CONF-8709157--1

DE88 000885

INITIAL HIGH-POWER TESTING OF THE ATF ECH SYSTEM*

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ABSTRACT

The Advanced Toroidal Facility (ATF) is a moderate aspect ratio torsatron that will utilize 53.2 GHz 200 kW Electron Cyclotron Heating (ECH) to produce nearly current-free target plasmas suitable for subsequent heating by strong neutral beam injection. The initial configuration of the ECH system from the gyrotron to ATF consists of an optical arc detector, three bellows, a waveguide mode analyzer, two TiO_2 mode absorbers, two 90° miter bends, two waveguide pumpouts, an insulating break, a gate valve, and miscellaneous straight waveguide sections feeding a launcher radiating in the TE_{02} mode. Later, a focusing Vlasov launcher will be added to beam the ECH power to the saddle point in ATF magnetic geometry for optimum power deposition. The ECH system has several unique features; namely, (1) the entire ECH system is evacuated, (2) the ECH system is broadband, (3) forward power is monitored by a newly developed waveguide mode analyzer, (4) phase correcting miter bends will be employed, and (5) the ECH system will be capable of operating short pulse to cw. Initial high-power tests show that the overall system efficiency is 87%. The waveguide mode analyzer shows that the gyrotron mode output consists of 13% TE_{01}, 82.6% TE_{02}, 2.5% TE_{03}, and 1.9% TE_{04}.

INTRODUCTION

The Advanced Toroidal Facility[1] (ATF), an $\ell = 2$, $m = 12$, moderate-aspect-ratio torsatron ($R = 2.1$ m, $a = 0.3$ m), is scheduled for completion in December 1987. Crucial to the success of planned high-beta studies is the production of nearly current-free electron cyclotron heated (ECH) plasmas for subsequent heating with high-power neutral beams. The development effort on ECH waveguide components began early in 1985. From the outset, a decision was made to develop, within budget restraints, waveguide components and technology that were truly innovative. Considerable experience with high-power vacuum waveguide transmission systems had been gained on the ELMO Bumpy Torus–Scale device (EBT-S) experiment[2] and later on the Radio Frequency Test Facility (RFTF) experiment.[3] Experience with evacuated waveguide systems showed that they are quite reliable and their power handling is more than adequate. Because no barrier windows are needed in evacuated systems, they can operate effectively at multiple frequencies. Finally, we recognized that development of evacuated ECH transmission systems will be essential if suitable windows cannot be found for continuous wave (cw) megawatt gyrotron designs.

Another important design criterion for the ATF ECH system was that the ECH system be cw compatible because the ATF device would ultimately run at steady state. Also, the ECH system should allow different frequencies to be used on ATF (28 GHz, 56 GHz, etc.) without substantial modifications to the waveguide system. The combination of these two criteria dictated that quasi-optical components be employed where cooling is straightforward and broadband performance is good. From ray tracing studies,[4] it was determined that an X-mode

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

launch at the second harmonic (f = 53.2 GHz, B = 0.95 T) was optimum for high-beta studies. The ECH system would also need to be flexible enough to permit O-mode launching at the fundamental. This meant that the ECH system would need to propagate a pure mode to the launcher. A decision was made to simply propagate the TE_{02} mode from the gyrotron to the launch without complicated intermediate mode conversions. Also, the TE_{02} can be simply converted into a high-directive polarized beam using a Vlasov launcher in conjunction with a grooved reflector for polarization control. Another constraint on the ECH system was that costs must be minimized. Accordingly, a 90-kV, 10-A cw gyrotron power supply was acquired from the phased-out EBT-S program in 1985.

SYSTEM DESCRIPTION

The ATF ECH system consists of a high-voltage dc power supply (90 kV, 10 A), the ECH site, the gyrotron socket, a 2-T superconducting magnet system, a 53.2-GHz 200-kW cw gyrotron oscillator, cooling systems for the gyrotron and waveguide system, the waveguide support platform, the waveguide transmission system, and associated instrumentation, controls, and interlocks for the ECH system. Although this paper deals mainly with waveguide system technology, the authors recognize that the high-voltage power supply requires the most resources for a successful ECH system. The initial configuration of the ATF ECH system is shown in Fig. 1. The inside diameter (ID) of the entire system is 6.35 cm. The system consists of an optical arc detector, three bellows, a waveguide mode analyzer, two TiO_2 mode absorbers, two 90° miter bends, two waveguide pumpouts, an insulating break, a gate valve, and miscellaneous straight waveguide sections ranging in length from 1.7 to 18 m. The intent of the design is to transmit the TE_{02} mode in vacuum from the gyrotron [illegible] simple TE_{02} waveguide launch at ATF. This launch will be upgraded to a foc[illegible], highly directive beam by a simple Vlasov launcher and a system of steering and polarizing mirrors, but we will not discuss this upgrade here.

