EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

EFDA–JET–CP(01)02-87

T.T.C. Jones, A.J. Bickley, R. Felton, P. Lamalle, K.D. Lawson,
G.P. Maddison, M. Mantsinen, J-M. Noterdaeme, S. Podda, E. Righi,
Y. Sarazin, A. Staebler, A.A. Tuccillo
and JET EFDA Contributors

Simulation of Alpha Particle Plasma Self-Heating using ICRH Under Real-Time Control

Simulation of Alpha Particle Plasma Self-Heating using ICRH Under Real-Time Control

T.T.C. Jones[1], A.J. Bickley[1], R. Felton[1], P. Lamalle[2], K.D. Lawson[1],
G.P. Maddison[1], M. Mantsinen[3], J-M. Noterdaeme[4], S. Podda[5], E. Righi[6],
Y. Sarazin[7], A. Staebler[4], A.A. Tuccillo[5]
and JET EFDA Contributors*

[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK*
[2]*EFDA-JET CSU-ERM, Culham Science Centre, Abingdon OX14 3DB, UK*
[3]*Association Euratom-TEKES, Helsinki University of Technology, Finland*
[4]*Association Euratom-Max Planck Institut für Plasmaphysik, 85748 Garching, Germany*
[5]*Association Euratom-ENEA, I - 00044 Frascati, Italy*
[6]*EFDA Close Support Unit, 85748 Garching, Germany*
[7]*Association Euratom-CEA, CE de Cadarache, F-13108, St Paul lez Durance, France*
**See appendix of the paper by J.Pamela "Overview of recent JET results", Proceedings of the IAEA conference on Fusion Energy, Sorrento 2000*

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference,
(Madeira, Portugal 18-22 June 2001)

1. INTRODUCTION

These experiments studied the dynamic behaviour of a deuterium plasma in which a component of the ICRH heating was applied in direct response to real-time plasma parameters (such as neutron rate). Since ICRH mainly heats the electrons, and is centrally deposited, this experimental arrangement simulates the plasma self-heating effect from alpha particles. A separately controlled component (of either ICRH or NBI) was used in the role of auxiliary heating, P_{aux}. A similar technique has been used previously in JET to gain some prior indication of the degree of electron heating which could be expected in DT discharges [1,2]. In those previous experiments, the DD fusion power (from the real-time measured 2.5MeV neutron emission) was scaled specifically by the ratio of fusion powers P_{DT}/P_{DD} (as computed for a similar DT discharge), and this amount of ICRH, $P_{\alpha,\ sim}$, was delivered to the plasma in response using the JET Real-Time Central Control network [3]; the value of Q (= $5P_\alpha/P_{aux}$), both simulated and in the corresponding DT discharges, was < 0.65. In the present experiments, $P_{\alpha,\ sim}$ was scaled by a larger factor in order to mimic the response of a plasma at much higher effective Q (> 10). From simple power balance considerations, three distinct operating regimes may be identified, depending on the value of Q. For $0<Q<Q_{runaway}$ the system is unconditionally stable. For $Q > Q_{runaway}$, a change of plasma thermal energy W results in a change of P_α (or $P_{\alpha,\ sim}$) greater than the increase of the loss power (P_{loss}) arising through transport mechanisms. In this second regime, the alpha power is expected to be subject to an unstable excursion but P_{aux} can be reduced to compensate, thus feedback control of the alpha power via P_{aux} should be possible. In the third regime, the plasma is fully ignited and the alpha power exceeds P_{loss}, so some burn control mechanism other than P_{aux} would then be required. One of the main aims of the present experiments was to demonstrate the qualitative features of the onset of "thermal runaway" in the unstable finite Q regime ($Q > Q_{runaway}$), and then to stabilise the runaway using feedback control of P_{aux}.

