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Development of high voltage power supply for the KSTAR 170 GHz ECH and CD system

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HIGHLIGHTS

- A 3.6 MW (−66 kV/55 A) gyrotron power supply system was developed for the 170 GHz ECH system in KSTAR.
- The main power supply includes a total of 32 PSM based HV power supply modules.
- The voltage regulation of individual HV power module and LV power module is 3 kV and 0.5 kV, respectively.
- The gyrotron is protected by means of a fast solid-state switch (MOS-FET).
- The HV switching system can turn off the 60 kV to the cathode within 3 μs in the event of gyrotron faults.

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ABSTRACT

A 3.6 MW (66 kV/55 A) DC power supply system was developed for the 170 GHz EC H&CD system in KSTAR. The power supply system consists of a cathode power supply (CPS), an anode power supply (APS) and a body power supply (BPS). The cathode power supply is capable of supplying a maximum voltage of −66 kV and a current of 55 A to the cathode with respect to the collector using pulse step modulation (PSM). The high voltage switching system for the cathode is made by a fast MOS-FET solid-state switch which can turn off the high voltage to the cathode within 3 μs in the occurrence of gyrotron faults. The APS is a voltage divider system consisting of a fixed resistor and zener diode units with the capability of 60 kV stand-off voltage. The anode voltage with respect to the cathode is controlled in a range of 0–60 kV by turning the MOS-FET switches connected in parallel to each zener diode on and off. For high frequency current modulation of the gyrotron, the parallel discharge switch is introduced between the cathode and anode in order to clamp the charged voltage in the stray capacitance. The BPS is a DC power supply with the capability of 50 kV/160 mA. The nominal operation parameter of BPS was 23 kV and 10 mA, respectively, and the voltage output is regulated with a stability of 0.025% of the rated voltage. The series MOS-FET solid-state switch is used for on/off modulation in the body voltage sychronizing with anode voltage. The parallel discharge switch is also introduced between the body and collector for high frequency RF modulation. This paper describes the key features of the high voltage power supply system of the KSTAR 170 GHz gyrotron as well as the test results of the power supply.

1. Introduction

The new electron cyclotron heating and current drive (EC H&CD) system operating at a frequency of 170 GHz is installed for plasma initiation, heating, current drive and MHD instability suppression [1]. As a RF power source, JAEA's ITER pre-prototype of 170 GHz, 1 MW CW gyrotron is delivered to the KSTAR in collaboration with JAEA. The gyrotron features 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 [2,3]. The gyrotron is successfully commissioned in KSTAR and used for the second-harmonic ECH-assisted startup in 2011 plasma campaign of KSTAR. For plasma experiments, a maximum pulse length of 10 s of a 0.6 MW EC beam was injected into the plasma for assisted start-up in order to reduce the flux consumption with the second harmonic condition at toroidal magnetic field of 3 T, and for auxiliary heating for long pulse operation of KSTAR with the third harmonic condition at toroidal magnetic field of 2 T [4].

For gyrotron operation, a new 3.6 MW high voltage power supply (HVPS) system consisting of a CPS, an APS, and a BPS is

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developed based on three key issues [5]. First is to quickly switch the DC beam current on/off within several microseconds to control the gyrotron operation. Second is to keep the stability of the acceleration field for the electron beam for stable gyrotron oscillation. Third is to optimize the CPD condition in the gyrotron operation. To operate the gyrotron, the solid-state DC current switches and the BPS for the CPD operation are adopted on this power supply system [6]. The CPS is capable of supplying a maximum voltage of −66 kV and a current of 55 A to the gyrotron cathode to provide the beam current and oscillation RF power. And the gyrotron is protected by means of a fast solid-state switch (MOS-FET), whose fast action limits the energy dissipated in an internal arc to 10 J. An anode power supply is employed to control the beam current. The anode voltage between the cathode and anode is applied by a 60 kV/200 mA APS which functions as the voltage divider circuit between the cathode and the anode by changing the opening and closing the solid-state switches connected in parallel to the zener diodes. This concept is originated in JAEA gyrotrons PS system that can be found in Ref. [7]. In order to satisfy the RF modulation requirements up to 5 kHz, the beam current modulation is realized by the on/off modulation of APS. Since the gyrotron requires a stabilized acceleration field, the HV DC power supply with the capacity of 50 kV/160 mA is used as BPS and the voltage output is regulated with a stability of 0.025% of rated voltage. The solid-state switch is also used to authorize HV pulse to the gyrotron body electrode while modulation is possible to up to 5 kHz synchronized with the APS circuit. The parallel discharge switch is also introduced between the body and collector in order to clamp the charged voltage in the stray capacitance between the body and the collector of the gyrotron. The same parallel discharge switch is introduced in JAEA in 2011. The test results are shown in Ref. [8]. This paper first describes the functional and interface requirements of the HVPS. This will be followed by descriptions of the design of the HVPS. Finally, this paper provides the operational results of the HVPS and the test results of the gyrotron.

