Interaction of Resonant Magnetic Perturbations with flows in toroidal geometry

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1. Introduction. A promising method to control large type-I ELMs is the application of Resonant Magnetic Perturbations (RMPs) [1]. RMPs penetration in the plasma was shown to be conditioned by the rotating plasma response [2,3]. In this paper, the interaction between RMPs and plasma flows is studied in toroidal geometry with X-point, using the non-linear resistive reduced MHD code JOREK [4]. The initial model was extended to include two-fluid diamagnetic effects, neoclassical poloidal viscosity, a source of toroidal rotation and RMPs physics. Simulations for JET-like size machine (*R=3m*, *a=0.8m*, B_t*=2.9T*) are presented here.

2. Model. It was demonstrated in modeling that diamagnetic effects play a major role in the screening of RMPs in the pedestal region with steep pressure gradients [2,3]. The diamagnetic velocity $\vec{V}^*_{i,e} = \vec{B} \times \nabla p_{i,e} / n_e e B^2 \approx -\tau_{IC} \nabla p \times \nabla \varphi$ was implemented in JOREK for electrons and ions. The plasma fluid velocity is represented as: $\vec{V}_i \approx \vec{V}_E + \vec{V}_{\parallel,i} + \vec{V}_i^*$, where $\vec{V}_{\parallel,i} = (\vec{V}_i \vec{B})\vec{B} / B^2$ and $\vec{V}_E = \vec{E} \times \vec{B} / B^2 \approx -\nabla u \times \nabla \varphi / B$. p is the scalar pressure, n_e the electron density, u the electric potential, T_e the electron temperature, φ the toroidal angle, and $\tau_{IC} = m_i R_0 / \left[e B_0 \sqrt{m_i n_e \mu_0} (1 + T_e / T_i) \right]$ is the normalized ion cyclotron frequency. A one-fluid model was used for energy: $T = T_e + T_i$; $T_e / T_i = 1$, but two-fluid diamagnetic effects are included in the model and in particular in the induction equation for the poloidal magnetic flux -ψ evolution. Typically $\tau_{IC} \approx 2.10^{-3}$ in JOREK units for JET-like simulations. A toroidal rotation source was introduced to maintain the rotation profile at the initial value ($S_V = -\mu_\parallel \Delta V_{\parallel, t=0}$). The central rotation frequency is $\Omega_{tor,0} = 38 krad/s$. As in [2], the neoclassical poloidal viscosity was taken from [5]: $\nabla \cdot \Pi_i^{neo} = \mu_{i,neo} m_i n_e (B^2 / B_\theta^2)(V_{i,\theta} - V_{\theta,neo}) \vec{e}_\theta$ where $V_{\theta,neo} = (-k_i / eB^2) \nabla T_i \times \vec{B} \cdot \vec{e}_\theta$ and $\vec{e}_\theta = -(R / |\nabla \psi|) \nabla \psi \times \nabla \varphi$. Typical values ($\mu_{i,neo} = 10^{-5}$ and k_i = *-1*) were taken constant in modeling for simplicity. The final set of equations includes additional terms in the induction, vorticity and parallel velocity equations compared to [4]. The magnetic perturbations generated by external EFCC (*n=2,* I_{coil}*=40kAt*) were calculated in the vacuum with the ERGOS code [6] and are imposed as boundary conditions for the magnetic flux (*n=2*): $\delta\psi_{\text{boundary}} = \delta\psi_{\text{RMP}}$. Consequently the magnetic flux self-consistently evolves, taking into account the plasma response. The central density and temperature are $n_{e0} = 6\times 10^{19}\,m^{-3}$, $T_{e0} = 5keV$, and $q_{95} \approx 3$. The viscosity is set $\nu=10^{-6}$ at the center for numerical reasons and the central resistivity is $\eta=5\text{x}10^{-8}$-10^{-7}. Both parameters follow a $T^{-3/2}$ dependence.

3. Equilibrium plasma flows. The sheath boundary conditions ($V_{\|} = \pm C_s$, where C_s is the sound speed) on the divertor plates generate a parallel flow in the SOL represented in *Fig.1*, where no diamagnetic and neoclassical effects are taken into account. Including the diamagnetic effects results in the formation of the equilibrium radial electric field with characteristic “well” in the pedestal region (*Fig.2).* If in addition the neoclassical poloidal viscosity is taken into account, the poloidal velocity (*Fig.3*) tends to the neoclassical value in the pedestal region: $V_\theta \to V_{\theta,neo} \propto -k_i \nabla T$. The sum of these effects, including the source of parallel velocity, gives strong (~$10^{-2}V_A$~10^4m/s) poloidal and toroidal flows (*Fig.4*) in the SOL and the pedestal.

