EFDA–JET–PR(10)60

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

ABSTRACT.

Fast ions were analysed in experiments focusing on fundamental ^{3}He minority and mode conversion ICRF heating in H plasmas and on 2nd harmonic heating of ^{3}He ions at 2.65T mimicking D-T plasma heating in ITER at half its nominal toroidal magnetic field. Gamma-ray spectrometry, neutral particle analysers and fast-ion lost diagnostics provided information on the generation of fast-ion populations and on the distribution of ICRH power among the species in various heating scenarios and for a large range of ^{3}He concentrations.

1. INTRODUCTION

Ion Cyclotron Resonance range of Frequencies (ICRF) heating has been successfully used to obtain bulk ion and/or electron heating in a variety of JET plasmas. Scenarios with ICRF Mode Conversion (MC) have earlier been studied on JET in different conditions using a ^{3}He minority in D and ^{4}He plasmas [1, 2]. Avoiding massive fast particle populations while heating the fuel ion species is one of the challenges scenarios for the next step fusion machines should address. Adopting ^{3}He as a minority is promising in that respect [3]. This scheme could also be used to modify dominant electron heating to ion one without significant populations of ICRF-accelerated fast ions.

This paper reports results of fast ion studies in two scenarios [4, 5]: (i) fundamental (N = 1, where N is the cyclotron harmonic number) minority and MC wave heating with ^{3}He in H plasmas (central $B_T(0) = 3.41T$, $f = \omega/(2\pi) \approx 32MHz$); and (ii) second harmonic (N = 2) heating ^{3}He ions ($B_T(0) = 2.65T$, $f \approx 52MHz$). The last scenario is a test-bed for the first non-activated ITER phase when it would be run at half its nominal magnetic field [5, 6]. Furthermore, ICRF heating of (^{3}He)-H plasmas at 2.65T is mimicking D-T plasmas from the RF wave absorption point of view. Indeed, ^{3}He and H having half the mass-to-charge ratio of T and D, applying ICRF heating at half the nominal field places the cyclotron layers in (^{3}He)-H plasmas at exactly the same location as those in D-T plasmas at full field ($B_T(0) = 5.3T$).

It is important to emphasise that because deuterium is the most commonly used working gas in JET and since ^{4}He plasma experiments were carried out preceding the here described experiments, a small amount of deuterium and helium released from the wall by recycling were present in all discharges. The concentration of D and ^{4}He was further enhanced due to the NBI duct ‘contamination’. It was found that the presence of the small quantities of C, D and ^{4}He in the plasma – in addition to the injected ^{3}He – gave rise to an additional mode conversion layer.

Fast ion studies in experiments with $\omega = \omega_c(H)$ Hydrogen *majority* heating at $B_T(0) = 2.65T$ and $f \approx 42MHz$ show no evidences of an energetic ion population with energies E>200keV created. This scenario is not covered in this paper. However, it allowed estimating the deuterium concentration in the plasma core with neutron spectrometry which is sensitive to the non-thermal deuterium population. Comparing the beam-target neutron rates with a reference discharge, it is found that the residual deuterium concentration was in the range of 4 – 7% in these experiments, a bit below the value inferred from visible spectroscopy. Hence, although no D was purposely injected in the machine, the D concentration is likely to be order ~7%.

Since the power deposition and redistribution between species depend on the ^{3}He concentration, X[^{3}He]≡ n_{3He}/n_e, the scan of the parameter is a very important instrument for the wave interaction physics studies. It was increased or scanned systematically from discharge to discharge using a real-time controlled ^{3}He injection. The minority concentration issue is very important here and it is discussed in [7]. Three different heating regimes could be distinguished depending on X[^{3}He]: (i) minority ICRF heating at X[^{3}He] <1.8%, (ii) mixed minority/MC heating at intermediate concentrations 1.8 < X[^{3}He]<5% and (iii) high concentration regime X[^{3}He] > 6%, in which MC heating is the dominant process.

Fast ion effects in these experiments were studied with γ-ray [8] and neutron spectrometry [9], neutral particle analysers [10, 11] and scintillator probe [12]. Gamma-ray spectrometry, now routinely used for the fast-ion studies in JET, is based on measurements of γ-rays which are born as a result of nuclear reactions between confined fast ions and the main plasma intrinsic impurities in JET (C and Be). This diagnostic provides therefore information on the fast ion tail in the MeV energy range. In (^{3}He)-H plasma experiments γ-ray energy spectra were measured with two independent devices, one with a horizontal and one with a vertical line of sight through the plasma centre. The first device is a BGO scintillation detector that is located in a well-shielded bunker and views the plasma quasi-tangentially. The γ-rays are recorded over the energy range 1-28 MeV. The second spectrometer is a new $LaBr_3$ scintillation detector, which replaced the earlier commonly used NaI(Tl) detector, viewing the plasma centre through a vertical 2m collimator. This spectrometer shares the collimator with the time-of-flight neutron spectrometer TOFOR [8] that provides information about the fast fuel ion distribution through analysis of the measured broadening of 2.5MeV DD-neutron spectra. Two Neutral Particle Analysers (NPA) are measuring the confined fast ion distribution function. The first NPA, which is viewing the plasma horizontally through the centre, detects simultaneously the H, D and T neutrals in the energy range 5 – 740 keV. The second NPA provides information on H, D, T, ^{3}He and ^{4}He neutrals in the energy range 0.3 – 4 MeV. It has a narrow vertical field of view with axis located at R = 3.07m which crosses the injected neutral beams. This detector is sensitive to fast ions generated by ICRH with banana orbit tips in the field of view.

