TO POSSIBILITY OF USAGE OF FMW PLASMA HEATING SCENARIOS IN THE ICR FREQUENCY RANGE IN THE TORSATRON REACTOR

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The problem of fast wave plasma heating in reactor-torsatron at the ICRF range in scenarios, optimal for fusion reactor, is numerically studied.

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1. INTRODUCTION

RF plasma heating methods using fast waves in ICRF range together with NBI and ECR methods are presently considered as the most perspective ones for achievement of plasma ignition in commercial thermonuclear reactor on the basis of magnetic confinement.

In conditions of reactor-torsatron the use of the RF methods becomes sharply complicated due to the next features. Possibility of creation the ports developed enough in the direction of small axis of plasma cord is very problematic due to location in this region of helical winding poles. Placing of the antenna systems out of the ports (like in heliotron LHD [1]) is quite acceptable in experimental devices, however in reactor conditions (high heat and radiation fluxes, complication of operating and etc.) such a scheme can be proved unacceptable from viewpoint of engineering criteria's.

2. STATEMENT OF PROBLEM

At Fig. 1a the scheme of torsatron cross-section in domain, where the large radius of plasma cord configuration is perpendicular to the main torsatron axis, is presented.

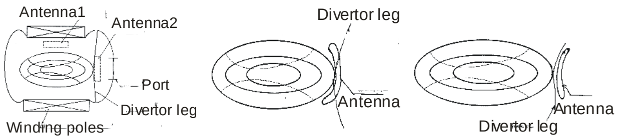

Fig.1 a) Toroidal torsatron cross-section at which large axis of plasma cord is perpendicular to torus main axis; b) conventional antenna placing near X-point of divertor (antenna- 1); c) antenna placing with antenna configuration non-conflicting with divertor surface (antenna- 2)

A scheme at which antenna is placed on the large radius of plasma cord ("antenna-2") is alternative one to conventional scheme ("antenna-1") of antenna placement. Antenna can be integrated in large enough port, which facilitates the decision of many technical questions of antennas work in the conditions of reactor.

However from physics viewpoint there arises some questions relating to peculiarities of such a scheme: antenna works in the regime of radiation in the large radius direction of plasma cord, the size of antenna in azimuthal direction is limited, antenna is near the divertor X-point and divertor surfaces. Therefore the main questions are: whether is possible effective wave excitation (what is efficiency of antenna work); whether is it possible to obtain the peaked enough profile of energy deposition in the cross-section of plasma cord in regime of wave excitation in the direction of large plasma cord; whether is it possible to combine antenna and divertor?

In Fig. 1b, c two variants of antenna placing in relation to a plasma cord are shown. Fig. 1b corresponds to optimal location of antenna (antenna-1) for achievement of maximal coupling with plasma (the surface of antenna is in vicinity plasma surface). However in this case antenna crosses divertor shoulders, that leads to the substantial loss of divertor plasma fluxes and it can be even unacceptable for reactor.

Fig. 1c corresponds to location and form of antenna (antenna-2), when divertor fluxes are totally saved, however coupling of antenna with plasma is weakened due to no optimal from electrodynamics viewpoint antenna configuration.

3. MODEL

The study of these problems is reduced to the boundary task for Maxwell equations, describing excitation, propagation and absorption of electromagnetic waves in inhomogeneous plasma. The model takes into account *2-D* - inhomogeneity of plasma (plasma density, *n(x,y)*, ion temperature, *T(x,y)* and also inhomogeneity of the confining magnetic field *H(x,y)* (Fig. 2 shows level lines of *H(x,y)*). Resolving of boundary task for wave equation

$$rot\times rotE+\omega^2/c^2\cdot\varepsilon(x,y)\cdot E=i\cdot 4\cdot\pi\cdot\omega/c^2\cdot J^{ext}(x,y), \qquad (1)$$

is performed on the base the method of fictive regions [2].

