ICRF Heating of JET Plasmas with the Third-Harmonic Deuterium Resonance

L–G Eriksson, M J Mantsinen¹, F G Rimini, F Nguyen², C Gormenzano, D F H Start and A Gondhalekar.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, UK.
¹Association Euratom– Tekes, Helsinki University of Technology, Department of Engineering Physics and MATHematics, Rakentajanaukio 2C, FIN-02150 Espoo, Finland
²Centrd’Etudes de Cadarache, 13108 St Paul lez Durance Cedex, France
ABSRACT

ICRF heating experiments with the third-harmonic deuterium resonance in the plasma centre have been carried out at the Joint European Torus (JET). These experiments were the first to demonstrate third-harmonic damping on initially Maxwellian plasmas. A record DD-fusion reaction rate for ICRF-only heating on JET was achieved. In contrast to TORE SUPRA results for a similar ICRF scenario, the power absorbed directly by electrons was found to be relatively low. The difference between JET and TORE SUPRA data is attributed to the good confinement of MeV ions in JET allowing substantial fast ion tails to develop and thus large damping at the third-harmonic resonance to take place. The discharges have been simulated with the PION code (self-consistent calculation of the evolution of distribution function and ICRF power deposition). To obtain reasonable agreement between the measurements and simulations, three additions to the PION code were necessary: (1) parasitic absorption at the plasma edge, (2) a particle loss term that removes particles above 4 MeV, i.e. the particles that were not confined in the discharges, and (3) a sawtooth model which accounts in a simplified way for the redistribution of fast ions at the sawtooth crashes.

1. INTRODUCTION

Ion cyclotron range of frequencies (ICRF) heating using fast magnetosonic waves is one of the major methods for auxiliary heating of tokamaks. Resonant absorption of the ICRF waves takes place when the cyclotron frequency of the ions, or its harmonic, is close to the wave frequency ($\omega = n\omega_i, n\geq 1$). In this paper we report on experiments and theoretical simulations of third-harmonic heating in JET. These experiments were carried out to study the relative importance of the various absorption mechanisms in deuterium plasmas with $\omega = 3\omega_{CD}$, in the plasma centre. In particular, the experiments aimed at assessing the strength of direct electron damping and investigating the role played in the cyclotron absorption process by the high-energy tail formation on the resonating deuterium distribution function. The influence of high-energy tail formation on second-harmonic heating of deuterium has been already studied on JET [1], but in these previous experiments the effects of second-harmonic heating have been difficult to separate from those of the dominating fundamental hydrogen absorption. In the experiments reported in this paper no resonance other than the third-harmonic deuterium resonance is located in the plasma centre, and therefore the effects of higher-harmonic heating can be analysed in more detail. In addition to improving our understanding of the absorption mechanism for higher-harmonic heating, the third-harmonic heating experiments provided useful information on the confinement and physics of energetic particles with orbit widths similar to those of 3.5-MeV alpha particles from DT-fusion reactions.
The absorption mechanism for heating at harmonics of the ion cyclotron frequency \( (\omega = n\omega_{ci}, n \geq 2) \) is a finite Larmor radius effect. The fast magnetosonic wave is elliptically polarised, and hence we can divide the electric-field component perpendicular to the background magnetic field in two components: one component \((E_+)\) rotates in the same direction as the ions and the other component \((E_-)\) is counter-rotating. To the lowest order, it is \(E_+\) that gives rise to absorption.

For second-harmonic interaction, for example, the resonating particle is accelerated during one half of its Larmor orbit and decelerated during the other half. If the perpendicular wave number is \(k_\perp\) zero, the acceleration and deceleration cancel each other. Thus, interaction takes place only when \(k_\perp \rho\) is finite, where \(\rho\) is the Larmor radius. For higher harmonics the picture is essentially the same.

