DEVELOPING LONG PULSE HYBRID SCENARIO IN DIII-D AND KSTAR FOR W-COMPATIBLE STEADY-STATE OPERATION TOWARD ITER

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An international joint task force, including the DIII-D and KSTAR tokamaks, seeks to demonstrate the compatibility of long-pulse high-performance operation in a tungsten wall environment. Through one week of joint experiments on each device, a steady-state (SS) hybrid scenario is successfully developed in DIII-D and transferred to the superconducting magnetic coil environment of KSTAR, achieving long-pulse operation (β_N=2.4 for 35s) with a tungsten divertor [1]. Long-pulse operation with high β_N and tungsten (W) as a plasma-facing component is a vital mission for the ITER steady-state goal (and possibly other future superconducting tokamaks with W operation), which needs urgent exploration and comparative studies. The SS-hybrid scenario in DIII-D is one of the promising candidates for a long-pulse scenario in ITER, enabling sawteeth-free high-confinement plasma operation with q_{min}>1 supported self-flux pumping from n=2 (or 3) core MHD activity [2]. However, the standard recipe leverages a fast I_P ramp, fast shaping rate, and delicate NB power control capabilities, which are less relevant for superconducting tokamaks. In addition, the compatibility of the SS-hybrid scenario with long-pulse operation with W-impurities remains a question.

A joint task force addresses these questions by leveraging each facility's unique strengths in timely, coordinated, iterative development collaboration, beginning by extending the SS-hybrid scenario in DIII-D [3] to be compatible with the operational constraints imposed by the superconductor in KSTAR [4] (so it can be more relevant to ITER and future reactors). These constraints include limited (slow) I_P ramp, shaping rate, and power control so that the scenario can be reproducible in KSTAR for cross-device study. By leveraging the strong capability of DIII-D in scenario development, a robust recipe of SS-hybrid scenario with 3/2 (or 4/3) core mode is successfully developed with these constraints, achieving β_N=3.2, H_{98}=1.3, q_{95}=5.8, and V_L~0. As shown in Figure 1, the new recipe enables access to an SS-hybrid scenario with a slow IP ramp rate (1.5→0.5MA/s), shaping, and stepwise (simple feedforward) NBI and EC heating (PNB, EC) sequence, as well as a relevant (KSTAR/ITER-like) shape, which is reproducible in KSTAR.

Unlike the standard SS-hybrid recipe on DIII-D, the comparison in Figure 1 shows that qmin in the newly developed recipe rapidly drops below unity due to slower I_P ramp and shaping, making sawtooth and fishbone activities larger. This has been a traditional challenge in hybrid scenario access when the I_P ramp and shaping rate are slower. Deterioration from sawteeth and fishbone activities can be minimized in the new recipe by optimizing the P_{NB} and P_{EC} sequence (not shown) to maintain q_{min}>1 during scenario formation, fostering the robust formation of 3/2 (or 4/3) mode for the hybrid scenario after 2.5 s, minimizing the deterioration of sawteeth and fishbone activities, and maintaining qmin above unity from self-flux pumping.

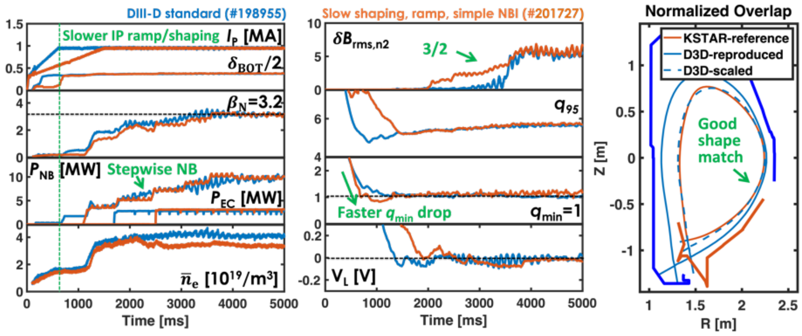

Figure 1. Comparison of standard (#198955) and newly developed (#201727) SS-hybrid recipes, including plasma current (I_P), triangularity (δ_{BOT}), heating ($P_{NB, EC}$), density (n_e), n=2 MHD amplitude ($\delta B_{rms, n2}$), safety factor (q), and loop voltage (V_L). Normalized shape overlap shows good agreement between the new recipe (#201727) and the KSTAR-reference shape.

