EFFECT OF THE MINORITY IONS ON THE ICRF HEATING OF FUSION PLASMAS

I.V. Pavlenko, I.O. Girka, B.I. Leviga
V.N. Karazin Kharkov National University, Kharkov, Ukraine

Additional plasma heating, for example ICRF (Ion Cyclotron Range of Frequencies) heating, allows heating only a group of the fuel particles which will initiate the thermonuclear fusion reaction. But the ICRF heating scenarios are sensitive to the small fractions of the impurities, the fusion products and the minority ions. Therefore the optimization of the fraction ratio between the fuel ions and other ion components is required. It takes into consideration the effect of the ion components on the heating mechanism, the power interchange between the plasma components and the power loss channels from the confinement volume. The conditions of transferring from minority heating regime to the mode conversion one is studied for the reactor relevant D-T experiments.

PACS: 52.50.Qt, 52.25.Os

INTRODUCTION

The tritium minority heating scenarios at ITER could provide an effective triton heating by the fast wave (FW) but the designed frequency range (40…55 MHz) is out of the required relation between the frequency and the magnetic field values. That is why a main attention is paid to the ICRF heating scenarios at second tritium harmonic and the minority heating of deuterium or He^3 (the hydrogen minority heating is not accessible also). The fusion reaction rate is largest for the D-T plasmas. Therefore the D-T experiments are most promising for the reaction ignition [1]. On the one hand the second harmonic tritium heating scenarios provide mainly the heating of the tritons from the tail of the distribution function. They transfer partially the power to the electrons through the collisions and leave partially the confinement volume due to the large Larmor radius orbits. It is observed at least for the experimental conditions of the JET tokamak when the core ion temperature is up to 10 keV. Thus the additional ICRF heating contributes mainly to electron but not to ion heating. On the other hand even the pure D-T experiments contain at least about 0.1 % of He^3 as a result of the tritium radioactive decay. It provides additionally the He^3 minority heating (co-located with the tritium second harmonic heating) even without the external He^3 injection [2, 3]. But the He^3 injection could be useful at initial stage of the D-T experiments to reach core ion temperature enough high for the effective ion heating at tritium second harmonic at second stage. That is why the sensitivity of the D-T experiments to the presence of He^3 ions should be studied carefully [4].

1. MINORITY HEATING AND MODE CONVERSION

Usually the relation between the ICRF frequency and magnetic field values in the JET D-T experiments was chosen to locate the second harmonic of tritium resonance in the plasma centre. For small concentrations of D and He^3 it provides almost the central T/He^3 heating and may be the deuterium minority heating at high field side (see Fig. 1). Without He^3 minority there is one evanescence layer for FW propagation near the plasma edge at high field side (it will be called "second evanescence layer"). He^3 injection introduces another evanescence layer near the plasma center at high field side (it will be called "first evanescence layer"). In the theory the FW reaching the evanescence layer can be converted to the short wavelength modes (Ion Bernstein Waves or Ion Cyclotron Waves). But only the He^3 minority heating is usually observed for small concentrations of He^3 (due to Doppler broadening of the cyclotron layer and its partial overlapping with the evanescence layer). In this case FW power is well absorbed by the minority ions (good single pass absorption) and does not reach the first evanescence layer. Increasing the He^3 concentration leads to shifting first evanescence layer to high field side and makes this layer wider. When fist evanescence layer is enough far from the cyclotron resonance layer but its width is not too large (to reflect back all coming power) there is a possibility of partial conversion and transmission of the FW power. The converted power can be absorbed effectively by electrons providing additional local electron heating. But the transmitted power can reach second evanescence layer. And then again there are three possible scenarios: a) if second evanescence layer is close to deuterium cyclotron layer, all transmitted power is absorbed by deuterons due to the minority heating (it is dangerous for the antenna operating if powerful heating is enough close to the edge); b) if second evanescence layer is enough far from the deuterium cyclotron layer but is enough narrow to convert part of coming FW power (a source of additional edge heating which should be avoided also); c) if second evanescence layer is enough far from the deuterium cyclotron resonance and enough wide to reflect mainly coming power (the reflected power can enhance the mode conversion near first evanescence layer). Here the recent developed theory [5] which is related to the cases b) and c) will be applied to explain a reason of possible additional local electron heating in plasma core and additional edge heating in the D-T experiments with He^3 injection.

