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GENERAL ATOMICS

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Performance of the ECH Transmission Lines and Launchers in DIII–D

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Abstract. The efficiency of the transmission line for the 110 GHz ECH system was measured in DIII–D using a low power rf source. The measured efficiency was about 10% lower than expected from theoretical analysis of the components. The launcher temperature increase during rf pulses was measured and the peak mirror surface temperature was inferred from a simulation.

INTRODUCTION

The ECH/ECCD transmission system on the DIII–D tokamak is comprised of six corrugated waveguide lines and three launchers. Each waveguide is designed for 1.0 MW, 10 s. pulses at 110 GHz and each launcher delivers power from two of the waveguides. Losses in the 31.75 mm diameter evacuated transmission system are expected theoretically to occur mainly at miter bends, approximately 1% per miter bend [1]. About 90% of the miter loss is due to mode conversion and 10% is resistive, which depends on the polarization orientation with respect to the plane of the miter bend. Measurements described in [1] on six mite bends assembled in series gave 0.4 dB (0.92%) loss per miter, in good agreement with the theoretical analysis. But low power measurements of the performance of complete transmission lines about 90 m in length and containing up to 12 miter bends indicated lower efficiency, prompting the present series of efficiency measurements.

The launchers are designed without water cooling for simplicity and avoidance of water leakage inside the tokamak vacuum vessel. With only radiative and limited conductive cooling, the launcher temperature must be monitored to prevent the melting of the rf reflecting surfaces of the mirrors. Although in normal long pulse operation over the course of a day, the surface temperatures are predicted to remain within limits, the mirror surface temperatures could be increased abnormally by surface arcing or plasma disruptions.

Poloidal and toroidal steering of the rf beams is provided using movable mirrors. Eddy current induced forces arising during disruptions are particularly problematic for the actuator assemblies on the movable mirrors, which have limited ability to react the forces. Therefore, mirror designs which minimize the volume of high conductivity copper while maintaining low resistivity reflecting surfaces have been developed. Because of the small volume of the metal, the thermal inertia of the movable mirror is relatively poor and particular attention must be paid to this component.

TRANSMISSION EFFICIENCY MEASUREMENT

The transmission efficiency measurement was performed using a low power rf source and diode detector. A schematic representation of the setup is shown in Fig. 1. The rf was generated by a 10 mW gun oscillator the output of which is converted from the $TE_{1,0}$ rectangular mode to the $HE_{1,1}$ hybrid mode that is used in the DIII–D ECH transmission line. The converted $HE_{1,1}$ wave passes through a phenolic mode filter, which reduces the undesired surface mode admixture during propagation. The filtered rf enters a corrugated wave guide section which can be a short piece of wave guide, ~50 cm long, for calibration or an actual transmission line or component for measurement. The receiver is a diode detector with another phenolic surface mode filter, an $HE_{1,1}$–$TE_{1,0}$ mode converter and an isolator in an arrangement symmetric to the transmitter. In this setup, some reflections at the receiver are unavoidable even with the use of an isolator before the detector. Therefore, standing waves can introduce errors in the measurement at fixed frequency. In order to minimize these errors, the frequency is swept. Figure 2 shows the frequency dependence of the detector signal for a short wave guide calibration test. The horizontal axis corresponds to a 0.2 GHz frequency sweep. The general trend toward larger received signal at higher frequency is primarily due to the frequency dependence of the source output power, but includes the uncalibrated frequency response of the detector.

In order to reduce errors from standing waves, the transmission efficiency was obtained by averaging the signal over the frequency sweep. The three step procedure was as follows: (1) Measure the frequency averaged signal with a short wave guide section (calibration). (2) Measure the frequency averaged signal with the component under test (measurement). 3) Return to the calibration setup and repeat the measurement. After verifying in (3) that there had been no change in generated power, the precision attenuator is adjusted to match the received signal from the “measurement”. The attenuation required to match the signal in (2) then indicates the transmission efficiency. Twelve separate calibrations over a five day period showed ±1% scatter in the calibration results. Therefore, the error of the measured efficiency is ±2%.

