EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(02)21

D. Mazon, X. Litaudon, D. Moreau, V.Pericoli-Ridolfini, L. Zabeo, F.Crisanti, P. De Vries,
R. Felton, E. Joffrin, A. Murari, M. Riva, G. Tresset and K.D. Zastrow

Active Control of the Current Density Profile in JET

Active Control of the Current Density Profile in JET

D. Mazon[1], X. Litaudon[1], D. Moreau[1], V.Pericoli-Ridolfini[2], L. Zabeo[1], F.Crisanti[2], P. De Vries[3], R. Felton[4], E. Joffrin[1], A. Murari[1], M. Riva[2], G. Tresset[1], K.D. Zastrow[4]
and contributors to the EFDA-JET workprogramme*

[1]Association Euratom-CEA, CEA Cadarache, F-13108, St Paul lez Durance, France
[2]Associazione Euratom-ENEA sulla Fusione, C.R. Frascati, 00044 Frascati, Italy
[3]Associatie EURATOM-FOM, TEC Cluster, 3430 BE Nieuwegein, The Netherlands
[4]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK
[5]Consorzio RFX Associazione ENEA-EURATOM per la Fusione, 4-35127 Padova, Italy
** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Physical Review Letters

ABSTRACT.

A successful demonstration of real-time, model-based control of the current density profile has been made in JET. The safety factor profile was reconstructed using magnetic and polarimetric signals. Various predefined q-profile targets have been reached - in the least square approximation - using Lower Hybrid Current Drive (LHCD) as the only actuator, with a feedback control loop using the measurements from five fixed normalised radii.

INTRODUCTION.

On the way towards an economical steady-state tokamak fusion power plant, the "advanced tokamak" [1] scenario has a large potential for achieving the required steady state plasma performance. This regime relies on a high plasma pressure at low current and on the optimisation of the current profile in controlled stationary conditions, without the need for a very large plasma volume or high toroïdal magnetic field. This leads to conditions where a large fraction of the plasma current is driven by the neoclassical bootstrap mechanism, which in turn results in a relatively modest requirement on the externally driven non inductive current. This requires the generation of a high confinement region in the plasma core, called an 'Internal Transport Barrier' (ITB) [2] which can be combined with an edge barrier known as an H-mode [3]. The exploitation of such regimes is conceivable in a fusion reactor and has stimulated extensive studies on the conditions where improved core plasma confinement is observed.

The successful results of the last JET experimental campaign [4-6] has shown that some key features of the "advanced tokamak" concept can be sustained in quasi steady-state. Quasi-stationary operation has been achieved in high performance discharges with a large bootstrap fraction, and where a well developed ITB was present on both the ion and electron channels,. In those experiments, a simultaneous feedback control of the electron temperature gradient using local quantities characteristic of the ITB strength [7] and of the neutron yield has allowed real-time control of the pre-requested quantities. The actuators were the ion cyclotron resonance heating power (ICRH) and neutral beam injection (NBI), respectively. The LHCD power, used in a pre-programmed way, played a central role first of all during the preheat phase in pre-forming the current density profile but also during the high power heating phase in achieving high performance and freezing during a resistive time the safety factor profile evolution. Indeed, the transport reduction observed in a number of tokamak devices has been associated with localised turbulence suppression, which is related with both magnetic and flow shears. Moreover, the strong correlation between the triggering of an internal transport barrier and the appearance of integer-q-magnetic surfaces at particular locations has also been shown [8, 9]. Active feedback control of the current density profile is thus a key point to trigger in a reproducible manner an ITB and to maintain it quasi-stationary. Up to now, control of the q-profile was performed through feedback control of the internal inductance parameter, li [10]. However li is a global quantity characterizing mainly the current density in the outer plasma layers and its control is not sufficient to maintain an optimum magnetic shear profile in ITB discharges. The only way for an efficient control is to get a real-time reconstruction of the current density profile. Efforts have therefore been made in order to develop an algorithm which provides a measurement of the q-profile in real-time [11, 12] and allows feedback control. The algorithm uses as inputs the signals of the magnetic and of the interferometer-polarimeter diagnostics. The topology of the last closed magnetic surface is determined on the basis of the external magnetic pick-up coils measurements. In order to complete the magnetic topology in the interior of the plasma, a flux surface parameterisation is used [13].