The power density absorbed by the resonating ions is given by

\[
\rho_{\text{abs}} = \int m v_\perp^2 D_{RF} \frac{\delta f}{\delta v_\perp} \, dv_\perp,
\]

where \(f\) is the distribution function of resonating ions, \(m\) is the mass and \(v_\perp\) is the perpendicular velocity. The diffusion coefficient scales as

\[
D_{RF} \propto \left[ E_+ J_{n-1} \left( \frac{k_\perp v_\perp}{\omega_{ci}} \right) + E_- J_{n-1} \left( \frac{k_\perp v_\perp}{\omega_{ci}} \right) \right]^2,
\]

where \(J_n\) is the Bessel function of first kind. From this expression one can see that the absorption for \(n \geq 2\) is weak at low perpendicular velocities, but increases with the perpendicular velocity until a maximum is reached, which for typical JET parameters occurs in the MeV range. Hence, the higher-harmonic damping for thermal plasmas is normally weak. This is the reason why third-harmonic damping has so far been observed mainly in discharges where the waves interact with neutral-beam-injected ions [2–4].

However, in order to obtain a significant third-harmonic absorption strength, it is in principle not necessary for the fast wave to interact with beam ions. Provided that the applied ICRF power density is high enough (i.e. \(E_+\) is large) and that the target plasma is sufficiently hot (i.e. large \(v_\perp\)) so that the higher-harmonic damping is not too weak initially, a high-energy tail will start to develop on the distribution function of the resonating ions. If the machine size and the plasma current are then large enough to confine the energetic ions, the absorption will be enhanced. As the high-energy tail evolves, more ions interact strongly with the wave and the absorption strength is further enhanced. Thus, it is possible to achieve significant damping with higher-harmonic interaction even if the distribution function of the resonating ions is initially Maxwellian. However, some time delay can be anticipated to allow for the fast ion distribution function to build up. The results presented in this paper demonstrate that all these conditions can be fulfilled in JET and that third-harmonic damping on initially Maxwellian plasmas takes place.
In competition with the third-harmonic absorption there is also direct electron heating via transit-time magnetic pumping (TTMP) and electron Landau damping (ELD). Direct electron damping depends strongly on the electron temperature and the parallel refractive index of the wave. By carefully avoiding hydrogen absorption at the plasma edge due to the fundamental and second-harmonic damping, significant direct electron damping was observed on TORE SUPRA during ICRF heating of deuterium plasmas with \( \omega = 3\omega_{\text{CD}} \) in the centre of the plasma [5]. However, such strong direct electron damping has not been observed in the JET discharges presented in this paper. As will be discussed later, a reason for this difference could be better confinement of high energy ions in JET.

The JET experiments were the first to demonstrate significant third-harmonic damping on initially Maxwellian plasmas. A record DD-fusion reaction rate of \( 1.8 \times 10^{16} \, \text{s}^{-1} \) for ICRF-only heating on JET was achieved. The DD-fusion reaction rate was found to scale with the sawtooth frequency, while the direct electron heating was found to be relatively weak. In addition, there is evidence which suggests the presence of a parasitic absorption mechanism at the plasma edge.

To properly model discharges with higher-harmonic heating, self-consistent calculations of ICRF power deposition and the distribution function of the resonating ions are required. The reason for this is the close interplay between the tail formation and ICRF power deposition. In this paper we use the PION code [1,6] to simulate the discharges. The code calculates, using simplified models, both the power deposition and the velocity distribution function; the absorption strength in the power deposition is consistent with the calculated distribution function. Three additions to the PION code were necessary in order to simulate the discharges: (1) parasitic damping at the plasma edge, (2) a particle loss term that removes particles with unconfined orbits, and (3) a sawtooth model that accounts, in a simplified way, for the redistribution of fast ions at the sawtooth crash. It was necessary to invoke the parasitic damping in order to explain the behaviour when the single-pass damping on deuterons and electrons was low. This was especially the case in the initial part of the heating phase when the deuteron distribution function was Maxwellian. Single-pass damping (third-harmonic + direct electron damping) is estimated to be 2.5–4\% for Maxwellian plasmas.