The Scintillator Probe (SP) allows the detection of lost ions at a single position outside the plasma, and provides information on the lost ion pitch angle between 35° and 85° (~5% resolution) and its gyro-radius between 3 and 14 cm (~15% resolution) with a time resolution of 2 ms. The scintillator probe is located just below the mid-plane of the machine. The light emitted by the scintillator due to fast ion strikes is transported through a coherent fibre bundle to a Charge-Coupled Device (CCD camera) and a photomultiplier array. An important point of the SP design is that the scintillator is protected from the detection of energetic D ions generated by Neutral Beam Injection (NBI). They are not of interest but could have huge flux, which could destroy the scintillator. A proper alignment of the collimator system reduces the D ion flux by a factor of about 5. Moreover, a 1μm Au foil shuts the aperture of the SP, which completely blocks these D and other thermal ions. The presence of the Au foil causes a slowing down of the energetic ions and hence to a decrease in the gyro-radius of the ions impinging on the SP. The distribution function of the ions emerging from the Au foil becomes broader; however, the pitch-angle broadening is less than 5%. In the case of He ions the foil also generates neutrals and a single charge fraction, He^+ that complicates the interpretation of the SP results. This important issue is discussed in the Annex.

The paper is organised as follows. The analysis of fast ion measurements during the fundamental minority and MC wave heating with ^3He in H plasmas is described in Section 2. The fast ion results obtained in experiments with the second harmonic heating ^3He ions is presented in Section 3. The paper is completed with a summary and conclusions.

2. ICRF PLASMA HEATING AT $\omega = \omega_C(^3He)$

In the here discussed experiments up to 4 MW of ICRH power (P_{ICRH}) was applied at $f \approx 32.5$MHz with dipole ($0\pi0\pi$) antenna phasing at the toroidal magnetic field of $B_T(0) = 3.41$T, placing the ^{3}He-ion cyclotron layer at $R_{IC} = 3.16$m, slightly away from the plasma centre ($R_0 = 2.97$m). On Fig.1, one can see that the fundamental IC resonance of deuterium ($N = 1$; $\omega = \omega_c(D)$) lies inside the plasma on the High Field Side (HFS). The Low Field Side (LFS) resonance $N = 1$ $\omega = \omega_c(H)$ is outside the plasma.

Two types of discharge scenarios in (^{3}He)-H plasmas were used for the MC studies (see Fig.2), one focusing on the study of heating, the other aiming at understanding the dynamics of rotation. In one case, about of 1.5MW of continuous 88keV deuterium NBI heating was applied together with 4Hz modulated ICRH, with power levels varying from ~2MW to 3.5MW. Another discharge type was used for the analysis of the RF induced plasma rotation (for details on the rotation aspects, see [7]): about 3.5MW of continuous ICRH was applied throughout the discharges while 100ms deuterium NBI blips (88keV and 130keV) were injected to assess the toroidal and poloidal bulk plasma rotation. In between NBI beam blips the ICRH power was modulated at 25Hz. These 2 types of scenarios highlight different aspects of energetic ion dynamics. Together they allow obtaining a good picture of how the fast particles are created in (^{3}He)-H plasmas heated by ICRF/NBI heating. In Fig.3, the time evolution of the ^{3}He concentration (inferred from edge spectroscopy measurements) in three different discharges is illustrated: ~0% – 1.2% (JET Pulse No: 79340), 0.3% – 4% (JET Pulse No: 79341) and 3% – 12% (JET Pulse No: 79352). As will be demonstrated in the present paper, the ^{3}He concentration is a key parameter determining the mechanism of redistribution of the ICRH power among the various plasma species in these experiments [7].

As it is expected, fast ^{3}He-ions accelerated by continuous ICRH have been found in the low X[^{3}He] discharges used for rotation studies. A typical illustration is found in JET Pulse No: 79340 for which the time evolution of several plasma parameters are shown in Fig.4. In this particular example, fast D ions were also observed in the beginning of the discharge, when the ^{3}He concentration is the lowest. Direct evidence of the energetic particle population in the plasma is given by the scintillator probe, which detects lost fast ions in the MeV range. On Fig.5 one can see the bright footprints of lost D ions (Fig.5a) and ^{3}He ions (Fig.5b) on the pitch-angle ('horizontal') and gyro-radius ('vertical') grid, which is calculated taking into account the details of the magnetic field at the probe. In the grid calculations, the gyro-radius value is directly related to the full kinetic energy of ions. The pitch-angle, θ, is defined by the following expression: $\cos\theta = v_{\|}/(v_{\|}^2+v_{\perp}^2)^{1/2}$. The location of species on the grid is defined by the positions of their Ion Cyclotron (IC) resonances in the machine. Taking into account the momentum conservation, the pitch-angles of resonant ions on the scintillation probe grid can be defined as $\theta_{res}\approx\arccos[(1-R_{IC}/R_{SP})^{1/2}]$ with $R_{SP}=3.825$m. The spot associated with deuterons is very close to the N = 1 D ion resonance (white line), whereas the other spot related to ^{3}He ions is located near the N = 1 ^{3}He ion resonance (red line).

The majority of the lost D ions have gyro-radii of about 8 cm and pitch-angles of ~ 55^0. Taking into account the slowing down in the Au foil, the initial energy of these D ions entering the SP is E_D ~ 1.1 MeV. Most of the lost ^{3}He ions have gyro-radii ~ 6 cm at a pitch-angle ~ 72^0. Calculation of the initial ^{3}He ion energy distribution has been made by means of modelling of the equilibrated charge fractions ^{3}He$^+$ and ^{3}He^{2+} in the Au foil (see Annex). Figure 6 shows the distribution function of the ^{3}He$^+$ and ^{3}He^{2+} ions emerging from the foil as function of the gyro-radius, for fast ^{3}He^{2+} ions impinging on the detector with a energy 1.1 MeV. A Gaussian curve with Full Width at Half Maximum (FWHM) of 0.35 MeV and a central energy of E_{3He} = 1.1 MeV has been fitted to the experimental profile at the pitch-angle 71^0. It looks like this curve represents a good approximation to the initial distribution of the lost ^{3}He ions from the plasma.

