Non-linear MHD modelling of Edge Localized Modes and their interaction with Resonant Magnetic Perturbations in rotating plasmas.

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1. Introduction. The intensive experimental and theoretical study of the Edge Localized Modes (ELMs) and methods for their control has a great importance for ITER [1]. The application of small external Resonant Magnetic Perturbations (RMPs) has been demonstrated to be efficient in ELM suppression/mitigation in present day tokamaks [2]. RMPs are foreseen as one of the promising methods of ELM control in ITER [3]. However in order to make reliable predictions for ITER, a significant progress is still required in order to understand the ELM dynamics and the interaction of RMPs with ELMs. In the present work the dynamics of a full ELM cycle including both the linear and non-linear phase of the crash and the possible explanation of the mechanism of the ELM mitigation/suppression by RMPs are presented based on the results of the multi-harmonic non-linear resistive reduced MHD modeling using the JOREK code [4]. These simulations are performed in realistic tokamak geometry including X-point and Scrape-Off-Layer (SOL) with relevant plasma flows: toroidal rotation, bi-fluid diamagnetic effects, and neoclassical poloidal friction, which have recently been included in the model [5], so that both the plasma rotation and the radial electric field are self-consistently described during MHD activity. The introduction of flows in the modelling demonstrated a large number of new features in the physics of the ELMs and their interaction with RMPs compared to previous results without flows [4]. JET and ITER parameters were used for modelling.

2. ELM modelling with flows. The detailed description of JOREK model with flows and neoclassical effects can be found in [5], here we just recall that the main flows used in modelling. The normalized fluid velocity (for ions) in JOREK units [5] is taken in the following form: \[ \vec{V} = -R^2(\nabla u \times \nabla \varphi) - \tau_{ic} \frac{R^2}{\rho} (\nabla p \times \nabla \varphi) + v_0 \vec{B}. \] Here the first term represents the \( \vec{E} \times \vec{B} \) convection, the second term is the ion diamagnetic drift and the last one is the motion parallel to the magnetic field. Here \( u \) is the electrostatic potential, \( \rho \) - is the mass density normalized to the central value, \( p = \rho T = \rho(T_e + T_i) \) is the normalized scalar total pressure, \( T_{e,i} \) are the electron/ion temperatures, \( \varphi \) – is the toroidal angle and \( R \)-the major radius. The magnetic field is represented in the form: \[ \vec{B} = F_0 \nabla \varphi + \nabla \psi \times \nabla \varphi \] [4], where \( \psi \) –is the poloidal magnetic flux, and \( F_0 = B_{\rho,0} R_0 \), \( B_{\rho,0} \) being the toroidal field on the magnetic axis. For simplicity here \( T_e / T_i = 1 \), but the model is bi-fluid, since the electron diamagnetic terms are kept in Ohm’s law [5]. The normalized diamagnetic parameter can be written as: \( \tau_{ic} = m_i / (2 e \cdot F_0 \sqrt{\mu_0 P_0}) \) For JET and ITER cases the typical value is \( \tau_{ic} \sim 4.10^{-3} - 4.510^{-3} \) and \( \tau_{ic} \sim 5.610^{-4} \) respectively. Both resistivity and viscosity are temperature dependent.
\(v_{\parallel}, \eta \sim (T / T_{\text{max}})^{-3/2}\). The Lundquist number in the center was taken \(S = 3.3 \times 10^8\) for ITER simulations and \(S = 5.5 \times 10^7\) for JET, which is for numerical reasons about two orders of magnitude smaller than the realistic values. The parallel conduction has a Spitzer-like temperature dependence: \(k_\parallel \sim K_{\parallel} (T / T_{\text{max}})^{3/2}\). Typically the ratio to the perpendicular conductivity in the pedestal was \(k_\parallel / k_\perp \sim 10^9\). The normalized neoclassical coefficients [6] were taken constant for simplicity as in [5]: \(\mu_{n, \text{neoc}} = 10^{-5}; k_i = -1\). A toroidal rotation source was introduced in the equation for parallel velocity to maintain the rotation profile at the initial value compensating losses due to the parallel viscosity \((S_v = -\mu_{\parallel} \Delta v_{\parallel 0})\). Bohm boundary conditions are set for the parallel velocity on the divertor plates: the parallel velocity is equal to the value of ion sound speed near the wall in the sheath entrance: \(V_\parallel = \pm C_s [4,5]\). Realistic JET parameters corresponding to the pulse #77329, similar to those used in [5], were used: \(R_0 = 2.9\, \text{m}, a = 0.89\, \text{m}, B_{\text{tor}} = 1.8\, \text{T}, q_{95} = 3.8\). The initial density and temperature values at the plasma center and in the pedestal are: \(T_e(0) = 6\, \text{keV}, T_{e, \text{ped}} = 1.8\, \text{keV}\), \(n_e(0) = 5.1 \times 10^{19} \, \text{m}^{-3}, n_{e, \text{ped}} = 3.31 \times 10^{19} \, \text{m}^{-3}\). The toroidal rotation profile is taken parabolic with central frequency \(\Omega(0) = 38\, \text{krad/s}\). The magnetic energy of modes \(n = 2, 4, 6, 8\) taken for ELM modelling with and without flows are presented in Fig.1. Note that after the linear growth, all modes are unstable during the non-linear phase (ELM crash), however \(n = 8\) remains the most unstable mode in both cases. Note also the stabilizing effect of the plasma flows which decreases the growth rates of the modes and the ELM size. The ELM power deposited on the inner and outer divertor targets are smaller and almost symmetric with diamagnetic drifts (Fig.2-3). This is closer to the experimental observations [7], compared to simulations without flows where the outer divertor received almost all ELM power because of the Low Field Side (LFS) location of the ballooning instability [4]. With the \(\vec{E} \times \vec{B}\) and diamagnetic advection taken into account, more density reaches the inner divertor than the outer.

