

Developments towards 1MW Gyrotron Test Facility at ITER-India

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Abstract. ITER-India, the Indian domestic agency for the ITER project, has the responsibility to supply a set of two high power Gyrotron sources (1 MW, 170 GHz, 3600 s) along with the auxiliary systems for Electron Cyclotron Heating & Current Drive applications. For such high power Gyrotron systems, one of the challenging areas is the system integration and establishment of reliable integrated system performance. ITER-India plans to establish the integrated Gyrotron system performance that essentially meets the ITER requirements in a Gyrotron Test Facility which is specifically being developed at ITER-India. This paper discusses about the recent updates towards the Test Facility development which includes, development of cost effective & modular Body Power Supply (BPS), Industrial grade prototype interlock & protection modules, a Gyrotron field simulator and cooling water distribution system.

1. Introduction

Gyrotron oscillators are capable of producing high CW RF power in the microwave and mm Wave frequency region and are widely used for ECRF applications on fusion devices [1]. ITER requires 20 MW of RF power at 170 GHz for which 24 sets of 1MW Gyrotron sources would be required [2]. ITER-India, the Indian domestic agency has the scope of providing two Gyrotron source sets [3]. The scope includes not only the Gyrotron tubes but also the associated auxiliary systems such as the control system, auxiliary power supplies, cooling manifold etc., along with the responsibility of demonstration of performance at site on a dummy load. The critical interfaces with High Voltage Power Supplies (HVPS), EC plant control system and waveguide transmission lines which are provided by other domestic agencies, are also to be taken into account while finalizing the system design. The integrated system performance with a reliability of >95%, as required by ITER is a challenge and requires considerable preparatory tests and debugging of the complete integrated system. Considering limited time window that would be available for each Gyrotron set to successfully complete the site installation and acceptance tests, it becomes essential that one has to recreate the closest possible test configuration and prior establish the performance in a test facility. With this objective in mind in Phase-1 of the project, ITER-India is developing a 1MW Gyrotron Test Facility (IIGTF) with the help of an ITER like test Gyrotron along with the other subsystems that are either prototypes or close to actual ITER deliverables.

2. Gyrotron Test Facility

The ITER-India lab building which caters to several ITER related facilities also houses the IIGTF at level three of the building. The Main High Voltage cathode Power Supply (MHVPS) for the IIGTF is located on the ground floor, a configuration that is similar to ITER. The IIGTF layout (Fig. 1) is grouped into several areas such as the HV area, Gyrotron & waveguide area, Cooling Manifold area, Auxiliary & control cubicle area, RF diagnostics & low power mm Wave area and control room etc. The HV area consists of Body High Voltage Power Supply (BPS), MHVPS Interface unit, Heater Transformer, HV disconnect switch etc. The Gyrotron area consists of the Gyrotron tube, Super Conducting Magnet (SCM) with other auxiliary magnet coils, Matching Optic Unit (MOU) along with a set of waveguide components and a CW

dummy load. The main control room is situated on the mezzanine floor from where the remote operation can be performed. The auxiliary power supplies and control cubicles are located under the control room. Cooling manifold area adjacent to the Gyrotron setup consists of the manifold along with a dedicated chiller for the SCM compressor.

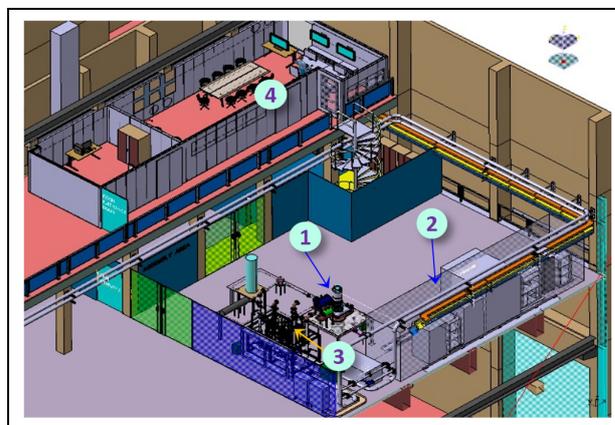


Fig. 1 : ITER-India Gyrotron Test Facility layout (1: Gyrotron set-up; 2: HV area; 3: Cooling Manifold; 4: Control room)

2.1. Test Gyrotron & Waveguide Set

To establish the integrated performance, a test Gyrotron close to ITER specifications, along with a set of waveguide components including a CW dummy load is under procurement (Fig. 2). The key specifications of the Gyrotron tube are shown in the Table 1.

