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RADIO FREQUENCY VACUUM FEEDTHROUGHS FOR HIGH-POWER ICRF HEATING APPLICATIONS[*]

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ABSTRACT

Frequently, high-power pulsed ion cyclotron range of frequency experiments are limited by breakdown at the vacuum feedthrough. This paper describes the development and testing of vacuum feedthroughs to increase both reliability and capability. The ultimate goal of the program is to develop a continuous-wave feedthrough for the next generation of fusion experiments. A feedthrough concept currently under investigation consists of a simple, cylindrical alumina ceramic brazed between tapered coaxial conductors. A prototype has been tested to voltage levels in excess of 100 kV for 100-ms pulses and 70 kV for 5-s pulses at 28 MHz. Insertion-voltage-standing-wave ratios are <1.15:1 for frequencies below 450 MHz. An upgraded water-cooled version being fabricated for use on TEXTOR will be described.

INTRODUCTION

Radio frequency (rf) heating of fusion plasmas in the ion cyclotron range of frequencies (ICRF) is now being widely applied to fusion experiments around the world.[1-3] It is currently envisioned that fusion reactors will use this method to supplement ohmic heating and neutral beam heating. Power levels are now in the multimegawatt range where state-of-the-art techniques must be used to handle high voltages and currents at radio frequencies. The barrier between the pressurized transmission line and the evacuated transmission line is a particularly crucial component because its failure affects not only the rf system but also the entire machine vacuum integrity in many circumstances. This component has also been the weak link in voltage handling for some contemporary pulsed experiments. The potential problems at the feedthrough are compounded by operation approaching steady-state, as will be encountered in the next generation of fusion experiments.

This paper describes the program at the Oak Ridge National Laboratory (ORNL) to develop and test feedthroughs for present-day and future fusion applications. A feedthrough development program has been under way at the Princeton Plasma Physics Laboratory for a number of years.[4] Their efforts have led to the successful development of a high-power feedthrough used in the ICRF heating experiments on the Princeton Large Torus (PLT). The PLT feedthrough uses a conical ceramic barrier between inner and outer coaxial conductors. The conductors are shaped primarily to reduce the component of the electric field along the surface of the ceramic. The present paper describes an alternative concept that uses a cylindrical ceramic barrier brazed between tapered inner and outer coaxial conductors. In this configuration, the electric field along the ceramic surface can also be made quite small. In addition, care has been taken to maintain a constant characteristic impedance along the length of the feedthrough by proper adjustment of the tapered angles of the conductors. This feature minimizes the insertion-voltage-standing-wave ratio (IVSWR) and eliminates internal reflections. The design affords the use of relatively simple fabrication techniques, and it can be easily adapted to long-pulse or continuous wave (cw) use.

FEEDTHROUGH CONCEPT

A simplified schematic of the feedthrough concept is shown in Fig. 1. Contours of constant potential have been superimposed on the figure.[5] In this case, the ceramic barrier is much longer than its diameter. This permits the construction of very gradual tapers on the inner and outer conductors, which in turn produces potential contours that are nearly parallel to the surface of the ceramic. The electric field ($\nabla\phi$) is consequently nearly perpendicular to the surface of the ceramic. The possibility of surface breakdown can thereby be substantially reduced or eliminated altogether.

A constant characteristic impedance results from the use of the straight tapers on inner and outer conductors. The value of the characteristic impedance for tapered lines is found approximately from

$$Z_f = \sqrt{\frac{L_\ell}{C_\ell}} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\,\ln\left[\frac{\tan\left(\frac{\theta_2}{2}\right)}{\tan\left(\frac{\theta_1}{2}\right)}\right] \qquad (1)$$

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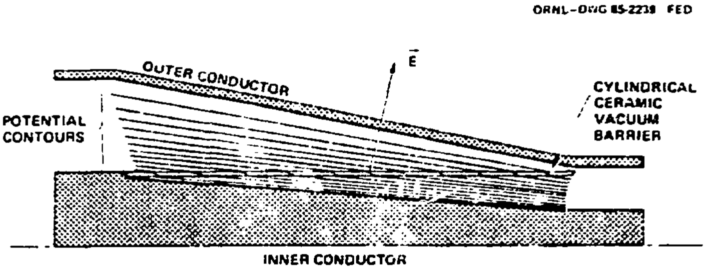

FIG. 1. ORNL feedthrough concept.

