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Exploration of RMP ELM control on ITER similar shape (ISS) in KSTAR

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Recent control advances at KSTAR enabled us to not only sustain the ITER-similar shape (ISS) in a stationary manner but also experimentally demonstrate the ISS-compatible RMP-ELM control in KSTAR for the first time, using the n=2, +90-deg phasing RMP, matching the ITER-like dimensionless parameters in lower single null (LSN) configuration with vastly contrasting upper/lower triangularities. The kinetic parameters of the ISS are different from the typical KSTAR configurations seen in ELM-RMP suppression experiments [Y.M.Jeon PRL 2012, Y.In NF 2019].

Achieving ITER relevant parameters in KSTAR has been a challenging target. The main difficulty lies in the fact that low edge safety factor requirement (q_{95} ~ 3.1 - 3.4) would result in kink-driven mode-locking easily, considering fundamental challenges of the independent control of highly up/down asymmetric triangularities with constraints by a large up/down symmetric central solenoid (CS). However, the establishment of the ITER relevant parameters in a superconducting device like KSTAR allows us to explore various ITER-related physics and engineering constraints, prior to the ITER-era.

In order to accomplish this ISS target, various advanced magnetic controllers have been implemented and executed in the real experiments, including enhanced vertical stabilization using inboard flux loop differences [Mueller FED 2019], a multi-input multi-output (MIMO) shape control design suitable for LSN shape and the real-time feedforward algorithm [Walker CCA 2016] that would minimize accumulation of integral gain errors.

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Figure 1: ISS discharges obtained in KSTAR (a) major parameters in time: Used 2 NB ion sources of total 3.0 MW (#22889) or 1 beam + 2 gyrotrons (#21368). From top to bottom, Ip [MA], q_{95}, β_N, mid-RMP current [kA/turn], edge Thomson [1e19 m^{-3}], and D_α. (b) Obtained shape at the shot #22889, t=5.5065s.

The experimental setup of the typical ISS discharge examples is shown in Figure 1. Using available combinations of 1-2 neutral beam sources and 2 ECH 105GHz gyrotrons, the ISS with 3 different levels of the toroidal rotation were created at the total power level of 3.0-3.6 MW. Two types of power combinations were frequently used in order to create different toroidal rotation levels: 1) Two neutral beam (NB) ion sources (up to 3.6 MW) or 2) one NB + 2 gyrotrons (up to 3.3 MW). As shown in Figure 1(a), the discharges match major ITER-like parameters, i.e. q_{95}= 3.2 - 3.4, β_N= 1.6 ~2.0, at the plasma current flattop Ip = 780 - 850 kA at B_T = 1.7~1.8T. The measured upper triangularity (δ_u) is around 0.5~0.55, and lower triangularity (δ_l) is fixed at 0.45, matching $\delta = (\delta_u + \delta_l)/2$ ~ 0.52 in the ITER shape: a typical ISS example is shown in Figure 1(b). The kinetic properties are, however, very different from the typical RMP-driven, ELM control experiments reported in similar q_{95} range in the ref [Y.In NF 2019]. For instance, the ISS shows relatively higher line averaged density n_e ~ 5-7 e19 m^{-3}, accompanied by high edge density pedestals with edge Thomson n_e ~ 2-3e19 m^{-3}. The edge electron collisionality is estimated as ν^* ~0.4-0.5 at the pedestal top ρ~ 0.89, using the definition at [Sauter PoP 1999] with the assumption of Z_{eff}~ 2.

At first the ELM control on the ISS by resonant magnetic perturbation (RMP) coils was attempted using n=1, +90-degree RMP configuration, but it disrupted the plasma instantly, as frequently observed in the typical low-q95 KSTAR configurations. However, from previous observations, the application of n=2 RMP is expected to be more manageable both for the typical low-q_{95} and for the ISS. In fact, we have found the n=2 RMP-driven, ELM-crash control was greatly affected by the absolute density level: In the highest electron density range, with line-averaged n_e ~ 7e19 m^{-3}, we were only able to observe a very low mode-locking threshold. Meanwhile, there were strong ELM-crash mitigations where the ELM frequency from 6-10 Hz to 100-120 Hz, even at relatively low level of RMP current = 1.3-1.5 kA/turn.

On the other hand, the ISS experiments with moderate level of density, at line-averaged n_e~5e19 m^{-3}, expecting lower edge collisionality than the cases above, showed more promising results: The RMP with n=2, +90-degree phasing showed a locking threshold of 3.1-3.3 kA/turn. Application of the RMP current below the locking threshold onto the ISS successfully accessed a marginal but clear ELM-crash suppression window for the first time at q_{95}=3.3-3.4, as shown in Fig. 2, for a short time of 200-600 milliseconds. The ELM-crash suppression was accompanied by 1) a global electron density pumpout (as measured at Thomson scatting density profiles and the line-averaged density), and 2) a characteristic β_N drop at the level between that of H- and L-mode. The experimental results suggest that the sustainable ELM-crash suppression window for this ISS is likely to be at a level of RMP current = 2.5 −2.9 kA/turn.

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In the near future experimental exploration is planned to robustly access the sustained RMP-driven, ELM-crash suppression on the ISS in KSTAR, helping us to articulate the main advantages of a superconducting device that is capable of a much longer pulses over hundreds of energy confinement time.

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