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DESIGN AND FABRICATION OF CIRCULAR AND RECTANGULAR COMPONENTS FOR ELECTRON-CYCLOTRON-RESONANT HEATING OF TANDEM MIRROR EXPERIMENT-UPGRADE*

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Abstract

The electron-cyclotron-resonant heating (ECRH) systems of rectangular waveguides on Tandem Mirror Experiment-Upgrade (TMX-U) operated with a overall efficiency of 50%, each system using a 28-GHz, 200-kW pulsed gyrotron. We designed and built four circular-waveguide systems with greater efficiency and greater power-handling capabilities to replace the rectangular waveguides. Two of these circular systems, at the 5-kG second-harmonic heating locations, have a total transmission efficiency of >90%. The two systems at the 10-kG fundamental heating locations have a total transmission efficiency of 80%. The difference in efficiency is due to the additional components required to launch the microwaves in the desired orientation and polarization with respect to magnetic-field lines at the 10-kG points. These systems handle the total power available from each gyrotron but do not have the arcing limitation problem of the rectangular waveguide. Each system requires several complex components. The overall physical layout and the design considerations for the rectangular and circular waveguide components are described here.

Introduction

The purpose of TMX-U, whose construction was completed in December 1981, is to investigate the thermal-barrier concept of mirror fusion. The thermal barrier is a potential profile depression that ECRH helps to establish and maintain in the end cells of a tandem mirror machine. ECRH is crucial to the establishment of both a potential peak at the outer 10-kG point and a potential dip at the 5-kG well in each end cell.

ECRH Development

For TMX-U, the 28-GHz, 200 kW gyrotrons have been crucial to the experimental successes. As the experiment was first being planned, several schemes for heating the 10- and 5-kG regions were considered. A rectangular waveguide strategy was selected because of the tight control that can be held over the microwave-horn locations and the electric-field polarization. After the success of the rectangular waveguide systems, we eagerly sought alternative waveguide ideas for greater efficiency, reliability, and power handling capabilities. We designed and installed two new circular systems with all new components and in the process a whole new family of interesting microwave elements emerged.

Rectangular System and Components

The microwave power from the gyrotron is generated in a predominantly circular waveguide mode (TE_{02}) and is coupled into rectangular waveguide (WR42) by an eight-arm coupler in a 2-1/2-inch waveguide (Fig. 1 shows a typical system). The rectangular waveguide supports only single-mode microwave power. By control of the microwave polarization, we broadcast the power in the efficiently absorbed extraordinary (X) mode. This rectangular system has several components with complex fabrication and microwave interest.

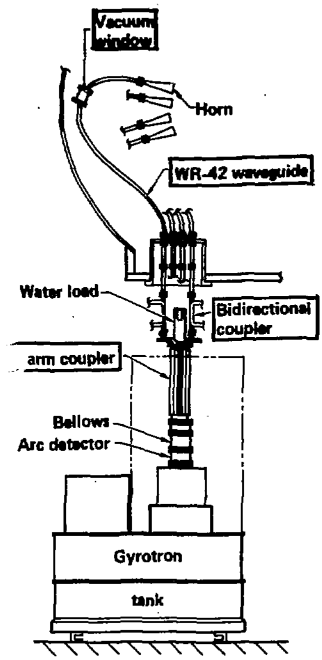

Figure 1. Rectangular waveguide system, showing the four main components.

Eight-Arm Coupler

A single eight-arm coupler made of copper waveguide brazed to 2-1/2-in. diameter circular waveguide, originally developed by General Atomic (GA) technologists, was used by LLNL quite successfully for the first system. Other designs of copper-plated aluminum were tried by GA that, although successful, had a limited full-power lifetime. At LLNL we sought alternate ways to successfully fabricate the basic design.

