JET–CP(98)23

Theoretical Analysis of ICRF Heating in JET DT Plasmas

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INTRODUCTION.

Heating with waves in the Ion Cyclotron Range of Frequencies (ICRF) is one of the main methods envisaged for auxiliary heating in ITER and in future reactors. There are several possibilities for heating a Deuterium Tritium (DT) plasma in a reactor. The main scenarios are: fundamental minority heating of deuterium ($\omega = \omega_{cD}$) in a tritium rich plasma ($n_D/(n_D + n_T) \sim 10 - 30\%$); and second harmonic heating of tritium ($\omega = 2\omega_{cT}$) in a 50:50 DT plasma. Both these scenarios have been tested during the recent DT campaign in JET [1]. An analysis of the experimental results by comparison with code simulations are presented in this paper.

The code used for the simulations is the PION code [2]. This code calculates the ICRF power deposition and the velocity distribution of the resonating ions. Furthermore, the influence of the velocity distribution function on the power deposition is taken into account. A model for redistribution of fast ions during sawtooth crashes [3] has been included in the PION code since the influence of crashes on the neutron profile has been found to be significant [1] during $\omega = \omega_{cD}$ heating. The code is based on simplified models and is therefore relatively fast. Furthermore, all input data to the code are taken directly from the JET data base.

FUNDAMENTAL MINORITY HEATING OF DEUTERIUM.

The scenario with fundamental minority heating of deuterium ($\omega = \omega_{cD}$) has for the first time been tested in JET. This proved to be a very successful scenario for achieving high Q-values with ICRF alone [1]. In Fig. 1 an overview of a discharge with $\omega = \omega_{cD}$ is shown. As can be seen, a Q of 0.25 was achieved with 6MW of RF-power alone. Furthermore, the ion temperature in the centre is almost equal to the electron temperature, indicating good ion heating. A comparison between the measured and simulated neutron rate is shown in Fig 2. The agreement is very good, with the calculated non-thermal contribution being as high as 90%. As can be seen, the inclusion of sawtooth redistribution only slightly modifies the calculated global neutron rate. According to the simulations the power partition among the absorbing species was as follows: 70% on deuterons; 15-20% on beryllium and carbon impurities; 10% direct electron damping via Electron Landau Damping (ELD) and Transit Time Magnetic

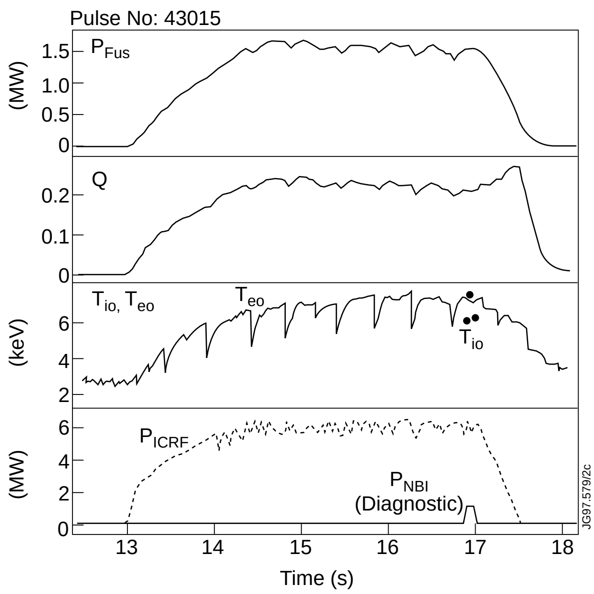

Fig. 1 Fusion power, Q value, central electron and ion temperatures and auxiliary heating powers for a discharge with $\omega = \omega_{cD}$ heating

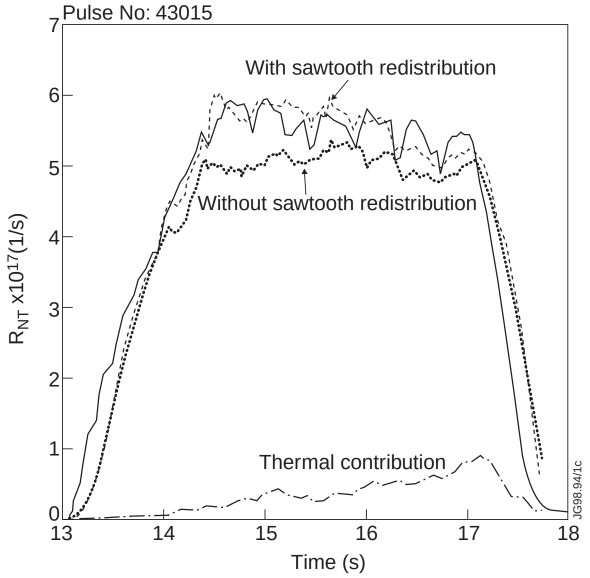

Fig. 2 Measured and simulated neutron yield for $\omega = \omega_{cD}$ heating.

