ICRF HEATING OF HYDROGEN PLASMAS WITH TWO MODE CONVERSION LAYERS

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ICRF mode conversion heating regime is widely used in present-day tokamaks. The theoretically predicted mode conversion enhancement due to the constructive interference of the fast wave reflected from the evanescence layer with a wave reflected from the high-field side cutoff was first experimentally identified in JET in (^{3}He)D experiments. This effect was recently tested in (^{3}He)H plasmas, which is one of the ICRF heating scenarios considered for the non-activated phase of ITER operation. Due to the presence of the intrinsic D-like impurities in JET (e.g., C^{6+}, ^{4}He) the supplementary conversion layer was produced in the plasma that defined the interference conditions. The different behavior of the conversion efficiency observed at various ^{3}He concentrations is analyzed in the paper on the basis of the theory of the fast wave mode conversion in plasmas with two evanescence layers.

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1. INTRODUCTION

ICRF mode conversion regime is being actively studied within the last years [1]. The attention paid to this scenario is caused by a number of important applications it has beyond plasma heating. Mode conversion has become a standard tool to do the transport analysis [2], it is used to drive plasma rotation [3], to generate non-inductive current drive, to pump-out impurities, to measure the ion species mix, etc. The principle of this scheme consists in the following. An ICRF antenna located at the low field side (LFS) of the tokamak launches the fast wave (FW) which propagates to the plasma center. At the ion-ion hybrid (IIH) resonance the FW is partially converted to short-wavelength mode which is commonly effectively damped on the electrons. The optimization of this heating scheme relies on the achievement of the proper conversion conditions. The Budden theory predicts that maximum 25% of the FW energy can be converted to short-wavelength mode when the FW tunnels through an isolated evanescence layer. The interference effect described by V. Fuchs et al. [4] allows to significantly enhance the conversion efficiency. The conversion enhancement is caused by the additional reflection of the FW transmitted through the evanescence layer from the high-field side cutoff. The optimal conversion conditions are achieved when the reflected waves have nearly equal amplitudes and the opposite phases. Within this model the conversion coefficient can reach the value of 100%.

The first experimental evidence of this effect was shown in JET for (^{3}He)D plasmas [5]. The experimental data of the power absorbed by electrons as a function of minority ^{3}He concentration, X[^{3}He] was found to be in fair accordance with the theoretical analysis and numerical modeling. It was shown that the electron absorption efficiency was an oscillatory function of X[^{3}He].

Recently, a series of experiments at JET was performed to test this idea in (^{3}He)H plasma [6]. Unlike the (^{3}He)D scenario, the latter is an inverted one, i.e. a scenario with a 'heavy' minority, $(Z/A)_{min}<(Z/A)_{maj}$. For the inverted scenario the evanescence layer is located between the LFS antenna and the minority cyclotron resonance. As the minority concentration is increased, the conversion layer shifts towards the LFS in contrast to the HFS layer shift for the regular scenarios. Moreover, as shown in the past experiments [7], the inverted (^{3}He)H scenario requires much lower X[^{3}He] to reach the mode conversion regime than the regular (^{3}He)D scenario. The aim of the (^{3}He)H heating experiments performed earlier at JET [7, 8] was to test the potential of this heating scenario for the non-activated phase of ITER operation. At this early ITER experimental stage predominantly hydrogen plasma will be used to minimize the activation of the tokamak components.

Before the shutdown of JET in 2009 most of the inner wall was made of carbon tiles. It resulted in the unavoidable presence of carbon in the plasma at a fairly high level enough to prevent the minority heating of deuterium in hydrogen plasmas [7, 8]. In addition, deuterium (as the most commonly used gas in JET) and ^{4}He (since (^{3}He)H heating experiments were performed after a ^{4}He campaign) ions were present in all discharges due to the recycling. Thus, the (^{3}He)H plasma was unavoidably contaminated with the D-like species, which from RF point of view acted as a single species with Z/A=1/2. The presence of these ions led to the production of a second conversion layer in the plasma. This resulted in a more complicated picture of the mode conversion physics than for the usual case of a single resonance.

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[*] *See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland*

2. MULTIPLE MODE CONVERSION LAYERS PHYSICS

The mode conversion coefficient in plasmas with two evanescence layers is found to be of the form [9]:

$$C = T_1T_2(1-T_1T_2)+4T_1(1-T_1)(1-T_2)\sin^2(\Delta\phi/2), \quad (1)$$

where $T_{1,2}$ are the transmission coefficients through the corresponding conversion layers. The constructive/ destructive role of the interference effects in mode conversion is determined by the phase difference

$$\Delta\phi = 2\Phi + \Psi_2 - \Psi_1. \quad (2)$$

The largest contribution to $\Delta\phi$ in (2) is given by the term 2Φ, which is defined by the distance between the conversion layers.