$$\begin{cases} R = R_{axis} + \Delta(\rho) + \rho_{cos}\,(\vartheta + \gamma(\rho)\sin\vartheta) \\ Z = Z_{axis} + rK(r)\sin\vartheta \end{cases}$$

Where r is the radial co-ordinate, R_{axis} and Z_{axis} the co-ordinates of the magnetic axis, $\Delta(\rho)$ the Shafranov shift ($\Delta<0$)), $\gamma(\rho)$ the triangularity and $K(\rho)$ the elongation. A systematic analysis of the results obtained from the equilibrium reconstruction code EFIT [14] has shown that the radial dependences of the plasma shift, elongation and triangularity can be expressed satisfactorily by the following monotonic relations for which the unknown coefficients are determined from the component of the poloïdal field at the edge, measured by the pick up coils and available in real-time:

$$\Delta(\rho) = \left(\frac{\rho}{\rho_{LCMS}}\right)^{\alpha} \Delta_{LCMS}\ ;\ K(\rho) = K_{axis} + a_2\left(\frac{\rho}{\rho_{LCMS}}\right)^{2} + a_4\left(\frac{\rho}{\rho_{LCMS}}\right)^{4}\ ;\ \gamma(\rho) = \gamma_{LCMS}\left(\frac{\rho}{\rho_{LCMS}}\right)^{\beta}$$

Once the magnetic surface geometry has been determined, the line integrated measurements of the interferometer are inverted with SVD techniques using the following parameterisation for the density:

$$n_e(\rho) = n_0\,(1 - \rho^2)\,(1 + p\rho^2 + q\rho^4) + n_w$$

This provides n_0, n_0p, n_0q, the pedestal value nw being scanned in order to minimize in the least square sense the difference between the experimental measurements and the calculated one. The method is similar for the determination of the poloïdal field through the polarimetric data which is taken along the same line of sight as the interferometer data [11]. The inversion procedure of these integral measurements provides the poloïdal field value on the determined magnetic surfaces and therefore allows the calculation of the safety factor profile q, since the toroïdal field is known. Comparison between the central density obtained from the previous algorithm and the LIDAR Thomson scattering diagnostic shows a fair agreement (Fig. 1). The same conclusion is reached for the safety factor profile obtained in real-time (each 25ms) compared to that obtained by EFIT constrained with polarimetry data (Fig.2).

Due to the strong non-linear couplings between pressure and current density profiles and to the multiple time scales involved in the transport processes, advanced feedback schemes have been developed to control high-β, high-bootstrap-fraction, ITB discharges and maintain the plasma in steady state, away from MHD limits. Schemes for tailoring the current profile had been examined earlier for ITER-FDR advanced scenarii [15], pointing out some of the main issues of the problem. These algorithms were based on decoupled loops controlling the scalar values of q(r) and Ψ(r) at two radii with devoted actuators. In order to come up with a more advanced control of the plasma profiles, a new approach, based on the identification of a linearized model of the plasma considered as a distributed- parameter system has been developed [16]. Using this method, more information on the spatial structure of the system can be taken into account and the non-local interaction between various quantities can be retained. Thus, a linearized Laplace transform model of the form $\mathbf{Q}(s) = \mathbf{K}(s)\ \mathbf{P}(s)$, where $\mathbf{Q}$ represents a safety factor difference vector and $\mathbf{P}$ an input power difference vector, is assumed around the target plasma steady state. The kernel K(s) can in principle be identified from small amplitude power modulation experiments around the target steady state, or by simulating such experiments using a predictive transport code. Then a truncated singular value decomposition (TSVD) of the steady state gain matrix, $\mathbf{K}(0)$, is performed yielding $\mathbf{K}(0) = \mathbf{W}\ \Sigma\ \mathbf{V}^{+}$ (with $\mathbf{V}^{+}$ the transpose matrix of $\mathbf{V}$) and this provides steady state decoupling between modal inputs $\alpha(s) = \mathbf{V}^{+}\ \mathbf{P(s)}$, and modal outputs $\beta(s) = \mathbf{W}^{+}\ \mathbf{Q}(s)$. Pseudo-modal control techniques can therefore be used by inverting the diagonal steady state gain matrix, Σ. In order to obtain a simple proportional-plus-integral feedback control with minimum (least square) steady state offset, we chose the controller transfer function matrix $\mathbf{G}(s)$ as follows

