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Non-linear MHD Rotating Plasma Response to Resonant and Non-Resonant Magnetic Perturbations.

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1. Introduction. Resonant Magnetic Perturbations (RMP) generated by a specific set of coils have been shown to be effective in eliminating or mitigating Type I Edge Localized Modes (ELMs) in H-mode plasmas [1,2]. ELM control by RMPs is strongly recommended for ITER [3,4]. The RMP co ils design for ITER is mainly based on the experimental criterion and "vacuum" field modelling suggesting that ELMs are suppressed when the Chirikov parameter $\sigma_{Chir}>1$ for $\sqrt{\psi} \geq 0.9$ [1-4]. However, compared to vacuum, RMPs could be very different in rotating plasmas [5]. In addition the experiments [1,2] have demonstrated that RMPs often lead to a global slowing down of the toroidal rotation and possible MHD modes locking. This paper presents non-linear MHD modelling of some expected effects from the presently proposed ITER RMP coils using DIII-D experiments with I-coils [1] for validation.

2. Reduced MHD model with RMPs. The non-linear cylindrical reduced MHD (RMHD) code [8] was adapted to take into account toroidal plasma rotation, resonant braking [5] and Neoclassical Toroidal Viscosity (NTV) due to the radial drift of trapped particles in helically perturbed magnetic field [6,7] . The equation for toroidal velocity is added to the model [8] in a form:

$$\frac{\partial V_z}{\partial t} + V_z \frac{\partial V_z}{\partial z} + \left[\Phi, V_z\right] + \vec{\nabla}_{//} p = S_{\mathrm{v}} + \nu_{//} \nabla^2 V_z + F_{RB} + F_{NTV}. \qquad (1)$$

Here plasma flow velocity is: $\vec{V} = \vec{V}_\perp + \vec{V}_{//}$, $\vec{V}_{//} = (\vec{V}, \vec{B})/B$, $\vec{V}_\perp \approx -\vec{\nabla}\Phi \times \vec{e}_z$, $V_z \approx V_{//,z}$, Φ- electrostatic potential, other variables and normalisation are described in [8]. The boundary conditions at *r=1* are zero for all perturbations except for the magnetic flux harmonic's amplitudes: which are approximated by amplitudes calculated in torus [3], $\psi_{nm}^{cyl}\big|_{r=1} \sim \psi_{nm,sep}^{vac,tor}$, n and m are toroidal and poloidal numbers. Resonant braking term is taken only for a mean flow [9-10]: $F_{RB} = \frac{-1}{2qR_0} \mathrm{Im} \sum_{m,n\neq 0} m \left[j_{nm}\psi_{nm}^* - \Phi_{nm} \left(\frac{\partial \Phi_{nm}^2}{\partial r^2} - \frac{1}{r}\frac{\partial \Phi_{nm}}{\partial r} \right)^* \right]$. The expression for F_{NTV} in low collisionality 1/ν–regime is taken form [7]: $F_{NTV} \approx -\frac{V_{ti}^2}{(R_0 q)^2 \nu_i^2} (b_{eff}^{1/\nu})^2 (V_z - V_*^{NC})$, where V_{ti}, V_*^{NC} are ion thermal and neoclassical toroidal velocities, ν_i-ion-ion collision frequency, $b_{eff}^{1/\nu}$ -is effective magnetic helical perturbation due to RMPs calculated in toroidal geometry in Hamada coordinates for vacuum fields [6,7,11]. In this work we privileged the realistic geometry in NTV calculations as suggested in [11], since RMP spectrum could be different in cylinder, so $b_{eff}^{1/\nu}$ profile is not changes in RMHD self-consistently, but is used as an input file.

3.RMP penetration time and screening by plasma rotation. The first step in this study was

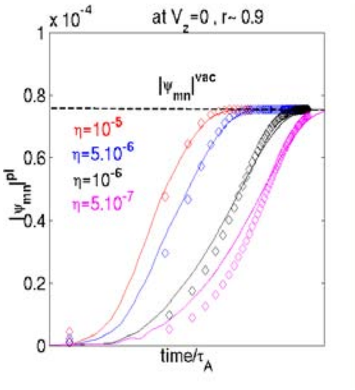

Fig.1. Time dependence of $|\psi_{n=-3,m=9}|$ *on the resonance surface* r_{res}*=0.9 in resistivity scan (*η_0*=const) w/o rotation.*

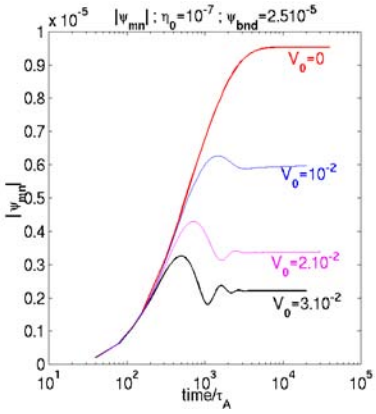

Fig.2. Time dependence of $|\psi_{n=-3,m=9}|$ *on the resonance surface* r_{res}*=0.9 in rotation scan* ψ_{bnd}*=2.510*$^{-5}$*.*

