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The Design and Performance of Waveguide Transmission Line Components for Plasma Electron Cyclotron Heating (ECH) Systems*

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Abstract — Over the past three years, General Atomics (GA) has developed and fabricated a variety of corrugated waveguide transmission line components for experimental fusion facilities in the U.S., Europe and Japan. Each of these facilities required ECH transmission line systems that efficiently transmit high power microwaves from newly developed gyrotrons to fusion plasmas for heating and current drive. These systems required low loss transmission of microwave power. To meet this requirement, GA has developed a variety of vacuum compatible transmission line components which consist of straight corrugated waveguides, calorimetric loads, switches, miter bends, polarizers, corrugated bellows, power monitors and d.c. breaks. Designed to operate at specific frequencies ranging from 82 GHz to 170 GHz with waveguide diameters of 32, 64, and 89 mm, the components have been fabricated to transmit as much as 1 MW of microwave power for a pulse length of 5 s. This paper presents the design criteria of selected components, and some of the measured performances of those components.

1. INTRODUCTION

To meet the demands of heating and the current drive of fusion plasmas in fusion reactors, new high frequency gyrotrons have been developed in the United States, Japan, Russia and Europe. With power levels approaching 1 MW levels, the gyrotron pulse lengths have been extended to increase the total energy delivered to the plasma. To deliver such high energy levels to the plasma, new transmission line components have been developed to transmit the microwave beam efficiently, with minimum energy loss and low beam reflection back to the gyrotron. A few of the new transmission line components and their power and pulse length capabilities are presented below.

2. COMPONENT DESIGN AND FABRICATION

A. Calorimetric Loads

Calorimetric or dummy loads are designed to measure the overall power in the gyrotron generated microwave beam. Dummy loads allow for this measurement prior to injecting the beam into the fusion plasma. The loads described below determine the overall power levels by absorbing a small percentage of the power each time the beam is incident onto the internal surface of the load. The energy is then transferred through the load walls and absorbed by water in cooling passages. The increase in water temperature then allows for a calorimetric measurement, which indicates the amount of energy in the microwave beam.

B. Dummy Load for LHD

For the Toshiba Corporation, GA developed a dummy load for the LHD device in Japan that could be operated under vacuum as well as in atmosphere. The load was designed to absorb 500 kW pulses for 100 milliseconds at a 1% duty cycle. Two different size dummy loads were designed and built to handle two different frequencies, 84 GHz and 168 GHz. Limited by the physical space available, the two load dimensions are 183 mm by 177 mm by 1183 mm and 183 mm by 177 mm by 1666 mm. Both loads have a 88.9 mm diameter corrugated waveguide port positioned 45 degrees off of the top surface of the load at one end. The angled waveguide projects the microwave beam onto a series of tiles located on the bottom and top internal surfaces of the load. The tiles are a carbon-carbon composite configuration which was chosen for its good microwave absorption and thermal conductivity capabilities. The microwave absorption capabilities minimize the arcing at the surface of the tile which is a concern when operating at 1 atm of pressure. During the first reflection of the beam in the load, approximately 5% of the beam power is absorbed by the tile and the rest is reflected to the top internal surface of the load. Another fraction of the beam power is then absorbed by the tile and the remaining beam is reflected to the bottom surface of the load. This is repeated until the energy of the beam is absorbed. The energy absorbed by the tiles is then transferred to a set of aluminum cooling blocks located on the top and bottom of the load. To assure good thermal conductivity, a copper/aluminum/rubber interface is sandwiched between the tiles and the cooling block. A series of springs provides a constant load on the tiles against the cooling blocks. The interface and springs system allows for thermal expansion/contraction of the tiles and cooling blocks without degrading the tiles or the load's vacuum seals.

C. Dummy Load for TCV

In conjunction with Spinner GmbH of Germany, GA

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designed and both companies manufactured six 500 kW, 2 s pulse length 82.6/118 GHz dummy loads. This circular shaped annulus load, 1270 mm in length and 432 mm in diameter, utilizes the entire internal surface of the load to absorb the microwave beam power. The stainless steel inner sleeve and end caps absorb approximately 1% of the beam power each time the beam is reflected off of the load's inner surface. The energy absorbed by the inner surface is transferred to water flowing at approximately 5.5 ℓ/min through the annulus and the end cap channels. This permits a calorimetric measurement of the injected power to be made for the 7% duty cycle load. The load has a 63.5 mm diameter waveguide port offset from the center of one end cap. This, along with 14 degree angled offset of the waveguide with the load end cap, assures that less than 2% of the microwave beam is reflected back into the waveguide. On the opposite end of the load is a 38 mm diameter port to allow the load to be evacuated prior to and during operation.

These loads have been installed on the TCV device in Lausanne, Switzerland and have been used successfully. Also, one of the loads was tested successfully at Thomson Tube Electroniques at 118 GHz for twenty 420 kW, 2 s pulses.

3. WAVEGUIDE SWITCHES

Microwave waveguide switches provide many advantages in the operation of a transmission line systems. The switch allows redirecting the microwave beam in a transmission line system without disconnecting/ reconnecting waveguides, breaking the system's vacuum and disturbing the waveguide alignment and positioning. Used in conjunction with a dummy load, a microwave switch allows for conditioning and maximizing the microwave beam power prior to injecting the beam into the plasma.