3. ELM precursors and filament dynamics. The rotation of the ELMs and their associated filaments during the ELM crashes was observed in many machines (KSTAR [8], ASDEX Upgrade [9], MAST[10]). The general observation is that an ELM precursor is observed in a time scale of about \(-0.2\,\text{ms}\) before the ELM crash rotating poloidally mainly in the electron diamagnetic (which is the same as the \(\vec{E} \times \vec{B}\) direction with poloidal velocity of about 5-10km/s, which is in the range of the values of the \(\vec{E} \times \vec{B}\) velocity in the pedestal. Approaching the ELM crash, this rotation usually decreases and sometimes is reversed for ELM filaments in SOL [10]. In the present modelling of ELMs with flows, we could reproduce these generic features of the dynamics of the ELM precursors and filaments. Without diamagnetic rotation, the instabilities at the onset of the ELM have a static growth (Fig.4-top), whereas the...
diamagnetic rotation makes the ELM precursors grow and rotate in the electron diamagnetic direction (Fig.4-bottom). It is known that the ideal ballooning modes are usually stabilized by diamagnetic rotation and in the plasma frame rotate in the ion diamagnetic direction at half the ion diamagnetic frequency \( \sim \omega_i^* / 2 \). In the laboratory frame, the total velocity of the mode should be considered as it was done in [12], where it was demonstrated analytically and numerically that the total velocity of the mode is approximately: \( \vec{V}_\text{mode} \approx \vec{V}_\text{EsB} + \vec{V}_i / 2 + \vec{V}_\parallel \). From the force balance equation, the radial electric field in JOREK units can be expressed as \([5]\): 

\[
E^r = -|\vec{\nabla} \psi| |\vec{\nabla} \psi| \tau_{ic} (|\vec{\nabla} \psi|, |\vec{\nabla} p|) / (\rho |\vec{\nabla} \psi|) + 1 / \rho_0 (\nu_0 B_0 - B_\parallel V_e^r) \cdot \vec{V}_\parallel. \]

It is easy to see that in the region of strong pedestal pressure gradients, the first term is dominant thus the radial electric field presents a characteristic negative “well” \([5]\). Hence the mode velocity is essentially poloidal in the pedestal and scales as \([12]\) \( \sim (\tau_{ic} - 0.5\tau_{ic}) (|\vec{\nabla} \psi|, |\vec{\nabla} p|) / (\rho |\vec{\nabla} \psi|) \).