The paper is organised as follows. The experimental results are described in section 2. In section 3 numerical modelling of third-harmonic heating is discussed and results from simulations with the PION code are presented. Finally section 4 summarises our results.
2. EXPERIMENTAL RESULTS

2.1 Overview

Experiments on third harmonic deuterium damping were carried out in deuterium plasmas, in single null X-point pumped divertor configurations with a plasma current of 2 MA and toroidal field in the range of 2 T. Initial results from the analysis of the discharges have been reported in Ref. [7]. Up to 13 MW were applied with the A2 ICRF antennas [8] at a frequency of 51 MHz. As shown in Fig. 1, a small volume plasma was used so that the third harmonic deuterium resonance was located at the plasma centre, while both the fundamental and the second harmonic resonance of hydrogen were marginally present in the scrape-off layer. Different launched power spectra were used, from dipole (0π0π and 0ππ0) to current drive phasing (± 90°). Unless specified, the experiments described in this paper were carried out with dipole phasing.

The time evolution of the main plasma parameters is shown in Fig. 2 for two discharges at different levels of ICRH power. Strong sawtooth activity is observed, and in both cases the ion and electron temperature are typical of L-mode regime when ICRF power is applied. Typically, the ion temperature, measured at r/a = 0.3 , is of the order of 2–3 keV, while the central electron temperature reaches 5.5 keV. The diamagnetic stored energy can be up to 4.5 MJ.

At high ICRF power, the DD-fusion reaction rate increases strongly with time during the heating phase. In discharge 35525, the record JET value, for ICRH only, of $R_{DD}=1.8 \times 10^{16}$ s$^{-1}$ is obtained. At the same time, the presence of an energetic deuterium tail is measured by the high-energy Neutral Particle Analyser (NPA) [9]. The measured deuterium counts at different particle energies are shown in Fig. 3 for discharge 35525 together with the measured DD-fusion reaction rate. A distribution function for ICRF-driven deuterons is deduced from these measurement (Fig. 4) for discharge 35525 at $t = 17$ s, showing clearly the deuterium tail extending into the MeV range.

A comparison with a NBI-only ELM-free discharge having similar plasma current, magnetic field, power level and DD-fusion reaction rate is shown in Fig. 5. The fusion reaction rate is achieved in different ways in the two cases: NBI-only discharges are characterised by high ion temperatures and have a large fraction of ions at energies up to the NBI injection energy of 80–140 keV. In the third harmonic heating case, on the other hand, a tail of a few very energetic deuterium ions is produced up to the MeV range and a high DD-fusion reaction rate is observed because of the increase of the DD-fusion cross-section by almost one order of magnitude when going from about 100 keV to its maximum around 3 MeV.

At lower ICRH power and density [Fig. 2 (b)] the DD-fusion reaction rate is nearly 20 times smaller than for discharge 35525. The strong scaling of the DD-fusion reaction rate with ICRF power is summarised in Fig. 6. The dependence of increase in the diamagnetic stored energy on the applied power has been found to be somewhat weaker (Fig. 7). It is interesting to note that no
increase in the plasma energy, electron temperature or DD-fusion reaction rate is observed at ICRF power levels below 4 MW.

2.2 Correlation between the DD-fusion reaction rate and the sawtooth frequency

As discussed above, the DD-fusion reaction rate depends strongly on applied ICRF power for JET discharges with third-harmonic deuterium heating. However, for some cases the fusion reaction rate is found to be about ten times smaller than in other discharges at a comparable ICRF power level (Fig. 6). A closer investigation of the discharges shows that there is a correlation between the fusion reaction rate and the sawtooth frequency: at high sawtooth frequencies, lower fusion reaction rates are observed. A better fit to the data is obtained when the fusion reaction rate is plotted as a function of \( f_{\text{sawtooth}} / P_{\text{ICRH}} \) as shown in Fig. 8. Here, is the total applied ICRF power and \( f_{\text{sawtooth}} \) is the sawtooth frequency.

A possible explanation, which we will explore in section 3.3, for the correlation between the DD-fusion reaction rate and the sawtooth frequency is that the fast ions are redistributed at the sawtooth crashes: this would decrease the third-harmonic damping in the centre and increase the role of competing absorption mechanisms. Candidates for the competing absorption mechanism are discussed in the following subsections. It is, however, difficult to determine what is the effect and what is the cause of the observed correlation. In some discharges the plasma conditions appear to have been such that the fast-particle pressure was enough to stabilise the sawteeth [10], and the fast-particle pressure was further enhanced. For other discharges the fast-particle pressure was not enough to stabilise the sawteeth and the fast-particle pressure was reduced even further by the sawteeth.