The entire waveguide system can be evacuated to 10^{-7} torr by two 510-L/s turbomolecular pumps, shown in Fig. 2. These pumps are isolated from the high-power microwaves by a perforated screen (1.3-mm-thick, 1.3-mm-diam holes on a 1.8-mm-square spacing) that has been rolled into a 6.35-cm-ID cylinder and seam welded. The mode conversion of the rolled screen on the TE_{02} mode was negligible. The effective speed of the pumpout is probably around 200 L/s because of the poor conductance of the perforated screen. Two pumpouts are required for the long horizontal waveguide run because of the low conductance of the 6.35-cm waveguide.

The waveguide flange is an adaptation of the unique EVAC high-vacuum flange shown in Fig. 3. This flange is similar to the well-known conflat flange design except that the clamping force is produced by two heavy-duty chains that radially compress a conical surface instead of by a conventional bolt circle. The waveguide inside dimension is aligned by a brass ring that slips over the EVAC flange and under the clamping chain. The copper gasket can be replaced with a Teflon gasket at locations where frequent flange assembly is required. The main advantage of the EVAC flange over conflat flanges is its quick assembly.

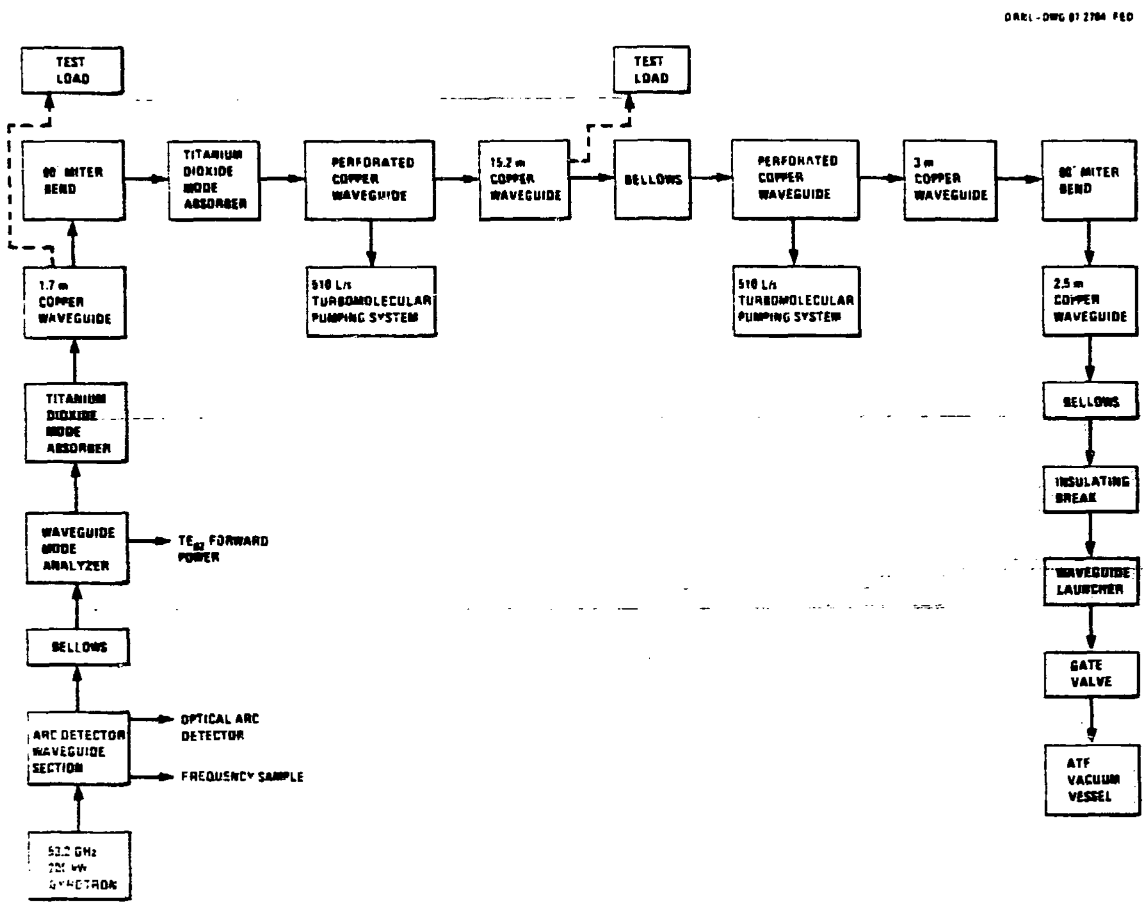

Fig. 1. The ATF ECH system, including the locations of the test load.

