OPERATION AND CONTROL OF 42 GHZ GYROTRON SYSTEM IN ECRH

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Abstract

Electron Cyclotron Resonance Heating (ECRH) is one of the essential RF heating system used for pre-ionization and heating experiments in tokamaks. The 42 GHz gyrotron system capable to deliver 500kW RF power for 500ms has been installed for operation with Aditya and SST1 tokamak. Gyrotron system consists of various auxiliary power supplies, water cooling system, crowbar unit and Data Acquisition and Control(DAC) system. Gyrotron operation requires a systematic and controlled operation of different power supplies. High voltage power supplies connected with cathode and anode needs more attention for pulsing the gyrotron tube for conditioning as well as for microwave output. As Gyrotron tube is an expensive microwave device, fast interlock circuits are implemented with FPGA for its protection during any abnormal event. DAC systems are designed and developed for gyrotron operation considering all safety measures and protection. Gyrotron system can be operated standalone as well as remotely through programmed time base trigger command from Central control system. VME based DAC and the other PXIe based DAC have been installed with the gyrotron system and are under operation with SST-1 and Aditya for safe and reliable operation of gyrotron. VME based DAC has been upgraded with NI Labview based GUI and control interface with new advance features. New PXIe based DAC system has been designed to operate both 42 GHz and 82.6 GHz gyrotron with a single console application. The essential part of gyrotron operation is pulsing the anode and cathode high voltages simultaneously with pre programmed delay and rise time with fast active interlocks. Gyrotron operation covers the start up sequence of power supplies, its pre-inspection and checking of different interlocks, HV pulse interface test and conditioning of gyrotron tube.

1. INTRODUCTION

The gyrotron is a high power microwave vacuum electronic device. It generates high-frequency electromagnetic radiation by stimulated cyclotron resonance of electrons moving through a strong magnetic field typically provided by superconducting magnet. The 42 GHz gyrotron system (Gycom make) is shown in Fig.1. It has been installed for ECRH [1 – 2] operation on Aditya and SST1 tokamak. It delivers 500kW of RF power @42GHz for 500ms duration at ~50kV cathode voltage and ~20A beam current with ~50% duty cycle. Transmission line of ~20 meter length laid between gyrotron and SST1 tokamak, also ~75 meter of transmission line laid between gyrotron and Aditya tokamak alongwith mirror based launcher to launch the power into tokamaks. RF microwave switches have been installed to select the launch of microwave power on tokamaks or water cooled dummy load. The ECRH power in fundamental O-mode(1.5T) & second harmonic X-mode(0.75T) is launched from low field side (radial port) of the tokamak. PXIe based DAC system is shown in Fig.2. It has been designed, developed and installed for gyrotron system operation. This paper explains steps necessary for gyrotron operation and control. It also showcases the features of DAC systems [4] for gyrotron operation, its software design, adopted methodology for development.

FIG. 1 42 GHz,500kW,500ms Gyrotron System

FIG. 2 PXIe DAC system hardware
2. GYRROTRON SYSTEM COMPONENTS

Gyrotron system components block diagram is shown in Fig.3. ECRH system operation involves integration, control and operations of many sub-systems like auxiliary power supplies (Anode, Cathode, Filament, Cryomagnet etc), crowbar unit and water cooling system. It essentially requires real time signal monitoring, data acquisition and control with post data processing and analysis. ECRH system comprises with ~ 32 Analog Inputs / 4 analog outputs and ~64 Digital IO in use. PXIe (PCI eXTensions for instrumentation) a rugged PC-based platform is selected for DAC system development. PXIe based DAC system[5] having 8 3U-slot PXIe chassis with pre-installed I/O cards is shown in Fig. 2. Gyrotron operation requires a systematic and sequential controlled operation of different power supplies. Cathode voltage and anode voltage are pulsed in a specific manner to get the required microwave power output. Central control interface has also been established with ECRH DAC for remote operation. As Gyrotron is operated at very high potential, Safety interlock circuits has been designed, developed and installed for gyrotron tube safety. It operates in fault conditions and removes high voltages within 10 µS from the tube.

