Mechanical Design of the Folded Waveguide for PBX-M and TFTR*

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ABSTRACT

The folded waveguide (FWG) antenna is an advanced Ion Cyclotron Range of Frequencies launcher being designed at Oak Ridge National Laboratory in collaboration with Princeton Plasma Physics Laboratory. The FWG offers a drastic increase in radio frequency (RF) power density over typical loop antennas. It also results in internal electric fields of much lower magnitude near the plasma. It is scheduled for installation on either the Tokamak Fusion Test Reactor (TFTR) or the Princeton Beta Experiment-Modified (PBX-M) tokamak in January 1996. The design objective is to provide an FWG that can withstand the thermal loads and disruption scenarios and meet the space constraints of both machines. The design is also intended to be prototypical for the International Thermonuclear Experimental Reactor (ITER). The FWG is fully retractable, and maintenance operations can be performed while the vessel remains under vacuum. The FWG can operate in fast-wave mode, or it can be retracted, rotated 90°, and reengaged for the ion-Bernstein wave launch. The polarizing plate completely covers the front of the antenna, except for slots cut at every other gap between vanes. This plate is interchangeable with plates of other configurations such as a 0-π dipole plate.

There are two design options. The first is a stacked and bolted FWG with a shear skin bolted to the side walls. The alternate design is an FWG with continuous side walls notched on the inside surface with a tapered slot for each vane. Each vane is also tapered along its length where it can be wedged into the side wall slot. Construction of a mockup of the alternate design to verify its integrity is in progress.

The FWG has been analyzed for TFTR disruption and thermal loads, which are more severe than the PBX-M loads. The electromagnetic forces were calculated by SPARK and then applied to a NASTRAN finite element model for stress analysis. Maximum temperatures of the polarizing plate and the graphite bumpers that frame it were analyzed using PThermal.

I. INTRODUCTION

The folded waveguide (FWG) antenna is an advanced Ion Cyclotron Range of Frequencies launcher being designed at Oak Ridge National Laboratory in collaboration with Princeton Plasma Physics Laboratory. It is scheduled for installation on either the Tokamak Fusion Test Reactor (TFTR) or the Princeton Beta Experiment-Modified (PBX-M) tokamak in January 1996. The design objective is to provide an FWG that can withstand the thermal loads and disruption scenarios and meet the space constraints of both machines.

II. DESIGN

The FWG hardware consists of the FWG, the coax feed, the ducts and gate valve at the PBX-M vacuum vessel port flange, the big bellows, the vacuum enclosure (VE), the support stand, and the drive system and port cover (Fig. 1).

A. Folded Waveguide

The alternate design option for the FWG has been adopted. The FWG is a four-sided box, 232.4 cm (91.5 inches) long, with a lap joint at each corner bolted with horizontal bolts. The vertical side walls are slotted lengthwise on the inside

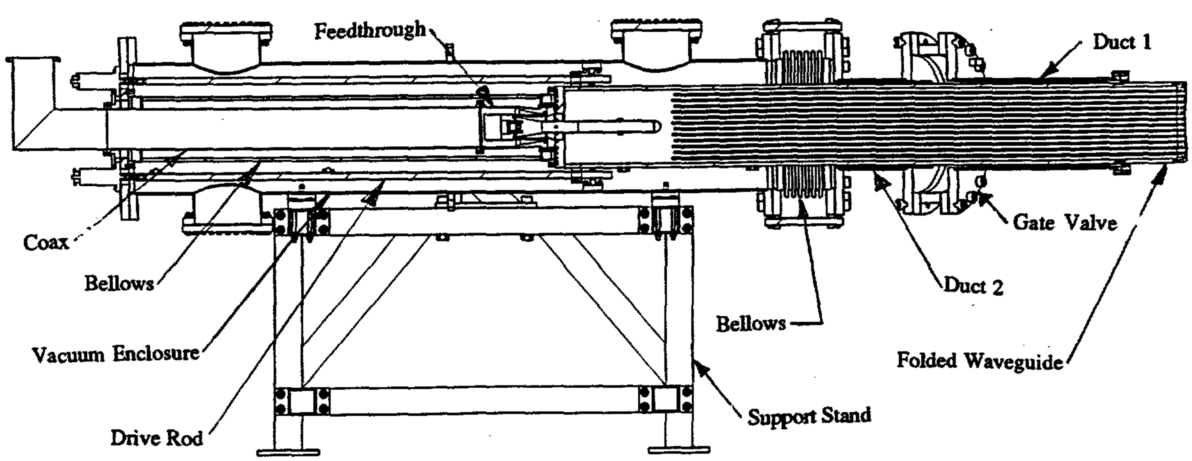

Fig. 1 Elevation view of the folded waveguide installed on PBX-M

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with tapered grooves. Twelve vanes (six on each side) are wedged into the grooves. Each groove and mating edge of the vane is tapered at a 6° included angle (Fig. 2). Because the vanes are wedged into the side walls to a depth equal to their thickness, the joint is as strong as if it were solid. Load tests verified that the wedged joint can withstand the maximum bending moment during disruption of 667.2 N-m/m (150 in-lb/in). The vanes do not span the length of the box; the last 40.6 cm (16 inches) of the box is hollow. There is a front plate called the polarizing plate and a back plate.

