

# A Review on Design, Development and Performance analysis of the Vacuum Feedthrough for ADITYA Tokamak

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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 this review paper is to develop a continuous-wave feedthrough for the next generation of fusion experiments. The feedthrough in the interface, which isolates the ADITYA Tokamak vacuum from that of the interface, becomes most critical and vulnerable to RF voltage breakdown and arcing. The use of dielectric material between inner and outer conductor introduces threat of surface discharge in vacuum condition. The feed through are very crucial, as its failure not only affects RF system but also the tokamak vacuum gets affected.

**Index Terms**—ICRF Heating, ORNL & TEXTOR vacuum feedthrough, RF Design criteria, RF Vacuum Window.

## I. 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. Power levels are now in the multi mega/Kilo watt 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. Here we developed and test feedthrough for present-day and future fusion applications.

Introduction to high power RF is essential part for future fusion reactor. The ion cyclotron resonance heating (ICRH) system[2] on ADITYA is employed as one of the auxiliary heating system to rise the plasma temperature. It uses second harmonic heating at 20-40 MHz frequencies with maximum 200kW power. The system comprises of RF generator, a set of SPDT switches toggling between 500ohm dummy load and ADITYA, a long 50-Ohm coaxial copper transmission line from RF generator to ADITYA hall, a matching network comprising of shunted short-stub tuner and a phase shifter, a vacuum interface section including a vacuum feed through and a shorted strip line fast wave antenna. The matching network matches the antenna impedance, which is of the order of a few ohms to the generator impedance of 50 ohm.

## II. OBJECTIVES

Vacuum Feedthrough is the part of Vacuum interface in Ion Cyclotron Resonance Heating (ICRH) system. Is basically developed for Separation of both the media a machine Vacuum and A Pressurize Transmission line developed from RF generator and ADITYA. There are many types of feedthrough which proposed by the different agencies like ORNL, TEXTOR, etc.

ADITYA is the first indigenously designed and built tokamak of the country. ADITYA, a medium size Tokamak, is being operated for over a decade. It has a major radius of 0.75m and minor radius of the plasma is 0.25 m. A maximum of 1.2 T toroidal magnetic fields is generated with the help of 20 toroidal field coils spaced symmetrically in the toroidal direction.

## III. LITERATURE REVIEWS

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. 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 multi megawatt 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. The Oak Ridge National Laboratory (ORNL) to develop and test feedthrough for present-day and future fusion applications.

#### A. ORNL Feedthrough concept

A simplified schematic of the feedthrough concept in ORNL as shown in fig 1. 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 is consequently nearly perpendicular to the surface of the ceramic[3]. The possibility of surface breakdown can thereby be substantially reduced or eliminated altogether.

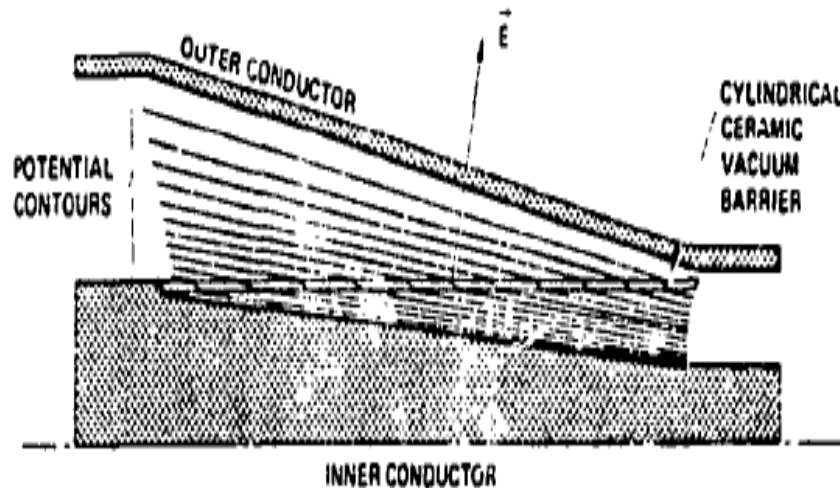


FIG 1. ORNL FEED THROUGH CONCEPT

A constant characteristic impedance results from the use of the straight tapers on inner and outer conductor.

#### B. TEXTOR Vacuum feedthroughs

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. Fig. 2 is a schematic drawing of the feedthrough built for TEXTOR. This design, equipped with 200 mm con flat flanges at both ends, is used at two locations in the coaxial.