The identification of the lost species is confirmed by the ion orbit calculations made backward in time from the hot spot positions on the SP. From Fig.7 one can see that the turning points of the ion orbits, where the velocity component along the magnetic field vanishes ($v_{\|}=0$), is located near the respective IC resonance layers for both D and ^{3}He ions.

The time evolution of the light emission intensity of the spots on the SP plate (see Fig.5c) shows that the D ion acceleration is going on during 200 ms of the first 130keV NBI-blip. After the blip the number of energetic deuterons is diminishing while the fast ^{3}He-ion population is growing. The neutron rate is peaked during the NBI blips due to beam-target DD-reactions (see Fig.4). However, the first neutron peak (at a beam blip 130keV) is the biggest one, comparing the 4 following others related to 88keV NBI blips. There is a similar 130keV NBI blip at the end of the discharge when $P_{ICRH}=0$. The only possible explanation of the neutron excess is a contribution to the neutron rate provided by a population of the ICRF accelerated D beam ions. It is important to note that acceleration of the beam D ions is more effective during 130keV NBI blip due to the finite Larmor radius effect of ICRH. One can clearly see that the acceleration of ^{3}He-ions occurs in the continuous ICRH phases, while the slowing down and related decrease of the energetic ion population is observed during the 25Hz power modulation phase, where the average ICRH power is about half its original value (Fig.5c). Although this modulation is too fast for ions to respond, the electron response is clearly seen in the ECE measurements [5]. It is important to note here that there is already a tendency of diminishing of ^{3}He ion losses (Fig.5c) with increasing of ^{3}He concentration during the X[^{3}He] scan from ~0% to 1.2%. Similar features are found in the discharge Pulse No: 79345 which scans X[^{3}He] from 0.4 to 1.8% at higher ICRH power. In this discharge the lost ^{3}He ions are more energetic.

Gamma-ray spectrometry confirmed the existence of confined energetic ^{3}He ions with $E_{3He} > 0.9$ MeV in all discharges with low X[^{3}He]. The γ-rays with energy $E_\gamma = 4.444$MeV from the ^{9}Be(^{3}He,pγ)^{11}B nuclear reaction were detected. This is a typical case for the low ^{3}He- tail temperature in JET discharges [8]. Figure 8 shows the integral spectrum recorded in several discharges and the time dependence of the 4.444MeV γ-ray intensity. The time-dependence is correlated with the ICRH power wave-form imposed in the rotation study discharges as shown in Fig.4.

A prominent effect of the ^{3}He concentration on the ^{3}He ion acceleration was observed in discharge Pulse No: 79341 (Fig.9), which is characterised by 4Hz modulated ICRH power with the X[^{3}He] scan from 0.3 to 4%. One can see the response both on fast ion losses and electron temperature $T_e(0)$ to the modulated ICRH power during the X[^{3}He] ramp-up. More details can be seen in Fig.10, where the zoomed ICRF power waveform and central electron temperature signal are superposed to the SP signal from the photomultiplier. Both the fast ion losses and $T_e(0)$ respond promptly to the ICRH power changes and demonstrate a saturating exponential growth starting with a nearly linear increase followed by a roll-over later on. The saturation can be observed both following the switch-on and switch-off of the RF power. The rise and the decay in the lost ion signal are faster than that of the electron temperature. This is an important observation for transport studies, deserving a separate study, outside the scope of the present paper. The important point for us here, as seen in Fig.9, is the fact that the fast ^{3}He losses are vanishing at $t \approx 8.8$s, where the ^{3}He concentration is estimated around X[^{3}He] $\approx$ 2.2%. The NPA with vertical field of view, which was tuned to detect ^{3}He atoms, demonstrates the same effect. The NPA data shown in Fig.9 is related to ^{3}He atoms with energies $E_{3He}>260$ keV. Figure 11 presenting the detected losses shows that in the beginning of the discharge the population of energetic ^{3}He-ions in the plasma is roughly the same as in the previous discharge (Pulse No: 79340; Fig.5) with maximum losses at $\theta = 72^0$ and $E_{3He} \approx 1.1$MeV. Furthermore, the γ-rays with energy $E_\gamma = 4.444$MeV from the ^{9}Be(^{3}He,pγ)^{11}B nuclear reaction were observed in the early time interval at low X[^{3}He] as well. Later in the discharge the losses were not detected and the population of the MeV ^{3}He-ions has fully disappeared. However, a continuous oscillation of the T_e and W_{DIA} with smaller amplitudes at the higher X[^{3}He] (see Fig.9) testifies of the fact that energetic ions are still in the plasma. An important point is that there is a hint on the building up of a population of energetic D-ions in this period of the discharge. It is found that the neutron rate is increased by ~ 20% while the ^{3}He-losses have vanished (Fig.12). That is only possible if a change of the ICRH power distribution among of the various species, leading to a growth of the energetic D ion population, occurs. This is confirmed by NPA tuned on deuterons with horizontal line of view, which demonstrates an increase of the D flux in the energy range 155-165 keV. The lack of D ion losses and of 3.089-MeV γ-rays from the ^{12}C(D,pγ)^{13}C nuclear reaction [8] indicate that only confined D ions with energies $E_D < 0.5$ MeV exist in the plasma in this period of the discharge. In a similar $X[^3He]$ scan carried out in the discharge Pulse No: 79343, the drop of the SP signal occurs at the same $X[^3He]$ value as in Pulse No: 79341. However, the neutron rate growth was not observed in this discharge because the ICRH power is decreased by ~25%. This again support the hypothesis of the changing of the ICRH power repartition between ^3He and D ions for $X[^3He] >$ 2.2%, when the first mode conversion regime is reached.

