RESONANT DOUBLE LOOP ANTENNA DEVELOPMENT AT ORNL*

D. J. Taylor, F. W. Baity, R. A. Brown, W. E. Bryan,
A. Fadnek, D. J. Hoffman, J. F. King, R. L. Livesey,
and R. L. McIlwain
Oak Ridge National Laboratory
Oak Ridge, TN 37831
(615) 576-0267

ABSTRACT

As part of the development of ion cyclotron resonant heating (ICRH) systems for fusion research, Oak Ridge National Laboratory (ORNL) has built resonant double loop (RDL) antennas for the Tokamak Fusion Test Reactor (TFTR) (Princeton Plasma Physics Laboratory, Princeton, NJ, US) and Tore Supra (Centre d'Etudes Nucleaire, Cadarache, France). Each antenna has been designed to deliver 4 MW of power. The electrical circuit and the mechanical philosophy employed are the same for both antennas, but different operating environments lead to substantial differences in the designs of specific components. A description and a comparison of the technologies developed in the two designs are presented.

I. INTRODUCTION

The TFTR and Tore Supra RDL antennas are based on the compact loop antenna concept.¹ Both antennas consist of current straps connected at top and bottom by tunable capacitors fed by a coaxial transmission line at a nonsymmetric feedpoint. The fronts of both antennas are protected by graphite-covered, water-cooled Faraday shields. The position of each antenna with respect to the last closed flux surface of the plasma can be changed by mechanical drive systems. Primary design and development problems result from high voltages (50 kV in the capacitors), high thermal loads, and large mechanical forces caused by disruptions.

The ORNL RDL antennas for TFTR and Tore Supra must operate in considerably different environments. Table 1 lists the antenna design parameters. The primary differences between the antennas are in the areas of operating temperature, rf pulse length, and

---

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

MASTER

range of travel of the drive mechanisms. TFTR operates from a baseline of room temperature with RF pulses that last 2 s. By comparison, the baseline temperature for Tore Supra is 150°C with RF pulses that last 210 s. Because previous papers have been presented on the design of the TFTR antenna, emphasis is placed on the Tore Supra antenna in this paper.²

II. CONFIGURATION

As a result of the electrical configuration, the RDL antennas for TFTR and Tore Supra are tunable over a wide range of frequencies. An electrical circuit of an RDL antenna is shown schematically in Fig. 1. In the figure, C_1 and C_2 represent variable capacitors. The " α " leg and the " $1-\alpha$ " leg represent the portions of the current strap attached above and below the "L-lead" (i.e., the coaxial feed line).

An isometric view of the RDL antenna for Tore Supra is shown Fig. 2 and a sectioned view is shown in Fig. 3. Because the center conductor is connected to the current strap away from the center of the strap, varying the capacitance of C_1 and C_2 results in large changes in antenna impedance. The variable impedance allows operation over a wide range of frequencies.

Because of the long rf pulses on Tore Supra, water cooling is required for the current straps. A stub is used to provide an entry point for the water. Its dimensions are sized so that the stub presents a high impedance over the frequency range of operation (35-80 MHz). The straps and related hardware have been designed to operate on a high-pressure water system (3.5-MPa supply pressure).

A water-cooled Faraday shield protects the current straps from the plasma. The rear row of cooling tubes in the shield is designed to be positioned 10-mm in front of the current straps. A center wall (septum) is built into the Faraday shield between the two current straps to reduce coupling between circuits. The septum also provides a place to attach the cooling tubes on the front of the shield.

Drive systems are used to position both antennas. The TFTR antenna has a gear/shaft drive mechanism built into the antenna support scheme. In contrast, the drive system for the Tore Supra antenna is designed to be bolted onto the completed antenna after the antenna is installed on the tokamak.

A specially developed ceramic vacuum feedthrough is used at the rear of the coaxial feedline to insulate the inner conductor from the outer conductor. Locating the insulated current feed point well away from the fronts of the capacitors allows the antennas to withstand higher voltages.

Another ceramic is used at the front end of the coaxial feedline to support the inner conductor against the outer conductor. Both the inner and outer surfaces of the ceramic are conical, as are portions of the inner and outer conductors at this joint. Placing a preload with a nut, bolt, and Belleville washers on the rear of the inner conductor holds the components together. The ceramic taper is designed to withstand torques of 43 N-m. The torques result from disruption eddy currents in the current straps, which tend to twist the straps about the center conductor axis like a propeller.