Table 1 : Typical specifications of Test Gyrotron

Parameter	Value
Frequency	170 GHz
Output Power	0.96 MW (o/p of MOU)
Pulse	1000 s
Efficiency	≥ 50%

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A liquid He free superconducting magnet along with other auxiliary coils provide the necessary magnetic field for the Gyrotron. A short section (~3.5 m) of 63.5 mm diameter, evacuated corrugated waveguide line terminated into a water cooled CW dummy load is considered for testing the Gyrotron. To facilitate the measurements during initial short pulse operation, an atmospheric short pulse dummy load is also planned that can be selected through a manually operated SPDT waveguide switch. A power monitoring bi-directional miter bend coupler with a typical coupling coefficient of ~80 dB is also included in the line to monitor the forward and reflected power along with the oscillation frequency. A MOU with adjustable mirrors will be used to efficiently (96%) couple the Gyrotron output with the waveguide. Additional power monitoring provision in the MOU is also being considered. A TMP based vacuum line is prepared to evacuate the waveguide line up to 0.01 Pa.

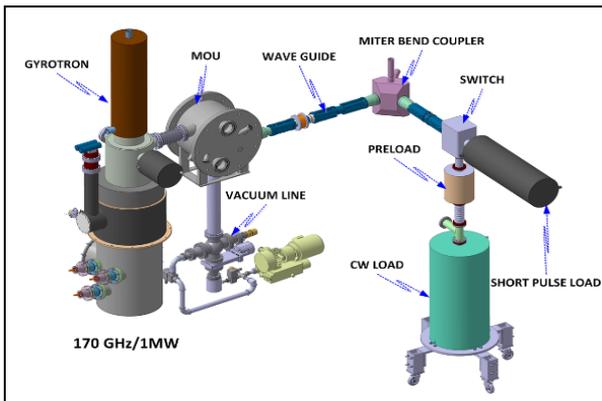


Fig. 2 : Schematic of Test Gyrotron & waveguide set test configuration

2.2. High Voltage & Auxiliary Power Supplies

For a diode type of Gyrotron, the common collector electrical configuration is considered for the IIGTF. For this configuration two HVDC power supplies namely MHVPS and BPS would be required. As shown in Fig. 3, the MHVPS drives the Gyrotron beam current and the BPS in addition to the MHVPS provides the necessary acceleration voltage.

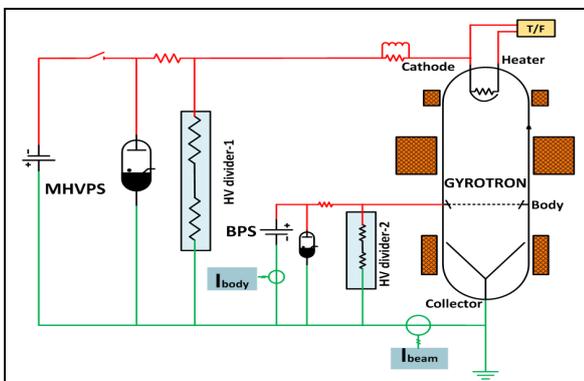


Fig. 3 : IIGTF HV Power Supply configuration

For IIGTF, an ITER like full scale prototype MHVPS with 55kV/110A in PSM topology is under development (Fig. 4). Long lead items such as the multi secondary transformers are already tested and installed at site. The manufacturing of Switched Power Supply (SPS) modules is currently ongoing.



