GA–A26849

ECH SYSTEM DEVELOPMENTS INCLUDING THE DESIGN OF AN INTELLIGENT FAULT PROCESSOR ON THE DIII-D TOKAMAK

by
D. PONCE, J. LOHR, J.F. TOOKER, R.C. O'NEILL, C.P. MOELLER,
J.L. DOANE, S. NORAKY, K. DUBOVENKO, Y.A. GORELOV,
M. CENGHER, B.G. PENAFLOR, and R.A. ELLIS

AUGUST 2010

GENERAL ATOMICS

DISCLAIMER

GA–A26849

ECH SYSTEM DEVELOPMENTS INCLUDING THE DESIGN OF AN INTELLIGENT FAULT PROCESSOR ON THE DIII-D TOKAMAK

by
D. PONCE, J. LOHR, J.F. TOOKER, R.C. O'NEILL, C.P. MOELLER, J.L. DOANE, S. NORAKY, K. DUBOVENKO, Y.A. GORELOV, M. CENGHER, B.G. PENAFLOR, and R.A. ELLIS*

This is a preprint of a paper presented at the 26th Symposium on Fusion Technology, September 27 through October 1, 2010, Porto, Portugal and to be published in *Fusion Engineering and Design.*

*Princeton Plasma Physics Laboratory, Princeton, New Jersey.

Work supported by the U.S. Department of Energy under DE-FC02-04ER546198 and DE-AC02-09CH11466

GENERAL ATOMICS PROJECT 30200
AUGUST 2010

GENERAL ATOMICS

ECH System Developments Including the Design of an Intelligent Fault Processor on the DIII-D Tokamak

D. Ponce, J. Lohr, J.F. Tooker, R.C. O'Neill, C.P. Moeller, J.L. Doane, S. Noraky, K. Dubovenko, Y.A. Gorelov, M. Cengher, B.G. Penaflor, and R.A. Ellis[a]

General Atomics, PO Box 85608, San Diego, California 92186-5608, USA
[a]Princeton Plasma Physics Laboratory, PO Box 451, Princeton, New Jersey 08543-0451, USA

A new generation fault processor is in development which is intended to increase fault handling flexibility and reduce the number of incomplete DIII-D shots due to gyrotron faults. The processor, which is based upon a field programmable gate array device, will analyze signals for aberrant operation and ramp down high voltage to try to avoid hard faults. The processor will then attempt to ramp back up to an attainable operating point. The new generation fault processor will be developed during an expansion of the electron cyclotron heating (ECH) areas that will include the installation of a depressed collector gyrotron and associated equipment. Existing systems will also be upgraded. Testing of real-time control of the ECH launcher polodial drives by the DIII-D plasma control system will be completed. The ECH control system software will be upgraded for increased scalability and to increase operator productivity. Resources permitting, all systems will receive an extra layer of interlocks for the filament and magnet power supplies, added shielding for the tank electronics, programmable filament boost shape for long pulses, and electronics upgrades for the installation of the advanced fault processor

Keywords: ECH, gyrotron, waveguide, control, field programmable gate array, fault

1. Introduction

The electron cyclotron heating (ECH) system on DIII-D is currently undergoing an upgrade and expansion, taking advantage of a long refurbishment period for the DIII-D program to allow for the mounting of a neutral beam line onto a tilting structure. During this period, a new gyrotron system will be added with a tube rated conservatively at 1.2 MW for a 10 second pulse length. The ECH waveguide lines will be re-routed along a more direct path to the DIII-D vessel, eliminating two miter bends per line. Refinement and testing of real-time control of the ECH launcher polodial drives by the DIII-D plasma control system (PCS) will be completed. The ECH control system will receive various upgrades. The control software will be revised to increase scalability and operator productivity. An extra layer of interlocks will be added to the filament control system to allow for unsupervised continuous operation. The interlocks in the magnet power supplies will be supplemented with a redundant system to increase reliability. Shielding will be increased for the electronics close to the gyrotron tanks to combat the effects of rf parasites. An advanced fault processor is being developed which will directly generate the high voltage references and dynamic filament reference, analyze signals to monitor gyrotron operation, act to prevent serious faults from occurring, and restart pulses if operation was prematurely suspended.