Pumping (TTMP); and, using the Budden formula [2], the mode converted power fraction is estimated to be about 5%. The calculated partition of the power going to the thermal plasma (via collision with fast deuterons and direct electron damping) shows that the power going to ions and electrons were comparable during most of the discharge, which is consistent with the measured ion and electron temperatures.

Good agreement between measured and calculated neutron rates has been found for discharges with moderate deuterium concentrations (around 10% or less). However, PION overestimates the neutron rate at high concentrations. The power deposition model in PION has a very simplistic description of mode conversion. This model may not be adequate to treat cases with high fractions of mode converted power, as is the case at high concentrations.

SECOND HARMONIC HEATING OF TRITIUM.

The absorption mechanism at second harmonic heating is a finite Larmor radius effect. As a result, the damping on tritons is expected to be poor during the initial phase of an ICRF heating pulse on JET, but should improve as the ion temperature increase and a high energy tail develops on the triton distribution function. Unfortunately, on JET the tail on the triton distribution function tends to consist of a small number of very energetic ions, which mainly heat the electrons through collisions and do not contribute much to the DT fusion reactivity (DT fusion cross-section peaks at around 100keV). These expectations are consistent with the experimental findings. In Fig. 3 an overview of two discharges is shown. In one discharge pure $\omega = 2\omega_{cT}$ heating was used whereas in the second a small amount of ^{3}He (~6%) was added. As compared to the $\omega = \omega_{cD}$ scenario, the neutron rate in the pure $\omega = 2\omega_{cT}$ scenario is about an order of magnitude lower. Furthermore, the ion temperature is significantly lower than the electron temperature, indicating less effective ion heating. A comparison between the simulated and measured neutron yield is shown in Fig. 4. Again the agreement is very good, with about 20% of the neutrons being non-thermal according to the calculations. In particular, note the good agreement during the beam blips, which indicates that the slowing down of the injected and ICRF heated tritons is classical. The partition of the power among the absorbing species is shown in Fig. 5. As the ion temperature increases and a tail develops on the triton distribution function, the power absorbed on the tritons increases and reaches about 45% of the ICRF power. If the influence of triton tail on the power deposition is neglected in the simulations, the fraction of the power

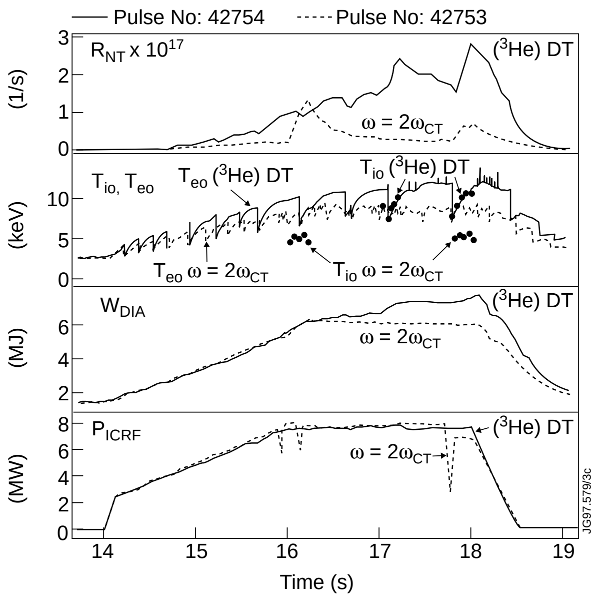

Fig. 3 Neutron rate, central electron and ion temperatures, diamagnetic energy and auxiliary heating powers for $\omega = 2\omega_{cT}$

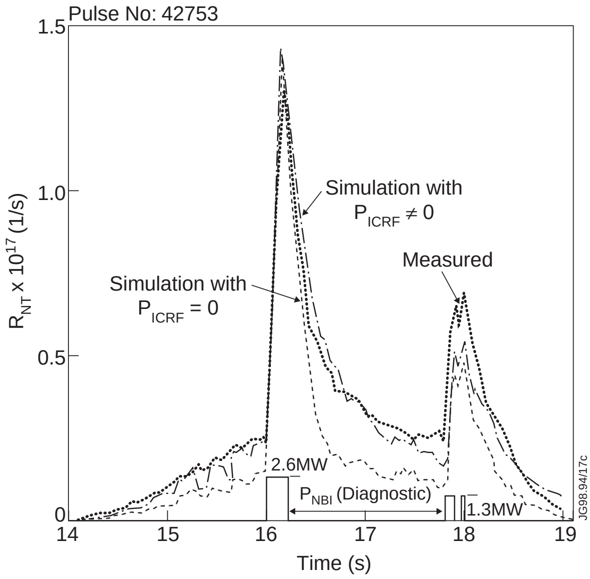

Fig. 4 Measured and simulated neutron rate for $\omega = 2\omega_{cT}$ *heating.and* (^{3}He)DT *heating.*

