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Analysis of Ion Cyclotron Waves and Alfvén Eigenmode in a Toroidal Helical Plasma

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A new version of the full wave code (TASK/WM) was developed based on the three-dimensional formulation [1] and applied to the analysis of the ICRF waves and Alfvén eigenmode (AE) in a toroidal helical plasma, such as the Large Helical Device (LHD) where promising experimental results have been obtained.

We employ the non-orthogonal flux coordinates (ψ, θ, ϕ) computed by the magnetohydrodynamic equilibrium code, VMEC [2]. We solve Maxwell's equation for wave electric field $\boldsymbol{E}$ with angular frequency ω,

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega \mu_0 \boldsymbol{j}_{\rm ext}$$

where $\boldsymbol{j}_{\rm ext}$ is the current flowing in the antenna. The dielectric tensor $tensor\epsilon$ represents the response of the plasma to the the wave electric field. It is calculated in the local orthogonal coordinates, $\hat{\boldsymbol{e}}_s = \nabla\psi/|\nabla\psi|$, $\hat{\boldsymbol{e}}_b = \hat{\boldsymbol{e}}_h \times \hat{\boldsymbol{e}}_\psi$ and $\hat{\boldsymbol{e}}_h = \boldsymbol{B}_0/|\boldsymbol{B}_0|$, and converted to the dielectric tensor in the non-orthogonal coordinates (ψ, θ, ϕ) by using the transformation matrix $\overleftrightarrow{\mu}$,

$$\overleftrightarrow{\epsilon} = \overleftrightarrow{\mu} \cdot \overleftrightarrow{\epsilon}_{sbh} \cdot \overleftrightarrow{\mu}^{-1}.$$

The wave field is expressed as a sum of Fourier components with poloidal mode number m and toroidal mode number n,

$$E(\psi, \theta, \varphi) = \sum_{mn} E_{mn}(\psi) e^{\mathrm{i}(m\theta + n\varphi)}.$$

Both poloidal and toroidal mode coupling due to the inhomogeneity of the plasma is taken into account. Specifying the parallel wave number

$$k_{\parallel}^{m'',n''} = -i\hat{\boldsymbol{e}}_h \cdot \nabla = m'' \frac{B^\theta}{|B|} + n'' \frac{B^\varphi}{|B|}$$

with m'' and n'' chosen to keep the symmetry of $\overleftrightarrow{\epsilon}$, we can describe the wave-particle interaction along the field line, e.g., Landau damping and cyclotron damping. Maxwell's equation is solved as a boundary value problem for given antenna current, we obtain the wave electric field and calculate the absorbed power density. The code uses the message passing interface (MPI) library for parallel processing on computer cluster.

We have analyzed the fast-wave minority heating (He+H) on LHD using the dielectric tensor for cold and hot plasmas. In this paper, we present the result using the cold plasma model with collisional damping. Figure 1 shows typical wave structures for $B_0 = 3.75\,\mathrm{T}$,

$R_0 = 3.9\,\mathrm{m}$, $N_\mathrm{h} = 10$, $f = 50\,\mathrm{MHz}$, $n_{\phi 0} = 8$, $n_{\mathrm{e}0} = 10^{19}\,\mathrm{m}^{-3}$, $n_\mathrm{H}/n_\mathrm{e} = 0.05$. In the actual experiment with $B_0 = 2.75\,\mathrm{T}$, the wave frequency corresponds to $f = 36.7\,\mathrm{MHz}$. The parameters of numerical computation are $N_{\mathrm{rmax}} = 100$, $N_{\theta\mathrm{max}} = 16$ and $N_{\phi\mathrm{max}} = 4$. The poloidal structure of the wave electric field ($\mathrm{Im}E_\theta$) and the power density absorbed by minority ions for four different toroidal angles are shown. The fast wave antenna located at outer side of the torus excites a standing wave and the power is absorbed near the minority ion cyclotron resonance surface. Since the resonance surface depends on the toroidal angle, the power absorption profile changes for different toroidal angles.

