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CW Operation of Corrugated Waveguide Transmission Lines for ITER ECH and CD System

R.A. Olstad, R.W. Callis, J.L. Doane, H.J. Grunloh, and C.P. Moeller

General Atomics, 3550 General Atomics Ct, San Diego, CA 92121-1122
olstad@fusion.gat.com

Abstract. The electron cyclotron heating and current drive system on ITER will use corrugated waveguide transmission line components in 63.5 mm inner diameter and operate at 170 GHz. The most recent version of the ITER Project Integration Document (PID dated January 2007) specifies that each of the 24 gyrotron sources will yield an rf output of 1 MW with 99.5% Gaussian content at the output of the matching optic units (MOU) and inject this power into the transmission line with ≥96% HE_{11} content for pulse lengths ≥500 s. In order to inject 20 MW into the plasma, the overall transmission line efficiency must be ≥83%. Accounting for losses in the upper and equatorial launchers and losses at the interface between the MOU and the waveguide, the efficiency of the ≈100 m long transmission lines between the MOU and the launchers must be ≥90%. This goal is feasible with components designed for low loss transmission of HE_{11} mode power. A recent review of low loss waveguide and miter bends indicates that for ITER conditions the 90% target is achievable if mode conversion can be minimized. The primary losses are due to mode conversion at the miter bends and waveguide joints, and mode conversion caused by deflections in the waveguide runs. Installation procedures needed to minimize mode conversion will also be presented. One option for increasing the assurance of meeting the 90% transmission line efficiency is to incorporate low mode conversion miter bends; modeling results on such a miter bend design will be presented.

In addition to the transmission efficiency of the transmission line components, it is critical that the components be designed to handle the heat load under 1 MW (and possibly 2 MW) cw operation. The thermal performance characteristics of the various components will be presented.

I. ITER SPECIFICATIONS FOR EC H&CD TRANSMISSION LINES

The most recent ITER Project Integration Document (PID) [1] calls for 24 evacuated low-loss transmission lines to inject 20 MW of power to the plasma at 170 GHz for pulse lengths ≥500 s. The rf power sources are gyrotrons with ≥1 MW output at the matching optics units (MOU). The EU is developing 2 MW coaxial cavity gyrotrons so they would like the transmission lines to be capable of 2 MW operation to match the performance they expect for the gyrotrons they will supply to ITER. While the PID calls for ≥500 s operation, pulse lengths up to 3600 s are desired for some of the ITER scenarios. For that pulse length, all transmission line components including the waveguides need to be designed for cw operation. Each transmission line consists of straight sections of circular corrugated waveguide, an in-line switch connected to a dummy load at the MOU, a number of miter bends, two of which are polarizer miter bends and one is a power monitor miter bend. Arc detection systems are to be incorporated in a majority of the miter bends. The transmission lines also include dc breaks, expansion segments, vacuum pumping sections, isolation valves, high power remotely-operated switches to direct the power between the upper and equatorial launchers, and a dummy load for calorimetric measurement of rf power. There are four upper launchers, each with eight transmission lines. Two launchers use switches to select either the upper set of four or the lower set of four. A flexible support structure of waveguides is needed at the gap between the tokamak building (which is on seismic supports) and the rf building (which is fixed to the ground) in order to accommodate relative displacement between the two buildings.

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. The maximum length of a transmission line is approximately 100 meters. 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.

The PID calls for water-cooling of the transmission line components, but air cooling for long straight sections of waveguide. Thermal management of the transmission lines will be critical to assure that all components stay at a safe operating temperature and that they maintain a high transmission efficiency.

II. LOSSES IN CORRUGATED WAVEGUIDE

The theoretical losses in 63.5 mm corrugated aluminum waveguide transmitting 170 GHz microwave power in the HE_{11} mode are very low. The calculated loss for pure HE_{11} transmission is only about 0.35% per 100 m, or 35 watts per meter for 1 MW HE_{11} transmission. However, imperfect waveguide joints, slight curvature of waveguide sections, and misalignments generate power in unwanted modes, but these modes also have low attenuation. Hence their direct effect on waveguide cooling requirements should be small, even though they can affect the overall transmission efficiency.

