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Recent Heating and Current Drive Results on JET

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ABSTRACT
An overview is presented of the results obtained on JET by the Heating and Current Drive Task Force (TF-H) in the period May 2000 – March 2001. A strongly improved Lower Hybrid (LH) coupling was achieved by optimising the plasma shape and by controlling the local edge density via the injection of CD_4. Up to 4MW have been coupled in type III ELMy H-mode and/or on Internal Transport Barrier (ITB) plasmas with reflection coefficients as low as 4%. Long lasting quasi steady-state ITBs have been obtained by adding the LH current to the bootstrap and beam driven components. Furthermore the use of LH in the pre-heat phase results in electron temperature in excess of 10keV, deep negative magnetic shear and strongly reduced power threshold for ITB formation. Preliminary results on ICRF coupling are reported including the effect of CD_4 injection and the commissioning of the wide band matching system on ELMy plasmas. IC CD scenarios have been studied in H and ^{3}He minority and used to modify the stability of the sawtooth to influence the formation of seed islands for the appearance of NTM. Up to 3MW of IC power was coupled in the high magnetic field fast wave CD scenario. Preliminary MSE measurements indicate differences in the current profiles between -90° and +90° phasing. Careful measurements of the toroidal rotation, in plasmas heated by ICRF only show some dependence on the position of the resonance layer. Finally the use of ICRF minority heating under real-time control, in response to measured plasma parameters to simulate the effect of alpha particles, is presented. ICRF heating results in ITER non-activated scenarios are reported in a companion paper.

INTRODUCTION
The JET facility is operated, since January 2000, under EFDA, the European Fusion Development Agreement [1]. In this new framework the scientific objectives are strongly “Next Step” oriented and the scientific programme is defined and conducted by scientists, from all European Laboratories, organised in Task Forces. In particular a Task Force “H”, for heating, has been set up to address all physics and technological issues connected with the Heating (H) and Current Drive (CD) systems foreseen for the next step, with emphasis on Ion Cyclotron (IC) and Lower Hybrid (LH) systems present in JET. Besides the IC heating capability, these two systems can provide on axis (IC), off axis (LH) CD and rotation (IC) allowing for profile and MHD control needed in all phases of the reference scenarios of the next step device [2]. Nevertheless for both systems the capability of coupling the power to ELMy H-mode or ITBs plasmas needs to be assessed. These issues have been addressed in the Task Force May 2000-March 2001 programme and corresponding progress are reported. In the LH section the progress in coupling will be illustrated together with the results obtained in Optimised Shear (OS) due to the capability of driving the current both in the pre-heat and in the heating phase. In the IC section result of IC CD, rotation as well as progress in the coupling understanding are reported; also, IC heating applied under real-time control by plasma parameters to simulate central heating by alpha particles, is reported. The results of the IC heating in D and He plasmas relevant for the non-activated phase of the Next Step are the content of a companion post deadline paper to this conference.

LOWER HYBRID EXPERIMENTS

LH coupling. The capability of LH waves to drive current in plasma density regimes and with efficiency relevant for the next step is well known [2,3]. Nevertheless they have hardly been used up to now on high performance plasmas because of the difficulty in keeping the launcher in a safe position while providing adequate density at launcher mouth. A combination of proper plasma shaping and local gas injection [4,5] has been developed on JET allowing for systematic operation with P_{LH} 3.5MW in H mode and Internal Transport Barrier (ITB) plasmas. Following previous results [6] deuterated methane (CD_4) is puffed into the plasma from a pipe toroidally close to the LH launcher. The injection of CD_4 during an ITB increases the density locally in the Scrape-Off-Layer (SOL) [6,7], whereas matching at best the plasma and the antenna shapes produces a SOL plasma uniform along the antenna. The difference in the gap plasma-antenna along the poloidal section has been reduced from the past 5cm, to less than 8mm, by a proper feeding of the poloidal field coils without affecting the X-point position important for a good ITB performance. At the optimum CD_4 injection rate (8×10^{21} el./s) the reflection coefficient decreases from about 10% to 4-5%, very close to the L-mode value. As shown in Fig.1 the LH power can only be maintained in the high power phase of discharges with CD_4 injection. No secondary unwanted effect on the quality of either the H or ITB mode is recorded as suggested also by the comparison of D_α signals in Fig.1. On the contrary, from preliminary indications, a control of the ELMs frequency and amplitude appears possible [4]. No significant increase of radiation or impurity influx is generally observed from either the limiter or the antenna and the accumulation of either methane or carbon on the walls is negligible. The low ionisation potentials of CD_4 and of all the neutral products of its dissociation, confine inside the SOL the effects of the methane puffing [8].

