GA-A24394

PERFORMANCE PARAMETERS AND DEVELOPMENT STATUS OF ECH TRANSMISSION LINE COMPONENTS SUITABLE FOR ITER

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This is a preprint of a paper to be presented at the IAEA TCM on ECRH Physics and Technology for ITER, Kloster Seeon, Germany, July 14-16, 2003, and to be printed in the *Proceedings*.

GENERAL ATOMICS PROJECT 04945
JULY 2003

Performance Parameters and Development Status of ECH Transmission Line Components Suitable for ITER

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1. Introduction

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 Forschungszentrum Karlsruhe (FZK) and other European Associations and European tube industry [1]. The U.S. is also developing 1.5 MW 110 GHz gyrotrons; results from this program could be applicable to the industrial 170 GHz gyrotrons for ITER [2]. This paper addresses the progress made by General Atomics in the various transmission line components suitable for use on ITER at 170 GHz, as well as at 120 GHz for plasma startup. 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.

In addition to the main transmission lines, there are corrugated waveguide components incorporated into the ECH launcher systems (equatorial and upper launchers). The status of the development of these components is also presented.

There is a great body of experience on the use of high performance corrugated waveguide transmission lines for ECH and 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 electron cyclotron heating and current drive. GA has designed and produced a 170 GHz transmission line for Kyushu University for 500 kW cw operation on the TRIAM-1M tokamak. All waveguides, miter bends, power monitors, bellows, pumpout tees, waveguide switches and DC breaks are in 63.5 mm diameter; tapers down to 31.75 mm are used to connect the larger diameter waveguide to a 31.75 mm CVD diamond transmission line window, stainless steel launcher, and dummy loads. 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.

The nine 63.5 mm transmission lines installed at CRPP on TCV were fabricated jointly by GA and Spinner GmbH and are suitable for 82.6 or 118 GHz/600 kW/2 s operation. Six transmission lines were also made by GA and Spinner for Tore Supra at Cadarache for operation at 118 GHz/210 s.

In addition, extensive experience has been obtained at General Atomics on six 110 GHz transmission lines at DIII-D with megawatt/10 s capability and lengths of about 100 m each. Similar components are used by JAERI in their four transmission lines on JT-60U.

The transmission line components addressed in this paper are, in approximate order starting at the gyrotron and moving toward the ITER vacuum vessel:

- RF Conditioning Unit (matching optics, polarizer pair, switch, 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
- Launcher waveguide and other components

2. RF Conditioning Units

The ITER ECH and CD design calls for an “RF Conditioning Unit” to convert the mm-wave power beam at the exit of the gyrotron to the waveguide HE_{11} mode and consists of matching optics and a pair of polarizers [3]. GA has built all of the components that constitute an rf conditioning unit, based on a so-called separated type, rather than an integrated type. The functions of an rf conditioning unit are accomplished with an MOU (or L-Box, described below), a pair of polarizer miter bends, a waveguide switch to direct mm-wave power to a dummy load, a gate valve after the switch, and connecting sections of waveguide.

GA uses MOU units with two mirrors on its 110 GHz three gyrotrons using boron nitride windows. These two mirrors are needed to correct the flattened gaussian profile gyrotron output to produce HE_{11} mode in the MOU output waveguide. If necessary, this same type of MOU could be used with ITER 120 GHz and 170 GHz gyrotrons. The interior of the MOU contains a water-cooled TiO_2-coated copper liner which would be suitable for operation at 1 or 2 MW cw. For true cw operation, it may be necessary to add some additional cooling and/or shielding to make sure there are no unacceptable hot spots.

As an alternative to the two mirror MOU configuration, a single mirror L-box configuration may be suitable for ITER. The L-box has the benefit of greater simplicity and lower cost. GA has good experience with using L-boxes on its most recent 110 GHz DIII-D gyrotrons made by Communications and Power Industries (CPI). These gyrotrons have CVD diamond output windows and have nearly gaussian output. The L-box made by CPI and GA uses a single mirror to focus the mm-wave beam at the output waveguide to match the waist size needed for HE_{11} mode propagation in the transmission line. A schematic of the L box is shown in Fig. 1. The L-box body is a standard commercially available stainless steel cross, coated on the inside with TiO_2. Cooling tubes are spot welded to the outside of the cross. The outside of the cross is then spray-coated with copper to provide good thermal contact for heat removal. For 1 or 2 MW cw use for ITER, the L-box configuration may need to be increased in size to provide a larger surface area for heat removal, depending on how much of the gyrotron output is not in pure gaussian mode. The L-boxes on DIII-D gyrotrons absorb about 5% of the gyrotron ouput, or about 50 kW.