where L_ℓ is the inductance per unit length, C_ℓ is the capacitance per unit length, and θ_2 and θ_1 are the angles made by the outer and inner conductors, respectively, relative to the axis of the feedthrough. This feature is particularly important for antennas that place the impedance-matching components inside the vacuum system in an integrated fashion with the antenna radiating element. Examples of such antennas include the resonant double loop,[6] now being developed at ORNL, and the U-slot antenna,[7] proposed by the McDonnell Douglas Astronautics Company. In these cases, the vacuum feedthrough is placed at the impedance-matched input (usually 50 ohms) to the antenna system where reflected power has been minimized. In this position it is important that the characteristic impedance of the feedthrough closely match the characteristic impedance of the transmission line to which it is connected, in order to minimize the IVSWR. The IVSWR of a feedthrough that is short compared to a wavelength is given approximately by

$$S_f \simeq \frac{a+b}{a-b} \; . \tag{2}$$

where

$$a = \left\{4 + \left[\beta\ell\left(\frac{Z_1}{Z_0} + \frac{Z_0}{Z_1}\right)\right]^2\right\}^{1/2}$$

$$b = \left[\beta\ell\left(\frac{Z_1}{Z_0} - \frac{Z_0}{Z_1}\right)\right] \; .$$

with $\beta = 2\pi/\lambda$, ℓ the feedthrough electrical length, Z the feedthrough's characteristic impedance, and Z_0 the characteristic impedance of the transmission line. As an example, for a feedthrough that has a characteristic impedance of 100 ohm, has a line length of $\lambda/4\pi$, and is connected to 50-ohm transmission line terminating in 50 ohms, the IVSWR is approximately 1.9. Peak power handling for the transmission system would be reduced by a factor of 1.9 unless additional matching equipment were used to compensate for the feedthrough mismatch. A 50-ohm feedthrough, on the other hand, would not degrade transmission performance in this situation.

Under normal operating conditions voltage and current at the impedance-matched point are modest even for power levels on the order of a megawatt (V ≈ 10 kV, I ≈ 200 A at 1 MW). Feedthroughs placed at this point, however, will still need to be designed for much higher voltages and currents in order to handle occasional accidents or fault conditions that could result in large mismatches.

PRELIMINARY TESTING

A test of the general concept was performed using the feedthrough diagrammed in Fig. 2. For this test version of the feedthrough, input and output connections are 3⅛ in. The large diameter portion of the feedthrough has a 9-in. inside diameter. The water jacket shown in Fig. 2 was not used in the tests described here. Analysis of potential contours indicates that the wave fields are directed at approximately a 45° angle to the surface of the ceramic. The impedance of the feedthrough has been designed to be close to 50 ohms. Constancy of impedance has not been optimized for this test. The measured IVSWR is less than 1.15:1 for frequencies below about 400 MHz.

High-voltage rf testing was accomplished using the experimental apparatus shown schematically in Fig. 3. Basically, the feedthrough is placed at the end of a section of coaxial transmission line that is somewhat greater than $\lambda/4$. The feedthrough is left open circuited at the end of this line section so that the input impedance is inductive. A capacitive tuning circuit impedance matches this inductance and the small equivalent resistance of the transmission line to a 50-ohm coaxial transmission line. A transmitter capable of 100 kW of cw operation over the frequency range 3 to 30 MHz drives the circuitry. The capacitive tuner is capable of impedance matching over the frequency range 20 to 30 MHz. Because of the $\lambda/4$ transformer section, high voltages are produced at the feedthrough end, whereas low voltages are maintained at the capacitive tuner. Voltages expected at the feedthrough can be estimated from

$$V^2 \simeq \frac{4PZ_0^2}{R}\left[\ell - \frac{1}{2\beta}\sin(2\beta\ell)\right]^{-1} \; , \tag{3}$$

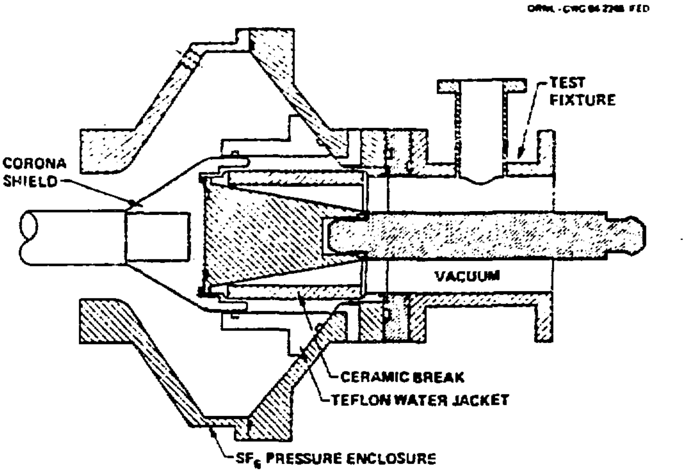

FIG. 2. Preliminary test version of the ORNL feedthrough.