2. ECH system expansion

The ECH gyrotron hall is being expanded to accommodate two new gyrotron tanks. In addition, an annex to the ECH electronics room and a new 100 kV high voltage power supply are being built to support and power these tanks. The first gyrotron added will be a Communications & Power Industries (CPI) 1.2 MW, 10 second, 110 GHz, depressed collector tube. This tube is expected to be delivered in 2011. The second tube has been specified to have a frequency of 117 GHz, placing the resonance at a smaller major radius in the DIII-D vessel when the magnet field is over 2 Tesla. This should result in increased current drive because of reduced electron trapping. The delivery date for this tube has not yet been determined. When these tubes are combined with the present system [1], power injected into DIII-D by ECH will exceed 5 MW.

3. Waveguide line upgrades

The waveguide line efficiency was revisited to determine if the power delivered to the DIII-D vessel could be increased while being cost-effective. Two solutions being pursued are the re-routing of the waveguide lines and replacement of the miter bends with lower loss units.

Other upgrades will also improve the performance of the system. For example, the in-line power monitors installed close to the DIII-D vessel are being replaced

author's email: dan.ponce@gat.com

with a miter bend that can provide a measurement of power that is independent of polarization.

3.1 Waveguide line re-routing

The 31.75 mm diameter waveguide lines are being rerouted from the gyrotron hall to the DIII-D hall along a more direct route. At least two miter bends and about 14 of the approximately 100 meters of waveguide will be eliminated from each line. Approximately 200 kW of extra power is expected to be delivered to DIII-D following the modification.

3.2 Low diffraction miter bend

A low diffraction miter bend is in development which is expected to reduce the loss per bend from about 1.5% to less than 0.5%. The new design includes a mode conditioning section before and after the mirror which will increase the length in each leg by about 25 mm compared with the present units. A relatively minor modification to the adjacent waveguide will be required to substitute the new units for the old ones. One waveguide line will be retrofitted with these bends and tested in late 2010. If the results warrant, new miter bends will be installed in all ECH waveguide lines.

3.3 Power monitor miter bend

Development on a four-port power-monitor miter bend is nearing completion. The prototype has proven to be useful in measuring mode content to improve the alignment of the rf beam as it is introduced into the waveguide. The new monitor will be installed in the DIII-D hall to allow for a polarization independent measurement of power injected into the DIII-D vessel [2]. A final round of testing at nearly 1 MW and 5 second pulse length will take place in late 2010.

3.4 Real-time launcher poloidal mirror movement

Electric motors have been specified and installed in the polodial drive of the ECH launchers. The launchers were designed, built, and refurbished by the Princeton Plasma Physics Laboratory. The motors will allow more accurate positioning of the polodial mirrors than could be accomplished with the previous air motors. Control of these mirrors with the DIII-D plasma control system (PCS) has recently been demonstrated. This system is currently being further developed to allow controlled real-time mirror movement during DIII-D shots. The expected scan rate is in excess of 20 degrees per second, providing a sweep across the tokamak upper half-plane in about 2 seconds.

4. ECH control and instrumentation system upgrades

The expansion of the ECH system will allow for the deployment of control and instrumentation system upgrades that have been in development. These upgrades will be incorporated on the new gyrotron tank system and on the other systems as resources allow. The present system has a networked and modular topology, with redundancy used to improve reliability. The system is mode sensitive, allowing operators to issue simple commands to reconfigure operations and deploy appropriate monitoring schemes. The system is designed with standards for the various interfaces so that components, including the gyrotrons, can be supplied by more than one manufacturer and can use different internal designs. This also allows the system to be maintained as components become obsolete. Details on the present system have been presented previously [3-4].

4.1 Software upgrades

The ECH control software is being revised to increase scalability. This includes avoiding user interfaces that display information for a fixed number of gyrotron systems. It also includes revising fixed sized internal data structures. Software modules that are currently hard coded for a specific system will be revised to accept parameters from an initialization file. This will allow more code to be reused.