Fig. 4 : Multi-secondary Transformer & 80kW SPS module mounted on test bench

For the BPS, where the required maximum ratings (35kV/100 mA) are modest in comparison to the MHVPS, it was felt that a PSM solution would be expensive and bulky. In view of this, an alternate cost effective modular solution using high voltage solid-state switch (push-pull type MOSFET) is being tested under a prototype development to meet the modulation requirement (DC-2 kHz). The concept of the prototype BPS is shown in the Fig. 5. The test setup consists of a conventional COTS power supply (100 kV/ 50 mA) with slow dynamics (~400 ms) terminated with a buffer capacitor which compensates the instantaneous peak loads during the switching transitions. The Gyrotron body circuit is represented with an equivalent RC load (350 kΩ or 850 kΩ ||1700 pF) which includes cable capacitance. A compact push-pull type solid-state switch (~ 300 x 350 x 150 mm³) from M/s BEHLKE is used as the fast switching element that provides the necessary fast dynamics. Some of the results obtained with this prototype setup are presented in Fig. 6 to Fig. 8.

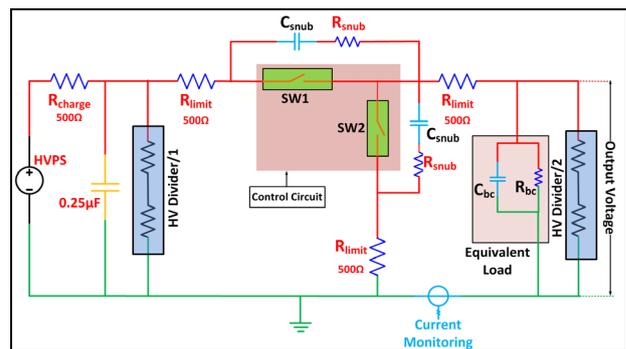


Fig. 5 : Schematic of the tests setup of prototype BPS using solid state switch

Fig. 6 shows the short pulse (50 µs) test results at 35 kV with an output voltage pulse rise and fall times about 5 µs. Fig. 7 shows the DC pulse at 35 kV of pulse length of 1 s. Fig. 8 shows the square modulation test results at 35 kV at 1 kHz for 5 ms duration. The voltage pulse characteristics across the load are quite satisfactory however, during the experiments it is also noted that the fast switching is resulting in excessive overshoots and undershoots across the switches which needs to be suppressed to safeguard the switch. To address the same, additional tests are ongoing with appropriate snubber elements. Further tests are to be carried out to assess the switch reliability. Also, the setup needs to be compactly organized to minimize the effect of stray reactive elements in the circuit.

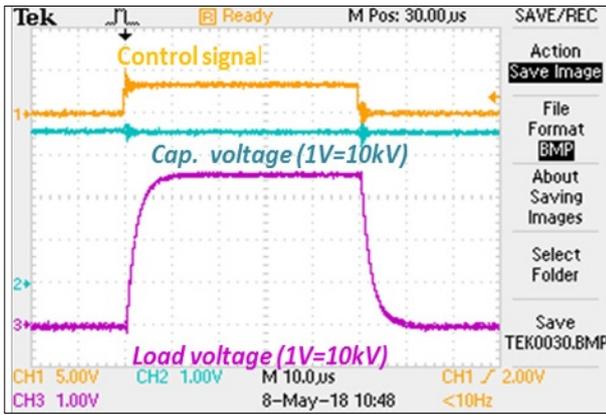


Fig. 6: Test result of 35 kV for 50µs (rise/fall time: ~5µs)