The task is decided in the cartesian coordinate system with coordinate normalization, at which the values $x=\pm0.5$, $y=\pm0.5$ correspond to location of metallic walls. Typical for torsatron configuration oblongness of plasma cord and magnetic surfaces was modeled by the parameter *EL* in the next equation

$$X^2+EL*Y^2=R^2, \qquad (2)$$

which, at R=Rm, describes the plasma boundary (edge magnetic surface). At 0<R<Rm and R=const the equation defines coordinates of the given magnetic surface on which it is true $n_i(x,y)=const$, $T_i(x,y)=const$.

Distribution of the magnetic field module in the cross-section of plasma cord was taken by typical for torsatron configuration in such a cross-section of plasma cord and was approximated by the next dependence:

$$H(x,y)=H_0(x=0,y=0)\cdot(1+0{,}48y^2-0{,}5x^2-1{,}2x). \qquad (3)$$

Different heating scenarios were explored. Below the heating regime of D-plasma with H-minority is given.

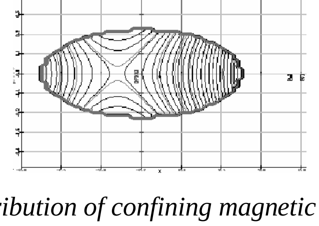

Fig. 2. Distribution of confining magnetic field H(x, y)

All coefficients in equation (3) depend on the next initial normalized parameters: $L_s=R_{max}\omega/c$, $N_A^2(0,0)=\omega_{pid}^2/\omega_{cid}^2$, $T_i(0)$, $\eta=n_H/n_D$, $N_{//}=c/V_{Zz}$, $W=\omega/\omega_{cid}(0,0)$, where R_{max} is the large radius of plasma cord, ω -circle wave frequency, ω_{pid} – bulk ion plasma frequency, ω_{cid} - bulk ions cyclotron frequency, Ti ion temperature in the center of cord, η -relative concentration of addition ions , $N_\parallel$– wave slowing-down along the axis of z for the given mode (v_Z–phase speed along the z-axis). Below there given results for the case $L_S = 3.4$, $T_i(0) = 15keV$, $\eta = 0.02$, $W = 2.01$ and for $N_A^2(0,0)$=625 and $N_A^2(0,0)$ =3200.

4. STUDY OF THE REGIMES WITH ANTENNA-1

The antenna system was modeled by a current layer with $divj = 0$ with configuration given in Fig. 1b, where the small radius of antenna surface curvature is R_{amin}=0.1, the large radius of the curvature R_{amax}=0.21 and corresponding center of curvature is located at R_0=0.49. The angular size of antenna is φ = 1.4. Below there given calculation results for separate longitudinal harmonics with different $N_\parallel$-values.

Regime of low density ($N_A^2(0,0) = 625$). As an example of regime with low density we present the results of study of mode with $N_\parallel$=6. In the Fig. 3 distribution of the module of electric field components and in Fig. 4 the specific power *D(x, y)* is presented.

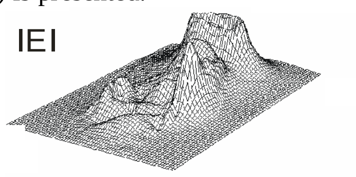

Fig. 3. Module of the electric field in the cross-section of plasma cord for the case $N_{//} = 6$ *and* $N_A^2(0,0) = 630$

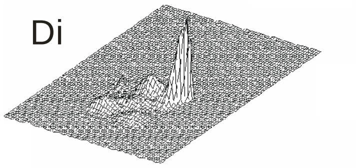

Fig. 4. Distribution of specific power, D_i*, absorbed by minority ions in the cross-section of plasma cord*

As it follows from pictures the dominant field is the field on antenna. The maximums of the electric fields on all pictures correspond to location of current layers (the Eu field has a different sign on neighbor current layers). In the same time in some region located on periphery of plasma cord and in an adjoining vacuum region the strong increase of the field, amplitude of which achieves the field amplitudes in area of antenna, takes place. This effect is the main peculiarity of this regime and illustrates the case, when intensive excitation of quasi-surface wave takes place. Earlier this effect first appeared in [2] is discussed in connection with its negative arising as an effect resulting to peripheral heating of plasma. In explored case, as it follows from Figs. 5,6 this effect leads to the overwhelming deposition of RF energy in a peripheral region, where ion-cyclotron frequency is close to frequency of wave. Consequence of this effect will be extraordinary low efficiency of plasma heating, at least, for the given mode. The structure of quasi-surface wave, its intensity and finally its role, in deposition of RF energy depends of many parameters, in particular, from the value $N_\parallel$. Therefore intensive excitation of quasi-surface waves, as follows from the performed study, takes place in the limited region of the values $N_\parallel$. Nevertheless the general effect of deterioration of energy-deposition profile becomes very substantial.

