Conditioning technique for high power RF vacuum transmission line components using multipactor plasma

Kishore Mishra¹, D Rathi, Siju George, Atul Varia, M Parihar, H M Jadav, Y S Srinivas, Raj Singh, Sunil Kumar and S V Kulkarni
Institute for Plasma Research, Bhat, Gandhinagar-382 428, INDIA
kmishra@ipr.res.in

Abstract. Multipactor is a low power, electron multiplication based resonance breakdown phenomenon in vacuum often observed in radio frequency (RF) and microwave systems. A multipactor discharge is often undesirable as it can create a reactive component that detunes the resonant cavities, generates noise in communication system and induces gas desorption from the conductor surfaces. Multipactor breakdown on dielectric surface is also a major concern for failure of vacuum window in klystrons, cyclotrons and accelerators. Despite of these, the multipactor discharge is not absolutely undesirable. Its usefulness is being explored in electron gun technology, plasma display technology, ICRH antenna conditioning etc. Since multipactor is a pure electron resonance phenomenon, it can happen without any gas being present in the system. Nevertheless, the massive electron bombardment on conductor surfaces removes substantial amount of adsorbed gas species and increases the neutral pressure. In the presence of neutrals these resonant electrons ionize the gaseous atoms and forms the plasma known as multipactor plasma. Many of the high power RF components used in the vacuum transmission line interface sections of ICRH system are having restricted access to surface condition them especially the inner conductors of transmission line sections and dielectric material of vacuum window. By suitably choosing the operating frequency and a minimum pressure, it is possible to form a multipactor plasma in the above components to condition them. Such a conditioning technique is adopted for conditioning of vacuum window and vacuum transmission line of ICRH system. In this paper, an overview of multipactor plasma, a brief description of the test set up, testing conditions and conditioning results are presented.

1. Introduction
Radio frequency (RF) heating in magnetically confined fusion devices [1] (TOKAMAK) has gained considerable importance in recent times. For generation of thermonuclear power, Tokamak plasma has to reach to ignition temperature according to famous Lawson’s criteria and ohmic heating alone cannot achieve this ignition temperature since joule-heating efficiency decreases with increase in plasma temperature and a most desirable steady state plasma discharge is limited by the onset of magneto-hydrodynamic instabilities that terminate it. RF heating at Ion Cyclotron Resonance Frequency (ICRF) is seen as a very successful and favorable method in increasing the ion temperature required for ignition. In tokamak ADITYA [2], ion heating at second harmonic with fast wave is currently employed.

The coupling of RF power to the plasma, i.e. the efficiency of generation of waves, which transfers the power to the central plasma, is greatly dependent on the effective load resistance ($R_0$) of an antenna-plasma system. Typically the magnitudes of $R_0$ are about a few ohms [3]. Since the RF generator and the transmission line from generator to antenna are of 50ohm characteristics impedance, a matching network is necessary to match the antenna impedance to 50 ohm for maximum transfer of RF power. For ADITYA-ICRH system [4], a phase shifter and shunted stub forms the matching network.
This inhomogeneity in impedance creates a high Voltage Standing Wave Ratio (VSWR) intermediate section between antenna and matching network thus making the very section vulnerable in terms of voltage withstanding capability [5]. Since the antenna is placed inside the tokamak vacuum vessel and the tokamak vacuum must be kept isolated from the external atmosphere as well as the pressurisable transmission line, which feeds the power to the antenna, a vacuum window is also necessary. The vacuum window protects the tokamak vacuum and at the same time it allows RF power to pass through. For making a smooth pressure gradient in transmission line, to minimize the permeation through vacuum window seals and to increase the voltage handling capacity, the intermediate section between antenna and matching network is separately evacuated and hereafter termed as vacuum transmission line (VTL) section. In addition, the antenna-plasma coupling is greatly influenced by local plasma density, plasma temperature and their gradients near antenna, [6] which can be suitably varied by changing the antenna plasma distance. This necessitates the radial movement of antenna for at least a few times the density scale length, which is typically 10mm at SOL for ADITYA. This is achieved by using double bellow and movable finger joint system in the above mentioned vacuum transmission line section.

