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ABSTRACT

JET discharges have plasma currents up to 6MA and Toroidal Fields up to 4T. The plasma parameters during discharges are determined by the action of a number of distinct systems. These systems can be divided into 3 groups; the Toroidal and Poloidal Field systems, the Fuelling Systems and the Additional Heating systems. The systems can either be programmed to follow pre-determined waveforms or they can be feedback controlled to achieve certain values of specific plasma parameters, as measured with JET diagnostics. This paper reviews the feedback control of plasma parameters using the three main digital control systems; the Plasma Position and Current Control system, the Density Feedback System and the Real Time Central Control system. It is planned to integrate these systems using the new ATM technology in the Real Time Data Network

1. INTRODUCTION

In order to achieve maximum performance and to carry out specific experiments in the JET tokamak it is essential to control a number of plasma parameters in real-time during discharges. This can be done by acting on the plasma with the appropriate actuators in a closed loop to achieve the required values of the plasma parameters, as given by diagnostic measurements. The main control systems used to perform this function at JET are (Fig. 1):

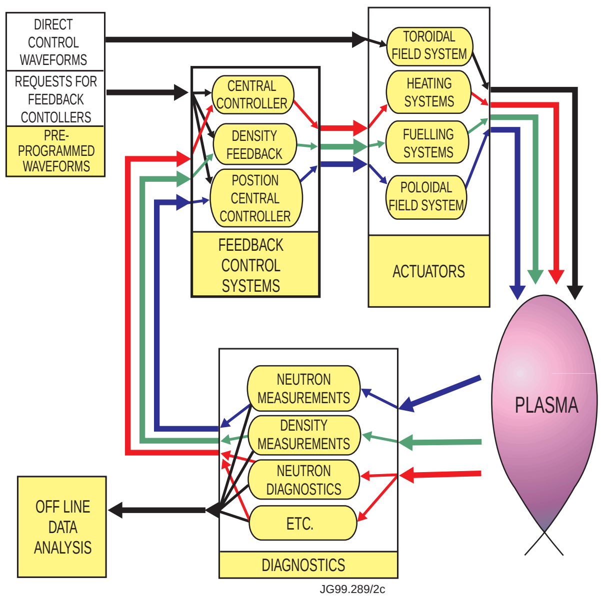

Fig.1 Overview of Plasma Feedback Control Systems at JET.

- The **Plasma Position and Current Control (PPCC)** system : Control of Poloidal Field (PF) coils currents, plasma current and shape using the PF amplifiers. PPCC consists of two independent systems: the Shape Controller (SC) and the Vertical Stabilisation system (VS).

- The **Plasma Density Feedback (PDF)** system: Control of plasma density using the Gas Introduction and/or the pellet Injection system. A secondary loop may be used to control a variety of other plasma properties, e.g. radiated power.
- The **Real Time Central Controller (RTCC)** system : A flexible system, receiving real-time data from a wide range of diagnostics, for feedback control of various plasma parameters using additional heating, Gas Introduction and/or the Pellet Injector.

2. THE ACTUATORS.

2.1. The Magnetic Field Systems

The **Toroidal Field (TF)** system consists of 32 coils, each with 24 turns. The current in the TF coils is limited to 75 kA, giving a maximum field of 4T at the centre of the vacuum vessel. Due to its slow response, the TF system is not used for any feedback control at present.

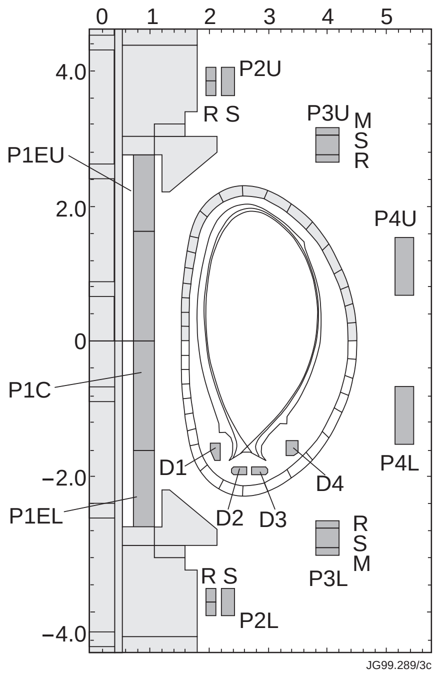

Fig.2 Poloidal Field Coil positions relative to the JET vacuum Vessel. Divertor Coils are inside the vessel.

