Development Of High Power Gyrotrons and Mm-wave Launcher For ITER

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***Abstract*— Oscillation at tri-frequency 170 GHz, 137GHz and 104GHz with more than 1MW were demonstrated with a high-order mode ($TE_{31,11}$) gyrotron developed for ITER. The successful modification of the ITER equatorial launcher design to enhance off-axis current drive performance and to ensures that mm wave beams from both middle and bottom beam row pass through the same BSM opening that leads to the increase of neutron shielding potential is performed.**

I. INTRODUCTION

An electron cyclotron heating and current drive (EC H&CD) system operating at 170 GHz and the pulse length of ≤3600 sec is to be installed in ITER. It consists of twenty-four 170GHz gyrotrons [1-3], the power supply to operate the gyrotrons [4], twenty-four waveguide-type transmission lines to guide millimeter wave power to the vacuum vessel [5, 6] and one equatorial port and four upper port electron cyclotron (EC) launchers [7-9]. These sub-components are prepared by Japan, Europe, Russia, US and India to the ITER site and assembled there.

The main specification of ITER gyrotron is to oscillate 170 GHz millimeter (mm) wave with power of more than 1 MW, a total electrical efficiency of more than 50% and nearly continuous wave (CW). Moreover, the full power modulation with 5 kHz is required to inject mm-wave power synchronously into rotating magnetic islands of plasma generated by MHD instability. Japan Atomic Energy Agency (JAEA) has developed a triode high power gyrotrons. The $TE_{31,8}$ mode gyrotron successfully oscillated power of 1 MW, a total electric efficiency of 55% and pulse duration of 800 s [1, 10]. Steady-state operation (3600s) with power of 0.8 MW and the 5 kHz full-power modulation applying anode voltage switching were also demonstrated [11, 12]. In order to oscillate more than 1 MW, heat load at the cavity wall have to be mitigated and the $TE_{31,11}$ mode gyrotron (see Fig. 1 [13]) is currently under development.

The equatorial launcher (EL) is required to inject 170GHz, 20MW millimeter (mm) wave beam power into the plasma. The EL was designed with toroidal steering capability of the mm-wave beam from 20º to 40º. Accommodating the recent need for more driven current at the peripheral region of plasma ($0.4<\rho<0.6$), the possible modification of EL beam injection geometry, specially from toroidal to poloidal steering function has been implementing. The toroidal angle is fixed to be 25 º and 20 º for co- and counter-injection, respectively. It was reported that the estimated driven current at $0.4<\rho<0.6$ for 15 MA and 9 MA scenario were 250~400 kA and 480~720 kA, respectively [14]. This result revealed that the modification of EL to poloidal steering (see Fig. 2) could double the driven current potential at off axis region of $0.4<\rho<0.6$.

In this paper, the oscillation characteristic of the $TE_{31,11}$ mode gyrotron for ITER and the mm-wave design modification of the ITER equatorial EC launcher associated with changing the beam steering geometry from toroidal to poloidal.

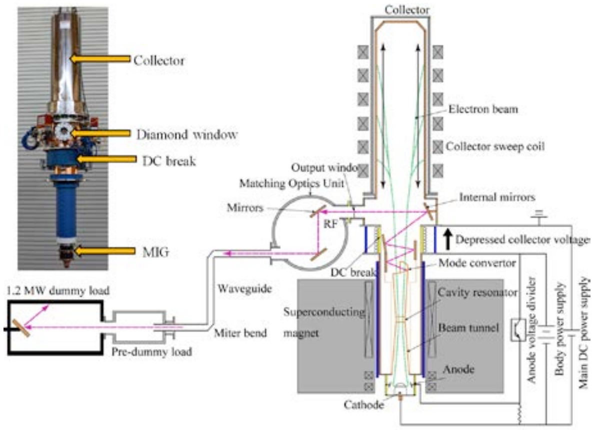

Fig 1 Photograph of $TE_{31,11}$ mode gyrotron (left) and schematic view of the high power experiment set-up for long pulse.

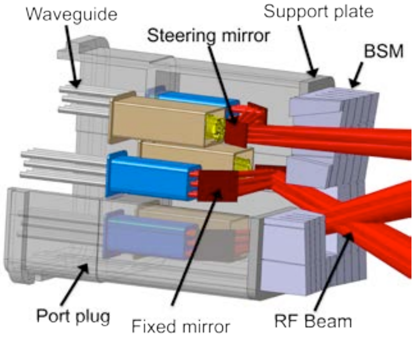

Fig. 2 Schematic view of the ITER EL design with poloidal steering function of injection beams.