The absorption profile strongly depends on the wave frequency. Figure 2 indicates the poloidal crosssection at $\phi = 0$ for $f = 42\,\mathrm{MHz}$ to $f = 53\,\mathrm{MHz}$. With the increase of wave frequency, the resonance surfaces approaches to the magnetic axis from the low field side (top and bottom) and the two surfaces touch each other at $f = 48\,\mathrm{MHz}$. For f above 49 MHz, only one resonance surface exists in a plasma and it shifts towards the inner side of the torus. The radial profiles of absorbed power density for various wave frequencies are shown in Figure 3. In the case of 49 MHz, the power deposition strongly localized near the magnetic axis. For frequencies below 49 MHz, the profile is rather broad since two resonance surfaces exist in a plasma. For frequencies above 49 MHz, the power absorption localizes near the single resonance surface. Figure 4 indicates that the antenna loading resonance weakly depends on the frequency for a rather wide range between 43 MHz and 52 MHz. The total power absorbed in a plasma is not sensitive to the deposition profile in the present cold plasma model. The effect of cavity resonance is not so strong as our previous two-dimensional analysis in linear helical plasmas [3] and experimental results.

The shear Alfvén eigenmodes, such as global Alfvén eigenmode (GAE), toroidicity-induced mode (TAE) and helicity-induced mode (HAE) may exist in a toroidal helical plasma, and can be destabilized by fast ions. The conditions for these three eigenmodes are

- **GAE**: single n, single m, near axis or reversed shear
- **TAE**: single n, multi m, poloidal mode coupling $(m, m+\ell)$
- **HAE**: multi n, multi m, toroidal mode coupling $(n, n+N_\mathrm{h}k)$

$$k_\parallel = \frac{\ell + N_\mathrm{h}kq}{2qR}, \qquad q = -\frac{m+\ell/2}{n+N_\mathrm{h}k/2}$$

In order to find the Alfvén eigenmode, we maximize the wave amplitude for fixed amplitude excitation by adjusting the complex wave frequency. Figure 5 shows an example of GAE near the magnetic axis ($q \sim -2$) with $f \sim 200kHz$. The central toroidal mode number n is 1 in this case.

In order to analyze ICRF waves in toroidal helical devices, the full wave code TASK/WM was extended to the three-dimensional configuration. Minority ion heating in LHD was studied with cold plasma approximation. The toroidal effect shifts the cyclotron resonance surface and therefore power deposition profile. Radial deposition profile is broader than those in tokamaks. Analysis of Alfvén eigenmodes in toroidal helical plasma is available. An example of core-localized mode was found.

The kinetic analysis including the collisionless cyclotron dumping and Landau damping and the finite gyro radius effects are in progress. Systematic analysis of Alfvén eigenmode in helical devices will be reported near future.