4. Rotating plasma response to RMPs. After equilibrium flows are established (typically after a few 10^3 Alfven times), the amplitude of the RMPs (*n=2*) is increased from zero up to *40kAt* on the typical time scale ($10^3 t_A$, where t_A is the Alfvén time) (*Fig.5*). Without RMPs, the *n=2* mode is stable. With RMPs, the *n=2* perturbation grows and saturates following the increase in RMP amplitude at the boundary (*Fig.5*). On *Fig.6*, the magnetic energy of the *n=2* mode is presented as a function of time for different resistivities ($\eta=5\text{x}10^{-8}$ and 10^{-7}) and different τ_{IC} (1×10^{-3} and 2×10^{-3}). After RMPs maximum amplitude is reached, three different regimes are found depending on the parameters (*Fig.6*). **i)** For a high resistivity $\eta=10^{-7}$ and a diamagnetic parameter $\tau_{IC} = 10^{-3}$ (smaller poloidal rotation), the islands generated by RMPs are “stuck” to the plasma and rotate at the poloidal rotation frequency: $f^* \approx mV_\theta / 2\pi r_{res}$. For this case, $m \sim 5$, $q(r_{res}) = m/2$. The magnetic energy and islands size are fluctuating at the same frequency *f**, indicating that the islands are successively facing maxima and minima of the RMP amplitude while rotating with static RMPs at the boundary. This regime possibly has similarities with non-linear Rutherford regime described in [7, 8]. The magnetic flux perturbation (*n=2*) with plasma response to RMPs is presented on *Fig.7*. The corresponding current responses are mainly

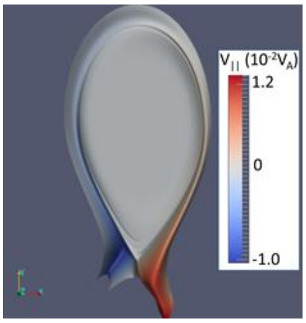

Fig.1. Typical SOL parallel flow without diamagnetic and neoclassical effects

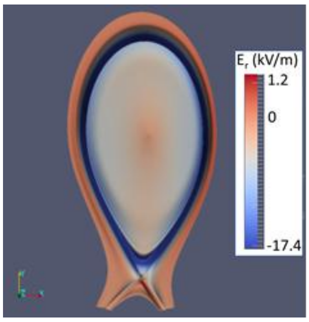

Fig.2. Equilibrium electric field with diamagnetic effects. Note the negative "well" in the pedestal region

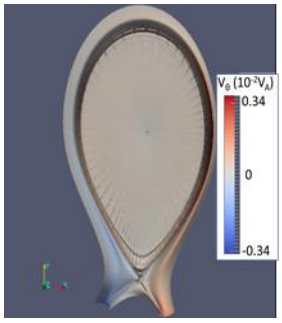

Fig.3. Poloidal velocity pattern with the diamagnetic and neoclassical effects included in the model

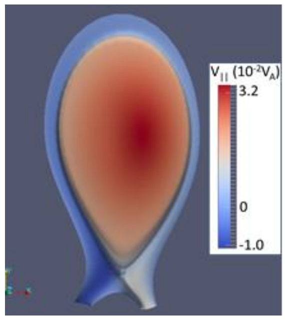

Fig.4. Toroidal flow with a source of toroidal rotation and all effects

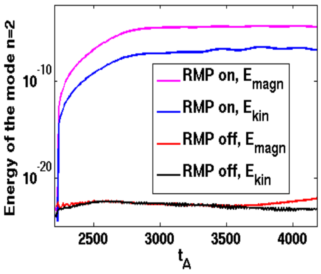

Fig.5. Magnetic and kinetic energies of the mode n=2 w/o (bottom) and with (top) RMPs

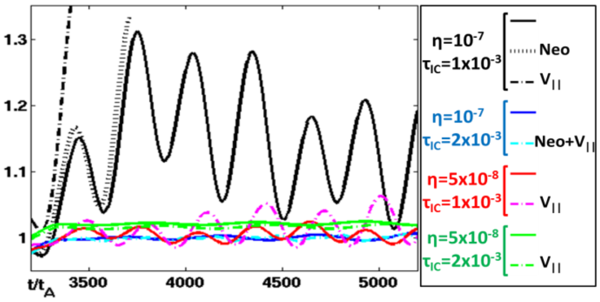

Fig.6. Magnetic energy of n=2 perturbation after RMP growth. Note the 3 regimes: highly oscillating energy (black) for high η & low τ_{IC}, smaller oscillations (red) for low η, static mode (blue&green) for high τ_{IC}