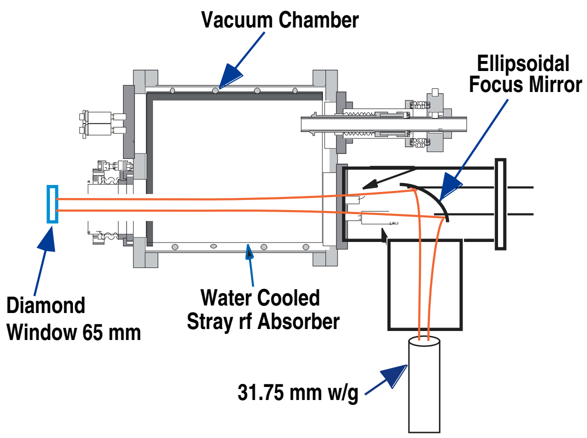

Fig. 1 L-Box configuration used on DIII-D gyrotron with gaussian output (later versions exclude the vacuum chamber between the gyrotron and the L-Box)

3. Polarizers

GA has made and delivered a 63.5 mm 170 GHz polarizer miter bend with actuator and controller to Kyushu University for 500 kW cw use on TRIAM-1M. The mirror is water-cooled with water flow directed from the backside of the mirror and removes heat from the hottest center part of the mirror just below the mirror surface. The design is suitable for operation up to 2 MW. GA has also made twelve 88.9 mm polarizer miter bends for NIFS at 168 GHz and 84 GHz and numerous 31.75 mm polarizer miter bends for JAERI and DIII-D. Separate polarizers for 120 GHz for ITER would need to be installed before the waveguide switches that direct the 120 GHz gyrotron ouput into the main transmission lines.

4. Waveguide Switches

GA delivered a 170 GHz 500 kW cw switch for use on TRIAM-1M. This switch, shown in Fig. 2, incorporates a water-cooled mirror with cooling provided by the use of vacuum bellows and sliding water lines. For truly cw operation, some water cooling of the aluminum switch body may be needed to remove microwave power deposited in the waveguide stubs, especially from mode conversion at the mirror in the diverted position. There is also a small amount of power that leaks through gaps between the waveguide stubs and the slider in the straight through or diverted position. Thermal analyses show that the switch is suitable for use at up to 2 MW cw for any polarization. 170 GHz switches can also be used at 120 GHz.

Fig. 2. 170 GHz 63.5 mm 1 MW cw waveguide switch made for Kyushu University.

5. Gate Valves

GA has worked with VAT in Switzerland to develop a design for high efficiency transmission of mm-wave power through the valve. The gate valve has corrugated inserts at the input and output as well as in the through position of the slider. There are only small gaps between the stationary and movable corrugated waveguide inserts so there is minimal microwave leakage into the gate valve body. This design is in use for the 31.75 mm transmission lines on DIII-D, TRIAM-1M, and LHD and will be used on KSTAR. The same basic design can be scaled up to 63.5 mm for ITER. For truly cw operation, some water cooling of the valve body may be needed to remove power lost in the waveguide inserts and that leaks into the valve body.

6. 1 MW cw Dummy Loads

Over the last several years GA has developed a compact dummy load designed for 1 MW cw operation at 110 GHz [4]. For ITER, this cw dummy load assembly would include an aluminum taper from 63.5 mm to 31.75 mm, a bellows section, a 31.75 mm Glidcop® waveguide corrugated to convert about 75% of the HE_{11} power into a surface wave which is absorbed at the inner surface of the waveguide, a tank load capable of absorbing 250 kW cw, and two calorimetry circuits (one for the attenuating section, one for the tank load). The