There is previous experimental evidence suggesting that fast ions could be affected by sawtooth activity. Recent NBI experiments at JET have shown that the redistribution of fast particles depends on the initial spatial width of their density profile: the redistribution is stronger when the density profile is narrow [11]. For sawtooothing plasmas in TFTR measurements using energetic neutral particle analyser in combination with lithium pellets show a significant outward transport of trapped fusion-born (3.5 MeV) alpha particles, while the alpha particles in the plasma core of sawtooth-free discharges are found to be well-confined [12]. There are also indications that ions accelerated to energies in the MeV range by ICRF heating are affected by sawtooth activity [1, 13].
2.3 Direct electron heating

One of the possible explanations for the observed lower fusion reaction rate at higher sawtooth frequencies is stronger direct electron heating. This possibility, however, is not supported by measurements. The power density going directly to electrons can be estimated from the slope of the electron temperature rise after a sawtooth crash; this method assumes that the electron temperature (and density) profile becomes flat at the sawtooth crash and hence that the energy conduction can be neglected. A more accurate method is to estimate the direct electron damping by measuring the change in the time derivative of the electron temperature at a rapid (<10 ms) switch-on or switch-off of the ICRF power. Here we use both methods.

Figure 9 shows as $n_e(0)\dot{T}_e(0)/P_{ICRH}$ a function of sawtooth frequency for the JET discharges with third-harmonic heating, where $n_e(0)$ is the central electron density, $P_{ICRH}$ is the applied ICRF power and $\dot{T}_e(0)$ is the time derivative of the central electron temperature from electron cyclotron emission (ECE) measurements during the rise phase after a sawtooth crash. As can be seen in Fig. 9, there is no direct correlation between $\dot{T}_e$ and the sawtooth frequency. The radial profile of the direct electron heating power in the plasma centre inside the mixing radius, measured at different power levels after a sawtooth crash and at a power switch-on, is shown for a typical third-harmonic discharge in Fig. 10. Fitting a Gaussian to the measured points and integrating over the plasma volume gives power levels for direct electron heating of the order of 1-2 MW while the total ICRF power is in excess of 10 MW. This is in good agreement with PION code results, which will be discussed in more detail in section 3.

The measurements discussed above indicate that the good direct electron heating observed with a similar scenario on TORE SUPRA is not found in JET. This is probably because of the better confinement of high-energy ions in JET. A similar result to that in JET has been obtained in TEXTOR, where no significant coupling of ICRF power was observed for a similar ICRF heating scenario [4]. Small amounts of ICRF power caused large density excursions on TEXTOR and attempts to force more power into the plasma lead to a disruption. Application of neutral-beam heating, designed to increase the electron temperature, resulted in third-harmonic damping on neutral-beam ions, while the direct electron damping remained low [4].

2.4 Parasitic absorption

Since the direct electron damping for third-harmonic heating was relatively low and showed no increase with the sawtooth frequency, other explanations for Fig. 8 have to be found. The possibility that not all of the ICRF power was coupled to the plasma for the discharges could be such an explanation. This possibility is further supported by the confinement properties of the
discharges. Figure 11 shows Dα-signal, applied ICRF power, total radiated power, H-mode power threshold, H-mode factor and electron density for discharges 35525 and 35529. Here the H-mode factor is measured relative to the ITER89-P scaling law [14], i.e., \( J_H = \frac{\tau_{E,\text{exp}}}{\tau_{E,\text{ITER89-P}}} \), where \( \tau_{E,\text{exp}} \) is the experimental energy confinement time and \( \tau_{E,\text{ITER89-P}} \) is the energy confinement time predicted by the ITER89-P scaling law.

The H-mode power threshold [15] for discharges 35525 and 35529 is estimated to be about 6–7 MW, and is therefore more than two times lower than the applied ICRF power (Fig. 11). Consequently, one would expect a transition into H-mode in both discharges. However, as we can see from the D-signals, H-mode factors and electron densities (Fig. 11), only discharge 35525 develops H-mode confinement while discharge 35529 remains in L-mode. This results clearly indicates that a part of the applied ICRF is not coupled to discharge 35529.