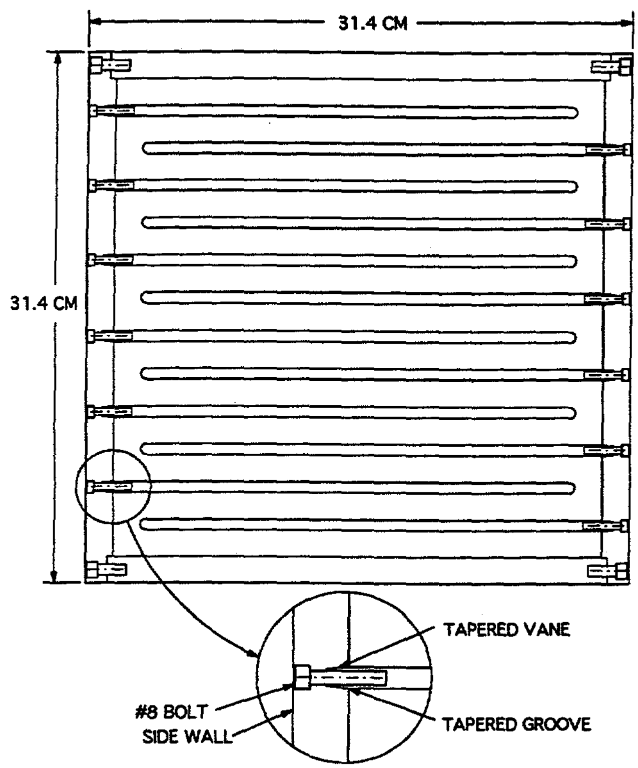

Fig. 2 Cross section of the FWG

The polarizing plate is assembled as shown in Fig. 3. The square flange of the plate is bolted to the four sides of the FWG box. The vanes extend beyond the FWG walls and are bolted to the backside of the polarizing plate. The front face of the polarizing plate is machined with a spherical radius that approximates the plasma contour. There are also rectangular windows cut at every other gap between vanes.

Graphite bumpers, 1.27 cm (0.5 inch) thick, are bolted to the side walls of the polarizing plate along its perimeter. The bumpers have a compound contour at the front with a full radius to bear the toroidal heat flux and the spherical radius to match the polarizing plate so that the bumpers overhang the polarizing plate uniformly by 5 mm (0.2 inches).

The FWG is stainless steel plated with 0.008 cm (0.003 inch) of copper. The polarizing plate, back plate, top, bottom, sides, and vanes are all plated before assembly. The tapered grooves in the side walls are machined after the side walls are plated. The front surface of the polarizing plate is coated with 6 microns of B_4C via physical vapor deposition.

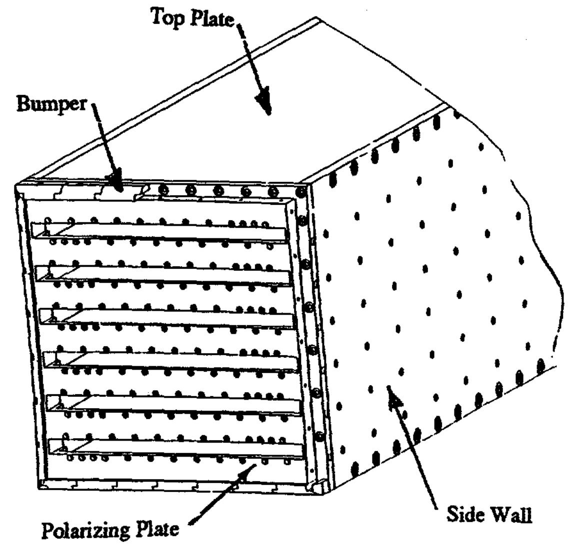

Fig. 3 Front section of the FWG with some bumpers removed

B. Coax Feed

The coax feed consists of the transmission line, the long bellows, the 50-ohm feedthrough, the inner conductor, and the side wall toucher. The feedthrough, which is a modified design of the feedthrough for the long-pulse antenna for DIII-D, is bolted directly to the FWG back plate. The inner conductor extends into the hollow of the FWG to within 5 cm (2 inches) of the end of the vanes. One end of the side wall toucher is clamped to the inner conductor, and the other end is mounted into two horizontal slots in the side wall which allow the toucher to be positioned anywhere along a 10-inch stroke for tuning (Fig. 4).

