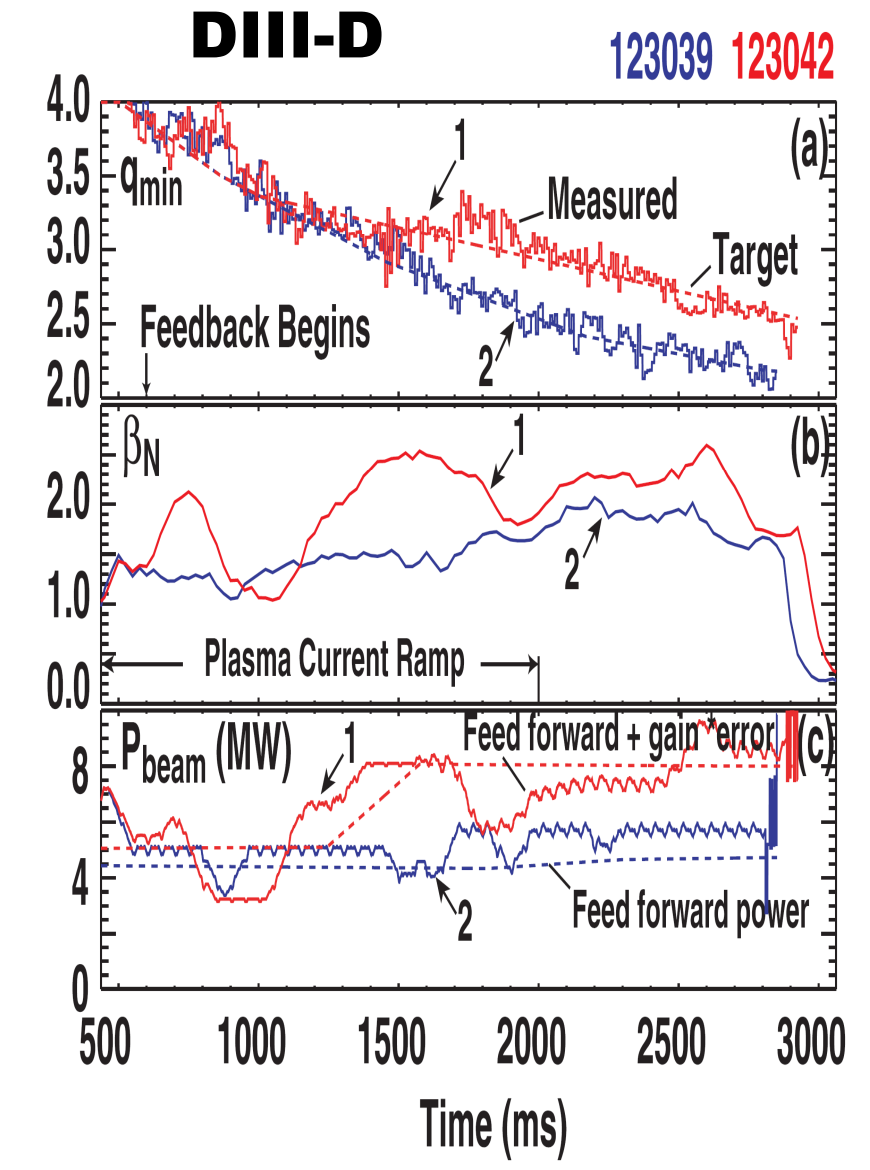
with L_i ∝ ⟨ β^2_θ⟩/ β^2_θ (a)

- **More recently***

  $n_{//\text{-}LHCD}$ ∝ Hard X Ray width representative of LHCD absorbed & J profile

[Wijnands Nuc Fus 1997,
Litaudon PPCF 1998,
*Joffrin Nuc Fus 2007]

RT control of minimum q, q_{min}



- **Feedback control of q_o or q_{min} during the plasma current ramp-up phase**
- **Change of plasma conductivity through electron heating**
  - ECRH or NBI
- **RT q-profile using MSE data**

[J. Ferron et al Nuc Fus 2006]

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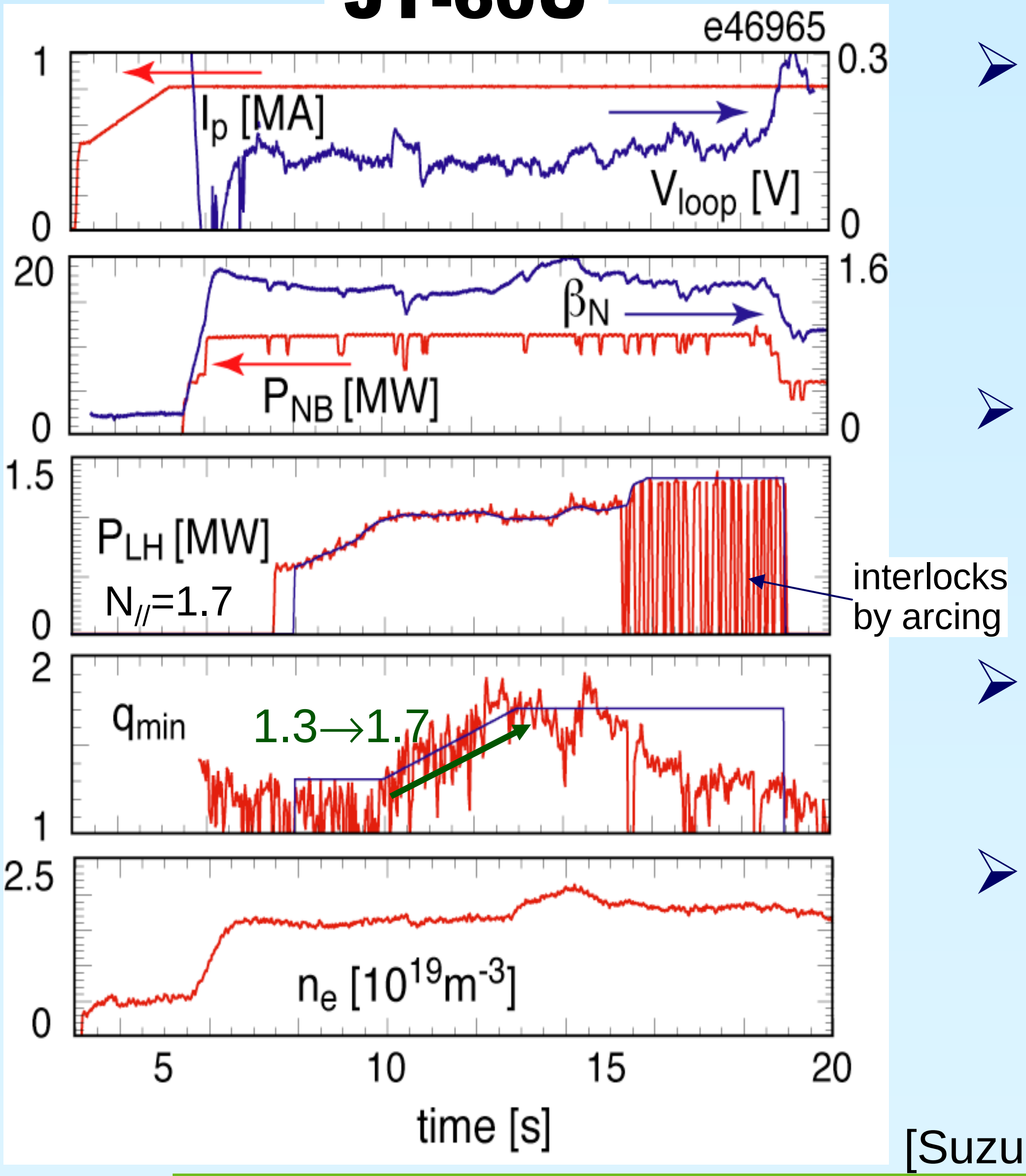
RT control of minimum q, q_{min}

JT-60U

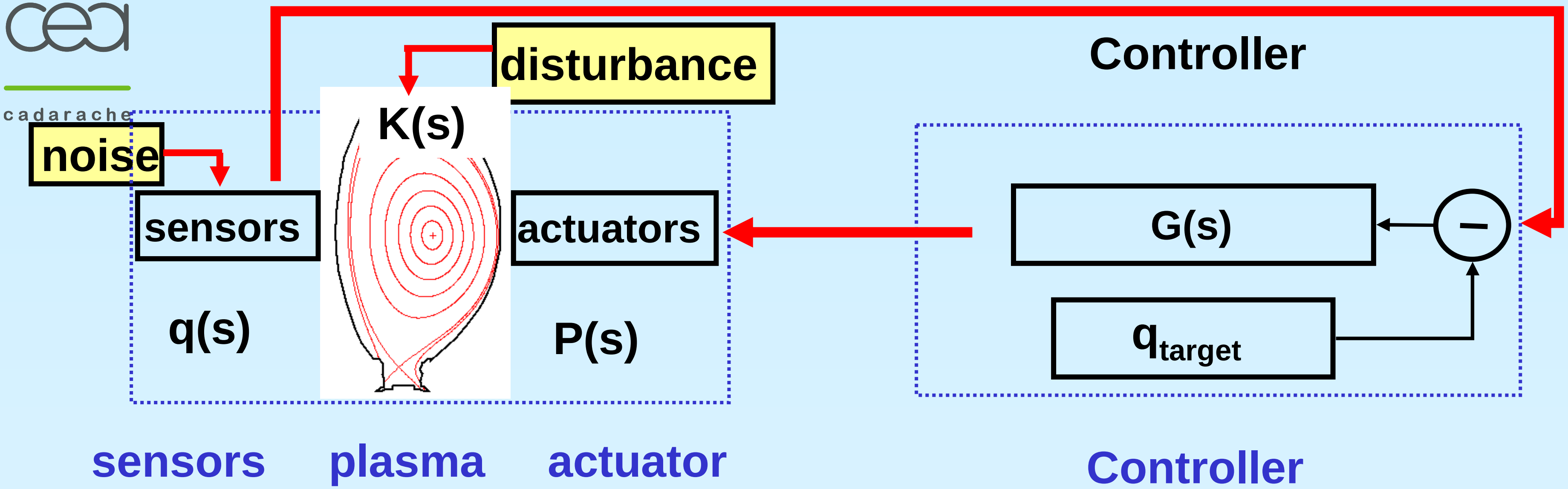


- **High-βp ELMy H-mode**
  - I_p=0.8MA, B_t=2.5T, q_{95}=5.8, n_e=1.8x$10^{19}m^{-3}$, β_p=1.2-1.5.
- **Off-axis LHCD control:**
  - $dP_{LHCD}/dt=\alpha(q_{min,ref} - q_{min})$
  - α=2MW/s
- **Without control**
  - q_{min} down to 1.3
- **Interaction j & T_e**
  - Requirement for T & J control

[Suzuki et al NF 2008]

Multi-Input-Multi-Output (MIMO) model based profile control

All transfer functions are in matrix form



$$\delta q(s) = K(s)\ \delta P(s)$$

$$\delta P(s) = G(s)\ \delta q(s)$$

First approach: control based on pseudo-inverse of the steady-state gain matrix

$$G(s) = g_c[1 + 1/(\tau_i s)]\ K(0)_{inv}$$

[D. Moreau et al Nucl Fus 2003, D. Moreau et al Nucl Fus 2008]