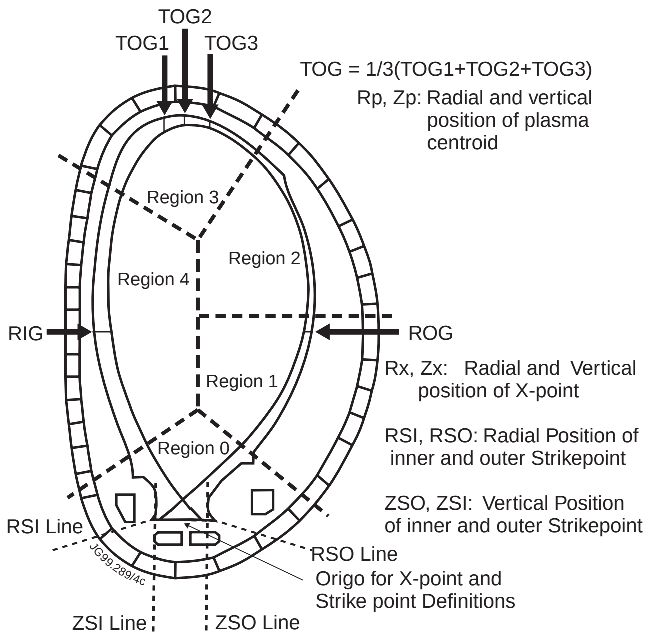

Fig.3 XLOC Regions and Plasma Position Parameters that can be controlled with the PPCC system.

The **Poloidal Field (PF)** system consists of 11 coils (Fig.2), some of which are split into independently powered sections. Table 1 shows the 10 independent amplifiers feeding the coils and the associated controllable plasma parameters as defined in Fig.3. The Fast Radial Field Amplifier (FRFA) applies voltage to the radial field coils according to a hysteresis characteristic in discrete steps of 2.5kV from -10kV to +10kV. The remaining amplifiers except the Flywheel Generator, are linear voltage amplifiers, with current and voltage limits. The PF amplifiers are controlled by PPCC.

Table 1: PF Amplifiers and associated controllable plasma parameters (Fig 3)

Amplifier	Coils	Max. Current	Plasma Parameter
Flywheel	P1E,P1C,P3M	40kA	Ip
PFX	P1C - P1E	35kA	RIG
PVFA 3+4	P4U + P4L	40kA	ROG, RIG, Rp
PVFA 3-4	P4U - P4L	±15kA	TOG, Zp
PSFA	P2S,P3S	40kA	
PDFA 1,2,3,4	D1,D2,D3,D4	40kA	Rx and Zx, RSI and RSO, ZSI and ZSO
FRFA	P2UM-P2LM+ P3UM-P3UL	2.5kA	Vertical Stability

2.2. The Fuelling Systems

The **Gas Introduction** system consists of 11 gas introduction modules (GIMs) capable of injecting a range of different gasses into to the torus at different locations, e.g. divertor region, midplane and top of the machine. One GIM is reserved for tritium injection. A gas matrix system allows connection of any gas to any module without manual intervention. The GIMs can be pre-programmed, or controlled from either PDF or RTCC.

The **Pellet Injection Centrifuge**, injects 4mm cubic pellets into the torus at speeds up to 500m/s and at frequencies up to10s^{-1}. Up to now, pellets have been injected at the midplane on the low field side, but a newly installed guide tube will allow inboard pellet launch. The fuelling from the pellet injector can be pre-programmed or controlled by PDF or RTCC.

2.3 The Heating Systems

The **Neutral Beam Injection (NBI)** system consists of 2 separate boxes each with 8 Positive Ion Neutral Injectors (PINI), capable of delivering ~ 20 MW of power in D° at, respectively, 80 and 140 keV. In addition, the NB sources can operate in Hydrogen, Helium and Tritium.