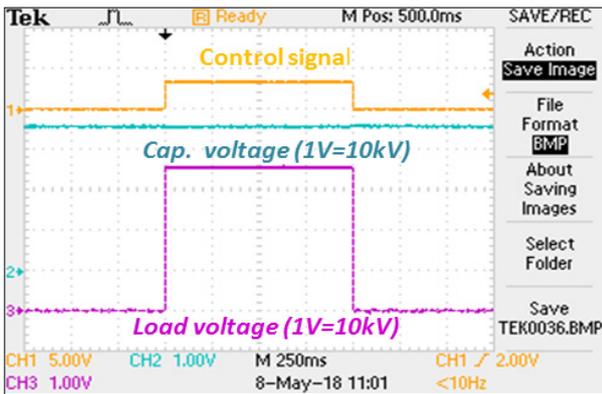


Fig. 7: Test result of 35 kV for 1 s

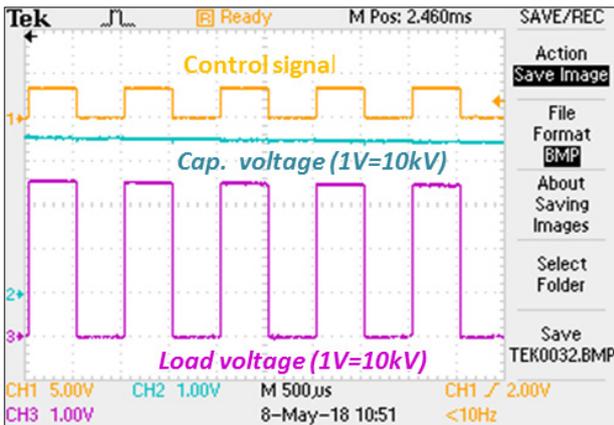


Fig. 8: Test result of 35 kV at 1 kHz Modulation

2.3. Control System

A Local Control Unit (LCU) is required for safe and reliable operation of Gyrotron system. A dedicated full scale ITER prototype LCU is planned for testing and commissioning of Test Gyrotron at IIGTF that will be developed in two phases using two different software platforms to minimize the operational risks. LabVIEW™ platform would be used in phase-1 and the ITER recommended CODAC platform & hardware would be used in phase-2 [4]. Fig. 9 shows the LCU architecture for Phase-1, having main functions of sequence control, monitoring, protection interlocks, data acquisition and Graphical User Interface (GUI). The sequence control and slow interlock functions of various sub-systems are implemented

using S7-300 Siemens® Programmable Logic Controller (PLC). Real-time Control and Data Acquisition will be implemented using PCI eXtension for Instrumentation (PXIe) system. Critical Interlock & protections requiring a fast response time (< 10 µs) which are implemented using hardwired FPGA device. The auxiliary power supplies are controlled and monitored by slow controller using serial communication protocol. Slow controller communicates with fast controller using NI-OPC server. All cooling parameters are monitored using Remote expansion module (ET 200M) of PLC. The complete system operation and real time data acquisition will be performed using LabVIEW based GUI.

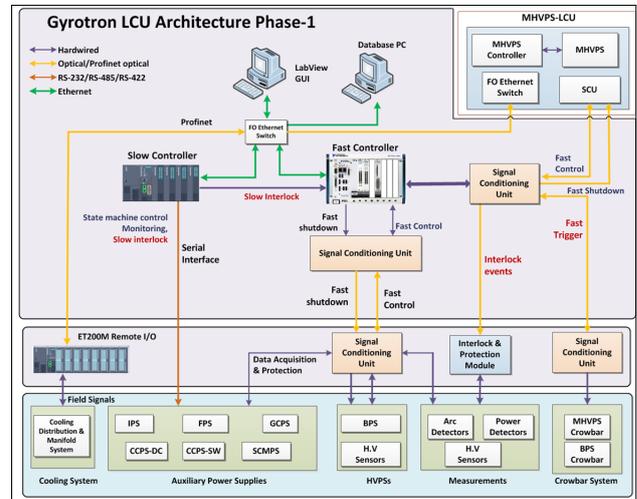


Fig. 9: LCU Architecture (Phase-1)

A Signal Conditioning Unit (SCU) is used for reliable transmission & interfacing of the field signals to control system. In this context, a prototype modular industrial grade fiber optic transmission link has been designed and developed based on the Voltage-to-Frequency (V/F) conversion technique (Fig. 10). Functional & EMC qualification tests have been carried out with satisfactory results [4] [5].