LHCD ON PRE-HEAT PHASE.

As a result of this new availability, the use of LH CD r/ a in OS experiments has increased dramatically especially in plasmas with high additional power. The basic OS scenario uses a fast current ramp-up to slow down the current diffusion and obtain plasmas with low magnetic shear, but monotonic q profile. This plasma is then heated at high power with Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH), while the plasma current is still being ramped up, to produce ITBs. When LHCD power, P_{LH}, is applied during the early phase of OS plasma, a reversed q profile is obtained. The plasma during pre-heat often exhibits an ITB on the electron temperature, Te, which is probably related to the reversed q profile. Ray tracing and Fokker-Planck calculations on a shot with deeply reversed shear and ITB on Te show that PLH is deposited inside the normalised small radius r/a~0.5. The LH current is peaked centrally at 2s, and near the ITB foot-point at 3s and 4s (r/a~0.4). The total LH current at 3s is ~500 kA, with P_{LH} 2.1MW, and line integrated density $n_e \approx 10^{19}$ m^{-3}. Transport modelling shows that the current driven by LHCD is necessary to create the reversed shear plasma, although the heating also plays a role [9]. By varying the LHCD power it is possible to control the q profile, from weakly to deeply reversed. The ITB observed during preheat gets wider and steeper when the LHCD power is increased, the radial position of the foot of the barrier is shown in Fig.2. When the LH produced reversed shear plasmas are heated with NBI and ICRH power, ITBs on T_e, T_i and ne are observed with a significant reduction of the threshold [10]. Wider ITBs on T_e during preheat generally produce better plasma performances. This technique allows high neutron yield to be achieved with the prospect to be maintained steady if adequate current profile control can be achieved.

LH CD ON MAIN HEATING PHASE.

ITBs are usually short lived, mainly because of detrimental MHD activity related to the strong pressure gradient or to the q profile, such as pressure driven kink modes or snakes [11]. One solution put forward to sustain ITBs is to control the current profile, thus maintaining the q profile in a favourable configuration. One of the OS experiments aims at producing plasmas with fully non-inductive current drive during ITB. It uses plasmas with high β_P, to favour high bootstrap current [12]. The plasma current, I_P, is low, 1.8-2.0MA, thus a significant fraction of the current can be driven by LHCD. This scenario has produced long-lived ITBs, the most remarkable one (Pulse No: 53521, Fig.3) lasting ~8s on the ion temperature and the electron density and ~12s on electron temperature. This plasma has magnetic field, B_T=3.4T, I_P = 2.0MA, n_e increasing from 2.4×10^{19} m^{-3} at 5.6s to 3.3×10^{19} m^{-3} at 10.6s and strongly peaking. Ray-tracing and Fokker-Planck calculations indicate that ~600-700 kA of current is driven by ~3MW of LHCD on that shot at 8s. The LHCD power deposition is determined by the electron temperature, and occurs mainly near the strong gradient on Te due to the ITB. Preliminary results from transport modelling show that 80% of the current is driven non-inductively by a combination of LHCD, bootstrap and NBI driven current. On shots at 1.8MA, the plasma loop voltage, decreases near or below 0 with LHCD, indicating that all the current is driven non inductively. In a few cases, LHCD is stopped or decreased after the start of the ITB, and the ITB is either lost or develops a strong pressure gradient and disrupts. Preliminary OS experiments at B_T = 3.4T, I_P = 2.4 MA, P_{NBI} = 17.0MW and P_{ICRH} = 4.0MW have produced an ITB lasting 3.8s on T_i, with 2.6MW of PLHCD. The best performances in reversed shear plasmas on JET have been obtained at higher I_P (up to 3.1MA). However, higher P_{LHCD} will be required to control ITBs at higher I_P.