Since copper recovery from arcs is better than aluminum, a solid copper billet was used. Atlas Machining from Detroit began development tooling for using Electron-Discharge Machining (EDM) processes to fabricate the basic eight arms in the bore of the billet. Figure 2 shows the basic eight-arm design. Test pieces show adequate dimensional stability and finish. A total of 42 electrodes were needed to bring the entire 19-in. length of the coupler to the correct dimensions. A counter bore was made on both ends, and another piece was brazed in for the tapered closure of

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the coupling slots. A final bore finishes the machining process. Additional handwork was done to remove burrs and excess braze material from the final bore. This coupler was brought to full-power operation and continually improved through conditioning. Four more couplers were fabricated in this manner and, once conditioned, all performed adequately.

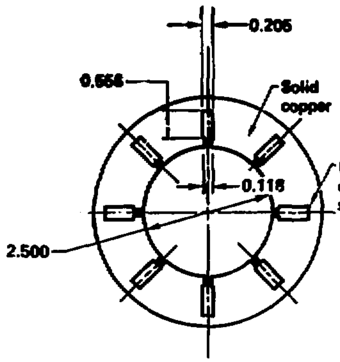

Figure 2. The eight-arm coupler (dimensions in inches). The eight rectangular arms couple 70% of the power.

Commercial Items

Two items of interest were purchased commerically. First, a corrugated waveguide surrounded by a stainless steel bellows provided mechanical isolation of the gyrotron from the waveguide system. Second, rectangular waveguide vacuum windows were installed just before the horn (See Fig. 1). These windows were pushed to the limits of their power-handling capabilities with 27.1 kW/cm^2 and failed at a rate of 25 to 33% per experimental run. This amounted to 8 to 11 windows out of 32 in three months.

The waveguide was also stressed with the same power level and occasionally arcs occurred in the waveguide. To eliminate arcs, we pressurized the waveguide with SF_6. All joints in the sytems had to be carefully aligned and fitted with a rf double sided O-ring flange. This was previously done for all the internal waveguide with an initial set of gaskets. The second set of gaskets were undersized and the sharp edge that was created in the waveguide initiated arcs. Quality control was clearly essential. The gasket was reworked and once properly assembled, the waveguide would pass the power successfully.

5-kG Components

All components of the rectangular waveguide system were replaced with circular pieces in August 1983. This entire waveguide system was based on a 2-1/2-in. diameter circular waveguide. The components can be separated into four functions: vacuum, power diagnostics, mode conversion, and protection diagnostics (see Fig. 3).

Vacuum Window

A Varian vacuum window is used for the vacuum barrier. This window is identical to the ones used on the gyrotron tubes. A water jacket is used to absorb modes trapped in the window. The water flow is included in the interlock chain to insure cooling and mode dampening. The average power density is 6 kW/cm^2 on the window.

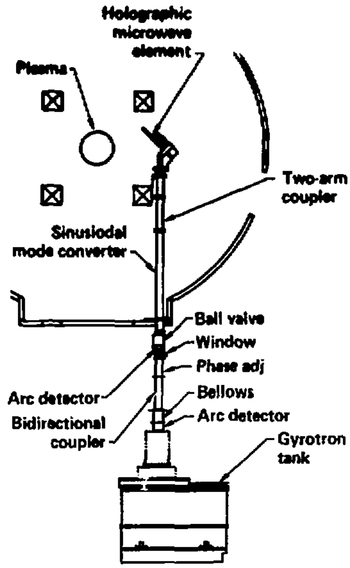

Figure 3. The 5-kG circular-system components.

Vacuum Ball Valve

Above the window is a modified ball valve (see Fig. 4) of LLNL design that permits the window to be removed from the vacuum vessel for inspection or repair. The ball valve was disassembled and fitted with a pump-out port and guard vacuum around the ball because of the difficulty in maintaining a leak-tight Teflon O-ring seal. In the ball-valve cavity, we placed microwave-absorbing material to prevent buildup of any power in the cavity. The throat of each side of the valve was shortened and fitted with stainless steel inserts that covered most of the Teflon O-ring and mated to the other waveguide components.

