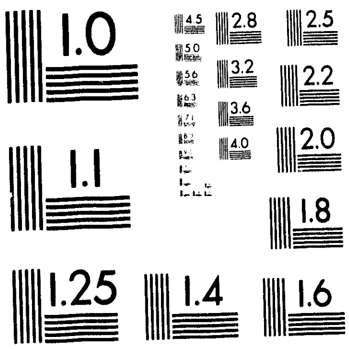
1.0
4.5
2.8
2.5
5.0
3.2
5.6
2.2
6.3
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

1 of 1

GA–A21439

OPERATIONAL UPGRADES TO THE DIII–D 60 GHz ELECTRON CYCLOTRON RESONANT HEATING SYSTEM

by

T.E. HARRIS and W.P. CARY

This is a preprint of a paper to be presented at the 15th IEEE Symposium on Fusion Engineering, October 11–15, 1993, Cape Cod, Massachusetts, and to be printed in the *Proceedings.*

Work supported by
U.S. Department of Energy
Contract DE–AC03–89ER51114

GENERAL ATOMICS PROJECT 3466
OCTOBER 1993

GENERAL ATOMICS

OPERATIONAL UPGRADES TO THE DIII–D 60 GHz ELECTRON CYCLOTRON RESONANT HEATING SYSTEM

T.E. Harris and W.P. Cary
General Atomics
P.O. Box 85608, San Diego, California 92186-9784

ABSTRACT

One of the primary components of the DIII–D radio frequency (rf) program over the past seven years has been the 60 GHz electron cyclotron resonant heating (ECRH) system. The system now consists of eight units capable of operating and controlling eight Varian VGE-8006 60 GHz, 200 kW gyrotrons along with their associated waveguide components. This paper will discuss the operational upgrades and the overall system performance. Many modifications were instituted to enhance the system operation and performance. Modifications discussed in this paper include an improved gyrotron tube-fault response network, a computer controlled pulse-timing and sequencing system, and an improved high-voltage power supply control interface. The discussion on overall system performance will include operating techniques used to improve system operations and reliability. The techniques discussed apply to system start-up procedures, operating the system in a conditioning mode, and operating the system during DIII–D plasma operations.

INTRODUCTION

The 60 GHz ECRH gyrotron system has been the source of microwave heating at DIII–D. There are eight high-voltage control units used to operate Varian's VGE-8006 60 GHz, 200 kW gyrotrons. Along with these units are their associated waveguide and microwave launch systems. Many modifications were instituted (over the years) to enhance the system operation and performance. Modifications discussed in this paper will be an improved over-current fault response system which decreases the amount of energy delivered to a gyrotron during a fault, a high-voltage power supply interface allowing selection of one of two available high-voltage power supplies, and a computer controlled timing system that is menu-driven and is interactive with the DIII–D CAMAC timing-control highway. Along with these modifications, this paper will also discuss operating techniques acquired through many hours of operation. These techniques, which aided in overall system performance during DIII–D operations and gyrotron conditioning, include system start-up with a cold- or a hot-filament cathode, a conditioning process which readies the system for ECH operations, and queuing gyrotrons coincident with DIII–D plasma discharge timing.

MODIFICATIONS

The modifications discussed in this section were implemented to improve gyrotron protection during an over-current condition, and to simplify the control system selectivity between a DIII–D Neutral Beam Accel power supply configured for negative polarity and the ECH power supply (ECHPS-1). Also included in this section is the addition of a computer controlled pulse timing system replacing the inefficient analog timing circuit located in the cathode control chassis and in each gun-anode control chassis. The design concept was to target specific points within the existing control system where improvements were needed and to make the modifications virtually transparent to the ECH control system. Some circuits needed only existing circuit cards modified, while other modifications required complete circuit card manufacturing with direct plug-in compatibility.

Over-Current Fault Control

One problem with the operating system was the lack of proper tube-fault response; tube-fault response is the action that the control system takes due to over-current conditions within the gyrotron. With an over-current, the high-voltage power supply pulse-command is terminated. This terminates the high-voltage pulse, thus eliminating the main current source.