The location and transparency properties of each of the conversion layers strongly depend on the concentrations of both minority species. Fig. 1 shows the spatial dependence of the FW wavenumber, $k^2_{\perp,\mathrm{FW}}$ as a function of X[^{3}He] and X[D]. It is clearly seen that with the increase of the minority concentration, be it X[^{3}He] or X[D], the corresponding conversion layer moves towards the LFS as for the present inverted scenario. But the mutual effect on the opposite conversion layer is inverse for ^{3}He and D ions. The X[^{3}He] increase leads to a shift of the D layer towards the HFS and to the decrease of its width, while the increase of X[D] results in the LFS shift of the ^{3}He layer. It also alters the width of the ^{3}He layer, which results in the significant reduction of the transition ^{3}He concentration at which the mode conversion regime is observed [7, 9].

The (^{3}He)H experiments referred to were performed at the magnetic field $B_0 = 3.4\ldots3.5$ T and with the antenna frequency f =32.5 MHz. This positioned the ^{3}He cyclotron resonance layer ~20 cm out of the plasma center to the LFS, the D cyclotron resonance was located at the HFS at $R \approx 2.4$ m (Fig. 2). As discussed, two mode conversion layers were present in the plasma: one layer was associated with ^{3}He ions, and another – with D-like ions.

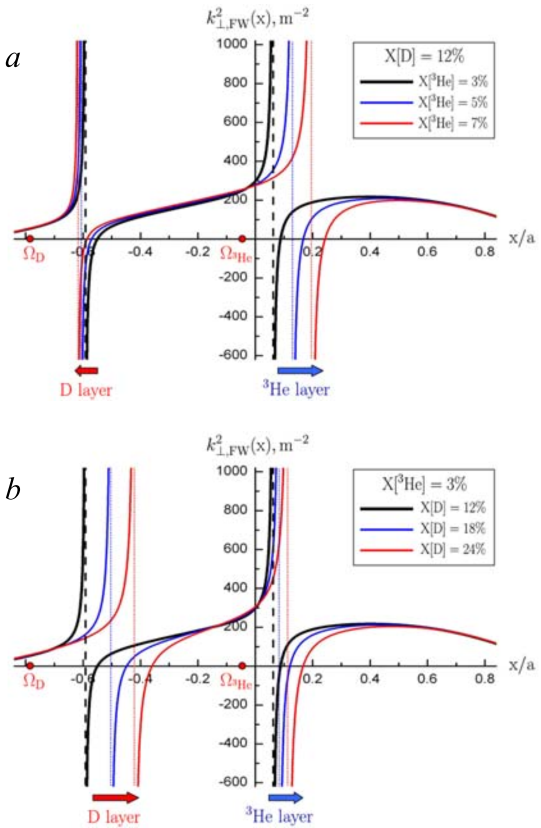

Fig. 1. FW dispersion as a function of X[^{3}He] and X[D], B_0=3.2 T, f=33 MHz

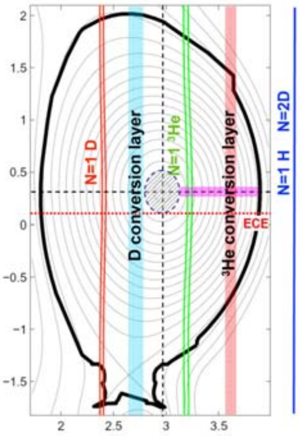

Fig. 2. Tokamak poloidal cross-section with the locations of the ^{3}He and D cyclotron resonance and mode conversion layers, B_0=3.46 T, f=32.5 MHz

Since the position of the conversion layers depends on the minority concentration it is important to implement the real time control (RTC) of the ^{3}He concentration. RTC scheme relies on the generalized Mantsinen law. It utilizes the definition of Z_{eff} and links relative divertor light intensities of species to the relative species concentrations [5]. It was found that the experimentally determined locations of the maxima of electron absorption (determined from the analysis of the temperature response to the RF power modulation) did not coincide with the locations of the conversion layers calculated from the dispersion study using the RTC data for X[^{3}He], the latter being representative for the divertor region and not necessarily for the core. A minimization procedure was implemented to establish the relation between the divertor and core ^{3}He concentrations. It turned out that a simple multiplicative factor of 1.6 allows to reconcile experimental and theoretical predictions.