Detailed information on these mode conversions is presented in a recent review article on the design of corrugated waveguides for ITER [2]. The main conclusions from this paper for ITER electron cyclotron heating (ECH) waveguides are:

- Losses from waveguide ellipticity, variations in waveguide diameter, and the offset of the axes of joined waveguides can all be kept small compared to other losses.
- It is critical to have uniform corrugation depth around the waveguide circumference. It is also important to avoid periodic variations in corrugation depth since this can lead to Bragg reflections.
- Losses from waveguide curvature can be kept low if the radius of curvature of each 2-m waveguide section is 2000 m or larger, or equivalently the deviation of the center of each waveguide section from a straight line is 0.25 mm or less. Waveguide curvature can readily be measured and aluminum tubes can be straightened to reduce the effects of curvature.
- The allowable tilt at a waveguide junction places stringent requirements on waveguide couplings. The tilt at each waveguide junction should be kept well below 0.001 radian (0.057 deg.) to avoid excessive losses from this mechanism.
- It is critical in installing the ITER transmission lines to avoid supporting the waveguide rigidly at an odd multiple of a half beat wavelength. The relevant beat wavelength is the beat wavelength to the modes coupled strongly to the HE_{11} mode by curvature. It is shown in Ref. 2 that for ITER, a suitable effective support spacing is between about 3.75 and 4.5 meters. For periodic spacings between 4.0 and 4.35 meters, the calculated loss is less than 0.02 dB/100 meters (or 0.5%/100 meters) at both 120 and 170 GHz.
- Thermal expansion or other longitudinal motion of the waveguide may induce bending that causes mode conversion. This motion can be taken up by bellows sections as described later in this paper, but another option is to allow the waveguide to bend slightly to accommodate the motion. This can be achieved by allowing miter bends to move, rather than having them fixed in place.

The mode conversion due to bending of the waveguide because of waveguide motion can be calculated based on the geometry and support methods used for the waveguide and miter bends. One possibility is to estimate the amount of motion during a pulse and set the transmission line layout in such a way that the waveguide does not have bending at the long-pulse operating temperature, although there will be bending at the beginning of a pulse [2-4].

III. LOSSES AT MITER BENDS

Miter bends are the one of the main contributors to transmission losses in ITER transmission lines. The fractional ohmic loss at a mirror in a miter bend is given by [5]:

$$\text{Ohmic loss} = 4(R_s/Z_0)\cos 45 \ \text{deg. (H-plane polarization)}$$
$$\text{Ohmic loss} = 4(R_s/Z_0)/\cos 45 \ \text{deg. (E-plane polarization).}$$

where R_s is the surface resistance, which is proportional to the square root of the bulk resistivity and also the square root of the frequency. Z_0 is 377 ohms, the impedance of free space. H-plane polarization is when the electric field is perpendicular to the plane defined by the miter bend arms; E-plane polarization is when the electric field is in the plane defined by the miter bend arms. At 170 GHz for ideal copper, 4 R_s/Z_0 is about 0.0011 at room temperature. In practice, surface roughness and elevated temperatures due to the cooling water and rf absorption increase the effective resistivity. The ohmic loss for the E-plane polarization is therefore about 0.002, (0.2%) or 2000 W for 1 MW incident, and 4000 W for 2 MW-incident. Similarly, the ohmic loss for H-plane polarization is about 0.1%. The mirror cooling design for GA miter bends has been upgraded to remove these power levels even for 2 MW cw operation by directing the water cooling channel toward the center of the mirror where the peak heat load is greatest [6]. With this optimized cooling of the mirror, the calculated maximum temperature rise of the mirror surface for 4000 W loss is only 70°C for a water flow rate of 0.13 l/s.