RT q-profile control with off-axis LHCD in low β-phase

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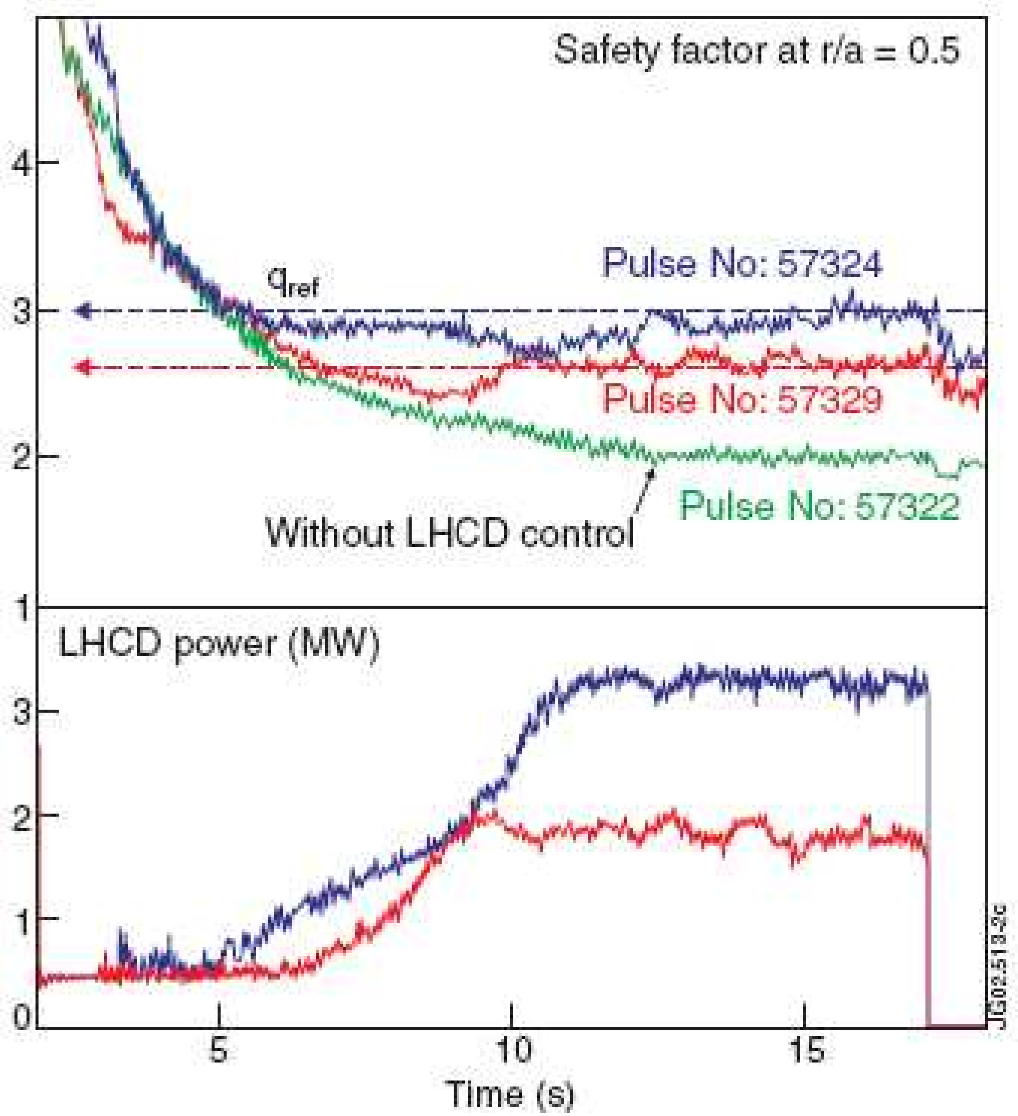
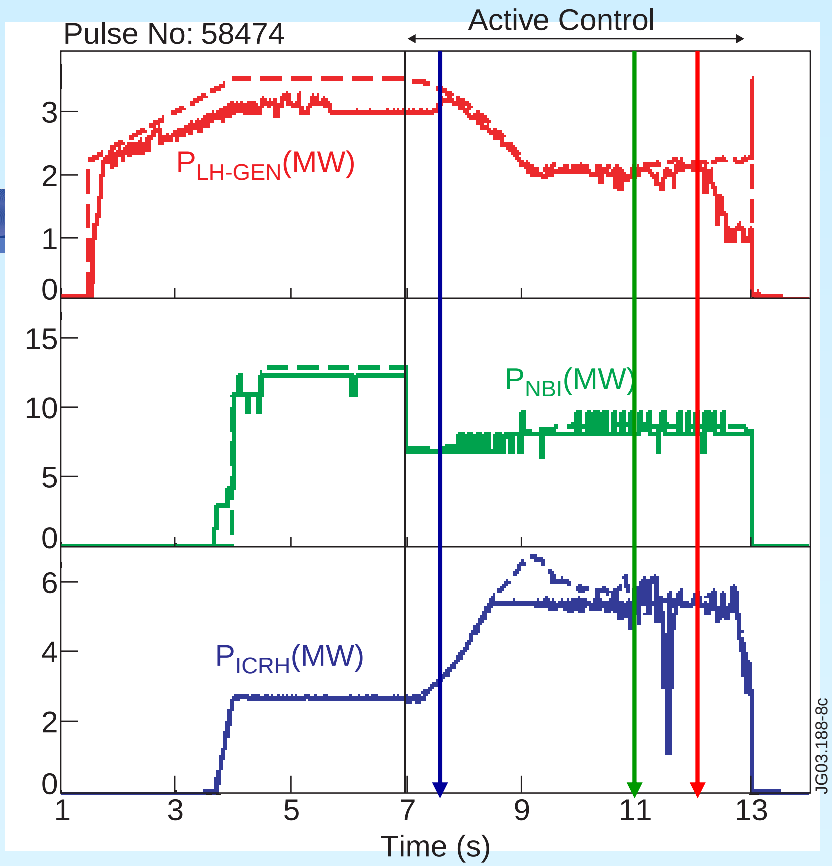


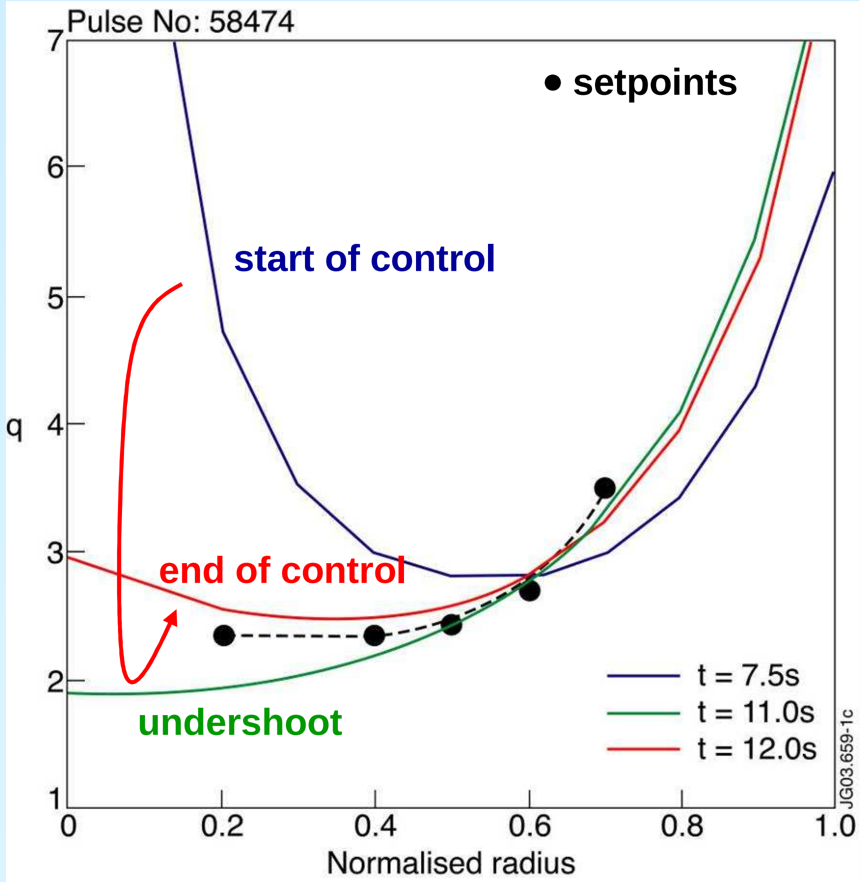
- **control in the prelude phase**
- **"Model Based" control on 5 q-values**
- **P_{LHCD} is controlled to minimise (q-q_{target}) in the least square sense**
- **Access to various q-profiles**

[D. Mazon et al PPCF 2003, D. Moreau et al Nucl Fus 2003]

RT q-profile control in high β-phase

Multi-Input, multi-output control
3 actuators: LHCD, ICRH, NBI



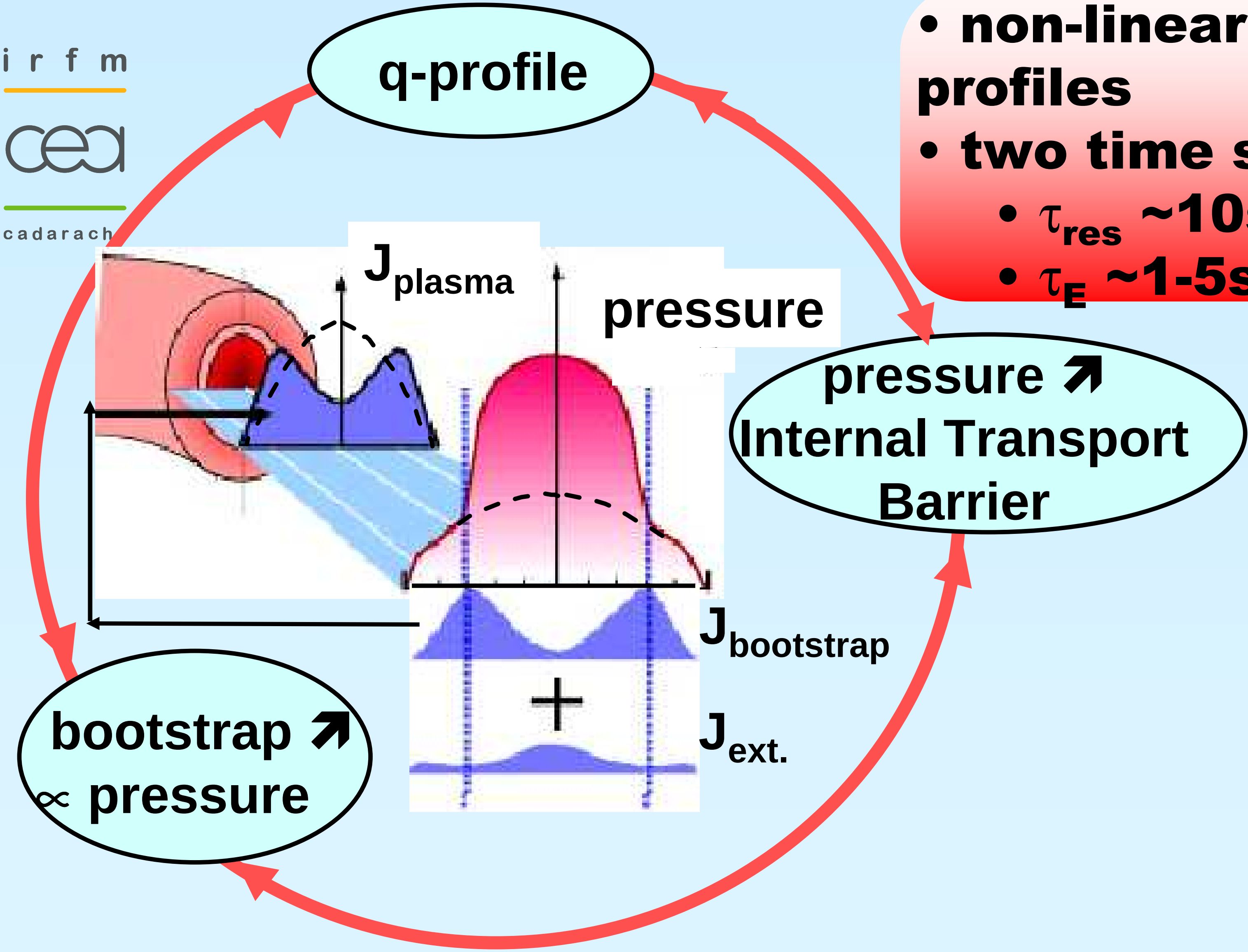


Model based SVD control: steady-state gain matrix deduced from open loop experiments

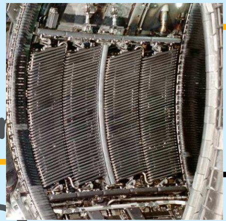
[D. Moreau et al Nucl Fus 2003]

