ELM-Suppression by n=1 RMP in KSTAR

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For a tokamak fusion reactor including ITER and a DEMO, it is essential to control ELMs (Edge Localized Modes) in high-confinement mode (h-mode) operations, due to its excessive heat and particle out-fluxes on to plasma facing components. Among various methods for an active ELM control, an application of small non-axisummetric magnetic perturbation (MP) has been investigated in KSTAR 2011, resulting in complete suppression of ELMs [1]. It is the first demonstration of ELM suppression by applying n=1 MPs, which has not been reproduced in other devices since the first observation in DIII-D using n=3 RMP [2].

Characteristics of ELM-Suppressed MP Discharges

A representative ELM-suppressed MP discharge (#5947) is shown in Fig. 1 in comparison with a reference ELMy H-mode discharge (#5953). The reference discharge has I_P=0.6MA with near double null D-shape (κ ~1.9 and δ ~0.7) at B_T=2.0T, q_{95}=6~7, and $\nu^*_{e,neo}$=0.5~1.0. The H-mode was accessed right after I_P flattop (~2.0 sec) with 1.4 MW-90 keV NBI heating and sustained for ~3.0 sec by pre-programmed plasma control. D2 gas fueling was applied only during the ramp-up phase for H-mode access.

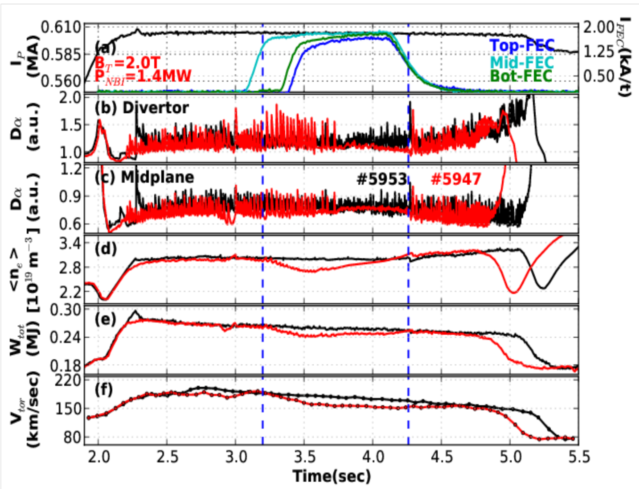

Figure 1: ELM-suppressed discharge (#5947) by applying n=1 MP in comparison with a reference ELMy H-mode discharge (#5953).

To control the ELMs, a n=1 RMP (Resonant Magnetic Perturbation) was applied from 3.0 to 4.5 sec with its maximum output currents (1.9kA/turn). As shown in D_α signals measured from divertor and midplane regions, the ELM spikes were initially (3.2~3.7 sec) enlarged with a reduction of frequency (i.e. ELMs were intensified), and then (3.7~4.3 sec) the spikes were disappeared (i.e. ELMs were suppressed) until the FEC (it's the coil name used for RMP application) currents decreased below a certain threshold level.

These distinctive two-phase ELM responses showed different evolutions of various global plasma parameters. In the initial ELM-intensified phase, many of parameters showed some degradations of around 10%, such as W_{tot}, β_P, V_{tor}, and n_e while $T_{e,core}$ and $T_{i,core}$ showed almost no change. Contrarily in the later ELM-suppressed phase, most of parameters became stationary except a gradual increase of n_e when ELMs were suppressed, which is a distinctive behavior compared with controlled densities in DIII-D ELM-suppressed RMP discharges [2].

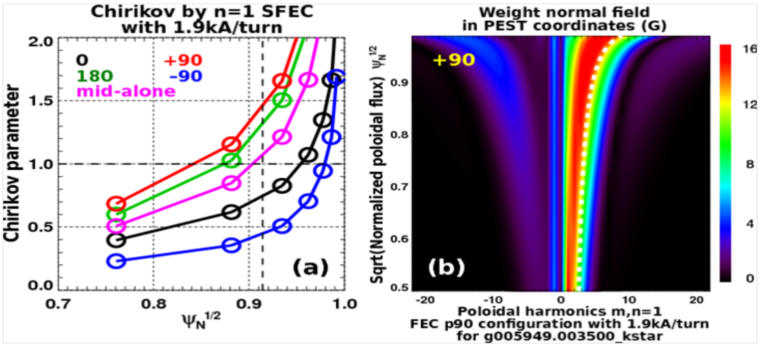

Figure 2: +90 phased n=1 was the best RMP configuration. (a) shows the estimation of Chirikov parameter for various n=1 MP configurations and (b) shows the pitch alignment between perturbed and unperturbed equilibrium fields for +90 phased n=1 MP.