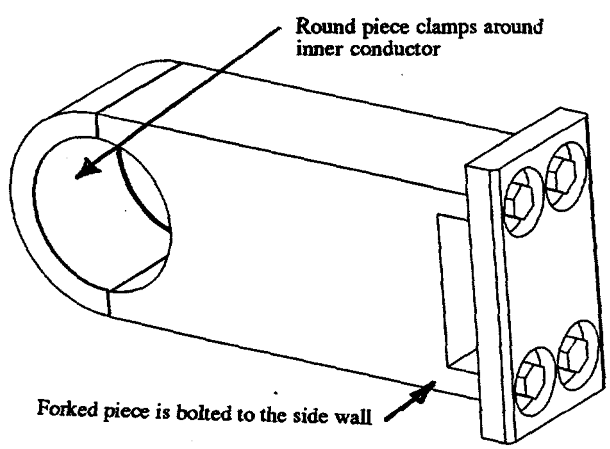

Fig. 4 Side wall toucher

Tuning is performed by pulling the FWG back into the VE and closing the gate valve. A port in the VE can be opened to reveal two wing nuts which tighten the vane toucher clamp. Once the nuts are loosened, the vane toucher can be repositioned, the port cover closed, the volume pumped down, the gate valve opened, and the FWG reinstalled into the vacuum vessel. The vacuum boundary between the VE volume and the transmission line on the air side of the feedthrough is established by a bellows with a 117-cm (46-inch) stroke to account for the FWG range of motion from retraction to engagement. The transmission line, which moves with the FWG, penetrates the concrete wall when installed on the PBX-M machine.

C. Ducts/Gate Valve/Bellows

To allow installation of a gate valve on the PBX-M machine that will fit within the space constraints, the valve must be angled 25 degrees off the port flange surface. A square duct is required between the port flange and the gate valve, and a second duct is bolted to the other side of the gate valve. At this radius from the machine centerline, the clearance is sufficient for the large bellows that allows lateral motion of the vacuum vessel relative to the fixed VE during a disruption. The moving components are supported by threaded rods attached to the PBX-M torque frame. This hanging support is not rigid and does not prevent the motion of the components during a disruption.

The innermost duct has wedged guides at the front to align the FWG at installation. There is a 0.051-cm (0.020-inch) horizontal and vertical clearance between the guides and the FWG to account for the differential thermal expansion during bakeout of the FWG. Rollers at the back of the second duct support some of the load of the FWG and help balance the load on the hanging support.

D. Vacuum Enclosure

The VE provides the vacuum boundary and support for the FWG. When the FWG is operated in the ion-Bernstein wave (IBW) mode (rotated 90°), this configuration is achieved by rotating the entire FWG/VE assembly. This operation is performed with the FWG retracted, the gate valve closed and the VE detached from the big bellows. The VE has 4 sets of rollers located on the bottom as well as the side of the inside wall to support the FWG in both fast wave and IBW modes.

E. Support Stand

The VE is bolted to the support stand, which supports the vacuum load on the port cover. The weight of the VE and FWG is supported by four ball casters, which allow the translation and rotation of the VE.

The support stand is a weldment of aluminum tubing. Electrical breaks at the toroidal cross members eliminate horizontal loops and thus prevent large disruption loads in the structure. It is shimmed with G10 for insulation where its pads are bolted to the floor.

F. Drive System/Port Cover

The drive system for the FWG consists of two threaded rods rotated by a common spindle on the port cover. The rods drive captured nuts bolted to the top and bottom of the FWG with enough play between the nut and its housing to prevent binding. The coupling from the rod to the ferrofluidic feedthrough shaft at the port cover does not allow any lateral loads to be applied on the rod.

III. ANALYSIS

The FWG was analyzed for disruption stresses, thermal stresses, and maximum temperatures. Disruption loads were calculated using SPARK. Details of this analysis can be found in [1].

A. Disruption Stress Analysis

Stress analyses based on TFTR disruption scenarios were performed on several models: the entire FWG, a single vane, a single vane with the side wall, and the polarizing plate.

The electromagnetic loads were applied to a NASTRAN finite element model of the entire FWG (including the polarizing plate), which consisted of plate elements with a coarse mesh (Fig. 5). The model was constrained vertically and horizontally at the vessel port guides and radially in the back. Maximum Von Mises stress for the electromagnetic load case that includes the vacuum vessel is about 1.1×10^8 N/m^2 (16,000 psi). This stress occurs in the vane where it is bolted to the polarizing plate. The IBW configuration was analyzed similarly, and the maximum Von Mises stress was found to be 3.4×10^7 N/m^2 (5,000 psi). This stress occured in the upper corner where it was held.

