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Prototype Development of the ITER EC System with 170GHz Gyrotron & Development of Dual Frequency Gyrotron and Launcher for the JT-60SA ECH/ECCD System & Development of Over 1 MW and Multi-Frequency Gyrotrons for Fusion

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A
To study the operational performance of ITER EC heating and current drive system (H&CD), a mock-up of the ITER mm wave system has been assembled using the high power long gyrotron test stand in JAEA. The prototype system is composed of the primary parts of the EC H&CD system, including: 170GHz gyrotron, power supply, transmission line (TL) and mock-up of equatorial launcher (EL) and control system. The gyrotron power was transmitted via the precise aligned TL (40m) with 7 miter bends to the EL achieving a 91% of HE11 mode purity. The experiments were realized using a mock-up of the conceptual EC control system based on the ITER Plant Control Design Handbook (PCDH). The system has achieved CW 5 kHz power switching, which demonstrates the compatibility for MHD control of ITER plasma. The modulation was achieved using a novel configuration of the electron beam acceleration power supply. In the experiment, stable 5 kHz of power modulation was demonstrated with minimized spurious frequency excitation at the ramp-up phase of each pulse., which satisfied the ITER criteria. The JAEA test stand is a flexible system with its center piece a frequency-step-tunable gyrotron at 170GHz/137GHz/104GHz. The output beam is radiated to the identical direction from the output window for each frequency, consequently the power was transmitted to the end of the TL at these three frequencies.

B
The development of a gyrotron and launcher operated at two frequencies, 110 GHz and 138 GHz, has made a significant progress toward electron cyclotron heating (ECH) and current drive (ECCD) in JT-60SA. High-power, long-pulse gyrotrons are required for the JT-60SA ECH/ECCD system which has the total injection power of 7 MW and the pulse duration of 100 s using 9 gyrotrons. The wave frequency in the original specification is 110 GHz, which is effective for off-axis ECH/ECCD to sustain a high-beta plasma at the toroidal field of 1.7 T. On the other hand, the higher frequency waves at 130 ~ 140 GHz enables ECH/ECCD in the core plasma region at the maximum toroidal field of 2.3 T in JT-60SA. However, a dual frequency gyrotron that can generate the target output power and pulse length (1 MW for 100 s) was not developed since it requires high oscillation efficiency to obtain high power and low diffraction loss to achieve long pulse, simultaneously. In 2011, we stared to develop a new dual frequency gyrotron (110 GHz, 138 GHz) equipped with a triode type electron gun to obtain high oscillation efficiency. High-power, long-pulse operations of the dual frequency gyrotron have been carried out since the last IAEA FEC. Developments of an ECH launcher with high reliability based on a linear-motion antenna concept and a polarizer with optimized groove depth, width, and period for dual frequency operation are also in progress. Main results are as follows: (i) Oscillations of 1 MW for 10 s were successful at both frequencies for the first time in the world as a dual-frequency gyrotron by optimizing electron pitch factor using the triode electron gun; (ii) Low diffraction loss and cavity Ohmic loss enabling 1 MW for 100 s and 1.5 - 2 MW for several seconds were experimentally confirmed, and a 100 MJ oscillation was achieved (0.51 MW, 198 s, 110 GHz), so far; (iii) An oscillation at 82 GHz was also successful as an additional frequency showing the possibility of the use of fundamental harmonic waves; (iv) Launcher optics design toward dual-frequency operations showed little difference in the poloidal beam width for these frequencies; (v) Prototype tests of a wide-band twister polarizer at both low power (< 1 mW) and high power (~0.25 MW, 3 s) showed promising results.

C
EC (Electron Cyclotron) scheme is quite promising tool for heating and current drive (H&CD) and plasma control for present and future devices up to Demo and Commercial reactors. Development of gyrotron is a key to open this promising door. Multi-MW and multi-frequency technologies are major issues to challenge for robust and cost effective reactor heating system. In University of Tsukuba, gyrotrons of wide range of frequencies from 14 GHz to 300 GHz have been developed for this purpose in collaboration with JAEA, NIFS and TETD. Over-1 MW dual frequency gyrotron of new frequency range (14 –35 GHz), where the reduction of diffraction loss and cathode optimization are quite important, has been developed for EC/EBW H&CD for GAMMA 10/PDX, QUEST, Heliotron J and NSTX-U. Output power of 1.25 MW at 28 GHz and estimated oscillation power of 1.2 MW at 35.45 GHz from the same tube have been achieved with the cathode angle improvement. This is the first demonstration of the over 1 MW dual-frequency operations in lower frequency, which contributes to the technology of wide band multi-frequency/multi-MW tube for Demo EC/EBW H&CD. The output power of 600 kW for 2 s at 28 GHz is also demonstrated. It is applied to the QUEST and has resulted higher EC-driven current than ever. Further, in the joint program of NIFS and Tsukuba for LHD ECH gyrotrons, a new frequency of 154 GHz has been successfully developed with a TE_28,8 cavity, which delivered 1.16 MW for 1 s, 0.3 MW in CW (30 minutes), and the total power of 4.4 MW to LHD plasma with other three 77 GHz tubes, which extended the LHD plasma to high T_e region. All these gyrotron performances are new records in each frequency range.

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