D-T Fusion with Ion Cyclotron Resonance Heating in the JET Tokamak

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Ion cyclotron resonance heating (ICRH) experiments have been carried out in JET D-T plasmas using scenarios applicable to reactors. Deuterium minority heating in tritium plasmas is used for the first time and produces 1.66 MW of D-T fusion power for an ICRH power of 6 MW. The Q value is 0.22, which is a record for steady state discharges. Fundamental He^3 minority ICRH, in both 50:50 D-T and tritium dominated plasmas, generates strong bulk ion heating and ion temperatures up to 13 keV. Second harmonic tritium ICRH is seen to heat mainly the electrons as expected for JET conditions. All three schemes produce H-mode plasmas. [S0031-9007(98)06143-2]

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Ion cyclotron resonance heating is the only method of heating majority ions, rather than electrons, in the dense core of a tokamak reactor. Radiofrequency (rf) power is used to excite a fast magnetosonic wave, to which the high density plasma is accessible. The wave is absorbed at a cyclotron resonance which is positioned in major radius (usually the plasma center) by the choice of magnetic field and rf frequency. The ions damping the wave are often accelerated to suprathermal energies, especially if they are a minority species. This energy is then transferred to the thermal ions and electrons by Coulomb collisions. If the energy of the absorbing ions is less than a critical value, power flows mainly to the thermal ions rather than to the electrons. The critical energy at which the power to the electrons equals that to the ions is given [1] by $E_{\mathrm{crit}} = 14.8 A T_e [\Sigma n_j Z_j^2 / n_e A_j]^{2/3}$ where A is the atomic mass of the energetic ions, n_e is the electron density, Z is the atomic number, the sum is over the thermal ion species, and T_e is the electron temperature. For fast deuterons in a tritium plasma, $E_{\mathrm{crit}} = 14.2 T_e$. In the JET D-minority experiments, T_e is about 7 keV and $E_{\mathrm{crit}} \approx 100$ keV, which is also the deuteron energy at which the deuterium-tritium (D-T) fusion cross section peaks. High fusion power is thus achieved at the same time as equal ion and electron heating.

Several ion cyclotron resonance heating (ICRH) schemes in D-T plasmas have been included in the design of the JET system [2] which thus covers a wide frequency band, 23–57 MHz. The same schemes are being considered for the ITER reactor [3]. Three of these scenarios are minority deuterium and minority He^3 at their fundamental resonances and majority tritium at its second harmonic resonance. Recent calculations [4,5] for ITER predict that each method can produce more than 50% ion heating on the route to ignition. The present experiments have demonstrated and assessed the fundamental deuterium scheme, which has never been used previously. Also, the physics and performance of all three methods have been studied for the first time in H mode, D-T plasmas heated predominantly by ICRH. The plasmas were similar to those expected in ITER in terms of shape, safety factor (q), normalized confinement time, and the behavior of edge localized modes (ELMs), which affect the first wall power loading.

The experiments were carried out in single null divertor plasmas with currents in the range 3–3.7 MA and with a toroidal magnetic field, B_{T}, of either 3.4 or 3.7 T. The plasmas were either close to 50:50 D:T or were tritium rich mixtures. The central electron density was set to a value between 3.3×10^{19} and 5.3×10^{19} m^{-3}. The ICRH power was launched from antennas with π phasing between strap currents giving a toroidal wave vector of 7 m^{-1}. The frequency (f) was 28 MHz for the D-minority experiments which placed the resonance, $f = f_{\mathrm{CD}}$, in the plasma center (f_{CD} is the deuterium cyclotron frequency). Similarly, the $f_{\mathrm{CHe^3}}$ and $2f_{\mathrm{CT}}$ resonances were placed on axis by using 34 MHz at 3.4 T and 37 MHz at 3.7 T.

The neutron emission from the D-minority scheme, (D)T, was optimized by varying the plasma density and D:T ratio and by maximizing the rf power (P_{rf}). The best result, for which D : T = 9 : 91, is shown in Fig. 1. With an ICRH power of 6 MW, the DT fusion rate reached 5.9×10^{17} s^{-1} corresponding to a fusion power (P_{fus}) of 1.66 MW. The peak Q value was 0.25, were $Q = P_{\mathrm{fus}}/(P_{\mathrm{rf}} + P_{\mathrm{OH}})$ and P_{OH} is the Ohmic power. The fusion power remains above 1.5 MW for the length (2.7 s) of the ICRH flat top, which is three energy replacement times. The steady state Q value ($= E_{\mathrm{fus}}/E_{\mathrm{in}}$) is 0.22 over this period. The ion temperature (T_i) was measured by active charge exchange spectroscopy (CXS) using neutral beam injection (NBI). The electron and ion temperatures in the plasma center are shown in Fig. 1. T_{io} reaches 6.6 ± 0.6 keV, and at the same time

