EPJ Web of Conferences 32, 02019 (2012)
DOI: 10.1051/epjconf/20123202019

Commissioning of 170 GHz, 1 MW EC H&CD in KSTAR

J. H. Jeong[1], K. Sakamoto[3], M. Joung[1], S. I. Park[1], H. J. Kim[1], W. S. Han[1], J. S. Kim[1], Y. S. Bae[1], H. L. Yang[1], J. G. Kwak[1], M. Kwon[1], W. Namkung[2], H. Park[2], M.H. Cho[2], K. Kajiwara[3], Y. Oda[3], J. Hosea[4], R. Ellis[4], J. Doane[5], and R. Olstad[5]

[1]National Fusion Research Institute, Daejeon, Korea
[2]Department of Physics, POSTECH, Pohang, Korea
[3]Japan Atomic Energy Agency, Naka, Japan
[4]Princeton Plasma Physics Laboratory, Princeton, USA
[5]General Atomics, San Diego, USA

Abstract. The newly installed electron cyclotron heating and current drive (EC H&CD) system with a frequency of 170 GHz was successfully commissioned and used for the second-harmonic ECH-assisted startup in 2011 operational campaign of the KSTAR. As a RF power source, ITER pre-prototype of 170 GHz, 1 MW continuous-wave gyrotron, is loaned from the Japan Atomic Energy Agency (JAEA). During the KSTAR 2011 plamma campaign, maxumum pulse length of 10 sec at 0.6 MW EC beam was reliably injected into the plasma and the 170 GHz second harmonic ECH-assisted start-up was successful leading to reduce the flux consumption at toroidal magnetic field of 3 T. As a result, the flux consumption until the plasma current flat-top was reduced from 4.13 Wb for pure Ohmic to 3.62 Wb (12 % reduction) for the perpendicular injection. When the EC beam is launched with toroidal angle of 20 deg in co-CD direction, more reduced magnetic flux consumption was obtained with 3.14 Wb (24 % reduction) compared with pure OH plasmas. In recent, the gyrotron has been successfully commissioned with the output power of 1 MW and the pulse duration of 20 sec in KSTAR. This paper presents successful commissioning of 170 GHz EC H&CD system in KSTAR as well as the heating and startup experimental results.

1 Introduction

The new electron cyclotron heating and current drive (EC H&CD) system operating at a frequency of 170 GHz is successfully commissioned and used for the second-harmonic ECH-assisted startup in 2011 operational campaign of the Korea Superconducting Tokamak Advanced Research (KSTAR). As a RF power source, ITER pre-prototype of 170 GHz, 1 MW continuous-wave gyrotron which is featured to have a triode-type magnetron injection gun (MIG), a cylindrical resonator working at 170 GHz with $TE_{31,12}$ mode, a water-cooled diamond window and a depressed collector is loaned from JAEA [1]. The Gaussian beam output from the gyrotron passes through an edge-cooled diamond window and is coupled to an HE11 corrugated waveguide via two phase correcting mirrors in a matching optics unit (MOU). The power coupled to the HE11 corrugated waveguide is delivered to the launcher by the transmission line which consists of 70 meters of 63.5 mm corrugated waveguide, 8 miterbends, waveguide switch, DC break, bellows and gatevalve. For the first 1 MW EC H&CD

system, 1-beam based 1 MW equatorial launcher is installed in the KSTAR Bay E-m [2]. The launcher has been designed and fabricated in collaboration with both Princeton Plasma Physics Laboratory (PPPL) and Pohang University of Science and Technology (POSTECH). During the KSTAR 2011 plasma campaign, maximum pulse length of 10 sec at 0.6 MW EC beam was injected into the plasma for the assisted start-up in order to reduce the flux consumption with the second harmonic condition at toroidal magnetic field of 3 T and as a auxiliary heating for the long pulse discharge operation of KSTAR with the third harmonic condition at toroidal magnetic field of 2 T. After the 2011 KSTAR plasma campaign, the gyrotron commissioning is continued to achieve 1 MW output from the gyrotron. As a result, performance of the gyrotron is improved with 1 MW for 20 sec in recent. This paper will focus on the developments and achievements of 1 MW/20 sec pulse operation. In section 2, 1 MW/170 GHz gyrotron will be introduced and the progress of the gyrotron performance will be described. In section 3, ECH-assisted start-up using the 170 GHz ECH/CD system in 2011 KSTAR plasma campaign is discussed.