Though the VTL is evacuated to give a better voltage withstanding capability, a lot of surface imperfections, adsorbed gas molecules and dust particles degrade the number. For better voltage performance, surface conditioning like baking, RF conditioning and plasma conditioning techniques are generally employed. During such conditioning of ADITYA-ICRH vacuum transmission line section, it is observed that a multipactor resonance zone exists for the operating frequency and geometrical dimensions of the above system. This is exploited to use it for conditioning of newly developed vacuum window as well as the VTL, details of which are discussed in subsequent sections.

2. Requirement of conditioning

The VTL section (figure 1) consists of a large number of high power RF components like reducers, bellows, movable finger joints, ceramic supports, vacuum windows with ceramic as dielectric, torque ring etc all of a nominal size of 8 inch. Due to stringent mechanical constraints, some of the components are forced to maintain a lesser inter conductor distance in comparison to rest of the line. Secondly the VTL is subjected to high VSWR regime and contained by vacuum less than 1E-6 Torr. High VSWR leads to higher instantaneous voltage gradient between the inner and outer conductors while ubiquitous vacuum between them can lead to a vacuum breakdown under certain conditions [7].

![Figure 1](image1.png)

**Figure 1.** The VTL of Aditya-ICRH system. 1-the torus vacuum vessel, 2-antenna, 3- vacuum window to isolate torus vacuum from that of VTL, 4- gas barrier to isolate VTL from pressurized transmission line, 5- vacuum system of VTL.

A high voltage breakdown in VTL section can occur due to a number of precursors. Application of high RF electric field to the surfaces of inner and outer conductors makes possible the escape of
electrons from metal surface by tunneling through potential barrier. The field emission current with application of RF voltage is exponentially dependent on the work function of the surface material and the electric field amplification factor due to micro protrusions [8]. These quantities are very sensitive to surface conditions, surface material, surface purity etc. The effect is more pronounced due to the micro-protrusions, sometimes called whiskers, where electric fields are amplified many folds on the top of these small spikes. The spikes appear due to various mechanical treatments applied during fabrication process with a characteristic size of 1nm to few microns can lead to electric field amplification factor of 10-500 [9]. The breakdown in VTL can also occur along the insulator surfaces at vacuum window. A large amount of residual gases and water vapours are adsorbed to the metallic conductor surfaces and ceramic surfaces. Atmospheric gases are trapped in minute crevice, cracks, grooves, and joints etc, which are also additional sources of residual gases in interface. During RF operation these gases can desorbs due to electron bombardment (explained in section 4), which may lead to sufficient high pressure that leads to Paschen limit for self-sustaining discharge. All these reasons limit high power RF operation of the VTL in particular and ICRH system as a whole.

3. Experimental set up
The antenna from the VTL is removed and is terminated by a water-cooled 80kW 50ohm coaxial dummy load. To reproduce the typical vacuum scenario during usual operation of ICRH system, two vacuum sections with different vacuum levels are deliberately made (figure 2). While vacuum section-1 represents that of the VTL, the vacuum section-2 corresponds to that of torus. Two ionization gauge

![Figure 2](image)

**Figure 2.** The test set up block diagram. (1) 80kW water-cooled CW 50 Ohm dummy load, (2, 4) Gas barrier, (3) Vacuum window, (5) flexible bellow to evacuate vacuum section-2, (6, 7) ionization gauges, (8) the pumping system, (9) arc detector

measures the vacuum level of two vacuum sections. An arc detector is employed at a 35mm view port on the VTL to detect any possible arcing during the RF power operation. The other side of the VTL is connected to RF generator through a matching network and it is matched to 50ohm at the operating
frequency of 29MHz. A directional coupler detects forward and reflected RF power. Since the system is matched, one would always expect zero or negligible reflected power during normal scenario. In an event of any malfunction like breakdown or arc, however one would detect increase in reflected power and large variation in its profile as seen in the data acquisition system (VME).

4. Conditioning of VTL
Several conditioning techniques can be used to reduce the non-ideal surface conditions discussed in section 2, like baking, low power RF conditioning, breakdown conditioning etc. Most of the components of the VTL are made of SS304L. To remove the adsorbed gas species and water vapour to a considerable level, a baking of more than 200º C for several hours is required [10,11,12]. The use of O-rings and edge-welded bellows in the VTL restricts the upper limit for baking. Also it is difficult to bake the inner conductor because of inaccessibility and vacuum region between outer and inner conductors. Hence the later two methods are seem to be more effective and are used for the above VTL including vacuum window.