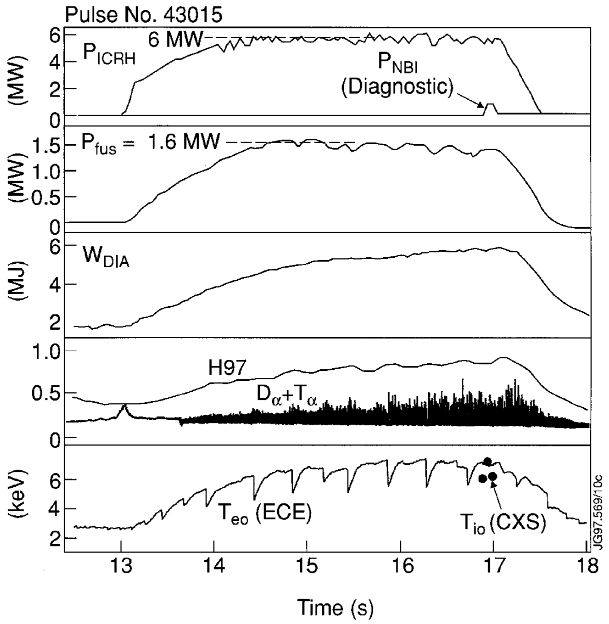

FIG. 1. H-mode plasma in which 6 MW of (D)T ICRH power gave $P_{\mathrm{fus}} = 1.66$ MW. ($I_p = 3.7$ MA, $n_{eo} = 5.1 \times 10^{19}$ m^{-3}).

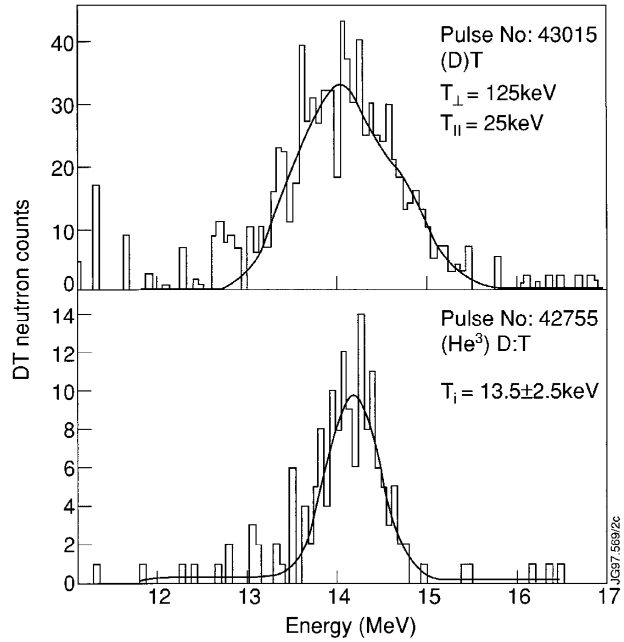

FIG. 2. Neutron energy spectra for (D)T and (He^3)DT ICRF heated H-mode plasmas.

$T_{eo} = 7.2 \pm 0.4$ keV. An H mode forms at 13.7 s, as shown by the appearance of ELMs modulating the Balmer-α emission, ($\mathrm{D}_\alpha + \mathrm{T}_\alpha$). The threshold power, defined as $P_{\mathrm{th}} = P_{\mathrm{rf}} + P_{\mathrm{OH}}\text{-}dW/dt$, is 4.2 MW compared with the value of 4.0 MW predicted by the scaling law $P_{\mathrm{th}} = 0.78\langle n_e\rangle^{0.75} B_{\mathrm{T}} R^2 A^{-1}$. This mass-dependent scaling is derived from recent JET DD and DT discharges [6]. In this expression $R(m)$ is the major radius, $\langle n_e\rangle$ is the average density in units of 10^{20} m^{-3}, B_{T} is in Tesla, and P_{th} is in MW. The H-mode confinement enhancement factor (H97), defined as the confinement time normalized to the ITERH-97P scaling law [7], reaches a value of 0.9 just before the NBI pulse. This enhancement factor, which fulfills one of the conditions for ignition in the ITER [7], corresponds to a stored energy (W) of 6.0 MJ and a confinement time $\tau_E = 0.87$ s. The ratio of the ELM period, ~4 ms, to τ_E gives an upper limit of 0.5% for the fraction of plasma energy released by each ELM, which is less than the ITER limit of 1% [8].