Although the pre-existing tube-fault circuitry was adequate, it did present erroneous fault conditions due to the charge-discharge characteristics of a pulsed high-voltage system. Each gyrotron and its associated high-voltage unit possesses an inherent capacitance. When the system is pulsed with high-voltage, a charging current will exist during the rise and fall of the high-voltage pulse. These charging currents exist primarily in the gun-anode and body circuits of the gyrotron and can exceed both circuits' nominal operating current level. A current shunt is used in both gun-anode and body circuits to yield a proportional voltage for fault-comparison and monitoring the respective currents.

There are two levels of over-current protection in both the body and the gun-anode circuits; modifications were made to each level. The high-level acts upon

Manuscript received October 12, 1993. This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

transient current which exceed a predetermined upper-level. The pre-existing circuitry allowed for an extraordinarily high-level of current to possibly exist either from a short-circuit or an over-voltage condition. At a reduced voltage level, the gun-anode-to-cathode circuit was properly ac compensated. Once compensated, the inherent capacitance was determined from using the known capacitance added for compensation and observing the charge-discharge spike during low-voltage tests. A charge-discharge time constant of $\sim 30\ \mu$sec was observed. Therefore, a single-pole low-pass filter with a 6.6 KHz bandwidth was inserted at the gun-anode fault-comparison circuit input. This allows for a conservative trip set-point on the low-level fault-comparison network. (*e.g.*, Varian specifies a nominal gun-anode current of < 3 mA. With the set-point set at 3 mA, the high-voltage will be terminated when the nominal current during a gyrotron pulse exceeds 3 mA). This same technique was used on the gyrotron body circuit. The body circuit does not need ac compensation and since the inherent capacitance is much smaller, the charge-discharge spike is much smaller.

A high-level fault is due to current transients within the gyrotron resulting from an internal spark-down. These faults have very fast excursions and can not be detected by the low-level fault-circuit in time to prevent dangerous consequences to the gyrotron. Two different techniques are used to detect a high-level fault in the body and gun-anode circuits. The body circuit uses the forward voltage drop of four diodes to drive an optical transmitter. The pre-existing circuit performed sufficiently; more robust components were added though, to handle the potential high current impulse during a fault-condition. The gun-anode shunt-voltage is used to detect a high-level fault within the gun-anode. A comparison circuit driving an optical transmitter compares the shunt-voltage against a pre-determined voltage level. The optical signal is transmitted via a fiber-optic to the current-limit board. The pre-existing circuit used a zener-diode clamp offering no selectivity and functioned in a non-fail-safe condition.

Both gun-anode and body-fault circuits each use a current-limit card. This card OR's both high and low level fault signals for the respective tube circuit. A single fault signal is then sent to the respective gun-anode control chassis located in the ECH control room. The modifications made to these cards includes the addition of the low-level filtering circuit for the respective tube circuit and reconfiguring the circuitry for fail-safe operation.

Both the gun-anode current and cathode current use the same type of telemetry network. This network consists of current shunts and a voltage-to-frequency (v-f)/frequency-to-voltage (f-v) link. The v-f cards have been redesigned and printed circuit cards manufactured. The new cards use a upgraded v-f module with a operating frequency of 3.5 to 5.5 MHz and a 80 kHz bandwidth. This card also has the high-level-current fault comparator circuit as mentioned above.

High-Voltage Power Supply Interface

The 60 GHz system can use one of two high-voltage power supplies; a negative polarity DIII–D Neutral Beam Accel high-voltage power supply or the DIII–D ECHPS-1 high-voltage power supply. The two power supplies have different manufacturers, thus having different control interfaces. Instead of reconfiguring the ECH control system every time a switch is made from one power supply to another, the main control interface chassis was redesigned and modified using pre-existing components. To switch the control of one power supply to the other, all the operator needs to do is push a button relative to the system desired. The proper logic levels and interlocks are set for the respective power supply when the desired button is depressed. Using existing components kept hardware cost low and all that was required was to rewire the ECH main control chassis.

Computer Controlled Timing

The pre-existing timing control system consisted of an analog ramp-comparator circuit located in the cathode control chassis and in each of the gun-anode control chassis. The pulse width was determined by thumbwheel switches which varied the control-ramp slope. This system had limitations and pulse widths would vary with temperature and component tolerances. Therefore, a new timing system has been installed which consists of an IBM AT computer, a CAMAC interface chassis, and a pulse control board located in the cathode control chassis and in each gun-anode control chassis. The computer addresses the CAMAC timing modules via a crate controller. The timing modules then direct the desired timing patterns to the cathode control chassis and the respective gyrotron gun-anode control chassis.

