LOWER DENSITY LIMIT FOR ACCESSING TO ELM SUPPRESSION USING N=4 RMP IN EAST

Y. Sun[1], X.M. Wu[1], Q. Ma[1], S. Gu[1], M. Jia[1], Y.Q. Liu[2], P. Xie[1], Y.F. Wang[1], A. Loarte[3], P.B. Snyder[4], X.X. Zhang[1], H. Sheng[1], G.Q. Li[1], K. He[1], Y. Liang[5], C. A. Paz-Soldan[6], J. Qian[1], B. Wan[1], H.H. Wang[1], X. Yan[1], Q. Zang[1], L. Zeng[7], T. Zhang[1]

[1)]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
[2)]General Atomics, PO Box 85608, San Diego, CA 921865608, USA
[3)]ITER Organization, Route de Vinon sur Verdon, 13115 St Paul Lez Durance, France
[4)]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[5)]Forschungszentrum Jülich, Jülich 52425, Germany
[6)]Columbia University, New York, NY 10027, USA
[7)]Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Email: ywsun@ipp.ac.cn

Understanding operational window for accessing to Edge Localized Modes (ELMs) suppression using Resonant Magnetic Perturbations (RMPs) is critical for extrapolating present results to future ITER so that type-I ELMs can be reliably controlled. Existence of windows in both edge safety factor (q_{95}) and line averaged plasma density ($<n_e>$) for ELM suppression using n=4 RMPs has been observed in low input torque plasmas in EAST experiment with q_{95} and plasma normalized beta (β_N) close to that in ITER high-Q operation. Different from previous observations in the other machines, there is not only an upper density limit but also a lower one for accessing to ELM suppression. Modelling results show that RMP with linear plasma response has a peak at intermediate plasma density and decays in both sides with increasing and decreasing density, which results in a minimal RMP field penetration threshold at intermediate plasma density. In this experiment, different densities result in different edge current profiles, which changes the eigenmode structure that causes a reduction of resonant plasma response in both low and high density cases and hence makes field penetration be more difficult shown in the nonlinear simulation. The modelled window of strongest resonant plasma response in terms of [$<n_e>$, q_{95}] agrees well with the observations of ELM suppression in EAST. Peeling-ballooning stability analysis shows that plasmas gradually approach peeling stability boundary caused by increase of edge bootstrap current as the plasma density decreases, which is consistent with the observation that ELMs come back again in lower density plasmas for fixed q_{95}. These findings indicate that linear modelling with full toroidal geometry can well predict the optimized RMPs for accessing to ELM suppression and reveals the important roles of pedestal current on ELM suppression, which need to be carefully considered in the application of high n RMPs for ELM suppression in future ITER.

ELM suppression using n=4 RMPs in ITER relevant low input torque plasmas has been successfully achieved in EAST [1]. The advantage of minor effects on energy confinement for high n RMPs has been demonstrated. In this experiment, the existence of both upper and lower density limits for ELM suppression has been observed, as shown in Fig. 1 (a-c) for three discharges with different densities, but other parameters are kept the same. In this experiment, it has $B_T \sim 1.6$T, $q_{95} \sim 3.65$, $\beta_N \sim 1.45$-1.6, and NBI torque is lower than the equivalent one for 33MW NBI in ITER. Optimal ELM suppression is achieved at intermediate line averaged plasma density around $<n_e> \sim 3.8 \times 10^{19} m^{-3}$ in discharge 94048, in which reliable ELM suppression was achieved start at t=5.2s till the switch off of RMP at t=7s. ELM suppression is less effective in both high and low density cases. Plasma density is controlled by change the feed forward gas fueling rate. Electron density and temperature profiles are shown in Fig. 1 (e) and (f). It is shown that the whole edge electron density steps down and pedestal top temperature steps up with decreasing line averaged density.

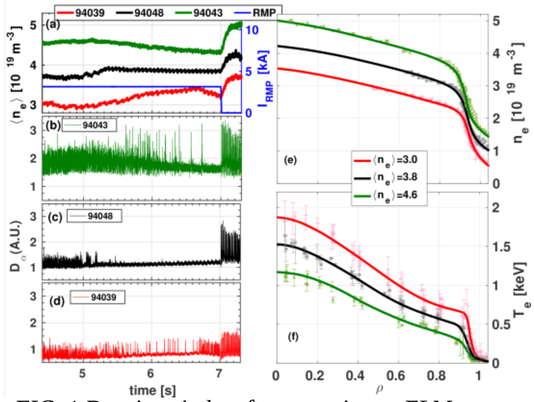

FIG. 1 Density window for accessing to ELM suppression using n=4 RMPs in EAST

MARS-F/Q code [2] has been employed for modeling linear/quasilinear plasma response for understanding this density window effects for accessing to ELM suppression with n=4 RMPs. The linear response in radial displacement near low-field-side midplane ξ_M, near the X-point ξ_X, and their ratio ξ_X/ξ_M are shown in figure 2(a-c), respectively. They show a clear dependence on both plasma density and q_{95}. The strength of ξ_X links to the strength of resonant harmonics from peeling-tearing like response, while that of ξ_M indicates the strength of non-resonant harmonics from kink like response. It is shown that strongest resonant plasma response indicated by the strength of ξ_X, and ξ_X/ξ_M has a narrow mountain ridge in the [n_e, q_{95}] domain, which aligns well with the domain that observed ELM suppression using n=4 RMPs in EAST. On the contrary, the ELM suppression cases are

