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CIRCULAR WAVEGUIDE SYSTEMS FOR ELECTRON-CYCLOTRON-RESONANT HEATING OF THE TANDEM MIRROR EXPERIMENT-UPGRADE*

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Abstract

Extensive use of electron cyclotron resonant heating (ECRH) in the Tandem Mirror Experiment-Upgrade (TMX-U) requires continuous development of components to improve efficiency, increase reliability, and deliver power to new locations with respect to the plasma. We have used rectangular waveguide components on the experiment and have developed, tested, and installed circular waveguide components. We replaced the rectangular with the circular components because of the greater transmission efficiency and power-handling capability of the circular ones. Design, fabrication, and testing of all components are complete for all systems. In this paper we describe the design criteria for the system.

Introduction

The TMX-U construction was completed in December 1981. The TMX-U was constructed to investigate the thermal-barrier concept of mirror fusion. The thermal barrier is a potential profile that ECRH helps 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. The potential peak is achieved by heating electrons so that they can escape over the magnetic mirror, thereby creating a local excess of ions (positive). The potential dip (not a negative charge, just less positive than the peak or the central cell) is established in the well by heating mirror-confined electrons to a collisionless regime, thereby enhancing their confinement.

The potential dip creates a barrier between the thermal electrons in the end cell and the hotter electrons in the central cell (the thermal barrier). The potential peak confines the ions of the central cell. Both confinements occur with a lower density in the end cell than in the central cell. Extrapolating this to a fusion reactor would lower the required energy input to the end cells and permit a higher Q.

Two rectangular waveguide systems originally transported the microwave power to the TMX-U plasma.[1] The rectangular system operated with an overall efficiency of 50% and also was subject to power-density arc limitations.

Two new circular waveguide systems for ECRH are presently installed on TMX-U. Two gyrotrons (one for each end cell) give power to the 5-kG minimum B-fields, and two gyrotrons (also one for each end cell) power the outer 10-kG B-fields . All systems use some identical components and some custom items. The waveguide runs for the 5-kG assemblies are identical to one another but the 10-kG assemblies are slightly different.

In an effort to increase the power available to heat the plasma in the correct mode and distribution, we improved the design by using the circular waveguide. The circular waveguide is able to handle the full power of a gyrotron output without the arcing problems of a rectangular waveguide. This is because of the zero-voltage boundary conditions and the lower power density in the waveguide. Both complex and simple methods of mode conversion as well as a simplification of vacuum seals met our requirements for a more reliable and efficient system.

Design considerations directly resulted from our experience with the rectangular system. We wished to maximize the power to the plasma in the X mode with a significantly greater efficiency than before and to preserve or to improve the protection of the system. We sought in four areas: window reliability, power maximization, efficiency in mode conversion, and protection circuits. An accompanying paper[4] details the specifics of most of the fabrications.

Window Reliability

The power density on the rectangular vacuum windows was 27.1-kW/cm^2. On the vacuum side of the window, an arc developed on the window surface and melted part of the ceramic before an arc-detection diagnostic could shut off the power. We used limits of 1 to 2 joules (80-μs duration) but the frequent occurrence of arcs eventually fractured the window. The windows were expensive and, because of their location inside the vacuum vessel, were difficult to replace once damaged. An easily replaceable window, preferably from the exterior of the machine, was desirable.

For the 5-kG positions, we used a commercially purchased window. This window (see Fig. 1) was placed below a ball valve modified for vacuum use (to be discussed later) and protected by an arc detector between the valve and window. The power density on this window is quite acceptable at 6.3 kW/cm^2. In the event of window failure, the valve could be closed and the window could be removed and replaced. In this way, experiments would be halted for a very short time, subsequent running resuming with little turnaround time.

