High Power Gyrotron Development for Fusion Application

Keishi Sakamoto, Ken Kajiwara, Atushi Kasugai, Yasuhisa Oda, Takayuki Kobayashi,
Koji Takahashi, Noriyuki Kobayashi, Shinichi Moriyama, Tsuneyuki Fujii
Japan Atomic Energy Agency (JAEA), 801-1 Mukoyama, Naka, Ibaraki, 311-0193 Japan

***Abstract*—Recent progresses in gyrotron development and related technologies are presented. The gyrotron demonstrated ITER relevant parameters at 170 GHz (1 MW, 800 s, 55 %), and proved a reliability with long operation period. Recently, one hour operation was obtained at 0.8 MW with the efficiency of 57 %, and total output energy of 190 GJ was recorded with 2 years operation. On the other hand, a power increase of 110 GHz gyrotron up to 1.5 MW was demonstrated on the electron cyclotron heating and current drive system of JT-60U.**

I. Introduction And Background

A 1MW 170GHz long pulse gyrotron is required for a power source of an electron cyclotron heating and current drive (EC H&CD) system on ITER (International Thermonuclear Experimental Reactor). The development of 1 MW CW-relevant gyrotron had been the objective of the Engineering Design Activities (EDA) of ITER since 1992. Recently, the stable 1MW 170 GHz oscillation was achieved at CW-relevant pulse duration (800 s) in JAEA. The efficiency is maintained at 55 % with the depressed collector in the hard self-excitation region [1]. The achieved parameters satisfy the basic criteria required for the gyrotron, i.e., 1 MW, 500 s and 50 %. Followed these, a power generation at higher mode is planned. And the possibilities of a power modulation and a rapid cavity field control, etc, are studied.

On the other hand, a 110 GHz electron cyclotron heating and current drive system is under working on the large tokamak JT-60 U in JAEA. The 110 GHz gyrotrons were developed by applying the technology of ITER 170 GHz gyrotron in 1999. Using one of the tubes, a power increase was carried out. In this paper, recent activities on these gyrotron developments in JAEA are described.

II. 170GHz gyrotron

The 170 GHz gyrotron has an oscillation mode of $TE_{31,8}$ in a cylindrical cavity, which is converted to the Gaussian beam by using an in-waveguide launcher and four mirrors in the tube. The power is outputted through a diamond window. The edge of the diamond disk is coated by copper to protect a brazing material from corrosion by cooling water. A magnetron injection gun (MIG) is triode type. The triode has an advantage that enables an active control of the beam parameters during the oscillation to access to the operation point of the maximum efficiency easily. The output power couples with the waveguide of 63.5mm in diameter via two-phase correlation mirrors in a matching optics unit (MOU), and 94.5 % of the output power was transmitted to a dummy load via 7 m evacuated transmission line. Here a power loss in the MOU is ~4.5 %.

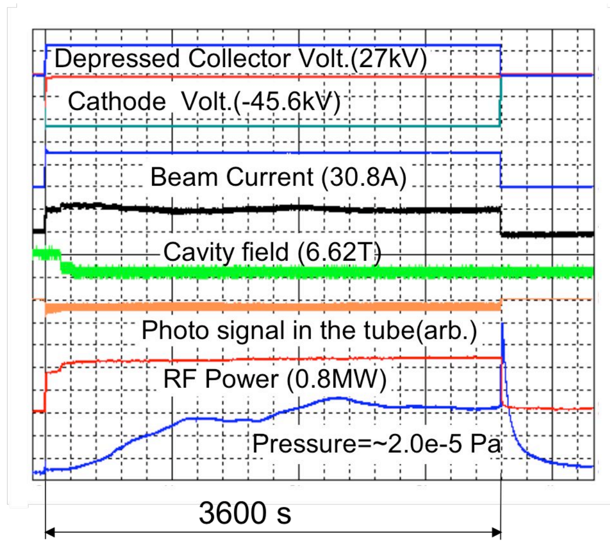

Fig.1: Time history of 1 hour operation at 0.8 MW.