The observation of T_{io} similar to T_{eo} suggests that the average energy of the suprathermal deuterons is close to $E_{\mathrm{crit}} \sim 100$ keV as is verified by neutron spectrometer and neutral particle analyzer (NPA) measurements. The energy spectrum of the D-T neutrons (Fig. 2) shows considerable Doppler broadening due to the fast deuterons. Note the difference between the (D)T and (He^3)DT cases, the latter producing neutrons by thermal reaction with $T_i \approx 13$ keV. The spectrometer [9] views the plasma vertically, and so the broadening is mainly from the fast ion gyromotion. The (D)T data are fitted with an anisotropic Maxwellian deuteron distribution with the perpendicular ($T_\perp$) and parallel ($T_\parallel$) temperatures as parameters. A thermal component is also added. The best fit is for $T_\perp = 125 \pm 25$ keV, $T_\parallel = 25 \pm 10$ keV, and 12% thermal fraction; the T_i and n_i profiles give a 10% thermal fraction. The value for $T_\perp$ agrees reasonably well with the high energy NPA [10] result, $T_\perp \approx 90$ keV, in the energy range 0.25–1.1 MeV.

The total neutron emission is hardly affected by sawtooth crashes (Fig. 1). However, the neutron profile monitor shows that the emission profile is strongly perturbed. A tomographic reconstruction of the profile data for pulse 42 792, which has 1.2 MW of fusion power for 4.7 MW of ICRH, is shown in Fig. 3. A sawtooth crash occurred at 15.825 s. The reconstruction shows the profiles just before and just after the crash. The central emissivity falls by 70% to produce a much broadened profile. Since the neutrons are from suprathermal reactions, we conclude that the sawteeth redistribute this fraction of fast ions from inside to outside the $q = 1$ surface (minor radius $r/a = 0.35$). Similar neutron profile changes occur for He^3 minority heating, in which the neutrons are from thermal reactions. Thus, the sawteeth affect thermal and suprathermal ions alike, at least up to 100 keV energy.

The (D)T results have been simulated using the PION code [11], which self-consistently calculates the power absorption and the development of the fast ion velocity distribution function. The code also allows [12] for the redistribution of the fast ions by sawteeth. The calculated and observed neutron emissions agree closely as shown in Fig. 4. There are no free parameters in this calculation.

Typical results obtained with He^3 minority heating in a 40:60 D:T plasma ($I_p = 3.3$ MA, $B_{\mathrm{T}} = 3.7$ T) are shown in Fig. 5. The ICRF power was 7.6 MW at a frequency

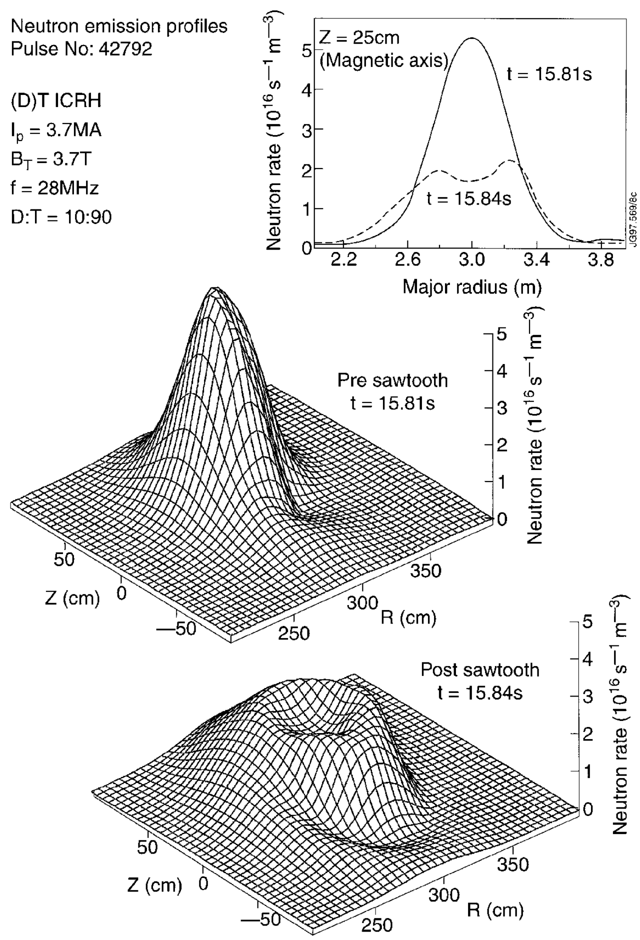

FIG. 3. Neutron emission profiles before and after a sawtooth crash akin to those seen on T_{eo} in Fig. 1. The (D)T reactions are due to rf accelerated deuterons with $\langle E_{\rm D} \rangle \sim 100$ keV.