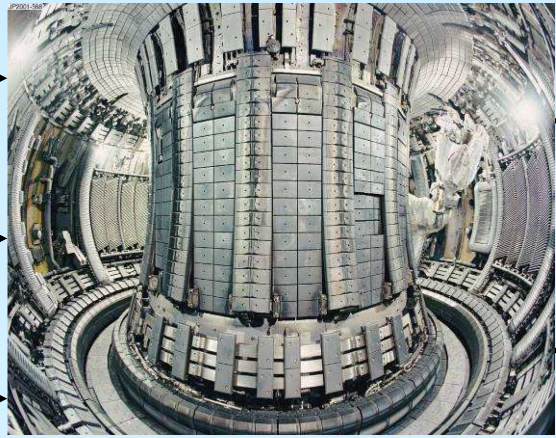
Control of kinetic & magnetic profiles

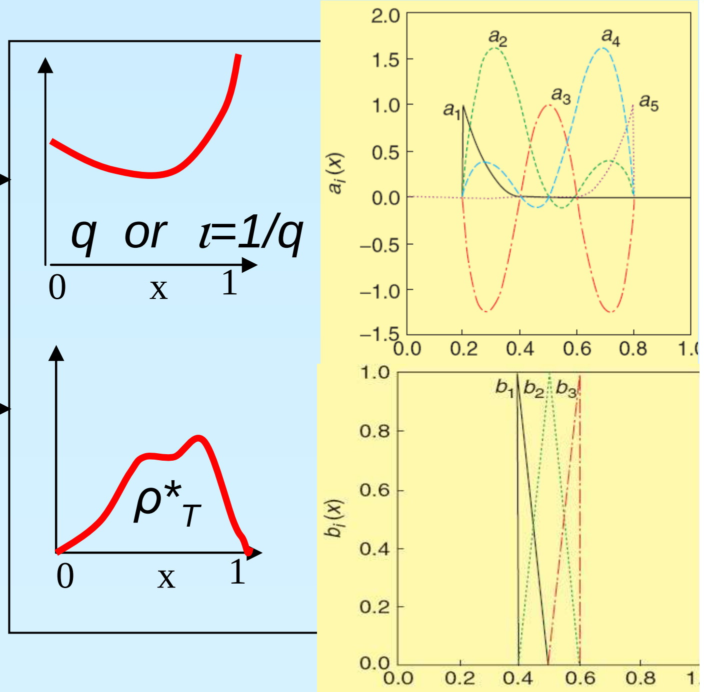
- non-linearly coupled profiles
- two time scales
  - τ_{res} ~10s-100s
  - τ_E ~1-5s



Control of kinetic & magnetic profiles







modulations around a reference steady-state:

$$
\begin{bmatrix}
K_{11} & K_{12} & K_{13} \\
K_{21} & K_{22} & K_{23} \\
K_{31} & K_{32} & K_{33} \\
K_{41} & K_{42} & K_{43} \\
K_{51} & K_{52} & K_{53} \\
K_{61} & K_{62} & K_{63} \\
K_{71} & K_{72} & K_{73} \\
K_{81} & K_{82} & K_{83}
\end{bmatrix}
\cdot
\begin{bmatrix}
\delta P_{ICRH} \\
\delta P_{LH} \\
\delta P_{NBI}
\end{bmatrix}
=
\begin{bmatrix}
\delta G\iota_1 \\
\delta G\iota_2 \\
\delta G\iota_3 \\
\delta G\iota_4 \\
\delta G\iota_5 \\
\delta G\rho_T^* {}_1 \\
\delta G\rho_T^* {}_2 \\
\delta G\rho_T^* {}_3
\end{bmatrix}
$$

Galerkin's projection of 1/q and ρ^*_T

[D. Moreau et al Nuc Fus 2008, T. Tala et al Nuc. Fus 2005]

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Control of kinetic & magnetic profiles

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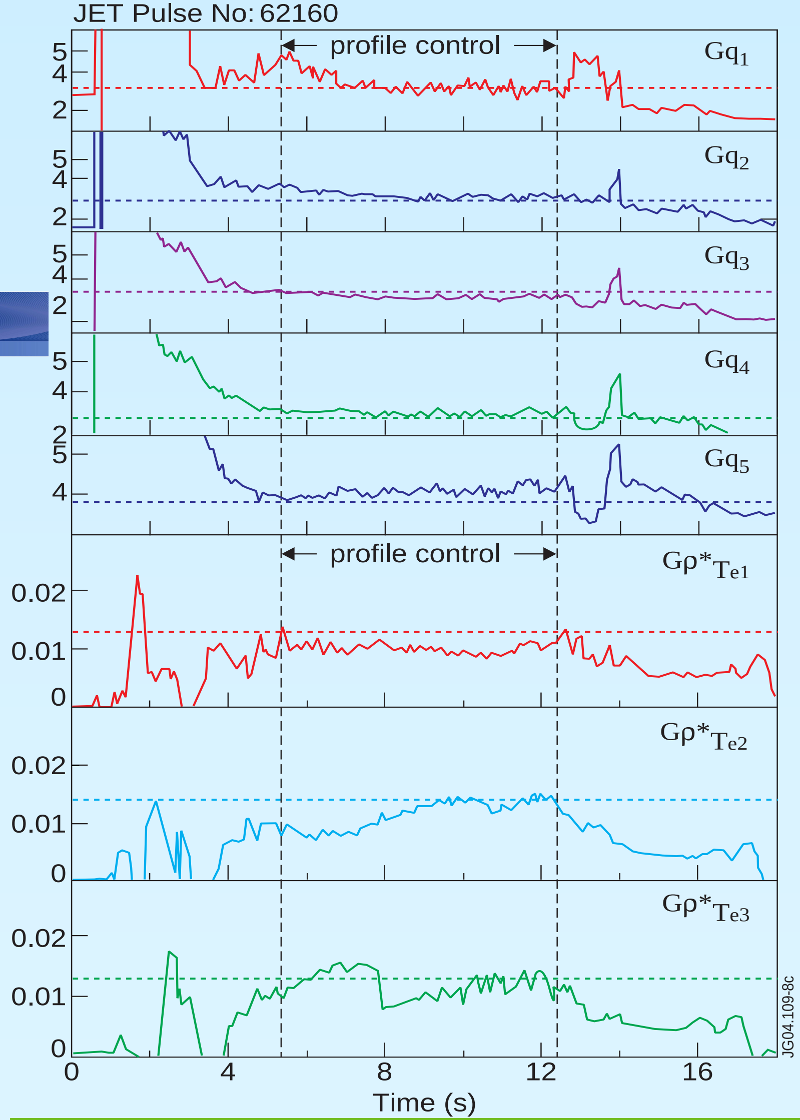
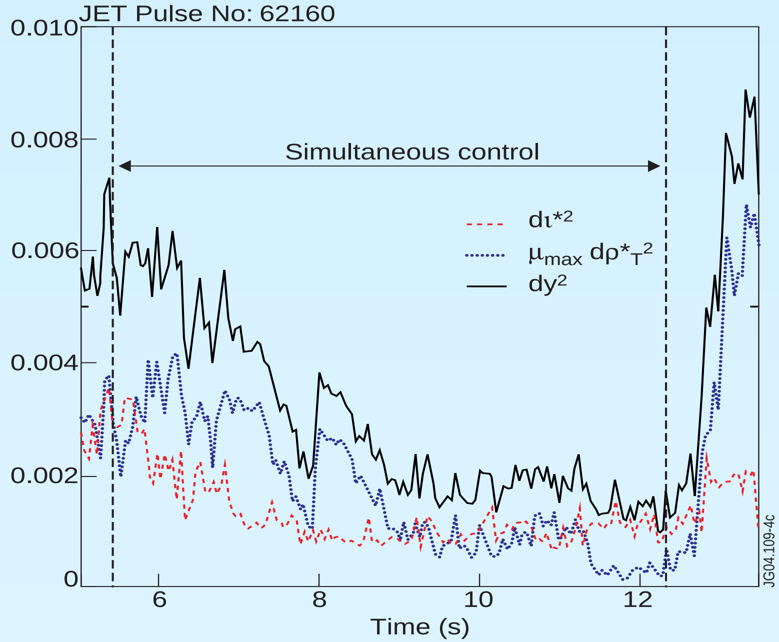
q profile and ρ^*_{Te} control



The controller minimizes quadratic error:

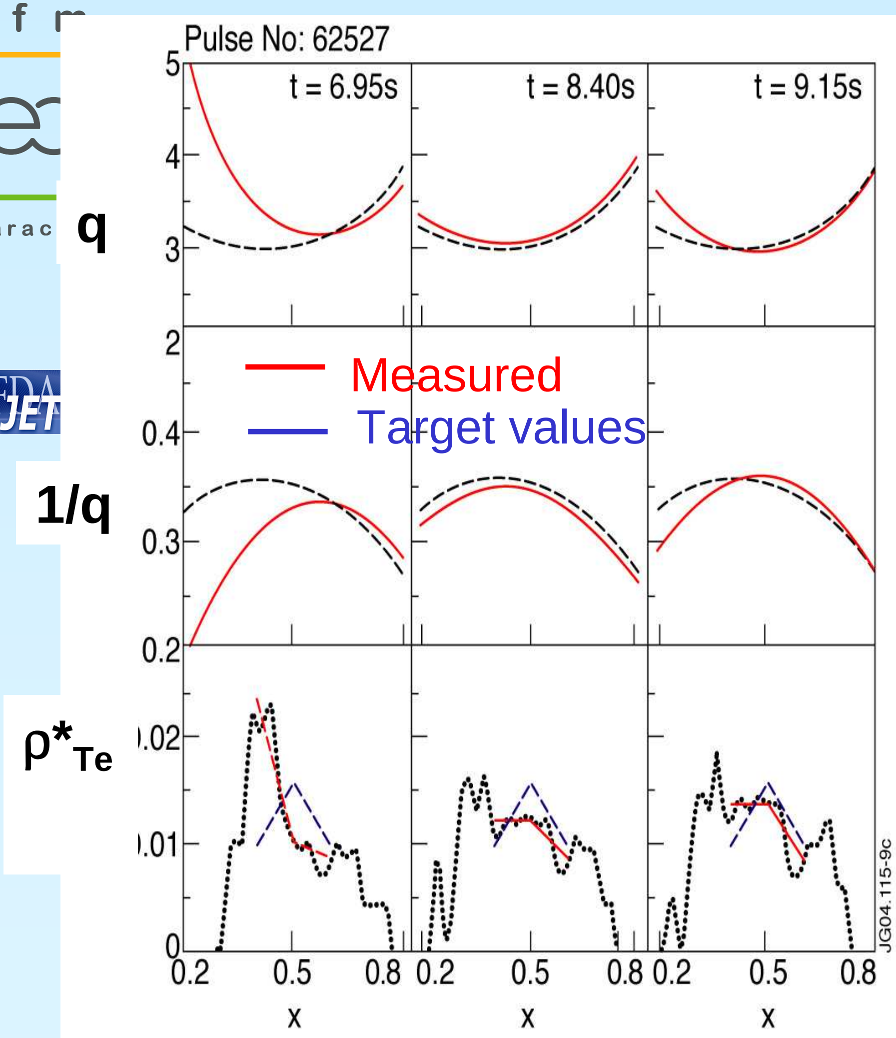
$$dy^2 = \int_{0.2}^{0.8} \left[\iota(x) - \iota_{\text{setpoint}}(x)\right]^2 dx$$

$$+ \mu \int_{0.4}^{0.6} \left[\rho^*_T(x) - \rho^*_{T_{\text{setpoint}}}(x)\right]^2 dx$$