The **Ion Cyclotron Radio Frequency (ICRF)** heating system can couple up to 15 - 20MW in the frequency range 23-57 MHz. The phase of the current in the 4 straps in each of 4 antennas can be varied to launch the appropriate wave spectrum. The antennas are fed by 16 2MW tetrodes. The coupled power depends strongly on the operating frequency, the plasma configuration and confinement.

The **Lower Hybrid Current Drive (LHCD)** system can couple up to 8MW of 3.7GHz microwave power to the plasma, via a waveguide array antenna with 12x32 separate waveguides. The antenna is powered by 24 500kW klystrons. The N// spectrum of the wave coupled to the plasma can be varied from 1.4 to 2.3. The antenna can be moved radially in real time at up to 5Hz to maximising the coupled power.

The powers from the 3 heating systems and the phase from the ICRH and LHCD systems are controlled by 3 local managers NBLM, RFLM and LHLM. Given that a PINI is either on or off, the NBI power varies in steps of ~ 1-1.5 MW and when values between achievable steps are required, NBLM modulates one PINI to obtain the correct average power. The local managers are VME based systems using 2-5 68k processors each. The power from the heating systems can be pre-programmed or controlled from RTCC via the local managers.

3. THE DIAGNOSTICS

3.1. The Magnetic Diagnostic System

Magnetic sensors inside and outside the JET vacuum vessel measure poloidal field tangential and perpendicular to the vacuum vessel at several toroidal locations. In addition full flux loops, measures the toroidal loop voltage at 8 poloidal locations near the vacuum vessel. The sensors measure the derivative of the magnetic fields. Analogue integrators are used to find the actual fields. Compensations, corrections and further calculations, deriving plasma current, vertical and radial moments etc. are carried out by a digital system using 8 C40 processors.

3.2. Plasma Boundary Determination

The **XLOC** algorithm determines the plasma boundary location in real time. In each of 5 regions a 6th order Taylor expansion is used to approximate the flux. The Taylor coefficients are those that make the expansion best fit the measured fields. The expansion is constrained by the requirement of continuous magnetic field across region boundaries and by the Grad-Shafranov equation. Knowing the flux, the plasma configuration (X-point or limiter) is determined and the position of the X-point, together with the plasma-first wall distances at a number of points are computed. The plasma position parameters (GAPs) available for control are defined in Fig 3. As XLOC does not take any plasma current into account, it only determines the flux exterior to the Last Closed Flux Surface.

3.3. Density Diagnostics

The line integrated electron density is measured at JET by **Far Infrared Interferometry** along 4 vertical and 4 horizontal sightlines. A less accurate estimate of the density is also obtained from **Visible Bremsstrahlung** measurements.

3.4. Other Diagnostics Providing Signals to the control Systems

Electron Temperature, Neutron Emission, Diamagnetic plasma Stored thermal transverse Energy, total and local Radiated Power, Poloidal Beta $\beta_{p,}$ and Internal Inductance l_i are among the large number of measured and derived quantities available in real time through the Real Time Signal Server (RTSS)

4. CONTROLLERS

4.1. Plasma Position and Current Control System (PPCC) (M. Garribba et.al.[1])

VERTICAL STABILISATION SYSTEM (VS) (M. Lennholm et.al.[2])

JET plasmas are vertically unstable with growth rates (γ) up to $700s^{-1}$. The main reason for the instability is the quadrupolar poloidal field used to achieve elongated plasmas, with higher elongation resulting in larger γ. The VS system uses magnetic Pickup Coil and Saddle Loop signals to estimate the Vertical Velocity Moment ($v_p I_p$) of the Plasma Centroid. FRFA voltage is applied to the radial field coils to bring $v_p I_p$ to zero. The equations governing $v_p I_p$ and the current in the radial field coils I_{FRFA} in response to application of FRFA voltage (V_{FRFA}) can be written in Laplace notation as:

