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ORNL COMPACT LOOP ANTENNA DESIGN FOR TFTR AND TORE SUPRA*

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Abstract

The goal of supplemental ion cyclotron resonant heating (ICRH) of fusion plasma is to deliver power at high efficiencies deep within the plasma. The technology for fast-wave ICRH has reached the point of requiring "proof-of-performance" demonstrations of specific antenna configurations and their mechanical adequacy for operating in a fusion environment. Oak Ridge National Laboratory (ORNL) has developed the compact loop antenna concept based on a resonant double loop (RDL) configuration for use in both the Tokamak Fusion Test Reactor (TFTR) and Tore Supra ICRH programs. A description and a comparison of the technologies developed in the two designs are presented. The electrical circuit and the mechanical philosophy employed are the same for both antennas, but different operating environments result in substantial differences in the design of specific components. The ORNL TFTR antenna is designed to deliver 4 MW over a 2-s pulse, and the ORNL Tore Supra antenna is designed for 4 MW and essentially steady-state conditions. The TFTR design embodies the first operational compact RDL antenna, and the Tore Supra antenna extends the technology to an operational duty cycle consistent with reactor-relevant applications.

Introduction

The TFTR and Tore Supra RDL antennas are based on the compact loop antenna concept. RDL antenna performance results from an electrical configuration consisting of a current strap connected top and bottom to tunable capacitors fed by a lossy coaxial transmission line at a nonsymmetric feedpoint. An electrical circuit of an RDL antenna is shown schematically in Fig. 1. The configuration of the RDL antenna allows for peak voltage to be moved away from vacuum feedthroughs to the ends of the current strap in a shieldable environment behind the Faraday shield. Voltages and currents on various elements have been computed as functions of plasma load for given antenna powers. Figure 2 is a plot of voltage and current for the TFTR current straps.

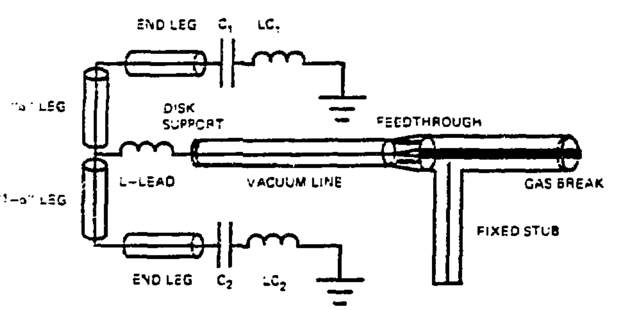

Fig. 1. The electrical circuit of the antennas. Because TFTR's current strap is not cooled, its circuit does not have the fixed stub.

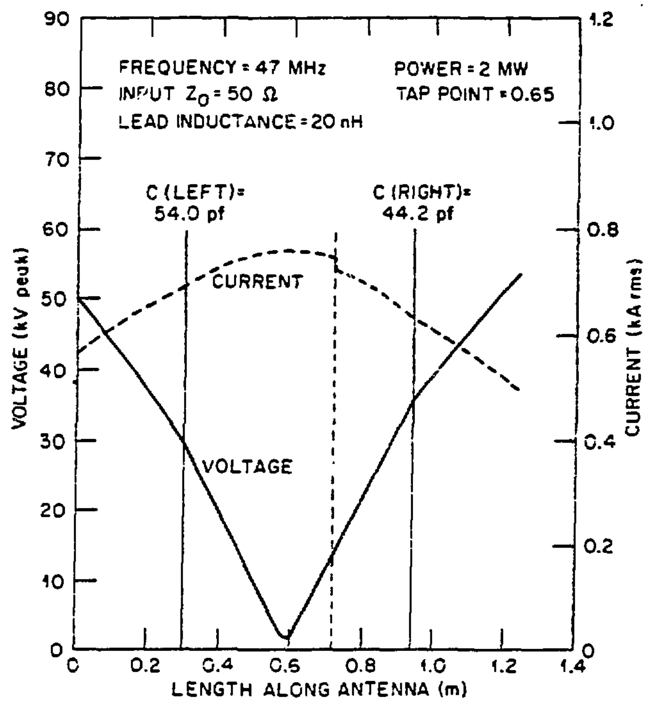

Fig. 2. Voltages and currents along the current strap. The C1 capacitor in Fig. 1 is at 0 m. The two vertical lines represent the beginning and end of the current strap, and the dashed vertical line is at the site of the feed point. This calculation is for the TFTR antenna with 2 MW at 47 MHz and a load of 6 Ω/m.