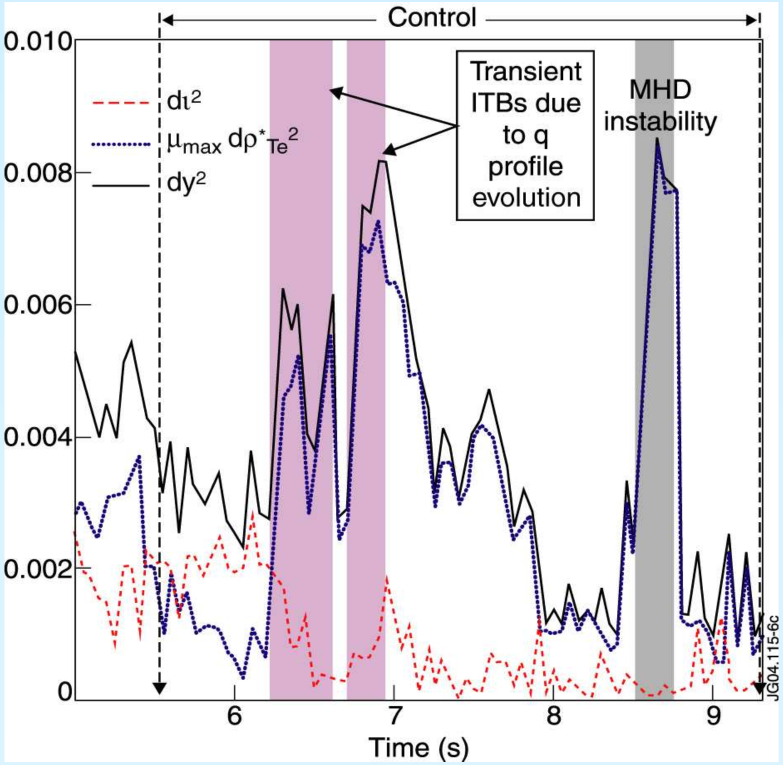


[Laborde et al., PPCF (2005), Moreau et al. Nuc Fus 2008]

Control of kinetic & magnetic profiles



- Limitation of steady-state gain matrix approach: controller response slow during fast events
- Development of an optimal control (time dependent model)



[Laborde et al., PPCF (2005), Tala et al Nuc. Fus 2005, Moreau et al Nuc Fus 2008]

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Two time-scale models
slow: magnetic profiles, fast: kinetic profiles

[Moreau et al Nuc Fus 2008]

Slow model: resistive time scale

$$\frac{d\Psi}{dt} = A_{slow} \cdot \Psi(t) + B_{slow}\, U_{slow}(t)$$

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

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

opt. feedback

Fast model: momentum / thermal confinement time scale, $\tau = \varepsilon t \quad \varepsilon \ll 1$

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

Fast controller :

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

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

opt. feedback

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Identification of a dynamical model
Future: closed loop experiments

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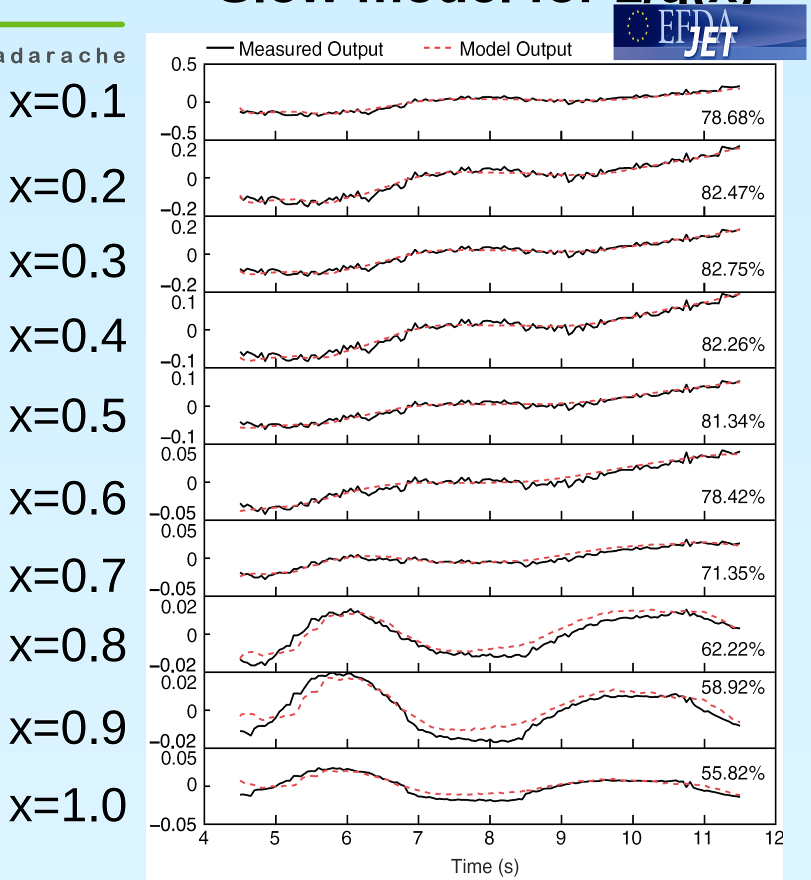
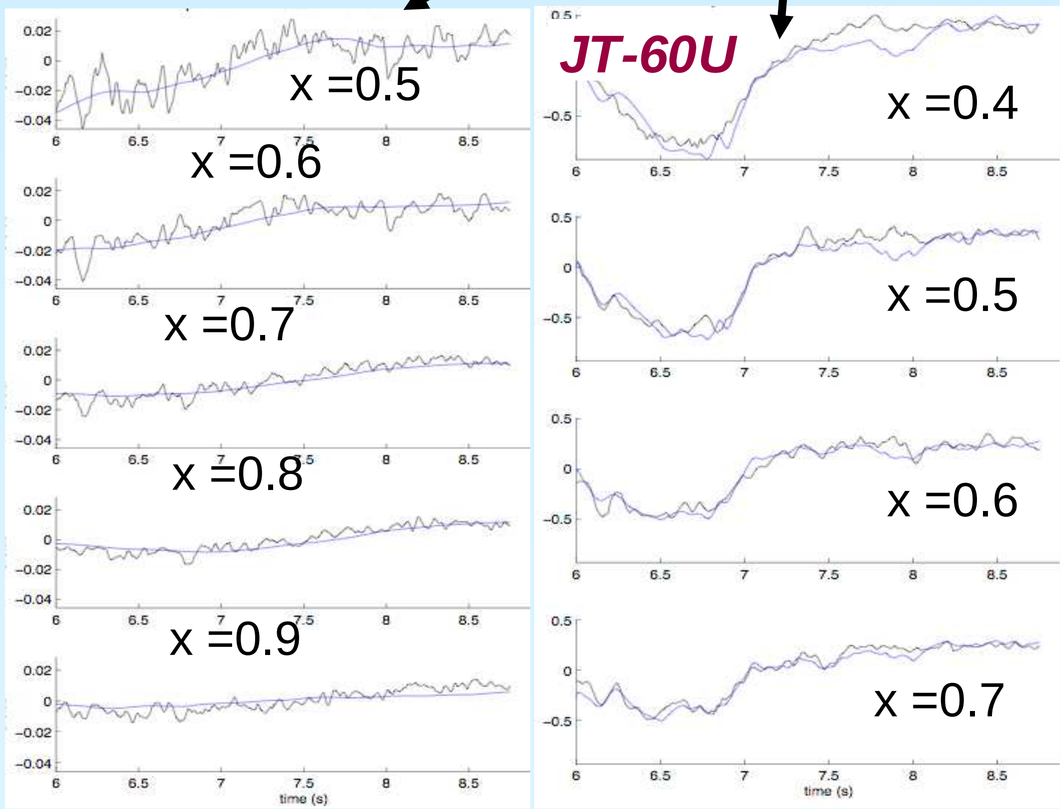
- **Generic approach: can be applied to any tokamak with any set of actuators and real-time measurements**
- **Model identified on JET, JT-60U and DIII-D (on-going)**

Slow model for 1/q(x)



1/q(x) & $V_\Phi(x)$



[Moreau et al Proc. 48th IEEE Conf. on Decision and Control China 2008]

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Modelling of real time control of Te and q

ITER model based profile control (CRONOS) : 12MA hybrid mode

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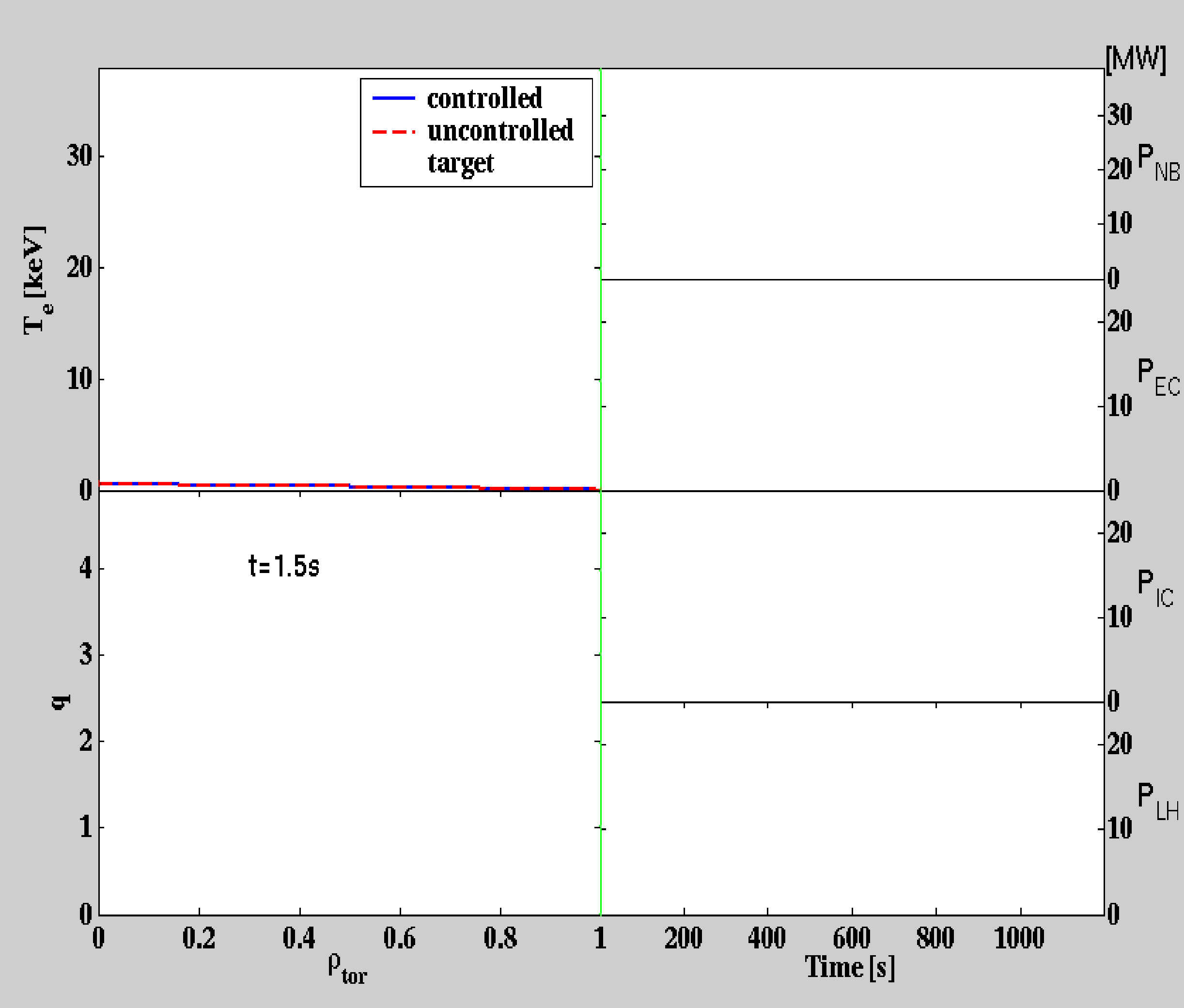
ITER

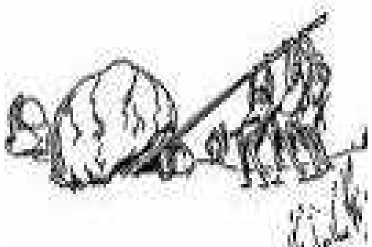
S.H. Kim *et al*, EPFL thesis Nº 4500

sub to PPCF



- q control @ 300s
- Te control @ 400s
- 4 actuators
- transport model based on global confinement scaling law
- real-time update of the static models

RT control in dominated bootstrap & α-heating regimes : open issues



- **existence of a stable and unique state with self-consistent pressure and current ?**
- **control at high I_{boot} with $P_{\alpha} \geq P_{add}$?**
  - rely mainly on q-profile control with minimum external CD?
  - pressure control requirements should be minimized
- **model based control?**
  - strong requirements in terms of integrated transport modelling
- **'simulate' in present day experiment α-heating with additional electron heating source**
  - Experiments performed on JET & JT-60U to mimick α-heating in standard ELMy H mode regimes: how to extend to non-inductive operation ?