Here the applied n=1 MP had +90 toroidal phase differences among three poloidal FEC coils providing n=1 MP each. As a consequence, it produced the best RMP configuration with n=1, which means the largest stochastic edge region and the best field alignment to plasma equilibrium fields as shown in Fig. 2.

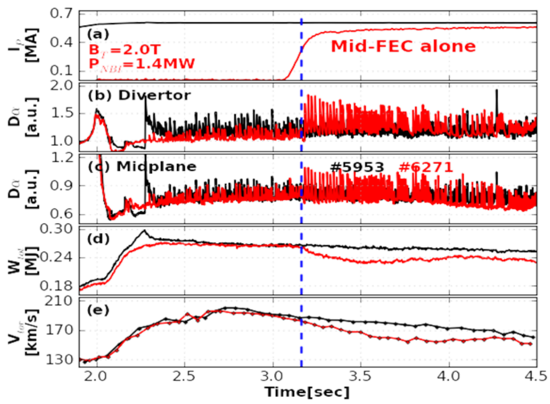

Figure 3: Mid-FEC alone apparently showed that ELM-intensification is an another special ELM response to RMP.

One naturally arising question was what or why the ELMs were intensified prior to being suppressed. Due to a certain issue of RMP power supplies, always there were ∼0.3 sec time delay on charging-up the RMP currents between mid-FEC and top-/bot-FEC coils. Actually, the ELM intensification occurred in this delayed phase as seen in Fig. 1. Therefore it is conjectured that the special magnetic spectrum provided by Mid-FEC alone may lead the ELM intensification. Indeed, a dedicated experiment with Mid-FEC coil alone shown in Fig. 3 revealed that the ELM-intensification was a characteristic response to the Mid-FEC alone, suggesting distinctive roles of both midplane and off-midplane coils on ELM control.

Saturated Pedestal Evolution on Edge T_e

Regarding the effect of RMP on edge thermal transport, we found an interesting observation from edge T_e evolution, which suggests an enhanced edge thermal transport by RMPs in the ELM-suppressed RMP discharge (See Fig. 4). In the initial ELM-intensified phase, sawteeth-like periodic pattern of edge T_e due to ELMs are clearly seen. However this periodic pattern was distorted during several (usually 3) cycles prior to ELM-suppression phase. Roughly 70∼80 % of inter-ELM period (marked by blue-color boxes) was distorted so that the monotonic evolution of edge pedestal forming was saturated into an intermediate level of T_e which is actually corresponding to the level of ELM-suppressend phase. This saturated behavior was found consistently in other diagnostics such as the D_α and the line-average electron density, n_e, as shown in the figure.

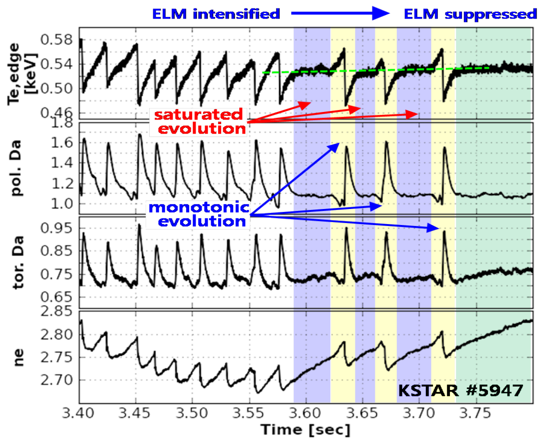

Figure 4: A saturated evolution of edge T_e pedestal by applied MP.

