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# High-Power Corrugated Waveguide Components for mm-Wave Fusion Heating Systems\*

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Considerable progress has been made over the last year in the U.S., Japan, Russia, and Europe in developing high power long pulse gyrotrons for fusion plasma heating and current drive. These advanced gyrotrons typically operate at a frequency in the range 82 GHz to 170 GHz at nearly megawatt power levels for pulse lengths up to 5 s. To take advantage of these new microwave sources for fusion research, new and improved transmission line components are needed to reliably transmit microwave power to plasmas with minimal losses.

Over the last year, General Atomics and collaborating companies (Spinner GmbH in Europe and Toshiba Corporation in Japan) have developed a wide variety of new components which meet the demanding power, pulse length, frequency, and vacuum requirements for effective utilization of the new generation of gyrotrons. These components include low-loss straight corrugated waveguides, miter bends, miter bend polarizers, power monitors, waveguide bellows, dc breaks, waveguide switches, dummy loads, and distributed windows. These components have been developed with several different waveguide diameters (32, 64, and 89 mm) and frequency ranges (82 GHz to 170 GHz). This paper describes the design requirements of selected components and their calculated and measured performance characteristics.

## 1. INTRODUCTION

Electron cyclotron heating (ECH) has become accepted as one of the most efficient and technologically attractive methods for adding energy to fusion plasmas. Until recently, the main limitation of using ECH heating has been the lack of high power mm-wave sources in the 82 GHz to 170 GHz range. Fusion devices with larger magnetic fields and higher plasma densities require higher frequency sources. The gyrotron, a high power mm-wave source, has been under development for a number of years in Russia, Europe, U.S., and Japan; and frequency, power level, and pulse length capabilities are continually improving.

The transmission line system from gyrotron to plasma must be designed to handle the high frequency, power, and pulse length with low losses and low reflection back to the gyrotron. The most demanding component for high power cw transmission is the window. Presently ECH power/pulse length that can be delivered to the plasma is limited by the performance of the window. The development status of ECH windows and other key components is presented below.

## 2. DIII-D GYROTRONS AND RECENT ECH HEATING RESULTS

The DIII-D program at General Atomics in San Diego is planning to install 10 MW of ECH power to provide the localized heating and current drive needed to execute the Advanced Tokamak program. The first 110 GHz 1 MW gyrotron of a 3 MW initial system is presently being commissioned [1]. This first gyrotron is a state-of-the-art internal-mode-converter gyrotron manufactured by GYCOM, a Russian company. This gyrotron was tested to 960 kW for 2 s into air in Russia. It is designed for cw operation, but the pulse length is limited by the performance of its boron nitride output window. In testing at the DIII-D facility during July 1996, the gyrotron has achieved 0.5 MW for 0.5 s both into a dummy load and into the plasma via transmission through an evacuated 31.75 mm diameter corrugated waveguide system. Increased power and pulse length are planned for late 1996. Two other MW-level 110 GHz gyrotrons manufactured by CPI are scheduled to be installed in late 1996-1997.

Recent experiments at DIII-D dramatically show the effectiveness of mm-waves in heating fu

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sion plasmas. Figure 1 shows that the deposition of 500 kW for 0.5 s into a low density plasma increased the central electron temperature from 3 keV to 10 keV. The power was transmitted to DIII-D using 40 m of small diameter (31.75 mm) evacuated corrugated waveguide with no evidence of breakdown [2]. Further electron temperature increases are expected when the power and pulse length are increased. Future ECH work at DIII-D will concentrate on profile control applications. A key component in obtaining the desired current profile for enhanced confinement regimes is the "off-axis" current driven with the millimeter wave system.

### 3. COMPONENT DESIGN CONSIDERATIONS

In order to transmit the microwaves from the gyrotron source to the plasma, the transmission line must meet a number of demanding requirements:

1. Low reflected power back to the gyrotron.
2. Low loss in the transmission line, i.e. < 10%.
3. Maintain mode purity so microwaves launch into well-defined locations in the plasma.
4. Ability to control the mm-wave polarization for optimal absorption in the plasma.
5. Ability to monitor the beam power.
6. Ability to operate at the desired frequency for high power operation at long pulse length.

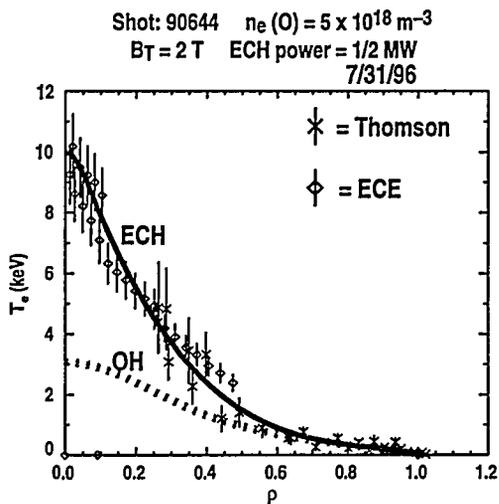


Fig. 1. Plasma electron temperature versus normalized minor radius with ohmic heating alone (OH) and with 0.5 MW/0.5 s ECH.

