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Testing of ITER-Class ECH Transmission Line Components at the JAEA Radio-Frequency Test Stand

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Abstract. Testing of prototypical ITER electron cyclotron heating transmission line components at representative ITER conditions has been carried out at the JAEA RF Test Stand (RFTS). Many 240 second pulses of ~600 kW 170 GHz power were transmitted reliably through these components. Based on these tests, it appears that the ITER requirement for 2 MW cw operation with high transmission efficiency is achievable. GA components tested in 2008 included polarizer miter bends, waveguides, very low diffraction loss miter bends (LDLMBs), and a dc break. Components tested in 2010 include an expansion section and polarizer miter bends with improved grooved mirrors. The tests showed that improvement in the polarizer mirror cooling is needed to support 2 MW operation. Measurements of the dc break showed that the temperature increase of the outer surface of the ceramic insulator was less than 10°C. The LDLMB tests showed that mirror losses were close to the theoretical prediction. Due to lower diffraction, losses in waveguides adjacent to the LDLMBs were much less than in those next to standard miter bends.

1. Introduction – ITER Transmission Line Requirements

Electron Cyclotron Heating and Current Drive (ECH&CD) needed for ITER is to be supplied by twenty-four (24) 1-2 MW EC systems [1]. The EC system is comprised of gyrotrons, transmission lines, and two launching antenna types located in the equatorial (EL) and upper (UL) ports. The operating frequency for the EC system is 170 GHz. Gyrotrons [2-4] operating between 1 and 2 MW, will be used for heating and current drive (H&CD) applications. The transmission lines [5] (63.5 mm evacuated HE_{11} corrugated waveguides) transmit the power from the gyrotrons to the launchers over a length of 10 m to 160 m. An in-line switch is used to direct the rf power in the waveguide to either the EL or UL, depending on the physics application.

The specialized components that are needed to complete an ITER transmission line (TL) include waveguides (WG), miter bends (MB), power monitor miter bends (PMMB), polarizer miter bends (PMB), waveguide switches (WS), dummy loads (DL), dc breaks (DCB), WG expansion sections (ES) (if needed), and waveguide pump-out sections (PO). All components are to be evacuated to better than 0.01 Pa to avoid breakdown, corrugated for low loss transmission of the rf power using the HE_{11} mode, and include some form of thermal management system to maintain the components at reasonable temperatures.

There are no EC systems in use today that operate at the ITER parameters. Therefore, to ensure that the EC System will meet all the ITER performance requirements and have high reliability, it is important to validate the designs of the waveguide and other components using EC power and pulse length as close to the ITER parameters as possible prior to production. For the last four years the only working EC test stand that has parameters close to those needed for ITER is the JAEA RFTS.

Under a US/Japan collaboration, General Atomics provided JAEA with several ITER prototype EC components to be tested on the RFTS. These included PMBs, LDLMBs, a DCB, an ES, and a fast WS. Three series of tests were performed between 2008 and 2010; results from these tests are reported below.

2. Test Setup

The RFTS gyrotron produces a 170 GHz, Gaussian rf beam, which is coupled into an evacuated (<0.1 Pa), 63.5 mm diameter corrugated transmission line system, using a two-mirror matching optics unit (MOU). From the MOU, the transmission line takes the rf beam through a short section of waveguide, then through two 90° MB, and then to a WS. The straight through port of this switch is connected to a short section of transmission line (~7 m), to a DL. The diverted port of the WS sends the rf beam through a relatively long section of transmission line (~30 m) to a laboratory where the rf beam is used to perform tests on various components. In the long transmission line section are two sets of MB pairs, which are used to raise the transmission line about two and a half (2.5) meters above the floor to allow personnel access to either side of the transmission line. Just after entering the test room there is a waveguide valve (WV), which allows the component under test to be disconnected from the transmission line without having to vent the entire line. Normally, tests are run at 600 kW for 240 s.