2 170 GHz, 1MW ECH system

Figure 1 shows the ITER pre-prototype of 170 GHz, 1 MW gyrotron and the configuration of the power supply system. The electron gun is a triode-type magnetron injection gun (MIG), which has a cathode, an anode and body terminals. The collector is grounded and a positive voltage is applied to the body terminal for the depressed collector operation. The resonator is a cylindrical cavity whose generation mode is $TE_{31,12}$ mode at 170 GHz where the interaction between the electron beam and the millimeter wave occurs. The RF beam radiated from the converter is transformed with four mirrors with TEM00 mode and is transmitted through an edge-cooled diamond window. The spent electron beam is absorbed by a collector. The electron energy is significantly reduced by the depressed collector configuration. The beam landing area is elongated in the axial direction using sweeping coils with 2 Hz and the shape of the coil current for sweeping is sawtooth-like to avoid a long stay at turning points [1]. Installation and initial commissioning on KSTAR is successfully carried out in collaboration with JAEA and the EC beam power of 0.65 MW at the window has been achieved before the KSTAR 2011 plasma campaign by the gyrotron commissioning. The norminal operation beam voltage (V_{BEAM}= V_{DEP}-$V_{CATHODE}$) of the gyrotron was 72 KV with the depressed collector voltage (=V_{DEP}) at 20 kV and the beam current was ~ 50 A. The voltage between cathode and anode terminal (V_{ak}=$V_{CATHODE}$-V_{ANODE}) is optimized at 42 kV. At these parameters, the total electric power efficiency was ~ 30 % for the gyrotron output and the maximum temperature at the collector is increased to 190°C during the 5 sec pulse. The power was measured using a water cooled dummy load system equipped with a calorimeter.

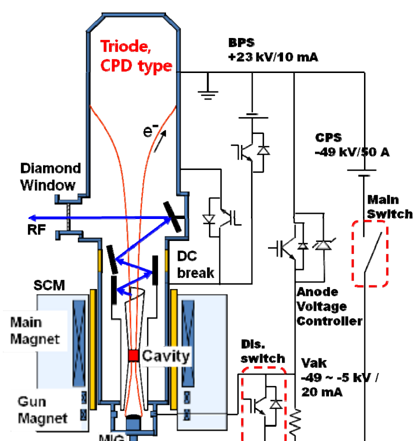

Fig. 1. 170 GHz, 1 MW gyrotron and the configuration of the power supply system

2.1 1 MW output achievement from the Gyrotron

After the 2011 KSTAR plasma campaign, gyrotron commissioning is continued to achieve 1 MW RF power from the gyrotron by the magnet position adjustment and RF beam alignment. The position of the magnet is scanned with x- and y- direction with the resolution of 0.3 mm and the final position is moved to x- direction about 0.6 mm from the origin. After the magnet position adjustment the ellipsoidal phase correction mirrors in the MOU are carefully adjusted again to align the center of the RF beam from the MOU into the center of the waveguide input with the parallel beam. In order to confirm the parallel beam injection to the waveguide, the related intensity distribution of the RF beam was measured according to the distance along the wave-propagation direction using the IR (Infrared) camera. After the magnet position adjustment and RF beam alignment, gyrotron operation parameters are scanned again to find the optimized operation-conditions. Because one of the merits of the triode MIG is that the pitch factor α (the perpendicular-to-parallel velocity ratio) of the electron beam can be controlled independently with other parameters by changing the anode voltage Vak. Consequently, electron beam parameters such as the electron cyclotron angular frequency in the resonator ω_{ce} and α can be optimized with the active control of Bc (cavity field) and Vak during the oscillation. In figure. 2, a) shows the test result of the cavity-field dependence of the gyrotron output and b) shows the depressed collector voltage dependence of the gyrotron output and its total efficiency. Here, the beam voltage is fixed at 72 kV and the beam current is ~50 A. By the active control of Vak and Bc, the beam parameters (ω_{ce}, α) are optimized for each datum in the hard excitation region. Consequently, high efficiency is obtained, e.g. ~40% at V_{DEP} = 23 kV, Vak=43 kV and the cavity field of 6.641 (magnet current of 109.3 A). The depressed voltage is increased to 24 kV for the higher efficiency, but in this condition the non-negligible external arc occurred around the insulation jacket and magnet. Therefore, the depressed voltage is maintained with 23 kV in order to avoid the significant external arc.