Using this technique, efficiency measurements were made on complete transmission lines, segments of lines and combinations of components. In order to connect with the measurements performed in [1], the transmission efficiency of six miter bends connected series was measured. In contrast with the previous measurements wchich gave, 0.92% loss per miter, the recent measurements gave 1.5% loss per miter. Straight waveguide loss had been calculated at 5% per 100 m for the 31.75 mm diameter corrugated wave guide at 110 GHz. Polarizing miter bends were calculated to have 1.5% loss per miter but were not measured separately. Using the theoretical calculations plus measurements on the existing components and waveguide lines, Fig. 3 was constructed to compare the expected and measured efficiencies. The measured losses are seen to be at least twice the theoretical expectation and in some cases 3.5 times the expectation.

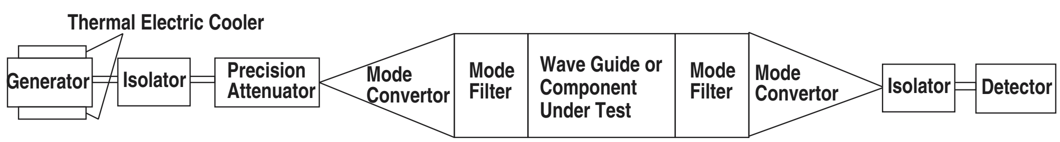

FIGURE 1. Schematic view of the set up.

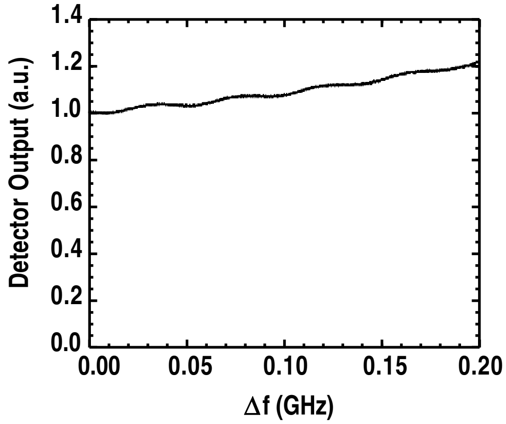

FIGURE 2. Frequency dependence of the calibration setup.

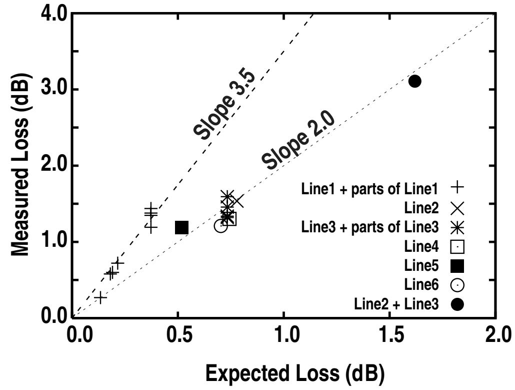

FIGURE 3. Transmission line efficiency. The horizontal axis is calculated using 1% loss per miter bend, 1.5% loss per polarizer and 5% W/G loss per 100 m.

Several additional tests were performed to attempt to identify problems with the measurements. One check was to fill the test waveguide with nitrogen to eliminate any moisture in the line. Another was to exchange the input and output mode converters, on the assumption that one converter could be generating appreciable non-$HE_{1,1}$ power. If one mode converter were faulty, the non-$HE_{1,1}$ mode will decay in the waveguide, and the interchanged converter setup will show a different transmission efficiency from the original. The angular distribution of rf which is radiated from the generator assembly (rf source + mode converter + mode filter) was also measured. In all checks, no evidence was found pointing to an error in the measurements. These investigations are continuing.