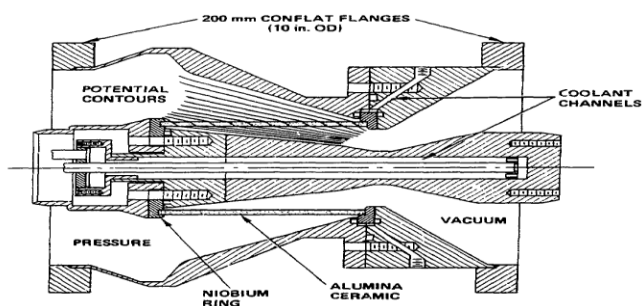


Fig 2. 50-ohm long-pulse RF feedthrough designed to TEXTOR specifications

In this case input and output connections have 8-in outer conductors. Water cooling is provided along the full length of the inner conductor, but only the narrow portion of the outer conductor is water cooled.

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 maybe several times higher than present experiments, in which case multifactor effects become significant.

## IV. VACUUM FEEDTHROUGH DEVELOPMENT

At ORNL the feedthrough development activities address these issues. A feedthrough having a characteristic impedance of 50ohm and employing a cylindrical ceramic has been developed. Versions of this design are now in use on TEXTOR, TMX-U, and Alcator-C[4]. Key features of the feedthrough is 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 50ohm is maintained.

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[5].

The voltage limits of the 50-ohm feedthrough have been measured on a test stand at 20 MHz for short pulses ( $\tau=100$  ms) with 2 atm of SFS 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.

The 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.

Here represented feed through concept by ORNL and TEXTOR are very difficult to design as highly complex design as well very difficult to fabricate. So we introduce feedthrough without any complexity and easy to fabricate we call it vacuum window as its similarity with the window used in Gyrotrons, klystron, and Magnetron. This design is much simpler than the design proposed by ORNL and TEXTOR

## V. INTRODUCTION TO COAXIAL VACUUM WINDOW

Introduction to high power RF is essential part for future fusion reactor. The interface section, which connects the matching network and antenna, suffers high VSWR. The feedthrough in the interface, which isolates the ADITYA vacuum from that of the interface, becomes most critical and vulnerable to RF voltage breakdown and arcing. The use of dielectric material between inner and outer conductor introduces threat of surface discharge in vacuum condition. The feedthrough is very crucial, as its failure not only affects RF system but also the tokamak vacuum gets affected.

A conventional and widely used feedthrough is achieved by tapered inner and outer conductor and brazing a long ceramic cylinder into it. A very successful design of feedthrough of ORNL utilizes the above method. Some different designs of feedthrough and their tests are described by Mutoh et. al. Nevertheless, the design concept is rather complicated and intricate care has to be taken while designing the tapered lines. The brazing of alumina cylinder to metal inner and outer conductor also makes the feedthrough mechanically and thermally weak. A little stress on the cylinder makes the braze point leak.

For ADITYA system one would require a feedthrough for rather low power of 200 kW and pulse for 100 msec for use in the interface. Here we present a simple coaxial vacuum feedthrough without any design complicity and simple to fabricate [6].

In this paper we describe the details of vacuum window.

## VI. RF DESIGN CRITERIA

In radio-frequency applications up to a few gigahertz, the wave propagates primarily in the transverse electric magnetic (TEM) mode, which means that the electric and magnetic fields are both perpendicular to the direction of propagation. The outer diameter is roughly inversely proportional to the cutoff frequency. The electric field is in the radial direction, varies as  $1/r$  and has no variation in  $\phi$  the direction. The magnetic field is in the  $\phi$  direction, and has the same variation with radius and given by,

$$E_r = \frac{V}{r \ln(b/a)}, \quad (1)$$

Where  $a \leq r \leq b$

$$H_\phi = \frac{I}{2\pi r} = \frac{V}{2\pi r Z_0} \quad (2)$$

Where, 'a' is the diameter of Outer conductor, 'b' is the diameter of outer conductor, 'r' is the distance between inner and outer conductor,  $Z_0$  is the characteristics impedance of coaxial, V is the applied voltage,  $E_r$  and  $H_\phi$  is the electric field component and magnetic field component in radial and circumferential direction respectively.

