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Low Frequency Heating And Particle Flow Driven by Ergodic Divertor Coils in Tokamaks

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Introduction Dynamic Ergodic Divertor (DED) coils have been proposed to study an effective heat exhaust, edge cooling, impurity screening, plasma confinement and stability at the plasma boundary (see motivation in Ref.1 and detailed description of DED coils for TEXTOR tokamak in Ref.2). Here, we discuss possibility using DED coils as an antenna to produce additional heating and plasma flow by Low Frequency (LF) fields ($f = 5 - 10$kHz) to modify relevant parameters at the plasma boundary. We analyze the dissipation and the penetration depth of LF fields at the rational magnetic surfaces $q_r = M/N$ where $q_r = 3 - 5$ is safety parameter near the plasma boundary. The coils are represented as an ideal helical antenna with current, $J_{\zeta,\theta} = J^{(M,N)}_{\zeta,\theta}\ \delta(r-b)\ exp[i(M\theta + N\zeta - \omega t)]$ and poloidal/toroidal wave numbers M/N depending on coil feeding[1,2]. Finally, we make first estimations of the poloidal and toroidal forces driven by the DED-coils in TEXTOR tokamak and Dynamic Ergodic Limiter in Tokamak Chauffage Alfvén Brésilien (TCABR) plasmas.

Here, two dimensional numerical kinetic[3] and MHD[4] codes developed for calculations of wave excitation and dissipation in Alfvén range of frequency in axissymmetric tokamaks are used for the analyses. The kinetic code calculates the distribution of electro-magnetic fields, wave dissipation profiles, and the impedance of the helical antenna for a given real frequency ω of the generator and toroidal wavenumber N of antenna in two ion-species magnetized plasmas with circular concentric magnetic surfaces. Only two poloidal sideband Fourier harmonics are considered in plasma equilibrium parameters. Pseudo-toroidal coordinates (defined by $R = R_0 + r\cos\theta$, ζ, and $Z = r\sin\theta$) are used, where R_0 is the major radius of the cross-section of the plasma column, of minor radius a. A multi-fluid MHD model is used in ALTOK code[4] with two dimensional inhomogeneity of plasma parameters and arbitrary cross-section of tokamak magnetic surface. LF fields and dissipation are calculated using 69x64 radial/poloidal mesh points and taking into account the Shafranov shift. The MHD model includes the natural electron-ion collisional dissipation and electron inertia in the parallel component of dielectric tensor that is valid for analyses of LF dissipation in the cold collisional plasmas

$k_{\|}v_{Te} \leq \omega, \nu_{ei}$. The Krook form of the collision operator used in the perpendicular component of dielectric tensor, $\varepsilon_{rr} \approx \varepsilon_{\perp\perp} \approx (1 + \nu_{i,ef}/\omega)(c/c_A)^2$, produces the ion collision dissipation (ion viscosity effect). The absorption profile is calculated via $W(r) = (\vec{\tilde{j}} \cdot \vec{E})$ in both codes. The poloidal and toroidal components ($F_\theta = F_\zeta R_0 M/rN$) of the momentum transfer force can be calculated via the value of LF field absorption $F_\zeta = W(r)N/(R_0\omega)$.

Plasma parameters and LF fields. To model conditions of LF field dissipation and ponderomotive forces induced by DED coils[1] in the frequency range (1-10 kHz) in tokamak plasma, we assume circular magnetic surfaces with simple fitted profiles of the plasma quantities: B = 2.2T, a = 0.64 m; R_0 = 0.61 m, antenna surface radius b = 0.184 m, wall radius d = 0.23 m for TEXTOR; and B = 1.1T, a = 0.18 m, R_0 = 0.61 m, b = 0.184 m, d = 0.23 m for TCABR. The temperature profile is $T_{e,i} = T_{e,i0}[(1 - (r/a)^2)^{\alpha_T} + 0.044]$, where the central electron and ion temperatures are T_{e0}/T_{i0} = 1800/900eV and α_T = 4 for TEXTOR, and 500/180eV, α_T = 2 for TCABR, respectively. The electron density profile is given by $n_e = n_0[(1-r^2/a^2)^{0.9}+0.1]$ with $n_0 = 6.10^{19}/m^3$ for TEXTOR and $n_0 = 3.10^{19}/m^3$ for TCABR. The ion density n_i is satisfied to the requirement of charge neutrality, $n_i = n_e$. The current profile is taken from the temperature profile according to Spitzer resistivity, and the values of safety parameter are $q_0 = 0.85, q(r = 42) = 5, q_a = 5.9$ for TEXTOR, and $q_0 = 1.1, q(r = 15.3) = 3, q_a = 4.4$ for TCABR, respectively.