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SIMULATION OF ALPHA PARTICLE PLASMA SELF-HEATING USING ICRH UNDER REAL-TIME CONTROL

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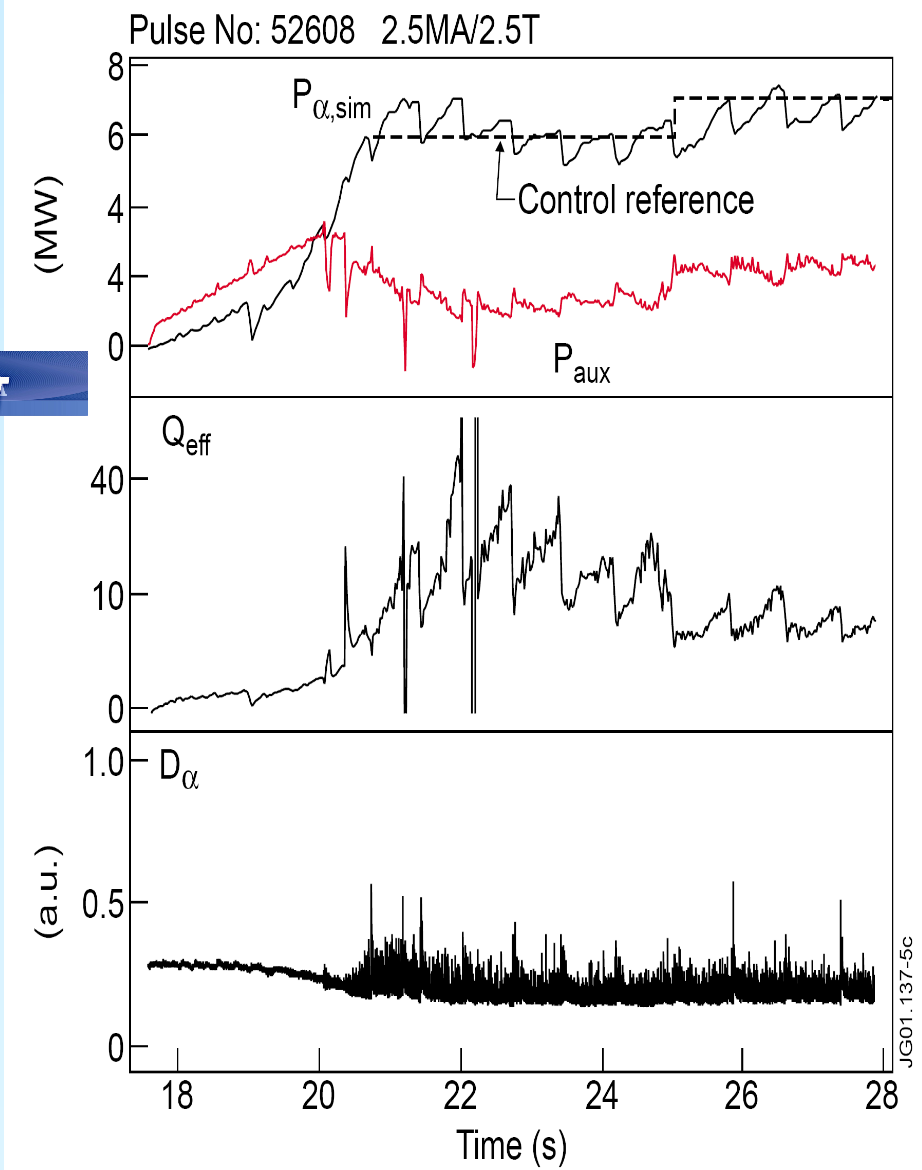
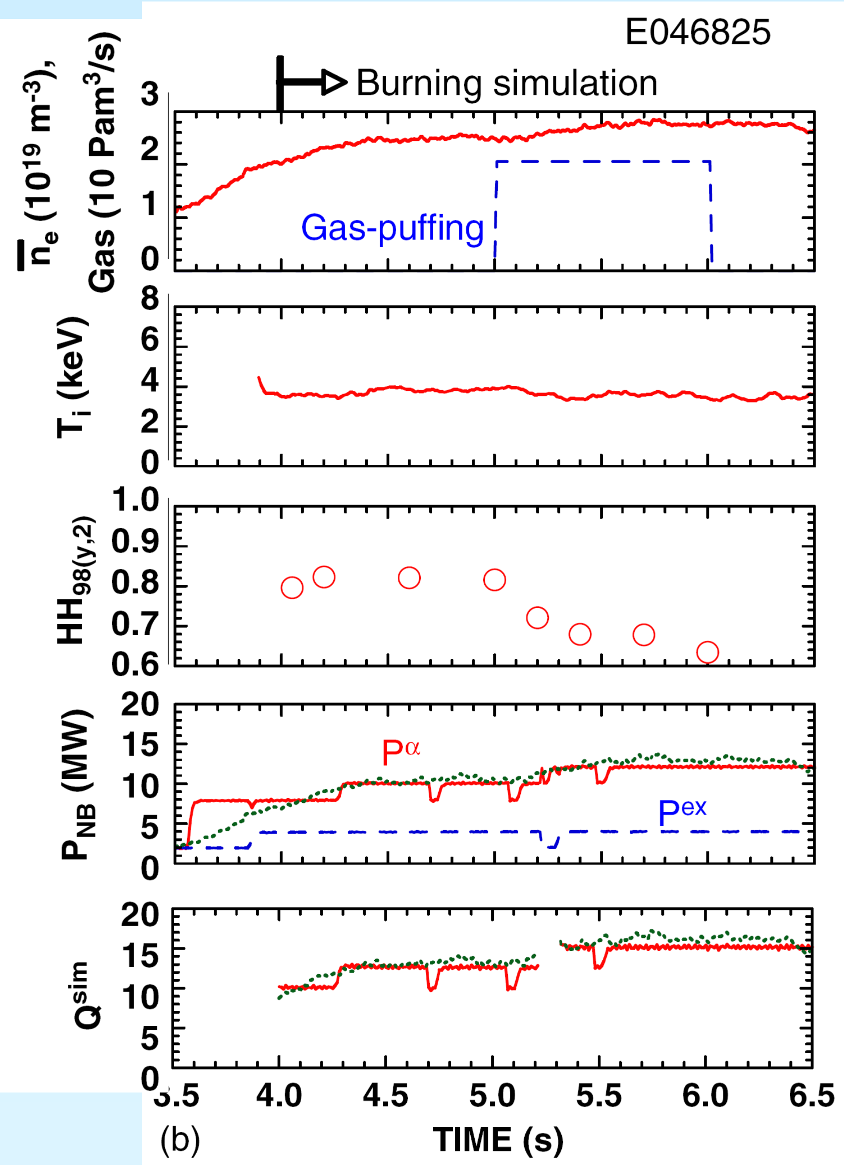
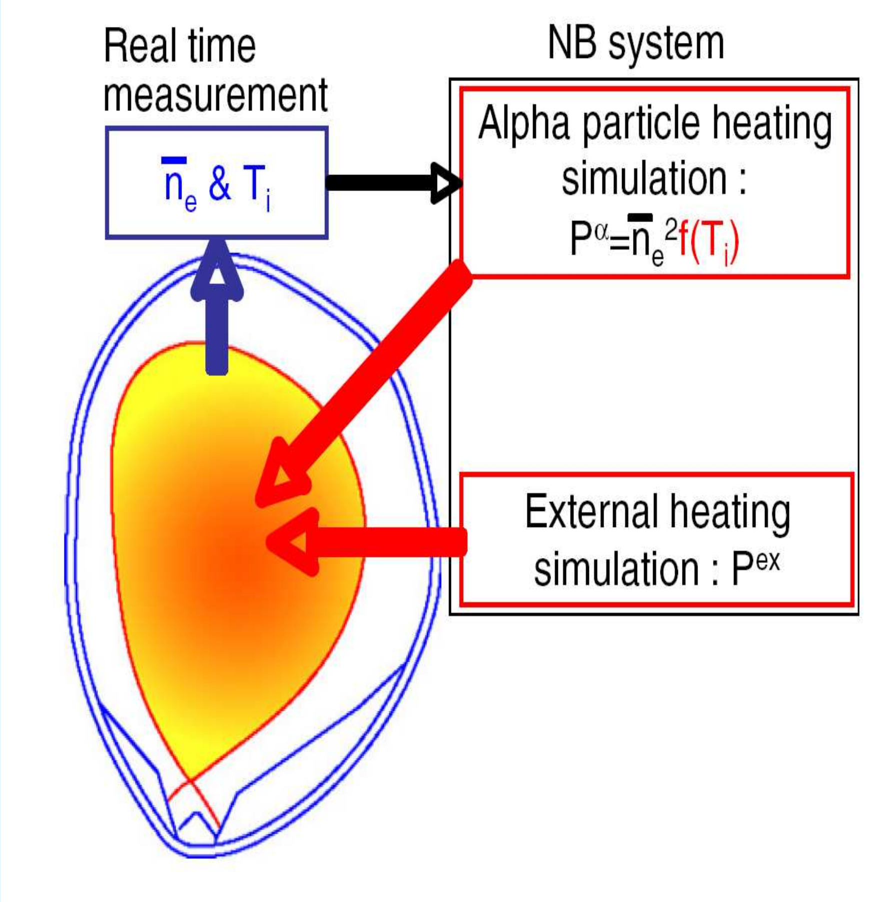


- ICRH applied in response to real-time measured plasma parameters (e.g. neutron rate) <u>simulating the self-heating effect</u>
- part of the external heating plays the role of auxiliary heating
- Demonstrate stable control of the simulated burn?

[T. Jones, EPS 2001]

SIMULATION OF ALPHA PARTICLE PLASMA SELF-HEATING USING NBI UNDER REAL-TIME CONTROL





[Takenaga et N Fus 2008]

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Mimick the self-alpha heating and self-driven current in present day non-inductive experiments

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- **Integrated fusion burn control experiment to prepare Long Pulse Operation on ITER & DEMO**
  - ICRH/ECRH 'mimic' the α-power → P_{α} and P_{fus}
  - ECCD/LHCD 'mimic' bootstrap → $f_{Boot} > 50\%$
  - Remaining powers for control → $P_{control}$

$$\rightarrow \quad Q_{eff} = P_{fus} / P_{control} \sim 5\text{-}20$$

- **Could be tested on long pulse tokamaks : Tore Supra, JT-60SA, EAST etc …**
- **"Proof of principle" through modelling using a simplified version of CRONOS, METIS**
- **Combination of H&CD powers & density actuators are required for burn control:**
  - Powers : fast and precise control
  - Density : slow and coarse control

Fusion burn simulation at high bootstrap fraction

- **high bootstrap burning plasma**
  - α-heating mimicked using ICRH/ECRH

$$P^{\alpha}_{ICRH} = g_{fus} R_{DD}$$ $$R_{DD} \propto n_D^2 f(T_i)$$ $$P^{\alpha}_{ECRH} = r_{ECRH} P^{\alpha}_{ICRH}$$

  - bootstrap mimicked using LHCD

$$P^{boot}_{LH} = \eta_{LH} I^{boot}_{LH}$$ $$I^{boot}_{LH} = g_{boot} I_{boot}$$