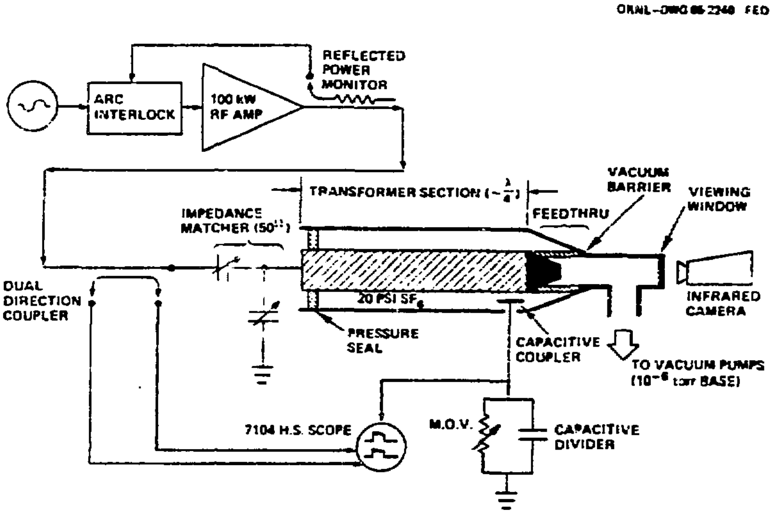

FIG. 3. High voltage rf test stand schematic.

where P is the forward power and R is the equivalent series resistance per unit length within the $\lambda/4$ transformer section. In practice, the $\lambda/4$ section is made of aluminum so that the equivalent series resistance R_ℓ at its input $(R \cdot \ell)$ is approximately equal to that of the parallel capacitor ($R_\ell \simeq$ 0.02 ohms) so that half of the power from the transmitter is dissipated in the capacitor and half in the transformer section. From Eq. (3), at a frequency of 25 MHz and for $\ell \simeq \lambda/4 = 300$ cm, $Z_0 = 50$ ohms, and $R \simeq 7.5 \times 10^{-5}$ Ω/cm, we find $V^2 \simeq 4.4 \times 10^5 P$. For example, to produce 100 kV at the feedthrough under these circumstances requires approximately 23 kW into the transformer section or 46 kW into the capacitive tuner. These estimates are within a few percent of what was measured experimentally.

In the tests, a calibrated capacitive voltage probe was used to monitor the voltage at the feedthrough, as indicated schematically in Fig. 3. Forward power into the tuning circuit was monitored using a directional coupler (also shown in Fig. 3). Drive power to the transmitter could be cut off in a few microseconds using an electronic attenuator in the drive circuitry. The attenuator was triggered on detection of excessive reflected power to protect components in the event of an arc.

The feedthrough was conditioned by repeatedly breaking down the feedthrough in vacuum using short, 1-ms pulses. After approximately 20 to 100 pulses, voltage standoff on the vacuum side increased by at least a factor of 2. Breakdown principally on the pressurized side of the feedthrough would occur after conditioning. With 20 psig of SF_6 on the pressurized side of the feedthrough, the following results were obtained:

Pulse length (s)	Breakdown limit (kV)
0.001	120
0.1	100
5.0	70

Subsequent to the preliminary tests described here, the feedthrough was adapted for use on the TEXTOR tokamak at the Institute for Plasma Physics, KFA, Jülich, Germany. The adaptation consisted principally of adding transition parts to mate with their connectors. To date, 130 kW has been applied to their antenna in vacuum using this non-optimized feedthrough. With plasma, 500 kW has been applied successfully with 1-s pulses.