In discharge Pulse No: 79352 a $X[^3He]$ scan from ≈3% to 12% was carried out (Fig.13). As expected from the previous results (Pulse No's: 79341 and 79343), the initial value of the ^3He concentration is too high for efficient acceleration of the ^3He ion minority. One can see that the neutron rate, MHD energy and temperature are gradually increasing during the discharge, indicating that a population of fast D ions is developing. A comparison of neutron rates and fast ion losses measured in discharge Pulse No: 79352 with the ones obtained in Pulse No: 79341 (low $X[^3He]$) clearly illustrate the scale of the energetic D ion population in the high $X[^3He]$ regime (Fig.14). At intermediate $X[^3He]$ values in the range 2.2% – 5.8%, the neutron rate in discharge Pulse No: 79352 is roughly the same as in Pulse No: 79341, and then increases an order of magnitude when $X[^3He]$ reaches 12%. This is confirmed by the increase of the ion losses for $X[^3He]>7\%$ from $t\approx8s$, when reaching the second mode conversion regime. The footprints of the losses for several time slices (shown in Fig.15) indicate that in this regime the main losses are related to 1.8-MeV D-ions in the discharge. Typical orbits of these ions calculated backward in time (Fig.16) evidence that ions are lost from the phase space region close to the passing-trapped ion separatrix. Neutron spectroscopy data shows that the fast D-ion population becomes significant when $X[^3He]>6\%$. This fact confirms the lost ion measurements and γ-ray observations.

The γ-ray measurements in the discharge Pulse No: 79352 show the presence of a population of confined D ions with energy $E_D > 0.5$ MeV in the plasma [14]. Both the vertical and the horizontal tangential spectrometers detected γ-rays with $E_\gamma = 3.089$ MeV from the $^{12}C(D,p\gamma)^{13}C$ nuclear reaction (Fig.17). This reaction has a high ICRH power threshold, as can be seen from Fig.18, where a comparison of the ICRH power and the 3.1MeV γ-ray rate is presented for discharges Pulse No: 79352 and Pulse No: 79349. Both discharges have similar high $X[^3He]$. In discharge Pulse No: 79349 the ICRH power dropped down from ≈ 3.6MW to ≈ 1.4MW at 48.8 s after which the population of the energetic D ions with energy $E_D > 0.5$ MeV substantially diminished in the plasma. It is important to note that according to neutron spectrometry assessments based on the assumption that the deuterium distribution is Maxwellian, the D ion tail temperatures were around 250 keV, in agreement with γ-ray spectrometry and NPA measurements.

A surprising outcome of the experiments was the detection of 4.44-MeV γ-rays in discharges Pulse No's: 79352 and 79349 with high $X[^3He]$. This peak is present in the spectrum of both the horizontal and vertical γ-ray spectrometer (see Fig.17). Since the MeV ^3He-ions do not exist in plasmas with high $X[^3He]$, the $^9Be(^3He,p\gamma)^{11}B$ reaction cannot be a source of these γ-rays. There are two possible reactions: either $^9Be(^4He,n\gamma)^{12}C$ and $^{12}C(p,p'\gamma)^{12}C$ could generate gammas with

E_γ = 4.439 MeV. Due to experiments that had been performed with ^{4}He plasmas just before the experiments reported here, small traces of ^{4}He gas were indeed present in these discharges. In principal, this ^{4}He minority could be accelerated by 3rd harmonic ICRF. However, it is worthwhile to note that the energy of accelerated ^{4}He-ions should be above the threshold E_{4He}~1.7 MeV in order to give rise to gammas from the ^{9}Be(^{4}He,nγ)^{12}C reaction. Hence, unless the ICRF waves can accelerate the ^{4}He ions efficiently, another source of the fast ^{4}He should be identified. Such a source of MeV ^{4}He ions in JET is the D(^{3}He,p)^{4}He fusion reaction, which produces both 3.6MeV α-particles and 15MeV protons [8,12] and relies on moderately fast either D or ^{3}He. The reactivity of the D(^{3}He,p)^{4}He reaction has a maximum in the range of effective tail-temperatures 200 keV - 400 keV. It is important to note that from $T_i \approx 17$ keV its fusion reactivity becomes higher than the D(D,n)^{3}He reaction reactivity and at $T_i \approx 90$ keV the ratio of the reactivities reach a maximum of ≈6.5. The reaction rate is depending on the densities of D and ^{3}He ions. In the examined discharges the D(^{3}He,p)^{4}He reaction rate could be substantially enhanced due to the presence of energetic D ion population and the high X[^{3}He] value. The main indicator of this reaction is its weak branch with the ratio ~10^{-4}, the reaction D(^{3}He,γ)^{5}Li, which gives rise to gammas in the broad energy range 11MeV - 17MeV. A hint that the fusion α-particle production is relatively high can be seen on Fig.17. The 17MeV γ-ray intensity is strongly correlated with ICRF power and with the rates of the reactions the ^{12}C(D,pγ)^{13}C and ^{9}Be(α,nγ)^{12}C. Figure 19 demonstrates the rate correlations between 17MeV, 3.1MeV and 4.44MeV γ-rays for discharge Pulse No: 79352 and for another high ^{3}He-concentration discharge (Pulse No: 79349). The power produced due to D(^{3}He,p)^{4}He fusion reaction could be assessed from the 17MeV γ-ray measurements with the tangential spectrometer. This spectrometer has been calibrated in the special experiments with D-NBI heating of ^{3}He plasmas. Assessments show that for the discharge Pulse No: 79349 the fusion power was P_{D3He}<5kW. However, at the end of the discharge Pulse No: 79352 the fusion power reached $P_{D3He} \approx$10kW.