Fractional mode conversion loss in an ideal miter bend propagating HE_{11} is given by [7]: Mode conversion loss = $0.55(\lambda/D)^{3/2}$.

At 170 GHz in 63.5 mm waveguide, this loss is 0.00255, or 0.011 dB. About half of this 0.011 dB mode conversion is to modes close to cutoff. In turn, about half of this very high order mode power is reflected and about half is transmitted. The total diffraction loss at a miter bend is then transmitted as follows:

0.0028 dB (0.065%) in modes close to cutoff in forward direction,
0.0028 dB (0.065%) in modes close to cutoff in reverse direction,
0.0055 dB (0.125%) in lower order modes in forward direction.

For these mode conversion losses when 1 MW HE_{11} power is incident on the miter bend mirror, 650 W is deposited from attenuation of the modes close to cutoff in each miter bend arm and adjacent waveguides. To estimate the cooling required, it is necessary to estimate the damping length for these modes.

In December 2006, Japan Atomic Energy Agency (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) of 63.5 mm waveguide, followed by a miter bend, an upward 1-m vertical run, another miter bend, an 8-m horizontal run, another miter bend, a downward 1-m run, and then a 3-m horizontal run to a gate valve and dummy load. After a 4-minute shot, the temperature of each waveguide section was measured using an infrared (IR) camera. Black tape was applied to the waveguides and waveguide couplings to increase their emissivity to close to 1.0. 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. In addition to the heating near miter bends, the JAEA data showed significant heating even 9 meters away from a miter bend or switch mirror. The temperature increase in these waveguide sections was about 10°C. Scaling this to an HE_{11} power level of 1 MW would give a temperature increase of 10 x 1000/460 = 22°C. The test results are preliminary and will be further analyzed and reported by JAEA staff in a future publication [6].

From examining the preliminary data generated at the JAEA test stand, two very important results are apparent. First, it appears that the modes close to cutoff that are generated at a miter bend or switch mirror have a decay length of about 5 meters. This is the length for the power in these higher order modes to decay to about 5% of its value at the mirror. Secondly, the waveguide temperature quite far from adjacent mirrors was higher than expected for pure HE_{11} transmission. The 10°C temperature increase midway between the switch and the first miter bend is appreciably higher than the 1.5 deg. increase that would be expected for the pulse length and power level used in the experiment. This expected 1.5°C increase was calculated from the following relationship: $\Delta T \le (P_{abs}\, w/\rho c_p A)$ where P_{abs} is the power absorbed per unit length, ρc_p is the waveguide material heat capacity in joules/ (cm^3-K), A is the waveguide cross-sectional area, and w is the pulse length. The less-than sign allows for a small amount of convection away from the waveguide. For aluminum 6061-T6 alloy, which is the waveguide material, ρc_p is 2.42 joules/(cm^3-K). The cross-sectional area A of 63.5-mm waveguide is about 12.5 cm^2 and the expected loss for HE_{11} transmission is 0.35 W/cm per MW.

The higher-than-expected waveguide temperature far from the mirrors may be due to absorption of the higher order modes far from cutoff, either generated at miter bends or because of waveguide curvature or tilts at waveguide junctions.

IV. WAVEGUIDE COOLING

GA has designed and fabricated water-cooling clamps to remove heat from both miter bend arms and waveguide sections [6]. For cw operation, the heat dissipated in waveguide arms can be removed using a cooling clamp on the outside of the coupling (figure 1). The cooling clamp uses a thermal interface material to get good heat transfer between the coupling and the cooling clamp. The couplings make good contact with the waveguides, so the thermal resistance is negligible between the waveguide and the coupling.

