# Real-Time Control of the Current Profile in JET

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**Abstract.** New algorithms using a truncated singular value decomposition of a linearised model
have been implemented in the JET control system. Using three heating and current drive
actuators (LHCD, NBI, ICRH), successful control of the safety factor profile has been achieved
in quasi steady state conditions where the loop voltage was small and a large fraction of the
plasma current was carried by the bootstrap current.

## INTRODUCTION

In order to control the current and pressure profiles in high performance tokamak
plasmas with internal transport barriers (ITB), a multi-variable model-based technique
has been proposed which offers the potentiality of retaining the distributed character
of the current and heat diffusion (distributed-parameter system) [1, 2].

Here, we describe first experiments using the simplest, lumped-parameter, version
of this technique. In section 3 only one actuator (LHCD) is used. In section 4, the first
experiments using a multiple-input-multiple-output controller to control the q-profile
with 3 heating and current drive actuators (LHCD, NBI, and ICRH) are reported.

## TRUNCATED SINGULAR VALUE DECOMPOSITION

Let $\mathbf{Q}(s)$ be the linearized Laplace response around the target equilibrium:

$$\mathbf{Q}(s) = \mathbf{K}(s) . \mathbf{P}(s) \qquad (1)$$

where $\mathbf{Q}$ represents a safety factor difference vector and $\mathbf{P}$ an input power difference
vector. The kernel $\mathbf{K}(s)$ can be identified from power modulation experiments around
the target steady state, or by simulations using a predictive transport code.
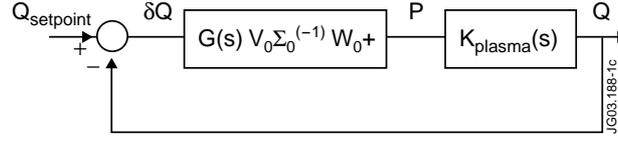
**FIGURE 1.** Control diagram used for the feedback control of the safety factor.

For the experiments described below, the steady state gain matrix $\mathbf{K}(0)$ was sufficient. A singular value decomposition is performed, yielding :
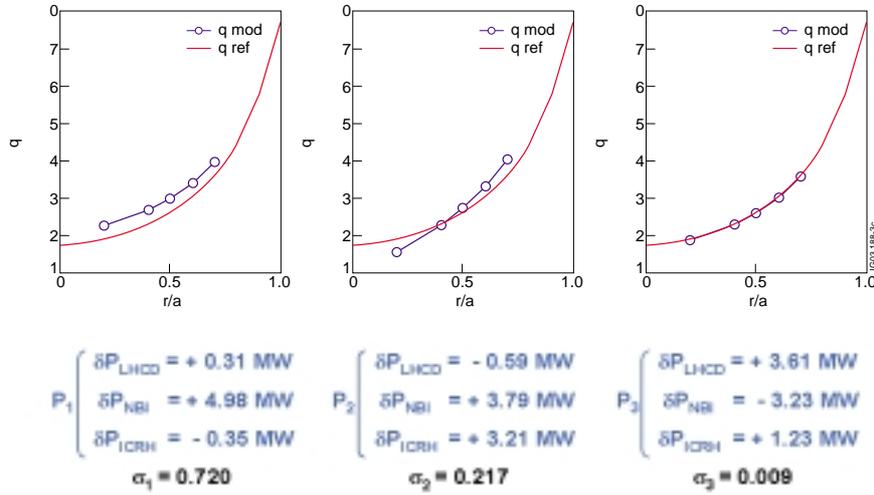
$$\mathbf{K}(s) = \mathbf{W(s)} \; \mathbf{\Sigma(s)} \; \mathbf{V(s)}^+ \tag{2}$$

and this defines decoupled modal inputs and modal outputs :

$$\mathbf{\alpha}(s) = \mathbf{V(s)}+. \; \mathbf{P}(s) \quad \text{and} \quad \mathbf{\beta}(s) = \mathbf{W}(s)+.\mathbf{Q}(s) \tag{3}$$

related by :

$$\mathbf{\beta}(s) = \mathbf{\Sigma}(s) \; . \; \mathbf{\alpha}(s) \tag{4}$$



**FIGURE 2.** Respective influence of the 3 identified singular input vectors on the q-profile when using simultaneously LHCD, NBI and ICRH as actuators. The full profile which appears in all frames corresponds to the reference equilibrium obtained with $P_{LHCD}$ = 3MW, $P_{NBI}$ = 7MW, $P_{ICRH}$ = 3MW, around which the system is linearized. The open circles on the left, central, and right frames show the q-profiles estimated from the model when adding the power combinations $P_1$, $P_2$, and $P_3$, respectively, to the reference case powers. $P_1$, $P_2$, and $P_3$, are proportionnal to the singular vectors, $V_1$, $V_2$, and $V_3$, but normalized to 5MW. $\sigma_1$, $\sigma_2$, and $\sigma_3$ are the corresponding singular values.