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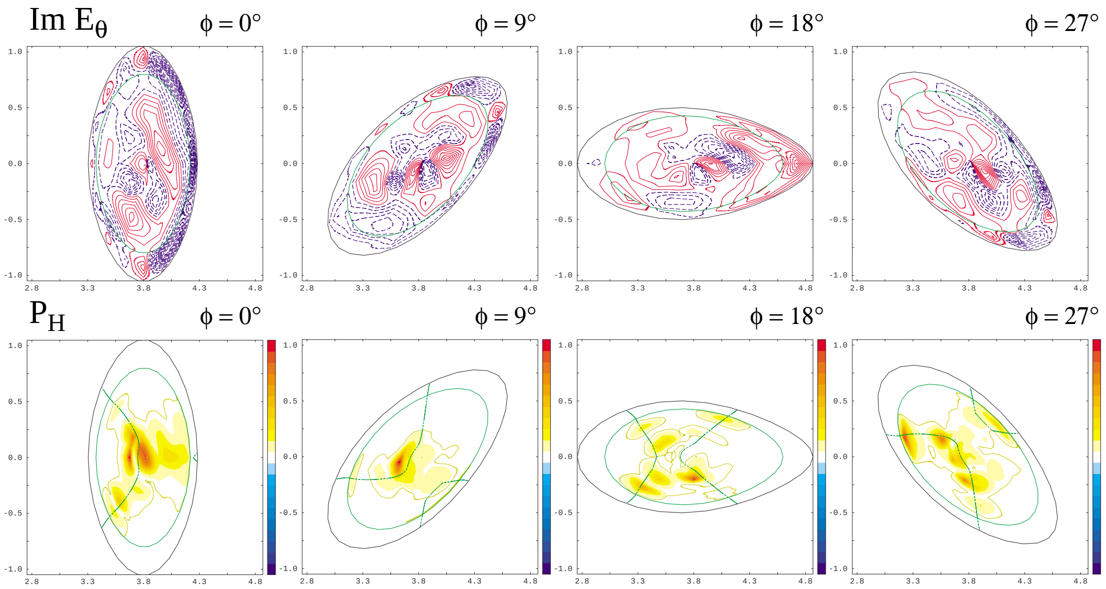

Fig. 1 Contour of the wave electric field (ImE_θ) and the power density absorbed by minority ions on poloidal crosssection at four different toroidal angles.