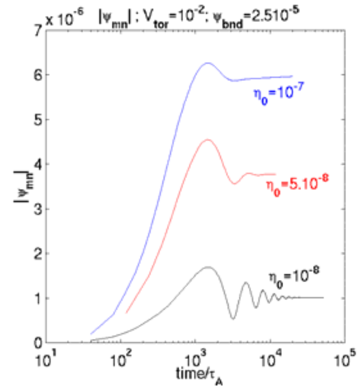

Fig.3.$|\psi_{n=-3,m=9}|$*on the resonance surface in resistivity scan at* V_0*=10*$^{-2}V_A$*,* ψ_{bnd}*=2.510*$^{-5}$*.*

to estimate single harmonic penetration without rotation. The perturbation $|\psi_{n=-3,m=9}|$on the surface $q_{(r=0.9)}=|m/n|$ as a function of time is presented in Fig.1 in resistivity scan. The approximation: $\psi^{pl}_{nm} \approx \psi^{vac}_{nm}(1-0.99e^{-t/\tau})$ valid at zero rotation is in diamonds (Fig.1). The penetration time *(*τ*)* for resonant harmonics roughly scales as a local current diffusion time $\tau \sim (1-r_{res})^2/\eta$ and for r_{res}*~0.9* (~pedestal top) is estimated τ*~600ms* for ITER *(*T_{ped}*=4keV)* and τ *~ 60ms* for DIII-D *(*T_{ped}*=2keV)*. In the following cases we adopted a more realistic resistivity profile: $\eta = \eta_{pl}\eta_{vac}/(\eta_{pl}+\eta_{vac})$, $\eta_{vac}=0.1$, $\eta_{pl}=\eta_0(p/p_0)^{-3/2}$ which mimics $\sim T_e^{-3/2}$ dependence. The pressure profile used here is typical for H- mode scenario.The rotation profile is parabolic with a central value V_0. The time dependence of $|\psi_{n=-3,m=9}|$ on the resonant surface for different V_0 is presented in Fig.2 showing that RMP decreases at stronger

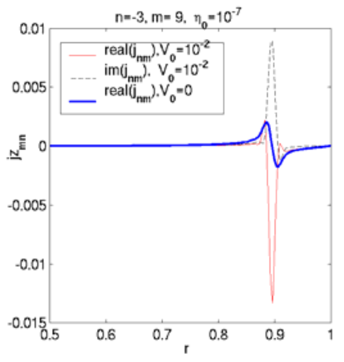

Fig.4. Toroidal current perturbation profile at zero rotation (bold) and at V_0*=10*$^{-2}$

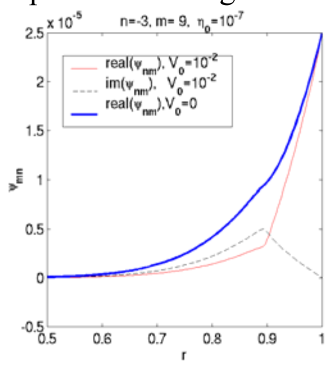

Fig.5. Flux perturbation profile without and with rotation V_0*=10*$^{-2}$ *corresponding to Fig.4.*

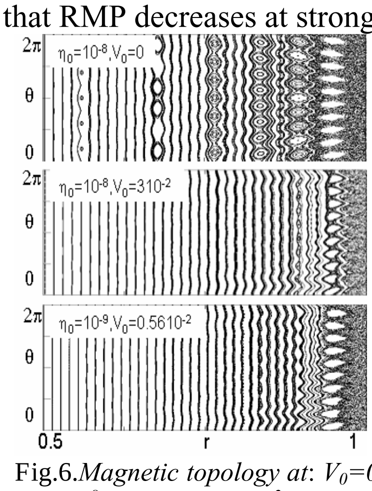

Fig.6.*Magnetic topology at*: V_0=0, η_0*=10*$^{-8}$ *(top)*; V_0*=310*$^{-2}$, η_0*=10*$^{-8}$ *(mid)*; V_0*=0.5610*$^{-2}$, η_0*=10*$^{-9}$ *(bot).*