2. EXPERIMENTAL SETUP

In an ideal experimental simulation of a burning reactor plasma, all plasma parameters X should scale according to a unique set of scale factors S_X, including all timescales, i.e. $S_X.X_{JET}(t_{JET})=X_{reactor}(S_t.t_{JET})$. The first step towards satisfying this condition is to choose a similar plasma regime and configuration as that foreseen for a reactor. For this reason the experiments were performed in the ELMy H-mode in a divertor configuration with $q_{95} \approx 3$. A qualitatively similar trajectory of the discharge was programmed as that foreseen for a reactor in terms of Paux and density ramp-up. The magnetic field, power level and density were therefore all chosen to ensure the L-H transition occurred towards the end of the Paux ramp. It was possible to meet these requirements, assuming a maximum of 10MW ICRH was available, at 2.5MA/2.5T. The similarity condition must, in particular, apply for the simulated alpha power, i.e. $S_P.P_{\alpha,\ sim}(T_{JET},\ n_{JET}) \approx P_{\alpha,Reactor}(S_T.T_{JET},\ S_n.n_{JET})$ where the scaling factors refer to powers P, temperatures T and densities n. If $P_{\alpha,\ sim}$ is taken to be proportional to the DD reaction rate in the JET discharge, the latter relation can be approximately satisfied for thermal reactions, but breaks down in the presence of significant beam-plasma reactions. Nevertheless, in the experiment it was important to utilise at least some NB heating in order that enough total power was available to exceed the L-H threshold by a significant margin at Q_{eff}>≈10, where $Q_{eff} = 5P_{\alpha, sim}/P_{aux}$. Two experimental scenarios were therefore investigated. It was found that when ICRH was superposed onto a baseline level of 2MW NBI, the observed change of DD reaction rate (ΔR_{DD}) varied as $T_e(0)$1.5-2.0, i.e. similar to the approximate scaling of RDT in the reactorrelevant temperature range. Therefore, in the first experiments $P_{\alpha, sim}(t)=C_\alpha.\Delta RDD(t)$; at maximum ICRH (≈10MW) the observed ΔRDD determined the value of the coefficient C_α such that $P_{\alpha, sim}(t) \approx 6.6$MW, leaving a remainder of ≈ 3.3MW ICRH in the role of Paux (i.e. Qeff≈10). The configuration of the JET real-time network for this experiment is shown in Fig.1. In a second series of experiments, the algorithm for P±,sim(t) was based on a parametrised fit to the volume-integral of thermal DT reaction rate RDT (for 50:50 D:T mix) in terms of Te(0), and volume average <Te>, <ne> , assuming Te=Ti and flat ne(r) profile i.e.

$$P_{\alpha, sim}(t) = C_\alpha . R_{DT, sim}(t) = C_\alpha . n_e(0)^2 . F(S_T.T_e(0), T_e(0)/<T_e>)$$

where $S_T=T_{reactor}/T_{JET}\approx 3$ and F is the parametrised fit function. C_α was again chosen to obtain $Q_{eff} = 5P_{\alpha, sim}/P_{aux} \approx 10$ at maximum ICRH power. The input parameters $T_e(0)$, $<T_e>$ and $<n_e>$ were available in real-time via the JET Real-Time Central Control network from ECE and interferometer measurements respectively.

3. RESULTS FOR EXPERIMENT 1: $P_{\alpha, sim}(T) \propto \Delta R_{DD}(T)$

Results obtained in the first scenario [$P_{\alpha, sim}(t) \propto \Delta R_{DD}(t)$] are presented in Fig.2, showing the evidence of onset of thermal runaway for $Q_{eff} \approx 8$; during this phase $dP_{\alpha, sim}/dt > dP_{loss}/dt$, until t=20.5s when the Paux component is deliberately reduced. For a plasma of stored thermal energy W, it may be shown [4] that for $P_{\alpha, sim} \propto W^\Psi$ and $\tau_E \propto P_{loss}{}^\upsilon$ ≈ a necessary condition for thermal runaway onset is $Q_{eff} > Q_{runaway} = 5 / (\psi + \psi\upsilon - 1)$. Assuming $\psi \approx 2$, this implies that during the non-steady conditions of the early H-mode phase in Fig. 2 the degradation of confinement with loss power is rather weak ($\upsilon \approx -0.2$). During the later phase of the H-mode, however, $P_{\alpha, sim}$ remains approximately constant (or declines slightly) at constant P_{aux}, implying a change in confinement behaviour. Sawteeth also appear to have a stabilising effect. In the experiments in Fig. 2, the P_{aux} component of ICRH was simply preprogrammed. In Fig. 3, a feedback term was added to the pre-programmed P_{aux} demand waveform, derived using a Proportional-Integral (PI) control algorithm where the error signal is the difference between the achieved $P_{\alpha, sim}$ and a reference value. The transfer function of the PI controller was of the form G(1+f/s) (in Laplace transform notation). Satisfactory performance of the controller was obtained for gain $G \approx (P_{\alpha, sim}/ P_{aux}) = Q_{eff}/5 \approx 3$, and $f < \approx (1/\tau_E)$. The achieved $P_{\alpha, sim}$ is compared with the reference level in Fig. 3, which includes a step increase during the H-mode phase. From PION code computations, ≈90% of the applied ICRH power was delivered to the electrons in these discharges. During the steady phases, it was estimated that the fast minority ion pressure was ≈30% of the total, with long slowingdown times