Pseudo-modal control techniques can be used by taking the steady state limits, $\mathbf{V}_0$, $\mathbf{\Sigma}_0$, $\mathbf{W}_0$, of $\mathbf{V}(s)$, $\mathbf{\Sigma}(s)$, $\mathbf{W}(s)$, and by inverting the diagonal steady state gain matrix, $\mathbf{\Sigma}_0$, where $[\mathbf{\Sigma}_0]_{i,j} = \sigma_i.\delta_{i,j}$. In order to obtain a simple PI feedback control with minimum (least square) steady state offset, we choose the controller $\mathbf{G}(s)$ as (Fig. 1) :

$$\mathbf{\alpha}(s) = \mathbf{G}(s) \; . \; \mathbf{\beta}(s) = g_c [1 + 1/(\tau_i.s)] \; \mathbf{\Sigma}_0^{(-1)} \; \mathbf{\beta}(s) \tag{5}$$

where $g_c$ is the proportional gain and $(g_c/\tau_i)$ is the integral gain.

The SVD expansion of $\mathbf{K}$ is truncated to retain the most significant singular values. In the example below (Fig. 2), 3 actuators are used (LHCD, NBI, ICRH), but $\sigma_3$ is small which indicates that the family of accessible profiles is only a 2-parameter family spanned by the first two singular vectors, $\mathbf{W}_{0,1}$ and $\mathbf{W}_{0,2}$. We then use the truncated operator with only $\sigma_1$ and $\sigma_2$ : $\mathbf{K}_{0,T} = \sigma_1 \mathbf{W}_{0,1}.\mathbf{V}_{0,1}^+ + \sigma_2 \mathbf{W}_{0,2}.\mathbf{V}_{0,2}^+$.
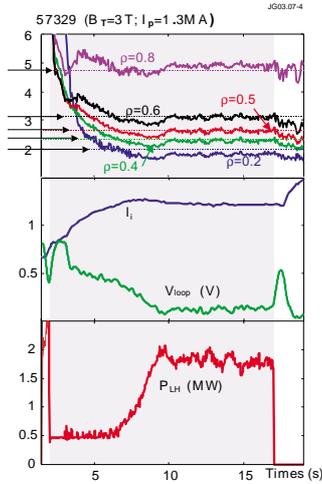
**FIGURE 3a.** Real-time control experiment with LHCD only (pulse #57329, $B_T$ = 3T, $I_p$ = 1.3 MA). Top : Safety factor at r/a = [0.2 0.4 0.5 0.6 0.8]. Centre : Internal inductance parameter, $l_i$, and loop voltage, $V_{loop}$.(Volts). Bottom : LHCD power (MW).
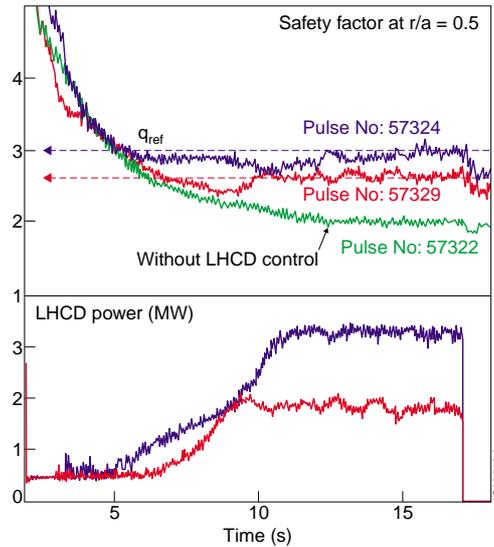
**FIGURE 3b.** Measured and requested q-values at a r/a = 0.5, and LHCD power for 2 controlled pulses (#57329 and #57324 $B_T$=3T, Ip=1.3MA). A pulse without control is shown for comparison (#57322). Control starts at 2s and stops at 17s.

