# 110/170 GHz High Power Gyrotrons for KSTAR ECH/CD System

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## Abstract

In NFRI, 110 GHz gyrotron is used for pre-ionization and electron cyclotron heating on KSTAR. Recently, a 170 GHz, 1 MW-class gyrotron is installed at NFRI and under conditioning in order to execute joint experiments of electron cyclotron heating and current drive using ITER prototype developed by JAEA on KSTAR. The major specifications and power output characteristics of 110/170 GHz gyrotrons will be presented. Also, their applications to the KSTAR plasma heating and current drive experiments will be briefly introduced.

**Keywords :** Gyrotron ECH KSTAR

## 1. Introduction

Fusion devices require an auxiliary source of energy to initiate the plasma and generate the conditions required for burning the fusion fuel [1]. Electron cyclotron (EC) wave is an effective method for electron cyclotron heating and current drive (ECH/CD) and the control of plasma profile in fusion experiment reactors. Many studies for ECH pre-ionization and assisted plasma startup were performed in Korea Superconducting Tokamak Advanced Reactor (KSTAR) and other devices [2-6]. KSTAR tokamak demonstrated the ECH assisted startup using 84/110 GHz second harmonic EC wave [6, 7]. In 2008 during the first KSTAR campaign, the ECH system was equipped with 84 GHz CPI gyrotron. The available EC power at the output window of the gyrotron was 500 kW and 350 kW EC beam power was injected into the plasma. For the second campaign in 2009, the frequency of EC wave changed from 84 GHz into 110 GHz because of the vacuum leak at the collector of the 84 GHz CPI gyrotron. For 2009 campaign we loaned a 1MW, 110 GHz gyrotron from General Atomics (GA). 110 GHz gyrotron was operated with an output power of 250 kW for 3 s pulse length at the terminal dummy load. During the third plasma campaign in 2010, KSTAR was operated with a toroidal field of 2 T for second harmonic 110 GHz EC heating [8]. ECH power of 350 kW was applied both before and after the onset of Ohmic discharge. Recently, in order to execute joint experiments of ECH/CD using 170 GHz JAEA gyrotron on KSTAR with JAEA institute we loaned a 170 GHz ITER prototype gyrotron from JAEA [9]. All of the transmission line components and power supply systems for 170 GHz gyrotron are installed at NFRI. During 2011 KSTAR campaign we will execute joint tests of 170 GHz gyrotron on KSTAR. In this paper the application of 110/170 GHz gyrotrons to the KSTAR EC system are described. In sections 2 and 3, experimental results of 110/170 GHz gyrotrons are presented, respectively. Conclusions are given in section 4.

## 2. 110 GHz Gyrotron

The 110 GHz GYCOM gyrotron was specified with an output power of 800 kW for 2 s pulse and 500 kW for 5 s pulse with the efficiency of 38%. The 110 GHz gyrotron was used to generate microwave power of 400 kW with pulse length of 2 s for ECH heating during the third and fourth KSTAR campaign in 2010 and 2011. The 110 GHz gyrotron features a diode type electron gun, TE$_{19,5}$ oscillation mode in the cylindrical cavity, Gaussian beam output through an edge cooled boron nitride window, and a collector. The 110 GHz gyrotron, shown in Fig. 1, generated the RF power of 430 kW with pulse length of 0.3 s at the dummy load. Figure 1(b) shows the measured output power at the dummy load as a function of cathode voltage and beam current. Power measurement based on calorimetric method was carried out using SUS tank dummy load near the tokamak. On the ECH pulse, water cooling temperature variation was measured using RTD sensors installed at coolant inlet and outlet of the dummy load. The Gaussian beam power is transmitted through output window of the gyrotron and coupled into a corrugated waveguide of 31.75 mm inner diameter with HE$_{11}$ mode via a matching optics unit (MOU). The EC wave generated from the gyrotron is transmitted to the launcher through about 42 meters of evacuated corrugated circular waveguide of 31.75-mm inner diameter. For operation of high power and long pulse, all thermo-loaded components of gyrotron such as cavity, anode, mirror, collector, and output window are water-cooled. The MOU mirror can be adjusted in two perpendicular axes by two knobs connected with the each mirror for beam alignment and has generally coupling efficiency of 80~85%. The biggest power loss component is the MOU for wave coupling between gyrotron and corrugated circular waveguide. In order to increase the delivery power of EC wave, it is necessary to minimize the power loss by misalignment.. After mirror adjustment infrared image and burn pattern was measured to confirm alignment state at the output of the waveguide in the MOU [8]. After mirror alignment of MOU, the power loss by coupling of the MOU is decreased by about 7%.Figure 2 shows configuration of KSTAR 110 GHz ECH transmission line system.