Ignoring thermal effects, the maximum power handling capacity of an air-filled transmission line is set by the dielectric breakdown voltage of air,  $E_d < 3 \times 10^6$  V/m. Heat dissipation due to attenuation losses can also be a limiting factor. For the coaxial geometry the electric field is maximum at  $r=a$ , and must not Exceed  $E_d$ . the maximum peak voltage  $V_p$  is given as,

$$V_p = aE_d \ln(b/a) \quad (3)$$

The maximum that can be transmitted is given by,

$$P_{\max} = \frac{V_p^2}{2Z_0} = \frac{\pi a^2 E_a^2}{\eta} \ln(b/a) = \frac{\pi a^2 E_a^2}{\eta} \frac{\ln(b/a)}{(b/a)^2} \quad (4)$$

Losses due to surface conductivity are given by the equation,

$$\alpha_s = \frac{1}{2} \frac{R_s}{\eta \ln(b/a)} \left( \frac{1}{a} + \frac{1}{b} \right) = \frac{R_s}{2\eta b} \left( \frac{b/a + 1}{\ln(b/a)} \right) \quad (5)$$

This for  $Z_0$  varies as  $1/b$ .

Recalling that skin depth varies as  $1/\sqrt{f}$  and  $\lambda_0 = c/f$ , we see that the attenuation of coaxial line increases with decreasing  $b$  and with increasing  $f$ . this would indicate that we would want the largest possible  $b$ , but we are again limited by  $f_c$  of higher order modes[8]. If we again include the effect of  $f_c$ , we can obtain the relationship,

$$\alpha = 0.67 \frac{\delta_s}{\lambda_0} f_c = \frac{0.044 f_c}{c} \sqrt{f},$$

$$\text{Since } \delta_s = \frac{0.066}{\sqrt{f}} \text{ for copper.} \quad (6)$$

In case of coaxial window, the mechanical design and fabrication can be difficult. Two vacuum seals are required (inner conductor to ceramic and outer conductor to ceramic). Also at high frequencies, the center conductor in the ceramic becomes very small and breezing is very difficult.

The impedance of coaxial line operating in the TEM mode is given by,

$$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \frac{b}{a} \text{ Ohm} \quad (7)$$

Where,  $\epsilon$  is the relative dielectric of the media between the center conductor and outer conductor. For vacuum or air where  $\epsilon=1$ , the ratio  $b/a=2.3$  for an impedance of  $50\Omega$ .

## VII. SCHEMATIC DIAGRAM OF COAXIAL WINDOW

Schematic diagram of RF Coaxial vacuum window is as shown in fig 3. fig shows that the dielectric work as the barrier for ADITYA tokamak and ICRH Tx-line[7], So that maximum power can transmit from ICRH to Tokamak.

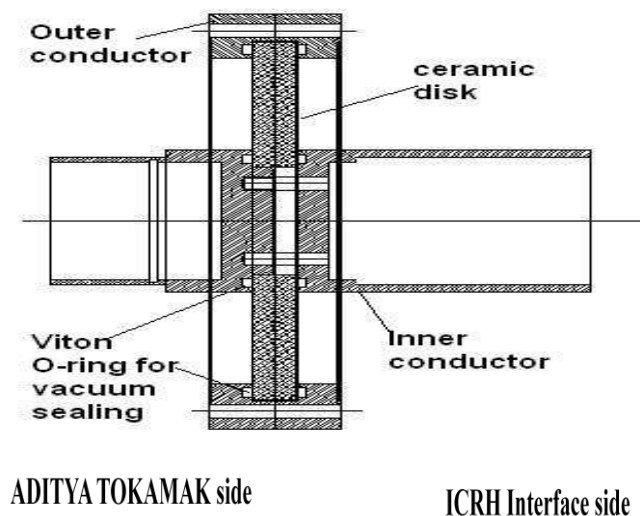


Fig.3 Schematic diagram of RF Coaxial Vacuum Window

so that it can easily match with the existing Tx-line. At the part of Dielectric the diameter of inner conductor is change to match it with 50-ohm. Here dielectric with creepage length should be used to avoid the surface break down.

## VIII. CONCLUSION

After this design and analysis it is clear that the design parameter of coaxial vacuum window is depends on three parameters which are dielectric constant, thickness of window, as well the applied frequency. With low dielectric material and lower thickness window will be more efficient for 20-40 MHz i.e. ICRH range of frequencies.

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