[$\tau_s / \tau_E \approx 0.4$]. This compares with values of ≈7% and 0.04 respectively for unthermalised alpha particles in the inductive Q=10 ITER reference H-mode scenario. It may be noted that the discrepancy in these dimensionless parameters, especially normalised timescales, can be expected to affect the relative dynamic behaviour of otherwise similar discharges and hence the reliability of the simulation.

4. RESULTS FOR EXPERIMENT 2: $P_{\alpha, sim}(T) \propto R_{DT}$,SIM(T)

Fig. 4 gives results of a discharge using the second scenario [$P_{\alpha, sim}(t) \propto R_{DT, sim}(t)$], which shows similar features as in Figs. 2 and 3, except that the thermal instability is more pronounced, reflecting the more "correct""density and temperature dependence of $P_{\alpha, sim}$. The P_{aux} component of the heating was controlled under feedback from t=20s in Fig.4 using similar values for the PI terms as in Experiment 1, and the excursion in $P_{\alpha, sim}$ was still satisfactorily stabilised. A further experiment was also performed in which NBI was used exclusively in the role of P_{aux}, whilst ICRH was exclusively used in the role of $P_{\alpha, sim}$ (Fig.5). This scenario was possible because the algorithm for $R_{DT, sim}$ is not affected by beam-plasma reactions, in contrast to the case in Experiment 1. The results showed similar features except that $P_{\alpha, sim}$ remained low (<1MW) until a sudden and uncontrolled excursion occurred at the transition to an ELM-free phase (at $P_{aux} \approx 7$MW). This behaviour can be explained by initially lower electron heating from the P_{aux} component using NBI, since the algorithm for $P_{\alpha, sim}$ depends on the measured T_e. During this ELM-free phase, the computed $P_{\alpha, sim}$ demand substantially exceeds the capability of the RF plant, especially since the coupling resistance is reduced significantly during ELM-free periods. However, the discharge subsequently entered an ELMy phase and under feedback control of P_{aux} (i.e. NBI) it eventually assumed roughly similar steady-state Q_{eff} as in the other experiments.

CONCLUSIONS

Thermal instability in an experimental simulation of a self-heated plasma with predominant electron heating in deuterium discharges has been demonstrated, and the thermal excursions successfully stabilised by feedback control. Two alternative algorithms for simulated alphaparticle heating were investigated, including a parametrised function for thermal reaction rate in an equivalent DT plasma based on real-time temperature and density measurements. There are fundamental limits to such scale-model experiments, e.g. it is not possible to preserve all the relevant dimensionless timescales such as τ_s / τ_E. This discrepancy will affect the dynamic behaviour; it is in fact not possible to satisfy all the required similarity conditions simultaneously, and this ultimately limits the fidelity of the experimental simulations. Nevertheless, several of the expected dynamic features of self-heated plasmas have been demonstrated in the present work.

ACKNOWLEDGEMENT

This work has been conducted under the European Fusion Development Agreement and is partly funded by Euratom and the UK Department of Trade and Industry

REFERENCES

[1]. P R Thomas *et al*, Phys Rev Lett **80** 25 (1998) 5548.

[2]. P R Thomas *et al*, these Proceedings.

[3]. N H Zornig *et al*, Proc 19th Symposium on Fusion Technology, Lisbon (1996).

[4]. N H Zornig, PhD thesis, Brunel University, UK (1998).