rotation leading to smaller islands in rotating plasmas.The screening of islands due to the rotation is stronger at lower resistivity (Fig.3). The rotating plasma response on RMPs consists in the generation of a narrow current layer on the resonant surfaces (Fig.4-5) [5,9,10]. The present modeling results confirm the screening factor for *visco-resistive* linear regime [5,3]: $\psi^{pl}_{mn}/\psi^{vac}_{mn}\big|_{res} \sim \eta^{5/6}/V_0$. The magnetic topology resulting from RMHD with rotation and F_{NTV}*=0* for RMPs spectrum: $\psi_{nm,r=1}=[9;8;...3]\cdot 10^{-5}$, *n=-3, m=5:11*, resonant at the edge (q_{95}*~3*) is presented in Fig.6. Notice that V_0*=3*x*10*$^{-2}$, η_0*=10*$^{-8}$ correspond to a *DIII-D*-like case: R_0*=1.8m*, central rotation *~10kHz,* and $V_0=0.56\mathrm{x}10^{-2}$, $\eta_0=10^{-9}$ is an ITER-like case: R_0*=6.2m, ~1kHz* [3]. One can see that in both cases central islands are screened, but still overlap for *r>0.9.* However, the role of the diamagnetic frequency in RMP screening should be estimated since it could be important especially in the pedestal region with steep gradients. In the present modelling there was almost no change in the rotation profile due to the resonant braking term $-F_{RB}$, since it is weak for typical RMPs modelled here.

3. Comparative modeling for ITER and DIII-D. During the design of the ITER ELM control coils [3,4], the vacuum spectrum was optimised to produce the required edge ergodisation at minimum current, but at the same time to avoid large central perturbations, potential triggers of MHD instabilities. One can expect that harmonics resonant in the plasma centre will be screened by plasma rotation for $r<r_{res}$ (Fig.6). As for non-resonant (not producing islands: $m/n<q(0)$) harmonics, RMHD modeling demonstrates that they penetrate on Alfven time scale and are not screened by plasma rotation, hence their impact on NTV could be important. Typically, one row coils and external coils far from the plasma contain larger non-resonant harmonics amplitudes and hence larger NTV compared to in-vessel multi-row coils [3,4], which is the latest RMP coils design strongly recommended for ITER [12] (Fig.8-top). Notice also the lower current needed for RMP coils close to plasma [3,4]. The damping time [10] : $t_{dam} \sim V_\varphi / F_{NTV}$ due to NTV was calculated here in toroidal geometry and vacuum fields for 3- row of 9 in-vessel coils at *50kAt* (*'in-VV'*) [13] and 18 one row coils around mid-ports (*'18pf'*) at peak current *110kAt* for *n=4* in ITER H-mode scenario [3] (Fig.7) in comparison with direct plasma braking measurement on DIII-D #127744 [13] for I-coil (*odd parity 4.65kA, n=3*). In Fig.8 for each of the RMP coils two curves are presented: vacuum fields with all harmonics taken into account (here *m=-18:18*, *n=4* for ITER and *n=3* for DIII-D) and for non-resonant part of the spectrum (total "screening" of resonant harmonics). The experimentally measured damping time [12] is in-between these two approximations (Fig.9). However NTV in "1/ν" regime is larger in ITER even for the optimum coils compared to DIII-D due to the lower ion collision frequency. The rotation profiles for ITER –like parameters with NTV due to non-resonant harmonics (perfect screening) for in-VV coils are presented on Fig.10. NTV is calculated for realistic equilibrium and coils geometry and used as a damping term in equation (1) of the RMHD code (see Sec.2): $F_{NTV} \approx -\alpha_{NTV} f(r)(\mathrm{v}_z - V_*^{NC})$, where *f(r)* is normalized to the maximum ($\alpha_{NTV} \approx 2.10^{-5}$) NTV profile, $\eta_0 = 10^{-8}, \nu_{0,//} = 3.10^{-7}$ (ν^{phys}*~1m²/s).* One can see that positive co-rotation is replaced on $\sim 10^6 \tau_A$ time scale by counter rotation due to NTV (Fig.9). Notice that initially screened central islands re-appear (Fig.10) when local toroidal rotation velocity $V \approx 0$, but than are screened again by counter rotation. Notice also that the approximate solution of the equation: $V_t \approx S_\mathrm{v} + \nu_{0,//}\nabla^2 V + F_{NTV}$ (dashed line on Fig.9) is a good approximation of (1) with

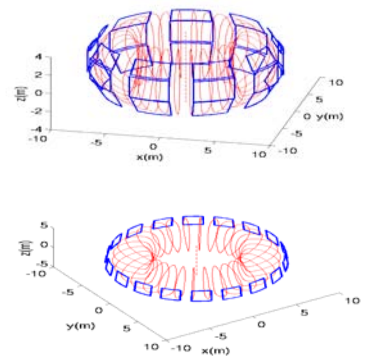

Fig.7. *Top:9 in-vessel RMP coils (in-VV) proposed for ITER, bottom: around 18 mid-ports (18pf). Plasma position is indicated in red.*