$$\begin{aligned} v_p I_p(s) &= \frac{-(c_1 + c_2\gamma)s}{(s+\tau)(s-\gamma)} V_{FRFA}(s) \\ I_{FRFA}(s) &= \frac{c_3(s-\alpha)}{(s+\tau)(s-\gamma)} V_{FRFA}(s) \end{aligned} \qquad (1)$$

where τ is the time constant for the Radial Field Coils, c_1, c_2 and c_3 are constants and $\alpha \cong \gamma$. To achieve: $V_p I_p$~0 and I_{FRFA}~0, the control voltage for FRFA V^c_{FRFA} is computed by VS as:

$$V^c_{FRFA} = -G_V \cdot v_p I_p + G_I \cdot \left[I_{FRFA} + k \int I_{FRFA} \right]; \; k\text{=constant} \qquad (2)$$

While VS controls the vertical velocity of the plasma, SC controls the vertical position. Due to the hysteresis characteristic of FRFA V_{FRFA} switches in a limit cycle rather than following V^c_{FRFA} linearly. The optimal choice of G_v and G_I depends on γ, which varies significantly, and often unpredictably during pulses. G_I and G_v are controlled during discharges by an adaptive control algorithm based on the following: a) The frequency with which the FRFA amplifier switches f_{sw} is proportional to $G_v \cdot \gamma$; b) The most robust behaviour of the system is achieved when f_{sw} is in a narrow band independent of γ; c) The best value of G_I/G_v is approximately constant. The adaptive controller adjusts G_v keeping G_I/G_v constant in order to make f_{sw} follow a pre-programmed reference f^{ref}_{sw}:

$$G_v = G^{FF}_v + G_A(f^{ref}_{sw} - f_{sw}); \;\; G_I = k_I \cdot G_v, \; k_I\text{=constant} \qquad (3)$$

where G^{FF}_v is a pre-programmed feed-forward waveform. Fig 4. Shows an example of the working of the adaptive controller: f_{sw} follows f^{ref}_{sw} well while G_v varies within certain imposed limits. When the limits are reached f_{sw} starts deviating from f^{ref}_{sw}. VS has a sampling time of 50-100µs. It is a VME based system using 4 C40 DSPs and 6 four channel 20kHz ADC cards linked directly to COM ports on the C40s. The delay in the closed loop is ~400µs mostly due to delay in FRFA.

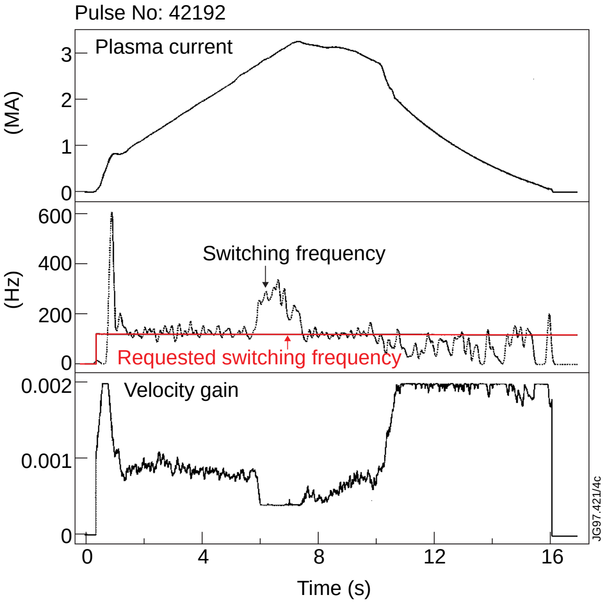

Fig.4 Vertical Stabilisation Adaptive Control: The Gain G_v in the VS controller is adapted in response to growth-rate variations in order to keep the FRFA switching frequency at the desired level.

