Non-linear MHD modelling of 3-D plasma edge with Resonant Magnetic Perturbations in DIII-D and ITER.

M. Becoulet\textsuperscript{1}, G.T.A. Huijsmans\textsuperscript{1,2}, D.M. Orlov\textsuperscript{3}, R.A. Moyer\textsuperscript{3}, T.E. Evans\textsuperscript{4}, S. Futatani\textsuperscript{5}

\textsuperscript{1}CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France
\textsuperscript{2}Eindhoven University of Technology, Eindhoven, The Netherlands
\textsuperscript{3}Center for Energy Research, University of California San Diego, La Jolla, CA 92093, USA
\textsuperscript{4}General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
\textsuperscript{5}Universitat Politècnica de Catalunya, Carrer de Jordi Girona, 1, 3, 08034 Barcelona, Spain

1. Introduction. Edge Localized Modes (ELMs) potentially represent an issue for the ITER divertor lifetime due to large transient heat and particle losses released in ELM relaxations \cite{1}. The application of small Resonant Magnetic Perturbations (RMPs) demonstrated the possibility of total ELMs suppression or mitigation of their size \cite{2}, motivating the use of such method in ITER. The important drawback of RMPs and intrinsic error fields in general is the complex magnetic topology at the edge and formation of a 3D Scrape of Layer (SOL) leading to the splitting of the separatrix, seen in experiment as helical “lobes” near the X-point. When crossing the divertor plates they form finger-like structures (“footprints”) and non-axisymmetric heat and particle fluxes observed in many RMP experiments \cite{3}. The non-axisymmetric divertor fluxes with RMPs can represent an issue in ITER leading to local high heat fluxes (“hot spots”) in the unprotected areas, additional material erosion and fatigue stress on the divertor components. In this work the characterisation of 3D plasma edge with RMPs was done using the non-linear MHD code JOREK \cite{4,5}. In was shown in previous work \cite{5,6} that a non-linear approach, two fluid diamagnetic effects, toroidal plasma rotation and neoclassical poloidal friction are the essential elements for the modelling of the non-linear plasma response to RMPs. In particular, the self-consistent interplay between RMP penetration, the evolution of radial electric field, the interaction with ELMs and heat and particle transport due to RMPs can be taken into account \cite{6}. In this work firstly, the validation of RMP model implemented in JOREK was done comparing simulation results with measurements of divertor particle flux splitting during ELM suppression experiment on DIII-D. Secondly, the results of JOREK modelling of ITER divertor magnetic footprints and divertor fluxes with RMPs generated by ELM Coils are presented for standard H-mode scenario at 15MA/5.3T.

2. DIII-D. In DIII-D, the FASTCAM diagnostic measures D\textsubscript{2} molecule emission near the divertor plates. It provides high temporal and spatial resolution of strike point splitting in particle flux due to RMPs in attached conditions \cite{3}. In spite of the usually expected screening of RMPs \cite{5}, the measured particle flux splitting on the contrary, in many cases, exceeds even vacuum modelling predictions \cite{3,7}. Note that more splitting is observed in the particle flux than in the heat flux as shown in Fig.1 for DIII-D pulse \#166439 ($Bt=-1.9T$, $Ip=1.52\text{ MA}$) for the inner strike point at a toroidal angle $\sim75^\circ$. The parameters of this shot and the RMP spectrum with dominant toroidal modes $n=1$ and $n=3$ \cite{7} were used for validation of the non-linear MHD plasma response model implemented in JOREK \cite{5}. The initial equilibrium was calculated using data from the EFIT EQDK file for \#166439 at 3300ms in an ELM suppression phase. Then, after equilibrium with flows was established in JOREK modelling (at $\sim0.5\text{ms}$), the vacuum RMPs were progressively ($\sim0.5\text{ms}$) increased at the computational boundary and JOREK run
was done until a full establishment of stationary RMPs after approximately \(\sim 1.5\) ms. The comparison of the flux perturbations in vacuum and with plasma response is shown in Fig.2. The grid was aligned with the inner divertor shape, where FASTCAM measurements were done. The comparison of the edge magnetic topology with and without plasma response is presented in Fig.3. Note that the stochastic layer with plasma response is narrower indicating screening of RMPs. It is clear from the comparison of the profiles of the magnetic flux perturbation harmonics \((n,m)\) in vacuum and plasma (Fig.4), apart from slightly amplified harmonic \((n=1,m=1)\), that all the harmonics are strongly screened at corresponding resonant surfaces \(q=m/n\), where their amplitudes decrease to a minimum. However due to the temperature dependent resistivity as the separatrix is approached the screening is smaller since response currents are smaller [5].