2. DEVELOPED HEATING SCENARIO

The main experimental values are taken from the JET D-T fusion discharge #41735 to check a possibility of transition from the minority heating regime to the mode conversion one. The ratio of the fuel component concentrations was D:T=10:90. The He^3 concentration before the ICRF heating stage was 4 % of the electron density. The magnetic field was 3.4 T and the operating frequency was 34 MHz. Central electron density was $3.4\cdot10^{13}$ cm^{-3}. The central ion temperature was not measured but it can be estimated as equal approximately to the electron one (about 10 keV). The ICRF antenna worked with the dipole phasing which means the maximum of the antenna spectrum at the toroidal mode number $n_{\varphi}=27$ (it is about $k_{\|}=6.75\ m^{-1}$).

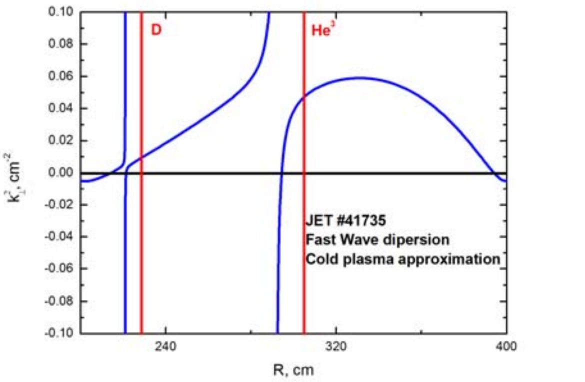

Fig. 1. FW dispersion curve in cold plasma approximation for the experimental conditions of JET discharge #41735. Positions of the cyclotron resonance layers (D, He^3) are shown

Lets start first from the FW dispersion curve in the cold plasma approximation to give a picture of the cyclotron and evanescence layer positions for the experiment (see Fig. 1). The estimation of the He^3 cyclotron resonance layer width gives about 7.5 cm for the thermal particles. Therefore the dependence of the evanescence layer width and its distance from the cyclotron resonance on the He^3 concentration is built in Fig. 2. Surely the range of the concentration up to 4 % corresponds to pure minority heating regime (there is not a hope that FW can reach first evanescence layer). For the range 4…8 % there is a competition between FW power amounts absorbed near He^3 cyclotron resonance and passed through it. So, the FW mode conversion could be expected for the He^3 concentrations above 8%. It should be noted that first evanescence layer width has a maximum at such dependence (see Fig. 2).

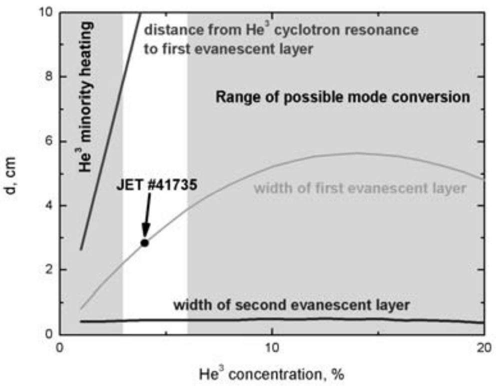

Fig. 2. Dependences of the distances on the He^3 concentration. Ranges of dominant minority heating and possible mode conversion are shadowed

The mode conversion analysis is carried out using: 1) Budden model [6] (allows estimating when FW transferring through the evanescence layer is essential and the mode conversion can be essential); 2) the triplet configuration model [7] (allows calculating the fraction of the mode converted power when the R-cutoff layer penetrates deeply into plasma from high field side) and 3) the multiplied mode conversion layer model [5] (allows calculating the mode conversion efficiency for few evanescence layers in plasmas).