In addition, the resilience of the scenario performance in the presence of W-wall and impurity is explored by imposing impurity seeding with W-Laser Blow-off (LBO) [5]. In Figure 2 (left), W-impurity is continuously injected into the plasma by W-LBO (10Hz injection) from the early H-mode phase before reaching the scenario target. In the early phase of scenario formation, large emissivity (>0.1MW/m^2) is measured from soft X-ray diagnostics due to W-impurity accumulation at the core. However, impurity accumulation and radiation are strongly reduced by on-axis ECH injection at 2.5s during scenario formation, consistent with the previous work [6]. Subsequently, further reduction of core radiation is observed when m/n=3/2 with 1/1 MHD mode appears at 3.5s, enabling access to the hybrid scenario with β_N=3.0. This reduced core radiation can be considered a result of MHD-induced impurity screening [7], which is the favorable advantage of a hybrid scenario with intrinsic core MHD modes. These results show promising compatibility of the developed SS-hybrid scenario with the W-environment.

A developed SS-hybrid scenario is transferred to KSTAR to demonstrate its compatibility in the superconducting coil and W-divertor environment. Although further adjustments are needed to access the target scenario, Figure 2 (right) shows joint experimental efforts successfully achieved the 35s long-pulse operation of a DIII-D-like hybrid scenario in KSTAR with β_N=2.4 and q_{95}=5.8. The n=3 core MHD is also presented throughout the discharge, maintaining q_{min}>1 and sawteeth-free plasma. Simultaneously, the core radiation is well maintained below f_{rad} <0.3 with mitigated W-impurity accumulation. The main modifications from the initial recipe are EC injection timing and additional divertor gas puffing. EC injection is shifted from 2.5s to the early discharge phase (0.5s) to minimize the loop voltage during the IP ramping stage, enable EC-assisted startup, and improve the stability of shaping control. In addition, earlier EC injections contribute to mitigating core W accumulation after transitioning to H-mode. At the same time, divertor gas puffing is applied to minimize the divertor sputtering caused by large ELMs during the early H-mode phase, thereby reducing W-impurity generation and core accumulation. This early gas injection leads to a 25% higher density (f_{GW}, Greenwald density fraction) than the reference scenario developed from DIII- D. Despite this success, a steady state (V_L~0) is not achieved in KSTAR, primarily due to the device's limited PNB heating capability and relatively high density. The enhanced NBI heating capability in the next campaign will resolve this limitation to achieve steady-state operation. In conclusion, this success advertises the SS-hybrid scenario as a compelling path for long-pulse operation in ITER with W-environment and shows a successful showcase of international joint experimental effort.

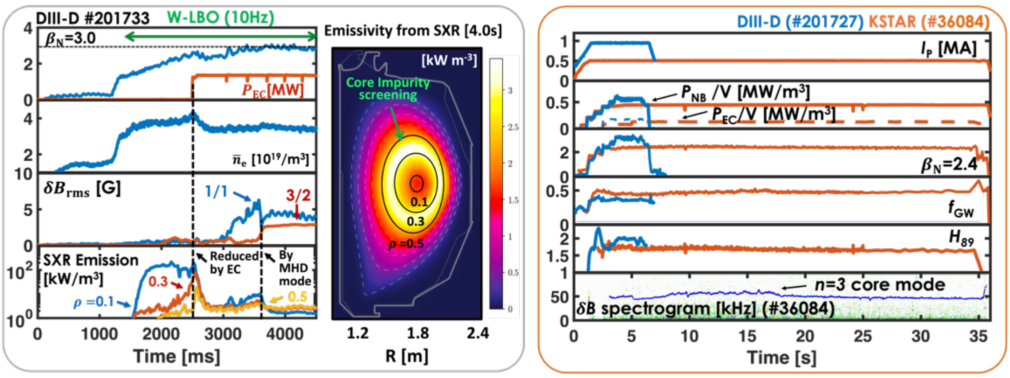

Figure 2. (left) Time trace of scenario formation with W-LBO injection starting at 1.5s. Time trace of SXR and 2D emissivity emission (at 4s) shows strongly mitigated W-accumulation by EC and core MHD (n=1,2) during target scenario formation. (right) The comparison between developed hybrid reference from DIII-D (#201727) and KSTAR (#36084). 35s long-pulse operation in KSTAR shows a good match with DIII-D's reference with core n=3 MHD mode.

ACKNOWLEDGEMENTS

This material is based upon work supported by the DOE Contract under awards DE-AC02-09CH11466 and DE-SC0020372. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-FC02-04ER54698, and R&D Program of "High Performance Tokamak Plasma Research & Development (EN2501-16)" through the Korea Institute of Fusion Energy (KFE) funded by Korea Ministry of Science and ICT (MIST).

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