# RESULTS OF ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE SYSTEM OPERATION IN THE INTEGRATED COMMISSIONING PHASE ON JT-60SA

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On JT-60SA, electron cyclotron heating and current drive (EC H&CD) system was developed as a high-power, long-pulse and multi-frequency system, with the maximum pulse length of 100 s. During the integrated commissioning phase of JT-60SA, two EC H&CD systems were operated: Unit 1 at 110 GHz with a small-diameter waveguide of 31.75 mm and Unit 2 at 82/110/138 GHz with a large-diameter waveguide of 60.3 mm. As a result of transmission efficiency evaluation, it is demonstrated that a 100 m class transmission line by a large diameter waveguide at multi-frequencies is capable of highly efficient transmission as designed. In the plasma experiment, a total of 1.51 MW of power from the two systems was injected into the tokamak, resulting in the achievement of the first plasma. After the first plasma, the EC H&CD system was used for almost all discharge sequences with a variety of injection configurations, demonstrating the reliability of this system. We also tried injection into the tokamak with a source power of 1.5 MW at 110 GHz from a single unit (Unit 2), and succeeded in 1 s injection. This result indicates the possibility of operating an EC H&CD system with a source power of 1.5 MW, which is important achievement for future high-power operation. According to the operational results of the integrated commissioning phase, a calculated transmission efficiency of 85-90% is expected for the designed transmission line layout for the next operating phase (initial research phase). For this phase it is expected to achieve the design target of 3 MW of total power injected into the tokamak with sufficient margin, and possibly 5 MW of injected power could be achieved by operation with a source power of 1.5 MW per unit.

In the development of the JT-60SA EC H&CD system, the individual components, such as the gyrotron, were designed for more than 1 MW, 100-second pulse operation, and three frequencies of 82, 110, and 138 GHz [1]. On the other hand, there were concerns about the feasibility of achieving high transmission efficiency in a full-scale transmission line with a transmission distance of nearly 100 m. In general, large-diameter waveguides increase transmission loss compared to theory due to misalignment. As reported in [2], the JT-60SA transmission line was successfully aligned with an accuracy of 1 mrad or less for connection of each waveguide, which results in the high transmission efficiency comparable to theory. However, the feasibility of the system in actual plasma operation has not yet been demonstrated, thus it is important to evaluate the system through the operation. In particular, the avoidance of interruption or damage due to unexpected arcing and the ability to reliably generate pulses of the required power and length are important aspects for plasma experiments.

During the integrated commissioning phase, the high-power millimeter wave generated by each gyrotron was injected into the tokamak vessel without plasma for the purpose of conditioning the TL components such as the torus window prior to the plasma experiment as a part of the integrated commissioning. As a result, it was possible to inject into the plasma 0.69 MW from Unit 1 and 0.82 MW from Unit 2 (total 1.51 MW) with a pulse length of 1 s from the first day of the plasma experiments. Unit1 was injected at 110 GHz for the second harmonic X-mode with vertical linear polarization, and Unit2 was injected at 82 GHz for the fundamental O-mode with horizontal linear polarization, resulting

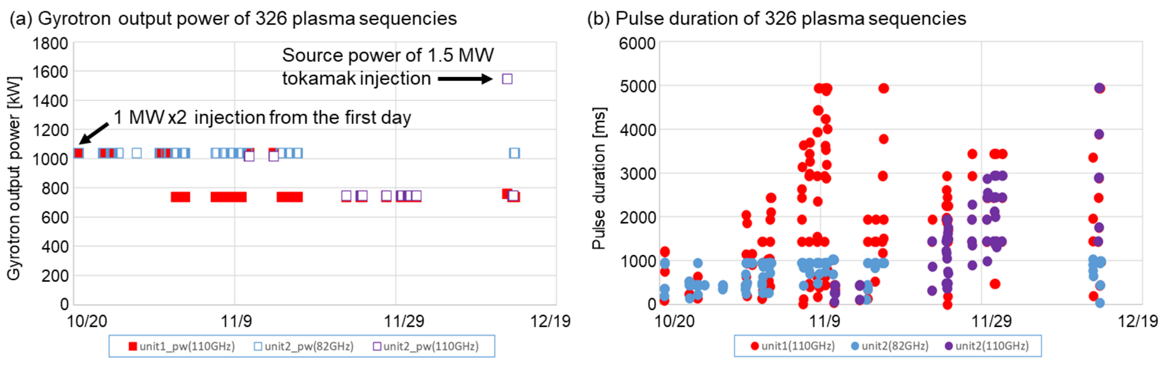


*Fig.1 Gyrotron output power and pulse duration of 326 sequencies during the integrated commissioning.*

