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ECH SYSTEM ON THE DIII-D TOKAMAK

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ABSTRACT

A significant upgrade to the 110 GHz DIII-D ECH system was completed last year. Two additional Communication and Power Industries (CPI) diode gyrotrons were installed and tested to half the designed pulse length of 10 s. For the 2008 experimental campaign, the DIII-D system comprised five long pulse CPI gyrotrons. One additional high voltage power supply is being tested to support operation of up to 6 gyrotrons simultaneously at full parameters. The five gyrotrons in operation have chemical-vapor-deposition (CVD) diamond windows that are monitored by infrared camera during full parameter testing and operation during plasma experiments. A sixth CPI gyrotron has been repaired after collector failure and is being conditioned for high power at DIII-D. New equipment for gyrotron collector heat load monitoring was tested and used to measure the collector power deposition profile. A new fast fault processing system based on FPGA technology is being commissioned.

I. THE DIII-D ECH SYSTEM

After completion of acceptance testing of the last of the current series of CPI gyrotrons in 2007, five of these tubes have been in routine operation on DIII-D. Overall gyrotron reliability for plasma experiments was 85.5% during the 2008 campaign. All these gyrotrons have a nominal rating of 1 MW rf output power at maximum pulse length of 10 s. All but one met the full output power specification. For long pulse operation during experiments, the magnet fields are slightly detuned for lower power, but higher reliability. Because collector lifetime is determined by cyclic fatigue from sweeping of the electron beam during long pulses, pulse lengths are limited administratively to 5 s maximum length. Typical parameters for the gyrotrons in the DIII-D complex are in Table I.

Gyrotron name	Pulse length (sec)	V_{beam} (kV)	I_{beam} (A)	Efficiency (%)	Installation date at DIII-D	P_{gen} (KW)	Status
s/n 101 (Scarecrow)	5	80	40	31	2002	980	Available
s/n 102 (TinMan)	5	78	40	30	2000	950	Conditioning
s/n 103 (Lion)	5	80	40	31	2002	980	Available
s/n 104 (Luke)	5	80	40	30	2005	970	Available
s/n 105 (Han)	5	80	40	22	2006	700	Available
s/n 106 (Leia)	5	80	40	31	2007	990	Available

Table I.

The DIII-D ECH transmission line system consists of six evacuated windowless transmission lines up to 100 m in length with transmission efficiency from 69% to 79%. As many as 12 miter bends are included in the waveguide lines with loss near 1.5% each for normal miters. Each line also has two polarizing mirrors with loss ~ 2% each. The system in its present configuration is shown in Fig.1.

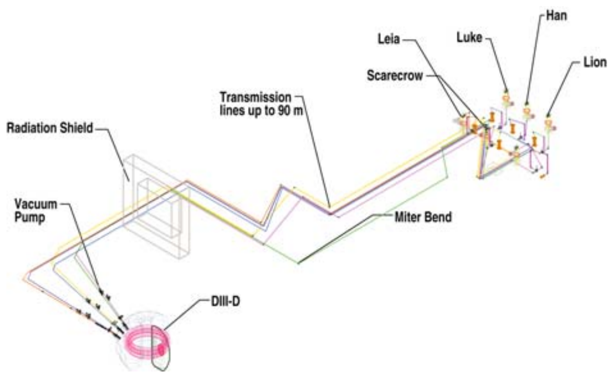

Figure 1. The gyrotron installation on the DIII-D tokamak.

II. COLLECTOR FAILURES

Beginning in 2001, the three gyrotrons from the first group delivered to DIII-D all failed due to collector leaks [1]. A thorough re-analysis of collector performance has been conducted for a 110 GHz, 1 MW, 10-s pulsed gyrotron, in order to identify design improvements and operational guidelines to ensure reliable, long-term operation. These analyses show that cyclic fatigue failures occurred in the electron beam collectors after extended periods of operation. The failures were located low in the collectors, where the beam footprint is smallest and the power density is highest. A new sweeping protocol, with 5 Hz sawtooth waveform, wider sweep and the electron beam biased higher in the collector, decreased the maximum power density on the internal collector surface from 1000 W/cm^2 to 600 W/cm^2, resulting in an increase in the predicted lifetime by about 60% to 50,000 full power 5 s pulses. A new RTD based collector temperature monitoring system was incorporated. It consists of 160 RTDs in 16 columns of 10 each mounted on the outside surface of each gyrotron collector. A new data acquisition system can map the collector load continuously and alarm on excessive temperature. Two typical collector maps are shown in Fig. 2 illustrating the reduced collector loading with the improved sweep. All collector maps show areas with hot spots. It is assumed that the non-uniformity of the collector heating reflects inhomogeneous electron emission from the gyrotron cathodes.