For the Aug-Sept 2008 tests the components were setup in the Test Lab, with a pair of PMBs connected between the WV and the DL. For the Dec. 2008 tests, components were connected to the short transmission line. Tests were performed on PMBs, LDLMBs, a DCB and standard MBs. The 2010 tests were done in the Test Lab on PMBs only.

3. EC Component Performance Expectations

The combined effects of ohmic loss and mode conversion reduce the transmission efficiency of the EC components. Mode conversion may not have a direct effect on the component generating the modes, but results in increased losses both upstream and downstream. For this analysis, mode conversion is segregated into two classes, low order modes (LOMs), which have long decay lengths, but add to the overall loss per meter, and high order modes (HOMs), which have short decay lengths, and add appreciable heating to the waveguides near the source of the HOMs. Also included is the loss associated with the HE_{11} mode (the primary transmission mode) and the linearly polarized (LP) modes. LP modes are generated at the MOU to TL interface, at miter bends and at other waveguide discontinuities but in general pass through the waveguide with low loss. Table I, lists the majority of the ITER EC components, and the level of predicted ohmic and mode conversion losses [6].

TABLE I: PREDICTED OHMIC AND MODE CONVERSION LOSSES FOR EC COMPONENTS

EC Component	Ohmic* (%) (H-Plane/E-Plane)	Mode Conversion (%)	
		LOM	HOM (Frwd/Rev)
Miter bend	(0.08/0.161)	0.13	0.0625/0.0625
Waveguide	HE_{11} – 0.0032 (m^{-1}) LP – >0.012 (m^{-1})		
WG switch	(0.08/0.161)	0.13	0.0625/0.0625
Expansion sec.		0.13	
DC break		0.002	
Polarizer MD	0.1225 $(S_G)(S_R)(S_T)^{\dagger}$ H 0.245 $(S_G)(S_R)(S_T)^{\dagger}$ E	$0.156^{\ddagger}$	$0.075^{\ddagger}/0.075^{\ddagger}$
Power Mon. MB	(0.08/0.161)	0.13	0.0625/0.0625
LDLMB	(0.08/0.161)	0.046	0.013/0.013

*All mirror losses are for room temperature smooth copper, loss needs to be corrected for surface roughness and temperature affects.
†S_G = surface geometry factor, S_R = surface roughness factor, S_T = mirror surface temp factor.
‡The polarizer mode conversion was increased by 1.2 over a standard MB, to account for added diffraction from the grooved mirrors.

Ohmic losses, for miter bend mirrors are measured calorimetrically. Mode conversion losses are estimated from the profile of the waveguide surface temperatures, measured with IR cameras, viewing the waveguides upstream and downstream from a component.

4. EC Component Tests Analysis

4.1. Model for Mode Generation Evaluation

From IR camera data (Fig. 1) it is evident that there is immediate heating of the waveguide before and after each MB, consistent with diffraction generated HOMs that travel in the forward and reverse direction from the MB. The surface temperature can be used to infer the power absorbed by using the mass and heat capacity of the aluminum waveguide and the pulse length. Since the LOMs and HOMs are generated locally and propagate away from the component, the power absorbed from the modes should follow a simple exponential decay profile. This decay profile can be determined from the ΔT profile. The waveguide surface temperature T_{WG} should follow an exponential decay, expressed as;

$$T_{WG} = \Delta T_0 \exp(-L/D_L), (°C) \quad . \tag{1}$$

Where ΔT_0 is the peak temperature (°C) rise at the component, L (mm) is the distance from the component, and D_L (mm) is the decay length of the temperature profile.

