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PROGRESS ON DESIGN AND TESTING OF CORRUGATED WAVEGUIDE COMPONENTS FOR ITER ECH&CD TRANSMISSION LINES

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Progress on Design and Testing of Corrugated Waveguide Components for ITER ECH&CD Transmission Lines

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***Abstract*—The performance requirement of 1 (possibly 2) MW cw at 170 GHz for ITER Electron Cyclotron Heating & Current Drive transmission line components is much more demanding than the 1 MW, 5 to 10 s performance, generally at 110 GHz, that has been demonstrated on present devices. The high ITER heat loads will require enhanced cooling and, for some components, new or modified designs. In addition to thermal management issues, the components must be designed to have very low losses in order to meet the ITER transmission line efficiency requirements. Testing at representative ITER conditions of some components has been initiated at the JAEA 170 GHz gyrotron test stand at Naka, Japan. In addition, testing of a complete prototype ITER transmission line is planned in order to validate the designs for use on ITER. The design changes that are being made for the various components to assure low loss transmission and acceptable component temperatures are presented.**

***Index Terms*—ITER, Heating and Current Drive, Fusion, ECH Transmission Lines.**

I. INTRODUCTION

THE ITER transmission line system consists of 24 evacuated low-loss transmission lines to inject 20 MW of power to the plasma at 170 GHz. The RF power sources are gyrotrons with 1-2 MW output at the matching optics units (MOU) [1]. Pulse lengths are to be ≥ 500 s, but up to 3600 s is desired for some of the ITER scenarios. For that pulse length, all transmission line components need to be designed for cw operation. The configuration of the transmission lines from the gyrotrons to the upper and equatorial launchers is shown in Fig. 1. Not shown is a flexible waveguide structure that will be needed at the gap between the Tokamak building and the RF building in order to accommodate relative displacement between the two buildings.

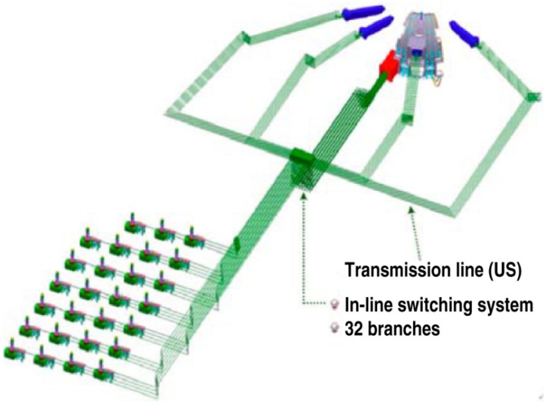

Fig. 1. ITER ECH&CD Transmission Line Configuration

A key requirement for the transmission lines is that they have a transmission efficiency of 83% or better in order for them to deliver 20 MW to the plasma from 24 MW output at the MOUs. To achieve this transmission efficiency, the waveguide components must be designed for high efficiency transmission, the number of miter bends must be kept to a minimum, and the waveguide sections must be precisely fabricated and aligned during installation. A recent analysis by MIT researchers [2] concluded that the theoretical losses of the ITER transmission lines is about 11% vs ITER's estimate of 14% (excluding losses in the launchers). Their analysis concludes that there is only a very small margin for error to meet this goal, and that losses could be reduced by using improved miter bends with lower losses.

II. LOSSES IN CORRUGATED WAVEGUIDE COMPONENTS

A. *Waveguides*

Theoretical losses in corrugated waveguide components for ITER were recently reviewed [3], [4]. The theoretical losses in 63.5 mm corrugated aluminum waveguide transmitting 170 GHz microwave power in the HE11 mode are very low, i.e. only about 35 watts per meter for 1 MW HE11 transmission. However, imperfect waveguide joints, slight curvature of waveguide sections, and misalignments generate power in unwanted modes. Nevertheless, these modes have low attenuation so they have little effect on waveguide cooling requirements. The various criteria for fabrication and installation tolerances are addressed fully in [3] and [4].

B. *Miter Bends*

Miter bends are one of the main contributors to transmission losses in ITER transmission lines. The fractional ohmic loss at an ITER copper miter bend mirror is estimated at 0.2%, or 2000 W for 1 MW power incident on the mirror in the highest loss polarization. GA miter bends have been upgraded to remove these power levels even for 2 MW cw operation by

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directing the water-cooling channel toward the center of the mirror where the peak heat load is greatest [5].

