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Transmission Lines Power Measurements for the 110 GHz Electron Cyclotron Heating System on DIII-D and Gyrotron Operational Performance

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Abstract — **Operational trends for the six-gyrotron electron cyclotron heating system on DIII-D are presented. Losses in the transmission lines were measured and values close to theoretical were attained for one of the lines with the existing components. Improved alignment and reduction of the number of miter bends in the lines will increase the power transmitted through the waveguide to the DIII-D tokamak.**

I. Introduction And Background

The electron cyclotron heating (ECH) system on the DIII-D tokamak consists of six gyrotrons operating at 110 GHz. The typical rf power injected into the tokamak at the end of each of the 90 m long, 31.75 mm diameter corrugated waveguide transmission lines ranges from 500 kW to 650 kW per gyrotron. To increase reliability, the gyrotrons are operated at about 85% of their maximum capability. The theoretical transmission efficiency is -1 dB (80%) and for some systems additional loss up to 10% occurs.

High power measurements of the losses in the corrugated circular waveguide transmission lines were performed. Re-alignment of the beam at the waveguide input led to increased transmission in three of the lines. The results of direct mode content measurements, waveguide temperature measurements, and infrared mode content measurements using phase retrieval analysis show an improvement in beam alignment resulted in reduced losses.

II. Results

In the past years the power generated in the DIII-D ECH system was gradually increased as more gyrotrons were added to the system. Up to 16.5 MJ were injected on a single tokamak shot over 5 seconds (3.3 MW total injected power) from the six gyrotrons. For shorter pulses (250 ms) up to 3.5 MW of ECH power were delivered to the tokamak. The power injected into the tokamak is calculated for each shot from calorimetry and the quoted power takes into account the measured losses in the transmission lines.

The total power generated at the gyrotrons, the total power injected into the tokamak and the sum of pulse lengths from all the gyrotrons show an increase over the last four years as the number of gyrotrons in the system increases from 4 to 6, as plotted in Fig. 1. The yearly shot by shot success rate remained between 83% and 85% during this time, even as the number of tokamak shots with ECH increased from 2100 in 2007, to 4400 in 2008, 3600 in 2009, and 5600 in 2010.

Parasitic emission from one gyrotron was observed when the VacIon pump current, proportional to the gyrotron internal pressure, was >1.6 μA. The presence of the parasite caused an extension of the gyrotron conditioning period and in some cases pick up on the fault signals stopped the shots short of the desired length. The conditions for the parasite onset were mapped in order to find regimes where it can be avoided. Two types of parasite were identified: the Type I occurs during the voltage ramp up or down, and the Type II occurs during the voltage flattop. The Type I parasite lasts less than 50 μs, has an onset when the gyrotron beam voltage reaches 56 kV, and is accompanied by gas production inside the gyrotron. It occurs for a beam sweep coil current interval of 17.4A±1.9A. The measured collector heating indicated that the parasite is present if the electron beam hits the collector over a particular area high in the collector. The spectrum of this parasite is a narrow peak with frequency ranging from 6.2 to 40 MHz. The Type II parasite appears during the flattop of the gyrotron voltage trace and stays on for up to several seconds.

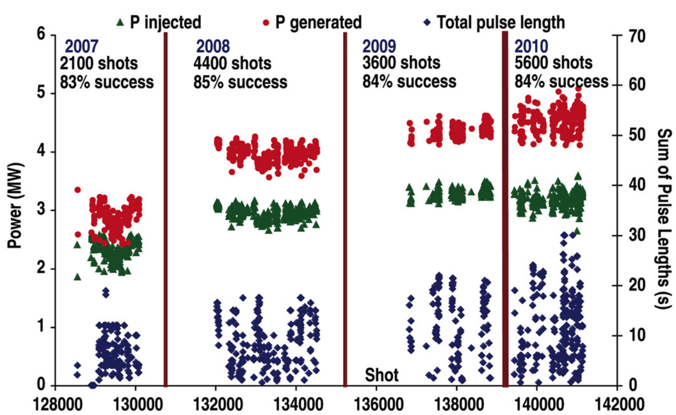

Fig.1 Total power generated from the gyrotrons, total power injected into the tokamak and total pulse length versus the shot number.

High power measurements of the losses in the transmission lines using dummy loads [1] have shown that the loss in the lines can be as low as -1 dB, the theoretical value [2] for the 11 to 12 miter bend lines using 0.06 dB loss for miter bends, 0.09 dB loss for the polarizing miter bends and 0.02 dB loss per 10 m of waveguide. Re-alignment work was performed.

The best alignment was determined from free space measurement for short pulses (less than 6 ms) as corresponding to the minimum beam input angle in the waveguide and smallest transverse offset of the beam at the waveguide input. The angular misalignment was reduced from as high as 2.4 degrees to 0.1±0.3 degrees for five of the systems (Table 1). The transverse offset was lower than 0.5 mm.