A. Switch for TCV

With a 1% duty cycle, this pneumatically operated switch, provided to TCV through Spinner GmbH, allows a 600 kW, 2 s 82.6 GHz microwave beam to pass directly or straight through the 240 mm by 240 mm by 815 mm switch or be directed 90 degrees from the input of the switch. The 90 degree redirect ion of the beam is accomplished via a 45 degree copper mirror which is mounted in an aluminum slider block assembly that moves up or down in the switch housing. The block also contains a corrugated waveguide for the direct or straight pass-through of the beam.

Two of the three 63.5 mm diameter corrugated waveguide ports of the TCV switch have an individual valve that permits the respective transmission line to be vacuum sealed. The individual transmission lines then can be brought up to atmosphere for reconfiguration or servicing without disturbing the vacuum of the other lines. This minimizes the pump-down time for the transmission line as well as minimizing the introduction of contaminants into internal areas of the lines. To indicate the position of each of the valves and the slider block, micro switches are mounted to each of the valves' and slider block's external pneumatic drive shafts. This assures that the microwave beam is properly directed in the waveguide system and minimizes the possibility of damaging the switch.

B. Switch for LHD

As with the dummy load, GA developed a rotor microwave switch for Toshiba Corporation to be used at LHD. The wide band switch, 80 to 170 GHz, is rated for 500 kW, 5 s pulses at 1% duty cycle and can be used under vacuum or at atmosphere. With a design criterion of making the unit as compact as possible, the switch is 420 mm in diameter and 200 mm in height. The pneumatically operated switch has three 88.9 mm diameter corrugated ports in which two of the ports are in-line with each other. The two in-line ports allow the microwave beam to pass directly through the switch. Internal to the switch is a large rotor which has a corrugated pass-through to allow the direct straight line transmission of the microwave beam. Positioned in the rotor is a 45 degree copper mirror which directs the microwave beam 90 degrees from the input axis when the mirror is in position. The mirror is positioned in front of the input port by rotating the rotor about the center axis of the switch. As with the TCV switch, micro switches are mounted on the rotor shaft to indicate the switch position.

4. POWER MONITOR/ARC DETECTOR MITER BEND FOR TCV AND TORE SUPRA

This miter bend, which allows a microwave beam to be redirected 90 degrees from its 63.5 mm diameter corrugated input, was designed and manufactured with Spinner for use in the TCV and Tore Supra waveguide transmission lines. The miter bend samples the microwave beam as it impinges on the miter bend mirror surface. The beam sample passes through an array of holes in the mirror surface and propagates through a vacuum sealed quartz wedge which extends from the internal mirror surface to the exterior of the miter housing. The beam is then launched from the quartz wedge into free space and is received by two WR-8 horns mounted radially 45 mm from the quartz wedge. The two horns capture the forward and reverse signal of the sampled beam, thereby providing signals proportional to the power levels of the transmission line microwave beam. The miter bends for Tore Supra are designed for 500 kW 210 s operation.

The arc detection system of the miter bend consists of two vacuum sealed optic fibers that pass from the internal mirror surface to the exterior of the miter housing. Each of the optical fibers is positioned in the mirror surface to detect an arc or a plasma discharge in the leg of the miter bend as well as in the attached waveguide line. The light from the arc or discharge is transmitted through the fiber to an optical sensor and a series of electronic components that generates a 5 V signal within 1 ms upon detecting the arc.

5. ROTATIONAL POLARIZER MITER BENDS FOR LHD

To allow optimization of the polarization of the microwave beam at LHD, a pair of rotational polarizer miter bends were designed and fabricated for the Toshiba Corporation. The 1 MW, 10 s pulse length miter bend set has a 1% duty cycle and was designed to operate at 168 GHz at 1 atm of pressure or under vacuum. The first miter bend mirror, which has a sinusoidal reflecting surface, determines the elliptical shape of the microwave beam as it is reflected from the mirror. The beam can range from being totally circular to being linear. The beam then is reflected off of the second sinusoidal miter bend mirror which orients or clocks the beam in relation to the waveguide. Each of the water cooled miter bend mirrors can be rotated to any angle without disturbing the vacuum or pressure level in the transmission line. This is accomplished with a motorized stage that is locally or remotely controlled. The position of each mirror is determined by an optical sensor switch and an optical encoder mounted on and in the motorized stage.

6. BELLOWS FOR TCV AND TORE SUPRA

The 63.5 mm diameter bellows were designed to allow for axial movement of the transmission line when the fusion apparatus thermally expands and contracts during operation and bakeout. Manufactured by GA and Spinner, the 82.6 GHz/118 GHz bellows are made of aluminum, and expand and contract 300 mm and 9.5 mm respectively. The bellows is housed in a coupling consisting of two clam shells. The coupling serves not only as protective covering for the bellows’ thin corrugated walls, but also assures that the bellows remains axially aligned during its stroke. The coupling also restrains the bellows from completely compressing when a vacuum is applied. The expansion/contraction capabilities of the bellows assist in assembly of the transmission line by allowing the compression of the bellows while installing adjoining pieces of transmission line components and then expanding to eliminate the spacing between the joints of the transmission line.

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