For X_{RTC}[^{3}He]<4% there are two conversion layers in the plasma. The conversion coefficient is defined by the formulas (1) and (2). ICRF heating efficiency has an oscillatory Fuchs-like dependence on X[^{3}He] with one clear maximum (Fig. 3). In the range 4%<X_{RTC}[^{3}He]<6.5% the ^{3}He conversion layer approaches the plasma edge. This regime is characterized by a poor antenna-wave coupling. Further increase of X[^{3}He] moves the ^{3}He conversion layer out of the plasma, and only a single D conversion layer remains in the plasma. In such conditions, a change of X[^{3}He] does not have such a pronounced effect on the phase difference $\Delta\phi$ (determined now by the distance between the D conversion layer and the high-field side R-cutoff) for smaller ^{3}He concentrations. The response of the heating efficiency to the change of X[^{3}He] is rather flat in this regime, which is typical of the triplet-model theory [4]. Within this model the conversion coefficient is given by $C = 4T_2(1-T_2)\sin^2(\Delta\phi/2)$. T_2 – the transmission coefficient through the D layer – is lower than in the two conversion layers regime due to higher ^{3}He concentration, which makes D conversion layer to be a semi-transparent.

The described conversion regimes have different sensitivity not only to the plasma composition, but also to the toroidal wavenumber, n_{tor}. Since the location of the high-field side cutoff depends critically on n_{tor}, the toroidal wavenumber dependence of the conversion coefficient is more pronounced in the second regime. Numerical simulations with the 1D full-wave code confirmed the presence of two mode conversion regimes with the different behavior to the variation of plasma parameters [6].

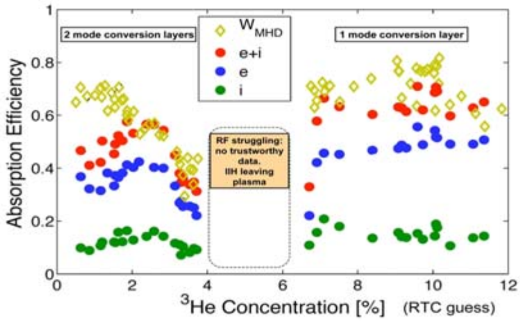

Fig. 3. ICRF heating efficiency as a function of ^{3}He concentration, $X_{RTC}[^3He]$

CONCLUSIONS

Recent (^{3}He)H heating experiments at the JET tokamak confirmed the essential role of the intrinsic D-like species in the ICRF mode conversion scenario. The presence of such ions leads to the generation of a supplementary conversion layer in the plasma, which for small ^{3}He concentrations defines the interference pattern in the plasma. For large X[^{3}He] only a single conversion layer associated with D ions is present in the plasma. The difference in the mode conversion coefficient behavior to the various experimental parameters observed in these regimes can be qualitatively explained by the Fuchs theory and its two mode conversion layers extension.

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ВЫСОКОЧАСТОТНЫЙ НАГРЕВ ВОДОРОДНОЙ ПЛАЗМЫ С ДВУМЯ ОБЛАСТЯМИ КОНВЕРСИИ

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Высокочастотный нагрев плазмы в режиме конверсии мод широко используется в современных токамаках. Теоретически предсказанное увеличение эффективности конверсии вследствие интерференции быстрой волны, отраженной от области непрозрачности, с волной, отраженной от отсечки со стороны сильного магнитного поля, было впервые экспериментально подтверждено в (^{3}He)D-экспериментах на токамаке JET. Данный эффект изучался в (^{3}He)H-плазме, которая рассматривается как один из сценариев ВЧ-нагрева во время начальной стадии работы ITER. Вследствие присутствия в плазме JET дейтериеподобных примесей (C^{6+}, ^{4}He) образовывалась дополнительная область непрозрачности, которая определяла условия интерференции волн. Различное поведение коэффициента конверсии, наблюдаемое при разных значениях концентрации ионов ^{3}He, анализируется в работе с помощью теории конверсии быстрых волн в плазме с двумя областями непрозрачности.

ВИСОКОЧАСТОТНЕ НАГРІВАННЯ ВОДНЕВОЇ ПЛАЗМИ З ДВОМА ШАРАМИ НЕПРОЗОРОСТІ

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Високочастотне нагрівання плазми в режимі конверсії мод широко застосовується в сучасних токамаках. Теоретично передбачене збільшення ефективності конверсії внаслідок інтерференції швидкої хвилі, що відбита від шару непрозорості, з хвилею, що відбита від відсічки з боку сильного магнітного поля, було вперше експериментально підтверджено в (^{3}He)D-експериментах на токамаці JET. Цей ефект нещодавно апробовано в (^{3}He)H-плазмі, яка розглядається як один із сценаріїв ВЧ-нагрівання на початковій стадії роботи ITER. Внаслідок присутності в плазмі JET дейтерієподібних домішок (C^{6+}, ^{4}He) утворювався додатковий шар непрозорості, що визначав умови інтерференції хвиль. Різна поведінка коефіцієнту конверсії, що спостерігалася за різної концентрації іонів ^{3}He, аналізується в роботі на основі теорії конверсії швидких хвиль в плазмі з двома шарами непрозорості.