Demonstration of 1 MW quasi-CW operation of 170 GHz Gyrotron and Progress of EC Technology for ITER

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Abstract. In the last two years, significant progress has been obtained in the development of electron cyclotron heating and current drive (EC H&CD) technology for ITER. On the 170 GHz gyrotron, 1.02 MW power generation was attained for 800 s pulse duration with an efficiency of 55 % at the first time in the world, which satisfies the ITER criteria of 1 MW, 500 s, 50 %, respectively. The total output of microwave energy from the gyrotron is 190 GJ. A ~0.97 MW, quasi-CW power transmission was proved using the ITER relevant waveguide system. The basic design was completed for the equatorial launcher, and a mock-up of key components, such as a steering mirror, were fabricated. These give a clear prospect for the success and accomplishment of the EC H&CD system on the ITER.

1. Introduction

In the ITER, EC H&CD system to inject RF power of 20 MW is planned [1]. Eight 170 GHz, 1 MW gyrotrons and an equatorial launcher will be delivered from the Japan Domestic Agency (JADA). As a power source of EC H&CD system, the developments of 1 MW/170 GHz gyrotron are also underway at Russia [2] and EU [3]. The development of the 170 GHz gyrotron at JAEA has been continued in the ITER-EDA (Engineering Design Activities) and ITA (ITER Transition Activities). After the technological breakthroughs of a depressed collector [4], demonstration of 170 GHz/ 1 MW oscillation at CW-relevant mode $TE_{31,8}$ [5] and a diamond window [6-8] in EDA, the effort has been continued for the demonstration of CW operation at 1 MW with an efficiency of 50 %. In 2003, the performance of 0.5 MW, 100 s operation was obtained [9]. In 2005, a pre-program control of the heater power of the magnetron injection gun (MIG) was introduced (heater boost) for suppression of decrease of the electron beam current during a shot due to the cathode cooling. These improvements enabled stable long pulse operations, 1000 s at 0.2 MW and 500 s at 0.3 MW [10]. After that, the quality improvement of the initial electron beam, suppression of the stray radiation in the gyrotron, etc. were achieved in addition to an improvement of the cooling capability [11].

As for the equatorial launcher development, the previous design was reviewed and improved to increase the reliability and to reduce the cost by simplifying the configuration and introducing the quasi-optical RF beam transmission in the launcher [12,13].

In this paper, the progress of the 170 GHz gyrotron and the equatorial launcher are reported.

2. Achievement of reliable long pulse operation of 1 MW 170 GHz gyrotron

The 170 GHz gyrotron of JAEA features a the triode type electron gun, $TE_{31,8}$ oscillation mode in the cylindrical cavity, Gaussian beam output through an edge cooled diamond window, and a depressed collector. A picture of the gyrotron (~3 m in height and ~800kg in weight) is shown in Fig.1. The collector is grounded and a positive voltage is applied to the body section for the depressed collector operation. The generated power is converted to a Gaussian beam by a built-in mode converter composed of a quasi-optical launcher and four internal mirrors. The Gaussian beam is then transmitted through an output window made of a synthesized diamond disk and coupled into a corrugated waveguide

(ϕ=63.5 mm) with HE_{11} mode via a matching optics unit (MOU) through an output window. The brazing part and the outer edge of the diamond disk was covered with a ~0.5 mm copper coating to avoid the direct water contact.

Many modifications were implemented into the latest design of the 170 GHz gyrotron, which was then tested at high power and long pulse in the JAEA RF test stand [14,15]. A configuration of the test stand including gyrotron, MOU, transmission line and load is shown in Fig. 2. The transmission line consists of 7m of straight waveguide and 2 miter bends all of which are water cooled. The RF load consists of a pre-dummy load (Teflon tubes with cooling water for RF absorption) and a main dummy load (1.25MW, Calabazas Creek Research, Inc.). The coolant flow and temperature rise of all cooling circuits (in the gyrotron, MOU, transmission line and load) are measured to provide a complete power balance of the entire test stand.