TEXTOR FEEDTHROUGH UPGRADE

A larger, more carefully designed feedthrough using the concept just described is currently being fabricated for use on TEXTOR. A diagram of this feedthrough is shown in Fig. 4. In this case input and output connections have 8-in. outer conductors. Water cooling is provided along the full

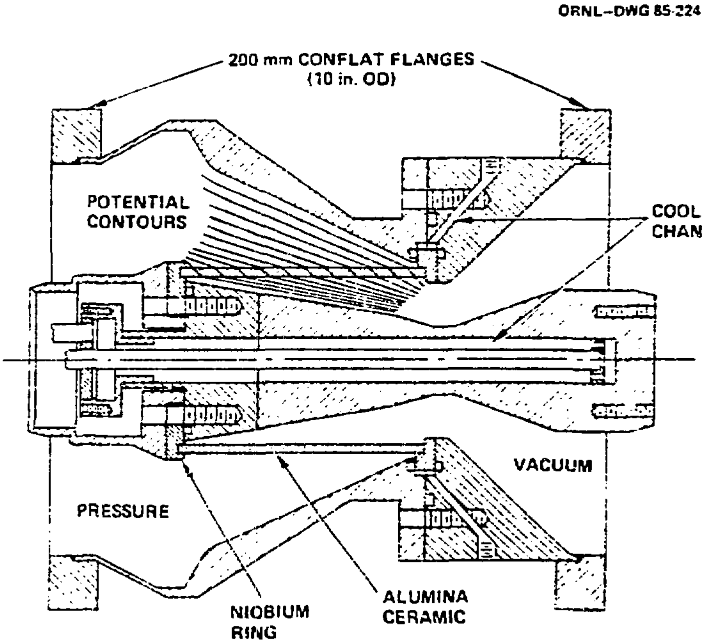

FIG. 4. Water-cooled feedthrough design for the TEXTOR tokamak.

length of the inner conductor, but only the narrow portion of the outer conductor is water cooled. Potential contours superimposed on Fig. 4 are evenly spaced at reasonable intervals with no electrical stress concentrations. Wave electric fields are more nearly perpendicular to the ceramic surfaces than was the case for the test feedthrough described in the last section. Much more care has been taken to maintain a constant characteristic impedance along the structure. Computer analysis indicates an IVSWR below 1.01:1 for frequencies below 200 MHz.

The ceramic in this case is a 94% pure Al_2O_3 brazed at each end to machined niobium rings. The rings are sandwiched between flanged parts on the inner and outer conductors. Metal O-ring vacuum seals are formed at the niobium rings. The whole structure can be easily disassembled for inspection or repair.

Testing similar to that described in the last section will be performed for this feedthrough except that pulse lengths will be extended. High-current testing will be performed in addition to high-voltage testing.

CW FEEDTHROUGHS

The ultimate goal of the ORNL feedthrough program is to develop a feedthrough capable of cw operation. An integral part of this program is the construction of a cw testing facility to qualify candidate feedthroughs. Preliminary work has been performed to design the cw feedthrough. Currently, the tapered conductor/cylindrical ceramic concept is being considered. For this application a standard 9-in. coax connection is used that tapers down to 3.9-in. coax at the narrow end of the taper. The basic problem in the design is devising an efficient cooling system for the conductors and the ceramic vacuum barrier. Finite-element, thermal stress analysis of the feedthrough will determine in detail the effectiveness of the cooling system.

Preliminary estimates of overall cooling requirements have been obtained analytically. Total power dissipated in the tapered metal surfaces is given approximately by

$$P_m = \left(\frac{1}{2} R_s I^2\right) \frac{\ell}{\pi(d_1 - d_0)} \ln\left(\frac{d_1}{d_0}\right) , \tag{4}$$

where R_s is the surface resistivity, d_1 and d_0 are the diameters of the large and small ends, respectively, and ℓ is the taper length. A reasonable design requirement for current in the feedthrough is $I = 2000$ A at 100 MHz. For copper surfaces, this translates into 2680 W absorbed by the outer conductor and 6190 W absorbed by the inner conductor. To carry away the heat, only 1–2 gal/min are required. Surface power density never exceeds 12 W/cm^2, implying only modest thermal transfer rates are required over all portions of the conductors.

Power absorbed within the ceramic can be estimated from

$$P_c = \pi V f \epsilon_0 \epsilon_r \tan \delta E_0^2 , \tag{5}$$

where V is the ceramic volume, ϵ_r is the relative dielectric constant of the ceramic, and $\tan \delta$ is the loss tangent. The field within the ceramic, E_0, can be estimated from

$$E_0 \simeq \frac{V}{t_1 + \epsilon_r t_2} . \tag{6}$$

where V is the voltage across the conductors and t_1 and t_2 represent the thickness of the ceramic and the vacuum gap, respectively. A reasonable design requirement for the feedthrough voltage capability is $V \simeq 100$ kV. This translates into $E_0 = 4770$ V/cm for a ceramic 0.5 cm thick and a vacuum gap of 2.3 cm. For a ceramic 15 cm long, the total power absorbed will then be approximately 567 W.