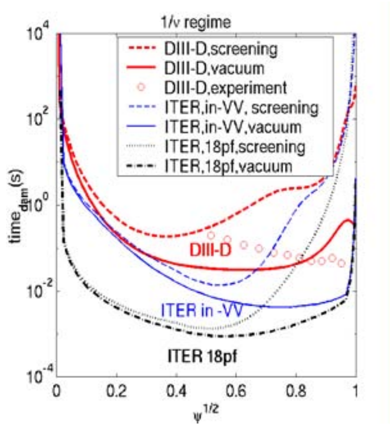

Fig.8. *Damping time due to NTV estimated for the 1/ν regime for ITER H-mode in-VV, 18 pf coils in comparison to DIII-D.*

a strong NTV compared to intrinsic parallel viscosity ($\alpha_{NTV} / \nu_{//} > 1$).Obviously the present

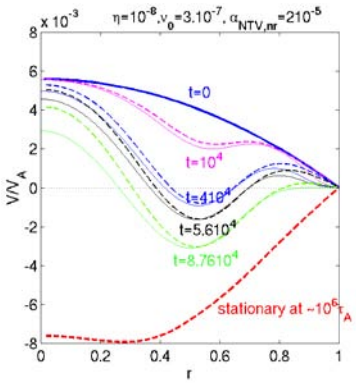

Fig.9. *Toroidal rotation profile (RMHD code) with NTV (in-VV coils in ITER): transition from co- to counter rotation.*

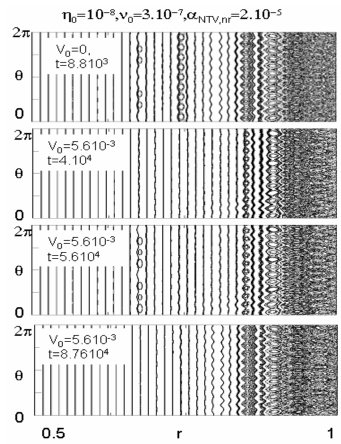

Fig.10. *Poincaré plots at $t=10^4$; $t=5.610^4$; $t=8.7610^4$. Corresponding rotation profiles are presented in Fig.10.*

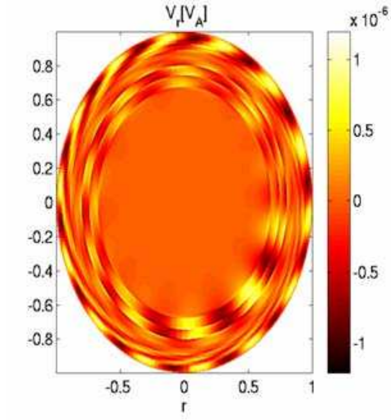

Fig.11. Convective radial velocity at $t=8.7610^4$ in RMHD modelling $k_{\perp}=10^{-7};\eta_0=10^{-8};V_A=7.10^6\,m/s$

results should be taken with caution since the exact predictions of rotation in ITER will depend on the intrinsic viscosity (on Fig.9 normalized $\nu_{//}$~3.10^{-7}, physical ~*$1m^2/s$*), sources, diamagnetic effects etc. However, due to the neoclassical effects, the counter rotation is very probable at weak intrinsic rotation and relatively large NTV in general [7]. Similar to [9,14] the convective *ExB* cells were observed in present modelling (Fig.11) suggesting an additional density transport due to RMPs observed in experiments [1,2].

4. Conclusions. A new development of the non-linear cylindrical reduced RMHD code [8] was done to take into account resonant and non-resonant magnetic perturbations generated by specific set of coils, toroidal rotation, resonant braking and NTV . It was shown that at zero rotation RMPs penetrate to plasma on the current diffusion time scale and for *r~0.9* (~pedestal top) is estimated *~600ms* in ITER and *~60ms* in DIII-D. It was demonstrated that screening of RMPs by plasma rotation is larger for stronger rotation and lower resistivity confirming results from [3,5]. It was shown that for typical ITER and DIII-D parameters central resonant islands are expected to be screened and that the edge magnetic field is stochastic. However, here the RMP's screening due to the diamagnetism was not taken into account and should be estimated. The damping time due to NTV in the '1/ν' regime at *r~0.5* is estimated as: t_{dam}*~100ms* for DIII-D I-coils and roughly corresponds to the experimental measurements [13]. Modelling of NTV in '1/ν' regime in ITER suggest that the *n=4* symmetry in-vessel multi-row coils *(in-VV, 50kAt,* t_{dam}*~10ms)* produce about one order of magnitude smaller NTV compared to one row mid-plane coils *(18pf,110kAt ,* t_{dam}*~1ms)*. If "1/ν" low collisionality regime is valid [7] the counter rotation is expected in ITER.

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