OVERVIEW OF THE KSTAR EXPERIMENTS AND FUTURE PLAN

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KSTAR project aims to develop high-performance operation scenarios for the demonstration reactor including control schemes to avoid critical events relating plasma instabilities [1,2]. The 2023 KSTAR campaign focused on deploying the new tungsten mono-block diverter cassette to validate plasma operations similar to previous seasons with a full carbon wall. Key adjustments were made to plasma startup and shape control considering the up-down asymmetry configuration. The currents on the poloidal field coil in the startup phase and the striking target point on the divertor plate during shaping phase are adjusted to compensate for the asymmetry.

The effects of tungsten on plasma performance were investigated by evaluating core plasma radiation loss, which is expected to increase significantly when tungsten impurities penetrate the core plasma. The 2D plasma radiation loss profile measured by IRVB clearly showed that significant core radiation typically occurs after the tungsten divertor installation. This was further confirmed by the fact that upper single-null plasma, with striking points located on the upper carbon divertor target, does not result in significant core radiation. A statistical analysis indicates that the plasma radiation fraction typically increased by a factor of 2, along with a degradation in plasma performance, after the installation of the tungsten divertor.

KSTAR has recently focused on developing plasma operation scenarios aimed at reducing core radiation loss by preventing tungsten impurities from being transported into the core plasma. It has been observed that plasma core radiation can be significantly reduced using the β-kicking NBI heating scenario, where most of the NBI heating is injected into the plasma after it enters H-mode and shape control is completed as shown in Fig.1. In addition, it has been found that boron powder injection is effective in reducing plasma radiation by lowering plasma density.

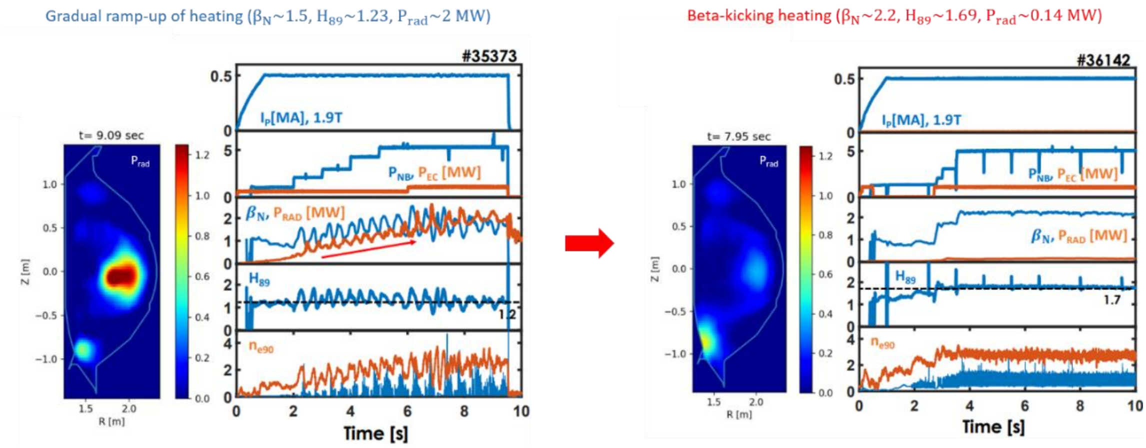

Figure 1. Development of the plasma operation scenario aimed at reducing core radiation

New tungsten divertor environment has been particularly beneficial for long-pulse lower single null (LSN) scenarios, such as high-β_p and hybrid, though upper single null (USN) scenarios face challenges due to the mixed carbon-tungsten environment [3]. The 2023 campaign prioritized evaluating these effects, focusing on new divertor commissioning. Major achievements included a record-breaking >100 s H-mode operation in the LSN configuration and the reproduction of high-ion temperature (~9 keV) and β_N ~ 3 in USN scenarios. The recent 2024 campaign builds on these efforts by examining the performance and stability limits of these scenarios in the new tungsten environment, particularly for H-mode operation in LSN while mitigating impurity accumulation. Our findings indicate that rapid access to high-performance states is crucial for minimizing tungsten accumulation, as it is strongly linked to the thermal pedestal. Additionally, controlling mode onset through β_N overshoot and early ELMs remains key.