ION CYCLOTRON EXPERIMENTS

Reliable high power ICRF operation requires sufficiently high antenna coupling resistance (R_c) for a given maximum voltage in the transmission lines. This resistance is dependent on the plasma shape and on plasma confinement modes (L, H, ITB) that affect the plasma edge density profile. At JET R_c, averaged over of the four straps of one antenna, was analysed with particular emphasis on the plasma shape dependenceand compared with different models [13]. For a given frequency and plasma scenario the dependence on plasma shaping was found statistically much less pronounced than on the mid-plane distance between the antenna and the last closed flux surface and on the antenna phasing. However, the statistical nature of the analysis does not preclude improving the coupling, in any given discharge, by slightly modifying the shape. Preliminary experiments show a beneficial effect of CD_4 gas puffs only on the ICRF antennas magnetically connected with the gas valve. Thus, reliable operation requires a small distance between the last closed flux surface and the antenna. However, for distances below a critical value, the minimum heating power required to cause L to H-mode transition increases sharply [14] while the antenna loading resistance also increases. This constraint can be overcome by first obtaining the H-mode at larger distance and subsequently decreasing the distance to further increase the RF power [15]. The differences in ICRH heating efficiency and edge interaction between monopole and dipole phasing of the JET A2 antennas have been also investigated. In monopole, central plasma heating was observed, with higher efficiency than reported in the past for these antennas, although only half as much as in dipole. When the four antennas are alternately phased in dipole and monopole heavy interaction with structures and release of bursts of particulate material [16] is observed. Much progress has been achieved commissioning the ICRF wide band matching system, with the fast frequency control loop now responding to ELMs [17]. Optimisation is continuing to demonstrate improved power delivery to an ELMy plasma. As part of the study to enhance the JET ICRH system with 3dB couplers the symmetry of the ELMs has been measured on two opposite antennas. Preliminary results indicate that the arrival time of ELMs can differ between 40 and 200μs.

IC CURRENT DRIVE.

D(H) minority CD, aimed at modifying the current profile around t he q=1 surface, has been studied in discharges with ramping magnetic field (B_T= 2.3→2.8T) and H resonance layer on the high field side. Sawteeth stabilisation, leading to monster sawteeth, was observed with $+90^o$ phasing corresponding to waves directed along theplasma current. With the -90^o phasing the sawteeth had a shorter period. However, monster sawteeth also appeared, but at higher field compared to +90° phasing. Both a flattening of the shear profile, around the q=1 surface, due to the minority CD [18,19] as well as fast particle pressure effects [20,21] inside the q=1 surface, influenced by an ICRF induced pinch in the presence of directed waves [22], could explain the observed behaviour. With fixed toroidal magnetic field (B_0 = 2.6T, f_{ICRF} = 42MHz), monster sawteeth were obtained with +90° phasing only, and the consequent crash produced a Neoclassical Tearing Modes [23]. Motional Stark Effect (MSE) measurements indicate a small difference in the current density profile around the q = 1 surface between $+90^o$ and -90^o phasing in agreement with the numerical simulations performed with the SELFO code [24] that takes into account the radial ICRF induced transport. A flattening of the safety factor profile is also measured with the MSE diagnostic in both phasing. Minority CD experiments with 3 He minority species were also carried out at low concentration (~0.5 %). Here longer sawteeth were observed with +90° phasing as compared to –90°, but no monster sawtooth appeared during BT ramp up (B_T=3.27→3.45T). A limited number of Fast Wave (FW) $\omega = 2\omega_H$ heating/CD discharges have been performed in +90° and dipole (0π0π) phasing at low magnetic field (B_0 = 1.7 T, f_{ICRF} = 56MHz). In these Deuterium RF-only plasmas, with low