7. Compact transmission because of limited real estate near fusion devices.

The components that need to be designed to meet the above requirements generally include some or all of the following: matching optics unit (MOU), taper, mode converter or mode filter, waveguide switch, dummy (calorimetric) load, straight waveguide, continuous curvature bends, miter bends, power monitor miter bend, polarizer miter bends, pumpout, bellows, d.c. break, window, and launcher.

The use of corrugated waveguide for transmitting mm-waves in the  $HE_{11}$  mode results in very low losses. For a 63.5 mm waveguide with corrugation geometry suitable for 100–300 GHz transmission, the losses versus frequency are as shown in Fig. 2(a). These losses were calculated using a space harmonic analysis of the corrugated waveguide to obtain the propagation constants and the electric and magnetic fields. Mode conversion in straight corrugated waveguide propagating  $HE_{11}$  mode is negligible. However, mode conversion can result from misalignment of waveguide supports, especially at higher frequencies [Fig. 2(b)]. At 170 GHz, the misalignment must be limited to 1 mm to keep losses down to 0.07 dB (1.6%) per 25 m.

In miter bends, losses are due to ohmic heating, mode conversion in ideal bends, and mode conversion due to mirror misalignment [3]. Results of loss calculations vs. frequency for aluminum mirrors are shown in Fig. 2(c). The dominant loss above 140 GHz is due to mirror misalignment, which was assumed in these calculations to be 0.001 radian. At 170 GHz, the total loss is about 0.05 dB, or 1.2%. These calculations show that low loss transmission can be achieved in a 63.5 mm waveguide system at 100–300 GHz.

### 4. REPRESENTATIVE RECENTLY-FABRICATED COMPONENTS

GA and its collaborating companies have recently fabricated or are presently fabricating ECH transmission lines for several major devices. In Europe, Spinner GmbH is prime contractor and GA is subcontractor to Spinner in delivering transmission line components to CRPP for the TCV device at Lausanne, Switzerland and to CEA for the Tore Supra device at Cadarache, France. The

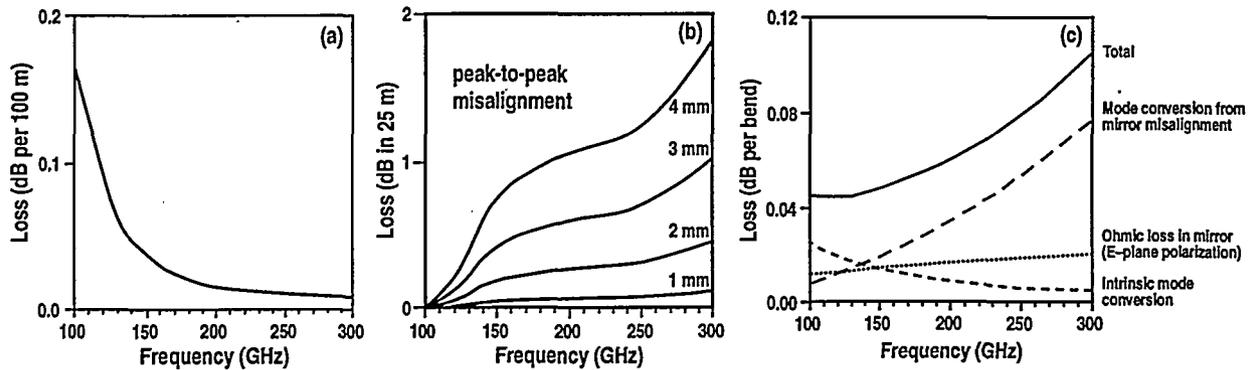


Fig. 2. Calculated losses in 63.5 mm waveguide components for 100–300 GHz HE<sub>11</sub> transmission: (a) straight corrugated waveguide, (b) waveguide with random misalignment every 2 m, and (c) miter bends.

components for both of these customers were designed by GA, and fabrication efforts are shared between the two companies. In Japan, GA recently supplied a number of specialized components to Toshiba Corporation, which is prime contractor for supplying transmission lines to NIFS for the LHD device at Toki, Japan. In addition to these collaborative efforts, GA fabricates components for DIII-D and other fusion devices worldwide.