The designs of the antennas for TFTR and Tore Supra are similar in principle; the primary differences result from the extended pulse length, higher power densities, and wider frequency range for Tore Supra. Table 1 lists the design parameters for the two antennas. Both are installed in horizontal midplane ports between adjacent toroidal field coils. Figure 3 shows the layout of the antennas (specifically, of the TFTR antenna). Each antenna contains two RDLs, each of which is capable of producing 2 MW for a total of 4 MW per port.

Tunable capacitors are provided in both the TFTR and Tore Supra antennas to permit operation over a wide range of frequencies while being matched to the correct impedance (50 Ω for TFTR and 30 Ω for Tore Supra).

Plasma coupling is varied on the ORNL RDL antennas by drive systems that allow the current strap to be moved relative to the outer edge of the plasma. Antenna performance may be

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Table 1. Antenna design parameters

Description	TFTR	Tore Supra
Power into the port (MW)	4	4
Power per current strap (MW)	2	2
Port dimension (cm × cm)	60 × 90	60 × 70
Total frequency range (MHz)	40–80	35–80
Frequency range, first band (MHz)	40–60	35–80
RF pulse length (s)	2	210
Capacitor designer	ORNL	Comet
Capacitor voltage (kV peak)	50	50
Capacitor current (A rms)	800	750
Capacitor electric field (kV/cm)	43	100
Antenna electric field (kV/cm)	23	23
Faraday shield losses (W/cm^2)	100	100
Antenna power density (W/cm^2)	1160	1520
Antenna motion range (cm)	11	30

tested from low plasma load up to the point where the antenna comes close enough to the plasma to test the mechanical limits of the antenna structure.

On both antennas, a single Faraday shield structure protects the loops. The Faraday shield, with its close proximity to the plasma, is the antenna component that experiences the harshest operating environment. The shields consist of two tiers of actively cooled Inconel tubes; the front tier is covered with semicircular graphite sleeves to minimize the introduction of high-Z impurities into the plasma from the Faraday shield.

Electrical Circuit Components

Capacitors

In the antenna circuit, the element most likely to limit power is the vacuum capacitor. The capacitors form a number of concentric, nested, ganged cylinders. Capacitance is varied by changing the overlapping surface areas of the concentric cylinders. This is accomplished by driving one cylinder with respect to the other. The capacitors for the TFTR antenna were designed and built at ORNL; the capacitors for Tore Supra are of commercial design by Comet LTD, Berne, Switzerland. In the ORNL design, one cylinder slides with respect to the other, and electrical contact is maintained by sliding finger stock. Comet relies on the flexing of a cooled bellows to provide contact through a range of motion. Each capacitor for TFTR has its own vacuum pump; the Comet capacitor is permanently sealed under high vacuum.

Voltage limits for the capacitors are determined by two characteristics: the electric field attainable on the ceramic barrier and that attainable between concentric cylinders. For TFTR, 43 kV/cm is needed for 50-kV operation; 100 kV/cm is needed for Tore Supra. Capacitors have been tested at ORNL for electric fields up to 120 kV/cm between cylinders.

The longer pulse length of the Tore Supra antenna provides more heating in the capacitor than does the relatively short pulse of TFTR. Initial tests of the water-cooled Comet capacitor show that it will handle 750 A rms at 80 MHz, steady state, thus demonstrating adequacy for the design. Final production models will be tested to verify acceptability for voltage, steady-state current handling, and mechanical strength of the ceramic housing.

