GA–A24769

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This is a preprint of a paper to be presented at the Joint 29th International Conference on Infrared and Millimeter Waves and 12th International Conference on Terahertz Electronics, Karlsruhe, Germany, September 27–October 1, 2004 and to be published in the *Proceedings.*

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Work supported by
the U.S. Department of Energy
under Contract DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
JULY 2004

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Recent Advancements in ECH Transmission Line Components For ITER and Other Devices

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Abstract

General Atomics continues to adapt its mm-wave transmission line components to meet the ever-more demanding requirements for DIII-D, ITER and other fusion devices in Japan and Europe. Components that are addressed include components for 1 to 2 MW CW operation and remote steering launcher waveguides.

1-2 MW CW Transmission Line Components

The most demanding requirement for the ITER ECH transmission lines is cw operation at 1 to 2 MW, depending on the ITER gyrotron output power. 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, General Atomics 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 use on ITER. The present ITER design calls for 63.5 mm inner diameter corrugated waveguide for operation primarily at 170 GHz, but also at 120 GHz for ITER startup. The main design change for ITER is the enhancement or addition of water cooling to present components. The expected heat loads on straight sections of corrugated waveguide and on miter bends have been evaluated. Temperatures of both types of components can be kept quite low through the use of water cooling clamps on waveguides and on miter bend waveguide arms, and by enhancing the water cooling of miter bend mirrors.

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 $\Delta T = q' L^2 \big/ 2kA$ 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. 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. Hence $q' = 0.64$ W/cm in the above formula for the more demanding case of 2 MW transmission. Cooling clamps with four cooling channels have been designed. They use a thermal interface pad to provide good thermal transfer. The cooling clamps may be attached anywhere on a central portion of any waveguide. 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 80 × 0.64 = 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.

Ohmic loss calculations on 63.5 mm miter bends with copper mirrors give a maximum heat deposition at 170 GHz of 0.19%, or 3800 W for 2 MW incident power. With 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. 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. 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.

Design improvements are also being made to DC breaks, waveguide bellows, power monitors, pump-out tees, in-line calorimeters and waveguide dummy loads to handle the high power long pulse operation at 170 GHz operation. Some design considerations for the ITER ECH application have been described previously [1].

Remote Steering Launchers

The present reference design for the ITER ECRH upper launcher is based on the remote steering concept [2]. For several years General Atomics (GA) has been developing the remote steering launcher concept in collaboration with JAERI [3-5]. This concept uses square corrugated launcher waveguide to transmit the ECH beam injected into the waveguide at a specified angle relative to the waveguide axis. The waveguide modes exiting the other end of the waveguide are reconstructed into a beam with the opposite angle of the input beam.

The precision of the corrugation geometry is very important for achieving the desired steering. GA fabricated square cross section copper corrugated waveguide with a corrugation depth tolerance of ± 0.007 mm for low and high power testing at JAERI's Naka site.

Results reported in Refs. 4 and 5 show that the output power in the desired direction over the range ± 12° is > 95% of the input power. No arcing occurred in testing to 0.8 MW for 1ms or 0.5 MW for 2s. The output beam had the same radiation pattern for electric field either parallel or perpendicular to the plane of steering, thereby confirming that the corrugation geometry calculated and fabricated for 170 GHz operation was correct. The radiation pattern for this launcher apparatus was modeled at 0°, 5° and 12°; the results were compared with precise low power measurements made at JAERI. The agreement between theory and measurements was excellent. Figure 1 shows the calculated radiation pattern at a steering angle of –12° and the measured patterns for E field in the perpendicular and parallel directions.

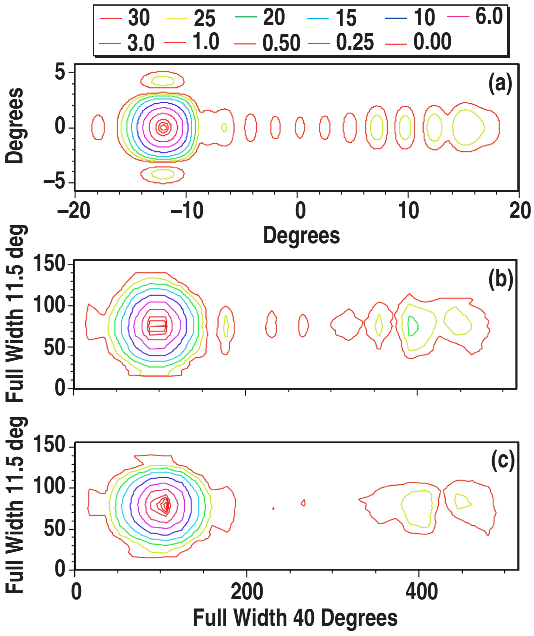

Fig. 1 (a) the calculated radiation pattern at a steering angle of –12°; (b and c) the measured patterns for E field in the perpendicular and parallel directions.

In addition to achieving the desired steering for E parallel or perpendicular to the plane of steering, it is important to preserve the polarization ellipticity. A finite difference time domain code was used to analyze a rounded corrugation shape to determine the depth at which waves having E in the plane of steering propagate at the same phase velocity as those having H in the plane of steering. To be able to estimate the required manufacturing tolerance of the corrugation depth, a wall reactance model was used to estimate the phase shift in a 170 GHz remote steering waveguide under fabrication for FOM. For a total launcher waveguide length of 4.35 m, an internal dimension of 44 × 44mm and a steering angle of 12°, a phase shift of 11° is calculated for a corrugation depth 0.006 mm larger or smaller than optimum. This phase shift is relatively minor and could be compensated by adjusting the input ellipticity as a function of steering angle.

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.

Acknowledgement

Work supported under General Atomics and by the U.S. Department of Energy under Contract DE-FC02-04ER54698.

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