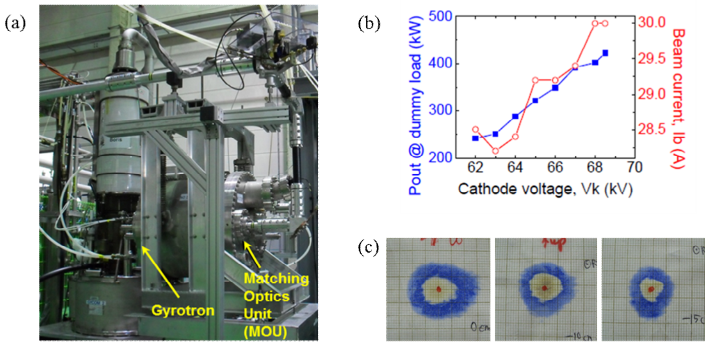


Figure 1. (a) Photograph of a GYCOM 110 GHz gyrotron, (b) measured output power of the gyrotron at the dummy load, and (c) beam pattern at the output of MOU measured using burn paper.

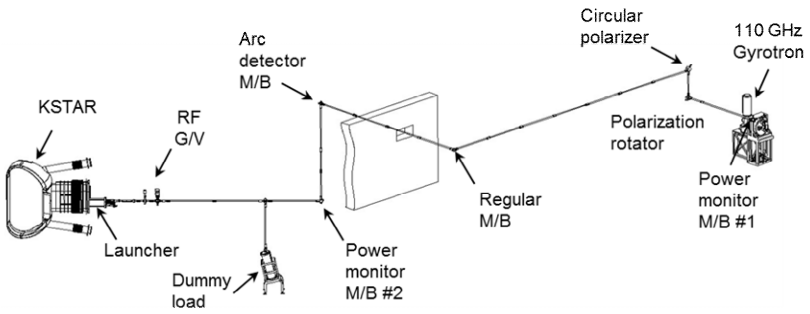
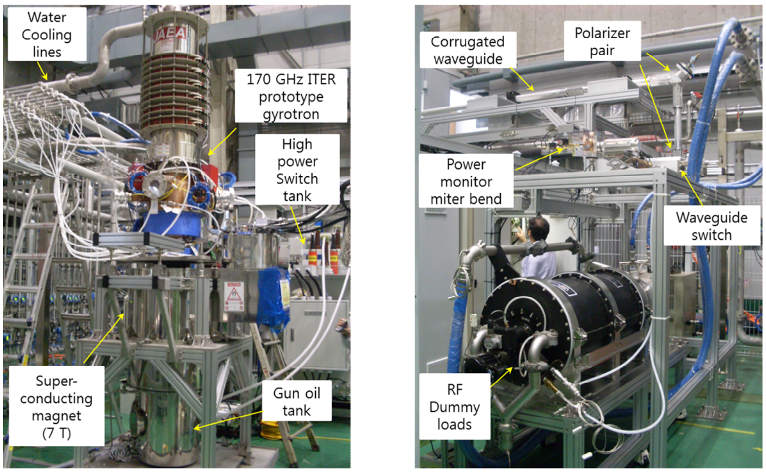


Figure 2. Layout of KSTAR 110 GHz ECH transmission line.