Broadband Increase of Magnetic Fluctuations

Another interesting observations regarding the effect of RMP is a characteristic change of broadband magnetic fluctuations as shown in Fig. 5. When ELMs were intensified by Mid-FEC alone, the magnetic fluctuation was reduced as shown on the left (a), whereas when ELMs were suppressed by n=1 RMP, the magnetic fluctuation was significantly increased as shown on the right (c). Basically these changes were in broadband (b and d), which are distinguishable from some coherent modes observed in some ELM-free H-modes, such as an edge-harmonic-oscillation (EHO) [4] or a weakly-coherent mode (WCM) [5].

Interestingly the broadband increase of magnetic fluctuation on ELM-suppressed phase was strongly correlated with the saturated pedestal evolution of edge T_e as shown in the expanded view, Fig. 5(d). The broadband increase of magnetic fluctuation was synchronized with the phase of saturated pedestal evolution of edge T_e. Therefore it is thought that these broadband increase of magnetic fluctuation may have a same physics origin with the saturated pedestal evolution of edge T_e. Thus understanding these correlated phenomena may be the key to resolve the physics mechanism of ELM-suppression by RMP.

Other Various ELM Responses to Different MPs

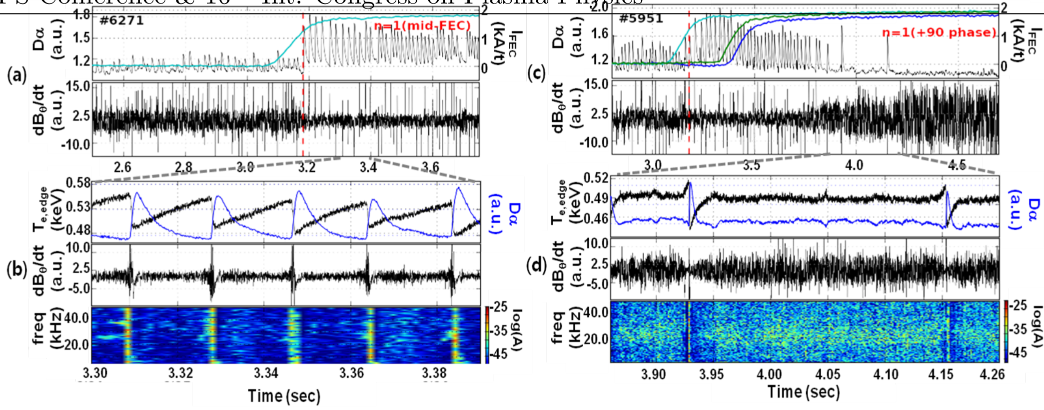

Figure 5: Distinctive broadband changes of magnetic fluctuation from different ELM-responses. A reduction of magnetic fluctuation on the left was observed with ELM-intensification by Mid-FEC alone, while a significant increase of magnetic fluctuation on the right was found with ELM-suppression by n=1 RMP. Both changes are in broadband.

Besides the ELM suppression and intensification, various ELM responses such as a strong mitigation by 0 phased n=1 MP (analogous with JET n=1 MP [6]) and a direct H/L back-transition (or locking) by 180 phased n=1 MP were observed. Even the application of n=2 MP with even parity preliminarily provided a possibility of ELM triggering as like in NSTX [7] as shown in Fig. 6. Although the observed variety of ELM responses needs further validations, it reveals out the importance of understanding the underlying ELM-RMP physics mechanism and of optimizing the magnetic spectra on ELM control.

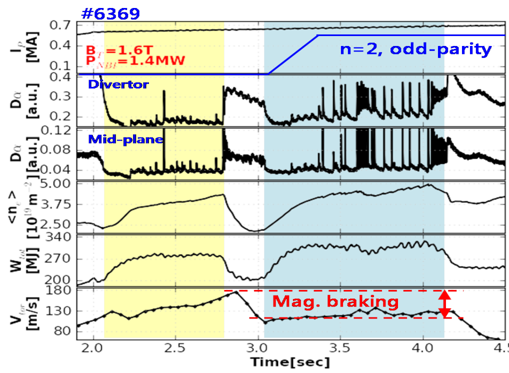

Figure 6: Application of n=2 MP with even parity triggered large type-I like ELMs with a strong magnetic braking on toroidal rotation

References

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