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

where gc is the proportional gain and (g_c/τ_i) is the integral gain. At the starting time of the control the operational point has been set to 2.5MW, a value which allows to stay within the accessible LHCD power capabilities. The most simple and direct application - as a “proof of principle” - of the general control scheme described above was to reach a predefined q-profile target in conditions where all other plasma parameters are maintained constant. The experiment was thus performed during an extended LHCD preheat phase and could be followed in a long-pulse machine by the application of the main neutral beam heating power for ITB triggering once the desired optimised q-profile target has been obtained, and then by a steady state high performance phase. The central line-integrated density was maintained constant at $2.7\times10^{19}\ m^{-2}$ during the whole pulse, a relatively low density which allows efficient LHCD. The toroïdal field was 3T and in order to be close to a non-inductive steady state regime and thus have a larger flexibility for obtaining non-ohmic reduced-shear q-profiles, the plasma current was chosen to be 1.3MA. A linearized model which links the values of q(r) at five fixed normalised radii (r/a = 0.2, 0.4, 0.5, 0.6, 0.8, with a the minor radius of the plasma and r the radial coordinate) to the input LH power was seeked and identified from simple step power changes during dedicated open loop experiments (one without LHCD and the other one with a constant LHCD power of 3.3MW). As only one actuator (LH power) is used, the steady state gain matrix **K**(0) is a [5x1] matrix. Thus, in the TSVD process we retain only the first left singular (5x1) vector, **W**, corresponding to the non-zero singular value, and Σ and **V** are scalars. The integral gain was chosen equal to unity and the proportional one equal to 0.5. The global result is shown in Fig.3 in a case with a monotonic reference target q-profile. The time traces of the measured and requested q-values as well as the LHCD power waveform, internal inductance and loop voltage are presented. We can see that the targets are reached and maintained during more than 7s in a non-inductive manner, the controller minimizing in the least square sense the difference between the 5 target q-values and the corresponding real-time measurements. Modelling of current diffusion using the CRONOS code [17] indicate that the stationnarity was reached (the resistive time is around 4s). The monotonic reference target has then been changed. A comparison between the time traces of the measured q-values at half normalised radius of 2 pulses with different targets, see Fig.4, shows the usefulness of the controller. The targets are reached and the respective LHCD power waveform behave differently, staying within the allowed limits. A comparison with a pulse in similar experimental conditions but without feedback control shows the efficiency of the LHCD control in preventing the monotonic relaxation of the q-profile towards a peaked ohmic profile.

Feedback control has also be performed successfully in the case of a reversed-q target (Fig.5). For that occasion, a new transfer function has been identified from 2 discharges with open loop LHCD, one with a constant power of 3.2MW and the other one with a constant power of 2MW leading respectively to a reversed and flat q-profile. In conclusion, using magnetic measurements together with data from the interferometer-polarimeter diagnostic has allowed to reconstruct the magnetic equilibrium in real-time in JET. This reconstruction has been extensively validated by comparing the results with those from the EFIT Grad-Shafranov solver. Then, a first successful demonstration of current profile control with various targets from monotonic to reversed q-profiles has been achieved during a low density phase using LHCD as the only actuator. These experiments open up the route to the real-time control of the q-profile in the presence of an ITB, at higher density and with a large bootstrap current component. Then, using the combined heating and current drive systems available on JET, the model-based algorithms described above can be generalized to the simultaneous control of both the pressure and current profiles in the aim of extending the duration of high performance ITB plasmas towards steady state operation.

REFERENCES

[1]. T.S.Taylor et al., Plasma. Phys. Control. Fusion, **39**, B47 (1997)

[2]. F.M Levinton et al., Phys.Rev. Lett. **75**, 4417 (1995).

[3]. F.Wagner et al., Phys.Rev. Lett. **49**, 1408 (1982).

[4]. D.Mazon et al., Plasma. Phys. Control. Fusion, **44**, 1087 (2002)..

[5]. F.Crisanti et al., Phys.Rev. Lett. **88**, 145004 (2002).

[6]. X. Litaudon et al., Plasma. Phys. Control. Fusion, **44**, 1057 (2002).