Fig. 10 : Prototype industrial Grade SCU (Fiber Optic link)

During the Gyrotron operation, critical faults such as internal arcs may arise which requires very fast interlock action to switch OFF the HV Power Supplies. Hence, a fast interlock system plays a very important role in ensuring the safe operation of Gyrotron system. Considering the criticality of fast interlock protections, two different types of prototype hardwired interlock modules are designed and developed, namely Distributed Interlock Module (DIM) and Centralized Interlock module (CIM). DIM is a single channel module distributed in the field where the analog signals are processed

near to the sensors & the logic part is implemented in fast controller (Fig. 11). CIM is a standalone module placed in the field, where the analog & digital signals are processed in a centralized single unit. Because of the faults criticality, both the modules will be used with one as hardware redundancy.



Fig. 11: Prototype Distributed Interlock Module (DIM)

An Industrial grade prototype Centralized Interlock and Protection Module (CIM) based on ITER-India design has been developed successfully which is shown in Fig. 12. The main features are two tier configuration with an additional hardware redundancy; FPGA based hardwired modular design; Fail safe logic; Total module response time <math><1.5\mu\text{s}</math>; Fiber optic interface; Fault Sequence & Spurious fault detection logic and EMC compliant as per IEC61000-4 (as a specific requirements). Functional & EMC qualification tests have been carried out with satisfactory results which are shown in Fig. 13 to Fig. 15. Full-scale fabrication of CIM system is currently ongoing.

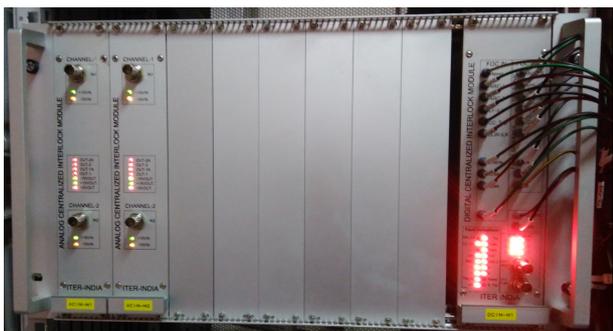


Fig. 12: Prototype Centralized Interlock and Protection Module (CIM)

Standard (Test Name)	Test Specifications / Levels	Results
IEC 61000-4-2:2008 (ESD)	Contact Discharge: ± 4 kV In-Direct Discharge : ± 8 kV	PASS Criterion A
IEC 61000-4-3:2006 (RS)	80 to 1000 MHz; 10 V/m	
IEC 61000-4-4:2012 (EFT)	± 1 kV	
IEC 61000-4-5:2014 (Surge)	± 1 kV	
IEC 61000-4-6:2013 (CS)	0.15 to 80 MHz; 10 Vrms	
IEC 61000-4-8:2009 (PFMF)	100A/m; 50 Hz; 3 axis	
IEC 61000-4-11:2004 (Volt. Dip)	70 % Res. Volt.; 25 cycle; 50Hz	
CISPR11:2015 (RE)	30MHz to 1GHz, 30-37 dB μ V/m	

