31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-1.177 (2004)

New RF heating module of the tokamak plasma in the frame of DINA code.

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New program module, based on the code ALTOK[1] was integrated into the Dina[2] code for calculations of wave excitation and dissipation in Alfvén, Ion Cyclotron **(**IC**)** and in Lower-Hybrid (LH) Range of Frequencies in axisymmetric tokamaks. This program module has been developed on the basis of computational codes ALTOK and ALTOK-E, where the full wave "curl–curl" equation with an anisotropic susceptibility tensor and harmonic dependence in time and toroidal angle ~exp$(in\varphi - i\omega t)$ are supposed for the components of the electromagnetic field. The ALTOK code is employed for the calculation of Ion Cyclotron Radio Frequency (ICRF) heating of a "cold" plasma model, where the standard scheme has been used to compute helical antenna impedance and electric field structure. The absorption is described by imaginary part of complex frequency. The ALTOK-E code is used to solve eigenvalue problem, which corresponds to full wave "curl–curl" equation for the electric field with an anisotropic susceptibility tensor. The code allows a direct calculation of the numerical spectrum for arbitrary cross section toroidal plasma configurations. This code was tested by calculations of wave excitation and dissipation in Alfvén and ICRF range of Frequency. The ICRF heating and current drive module is called from DINA code transport module time by time to correct profiles of heating and current drive. Between calls interpolation is used for these profiles. There is no each time step call is necessary because ICRF module is time consuming.

At this work the problem of excitation in cold axisymmetric two-component (ions and electrons) plasma of oscillations of following type is considered:

$$E(t,r,\varphi,z) = E(r,z)\exp(-i\omega t + in\varphi),$$

with external alternative currents:

$$J_\varphi \approx J_0 \sin\left(\frac{\pi\, n}{I} z\right), \qquad J_z \approx J_0 \cos\left(\frac{\pi\, n}{I} z\right) \quad ,$$

where m, n are toroidal and poloidal wave numbers.

Distribution of high frequency field is described by equation for complex amplitude of electric field E:

$$(rot\,rot\,E) - \omega^2 E / c^2 - \omega^2 4\pi\, i(J + J_{ext}) / c^2 = 0,$$

and Ohm's low for currents induced in the plasma: $J = \hat{\sigma}E$, where $\hat{\sigma}$ is tensor of cold magneto-active plasma conductivity [3]:

$$\hat{\sigma} = \begin{bmatrix} \sigma_\perp & i\sigma_\times & 0 \\ -i\sigma_\times & \sigma_\perp & 0 \\ 0 & 0 & \sigma_\parallel \end{bmatrix}$$

$$4\pi\, i\sigma_\perp / \omega = \sum_s \Omega_{Ps}^2 / \left(\Omega_{Bs}^2 - \omega^2\right)$$

$$4\pi\, i\sigma_\times / \omega = -\sum_s \Omega_{Bs}\Omega_{Ps}^2 / \left(\omega\left(\Omega_{Bs}^2 - \omega^2\right)\right)$$

$$4\pi\, i\sigma_\parallel / \omega = -\sum_s \Omega_{Ps}^2 / \omega^2$$

$$\Omega_{Bs} = Ze_s|B| / \left(M_s^* c\right),\quad \Omega_{Ps}^2 = 4\pi N_s \left(Z_s e\right)^2 / M_s,\quad M_s^* = M_s(1 + i\nu/\omega).$$

Absorption is modeled by adding artificial collision damping frequency ν into components $\sigma_\perp$, $\sigma_\times$.

Energy absorbed by plasma is given by:

$$\left\langle \frac{\partial W}{\partial t} \right\rangle = \frac{1}{8\pi} i\omega\varepsilon_0 \left(\varepsilon^* - \varepsilon\right) E\, E^*,\quad P = \int \left\langle \frac{\partial W}{\partial t} \right\rangle \partial V.$$

Tensor components are written at curvilinear non-orthogonal coordinate system, connected with magnetic lines of equilibrium field. This problem is solved by use of numerical scheme constructed on the basis of mathematical support operators method at non-uniform orthogonal grid [4].

As an example of application of given method the simulation of quasi-stationary regimes of T11-M tokamak has been carried out and the optimal parameters for ICRF heating of this device were selected. Now results of simulation will be presented.

Let us recall T11-M tokamak parameters: major radius is R=70 cm, minor radius is 20 cm, toroidal magnetic field on the axis can vary as 1÷1.25 T, and change proportional to inverse major radius R, average plasma density is ~ $5*10^{13}$ cm^{-3}, and it's profile shape is close to parabolic.

Simulations were carried out for mixture of H+D, content of hydrogen was varied at limits 1÷10%. There were also calculations with a small addition of resonant Li ions. The frequency of antenna radiation, magnetic field at the plasma axis and average density were varied during calculations.

Simulation results showed that location of absorption zones were changed in accordance with dispersion property of “cold” tensor. If frequency changes from 12MHz to 27MHz, then at low frequencies firstly the zone of low absorption by deuterium at the region of high magnetic field is appear, and after, with increasing of the frequency the zone of absorption by deuterium leaves the area of plasma column and at the center of plasma MHD oscillations were observed.