If no active cooling is provided for the ceramic, an upper bound on its ultimate temperature can be estimated by assuming the temperature is dictated only by attainment of radiative equilibrium with the outer conductor. An approximate expression for the temperature reached in this situation is given by

$$T_1^4 = \frac{q}{\sigma A_1}\left[\frac{1}{e_1} + \frac{A_1}{A_2}\left(\frac{1}{e_2} - 1\right)\right] + T_2^4 , \tag{7}$$

where q is the power absorbed in the ceramic from the incident rf power; σ is a constant equal to 2.4×10^{-10} W/cm^2/(K)^4; e_1 and e_2 are the emittances of the ceramic and copper outer conductor, respectively; A_1 and A_2 are the areas of the ceramic and outer conductor, respectively; and T_2 is the temperature of the outer conductor. For our exemplary cw feedthrough we find that the equilibrium temperature reached by the ceramic is on the order of 200°C if the outer conductor temperature can be maintained near room temperature.

Only a small amount of active cooling is required to bring the temperature of the ceramic down considerably. If one surface of the ceramic were cooled and if we assume, as a worst case, that all of the power in the ceramic is absorbed on the opposite surface, the temperature drop across the thickness of the ceramic would be given by

$$\Delta T = \frac{q t_1}{k A_1} , \tag{8}$$

where k is the thermal conductivity. For an alumina ceramic with $k = 0.18$ W/cm/K, we find $\Delta T = 3.5$°C. For a water flow over the ceramic surface of only 0.2 gal/min, the ceramic temperature will remain below ~14°C.

It is anticipated at the present time that water cooling of the ceramic will eventually be used. This will be done not just to carry away heat from power absorption at ion cyclotron frequencies but also to prevent heating of the ceramic by higher frequency microwaves coupled from other wave heating systems used on the fusion device. For example, cw, multimegawatt lower hybrid current drive/heating and electron cyclotron heating may be used in fusion devices. These schemes occur at multiple gigahertz frequencies. At these frequencies, strong absorption can occur in ceramics. Water, being a strong absorber of microwaves, can be used not only to cool the ceramic but also to prevent the formation of microwave standing waves within the ceramic. Water cooling can be easily introduced by using concentric ceramic cylinders with a small coolant passage between the cylinders. Use of high-purity aluminas can also help to reduce the microwave power absorption within the ceramic.

REFERENCES

1. J. HOSEA and PLT GROUP, "PLT Cyclotron Range of Frequencies Heating Program," in *Heating in Toroidal Plasmas* (Proc. 4th Int. Symp., Rome, March, 1984), vol. 1, p. 261.
2. K. ODAJIMA et al., "Second Harmonic Heating Experiment in the HFT-2M Tokamak," in *Heating in Toroidal Plasmas* (Proc. 4th Int. Symp., Rome, March, 1984), vol. 1, p. 243.
3. TFR GROUP, "ICRF Results on TFR at Megawatt Power Levels," *Plasma Physics*, **24**, 61 (1982).
4. N. GREENOUGH and G. GROTZ, "High Voltage RF Coaxial Vacuum Bushing Design Considerations," in *Engineering Problems of Fusion Research* (Proc. 9th Symp., Palmer House, Chicago, 1981), p. 844.
5. J. H. WHEALTON, R. J. RARIDON, D. J. HOFFMAN, T. L. OWENS, M. A. BELL, A. M. GOSWITZ, F. W. BAITY, and W. R. BECRAFT, "Theory of Feedthroughs: Waveguide Transmission and Voltage Characteristics of High Power Current Feeds for ICRH" (proceedings of this meeting).
6. T. L. OWENS, D. J. HOFFMAN, F. W. BAITY, "Inductive Array Couplers For High Power ICRH," *Bull. Am. Phys. Soc.*, **29** (8), paper 2U20 (1984).
7. J. H. MULLEN, "High Power ICRH Launcher Design," *Bull. Am. Phys. Soc.*, **28** (8), paper 1T14 (1983).