

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

T T C Jones<sup>1</sup>, A J Bickley<sup>1</sup>, R Felton<sup>1</sup>, P Lamalle<sup>2</sup>, K D Lawson<sup>1</sup>, G P Maddison<sup>1</sup>,  
M Mantsinen<sup>3</sup>, J-M Noterdaeme<sup>4</sup>, S Podda<sup>5</sup>, E Righi<sup>6</sup>, Y Sarazin<sup>7</sup>, A Staebler<sup>4</sup>,  
A A Tuccillo<sup>5</sup> and the contributors to the EFDA-JET Work Programme\*

<sup>1</sup> *Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK*

<sup>2</sup> *EFDA-JET CSU-ERM, Culham Science Centre, Abingdon OX14 3DB, UK*

<sup>3</sup> *Association Euratom-TEKES, Helsinki University of Technology, Finland*

<sup>4</sup> *Association Euratom-Max Planck Institut für Plasmaphysik, 85748 Garching, Germany*

<sup>5</sup> *Association Euratom-ENEA, I - 00044 Frascati, Italy*

<sup>6</sup> *EFDA Close Support Unit, 85748 Garching, Germany*

<sup>7</sup> *Association Euratom-CEA, CE de Cadarache, F-13108, St Paul lez Durance, France*

## 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,  $P_{\text{aux}}$ . 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  $P_{\text{DT}}/P_{\text{DD}}$  (as computed for a similar DT discharge), and this amount of ICRH,  $P_{\alpha,\text{sim}}$ , was delivered to the plasma in response using the JET Real-Time Central Control network [3]; the value of  $Q$  ( $= 5P_{\alpha}/P_{\text{aux}}$ ), both simulated and in the corresponding DT discharges, was  $< 0.65$ . In the present experiments,  $P_{\alpha,\text{sim}}$  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  $0 < Q < Q_{\text{runaway}}$  the system is unconditionally stable. For  $Q > Q_{\text{runaway}}$ , a change of plasma thermal energy  $W$  results in a change of  $P_{\alpha}$  (or  $P_{\alpha,\text{sim}}$ ) greater than the increase of the loss power ( $P_{\text{loss}}$ ) arising through transport mechanisms. In this second regime, the alpha power is expected to be subject to an unstable excursion but  $P_{\text{aux}}$  can be reduced to compensate, thus feedback control of the alpha power via  $P_{\text{aux}}$  should be possible. In the third regime, the plasma is fully ignited and the alpha power exceeds  $P_{\text{loss}}$ , so some burn control mechanism other than  $P_{\text{aux}}$  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 ( $Q > Q_{\text{runaway}}$ ), and then to stabilise the runaway using feedback control of  $P_{\text{aux}}$ .

## 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.  $S_X \cdot X_{\text{JET}}(t_{\text{JET}}) = X_{\text{reactor}}(S_t \cdot t_{\text{JET}})$ . The first step towards satisfying this condition is to choose a

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\* 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)

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  $P_{\text{aux}}$  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  $P_{\text{aux}}$  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.  $S_P \cdot P_{\alpha, \text{sim}}(T_{\text{JET}}, n_{\text{JET}}) \approx P_{\alpha, \text{Reactor}}(S_T \cdot T_{\text{JET}}, S_n \cdot n_{\text{JET}})$  where the scaling factors refer to powers  $P$ , temperatures  $T$  and densities  $n$ . If  $P_{\alpha, \text{sim}}$  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  $Q_{\text{eff}} \approx 10$ , where  $Q_{\text{eff}} = 5P_{\alpha, \text{sim}}/P_{\text{aux}}$ . Two experimental scenarios were therefore investigated.

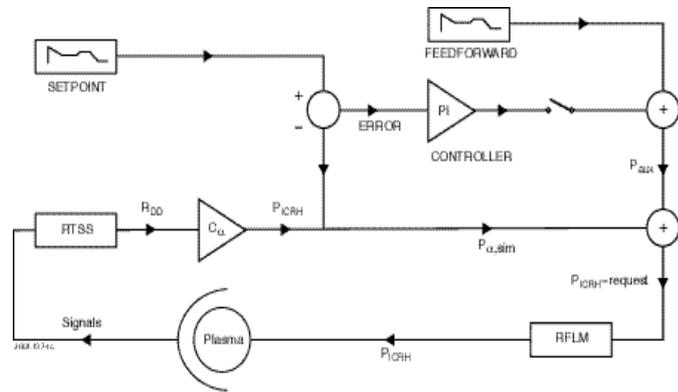
It was found that when ICRH was superposed onto a baseline level of 2MW NBI, the observed change of DD reaction rate ( $\Delta R_{\text{DD}}$ ) varied as  $T_e(0)^{1.5-2.0}$ , i.e. similar to the approximate scaling of  $R_{\text{DT}}$  in the reactor-relevant temperature range. Therefore, in the first experiments  $P_{\alpha, \text{sim}}(t) = C_{\alpha} \cdot \Delta R_{\text{DD}}(t)$ ; at maximum ICRH ( $\approx 10\text{MW}$ ) the observed  $\Delta R_{\text{DD}}$  determined the value of the coefficient  $C_{\alpha}$  such that  $P_{\alpha, \text{sim}}(t) \approx 6.6\text{MW}$ , leaving a remainder of  $\approx 3.3\text{MW}$  ICRH in the role of  $P_{\text{aux}}$  (i.e.  $Q_{\text{eff}} \approx 10$ ). 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  $P_{\alpha, \text{sim}}(t)$  was based on a parametrised fit to the volume-integral of thermal DT reaction rate  $R_{\text{DT}}$  (for 50:50 D:T mix) in terms of  $T_e(0)$ , and volume average  $\langle T_e \rangle$ ,  $\langle n_e \rangle$ , assuming  $T_e = T_i$  and flat  $n_e(r)$  profile i.e.