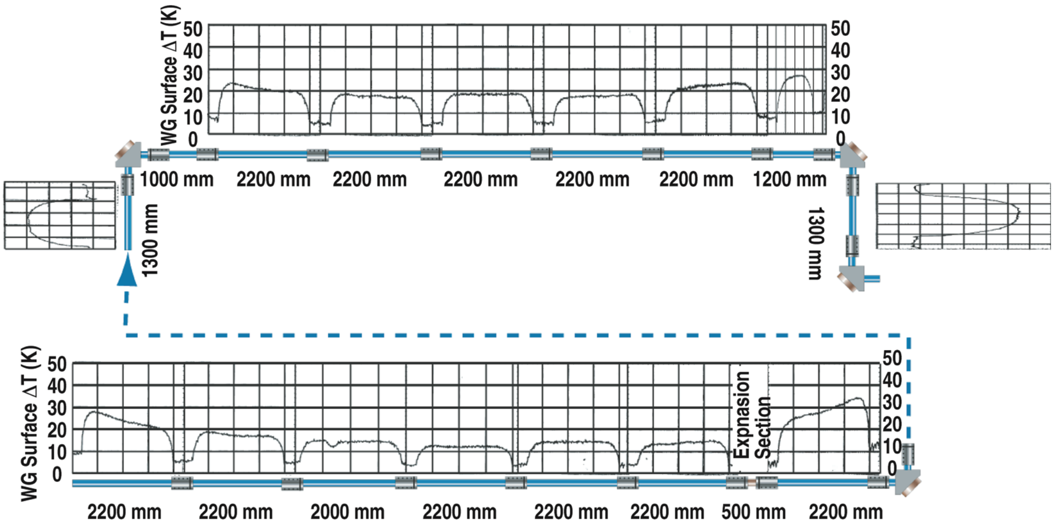

FIG. 1. Delta T measurements of the 33 m transmission line tested at the JAEA RFTS in 2010.

Using the predicted mode conversion percentages identified in Table I, a model was developed that used the loss rates of Table II. Where $P_{abs\ LOM}$ and $P_{abs\ HOM}$, are the peak power loss rates for the waveguides caused by the LOMs and HOMs created by the MBs or other components. The peak temperature rise, ΔT_0, is then derived from the loss rate using the heat capacity of aluminum, the volume per unit length of the waveguides, and the pulse length.

Figure 2 shows a graph of the TL surface temperature that the model predicts for a power level of 600 kW, 240 s, as a function of distance from the WS. Data from IR camera measurements show a good correlation, but there are some differences in the power absorption of HOMs for PMBs and standard MBs. Negligible change in the HE_{11} content was detected after the PMBs as the output polarization was changed.

TABLE II: EC COMPONENT LOSS MODEL USED TO CALCULATE WG SURFACE TEMPERATURES

	Model (HE_{11} – 93%)					
EC Component	**Ohmic Loss Measured (kW)**	**Ohmic Loss Theory (kW)**	**$P_{abs\ LOM}$ (W/mm)**	**$P_{abs\ HOM}$ (W/mm)**	**D_{LOM} (mm)**	**D_{HOM} (mm)**
Miter bend			0.019	0.156	20,000	2,500
Waveguide	85 W/m	23 W/m				
Expansion section			0.0065	0.052	20,000	2,500

4.2. Low Diffraction Loss Miter Bend (LDLMBs)

A pair of LDLMBs were tested in the short section of the JAEA RFTS. The short section has seven (7) meters of waveguide, two standard MBs and passes through the WS without being diverted. As with the tests of the PMBs and MBs, IR camera data was used to evaluate the mode conversion characteristics of the LDLMBs. Figure 3 shows that the measured temperature increase of the LDLMB nearest to the gyrotron is noticeably larger than for the LDLMB further from the gyrotron. Since there is little LOM and HOM mode conversion by the LDLMs, there is lower heating of the down-stream LDLMB. The measured mirror ohmic loss of 0.22% is close to the theoretical 0.16%, when corrections are made for surface roughness and high mirror surface temperature.