Regime of high density ($N^2a(0,0)$=3200). As an example of high plasma density regime we'll present the results for similar to the previous case but with the mode $N_{//} = 6$. As it follows from Fig. 5 intensive enough quasi-surface wave in vicinity of antenna only is excited. However in the reminder region, in particular, in the ion cyclotron resonance region near periphery of plasma cord, its intensity is rather weak. In the same time the RF field gains character peaked well enough near the axis (region of small y) of wave channel.

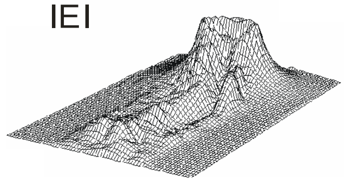

Fig. 5. Module of the electric field in the cross-section of plasma cord for the case $N_{//} = 6$ *and* $N_A^2(0,0) =$ *3200*

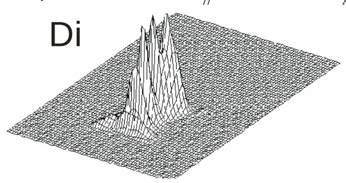

Fig. 6. The same as in Fig.4 excepting $N_A^2(0,0) =$ *3200*

For the regimes with a high density this effect (effect of localization of wave channel) is saved in the region of values $N_\parallel$ wide enough. The region of $N_\parallel$, where there begin to act role quasi-surface waves with increasing of density shifted in the region of low $N_\parallel$. So, for example, at $N_\parallel$=3, as it follows from Fig. 6, the effect of localization of wave channel is expressed weaker and the effect of superficial energy-deposition already begins to arise, though in common the profile of energy-deposition remains quite acceptable. It should be noted that effect of quasi-surface wave excitation is defined foremost by the gradient of density but not the density value in the cord center. Therefore for the weaken gradient profiles of plasma density (in comparison to parabolic profiles used in the given study), typical for the traps of stellarator type, the regime of high density comes at more low value of plasma density in the center of cord, than following from the given series of examples.

5. STUDY OF THE REGIMES WITH ANTENNA-2

As an example of the use of antenna "no conflicting" with divertor (Fig. 1c) the results of study of antenna, having sizes similar to antenna of the type 1, are presented (R_{amax}=0.21, R_{amin}=0.1 φ = 1.4), however with reverse curvature (R_0 = 0.79). In the Figs. 7, 8 the results of calculations for the case of low density are given (($N_A^2 = 630$). As follows from comparison with a Fig. 1c, where distribution of the module of the RF field in the cross-section of plasma cord is shown, with similar plasma parameters but for the case of application of antenna of type 1, picture of distribution of the field few differ in spite of strong distinction of configurations of antennas. Distinction in distribution of the fields takes place only in region of antenna due to different configurations of antennas. At that the field amplitudes on antenna also are practically identical, that reflects the equivalence of reactive impedances of these two antennas.

Comparison of Fig. 9, where distribution of specific power deposited due to absorption of electromagnetic waves in the region of cyclotron resonance is given, with similar one for antenna 1 shows that and the profiles of energy-deposition are practically identical.

Distinction between the antennas 1 and 2 takes place only in the amount of active flux of RF power, determining brought in antenna the active impedance $R_A \approx P_A / J_A$ (J_A is antenna current, P_A-active flux of RF energy). An active -local vector flux was calculated as $P_A(x) = \int_{y_{min}}^{y_{max}} P(x,y)dy$, where $P(x,y)$ is vector of Poyting. Obviously, that $P_A(x) = P_0 = const$ at $x_r < x < x_a$, where x_r - maximal coordinate on an axis x at which cyclotron absorption is yet substantial, x_a - minimum coordinate on an axis x, where the value of external current is different from a zero (current of antenna). Constancy of P_A in this region was a criterion for the control of exactness of calculations.