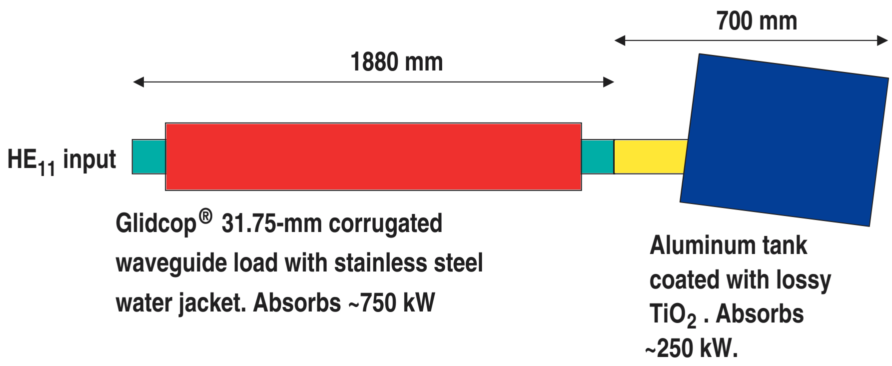

Fig. 3. Schematic of 1-MW CW load.

attenuating waveguide is surrounded by a water jacket to remove the deposited power. This type of load is in use at DIII-D on all six of its gyrotrons and has been tested to 1 MW 5 s, which is long compared to its time constant. One of these loads is also in use at JT-60U. A schematic of this load is shown in Fig. 3. GA is presently developing a 170 GHz version of this load. The main change is to very precisely machine the appropriate fine corrugation geometry in the Glidcop ® waveguide section to achieve the desired attenuation at 170 GHz. The concept can be readily modified for operation at 2 MW by adding an additional Glidcop® 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.

7. DC Breaks

GA has delivered a 63.5 mm dc break to Kyushu University for operation at 500 kW cw at 170 GHz. The dc break has a gap of approximately 2 mm between the metal surfaces of the waveguides to hold off 5 kV. At 500 kW the leakage through the gap is only 10 watts. The calculated leakage into air around the dc break is less than 1 watt for 500 kW of transmitted power. For ITER, operation at 1 or 2 MW cw would require design modifications to keep temperatures at acceptable levels. Options that are under consideration include the addition of cooling, a reduction in gap width while still holding off 5 kV, and replacement of the glass-reinforced epoxy laminate absorber by a ceramic material with higher thermal conductivity.

In addition to the 170 GHz dc break for Kyushu University, GA and GA/Spinner have made numerous dc breaks in 63.5 mm, 60.3 mm and 31.75 mm waveguide for CRPP, CEA, JAERI, NIFS and DIII-D for operation at 82.6 GHz, 118 GHz, and 110 GHz at various power levels and pulse lengths.

8. Corrugated Aluminum Waveguides

GA has fabricated over 2000 meters of corrugated waveguide in diameters over the range 31.75 mm to 88.9 mm for operation at frequencies of 28, 60, 82.6, 84, 110, 140, 168, 170 and 245 GHz. Most of these waveguides are corrugated in 2-m lengths and cut to shorter lengths as required for particular transmission line layouts. In 63.5 mm waveguide, the most suitable waveguide for ITER is a broadband waveguide capable of operation over the range 50 to 220 GHz. This waveguide is used for the TRIAM-1M transmission line. There is an open issue on whether such waveguide will need to be water-cooled for ITER. The ohmic heating at 170 GHz is calculated at 32 watts per meter. For pulse lengths of 1000 s, the calculated wall temperature rise for this waveguide is only 8.4°C for 1 MW transmission with free air convection at the waveguide surface. For cw operation, the calculated temperature rise is 27°C. Even with 2 MW transmission, the temperature rise of 54°C would be acceptable. The real need for water cooling comes for waveguide adjacent to miter bends. The higher order modes generated at miter bends are absorbed more strongly in the waveguide than is the HE_{11} mode.

Such water cooling could readily be handled by attaching water cooling clamps. Cooling clamps separated by an average of 20 cm for about 2 meters on either side of a miter bend with 2 MW transmission would be sufficient. If the waveguides in the array of transmission lines are closely spaced so that free convection is not applicable, forced air convection could be used to keep the waveguides cool enough.