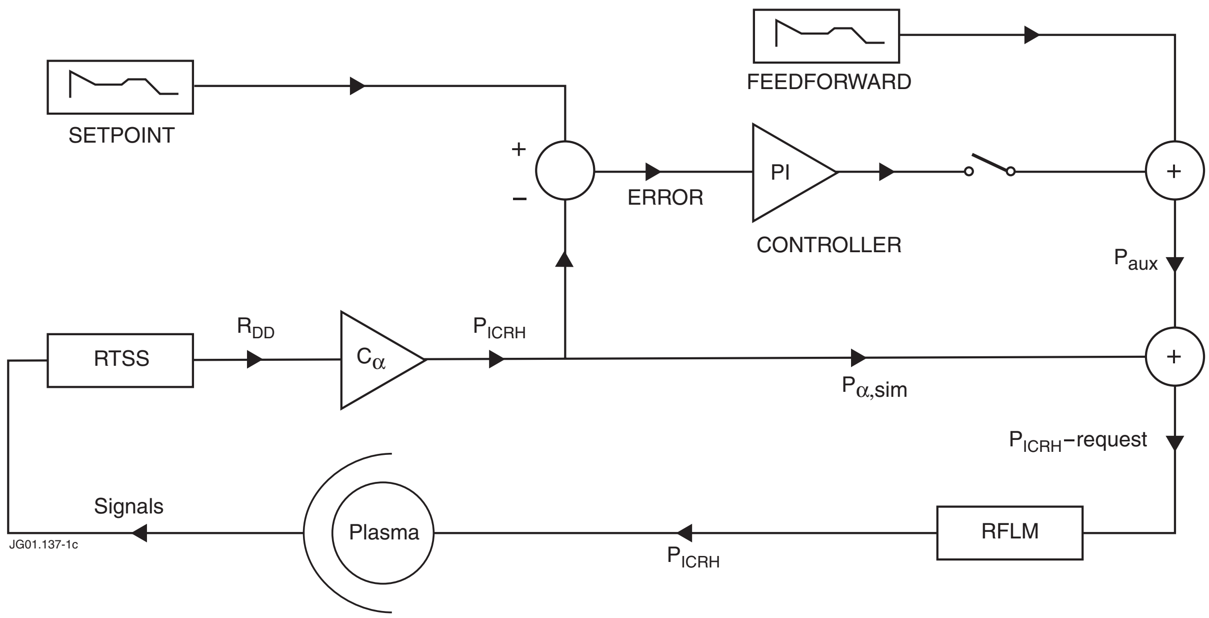

Figure 1: Experimental set-up: RTSS = Real-Time Signal Server, RFLM=RF Local Manager. The Local Managers control the delivered power in.

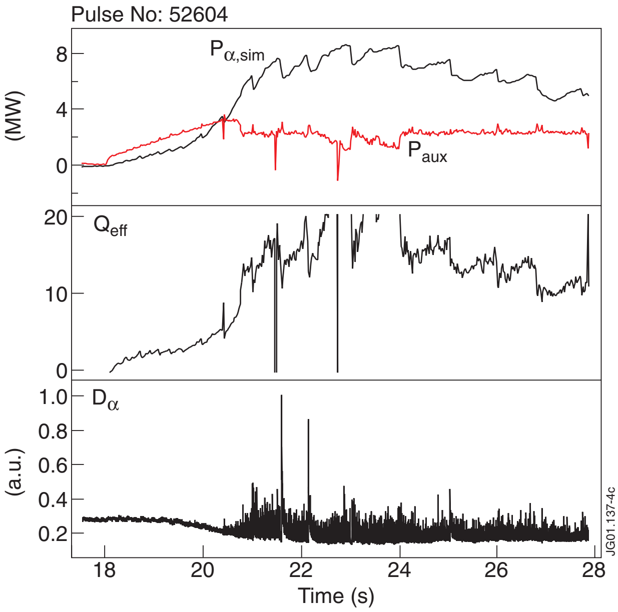

Figure 2: ICRH in roles of P_{aux} and $P_{\alpha,\ sim}$. There is a constant 2MW 'baseline" of NB heating (not shown).

