UCRL- 89241
PREPRINT

CONF-831203--131

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UCRL--89241

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IEEE 10TH SYMPOSIUM ON FUSION ENGINEERING
FRANKLIN PLAZA HOTEL
PHILADELPHIA, PA
December 5 - 9, 1983

December 1, 1983

Lawrence Livermore National Laboratory

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FUNDAMENTAL MODE RECTANGULAR WAVEGUIDE SYSTEM FOR ELECTRON-CYCLOTRON RESONANT HEATING (ECRH) FOR TANDEM MIRROR EXPERIMENT-UPGRADE (TMX-U)*

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Abstract

We present a brief history of TMX-U's electron cyclotron resonant heating (ECRH) progress. We emphasize the 2-year performance of the system, which is composed of four 200-kW pulsed gyrotrons operated at 28 GHz. This system uses WR42 waveguide inside the vacuum vessel, and includes barrier windows, twists, elbows, and antennas, as well as custom-formed waveguides. Outside the TMX-U vessel are directional couplers, detectors, elbows, and waveguide bends in WR42 rectangular waveguide. An arc detector, mode filter, eight-arm mode converter, and water load in the 2.5-in. circular waveguide are attached directly to the gyrotron. Other specific areas discussed include the operational performance of the TMX-U pulsed gyrotrons, window and component arcing, alignment, mode generation, and extreme temperature variations. Solutions for a number of these problems are described.

This system was chosen because, at the time, it required fewer inventions and utilized standard technology as much as possible. We realized at the outset that we would be giving up power in transmission efficiency. However, it was felt that reliability of the system and our ability to put power in a given polarization and a specific area would be greatly enhanced.

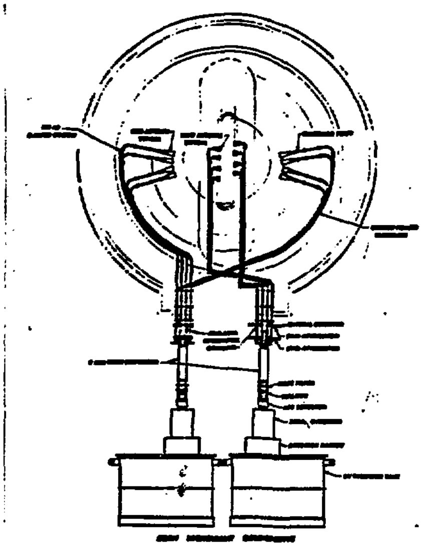
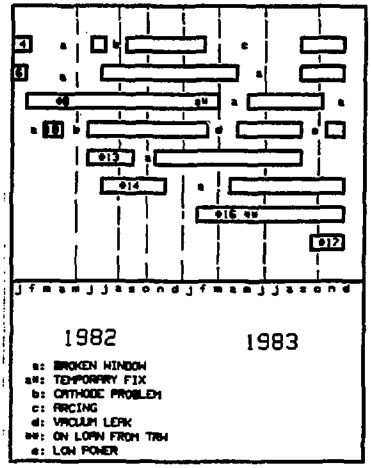


Fig. 1

The two-year performance indicated that although we used standard technology, we used it at a higher frequency and higher power level than had been routinely done. We discovered a number of problems which limited our performance. We will highlight these problems in greater detail as we describe the individual subsystems. The ECRH system is illustrated in Fig. 1. We will not discuss the cathode-pulsed modulator or high-voltage tank as they have already been the subject of a paper in the 9th Symposium by D. N. Griffin.[1] These two systems have some problems in trouble shooting and control. We are in the process of redesigning these systems and they will probably be the subject of papers at future symposiums.

Gyrotrons

The gyrotrons have been the source of a number of system problems. We have had difficulty in breaking windows on the tubes themselves and this has required having 100% spares for the system. When a window broke, it was necessary to send the tube to Varian Associates to have the cathode replaced, along with anything else that may have been damaged by the water. The tube was then reevacuated and reprocessed. This would take anywhere from six weeks to six months depending on the state of spare parts and backlogs at Varian. Even with 100% spares we were sometimes not able to operate four gyrotrons at once.



a: BROKEN WINDOW
a*: TEMPORARY FIX
b: CATHODE PROBLEM
c: ARCING
d: VACUUM LEAK
**: ON LOAN FROM TRW
e: LOW POWER

Fig. 2

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

The gyrotrons have failed in a rather periodic way and the amount of time the tube is operated seems to be incidental to the failure. The failure occurs most often in the braze on the air side of the window although we have had failures on the vacuum side as well. With some encouragement from LLNL, Varian Associates agreed to replace the single-disk beryllia window with a double-disk window using alumina with FC75 (a 3M florocarbon) as coolant between the two windows. This window has solved the problem of having to send the tube back to Varian for repairs. We have broken two of the new windows, always the window on the air side, and they were repaired on-site in less than four hours. These two windows were broken on the same tube and illustrate a problem that occurred with the new windows. The gyrotron tended to put out multiple-frequency oscillations causing reduced efficiency of the gyrotron and high reflections in the waveguide transmission system caused by poor matches at frequencies other than 28 GHz. This problem has been greatly reduced by modifying the gyrotron interaction cavity. The tubes we are presently receiving appear to be single-frequency and high-efficiency devices.

