EC21
ITER Organization, France
June 20, 2022

Design of Stray Radiation Sensor for ITER ECE Diagnostic

Presented by: Suman Danani

S. Danani[1], Sheetal Punia, Ravinder Kumar[1], Hitesh Kumar B. Pandya[1,2], Vinay Kumar[1,2] , Chetna Chauhan[3]

[1]*ITER-India, Institute for Plasma Research, Gandhinagar 382428, India*

[2]*Homi Bhabha National Institute (HBNI), Mumbai 400094, India*

[3]*Institute of Technology, Nirma University, Ahmedabad 382481, India*

Motivation

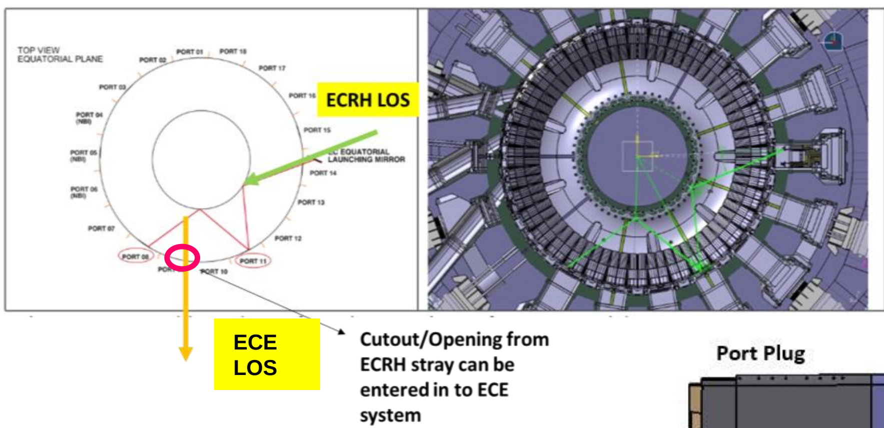
Develop a Stray Radiation Sensor for ITER ECE Diagnostic to detect the stray radiation power incident on the system.

Introduction

- **The Electron Cyclotron Emission (ECE) diagnostic has a primary role in the measurement of electron temperature profile and electron temperature fluctuations in ITER.**
- **This diagnostic shall be exposed to significant power due to unabsorbed Electron Cyclotron Heating (ECH) power in the plasma.**
- **The expected stray power loads could be a few watts, and therefore, the protection of millimetre wave components is one of the design challenges for ITER ECE diagnostic.**
- **The stray radiation protection system includes sensors, a band stop notch filter, and a shutter to stop the RF stray radiation from being incident on the sensitive components.**
- **The sensors will be mounted on the ECE transmission line at various locations, and shall be used for real-time power monitoring of the stray radiation.**

Stray radiation loads applicable to the ECE diagnostic

Stray radiation load case		Power density	Power load on Ex-vessel ECE components for 100 mm dia. opening	Location
ECRH	Background power	268 kW/m^2	2.1 kW	Everywhere
	Cross polarization power	1.25 MW/m^2	9.8 kW	Everywhere
CTS	Background power	7 kW/m^2	55 W	Everywhere



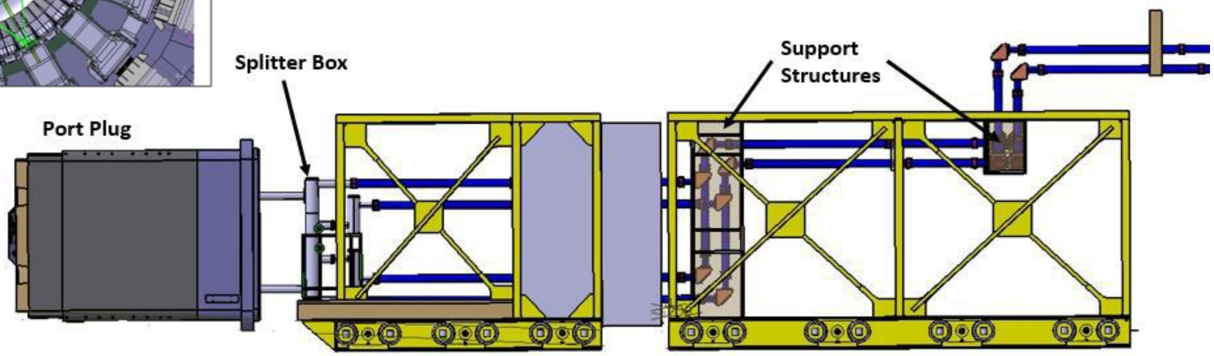


Figure 1: CAD model of ECE diagnostic system

Sensor Design

- A novel Stray radiation sensor at 170 GHz is designed for ITER ECE Diagnostic, based on the microstrip technology and possesses characteristics like high detection sensitivity, high bandwidth, and good power handling capability.