In the following we call parasitic absorption the mechanism which appears to have prevented the coupling of a large fraction of the applied ICRF power to the plasma. This parasitic absorption seems to take place in the scrape-off layer since the power absorbed by this mechanism does not appear in the measured plasma energy content. The reason why the parasitic absorption appears to play an important role for the JET discharges with third-harmonic heating is the weak single-pass absorption for these discharges. For a Maxwellian plasma the single-pass (third-harmonic + direct electron) damping is estimated to be 2.5–4%. These observations are comparable to DIII-D results where degradation of fast-wave current drive has been observed due to parasitic coupling when the first-pass absorption was less than 8% [16].

The nature of the parasitic absorption in JET is at the moment unknown. The candidates responsible for the parasitic damping include mode conversion and hydrogen damping at the plasma edge, parasitic decay activity, wall loss and sheath formation. Simulations with the FEM code [17], however, have not revealed candidates for possible mode conversion at the edge plasma. Furthermore, according to LION [18] code calculations, absorption by the first and the second-harmonic hydrogen resonance, when the corresponding resonance is moved just inside the plasma, is too weak compared to direct electron heating to explain the observations. There is experimental evidence for parametric decay activity, but no significant difference has been observed between discharges with relatively high and relatively low sawtooth frequencies. Present models for sheath formation also have difficulties to explain the observations since no significant differences between the 0π0π-phasing and 0pp0-phasing have been observed (see Fig. 6). Hence, no conclusive explanation for the mechanism giving rise to the parasitic absorption has yet been found. The role of stochastic ion heating in the vicinity of the fundamental and second-harmonic hydrogen resonance [19] remains still to be assessed.
3. SIMULATION RESULTS

3.1 Reference simulation without parasitic damping

Because of the close interplay between the development of the high-energy tail and the power deposition for higher-harmonic heating, the two phenomena have to be calculated self-consistently. In this paper we use the PION code [1, 6] to simulate the third-harmonic heating experiments. PION is a time-dependent code which calculates the ICRF power deposition and the velocity distribution function of the resonating ions. At the beginning of each time step the power deposition is calculated; the output is then used to calculate time evolution of the distribution function with a Fokker-Planck model; the output from the Fokker-Planck calculation at the end of the time step is used in the power deposition at the next time step; this procedure is repeated until the end of the calculation.

The power deposition is calculated by first Fourier decomposing the launched wave in the toroidal direction; the power deposition is then calculated for each toroidal mode number according to the model described in Refs. [20, 21]. This model was partly obtained by analysing results from the full wave code LION [18]. Consequently, the deposition profiles provided by the model are normally in good agreement with those of the LION code. Owing to finite Larmor radius effects, the absorption strength depends on the distribution function of the resonating ions. In order to take this into account, the dielectric tensor components used in the power deposition are updated, using results from the Fokker-Planck calculation, at the beginning of each time step according to the procedure described in Ref. [6].

The distribution function of the resonating ions is calculated with a time-dependent 1D Fokker-Planck equation [1]. Effects due to finite orbit widths are taken into account by assuming that the fast ions have turning points close to the cyclotron resonance (i.e. where \( \omega = n \omega_{ci} \) ) and then averaging the collision coefficients over the resulting orbits. Furthermore, the averaged square parallel velocity, which is used to determine the Doppler broadening of the cyclotron resonance in the power deposition calculation, is obtained from an ad hoc formula derived in Ref. [22].

