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ECH MW-Level CW Transmission Line Components Suitable for ITER

Robert Olstad*, John Doane, and Charles Moeller

General Atomics PO Box 85608 San Diego CA 92186-5608

*Phone: (858) 455-4060; Fax: (858) 455-2838; e-mail: olstad@fusion.gat.com

Abstract. The ECH transmission lines for ITER will require performance parameters not yet entirely demonstrated in ECH systems on present magnetic fusion energy machines. The key performance requirements for the main ITER transmission lines are operation at 1 MW for pulse lengths of 400 s up to 3600 s (essentially cw) at a frequency of 170 GHz. An additional consideration for transmission line performance is the possibility that ITER will use 2 MW coaxial cavity gyrotrons currently under development by Forschungs-zentrum Karlsruhe (FZK) and other European Associations and European tube industry. This paper addresses the progress made by General Atomics in the various transmission line components suitable for use on ITER. ITER design documents call for a corrugated waveguide inner diameter of 63.5 mm; many components have already been fabricated in this diameter, and those that have been made in other diameters (namely 31.75 mm and 88.9 mm) can readily be modified to a 63.5 mm i.d. design. In some cases, water cooling must be added to present designs to remove heat deposited during cw operation of the components.

1. Introduction

The ECH system for ITER will have demanding performance requirements not yet demonstrated in any ECH transmission line. The most demanding new requirement is for cw operation at power levels of 1-2 MW, depending on the type of gyrotron eventually selected. There is a great body of experience on the use of high performance corrugated waveguide transmission lines for electron cyclotron heating and current drive (ECH&CD) on fusion devices. Over the past 20 years, General Atomics (GA) has developed high performance corrugated waveguide transmission line components for low-loss transmission of high power microwaves for these applications. GA has designed and produced a 63.5 mm diameter 170 GHz transmission line for Kyushu University for 500 kW cw operation on the TRIAM-1M tokamak, and GA is presently designing and fabricating various 63.5 mm diameter transmission line components for 2 MW cw operation in a prototypical ITER 170 GHz transmission line to be installed at a test facility at CRPP in Lausanne, Switzerland [3]. GA has also provided 31.75 mm and 63.5 mm 170 GHz transmission line components to JAERI for 1 MW/10 s operation in their 170 GHz gyrotron testing laboratory. Similar components were also provided to NIFS for 168 GHz operation on the LHD device. GA has built numerous other transmission lines for 110 GHz, 118 GHz, and 82.6 GHz operation for GA's DIII-D device, JAERI's JT-60U and, in conjunction with Spinner GmbH, for TCV at Lausanne, and Tore Supra at Cadarache.

2. Development Status of ITER Transmission Line Components

The development status of GA's transmission line components was summarized at the IAEA Technical Meeting on ECRH Physics & Technology for ITER held July 2003 [1]. Since that meeting, GA has performed additional analyses of heat loads on various components and made design modifications to handle the 1-2 MW cw performance requirement. The reference transmission line components are, in approximate order starting at the gyrotron and moving toward the ITER vacuum vessel: RF conditioning Unit (includes matching optics, polarizer pair, switch, and gate valve), 1 MW cw dummy load, DC break, corrugated aluminum waveguide, power monitor miter bend, miter bend, expansion section / bellows, pumpout, stainless steel corrugated waveguide, rupture disk section, CVD diamond window assembly, and launcher waveguide and other components [2].

Present systems generally operate near 1 MW for up to 10 seconds, or at reduced power for longer pulse lengths. In anticipation of ITER needs, GA is in the process of evaluating its present transmission line component designs to determine what design changes will be needed to make the components suitable for 1-2 MW cw operation. The main design change for ITER is the enhancement or addition of water cooling to present components.

3. Corrugated Aluminum Waveguide Cooling

The expected heat load on straight sections of corrugated waveguides has been evaluated. The calculated ohmic loss of the HE_{11} mode at 170 GHz is about 32 watts per meter when 1 MW is transmitted, or about 64 watts per meter when 2 MW is transmitted. This heat can be removed by one of several means: enclosing the ITER transmission lines in ducts with forced air cooling, enclosing the waveguide in water jackets, wrapping the waveguides with water cooling tubes in good thermal contact with the waveguide, or by using water cooling clamps spaced periodically along the length of the waveguide. It is this latter approach that is analyzed here and is the one that will be used on the test facility at CRPP. Cooling clamps with four cooling channels have been designed (see Fig. 1). They use a thermal interface pad between the waveguide and the clamps to provide good thermal transfer. The cooling clamps may be attached anywhere on a central portion of any waveguide. Waveguide cooling was modeled by considering the temperature rise midway between two cooling clamps separated by length 2L. The temperature rise at this location is given by $\Delta T = q' L^2 / 2kA$, where q' is the power absorbed per unit length, k is the thermal conductivity of the waveguide material, and A is the waveguide cross-sectional area. For 6061-T6 aluminum, the thermal conductivity is 1.67 W/cm-K near room temperature, and it is insensitive to temperature. The cross sectional area is about 12.5 cm^2. For example, with L =40 cm and 2.0 MW transmitted in the HE_{11} mode, we find that ΔT=25°C. In this case, the power that must be removed at each clamp is 80x0.64=51 watts. The calculated temperature rise across the thermal interface pad is about 2°C, and the film drop between the water and clamp is less than

1°C for a flow rate of 0.1 liter per second in two channels connected in series. The calculated water temperature rise from inlet to outlet is only around 0.1°C.