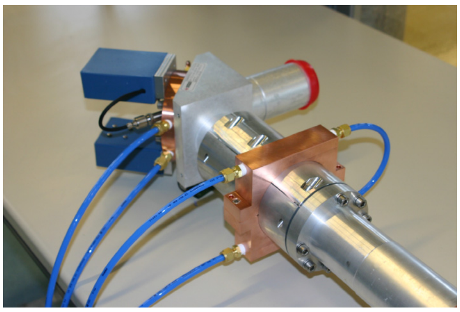

FIG. 1. Arc detector miter bend delivered to CRPP for their 2 MW gyrotron test stand, showing waveguide coupling with water-cooling clamp and 63.5 mm waveguide.

There are several possible ways to remove the heat generated in waveguides adjacent to miter bends. For high heat loads, a water jacket may be the best way to remove the heat. General Atomics (GA) recently made a simple water jacket for a 2-m waveguide attenuator for a non-fusion customer (figure 2). The design was for a stainless steel waveguide (29 mm od) with stainless steel jacket. It uses spirally wrapped stainless steel tubing in the gap between the waveguide and the jacket to provide a good cooling channel to assure uniform water flow over the waveguide outer surface and uses self-lubricating O-rings between waveguide and water jacket at the ends to allow for relative motion of waveguide and jacket. This design could readily be adapted for use on 63.5 mm waveguide.

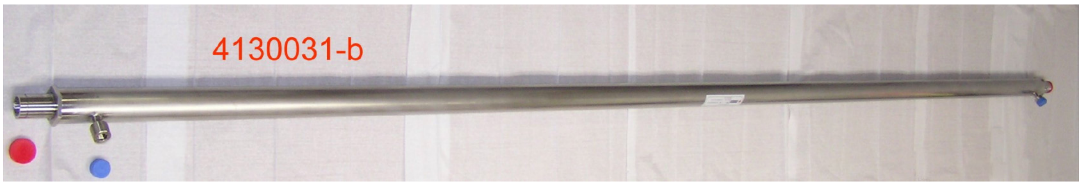

FIG. 2. Stainless steel water jacket around stainless steel waveguide attenuator.

Another option would be to use water-cooling clamps. For a relatively high heat load, such as might exist between two miter bends a meter apart, the heat load could be as high as 1000 W/m for 2 MW transmission. For 2 MW cw operation, cooling clamps spaced every 20 cm would result in a waveguide temperature increase of about 25°C midway between adjacent clamps. For 500 W/m, cooling clamps spaced every 30 cm would also result in about 25°C temperature increase midway between adjacent clamps. Such clamps can also be used on waveguide far from miter bends.

A third option is to use water-cooling bars clamped or bonded to the waveguide. This option is similar to a waveguide cooling system used by NIFS for experiments with about 150 kW at 84 GHz transmitted in 31.75 mm waveguide in very long pulses. To cool their waveguide they used water-cooled thin copper jackets that were clamped all along the waveguide [9]. One waveguide cooling approach that GA is developing is the use of aluminum cooling bars in which stainless-steel water-cooling tubes are inserted. A short section of a prototype-cooling bar is shown in figure 3. A 1-m long bar is being fabricated and will be tested in the lab to determine how effective it is in removing heat from a waveguide section with internal heating. Waveguide temperature will be measured for various means of attaching the stainless tubing to the aluminum bar and for attaching the aluminum bar to the waveguide. One or more of these bars can be attached to the waveguide to increase heat removal and to prevent thermal warping of the waveguide. Methods being considered for attaching the aluminum bars to the waveguide are simple mechanical contact using hose clamps, as well as the use of thermal grease or thermal epoxy to reduce contact resistance. These cooling bars can also be used on waveguides far from miter bends. Since they remove heat along the length of the waveguide, the waveguide thermal expansion is less than with the use of cooling clamps.

