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ICRF ANTENNA AND FEEDTHROUGH DEVELOPMENT AT ORNL*

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Abstract: The RF technology program at Oak Ridge National Laboratory is highlighted. Simply stated, the objective of the program is to develop the technology for ion cyclotron range of frequencies heating of the fusion machines leading up to a reactor. Results from an investigation of the importance of current strap shaping in compact antenna design are presented. Designs of the Doublet III-D and Advanced Toroidal Facility compact loop launchers are described, as are the vacuum feedthroughs for the West German tokamak TEXTOR and the Tandem Mirror Experiment Upgrade (TMX-U).

Introduction

The goal of the RF technology development program at Oak Ridge National Laboratory (ORNL) is to provide the technology required for heating fusion plasmas to breakeven with RF waves in the ion cyclotron range of frequencies (ICRF). This goal involves the investigation (theoretically and experimentally) of new concepts for various components and the fabrication of hardware for present-day fusion experiments throughout the U.S. and EURATOM programs. Compact loop launchers are being designed for Doublet III-D (DIII-D), Tore Supra, and the Advanced Toroidal Facility (ATF).[1-4] Fifty-ohm vacuum feedthroughs of ORNL design have been installed on TEXTOR, TMX-U, and Alcator-C.[3] Faraday shield designs that are easily cooled and highly transparent to RF have been developed.[5] Tests of materials for use in contact with the plasma have been conducted.[6]

Launcher Development

Desirable features of ICRF launchers for present and future large machines include easy insertion and removal, high-power handling, the capability to match over a wide range of plasma loads, and high electrical efficiency. Compact loop designs such as the cavity antenna and the resonant double loop (RDL)[1,3] are promising in these respects. These compact loop antennas greatly reduce (or even eliminate) the requirements for external matching equipment. The circuit analysis of the RDL is presented in Ref. [2].

Current Strap Shaping

All compact loop antennas consist of a recessed current strap surrounded by conducting walls with a Faraday shield covering the plasma side. To maximize the RF magnetic field at the plasma (and, thus, the coupling efficiency of the antenna), proper shaping and placement of the current strap are essential. These have been investigated experimentally in the laboratory, using a setup shown schematically in Fig. 1. Four different cross sections were used for the current strap (as shown in the figure); the distance x from the front of the current strap to the absorber (simulating the plasma) was variable, as was the position a of the back plane relative to the Faraday shield. The distance d from the front of the Faraday shield to the absorber and the width b of the cavity were held constant for all measurements.

The position of the back wall has minimal effect unless it is closer to the current strap than the distance from the current strap to the Faraday shield, in which case both the antenna inductance and the loading resistance are reduced. The distance of the current strap from the Faraday shield, or the depth of the current strap, has a dominant effect on the RF magnetic field measured at the plasma surface but little effect on antenna inductance; that is, the RF voltage required to produce a given power flux at the plasma increases rapidly with increasing current strap depth. The implication of this result is that to maximize the power transferred to waves in the plasma, it is necessary to place the current strap as close to the Faraday shield as is possible without causing breakdown. The width of the current strap also is an important parameter for optimizing performance. Increasing the strap's width has a two-fold effect: it decreases the coupling to the load and decreases the inductance. This results in an increased current requirement and a decreased voltage requirement for a fixed input power [$P = (V/\omega L)^2 R$, $P = I^2 R$]. Table I summarizes these results for an assumed 40-cm strap length, 55-MHz operating frequency, and power of 1 MW. The equivalent plasma resistance is assumed to be five times the resistivity of the magnetic loading material used in the experiment.

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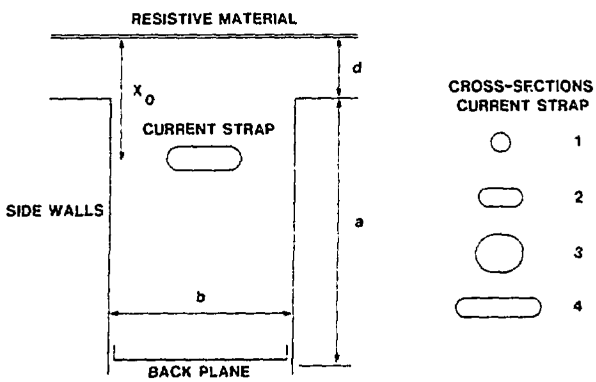

Fig. 1. Current strap shape and placement.