9. Power Monitor Miter Bends

GA and GA/Spinner have delivered many power monitor miter bends to monitor forward and reflected power in the various transmission lines they have delivered. Most applicable to ITER are the 63.5 mm 170 GHz power monitors delivered to Kyushu University and JAERI. While Kyushu's requirement is for 500 kW cw operation, the power monitor is suitable for operation up to 2 MW for any polarization. For each of two cooling channels in the mirror, two holes are machined obliquely and are connected near the center of the mirror not far from the region of the mirror surface where the coupling cutoff holes are located. Coolant flow of 6 liters per minute is needed for 1 MW cw operation. For ITER, power monitors designed for use at 170 GHz can also be used at 120 GHz, although with reduced sensitivity.

10. Miter Bends

These are standard components that have been produced at various diameters and frequencies. The Glidcop® mirrors have water-cooling channels directly machined into them. If desired, optical fibers can be mounted into the mirror for arc detection. Such 63.5 mm miter bends are in use at TRIAM-1M. They are suitable for operation up to 2 MW. Miter bends designed for 170 GHz would also be suitable for 120 GHz operation.

11. Expansion Sections/Bellows

GA has made aluminum waveguide bellows sections in both 63.5 mm diameter and 31.75 mm diameter for devices in Europe, Japan and the U.S. The waveguide corrugations are machined directly into the aluminum, and deep corrugations in the two flexible sections of each bellows provide flexibility of +0.5/-3 cm axial motion. The 170 GHz bellows provided to Kyushu University are suitable for 500 kW CW operation at 170 GHz, but they are also suitable for use at 120 GHz. For 1 MW 170 GHz cw operation, the inner surfaces of the flexible bellows section will reach a temperature about 28°C higher than that of the adjacent regular corrugated waveguide because of the low thermal conduction through the thin-walled sections. With natural convection to air, the adjacent waveguide will have a temperature rise of about 27°C, so the bellows maximum temperature could be about 80°C. This would be acceptable. However, if the bellows is located near miter bends, the losses will be higher so water-cooling of the adjacent waveguide would be prudent. Similarly, for 2 MW cw operation the adjacent waveguides should have water-cooling clamps, and the center rigid section of the bellows should also be water-cooled.

12. Pumpouts

GA recently developed a new type of pumpout which is called a low conductance gap-type pumpout. This type of pumpout is suitable for the ITER transmission lines which require a vacuum of only 10^{-2} Pa (7×10^{-5} torr) since vacuum windows are installed in the lines near the torus. This type of pumpout consists of a standard four-way cross with conflat flanges. There is a short gap (≈ 1 mm) between the input and output corrugated waveguides protruding into the interior of the housing. The ITER waveguide is pumped at the MOU (or L-box) and at an intermediate location toward the torus window. The conductance of 50 m of 63.5 mm waveguide is only about 0.6 liters/s, whereas the conductance of a 1 mm gap in 63.5 mm waveguide is about 12 liter/s, which is therefore more than adequate. The microwave leakage through the 1 mm gap is only about 5 W for 1 MW 170 GHz transmission, or about 10 W for 2 MW transmission. Leakage at 120 GHz would be about 70% greater than these values. These microwave leakage levels will be absorbed at the walls of the cross and dissipated by natural convection, even for cw operation. To date, GA has only made 31.75 mm gap-type pumpouts, but the scale up to 63.5 mm is straightforward.

13. Stainless Steel Corrugated Waveguides

For waveguides that are going to experience temperatures greater than the reliable maximum operating temperature of aluminum (i.e. 150°-200°C), stainless steel corrugated waveguides are often used. Stainless steel waveguides are typically used for ECH launchers where bakeout temperatures greater than 300°C are often required and where plasma heat loads can be significant. GA has made stainless steel corrugated waveguides in 1 to 2 m lengths in 88.9 mm for LHD, 63.5 mm for Tore Supra, 60.3 mm for DIII-D, and 31.75 mm for TRIAM-1M and Riso National University. For 1 MW or greater cw operation, stainless steel waveguide will need to be water-cooled because of its higher microwave losses. The calculated loss in stainless steel waveguide at 1 MW, 170 GHz in 63.5 mm waveguide is about 130 watts per meter. Water cooling is best accomplished by use of a water jacket. GA has also made DIII-D launcher waveguides in Glidcop®. The advantages of Glidcop® are its low microwave loss, its ability to handle high continuous temperatures, and its high thermal conductivity. However, its high electrical conductivity has to be considered in designing waveguide supports to handle disruption loads.