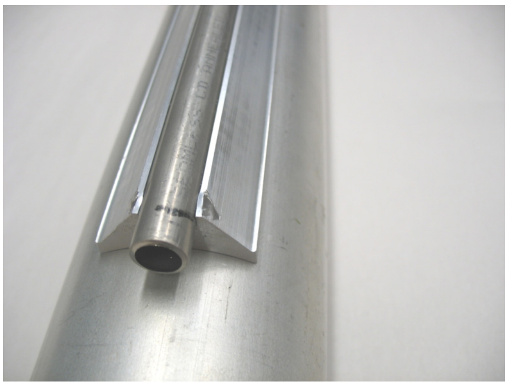

FIG. 3. Sample of aluminum water-cooling bar with stainless steel cooling tube on 63.5 mm aluminum waveguide.

V. VERY LOW LOSS MITER BENDS

The source of heating on larger diameter waveguides at high frequencies has mainly been residual diffraction losses at miter bends. It is possible to eliminate virtually all of these diffraction losses. If these diffraction losses are eliminated at all miter bends the attenuation in straight corrugated waveguide is theoretically so small that only minimal cooling would be necessary for a 1 MW 63.5-mm 170 GHz transmission line. This 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 [10]. At 170 GHz in 63.5-mm waveguide, a corrugated taper 0.9 meters long can produce this conversion with very high efficiency. Such a miter bend design is most practical for regular and power monitor miter bends, but more difficult to implement for polarizer miter bends and waveguide switch mirrors. 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. In these low loss miter bends with taper and larger curved mirrors, virtually none of the incident power misses the mirror, so higher order modes near cutoff are not generated. Two of these miter bends are being fabricated to verify their calculated performance.

Use of such very low loss miter bends on ITER would have the benefits of increasing the overall transmission efficiency, easing the cooling requirements adjacent to miter bend mirrors, and reducing the thermal expansion of the waveguide. This latter benefit would make it easier to have transmission lines without bellows. The disadvantages of such miter bends is that the miter bend housing is larger (88.9 mm design vs 63.5 mm design), and this could create problems in the layout of the ITER transmission lines. Also there would need to be almost a 2-m separation between adjacent miter bends to accommodate the length of the tapers. If the purpose of a pair of miter bends is to change the direction of the beam by some angle other than 180 deg., this may be achievable in a single housing containing two mirrors. The overall cost of the tapers and larger miter bend housing and mirror may be larger than the savings from increased transmission efficiency and reduced cooling requirements for the adjacent waveguides. These very low loss miter bends would be especially useful if the ITER transmission lines need to transmit 2 MW.

VI. OTHER ITER TRANSMISSION LINE COMPONENTS

Transmission efficiency and thermal performance considerations of other transmission line components are as follows.

Waveguide Bellows. Figure 4 shows a 63.5 mm bellows suitable for up to 2 MW cw operation for HE_{11} transmission. The thin-walled aluminum flexible sections under the special couplings can be kept at acceptable temperature for up to 2 MW operation by adding a water cooling clamp in the central stiff region, as well as on the couplings. If the bellows is to be located in ITER transmission lines at a location where there is a significant fraction of higher order modes present, the heat deposition in the flexible sections may be too high to be adequately removed via conduction to the water-cooling clamps. If that is the case, there are several options: a) eliminate the bellows and instead allow for movement of the waveguide and miter bends in various sections of the transmission line, b) add deep grooves in the waveguide at each end of the bellows to attenuate some of the higher order modes before reaching the aluminum 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.

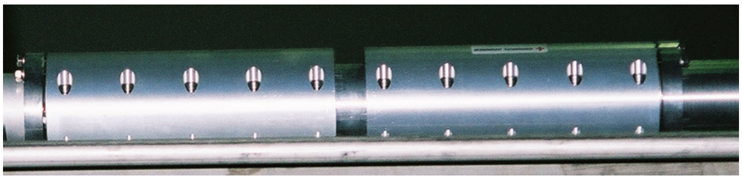

FIG. 4. 63.5 mm bellows suitable for use up to 2 MW HE_{11} transmission.