The orbit calculations show that indeed some of 15MeV fusion protons could also be confined in plasmas with $B_T(0)$ = 3.41T, and they could contribute to the 4.44MeV peak via the reaction ^{12}C(p,p'γ)^{12}C though cannot be distinguished from the 4.44MeV γ-rays generated by α-particles in the reaction ^{9}Be(α,nγ)^{12}C. It is also impossible detecting losses of these energetic protons with the SP since their gyro-radius exceeds the available range of the device.

Since it was performed at constant X[^{3}He] ~ 9% with a gradual electron density ramp-down (see Fig.20), discharge Pulse No: 79349 is rather interesting for the study of fast ion dynamics. The electron density was reduced by approximately 14% while the electron temperature increased ≈50% during the period 5.5s – 9.8s. As can be seen from Fig.16, the 3.1MeV γ-ray rate is systematically growing in this discharge, indicating that deuterons are gradually accelerated to higher energy as the slowing down time increases by more than a factor of 2. This is consistent with the dynamics of the ICRH driven losses recorded with the SP. Figures 21a and 21b show the footprints of losses at t = 6s with the line integrated density n_el~6.1e+19 m^{-2} and t = 9s (n_el~5.6e+19 m^{-2}). A clear difference is seen in the loss gyro-radius (Fig21c) and pitch-angle (Fig21d) profiles. At t=9s, the lost D ions are more energetic and a bit closer to the plasma centre than in the beginning of the discharge. The loss modelling based on the equilibrated charge fractions of ^{4}He ions shows that the footprint at t = 9s (Fig.21b) could be produced by fusion α-particles. Figure 22 represents the comparison of the calculated loss distribution with experimental one. The best fit has been obtained with Gaussian at E_{4He} = 3.9 MeV and FWHM = 1.5 MeV. In this case the hot spot on the scintillator was produced by the $^4He^{2+}$ ions, while the $^4He^+$ ions had a gyro-radius, which exceeded the size of the detector. The orbit calculations show that due to the equal charge to mass ratio D ions and ^{4}He ions have very similar orbits that characterise marginally circulating counter-going ions near the trapped-passing separatrix in phase space (Fig.23).

Similar results as the ones obtained in discharge Pulse No: 79352 were found in discharge Pulse No: 79353 (Fig.24), with a high X[^{3}He] scan (2 – 12%) during the rotation study experiments. The difference between the discharges is the absence of NBI in discharge Pulse No: 79353. Deuterium ion losses with maxima at 1.8 MeV and 3.1MeV gammas were detected when X[^{3}He]> 7%. In the rotation discharge Pulse No: 79350 (Fig.25), with electron density evolution similar to discharge Pulse No: 79349 but at X[^{3}He]≈6-7%, the energetic D ions were not observed with SP nor by means of γ-diagnostics. The fact that the energetic D ions appear at X[^{3}He]> 7% is consistent with the results obtained in discharges 79349, 79352 and 79353.

The observed MeV D ions at high ^{3}He concentration is consistent with a model developed in [1] that if the resonance condition for the D-beam ions is fulfilled near the vicinity of the ICRF MC layer, due to large Doppler shift, strong wave particle interaction can occur. For these H-He^3 plasmas, there are two MC layers. One is D-He^3, and the other is H-He3. Increasing X[He^3], the D-He^3 MC layer is moved toward to the D resonance, thus more D beam ions can interact effectively. Thus, the ICRF heated D beam ions absorb the wave power at their Doppler shifted resonance, which is close to the plasma centre.

3. ICRF HEATING AT $\omega = 2\omega_C(^3He)$

The second harmonic ^{3}He heating scenario was studied in L-mode discharges at f≈51.5MHz, $B_T(0)$ = 2.65T. Up to 5.5MW of ICRF power with dipole phasing was coupled to the plasma with typical central electron densities of $n_e(0) \approx 3 \times 10^{19}$ m^{-3}. Depending on the applied deuterium NBI power (P_{NBI}<8MW) central electron temperatures were in the range T_e = 2-4keV. The ^{3}He concentration, was varied from X[^{3}He] = 5% to 25%. In these experiments the N = 2 ion cyclotron resonance of ^{3}He ions is located at R≈3.15m. There are two other IC resonances (Fig.26), N = 1 H (also N = 2 D) and N = 3 D (also ^{4}He), in this scenario that could cause a parasitic absorption of ICRH power by H, D and ^{4}He ions in some conditions.