14. Rupture Disk Section

The ITER ECH design calls for a rupture disk section near the torus window. According to Ref. 3, “when a high pressure accident happens in the vacuum vessel, the isolation valve closes. If the isolation valve shut-off fails, the rupture disc breaks and contaminated steam is conveyed by parallel ducts into the Vent Detritiation System.” GA has not designed such a rupture disk section, but would have the capability to do so once the desired performance parameters are specified.

15. CVD Diamond Window Assemblies

GA has delivered two types of CVD transmission line window assemblies: a hard braze design [Fig. 4(a)] and a Helicoflex® design [Fig. 4(b)]. The ITER design calls for a hard braze

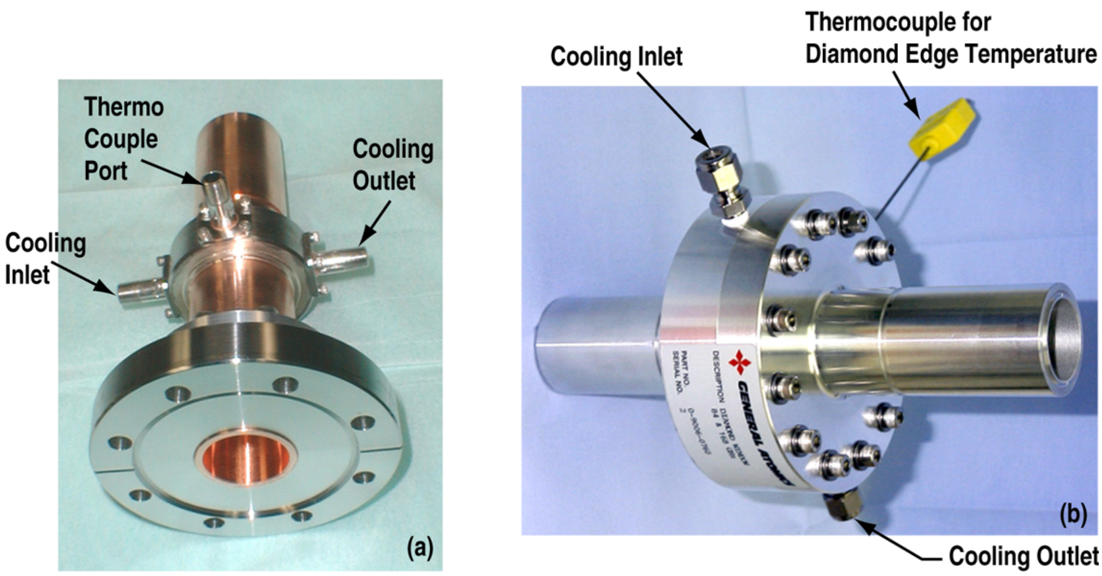

Fig. 4. (a) 31.75 mm CVD diamond window using hard braze design, (b) 31.75 mm CVD diamond window using Helicoflex ® metal seals.

design, but the simplicity of the Helicoflex® design may still make it worthy of consideration. To date, GA has made its CVD transmission line windows in 31.75 mm using diamond disks either one wavelength thick (170 GHz for TRIAM-1M, 168 GHz LHD) or one half wavelength thick (84 GHz for LHD). The hard braze design has the diamond disk brazed to a sealing ring which is brazed to two sections of corrugated copper waveguide. A water cooling jacket surrounding the diamond provides edge cooling of the diamond. The potential use of this window at Kyushu University is up to 500 kW cw, but calculations show that operation at 1 MW cw should be acceptable. Since the Helicoflex® design [5] does not use any brazes, the waveguide stubs were made from aluminum, but copper or stainless steel could also be used. Calculations and experiments show that there is very good thermal conduction from the diamond disk through the crushed Helicoflex seals to the window body. Operation at 1 MW cw is predicted to result in a peak diamond temperature about 90° above that of the bulk metal window housing, assuming a loss tangent of the diamond of 5×10^{-5} at 170 GHz and a window thickness of 1.5 wavelengths. It appears that water cooling of the housing itself, rather then the diamond directly, may be adequate, especially for a copper or aluminum body. For use on ITER, either design could be scaled up to 63.5 mm. Further analyses and experiments are needed to confirm their suitability for 1 MW or 2 MW cw operation on ITER.