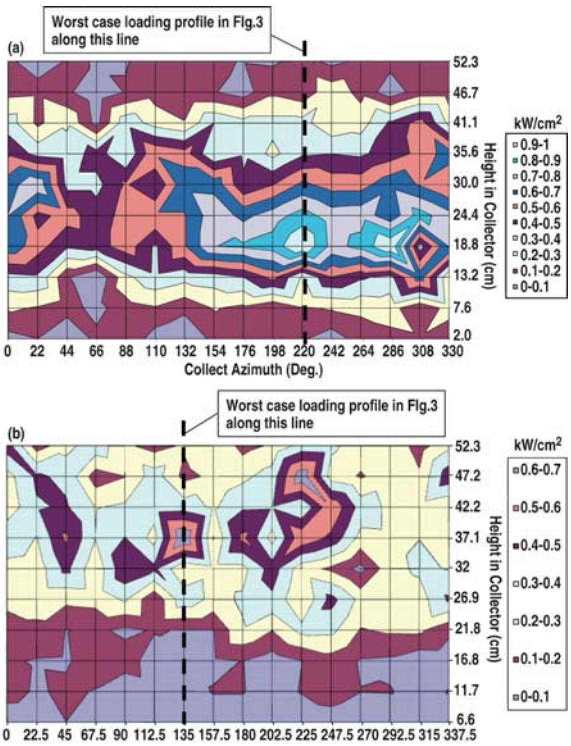

Figure 2. (a) Typical collector map for old sweeping with sinusoidal waveform and 4 Hz; (b) New collector loading with sawtooth sweeping, biased to the top, wider sweep and 5 Hz.

In Fig. 3, the power densities are plotted for two typical cases for which the collector power loading maps are shown in Figs. 2(a) and 2(b). The power density profiles were taken at azimuthal locations indicated by dashed lines in Figs. 2(a) and 2(b) where the highest peak temperatures were measured. Peak loading was reduced with new sweeping by nearly a factor of 2.

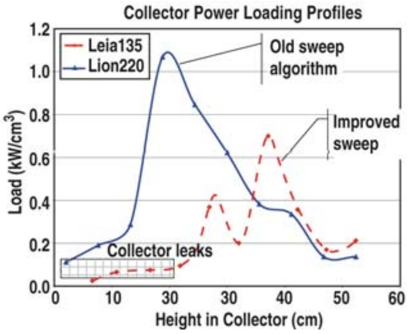

Figure 3. Vertical distribution of electron beam load on collector for two cases of sweeping, sinusoidal and sawtooth and with the electron beam biased both low and high in the collector. Highlighted area shows where collector leaks occurred on first group of gyrotrons received at DIII-D.

III. CONTROL SYSTEM

There have been several upgrades to the control system for the DIII-D gyrotrons. The integrated control system consists of individual gyrotron control computers networked to control, status and data servers. The servers are also networked to operator console computers. On two systems a fast fault system, based on field-programmable gate array (FPGA) technology has been implemented.

The control and instrumentation system for the DIII-D gyrotrons is a networked, modular system which uses redundancy to improve reliability. The system is mode sensitive, allowing the operators to configure and monitor operations by issuing simple mode commands. 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 even differences in design can be accommodated.

Several upgrades to the system have recently been accomplished. Many of these have been in support of the new collector sweeping profile, including parameterizing the sweeper reference generator software, installing higher voltage sweep magnet power supplies, and installing the new collector temperature data acquisition system. One upgrade, which will allow for future advanced operation of the EC system, is the implementation of a fault processor system based upon FPGA technology.

The FPGA and reconfigurable Input/Output technology are ideal for applications requiring custom hardware. The block diagram of the FPGA fault system can be modified in response to changing requirements, which greatly enhances flexibility, improves reliability and decreases the time required to make modifications. The FPGA based fault processor has demonstrated flawless reliability. Like the rest of the control system, the FPGA firmware is programmed using LabVIEW and has sufficient resources to closely interact with the control computers. The fault response of the processor can be tailored to the current operating mode. New features and features previously handled off-board have been incorporated into the fault processor. These include HV equal reference tracking, RF dropout, HV run-on, pulse length limitation, duty cycle limitation, and watchdog monitors. A near term upgrade to the fault processor will be the on-board generation of the HV references. This will allow the processor to immediately re-start a pulse, with proper start-up ramps, following minor faults such as RF dropout. During machine operations, pulse re-start could be attempted after more serious faults, such as cathode over-current, if they can be cleared without a HVPS crowbar and there is no indicated trauma to the gyrotron. On-board generation of the HV references will also enable easier implementation of the system response to the modulation signal from the DIII-D plasma control system.

IV. SUMMARY

Five gyrotrons that have been tested to 1 MW, 5 s rf pulses, have been operational for plasma experiments on DIII-D during 2008. A new collector sweeping algorithm was incorporated for all gyrotrons, which decreased collector loading from 1000 kW/cm^2 to ~ 600 kW/cm^2 with a predicted lifetime increase by about 60% up to 50,000 pulses of 5 s duration. A control system modification increased the flexibility of the ECH fault handling system. Gyrotron reliability reached 85.5% in 2008 during a period including major modifications and upgrades to the DIII-D system.

REFERENCES

[1] K. Felch, *et al.*, Proc. 14th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Santorini, Greece, (2006).

ACKNOWLEDGMENT

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