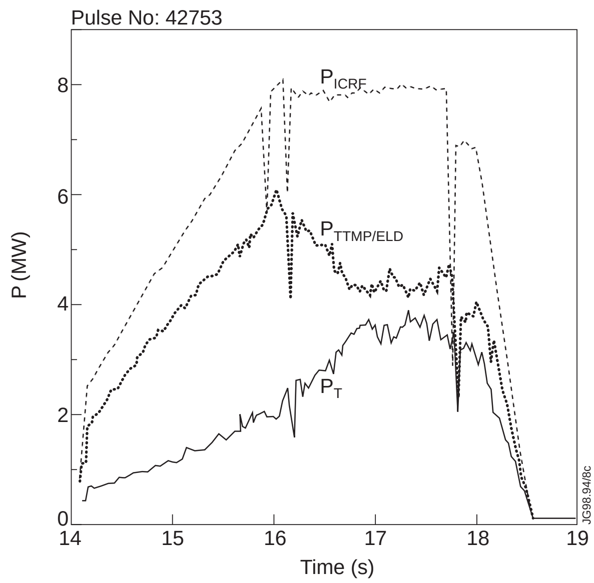

Fig. 5 Partition of absorbed power for $\omega = 2\omega_{cT}$ *heating.*

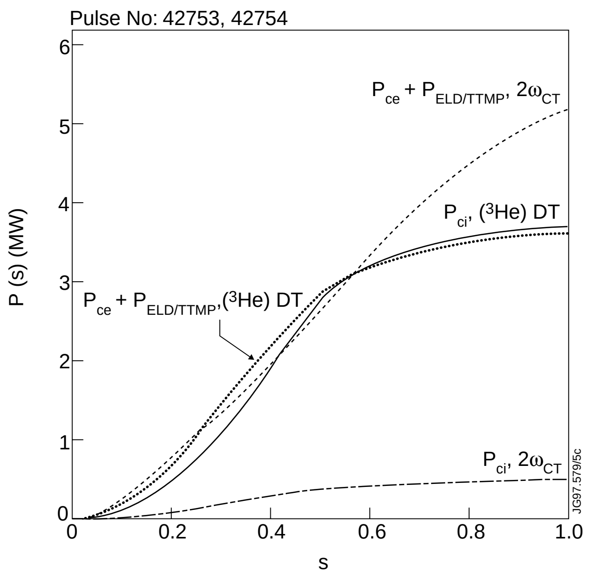

Fig. 6 Profiles of volume integrated thermal ion and electron heating power densities for $\omega = 2\omega_{cT}$ *and* (^{3}He)DT *heating.*

going to tritons is only 10%, which clearly shows the importance of the high energy tail for the absorption. The simulations also suggest that about a 1 MW of the coupled 8 MW of power is being lost by energetic tritons with orbits intersecting the wall.

When a few percent of ^{3}He is added, the ion heating, as can be seen in Fig. 3, is dramatically improved. The code simulations suggest that most of the power is now absorbed by the ^{3}He minority ions ($\omega_{c^3He} = 2\omega_{cT}$). The high critical velocity for the ^{3}He ions together with the fact that ions are accelerated more uniformly in velocity space lead to good ion heating. The calculated profiles of the volume integrated thermal ion and electron heating power densities, averaged over a sawtooth period, are shown in Fig. 6. As can be seen, the ion heating is much better when a few percent ^{3}He is included.

CONCLUSIONS.

The physics on which the PION code is based seems sufficient for describing most of the global behaviour ICRF related quantities for the ICRF heating scenarios tested in the recent DT campaign at JET. The calculations suggest that a high non-thermal yield and good ion heating can be obtained with $\omega = \omega_{cD}$ heating in a tritium rich plasmas. However, discrepancies between the PION calculations and measurements appear at high deuterium concentrations, possibly due to significant mode conversion. To improve the ion heating during $\omega = 2\omega_{cT}$ heating in JET, a few percent of ^{3}He needs to be added. However, it should be noted that PION simulations carried out for ITER suggest that pure $\omega = 2\omega_{cT}$ can provide adequate ion heating in ITER if an appropriate path to ignition is followed [4].

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