The software is also being revised to increase operator productivity. Performance issues will be addressed so that the software is more responsive to operator input. The user interface design will make it easier for operators to switch between and track tasks, recall setups, review settings, and handle multiple gyrotron systems simultaneously.

The data acquisition system is being upgraded to give the operators a near real-time display. The goal is to provide an interface that is more flexible than the oscilloscopes installed at the operator consoles while being just as responsive. The upgrade will include the direct transfer of the data to the DIII-D database over a network connection. This will allow a CAMAC based data acquisition system to be retired.

4.2 Filament reference programming

The gyrotron filament voltage reference is currently determined by two set-points; an idle reference and a boosted reference. A switch, controlled by the pulse timing system, directs the boosted reference to the filament power supply a few seconds before a gyrotron pulse. On upgraded systems, the filament reference will be directly generated by the advanced fault processor. This will allow for more complex boosting waveforms to be used during a pulse sequence, refining control of the gyrotron beam current. This will also allow the filament to be modulated as requested by the fault-mitigation logic in the advanced fault processor.

4.3 Filament interlock redundancy

Keeping the filaments warm over-night during experimental periods is expected to increase the stability of gyrotron operation, especially during the first few hours of the day. To enhance the probability that this can be accomplished without increasing the risk of a failure, redundant interlock logic will be added to the filament power supply permit.

4.4 Magnet power supply interlock redundancy

An extra layer of interlocks will also be added that monitors the magnet currents to compensate for a deficiency discovered in the interlocks incorporated in the magnet power supplies. The new interlocks will have multiple levels of monitoring for each circuit. Remotely programmable tight high and low levels will monitor set-point compliance. A wider range of high and low limits will define the permitted operating window. Out-of-bounds limits will be used to detect and shut down run-away power supplies. Frequency monitoring might also be included to provide a redundant interlock for collector magnet sweeping power supplies.

4.5 Increased electronics shielding

Shielding will be increased for the electronics located close to the gyrotron tanks in response to recent suspected episodes of fault indications induced by parasitic rf noise of around 100 MHz. The controls in the electronics annex supporting the new tanks will also include extra shielding. The annex is surrounded by four high voltage power supplies and the expanded gyrotron hall, all significant sources of electrical noise.

5. Intelligent fault processor

A new generation fault processor is in development which is intended to increase fault-handling flexibility and reduce the number of incomplete DIII-D shots due to gyrotron faults. The processor, which is based upon a field programmable gate array (FPGA) device, will analyze signals for aberrant operation and ramp down high voltage to try to avoid hard faults. The processor will then attempt to ramp back up to an attainable operating point. One of the most common faults is the loss of rf generation. If not caught quickly enough, this can lead to secondary faults such as high internal pressure, internal arcing, or high body current; all of which require more recovery time than the initial fault. By ramping high voltage down immediately in response to the loss of rf generation, it is anticipated that in many cases operation can be resumed in time to still contribute in a meaningful way to the DIII-D shot.

5.1 FPGA-based design

An FPGA based fault processor has been in use for three years on one gyrotron system and two years on another. They have proven to be exceptionally reliable in performing the traditional function of a fault processor, terminating pulses in response to detected faults. The processor responds within about 1 μs and can discriminate a first fault when multiple events are separated by more than 40 ns. This version includes watchdog functions, pulse length counting and limiting, duty cycle limiting, and confirming that high voltage tracks the reference. Limits are set with digital precision. Communication with the control system allows the fault response to be automatically tailored to the current operating mode.

An FPGA essentially behaves like programmable discrete logic. Thus, it executes functions in parallel, deterministically, and independently. Numeric and Boolean registers can be read or written to remotely. The board used for the advanced fault processor includes counter/timers, analog input and output, and digital input and output. Loops can be executed in 25 ns, 16 bit analog signals can be input at 750 kHz and output at 1 MHz, and digital signals can be transferred at 40 MHz. An FPGA has high reliability while maintaining the reconfigurability desired for advanced logic design research.