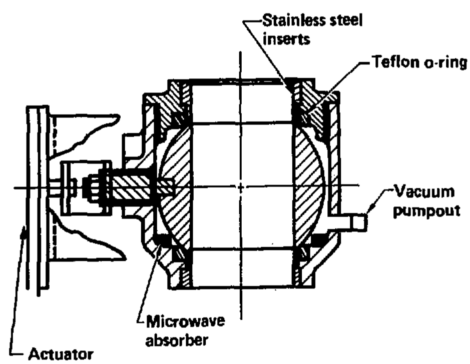

Figure 4. Modified ball valve that is microwave compatible.

The ball valve is aligned before being attached to the machine. An external adjustment on the pnuematic actuator permits rotational adjustment to give the best edge-alignment possible. The actuator shaft is carried through the ball valve and a microswitch interlock prevents the gyrotron tube from being fired into a closed valve. This also provides visual indication of the valve position.

We can inspect the window by pumping on the ball-valve body and removing the window. Since the ball valve is not completely vacuum tight, the window maintenance is done when there is sufficient time for the main-vessel vacuum to recover. The machine will typically go into the micron range while the window is being worked on. Once the window is replaced, the guard vacuum is continued so that leakage through the actuater-shaft seal will not be seen by the main machine vacuum.

Above the window and valve is the vacuum feed-through. A section of waveguide is welded into a stainless steel bellows and permits slight adjustment of the waveguide height and alignment.

Diagnostics Couplers for Power

Two 60-dB couplers monitor power in the waveguide. The first coupler monitors the forward TE_{02} mode and the reverse multimode. The gyrotron output is mostly in the TE_{02}. Bringing the tube up to its full operating parameters is done by monitoring this mode. The reverse arm protects from reflections or arcs in the system.

The second coupler has two forward arms that monitor TE_{01} and TE_{02} modes. This coupler is placed after the TE_{02}- to TE_{01}-mode converter. To maximize the conversion from TE_{02} to TE_{01}, we can adjust the beat wavelength phase by introducing waveguide of eighth-, quarter-, half-, and full beat wavelengths before the mode converter. In Fig. 5, we show the different conversion efficiencies versus the phase relationship between the two modes when they enter the converter. Both modes are monitored to maximize the conversion.

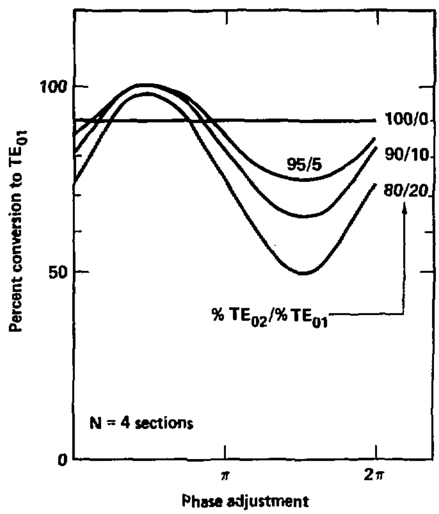

Figure 5. Conversion of a mixture of TE_{01} and TE_{02} modes to nearly 100% TE_{01}.

Mode Conversion

The TE_{01}-TE_{02} coupler diagnoses the conversion efficiency. The first mode conversion to TE01 takes place in the circular waveguide. By modulating the diameter of the waveguide, we converted the TE_{02} mode into TE_{01}. Figure 6 shows a single section of mode converter for 2-1/2-in.-diameter waveguide. Figure 7 shows the mode pattern after each sinusoidal

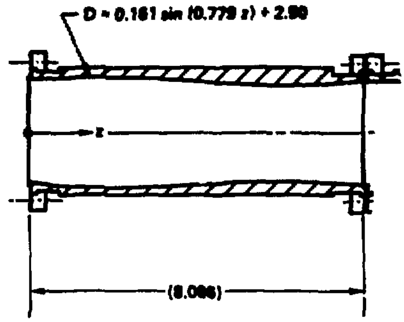

Figure 6. A cross section of the TE_{01}-TE_{02} mode converter showing sinusoidal modulation.

