Topics: TEC - Fusion Energy Technology

Qualification of the European gyrotrons and power supplies of the Electron Cyclotron Heating and Current Drive system of ITER

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The Electron Cyclotron Heating and Current Drive system (ECH) system is emerging as the reference plasma heating system of present and future devices. This is attributed to its effective coupling into the plasma [1], the limited impact on the neutronics shielding of future reactors, the modularity of the system that maximizes the reliability and availability, and its versability in providing multiple essential plasma functions, such as the control of instabilities occurring in high performance plasmas. In ITER, the ECH system will inject 40 MW to 67 MW of electromagnetic continuous waves into the plasma at the frequency of 170 GHz, playing a crucial role in all plasma phase operations to achieve ITER's objectives.

The millimeter waves are generated in diode-type gyrotrons connected to High Voltage (HV) power supplies. These gyrotrons and HV power supplies constitute the ECH power generation system, which employs technologies that are at an advanced readiness level for plant operation. Fusion for Energy (F4E), responsible for the European contribution to ITER, is tasked with procuring 8 out of the 12 High Voltage (HV) Power Supplies and 6 out of the 24 gyrotrons of the ITER ECH original baseline.

The EC HV Power Supplies comprise 8 HV power supply units, each capable of delivering up to 55 kV DC regulated voltage and up to 110 A current, which are configured to feed 2 gyrotron cathodes in parallel. Additionally, there are 16 units dedicated to modulating the body voltage, providing up to 35 kV DC, thereby establishing the total gyrotron acceleration voltage. The selected design concept for the EU power supplies represents an advancement of the solid-state Pulse Step Modulator (PSM) technology, which provides high efficiencies and compact layouts. The design incorporates specialized multi-winding transformers, which are powered by the 22 KV and 400V AC electrical distribution system of ITER. The secondary windings feed relatively small modules with rectifiers and switches connected in series. In addition, some of the switching modules allow pulling the current from the load, thus minimizing the energy delivered in case of fast shutdown request (e.g., internal gyrotron discharge). Moreover, the body HV power supply, which needs to rapidly discharge substantial current due to capacitive nature of gyrotron body load, incorporates an additional DC/DC converter in the modules.

The EU ECH power supplies were fully validated with analyses and type tests, showing excellent functional performance exceeding the stringent technical specifications that are key for the gyrotrons and ECH system operation and reliability, such as voltage stability, dynamics (e.g., 5 KHz power modulation as required for NTM plasma stabilization) and very low energy dissipation in case of fast shutdowns. At present, the installation of the power supplies in ITER is completed following optimization measures to enhance EMC overall behaviour [2], and the commissioning and site acceptance tests are progressing.

The ECH gyrotrons, including a high-power vacuum tube, a super-conducting magnet and various auxiliaries, are each capable of delivering 1 MW at the frequency of 170 GHz continuous wave (CW). The F4E procurement package covers the Final Design Review (FDR), manufacturing, assembly, factory testing, and, at ITER site, installation, commissioning and acceptance testing of the 6 gyrotrons.

The design of the EU gyrotron for ITER was developed by the EGYC Consortium (KIT, SPC, CNR, HELLAS) and the EU manufacturing industry (Thales), under the coordination of F4E, taking advantage of the successful production of the CW gyrotrons at 140 GHz by Thales for the W7-X stellarator [3]. The EU gyrotron for ITER has been successfully qualified with both the industrial gyrotron prototype and the first series tube for DTT produced by Thales [4], with the tests at the KIT [5] and SPC [6], [7] test facilities. The units tested have demonstrated excellent and very stable performance [5] at 1 MW power range level, with excellent stability on critical parameters such as the frequency, vacuum level, beam current, calorimetry measurements, temperatures on the inner parts of the gyrotron, mode purity, and absence of parasitic oscillations and mode switch at long pulses (above 100 s) [7].

Moreover, the EU gyrotron has demonstrated repeatability and reliability with successful consecutive pulses, when operated with ITER-like power supplies and controlled via an ITER-type Plant Control system [8] ensuring safe gyrotron operation as well as correct monitoring of the gyrotron diagnostics (e.g., frequency shift, mode purity, parasitic oscillations). The six EU gyrotrons for ITER will be delivered in the period 2027-2029 following the FDR by mid-2025.

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