As a consequence, in the laboratory frame typically the \( \vec{E} \times \vec{B} \) direction (which is also electron diamagnetic one) determines the direction of the mode rotation with approximately half of the \( \vec{E} \times \vec{B} \) velocity estimated where the pressure gradient is maximum and where the most unstable mode is localized. Approaching the ELM crash (during the edge ergodisation phase), the slowing down of this rotation is observed in modelling, similar to experiments \([10]\). The filaments of density grow outside the separatrix and are cut off from the main plasma by strong sheared flows, producing “blobs” which then are transported to the divertor plates following the ion fluid velocity. Note also that a generation of strongly sheared mean \( (n=0) \) poloidal flow takes place in the non-linear phase of an ELM via Maxwell stress (non-linear coupling between the magnetic flux and the current perturbations in the vorticity equation) \([4]\). At the same time, during the ELM crash, both the diamagnetic velocity and the Maxwell stress term decrease as the pressure gradient (drive for ballooning modes) decreases during the relaxation. As a consequence, the resulting velocity of the ELM filaments usually represents a complicated and not very regular motion compared to the ELM precursor linear phase. Also main \( n \)-number of the filaments seen in the non-linear phase could change because of the non-linear triggering of other harmonics. In Fig. 4-5 a single most unstable toroidal harmonic \( (n=6) \) was modelled, hence this change of \( n \)-number could not be observed. The ELM filaments dynamics in the non-linear phase with multi harmonics is still under investigation with the JOREK code.

**Fig.4.** Magnetic flux perturbations (here \( n = 6 \), for three different times \( \sim 20 \) Alfvén times between each image). Without diamagnetic effects (top) and with diamagnetic effects (bottom), \( \tau_{ic} = 4.510^{-3} \).

**Fig.5.** Density filaments rotation in the non-linear phase of an ELM (parameters are the same as for Fig.4). Note the detachment of “blobs” from the main plasma. Electron and ion diamagnetic directions are indicated on the plot.

### 4. Multi-cycle ELMy regimes.

In the ELM modeling without flows \([4,12]\), the ELM crash was generated by the chosen initially unstable pressure profile. The unstable modes remain unstable for a long time after the crash, even if the pressure gradient (drive for ballooning modes) is strongly decreased. In modelling, this residual MHD activity prevents the pedestal from building-up again, so up to now the cycling regime was not modelled without flows. In
the present work, the diamagnetic two-fluid effects were found to be the most important factor in accessing multi-cycle regimes in modelling. The phenomenology is similar to the one discovered in the non-linear MHD modelling of sawteeth [13], where it was demonstrated that the diamagnetic effects played a stabilizing role for the residual MHD activity, permitting sawtooth cycling in modelling. The existence of a certain diamagnetic threshold for cycling regimes was also pointed out in [13]. Similarly to this, in the ELM modelling with JOREK, the “MHD turbulence” triggered during the ELM crash is rapidly stabilized by the diamagnetic flows, allowing for the pressure gradient to recover after an ELM crash. The typical behavior of the magnetic energy of a medium $n=6$ ELM is presented in Fig.6. Here the JET parameters (#77329) described in Sec. 2 were used, but the diamagnetic parameter and the heat source were slightly (~10%) increased to achieve cycling regime, which apparently has a certain threshold similar to [13]. Since higher $n$-harmonics were strongly stabilized by the diamagnetic effects [11] (the test is not presented here), only the most unstable harmonic $n=6$ and the axisymmetric component $n=0$ were kept in this case to save computation time. After a few first transient crashes, the memory of the initial pressure profile is lost and the plasma reorganizes into a self-consistent cycling state. Thus, the ELM frequency and size do not depend any more on the initial conditions, but depend on the diamagnetic rotation which has a stabilizing effect on the ELMs and on the residual MHD after a crash. This allows the applied heating power to build up the pedestal pressure again until the next ELM triggering threshold is reached. Note however that up to now only cycles of small and frequent ELMs (~500Hz-1kHz) were modelled so far [15]. The main reason is that the diamagnetic stabilization strongly decreases during larger relaxations of the pressure profile (occurring for larger ELMs), leading to a much longer in-between ELM time, inaccessible in our modelling due to restrictions in available supercomputer time. ELM cycling regimes are described in more details in [15].

5. Non-linear interaction of ELMs with RMPs. The ELM mitigation by RMPs was demonstrated in multi-harmonic modeling for realistic JET parameters (#77329) and a realistic RMP spectrum generated by EFCC coils, with a dominant toroidal number $n=2$. In a typical JOREK run, initially the equilibrium with flows is obtained for the toroidal harmonic $n=0$ (axisymmetric component) on a time scale of ~1ms [5]. After that, for ELMs modelling, other harmonics are initialized in the plasma at “noise” level (~10$^{-25}$). In the case of RMPs,

![Image](image1)

**Fig.6.** Magnetic energy of the $n=6$ mode in multi-cycle ELMy regime for JET parameters.

![Image](image2)

**Fig.7.** Magnetic energy of $n=2$:8 modes for a natural ELM (most unstable $n=8$ mode) and for the ELM mitigated by (n=2,40kAt) RMPs.