For the 10-kG positions the solutions were less simple. The waveguide required pressurizing above the 10-kG resonance so that the microwave could be broadcast "downhill" into the resonance. This means the window is again accessible only while the machine is at air. Because of this, we made two types of design changes (see Fig. 2). The window was designed so that repairs would be made quickly and cheaply, and additional window protection was installed. For example, to minimize the reflections and trapped modes inside the window, we made the window of quarter-wavelength-thick quartz. The seal for the window to the waveguide flange was originally of teflon, which does not absorb the 28 GHz microwave readily. This was eventually replaced with a natural rubber O-ring that provides a softer sealing surface in contact with the window and also does not readily absorb the microwave. The diameter of the window was chosen to reduce trapped modes by matching the voltage distribution profile in the radial dimension with the free-space vacuum conditions that will exist on the edges. This allows a trapped radial mode to couple out rather than reflect and be trapped. The power density on this window was also acceptable at 18.7 kW/cm^2.

To enhance protection by avoiding or minimizing arcs, we installed an arc detector just on the vacuum side of the window. Arc detectors will be discussed in a later section (Protection).

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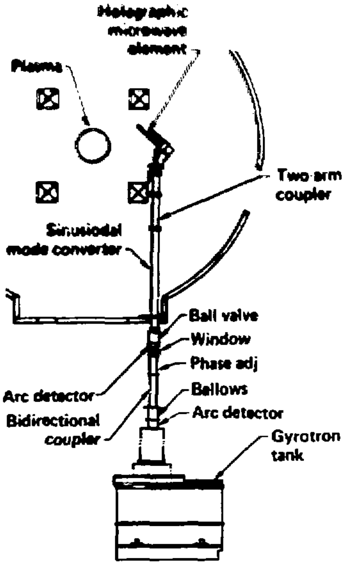

Fig. 1. The 5-kG circular-system components.

Maximization of Power

The rectangular 5- and 10-kG systems showed only 50% efficiency under their best operating conditions. The new circular systems increase efficiency in two ways: maximize the power and maximize the mode conversion. A two-arm bidirectional coupler furnishes the diagnostic information for maximizing tube power. The major gyrotron mode is TE_{02}, and one arm of the coupler is designed to read 60 dB of the TE_{02} power. By monitoring this mode, we brought the gyrotron up to maximum power.

Mode Conversion from TE_{02} to TE_{01}

Once the tube power is maximized, two mode conversions must take place before the microwave is in the correct mode to couple into the plasma. In both the 5- and 10-kG systems, we make the first conversion (to the TE_{01} mode) by passing the microwave through a diameter-modulated full-mode converter (see Fig. 3). To maximize the conversion from TE_{02} to TE_{01}, we must adjust the phase at which the TE_{02} enters the mode converter. We fabricated pieces of straight waveguide in full-, half-quarter, and eighth-beat wavelengths so that the correct phasing could occur. If the phasing were not correct, the conversion would still occur but not in an optimum fashion. Both theoretical predictions and experimental results show that 98% of the TE_{02} can be converted into TE_{01}. If not optimized, the conversion can go as low as 50% (power not lost, just unconverted), which is not desirable because of the final conversion to X mode. A second coupler of slightly different design monitors the mode conversion after the converter sections. A two-arm, forward, 60-dB coupler monitors TE_{01} and TE_{02} modes. By adjusting the beat wavelength phase between the TE_{01} and TE_{02} as they enter the mode converter, we maximize TE_{01} power (see Fig. 4).

Mode Conversion from TE_{01} to X

The final mode conversion takes place outside of the waveguide for all systems. A holographic microwave element used for the 5-kG systems is shown in Fig. 5. The design of this element is discussed in Ref. 2. Briefly, the copper reflector focuses the power and selectively twists the polarization so that the entire reflected beam is in the X mode and is efficiently absorbed by the plasma. Low-power tests show 90 to 95% efficiency at conversion, the remaining power being reflected with cross polarization.

