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ICRF HEATING TECHNOLOGY DEVELOPMENT ACTIVITIES AT OAK RIDGE NATIONAL LABORATORY*

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I. INTRODUCTION. The rf technology program at the Oak Ridge National Laboratory (ORNL) is developing the components needed for heating in the ion cyclotron range of frequencies (ICRF) on future fusion machines, such as the Compact Ignition Tokamak. Components produced in this program are already in use on experiments throughout the world, including Doublet III-D (DIII-D), TMX-U, Alcator-C, and TEXTOR. Designs have been developed for implementation on Tore Supra and ASDEX. Recent developments in vacuum feedthroughs, compact loop antennas, high-current capacitors, and folded waveguides are discussed in this paper.

II. VACUUM FEEDTHROUGHS. The first product of the ORNL rf technology program was the 50-Ω vacuum feedthrough with a cylindrical ceramic. This feedthrough has now received field testing under a variety of operating conditions as a result of its immediate application at several laboratories. Attractive features of this basic design include high voltage and current capability, a demountable ceramic assembly, cooling passages for steady-state operation, low insertion voltage standing-wave ratio, and wide frequency bandwidth.

Figure 1 is a schematic drawing of the feedthrough built for TEXTOR. This design, equipped with 200-mm conflat flanges at both ends, is used at two locations in the coaxial

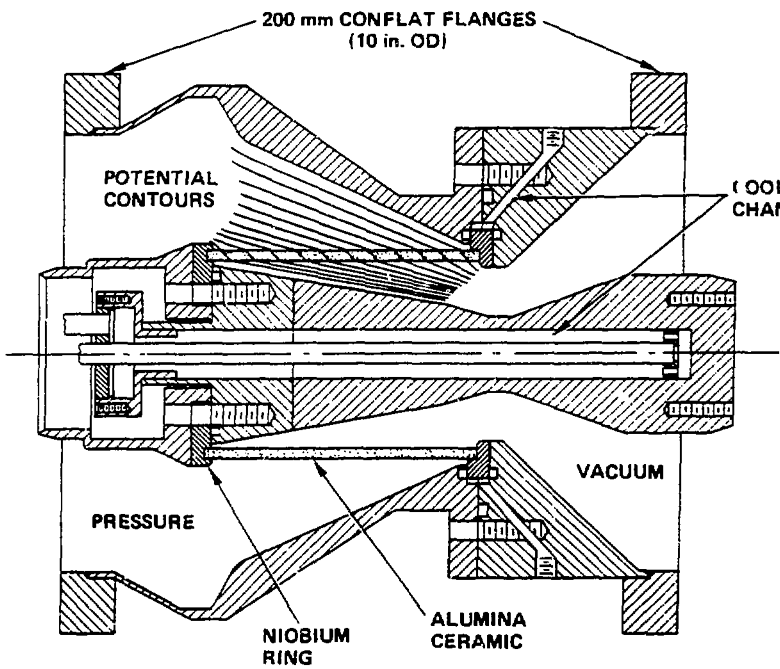

Fig. 1. 50-Ω long-pulse rf feedthrough designed to TEXTOR specifications.

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transmission line: near the antenna, with vacuum on both sides of the feedthrough, and at a second position farther from the antenna, operated with nitrogen pressurization on one side. Two versions of this feedthrough were constructed: one with niobium end caps for the ceramic and one with copper end caps. Figure 1 shows the ceramic with the niobium end caps. The niobium proved to be superior in voltage rating, reaching peak voltages greater than 150 kV for 100-ms pulses, but the braze joint could not be made reliably and was somewhat fragile. For subsequent versions of this feedthrough, a tapered copper-to-ceramic braze was used. In both cases, the braze alloy used was Ticusil, and no metalizing of the 96% alumina ceramic was done. For this design, the ultimate voltage rating depends on the pressurization since breakdown always occurs on the pressurized side. For the case of the copper end caps, nickel and gold platings were applied and tested for effects on voltage breakdown, with some improvement. Table 1 summarizes the voltage breakdown limits for the various cases.

Table 1. Feedthrough Voltage Standoff in Kilovolts
(All tests at 25 MHz, 5 s; peak voltage)

Pressure, gauge (atm)	Material brazed to ceramic		
	Niobium	Copper	Nickel
0 (N_2)	80	34	42
1 (N_2)	92	40	57
2 (N_2)		48	75
0 (SF_6)		60	75
1 (SF_6)		80	>88

A prototype 25-Ω feedthrough has been fabricated for ASDEX. This feedthrough incorporates a buffer vacuum between the machine vacuum and the pressurized transmission line. The structure maintains the external dimensions of existing ASDEX feedthroughs. A schematic diagram is shown in Fig. 2. The ceramic is brazed to the hourglass outer conductor. The inner conductor is sealed to the ends of the ceramic cylinder by means of Helicoflex seals. This design should possess greater mechanical strength than the 50-Ω design. A potential disadvantage is that the ceramic cannot be as easily replaced as in the 50-Ω feedthrough in case of a failure in the braze joint.