$$P_{\alpha, \text{sim}}(t) = C_{\alpha} \cdot R_{\text{DT}, \text{sim}}(t) = C_{\alpha} \cdot n_e(0)^2 \cdot F(S_T \cdot T_e(0), T_e(0)/\langle T_e \rangle)$$

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

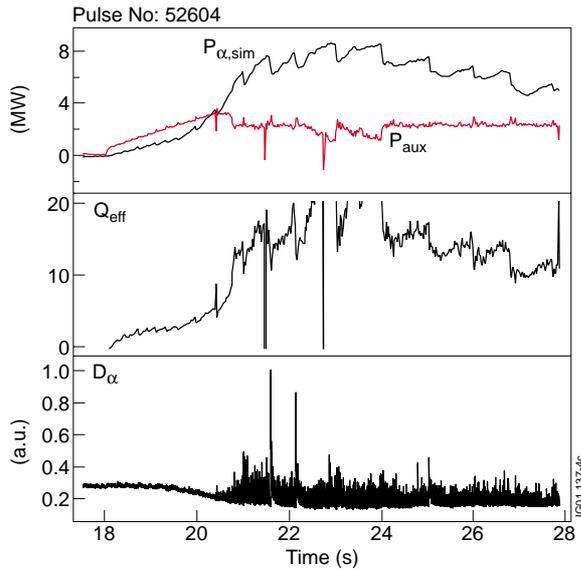
### 3. Results for Experiment 1: $P_{\alpha, \text{sim}}(t) \propto \Delta R_{\text{DD}}(t)$

Results obtained in the first scenario [ $P_{\alpha, \text{sim}}(t) \propto \Delta R_{\text{DD}}(t)$ ] are presented in Fig.2, showing the evidence of onset of thermal runaway for  $Q_{\text{eff}} \approx 8$ ; during this phase  $dP_{\alpha, \text{sim}}/dt > dP_{\text{loss}}/dt$ , until  $t=20.5\text{s}$  when the  $P_{\text{aux}}$  component is deliberately reduced. For a plasma of stored thermal energy  $W$ , it may be shown [4] that for  $P_{\alpha, \text{sim}} \propto W^{\psi}$  and  $\tau_E \propto P_{\text{loss}}^{-\nu}$  a necessary condition for thermal runaway onset is  $Q_{\text{eff}} > Q_{\text{runaway}} = 5 / (\psi + \nu\psi - 1)$ . Assuming  $\psi \approx 2$ , this implies that during the non-steady conditions of the early H-mode phase in Fig. 2 the degradation of

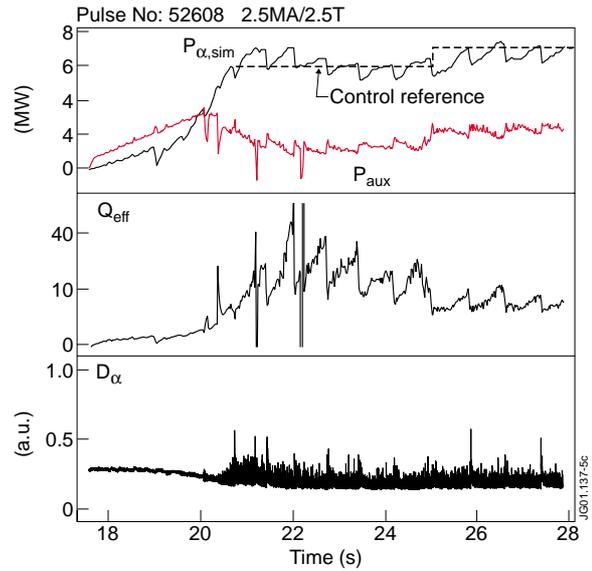


**Fig.1** Experimental set-up: RTSS = Real-Time Signal Server, RFLM=RF Local Manager. The Local Managers control the delivered power in

