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DESIGN AND TESTING OF ITER ECH AND CD TRANSMISSION LINE COMPONENTS

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GENERAL ATOMICS

DISCLAIMER

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Abstract

Initial testing on the Japan Atomic Energy Agency Gyrotron Test Stand of ITER-relevant TL components, has shown reasonable efficiencies, but identified that trapped modes between closely located miter bends, as well as mode conversion at miter bends can lead to excessive heating of the connecting waveguides. General Atomics has designed, built, and will test components to address this issue as well as ITER relevant components that have not been tested at the levels of 1 MW, 170 GHz, for extended pulse lengths. Some of the components that will be tested are ultra low loss miter bends, dc breaks, polarizers, power monitors, bellows, waveguide switches, waveguide cooling clamps, etc. Details of the components and test results will be presented.

1. Introduction

The Electron Cyclotron Heating and Current Drive System (ECH & CD) envisioned for ITER has the objective of delivering 20 MW of rf power to the plasma from twenty-four 1 MW electron cyclotron (EC) systems. Each EC system consists of a 1 to 2 MW, 170 GHz continuous wave (cw) gyrotron connected to a transmission line, which transports the rf power from the gyrotron to either the Equatorial Launcher (EL) or to one of the four Upper Launchers (UL) [1]. The selection of the EL or the UL is provided by the use of a fast (~1 s) remotely controlled waveguide switch located in each transmission line.

The proposed layout of the EC system is in the process of being revised as the result of the ITER 2007 design review. A new rf building (RFB) is being proposed to be built adjacent to the assembly hall, which will house the EC and IC power supplies and rf generators [1]. Even though the incorporation of the new RFB into the plan adds an additional 30 m of waveguide length, the new routing plan actually has lower rf loss, owing to the total number of reflections from miter bends and similar transmission line components, such as waveguide switches etc., being reduced from 8-12 (2007 layout) to 7-9 (2008 layout). Han [2] has estimated that the transmission line losses, from nine-miter bend reflections is 8.25% neglecting the MOU to transmission line (TL) insertion and launcher losses. For this and past evaluations of losses in miter bends, it has been the standard to estimate the diffraction losses from plain mirror 90° miter bends to be equivalent to the losses through a gap in a waveguide, where the gap is equal to the waveguide diameter [3]. However, recent analysis by Tax [4], indicates that when higher order modes (HOMs) (such as HE_{12}) are present, the mode conversion in a miter bend can be amplified. These increased losses at miter bends from HOMs maybe the explanation for the observed (although marginally) higher losses in the transmission line tested [5]. Of more concern was the observation that most of the lost energy appeared in the waveguide sections adjacent to each miter bend (within a meter or so), indicating that the losses were the result of the generation of excessive amount of HOMs.

Although the final ITER transmission line specifications have not been finalized, General Atomics (GA) has identified several changes to its standard 1 MW class waveguide components that should be investigated to provide ITER with robust components that could support up to 2 MW cw at 170 GHz. Components and tests plans at JAEA are presented below.

2. Component Design and Testing Objectives

The design improvements for transmission line components anticipated for ITER, have been reported previously [6,7], however this will be the first time that components with these improvements will be subjected to high power and long pulses. The test objectives for each of the components are delineated in the following subsections.

A. Waveguide Switch

The GA waveguide switch has been redesigned so that it can operate with a switching time of ~1 s, and active water cooling has been added to the mirror so that it can support 2 MW rf power for the requisite 30,000 shots during the ITER lifetime without fatigue failure of the copper mirror. To test the switch power-handling capability the switch port for the diverted beam will be connected to the long pulse dummy load at the end of over 40 m of transmission line. The straight-through port of the GA switch will be connected to a short pulse dummy load, so that the switching function can be tested.

B. DC break

The dc break has been redesigned using ceramic insulators to accommodate high-power long-pulse operation. The measurements on the dc break will include temperature measurements of the alumina insulating ring and dc break waveguide segments. For 1 MW HE_{11} propagation, the calculated temperature rise of the ceramic for long pulse operation is about 5°C higher than that of the waveguide segments [3]. The rf leakage through the ceramic will also be measured. Since the rf leakage is sensitive to the presence of high order modes the plan is to have the dc break located between the two low loss diffraction miter bends. The higher order mode content at that location should be relatively low. Figure 1 shows a photo and an outline drawing of the dc break.