- **Fuelling, Heating/CD feedback control**

$$P_{ICRH} = P^{\alpha}_{ICRH} + P^{control}_{ICRH}$$ $$P_{ECRH} = r_{ECRH} P^{\alpha}_{ICRH} - P^{boot}_{LH} + P^{offset}_{ECRH}$$

$$P_{LH} = P^{boot}_{LH} + P^{control}_{LH}$$

$$\bar{n} = \bar{n}_0 + \bar{n}^{Control}$$

Slow time scale

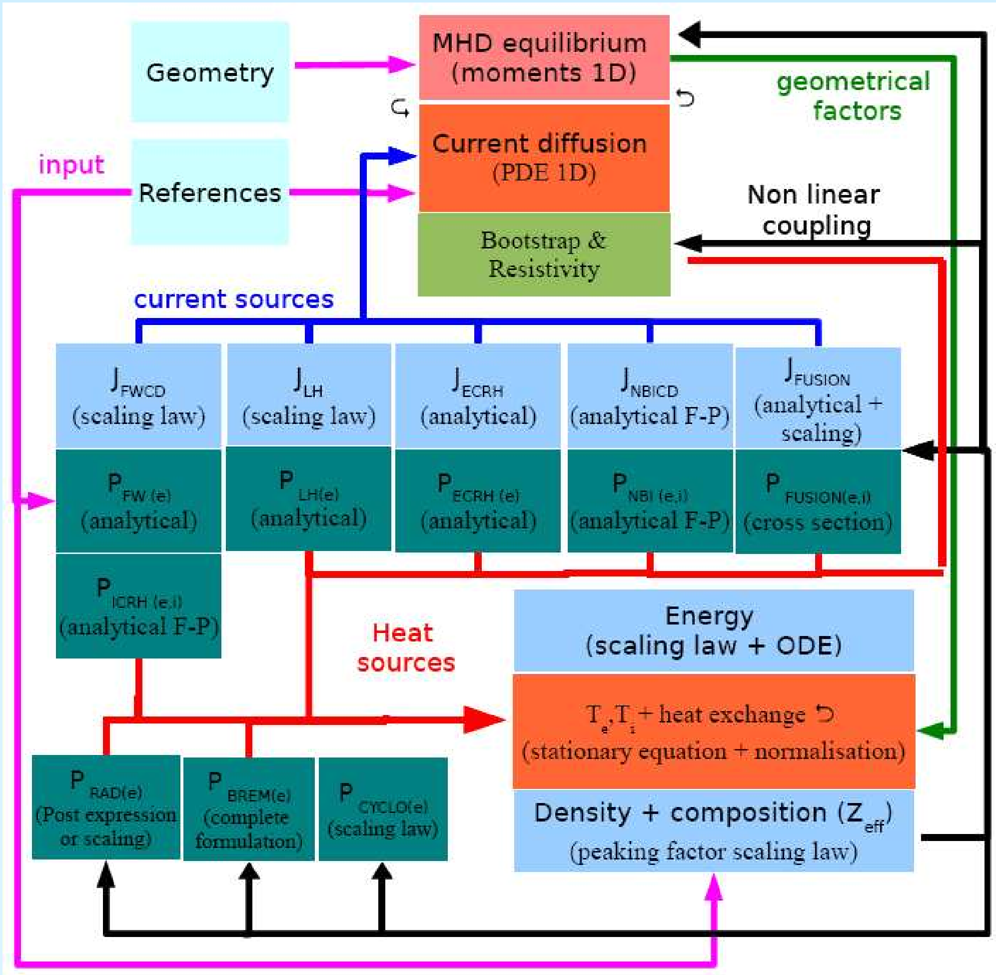
- **Equivalent f_{boot} and Q**

$$f_{boot} = \frac{(1+g_{boot})I_{boot}}{I_P}$$ $$Q = \frac{P_{fus}}{P_{ICRH} + P_{LH} + P_{ECRH} - (1+r_{ECRH})P^{alpha}_{ICRH}}$$ $$P_{fus} \approx 5(1+r_{ECRH})P^{\alpha}_{ICRH}$$

METIS : A tool for (burn) control simulation

METIS work-flow organisation

- Mixed 0D and 1D equations
- Coupled to "Simulink" for real time control design
- Fast dynamic simulation
  - ~ 1minutes for 300 time slices
  - 2s per time slice when coupled to Simulink
- Included in the CRONOS suite to prepare integrated modelling



[Artaud, Litaudon et al EPS 2008]

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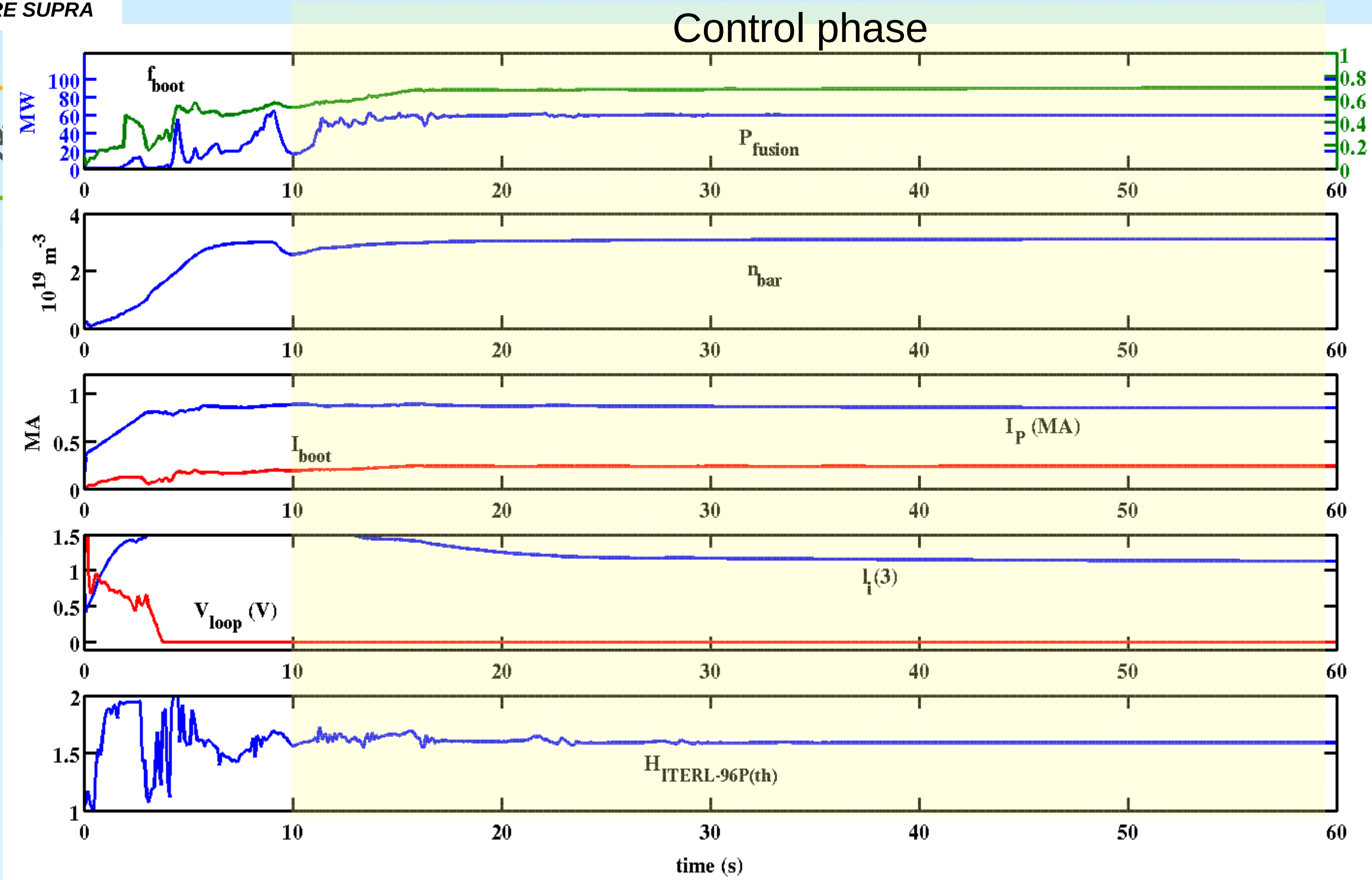
TORE SUPRA

Modelling of Burn control with ITB: Q~15 at f_{boot}~70% at V_{loop}=0



Modelling of Burn control with ITB: Q~15 at f_{boot}~70% at V_{loop}=0

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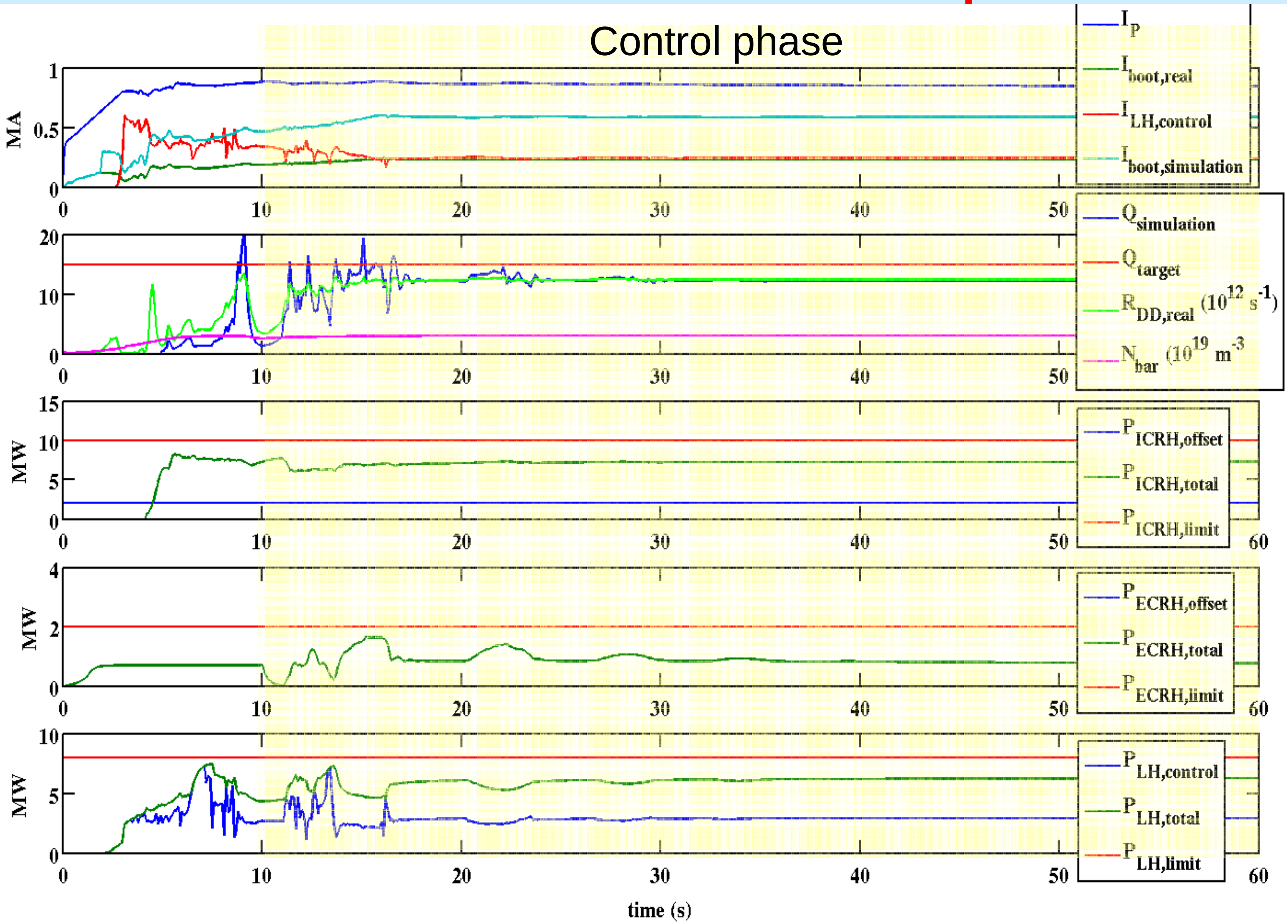
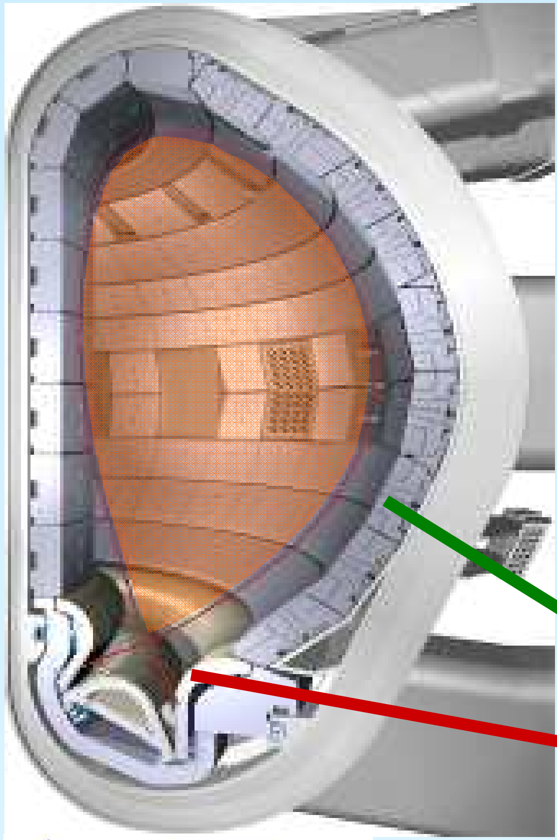
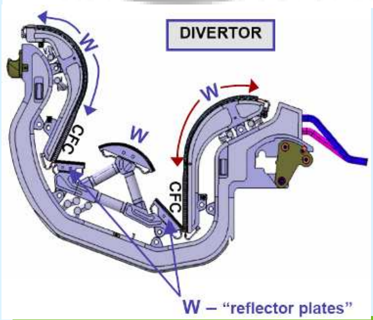
TORE SUPRA