FIG. 3 Gyrotron System components in ECRH.

DAC system requirement and gyrotron operation procedure is discussed in next sections.

3. ECRH DAC SYSTEM

PXIe based ECRH DAC system hardware and software components are listed as follows:

3.1 Hardware

PXIe boards have been installed in NI make 8-slot PXI express 3U chassis.

— PXIe 1082 PXI express chassis (bandwidth more than 1GB/s)
— PXIe 8135 RT core i7 -3610QE 2.3 GHZ Controller (win 7 & optional bootable with LabVIEW -RT)
— PXIe 6363 X series multifunction DAQ card(32 SE AI, 2 M samples/s aggregate,4 AO & 48 DIO)
— PXIe 6356 X series simultaneous fast sampling DAQ card (8 AI -1.25 Ms/s/channel,2 AO & 24 DIO)
— PXI 7842 R RIO FPGA board (Virtex 5- Lx50 multifunction reconfigurable IO,8 AI,8 AO,96 DIO)

3.2 Software


ECRH DAC system consists of following modules to fulfil operational needs of gyrotron on SST1 tokamak.

— Signal conditioning rack
— Monitoring, control and acquisition software
— Fast protection with FPGA
— RHVPS control interface with ECRH DAC
— SST1 central control interface with ECRH DAC
— Data analysis and storage

The ECRH DAC integrates all discrete power supplies operation on single GUI console screen. It acquires 48 digital and 32 analog inputs(+/−10V) signals. It has 4 analog outputs and 48 digital output. Due to high operating potential of gyrotron all the associated electronics circuitry would be designed with adequate isolation for the safety of DAC system as well as human. Fiber optic Transcievers (HFBR 1521Z & 2521Z) and cables are used for field signal connections. PXie 6363 card is used for monitoring as well as acquisition of the signals with selectable rates and PXie 6356 is used for acquiring the critical fault signals data at very high sample rate of 1 MHz. Acquired system data are stored online on PXie system and stored in a binary file on host PC after the shot. The fast and slow interlocks with crowbar circuit are implemented using PXI 7842R RIO FPGA board for gyrotron protection. In case of any fast interlock fault signal(Arc detectors, video arc, dI/dt, vac-ion,beam over voltage,beam over current and anode over current signal) detection during operation, it initiates a crowbar signal to activate the ignitron trigger modules to fire ignitron and puts the crowbar system in conduction which passes the fault current and removes cathode and anode high voltages within 10 μS. The sequence of interlocks data are also stored for later on analysis of fault occurrences. A dedicated data analysis module has been developed using NI LabVIEW for data visualization & management for after shot analysis. PXie DAC Main operation GUI console and data analysis module is shown in Fig.4.

4. GYROTRON OPERATION

Gyrotron operation requires a sequential and interlocked operation of all the sub systems connected to it in standalone as well as in remote mode with central control. It requires continuous monitoring of voltage and current signals of different power supplies along with its status on GUI screen.

In 42GHz ECRH system different power supplies are connected to the gyrotron and operated by dedicated PXie based control system. Water cooling system is connected for excess heat removal in different parts of gyrotron system i.e Collector, MOU(Matching Optical Unit), Dummy load, window, transmission line etc. The data logger are used to monitor the flow, temperature and pressure in different parts of gyrotron tube.

4.1 HV Test and conditioning of 42 GHz gyrotron

In gyrotron operation, sequential start up of water cooling system, cryomagnet, ion pump and filament PS are carried out for its predefined operating values. After checking required Liquid Helium level in cryomagnet, gyrotron water cooling is started as gyrotron operation start up procedure. Once water flows in cathode, window, MOU, ion pump and other parts of gyrotron are reached at preset values and remained within defined limit, Cryomagnet power supply is energized and raised cryomagnet current upto 28.2 A in 25 minutes.