Current Straps

Width of the current straps is dictated by port width. In addition, studies at ORNL indicate that, to minimize strap inductance while maximizing antenna/plasma rf flux linkage, the current strap should occupy approximately 50% of the cavity width.[1] The current straps for each loop are separated from each other by a solid dividing wall within the Faraday shield structure to reduce flux linkage between straps. A minimum radial separation of 15 cm is maintained between the current straps and the cavity back wall to minimize backplane currents.

Flux linkage to the plasma is controlled by the proximity of the current strap to the plasma edge. The curvature of the current straps for both antennas matches plasma poloidal curvature to maintain a constant spacing between the straps

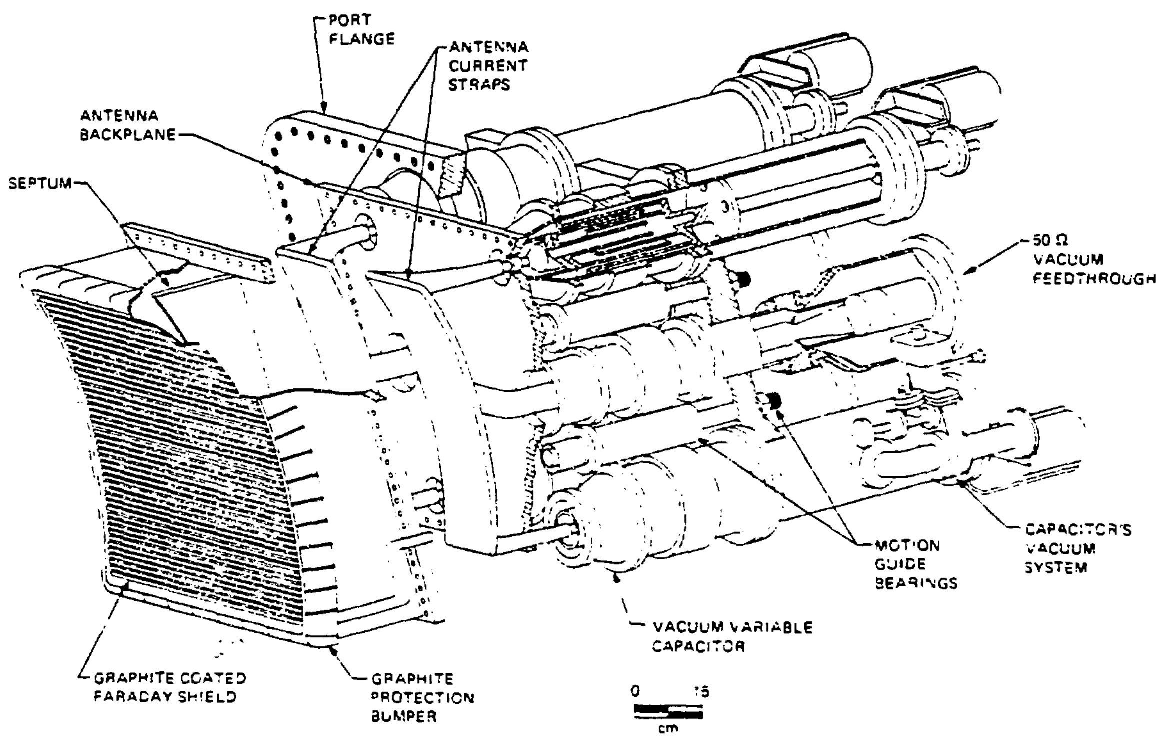

Fig. 3. The antenna for TFTR.

and the plasma. In the Tore Supra antenna, toroidal curvature is designed into the straps as well in an attempt to maintain equal spacing. Once again, the longer pulse lengths of Tore Supra also require that the currents straps be actively cooled. not only to cool the straps but also to cool the front ends of the Comet capacitors.