The technologies of steady state oscillation (to control the beam current) and changing the pitch factor ($v_\perp/v_\parallel$, where

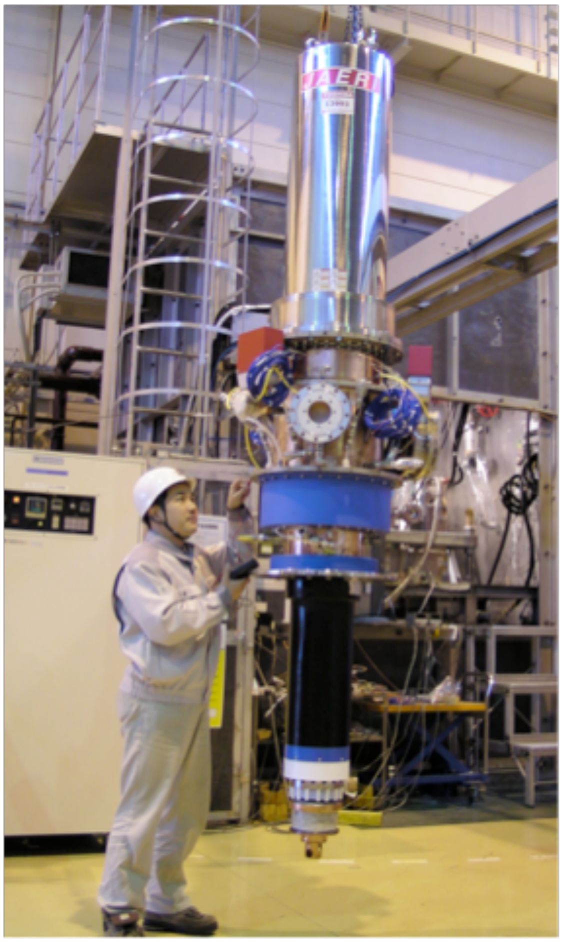

Fig.1. 1MW-170GHz Gyrotron for ITER.

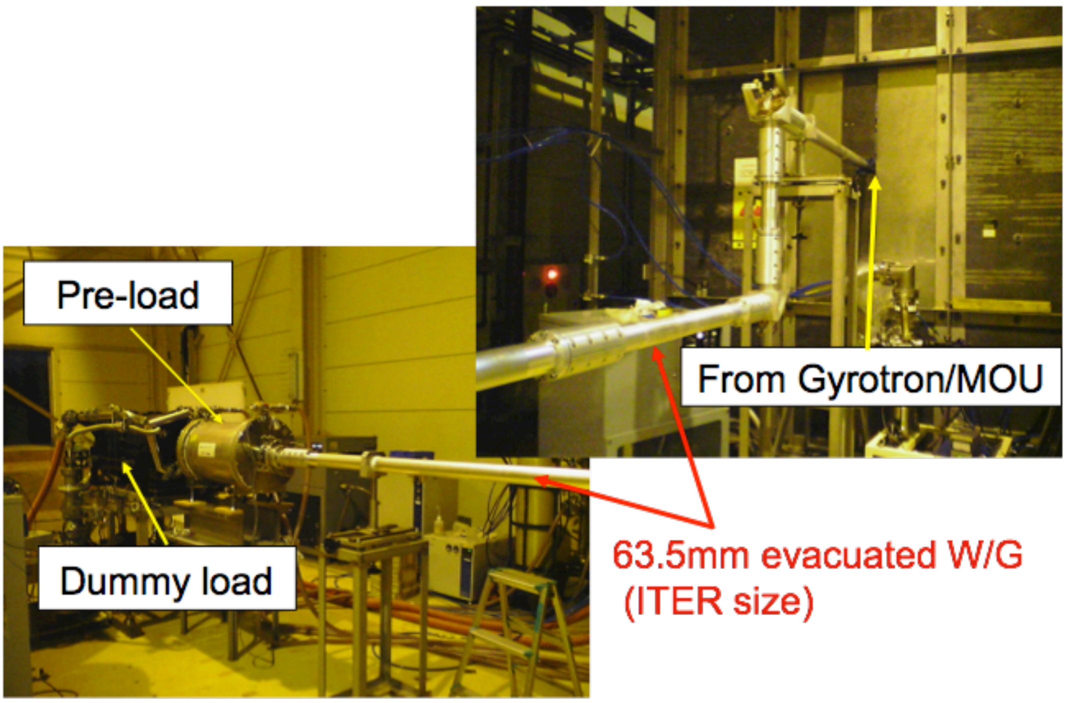

Fig.2 .Transmission line and dummy load for long pulse operation.