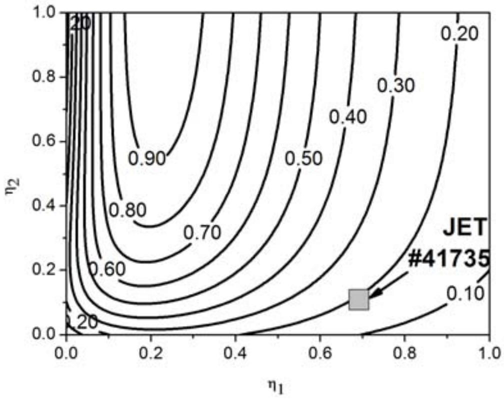

Fig. 3. Contour lines of the maximal possible mode conversion coefficient C and position of the JET experiment

Numerical analysis of the JET #41735 experimental conditions shows that they correspond to the 3) mode conversion model. Then the FW mode conversion coefficient is defined from:

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

where Φ is a phase difference between the waves reflected from first and second evanescence layers, $T_1 = e^{-\pi\eta_1}$ and $T_2 = e^{-\pi\eta_2}$ — the FW power tunneling coefficients through first and second evanescence layers respectively. Last are defined by the tunneling factors η_1 and η_2:

$$\eta_{1,2} = \frac{2}{\pi}\int |k_{\perp}(x)|dx\,, \quad (2)$$

where the integrals are taken over the range of the corresponding evanescence layer (negative values of the perpendicular wave number).

In such a way the maximal possible fraction of the mode converted power is defined by formula:

$$C_{max} = T_1T_2(1-T_1T_2)+4T_1(1-T_1)(1-T_2)\,. \quad (3)$$

Fig. 3 shows the position of the JET experiment on the contours of (3). But 4 % concentration of He^3 is still good minority heating condition to avoid an essential mode converted fraction. That is why He^3 fraction has to be increased to 8 % (minimal required to avoid a perfect single pass absorption due to minority heating) in the numerical analysis. Such He^3 concentration increasing shifts the experimental condition to 2) mode conversion model. Tunneling factor η_1 reaches value 1.1. It corresponds to the case when FW transmission is negligible and most FW power is reflected back to the antenna allowing the second pass absorption by He^3. That is why we propose to decrease the FW frequency to shift the resonances on 40 cm to the low field side. The experimental conditions become again corresponding to 3) mode conversion model which predicts up to 20 % of mode converted power.

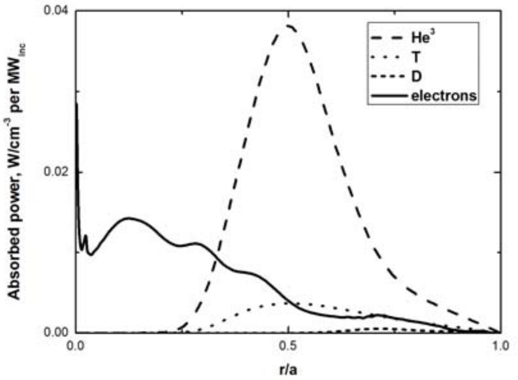

Fig. 4. Radial distribution of the absorbed power for the developed experimental scenario. Possible contribution from the mode conversion is seen as increased electron absorption

Last experimental conditions were simulated with full wave code TORIC [8] to prove or disprove the predictions of 3) mode conversion model. Fig. 4 presents the radial dependence of the power absorbed by the different plasma species. Since TORIC operates with the Maxwellian distribution functions the tritons from the tail of the distribution function (a loss cone of the first orbit losses) have been excluded from the power balance analysis.

CONCLUSIONS

The reactor relevant T-D experimental conditions were tested for transferring to the mode conversion regime with increasing He^3 concentration. There are different analytical models of mode conversion but the multiplied mode conversion layer model developed for the case of few evanescence layers in plasmas corresponds to the experimental conditions. It has been used to predict the fraction and position of the mode conversion. The prediction has been tested by the full wave simulation of the scenario with the power balance correction from Fokker-Planck simulations. The results allow to hope that the developed model works in the framework of its approximation.