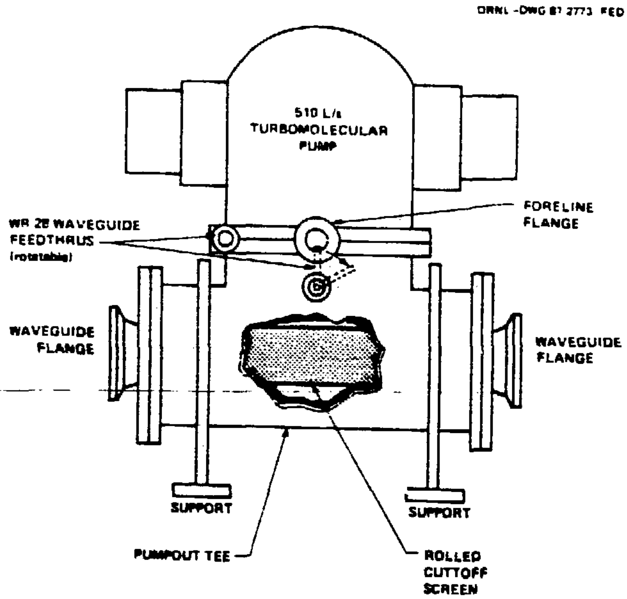

Fig. 2. Cutaway of a waveguide pumpout section.