16. Launcher Waveguide and Other Components

The stainless steel waveguide discussed above is suitable for conventional circular cross section corrugated launcher waveguide. For remotely steerable launchers, square cross section corrugated waveguide made from copper is most appropriate because losses in stainless steel are too high for the higher order modes present in the remote steering beam. GA originated the remotely steerable concept and has developed fabrication techniques for making very precise corrugation geometry and for welding the corrugated plates together to make square cross section waveguide [6]. GA is developing remotely steerable launchers in collaboration with JAERI, as discussed in Ref. [7]. Other researchers in Europe, Russia and Japan are also working on Remote Steering Launcher development, as presented in other papers in this Technical Meeting. Figure 5(a) shows a corrugated copper plate machined with dimensional tolerance in the corrugations of ±0.006 mm. A remotely steerable 170 GHz launcher using such corrugated waveguide is presently undergoing high power testing at JAERI. GA's first attempts at welding corrugated plates did not result in perfectly leaktight welds, presumably because the welding operation was not done in a sufficiently inert atmosphere. The leaks were, however, repaired so that JAERI could conduct meaningful high power tests. GA recently designed and

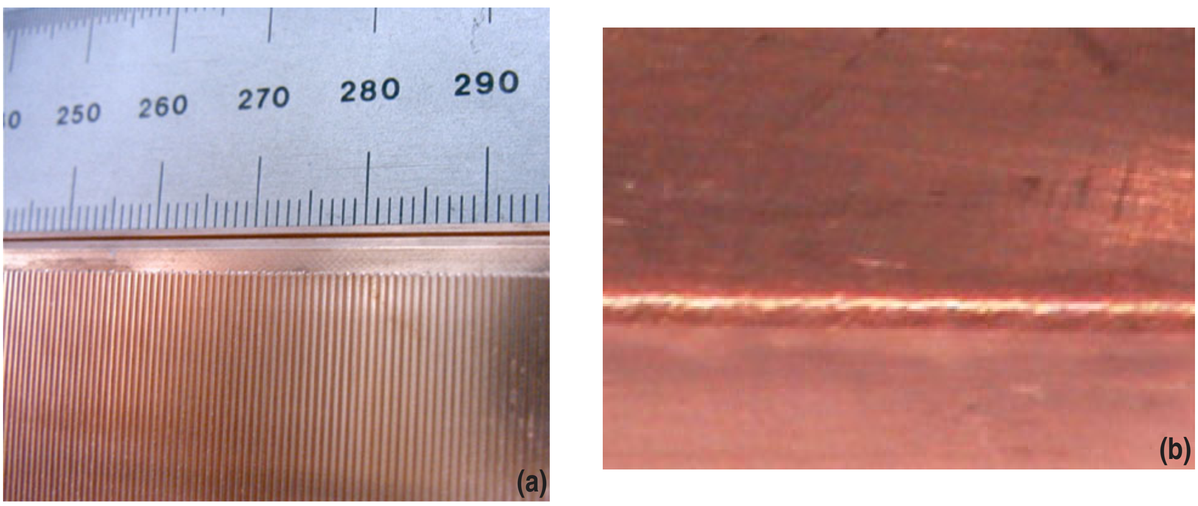

Fig. 5. (a) Precision corrugated copper bar for remotely steerable launcher waveguide, (b) Test weld on copper plates using new inert atmosphere TIG welding apparatus.

fabricated a custom welding apparatus to use TIG welding to weld corrugated copper plates together and to weld copper end seals to the waveguide in an inert atmosphere. Initial tests were very successful in producing leaktight welds. Figure 5(b) shows the high quality weld bead on a short section of test (non-corrugated) waveguide. Fabrication of welded corrugated copper waveguides, including welding "picture frame" sealing surfaces to the ends for use with Helicoflex® seals, is underway.

