Test and Commissioning of 82.6 GHz ECRH system on SST-1

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Abstract
Electron Cyclotron Resonance Heating (ECRH) system will play an important role in plasma formation, heating and current drive in the Superconducting Steady state Tokamak (SST-1). Commissioning activity of the machine has been initiated. Many of the sub-systems have been prepared for the first plasma discharge. A radial and a top port have been allotted for low field side (LFS) and high field side (HFS) launch of O and X- modes in the plasma.

The system is based on a gyrotron source operating at a frequency of 82.6±0.1GHz (GLGD-82.6/0.2) and capable of delivering 0.2 MW / 1000s with 17% duty cycle. The transmission line consisting of ~15 meters length 63.5mm corrugated wave guide, DC break, wave guide switch, mitre bend, polariser, bellows that terminates with a vacuum barrier CVD window. A beam launching system used to steer the microwave beam in the plasma volume is connected between the end of the transmission line and the tokamak radial and top ports. A VME based real time data acquisition and control (DAC) system is used for monitoring, acquisition and control. Hard-wired interlock operates a rail-gap based crowbar system in less than 10µs under any fault condition. Burn patterns are recorded at various stages in the transmission line. The gyrotron is tested for ~200kW / 1000s operation on a water dummy load. Transmission line is tested at various power levels for long pulse operation. The paper highlights the experimental results of successful commissioning of the system.

1. Introduction

It has been observed that electron cyclotron resonance (ECR) assisted ohmic plasma formation in tokamaks has many advantages over conventional discharges. Lower loop voltage operation, volt-seconds budgeting, better wall plasma interaction scenario, wide parameter space of operation are some of the salient feature of ECRH [1,2,3,4] assisted ohmic discharge in tokamaks. In the presence of superconducting toroidal and poloidal field coils slower plasma current ramp up is desirable in the start up phase. To reduce the volt-sec requirement for a slow rise of plasma current, preionization during startup is beneficial. With this aim an ECR system has been commissioned to integrate to SST-1 tokamak.
A 82.6GHz ECRH system will be used to achieve reliable start-up of Steadystate superconducting tokamak (SST-1). The system would also be used to carry out electron cyclotron resonance heating (ECRH) and electron cyclotron current drive (ECCD) experiments. In SST-1, the ECRH power would be launched from the low field side (radial port) as well as from the high field side (top port).

This paper discusses the experimental results obtained during successful commissioning of the gyrotron into a calorimetric dummy load together with the transmission line and characterization of low field side launcher.

2. Gyrotron Source

The microwave source is a gyrotron with model no. GLGD-82.6/0.2, sr.no.01. It has been supplied by Messer's Gycom, Russia. The gyrotron delivers 200kW CW (continuous wave) power at a frequency of 82.6±0.1GHz. The maximum pulse duration for 200kW output power from the gyrotron is 1000s. The salient technical features of the gyrotron are shown in table 1. All the components of the source are cooled with De-Mineralized (DM) water. Output power from the source is extracted through a CVD window. The window is cooled with DM water mixed with CC-15. A pH value ~ 9.0 is required to be maintained. The gyrotron has an internal mode converter and a superconducting magnet is used for generating the required axial magnetic field.

| Parameters:                                | Depressed Collector |
|-------------------------------------------|---------------------|
| Gyrotron type                              |                     |
| Frequency                                  | 82.6±0.2GHz         |
| Power                                      | 200 kW / CW (Continuous Wave) |
| Pulse duration                             | 1000s               |
| Duty Cycle                                 | 17%                 |
| Gyrotron output                            | Lateral             |
| Output mode (with internal mode converter) | TEM$_{00}$ – Gaussian beam |
| Output window                              | CVD diamond         |
| Magnet of gyrotron                         | Cryo-cooled         |
| Critical crater energy                     | 10 Joule            |
| Life time                                  | 10000 filament hours|

3. Gyrotron test set-up with calorimetric dummy load

The gyrotron is first successfully installed into the cryomagnet assembly. The matching optic unit (MOU) is then connected to the gyrotron output. Alignment of mirrors in the MOU is ensured by registering burn pattern at the exit of the MOU. Figure 1 depicts the burn pattern at the exit of MOU.

A mitre-bend with a bi-directional coupler is used to connect the calorimetric water dummy load to the MOU, which is connected to the gyrotron. The gyrotron power and duration is gradually
increased to reach 200kW/1000s operation. The calorimetric reading using picotherm meter – 2 and forward power measured by the detector in the mitre bend match reasonably well. The picotherm meter-2 is a multi functional meter for calorimetric measurements at water dummy load. This meter is manufactured by M/s. ABB, Germany and measures inlet/outlet temperatures, temperature difference, mass flow rate and power etc. The experimental set-up of the gyrotron connected to the calorimetric dummy load is shown in figure 2.