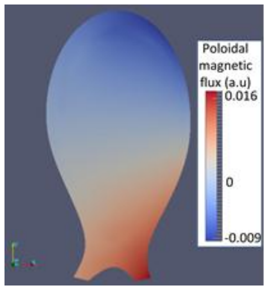

Fig.7. Magnetic flux perturbation n=2 due to RMPs at t-$t_{start\ RMP}$=1000t_A (η=5.10^{-8}, $\tau_{IC}=10^{-3}$)

generated on the resonant surfaces *q=m/n* (*Fig.8*). Periodic density and temperature fluctuations are also observed in this regime. At the maximum RMP amplitude, edge islands overlap forming an ergodic layer, while the central island (at *q=3/2*) is screened (*Fig.9*). **ii)** At lower resistivity ($\eta=5\times10^{-8}$) and $\tau_{IC}=10^{-3}$, the magnetic energy of the *n=2* mode decreases compared to the previous case (*Fig.6*) confirming the findings of [2] where more screening of RMPs was observed at lower resistivity. In this regime, the islands are almost static with smaller oscillations in amplitude. **iii)** For stronger diamagnetic rotation ($\tau_{IC}=2\times10^{-3}$) at $\eta=10^{-7}$, the magnetic energy of *n=2* decreases (compared to $\tau_{IC}=1\times10^{-3}$), suggesting more screening of RMPs by the plasma at stronger rotation. In this case, edge islands are locked to the static RMPs, producing, however, static density and temperature perturbations (*Fig. 10*). In this regime, the toroidal rotation source and the neoclassical effects do not affect the *n=2* mode, which remains static. Contrarily, in the other two regimes, the toroidal velocity and the neoclassical viscosity amplify the oscillation of the perturbation mode and change the rotation frequency of the islands, since the poloidal rotation is modified. The multi-toroidal harmonics *n=0, 2, 4* simulation, with $\eta=1\times10^{-7}$ and $\tau_{IC}=1\times10^{-3}$, is presented on *Fig.11*. Without RMPs, the mode *n=4* is more unstable compared to the almost stable *n=2* mode (*Fig.11*). The same simulation with RMPs switched on (*Fig.11*) shows that the dynamics of the *n=4* mode is changed and *n=4* couples with the *n=2* mode. Besides, both energies of the modes *n=2* and *4* fluctuate at the same frequency *f**, since the *(n=4, m~10)* edge islands rotate at the same velocity as the (*n=2, m=5*) edge islands.

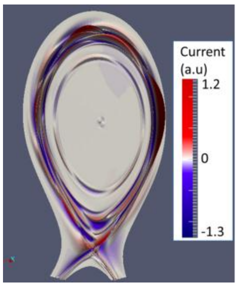

Fig.8. Current perturbations due to RMPs

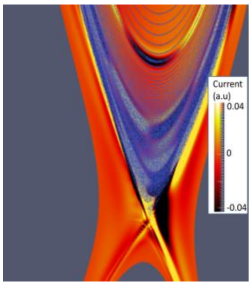

Fig.9. Edge magnetic topology with current perturbations

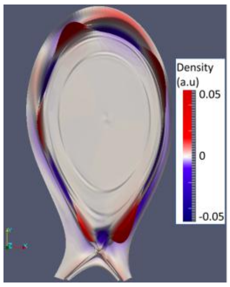

Fig.10. Density perturbation with RMPs

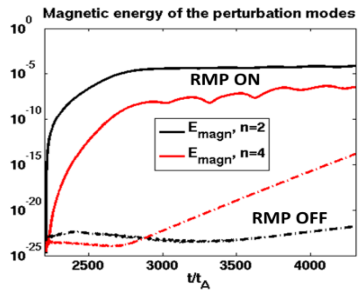

Fig.11. Magnetic energy of the n=4 and n=2 modes, without RMPs and with RMPs n=2

5. Discussion and conclusions. RMP penetration into the plasma was studied with the non-linear MHD code JOREK with diamagnetic and neoclassical effects taken into account. The screening of RMPs by the plasma rotation is stronger at lower resistivity and higher diamagnetic flows. Three regimes were observed in the modeling of RMPs. At relatively high resistivity ($\eta=1.10^{-7}$) and smaller diamagnetic rotation ($\tau_{IC}=1.10^{-3}$), rotating and oscillating islands were observed at the edge leading to density and temperature fluctuations. The frequency of the rotation, oscillations and fluctuations is in the range of the poloidal rotation frequency for the edge resonant harmonics (around a few kHz). An intermediate regime when islands are slightly oscillating and almost locked was observed at low resistivity ($\eta=5.10^{-8}$), with $\tau_{IC}=1.10^{-3}$. Finally static islands locked to external RMPs were obtained at higher poloidal rotation ($\tau_{IC}=2.10^{-3}$). The possible link between these regimes and the difference in ELM mitigation at high and low collisionality [1] is under investigation. The multi-harmonics modeling showed that the application of *n=2* RMPs changed the dynamics of the unstable (without RMP) *n=4* mode, suggesting the possible coupling of the RMPs with intrinsic MHD modes.

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