Arc Detectors

In an effort to protect the gyrotron window, an arc detector was installed that looked directly at the gyrotron window. This device, as delivered to us, was not satisfactory. It tended to indicate arcs when they were not present and if the sensitivity was reduced to the point where it did not do this, arcs were not adequately indicated. In an effort to protect the gyrotron, we devised a system that used a directional coupler as a sensing device rather than the light emitted by arcs. We sensed the forward power in the directional coupler and if this power dropped by more than 25%, it indicated an arc behind the coupler. We also sensed the reflected power in the directional coupler and if this increased by a significant amount, it indicated an arc beyond the coupler. We installed one of these directional couplers in each arm of the eight-arm mode converter giving 32 forward and 32 reflected power monitors for the four gyrotrons. The performance of this system was quite satisfactory and could be set to sense arcs in the system with a wide range of sensitivity. It was very fast and would tend to trip on spurious noise in the system. We installed a filter in the post-detection circuits to slow the system down to a 0.5-ms response that would sufficiently limit the amount of energy in an arc so that no damage would occur to the system.

Mode Filter

The mode filter used was designed by Varian Associates and consisted of a number of disks with a 2.5-in. internal diameter. Metal disks and nonconducting disks were alternated. The nonconducting disks were made lossy by putting a water column behind them. This filter should highly attenuate noncircular modes. We used the filter in all of the systems, however, many tests were run without the filters and it was difficult if not impossible to see any contribution to performance by adding the filters.

Flexible Bellows

A flexible bellows was installed to prevent excessive forces from being applied to the gyrotron window. This bellows, manufactured by GA Technologies, consisted of an electroform copper bellows with a 2.5-in. minor internal diameter and stainless steel outer bellows to give strength (Fig. 3). This device performed very well and gave adequate protection to the gyrotron as well as making the system much less sensitive to vertical alignment.

Eight-Arm Mode Converter

The eight-arm mode converter has its input in 2.5-in. circular waveguides and its outputs are eight WR42 rectangular waveguides. It is terminated in a water load in the 2.5-in. waveguide.

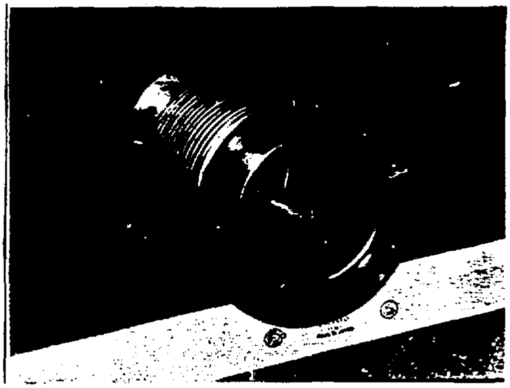

Fig. 3.

The eight-arm mode converter was designed by GA Technologies and subsequently modified by LLNL. A description of this device is included in Brian Felker's paper entitled "Design and Fabrication of Circular and Rectangular Components for ECRH on TMX-U."[2]

The major electrical problems encountered in this device have been breakdown at high-power levels. Operation was reliable to 100 kW with frequent breakdowns to 150 kW and unreliable operation beyond that. This problem was solved by pressurizing the waveguide with sulfurhexofluoride allowing us to operate to input powers of about 170 to 180 kW, where breakdowns in other parts of the system prevented higher power operation.

Other problems that were encountered were mode problems in the gyrotron interacting with the eight-arm coupler. The coupler was designed to operate with the TE02 mode in the 2.5-in. waveguide.

When the gyrotron output was in some other mode, either different field configuration or frequencies, the coupler would not operate properly and would arc at very low power. This problem was solved by paying very careful attention to the gyrotron parameters such as beam current, anode voltage, and the currents in the gyrotron magnets.

When properly operated, this device was very satisfactory. It had efficiencies close to 90% and was capable of operations up to 200 kW when the arms were properly terminated.