Fig. 13: Summary of EMC Test performance of CIM

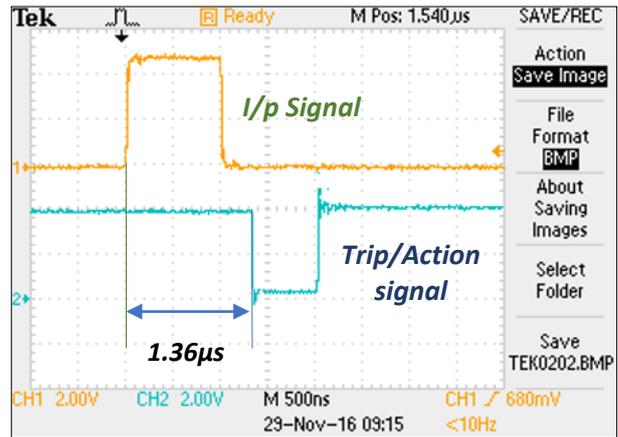


Fig. 14: Test Result of response time ($\sim 1.36 \mu\text{s}$) of CIM

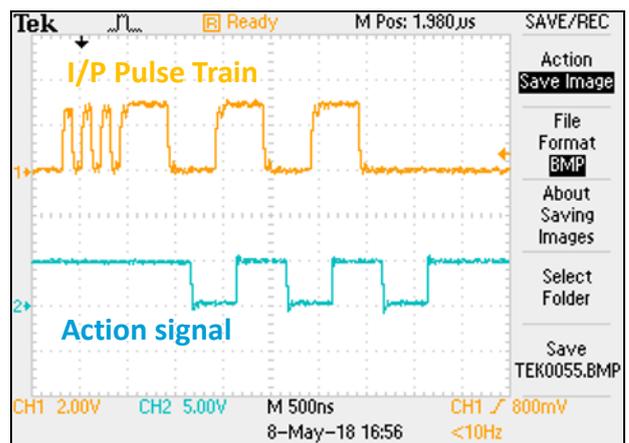


Fig. 15: Test Result of Spurious fault detection logic of CIM

Considering the LCU design and operational aspects, it is important to perform integrated testing & validation of the LCU functions, before using it for the actual Gyrotron operation. This will also improve the reliability and safety of overall system. As various Gyrotron sub-systems are under development & procurement phase for IIGTF, a Gyrotron field simulator is being developed that will emulate field sub-systems and will be used as a test bench to qualify the LCU functionality.

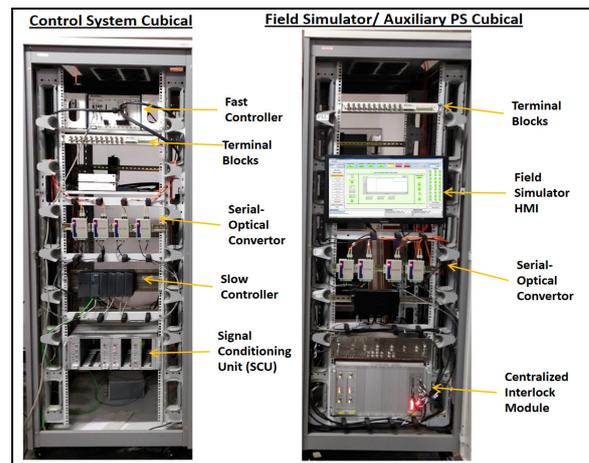


Fig. 16: Field Simulator & Control cubicle arrangement

Most of the auxiliary power supplies have serial interface for control, and hardwire interface for monitoring & protection, while the HVPS has a dedicated hardwire interface with LCU. LabVIEW GUI is used to simulate the behaviour of the auxiliary power supplies. The HVPS signals are simulated using Real time PXIe controller. A LabVIEW based GUI is developed to operate the field simulator. As shown in Fig. 16, the LCU components are arranged in a cubicle as per actual configuration, while the field simulator hardware is arranged in another cubicle that will be replaced with actual subsystems during the Gyrotron operation.

2.4. Cooling Distribution System

For 1MW Gyrotron test stand with a typical Gyrotron efficiency of 50%, a total of 2MW of thermal load would be generated. Half of the load would be received across various Gyrotron components (such as the collector) and the remaining half would be received in the output RF dummy load. In order to maintain the components well within their permissible operating temperature, the heat load must be effectively dissipated through active water cooling. For IIGTF cooling distribution system, a heat load of 2.5 MW at an effective efficiency of 40% is considered. Considering the typical flow rate requirements of 1MW class Gyrotron and the RF dummy load, a total of 2700 LPM is finalized for the IIGTF. An existing cooling water plant that can provide the required low conductivity water at room temperature with a pressure head of 6-7 bar is being utilized for the purpose. The main cooling parameters for the IIGTF cooling distribution system are listed in the Table 2.