Hydrogen concentration (1-2%), clear evidence of second harmonic H heating were found with Neutral Particle Analysers, whereas no fast deuterons due to $\omega = 4\omega_D$ heating were detected. Further experiments have been carried out by Task Force M to avoid seed island formation at the q=3/2 surface, allowing to increase the β_N threshold for NTM onset, thus leading to performance improvement [23]. For the first time on JET, some moderate RF power (2-3 MW, see Fig. 4a) has been coupled in a FWCD scenarioat high toroidal magnetic field [25] without efficient ion cyclotron absorption in the plasma (B_0 = 3.45T, f_{ICRF} = 37MHz, I_p = 2.5MA). MSE data show a difference in current density profile at centre between +90^o and −90^o (Fig.4b), leading to a difference of central current of 300 kA. Simulations by the ALCYON code [26,27] estimates 60kA/MW to be driven by ICRF in the +90° phasing case. In additional experiments with LH preheating, central electron temperatures of 6keV are obtained with 4.2MW of RF power. On the previous scenario, the addition of 7.5MW of NBI triggers an electron ITB and T_e(0) rises to 8keV. This latter result is very promising for future JET experiments in advanced tokamak scenarios.

IC INDUCED ROTATION.

A systematic study was made of the toroidal rotation, and in particular of its radial profile, for a large set of parameters (L/H mode, position of resonance layer, antenna spectrum) [28]. Since the experiments rely on short pulses of neutral beam injection (blips) to measure the rotation by looking at the Doppler shift of the resonant charge exchange line of C, it is of utmost importance to check that the measured rotation is not affected by the measuring beam itself. The overall rotation profiles start to evolve by the end of the beam blip which lasted for 200ms. The value of the central rotation is affected more quickly (on order of 50ms). The very first profile however, taken during the short beam blip, can be seen as representative of the rotation profile before the beam blip. This was independently confirmed by looking at the time evolution, due to the blip, of mild central MHD modes. In L-mode plasmas heated by ICRF only (H minority in D), the rotation profiles show a distinct maximum off-axis and in the co-current direction. The rotation profiles depends on the position of the resonance layer: a HFS location of the resonance layer leads to a slightly larger value of this maximum than for a LFS position of the resonance layer. The difference between a co and counter direction of the antenna spectrum is small.

IC HEATING SCENARIOS IN ^{4}HE PLASMAS.

An extensive series of ICRF heating experiments has been carried out in ^{4}He plasmas, with emphasis on ICRF heating scenarios for the non-activated phase of ITER [29]. The (^{3}He) ^{4}He scenario was studied systematically by scanning the ^{3}He concentration from the minority ^{3}He regime up to the mode conversion regime. At low ^{3}He concentration, the first direct observation of ICRF-induced pinch [30] of ^{3}He minority ions was made with a gamma ray emission profile monitor [31]. At high ^{3}He concentration, the mode conversion regime was explored in detail for the first time on JET. Control of the off-axis mode-conversion power deposition was demonstrated by adding ^{3}He puff during ICRF heating. The conditions for accessing the H-mode in plasmas of various isotope composition from dominantly ^4He to dominantly D were studied for several ICRF scenarios. All scenarios triggered the H-mode. Preliminary results show that the threshold is about 65% higher in ^4He than in D. Experiments have also been carried out for the first time in ^4He plasmas with ICRF power applied at the third harmonic of ^4He beam ions, with the objective of creating a strong ^4He tail for alpha particle studies [29]. In these experiments clear experimental evidence for an alpha tail has been obtained with a gamma ray diagnostic based on the reaction $^9Be(\alpha, n\gamma)\,^{12}C$ [32]. In the presence of a strong ^4He tail, Alfvén eigenmodes, sawtooth stabilisation and H-mode induced by alpha particle heating were observed for the first time on JET. The results, of this part of the Task Force activity, are presented in the companion post deadline paper [29].

SIMULATED ALPHA PARTICLE SELF-HEATING EXPERIMENTS.