Gyrotron	HE_{11} Mode Content (%)	Beam Tilt Angle (Deg)	Measured Line Transmission (dB)	Theoretical Transmission (dB)	ΔT Waveguide for 1 s Pulse (˚C)	Loss in MOU (%)	Total Transmission Including MOU (%)
Leia S/N 106	89	0.1	-1.03±0.12	-0.92	2.5	5.4	74.5
Scarecrow S/N 101R	88	0.1	-1.46±0.16	-0.98	5	3.8	69.7
Lion S/N 103	92	0.1	-1.04±0.10	-0.98	2.3	3.3	75.9
Luke S/N 104	85	0.75	-1.51±0.12	-0.98	4	7.9	69.3
Han S/N 105	91	0.1	-0.84±0.24	-0.98	2.5	4.5	78.7
Tin Man S/N 102	87	0.1	-0.92±0.17	-0.98	2	2.8	78.7

Table 1. Measured HE_{11} mode content, measured loss in the lines, theoretical loss in the lines, temperature increase in each transmission line for 1 s pulses, and the misalignment angle.

The mode content in each of the transmission lines was measured using the infrared rf beam image on a target positioned at 30 cm, 40 cm, and 50 cm from the output of a waveguide replacing the normal transmission line. The measurements showed the low loss HE_{11} mode content was over 85% for all the lines following the alignment (Table 1).

Owing to the improved angular alignment of the rf beam, the measured efficiency for four of the transmission lines was lower than -1.1 dB, close to the -1 dB theoretical value (Table 1). The power loss in the line was determined from the difference in the power measured in a dummy load at both ends of the transmission line. The higher transmission resulted in 87 kW (19%) increase in the power measured at the DIII-D end of the Tin Man S/N 102 line after the alignment. Losses were high in the Scarecrow S/N 101R line even after alignment, possibly due to a high loss element in the line.

The effect of the misalignment on the losses was verified in high power measurements. The rf power was measured in a dummy load placed after 2 miter bends and 5 m of waveguide for 1 second pulse length, as an up/down misalignment was deliberately introduced in the line. Measurements showed a reduction in the power measured in the dummy load with misalignment (Fig. 2). The increase in the power loss in the waveguide and miter bends resulted in a decrease in the power in the dummy load. This confirmed that the best alignment position, obtained for short pulse lengths, also corresponds to lower losses for long pulse lengths.

The waveguide temperature increase due to rf losses in the line was measured and is shown in table 1. ΔT is higher for the two systems with higher losses, Scarecrow S/N 101R, and Luke S/N 104. For the Tin Man S/N 102 line, the temperature dropped from 4.5 to 2 degrees after the alignment.

New diagnostics were developed and tested for the alignment and power measurement. A new 4-port miter bend, sampling 1 W per 1 MW transmitted power, can be used as an rf monitor. The 4-port miter bend showed an HE_{11} mode signal proportional to the transmitted power measured in the load. A new mode selective directional coupler mounted on a pickoff port sampling forward power samples three modes that can be found in the waveguide: HE_{11}, TE_{01} and HE_{21}. The mode content in the line is shown in Fig. 2 as the beam angle and axial offset at the waveguide input were changed intentionally around the well aligned position of "0" misalignment. The best alignment corresponds to maximum HE_{11} and minimum TE_{01} and HE_{21} measured signals. This set-up can be used for routine beam alignment.

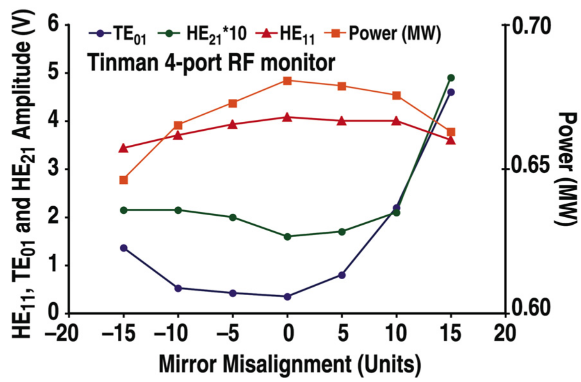

Fig. 2. Amplitude of the fundamental HE_{11}, and contaminant HE_{21} and TE_{01} signals from the 4-port rf monitor for the gyrotron Tin Man S/N 102 versus the up/down misalignment.

III. CONCLUSIONS

Improvements in the beam alignment procedure led to an increase in the power delivered at the tokamak through the transmission lines. Power loss measurements, waveguide temperature measurements and mode content measurements were used to confirm improved transmission in the lines.

A new 4-port rf monitor was tested. A directional coupler was used with the 4-port rf monitor to sample the HE_{11}, TE_{01} and HE_{21} modes, and it was shown that the amplitude of the signals can be used to perform the beam alignment.

Additional work on the two worst lines is in progress. A new layout of the transmission lines will reduce the number of miter bends and the length of the lines, leading to an estimated 150 kW total rf power increase for the entire system at DIII-D with no additional gyrotron power.

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