III. 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 moving 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, Bern, Switzerland. Comet relies on the flexing of a cooled bellows to provide contact through a range of motion. The size of this bellows was increased as a result of testing at ORNL, where modes of failure in commercially available capacitor designs were investigated.³ Each capacitor for TFTR has its own vacuum pump; the Comet capacitor is permanently sealed under high vacuum.

Custom capacitors were used on TFTR because schedule considerations would not allow time to develop and test a commercial product. In the interim between designing antennas for TFTR and Tore Supra, testing has determined that commercial capacitors exceed what is required for the current design. The Comet capacitor to be used in the Tore Supra antenna was recently tested to 55 kV and 800 A for 40 s simultaneously at 65 MHz. Design points for this frequency are 50 kV and 750 A for 30 s. The resulting internal electric fields in the capacitors reached 120 kV/cm between cylinders (100 kV/cm is required).

The longer pulse of the Tore Supra antenna provides more heating in the capacitor than does the relatively short pulse of TFTR. Because the maximum allowable temperature for the Comet capacitor is 80°C, cooling water must be supplied to the capacitor. The capacitor internals are cooled by a low-pressure/temperature (300-kPa/25°C) water system. The front of the capacitor is cooled by the same water used to cool the current straps. The water is routed through the current straps

and current strap connector housings to a copper cooling flange bolted to the front of the capacitor. A nickel weld overlay on the copper cooling flanges allows them to be Tungsten-Inert-Gas (TIG) arc welded to the stainless steel current strap components. The total heat load to be generated on the front of the capacitors is expected to be 4 kW per capacitor.

IV. 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 between the side wall and the septum in the Faraday shield support structure.⁴ 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 changing the proximity of the current strap to the plasma edge. The curvature of the current straps for both antennas matches the poloidal curvature of the plasma to maintain constant spacing. In the Tore Supra antenna, the current straps are tapered across their width to provide more constant spacing to the toroidal curvature of the plasma.

The Tore Supra stainless steel current straps are machined TIG weldments with internal cooling channels designed for 3.5-MPa (525psi) water pressure. The normal operating temperature for the Tore Supra antenna is 150°C. Because the water supplied to the current strap will be at 50°C, differential thermal expansion between the current straps and the rest of the antenna is considerable. The resulting loads are reduced in two ways: (1) the resonant cavity back-plate on which the capacitors are mounted is made of Inconel 600, which has a lower thermal expansion coefficient than does stainless steel; and (2) the capacitors are attached to bellows, which transfer load from the current strap/capacitor assembly to the resonant cavity. The bellows are designed to withstand 1.5-mm of transverse deformation - well beyond the expected 0.5-mm cyclic thermal excursion.

V. FARADAY SHIELD

The Faraday shields have two primary functions: (1) transmission of the desired rf wave component and polarization; and (2) protection of antenna components from the harsh environment of the hydrogen plasma. The shields are designed to have circuit characteristics that minimize voltages and electric fields and maximize power throughout the system. Mechanically,

the shield is designed to withstand high heat fluxes as well as disruption-induced forces.

The shields consist of two tiers of actively cooled Inconel 625 tubes TIG welded into an Inconel support structure. The front tier is covered with semicircular graphite sleeves to minimize the introduction of high-Z impurities into the plasma from the Faraday shield. 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. All tubes and the inside of the Faraday shield support structure are copper plated to a thickness of 0.05-mm.

POCO AXF-5Q grade graphite (Poco Graphite, Inc.) is used for the manufacture of tiles, which are furnace brazed to the front tier tubes using Ticusil braze alloy (GTE Products Corp.). A great deal of effort has gone into the development of this brazing process to optimize the braze joint. By controlling temperature, fit-up of parts (at braze temperature), cleanliness, and pressure applied to the joint, bonding in these joints covers 85% of the surface area consistently without significant cracking.⁵ POCO AXF-5Q graphite was selected for this joint because a stress analysis predicted that its combination of strength, elasticity, coefficient of thermal expansion, and fine grain structure best matched the process being used. The tubes on the face of the shield are designed for heat fluxes averaging 175 W/cm^2 with peak fluxes of 275 W/cm^2 for both antennas.