SHAPE CONTROL SYSTEM ([3] S.Puppin et.al. [4] F.Sartori. et.al)

The Shape Controller(SC) is responsible for achieving the desired plasma current, shape and position. Using XLOC it computes the position of the last closed flux surface from magnetic measurements. For each of the 6 first rows in table 1, SC can control either the amplifier current(s) or one of the (sets of) plasma parameters. The 11 controllable plasma parameters (GAPs) $\overline{\mathbf{X}}$ are a non-linear function of the PF coil currents $\overline{\mathbf{I_C}}$. The coil currents and the plasma current $\mathbf{I_p}$ are further linked through the matrix of mutual inductances. Linearising and assuming that the plasma resistivity is zero, the following equations expressing all the control parameters in terms of the PF coil currents can be written:

$$\begin{pmatrix} \Delta\overline{\mathbf{X}} \\ \mathbf{I_p} \\ \overline{\mathbf{I_C}} \end{pmatrix} = \begin{pmatrix} \overline{\overline{\mathbf{B}}} \\ \overline{\overline{\mathbf{M_p}}} \\ \overline{\overline{1}} \end{pmatrix} \cdot \overline{\mathbf{I_C}} \tag{4}$$

Where $\overline{\overline{\mathbf{B}}}$is a 9x11 matrix, $\overline{\overline{\mathbf{M_p}}}$ is a 9x1 matrix and $\overline{\overline{1}}$ is the 9x9 unitary matrix. The coil currents are determined from the amplifier voltages $\overline{\mathbf{V_A}}$ through

$$\overline{\overline{\mathbf{M_r}}} \cdot \frac{d}{dt}\overline{\mathbf{I_C}} + \overline{\overline{\mathbf{R_C}}} \cdot \overline{\mathbf{I_C}} = \overline{\mathbf{V_A}} \tag{5}$$

where $\overline{\overline{\mathbf{M_r}}}$ is the reduced mutual inductance matrix for the coils, derived by eliminating the plasma current from the full 10x10 matrix using the assumption of 0 plasma resistivity and $\overline{\overline{\mathbf{R_C}}}$ is a 9x9 diagonal matrix containing the coil resistances.

The control algorithm employed is a de-coupling control algorithm. It calculates the voltage requests $\overline{\mathbf{V_c}}$ for the amplifiers from the measured and reference values of the controlled parameters ($\overline{\mathbf{Y}}$ and $\overline{\mathbf{Y_{ref}}}$). Taking only the rows corresponding the 9 parameters selected for control from (4) and defining the Transition Matrix $\overline{\overline{\mathbf{T}}}$ (4) becomes: $\overline{\mathbf{Y}} = \overline{\overline{\mathbf{T}}} \cdot \overline{\mathbf{I_C}}$. Using (5) this gives:

$$\frac{d}{dt}\overline{\mathbf{Y}} = \overline{\overline{\mathbf{T}}} \cdot \frac{d}{dt}\overline{\mathbf{I_C}} = \overline{\overline{\mathbf{T}}} \cdot \overline{\overline{\mathbf{M_r}}}^{-1}\left(\overline{\mathbf{V_A}} - \overline{\overline{\mathbf{R_C}}} \cdot \overline{\mathbf{I_C}}\right) \tag{6}$$

Defining the controller action as:

$$\overline{\mathbf{V_c}} = \overline{\overline{\mathbf{R_C}}} \cdot \overline{\mathbf{I_C}} + \overline{\overline{\mathbf{C}}} \cdot \overline{\overline{\mathbf{M_r}}} \cdot \overline{\overline{\mathbf{T}}}^{-1}\left(\overline{\mathbf{Y_{ref}}} - \overline{\mathbf{Y}}\right) \tag{7}$$

where $\overline{\overline{\mathbf{C}}}$ is a diagonal matrix, the closed loop equation becomes:

$$\frac{d}{dt}\overline{\mathbf{Y}} = \overline{\overline{\mathbf{C}}} \cdot \left(\overline{\mathbf{Y_{ref}}} - \overline{\mathbf{Y}}\right) \tag{8}$$

This represent 9 independent loops with 9 time constants defined by the values in $\overline{\overline{\mathbf{C}}}$. Fig. 5 shows the Control Algorithm including a Feed-Forward term.