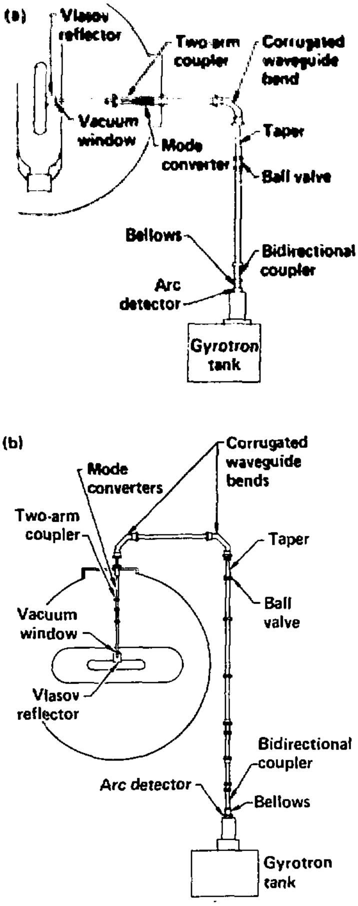

Fig. 2. The 10-kG circular-system components: east assembly (a) and west assembly (b).

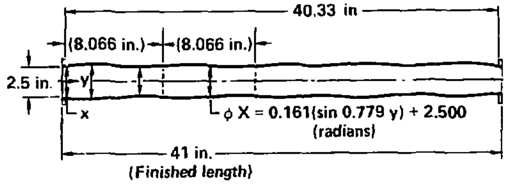

Fig. 3. A diameter-modulated full-mode converter.

Figure 6 shows a Vlasov reflector used in the 10-kG systems. This very compact and elegantly simple component converts from circularly polarized TE_{01} to a linearly polarized beam with 99% efficiency. Depending on the orientation of the beam to the magnetic field it

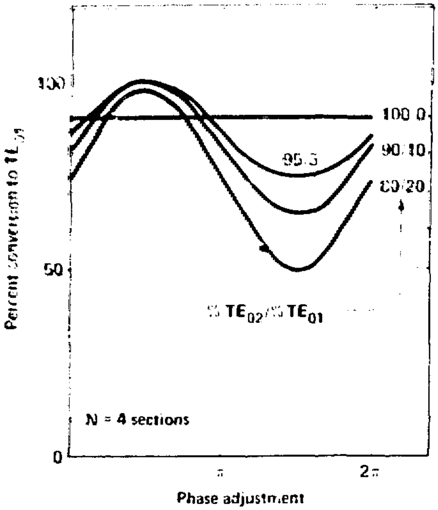

Fig. 4. Conversion of mixture of TE_{01} and TE_{02} modes to nearly 100% TE_{01}.

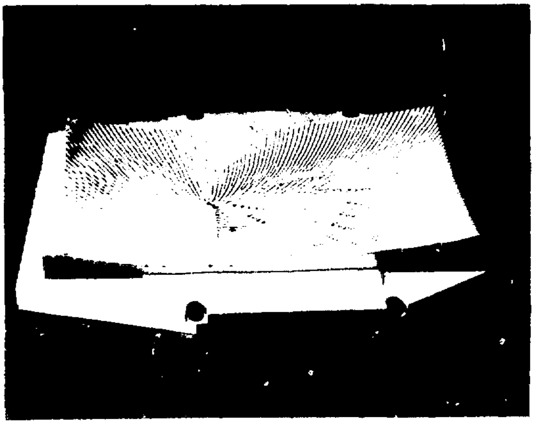

Fig. 5. A holographic microwave element that changes the TE_{01} mode into a focused extraordinary (X) mode.

can be in either the X or O mode. This reflector has limited beam dimensions of 3 by 5 cm . It was used in the 10-kG system because of the physical constraints of having to fit inside the C-coil and the 10-kG field and of having the correct aiming but not interfering with the plasma (see Fig. 6).