The model of a single vane and the model of a single vane with the side wall are plate element models with a fine mesh. These models were loaded with electromagnetic loads interpolated from the SPARK model. Conservative results from these two analyses are that the maximum stress in the vane is 1.6×10^8 N/m^2 (23,000 psi) at the polarizing plate. The reaction moment at the face plate is 580 N-m/m (130 in-lb/in) at the tip of the vane; this load requires high-strength bolts between the front plate and the vanes. The reaction moment at the side wall is 670 N-m/m (150 in-lb/in). A very conservative analysis of the polarizing plate used a model of plate elements constrained in the corners. The electromagnetic loads of the entire FWG were applied to the model, and the maximum Von Mises stress was found to be 1.9×10^8 N/m^2 (28,000 psi) at the constraints.

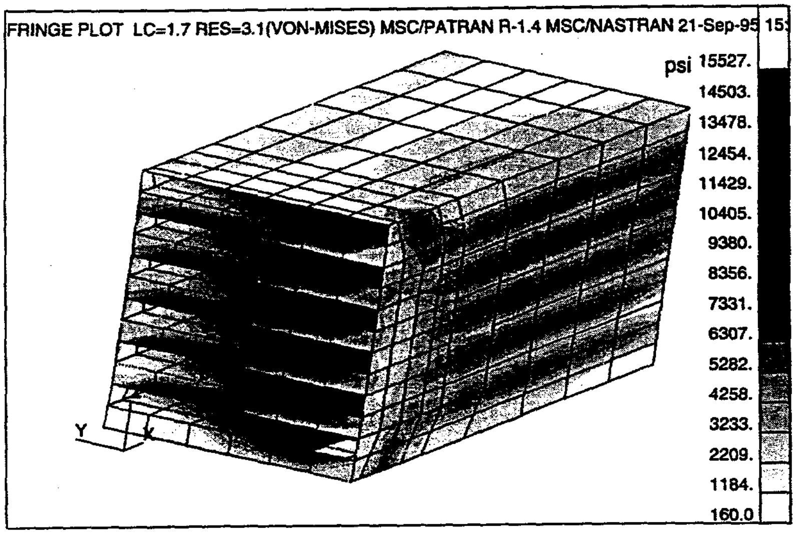

Fig. 5 Finite element model of the entire FWG with polarizing plate

B. Thermal Analysis

The graphite bumpers were analyzed using PThermal.
Table 1 shows the criteria and results. Cooling was assumed as radiation from free surfaces with an emissivity of 0.8 and conduction through bolted surfaces modeled as radiation with an emissivity of 0.4. If the FWG is installed on TFTR, active cooling may be required on the bumpers. The polarizing plate was also analyzed using PThermal. Table 1 shows thermal analysis parameters for the FWG.

IV. FABRICATION STATUS

All components of the FWG are under construction. The FWG box with its vanes, polarizing plate, back plate, and graphite bumpers are being fabricated in-house. Numerical control programming began in late July. The construction of the ducts, vacuum enclosure, side wall touchers, vacuum feedthrough, drive system, and support stand has been subcontracted to vendors. The overall assembly will be performed by the Fusion Energy Division of Oak Ridge National Laboratory for testing on the Radio Frequency Test Facility before shipment to Princeton Plasma Physics Laboratory in December.

REFERENCES

[1] J. J. Yugo, D. L. Conner, C. H. Fogelman, and T. S. Bigelow, "Plasma disruption force and stress analysis of a folded waveguide launcher for PBX-M," *Proceedings of the IEEE/NPS Symposium on Fusion Engineering,* Champaign, Illinois, Oct. 1-5, 1995.

Table 1
Thermal Analysis Parameters for the FWG for PBX-M or TFTR

	Polarizing Plate	Polarizing Plate	Bumpers	Bumpers
Machine	PBX-M	TFTR	PBX-M	TFTR
Toroidal Heat Flux (W/cm^2)			500 $e^{(-x/1.5\ cm)}$	1500 $e^{(-x/1.0\ cm)}$
Plasma Heat Flux(W/cm^2)	40	50		
Maximum RF Heat Flux(W/cm^2)	10	10		
Duty Cycle	0.3 seconds every 3 minutes	2 seconds every 5 minutes	0.3 seconds every 3 minutes	2 seconds every 5 minutes
Maximum End-of-Pulse Temp (°C)	66	138	350	1330