The conditions for validity of kinetic and MHD codes are satisfied in a periferical region with width approximately equal one third of minor radius, for a frequency band (*cold plasma*) that is determinated by inequalities,

$$k_{\|}v_{Ti} << k_{\|}v_{Te} \leq \omega \approx k_{\|}c_A; \text{or } k_{\|}v_{Ti} << \nu_{ii}, k_{\|}v_{Te} \leq \omega \approx k_{\|}c_A \leq \nu_{ei} \qquad (1)$$

In this case, the slow quasi-electrostatic wave has a very short wavelength and dissipates because of collisions near mode conversion point at the plasma boundary. Both codes demonstrate that total LF field dissipation strongly diminishes with growing poloidal and toroidal wavenumber for the same resonant magnetic surface. In Fig.1a-f, the density, dissipated power and radial electric field are calculated with the cylindrical kinetic code for different coil combinations $[M/N]$ in TEXTOR. In this case, we have two local Alfvén wave resonances at the rational magnetic surfaces, $k_{\|} = 0$. We can also observe that LF field dissipation, which is localized in two mode conversion points for low $[M/N]$ (d), is overlapped for high M, N in Fig.1f.

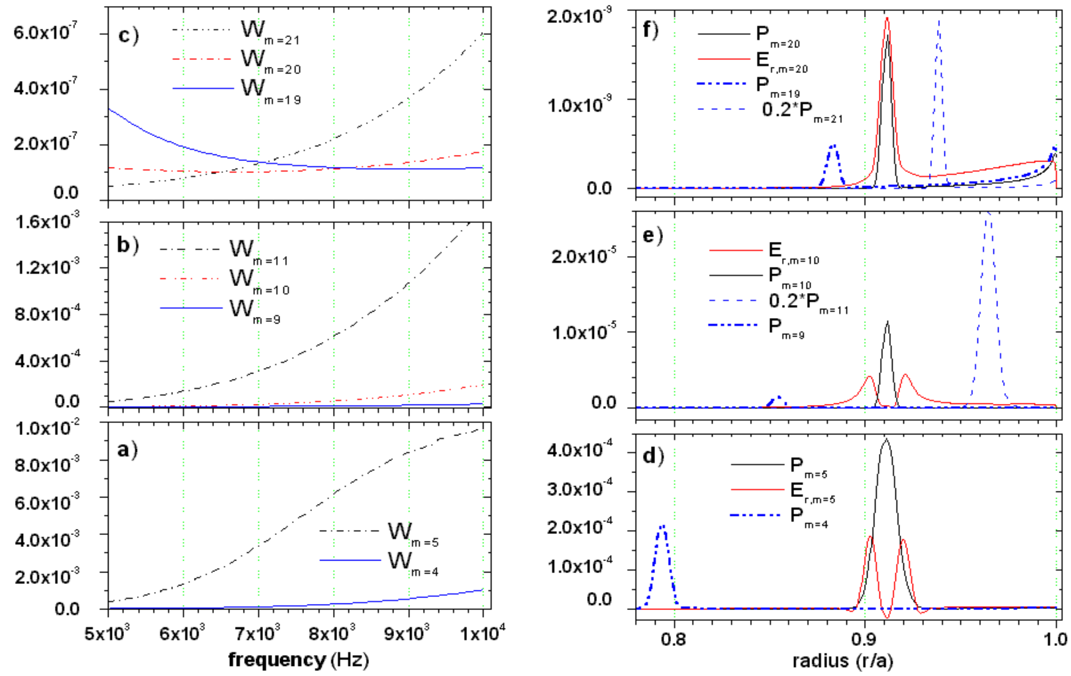

Fig.1a-f. *Plot of total dissipated power (a-c), and their density and the radial electric field (d-f) in a.u. for different coil combinations [M/N] in TEXTOR: (a,d) [5,4/1]; (b,e) [10±1/2] and (c,f) [20±1/4].*

To analyze the poloidal mode coupling effect produced by toroidicity, we calculate LF fields and dissipation for 10 kHz frequency and $[M/N] = 3/1$ coil configuration using the MHD code. In Fig.2-3, we present the distribution of the radial electric field and dissipation over the TCABR cross-section. Here, we can observe that the mode coupling effect produces additional dissipation in $M \pm 1$-sideband harmonic resonances ($q = 2, 4$).

