Start-up of plasma operation and control in the large superconducting tokamak JT-60SA

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JT-60SA first plasma with the plasma current of I_P~0.13 MA was achieved on October 23rd, 2023. Plasma breakdown was obtained at low toroidal electric field of $E_{//}$~0.12 V/m with a Trapped Particle Configuration (TPC) and Electron Cyclotron Heating (ECH) assist. Stable divertor plasma with I_P flat-top of 1 MA was achieved within one month after the first plasma. This paper presents the main scientific results of the first plasma operation and plasma control studies in JT-60SA clarifying the issue of starting plasma operation in a new large superconducting machine. The results can make contributions for ITER especially in the first operation campaign.

The EC-assisted low $E_{//}$ breakdown was success in both TPC and Field Null Configuration (FNC). The TPC start-up has the advantage of a wider applicable regimes of the poloidal magnetic field error (~1.5 mT) and the initial plasma current compared to the FNC start-up. Operation spaces of the TPC start-up with the second harmonic EC wave as well as the fundamental EC wave were examined in the prefill gas (0.1-7 mPa), the toroidal magnetic field (B_T=1.70, 1.79, 2.04 T) and ECH power (P_{ECH}=0.5-1.6 MW). Magnetic field of the breakdown was optimized with the inverse reconstruction method [1]. The ECH power and timing, and fueling were optimized to mitigate runaway electron generation at the current ramp up phase. The first plasma was obtained next operation day. Initial plasma current of I_P~0.1 MA was ramped up to ~0.3 MA with the Plasma Current Centroid (PCC) scheme which is beneficial control scheme at large disturbances of CCS due to estimation errors by large eddy current. Plasma shape and equilibrium were controlled with Cauthy-Condition Surface (CCS) scheme which work well above I_P~0.3 MA. Divertor configuration with I_P~1 MA was obtained with the CCS scheme and sustained stably until the flux consumption of the Central Solenoid (CS) coils. The stable plasma discharges from breakdown, I_P ramp-up, flat top and ramp-down to about I_P~50 kA were realized by using an adaptive voltage allocation (AVA) scheme, which adjusts the control gains automatically to avoid voltage saturation [2]. The developed Vertical Displace Event (VDE) predictor using machine learning and AVA scheme [2] was validated with plasmas. Deliberate upward and downward VDEs was demonstrated. Disruption database has been constructed, which are likely categorized as VDE, radiative disruption and n=1 mode driven disruption. The controllability of plasma current and shape/equilibrium was examined with He working gas to minimize wall recycling. Stable I_P=1 MA divertor plasma with H_2 gas was also obtained by optimizing fueling and I_P build-up scenario. The line averaged density at the I_P flat-top phase was around $0.5x10^{19}$ m^{-3}, and the central electron temperature increased from 1.5 keV to 2 keV with P_{ECH}~0.5 MW. After the H_2 gas discharges, systematic EC wall cleaning test was conducted to examine favourable condition to remove H_2 from the 1st wall. The effect of fundamental wave and second harmonic wave were compared for different poloidal magnetic configurations and B_T conditions.

[1] H. Urano, et. al., Nucl. Fusion 60 (2020) 066002
[2] S. Inoue, et. al., Nucl. Fusion 61 (2021) 096009