In the high power experiment at CW mode, the power balance was measured calorimetrically. The output power from the window was 1020 kW, a power deposition to a collector was ~740 kW, and a stray radiation from relief windows was 24 kW. Total Ohmic-loss power to inner components of the gyrotron was 63 kW. The total measured power agrees well with the input power of the electron beam ~1850 kW [2]. The measured maximum efficiency was ~60 % at 0.6 MW output.

For the practical use, reliability of the gyrotron is an important issue. This gyrotron has been working since March of 2006. In June 2008, one hour operation was

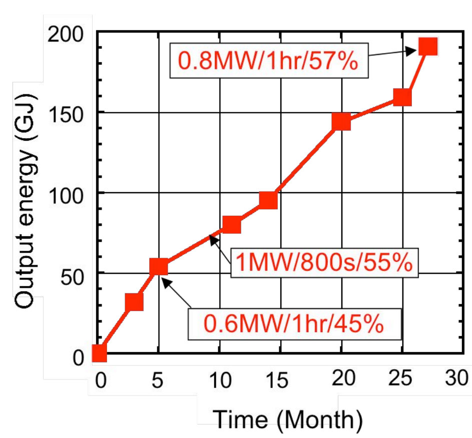

Fig.2: Accumulated output energy of 170 GHz gyrotron.

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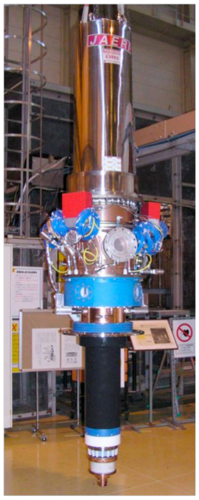

Fig.3: Picture of 170 GHz gyrotron of $TE_{31,12}$ mode oscillation.

demonstrated at 0.8 MW output as shown in Fig.1. The beam voltage is ~72.6 kV, depressed collector voltage is 27 kV and the beam current is ~30.8 A. The efficiency is kept at 57 % in the hard self-excitation region. No arcing was observed and the pressure is nearly constant at ~2.0×10^{-5} Pa. The pressure increase is always observed after the end of the long pulse operation. This phenomenon must be caused by the gas released from the collector and/or electron gun, where the negative high voltage is applied against the body section. By this potential, positive ions are accelerated and the ion deposition occurs during the operation, i.e., the tube acts as a large ion pump. After the shot, the pressure is increased by the gas release.

In the plasma heating experiment, repetitive operation is inevitable. As a preliminary experiment, the gyrotron was operated at 0.8 MW with a pulse duration of 400 s for every 30 min, which is similar repetitive rate of ITER operation. The base pressure returned to the original level before the next shot begins. Between the pulses, no conditioning shot was required. This gives a clear prospect for a nuclear fusion experiment.

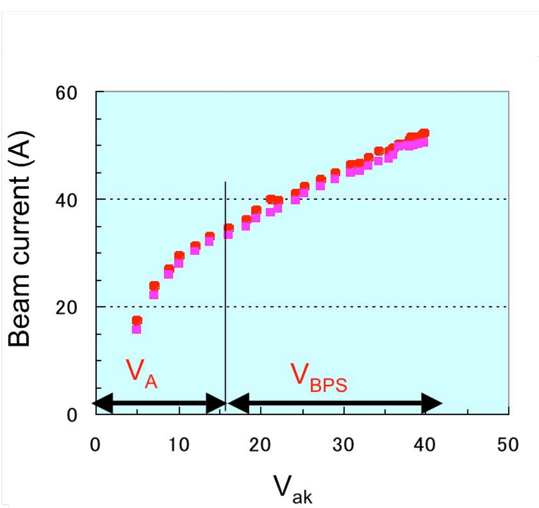

Fig.4: Anode voltage V_{ak} dependence of the beam current.

In Fig.2, time history of the output energy from the gyrotron window is shown. After the operation of more than 2 years, 190 GJ of the output energy was recorded, which is an evidence of the gyrotron reliability.

In the next stage, the R&D at higher mode oscillation is planned. For a short pulse gyrotron, the power output of ~1.6 MW was proved at 170 GHz. The oscillation mode was $TE_{31,12}$. Using the same cavity and the MIG, a long pulse gyrotron is fabricated as shown in Fig.3. The experiment will be started in fall of 2008. The appearance and the configuration is the same with the above mentioned $TE_{31,8}$ mode gyrotron. The collector and the diamond window are also the same. The gyrotron will contribute to the research of the higher mode oscillation, which will lead to the longer life-time of the cavity and/or the higher power oscillation.