It is important to emphasise that γ-ray spectrometry confirms the existence of confined energetic ^{3}He ions in the experiments with ICRF heating at $\omega = 2\omega_c(^3He)$. However, the density of the fast ions in the MeV range is much less than in the in the experiments with ICRF heating at $\omega = \omega_c(^3He)$. Figure 27 represent gamma-ray spectrum (in black), which was obtained by integration of the recorded spectra in discharges Pulse No's: 79361, 79362 and 79363 that had a similar scenario and parameters (see Fig.28). The γ-ray spectrum modelling code GAMMOD [8] was used for the identification of fast particles that exist in the plasma and give rise to the observed γ-ray emission. The calculated spectrum is shown in Fig.27 in red colour. The performed modelling allowed to infer that γ-rays from the $^9Be(^3He,p\gamma)^{11}B$ and $^{12}C(^3He,p\gamma)^{14}N$ reactions were observed. The GAMMOD reaction rates indicate that the ^{3}He-ions had energies below $E_{3He} \approx 2.0$ MeV. Also, the absence of the 3.1MeV γ-rays from the $^{12}C(D,p\gamma)^{13}C$ reaction indicates that the D ions had energies below $E_D \approx 0.5$ MeV [14]. There is no evidence that deuterons and ^{3}He ions contribute to the fusion reactions $D(^3He,p)^4He$ and $D(^3He,\gamma)^5Li$ (the background deuterium fraction is roughly the same as in the N = 1 ^{3}He experiments described earlier). The absence of 17MeV gammas from the reaction $D(^3He,\gamma)^5Li$ suggests that the density of fusion products (alphas and protons) is negligible to contribute to the 4.44MeV γ-ray yield through the $^9Be(^4He,n\gamma)^{12}C$ and $^{12}C(p,p'\gamma)^{12}C$ reactions.

The lost ion diagnostics also confirm the existence of fast ions in the MeV energy range. A strong correlation of losses and γ-ray emission was found. It is clearly seen in Fig.29, which represent the data from the discharges Pulse No: 79361. The γ-ray rate was integrated over the energy range 2MeV-7.5MeV, where the ^{3}He ion nuclear reactions are contributing. The footprints of the losses shown in Fig.30 are related to the modulated ICRF power period (a) and non-modulated interval (b). One can see that both hot spots lie in the area between the N = 2 ^{3}He ion cyclotron resonance (white line) and the N = 3 D ion cyclotron resonance (red line). However, since the losses are in a strong correlation with gammas and flux of ^{3}He neutrals with E_{3He}>400 keV measured with the vertical NPA (see Fig.28), the fast ^{3}He ions are the most probable loss particles in this case. The horizontal NPA tuned to deuterium did not detect a measurable flux in this case. The modelling of the initial ^{3}He ion distribution shows that the $^3He^+$ equilibrium charge fraction is much stronger than $^3He^{2+}$ (Fig.30c). The best fit to the experimental loss distribution over gyro-radius was carried out for the Gaussian with central energy E_{3He} = 1.6MeV and FWHM = 0.6MeV. The orbits of lost ^{3}He ions with total kinetic energies 1.6 MeV and 1.0MeV calculated backward in time from the hot spot on scintillator at 69^0 are shown in Fig.31. The turning points of the lost trapped orbits lie between two resonant layers, i.e. ions are coming from the phase space close to these IC resonances.

In two similar discharges Pulse No's: 79356 (P_{ICRH}≤3.3MW) and 79357 (P_{ICRH}≤5.9MW), fast ion losses were observed when a high ICRH power is combined with ~7MW of deuterium NBI power (Fig.32). In the beginning of the discharge Pulse No: 79357 (NBI-only heating phase), only the prompt DD-fusion product losses of p (3MeV) and T (1MeV) are observed (Fig.33a). The 3MW ICRF heating applied at t = 4.5s did not change the loss picture; the fusion product losses still dominate in this period. It is clearly seen in Fig.32 that a dramatic change in the loss rate occurred when the ICRH power was increased to 6MW (t = 6s): the SP signal starts to increase strongly up to t = 7s after which the ICRH power dropped down to 4.6MW. A further decrease in the losses happens at the start of the ICRH power modulation (i.e. when the effective ICRH power is further reduced), and finally the losses disappear when the NBI power was reduced to 1.3 MW as $T_e(0)$

dropped down from 3.2 keV to 2.1 keV, and the slowing down of the ions is reduced by a factor of roughly 2. Note that the fluxes of D and ^{3}He atoms are strongly correlated with the observed fast ion losses. The footprint of the losses during the P_{ICRH} = 6MW heating phase (t = 7s) is shown in Fig.33b. One can see that in this case the loss spot is closer to the N = 3 D ion cyclotron resonance (red line) than to the N = 2 ^{3}He resonance (white line), indicating that fast D (rather than ^{3}He-ions) are predominantly lost in these conditions. However, neutron rate changes in this period are moderate and do not reflect the changes in the D energy distribution. Hence, the beam-target and beam-beam reactions are main source of the neutrons, and population of accelerated D ions is rather low. The ^{3}He concentration was in the range of 8-12% when losses appeared. From the N = 1 ^{3}He experiments we learned that ^{3}He ions cannot be accelerated to MeV energies if X[^{3}He]>3%. However, the N = 2 ICRH acceleration in phase space is very different from the N = 1 acceleration, and the concentration dependence for the N = 2 case is expected to differ from that of the N = 1 ICRH heating scenario, as will be documented later.

In discharges with a ^{3}He concentration ramp-up from X[^{3}He]≈3% to 20% (Pulse No: 79358) and X[^{3}He]≈3 to 25% (Pulse No: 79359) the ICRH power was square modulated at 4Hz with power switching between ~1MW and 5MW (see Fig.34). These pulses were done with low NBI power and in both cases the fast ion losses and D and ^{3}He neutral fluxes only become visible when X[^{3}He]>17% (Fig.34). Note that although the electron temperature responds to the ICRH power modulation throughout the discharge (as it was observed in the N=1 ^{3}He experiments discussed in the previous section), the ion temperature and fast ion losses only become sensitive to the ICRH power modulation at high X[^{3}He] values. Since the neutron rate has a rather weak modulation, the D ions do not seem to play a main role in the ICRH power absorption. Weak D ion heating is taking place as the neutron rate has a growth tendency when X[^{3}He]>15% (Fig.34). Since the neutron rate does not respond directly to the ICRF power modulation, the increase in the bulk D temperature is probably not associated to direct ICRF absorption but rather to the collisional momentum exchange with the accelerated ^{3}He ions, whose ICRF absorption becomes more efficient at X[^{3}He]>15%.