- This stray radiation sensor is a Schottky Diode rectenna, known for high-power and high-speed millimetre wave detection capability.

- It includes a microstrip antenna, a matching circuit, a diode, and a low pass filter.

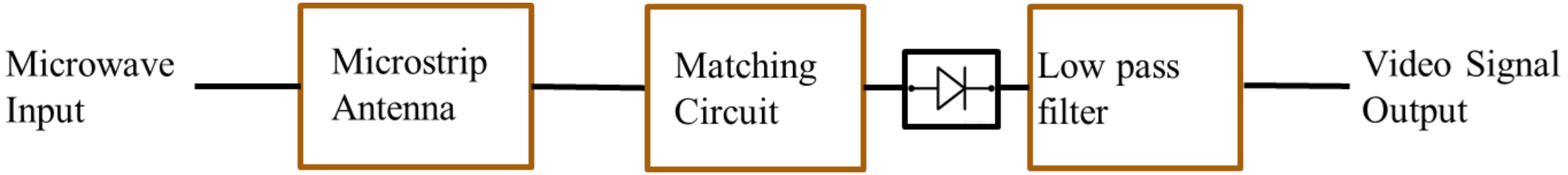


Figure 2: Schematic of Stray radiation sensor.

Design Requirements

❖ **Antenna**

- Wide Reception Angle
- High Gain
- Low Side-lobe-level
- $VSWR<2$
- S-parameter $<-30dB$

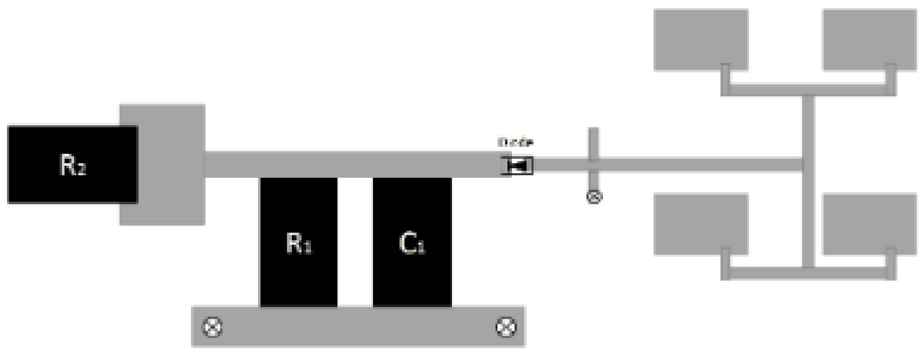


Figure 3: The layout of 2 ×2 patches rectenna with a single half-wave Schottky rectifier

❖ **Rectifying Circuit**

- Low Pass Filter

To filter out high-frequency signals and only output low-frequency signals related to power.

- Schottky Diode

Better rectification of the signal

- Matching Circuit

Better impedance matching to reduce the reflection, so that the microwave power enters the diode as much as possible, improving the detection sensitivity.

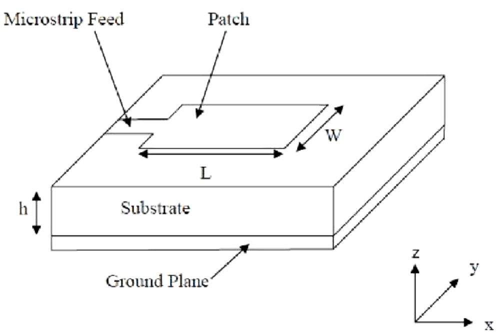
Design of Antenna

Microstrip Antenna

This is a key element in the design of sensor and must sense all the power expected to be incident on the ECE components.

A microstrip antenna system is designed which will collect the stray electromagnetic energy entering through the port and convert it into electrical energy to be measured by the detector.

The microstrip patch antenna is a single-layer design consisting of four main parts: (i) Patch (ii) Substrate (iii) Ground plane (iv) Feeding part.