Plasma Facing Components: Wall scenario compatibility

ITER





Wall Scenarios Compatibility:

- maximum performance
- minimum T-retention
- minimum erosion
- maximum life-time of PFC

- **ITER plasma facing components**
  - Be wall
  - Divertor: W-baffle + CFC
  - CFC/W changeout during shutdown preceding D and D-T phase
- **All components actively cooled!**

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Plasma Facing Components: Wall scenario compatibility, R&D in EU

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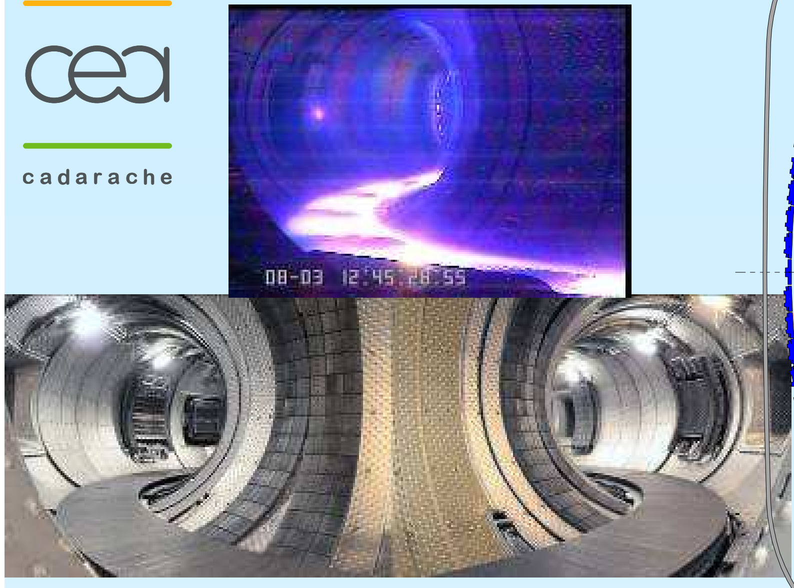
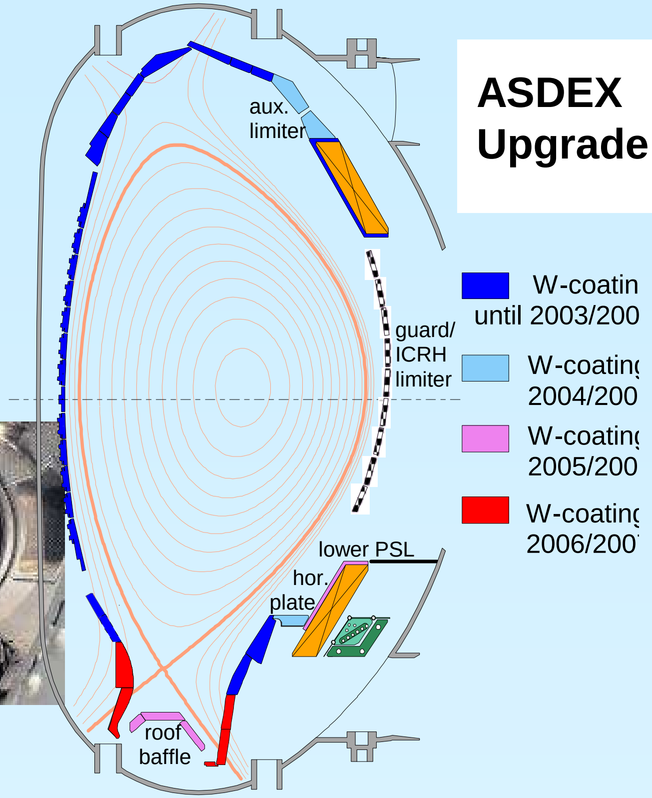
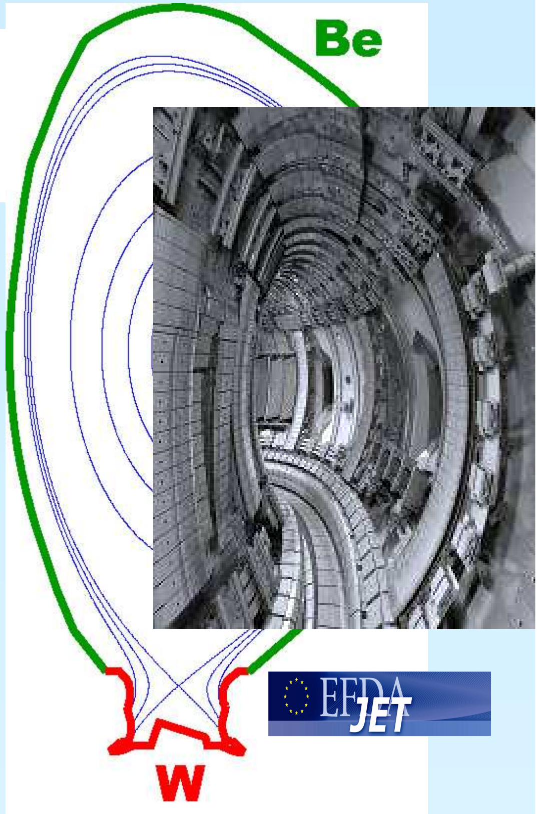
TORE SUPRA







➢Effort in EU tokamaks to investigate PFC-scenario issues

- **Tore Supra:** long pulse operation with actively cooled CFC components
- **ASDEX Upgrade**: conversion to all tungsten PFCs complete
- **JET**: installation of beryllium wall and tungsten divertor in 2010

Steady-state scenario and Wall compatibility issue

- **Control steady-state fusion performance**
  - control of kinetic & magnetic energy (confinement & stability) including impurities
  - control fully non-inductive operation

boundary conditions core plasma

simultaneously with

Core conditions

- **Control of power & particle exhaust**
  - Control transient & stationary power loads
  - Control of fast particle losses
  - Control of particle exhaust & recycling according to fuelling requirements, capacity of Tritium extraction plant & necessary Helium removal

[Litaudon et al EPS PPCF 2007]

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simultaneous control of transient (ELMs) and stationary power load

ASDEX Upgrade

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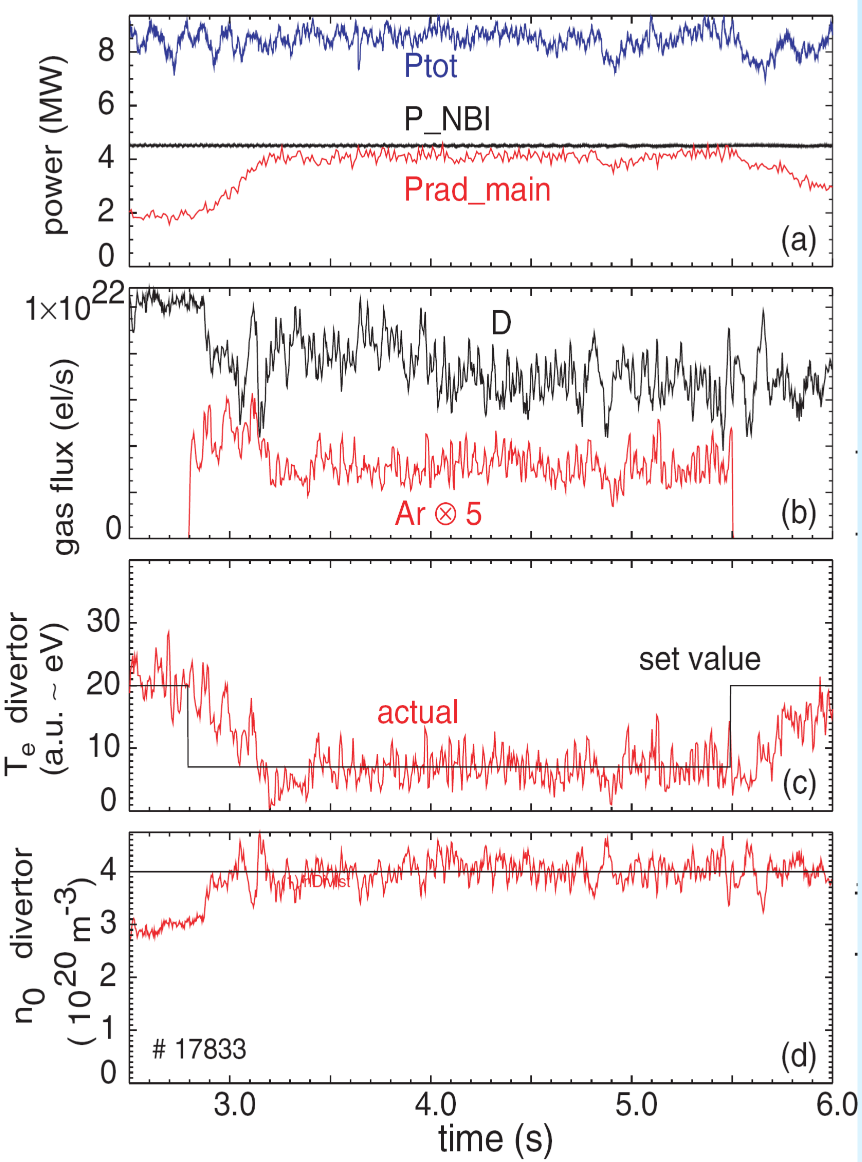
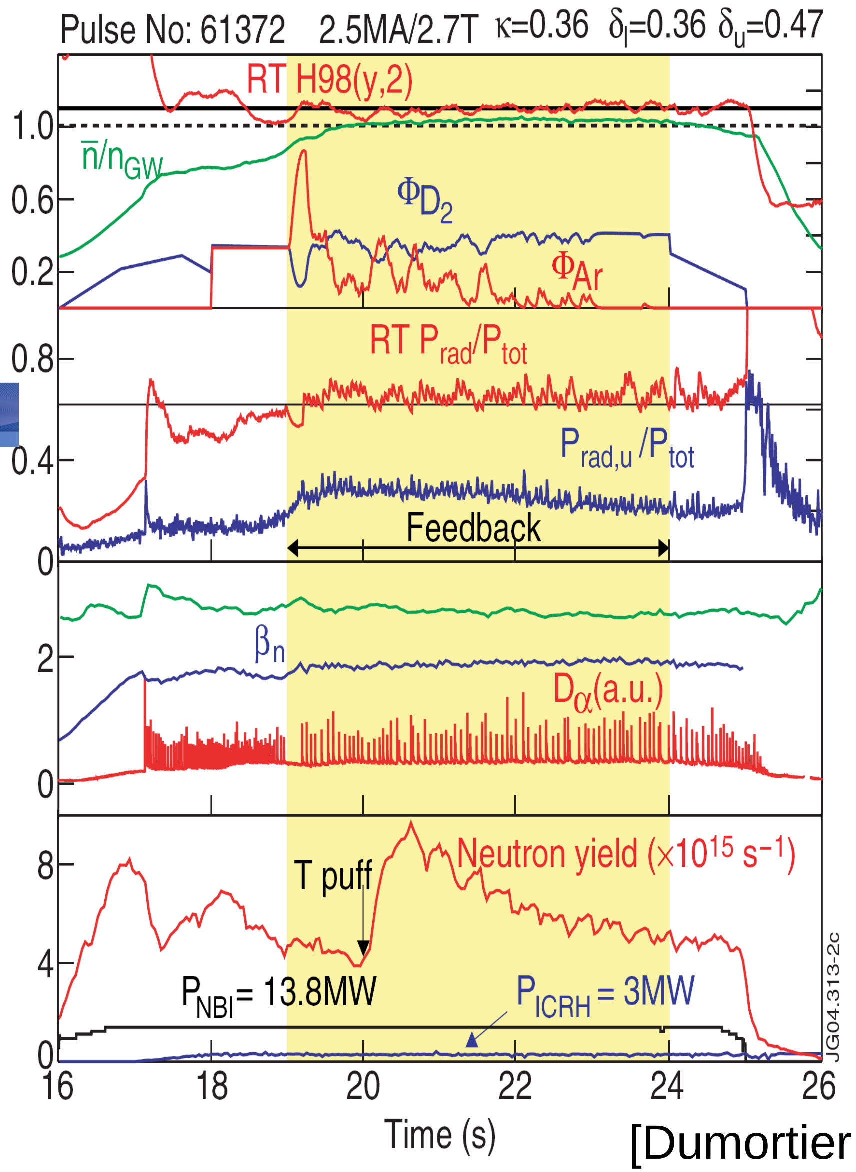