$v_\perp$ and $v_\parallel$ are velocity component perpendicular and parallel to the magnetic field, respectively) during the oscillation, which is a source of rf energy, were combined. The maximum efficiency was achieved by actively controlling the anode voltage of MIG and the cavity magnetic field B_c The gyrotron succeeded in stably-shifting the operating region to the hard-self-excitation region, which achieved higher efficiency compared with the normal operating region [16]. As a result, the oscillation efficiency of 55% was attained with 1 MW output power for 800 s pulse duration greatly exceeded the required performance for the ITER gyrotron. In Fig. 3, a typical time history of the long pulse operation is shown. Here, the beam voltage is 72.8 kV, the depressed collector voltage is V_{CPD}=24.5 kV and the beam current is 38 A, and an oscillation time of 1100 s. The oscillation initially starts in the soft excitation range at B_c=6.70 T and the voltage between cathode and anode terminals of V_{anode} =40kV. Then, the V_{anode} was raised to 42 kV several seconds after the oscillation was started. Next, B_c was decreased from 6.70 T to 6.625 T to increase the output power to ≥1.0 MW for >800 s achieving twice the expected standard burn time of ITER. This is the first demonstration of 170 GHz gyrotron that satisfies the requirement of the EC H&CD system of the ITER.

Furthermore, the quasi-steady state oscillation of 1 hour with 0.8 MW output power and 57% efficiency was achieved, which is necessary for the steady state operation phase planned for ITER. Up to now, (September 2008), total output RF energy exceeded 190 GJ without trouble, which is an evidence of the reliability, as shown in Fig. 4. These achievements are the great steps in the progress of the ITER project. The physics mechanism of the high efficiency oscillation in the hard-self-excitation region was clarified experimentally at the same time. This progress will advance the stabilization and expansion of gyrotron performance, and it will greatly contribute to the improvement in the plasma heating system in the ITER

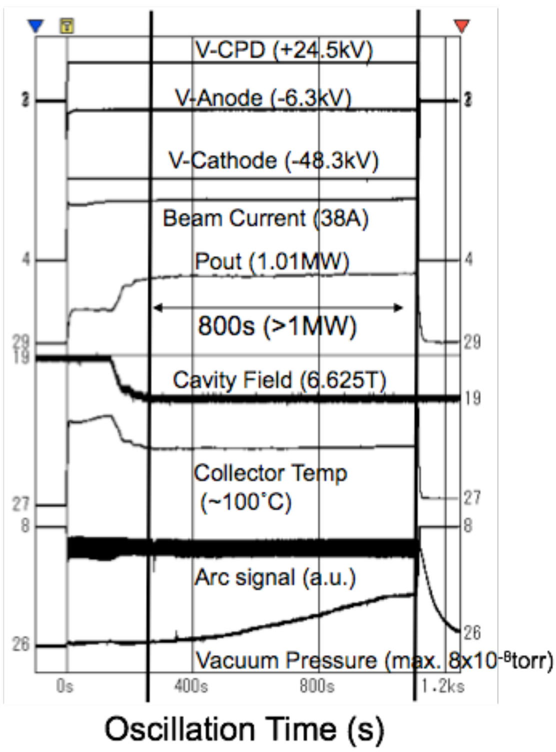

Fig.3. Typical time history for operation of 170 GHz gyrotron at 1.0 MW output. Efficiency is 55 %..