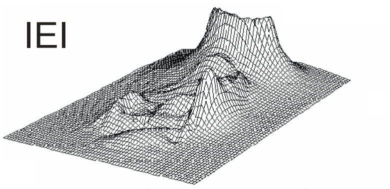

Fig. 7. Distribution of the module of the electric field in the cross-section of plasma cord for the case $N_\parallel$*=6 and* $N_A^2(0,0) = 625$ *for antenna of the type 2*

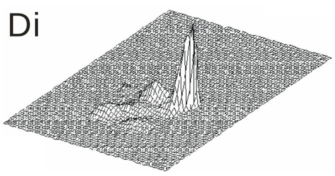

Fig. 8. Distribution of specific power D_i *absorbed by the resonance ions of minority in the cross-section of plasma cord for the case* $N_{//} = 6$ *and* $N_A^2(0,0) = 625$

Comparison of P_0 for two types of antennas, shows that distinction between them at equality of parameters of plasma unexpectedly is comparatively small ~15%. Antenna of the type 2 will have the active impedance brought in below 15%, than for antenna of the type 1. It reflects an important fact: in spite of strong distinction between the forms of antennas the active impedance brought in decreasing comparatively few in antenna of antenna 2 in comparison with antenna 1.

A similar character of distributing of the field (Fig.9) and profile of deposition of energy takes place and in the regime of high density, that allows to conclude about respectively small distinction from point of application of these two antennas with a quite different influence on a divertor surface.

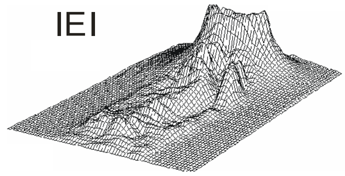

Fig. 9. The same as in Fig. 7 excepting $N_A^2(0,0) = 3200$

6. CONCLUSIONS

Applying the Fast Wave methods of plasma heating in ICRF range in reactor - torsatron it is possible to realize a scenario with placing of antenna in region of X-point of divertor, working in regime of wave radiation in direction of plasma cord large radius. Thus in regimes with high enough plasma parameters (density, temperature) the picked profile of energy-deposition can be obtained.

Lowering of these plasma parameters can lead foremost to more peripheral deposition of energy. This effect can arise at plasma parameters substantially below, than reactor parameters.

Analysis showed that there exist the hope to combine antenna with divertor keeping picked well enough profile of energy-deposition and acceptable antenna efficiency. The final answer for this extraordinary question, defining destiny of ICR heating method in conception of reactor-torsatron, can be obtained only after study, based on the more exact model and also searching most optimal scheme of such antennas.

Taking into account the number of technical advantages of antenna placing in the domain of divertor X-point such a scheme can become a basic one in the application to reactor-torsatron.

For receiving of complete information for such scenario of RF heating, especially for relatively small systems with lower, than reactor parameters, development of models taking into account foremost 3-D plasma inhomogeneity and non locality of dielectric tensor is needed.

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ИСПОЛЬЗОВАНИЕ БЫСТРЫХ МАГНИТОЗВУКОВЫХ ВОЛН В ОБЛАСТИ ИЦР ДЛЯ НАГРЕВА ПЛАЗМЫ В РЕАКТОРЕ-ТОРСАТРОНЕ

А.В. Лонгинов

Численно исследована проблема использования ВЧ-методов нагрева плазмы в области ИЦР в торсатроне-реакторе в сценариях, оптимальных для термоядерного реактора.

ВИКОРИСТАННЯ ШВИДКИХ МАГНІТОЗВУКОВИХ ХВИЛЬ В ОБЛАСТН ІЦР ДЛЯ НАГРІВАННЯ ПЛАЗМИ В РЕАКТОРІ-ТОРСАТРОНІ

А.В. Лонгінов

Чисельно досліджена проблема використання ВЧ-методів нагрівання плазми в області ІЦР в торсатроні-реакторі в сценаріях, оптимальних для термоядерного реактора.