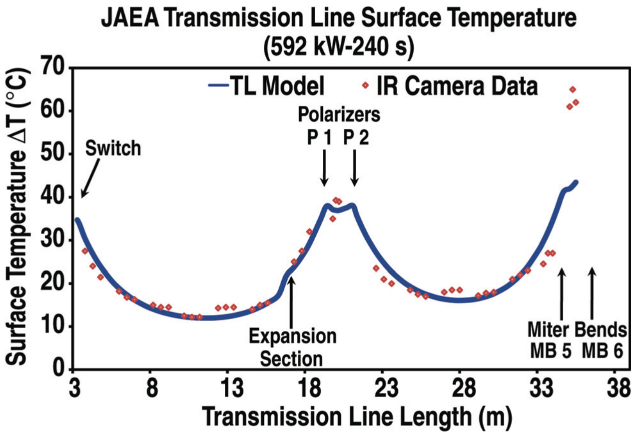

FIG. 2. Transmission line surface temp. measured using an IR camera, compared to the model described in Sec. 4.1.

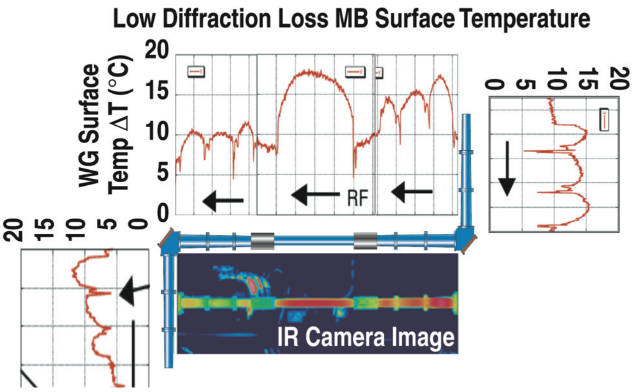

FIG. 3. Displayed are the IR camera image and the inferred surface delta temperature increases of the LDLMBs tested.

4.3. Polarizer Miter Bends (PMBs)

Pairs of miter bends equipped with rotatable grooved mirrors, which in tandem can produce arbitrary polarization angles and ellipticity, were tested on the JAEA RFTS in 2008 and 2010. Polarizer mirror P1 has the deeper grooves, and mainly rotates the incoming polarization. Polarizer mirror P2 mainly changes the ellipticity of the polarization. At 45° incidence, as in a miter bend, the effect of each of these mirrors is generally rather complicated. Nevertheless, for a given output polarization from the pair, there is normally at least one solution for the rotation angles of these mirrors. For both tests, PMB P1 was placed closer to the gyrotron than PMB P2, since that arrangement allowed the largest number of solutions. When there are more possible solutions, then it is more likely that a "low-loss" solution can be found. The tests in 2008 and 2010 each included over 20 settings of the mirror pairs, corresponding to a wide variety of output polarizations and expected losses.

The PMB tests in 2008 had the bend of the PMBs in the horizontal plane, which was also the plane of the incident linear polarized rf beam (Fig. 1). For linear polarization this orientation is referred to as an E-Plane Bend, and has the highest loss of any orientation [8]. The PMB tests in 2010 were performed with the polarizer miter bend pair in the vertical plane, and the incident polarization in the horizontal plane. For linear polarization, this orientation is called an H-Plane bend.

In both tests, it was observed that the ohmic loss was a strong function of the orientation of the grooves with respect to the polarization angle of the rf field. This was expected, since the electric field sees a different effective surface area depending on the polarization orientation with the mirror groves. As can be seen in Fig. 4, the ohmic loss on mirror P1 can vary more than a factor of seven (7) as the mirror is rotated from 0° to 90°.

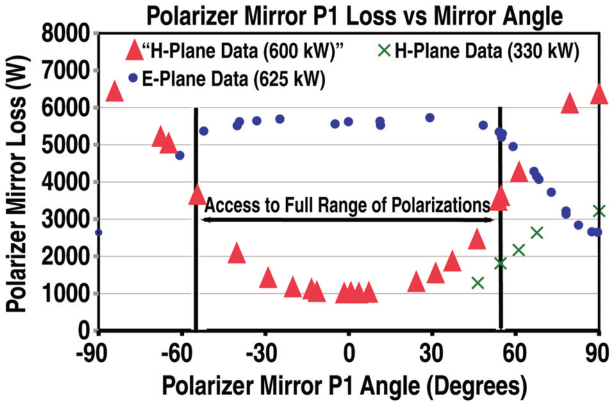

FIG. 4. Polarizer Mirror P1 ohmic losses for gyrotron power levels of approximately 600 kW and 330 kW at the end of 240-second pulses. The grooves in the mirror are perpendicular to the plane of the bend when the Mirror Angle is 0°. "H-plane" and "E-plane" refer to the incident polarization.