# CONTROL OF THE SAFETY FACTOR PROFILE WITH LHCD

The first, simplest - and in some sense trivial - application of the lumped parameter SVD control scheme was to reach a predefined q-profile with only one actuator, namely LHCD, but 5 q-setpoints. The accessible targets are restricted to a one-parameter family of profiles and must therefore be chosen reasonably. Applying an SVD technique with 5 points, rather than only one, can be an advantage if the q-profile "rotates" when varying the power. It may not allow to reach any one of the setpoints exactly, but minimizes the error on the profile shape (e.g. weak or reversed shear), contrary to a control of $l_i$. Such an experiment was performed during an extended LHCD preheat phase [3], a usual prelude to the formation of ITB's in JET. The central line-integrated density was $2.7 \times 10^{19} m^{-2}$ to allow for efficient LHCD. The toroidal field was 3T and the plasma current was 1.3 MA so as to approach a full non-inductive regime. A linearized model which links the values of q(r) at r/a = 0.2, 0.4, 0.5, 0.6, 0.8 to the input LH power was identified from simple step power changes. The q-profile reconstruction uses the real-time data from the magnetic measurements and from the interfero-polarimetry, and a parameterization of the magnetic flux surface geometry [4, 5]. The output signals are available every 50 ms.

The effectiveness of the controller in achieving, and maintaining in steady state, various q-profiles can be seen on Fig. 3.

# CONTROL OF THE q-PROFILE WITH LHCD, NBI AND ICRH

The second set of experiments conducted so far and using the proposed SVD technique (Fig. 3) was a first attempt at using the 3 available heating and current drive systems to control the q-profile during a strong heating phase, in an ITB scenario with moderate bootstrap current. The toroidal magnetic field was 3T and the scenario started with a reversed shear 2.5 MW LHCD preheat phase during which the plasma current was ramped up to 1.8 MA, at a line-integrated plasma density around $3 \times 10^{19}$ $m^{-2}$. At 4.3 s, 12.5 MW of NBI and 3 MW of ICRH power were applied resulting in the triggering of an ITB and, starting at 7 s, the plasma current was ramped down to a final 2-second-long 1.5 MA plateau. The determination of the steady state responses to variations of the heating and current drive powers was made from the analysis of four dedicated discharges, including the reference discharge around which the system is to be linearized. The result is shown on Fig. 4.
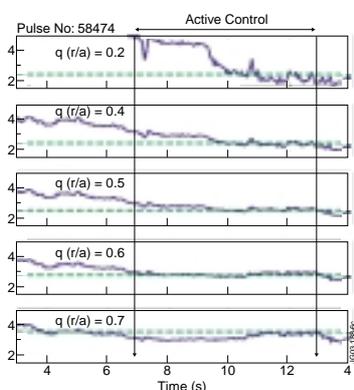


**FIGURE 4a**. Measured and requested time traces of q(r/a) at the 5 radii selected for the control experiment with LHCD, NBI and ICRH (pulse #58474, $B_T$ = 3T, $I_p$ = 1.5 MA).
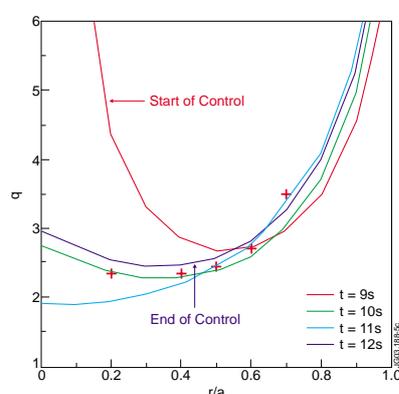
**FIGURE 4b**. Same as in Fig. 4a (pulse #58474, $B_T$ = 3T, $I_p$ = 1.5 MA) : q-profiles at four times between 47 s and 52 s. Pluses represent the 5 setpoints.

## CONCLUSION

A successful control of the safety factor profile was obtained with a lumped-parameter SVD algorithm. This provides an interesting starting basis for a future experimental programme at JET, aiming at the sustainement and control of ITB's (q(r) and $\rho_T^*$ criterion) in fully non-inductive plasmas with a large bootstrap current.

## REFERENCES

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