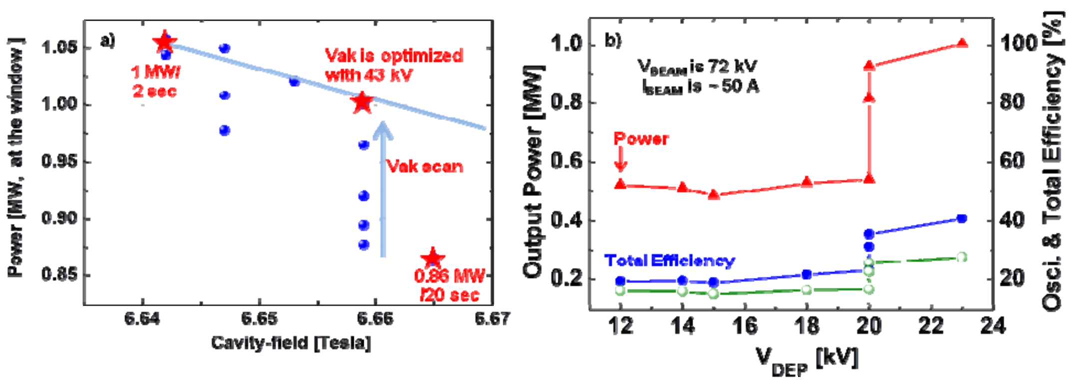

Fig. 2. The beam parameters are optimized by the control of Vak and Bc. a) shows the cavity-field dependence of the gyrotron output and b) shows the depressed collector voltage dependence of the gyrotron putput and efficiency.

2.2 Long pulse test of the 1 MW, 170 GHz ECH&CD system

During the pulse extension at the specified 1 MW output power, the temperature rise due to the RF loss in the transmission line was monitored by the K-type thermocouple sensors. Especially, the temperature at the inner side of the MOU output flange increased to 95°C for 10 s pulse. So, the cooling jacket brazed with water cooling copper tubes for water cooling is used surround the MOU flange. And also, it is confirmed that the rise in temperature was lower than 10°C with no damage in the waveguide components.

Figure 3 shows the waveform of a 20 sec operation at 1 MW. This figure shows the applied voltages, beam current (~50 A) and RF signal using the diode detector from the gyrotron. The calorimetric power from the gyrotron window was 1.11 MW with the efficiency of 40 %. In this operation, the collector temperature increased to 140°C temporary and then saturated during the pulse. During the 20 sec pulse, the power level was gradually decreased due to the cathode emission cooling. As a result, the average power was decreased about 0.8 MW at the dummy load. So, the cathode-heater control has been demonstrated for the beam current compensation of the cathode temperature decrease due to electron emmission. As a result, decrease of the beam current can be suppressed just a little. However, the test result was not effective during the 20 sec and the oputput power dose not change because the cathode heater has a large heat capacity and the temperature response on the electron emmitter is delayed a few minutes [3].