![Image](image3)

**Fig.8.** Power to outer and inner divertor targets in unmitigated and mitigated ELMs by (n=2,40kAt) RMPs, and normalized magnetic energies on the modes $n=2$:8.

the vacuum amplitude is set at the boundary for the harmonic of magnetic perturbation (here $n=2$ at 40kAt in EFCC) and increased in time until stationary conditions are reached [5], resulting in a 3D equilibrium. Then the other harmonics are initialized to study the interaction of the ELMs with RMPs. In Fig.7 the time evolution of the magnetic energy is presented for
two cases. The first one corresponds to the non-linear modelling of an unmitigated ELM where the harmonics \( n=0 \) and \( n=2,4,6,8 \) (even harmonics) are taken into account. As shown by the numerical tests (not presented), the growth rates of the \( n>8 \) modes are smaller due to the diamagnetic stabilization [11] and modelling with \( \Delta n=1 \) (even and odd harmonics) also gave similar results so odd and \( n>8 \) harmonics were excluded from the modelling to save computational time. The axisymmetric \( n=0 \) component is non-linearly coupled to all harmonics, permitting the self-consistent modelling of the profile evolution due to ELMs and RMPs. Note that in the linear phase of natural ELM the most unstable mode is \( n=8 \) and the \( n=2 \) mode is linearly stable. Approaching the ELM crash (maximum of magnetic energy for \( n=8 \)) all modes grow due to the non-linear coupling but \( n=8 \) remains the largest one. After the crash, the magnetic energy starts to decrease since the transport generated during the ELM [4] leads to a relaxation of the edge pressure profile, removing the drive for the ELM instability. Note also that for a linear run (without mode coupling) only the \( n=2 \) mode remains stable (Fig.7). In the second case (Fig.7), \( n=2 \) RMPs were applied at the computational boundary and progressively increased until the magnetic energy of the RMP reaches a stationary value. After that, the other modes \( n=4,6,8 \) are included into the simulation. In this case the behavior of all modes is quite different: the magnetic energies of the \( n=4:8 \) oscillate in time with similar maximal amplitudes, much smaller than the amplitude on \( n=8 \) mode in the unmitigated ELM. The power and heat fluxes on the divertor plates are reduced by about a factor of ten with RMPs (Fig.8). Detailed analysis [16] showed that these mitigated ELMs represent small relaxations mainly due to the non-linearly driven modes by the imposed \( n=2 \) RMPs. The modes, strongly coupled to RMP, are growing from initially large amplitudes (Fig.7) and quickly reach a sufficient level to induce transport towards the SOL in addition to RMP. The magnetic energy now is distributed between the modes \( n=2,4...8 \), increasing the energy of the \( n=2,4,6 \) harmonics and decreasing the energy of the \( n=8 \) mode compared to the natural ELM case. Thus the ELM energy tends to “cascade” non-linearly towards lower \( n \)-numbers, feature observed for example in KSTAR RMP experiments [17]. As a result, the relaxations due to the multi-modes can manifest themselves as more frequent small ELMs or MHD turbulence, similar to Type II ELMs [18]. This provides a sufficient continued transport and hence prevents large ELM crashes due to a single most unstable mode which has no time to grow. It is important to note that with RMPs the “ballooning” nature of the modes changes to tearing-like parity \( (\psi_{n,m} \neq 0) \) on the corresponding rational \( q=m/n \) surface as compared to the ballooning–like parity \( (\psi_{n,m}=0 \quad on \quad q=m/n) \), see Fig.9, since they are driven by external RMPs which usually are not zero on the rational surfaces for \( n>2 \) unless they are totally screened [5]. The change of parity for the driven modes is clearly seen from the comparison of the edge magnetic topology (Fig.10). For the case of the natural ELM, one observes a typical ballooning distortion of the magnetic surfaces due to the \( n=8 \) mode (Fig.10(a)). The corresponding “footprints” in the outer divertor show a clear \( n=8 \) structure (Fig.11(a)). The magnetic topology only with \( n=2 \) RMPs (Fig.10(b)) indicates that only the very edge is ergodic: this is due to the rather strong screening of the RMPs by rotation in the pedestal region [5]. The corresponding footprints (Fig.11(b)) show a typical \( n=2 \) structure. In the ELM regime mitigated by \((n=2)\) RMPs, the very edge keeps mainly an \( n=2 \) structure, but new island chains \((m/n=9/4, 14/6 \text{ and } 15/6)\) occur on the rational surfaces (Fig.10(c)). The corresponding footprints keep the \( n=2 \) structure imposed by external RMPs, being modulated by the presence of \( n=4,6,8 \) modes(Fig.11(c)). More details about footprints one can found in the dedicated paper [20]. Note that similar footprints of ELMs with RMPs were reported in DIII-D experiments [19]. Note however that a regime of total ELM suppression can be obtained if the RMP amplitude in the plasma is large enough such that a sufficient transport is produced, capable to reduce the pedestal pressure gradient under the peeling-ballooning limit [2 and Ref therein]. The comparison of ELM cycling regime where diamagnetic term was
artificially increased by \(-10\%\) with most unstable \(n=6\) mode (used in Sec.4, Fig.6) showed that in this case, a \(40kAt\) EFCC current is not sufficient to mitigate ELMs (Fig.12), probably because of the stronger screening of RMPs by larger diamagnetic rotation in this case [5]. On the contrary, the cyclical ELM relaxations due to the \(n=6\) mode, observed without RMPs, are suppressed when a two times larger current (\(80kAt\)) is applied in EFCC (Fig.13). In this case, the continuous transport produced by RMPs and driven even harmonics is sufficient to keep the plasma stable for ballooning/peeling modes.