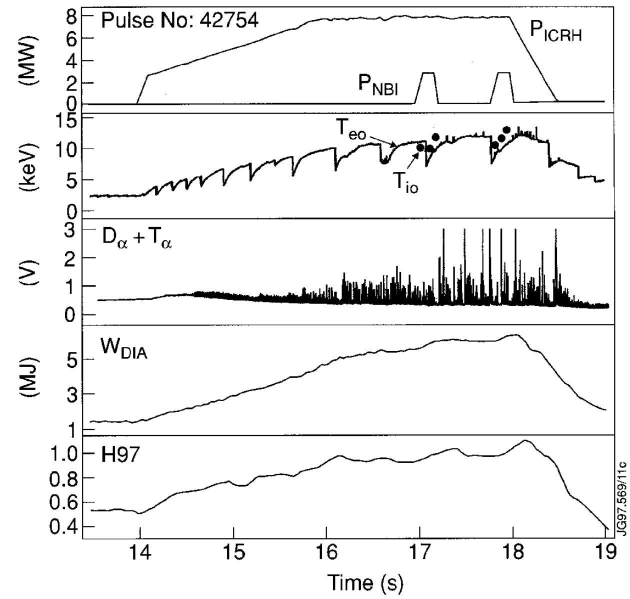

FIG. 5. Plasmas parameters for a 3.3 MA, 3.7 T discharge with 6.5% He^3 minority heating and 40:60 D:T.

of 37 MHz. An H mode occurs at 14.5 s, at which time $P_{\rm th} = 3.6$ MW in precise agreement with the scaling law [6]. The confinement increases during the power ramp and reaches H97 = 0.95 just before the diagnostic NBI pulse. The plasma energy is 6 MJ. The fast ion energy content is 0.6 MJ in agreement with the PION code prediction. The neutron emission is entirely from thermal reactions and reaches 1.8×10^{17} s^{-1} ($P_{\rm fus} = 0.5$ MW). The NBI pulses provide both T_i and He^3 density measurements. In pulse 42 754 the central He^3 density is 6.5% of the total ion density. In this case,

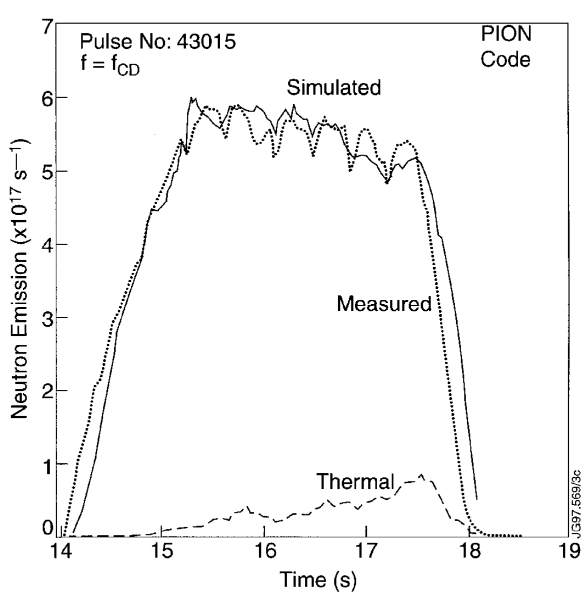

FIG. 4. Comparison of observed and calculated neutron emission produced by the (D)T scenario.

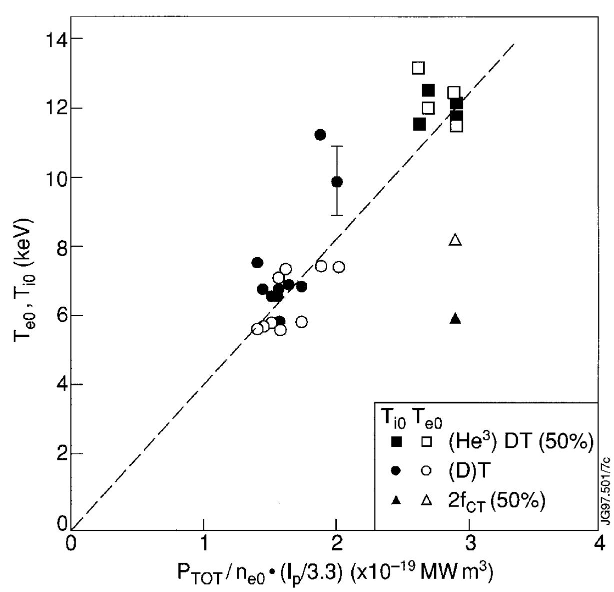

FIG. 6. T_{io} and T_{eo} values plotted against power per particle, corrected for changes in confinement with I_p. Large fast ion orbits reduce T_{eo} and T_{io} for the $2f_{\rm CT}$ case.