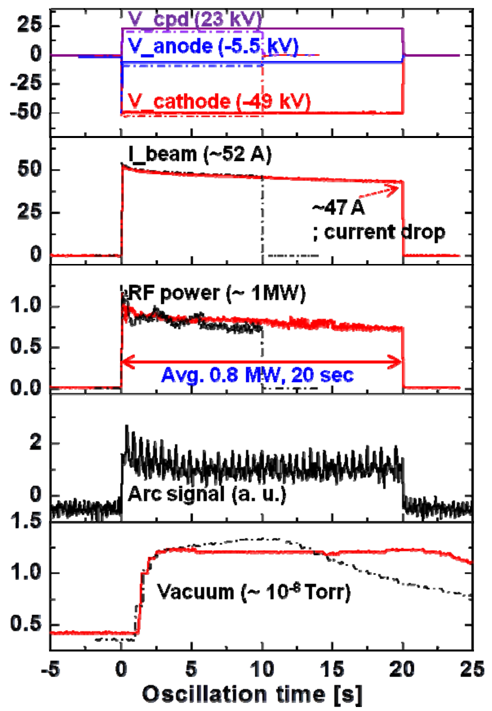

Fig. 3. Time evolution of 20 sec operation of the 170 GHz gyrotron at 1.0 MW. The efficiency is 40 % with depressed collector.

3. Experimental results in 2012 KSTAR plasma campaign

For the first experiment of 170 GHz ECH assisted start-up in KSTAR, the EC beam power of 0.4 MW was launched from the low field side by a steering mirror on the pivot located at 30 cm below the centre of the equatorial plane. In Fig. 4, second harmonic EC-assisted plasma startup is compared to the KSTAR pure ohmic startup which is defined as discharges without ECH during the startup. As a reference shot, initial Ohmic breakdown is occurred by the inductive loop voltage at t=0 ms which is generated by the decay of the flat current levels of the Ohmic CS (Central solenoid) coils and PF (Poloidal field) coils. The magnet power supplies use a blip resistor insertion system which switches the current flow through the resistor and makes the flux change by natural current decay with an LR^{-1} time scale. After the 100 msec from the initial breakdown the feedback phase is started. All coils are feedback controlled to maintain the pre-programmed plasma current and plasma position at R=1.8 m. The plasma current ramp-up rate is set to 0.24 MAs^{-1} until the flattop phase of 0.6 MA.