These experiments studied the dynamic behaviour of a deuterium plasma in which a component, $P_{\alpha,sim}$, of the ICRH heating was applied in direct response to real-time plasma parameters (such as neutron rate), using the JET Real Time Central Control network [33]. Since ICRH, via fast ions, 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 [34]. 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). 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}. 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 time-scales, i.e. $S_X \times X_{JET}(t_{JET}) = X_{reactor}(S_t \times t_{JET})$. The first step towards satisfying this condition is to choose a similar plasma regime as that foreseen for a reactor, e.g. ELMy H-mode, and to follow a similar trajectory of the discharge as that foreseen for a reactor in terms of P_{aux} and density ramp-up; the magnetic field and density were therefore chosen to ensure the L-H transition occurred towards the end of the P_{aux} ramp. The similarity condition must, in particular, apply for the simulated alpha power, i.e. $S_P \times P_{\alpha,sim}(T_{JET}, n_{JET}) = P_{\alpha,Reactor}(S_T \times T_{JET}, S_n \times n_{JET})$ where the scaling factors refer to powers P, temperatures T and densities n. Two experimental scenarios were investigated. It was found that the change of DD reaction rate ΔR_{DD} observed when ICRH was superposed onto a baseline level of 2MW NBI scaled as $T_e(0)_{1.5\text{-}2.0}$ i.e. similar to the approximate scaling of R_{DT} in the reactor relevant temperature range. Therefore, in the first experiments $P_{\alpha,sim}(t)=C_\alpha \times \Delta R_{DD}(t)$. In a second series of experiments, the algorithm for $P_{\alpha,sim}(t)$ was based on a parameterised fit to the volume-integral of thermal DT reaction rate RDT (for 50:50 D:T mix) using real-time measurements of $T_e(0)$, volume average $\langle T_e \rangle$ and $\langle n_e \rangle$ assuming $T_e = T_i$ and flat $n_e(r)$ profile i.e. $P_{\alpha,sim}(t) = C_\alpha \times R_{DT,sim}(t) = C_\alpha \times n_e(0)^2 \times F(S_T \times T_e(0), T_e(0)/\langle T_e \rangle)$ where

$S_T = T_{reactor}/T_{JET} \approx 3$; F is the parameterised fit function. In both experiments C_α was chosen to obtain $Q_{eff} = 5P_{\alpha,sim}/P_{aux}$ 10 at maximum ICRH power. Results obtained in the first scenario $[P_{\alpha,sim}(t) \propto \Delta R_{DD}(t)]$ are presented in Fig.5, showing the onset of thermal runaway for $Q_{eff} > \approx 8$ with subsequent stabilisation achieved using proportional-integral feedback control via the P_{aux} component of ICRH. Fig.6 shows results of a discharge using the second scenario $[P_{\alpha,sim}(t) \propto R_{DT,sim}(t)]$, which shows similar features as in Fig.5, except that the thermal instability is more pronounced, reflecting the more “correct” density and temperature dependence of $P_{\alpha,sim}$. During the steady phases of these discharges, it was estimated that the fast minority ion pressure was ≈30% of the total, with long slowing-down 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-FEAT reference scenario. This discrepancy affects the dynamic behaviour; it is in fact impossible to satisfy simultaneously all the required similarity conditions. Nevertheless, several features of self-heated plasmas are demonstrated.

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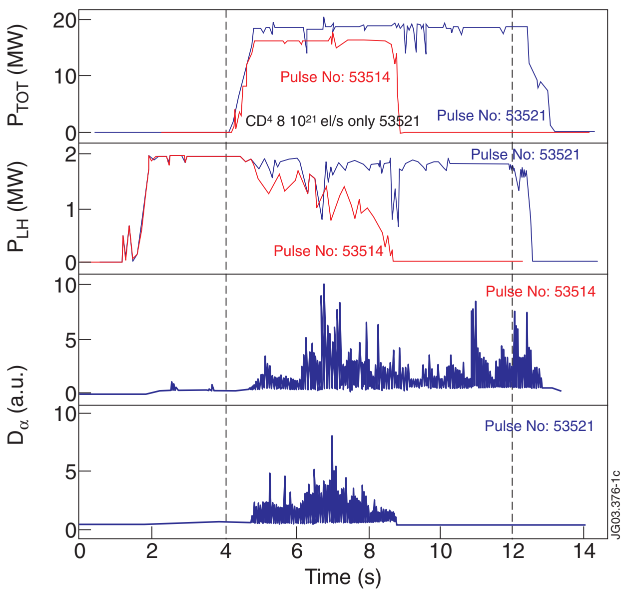


Figure 1: a) Time evolution of total power: NBI plus 4MW ICRF; b) LH Power; c-d) D_α in the two discharges with and without CD_4