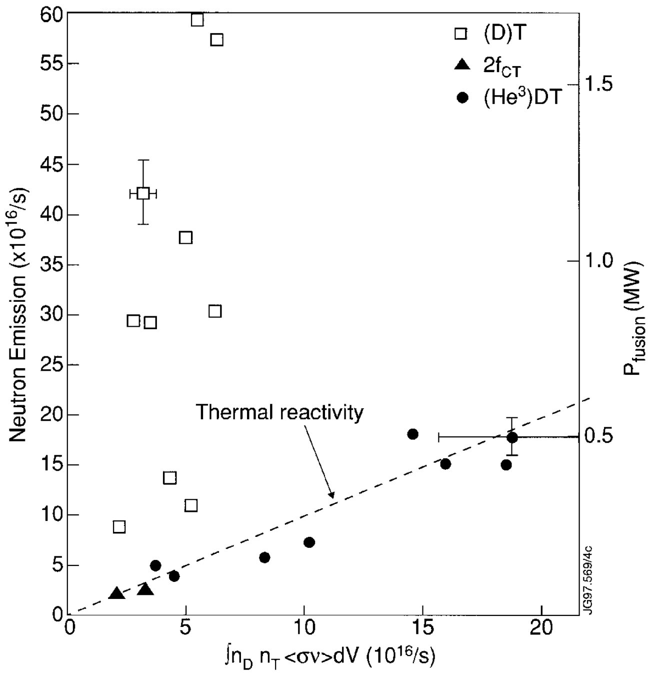

FIG. 7. Observed neutron emission versus thermal reactivity, emphasizing the suprathermal origin of the (D)T emission.

T_{io} reaches 12.5 keV, for $n_{eo} = 3.6 \times 10^{19}$ m^{-3}, and exceeds the electron temperature of 11.5 keV. Similar results are found with 10% He^3.

The Doppler broadening of the neutron spectrum due to the high central T_i can be seen in Fig. 2 for a 10% He^3 case. These data give $T_i = 13.3 \pm 2.5$ keV, in agreement with the CXS result, $T_{io} = 13 \pm 1$ keV. The near equality of T_i and T_e suggests that the ion and electron heating rates are similar, as is predicted by the PION code. For 6.5% He^3, the calculated power flows to the ions and electrons are 45% and 55% of $P_{\rm rf}$, respectively. Included in the electron heating is direct absorption by transit time magnetic pumping and Landau damping (10% of $P_{\rm rf}$). For 10% He^3, the fractions are 55% and 45%, respectively.

The JET results contrast with He^3 minority ICRH in supershots in the Tokamak Fusion Test Reactor (TFTR) where the rf power is absorbed mainly by high temperature tritons at the $2f_{\rm CT}$ resonance [13,14].

The temperatures for all three schemes are shown in Fig. 6. For the He^3 scenario the values lie around $T_{io} = T_{eo}$. For the (D)T scheme, T_{io} mostly exceeds T_{eo}. The $2f_{\rm CT}$ scheme mainly heats electrons ($T_e \approx 1.4 T_i$).

The highest neutron emission with $2f_{\rm CT}$ heating is 2.5×10^{16} s^{-1} in a 3.3 MA, 3.7 T plasma with D:T = 40:60, $n_{eo} = 3.2 \times 10^{19}$ m^{-3}, and $P_{\rm rf} = 8$ MW. An H mode is formed with H97 = 0.7. As shown in Fig. 7, the reactivity is close to thermal and is 15% of that with (He^3)DT under similar conditions. The reduced neutron production stems from the lower value of T_{io} (5.8 keV) compared with $T_{io} \approx 12.5$ keV for (He^3)DT. The observation of $T_e > T_i$ and a fast ion energy content of 1 MJ is evidence for a high energy triton tail such as those measured in TFTR, rf-only plasmas [15]. In the JET discharges there are toroidal Alfvén eigenmodes, which are excited by the precession resonance of very fast trapped ions. Neither the (D)T nor the (He^3)DT pulses generate these modes.

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