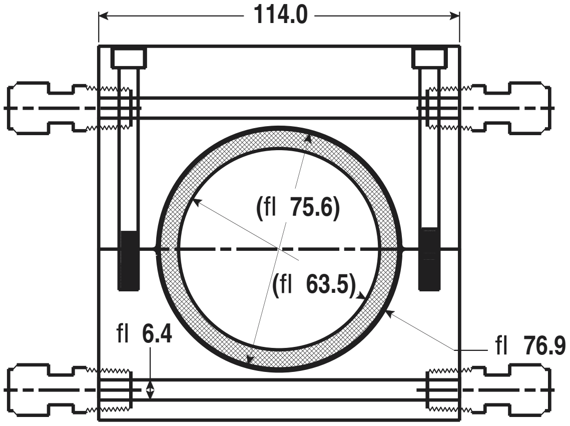

Fig. 1. Schematic of waveguide cooling clamp

4. Miter Bend Cooling

There are three sources of power losses in miter bends: ohmic losses at the mirror, mode conversion losses at an ideal miter bend, and mode conversion losses due to imperfect alignment of the mirror at 45° relative to the input and output axes of the miter bend.

The fractional ohmic loss at a mirror in a miter bend is given by:

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

$$\text{Ohmic loss} = 4(R_s/Z_0)/\cos 45^\circ \text{ (E - plane polarization)},$$

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. The worst-case polarization is the E-plane polarization, when the electric field is in the plane of the bend. At 170 GHz for ideal copper, $4R_s/Z_0$ is about 0.0011 at room temperature. In practice, surface roughness effects increase the loss by around 20%. The ohmic loss for the E-plane polarization is therefore about 0.0019, (0.19%, or 0.008 dB). With 2 MW incident, this is about 3800 watts. The mirror cooling design has been upgraded to remove this power level for cw operation by directing the water cooling channel toward the center of the mirror where the peak heat load is greatest (see Fig. 2). With this optimized cooling of the mirror, the calculated maximum temperature rise of the mirror surface is only 66° C for a water flow rate of 0.13 liter/second.

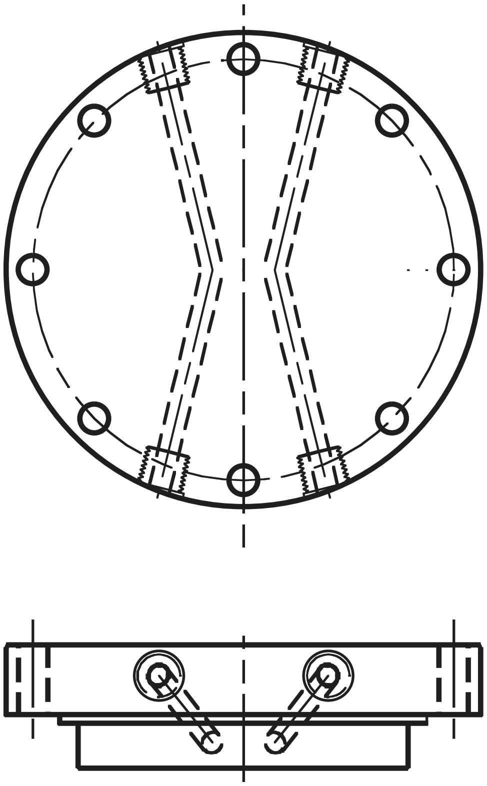

Fig. 2. Schematic of miter bend mirror cooling scheme

The fractional mode conversion loss in an ideal miter bend propagating HE_{11} is $0.55(\lambda/D)^{3/2}$. Mode conversion losses into modes close to cutoff at such a miter bend is calculated to be 0.065% transmitted and a similar amount reflected, or 1300 W in each direction for 2 MW incident power. Based on experiments at GA, the damping length of these very high order modes is estimated to be 1.6 meters. The power absorbed in each corrugated miter bend arm is estimated at 450 W. This power can be removed using a similar water-cooling clamp as described above, but which clamps to the waveguide coupling rather than the waveguide directly. For a flow rate of 0.1 liter per second, the water temperature rise is only about 1°C.