[7]. G. Tresset et al., Nucl. Fusion **42**, 520 (2002).
[8]. C.D. Challis et al Plasma. Phys. Control. Fusion, **43**, 861 (2001).
[9]. E. Joffrin, et al., Plasma. Phys. Control. Fusion, **44**, 1739-1752 (2002).
[10]. T.Wijnands et al., Nucl. Fusion **37**, 777 (1997).
[11]. L.Zabeo et al., Plasma. Phys. Control. Fusion, **44**, 2483-2494 (2002).
[12]. M. Riva et al., Proc. 22th Symp on Fusion Techn. (SOFT) (Helsinki, Finland) (2002).
[13]. J.P Christiansen et al., Journal of computational Physics **73**, 85 (1987).
[14]. L. Lao et al., Nucl. Fusion **30**, 1035 (1990).
[15]. D. Moreau, I. Voitsekhovitch, Nucl. Fusion **39**, 685 (1999).
[16]. D. Moreau et al, Proc. of the 3 nd IAEA TCM on Steady State Operation of Magnetic Fusion Devices, May 2002 ; to be published in Nucl. Fusion.
[17]. V. Basiuk et al., Nucl. Fusion (2002) to appear.

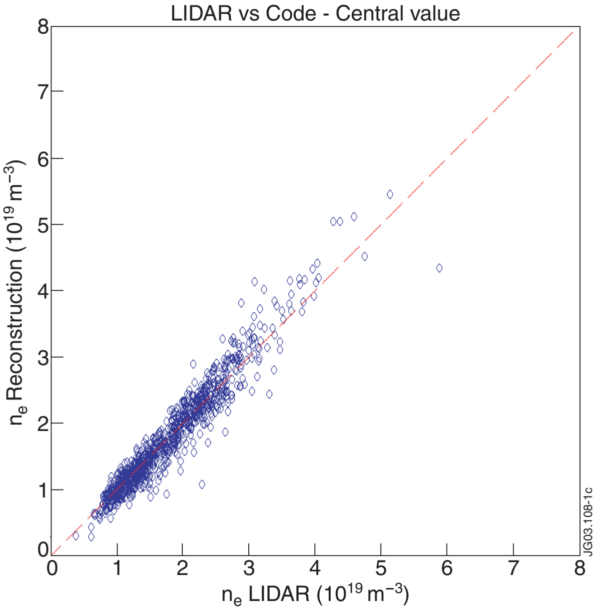

Figure 1: Comparison of the Thomson Scattering (LIDAR) central density value with the one obtained by the inversion technique.

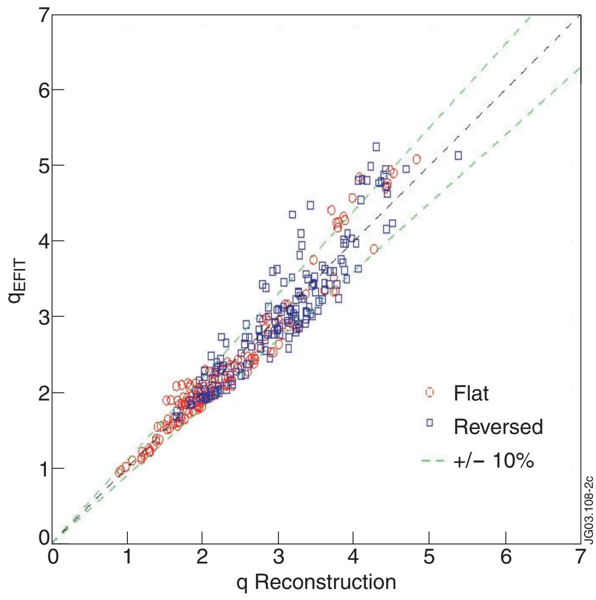

Figure 2: Comparison between the real-time safety factor and the one obtained from EFIT + polarimetry.