- **Exhaust power controlled by impurity injection:**
  - noble gases usually chosen
  - limit heat flux & divertor temperature to minimize erosion
- **Feedback control of gas flow:**
  - radiated power to be actively adjusted
  - heat flux to target adjusted in response to variations in loss power (fusion power)

[P Lang et al Nucl. Fusion 2005]

Simultaneous real time control of core confinement and heat exhaust



- **Control of confinement by acting on D_2 flux**
  - Highest density at a given confinement
- **Control of p_{rad}/p_{tot} by acting on Argon flux**
  - reduce divertor heat load
- **Control matrix from open loop exp.**

$$\begin{pmatrix} \Delta(P_{rad}/P_{tot}) \\ \Delta H98(y,2) \end{pmatrix} = \underline{\underline{\mathbf{M}}} \begin{pmatrix} \Delta\Phi_{D_2} \\ \Delta\Phi_{Ar} \end{pmatrix}$$

[Dumortier P. et al EPS 2004]

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Simultaneous real time control of core confinement and heat exhaust

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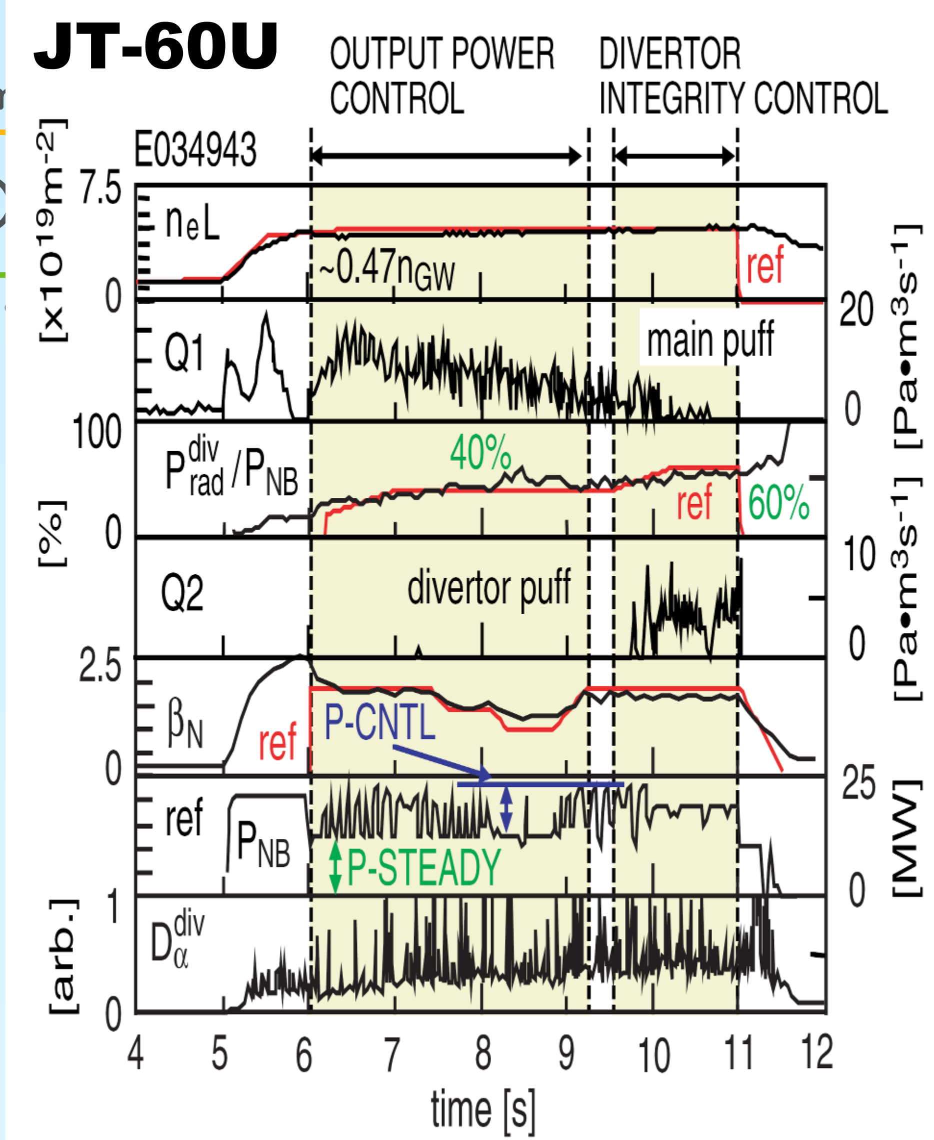
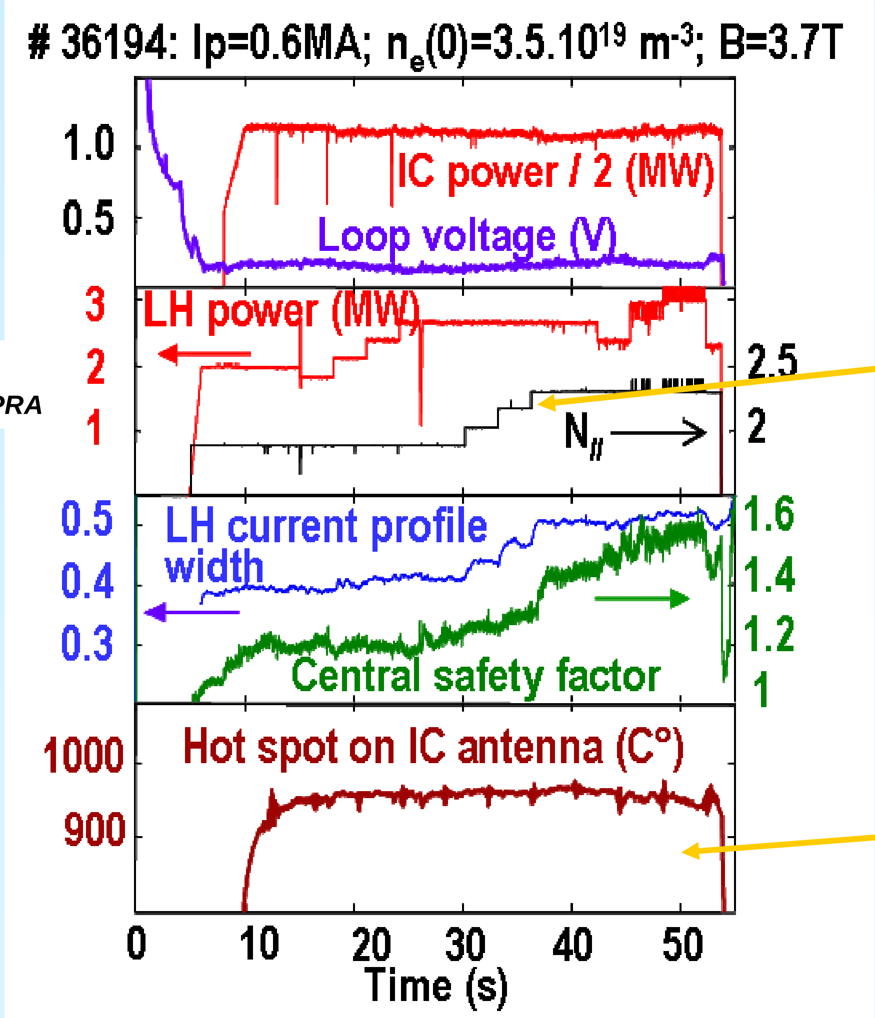


[Fukuda et al FST 2002]

- **Simultaneous control of**
  - Density by gas puffing near the top of the vessel
  - Divertor radiation by gas puffing in divertor
  - Energy content by NBI power
- **Non-diagonal matrix control between actuators & sensors deduced from open loop experiments**

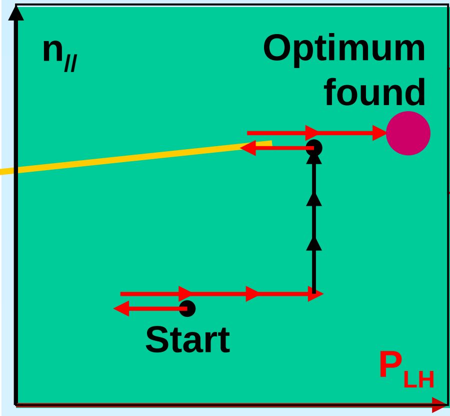
Simultaneous Profile and Heat load control

« Search optimisation » algorithm

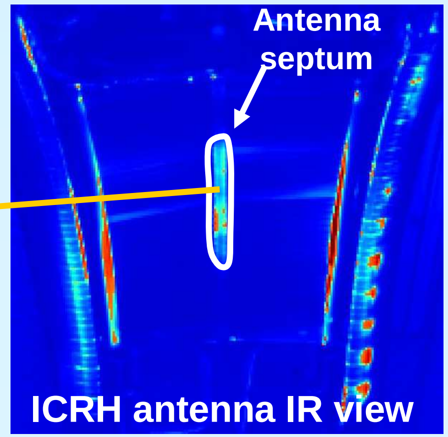


$n_{//}$ and P_{LH} → Current profile

P_{LH} , P_{ICRH} → Surface Temp.



Target: broadest current profile



[Joffrin Nuc Fus 2007, Barana, Fus Eng Des 07]

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CONCLUSION & FUTURE DIRECTION

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- **New & active field of research that needs a wide range of knowledge from plasma physics to control engineering, experiments & modelling**
- **Major & recent experimental progress to tackle real time control issues for steady-state tokamak operation**

Challenging issues for future research direction

- **Integrated modelling towards tokamak simulator ?**
  - Develop generic methods, modelling of RT diagnostics, control loops, plasma physics, tokamak control system etc
- **integration and compatibility of the control schemes ?**
  - integrate control of fusion performance & stability with control of power and particle exhaust during the whole plasma operation
- **demonstration of the controllability of bootstrap-dominated regime with dominant α-heating ?**
  - experiments & modelling