Protection

We also considered the preservation and improvement of the system protection from arcs and reflections. Both the 5- and 10-kG systems contain two arc detectors with fail-safe testing. Three arc detectors of identical design are used: two on each 5-kG assembly and one on each 10-kG assembly. This design uses two fiber-optic cables per arc detector: One looks at the window it is protecting and the other looks at the first fiber-optic. For the safety system to operate correctly, a test pulse of light that travels down the second fiber-optic must be received through the first. If no signal is received, repairs of the fiber-optic are initiated. A second style of arc detector is used inside the TMX-U vessel to protect the 10-kG window. A single fiber-optic bundle, because of the limited space, views the quartz from the vacuum side. This design does not include a second test bundle but testing can be done periodically by removing an exterior piece of waveguide and by flashing light towards the window.

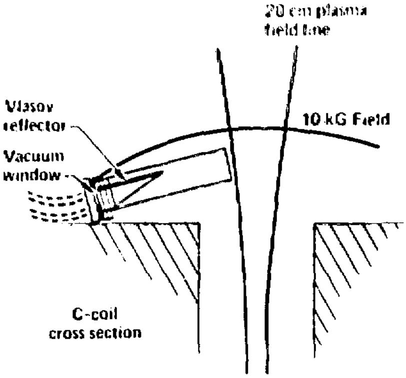

Fig. 6. The Vlasov reflector. The reflector must fit into the allowable volume.

The two arm bidirectional coupler is also used as a safety diagnostic. The reverse arm on this coupler is multimode and receives signals from reflected power. If this signal becomes too large or erratic the gyrotron power is interrupted.

Trapped modes in the waveguide represent more subtle but just as troublesome a problem. The 5-kG system does not appear to have any problems with respect to mode sensitivity or trapped modes. The waveguide is all straight line and very open. The 10-kG system has two 90-degree bends and an 18-degree bend in the west assembly and one 90- and one 18-degree bend in the east assembly. These waveguide runs also taper down from 2-1/2 inches in diameter to 1-3/8 inches (see Fig. 2a and b). Possibilities exist of trapped modes between each gyrotron and taper and between one bellows bend and another. To reduce the likelihood of problems in these areas, we installed mode filters and sections of lossy waveguide. The mode filters are produced commercially and were used on the rectangular as well as the circular systems. The lossy sections of waveguide are stainless steel instead of the copper, which was used in many other areas. These stainless steel waveguides can be easily removed and replaced with copper as needed. Additional sections of waveguide that have been flame-sprayed internally with chromium oxide are more lossy than the stainless steel but are not yet installed in the system.

Besides arc protection, we also maintain mechanical protection for the four gyrotrons. Corrugated waveguide with a stainless steel outer bellows is used just above the gyrotron tube to isolate it from the rest of the waveguide structure.

Test and Initial Operating Results

Tests are performed on the components at low power to map the power density and polarization. These results are presented in Ref. 3. The 5-kG systems have a maximum efficiency of 93% efficient in delivering power to the plasma in X mode. For the 10-kG system the X-mode is a maximum of 80% efficiency depending on which components of lossy waveguide are used.

After four weeks of running, the 5-kG systems are at full power, and the 10-kg systems are at greater than 120 kW per position. The previous maximum was 50 kW per position. By the end of the debug cycle, we hope to have all the gyrotrons at full power.

Summary

The circular waveguide systems improved the ability of ECRH to handle full-power delivery of 28-GHz microwave to the plasma. Improvements made to the 5-kG system allow replacement of the windows, maximization of the power to the plasma, greater efficiency and enhanced simplified protection. The 10-kG system improvements consisted of reducing the number of components, protection of the internal window, maximization of the power to the plasma, and greater efficiency. The protection was also enhanced by simplification.

Full-power tests verified the power-density capabilities of the components and of the systems prior to installation. Low-power tests verified the component's microwave functional conformance with theoretical predictions. Initial operation in the TMX-U machine proved the capability of all components in their respective systems.

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