A rather good correspondence with the particle flux splitting measurements and magnetic footprints with plasma response was obtained (Fig.5-6). Actual heat and particle fluxes were not estimated in the present work since divertor physics such as recycling of neutrals and radiation were not included in the model and they seem to be essential [7]. The development of more sophisticated divertor physics model in JOREK is an ongoing work [8], but it is out of scope of the present paper.

3. ITER. The 3D SOL magnetic topology and divertor heat and particle fluxes were estimated for standard ITER H-mode scenario 15MA/5.3T during application of RMPs using the same
non-linear model as in Sec.2. The geometry of ITER ELM Coils and relative phasing of currents were taken similar to [9]. In particular the currents in upper, middle, and low coils (nine coils in each row) were taken from the results of the optimisation of linear MHD plasma response [9]:

\[ j_{\text{up}} = A \cos(n(\varphi_{\text{up}} + \varphi_{\text{up}}(i-1)) + \Phi_{\text{up}}) \cdot \pi / 180) \]
\[ j_{\text{mid}} = A \cos(n(\varphi_{\text{mid}} + \varphi_{\text{mid}}(i-1)) + \Phi_{\text{mid}}) \cdot \pi / 180) \]
\[ j_{\text{low}} = A \cos(n(\varphi_{\text{low}} + \varphi_{\text{low}}(i-1)) + \Phi_{\text{low}}) \cdot \pi / 180) \]
\[ \varphi_{\text{up}} = 26.7^\circ, \varphi_{\text{mid}} = 40^\circ, \varphi_{\text{low}} = 0^\circ; A=45kA, n=3, i=1-9. \]

After establishing the plasma equilibrium with flows, the vacuum RMP fields were progressively increased to the maximum value during \( \approx 0.8ms \) on the boundary of the JOREK grid which includes the realistic shape of the ITER wall and divertor (Fig.7). The time evolution of plasma thermal energy and magnetic energy of \( n=3 \) mode are presented in Fig.8. The magnetic topology near the X-point and the divertor heat fluxes are presented in Fig.9, where the color code indicates the initial electron temperature at the starting point in the pedestal of the magnetic field line. Here the normal to the divertor target heat flux was calculated as follows:

\[ \Gamma_{\text{div},n} = \gamma_{\text{sheath}}(n,T\vec{V},\vec{n}), \]

where \( n_e, T = T_e + T_i, \vec{V} \) are correspondingly electron density, temperature and plasma velocity on the target and \( \vec{n} \) is a normal to the surface vector. A sheath heat transmission factor \( \gamma_{\text{sheath}} = 5.2 \) was used in modelling. Since the thermal energy is still evolving on the time scales accessible for modelling in the following we normalize the heat flux to: \( 100/(dW_{th}/dt + S_{\text{heat}})[MW] \), considering \( 100MW \) total heating power in stationary regime \( (dW_{th}/dt = 0) \). Note however, that
switching on the RMP in such a short time and the drop of plasma thermal energy could lead transiently to rather high heat fluxes in the divertor (up to \(\sim100\text{MW/m}^2\)), hence the timing of RMPs ramp up should be optimised, which we leave for the moment for the future work. Typical for the RMP phase, convective density transport especially near X-point is illustrated in Fig.10. The magnetic footprints, divertor heat and particle fluxes for the inner and outer divertor are presented in Fig.11-13 respectively as a function of the length along the plates and the toroidal angle. Here the upper point of the inner divertor corresponds to \(L_{div}=0\). The heat and particle flux profiles at toroidal angle 180° are presented at Fig.14-15. Note that similar to DIII-D observations the splitting of the strike points is more pronounced on the particle flux.

4. Conclusions. Inner strike point magnetic footprints splitting due to RMPs obtained in modelling using the non-linear resistive MHD code JOREK showed rather good correspondence to particle flux splitting measured by FASTCAM on DIII-D. Initial results of ITER divertor magnetic footprints and divertor fluxes splitting with RMPs \(n=3, 45\text{kAt}\) were calculated for standard H-mode scenario 15MA/5.3T. For more quantitate estimations more divertor physics will be included in the future work.

Acknowledgements: This work has been supported by EUROFUSION CfP-WP19-ENR-01/MPG-03, IO/CT/18/430000 and US DOE under DE-FC02-04ER54698, DE-FG02-05ER54809 and DE-SC0018030. The views and opinions expressed herein do not necessarily reflect those of the European Commission, DOE, ITER.

[7] D Orlov et al 60th APS Division of Plasma Physics, Portland, Oregon, Nov 5-9, 2018
[8] G Huysmans et al, this Conference