in a successful plasma start-up and a first plasma with a plasma current of ~130 kA. After the success of the first plasma, we operated EC H&CD systems in almost all 326 discharge sequences, which suggests the high system reliability (Fig.1). Since the conditioning without plasma was limited to 1 s to avoid damage to the vacuum vessels, additional conditioning was required for injections with pulse durations longer than 1 s. This conditioning was performed by millimeter wave injection into the plasma instead of a vacuum, and approximately 70 sequences of plasma injection were required to extend the pulse up to the 5 s which is the limit of the power supply of the gyrotron system in the integrated commissioning phase. To demonstrate flexible operation for both plasma start-up and additional heating at the Ip flat-top, a multi-pulse injection sequence was also developed where a 2.5 s pulse was commanded first for plasma breakdown and Ip ramp-up, followed by a few seconds pause, and then another pulse of 1.5 s was commanded at the flat-top of the plasma current (Fig.2). After the successful of these 1 MW operations, the higher power operation was also attempted. While the availability of the 1.5 MW gyrotron operation for 5 s had been confirmed by operation on dummy load, further TL conditioning was required because a transmission power of >1 MW was never experienced for any of the TL components. As a result after the several shots of conditioning, 1.5 MW power operation was successfully achieved. The injection power into the tokamak by a single unit is ~1.3 MW taking into account the transmission efficiency. This result demonstrates the possibility to further increase the total heating power.

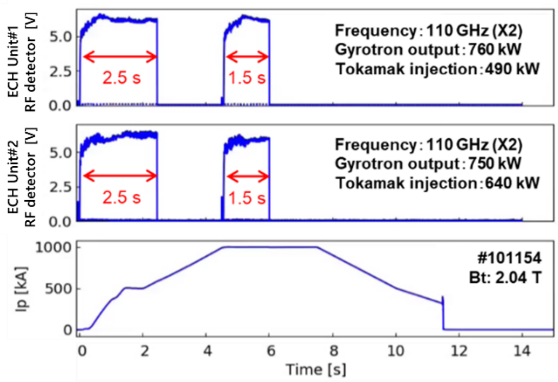


*Fig.2 Waveforms of multi sequence injection where the pulses are injected twice at the beginning of the discharge and the flat-top of the plasma current.*

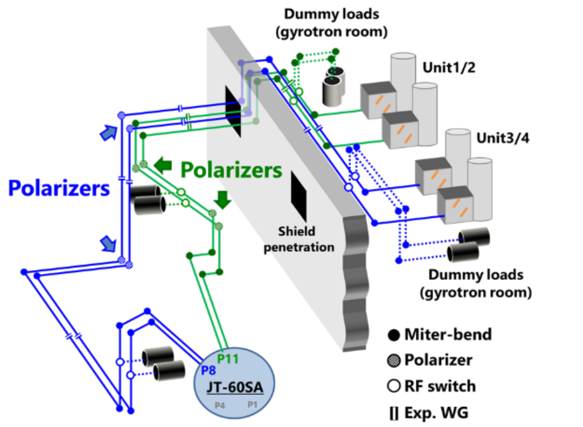


*Fig.3 Designed layout of the TLs for the initial research phase. The expected transmission efficiency is higher than 85%.*

As the operational results of the integrated commissioning phase have demonstrated the TL installation with an accuracy of less than 0.8 mrad and the feasibility of the overall system, a layout of four units of TLs has been designed for the next operational phase of the initial research phase (Fig. 3). Each TL is expected to have a calculated transmission efficiency of 85-90%, exceeding the design target by more than 5%. Thus, the total power injected into the tokamak is expected to be above the design target of 3 MW, and injection of 5 MW could be achieved by operating each unit at 1.5 MW source power.

This achievement demonstrated the multi-frequency, high-power and long-pulse millimeter wave to be delivered to the tokamak with low-loss transmission by large-diameter waveguides in JT-60SA operation. Furthermore, the TL design for the initial research phase has been completed, and procurements of TL components and sub-systems based on the designed TL specification have been started by both JA and EU. These results also contribute greatly to the feasibility study of transmission systems using large-diameter waveguides for ITER and future DEMO reactor designs.

## REFERENCES

[1] T. Kobayashi H. Yamazaki et al. Nucl. Fusion, 62(2), 026039, 2022.
[2] H. Yamazaki et al. Fusion Eng. Des., 196, 114015, 2023.