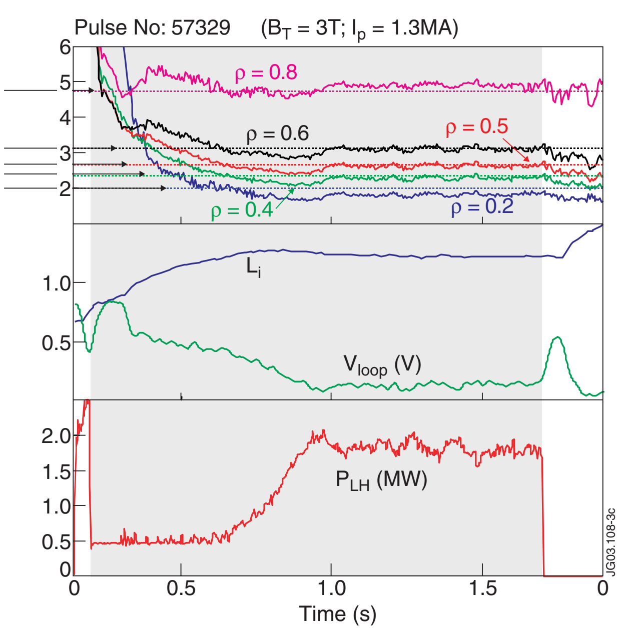

Figure 3: Time evolution of the LHCD power waveform and of the measured and requested q values at 5 radii for a controlled pulse (Pulse No: 57329 B_T=3T, I_p=1.3MA). Dashed lines are the pre-set reference q values. Control starts at 2s and stops at 17s.

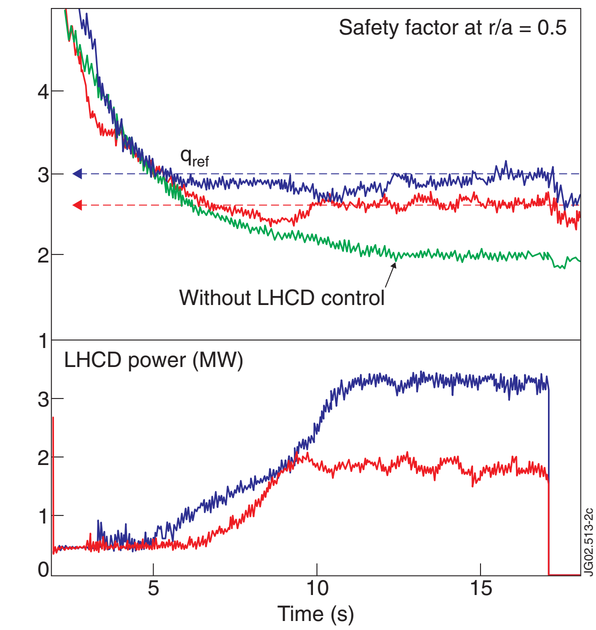

Figure 4: Time evolution of the LHCD power waveform and of the measured and requested q-values at a normalised radius of 0.5 for 2 controlled pulses (Pulse No: 57329 and Pulse No: 57324 B_T=3T, I_p=1.3MA). A pulse without feedback control is presented for comparison (Pulse No: 57322 B_T=3T, I_p=1.3MA). Control starts at 2s and stops at 17s.

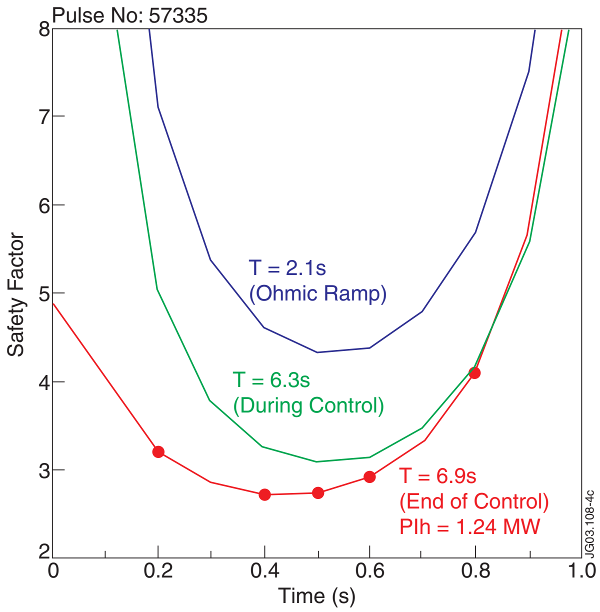

Figure 5: Real-time control of the q-profile (5 values at 5 radii) in a reversed shear case using model-based control with LHCD as actuator (Pulse No: 57335, B_T=3T, I_p=1.3MA). The reference target represented with red circles is reached at t=13s. Control starts at 4s and stops at 17s.