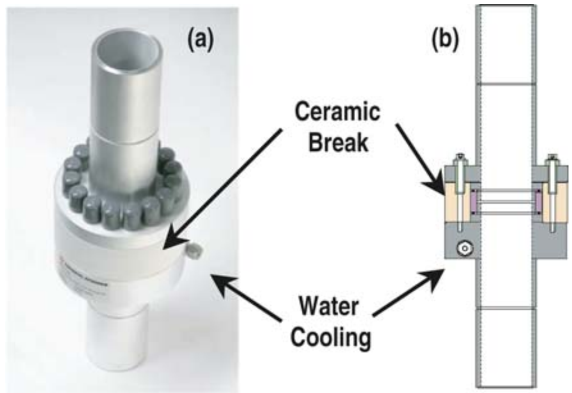

Fig. 1. Waveguide, 63.5 mm, 5 kV dc break designed for ITER. (a) Photo of dc break, (b) outline drawing showing the location of the nested ceramic cylinders used for vacuum sealing the gap between waveguides and to provide the structural alignment to maintain low mode conversion across the gap.

C. Low Diffraction Loss Miter Bend

Since mode conversion in simple 90° miter bends is the major loss function identified for the ITER EC transmission line [2], GA has developed [6,7] a new low diffraction loss miter bend (Fig. 2). Not only does this new miter bend increase the transmission line efficiency, it has the side benefit of reducing the heating in adjacent waveguides. The main measurements that will be made for the low diffraction loss miter bends will be measurements of temperature along the length of the tapers and waveguides, by IR imagery. If the design calculations are correct, the losses ideally will only be ~35 W/MW-m for HE_{11} propagation, especially for the section between the two low diffraction loss miter bends.

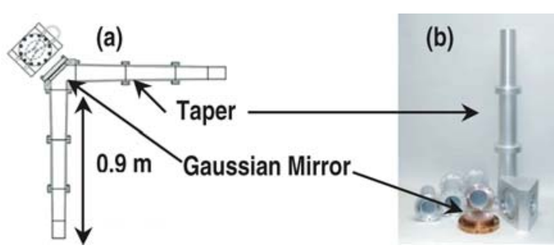

Fig. 2. (a) Schematic of low diffraction loss miter bend, showing the 0.9 m tapers that convert the HE_{11} waveguide mode to a Gaussian and the curved 88.9 mm diameter Gaussian Mirror (b) assembly of tapers and housing for low diffraction loss miter bend.

D. Miter Bend With HOM Choke Grooves

It appears that the high order modes generated in miter bends dissipate over the waveguides connected to either end of the miter bend. Since this dissipation leads to waveguide heating, and it may not be practical to provide cooling at all locations in the transmission line, it maybe prudent to have a miter bend design that captures the HOMs before they exit the miter bend itself. GA has developed a new high-order-mode-absorbing waveguide section, which is attached to a basic miter bend housing (Fig. 3). These waveguide sections have much deeper corrugations than in regular corrugated waveguide to force dissipation of these modes more rapidly. Measurements of the water temperature rise in the cooling tubes wrapped around the HOM-absorbing sections will give an indication of the magnitude of the power trapped, as well as the measurements of the temperature of the adjacent waveguides. These measurements should confirm that the HOMs generated at the miter bend attenuate more rapidly in the deep groove sections than in regular corrugated waveguide.

