GA–A26150

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

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JUNE 2008

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 15th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating to be held in Yosemite National Park, California on March 10–13, 2008 and to be published in the Proceedings.

Work supported by
General Atomics Internal Funding

GENERAL ATOMICS PROJECT 49008
JUNE 2008

GENERAL ATOMICS

ABSTRACT

The performance requirement of 1 (possibly 2) MW cw at 170 GHz for ITER Electron Cyclotron Heating and Current Drive transmission line components is much more demanding than the 1 MW 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. Plans for testing additional components, both at JAEA and in the US will be presented. The US ITER Project Office (USIPO) plans to test a complete prototype ITER transmission line in order to validate the designs for use on ITER, and GA is providing some components to the USIPO for initial tests.

1. ITER REQUIREMENTS

The ITER transmission line system [1] consists of 24 evacuated low-loss transmission lines to inject 20 MW of power into the plasma at 170 GHz for pulse lengths ≥ 500s. The RF power sources are gyrotrons with 1-2 MW output at the matching optics units (MOU). 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 main transmission lines to the equatorial launcher are about 100 m long. In addition, there are 32 transmission lines, each about 40 m long, to re-direct power to four upper launchers. Switches are used to direct power to 24 of the 32 upper launcher transmission lines at any one time. The actual layout is being developed now and is expected to be finalized during the summer of 2008.

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 the 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. The predicted losses may change for the final detailed layout being developed by the ITER parties.

In addition to the high transmission line efficiency requirement, the components must have good thermal performance to make them suitable for cw operation. The components are to be designed for the whole ITER lifetime of 30,000 pulses. The transmission line vacuum pressure must stay below 10E-2 Pa to minimize the risk of arcing throughout a long pulse shot.

2. GENERAL ATOMICS TRANSMISSION LINE COMPONENTS

2.1. LOW-LOSS CORRUGATED WAVEGUIDE

Theoretical losses in corrugated waveguide and corrugated waveguide components for ITER were recently reviewed [3,4]. The theoretical losses calculated using space-harmonic analysis for HE_{11} mode transmission of 170 GHz microwave power in 63.5 mm corrugated aluminum waveguide are very low, i.e. only about 35 watts per meter for 1 MW HE_{11} transmission. This power is deposited at the walls of the waveguide and needs to be removed for cw operation. In addition, imperfect waveguide joints (from tilt or offset), slight curvature of waveguide sections as fabricated, and curvature due to gravity sag and misalignment of supports couple power in the HE_{11} mode into power in other modes. These non-HE_{11} modes are low order modes having higher attenuation than for HE_{11}. The various criteria for fabrication and installation tolerances are addressed fully in Refs. 3 and 4.

2.2. BASIC MITER BENDS

Miter bends are one of the main contributors to transmission losses in ITER transmission lines. Losses are due both to ohmic losses at the mirror and diffraction losses in making the transition from waveguide to the mirror and back to waveguide. The fractional ohmic loss at an ITER copper miter bend mirror at room temperature is estimated at 0.17% or 1700 W for 1 MW power incident on the mirror in the highest loss polarization (i.e. E-plane polarization). This power can readily be removed by water cooling of the mirror. GA miter bends have 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 [5]. Thermal, stress and strain analyses, using Cosmos Works software, were performed on the cooling of the oxygen-free copper miter bend mirrors under the most demanding ITER conditions, namely with 2 MW incident with E-plane polarization. At room temperature, the power absorption with E-plane polarization is 3400 W. The temperature dependence of copper resistivity was accounted for in the model. For a water temperature of 25°C and a flow rate of 19 liters per minute in each of the two cooling channels, the peak temperature at the center of the mirror is 131°C and maximum strain is less than 0.1%, corresponding to over 30,000 cycles to failure. From this analysis it can be concluded that the miter bend design is suitable for 2 MW cw operation.

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 HE_{11} 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.