Effects due to finite orbit widths can play an important role in the JET third-harmonic heating scenario since the plasma current is low and very energetic ions are created. For the magnetic field and the plasma current used in the discharges with third-harmonic heating, particles with energies above about 4 MeV were so energetic that they intersected the wall. To take this into account, a particle loss term that removes particles above 4 MeV was included in the PION code. In order to maintain the experimental density of deuterons, a source term adding thermal particles was used.
The PION code can use as input either plasma parameters and profiles from the JET experimental data base, or data provided by the user. To demonstrate the basic physics effects of third-harmonic heating, we specify the back-ground plasma parameters so that they do not change during the simulation. In Fig. 12 the time-evolution of the distribution function and power deposition are shown for this reference simulation. Here, the toroidal magnetic field at the axis is 2.25 T and 10 MW of ICRF power with the wave frequency of 51.3\,\text{kHz} is applied in the 0\pi0\pi–phasing. The plasma consists of deuterium with a central density of \(2.8\times10^{19}\,\text{m}^{-3}\) and of hydrogen, beryllium and carbon (with a density equal to about 4.3%, 1.7% and 1.7% of the deuterium density, respectively). Both the central ion and central electron temperature are 2.5 keV, and the density and temperature profiles are assumed to be of the form \(n, T = n_0, T_0 (1–0.9s^2)\alpha_n,\alpha_T\), where \(\alpha_n = 0.25,\ \alpha_T = 1,\ \text{s} = \sqrt{\psi/\psi(a)}\), and \(\psi(a)\) is the poloidal flux function at the plasma edge. In this calculation no parasitic damping is taken into account.

As can be seen in Fig. 12(a), direct electron damping dominates in the beginning of the simulation, while later the third-harmonic damping starts gradually to dominate. The creation of an energetic tail is illustrated in Fig. 12(b). Gradually more and more ions interact with the wave until a steady state is reached. In the steady state the fast-particle energy content is 0.73 MJ. Due to finite-orbit-widths effects the profile of the collisional power transfer from fast ions to electrons is broader than the third-harmonic damping profile. These profiles in the end of the calculation are shown in Fig. 12(c). Most of the power that is absorbed by the third-harmonic resonance is transferred collisionally to electrons, while the power to the ions remains small [Fig. 12(a)]. The importance of confining high-energy ions for the third-harmonic absorption is illustrated in Fig. 13, where the integral \(\int_0^E (dp/dE’)dE’\) in the plasma centre is plotted as a function of energy \(E\). As can be seen, most of the ICRF power is absorbed between 1 and 4 MeV. Thus, it is vital for the third-harmonic damping that the ions in the MeV range are confined. A probable explanation for the observed strong direct electron heating on TORE SUPRA for a similar heating scenario is therefore lack of high-energy ion confinement.

It should be noted, however, that the PION code does not include all effects that are relevant for third-harmonic heating. In particular, wave-induced spatial diffusion is expected to play some role for the very energetic ions created during third-harmonic heating. A more detailed analysis of this effect will be the subject of a future study. Another effect which is difficult to estimate is the influence of possible adiabatic barriers [23-26]. In the simulations presented below we have assumed that there are no adiabatic barriers. However, by introducing a cut-off in the ICRF operator at high energies we have qualitatively investigated the effect of an adiabatic barrier and in general have found worse agreement with experimental data than in the absence of such a barrier.
3.2 Discharges with relatively low sawtooth frequency

PION simulations using experimental data as input and where parasitic absorption at the plasma edge (single-pass absorption of the order of 5–10%) and particle losses above 4 MeV are taken into account are able to predict the DD-fusion reaction rate for the two best performing discharges 35525 (0pp0-phasing) and 35526 (0p0p-phasing). Figure 14 shows the comparison between the measured and simulated DD-fusion reaction rates for these discharges. The agreement is reasonably good in spite of simplifications in the modelling. In particular, the model is able to predict the delayed onset of the increase in the DD-fusion reaction rate after the ICRF power is switched on. This is found to be possible only when parasitic absorption is taken into account. Furthermore, the rise in the DD-fusion reaction rate at the end of the ICRF phase is, according to the simulation, due to the increasing deuterium density. As a result of the increasing density the fast ions become less energetic, i.e. less orbit losses occur while the fraction of fast ions stays roughly constant. The DD-fusion reactivity, which is dominated by reactions between fast and thermal ions, therefore increases with the bulk deuterium density. It is also interesting to note that if the cut-off energy of 4 MeV above which the particle losses are included in the PION code is decreased to 3 MeV, the simulated DD-fusion reaction rate for discharge 35525 decreases by more than a factor of two, and hence the agreement with the measured DD-fusion reaction rate is lost. This result clearly illustrates the good confinement of high-energy ions in JET. On the other hand, when the cut-energy is increased to 5 MeV in the calculations, the neutron rate is overestimated.