REFERENCES

1. L.-G. Eriksson, M. Mantsinen, V.P. Bhatnagar, et al. Theoretical Analysis of ICRF Heating in JET D-T Plasmas // *Nuclear Fusion.* 1999, v. 39, p. 337-352.
2. D.F.H. Start, J. Jacquinot, V. Bergeaud, et al. Bulk Ion Heating with ICRH in JET DT Plasmas // *Nuclear Fusion.* 1999, v. 39, № 3, p. 321-336.
3. JET and TFTR teams, presented by D.F.H. Start. ICRF Results in D-T Plasmas in JET and TFTR and Implications for ITER // *Plasma Physics and Controlled Fusion.* 1998, v. 40, № 8A, p. A87-A104.
4. Ye.O. Kazakov, V.G. Kiptily, S.E. Sharapov, et al. Study of ICRH Scenarios for Thermal Ion Heating in JET D–T Plasmas // *Report EFDA–JET–PR(11)50.* 2011, JET-EFDA, Abingdon.
5. Ye.O. Kazakov, I.V. Pavlenko, D. Van Eester, et al. Enhanced ICRF (Ion Cyclotron Range of Frequencies) Mode Conversion Efficiency in Plasmas with Two Mode Conversion Layers // *Plasma Physics and Controlled Fusion*. 2010, v. 52, p. 115006.
6. K.G. Budden. *The Propagation of Radio Waves.* Cambridge: Cambridge University Press, 1985.
7. V. Fuchs, A.K. Ram, S.D. Schultz, et al. Mode Conversion and Electron Damping of the Fast Alfven Wave in a Tokamak at the Ion-Ion Hybrid Frequency // *Physics of Plasmas*. 1995, v. 2, p. 1637-1647.
8. M. Brambilla. Numerical Simulation of Ion Cyclotron Waves in Tokamak Plasmas // *Plasma Physics and Controlled Fusion*. 1999, v. 41, p. 1-34.

Article received 20.09.12

ВЛИЯНИЕ ИОНОВ МАЛОЙ ДОБАВКИ НА-ВЧ НАГРЕВ ТЕРМОЯДЕРНОЙ ПЛАЗМЫ

И.В. Павленко, И.А. Гирка, Б.И. Левига

Дополнительный нагрев плазмы, например, ВЧ-нагрев, позволяет нагревать только группу частиц топлива, которые будут инициировать термоядерную реакцию. Но сценарии ВЧ-нагрева чувствительны к малым фракциям примесей, продуктов реакции и ионов малой добавки. Поэтому требуется оптимизация процентного соотношения между ионами топлива и прочими ионами. Она должна принимать во внимание влияние ионных компонентов на механизмы нагрева, обмен энергией между компонентами плазмы и каналы ухода энергии из объёма удержания. Условия перехода от режима нагрева ионов малой добавки к режиму конверсии мод изучаются для перспективных экспериментов с дейтериево-тритиевой плазмой.

ВПЛИВ ІОНІВ МАЛОЇ ДОБАВКИ НА ВЧ-НАГРІВАННЯ ТЕРМОЯДЕРНОЇ ПЛАЗМИ

І.В. Павленко, І.О. Гірка, Б.І. Левіга

Додаткове нагрівання плазми, наприклад, ВЧ-нагрівання, дозволяє нагрівати тільки групу частинок палива, які будуть ініціювати термоядерну реакцію. Але сценарії ВЧ-нагрівання є чутливими до малих фракцій домішок, продуктів реакції та іонів малої добавки. Тому є необхідність в оптимізації відсоткового співвідношення між іонами палива та іншими іонами. Оптимізація повинна приймати до уваги вплив іонних компонентів на механізми нагрівання, обмін енергією між компонентами плазми та канали втрати енергії з об’єму утримання. Умови переходу від режиму нагрівання іонів малої добавки до режиму конверсії мод вивчаються для перспективних експериментів з дейтерієво-тритієвою плазмою.