Table 1. Effects of increasing strap width

Current strap shape	R (mΩ/cm)	L (nH/cm)	V_{max} (kV peak)	I_{max} [A (rms)]
1	11.41	5.55	72	659
2	9.23	3.70	56	739
3	6.64	3.23	54	875
4	3.91	2.09	47	1140

Some tradeoff of voltage for current can be made by adjusting the current strap width, insofar as both inductance and loading decrease as the width is increased. This latter conclusion is strictly valid only for the case in which the objective is to deposit the maximum wave energy into the absorber; no account has been taken of the $k_{\parallel}$ spectrum required for optimum ion heating.

Low-Power Cavity Antenna for Doublet III-D

For the first year of DIII-D operation, a low-power cavity antenna has been designed to measure plasma loading under a wide range of operating conditions. A vacuum variable capacitor is incorporated into the design to cover a wide range of frequency, covering the fundamental ICRF and several harmonics for hydrogen and deuterium plasmas. The antenna is inserted through one of the large

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outside midplane ports and is movable radially. The antenna is shown schematically in Fig. 2.

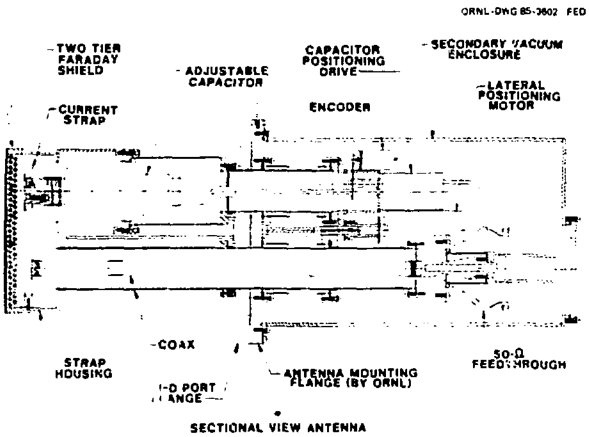

Fig. 2. Doublet III-D antenna.

The antenna has to meet the material, mechanical, and thermal requirements of DIII-D. All parts of the antenna seen by the plasma are covered by graphite. The outer housing of the antenna is made of Inconel. The inside of the housing and the current strap are plated with 100 μm of copper to reduce ohmic losses. The entire structure is supported from the cover flange for the port and is capable of withstanding disruption loads of 3 atm. All parts of the antenna structure within the primary vacuum of DIII-D can be baked to 200°C. Under the anticipated operating conditions for the first year of DIII-D operation, radiative and conduction cooling have been determined to be sufficient to keep all components of the antenna within acceptable temperature limits; therefore, the antenna is not actively cooled.

The Faraday shield consists of two layers of staggered 1-cm-diam Inconel tubes. This configuration is nearly opaque optically but has been shown to be highly transparent to RF fields. The tubes are copper plated and have a 3-mm graphite coating on the plasma side. The Faraday shield is shown in Fig. 3. An actively cooled Faraday shield of similar design was experimentally shown to be capable of withstanding steady-state heat fluxes of 4 kW/cm^2 on a test stand.[6]

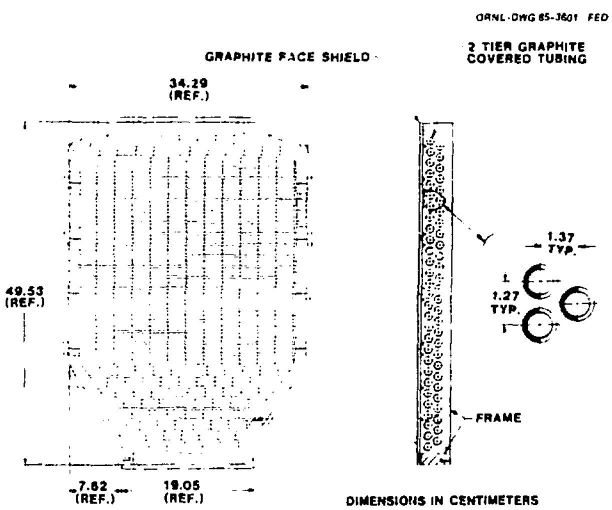

Fig. 3. Faraday shield.