Another confirmation of the fact that D ion acceleration is negligible was found in Pulse No: 79363 with strong n = 2 MHD perturbation in the interval from 5.5s to 6.5s. Hot spots on the JET wall were observed during this period. Figure 35 shows how the instability affects $Z_{eff,}$ electron density, the neutron rate, ion temperature and fast ion losses. It is clearly seen that the ion temperature correlates with losses. Since we observe the ICRH driven losses, the loss rate is proportional to the fast ion concentration. Indeed, the loss increase leads to the decrease of the ion temperature; hence the ion temperature depends on the ^{3}He ion absorption. However, neutrons do not correlate with ion temperature entirely as they are mainly generated in beam-target DD-reactions. This statement has been fully supported by results of TRANSP calculations – neutrons in this discharge are produced in beam-target and beam-beam DD reactions. The increase of the plasma density due to the impurity influx by a factor of 1.6 at t = 6s and decrease of $T_e(0)$ in the period from 5.5s to 6.0s (leading to the reduction of the slowing down time) affects both the D beam deposition and ICRF diffusion, which defines the neutron rate and the efficiency of ^{3}He ion acceleration by ICRF. As a result the neutron rate and losses are gradually decreasing to reach a minimum at t = 6s.

It is found that the fast ion loss rate strongly depends on the applied NBI power. The comparison of the pulses with the same modulated ICRH power waveform and different injected NBI power is presented in Fig.36. One can see that in the P_{ICRH} = 8MW period of discharge Pulse No: 79362 the loss rate is roughly 10 times higher than in discharge Pulse No: 79361 with the P_{NBI} = 2.6MW beam injection. The ^{3}He atom flux with energies E_{3He}>400 keV detected by the vertical NPA is strongly correlated with losses and ICRH.

There is a dependence of the fast ion losses on X[^{3}He] depicted in Fig.37, where the signals recorded during periods of continuous ICRF heating without NBI are presented. One can see that the losses and ^{3}He neutrals are somewhat more intensive at higher X[^{3}He] values. It is important to note that the main features of the fast ion losses, i.e. footprints on the SP, are the same for the modulated ICRF heating with NBI and in the case of the continuous ICRF-only heating.

4. SUMMARY AND CONCLUSIONS

The paper presents the results of the analysis of the fast ion population and the ICRH power redistribution between different species in various heating scenarios in H plasmas with injected ^{3}He and with small quantities of D and ^{4}He, coming both from NBI injection and released from the wall by recycling. The ^{3}He concentration, which is a very important parameter for wave interaction physics studies, was increased or scanned systematically from discharge to discharge in the range from X[^{3}He] = 0% - 25% using a real time controlled gas puffing system. Fast ions were studied with γ-ray and neutron spectrometry, neutral particle analysers and scintillator probe for fast ion loss measurements.

In the first scenario we studied the fundamental N = 1 ^{3}He minority and MC wave heating with up to 4 MW of ICRH power at B $B_T(0)$ = 3.41T and f≈32MHz with dipole antenna phasing. The ^{3}He ion cyclotron layer was at R_{IC} = 3.16m on the low field side and the fundamental N = 1 D resonance at R_{IC} = 2.4m on the high field side.

In this scenario fast ^{3}He ions accelerated by ICRH in the MeV energy range have been detected in the low X[^{3}He] discharges with γ-ray spectroscopy, NPA and SP. In the experiments with the X[^{3}He] scan it was found that at the ^{3}He concentration estimated around ≈ 2.2% the ^{3}He ion losses disappeared while a population of energetic D ions is gradually building up due to a redistribution of the ICRH power between species when reaching the first mode conversion regime. This is confirmed by the prominent increase of the D ion losses when X[^{3}He]>7%, in the second mode conversion regime. Thus, the ICRF heated D beam ions effectively absorb the wave power at their Doppler shifted resonance, which is close to the plasma centre.

Neutron spectroscopy and NPA data confirms that the fast D ion population becomes significant when X[^{3}He]>6%. Both losses and $T_e(0)$ respond promptly to the ICRH power changes during the 4Hz modulation and demonstrate an exponential (saturating) growth at the start and following decay in the power notch, but the loss rate evolution and decays is faster than that of the electron temperature. A decrease of the energetic ion population is observed during the 25Hz ICRH power modulation phase since the power variations are too fast compared to the ion power absorption/redistribution dynamics and the average power level is decreased.

In experiments with high X[^{3}He], γ-ray spectrometry confirmed the existence of fast ^{4}He-ions with $E_{4He} > 1.7$ MeV. There are two sources for the MeV ^{4}He ions in the studied plasmas: (i) second harmonic ICRH acceleration of small traces of residual ^{4}He that were present in these discharges; (ii) product of the he D(^{3}He,p)^{4}He fusion reaction, which produces 3.6MeV α-particles and protons at 15 MeV. In these discharges the reaction rate was substantially enhanced due to the presence of MeV D ions at high X[^{3}He] values. It was found that 17-MeV γ-rays from the D(^{3}He,γ)^{5}Li reaction are strongly correlated with ICRF power and with the rates of the ^{12}C(D,pγ)^{13}C and ^{9}Be(^{4}He,nγ)^{12}C reactions. The orbit calculations show that D- and ^{4}He-ions have very similar orbits that characterise marginally circulating counter-going ions near the trapped-passing separatrix in phase space.