Additional design problems in the current strap result from (1) differential thermal expansion between the current strap and the cavity back wall to which the capacitor is affixed and (2) disruptions. Figure 4 shows the resultant loads in the TFTR antenna caused by these situations.

Differential thermal expansion of a completely rigid system would apply bending stresses to the ceramic in the capacitors. These stresses are reduced in TFTR by reducing the stiffness of the current strap and the strap lead that connects the strap to the capacitor front. To reduce the stresses caused by differential thermal growth in the Tore Supra capacitor, the capacitor is designed to be mounted on a diaphragm plate, which allows for angular deflections of the capacitor with respect to the cavity back wall.

Disruptions result in eddy currents in the current straps, which tend to twist the straps about the center coaxial axis like a propeller. To resist this torque, a ceramic wedge is placed in the coaxial line annulus as shown in Fig. 5. The ceramic is machined with a self-holding friction taper on the inside and outside diameters. Corresponding tapers exist on the inner and outer conductors. The coaxial line is designed to be tightened with nuts at the rear of the antenna to preload the ceramic wedge at the front of the coaxial tube.

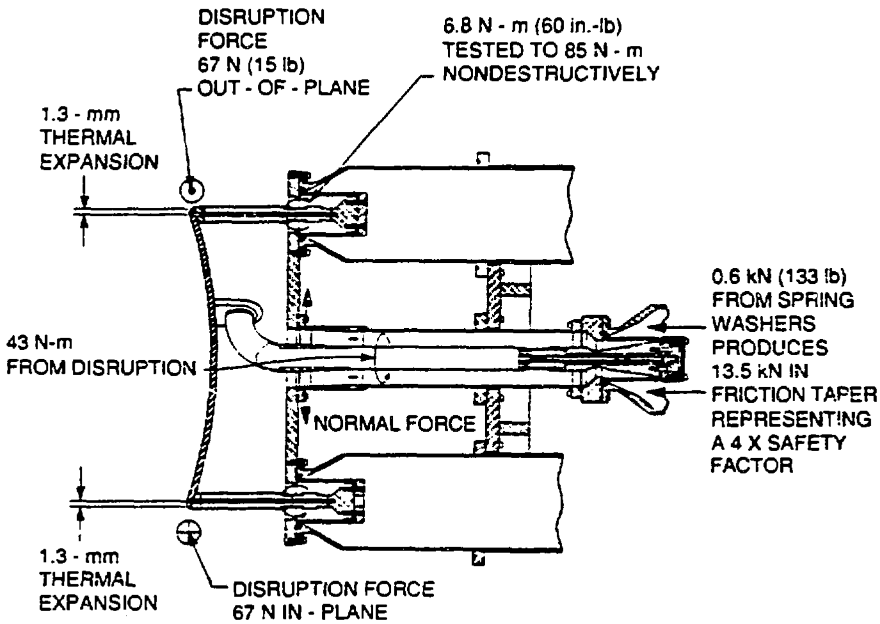

Fig. 4. ORNL RDL antenna current strap forces.