Further increase of frequency leads to situation when conditions for cyclotron resonance heating by hydrogen is fulfilled, and then with increasing antenna radiation frequency absorption layer is moved to the direction of higher magnetic field. Varying magnitude of magnetic field, average plasma concentration, it’s content, toroidal and poloidal wave numbers we obtain optimal absorption profile at T11-M device at the regime of hydrogen minority in deuterium plasma, that is requirement that absorption of ICRF power is maximum at the center of plasma.

The space distribution of radial electric field on tokamak poloidal cross section for device parameters: B_0=1.25T, n=7.2*10^{13}cm^{-3}, a=20cm, 5%H, 95%D, *m*=1, *n*=-1 (which correspond to the case of optimal absorption of ICRF power) is given at the Fig.1(at relative units).

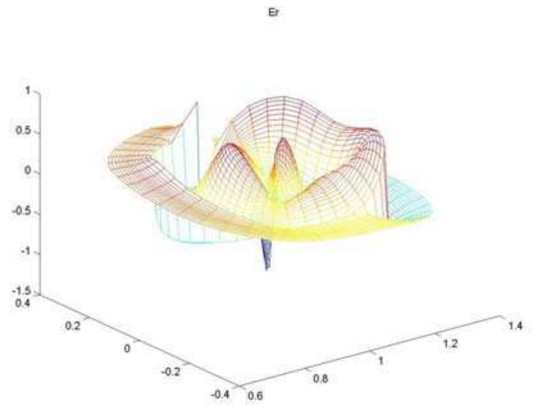

Fig1. Distribution of radial field of ICRF radiation for T11-M:. B_0=1.25 T, n(0)=7.2*10^{13} cm^{-3}, a=20 cm.5%H, 95%D, *m*=1, *n*=-1, *f*=19.5 *MHz*.

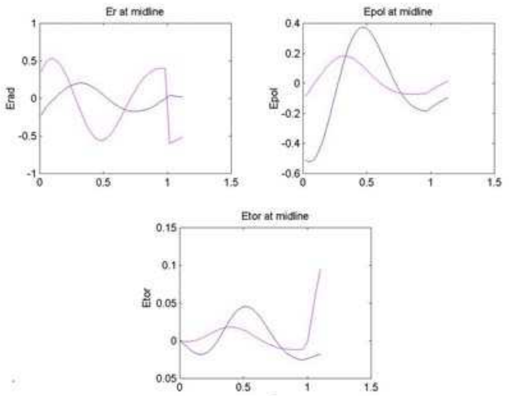

Fig.2. Radial, poloidal and toroidal field distribution of ICRF radiation for T11-M on plasma cross section. B_0=1.25 T, n=7.2*10^{13} cm^{-3}, a=20 cm.5%H, 95%D, *m*=1, *n*=-1, *f*=19.5 *MHz*.

At the Fig.2 the distribution of radial, poloidal and toroidal fields along the line which begins from axis of tokamak is presented. On the Fig.3 the absorption profile (at relative units) is given. As seen from figure, at chosen parameters, absorption takes place near the center of plasma column.

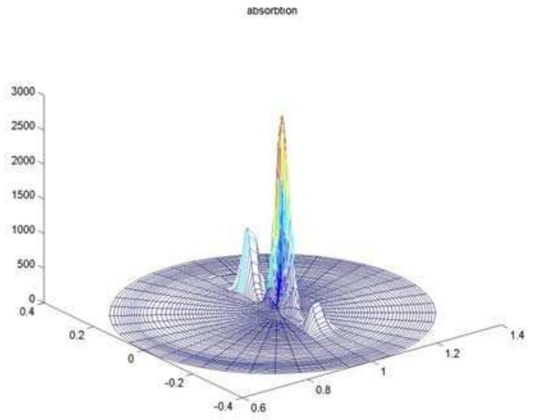

Fig. 3. Absorption zone of ICRF radiation for T11-M. B_0=1.25 T, n(0)=7.2*10^{13} cm^{-3}, a=20 cm, 5%H, 95%D, m=1, n=-1, f=19.5 MHz

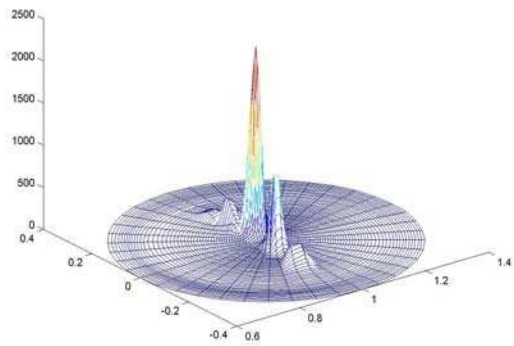

Fig. 4. Absorption zone of ICRF radiation for T11-M. B_0=1.25 T, n=7.2*10^{13} cm^{-3}, a=20cm.5%H, 90%D, 5%Li, m=1, n=-1, f=19.5 MHz.

At the current work the role of Li on absorption properties of media has been studied. The profile of absorption of ICRF radiation for mixture 5%H, 90%D, 5%Li is shown at the Fig. 4. From comparison of Fig.3 and Fig.4 it seen that effect of Li on absorption is weak.

Thus with the help of carried out simulations it was obtained that optimal profile of absorption of ICRF radiation takes place at tokamak parameters: B_0=1.25T, n=7.2*10^{13} cm^{-3}, a=20. For wave numbers *m*=1, *n*=-1 and at plasma composition 5%H, 95%D. Addition of Li up to 5 % does not lead to reduction of the power absorption of ICRF radiation.

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