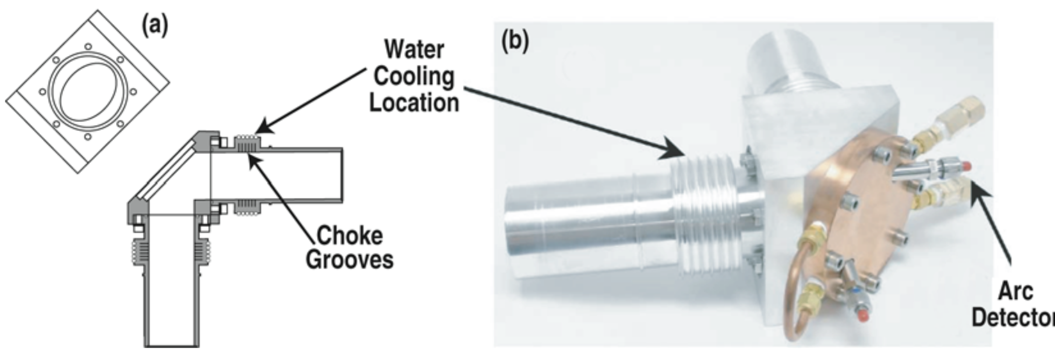

Fig. 3. Arc detector miter bend with higher-order mode absorbing sections on miter bend arms, (a) diagram of miter bend showing location of choke grooves, (b) photo of miter bend showing location where the water cooling tubes will be located.

E. Fast-acting Polarizer Miter Bends

It is expected that the nominal 36 s slew rate of the polarizing mirrors used on DIII-D and other fusion EC systems will be to slow for ITER. Thus, GA has developed a fast acting polarizer mirror drive that can be mounted on a basic 63.5 mm miter bend housing (Fig. 4). This fast acting mirror drive could in theory rotate the mirror 90° in 0.1 s, but for reliability and accuracy it will probably be limited to a slew rate of no more than 1 s/90°. Also, recent experiments show that the ohmic heating of polarizer mirrors maybe several times that of basic miter bend mirrors [8]. A new model of microwave absorption on the polarizer mirror vs incident polarization angles has been developed, based upon space harmonic field formulations, and tests of this model are crucial to evaluating if the power handling capability of the polarizers can be extended to 2 MW for all incident angles.

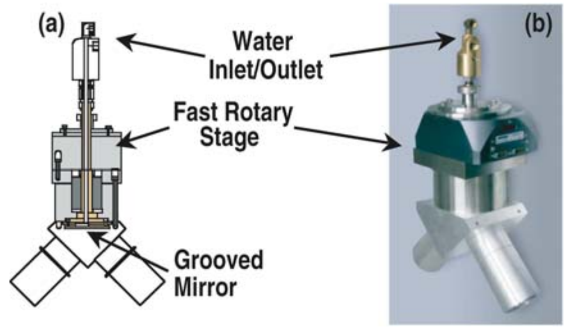

Fig. 4. Fast-acting polarizer miter bend, (a) outline drawing of a fast acting mirror drive mounted to a basic 63.5 mm miter bend body, (b) photo of fast acting polarizer miter bend sent to JAEA for testing. Note: water-cooling inlet/outlet on coaxial vacuum rotary joint, and rotary drive stage mount on top of miter bend body.

The critical tests on the polarizer mirrors will be to measure the temperature rise in the water-cooling circuit for each of the two mirrors. These measurements will be made as a function of the two mirror rotation angles. Losses at each mirror will be calculated from the water temperature increases and compared with results of the GA microwave absorption model for the same rotation angles and input polarization. The temperature of the waveguides adjacent to the polarizer miter bends will also be measured at various positions along the waveguides, using both RTD temperature sensors and IR camera measurements. The corresponding losses in the waveguide will be calculated and compared with the expected diffraction losses in higher order modes near cutoff generated by the miter bends.

F. Waveguide Cooling Bars

The results from the tests of 63.5 mm waveguide on the JAEA Gyrotron Test Stand [5] showed waveguide heating near the miter bends of ~490 W/m which scales to 1060 W/m for ITER and twice that when the EC systems are used at 2 MW. Tests performed at GA indicate that 1 kW/m heating would produce a waveguide wall temperature of ~300°C (Fig. 5). To minimize the impact of such waveguide heating it is prudent to incorporate some form of cooling, at least near miter bends. Any cooling concept should be economical, adjustable for random lengths, and easy to install in the field. The concept GA is proposing is a pair of cooling bars clamped on opposite sides of the waveguide. These longitudinal bars keep the temperature almost uniform along the length, and by using two bars, the chance of thermally induced deflections of the waveguide is minimized. The bars are made from extruded aluminum with a stainless steel cooling tube pressed into the top of the bar (Fig. 6). Tests indicate an almost order of magnitude temperature reduction by just clamping a cooling bar to the waveguide without any thermal transfer enhancement methods (at 850 W/m a ΔT rise of 31°C when bare cooling bars are used vs 245°C rise without cooling), and another factor of two when thermal grease is used (a ΔT rise of only 16°C at a power input of 850 W/m) (Fig. 5.).