Table 2 : Main Parameters of Cooling distribution system

Parameter	Value
Coolant	Water
Heat Load	2.5 MW
Flow rate	2700 LPM
Water Temperature	< 35 °C
Inlet Pressure Head	6-7 bar (typical)
Conductivity	< 1 μS/cm
Monitoring	Flow, Temperature, Pressure & Conductivity



Fig. 17 : Gyrotron Cooling Distribution Manifold

A cooling distribution system consisting of a main header & distribution manifold has been designed, manufactured and commissioned recently. A 6” stainless steel header line connects the plant and the Gyrotron distribution manifold. A cooling manifold with 22 inlet and outlets, which are grouped into 6 main branches depending upon the pressure and flow requirements, provides the dedicated input and output tapping points for each of the Gyrotron and waveguide cooling circuits. Each circuit is provided with necessary flow, temperature and pressure monitoring sensors. All necessary sensor parameters are locally displayed as well as remotely monitored and acquired through PLC system. Fig. 17 shows the actual image of the recently installed cooling manifold. Fig. 18 shows the general I&C configuration for the cooling distribution system. Fig. 19 shows the flow test results acquired through PLC in LabVIEW based GUI during the commissioning.

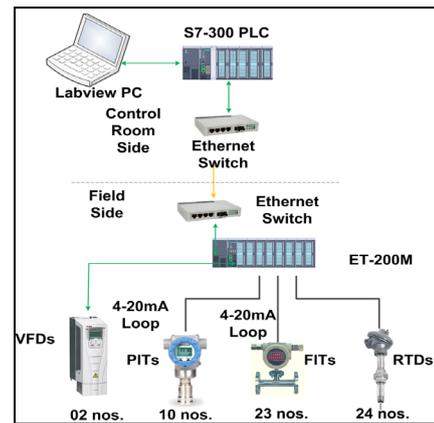


Fig. 18: General I&C configuration for the IIGTF Cooling distribution system

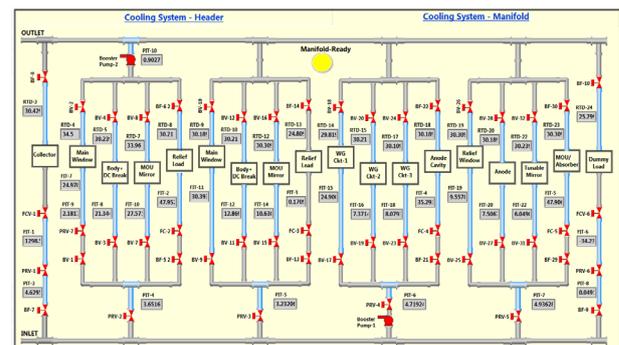


Fig. 19: Flow distribution & other parameters captured during commissioning

2.5. Diagnostics

For the IIGTF, different diagnostics are established or being planned to measure and characterize the Gyrotron output RF beam performance parameters such as the output RF power, RF frequency, RF beam mode purity etc. The generated output power would be measured and monitored using the reliable calorimetric measurements of the RF Dummy load water circuit. As the CW dummy loads typically have long time constants of the order of tens of seconds, a short pulse dummy load would be utilized in case of short pulse operation and the pulse integration techniques would be used to estimate the power. Also for instantaneous RF power monitoring, calibrated Schottky diode detectors mounted on the waveguide directional coupler would be used. For the frequency measurements, a spectrum analyzer suitably connected to the directional coupler

coupling port would be used. As the spectrum analyzer has a minimum sweep time (~ 5 ms), a real-time frequency measurement setup is also being planned. With the real-time frequency measurements over an appropriate frequency band, it would be possible to detect the Gyrotron out of mode oscillation by detecting the frequency shift. There would be two band pass filters: one for wide band detection (166-172 GHz) and other is for narrow band detection (169.5-170.5 GHz). The detailed scheme using a heterodyne mixer and the output filter banks is shown in the Fig. 20.