III. COMPACT LOOP ANTENNAS. A low-power prototype cavity antenna has been installed on DIII-D.[1] The primary purpose of this antenna is to measure plasma loading for a wide range of plasma conditions and frequencies and to compare the results with calculations by GA Technologies and ORNL. The antenna can be moved radially over a small range. The antenna has a Faraday shield consisting of two layers of copper-plated Inconel rods with 1.5-mm-thick graphite plates brazed to the rods on the plasma side. Extensive thermal and stress analysis calculations were performed for this antenna to verify the survivability of the design under the worst-case tokamak conditions, such as major disruptions. The results of this analysis are applicable to other large tokamaks, providing a useful base for other compact loop designs, including Tore Supra. Because the prototype antenna will only operate at low power

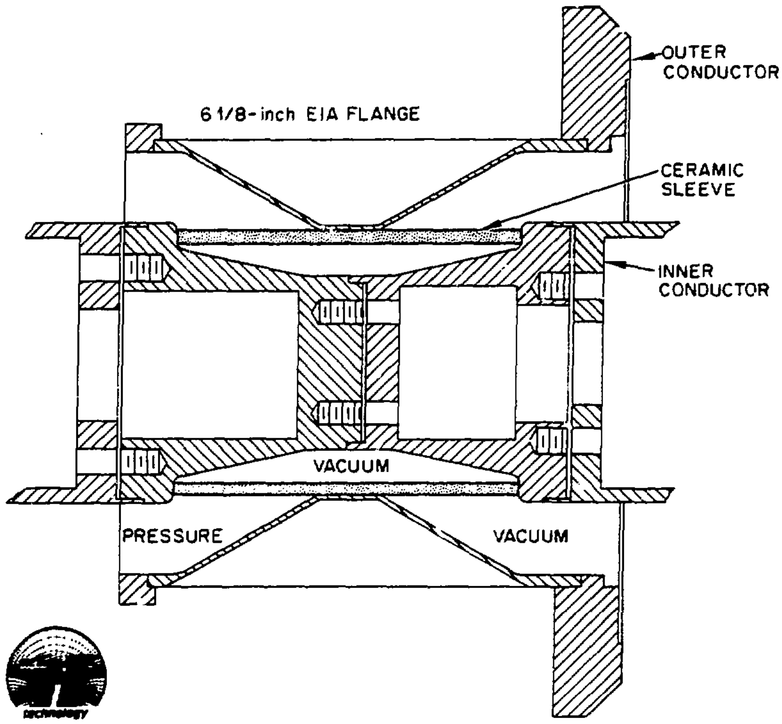

Fig. 2. 25-Ω rf feedthrough designed to ASDEX specifications.

during the first year of DIII-D experiments, inertial cooling was determined to be adequate, and active cooling will not be used.

A development version of a high-power DIII-D cavity antenna is under construction for use in the Radio-Frequency Test Facility at ORNL. It will be operated during the second half of 1986 when the 1.5-MW transmitter becomes operational. This antenna was designed for easy modification so that new antenna components can be easily tested at high power in a plasma environment.

A preliminary engineering design has been done for a resonant double loop (RDL) antenna[2,3] system for Tore Supra. This design consists of two RDL antennas side by side behind a common Faraday shield. The entire structure is mounted in a large port and can be moved radially to couple to plasmas with different minor radii. The antenna incorporates water cooling, allowing operation for 30-s and 210-s plasma pulse lengths With improved vacuum variable capacitor design, it appears possible to couple 2 MW per loop over the frequency range 35 to 80 MHz.

IV. HIGH-CURRENT CAPACITORS. A key to the success of compact loop antennas in coupling several megawatts of power to a fusion plasma is the development of a vacuum variable capacitor with higher current capacity (~1 kA) than commercially available units. In addition, the internal inductance of the capacitor must be minimized to allow operation at frequencies up to 80 MHz and possibly higher. An improved design was devised based on postmortem analysis of an existing design. The capacitor industry was approached with this new application, with the result that both Comet (Bern, Switzerland) and Jennings (San Jose, California, U.S.A.) have agreed to build prototype units which will be tested at full parameters on a test stand at ORNL during 1986.

V. FOLDED WAVEGUIDES. A new waveguide configuration, known as the folded waveguide,[4,5] is a promising candidate for ICRF heating on large, high-field machines where second harmonic heating occurs at frequencies on the order of 100 MHz. The folded waveguide can easily be configured to conform to existing port sizes, which are usually larger in the poloidal dimension than in the toroidal dimension for most tokamaks. An advantage of the folded waveguide over ridged waveguide designs is that the rf electric fields at the mouth of the guide are near a minimum.

The folded waveguide can be envisioned as a rectangular waveguide several times wider than its height which is folded accordion-style several times. The cutoff frequency can be made arbitrarily low for a given envelope by increasing the number of folds. The magnetic field at the mouth of the guide reverses at each fold, so the guide is fitted with an aperture plate to permit only the desired polarization to couple to the plasma.

Measurements on a low-power scale model have confirmed the basic operation of the folded waveguide. Three-dimensional code calculations are in progress.[6]

VI. SUMMARY. Compact loop antennas have been installed on DIII-D and designed for Tore Supra. Two keys to the successful high-power operation of compact loops, enhanced vacuum variable capacitors and low-impedance feedthroughs, are under development. For higher frequency applications ($f > 100$ MHz), the folded waveguide, which offers several advantages over ridged waveguides, is under investigation.

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