Descriptions of typical components are:

#### 4.1. Waveguide Switch for TCV, Lausanne

GA designed and fabricated waveguide switches for Spinner for use on the TCV device at Lausanne. This is a critical component because it enables the gyrotron to stay conditioned by diverting its power to a dummy load between plasma shots. To make the switch, three short 63.5 mm corrugated aluminum waveguides are inserted into the walls of an aluminum housing. Vacuum seals between waveguides and housing are made using metal Helicoflex seals. A pneumatically-controlled linear vacuum feedthrough moves a hardened block inside the housing. In the normal position, the mm-waves pass straight through a corrugated hole in this block from input to output waveguide. In the switched position, a copper mirror diverts the power to the third waveguide at 90° to the others. Pneumatically-controlled vacuum valves can close off either of the output waveguides so they can be at atmospheric pressure while maintaining vacuum in the remaining waveguides. The switches are currently being tested at Lausanne.

#### 4.2. Transmission Line Components for TCV and Tore Supra

Spinner and GA jointly fabricated corrugated waveguides, bellows, miter bends, power monitor miter bends, pumpouts, and d.c. breaks for TCV and Tore Supra. Straight waveguides and miter bends are used to guide the mm-waves from the gyrotron source to the fusion device. Power monitor miter bends are devices for sampling the beam to determine its power level. Bellows are useful to accommodate thermal expansion and contraction of a line during bakeout cycles. All of these components have been successfully tested using 500 kW 1.6 s pulses on one evacuated line at Lausanne.

Spinner and GA also jointly fabricated a dummy load designed for 500 kW 2 s operation for TCV. One of the loads has been tested at Thomson Tubes Electroniques for over twenty 420 kW, 2 s shots using their 118 GHz gyrotron. The loads are now being tested at Lausanne with 500 kW 82.6 GHz 1.6 s pulses. GA also fabricated a similar dummy load for DIII-D designed to handle 500 kW for 10 s. The Lausanne loads absorb power in the stainless steel body; the DIII-D load uses an Inconel liner to handle the longer pulse lengths and consequent higher temperatures.

#### 4.3 Dummy Load for LHD, Toki

This year, GA fabricated four dummy loads (3 at 168 GHz, 1 at 84 GHz) for Toshiba for use on the LHD device. A particularly demanding requirement was that they operate both under vacuum and at 1 atm. This prevented use of materials that would

absorb too much energy from the incident beam and cause arcing or plasma discharge in the low density gas in front of the hot surface. Toshiba's specifications called for the load to handle 500 kW for 100 ms with a 1% duty cycle, with <2% reflected power.

To achieve this performance, a carbon-carbon composite material was found with suitable thermal, electrical, and mechanical properties. The loads were designed to have enough bounces so that more than 98% of the power is absorbed by the time the mm-wave beam returns to the input waveguide. Low power reflection measurements on the 84 GHz load showed the reflected power in the HE<sub>11</sub> mode to be less than 0.5%. High power tests on this load will be performed at Toki later this year.

#### 4.4. Polarizer Miter Bends for LHD, Toki

GA also fabricated four pairs of 88.9 mm miter bend polarizers for Toshiba for the LHD. The mirrors are remotely rotatable to achieve any arbitrary polarization and with ellipticity varying from 0 to at least 30°. The first miter bend acts as a circular polarizer to produce the desired ellipticity. The second mirror acts as a polarization rotator to achieve the desired polarization. The 84 GHz polarizer geometry was confirmed by measurements at GA in which a linear polarized beam was rotated to achieve output polarization varying from -90 to +90 degrees. The desired output polarization was achieved as predicted, with <0.2% of the power in unwanted polarization. The copper mirrors are water-cooled to enable operation at 500 kW for 10 s under vacuum or at 1 atm.

#### 4.5. Distributed Window for DIII-D

GA has been developing distributed windows for use with high-power long-pulse gyrotrons. A 10 cm × 10 cm 110 GHz distributed window consists of 42 sapphire strips separated by water-cooled metal vanes. The geometry of the sapphire and vanes is such that the mm-waves pass through the sapphire with low loss (4%) and low reflection (1%) [4]. A window made last year was tested at CPI at 200 kW with a reduced beam diameter. The tests demonstrated that the window can handle a power density and pulse length equivalent to that in

a full size 1.2 MW cw beam with peak-to-average power ratio of 2.7. A new window is presently being fabricated for use on a CPI 110 GHz gyrotron for DIII-D. GA is also developing prototype and full-size 170 GHz windows with improved fabricability, decreased losses and increased bandwidth.

## 5. SUMMARY AND FUTURE PROSPECTS

The use of mm-waves for plasma heating and current drive/profile control can greatly impact the progress in the development of magnetic fusion as an energy source for the future. A crucial aspect of being able to use the new mm-wave gyrotron sources is having efficient transmission line systems. GA intends to continue to be a leader in designing and making advanced ECH components to meet the demanding requirements of these applications.

## 6. ACKNOWLEDGMENTS

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