The third-harmonic deuterium absorption, direct electron absorption and the parasitic absorption as given by the PION code are shown in Fig. 15(a) for discharge 35525. As one can see, the third-harmonic damping starts to dominate quite early in the discharge while the direct electron damping remains below 2 MW. This result is in good agreement with the measurements of the electron re-heating in the centre as discussed in section 2. The experimental fast-ion energy content can be obtained by taking the difference between two different measurements of the plasma stored energy [1]. The simulated fast-particle energy content in Fig. 15(b) is also in good agreement with the experimental estimate.

3.3 Discharges with higher sawtooth frequency

When the sawtooth frequency is higher than in discharges 35525 and 35526, PION tends to overestimate the DD-fusion reaction rate. A possible explanation for this is, as discussed in section 2, that the fast deuterium tail ions, in particular the turning points of trapped ions, are expelled by the sawteeth from the plasma centre, which consequently decreases the single-pass absorption and increases the possible parasitic absorption. To simulate the discharges with high
sawtooth frequency, a sawtooth model was implemented in the PION code. In the model a given fraction of fast ions is redistributed from the plasma centre at the sawtooth crashes.

With the sawtooth model we are able to simulate the discharges with the higher sawtooth frequencies reasonably well. Figure 16 shows the measured and simulated DD-fusion reaction rate with and without the sawtooth model for discharge 35319 (see Fig. 2 for the main plasma parameters). When the number density of the tail is decreased by 70% at the sawtooth crash, the agreement with the measurement is reasonably good, while without the sawtooth model the DD-fusion reaction rate is overestimated by more than a factor of two. Figure 16 shows also the power absorbed at the third-harmonic resonance and direct electron damping simulated with and without the sawtooth model. As can be seen, the main difference is in the third-harmonic damping while the direct electron damping remains almost unchanged. In the simulation the power not absorbed at the third-harmonic resonance in the presence of sawteeth is absorbed by the parasitic absorption mechanism.

4. SUMMARY AND DISCUSSION

ICRF heating experiments with third-harmonic deuterium resonance in the centre of the JET plasma have been analysed. These discharges were the first to demonstrate third-harmonic damping on initially Maxwellian plasmas. In addition, H-modes and record DD-fusion reaction rate on JET for ICRF alone were achieved with these discharges. Other typical features of the discharges include the correlation between the DD-fusion reaction rate and the sawtooth frequency, relatively low direct electron heating and parasitic absorption at the plasma edge.

The discharges have been successfully simulated with the PION code that calculates self-consistently, using simplified models, the evolution of power deposition and the distribution function of the resonating ions. To obtain reasonable agreement with the experiments, three additions to the PION code were necessary. Firstly, an ion loss term representing lack of deuteron confinement at high energy due to low plasma current was included in the code. The cut-off energy for the discharges reported here was 4 MeV. When the cut-off energy was decreased to 3 MeV, the DD-fusion reaction rate for the best-performing discharges was underestimated by a factor of two. This indicates that ions up to energies of a few MeV can be confined in JET with a plasma current of 2 MA. Secondly, parasitic absorption had to be taken into account in the simulations. The parasitic absorption takes place at the plasma edge, since the power absorbed by this mechanism does not appear in the measured plasma energy content. The reason why the parasitic absorption appears to have played such an important role for the JET discharges with third-harmonic heating is the weak single-pass absorption due to direct electron heating and third-harmonic damping for these cases. Several candidates for the parasitic absorption have
been considered, but a conclusive explanation remains still to be found. Finally, a sawtooth model was developed to take into account in a simplified way the redistribution of fast ions at sawtooth crashes. The redistribution of fast ions is one of the possible explanations for the observed correlation between the DD-fusion reaction rate and the sawtooth frequency. With the sawtooth model reasonable agreement with the measurements could be obtained for discharges with a relatively high sawtooth frequency.