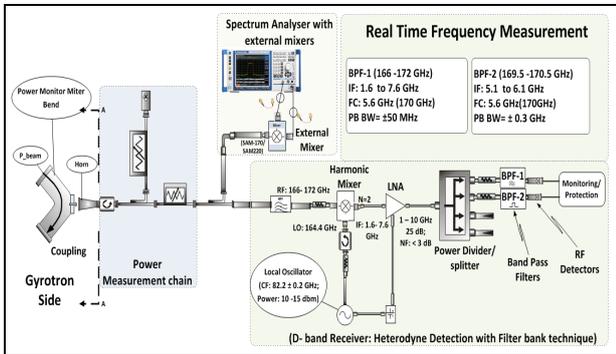


Fig. 20 : Gyrotron output RF beam Frequency measurement scheme

Good Gyrotron output beam mode purity of the order of 95% is required to minimize waveguide transmission line and coupling losses. Amplitude and phase profiles of the beam are needed to estimate the mode content. A non-contact measurement technique is typically employed to estimate the relative amplitude profile of a high power RF beam. The phase profile is determined using phase retrieval techniques in which radiated beam amplitude measurements taken at different distances along the direction of the beam propagation would be used to retrieve the phase [6]. Fig. 21 shows the schematic of the setup which includes an IR camera, a translating stage to mount a target paper along with an IR camera, a reflector and a beam dump.

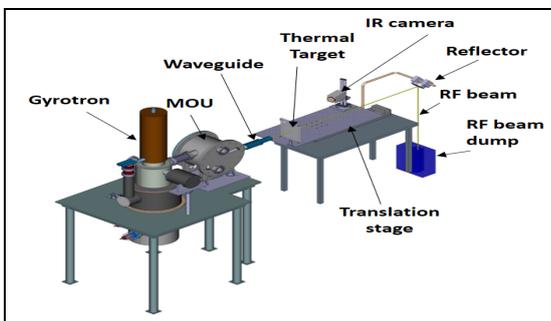


Fig. 21: Mode purity measurement scheme

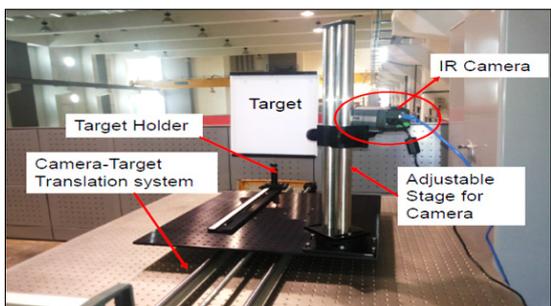


Fig. 22: Mode purity measurements Setup using IR camera

The temperature data of the target, after being irradiated by RF beam would be recorded by the IR camera at different locations. This data is used to retrieve the phase using a numerical program prepared in Matlab[®] based on irradiance moment theory [7]. The IR thermography setup as shown in Fig. 22 has been established at IIGTF for determination of the mode purity.

3. Summary

ITER-India, the Indian domestic agency for the ITER project is developing a 1MW Gyrotron test facility to establish the integrated Gyrotron system performance that meets the ITER requirements. The general arrangement of various subsystems of IIGTF and their layout has been finalized. To enable the integrated testing, a Test Gyrotron with close to ITER specifications (170 GHz, 1 MW, 1000 s) along with a corrugated waveguide set including RF load is finalized and the same is currently under procurement. Details of High Voltage power supplies and their development status presented. A PSM based MHVPS (55kV, 110 A) that also serve as a full scale ITER prototype is under development. For the Gyrotron BPS (35 kV, 100 mA), a cost effective and modular solution using high voltage solid-state switch is adopted for prototype development to meet the fast switching and high frequency modulation requirement. Promising initial test results on an equivalent RC load have been achieved and further testing is ongoing. Towards development of Local Control Unit (LCU), prototype design and development activities have been carried out. Under this, a prototype industrial grade Centralized Interlock Module (CIM) has been designed, developed and tested successfully against EMC compliance. The main features of CIM includes fail-safe logic, fault sequence & spurious fault detection logic using FPGA with a total response time $\sim 1.5\mu\text{s}$. Further a LabVIEW[™] based Gyrotron field simulator is being developed to test the LCU's hardware & its software applications. In order to remove the significant thermal heat loads (~ 2.5 MW) across various components of Gyrotron system, the active cooling water distribution system (2700 LPM, 6 bar) has been designed, developed, and commissioned. Various diagnostics for measurement of output RF power, RF frequency, and RF beam mode purity are considered and some of the setups have been established. Additionally a real time frequency measurement system for spurious mode detection is also being taken up for development.

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