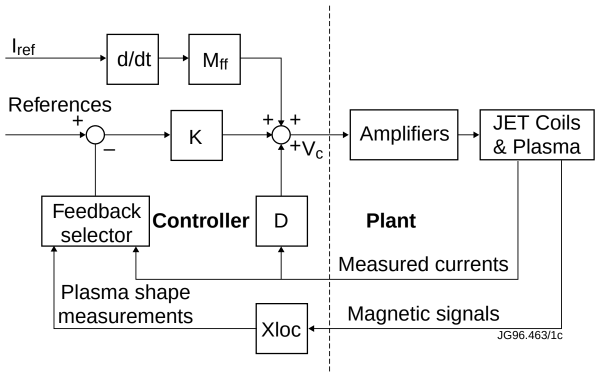

Fig.5 Shape Controller Block Diagram: Showing the Control Matrix $\boldsymbol{K} = \overline{\overline{\mathbf{C}}} \cdot \overline{\overline{\mathbf{M_r}}}$*, The resistive compesation matrix* $\boldsymbol{D} = \overline{\overline{\mathbf{R_C}}}$ *and the Feed Forward Matrix* $\boldsymbol{M_{FF}}$.

In certain cases the desired parameters cannot be controlled - when limits are reached, or when the plasma is touching the first wall. In these cases SC automatically switches to controlling a different set of parameters. SC shuts down the plasma in a controlled manner in response to certain external or internal triggers eg. disruption precursors. SC has a sampling time of 2ms. It is a VME based system using 5 C40 DSPs.

4.2. Plasma Density Feedback (M.Gadeberg et.al[5])

The plasma density feedback system comprises 2 separate control loops. The Primary Density Feedback loop controls the main plasma density as measured by either interferometry or bremsstrahlung, while the secondary loop can be used to control a range of parameters. Both loops use the GIMs and/or the Pellet centrifuge as actuators. The effect on the plasma density of opening a GIM depends on the pressure in the GIM, the length of pipe from the GIM to the injection point in the torus, the location of the injection point, the plasma configuration etc. The time constants involved are of the order 0.1-0.5s. The Control algorithm used by both loops can be a simple PID controller with feed forward:

$$V_{GIM}(s) = K_c\left(1+\frac{1}{s\cdot T_I}\right)\left(\frac{1+s\cdot T_D}{1+s\cdot\frac{T_D}{\alpha}}\right)\left(n_{ref}(s)-n_{meas}(s)\right)+V_{FF}(s) \tag{9}$$

where V_{GIM} is the percentage opening of the relevant GIMs, T_I and T_D are the integral and derivative time constants respectively, and α the derivative range. n_{ref} and n_{meas} are the reference and measured densities respectively and V_{FF} is a pre-programmed feed-forward waveform. For the primary loop an adaptive controller is available as an alternative (H.E.O Brelen, et.al.[6]). The adaptive controller works by measuring the plant transfer function and adapting its own control function in real time with the aim of achieving optimal performance. The adaptive controller offers tighter control of the density as long as the plasma parameters evolves sufficiently slowly. PDF is a VME system using a 33MHz 68040 processor. The sampling time is 100ms.

4.3. Real Time Central Controller (Q.A.King, H.Brelen[7])

The Real Time Central Controller(RTCC) is a user programmable flexible system which can control a large number of plasma properties, by using the Additional Heating and Fuelling systems as actuators. The best way to illustrate the capability of this system is through an example:

CONTROL OF NEUTRON YIELD: In so-called "optimised shear" discharges, an "internal transport barrier" forms when additional heating power is applied during the current ramp up phase. With the internal transport barrier present the confinement time is significantly improved, leading to high neutron production.

Achieving and maintaining this improved confinement requires: a) That the additional heating is applied when the plasma current profile, which is developing continuously has reached a specific shape. b) That sufficient additional heating power is applied to maintain good confinement, c)That the additional heating power does not exceed the MHD instability threshold.

To fulfil these requirements the RTCC system has been used. Real time estimation of the q value at the centre of the plasma is used to trigger the switching on of the additional heating. After this, part of the neutral beam heating power P_{NBIC} is controlled in a closed loop to make the measured neutron yield N_{meas} follow the reference N_{ref} up to a predefined maximum level, which is maintained as long as possible. The remaining NBI and ICRH powers are pre-programmed. As the neutron yield is approximately proportional to the square of the additional heating power the following control equation is used:

$$P_{NBIC} = K \cdot \left(\sqrt{N_{ref}} - \sqrt{N_{meas}}\right) + P_{FF} \tag{10}$$

where K is a constant and P_{FF} is a feed-forward term. Fig. 6 shows the resulting control behaviour. The reference is followed well until an ELM terminates the high performance at 5.48s.