The computer contains all the timing software needed to operate the gyrotron system. The timing parameters such as pulse width and repetition rate are entered into the computer by the system operator. There are several video pages the system operator can select depending on the desired gyrotron system operating scheme. When the ECH program is initiated, the operator is prompted to select one of four operating schemes from the top level video page.

CATH — This mode is used for conducting high-potential tests of the gyrotron system with the high-voltage power supply.

XGYRO — This mode is used to test two or more gyrotrons, with each output terminated into a water load.

GYRO — This mode is used to test an individual gyrotron with its output terminated into a water load.

DIII–D — This mode is used to synchronize the timing sequence of one or more gyrotrons with the timing sequence of the DIII–D tokamak operation.

After a particular operating scheme is chosen, another video page is displayed. This page allows the operator to alter timing parameters and initiate the selected timing-mode program.

The CAMAC crate contains the timing hardware driven by the computer software. The crate control module sends and receives the interrupt and timing information to and from the computer. The controller directs the timing information to the timing buffer and register modules. The buffer module holds the timing information until it becomes time to send it to the cathode and gun-anode control chassis. The timing information passes through the timing register module which consists of a series of switches. The switch pattern used in the register module depends on the gyrotrons chosen to pulse. Therefore, the proper timing signal will be directed to the desired gyrotrons. Along with these modules are the DIII–D timing-receiver module and an interrupt module. The timing-receiver produces a timing pulse, synchronized with DIII–D operations, which provides inputs to the interrupt module. There are also hardware interlocks which provide an input to the interrupt module. The interrupt module then sends software interrupts via the crate controller to the active computer timing program. If operating gyrotrons with the DIII–D video page, then a timing-receiver interrupt will cause the conditioning program to halt and load the ECH timing sequence synchronous with a DIII–D tokamak discharge into the timing buffers. An interlock interrupt will halt the timing program until the interlock is cleared. Other modules used are two 32-channel, 64 kB digitizers. These digitizers acquire ECH data during a DIII–D shot for transfer to the DIII–D data acquisition system.

The other component in this timing system is a pulse-control card located in the cathode chassis and each gun-anode control chassis. This card receives the raw timing signal from the CAMAC timing buffers and applies contingencies to allow safe operation of the ECH system. For the cathode chassis, a power supply pulse-command is issued contingent upon high voltage being available, a pulse permissive from the DIII–D control room, and no gyrotron over-current fault condition. If any of these events exist when a raw timing signal is sent, then the pulse command to the high-voltage power supply is blocked. If the pre-pulse events are satisfied and a pulse command is sent, then a conditional pulse command will be passed to the power supply and will be terminated immediately in the case of a pulse-contingency breach. The gun-anode pulse-control card functions similarly to the cathode pulse-control card. This card receives a raw gun- anode timing pulse and also applies contingencies. The constraining events are that there must be a conditional cathode command and there must not be a wave guide related fault. If, during a gun-anode pulse, a wave guide related fault occurs, then the gun-anode conditional command will be blocked for 20 msec and then allowed to continue; this is referred to as a retry and the number of gun-anode re-tries is selected by the operator before the pulse.

OVERALL SYSTEM PERFORMANCE

Before the DIII–D operation campaign begins, the 60 GHz gyrotron system is inspected and tested. This includes high-voltage circuit inspection, fault-card testing, and diagnostic-telemetry calibration. Once this system checkout process is complete, then the following operational modes can be executed.

System Start-Up Procedures

There are two techniques used for system start-up; a cold start and a hot start. The state of the cathode filaments dictates which technique to use.

A cold start is performed when the main control power has been off and the system has been shutdown, *i.e.*, the filaments have been off and the cathode is cold. Therefore, filament voltage must be applied slowly until the nominal current is flowing through the filaments. The current is raised at a 1 A/sec rate to approximately 1.05 times the normal operating current value. This filament current level is maintained until the filament voltage rises to the normal operating value. The filament current is then adjusted and regulated to the nominal operating level as per the previous operation tables or the manufacturer's specified test level. The cold start is performed at least 48 hours before the gyrotrons are needed for DIII–D plasma operations.