Development of the advanced scenario has been further enhanced by international collaboration. A new joint activity between DIII-D and KSTAR was launched in the 2024 campaign. As a preliminary experiment, a high poloidal beta scenario, designed to align with the constraints of KSTAR and be applicable to its operations, was successfully demonstrated in the DIII-D experiment, with the goal of implementation on KSTAR. Experimental results indicate that high-density, high poloidal beta discharges with large-radius ITB formation were successfully achieved. However, the improvements in confinement and overall performance were somewhat weaker compared to those observed in DIII-D. Further optimization of tungsten impurity control is expected to enhance performance by reducing radiative power losses in future experiments.

Control schemes to avoid critical events were tested on new divertor environments. The real-time integrated RMP scheme has been significantly upgraded for new tungsten divertor compatible shape and tested successfully in

KSTAR 3D magnetic field experiments [4,5]. It is observed that regardless of the triangularity, L-H transition power thresholds with tungsten divertor is consistently higher than that with carbon divertor. Effects of edge-localized RMPs on L-H transition in USN was found to either delay L-H transition or trigger H-L back-transition. The disruption event characterization and forecasting (DECAF) system [6] successfully tested on the KSTAR device. Expanded events framework of DECAF was enabling precise detection of issues such as plasma current anomalies, vertical instabilities, MHD mode-locking, and impurity radiative collapses. The multi-tiered warning system of DECAF delivers early predictions leveraging extensive international tokamak databases to optimize plasma stability and performance.

Real-time divertor detachment control methods have been advanced using a surrogate model. It has been shown that ion saturation current in the divertor region can be controlled to the target value by injecting nitrogen in real-time, according to the amounts estimated by the surrogate model during the plasma discharge. Additionally, it has been demonstrated that the maximum position of plasma radiation in the divertor region can be controlled in real-time using 2D plasma radiation measurements from an IRVB and a feedback control algorithm for nitrogen gas.

Studies on turbulence and transport physics aims to enhance the understanding of transport and confinement physics in the tungsten divertor. These studies encompass turbulence characterization, transport bifurcation, MHD turbulence interaction, turbulence interactions with fast particles, and high Z-impurity transport. Based on experimental observations, verification and validation studies of the transport models are actively ongoing utilizing advanced fluctuation measurement diagnostics in the tungsten divertor environment.

Heating & current drive systems and diagnostics were upgraded to support the high-performance operation. The NBI-2 β_N feedback control system, which employs integral control method, dynamically adjusts beam power, enabling continuous actuation without plasma perturbation. By actively maintaining the target plasma pressure, it effectively mitigates performance degradation caused by mild MHD activity. This development contributes to the progress of steady-state operation through NBI in KSTAR. Several diagnostics equipped the real-time measurements capabilities. In addition to the magnetic diagnostics and interferometer, ECE, ECE imaging and CES diagnostics supported DECAF system. The MSE system and Lyman-α spectroscopy have made progress in automation and real-time data process. A real-time Thomson system has been developed based on the neural network method. Advances are made in high-accuracy and fidelity fitting of the profile data which can be used in transport modelling and in machine-learning base profile calculations.

These activities will continue at KSTAR with additional upgrades to implement a burning plasma experimental environment. Firstly, the current carbon-based plasma facing components will be replaced with tungsten-coated tiles to achieve full tungsten wall condition. In addition, a new KSTAR plasma control system based on the ITER real-time framework will be developed. These upgrades could resolve key issues to prepare for successful ITER operation. In the long term, we will modify the interior of the KSTAR vacuum vessel to expand the plasma area, install additional heating and current drive devices, and analyze the experimental results of KSTAR in conjunction with the simulation results of virtual KSTAR to address the key issues required for high performance operation in burning plasma.

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