LAUNCHER TEMPERATURE MEASUREMENT

The temperatures of the launcher mirrors were inferred from measurements using Resistance Temperature Detectors (RTDs), which are attached to the back surfaces of the mirrors. In order to infer the peak surface temperature from the back surface measurements, it is necessary to simulate the thermal propagation of the mirror. The movable launcher mirrors, which have the poorest heat transfer to ambient, have a unique laminated design, which is shown in Fig. 4. A thin Glidcop reflecting surface is supported by the laminated structure of stainless steel and Glidcop. The stainless steel serves to reduce the eddy current forces at disruptions and to increase the mechanical strength. For such a complex structure, a three dimensional thermal simulation is required. The simulation, performed with the finite element code COSMOS, includes the temperature dependence of the electrical resistivity for copper. The resistance doubles at 800°C compared to room temperature.

A recent study has shown the necessity for calibration of the thermal impedance between the mirror and the RTD since the usual thermal grease cannot be used [2]. The thermal impedance is determined by comparing the simulation and a calibration in which a point on the mirror surface is held at 0°C and the RTD response is measured. Using the thermal impedance determined in this way, the surface temperature during rf injection can be estimated by comparing the simulation and the measurement. There was agreement between measurements and simulation, when the temperatures were compared 200 s after the pulse thus validating the model.

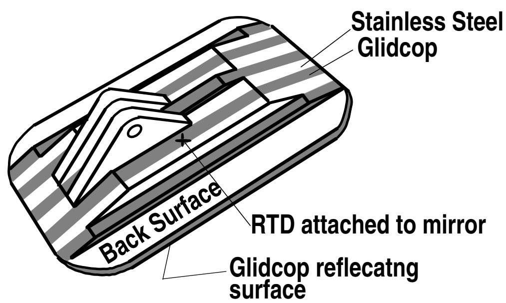

FIGURE 4. Schematic view of the movable mirror.

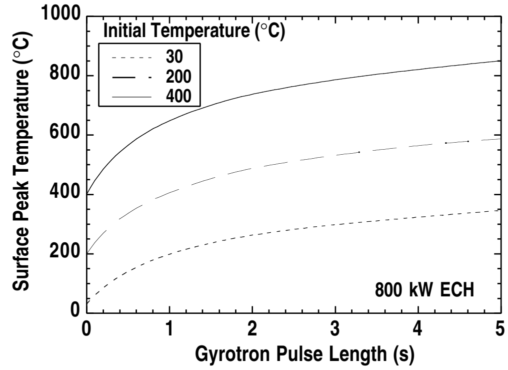

FIGURE 5. Peak surface temperature as a function of the gyrotron pulse length. The initial temperature was changed in the three cases.

Based on this result, the peak surface temperature of the mirror at the center of the rf beam can be calculated as a function of the pulse length with the initial temperature as a parameter (Fig. 5). The rf beam radius on the movable mirror was 5.5 cm and the rf power absorption fraction was assumed to be 0.21% with the angle incidence θ defined as the angle between the normal to the surface and the rf beam of 56°. The absorbed power scales as $1/\cos\theta$. As shown in Fig. 5, if the initial temperature is 400°C, the mirror surface temperature will exceed the maximum target value of 800°C in less than 4 s. Usually, the baseline temperature of the movable mirror increases by about 100°C at the end of a day of operation with many 2 s rf pulses and injected power of 700 kW. Therefore, the surface temperature will never exceed 600°C. However, there is a possibility of occasional arcs at the surface, which can cause an anomalously high baseline temperature. To prevent such events, an alarm with set point of 300°C as measured by RTDs has been installed.

SUMMARY

Transmission efficiency measurements using a low power rf source shows a lower transmission line efficiency for the DIII–D ECH system than predicted by theory. There is a possibility that high order modes have contaminated the measurements. This investigation continues. The launcher temperature simulation shows that even if the initial mirror temperature is 300°C, the peak temperature during an 800 kW, 5 s pulse is less than 800°C.

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