4.1. Low power RF conditioning. The low power RF conditioning is important because it is very effective in reducing the adsorbed gas species clinging to the conductor’s surfaces exposed to vacuum. It not only helps in attaining a clean vacuum but also cleans the surface to a large extent favourable for high power operation of the system [13]. In the present experiment, short RF pulses of 10 msec duration applied with a power starting as low as 100W with a negligible reflected power. The base pressure in the vacuum section-1 and 2 before application of RF pulse is found to be 2.7E-7mbar and 1.4E-4 mbar respectively. The effect of conditioning is evident from the immediate pressure rise in both the sides of the vacuum window as detected by the two ionization gauges. The artifact of RF interference on the ionization gauges is ruled out by the fact that, pressure rise (as displayed in its controller display) starts immediately after application of 10ms RF pulse and continues to rise for another couple of seconds approximately before it starts reducing. This delay is obvious as the adsorbed gas species from the conductor’s surfaces by electron bombardment accelerated under RF electric field, takes finite time to reach the ionization gauge collector against the poor conductance from their place of origin to the gauge. As the RF pulse is removed and hence there exists no source of desorbed gas molecules, the gauge pressure starts falling after a few seconds. The subsequent RF pulses are applied with sufficient time delay so that the base pressure comes back to a stable apparent ultimate value.

As the RF power increased beyond 700W, faint glow discharge is observed inside the interface, detected by arc detector and visually observed through the view port. As the RF power increases the glow becomes prominent and disappears once the power is pushed beyond 7kW. Basically a power window of 700W to 7kW is observed where a glow discharge is observed inside the interface. This observation is repeated and confirmed that a power window exists below and beyond which no glow like discharge is obtained. Such a discharge with a power window can be explained on the basis of multipactor resonance induced glow discharge effect, which is explained in the next section.

4.2. Multipactor plasma conditioning. A voltage breakdown occurs when the generation of electrons is greater than the removal of electrons from the intermediary gas present between the two conductors. In the case of RF voltage breakdown, the two main electron generation mechanisms are ionization of the gas by electron collision, and secondary electron emission from the two conductor’s surfaces. Removal mechanisms include diffusion, drift, recombination, and attachment. These different types of electron production and loss mechanisms are discussed in References [14,15]. When pressure is sufficiently low so that the electron mean free path is longer than the inter conductor separation, then the dominant electron generation mechanism is secondary emission. This particular breakdown phenomenon is known as multipactor resonance breakdown [16].

A multipactor resonance breakdown can be started by a single free electron that may be present inside and can readily travel between the inner and outer conductors of VTL without undergoing
collisions with the gas molecules present. With application of RF power, an oscillating electric field is set between the two conductors and these electrons accelerated towards any of the conductors and collide with them. If the primary accelerated electrons have sufficient energy then the secondary electrons may emit from the conductor surfaces subject to condition that it has secondary electron emission coefficient greater than one. If the polarity of the electric field reverses at this time then, the emitted secondary electrons will be accelerated across the gap towards the other conductor. If the transit time of the electrons across the gap is one half cycle of the RF field, the secondary electrons formed by the initial electrons become primary electrons for the next half cycle to form another group of secondary electrons. If the amplitude of electric field, the RF frequency and inter conductor distance is favorable, then a large electron densities rapidly build up in the gap and breakdown results. Where the transit time of the electrons is an odd integral multiple of one-half cycle, multipactoring would also occur and are referred as the higher order multipacting modes [17].

If the applied RF power is low enough, then the electrons collide the conductor surface with lower energy and secondary emission may be diminutive and subsequently a low power limit for multipactor resonance exists. As the RF power goes beyond a certain level, the primary electrons are accelerated fast enough to reach the opposite conductor before the electric field reversal. The secondary electrons thus emitted are pulled back to the conductor and detunes the resonance effect. Hence there is a higher power limit of multipactor resonance for a particular frequency and system dimension. This lower and upper limit of multipactor resonance breakdown creates a power window, which is the one of the most prominent signatures of such breakdown. Since only electrons are involved in this process, the multipactor resonance breakdown exists without any gas being present. Nevertheless, in the presence of gas molecules in an intermediate pressure range, enough secondary electrons can be produced by ionization and a gas discharge is sustained. Such a discharge is known as multipactor induced glow discharge or ‘multipactor plasma’ in short [18].