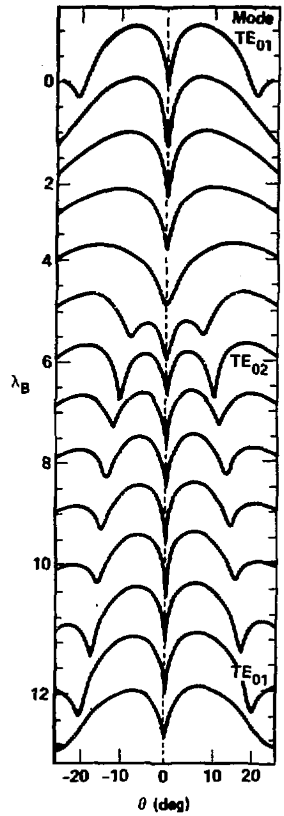

Figure 7. Change from TE_{01} to TE_{02} and back again with increasing numbers of mode converters.

modulation of the converter (see Refs. 1,2). Four sections of converter are used in the system because part of the output power of the gyrotron is also in TE_{01}. Figure 5 shows that with proper phase adjustment the majority of the power can be converted into the desired TE_{01} mode.

The final mode conversion to linear polarization is done outside the waveguide and before entering the plasma. A holographic microwave element (shown in

Fig. 8), also called a kinoform or focusing polarizing reflector, does a phase transformation, selectively twists the circular TE_{01} beam into a linearly polarized one and focusses the power onto the plasma. The method used to design and fabricate this item were developed at LLNL in the spring of 1983. A 5-axis Sundstrand milling machine was programmed using detailed output and the APT-IV CDC-7600 code.[3,4] The development of this component[5] has opened up a whole new family of microwave elements with extremely useful applications.

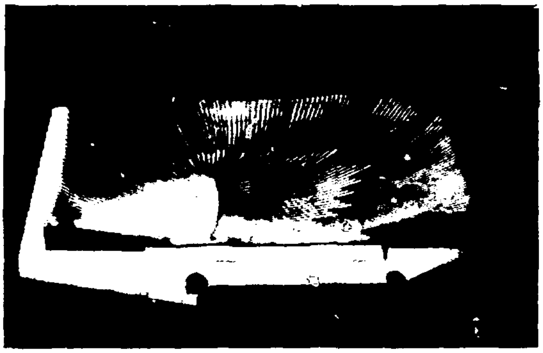

Figure 8. A holographic microwave element that changes the TE_{01} mode into a focused extraordinary (X) mode.

Protection

Four types of protection devices are used on the ECRH systems: Two are passive while the other two are actively interlocked diagnostics.

Protection from mechanical shock is provided by a corrugated waveguide bellows placed above the gyrotron window. This permits isolation of the gyrotron from vibrations, ground or machine movement.

Mode filters can be used to dampen out noncircular modes or trapped modes that may disturb the gyrotron operation. Four types of filters have been fabricated. Only one type has been used on the 5-kG system: a Varian mode filter that reduces noncircular modes. The 5-kG system does not seem susceptible to trapped or non-circular modes. The other types of filters are simply straight sections of waveguide made of different materials that have lower transmission efficiences (losses) than the copper waveguide. In using them, we lose power but damaging trapped modes are eventually removed. These are used in the 10-kG system rather than in the 5-kG sytem.

Arc detectors and the bidirectional couplers are the active protection devices. The reverse arm of the bidirectional is interlocked for a large reflected signal. Also, an erratic reverse signal (arcing) causes the tube to shut off. A more direct arc detector is placed above the gyrotron window and above the vacuum window of the system. Two fiber-optics are used in each detector, one for the actual arc-detection and the other as a test or bias for the first. A pulse of light can be passed down the test line, and if the first does not recieve an interrupt, signal repairs can be initiated. Also, this second line can be used to lower the interrupt threshold by biasing the first with light.