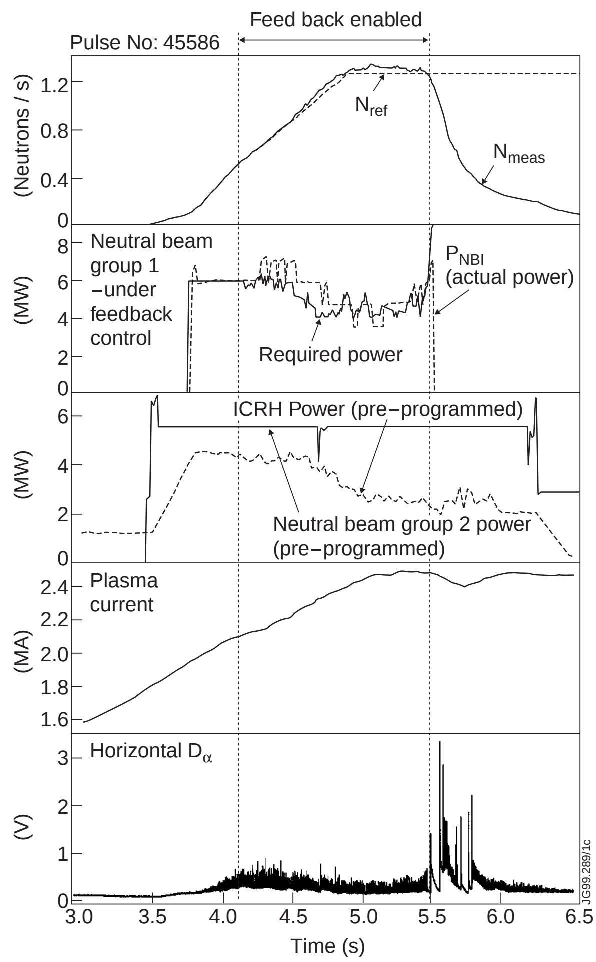

Fig.6 Neutron Yield Control: The Measured Neutron Yield is made to follow the Reference by varying the NBI power. The High Performance phase is terminated by an ELM, and the feedback control is discontinued.

Other control schemes have been implemented using RTCC (N.Zornig, et al.[8]). Among these the following are worth mentioning: Control of the radiated power from the divertor using impurity injection, Control of the internal inductance using Lower Hybrid Current Drive, Control of the plasma stored energy using Neutral Beam Injection and plasma burn simulation using Ion Cyclotron Resonance Heating. In addition the system is routinely used to reduce the neutron production by switching off the additional heating, if a pulse is deemed not to be performing sufficiently well. RTCC is a VME system using 2 68k processors. The sampling time is 10ms.

5. COMMUNICATION

As the many systems used for plasma control are spread over a large area on the JET site, real time communication of diagnostic signals, control signals etc. is needed. At present a host of different technologies are used: Analogue electrical and optical signals, TAXI-links, Transputer-links, Reflective Memory and Private ETHERNET. A project is ongoing to rationalise the communication using ATM (Asynchronous Transfer Mode) technology to build a new Real Time Data Network (RTDN) (R. Felton et.al. [9]). ATM was chosen because: a) It provides sufficient speed for all but the most demanding applications (PPCC-VS); b) Private bandwidth can be allocated for each signal path through the network. This assures that essential systems cannot be compromised by non-essential network traffic. c) Data can be "multicast" from one system to several other systems, making real time data widely available. The heart of the ATM network is a central switch which routes the signal from sender to receiver. It has 16 155 Mbps ports and 2.5 Gbps switch fabric. The end to end latency is <250μs. For our existing 68k and C40 systems a Power PC with an ATM interface card provides the link to the network. At present RTDN transmits data from PPCC-SC and RTSS to several other systems including a real time display. The majority of JET's real time systems will be connected to the network over the coming years.