Figure 1. Burn pattern at the output of MOU

The forward power, anode voltage, filament current and cryomagnet current as measured during the pulse are highlighted in figure 3. The forward power delivered to the calorimetric load is gradually increased by increasing the anode voltage (up to 19kV) and beam voltage (up to 44.5kV) to reach finally ~200kW. In order to achieve 200kW output power from the gyrotron, the anode voltage is varied gradually from 16kV to 19kV and beam voltage from 40 kV to 44.5kV. The steps noticed in the power level correspond to the variation in the anode and beam voltage, which are gradually varied during the pulse. The frequency of the gyrotron has been measured using a spectrum analyzer (Model No.: HP8562B). The measured frequency is 82.815 GHz.

Figure 2. Gyrotron test set-up with mitre-bend and dummy load for CW operation
4. Transmission line

Two DC breaks to isolate the transmission line from the tokamak as well as from the gyrotron are mounted at the two ends of the transmission line. Approximately ~12 meters of corrugated waveguides are used to transmit the microwave power from the gyrotron to the beam launcher. A waveguide switch is provided in the line to switch power between the dummy load and the transmission line. One mitre-bend and one polariser along with the corrugated waveguide are used in the line to carry the power to the launcher. The polariser is located in the proximity of the exit of transmission line. Bellows are used for flexibility in the line. The line terminates with a vacuum barrier CVD window. Figure 4 shows the schematic of transmission line for low field side launch.
Initially the transmission line is erected and aligned with the help of a laser. Then the transmission line is connected to the gyrotron. High power test is carried out and burn pattern is checked near the tokamak end of the transmission line. The burn pattern highlighted in figure 5 shows that the transmission line is aligned and gaussian nature of the beam is maintained after traversal of the beam through ~15m long transmission line.

![Figure 5. Burn pattern at the exit of the transmission line](image)

5. Launcher

During the initial phase of operation in SST-1, ECRH power launch is planned from low field side radial port. The launcher consists of two stainless steel mirrors, one focusing and one plane mirror. Plane mirror is rotatable and has provision to steer the beam in the plasma volume. The launcher has been tested for UHV compatibility and characterized with low microwave power source [5]. Microwave characterization of launcher with low power microwave source shows that measured beam radius at various distances are in close agreement with the calculated values figure 6.

![Figure 6. Beam radius vs. distance (low power microwave characterization of LFS launcher)](image)

6. Power supplies for the gyrotron:

The High Voltage Power Supply (HVPS) is capable of delivering 0-60kV @ 10A load current. The crowbar protection system consists of a rail-gap, which is pressurized with dry N₂ at an appropriate pressure. The 10 joule wire-burn test for operation in <10µs has been satisfactorily carried out prior to operation of the gyrotron [6,7].
The Anode modulator power supply (AMPS) is capable to deliver 30kV/300mA. The power supply can be operated in stand-alone / slave mode to the data acquisition and control (DAC) system. During crowbar operation of HVPS, the AMPS is also turned-off within 10µs. The cryomagnet power supply (CMPS) is used to energize the cryomagnet, which is cooled to liquid helium temperature. It is capable of delivering 100A @ ~ 0V. The CMPS can be operated in stand-alone or slave mode to the DAC. The filament power supply (FPS) delivers 20A/35V to heat the filament of the gyrotron. It has a high voltage isolation of 60kV with respect to ground. The schematic of all the power supplies connected to the gyrotron is shown in figure 7.

![Figure 7. Schematic of layout of power supplies with respect to the gyrotron](image)

7. Data Acquisition and Control (DAC) system:

A VME based real time DAC system has been developed for monitoring, acquisition and control the ECRH system. The system will act as slave during SST-1 operation with central control system. All the power supplies can be controlled remotely through a computer using VME processor and VMS board. There are 13 analog input channels, 5 analog output channel, 22 input digital channels and 19 output digital channels. In order to avoid ground loop problem, each signal is optically isolated for 1.5kV. Timer modules are used to generate anode pulse with proper parameter settings. Two levels of interlocks are incorporated for the safety of the gyrotron system. Fast interlocks are hard wired and are used for removal of the high voltage within 10µs in the event of any fault during operation. The arc-detectors, emergency off, dI/dt and vac-ion are fast interlocked and operate crowbar system in 10µs. Slow interlocks (≤ 50ms) are initiated from the VME. Failure in water-cooling system, filament trip, cryomagnet current anomalies are interlocked with the HVPS.

The real time application software has been developed on VXWorks real time operating system (RTOS) in C++. The application software has been modeled using object-oriented technology in unified modeling language (UML). The graphical user interfaces (GUI) have been developed
using TCL/TK on linux OS. The database server is an oriented network file system (NFS) based server.

8. Conclusion

The gyrotron for the ECRH system on SST-1 has been successfully erected and tested on a water dummy load and tested for 200kW and 1000s pulse operation. Transmission line has been erected from the gyrotron to SST-1 and tested for pulsed operation by verifying the burn pattern at the exit of the line. Launcher has been checked for UHV compatibility and ultimate vacuum achieved is better than 5x10⁻⁹ mbar with a leak rate better than 1x10⁻⁹ mbar lt/s. The CVD diamond window at the end of the transmission line has also been tested for UHV compatibility.

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