5.2 Fault processor logic

The fault processor in development will be a hybrid design, incorporating a traditional termination-on-fault unit, an intelligent fault prevention unit, and a resuscitation unit. The traditional unit will have superior status, independently acting on fault signals to protect the gyrotron from damage. The intelligent unit will attempt to prevent terminating fault conditions from occurring. It will analyze signals in real time to classify operating conditions and determine new command increments. The resuscitation unit will assess the condition of the gyrotron and the high voltage power supplies following a terminating fault or soft ramp-down to determine when operation can be restarted.

5.3 Generation of high voltage and filament references

To facilitate control over operation of the gyrotron, the fault processor will directly generate the references for the cathode and body high voltage power supplies and, as was previously discussed, for the gyrotron filament power supply. This can be done at a rate of 750 kHz, which is more than adequate. The parameters determining the shape of the high voltage references will be set by the gyrotron operators. These parameters include the flat top voltage, initial ramp rate, final ramp rate, modulation frequency and shape, and if external modulation from the DIII-D PCS should be accepted. If desired, different power supply regulation schemes can be programmed, as well as various responses to external modulation inputs and timing signals.

5.4 Monitoring of critical faults

The fault processor will still terminate within about 1μs on critical faults, behaving like a traditional unit. The critical fault list includes excessive cathode or body current and excessive window light. Critical fault indications are generated by monitoring electronics located in close proximity to the gyrotron tanks. Optical fiber directs these digital signals to receiving units interfaced to the fault processor. The FPGA logic for critical faults will act independently of other fault processor functions. This is to insure that the level of safety of the gyrotron currently experienced will not be compromised.

5.5 Monitoring of operational anomalies

The fault processor will monitor operating signals to determine compliance with expected performance. If anomalies are detected, the processor will immediately ramp down high voltage references in an attempt to prevent a critical fault from occurring. Anomalous conditions will include the loss of rf generation, reflected rf, rapid changes in cathode and body currents, rapid changes in window light, cathode and body voltage tracking irregularities, and various slow interlock signals.

5.6 Conditions for pulse restart

The fault processor will determine the probable success of restarting a pulse. It will do this by monitoring signals and recent events, such as VacIon current and voltage signals, the number and type of faults that have occurred, the state of the high voltage power supplies and the amount of time left in the pulse. It will use this information to determine if and when to restart a pulse.

5.7 Interacting with signals from DIII-D

There are times that the gyrotrons cannot begin a pulse as originally requested according to the shot parameters. It could be that the DIII-D vessel magnetic field or plasma current is out-of-bounds. It could also be that an external modulation signal is requesting low or no gyrotron power until an experimental event occurs. In these cases, the fault processor will place the pulse on hold until conditions are satisfactory. In the specific case of external modulation, requesting low or no rf power for an extended period can result in collector overloading. To prevent this, the fault processor will not ramp up the high voltage references until some minimum power is requested. If the power request subsequently falls below a minimum and remains there, again potentially leading to collector overloading, the fault processor will ramp down operation until sufficient power is again requested.

6. Conclusions

The upgrades underway on the ECH system will result in more power delivered more reliably and with better monitoring to the DIII-D vessel. A new gyrotron and upgrades to the waveguide lines should add over 1 MW of injected power. The intelligent fault processor should increase reliability by reducing trauma to the gyrotrons and by immediately retrying shots that did not start properly. Leaving the gyrotron filaments warm over-night is expected to result in more stable operation. The new power-monitor miter bend and control system upgrades will improve the ability to monitor operations and control multiple gyrotrons simultaneously.

Acknowledgments

This work was supported by the US Department of Energy under DE-FC02-04ER54698.

References

[1] J. Lohr, et al., Bull. Am. Phys. Soc. **53**, 257 (2008).

[2] M. Cengher, et al., Bull. Am. Phys. Soc. **54**, 166 (2009).

[3] D. Ponce, et al., “The DIII-D Multiple Gyrotron Control System,” Proc. of the 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California, Vol. 1 (Institute of Electrical and Electronics Engineers, Inc., Piscataway, New Jersey) p. 552.

[4] D. Ponce, et al., “The DIII-D Multiple Gyrotron Control System,” Proc. of the 19th IEEE/NPSS Symposium on Fusion Engineering, Atlantic City, New Jersey (Institute of Electrical and Electronics Engineers, Inc., Piscataway, New Jersey, 2002) p. 184.