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## DISCLAIMER

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## ABSTRACT

The measurement of the power injected by the electron cyclotron heating (ECH) system in the DIII-D tokamak is a critical requirement for analysis of experiments, for tuning the gyrotrons for maximum power and efficiency, for tracking long-term operational trends and for providing a warning of problems with the system. The ECH system at General Atomics consists of six 110 GHz, 1 MW class gyrotrons. The rf power generated by each gyrotron is determined from calorimetry, using the relevant temperature and flow measurements from the cooling circuits of cavity, matching optics unit and dummy loads. The rf pulse length and time dependence are measured using an rf monitor at the first miter bend in the transmission line. The direct measurement of the efficiencies of four of the transmission lines was performed using a high power, small dummy load (SDL) placed alternately in 2 positions of each DIII-D waveguide line, at accessible points close the beginning and the end of each line. Total losses in the transmission lines range from 21.2% to 30.7%. Experimental results are compared to theoretical predictions of the performance of the components and waveguide lines.

# I. INTRODUCTION

The electron cyclotron heating and current drive system on DIII-D consists of up to six gyrotrons in the 1 MW class with pulse lengths of up to 10 s and 110 GHz output frequency. The power generated by the gyrotrons is routinely measured calorimetrically using either heating of the gyrotron interaction cavity or the dummy loads placed close to the gyrotron. The generated power is transmitted from the gyrotrons to the DIII-D tokamak through $\sim 100$ m of corrugated 31.75 mm diameter waveguide carrying the $HE_{1,1}$ mode [1]. It is necessary to have a reliable measurement of the rf power injected into the tokamak, which requires accurate knowledge of the efficiency of the transmission lines. Until now, estimates of the losses in the transmission lines were based on the theoretical calculation found in [2]. Low power measurements of the losses in the elements of the transmission line [3] have shown 1.5% loss per miter bend and more than 10% loss per 100 m of corrugated waveguide. The theoretical attenuation in 100 m of corrugated waveguide is 0.2 dB (4.7%) [4]. We report a direct high power measurement of the efficiencies of transmission lines, using a high power, small dummy load (SDL) placed at the beginning and at the end of four of the DIII-D transmission lines.

## II. MEASUREMENT OF POWER FOR THE ECH SYSTEM ON DIII-D

A schematic of a gyrotron and the transmission line is presented in Fig. 1. Each gyrotron is connected to a matching optics unit (MOU), followed by the waveguide transmission line. From the MOU to the permanent dummy loads, a waveguide compact dummy load (CDL) followed by a backstop dummy load (DL), the waveguide transmission line is 7 meters long and includes five miter bends, one of which is a polarizing miter bend. The measurements of the losses were performed between positions 1 and 2 in Fig. 1. Between these two positions the length of the transmission line is ~ 90 m and includes 7 miter bends, one of which is a polarizing miter bend.

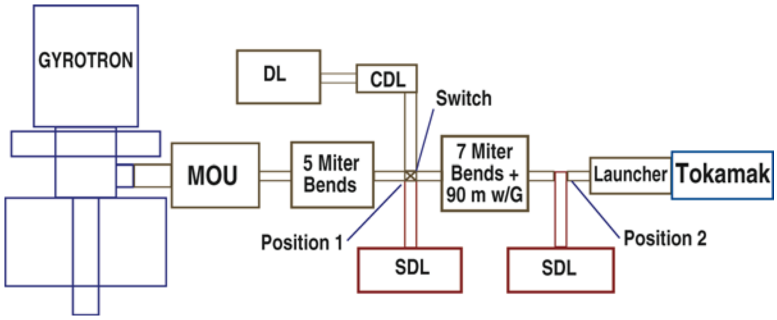


Fig. 1. Schematic of the experimental set-up for line loss measurements.

The generated power from each gyrotron can be measured from the gyrotron cavity calorimetry using a relationship between the cavity power loading and rf production determined for each gyrotron during factory testing. The rf pulse is detected at the first miter bend in the transmission line to determine the time dependence of the power signal and the pulse length. The gyrotrons were operated at about 15% lower power than the maximum achievable in order to have a high reproducibility and reliability for these measurements.

The power loss in the MOU and the power at positions 1 and 2 were measured calorimetrically by measuring the heating of the cooling water of the MOU or dummy loads located at these positions.

The calorimetric method for measurement of rf power from the gyrotron or in the transmission line is based on the measurement of heating due to rf and of the flow in the cooling circuits of the gyrotron. The water temperature measurement shows a time-dependence like the one for the dummy load cooling circuit in Fig. 2.