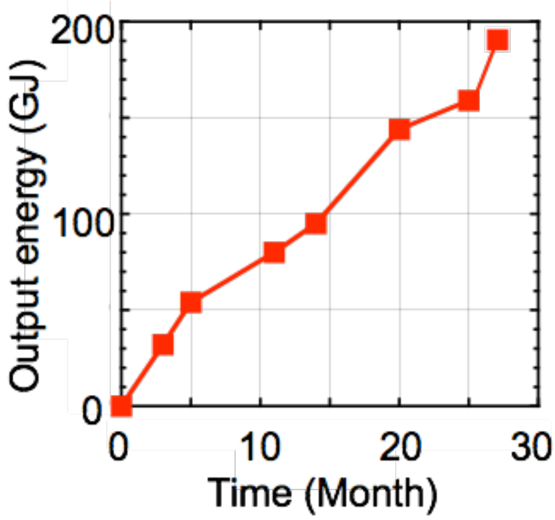

Fig.4. History of progress of output energy of 170GHz ITER gyrotron.

3. High Power transmission and development of equatorial launcher

The output power from the window couples with the corrugated waveguide through the matching optics unit (MOU), as with the ITER transmission line. The power was transmitted to the dummy load with the evacuated waveguide of 40 m with seven miter bends. In Fig. 5, the picture of high power transmission line with 40 m long. It was identified that the transmission efficiency from the gyrotron window to the dummy load was 92 %, where the loss in the MOU is 4 %.

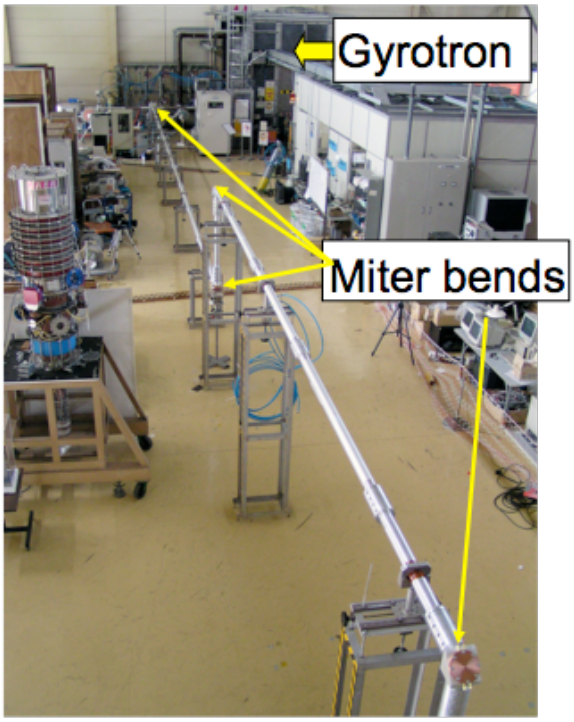

Fig. 5. High power transmission line with 40m.

As for the equatorial launcher, the basic design has been performed. In Fig.6, the conceptual view of the equatorial launcher is shown. Fig.6 (a) is the reference transmission line and Fig. 6 (b) is the Quasi-Optical (QO) arrangement of line for the ITER equatorial launcher that JAEA has recently proposed in order to reduce the heat load on the steering mirror. The three RF beam groups (24 total beam lines) are injected into the plasma independently. The injection angle is controlled by a steering mirror.