Analysis of the JET discharges with third-harmonic heating of deuterium indicates that the theoretical picture of higher-harmonic heating is generally correct. This gives confidence in future experiments and simulations of ICRF heating at higher harmonics of an ion cyclotron frequency in JET and in future reactors.

**Acknowledgements**

The authors gratefully acknowledge the support of the JET experimental team, and in particular of the Task Force T and the RF Division personnel. The work carried out by two of the authors (MM and FN) was done under task agreements between JET Joint Undertaking and Association EURATOM-TEKES (MM) and JET Joint Undertaking and Association EURATOM-CEA (FN).

**References**


Fig. 1 Location of the different ion cyclotron layers on a poloidal view of the plasma. The third harmonic deuterium resonance is located at the plasma centre, while both the fundamental and the second harmonic resonance of hydrogen are marginally present in the scrape-off layer.
Figure 2 ICRF power, total radiated power, DD-fusion reaction rate, plasma diamagnetic energy, line-averaged electron density and central electron and ion temperature (Top) for discharge 35525 and (Bottom) for discharge 35319.
Figure 3 ICRF power, DD-fusion reaction rate, and deuterium counts measured by the neutral particle analyser (NPA) at 287, 455, 680 and 1100 keV for discharge 35525.

Figure 4 Deuterium distribution function measured by NPA at t = 17 s for discharge 35525.
Figure 5 Comparison of plasma parameters for NBI-heated discharge 34489 and for discharge 35525: DD-fusion reaction rate, central electron temperature, line-averaged electron density, plasma diamagnetic energy, NBI and ICRF power, and plasma current.

Figure 6 DD-fusion reaction rate as a function of ICRF power for all JET discharges with third-harmonic heating. Note that the plasma density increases with the increasing ICRF power.
Figure 7 Change in the plasma diamagnetic energy as a function of the applied ICRF power.

Figure 8 Measured DD-fusion reaction rate as a function of $f_{\text{sawtooth}}/P_{\text{ICRH}}$, where $P_{\text{ICRH}}$ is the applied ICRF power and $f_{\text{sawtooth}}$ is the sawtooth frequency.
Figure 9 Central electron re-heating power density divided by the total ICRF power as a function of sawtooth frequency for discharges with third-harmonic heating.

Figure 10 Direct electron heating profile in the plasma centre inside the mixing radius for discharge 35526 as measured from the change in the slope of the electron temperature at a power switch-on to 5.9 MW of ICRF power (cross), and as measured from the slope of electron temperature during the rise phase after a sawtooth crash at 7 MW (circle), 10 MW (square) and 12 MW (triangle) of ICRF power.
Figure 11 $D_\alpha$-signal, applied ICRF power, total radiated power, H-mode power threshold, H-mode factor relative to ITER89-P scaling law, and line-averaged electron density (Top) for discharge 35525 and (Bottom) for discharge 35529.
Figure 12 (a) The time evolution of third-harmonic and direct electron damping and the collisional power transfer to electrons and ions as given by PION. The total ICRF power is 10 MW. No parasitic damping is taken into account.

Figure 12 (b) The logarithm of the simulated deuterium distribution function at \( t = 0, 0.1, 0.2, 0.3, 0.4, 0.6, 1.0 \) and 2.0 s.
Figure 12  (c) Comparison between simulated third-harmonic damping profile and profile of the collisional power transfer to electrons. Here, the collisional power transfer profile has been multiplied by a factor of five.

Figure 13 The integral $\int_{0}^{E} \frac{dp_{D}}{dE'} dE'$ as a function of energy $E$ in the plasma centre.
Figure 14 Comparison between the measured and the simulated DD-fusion reaction rate (Top) for discharge 35525 and (Bottom) for discharge 35526.
Figure 15 (Top) Simulated power partition between parasitic, third-harmonic and direct electron damping and (Bottom) comparison between the measured and simulated fast particle energy content for discharge 35525.
Figure 16 (Top) Comparison between the measured and the simulated DD-fusion reaction rate with and without the sawtooth model for discharge 35319. (Bottom) Power absorbed by the third-harmonic resonance and by direct electron damping simulated with and without the sawtooth model for discharge 35319.