III. 110GHz gyrotron

In JT-60U, the 110 GHz EC H&CD system is under operation. The power source is a 110 GHz 1 MW class-gyrotron. The oscillation mode is $TE_{22,6}$, which is capable of 1.5 MW operation. The original JT-60U EC H&CD system was built by 2001 composed of four gyrotrons. Up to now, 10 MJ (2.8 MW, 3.6 s) was injected into plasmas.

Using one gyrotron, the high power test has been carried out to increase the heating power. By increasing the beam current, high power oscillation up to 1.5 MW for 1 s has been attained in the dummy load operation. The beam voltage and beam current were 86 kV and 62.8A, respectively. The depressed collector voltage is 30 kV [3]. To increase the efficiency further, the internal mode converter system is improved. The experiment will be started soon.

IV. Power Modulation

In ITER, high frequency power modulation up to 5 kHz will be required for suppression of neo-classical tearing mode. For this purpose, the body power supply which is capable of 5 kHz modulation at CW mode will be adopted on ITER [4]. Here, the beam voltage is modulated by controlling the beam retarding voltage between the collector and the body V_m. When the modulation is applied, the collector heat load increases since the non work-out electron beam impact the collector in the no oscillation phase of the modulation. In JAEA gyrotron test stand, the modulation voltage of the body V_m reduces the anode-cathode voltage to (V_{ak}-V_m) since the anode-body voltage is kept constant. Since the beam current decreases as V_{ak} does as shown in Fig.4, the heat load is mitigated by the current decrease. Furthermore, if the anode modulation is added with synchronized operation, the beam current could be reduced to zero. Consequently, the collector

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Fig.5: Super conducting magnet of 7T with liquid He free. Rapid sweeping of the central magnetic field is available.

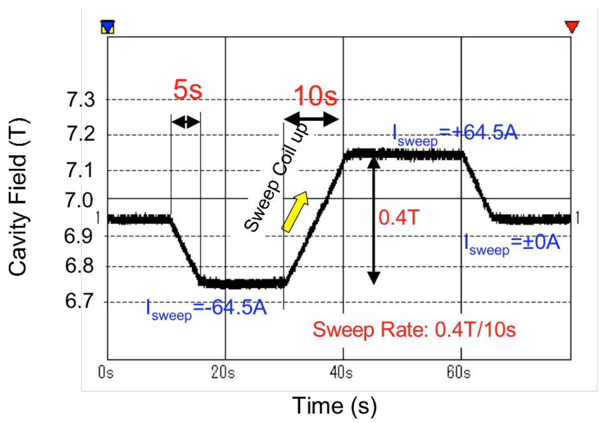

Fig.6: Experimental result of fast sweeping of central field.

heat load is reduced significantly. If this operation is available, the beam current could be raised to increase the peak oscillation power in the identical gyrotron.

V. Rapid control of cavity field

For the rapid control of cavity field, a He-free super-conducting magnet (SCM) with an additional super conducting sweeping coil was developed. The objective of the SCM is to study the rapid frequency control, adjustment of oscillation condition, etc. Inside of a main solenoid coil, a rapid sweeping coil is located. The rapid sweeping coil is composed of an inner coil and an outer coil that act as a magnetic shield to minimize the induced current on the main coil. Fig.5 is a picture of the liquid He free magnet. A diameter of a room temperature bore is 240 mm, and the 7 T at the center. Using commercially available DC power supply, the magnetic field sweeping was demonstrated with a speed of 0.4 T/10 sec at 7T as shown in Fig.6. By the combination with the beam voltage and anode voltage control, rapid frequency control system of the gyrotron will be available.

VI. Conclusion

The basic parameters of 170 GHz gyrotron for ITER application have been demonstrated. The reliability test is underway by the demonstration of the long operation periods. On 110 GHz gyrotron, 1.5 MW/1 s was demonstrated for the application of EC H&CD experiment on JT-60U. The gyrotron technology (power modulation and rapid field control) is in progress, which will make the EC H&CD more attractive for fusion reactor.

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