## 3. 170 GHz Gyrotron

The 170 GHz ITER prototype gyrotron developed in JAEA has a triode-type electron gun with a depressed collector and a diamond window. The magnetron injection gun (MIG) is the same configuration with the $TE_{31,8}$ gyrotron [10]. The prototype of 170 GHz JAEA gyrotron was designed for CW operation. The cavity oscillation mode for the 170 GHz ITER prototype gyrotron is $TE_{31,12}$ mode to operate at high power of 1.5 MW [9]. By increasing the oscillation mode, the cylindrical resonator diameter increases and the heat load on the resonator wall significantly decreases. The collector is grounded and a positive voltage is applied to the body for the depressed collector operation. The MIG makes a hollow beam of gyrating electrons with the energy of ~70 keV, which is injected into a cylindrical cavity. 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 of 63.5 mm inner diameter with $HE_{11}$ mode via MOU. In 2010 a preliminary operation was executed in JAEA. In this experiment the gyrotron produced the output power of 800 kW over 100 s pulse at the window.

KSTAR 170 GHz ECH/CD system includes the 170 GHz gyrotron, high voltage power supplies, transmission line components, dummy loads, polarizers, waveguide switches, launcher, and control system. In 2011, the 170 GHz gyrotron, MOU, and 1.25 MW main dummy load were transferred from JAEA to NFRI. The 170 GHz gyrotron was installed in a cryogen free superconducting magnet of 7 T. The gyrotron, high voltage power supplies, dummy loads and transmission line system including power monitor miter bends, waveguide switch, and miter bend polarizers are shown in Fig. 3. The total transmission line consists of 60 meters of straight waveguide and 8 miter bends. All of the transmission line components designed and fabricated by GA are installed at NFRI and its evacuation was tested successfully without no leak. The miter bends and switch are water cooled, while the 63.5 mm corrugated waveguide is air cooled. The RF dummy loads consist of a pre-dummy load and CCR, Inc. 1.25 MW main dummy load. A pre-dummy load consists of many turns of Teflon tube with cooling water around the Al cylindrical tank for RF absorption. High power supply consists of a cathode power supply (CPS), an anode power supply and a body power supply. The CPS has a capability of -66 kV with 60 A to the cathode with respect to the collector. There is a voltage divider between the cathode and anode, which gives an adjustable anode voltage. DC voltage generation is based on the pulse step modulator principle. The high voltage switching system composed of MOSFET fast semiconductor switches. The high-speed MOSFET switches can remove the high-voltage within 3 μs and the total dissipation energy of 0.5 J is observed by the shorted circuit test. The beam current can be controlled by the anode voltage which offers 2 kHz modulation at any voltage between 0 to 50 kV.



(a) (b)

Figure 3. (a) Photograph of 1 MW-170 GHz gyrotron installed in 7-T superconducting magnet and (b) transmission line system with dummy loads.

For 2011 campaign, especially for ECH/CD on KSTAR the 170 GHz JAEA gyrotron is under commissioning at NFRI. 170 GHz ECCD will be utilized for the control of Neo-classical Tearing Mode, saw-teeth mode, and MHD instabilities as well as EC-assisted plasma startup.

## 4. Conclusion

The 110 GHz/ 400 kW GYCOM gyrotron was successfully commissioned at the KSTAR from the second campaign. The 110 GHz ECH system is essential for the plasma startup using the second harmonic EC resonance at the toroidal magnetic field of 2 T. The 170 GHz ITER prototype gyrotron was loaned from JAEA based on collaboration agreement on the joint experiments with 170 GHz gyrotron between NFRI and JAEA. For 2011 campaign a170 GHz, 1MW-class gyrotron is under commissioning at NFRI.

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