When the electric field is parallel to the grooves, very little field can penetrate the grooves, since their spacing is less than one-half wavelength. This situation corresponds to the minima in the losses in Fig. 4, which occur for 0° mirror rotation angle in the "H-plane" case and for ±90° mirror rotation angles in the "E-plane" case. The actual loss is determined by the tangential magnetic fields. Since the component of the incident magnetic field parallel to the mirror grooves is higher for the minima in the "E-plane" case, the minimum losses are higher for that case than for the "H-plane" case.

Another factor that should affect the ohmic loss is the surface resistance (R_s), which depends on surface roughness (S_R) and the surface temperature (S_T). For the 2008 tests, the mirror surfaces were machined by a wire electron discharge machining process (wire EDM), which had a rough appearance. Before the 2010 tests, the polarizers were disassembled and the mirror surfaces were re-machined, producing a shiny surface, which was expected to be smoother. However, little effect of this change was noticed in the measured losses.

Thermal analyses indicated that the stresses on the mirrors would be acceptable if the total absorbed power is about 6700 watts or less. These analyses included the effect of temperature-dependent surface resistance. For the 2010 tests, all the desired output polarizations could be achieved with P1 mirror rotation angles of 55° or less, a relatively low loss region. For the mirror rotation angles that are "low-loss solutions" for a given output polarization, the maximum measured loss on either mirror in the 2010 tests was 0.42%. For the 2008 tests, the corresponding maximum loss was 0.69%. We can conclude that with the 2010 orientation of the incident polarization and the polarizers, 1 MW CW operation would be achievable, since 4200 watts is comfortably less than the 6700-watt limit. For the 2008 cases, 1 MW operation could be marginal for some polarizations.

In the meantime, a polarizer mirror with improved cooling has been designed and built. Thermal analyses for this mirror indicate that at a total absorption of 9300 W, the peak stresses are still well below the yield stress of Glidcop® material. Hence 2 MW operation with those mirrors should be feasible, provided that the orientation of the incident polarization and the polarizers is chosen to correspond to that of the 2010 tests. Somewhat different orientations may also be possible.

Finally, it was reported in Sec. 4.1 that the PMBs performed as expected with respect to mode conversion, with at most some slight changes in the mode conversion occurring as the grooved mirrors were rotated.

4.4. Expansion Section (ES)

For ITER's needs, GA, has created a new design of a waveguide expansion section (ES), based on two corrugated telescoping sections. To maintain vacuum integrity, a stainless steel bellows surrounds the telescoping sections. The designed compression range is 30 mm. To minimize heating of the telescoping sections the parts are fabricated from copper, which minimizes ohmic losses and enhances thermal conduction. Figure 5 shows a picture of the ES with the outer shield removed to show the vacuum bellows. The operation of the expansion section was measured using laser displacement transducers. Figure 6 shows a 5.33 mm compression of the ES during a 367 s pulse. The compression is smooth and linear during the pulse.

FIG. 5. Photo of transmission line expansion section. Shield is removed to show the vacuum welded bellows connected to the two end flanges.

Since the gap between the telescoping sections varies as the ES compresses (gap decreases) or expands (gap increases), the expected mode conversion is not exact, but on average is estimated to be 0.33%, mostly of LOMs. Mode conversion heating of the transmission line connected to the ES is apparent in Fig. 2.