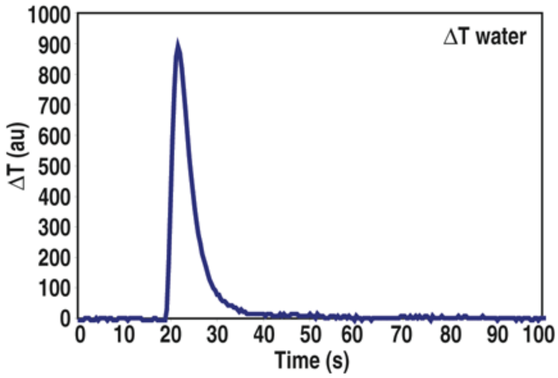


Fig. 2. Typical raw data showing temperature variation in the cooling water circuit of the small dummy load for a 400 ms shot from the gyrotron VGT-8110 S/N 101R.

The average power for each shot is calculated as:

$$P = \frac{C \cdot \int (F \cdot \Delta T \cdot dt)}{t_p} \quad , \tag{1}$$

where $P$ is the power, $C = 4.184*10^6 \ \mathrm{W}/\left(\mathrm{m}^3/\mathrm{s}\right)/°\mathrm{C}$ is a constant, $F$ is the flow (in $\mathrm{m}^3/\mathrm{s}$), and $t_p$ is the pulse length.

The power close to position 1 is measured routinely using a compact waveguide dummy load in series with a backstop dummy load used to absorb the power that is not absorbed in the waveguide dummy load. A waveguide switch can route the rf to these two loads or to the tokamak path, which is connected for these measurements to the SDL. The portable SDL was installed in the line close to the tokamak or close to the gyrotron. The SDL is a barrel-shaped aluminum load with interior $\mathrm{Ti0_2}$ coating having a pulse length limit of 400 ms at 1 MW. It was installed in the line at positions 1 or 2.

The losses between positions 1 and 2 were measured using the SDL for four of the six transmission lines: VGT-8110 S/N 101R, VGT-8110 S/N 103, VGT-8110 S/N 104 and VGT-8110 S/N 105. The power measured at position 1 is the input power, and power measured at position 2 is the output power for the measurement of the losses in the accessible portion of the transmission lines.

The primary data used for analysis was the change in the coolant temperature for water flowing through the SDL as a function of time. Temperature shown in Fig. 2 for a 400 ms shot from the gyrotron VGT-8110 S/N 101R, where the water flow through the load was $1.96*10^{-3} \ \mathrm{m}^3/\mathrm{s}$, was measured in arbitrary units and the power was calibrated separately. The calibration of the measurement was performed using a heater with measured rms voltage and current to heat the water flowing through the dummy load. The energy delivered by the heater was used to determine the calorimetric response to a known input energy and this was compared with the response to the absorbed rf. The calorimetric response for calibration and measurement were integrated numerically. The total energy for the calibration was approximately matched to the energy in the measurement.

The total loss in each transmission line is determined from the sum of the measured losses in the MOU, the theoretical estimated losses between the MOU and position 1 and the measured losses between positions 1 and 2 in the transmission line, and does not include the losses in the launcher.

## III. HIGH POWER MEASUREMENTS OF THE LOSSES IN THE TRANSMISSION LINE

The power measurements for the four gyrotrons are summarized in Table 1.

Table 1. Powers and losses for the gyrotrons VGT-8110 S/N 101R, VGT-8110 S/N 103, VGT-8110 S/N 104 and VGT-8110 S/N 105.

| Gyrotron | Power loss in MOU (kW) | Total power DL and CDL (kW) | Power SDL position 1 (kW) | Power SDL position 2 (kW) | Theory loss from MOU to pos. 1 (%) | Theory loss from position 1 to 2 (%) | Measured loss from position 1 to position 2 (%) | Total loss in the line |
|---|---|---|---|---|---|---|---|---|
| VGT -8110 S/N 101R | 36 ±13 (3.8%) | 600 ± 31 | 647 ± 29 | 522 ± 17 | 7.7 | 13.5 | 19.2 ± 4 | 28.3% (-1.45 dB) |
| VGT -8110 S/N 103 | 24 ±7 (3.3%) | 554 ± 18 | 537 ± 1 1 | 445 ± 9 | 7.7 | 13.5 | 17.0 ± 2 | 26.0% (-1.30 dB) |
| VGT -8110 S/N 104 | 65 ±17 (7.9%) | 540 ± 48 | 606 ± 16 | 494 ± 14 | 7.7 | 13.5 | 18.4 ± 3 | 30.7% (-1.59 dB) |
| VGT -8110 S/N 105 | 27 ±10 (4.5%) | 397 ± 16 | 413 ± 22 | 370 ± 11 | 7.7 | 13.5 | 10.5 ± 5 | 21.2% (-1.03 dB) |

The power from each gyrotron was measured using the power from cavity loading to normalize the efficiency measurements to the generated power over several days of tests.

