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STATUS UPDATE ON THE DIII-D ECH SYSTEM

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GENERAL ATOMICS

DISCLAIMER

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*Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, MA
‡Plasma Physics Laboratory, Princeton University, Princeton, NJ

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INTRODUCTION

The gyrotron system on the DIII-D Tokamak is comprised of six Communications and Power Industries (CPI) diode tubes operating at 110 GHz. Five of the six gyrotrons have been tested at 1 MW, 5 s pulses and 500–600 kW 10 s pulses and one has generated about 80% of these powers. The maximum rf power injected into DIII-D at the second harmonic of the electron cyclotron (EC) resonance has been 3.5 MW during simultaneous 5 s pulses of all six gyrotrons. The gyrotron thermal design is adequate for 10 s pulses at 1 MW, but the pulse length is presently limited to 5 s to prolong the collector fatigue lifetime.

Significant upgrades to the rf transmission system were made in 2010. In order to increase the total efficiency of the rf transmission, all six waveguides have been rerouted to decrease the total number of miter bends by 15, increasing the transmitted power by 200 kW for the entire system. The angular alignment of rf beams after the matching optics unit (MOU) focusing mirrors at the waveguide input has been improved. The launcher mirrors have all been redesigned for improved heat transfer and fatigue lifetimes. Both poloidal and toroidal steering mirror motion now uses electric motors in place of air turbines, yielding higher speed poloidal scans and greater positioning accuracy.

Preparation for installation of a 7th gyrotron has been in progress since August 2010. The frequency of this depressed collector diode gyrotron will be 110 GHz, with output rf power expected to be 1.2–1.3 MW. The 8th gyrotron for the DIII-D system is in the design stage. Also a depressed collector diode tube, this gyrotron is being designed for 117.5 GHz, 1.8 MW output in short pulses with operational parameters of 10 s pulses at 1.5 MW generated.

1. GYROTRONS

Six CPI gyrotrons with chemical-vapor-deposition (CVD) diamond windows have been in routine operation on DIII-D since 2008 [1]. Despite the increasing number of gyrotrons, the overall gyrotron reliability for plasma experiments remained stable at more than 82%. After repairing the collector failures of the first three gyrotrons and improving the collector sweep method at both CPI and DIII-D [2], no additional collector problems were encountered on this type of gyrotron. Calorimetric monitoring of the gyrotron internal losses has been providing additional information for optimal operation and for the output rf power estimation. Direct rf power measurements were completed with a high power, long pulse dummy load from Calabazas Creek Research [3] installed near the tokamak launchers. This information has been used, and continues to be, for the correction of the internal gyrotron ohmic losses in full power operation and for an estimation of a total injected rf power inside the DIII-D vessel.

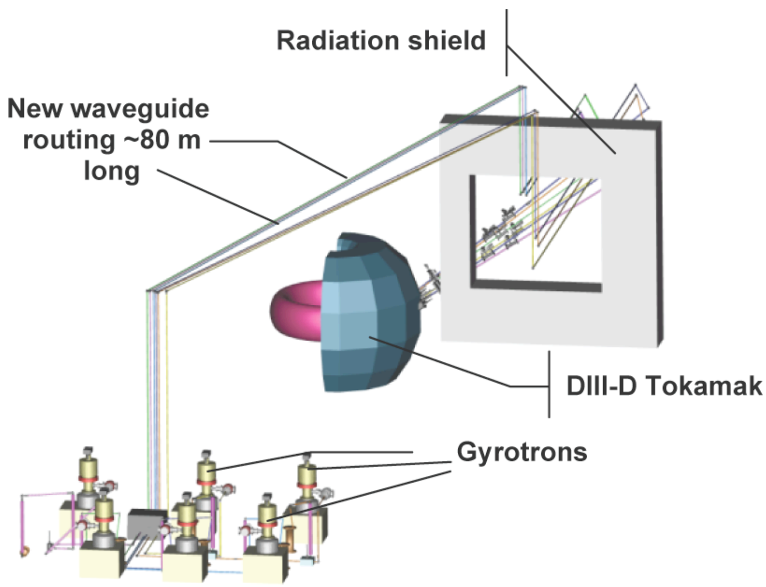

Fig. 1. DIII-D ECH system layout.

Although all six CPI gyrotrons of the VGT-8110 series have CVD diamond windows, the parameters of these windows are different. The first three tubes have a diamond disk diameters of 57 mm and disk thickness of 1.14 mm with $\tan\delta=1.4\times10^{-4}$. The others have a disk diameter of 73.5 mm and thickness of 1.71 mm and $\tan\delta=1.0\times10^{-4}$. The apertures of all the windows are the same: 50.8 mm. The last three tubes of this gyrotron production series have polished diamond disks that allow us to monitor the light output from the gyrotrons.

2. WAVEGUIDE TRANSMISSION LINES

The DIII-D ECH transmission line system is comprised of six evacuated windowless transmission lines up to 80 meters in length with transmission efficiency from 72.4% to 80.9%. Each waveguide line includes an MOU with focusing mirror, waveguide dummy load switch, waveguide isolation valve, two polarizers and up to ten miter bends. The corrugated waveguides are circular with a diameter of 31.75 mm. The waveguides are pumped to an internal pressure of 1.33×10^{-4} Pa.