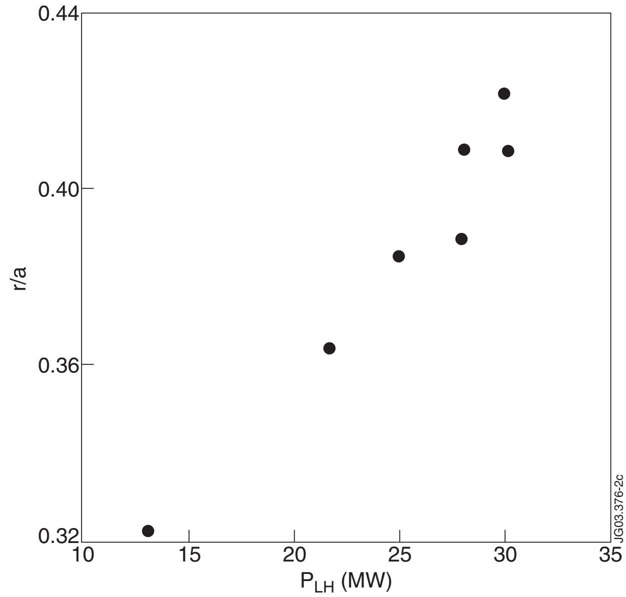


Figure 2: Position of the foot point of the ITB observed on T_e during pre-heat, as a function of the LHCD power. The values are taken at 3.5s.

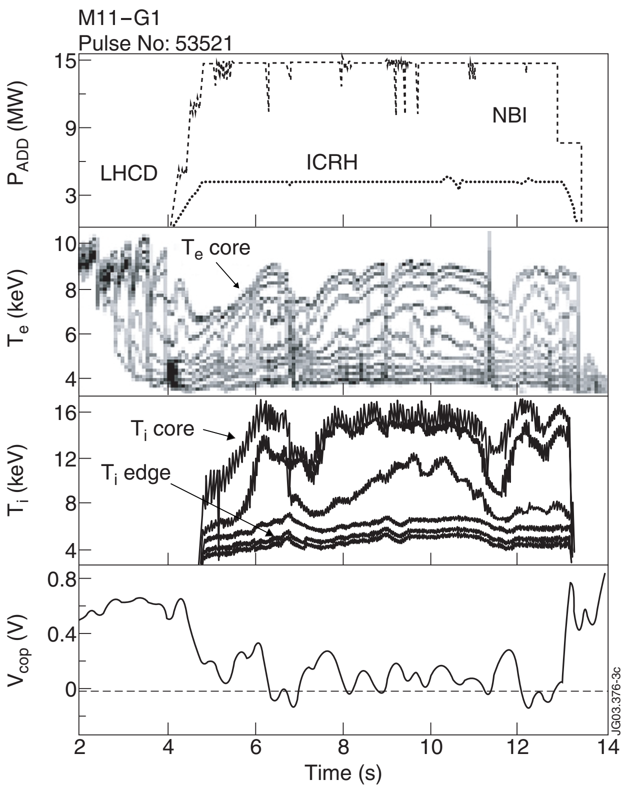


Figure 3: Time evolution of additional power on top graph, Te and Ti on the middle graphs, and vloop on the bottom graph. The presence of the ITB is seen as an increase in the core temperature.