4.5. DC Break (DCB)

The ITER ECH system requires (DCBs) at both ends of the TL. A DCB is basically two sections of corrugated waveguide separated by a small gap. A chamber is assembled around the gap to maintain the vacuum integrity and alignment of the two waveguide sections. To maintain the voltage isolation the chamber incorporates a ceramic ring that supports the vacuum conditions and the needed voltage standoff.

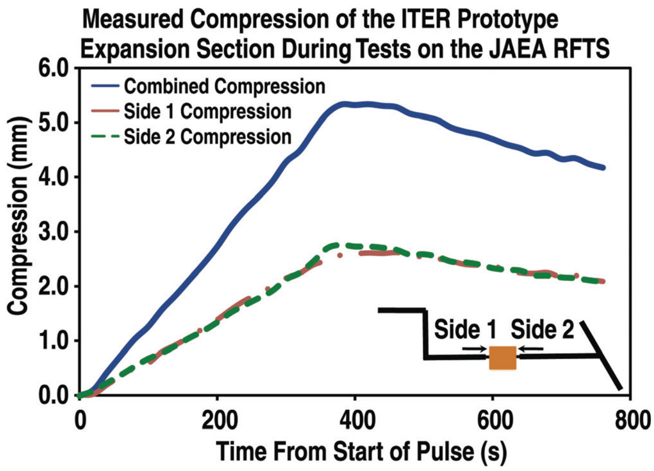

FIG. 6. Measured compression of the expansion section during a 367 s pulse. A compression of 5.33 mm was obtained.

When there is a gap in a waveguide, no matter how short or aligned, there will be rf leakage from the gap. The design of the DCB, tested on the JAEA RFTS, has an estimated rf leakage of 20 W when supporting 1 MW at 170 GHz. The test, shown in Fig. 7, indicated a temperature rise of the ceramic surface of 8°C during tests of 600 kW, 367 s. This projects to a 27°C surface temperature rise when used at 2 MW, which is reasonably below the 50°C rise design limit. Radiation leakage, 50 cm from the surface, was found to be ≈0.2 mW/cm^2, which is equiv. to 0.7 mW/cm^2 at 2 MW. This is well below the 5 mW/cm^2 safety standard. If the mode content of the transmitted rf results in higher rf leakage the temperature of the ceramic ring can be stabilized by water-cooling a flange connected to the ceramic.

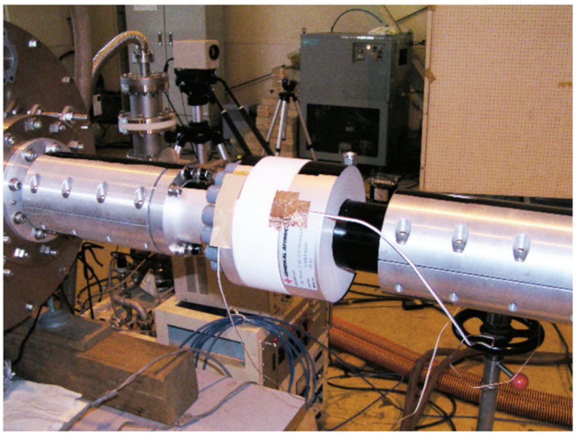

FIG. 7. Photo of the dc break being tested on the JAEA RFTS. Visible is the TC used to measure the ceramic break surface temperature. Delta T rise was 8°C for a 600 kW, 240 s pulse. Measured radiation was ≈0.2 mW/cm^2 at 50 cm.

5. Summary

Tests were performed on several ITER Prototype EC components. Most of the test were performed at ~600 kW for pulses of 240 s. Most of the components performed as predicted, with the exception of a higher ohmic loss in the waveguides. It was initially speculated that this was an artifact of the low level of the HE_{11} mode present in the 2008 tests, however a lower loss rate was not achieved when the HE_{11} mode content was 93% in the 2010 tests. The loss in the polarizer mirrors was greater than expected, but was eventually clarified when anisotropic roughness and temperature affects were included in the model. It will be a challenge to design a polarizing mirror for 2 MW operation, without limiting the polarization adjustment capability.

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