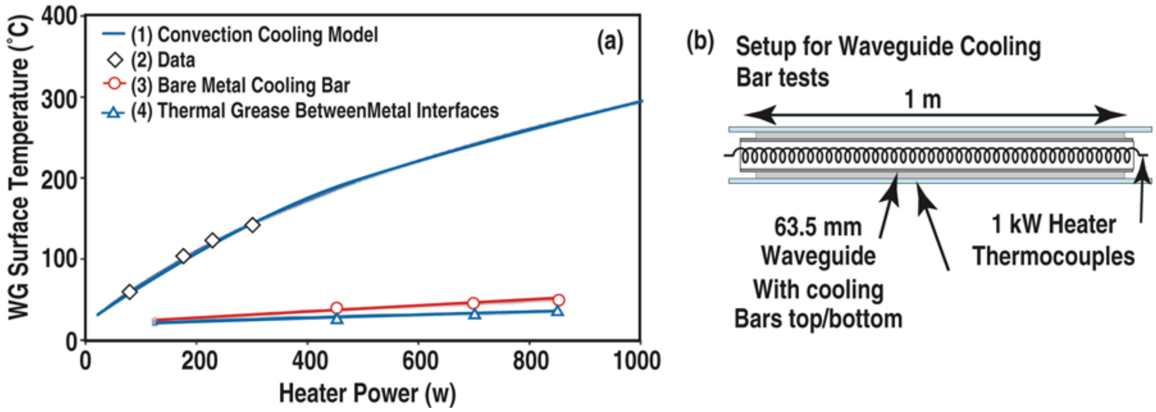

Fig. 5. Waveguide surface temperatures as a function of the internal heater power, (a) (1) model of free convection cooling only, (2) convection cooling data, (3) 9 l/m water flow bare metal to metal, (4) 9 l/m water flow thermal grease used between each metal to metal interface. (b) Setup for waveguide surface temperature measurements.

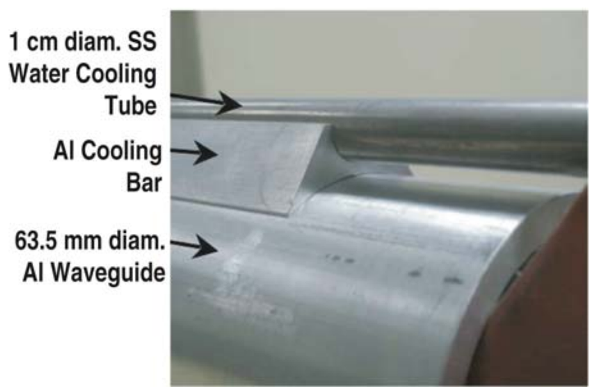

Fig. 6. Cooling bar concept, consisting of an aluminum bar manufactured to conform to the waveguide outer surface, and a stainless steel cooling tube pressed into a channel down the middle of the bar. Two bars are used per waveguide. Metal to metal interfaces may or may not use thermal grease to enhance thermal removal performance.

3. Conclusions

The ITER Design Review process that took place in 2007 identified several changes in the EC system that has increased the challenges of providing robust transmission line components. In particular the desire to have the transmission line support higher rf powers of up to 2 MW, so that future gyrotron performance enhancements can be utilized by ITER, has added increased thermal loads on mirrors in miter bends and miter bend like components (e.g. switches). GA has made refinements to most of the waveguide components planned for ITER and has produced prototypes of these new designs, which are planned to be tested on the JAEA Gyrotron Test Stand at Naka, Japan, in the summer of 2008. The testing is part of the US/Japan RF Technology Exchange program.

In addition to the prototype components, testing of a new waveguide-cooling concept will be performed. During the 2006 JAEA testing campaign it was determined that the waveguides adjacent to miter bends were becoming excessively hot, most likely resulting from the short dissipation length of HOMs generated in standard miter bends. In addition to managing the temperature of the waveguides with cooling bars, a low diffraction loss miter bend design will be tested, which if successful will avoid the generation of these short dissipation modes and decrease the need for cooling, ultimately resulting in more power to reach the ITER plasma.

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Acknowledgments

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