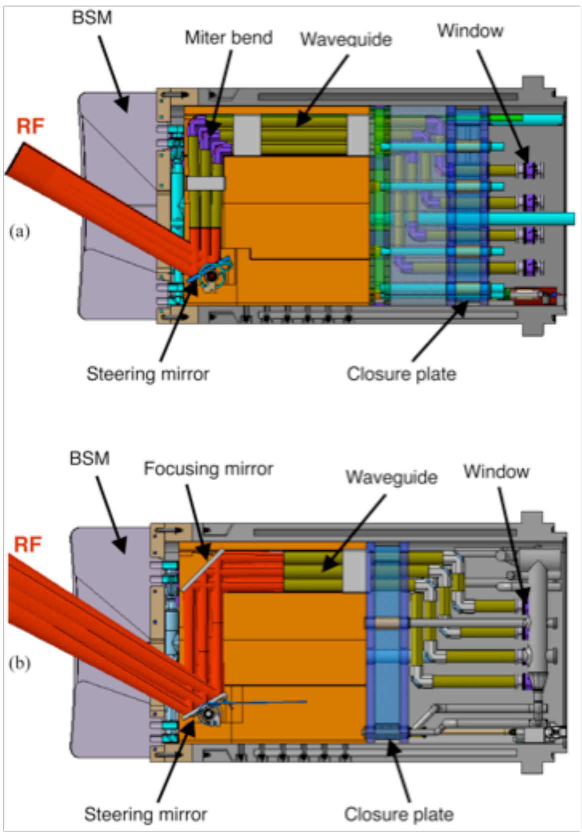

Fig. 6. Differences between (a) the reference transmission line and (b) the QO arrangement of line for the ITER equatorial launcher.

The miter bends and the adjacent waveguides are removed. Instead, a large fixed focusing mirror is introduced at the location of the bends and the beams are reflected toward the steering mirror. By expanding the beam size, the powers of adjacent beams are overlapped, consequently, the peak power density on the mirror was reduced by 1/3 compared with the conventional waveguide transmission. In addition, the configuration of the transmission line was significantly simplified by minimizing the vacuum area in the launcher. These contribute to the cost reduction and the reliability enhancement.

The technical issues for the application of QO transmission system areas follow;

(a) Transmission efficiency in the QO region,
(b) Minimization of beam duct,
(c) Heat load on the mirrors and structural effectiveness of mirrors,
(d) Nuclear shielding capability.

Analysis of mm-wave propagation using the code ZEMAX® of thermo-mechanics for a steering mirror [17], and of one of the front shield modules have been performed so as to evaluate the issues (a)~(c).

In order to minimize heat loads on the steering mirror and obtain as a high transmission efficiency in the QO region as much as possible, the optimization calculation was carried out. The field pattern on both the focusing and the steering (flat) mirror are shown in Fig. 7(a) and (b). The magnitude of the heat load is shown in dB. Maximum heat load on the fixed focusing and the steering mirror are 2.69 MW/m^2 and 1.27 MW/m^2, respectively. Electrical surface resistivity of the steering mirror and the focusing mirror are supposed to be 1.22x10^{-7} Ωm and 3.28x10^{-8} Ωm, respectively. These values are determined under the assumption of beryllium coating on the steering mirror and of the copper alloy for the focusing mirror. The ambient temperature for both values is 250 ºC. The heat load on the steering mirror was reduced by approximately 1/3, compared to the reference design.

The position of the closure plate is moved forward the plasma side and most of the waveguides components are removed from the vacuum side. This modification minimizes the chances of the water leakage into the vacuum since most of connecting points of the cooling water tubes can be removed from the vacuum side.

Based on the design, the launcher mock-up was fabricated to test the transmission properties of waves in the QO arrangement and to explore fabrication issues on the fabrication and their solution. Fig. 8 shows the photograph of the mock-up. One of the eight waveguide lines will transmit high power RF. The low and high power tests will be carried out soon.