2.3. LOW DIFFRACTION 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 [6,7]. At 170 GHz in 63.5-mm waveguide, a corrugated taper 0.9 m long can produce this conversion with very high efficiency. The housing for the curved mirror is similar in size to a standard 88.9 mm miter bend. The calculated mode conversion for this low diffraction loss miter bend configuration is ~ 0.08% (one-third that for a standard miter bend), and almost none of this residual mode conversion is in modes close to cutoff so higher order modes near cutoff are not generated. Two of these miter bends have been fabricated and will be tested at JAEA 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. A disadvantage of such miter bends is that the housing is larger (88.9 mm design versus 63.5 mm design), and this could create problems in the transmission line layout. Another potential disadvantage is that the design is narrow band and would not function well if ITER were to use two- or multiple-frequency gyrotrons at some point during ITER's lifetime.

2.4. POWER MONITOR MITER BENDS

In GA's power monitor miter bends, there is a linear array of coupling holes at the center of the Glidcop® dispersion strengthened copper mirror. The heat conduction in the region of the holes is not as effective as for a standard miter bend mirror, so particular care needs to be taken in the design to assure that thermal stresses do not exceed the Glidcop® yield stress. After many cycles, the regions between the holes may crack, although that is not likely to cause a leak to the nearby water channels. Design changes and associated thermal and stress analyses 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. These analyses have already shown that the power monitor can reliably operate for the ITER lifetime for 1 MW with H-plane polarization. Further design modifications are being evaluated to enable operation at 1 MW with E-plane polarization or 2 MW with H-plane polarization.

2.5. 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, in comparison to 36 s for standard polarizers. Recent experiments show that the ohmic heating of polarizer mirrors may be several times that for standard flat miter mirrors [8]. Analyses are underway using a space harmonic field formalism to calculate the microwave absorption at a polarizer mirror vs. incident polarization and mirror angles. Using these modeling results and thermal and stress analyses indicates that the current cooling geometry of the polarizer mirror is suitable for 1 MW cw operation using optimized mirror rotation angles for the pair of polarizer miter bends used to achieve any output polarization. A new polarizer mirror design uses a more complicated cooling path with increased cooling capability. Thermal, stress and strain analyses are underway using Cosmos Works software to determine the suitability of this design for 2 MW cw operation.

2.6. OTHER ITER-RELEVANT ECH TRANSMISSION LINE COMPONENTS

Other components under development by General Atomics for potential ITER use include waveguide switches, waveguide bellows, DC breaks, and waveguide cooling bars. The development status of these components has been reported previously [4,5,9].

2.7. EXPERIMENTS TO VERIFY PREDICTED COMPONENT PERFORMANCE

2.7.1. Transmission Line Testing at JAEA 170 GHz Gyrotron Test Stand

In 2006, GA provided components to JAEA for testing at the JAEA 170 GHz gyrotron test stand. Preliminary test results have been reported by JAEA staff [10]. In addition to the GA components already provided (corrugated waveguides, miter bends and a power monitor miter bend), GA is providing additional components for testing under the US/Japan RF Technology Exchange. These additional components include (a) waveguide switch, (b) polarizer miter bend pair with fast (~0.1s) full rotation, (c) miter bend pair with a deep corrugation section in each arm to absorb high order modes, (d) pair of low diffraction loss miter bends, (e) DC break with ceramic insulators, (f) additional sections of 63.5 mm corrugated waveguide, (g) additional waveguide couplings, and (h) cooling bar pairs for use on 2-m and 1-m length waveguides. These tests will begin July 2008 and will either validate the component designs or show where design improvements are needed.

2.7.2. Transmission Line Testing at ORNL Test Stand for the US ITER Project Office

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 [11]. A resonant ring configuration is being developed at ORNL to use in conjunction with a 0.5 MW 170 GHz gyrotron to enable testing the line at 1-2 MW.

GA is presently fabricating a number of 63.5 mm 170 GHz waveguide components for testing by the US ITER Project Office. These components include a waveguide switch, polarizer miter bends and controller, arc detector miter bend, plain miter bends, pumpout tee, waveguide gate valve, waveguide bellows, 2-m lengths of waveguide and extruded couplings.

3. 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, operation at 1 MW cw does not appear to be a problem, 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. The planned high power testing of components at JAEA and ORNL will provide valuable information to assure that components are designed to satisfy the ITER performance requirements.

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ACKNOWLEDGMENT

This work supported by General Atomics internal funding. The collaboration between General Atomics and K. Sakamoto, K. Takahashi and K. Kajiwara at JAEA, Naka, Japan is greatly appreciated.