The front edges of the Faraday shield structure are protected from the toroidal energy flow of the plasma by an array of bumper limiters. A sectioned view of the bumpers is shown in Fig. 4. The limiters consist of POCO AXF-5Q graphite tiles attached to molybdenum or stainless steel bases. Because of the relatively short pulses on TFTR, the graphite is allowed to heat and cool inertially. A mechanical attachment of 1-cm-thick graphite to stainless steel bases bolted to the support frame is sufficient for removal of heat between pulses.

The long pulses of Tore Supra require active cooling of the graphite bumpers. Individual bumpers consist of 3-mm-thick graphite tiles brazed onto machined TZM (titanium, zirconium, molybdenum) alloy components with Ticusil braze alloy. An array of bumpers is then gang-brazed onto copper cooling tubes with Incusil braze alloy. The bumper assembly is then bolted to the Faraday shield structure. A nonlinear stress analysis, of several material combinations was used to select POCO AXF-5Q graphite, TZM alloy, and oxygen-free - high-conductivity (OFHC) copper for the bumper assemblies. Peak stresses in the graphite tiles are predicted to be 41-MPa (6000 psi). Peak strains in the copper cooling tubes are expected to be 0.05-mm at temperatures of 220°C . Successful tests of bumper subassemblies have been performed using neutral beams to simulate plasma heat fluxes. Elevated-temperature fatigue tests of OFHC copper tubing have also been successfully performed.

Peak heat fluxes for the bumpers are expected to be 2 kW/cm² for TFTR and 1 kW/cm² for the Tore Supra. A radial decay of energy deposition on the bumper of 0.75-2.5 cm is expected. Decay over a wider range than 2.5 cm for the Tore Supra antenna may require the addition of active cooling for the side walls of the Faraday shield structure. Initial operations of the antenna are expected to provide the data needed to make this determination.

The TFTR Faraday shield is cooled by a 1.4-MPa (200 psi), 25°C demineralized cooling water system. The Tore Supra Faraday shield is cooled by a 3.5-MPa (525 psi), 150°C demineralized cooling water system.

VI. CONCLUSIONS

The antennas built for TFTR and Tore Supra are similar in configuration and operation. However, each antenna presents unique engineering problems. In some respects, the antenna for Tore Supra is simpler than the antenna for TFTR because there are fewer moving parts and because commercial capacitors are included in the design. Extended rf pulse length and high ambient temperatures in Tore Supra greatly increase the difficulty in design and fabrication of the Tore Supra antenna. The areas that were most difficult to work on because of thermal stresses were the current straps and the bumper assemblies.

VII. REFERENCES

1. D. J. Hoffman et al., "Experimental Measurements of the Ion Cyclotron Antennas' Coupling and RF Characteristics", Fusion Technology, 8, #1, 2A, 1985
2. D. J. Hoffman et al., "The Design of High-Power ICRF Antennas for TFTR and Tore Supra", Applications of Radio-Frequency Power to Plasmas (Proc. of the 7th Topical Conference, Kissimmee, FL) 129, 1987.
3. F. W. Baity et al., "ICRF Antenna and Feedthrough Development at ORNL", Proc. of the 11th Symp. on Fusion Engineering, Austin, TX, November 18-22, 1985, IEEE Cat. No. CH 2251-7.
4. W. H. Power et al., "Capacitor Analysis for RF Antennas", Proc. of the 12th Symp. on Fusion Engineering, Monterey, CA, October 12-16, 1987, IEEE Cat. No. 87CH2507-2.
5. J. F. King et al., "Material Tests and Analyses of Faraday Shield Tubes for ICRF Antennas", these proceedings.

TABLE I
Antenna Design Parameters

	TFTR	Tore Supra
Power into the port (MW)	4	4
Power per current strap (MW)	2	2
Port dimension (cm x cm)	60 x 90	60 x 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)	100	100
Antenna power density (W/cm ²)	1160	1520
Antenna motion range (cm)	11	30

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FIGURE CAPTIONS

- Fig. 1. The Electrical Circuit of the Antennas.
- Fig. 2. The Antenna for Tore Supra.
- Fig. 3. Sectioned view of the Tore Supra Antenna showing primary components.
- Fig. 4. The Toroidal Bumper Limiter for the Tore Supra Antenna.

FIGURE 1

Circuit Model

ORNL-DWG 87-2315R FED

FIGURE 2
(TENTATIVE)

FIGURE 3

ORNL LONG PULSE ICRF ANTENNA FOR TORE SUPRA

ORNL-DWG 88-3186 FED

FIGURE 4