10-kG Components

A comparison of Figs. 3 and 9 shows the similar components of the 5- and 10-kG systems. Different components start above the taper. The 10-kG system contains the same functional components (vacuum, power diagnostics, mode conversion, and protection diagnostics) as the 5-kG system but also encompasses two additional components, corrugated waveguide bends and tapers. For the 10-kG system, the final mode conversion to linear polarization is done with a Vlasov reflector[6] rather than with a holographic microwave element.

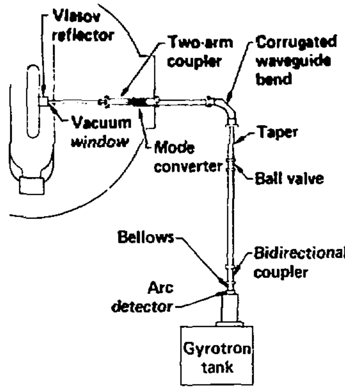

Figure 9. The 10-kG circular-system components, showing six main functions.

Vacuum

The 10-kG system uses the same ball valve as the 5-kG system. Because of system differences, it does not perform the exact same function but in the event of a window failure the valve is closed to minimize the amount of atmosphere that can enter the vacuum vessel.

In the vacuum area the main difference between the 5- and 10-kG systems is that the 10-kG window is deep inside the machine. Above the fundamental 10-kG resonant zone, the waveguide must be pressurized with gas. To allow this, the window must be the last component before the Vlasov reflector. All the waveguide components inside the machine must be vacuum tight.

There is limited room for the window and reflector because of the constraints of pressurizati... ve cyclotron resonance, of plasma size, and of ... wall. Figure 10 shows a cross section of the C-co... gnet on which the Vlasov reflector is aimed at the plasma. The reflector must fit between the mod-B surface of 10 kG and the limiting plasma radius. We made several design iterations before selecting a waveguide size that had the correct characteristics for a Vlasov reflector to fit into this small area.

These physical constraints demand that the window be a simple and compact design. A quartz window one-quarter wavelength in thickness is set between flanges with a natural rubber O-ring and a Teflon pad. (The design originally called for a Teflon O-ring, but difficulties in compressing it without destroying the window prompted the exchange of materials.) The design has been proof tested under full power and duration of gyrotron operation. Also, high power operation (120 kW) over the past 4 weeks shows no problems with the natural rubber.

Power Diagnostics

The same bidirectional coupler design is used for the gyrotron tuning as in the 5-kG system. For the

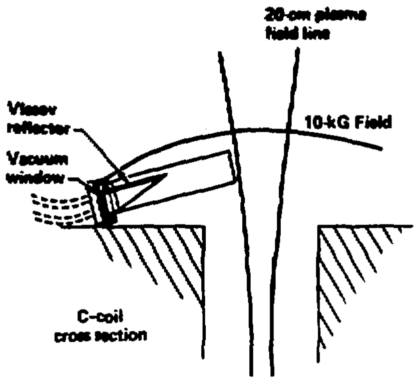

Figure 10. The Vlasov reflector. Reflector must fit into allowable volume.

TE_{01} and TE_{02} coupler, a similiar design was used but was based on the smaller waveguide size. This coupler also must be vacuum tight. We brazed the two arms to the coupler after the coupling holes were drilled. Some rebrazing and hand work had to be done to make the coupler an acceptable vacuum component.

Mode Conversion

The mode converters for the 10-kG system were also based on the same design as those for the 5-kG system. The smaller waveguide size made the components much more compact and easier to fabricate. The equations for both of the $TE_{01}/_{02}$ mode converters can be found in Ref. 7.

The final conversion from TE_{01} to linear polarization (X mode) occurs in the small space of the Vlasov reflector (shown in Fig. 11). A cylindrical parabolic reflector is placed with its focus coincident with the axis of the waveguide. The microwave power eminating from the waveguide in TE_{01} mode is linearly polarized by reflection from the parabolic surface. This beam is very small (3 by 5 cm) but it is approximately 99% linearly polarized. Various focal distances were investigated as were off-axis parabolic reflectors. The beam size could be made larger but at the expense of polarization purity. As an example, a 3-by-10-cm beam was attained that had 90% correct polarization and 10% cross polarization. This was achieved by using a larger parabola and placing the axis of the waveguide between the focus and the parabola.