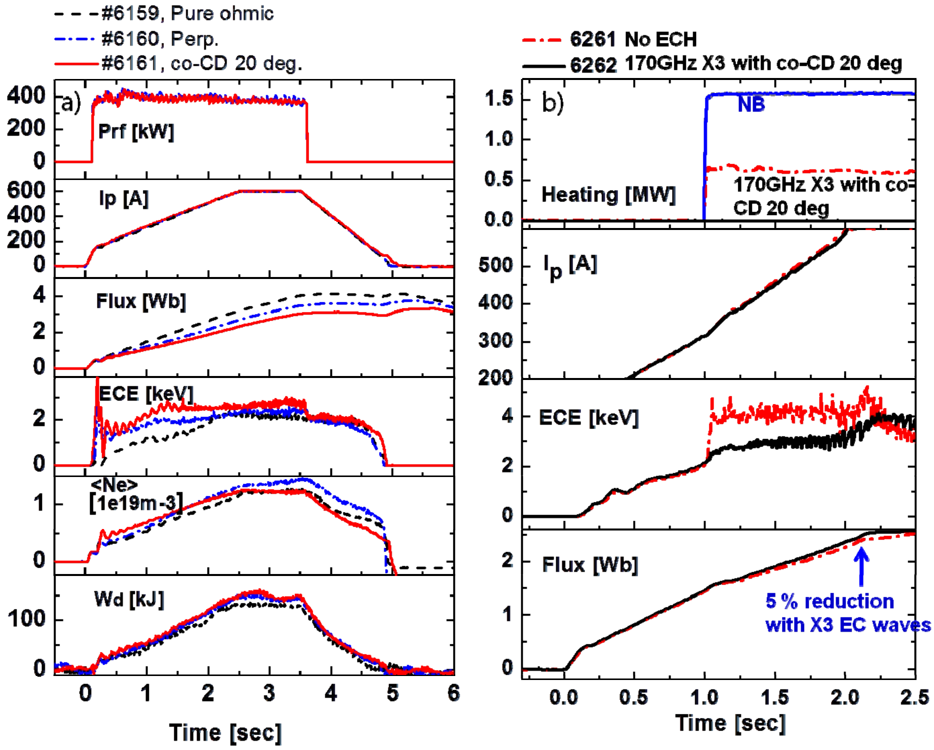

Fig. 4. ECH injection angle dependence of the 0.4 MW ECH X-mode for the second-harmonic (a) and third-harmonic (b) case.

The waveforms of ECH-assisted start-up using the second harmonic EC beam is shown in Fig. 4 a). For the pure ohmic start-up as a reference shot, the loop voltage at the breakdown is ~3.7 V and the flux consumption up to the start of the current flat-top is $\Delta\Phi=\int V_l dt$~4.13 Wb and its stored energy is increased up to W_d~132 kJ. For the ECH assisted start-up with the X2 perpendicular injection, the flux consumption at the start of the current flat-top is reduced $\Delta\Phi$~3.62 Wb and the stored energy is increased to W_d~148 kJ. When the EC beam is launched with toroidal angle of 20 deg in a co-CD direction but it has same RF power of 0.4 MW, the more reduction of the magnetic flux consumption is obtained with $\Delta\Phi$~3.14 Wb and the stored energy of the plasma is increased to 156 kJ at the current flat-top current phase. Figure 4 b) shows the third harmonic heating experiment using the 170 GHz EC-wave which is attempted in L-mode and H-mode discharge at toroidal magnetic field of 2 T. The most effective EC launch was also 20 degree to a resonance position in the co-CD direction to the toroidal magnetic field. It could also provided additional heating during the current ramp-up phase so that T_e increased from 2 keV to 4 keV and the magnetic flux consumption is reduced about 5 % by the X3 EC-waves.

4. Conclusions

The new electron cyclotron heating and current drive (EC H&CD) system operating at a frequency of 170 GHz is successfully commissioned and used for the second-harmonic ECH-assisted startup in 2011 operational campaign of the KSTAR. For the plasma experiments, maimum pulse length of 10 sec of 0.6 MW EC beam was injected into the plasma for the assisted start-up in order to reduce the flux consumption with the second harmonic condition at toroidal magnetic field of 3 T, and for the auxiliary heating for the long pulse operation of the KSTAR with the third harmonic condition at toroidal magnetic field of 2 T. Most of the experiments show that when the EC wave injected into the plasma the electron temperature is increased during the ramp-up and also, the flux consumption to the plasma current flat-top was reduced compared with pure ohmic startup. The most effective EC launch was toroidal angle of φ=20 degree in the co-CD direction to the toroidal magnetic field. Therefore, the success of the 170 GHz ECH assisted startup in KSTAR encourages the use of the second harmonic 170 GHz on the ITER first plasma campaign.

References

1. K.Sakamoto, A.Kasugai, K. Kajiwara, K. Takahashi, Y. Oda, K. Hayashi, N. Kobayashi, *Nucl. Fusion*, **49**, 095019 (2009)
2. Y. S. Bae, M. Joung, H. L. Yang, W. Namkung, M. H. Cho, H. Park, R. Prater, R. A. Ellis, J. Hosea, Fusion Science and Technology **59** (4), 640 (2011)
3. S. Moriyama, T. Kobayashi, A. Isayama, M. Terakado, M. Sawahata, S. Suzuki, K. Yokokura, M. Shimono, K. Hasegawa, S. Hiranai, K. Igarashi, F. Sato, T. Suzuki, K.Wada, S. Shinozaki, M. Seki, A. Kasugai, K. Takahashi, K. Kajiwara, K. Sakamoto, T. Fujii, *Nucl. Fusion*, **49**, 085001 (2009)