This low-power cavity antenna will be replaced after the first phase of DIII-D operation with a high-power, long-pulse compact loop antenna that is actively cooled.

Prototype ATF Antenna

A resonant double loop was selected for the prototype ICRF heating antenna for the ATF stellarator. The antenna mounts on one of the large outside midplane ports. Available are 400 kW of steady-state power in the 5–30 MHz range for fast-wave heating in pure hydrogen and at the ion-ion hybrid resonance. The shape of the ATF vacuum vessel precludes placement of the antenna under the helical field coils, as in most stellarator experiments. The antenna current strap is aligned nearly perpendicular to the helical magnetic field in the vicinity of the antenna. An artist's conception of the antenna mounted in ATF is shown in Fig. 4. The Faraday shield and the current strap are matched to the curvature of the plasma surface, and the entire antenna structure is designed to be movable to vary the separation between the plasma and the Faraday shield. Electron orbit calculations indicate that limiters will be required on either side of the antenna to intercept the particle flux emanating from the plasma.

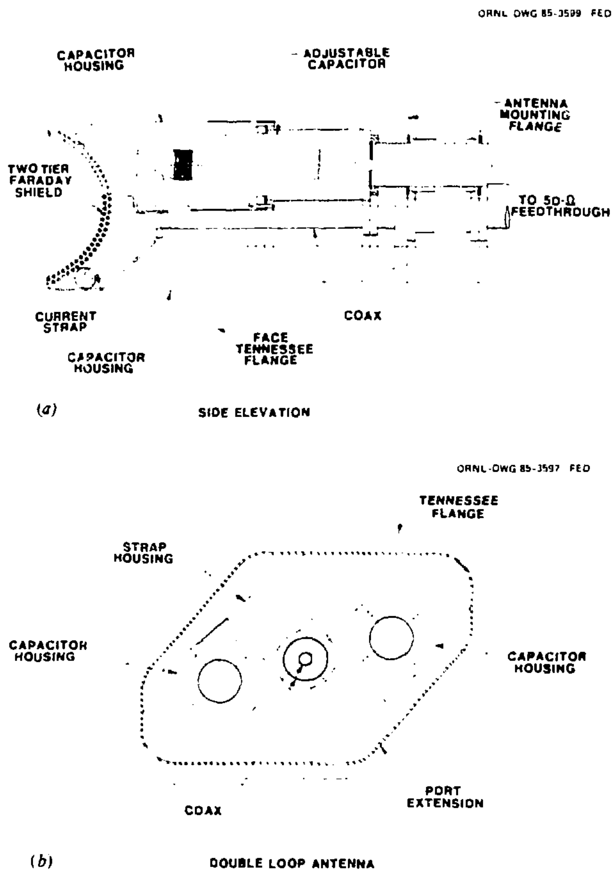

Fig. 4. Prototype ATF antenna: (a) side view, (b) end view.

Subsequent ICRF heating launchers will be actively cooled to provide steady-state or long-pulse heating power for later phases of ATF operation.

Vacuum Feedthrough Development

One of the critical components in most ICRF heating systems today is the RF vacuum feedthrough. Voltage breakdown at the feedthrough often determines the maximum power that can be delivered to the plasma. In addition, feedthroughs for future machines will need to operate for long pulses or steady state and will probably need to be actively cooled. Depending on the type of ICRF heating employed, the RF frequency for future machines may be several times higher than present experiments, in which case multipactor effects become significant. At ORNL the feedthrough development activities address these issues.

A feedthrough having a characteristic impedance of 50 Ω and employi .g a cylindrical ceramic has been developed. Versions of this design are now in use on TEXTOR, TMX-U, and Alcator-C. A schematic of this feedthrough is shown in Fig. 5. One of the key features of the feedthrough is evident from the potential contours shown; that is, the potential gradient along the surface of the ceramic is small. Also, the minimum gap between inner and outer conductors occurs on the vacuum side where the dielectric strength is high. The conductors are shaped such that an impedance of 50 Ω is maintained. Measured VSWR of the feedthrough was less than 1.02:1 for frequencies below 100 MHz.