Protection

The same types of protection are provided to the 10- as to the 5-kG system. Mode filters and lossy sections are needed more in the 10-kG system. Presently, stainless steel waveguide is used between the 90-degree corrugated bellows to dampen out any trapped modes but can be easily replaced with more efficient copper waveguide as needed.

Active diagnostics include couplers having exactly the same functions as described in the 5-kG system. The arc detector next to the gyrotron is also the same design but the arc detector at the internal vacuum window differs slightly. The limited space precluded the option of two fiber-optics. A single bundle looks at the vacuum side of the window. To test for functionality, we remove the waveguide outside the vacuum wall and point a light flash towards the window. The quartz is clear and transmits the light adequately for testing purposes.

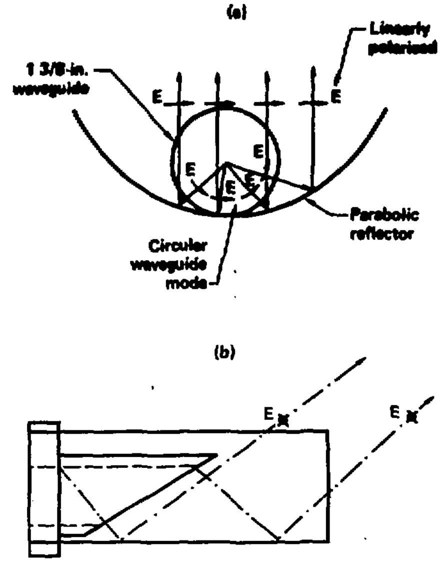

Figure 11. The reflector converts from circularly polarized TE_{01} to linearly polarized X mode.

Tapers

Already mentioned is the taper from the 2-1/2-in. waveguide to the 1-3/8-in. waveguide. This design is based on Ref. 8. The taper is parabolic and calculated to minimize the conversions from TE_{02} to TE_{01} and TE_{03}. Fabrication is done by nickel plating an aluminum mandrel and welding on stainless steel flanges. The mandrel is fabricated on a numerically controlled lathe using the CDC-7600 computers and the APT-IV program modified by LLNL.

Corrugated Waveguide Bends

The 10-kG system requires one 90-degree bend on the east end of the machine and two 90-degree bends on the west end. To accomplish this with minimum mode conversion, we designed corrugated waveguide that would allow the 90-degree bend in a small volume. To minimize mode conversion and loss, this bend must conform to a specific curve that is based on a constantly changing radius,[9]

$$R = R_0/\cos \frac{\pi \ell}{2L} .$$

The present radius is R, the minimum radius R_0 is 12.5 inches, L is one-half the bend length, and ℓ is the distance along L. A graphical layout of this curve was used to fabricate a support for the bellows.

The development and fabrication method for the nickel and copper bellows was done by the University of California at San Diego. To get the plating material into the grooves, a coil is wound around the mandrel. An ac field is applied to the coil while the electro-deposit process is occurring. This enhances the plating in the groove bottom. The plating thickness is approximately one-third as thick at the bottom as at the outside of the groove.

Initial Operating Results With Circular Components

All components were high-power tested individually as well as operated as a system. High-power operation required some debug, and design changes were implemented without major modification. The most important result is the high-power operation of the two systems. The 5-kG systems are operating well without modification. The 10-kG systems are operating with some mode and arcing anomalies, but power to the plasma is at higher levels than was previously attained by the rectangular system. We are installing lossy sections and mode filters to quiet the undesirable modes.

Future Improvements

The continuing use of ECRH will require continued development. The immediate needs of the systems are in the diagnosis of mode purity and of power to the plasma. Increasing the diagnostic accuracy of the bidirectional and the two-arm couplers will aid in doing this. Improvements in maintaining mode purity are being investigated through low-power tests on the taper and on the bellows. Because of their simplicity and compactness, Vlasov reflectors with wider beams remain an item of interest.

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