Fig.9. Some selected harmonics \(n=6, m=14-19\), resonant at the edge) amplitudes to illustrate the tearing-like parity of the modes driven by \(n=2\) RMP in mitigated ELMs.

Fig.10. Edge magnetic topology (Poincare plot) for natural ELM due to mainly \(n=8\) mode (a), with RMP \(n=2,40kAt\)- (b), with mitigated by RMPs ELMs(c). Coordinates are geometrical poloidal angle and normalized poloidal flux.

Fig.11. Footprints in the outer divertor in the natural \(n=8\) ELM - (a), with RMP \(n=2(40kAt)\)- (b), with mitigated ELMs(c). Brighter colors indicate longer connection length.

Fig.12. Magnetic energy in cycling regime without RMP (in red) and with RMP \((n=2,40kAt)\), \(n=4,6,8\). Main unstable \(n=6\). No mitigation in this case.

Fig.13. Magnetic energy in cycling regime without RMP (most unstable \(n=6\)-in red) and for \(n=2\):8 modes during ELM suppression by RMP \((n=2, 80kAt)\).

6. Mitigation of ELMs in ITER. For the first time, the interaction between ELMs and RMPs in the ITER standard H-mode scenario at 15MA/5.3T was modelled. Central and pedestal temperatures and densities were: \(T_e(0)=17.6\) keV, \(T_{e,ped}=5.5\)keV \(n_e(0)=1.1.10^{20}\)m\(^{-3}\), \(n_{e,ped}=9.10^{19}\) m\(^{-3}\); the toroidal rotation profile is parabolic with a central frequency \(-1kHz\). A realistic \((n=3)\) spectrum generated by the ITER RMP coils, calculated with the ERGOS code,
was used as in [5]. The modelling of the ITER case represents particular difficulties because of the larger tokamak size. Hence for numerical reasons the number of harmonics were limited here by $n=3,6,9$ and the current in RMP coils was taken $\sim 35kAt$. This is lower than the maximum available current in the ITER RMP coils ($\sim 90kAt$), since for the moment at larger RMP current the convergence could not be achieved yet. However for this particular case the

behavior of the ELMs with RMPs (Fig.14) is quite similar to the JET mitigation case (Fig.7-8). Indeed the natural ELM is due to the most unstable $n=9$ mode and then $n=3,6$ modes are triggered in the non-linear phase (Fig.14). When RMPs are switched on, all modes $n=3,6,9$ produce a continuous MHD turbulence behavior similar to Fig.7-8. On Fig.15 the plasma density profile plotted over a line near the X-point (see line position on Fig.16-18) is presented for three cases: a natural ELM crash (Fig.16); with $n=3$ RMPs only (Fig.17); and with ELMs mitigated by RMPs (Fig.18). One can see that mitigated ELMs increase the particle transport, but in a continuous way which permits to avoid large ELM crashes induced by the medium $n$ unstable modes (here $n=9$).