Dc Breaks. To handle 1-2 MW cw power in the dc break, the G-11 plastic insulators used in our standard design have been changed to alumina (94% pure) for ITER applications. A prototype 5 kV 63.5 mm dc break with all ceramic insulators has been fabricated (figure 5) and is ready for testing in a high power long pulse ECH testing facility. The fractional power radiated from a gap of width g in waveguide of diameter D propagating HE_{11} with a wavelength λ is given by [7]:

$$\text{Fractional radiated power} = 0.55\left(\frac{g\lambda}{D^2}\right)^{3/2} \quad . \tag{1}$$

A 2.5-mm gap is sufficient to hold off 5 kV. The radiated power from such a gap for ITER conditions is 0.002%, or 20 W for 1 MW transmission. The temperature rise in 94% pure alumina ceramic rings due to the absorption of the power radiated from the gap is described in Ref. 4. Those results showed that the alumina ceramic rings would be about 5°C hotter than the adjacent aluminum for HE_{11} power of 1 MW. The waveguide segments on each side of the ceramic can be cooled with built-in cooling channels, or water-cooling clamps can be used as described previously. These results assume that HE_{11} is propagating through the waveguide. If higher order modes are present, such as would occur if the dc break is near a standard miter bend or if the gyrotron output is misaligned when it is injected into the waveguide, leakage through the gap in the dc break would be larger than assumed here. If the fraction of power in higher order modes is too high, a provision for cooling the ceramic would be needed. Another option is to use deep grooves in the waveguide sections on each side of the gap to remove some of the higher order modes, as described above for the bellows. Testing a dc break in a high power long pulse transmission line would provide valuable information on dc break performance under representative ITER conditions.

FIG. 5. Prototype ITER 63.5 mm dc break using all ceramic insulators.

Waveguide Switches. It has previously been reported [11] 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.

Calculations on the present design show that a 63.5-mm switch mirror can handle 2 MW for up to 5000 cycles for arbitrary polarization, but can handle 2 MW for up to 10,000 cycles for circular polarization. For 1 MW operation, the present switch design can handle up to 10,000 cycles for arbitrary polarization. The switch design has 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 is pending to verify the improved performance of the modified design. A prototype ITER waveguide switch will be fabricated this year.

Polarizer Miter Bends. Recent experiments show that the ohmic heating of polarizer mirrors may approach 0.5% for certain polarizations, in comparison to the 0.1% ohmic heating for standard miter bends. Finite element analysis of polarizer mirror cooling is underway to assure that polarizer cooling is adequate for 1-2 MW operation. GA has designed and fabricated a polarizer miter bend with fast rotation capability. Mirror rotation through 90 deg. in times as short as 0.1 s was demonstrated. A fast mirror rotation may be needed for ITER since the rotation time for standard polarizer mirrors is comparatively slow at about 36 seconds to rotate 90 deg.

VII. CONCLUSIONS

The calculation of transmission efficiency for ITER transmission lines is not a simple task. The calculation of losses for individual components such as miter bends and dc breaks is relatively straightforward, but the losses due to such things as waveguide tilts and waveguide curvature are difficult to predict because they depend on manufacturing tolerances and the care taken in aligning the waveguide components. It is also difficult to calculate the effects of changing waveguide temperature during a pulse and the effects of changes in cooling water input temperature. The layout of the ITER transmission lines has not been finalized, so it is not possible to ascertain whether the 90% transmission line efficiency will be met. The use of very low loss miter bends would certainly help in meeting that target. As a complement to the theoretical calculations of transmission efficiency and thermal performance, it is critical to measure transmission line and individual component performance in a prototype ITER transmission line test stand. The US ITER Project Office is planning to establish such a test stand. Results from experiments on this test stand will feed back into component designs and possibly into the design of the ITER transmission lines themselves.

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