In addition to rerouting the wavguides, the alignments of the rf beams to the first waveguide were improved. At the waveguide input the Gaussian rf beam excites the HE_{11} waveguide mode with a maximum efficiency of 98%. At small tilt angles, Θ (less than 2 deg), and small offsets, Δ (less than 3 mm), the purity fractional decrease for the HE_{11} mode scales as Θ^2 and Δ^2, respectively.

The overall performance of the transmission lines is dependent on the input alignment. To estimate the quality of the rf beam after the reflection from the MOU mirror, the gyrotron beam was measured by an infrared camera at varying distances from the mirror after passage through ~40 cm of waveguide. Based on these data, the mode content for every rf line was calculated and the alignment was adjusted. The purity of HE_{11} mode in the rf beam for the best line is 94.4% (see Table 1).

Table 1
Alignment Results of RF Beams into the Waveguide Transmission Lines and Final Mode Content of HE_{11}

	Tilt Angle (deg)		Offset (mm)		HE_{11} (%)
	Before	**After**	**Before**	**After**	
Lion	1.00	0.10	0.84	0.40	92
Scarecrow	1.58	0.14	3.20	0.16	88.3
Tin Man	2.44	0.10	2.00	0.20	91.4
Leia	0.50	0.10	1.50	0.50	94.4
Luke	1.87	0.40	2.00	0.40	84.6
Han	0.06	0.06	0.25	0.25	90.9

3. LAUNCHERS

Three fully articulating dual launchers [4], which can steer the rf beams poloidally and toroidally through ±20° in each direction are installed on DIII-D. All are designed and built by Princeton Plasma Physics laboratory. Each launcher has a fixed focusing mirror followed by a flat steering mirror. Two of the six focusing mirrors were damaged during the past two experimental campaigns on DIII-D. The focusing mirrors were made from stainless steel with a thin layer of copper on the surface. A finite element thermal calculation predicts that these mirrors should withstand a front surface temperature of 880°C for pulse lengths up to 10 s with incident rf power of 850 kW from the existing gyrotrons, Fig. 2.

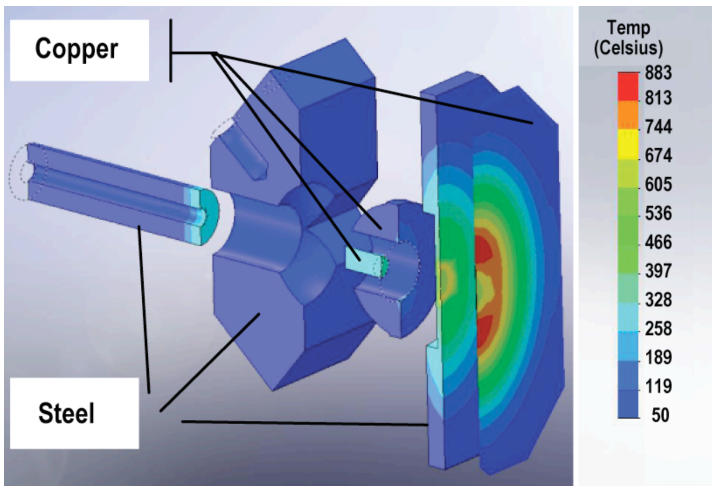

Fig. 2. Old design of a fixed focusing launcher's mirror after 5 s rf pulse with incident rf power of 850 kW.

However, in 2008 local stress cracking of the copper surface was found on some focusing mirrors. In some cases, the copper was melted exposing the stainless steel to the rf beam. Rapid thermal runaway and extensive melting resulted.

An upgrade of the launcher mirrors was completed in 2011. All focusing mirrors were replaced by new ones from solid Al-15 Glidcop construction. A finite element electromagnetic analysis, made by Princeton Plasma Physics Laboratory (PPPL), indicates that a solid Glidcop mirror will withstand electromagnetic forces during disruptive tokamak shots. The design goal for these mirrors is to allow the operation of gyrotrons with 1.5 MW output rf power (1.2 MW at the launcher) for 10 s pulses every 15 minutes. The solid Glidcop mirror has superior thermal and stress performance over the stainless mirror with the plated copper design. Stresses in the critical reflecting surface region are in the range that should provide a fatigue life of nearly 4000 tokamak shots with rf pulses of 10 s. It is expected that these mirrors will be replaced periodically.

The existing steerable mirrors of the launchers are made from stainless steel, copper plated on the front surfaces, with inlaid copper bars. The design allows for heat diffusion while minimizing eddy current forces. The steerable mirrors were also beginning to develop slight dimpling on surfaces near the center and which was evidence of thermal fatigue. The new design, also installed on all launchers, has steerable mirrors made from a more substantial copper block with inlaid stainless steel bars brazed in place.

4. SUMMARY

Six gyrotrons at 110 GHz have been in routine operation on plasma experiments on DIII-D since 2002. New rf beam alignment and the rerouting of all six waveguides have increased the total efficiency of the transmission lines. Upgraded versions of the PPPL launchers, particularly the new design of the focusing and steerable mirrors, open up possibilities for the operation of new gyrotrons with output power of 1.5 MW and with pulse length up to 5 s.

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