![FIG. 4 PXie DAC GUI Console and Data analysis tool developed in NI LabView](image-url)
Cryomagnet current is raised with ramp up algorithm through DAC or manually as per the requirement. Ion Pump power supply would be started just after cryomagnet current reached at 50% of its set value. Filament interlock with gyrotron water cooling system is checked before Filament Power Supply (FPS) is switched on. Filament voltage ramped up slowly for preset value. Filament current of 18.7 A would be achieved in 25-30 minutes. All power supply status are monitored and controlled by ECH console PC shown in Fig. 4 and target PXIe hardware system.

Real gyrotron operation starts with high voltage conditioning. The Regulated High Voltage Power Supply (RHVPS)[3] is connected to cathode of the tube. The control signal interface between RHVPS and ECRH DAC has been implemented with failsafe logic having 100 meters of fiber optic cables with repeater in between. High voltage DC power supplies connected with cathode and anode are operated for pulsing the gyrotron tube for conditioning it as well as for microwave power output. Since Gyrotron tube is a delicate microwave device, FPGA based Fast interlock circuit is implemented for its protection during any fault conditions. Two series Ignitron based HV crowbar system has been installed for the protection of gyrotron, which removes HV within 10 µS. The Gyrotron can be operated standalone as well as remotely through programmed time base hardware trigger from Central Control System.

4.2 ECRH Pulse generation

The main operating parameters limit of Gyrotron are beam voltage: -50kV, beam current: 20A, anode voltage: +20kV, cryomagnet current: 28.2A and filament power ~ 630W.

![FIG 5. ECRH Pulse requirement](image)

![FIG 6. Actual ECRH pulse generated with PXIe DAC system](image)

The ECRH pulse requirement for SST1 and Aditya tokamak operation is shown in Fig.5. The essential part of Gyrotron operation is pulsing the anode and cathode high voltages simultaneously with pre-programmed delay and rise time with fast active interlocks. RHVPS control interface with ECRH DAC is checked with back to back signal monitoring before energizing the HV transformer. Once the HV control interface check is completed, gyrotron HV conditioning carried out with pulsing (~30ms -70ms) the cathode voltage in steps of 5kV till 35kV and monitor the beam current (max. 15A) maintaining ion pump current well below 70 µA. After 35kV of cathode voltage, anode voltage pulse (7-18kV) would be applied to gyrotron for 30-500 ms to get 50-500 kW of microwave power output. In order to optimize the power, the beam & anode voltages increased successively to its normal values (BeamV 42 to 45 kV, AnodeV 12-17 kV). ECRH power has been launched on dummy load and tokamak for experiments. The actual ECRH pulse generated with DAC is shown in Fig 6.

Conclusion

During operating gyrotron with PXIe DAC software, task transition delay of 1-2ms is noticed. These may lead unwanted delay of 2-3 ms in crowbar action during sudden fall of cathode voltage. In gyrotron operation cathode voltage must be present while applying anode voltage, so to avoid loop or task transition delay effects hardwired HV feedback interlock is implemented for instant crowbar action in absence of real cathode high voltage on gyrotron. Also digital input filters have been implemented to remove spurious intakes as input to fast
FPGA interlock circuit which disturbed the overall gyrotron operation. The 42 GHz gyrotron system is now under use with SST1 and Aditya tokmak for pre-ionization and heating experiments. It is successfully operated with PXIe based data acquisition and control system having all necessary safety precautions implemented with FPGA based protection circuits. The ECRH pulse of ~225kW,131ms duration on dummy load is shown in Fig. 7.

**FIG 7. ECRH Pulse of ~225 kW, 131 ms duration on dummy load**

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REFERENCES

[5] “PXI Based Data Acquisition and Control System for ECRH Systems on SST-1 And Aditya Tokamak” Fusion Engineering and Design 112 (2016) 919–923