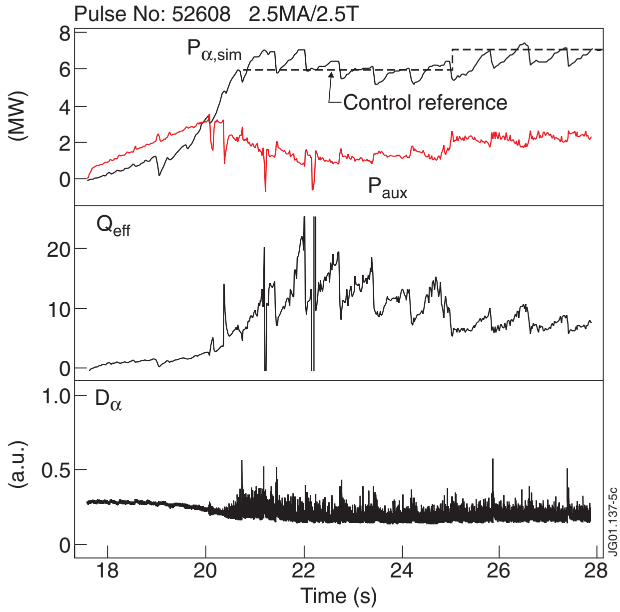

Figure 3: Step-change increase in $P_{\alpha,\ sim}$ demand achieved via feedback control on P_{aux}.

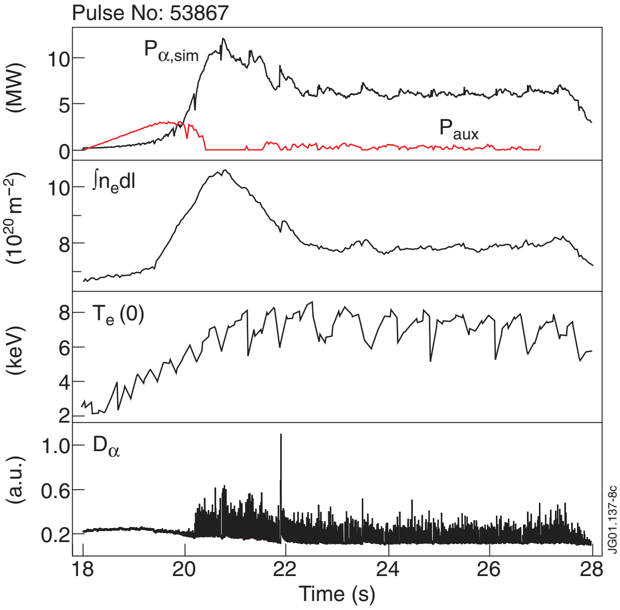

Figure 4: $P_{\alpha,\ sim}$ scaled from parametrised fit to DT reaction rate in equivalent DT plasma using T_e, n_e as input. ICRH is used in roles of P_{aux} and $P_{\alpha,\ sim}$. There is a constant 2MW 'baseline" of NB heating (not shown).

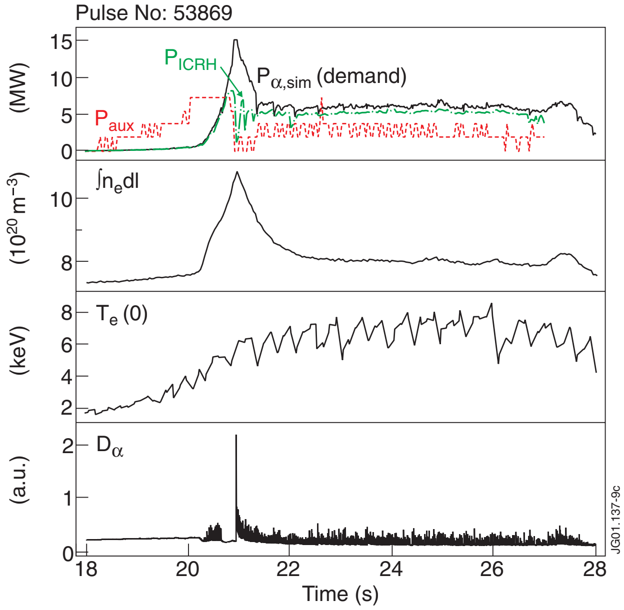

Figure 5: Discharge with ICRH and NBI used separately in roles of P_{aux} and $P_{\alpha,\ sim}$ respectively.