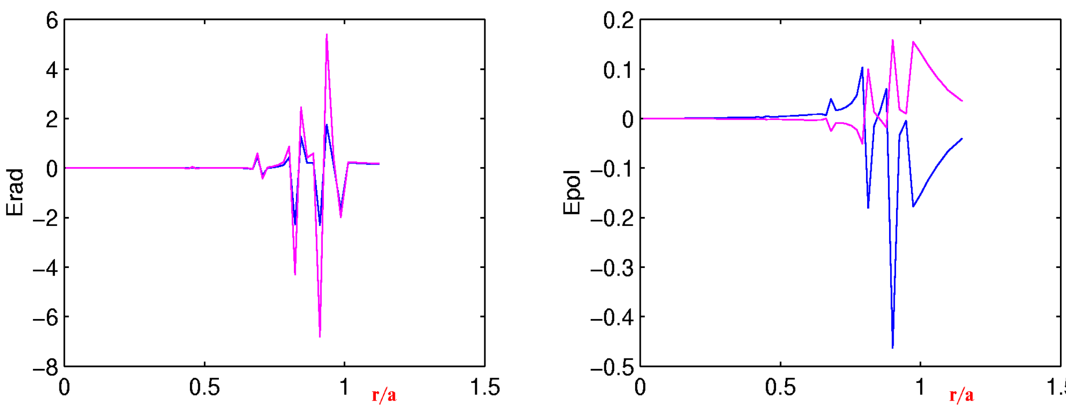

Fig.2. *Plot of the radial and poloidal electric field in a.u. over minor radius (r/a high field side) for*

$f = 10kHz$ and [3/1] coil combinations in TCABR

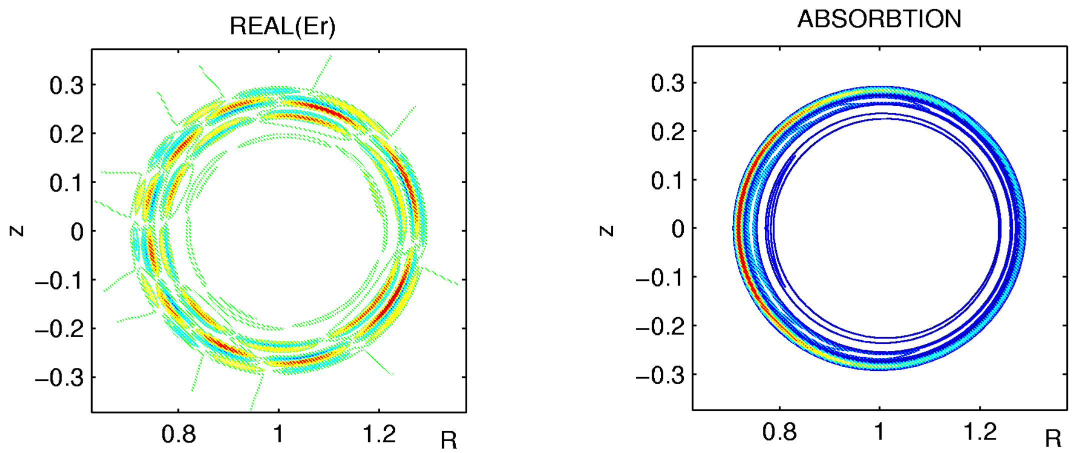

Fig.3. *Plot of dissipated power and radial electric field (maximum is in red and minimum is blue) over TCABR cross-section in the same conditions as in Fig.2.*

The same effect is found in the MHD calculations for TEXTOR with $[M/N] = 5/1$ coil.

Balancing the poloidal component of the driving force[5] with poloidal neoclassical viscosity in the collisional regime and the toroidal component with confinement losses,

$$F_\theta = m_i n_i \chi_{\text{neo}}(V_\theta - \kappa v_{Ti}),\ \ F\zeta = m_i n_i \chi_\zeta V_\zeta;\ \chi_{\text{neo}} = 1.5(v_{Ti}/R_0)^2/\nu_i,\ \chi_\zeta \approx a^2/(a-r)^2 \tau_E$$

where κv_{Ti} is residual plasma rotation and τ_E is the energy life time, we can estimate the toroidal and poloidal flow velocity about 2-5 km/s for the absorption density about 0.5W/cm^3 at the resonant magnetic surface.

Conclusion. The analysis of the poloidal/toroidal forces driven by the low frequency fields induced by DED-coils in TEXTOR and TCABR plasmas shows that

- the ion collision viscosity play fundamental role in low frequency field dissipation;
- toroidicity effects produce strong poloidal mode coupling between the sideband local Alfvén resonances;
- the momentum transfer force produced by 20 kW of LF dissipation can drive toroidal and poloidal flow about 2-5 km/s in TEXTOR and 5-10 km/s in TCABR at the resonant magnetic surface.

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