Design wavelength $\lambda_0 = 1.76mm$ $(f = 170\ GHz)$

Substrate selection:

Substrate material: RO3003, $\epsilon = 3$, h = 0.254 mm

- Dielectric constant ($12 > \epsilon > 2.2$), low ϵ is preferred for better efficiency
- Substrate Thickness $0.01\lambda_0 < h < 0.05\lambda_0$

Small h, low ϵ – larger bandwidths and higher efficiency

Table 1: Patch Dimensions

Parameter	Specification
Patch Material	Gold or copper
Patch Shape	Rectangular
Patch Length	$\frac{\lambda_0}{3} < Lp < \frac{\lambda_0}{2}$
Patch thickness	$t \ll \lambda_0$

- Width and length of patch are given by following expressions:

$$W_p = \frac{v_0}{2f}\sqrt{\frac{2}{\varepsilon + 1}} \qquad L_p = \frac{1}{2f\sqrt{\varepsilon_{eff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L_p$$

$$\frac{\Delta L_p}{h} = 0.412\,\frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W_p}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W_p}{h} + 0.8\right)}$$

ε_{eff} is the effective dielectric constant, which accounts for fringing and wave propagation in the feedline defined as:

$$\varepsilon_{eff} = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2}\left[1 + 12\frac{h}{W_p}\right]^{-1/2}$$

- The length & width of the ground plane is determined by using the relation $L_g = 6h + L_p$ and $W_g = 6h + W_p$, respectively.

- The width of microstrip feedline W_f is related to its characteristic impedance as follows:

$$Z_T = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left(\frac{8h}{W_f} + \frac{W_f}{4h}\right)$$

- For antenna design, inset-fed microstrip feed is opted, which has advantages of overcoming narrow-bandwidth constraints and capturing more signals with improved accuracy.
- The feeding point can be calculated using the relation

$$R_{in}(x = x_0) = \frac{1}{2G_r}\cos^2\left(\frac{\pi x_0}{L_p}\right)$$

where G_r is the conductance given as $G_r = \frac{1}{90}\left(\frac{W_p}{\lambda_0}\right)^2$

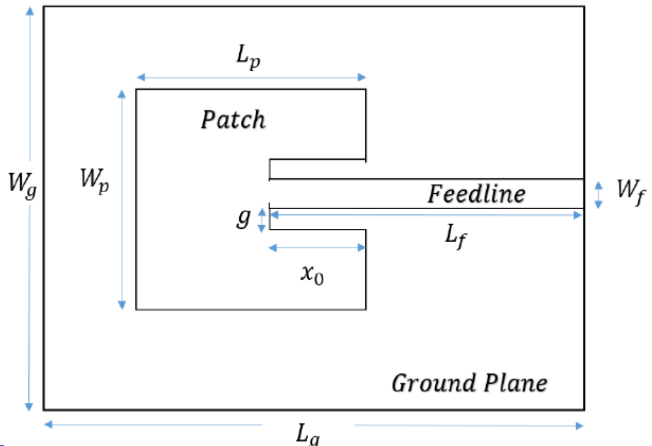
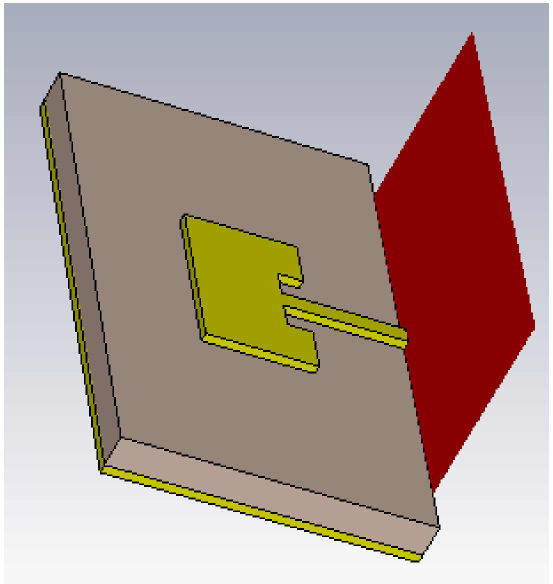


Table 2: Design parameters evaluated for a single patch element

Parameter	Value
Operating frequency (f)	170 GHz
Thickness (h)	$0.254\ mm$
Length of Patch (L_P)	$0.3\ mm$
Width of Patch (W_p)	$0.6239\ mm$
Cut Width (g)	$0.1\ mm$
Cut Depth (x_0)	$0.101\ mm$
Path Length (L_f)	$0.355\ mm$
Feed Width (W_f)	$0.063\ mm$

Simulation of Antenna Array in CST MW Studio

- An antenna array gives the advantage of wide angle reception and better power handling capability.
- The quarter-wave transformer is used to match impedance between the feeding line and the patch to reduce reflection losses.