At 170 GHz in 63.5 mm waveguide, mode conversion losses at miter bends total about 0.25% [4]. These mode conversion losses are distributed approximately as 0.065% in modes close to cutoff in the forward direction, 0.065% in modes close to cutoff in the reverse direction, and about 0.125% in lower order modes in the forward direction. When 1 MW HE11 power is incident on the miter bend mirror, about 650 W is deposited from attenuation of the modes close to cutoff in each miter bend arm and adjacent waveguide. These losses are the main contributor to waveguide heating.

C. Power Monitor Miter Bends

In GA's power monitor miter bends, there is a thin structure around the coupling holes which becomes hot, and the corresponding stresses can exceed the yield stress of the copper material. After many cycles, the regions between the holes may crack, but that is not likely to cause a leak to the nearby water channels. Design changes are being made to reduce the thermal stresses by reducing the number of coupling holes and/or by increasing the thickness of the web containing these holes.

D. Polarizer Miter Bends

GA has designed and fabricated a polarizer miter bend with fast rotation capability, i.e. mirror rotation through 90° in 0.1 s vs. 36 s for standard polarizers. Recent experiments show that the ohmic heating of polarizer mirrors may be several times that for standard miter bends. Thermal modeling indicates that a polarizer mirror power handling capability may only be 1 MW for the most unfavorable polarization and mirror rotation angle before yielding occurs. If polarizers need to be designed for > 1 MW operation, tapers could be made to a larger diameter polarizer miter bend or, as preliminary design indicates, a more complicated structure for the polarizer mirror could provide the required increased cooling capability.

E. Very Low Loss Miter Bends

Miter bend diffraction loss can be nearly eliminated in principle by converting the HE_{11} mode to a Gaussian mode and using a slightly curved mirror in an expanded housing [6]. At 170 GHz in 63.5-mm waveguide, a corrugated taper 0.9 meters long can produce this conversion with very high efficiency (Fig. 2). The curved mirror can conveniently be housed in a standard 88.9 mm miter bend housing. The calculated mode conversion for this very low loss miter bend configuration is < 0.1%, and almost none of this residual mode conversion is in modes close to cutoff. Two of these miter bends are being fabricated to verify their calculated performance. Their use on ITER would increase the overall transmission efficiency, ease the cooling requirements adjacent to miter bend mirrors, and reduce the thermal expansion of the waveguide. This latter benefit would make it easier to have transmission lines without bellows. The disadvantage of such miter bends is that the housing is larger (88.9 mm design vs 63.5 mm design), and this could create problems in the transmission line layout.

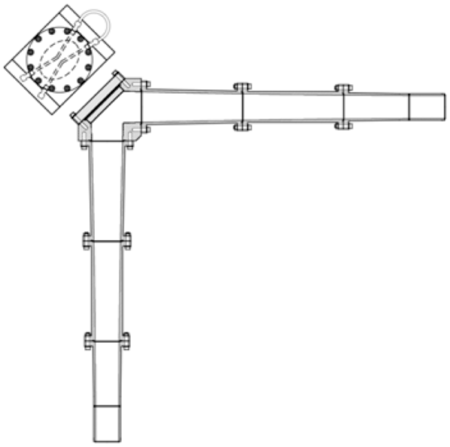

Fig. 2. A 170 GHz 63.5 mm miter bend with conversion to a Gaussian beam near the mirror.

F. Waveguide Switches

It has previously been reported [7] that the incident polarization on the switch mirror may need to be controlled to limit the ohmic losses at the mirror surface if the switch is to operate 2 MW cw in the diverted position. The critical issue is how many thermal cycles the copper mirror must survive before failure due to thermal fatigue. For 1 MW operation, the present switch design can handle up to 10,000 cycles for arbitrary polarization. The switch design has recently been modified so that the cooling channels are closer to the mirror surface to reduce the peak mirror temperature. A finite element analysis of the mirror cooling shows that this enhanced cooling design eliminates thermal fatigue life as a concern for up to 2 MW operation for any polarization. A prototype ITER waveguide switch with this new design is presently being fabricated.