confinement with loss power is rather weak ( $\nu \approx -0.2$ ). During the later phase of the H-mode, however,  $P_{\alpha, \text{sim}}$  remains approximately constant (or declines slightly) at constant  $P_{\text{aux}}$ , implying a change in confinement behaviour. Sawteeth also appear to have a stabilising effect. In the experiments in Fig. 2, the  $P_{\text{aux}}$  component of ICRH was simply pre-programmed. In Fig. 3, a feedback term was added to the pre-programmed  $P_{\text{aux}}$  demand waveform, derived using a Proportional-Integral (PI) control algorithm where the error signal is the difference between the achieved  $P_{\alpha, \text{sim}}$  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  $G \approx (P_{\alpha, \text{sim}}/P_{\text{aux}}) = Q_{\text{eff}}/5 \approx 3$ , and  $f < \approx (1/\tau_E)$ . The achieved  $P_{\alpha, \text{sim}}$  is compared with the reference level in Fig. 3, which includes a step increase during the H-mode phase. From PION code computations,  $\approx 90\%$  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  $\approx 30\%$  of the total, with long slowing-down times [ $\tau_s/\tau_E \approx 0.4$ ]. This compares with values of  $\approx 7\%$  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.



**Fig. 2** ICRH in roles of  $P_{\text{aux}}$  and  $P_{\alpha, \text{sim}}$ . There is a constant 2MW ‘baseline’ of NB heating (not shown)

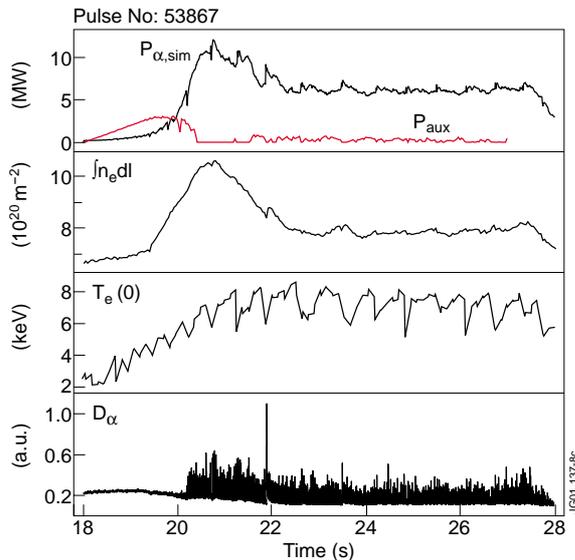


**Fig. 3** Step-change increase in  $P_{\alpha, \text{sim}}$  demand achieved via feedback control on  $P_{\text{aux}}$

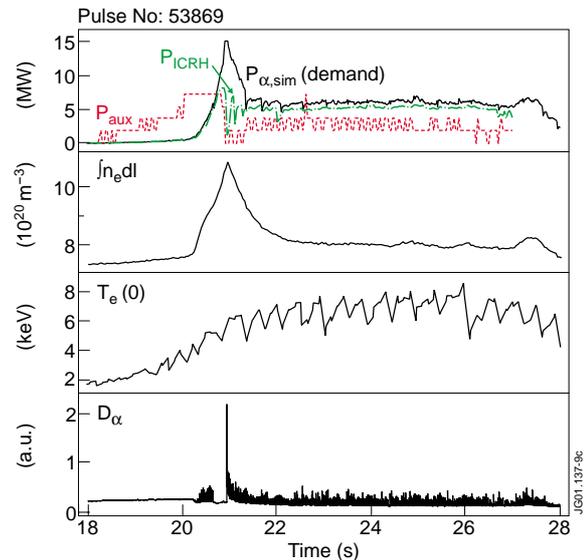
#### 4. Results for Experiment 2: $P_{\alpha, \text{sim}}(t) \propto R_{\text{DT}, \text{sim}}(t)$

Fig. 4 gives results of a discharge using the second scenario [ $P_{\alpha, \text{sim}}(t) \propto R_{\text{DT}, \text{sim}}(t)$ ], 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  $P_{\alpha, \text{sim}}$ . The  $P_{\text{aux}}$  component of the heating was controlled under feedback from  $t=20$ s in Fig.4 using similar values for the PI terms as in Experiment 1, and the excursion in  $P_{\alpha, \text{sim}}$  was still satisfactorily stabilised. A further experiment was also performed in which NBI was used exclusively in the role of  $P_{\text{aux}}$ , whilst ICRH was exclusively used in the role of  $P_{\alpha, \text{sim}}$  (Fig.5). This scenario was possible because the algorithm for  $R_{\text{DT}, \text{sim}}$  is not affected by beam-plasma reactions, in contrast to the case in Experiment 1. The results showed similar features except that  $P_{\alpha, \text{sim}}$  remained low ( $<1$ MW) until a sudden and uncontrolled excursion occurred at the

transition to an ELM-free phase (at  $P_{aux} \approx 7\text{MW}$ ). 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.



**Fig. 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)



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

## 5. 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 alpha-particle 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  $\tau_s / \tau_E$ . 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.

## References

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- [3] N H Zornig *et al*, Proc 19<sup>th</sup> Symposium on Fusion Technology, Lisbon (1996)
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