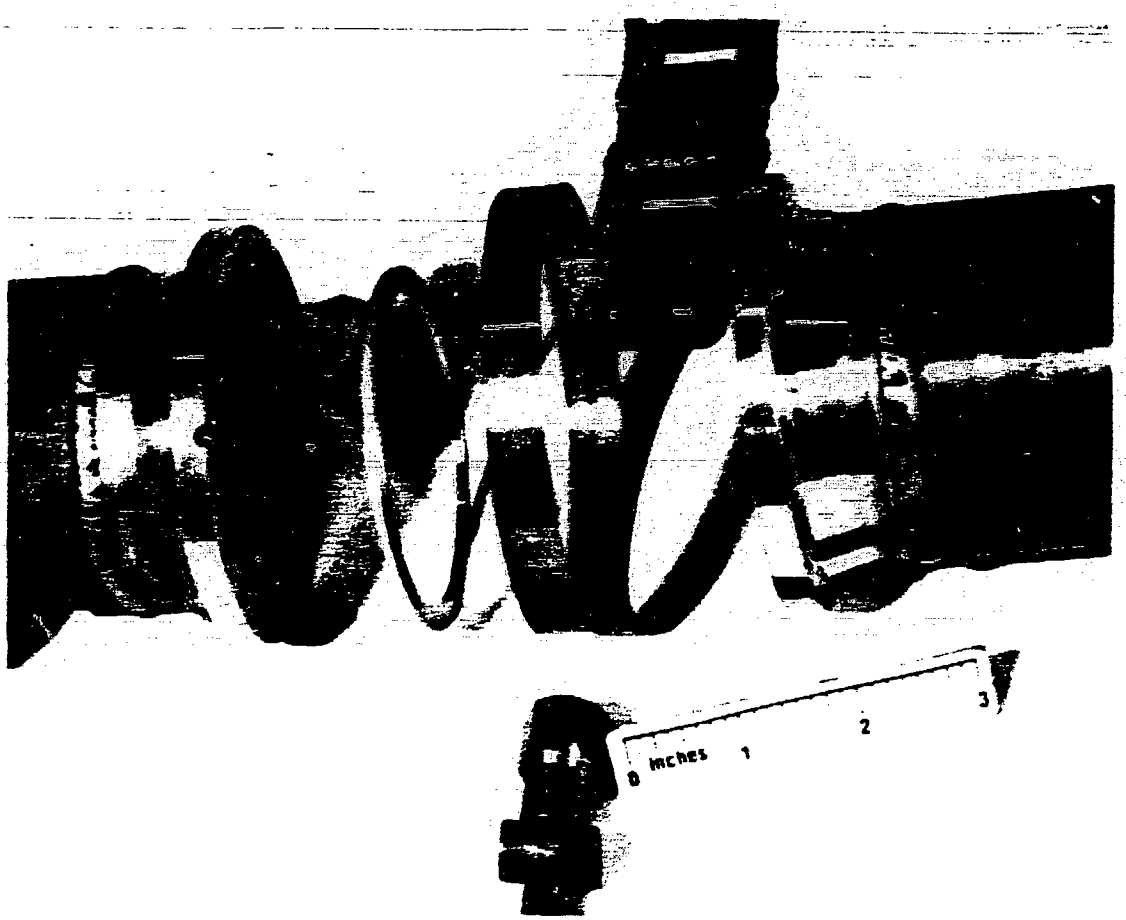

Fig. 3. The vacuum waveguide flange.

The 90° miter bends used in the system have very favorable frequency scaling, as shown in Fig. 4. The bends can be easily cooled for cw operation, and they are compact and easily fabricated. None of these requirements can be readily satisfied

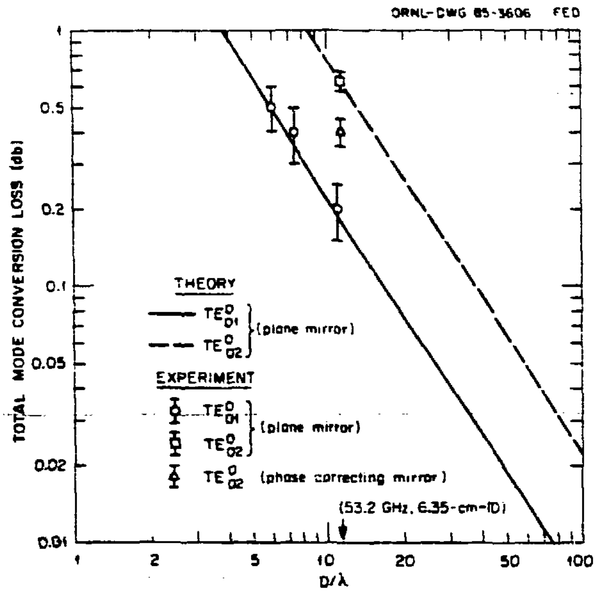

Fig. 4. Total mode conversion loss vs D/λ for a 90° miter bend.

by corrugated bends. The only advantages of corrugated bends over the miter bend are that they have lower mode conversion loss for the TE_{02} mode and that they are easier to install because of their mechanical flexibility. Miter bends with phase-correcting mirrors, however, have demonstrated improved performance. As an example, in comparison with a plane mirror, a simple ellipsoidal mirror with a central deflection of 0.4 mm improved the total mode conversion loss measured in cold test from 0.62 to 0.4 dB. These mirrors are being fabricated for the ATF ECH system, and meanwhile plane mirrors are being used for initial high-power tests.

Figure 5 shows a waveguide mode analyzer which consists of a linear array of rectangular apertures, parallel to the waveguide axis, that are electro-discharge machined into a flat on the outside wall of the 6.35-cm-ID waveguide. The coupling values and spacing of the apertures are optimized to focus the first four circular electric modes into adjacent discrete beams that can be resolved by a pickup horn swept at 1.03 m from the waveguide axis. Two rows of holes spaced 90° apart provide rejection of the TE_{22} mode, whose guide wavelength is very close to the desired TE_{02} mode. A layer of high-vacuum tape provides the vacuum interface, although a thin strip of mica may be required for high-power operation.

Two mode absorbers are used, one between the gyrotron and first miter bend and one between the first and second miter bends to selectively damp modes with radial electric fields. The mode absorbers are 6.35-cm waveguide sections that have

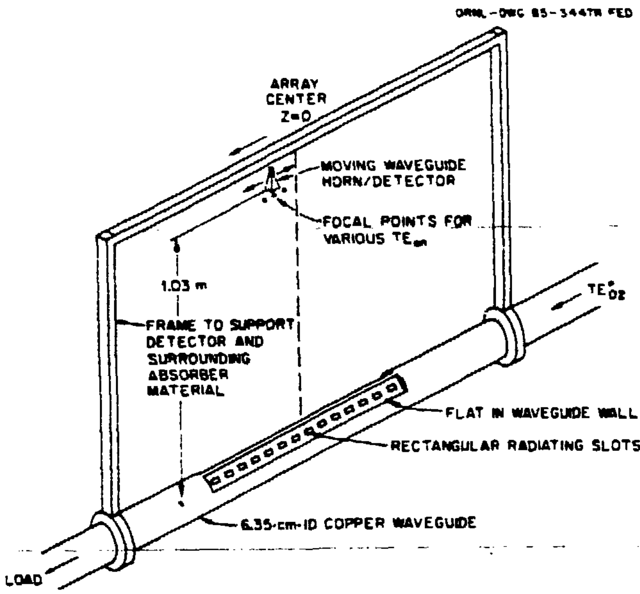

Fig. 5. The waveguide mode analyzer.

been plasma sprayed on the inside with a mixture of TiO_2 and Fe_2O_3. Attenuation for the TE_{02} mode was measured in cold test to be 0.16 dB/m compared with 10.9 dB/m for the TE_{11} mode.