GA is also developing a technique for making square cross section miter bends suitable for a steering range up to ± 12.5 degrees. In experiments so far, the presence of miter bends in the line degrades the steering performance, especially for the electric field in the steering plane and for steering angles greater than ±10 degrees. If remote steering is used on the upper ITER launcher, which requires steering of ±5 degrees, it may not be necessary to use miter bends to reduce neutron streaming. If remote steering is going to be used on the equatorial launcher, it will be necessary to incorporate miter bends in the launcher waveguide, so good performance up to ±12.5 degrees will be required. GA has also developed a mirror box for the remote steerable mirror. The design being tested at JAERI uses a water-cooled mirror and allows translation and rotation of the mirror to cover the required steering range. This design could serve as a prototype for ITER.

The present reference equatorial ITER launcher design (not remotely steerable) calls for miter bends and expansion sections. Miter bends can readily be made out of stainless steel and they would require water cooling. Stainless steel bellows are not feasible, however, because of the low thermal conductivity of stainless steel and there is no practical way to water-cool the thin-walled flexible sections. Bellows made out of Glidcop® could be made, however. Because of Glidcop's high thermal conductivity, it would only be necessary to cool the rigid copper waveguide sections on either side of the flexible sections. If this bellows is to be welded to adjacent stainless steel waveguide, copper-to-stainless steel transition sections can be fabricated by a HIPing process. These transition sections could then be welded to the stainless steel waveguides and the Glidcop® bellows.

Other critical aspects of ITER equatorial and upper launchers, such as front-steering launcher mirrors, mirror actuators, and neutron shielding, are not addressed here because GA is not presently directly involved in the design of these components. These components must operate in a neutron irradiation environment and involve very high heat fluxes on mirror and plasma-facing surfaces. ITER activities on these components are discussed in other papers in this Technical Meeting.

17. Other Components for Possible Use on ITER

GA has just recently developed an in-line calorimeter for use on DIII-D transmission lines. This component has a small waveguide gap surrounded by a cavity with RTD thermocouples attached to a microwave absorbing surface. Assuming the power in the waveguide is HE_{11} mode, the expected temperature rise in the absorbing material can be calculated. One of these in-line calorimeters was recently installed near the end of a DIII-D transmission line. The results of initial tests shown in Fig. 6 are in very good agreement with the total power calculated at the end of the line based on calculated waveguide and miter bend losses and gyrotron output power levels determined calorimetrically from the boron nitride and MOU water cooling circuits. For long pulse/cw ITER use, the temperature rise in a water cooling circuit will need to be measured instead.

18. Conclusions

This paper has reviewed the status of transmission line component development as it relates to ITER. None of the 170 GHz components have yet been demonstrated at truly 1MW cw, but the components that come closest to this performance are the 63.5 mm corrugated aluminum waveguides, miter bends, power monitor miter bends, polarizer miter bends, and waveguide switches. Components that are readily adapted to ITER use at 1-2 MW cw (such as by modifying corrugation geometry for 170 GHz, modifying design to 63.5 mm size, or adding water cooling) are MOUs or L-boxes, gate valves with corrugated inserts, dummy loads, gap-type pumpouts, DC breaks, bellows, and stainless steel corrugated waveguides. Components still needing the most design and/or demonstration at 1 or 2 MW in ITER-relevant environments are CVD diamond windows, rupture disk sections, and remotely steerable launcher systems.

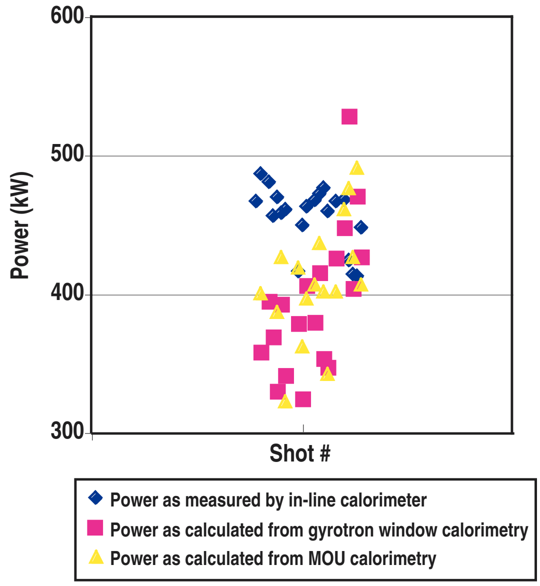

Fig. 6. ECH power level near DIII-D torus as determined using in-line calorimeter, and as calculated from measured gyrotron window and MOU calorimetry.

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