For the gyrotron VGT-8110 S/N 105 the power was also measured using a planar octanol load [5]. The power measured was $603 \pm 51$ kW immediately following the gyrotron, and $577 \pm 35$ kW when the MOU was in place between the gyrotron and the octanol load, indicating 26 kW loss in the MOU. The measurement is within the error bar of the $27 \pm 10$ kW kW loss in MOU. This octanol load power measurement also provided a check on the power measured from cavity loading (found to be $601 \pm 16$ kW), confirming the accuracy of the cavity coefficient determined during factory testing for this gyrotron.

The power loss in the four MOUs was measured using the calorimetric method and was lower than 4.5% for three of the MOUs (see Table 1). A tilt in the horizontal propagation angle of the beam from the gyrotron window could lead to the higher loss in the MOU for VGT-8110 S/N 104.

For the losses from the MOU to position 1 of the dummy load, the theoretical numbers for the power loss in the miter bend based on Ref. 2 were used: 1.4% (-0.06 dB) loss per miter bend and 2% (-0.09 dB) loss per polarizing miter bend.

The sum of powers in the combination of CDL and DL, installed at position 1, was measured by changing the waveguide switch to select the path to these loads. In this configuration, the power from the gyrotron is dissipated in both the CDL and DL connected in series. Then the switch path was changed to the SDL for measurements with this load.

The powers measured by the SDL in positions 1 and in position 2 are plotted for the gyrotrons VGT-8110 S/N 101R, VGT-8110 S/N 103, VGT-8110 S/N 104 and VGT-8110 S/N 105 in Fig. 3 and summarized in Table 1. The transmission efficiency between positions 1 and 2 is the ratio between the average measured powers at these two positions. The theoretical losses for this portion of the transmission line, considering a 1.4% (-0.06 dB) loss per miter bend, 2% (-0.09 dB) loss per polarizing miter bend [2] and 0.2 dB per 100 m of waveguide [4] are 13.5% in each line. This value is within the standard deviation of the measurements only for VGT-8110 S/N 105. The other three transmission lines have higher losses.

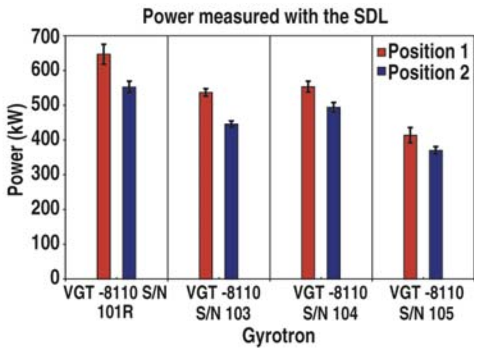


Fig. 3. Power measured with the dummy load at position 1 and at position 2.

The rf power lost to waveguide heating between the MOU and position 1 was evaluated by direct measurements of the waveguide temperature increase during a pulse, using resistance temperature devices (RTDs) and an infrared camera. Both diagnostics showed similar temperature values. The power necessary to heat the waveguide to the measured temperatures ranged from 90 kW for VGT-8110 S/N 105 to 180 kW for VGT-8110 S/N 101R.

The total waveguide line efficiencies for each gyrotron are summarized in Table 1. For each gyrotron the losses are the contribution of the measured losses in the MOU, the theoretical losses between MOU and position 1, and losses measured between positions 1 and 2.

## IV. CONCLUSIONS AND FURTHER PLANS

The losses in four of the six DIII-D ECH transmission lines were measured at high power using the calorimetric method and a dummy load, which was placed close to the gyrotron and close to the tokamak. The total loss in each of the transmission lines was: 29.8 % for VGT-8110 S/N 101R, 26.6 % for VGT-8110 S/N 103, 32.9 % for VGT-8110 S/N 104 and 22.7 % for VGT-8110 S/N 105. Although the losses exceed theoretical estimates, this performance of the transmission line did not result in damage of the components. The losses in the transmission lines are used to calculate the power transmitted to DIII-D on a shot-to shot basis.

Further investigations are necessary to identify the specific loss contribution of each component of the transmission lines.

Further plans include the more detailed measurement of the power lost to waveguide heating, and measurement of the purity of the $HE_{1,1}$ mode in each line.

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