The development of the ATM network, will enable better integration of the different control systems. The main new possibility that it brings is the linking of the PPCC-SC system with the other control systems. This will enable the development of algorithms that uses the Poloidal Field Coils to control new parameters, such as l_i and q. The link with PPCC will also make it possible to de-couple the PPCC control from the additional heating and density control. This would clearly be beneficial in improving the Plasma Current control. The loop gain in the plasma current control loop changes dramatically when significant heating is applied. If PPCC had the information of the application of the heating, or better of the plasma temperature a better control could be achieved.

With the ATM network in place all the main actuators will be available to a central control system, together with a vast range of diagnostic signals. As is already the case for the RTCC system the number of different control schemes that can be envisaged is only limited by our own imagination. Any plasma parameter that can be measured in real time, and which is influenced in a deterministic way by our actuators, can potentially be controlled in closed loop.

6. CONCLUSION

Feedback Control of the main JET plasma parameters - Plasma Current, Shape, Position and Density is carried out by the PPCC and PDF systems. These systems offer good flexibility in planning and executing JET experiments. A vast array of other Plasma Parameters can be controlled using the RTCC system to control heating and fuelling systems. With the introduction of the ATM network more systems become available for the RTCC system, while de-coupling of the various existing control systems become feasible.

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NOMENCLATURE

D°	Deuterium
N//	Parallel Wave Index
βp	Poloidal Beta
l_i	Internal Inductance
γ	Plasma Growth Rate
$(v_p I_p)$	Vertical Velocity Moment =Plasma Vertical Velocity multiplied by Plasma Current
I_{FRFA}	Fast Radial Field Amplifier Current
V_{FRFA}	Fast Radial Field Amplifier Voltage
s	Variable in Laplace Domain
τ	time constant for the Radial Field coils
c_1	constant
c_2	constant
c_3	constant
$\alpha \cong \gamma.$	
V_{FRFA}^c	control voltage for FRFA
G_v	Velocity Gain in Vertical Stabilisation
G_I	Current Gain in Vertical Stabilisation
f_{sw}	FRFA switching Frequency
f_{sw}^{ref}	FRFA Switching Frequency reference
G_v^{FF}	feed-forward waveform
G_A	Adaptive Gain Controller
k_I	Current/Velocity Gain Ratio
$\overline{\mathbf{X}}$	Vector of Controllable Plasma Parameters
$\overline{\mathbf{I_C}}$	Vector of PF coil currents
Ip	plasma current
$\Delta\overline{\mathbf{X}}$	Vector of plasma parameter deviations from point of linearisation
$\overline{\overline{\mathbf{B}}}$	9x11 matrix relating plasma parameters to coil currents
$\overline{\overline{\mathbf{M_p}}}$	9x1 matrix giving Plasma current as function of coil currents
$\overline{\overline{1}}$	9x9 unitary matrix
$\overline{\mathbf{V_A}}$	Vector of Poloidal Field amplifier voltages
$\overline{\overline{\mathbf{M_r}}}$	reduced mutual inductance matrix
$\overline{\overline{\mathbf{R_C}}}$	9x9 diagonal matrix containing the coil resistances
$\overline{\mathbf{V_c}}$	vector of voltage requests
$\overline{\mathbf{Y}}$	vector controlled parameters (measured)
$\overline{\mathbf{Y_{ref}}}$	reference vector for controlled parameters

$\bar{\bar{\mathbf{T}}}$	Transition Matrix
$\bar{\bar{\mathbf{C}}}$	Diagonal Matrix containing 9 time constants
V_{GIM}	percentage opening of GIM
K_c	constant
T_I	integral time constant
T_D	derivative time constant
α	derivative range
n_{ref}	rteference density
n_{meas}	measured density
q	ratio toroidal/Poloidal Field
P_{NIBC}	feedback controlled neutral injection power
N_{meas}	measured
N_{ref}	reference neutron yield
K	constant
P_{FF}	Neutral Beam Power feed-forward term