2. Requirements of power supply

2.1. Specifications of 170 GHz gyrotron

Schematic diagram of the 170 GHz, 1 MW gyrotron and the configuration of the power supply system is shown in Fig. 1. The electron gun is a triode-type MIG, consisting of a cathode, an anode and body electrodes [2,3]. The collector is grounded and a positive voltage is applied to the body terminals for CPD operation. The electron beam is emissioned by the electric field between the cathode and the anode, and accelerated by the cathode body voltage. The APS is employed for the beam current control independently of the beam acceleration voltage. The BPS is also employed to apply a potential to the body electrode for the depressed collector to reduce the collector heat flux as well as to improve the overall efficiency of the gyrotron. The 170 GHz RF oscillation occurs at the cavity region through the interaction between the electron beam and the static axial magnetic field. The electron beam is then decelerated and depressed by the positive body–collector voltage. The electron energy is significantly reduced by the CPD configuration and the spent beam is absorbed by a collector which is grounded. The beam landing area in the collector is elongated in the axial direction using sweeping coils with 2 Hz and the shape of the coil current for sweeping is saw tooth-like to avoid a long stay at the turning point [2,3]. The nominal operation beam voltage of the gyrotron was 72 kV with the depressed collector voltage at 23 kV and the beam current at ~50 A. The anode voltage between the cathode and anode is optimized at 43 kV with the magnetic field of 6.641 T in the cavity region. At these parameters, the maximum efficiency

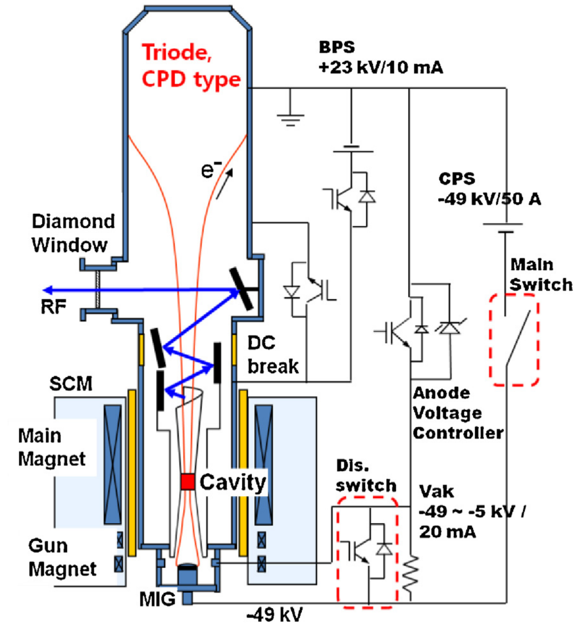

Fig. 1. Schematic diagram of the gyrotron and the configuration of the power supply.

of the gyrotron was ~40% at the beginning of the pulse with the RF power of 1 MW [4]. In order to acquire a stable oscillation, the cathode voltage is regulated within ±1% (±0.5 kV) of stability using the feedback control of LV power modules. The minimum pulse step of the CPS output is compromised between the numbers of LV power module and the stability of RF oscillation from gyrotron to reduce the cost of power supply.

2.2. Operational requirements

The waveform of the RF power to be injected in the different plasma scenarios has an influence on the HV power supply requirements. The 170 GHz EC H&CD power supply is designed for maximum pulse duration of 300 s and the ripple voltage should be less than ±0.5 kV for the stable RF oscillation from the gyrotron. In order to stabilize plasma MHD instabilities, the EC H&CD RF power requires modulation at frequencies of up to ~5 kHz. For 170 GHz gyrotron, the output power can be modulated using either synchronous modulation of the BPS and APS or modulation of the APS alone. It offers the advantage of interrupting the beam current during modulation, and relaxing the CPS modulation requirements (no modulation needed). And the duty cycle of modulation for both of APS and BPS can be selected in a range of 20–80% for a pulse but in cannot be changed during the pulse. This scheme can provide full power modulation up to 5 kHz. Additionally, the HV switch is considered instead of conventional crowbar system to protect gyrotron from arc faults. The MOS-FET switch is installed nearby the gyrotron to minimize the fault energy by the stray capacitance caused by long distance of HV cables between the CPS and gyrotron. The HV switch should stop the high voltage as fast as less than 4 μs, ensuring the limited arc energy inside the gyrotron tube. The EC H&CD power supply is developed in the following way to acquire the desired features.

- Cathode to collector voltage (V_K) should have a fast recovery time.
- It should have minimal indoor/outdoor space requirements.
- It should provide flexibility for allows operation over a wide range of voltages (0–60 kV) and the ripple voltage of the power supply should be less than ±0.5 kV for the stable RF oscillation from gyrotron.