WR42 Waveguide

The WR42 waveguide system was composed of twists, elbows, custom-formed waveguide, and pressure flanges. The major problems encountered in this system were with the pressure flanges. These were an aluminum WR42 waveguide flange approximately 0.1 in. thick with a gasket on both sides (Fig. 4). This device was made by Parker Kenifax Corp. and involved scaling their standard product higher in frequency to 28 GHz in WR42 waveguide. The dimensions on this device turned out to be extremely critical. It tended to have sharp corners on the inside causing arcs in the waveguide. The final solution to this was to hand-work the flanges so that there was no discontinuity where the WR42 waveguides bolted together. Another problem that existed was in the twists. It is possible for a second mode to exist at 28 GHz in the WR42 waveguide and it was necessary to make the twists at least 24 in. long not to excite this mode. Since it was impractical to use that long a twist, we elected to make a short taper to a waveguide which was 0.378 in. wide, make the twist in a waveguide whose dimensions would not allow the existence of a second mode, and then taper back up to WR42 waveguide. This allowed the twist to be made in five inches. This solution could have allowed a trap mode to exist in the WR42 waveguide, but since the second mode is very close to cutoff, it is quite lossy and hard to excite.

Fig. 4.

Barrier Windows

The barrier window used was a half-wavelength alumina block in the WR42 waveguide. This window was designed by Varian Associates and had been used on high average-power klystrons. The problems associated with the window were trapped modes and arcing.

Trapped modes were calculated by Varian and the thickness of the window was reduced to a nonoptimum dimension to prevent exciting the TE02 mode. The final VSWR of the window was less than 1.5. The window appeared to work well at low power but there was some indication of a trap mode when arcing occurred. This was illustrated by the burn pattern caused by the arcs on the back of the window (Fig. 5). The 1.5 to 1 VSWR slightly reduced the amount of transmitted power, but was no real problem to the system. Arcing occurred on the vacuum side of the window rather than the pressure side of the window. The window did not appear to be contaminated with titanium from the getters. Great pains were taken to visually isolate the window from the getter wires. Analysis was performed on the debri left on the window and appeared to consist mainly of copper and gold. There was not more than a trace of titanium present. These arcs occurred on all of the systems in the TMX-U vessel but were most prevalent with windows whose antennas were oriented up from the bottom of the vessel indicating that dust particles may have started the arc. The peak power through the window was normally above 8 kW when the arcing occurred. This result indicated that at levels of approximately 20 kV/cm breakdown would occur. The normal procuredure on a window that arced severely was to disconnect it from the eight-arm mode converter and replace it with a dummy load. This caused a 12.5% reduction in power at that point in TMX-U but otherwise allowed the system to be operated.

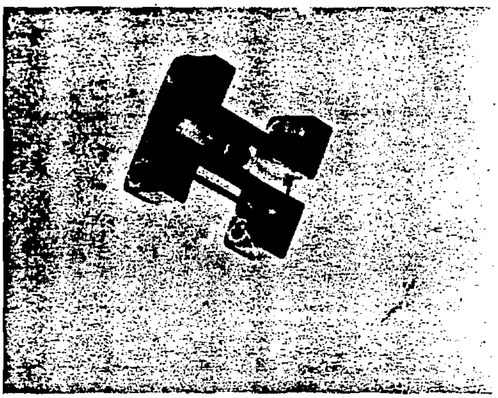

Fig. 5.

Antennas

The antennas used were simple rectangular horns generated by expanding the WR42 waveguide. The antenna pattern from these horns was satisfactory for the requirements of the physics of the machine and, other than a slight problem with alignment, was one of the most reliable parts of the system.

Conclusion

Operation of the ECRH System in the TMX-U over the past two years has been very satisfactory. The ECRH was able to deliver close to predicted power to the plasma. The system has operated reliably. It suffered somewhat excessive maintenance problems, however, most of the repairs were accomplished in hours rather than days. All of the hardware designed into the system operated and no major modifications were necessary.

In addition to operating the ECRH over the past two years, we have gained invaluable experience with high powered microwave systems. The operation of a gyrotron is no longer all art and no science. We have developed some systematic approaches to its operation. Arcs in the waveguide system can be distinguished from moding in the gyrotron and problems with gyrotron windows can be determined by looking at the shape of the power pulse. We have the operation of high power microwave systems in hand and are ready to now tackle the problem of getting more ECRH power into the TMX-U.

References

(1) D. H. Griffin et al., "Electron Cyclotron Resonance Heating in the Tandem Mirror Experiment (TMX)," Proceedings of 9th Symposium on Engineering Problems of Fusion Research, (1981).

(2) B. Felker et al., "*Design and Fabrication of* Rectangular and Circular Waveguide Components for Electron Cyclotron Resonant Heating (ECRH) of the Tandem Mirror Experiment-Upgrade (TMX-U)," Proceedings of 10th Symposium on Fusion Engineering, (1983)