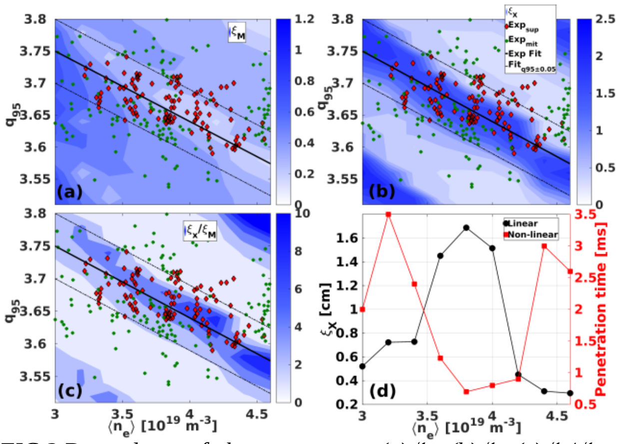

FIG 2 Dependence of plasma response (a) ξ_M, (b) ξ_X, (c) ξ_X/ ξ_M on density and q_{95}, superimposed with regimes achieved ELM suppression (red diamonds) and mitigation (green circles) cases. (d) is ξ_X (black circles) and nonlinear penetration delay time (red squares) for q_{95} ~ 3.65 case.

located at the valley of non-resonant kink plasma response. There is an increase of non-resonant kink plasma response with decreasing plasma density because of increased plasma beta. This means ELM suppression is closely related to peeling-tearing type resonant plasma response. In fixed q_{95} cases shown in figure 2(d), the linear plasma response at intermediate density exhibits the strongest resonance, which makes it easier at this density to penetrate in the quasilinear simulation. Here, we used the time delay for penetration with a fixed coil current as a measure of penetration threshold for simplicity. Both high and low densities are unfavorable for RMP field penetration. The loss of ELM suppression at low density with fixed q_{95} because resonant q_{95} window shifted upwards as density decreases, which is caused by change of eigenmode structure due to changes of edge pressure and bootstrap current profiles. This is different from previous understanding of density dependence based on resistive layer physics in the studies of density scaling for field penetration threshold. The high-density limit observed here is also not due to higher penetration threshold but due to shift of resonant response window. The shift of suppression window suggests linear plasma response to high *n* RMPs is very sensitive to kinetic profiles especially edge current profile, although q_{95} is fixed. This explains why we observed both upper and lower density limits for accessing to ELM suppression in this experiment.

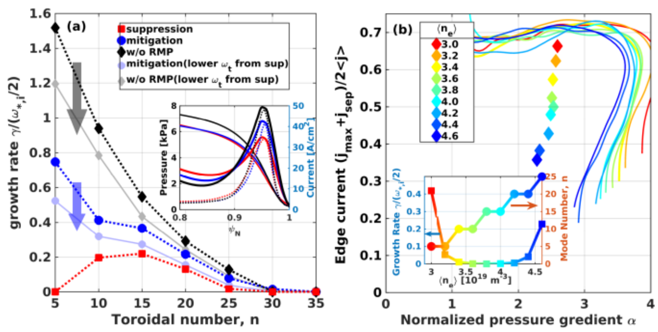

FIG 3 (a) Growth rates of peeling-ballooning modes at different phase, i.e. without RMP (black diamonds), ELM mitigation (blue circles) and suppression (red squares) with subgraph for pedestal pressure and bootstrap current in the three cases. (b) Plasma regimes during density scan against peeling-ballooning boundaries with subgraph for dependence of growth rate on plasma density for fixed q_{95}~3.65.

To check the consistence between pedestal stability changes and ELM control effects at different phases, ELITE[3] code is employed to model the pedestal stability. Figure 3(a) shows the modeled growth rate of peeling-ballooning modes in three different phases in discharge 94048, i.e. the reference case without RMP (t =7.25s, black diamonds) and cases with ELM mitigation (t=4.5s, blue circles) and suppression (t=6.5s, red squares). It is shown that the dominant modes in this type-I ELMy H-mode without RMP are low-*n* peeling-ballooning modes (PBMs), which growth rates are significantly reduced after the application of RMPs, especially during the phase with RMP ELM suppression. The stabilization effect mainly comes from the reduction of pedestal bootstrap current after the application of RMPs. Additionally, considering the rotation braking effect, we found that lower rotation can also reduce the growth rate of low-*n* modes, as shown by light-lines in Fig. 3 (a). This result indicates that lower rotation is beneficial for peeling-ballooning stability, which is consistent with observed ELM control effects in low input torque experiments [1]. To understand the density window effects, density dependence of operational regimes and growth rates of PBMs are shown in Fig. 3(b). It is shown that plasmas gradually approach peeling stability boundary caused by increase of edge bootstrap current as the plasma density decreases, which is consistent with the observation that ELMs come back again in low density plasmas for fixed q_{95}. Intermediate density lies in the most stable region against PBMs, which also consists with that optimal ELM suppression only achieved at intermediate plasma density.

In summary, the modeling of plasma response and peeling-ballooning stability well explained the reason why ELM suppression by *n*=4 RMPs has both upper and lower density limits. The changes of pedestal bootstrap current, which influence both plasma response to RMPs and stability of peeling-ballooning modes. The combined effects determine the RMP ELM suppression window. These findings provide a possible way to find optimized path that keep ELM suppression using high-*n* RMPs in scenario development for high-*Q* operation in ITER.

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