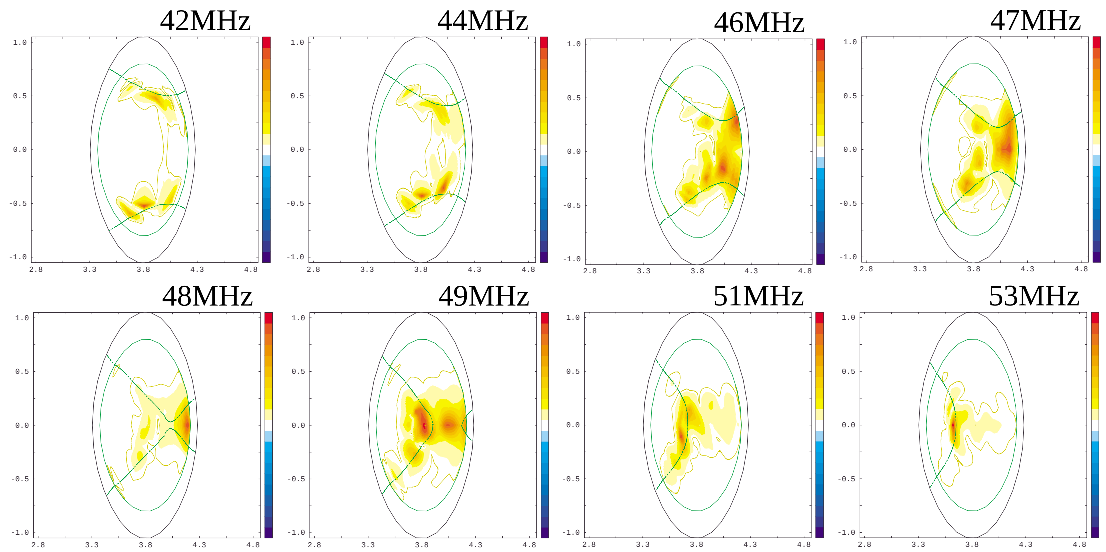

Fig. 2 Frequency dependence of poloidal power deposition profile

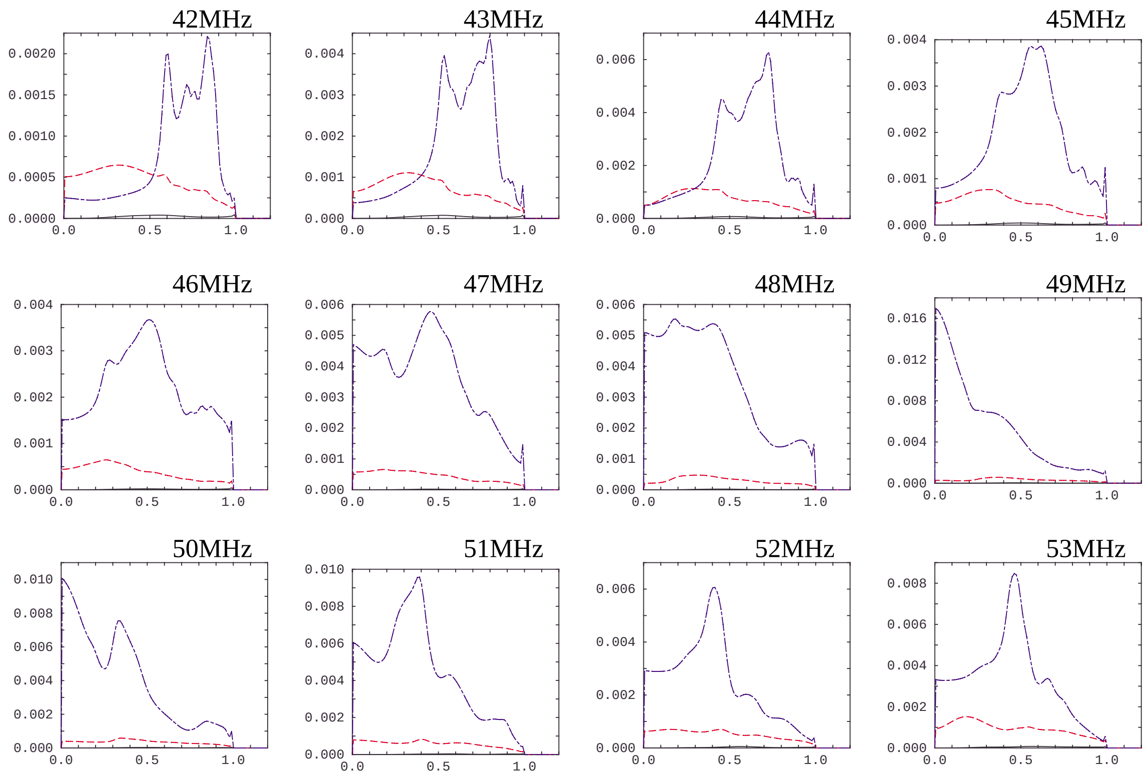

Fig. 3 Frequency dependence of radial power deposition profile

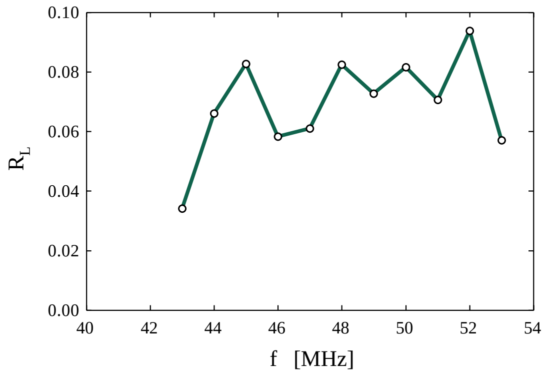

Fig. 4 Frequency dependence of antenna loading resistance

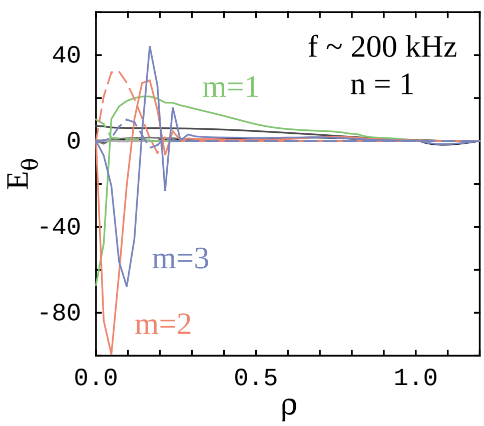

Fig. 5 Example of the GAE mode localized near the axis