G. Waveguide Bellows

The thin-walled aluminum flexible sections in the GA bellows can be kept at acceptable temperature for up to 2 MW HE_{11} operation by using water-cooling clamps on each side of the flexible sections [5]. If higher order modes are present, the heat deposition in the flexible sections may be too high to be adequately removed via conduction to the water-cooling clamps. In that case, other options are: a) eliminate the bellows and instead allow for movement of the waveguide and miter bends, b) add deep grooves in the waveguide at the ends of the bellows to attenuate some of the higher order modes before they reach the flexible sections (this has been done successfully on DIII-D 31.75 mm bellows), or c) use an alternative bellows design in which corrugated sliding sections are used to accommodate expansion and contraction in the transmission line.

H. DC Breaks

To handle 1-2 MW cw power in the DC break, the design has been modified to have all-ceramic insulators. A prototype 5 kV 63.5 mm DC break with a 2.5 mm gap has been fabricated and is ready for high power testing. The theoretical radiated power is 20 W for 1 MW HE_{11} transmission [4]. If the level of higher order modes is too high, a provision for cooling the ceramic would be needed and/or deep grooves could be machined into the waveguide sections on each side of the gap to remove some of the higher order modes.

I. *Waveguide Cooling*

There are several possible ways to remove the heat generated in waveguides, especially those adjacent to miter bends: (a) use a water jacket, (b) use water cooling clamps or (c) use water-cooling bars clamped or bonded to the waveguide [4]. Two 1-m long bars (into which stainless steel cooling tubes have been inserted) have been fabricated and are being tested in the lab to determine their effectiveness. A heating tape generating up to 1 kW was inserted into the waveguide, and the waveguide temperature will be measured. The aluminum bars are attached to the waveguide using hose clamps, and thermal grease or thermal epoxy may be used to reduce contact resistance. Since this cooling arrangement removes heat along the entire length of the waveguide, the waveguide thermal expansion is less than with the use of cooling clamps.

III. STATUS OF EXPERIMENTS TO VERIFY PREDICTED COMPONENT PERFORMANCE

MIT is setting up a laboratory for performing low power measurements on prototype 170 GHz ITER transmission line components provided by GA [2]. The initial focus of their effort is to measure and model the ohmic and mode conversion loss mechanisms in miter bends.

In order to develop and qualify the ITER transmission line components prior to procurement of the full set of 24 transmission lines, a 170 GHz complete prototype transmission line is being planned by the US ITER team [8]. A resonant ring configuration is being tested at ORNL to use in conjunction with a 0.5 MW gyrotron to enable testing the line at 1-2 MW. The specific performance requirements, component designs, and layout of the ITER transmission lines are still evolving. Issues being addressed include seismic isolation, vessel motion, thermal expansion of waveguide, tritium barriers, and integration of the transmission lines into the ITER tokamak and RF buildings.

In December 2006, JAEA staff performed some experiments using their prototype ITER 170 GHz gyrotron to inject power into a 63.5 mm diameter transmission line. An estimated 460 kW was diverted at a waveguide switch into a transmission line consisting of a long straight section (18 m) followed by a section containing 4 miter bends, additional waveguide, a gate valve and a dummy load. After a 4-minute shot, the temperature of each waveguide section was measured using an IR camera. The apparent temperature of the waveguide sections adjacent to the switch and miter bends was significantly higher than the temperature of the waveguide sections at the middle of the 18-m run. The JAEA data also showed significant heating (10°C increase) even 9 meters away from a miter bend or switch mirror. This 10°C temperature increase is appreciably higher than the 1.5° increase that would be expected for pure HE_{11} transmission for the pulse length and power level used in the experiment [4]. This may be due to absorption of higher order modes far from cutoff, either generated at miter bends or generated by waveguide curvature or tilts at waveguide junctions. The test results are preliminary and will be further analyzed and reported by JAEA staff in a future publication [9].

The GA components tested thus far at the JAEA facility include corrugated waveguides, miter bends and a power monitor miter bend. Discussions are underway for collaboration between GA and JAEA for testing other prototypical ITER components, including a DC break, very low loss miter bends, a waveguide switch and polarizer miter bends.

IV. CONCLUSIONS

Excellent progress is being made in developing new component designs and modifying existing designs to meet the challenge of high transmission line efficiency and the thermal management demands of 1-2 MW cw operation. While final specifications for ITER transmission line components have not yet been determined, there do not appear to be any showstoppers to 1 MW cw operation, and operation at levels up to 2 MW cw appears to be feasible. It remains critically important to test components at the high power, long pulse conditions the components will encounter on ITER to validate designs and to determine where improved designs may be needed. Good progress is being made toward the goal of testing individual components as well as an entire prototype transmission line at representative ITER conditions.

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