II. RESULTS

Figure. 3 shows the coupling coefficients of co-rotating and counter-rotating modes, which are adjacent to $TE_{31,11}$ (main mode), as a function of injected electron-beam-radius. Coupling coefficient peaks of co-rotating $TE_{30,11}$ and $TE_{32,11}$ modes and of counter-rotating $TE_{28,12}$ and of $TE_{29,12}$ modes are close to that of co-rotating $TE_{31,11}$ mode. Based on this fundamental characteristic, oscillation experiment was carried out. In the initial phase of oscillation, mode competition with counter-rotating $TE_{29,12}$ mode was observed on the higher magnetic field side which caused arcing in the gyrotron. Arcing leads to the incremental internal pressure of the gyrotron and the oscillation must be stopped. In order to avoid the excitation of the counter-rotating mode, the start-up oscillation scenario controlling voltage between the anode and cathode, which corresponds to controlling the pitch factor, was introduced at the initial phase of operation. Then, a stable oscillation of $TE_{31,11}$ mode was successfully achieved from the beginning of pulse. Output power of 1.24 MW with a total electric efficiency of 43% was obtained under this condition. Oscillation of output power / total electrical efficiency at frequency of 170GHz, 137GHz and 104GHz are 1.24MW/45%, 1.01MW/42% and 1.03MW/41%, respectively were also successfully demonstrated.

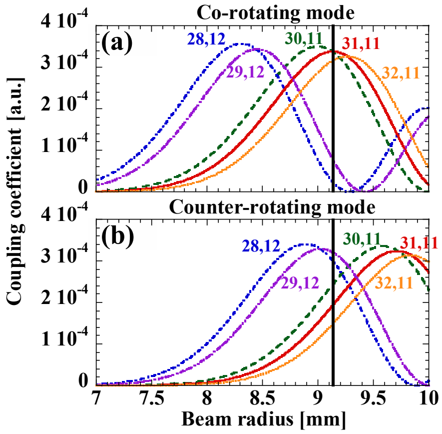

Fig 4 Coupling coefficient of (a) co-rotating and (b) counter-rotating mode adjacent to $TE_{31,11}$ mode.

Steady-state operation with 0.6 MW / 1000 sec and 1MW / 200 sec were also demonstrated. The beam voltage, the CPD voltage, and the anode-cathode voltage are V_{beam} = 72.5 kV, V_{CPD} = 25.5 kV, and V_{ak} = 37.5 kV, respectively. The beam current after 100 s was kept to I_{beam} ~ 30 A by pre-programing of the cathode heater boost. The oscillation started at magnetic field of 6.667 T and it was decreased by 70 G after the beam current was saturated. Since the counter-rotating $TE_{29,11}$ mode could be oscillated at this magnetic field, the start-up scenario mentioned described above was applied to prevent the mode excitation. As a result, the expected main mode was oscillated from the beginning of the pulse and the long pulse operation was successfully performed.

The mm-wave design rearrangement is performed by the optimization calculation of mm-wave beam propagation using the commercial optical design code, ZEMAX®, which uses both angular spectrum for near field and Fresnel diffraction for far field. The mm-wave propagation is calculated with a set of nine virtual apertures; eight waveguide outlets located in the same plane, two mirrors, two beam ducts between the mirrors, three apertures corresponding to BSM opening space and plasma target. In the calculation, it was assumed that a pure HE_{11} mode wave is propagated in the waveguides and radiated from their outlet. The steepest descent method was applied as optimization algorithm to obtain and optimize the mm-wave design parameters such as the vertical and horizontal installation angle of each waveguide, size and shape of the mirrors, size of beam ducts and BSM openings.

Figure 4(a) and 4(b) show the dependence of transmission efficiency on each aperture position for top beam row at poloidal beam angle of 10 º and -10 º, respectively. M1, M2, BD1~2, BM1~3 and Pl are the location of the fixed mirror, steering mirror, beam ducts between the mirrors, BSM openings and plasma target, respectively. The configuration of waveguide installation for each segment is 3 x 2 x 3 structure and Beam 1~3, Beam 4~5 and Beam 6~9 indicate the transmission efficiency of radiated beam from top, middle and bottom waveguides, respectively. The solid line shows the averaged transmission efficiency of eight beams. The optimized solution of the mm-wave design to satisfy a transmission efficiency of mm-wave propagation of 99 % from the waveguides to BSM opening was successfully obtained. The largest degradation of transmission efficiency occurs at the steering mirror and inside of BSM opening. It is expected that this can be reduced by enlargement of the aperture's size.

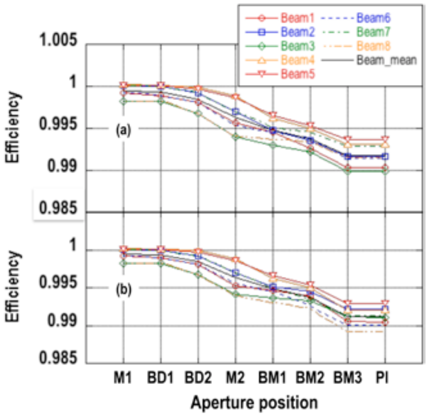

Fig. 3 Dependence of transmission efficiency on the aperture positions for top beam row, (a) + 10 º and (b) -10 º injection.

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