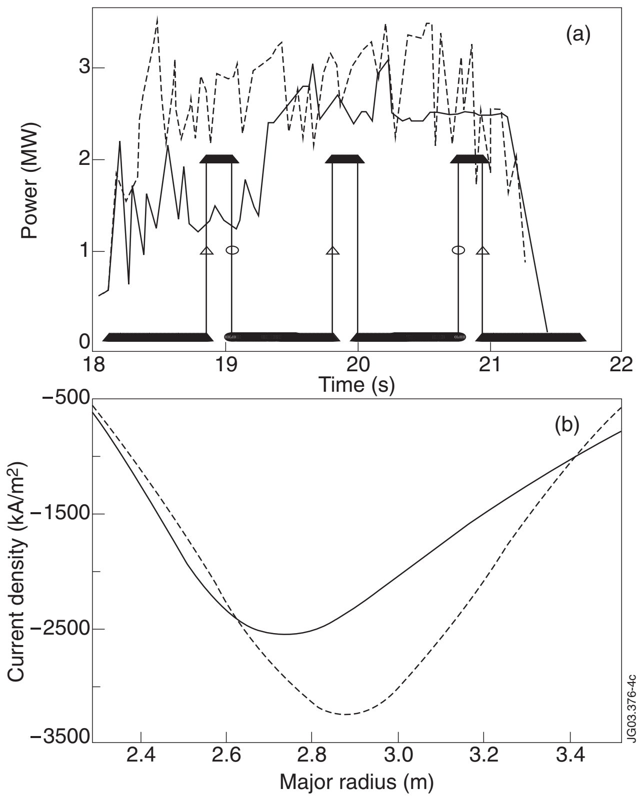
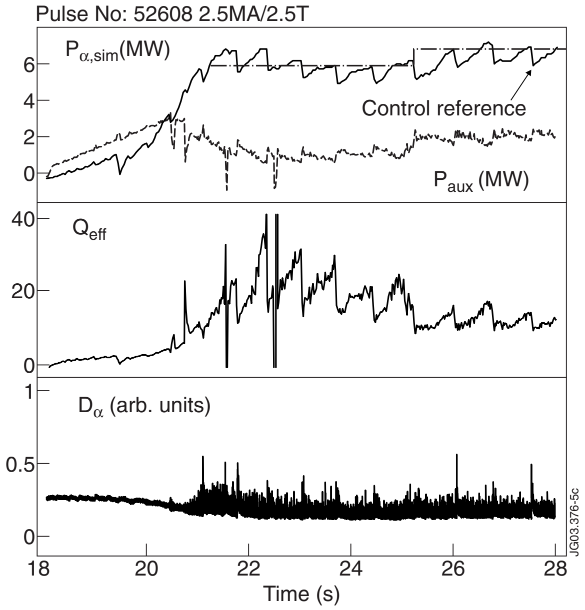


Figure 4: a) Injected powers: bold line ICRF $+90^o$, dashed line ICRF -90^o, circle/triangle NBI. b) current density profile at t = 20.9s measured by MSE, bold line $+90^o$, dashed line -90^o



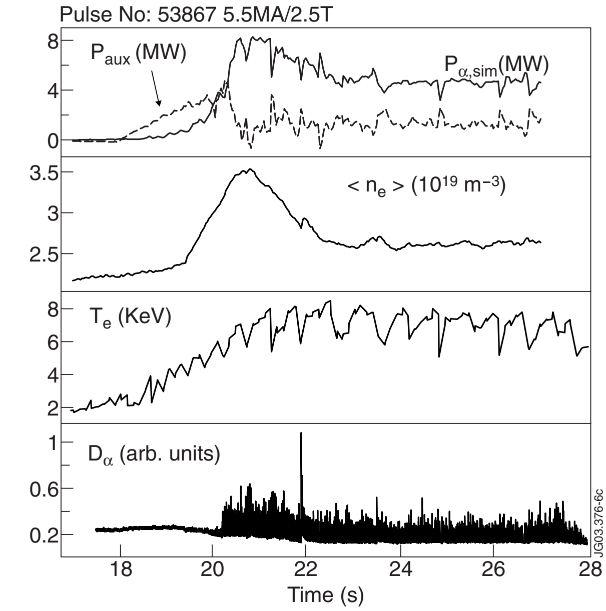


Figure 5: Simulated self-heated plasma experiment in which a component of ICRH is applied in proportion to the measured change in DD reaction rate ($P_{\alpha,sim}$). A separate component of the ICRH is used in the role of auxiliary heating (plus constant 2MW NBI), under feedback control after t=20.5s thus stabilising the simulated "thermal runaway". Q_{eff} is defined in the text.

Figure 6: Simulated self-heated plasma experiment in which a component of ICRH is applied in proportion to a parameterised fit to thermal DT reaction rate ($P_{\alpha,sim}$). A separate component of the ICRH (P_{aux}) is used in the role of auxiliary heating (plus constant 2MW NBI), under feedback control after t = 20.5s thus stabilising the pronounced "thermal runaway" effect