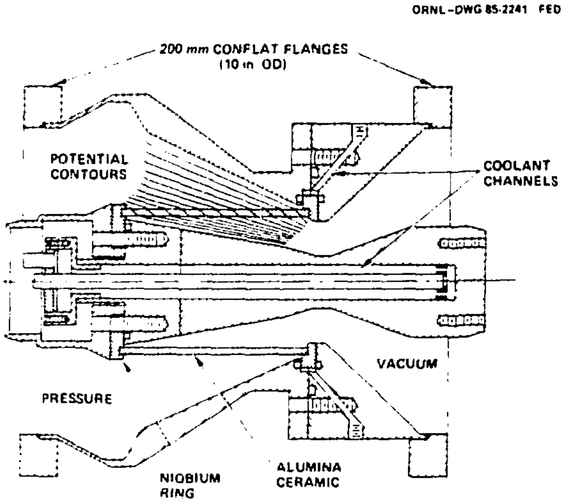

Fig. 5. 50-Ω RF vacuum feedthrough.

The ceramic is brazed to metal flanges at each end, and the feedthrough is sealed using either elastomers or Helicoflex seals. This feature allows the ceramic to be replaced easily in the event of a vacuum failure. Early versions of this ceramic assembly were made with a butt braze to niobium flanges. Later versions use a direct ceramic-to-copper tapered braze joint. Ticusil, which is compatible with the requirements of most fusion experiments, is used as the braze alloy. The copper braze joint allows some flexibility in the inner conductor of the feedthrough.

The voltage limits of the 50-Ω feedthrough have been measured on a test stand at 20 MHz. For short pulses (≤100 ms) with 2 atm of SF_6 on the pressure side, the voltage limit was >150 kV. The feedthrough has been operated continuous wave (CW) at a voltage of 55 kV with nitrogen on the pressure side. With cooling on the ends of the ceramic, this design is capable of operation for several seconds at a power level of 1 MW. For higher CW power levels, a second concentric ceramic can be added to cool the surface of the ceramic by flowing water in the space between the two ceramic cylinders.

A 25-Ω feedthrough is under development with potential application on machines with low-impedance transmission lines, such as the West German tokamak ASDEX and the Joint European Torus (JET). A schematic of this design is shown in Fig. 6. The

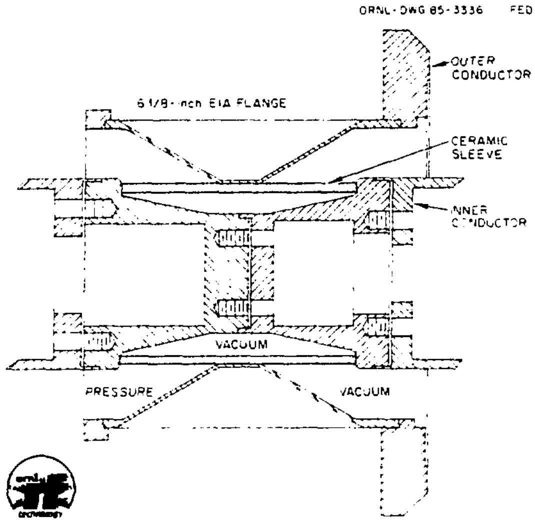

Fig. 6. 25-Ω RF vacuum feedthrough.

feedthrough incorporates a buffer vacuum region between the pressure side and the machine vacuum. This configuration is preferable to the use of two separate feedthroughs to provide a buffer vacuum because it avoids the expense of the second feedthrough and reduces the possibility of multipactor breakdown by eliminating the vacuum transmission line between the two feedthroughs.

Summary

All aspects of the technology of ICRF heating of breakeven plasmas are under development at ORNL. ICRF launcher concepts, Faraday shield design and materials, and vacuum feedthroughs are active topics under investigation. ORNL feedthroughs are already in operation on several fusion experiments. Compact loops are planned for DIII-D and ATF and are being considered for Tore Supra.

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