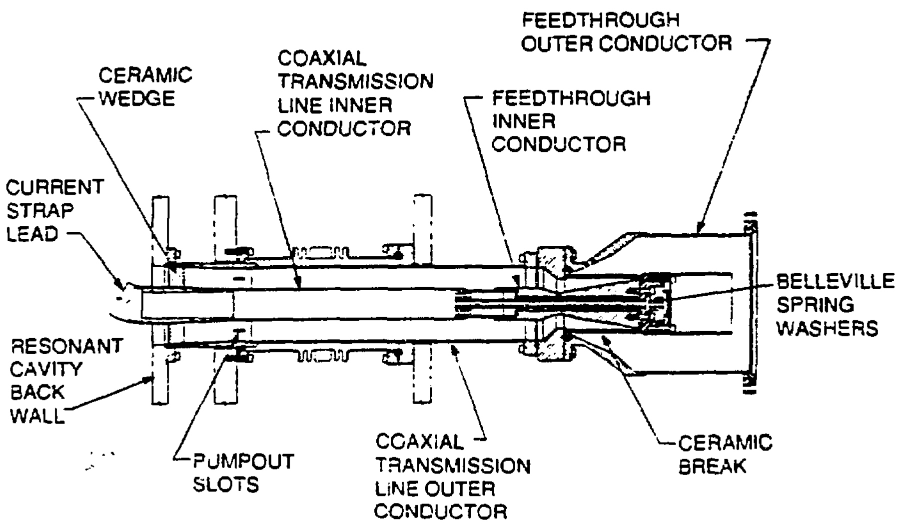

Fig. 5. ORNL RDL antenna coaxial/feedthrough subassembly.

Support Structure

Drive System

Both antennas contain drive systems that move the antenna radially in and out with respect to the plasma. The drive for the TFTR system is designed as an integral part of the load-bearing system of the support structure. A 5-cm buttress-threaded rod moves the antenna and supports it against radial disruption loads and vacuum loads. Four Inconel 718 guide rods mounted in Vespel bushings provide bearing support and transfer load to the port cover flange. Analysis by Princeton Plasma Physics Laboratory shows that severe disruptions may transfer 52 kN (11,600 lb) of transverse force to the end of a rod.[2]

The Tore Supra design has two port-mounted guide bearings and two externally mounted rods. The external rods will be used to move the antenna. A single large bellows isolates the moving parts from fixed parts.

Faraday Shield

The Faraday shields for these antennas must survive in the plasma edge environment. Design criteria call for the shield to handle rf losses of up to 20% of the total rf power. Additional thermal loads on the antenna include plasma radiation and disruption loads. Average design heat fluxes amount to 225 W/cm^2.

The shields consist of two tiers of actively cooled Inconel 625 tubes welded into a support structure; the front tier is covered with semicircular graphite sleeves to minimize the introdution of high-Z impurities into the plasma from the Faraday shield. Front tubes are initially copper plated before being furnace brazed to attach the POCO AXF-5Q graphite tiles with TICUSIL braze alloy. All tubes are gas tungsten arc welded into each side of a welded and machined Inconel 625 support structure. Front and rear tubes are separated by a nominal 3-mm gap, allowing 85% flux transmission through the shield while offering good fabricability and cooling capability. The tubes are cooled by demineralized water at 10 bar, 40°C for TFTR and 35 bar, 150°C for Tore Supra.

To protect the front edges of the Faraday shield structure from the toroidal energy flow of the plasma, the front of the structure is covered with graphite bumper limiters. The bumpers are designed to withstand 2 kW/cm^2 with a radial decay of 1.5–2.5 cm. Because TFTR has relatively short pulses, the graphite is allowed to heat and cool inertially. Bumpers, approximately 1 cm thick, are bolted to the Faraday shield cooling manifold.

The long pulses of Tore Supra require cooling of the graphite bumpers. Graphite is brazed onto TZM (titanium, zirconium, and molybdenum) alloy to make individual bumpers. Several bumpers are subsequently gang brazed onto copper cooling tubes before being mounted to the Faraday shield structure.

Conclusions

The 4-MW RDL antennas for TFTR and Tore Supra are designed to maximize power output and provide operational flexibility while providing sufficient mechanical strength to survive the harsh operating conditions close to a plasma. Many tests and analyses have been made to ensure that these antennas will work reliably. Many other tests are yet to be conducted to determine ideal operating frequencies and plasma loadings. Testing of the ORNL RDL antenna at TFTR should begin in late 1987 to verify the plasma heating performance of the design. Testing at Tore Supra will not begin until mid-1988.

References

[1] F. W. Baity et al., in "ICRF Antenna and Feedthrough Development at ORNL," in *Proceedings of the 11th Symposium on Fusion Engineering, Austin, Texas, November 18-22, 1985*, IEEE Cat. No. CH 2251-7.

[2] James Bialek, Princeton Plasma Physics Laboratory, private communication to D. W. Swain, Oak Ridge National Laboratory, 1986.