HIGH-POWER TESTS

Initial high-power tests were conducted with a high-power Varian-style water load substituted for the first miter bend in the system. Both mode absorbers were also water cooled. The bellows above the gyrotron and the pumpout cutoff screens are initially not water cooled, and this precluded cw operation. Power is calculated by measuring the water flow rate and the temperature rise between inlet and outlet for each of the waveguide components. Most results were obtained by repetitively pulsing the gyrotron for 5 ms on and 130 ms off. The trigger was synchronized to the 60-Hz line frequency. In high-power operation, the base pressure of the waveguide system was 5×10^{-7} torr. Detectors were placed on the high-vacuum side and the foreline side of the turbo pump to monitor the microwave power. Attenuation of the pumpout screen at 53.2 GHz was measured in the laboratory to be 23 dB for an isotropic, unpolarized radiation source. In actual operation, power coupled through the screen was about 40 dB down from the gyrotron output power. The typical attenuation from the high-vacuum side to the foreline is about 30 dB. At 200 kW, this results in a total leakage power of 20 W through the screen, of which about 20 mW is seen by the pump motor.

About 95% of the gyrotron power was delivered to the load, and the remaining 5% was absorbed by the first mode absorber. This larger attenuation than that measured in cold test was probably caused by some noncircular modes in the gyrotron output, which would have much higher attenuation in the mode absorber than the TE_{02} mode. The waveguide mode analyzer was used to scan the circular electric mode spectrum of the gyrotron, which was shown to consist of 13% TE_{01}, 82.6% TE_{02}, 2.5% TE_{03}, and 1.9% TE_{04}. Also, the TE_{02} mode signal was a linear function of calorimetric power measured in the water load and mode absorber. The radiation pattern for the analyzer is shown in Fig. 6. Boiling in the water load was observed as an audible click that coincided with the microwave pulse, even at flow rates as high as 7 L/s. This condition limited the 200-kW pulse to about 8 ms to preclude boiling.

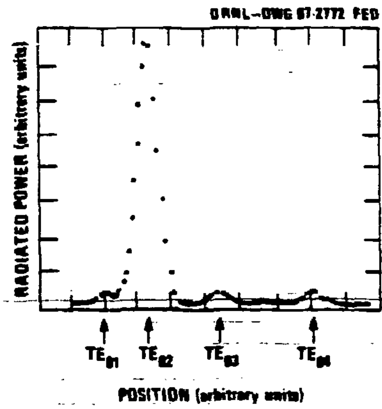

Fig. 6. The radiated power pattern from the waveguide mode analyzer.

The first miter bend was replaced and the load was relocated to just before the second waveguide pumpout section. The load absorbed about 89% of the gyrotron output power, while the first and second mode absorbers took 4% and 7% of the gyrotron output power, respectively. To prevent boiling at 200 kW for pulses longer than 8 ms, a preload was added to the water load. The preload consisted of a 10-cm radius-of-curvature bend followed by a 30.5-cm length of TiO_2-coated waveguide. The purpose of the bend was to forward convert the TE_{02} power into modes with higher losses in the preload and thus lower the power incident on the water load. Using this configuration, the water load absorbed 60%, the preload absorbed 28%, and the first and second mode absorber took 5% and 7%, respectively, of the gyrotron output. With the addition of the preload, no audible boiling noises were heard at the full 200-kW output power of the gyrotron for pulse lengths up to 130 ms.

Finally, the second miter bend was added to the system before the preload, and the water load absorbed 63%, the preload absorbed 24%, and the first and second mode absorbers took 5% and 8%, respectively. The higher loss in the second mode absorber with the addition of the second miter bend was probably the result of mode trapping between the two bends. The overall efficiency for total power delivered to ATF is expected to be close to the 87% (63% + 24%) measured. Current efforts are focused on improving the reliability of the ECH system and on measuring the output mode purity of the system.

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