Fast ion measurements in experiments with $\omega=\omega_c$(H) hydrogen majority heating at $B_T(0) = 2.65$T and $f \approx 42$MHz show the absence of evidences of energetic ion population with energies E>200keV. The dynamics of the fast ion population redistribution was also studied in discharges with second harmonic heating of ^{3}He-ions at $B_T(0) = 2.65$T and $f \approx 52$MHz, which is a test-bed for the ITER non-activated scenario at half its nominal magnetic field. Up to 5.5MW of ICRF power with dipole phasing was injected into the plasma together with deuterium NBI power (P_{NBI}<8MW). The X[^{3}He] was varied from 5 to 25%. In these experiments the N = 2 ion cyclotron resonance of ^{3}He ions is located at $R \approx 3.15$m. Another IC resonance present, N=3 D(^{4}He) caused a parasitic absorption of the ICRH power by D and ^{4}He ions in some conditions.

Gamma-ray spectrometry confirmed the existence of confined energetic ^{3}He ions in these experiments. The absence of γ-rays from the ^{12}C(D,pγ)^{13}C reaction indicates that D ions had energies $E_D < 0.5$ MeV. Also, there are no evidences that deuterons contribute to the fusion reactions D(^{3}He,p)^{4}He and D(^{3}He,γ)^{5}Li. However, the lost ion diagnostics confirmed existence of fast ions in the MeV energy range. The observed loss spot on SP lies between the N = 2 ^{3}He to the N = 3 D ion cyclotron resonance. The calculated orbits of ^{3}He ions from the hottest points on the SP confirm that ions are coming from the phase space close to this IC resonance.

There is some evidence that the D ions also accelerated by ICRF. It was found that electron temperature and losses are modulated but the neutron rate is not modulated suggesting that the D ions do not play a major role in the parasitic ICRH power absorption. However, a weak D ion heating was taking place at the low NBI power and high X[^{3}He] values that becomes visible as a small modulation in the neutron rate. Another confirmation of the fact that the D ion acceleration is small was found in a pulse with strong MHD perturbation. A strong dependence of loss rate on the applied NBI power was observed.

The dependence of the measured losses on the ^{3}He concentration is relatively weak. However, losses are larger at higher X[^{3}He] values. The main features of the losses are the same both for the modulated ICRF heating with NBI and for continuous ICRF-only heating.

The present paper demonstrates that measurement of the ICRH drive ion losses is very useful for the interpretation of heating scenarios, and helps understanding the dynamics of the fast ion subpopulations, supporting results from γ-ray spectroscopy and NPA. More generally, the synergy of the fast ion diagnostics allows making a broad picture of the physics of the redistribution of the absorbed ICRH power in complicated heating scenarios of JET.

ACKNOWLEDGEMENTS

This work, part-funded by the European Communities under the contract of Association between EURATOM and CCFE, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also part-funded by the RCUK Energy Programme under grant EP/I501045.

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ANNEX

When a He^{2+} ion passes through the Au foil it suffers a large number of collisions with the Au atoms and may capture or loose electrons. After a large number of such collisions the He beam becomes ‘charge equilibrated’, that is, each charge state is established. The equilibrium charge fractions, He^0, He^+ and He^{2+}, are determined by the relative magnitudes of the electron-capture and electron-loss cross sections for He ions and depend on the ion velocity. It was found that He beam already reaches charge equilibrium after passing through a 1 μg cm^{-2} target. The thickness of the Au foil installed in the SP is much larger, about 1.9 mg cm^{-2}, and one may confidently assume that a MeV He beam is in charge equilibrium after passage through this foil. Calculations made with SRIM-2010 [15] indicate that only He ions with an energy exceeding 730 keV and D ions with an energy exceeding 210 keV escape from the target.

The energy dependence of the charge exchange process for He ions may be described in terms of the charge-state fractions F_0, F_1 and F_2 of an equilibrated He beam. Results of the measurements of the He charge fractions in the energy range 0.2MeV – 6MeV passing through a thin carbon target [16] were used for the analysis and interpretation of the losses in these experiments. For a carbon target the ratio of the equilibrium charge fractions F_1 and F_2 of the He^+ and He^{2+} ions was approximated by $F_1/F_2 \approx 0.284E^{-2.13}$ [16]. Since the foil consists of Au, these data should be extrapolated to the atomic number $Z = 79$.

The yield of $^3He^+$ ions produced by a $^3He^{2+}$ beam in C, Al, Ni, Ag and Au thin targets has been measured at 68MeV, 99MeV and 130MeV for the determination of the electron-capture cross sections σ_c [17]. Figure 38 (left) shows the Z dependence of the electron-capture to the electron-stripping cross section ration, σ_c/σ_s, at 68 MeV. It has been found that the measured Z dependence of σ_c/σ_s is in fair agreement with Bohr’s theory [18]. In the energy range 12-24 MeV the same Z dependence was observed in [19]. The F_1 fraction data at 12 MeV obtained in [19] are shown in Fig.38 (right). Taking into account results of the measurements [16] and extrapolating the data obtained in [17, 19] to the energy range 1-6 MeV, one can infer that for the Au foil $F_1/F_2 \approx 1$ at $E(^3He) = 0.75$ MeV; thus for an Au foil this ratio is a factor of 5 higher than for a carbon foil. According to the Bohr’s theory in the free collision approximation, the Z-dependence of the ratio of electron-stripping and capture cross sections is $\sigma_s/\sigma_c \sim Z^k$ with $k = 1/3$ for the intermediate Z values. This dependence is in agreement with the experimental data. The energy dependency of the ^3He charge-state fractions F_0, F_1 and F_2 for the Au foil calculated on the base of measurements [16, 17, 19] and used in this paper are shown in Fig.39. Modelling of the lost ^3He ion footprints on scintillator shows that at high ^3He energies the best fits to experimental data are obtained with the exponent k in the range 1/3-2/3.