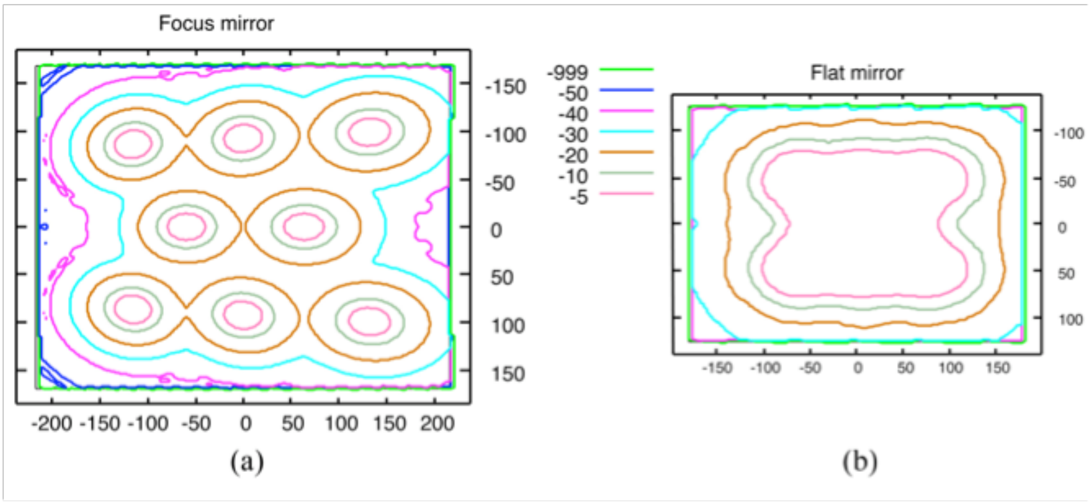

Fig. 7 The field pattern on (a) focusing and (b) steering (flat) mirror. The field strength is shown in dB. Units of transverse and vertical axes are shown in mm.

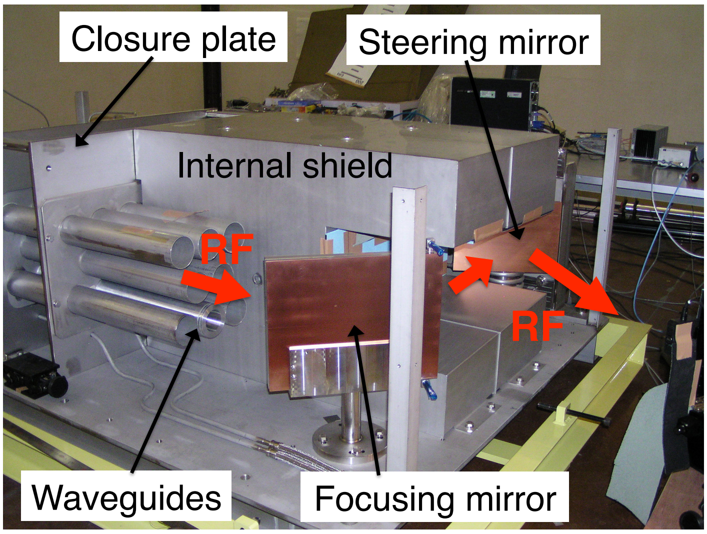

Fig.8. Photograph of the mock-up of QO equatorial launcher.

4. Conclusion

In Japan Atomic Energy Agency, the development of the 170 GHz gyrotron for the ITER have been carried out and achieved the 1 MW with the total efficiency of 55% for 800 s with the advanced operation scenario. In Fig. 9, the progress of the gyrotron development in JAEA is shown. The 1MW power source enables the R&D of launcher and transmission line, which provide important data for the design of the EC H&CD system. The effort will be continued for the procurement of reliable EC H&CD system on time for the ITER.

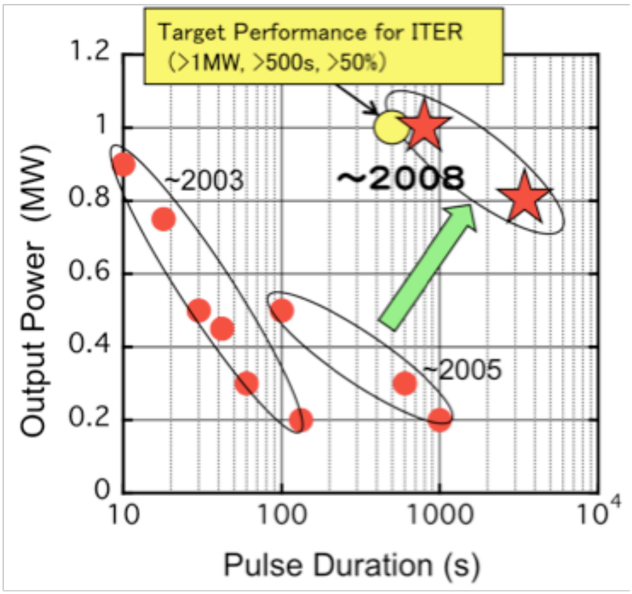

Fig.9. Progress of 170 GHz gyrotron performance of JAEA. Red stars indicate the data after IAEA 2006.

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