The filament current and voltage are at their nominal values for a hot start. Once the operation campaign begins, the gyrotron filaments are left on for the duration of the operating period. This allows for quick start-up on DIII–D operation run days and reduces the amount of thermal cycling of the filaments. However, there are circumstances which develop which require the 60 GHz system to be shutdown. After these events pass, a cold-start must be performed.

Conditioning Mode

Once the start-up is complete, gyrotron conditioning can begin. Conditioning must be performed the week prior to a DIII–D operation period and then daily during the operation period. For both cases, the conditioning routine is virtually the same. Serial and parallel gyrotron conditioning are the two modes used.

The parallel mode instructs all selected gyrotrons to pulse at the same time. Individual gyrotron commands and the cathode command can be blocked by the operator by using the control switch located on each chassis. This switch allows the operator to block pulsing without stopping the timing program. This is helpful when isolating a troublesome gyrotron and still maintaining conditioning for the remaining gyrotrons. Using the control switch, an operator can turn each gyrotron on and monitor its individual tube and wave guide parameters, *e.g.*, cathode current, forward power, gun-anode current, and gyro-window light. After the tube parameters have been set for each gyrotron selected for pulsing, then the gyrotron pulse width can be extended to 100 msec in 20 msec increments. The repetition rate is maintained at 0.1% to prevent the wave guide located within the DIII–D vacuum vessel from overheating. The gyrotrons, as a group, are pulsed ten times at each 20 msec plateau.

The gyrotron pulse timing is then configured to serial mode at the 100 msec pulse width level. In this mode the gyrotrons are pulsed sequentially. The repetition rate for any one gyrotron is still maintained at or below 0.1% by adjusting the null-time between individual gyrotron pulses, *e.g.*, the fewer gyrotrons selected, the greater the null time between individual gyrotron pulses. The gyrotrons are then ready for plasma operations once the conditioning pulse is at 100 msec. Using this conditioning technique from a hot-start condition, the selected gyrotrons are ready for DIII–D plasma operations in twenty to thirty minutes.

DIII–D Plasma Operations

When the ECH system is conditioned and ready for DIII–D plasma operations, the session leader for that day's experiment determines ECH timing relative to the DIII–D plasma shot. The session leader gives this information to the ECH operator for that day. The ECH operator then enters the timing information into the ECH computer. Twenty seconds before time-equal-zero of the DIII–D plasma shot ($t_{\mathrm{DIII-D}} = 0$), the conditioning program is halted. The ECH timing pattern for the plasma shot is now loaded into the timing buffers located in the CAMAC crate. Once loaded the information is locked in ten seconds before $t_{\mathrm{DIII-D}} = 0$. After the plasma discharge and shot data has been acquired, the conditioning program resumes.

There are a few DIII–D machine-related interlocks which remove the ECH pulse-permissive. During a plasma shot, there must be plasma current, there must be proper toroidal field current, and there must be no overheating of the ECH transmission line located inside the DIII–D vacuum vessel. During between-shot conditioning, along with the transmission line overheating interlock, a particular group of diagnostic shutters must also remain closed. The diagnostics protected by these shutters are sensitive to microwave power. Therefore, the shutters remain closed during ECH conditioning and if opened then ECH conditioning is halted.

CONCLUSION

The modifications and operating techniques discussed in this paper were implemented to improve the 60 GHz ECH system performance. Having a reliable over-current fault system is paramount in a multiple gyrotron system. It must minimize the amount of energy deposited to the delicate components housed within the gyrotron and it must be reliable so the operator has confidence in the fault information necessary for making appropriate operating decisions. The ECH Main Control chassis can now interface with either high-voltage power supply ensuring the proper logic levels and interlock status is transceived between the ECH control room and the selected power supply. An operator can configure gyrotron pulse sequencing to accommodate DIII–D operations, ECH conditioning, or troubleshooting ECH system problems using the computer-controlled timing system. The operating techniques discussed have been proven, from operation period to operation period, to be effective in system start-up and getting the system prepared for DIII–D plasma operations.

DATE
FILMED
12/7/93
END