7. Conclusions. The non-linear resistive reduced MHD code JOREK [4,5] in toroidal geometry with X-point and SOL and with relevant plasma flows (toroidal rotation, bi-fluid diamagnetic effects and neoclassical poloidal friction) was used to study the ELM dynamics in the linear and non-linear phases and the interaction of ELMs with RMPs. Firstly, the full ELM dynamics with flows was studied. It was found that in the linear phase, the density, temperature and poloidal flux perturbations due to the most unstable ballooning mode are growing and rotating in the electron diamagnetic direction with regular velocity of the order of half the diamagnetic velocity estimated in the pedestal region where mode is located and where the pressure gradient is maximum. Approaching the ELM crash, the rotation starts to decrease when the magnetic reconnections and edge ergodisation occurs. During the highly non-linear phase of the ELM crash, the rotation of the ELM filaments is a more complicated picture resulting from the evolution of the $\mathbf{E} \times \mathbf{B}$ and diamagnetic flows (due to the relaxation of the pressure profile), from the strong sheared $n=0$ flow non-linearly generated by the ELM itself (via Maxwell tensor [4]) and finally from the parallel flow in the SOL. With flows, the

![Fig.14. Magnetic energy on $n=3:9$ modes in unmitigated and mitigated by RMP ($n=3,35kAt$) ELM in ITER.](image1)

![Fig.15. Edge density profile in ELM (full red line: before, in dashed: after) and during ELM mitigated phase (full black: RMP $n=3$, dashed: with $n=3:9$).](image2)

![Fig.16. Density in ELM ($n=3,6,9$; most unstable mode was $n=9$) in ITER (15MA/5.3T scenario).](image3)

![Fig.17. Density with RMP only ($n=3,35kAt$) in ITER.](image4)

![Fig.18. Density in ELMs mitigated by RMP ($n=3,35kAt$) ($n=3,6,9$ modes were taken for modelling).](image5)
power deposited on the inner and outer divertor targets were found to be almost symmetric, which is closer to the experimental observations [7], compared to the previous modelling of ELMs without flows. The non-linear MHD simulations of multi-cycle ELMy regimes were demonstrated. The stabilizing role of the diamagnetic rotation is found to be a key factor in accessing these regimes. Finally, the new modeling results of the interaction between ELMs and RMPs were presented for JET and ITER parameters. The ELM mitigation by RMPs was demonstrated in multi-harmonic modeling in both cases. The peak power reaching the divertor is found to be mitigated by almost a factor of ten by RMPs in the JET case. Mitigated ELMs in JET simulations show small relaxations mainly due to the non-linearly driven modes \((n=4, 6, 8 \text{ etc})\) coupled to the externally imposed RMPs \((\text{EFCC, } n=2)\). These modes have a tearing-like structure and produce additional islands, increasing the edge ergodisation and hence the edge heat and particle transport. The divertor footprints of the mitigated ELMs exhibit structures created by RMPs, however slightly modulated by the presence of other harmonics, feature also observed in the RMP experiments [19]. Complete ELM suppression was also demonstrated in modelling at larger RMP amplitude and larger diamagnetic parameter as compared to mitigated ELMs case for JET-like parameters. However, the main key factors to achieve ELM suppression are still not clear, because of the complexity of the self-consistent non-linear plasma response to RMPs in each specific case probably explaining absence of general trend in RMP experiments [2]. A similar ELM mitigation due to the non-linear interaction between \((n=3)\) RMPs and \((n=3, 6, 9)\) ELMs were obtained for ITER parameters, however at reduced RMP coils current \(\sim 35kA_t\), compared to the maximum achievable value \(90kA_t\) [3]. Due to numerical restrictions, a relatively high resistivity was used for both the JET and ITER cases, hence the proposed mitigation mechanism could be valid for the high collisionality ELM mitigation scheme where ELM crashes are replaced by magnetic turbulence [18]. Further modelling for ITER with more relevant parameters is still needed to define if ELM suppression by RMPs is achievable in ITER.

**Acknowledgments.** This work has benefited from financial support from the National French Research Program (ANR): ANEMOS (2011), E2T2(2010), from the Grant Agency of the Czech Republic under Grant No. P205/11/2341 and Czech Science Foundation under grant GA14-35260S and Eurofusion Enabling Research project WP14-ER-01/CEA-01. This work was granted access to the HPC resources of Aix-Marseille University, CCRT-CURIE (France) supercomputer within project GENCI, PRACE and HELIOS supercomputer (IFERC-CSC, Japan).

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