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Toward holistic understanding of the ITER-like RMP ELM control on KSTAR

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KSTAR has clarified a set of unresolved 3-D physics issues that could be addressed in the ITER-like in-vessel 3-row, resonant magnetic perturbation (RMP) configurations. In particular, considering that one of the most critical metrics of RMP ELM-crash control would require the compatibility with the divertor heat fluxes under the given material constraints, a series of intentionally misaligned RMP configurations (IMC)[1,2] have been explored to reveal the relationship between RMP ELM control and divertor heat fluxes. Specifically, taking advantage of the time-resolved IR camera, each rotating IMC in either 3-row or a combination of 2-row IMCs helped us diagnose the 'wet'area of divertor in the vicinity of ELM-crash-suppression; ELM-crash-mitigation, ELM-crash-suppression, and mode-locking.
First of all, we have articulated the contrasting effect of kink (i.e. "away"phasing) vs anti-kink (i.e. "toward" phasing) responses on the ELM-crash suppression, as shown in Figure 1.

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Starting from a sub-marginal level of RMP current in a typical n=1, 90 deg phasing, the 3-row IMC in kink phasing (in red) becomes more kink-influenced, demonstrating the synergistic benefit of 'kink'phasing in ELM-crash-suppression. In contrast, the 3-row IMC in the anti-kink phasing (in green) becomes more insensitive to ELM-crashes at the sub-marginal level of RMP. In a way, this helps us recast the "away"and "toward"phasing as kink and anti-kink phasing respectively, as schematically shown in the lower left inset of Figure 1. Such experimental observation is in excellent agreement with what ideal MHD theory predicts [3]. Previously, we had shown the divertor heat flux broadening with 3-row IMC-driven ELM-crash-suppression in both "away(kink)" and "toward (anti-kink)"phasings, while no such broadening was observed in the 2-row IMCs with top/bottom coils [3]. Now, we have newly observed that the 'wet'area of ELM-crash-mitigation got more broadened than that of ELM-crash-suppression (not shown here), based on these 3-row IMC discharges.
Also, we have further investigated whether or not 2-row IMCs would be fundamentally deficient in divertor heat flux broadening during ELM-crash-suppression. In the earlier study, no mid-row was involved in the 2-row IMCs, although the mid-row is much more influential than the other off-mid rows. To clarify this issue, a set of 2-row IMCs, including mid-row, has been explored. Figure 2 shows the time evolutions of various plasma parameters and 'wet'area, where each phasing of 2-row IMC varies by the denoted angle in shades incrementally from a typical n=1, 90 degree phasing angle in the anti-kink direction. Throughout the whole IMC application period, the 2-row IMC-driven, ELM-crash-suppression has been accomplished, as shown at the bottom of Figure 2 (a). At the same time, no evidence of the divertor heat flux broadening can be found on the 'wet'area in this combination of middle/bottom row IMCs, as shown in Figure 2(b).

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Even for kink phasing in the 2-row IMCs with middle/bottom coils (as shown in Figure 3 (b)), a similar outcome has been obtained. Thus, it is a fair conclusion that the divertor heat flux broadening would require a third row, suggesting that the dispersal of the divertor heat flux in 3-row IMCs cannot be driven by helically structured 2-row IMCs alone. Nonetheless, no physics mechanism of the 3-row IMC-driven, divertor heat flux broadening during ELM-crash-suppression has been understood yet, while several hypotheses are being assessed[1]. Interestingly, we have found that middle/bottom rows are much more effective in suppressing the ELM-crashes than top/mid rows, revealing strong up/down asymmetry in lower-single-null (LSN) plasmas, as shown in Figure 3.

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Considering that the 3-row IMC-driven, ELM-crash-suppression in kink phasing have been securely obtained at 2.3 kA, a set of 2-row IMCs have been designed to compensate a missing off-mid row current (mid: 2.3 kA, off-mid: 4.6 kA). Surprisingly, such conditions led to a vastly contrasting outcome, proving a much more effective coupling of middle/bottom rows in ELM-crash-suppression than that of top/middle rows. In fact, there was a much lower threshold of ELM-crash-suppression in the combination of middle/bottom rows, even suggesting no need of top row (not shown here). This is reminiscent of the critical influence of X-point on RMP ELM control studied in MASTn_e, though it was related to ELM-crash-mitigation, rather than ELM-crash-suppression.
Overall, the KSTAR has established a new holistic understanding of ITER-like RMP ELM control, elaborating various subtle points in the vicinity of ELM-crash-suppression and 'wet'area on divertor. These new findings in 3-D physics is expected to help us further reduce the uncertainty associated with 3-row ITER RMP.

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