During multipactor a large amount of gas adsorbed on the inner and outer conductor surface of the VTL is released and nontrivially contribute to the conditioning effect. Also these gas species along with the multipactor resonant electrons forms the multipactor plasma inside the interface between the inner and outer conductors, which is visually seen from the view port. Since multipactor resonance itself has a power window as discussed above, the multipactor plasma in this experiment has also not been observed beyond this power window.

Figure 3. Improvements of vacuum levels in (a) vacuum section-1 and (b) vacuum section-2, clearly indicates the effect of RF conditioning. The effect is more prominent in vacuum section-2 due to higher surface imperfections and impurities during fabrication process.
The multipactor plasma has been observed from 700W to 7kW power window for the current experimental set up. As the number of shots progresses, the rise in pressure decreases while the base pressure in the vacuum section 1 and 2 decreases gradually (figure 3 a, b). With this the glow becomes faint gradually which signifies the conditioning effect. After the conditioning, the power is pushed through beyond 7 kW and gradually increased up to 70kW [19]. During this no multipactor plasma or arc has been detected by arc detector, which was being observed at higher powers before the above conditioning. The RF pulse width is gradually increased from 10msec to 100msec for each power level up to 70kW. A series of 10 pulse trains with 50% duty cycle is also applied. Since typical ICRH operation on ADITYA is of 100msec duration, longer pulse test is not required. The complete VTL along with all of its RF components including the newly developed vacuum window is tested for 70kW RF power at 29MHz frequency.

5. Summary
The vacuum transmission line (VTL) section of ADITYA-ICRH system is modified with replacing antenna with a 50ohm dummy load for testing and conditioning purpose. The vacuum levels are adjusted similar to normal operating conditions with ADITYA. The test set up is conditioned with low power RF pulse to get ease of adsorbed gas species, dust particles and micro protrusions for better power handling capability. During the conditioning test, multipactor plasma is observed with an explainable power window. The power window where multipactor plasma observed is found to be from 700W to 7kW beyond which no such glow discharge is seen. During the above conditioning a large increase in pressure is seen inside the VTL and as the conditioning progresses, a remarkable improvement in base pressure is observed. After this, the VTL is successfully tested up to 70kW of RF power at 29MHz frequency without any arc or local breakdown. The experiment shows that there is a definite multipactor resonance zone exists in the VTL for the normal operating scenarios. For other sizes of transmission line components, the operating frequency can be suitably tuned to achieve a multipactor zone inside it and can be conditioned by the above method. The possibility of creating similar multipactor plasma in the ADITYA ICRH antenna and conditioning it is to be explored.

References
[1] Wessen J *Tokamaks* (Clarendon Press, Oxford)
[2] Bhatt S B et al 1989 ADITYA: The first Indian tokamak *Indian J. Pure Appl. Phys.* 27 710
[3] Saigusa M 1994 *Fusion Eng. Design* 24 47
[4] Bora D, Kulkarni S V, Mukherjee A et al. 2005 *Sadhana* 30-1 21
[5] Moreno T 1989 *Microwave transmission design data* (Artech House Inc, MA-02062) 32
[6] Collestock P L 1988 *J. of Vac. Sc. & Tech.-A* 6-3 1975
[7] Monakhov I, Bobkov V 2007 EFDA-JET-CP(07)01-04
[8] Luong M 1997 *J. Phys. D: Appl. Phys.* 30 1248
[9] Bobkov V 2003 Studies of high voltage breakdown phenomena on ICRF antennas *Max-Planck-Institut fur Plasmaphysik, EURATOM Association Garching, Germany*
[10] Roth A *Vacuum Technology* (Elsevier Science Publication)
[11] Seung-Soo Hong 2004 *Meas. Sci. and Technol.* 15 359
[12] Bacher J P 2003 *J of Vac Sc and Technology-A* 21(1) 167
[13] Kaye A 1994 *Fusion Eng. and Design* 24 1-21
[14] Howatson A M 1976 *An introduction to gas discharges* (Pergamon Press)
[15] Brown S C 1959 *Basic Data of Plasma Physics* (John Wiley & Sons)
[16] Kishen R A 1998 *Physics of Plasma* 5-5 2120
[17] Hatch A J 1958 *The Phy Rev* 112-3 681
[18] Hohn F 1997 *Phys of Plasma* 4-4 940
[19] Mishra Kishore et. al. 2008 Recent advances & upgradation of icrh system on ADITYA, IPR/RR-420