Mode conversion from imperfect alignment of the mirror has power that is proportional to the square of the misalignment angle θ. Since the net angular error is twice the misalignment angle, the mode conversion is equivalent to that at a tilt of angle 2θ. For small θ, the only significant mode conversion is to HE_{21} and to TE_{01} (or TM_{02}), depending on the polarization. The total fractional mode conversion power from mirror misalignment is then $2(0.233\pi D 2\theta/\lambda)^2$. At 170 GHz, for $\theta = 0.05°$ (about 0.9 milliradian), in 63.5-mm waveguide, this mode conversion is then about 0.0042, or 0.018 dB. This is larger than the total mode conversion at an ideal bend. However, the HE_{21} and TE_{01} (or TM_{02}) modes have low attenuation and do not contribute significantly to heating of the miter bend arms.

5. DC Break

To handle 1-2 MW cw power in the DC break, the G-11 plastic insulators used in our present design can be changed to alumina (94% pure). The fractional power radiated from a gap of width g in waveguide of diameter D propagating HE_{11} with a wavelength λ is $0.55\left(g\lambda/D^2\right)^{3/2}$. A 2.5-mm gap is sufficient to hold off 5 kV. Such a gap radiates approximately 40 watts when 2 MW is transmitted in the HE_{11} mode. For long pulses, G-11 has insufficient thermal conductivity to maintain a low temperature with this amount of power absorbed. Ideally, the large insulating ring should absorb almost all of the radiated power and then conduct it to the nearby aluminum (see Fig. 3).

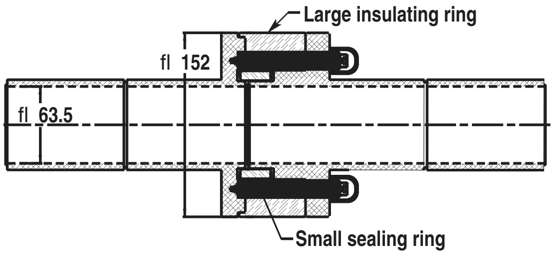

Fig. 3. Schematic of DC break

The absorption through a slab of dielectric with thickness L is approximately $8.686\pi\sqrt{\varepsilon_r}\tan\delta(L/\lambda)\ dB$, where ε_r is the relative dielectric constant and $\tan\delta$ is the loss tangent of the material. This formula neglects reflections, but is useful when the absorption is high.

Based on a review of published data on the loss tangent of alumina of various purities at various frequencies, we estimate that the loss tangent of the 94% pure material is on the order of 0.01 at 170 GHz. Using the above formula with $\varepsilon_r = 9$, $\tan\delta = 0.01$, and L= 30 mm (the radial distance through the large insulating ring), we find that the absorption is about 14 dB. The corresponding absorption through the small sealing ring of alumina is 3.7 dB. The peak temperature rises in both rings relative to nearby aluminum are on the order of 10°C when 40 watts radiates out the gap. Hence no direct cooling of the ceramics is required.

Waveguide cooling clamps as described above can be installed on the DC break waveguide segments. The total expected loss in the DC break is the loss of the waveguide (64 watts/meter for 2 MW transmission, or 35 watts) plus the power absorbed in the insulators (about 40 watts). Hence the absorbed power is relatively small.

6. Design Changes in Other Components

Design changes are also being made in other components to assure their suitability for use on ITER. Waveguide bellows are being slightly redesigned to reduce the potential for binding, and a water cooling clamp is being added to the central stiff region of the bellows to remove heat from the adjacent flexible sections. An in-line power monitor device now in use at DIII-D for 110 GHz 10s operation [4] can be modified for 1-2 MW cw operation by replacing RTDs with a water cooling channel and calorimetry circuit. Polarizers and power monitors have already been designed and fabricated for operation at 170 GHz and are suitable for cw operation up to 2 MW with the inclusion of water cooling clamps to remove heat deposited in the miter bend legs. A number of 110 GHz compact waveguide loads have been fabricated for 1 MW cw operation and are now in use at DIII-D [5], and one such load is also in operation at JAERI’s JT-60U tokamak. GA’s waveguide corrugating machine is being modified to make it easier to achieve the corrugation depth accuracy needed for a 170 GHz version of the load. As described in Ref. [1], the concept can readily be modified for operation at 2 MW by adding an additional copper waveguide attenuating section capable of absorbing 50% of the input HE_{11} power before the remaining 1 MW enters the standard 1 MW compact load.

GA is also continuing to develop square corrugated waveguide for remote steering applications such as the ITER upper launcher. Excellent low and high power results have been obtained over a steering range of ± 12° on a prototype 170 GHz launcher at JAERI’s Naka site under a GA/JAERI collaboration [6]. GA is presently fabricating an advanced version of the square corrugated waveguide for FOM for 2 MW short pulse testing at FZK-Karlsruhe and later, with the addition of water cooling, for 2 MW cw testing at CRPP [7,8]. This advanced version has rounded corrugations to reduce the chance of breakdown, and is designed to closely maintain the polarization ellipticity of the beam.

7. Conclusion

Excellent progress is being made on the designs of ECH transmission lines and remote steering launchers for use on ITER and other fusion devices requiring high power long pulse operation. Demonstration of the expected performance at ITER-relevant conditions is needed before such components are used on the ITER device.

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