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# Achievements and Lessons Learned from JT-60SA's Integrated Commissioning towards DEMO

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Successful startup of fusion devices is achieved through various research and development efforts. This talk will highlight significant milestones in the integrated commissioning of JT-60SA, leading to the realization of its first plasma.

A first central topic will be the establishment of the low-voltage breakdown scheme with Trapped Particle Configuration (TPC) technique, essential for ITER and similar large-scale tokamaks. In JT-60SA, we have successfully achieved its first plasma operation under the constraint of a low toroidal inductive electric field of 0.15 V/m. A plasma start-up scenario, leveraging the effective confinement of electrons accelerated by the electron cyclotron wave, proved to be instrumental in reaching this milestone under the challenging conditions. The demonstration of plasma start-up using second harmonic electron cyclotron heating, with an applied toroidal electric field of 0.15 V/m, strongly validates the feasibility of achieving first plasma operation in ITER.

The second topic will be the robust control methods established to operate under the challenging constraints of voltage ratings for the integrated commissioning of the coil system and the presence of substantial eddy currents, culminating in the swift attainment of a 1.2 MA diverted plasma within just under two months of operation. We developed two control logics [S. Inoue et. al., Nuclear Fusion 61, 096009 (2021)] to accelerate the commissioning of JT-60SA. First, we developed ISO-FLUX control scheme based on the Plasma Current Centroid (PCC), which assumes filamentary currents in plasma and redundantly controls not only the position but also the shape under the ISO-FLUX control framework. Robustness of the PCC were validated in JT-60SA experiments, where the PCC scheme provides the good controllability in the existence of large eddy-currents to the plasma current such as just after the breakdown (~25% of plasma current), which could affect the reconstruction accuracy of the plasma position and the boundary. Even just after the breakdown, the severe condition for the boundary reconstruction, we achieved Z=±25cm position control with the PCC scheme in JT-60SA, while the control was failed with the plasma boundary control. Second, an Adaptive Voltage Allocation scheme (AVA) was developed to resolve the interference between the plasma shape control and the plasma current control. As shown in figure (a), $I_p$ was ramped up to 500 kA at 1 s, maintained at a flat top until 2 s, and then increased to 700 kA. Feedback control commenced at 1 s. Following the initiation of feedback control, a discrepancy between the targeted and actual values of $I_p$ was observed, which caused voltage saturation as shown in figure (b) in the absence of the AVA scheme. On the other hand, in the case with the AVA, the automatically adjusted gain, $G_{X,AVA}$, optimized the balance between the plasma current and the position and the shape control, which can be seen as the drop of the $G_{X,AVA}$ in figure (c). In the absence of the AVA, the vertical/horizontal shape control failed as shown in figure (d) and (c), which are successfully resolved by introducing the AVA scheme, and achieved successful ramp-up to 700 kA.

The third topic will be the direction control of vertical displacement event was tried in the real experiment for the first time, and was achieved with our new Vertical Instability (VI) predictor, which was also developed with the machine learning technique and newly introduced proxies for vertical instabilities obtained by AVA scheme [S. Inoue et. al., Nuclear Fusion 62, 086007 (2022)].

Lastly, we will explore the EC wall cleaning tests conducted to optimize conditions for hydrogen removal from the first wall, comparing the effectiveness of fundamental and second harmonic electron cyclotron waves across different magnetic configurations. This process is crucial for maintaining plasma purity and enhancing overall tokamak performance.

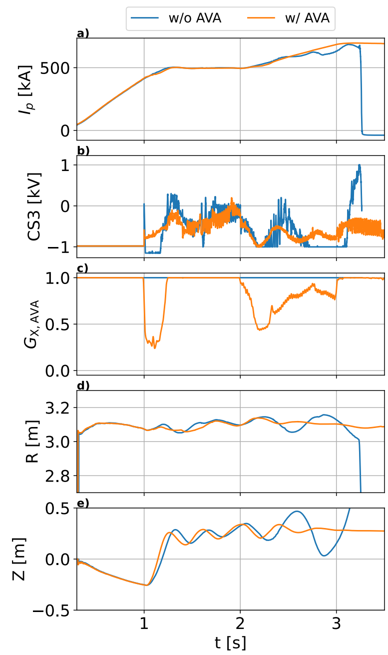


Fig. Temporal evolution of a) plasma current, b,c) radial/vertical position of plasma current centroid, d) $G_{X,AVA}$, and e) ECRF injection command. In the case w/o AVA (blue lines), the AVA scheme is turned-off, while is activated in the w/ AVA case. $I_p$ is ramped-up to 700 kA by using the AVA scheme with diverted shape.