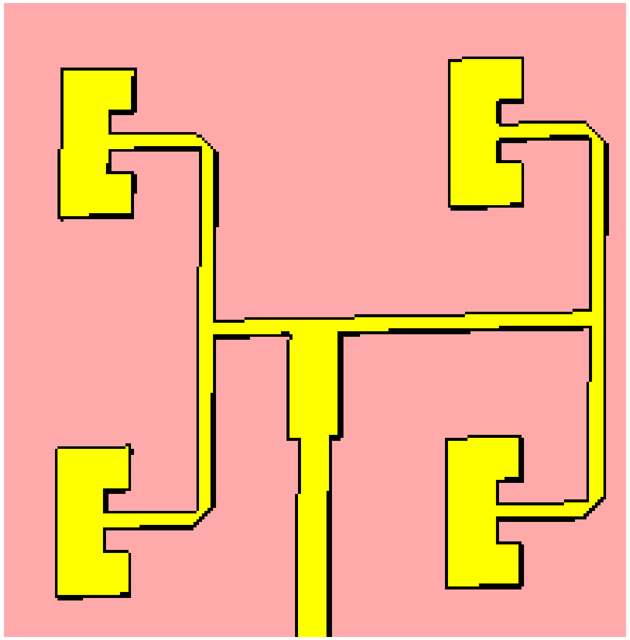


Figure 4: CST model of (a) individual patch and (b) 2×2 patch antenna array for 170 GHz resonant frequency.

CST Simulation Results

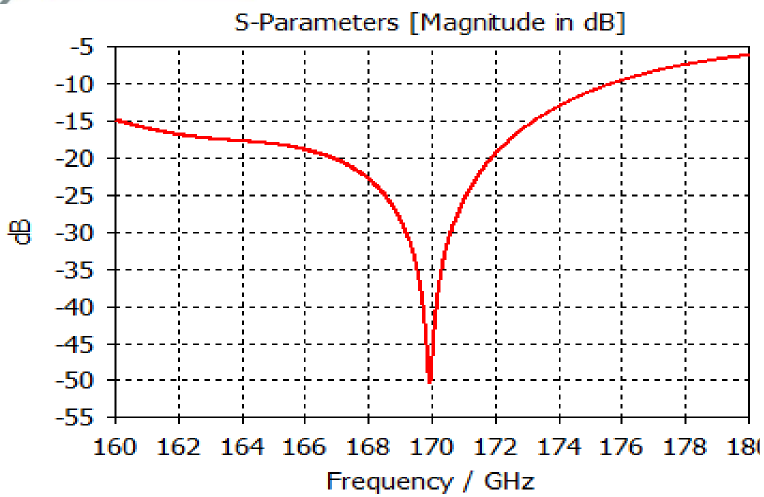
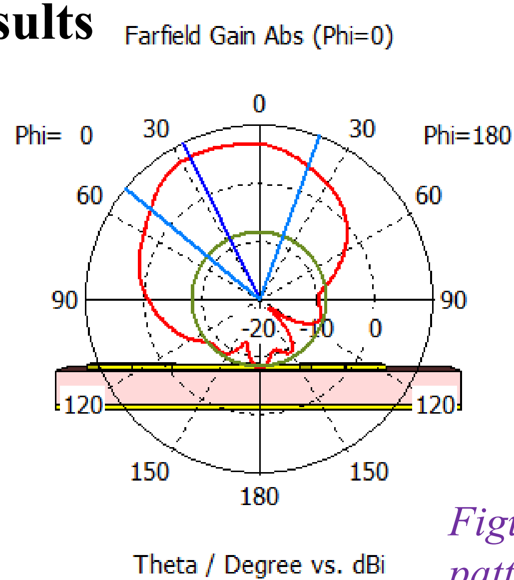


Figure 5: Variation of S-parameter with the frequency of incident radiation



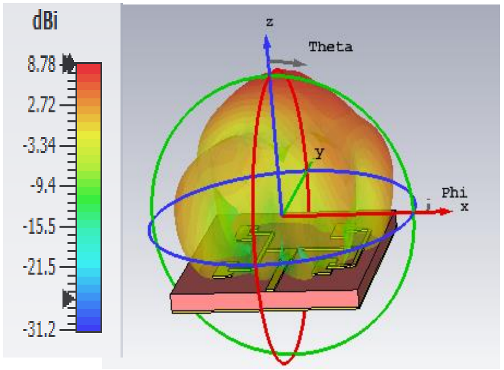


Figure 6: Far field radiation pattern of antenna array

Table 3: Characteristics of antenna array

Parameters	Antenna Array
S-Parameter (S_{11})	-50 dB
VSWR	≤ 2
Bandwidth	12%
Gain (IEEE)	8.78 dBi
Side Lobe Level (SLL)	-15.5 dB
Angular width (3dB)	70.5^0
Total Efficiency (@170GHz)	79%

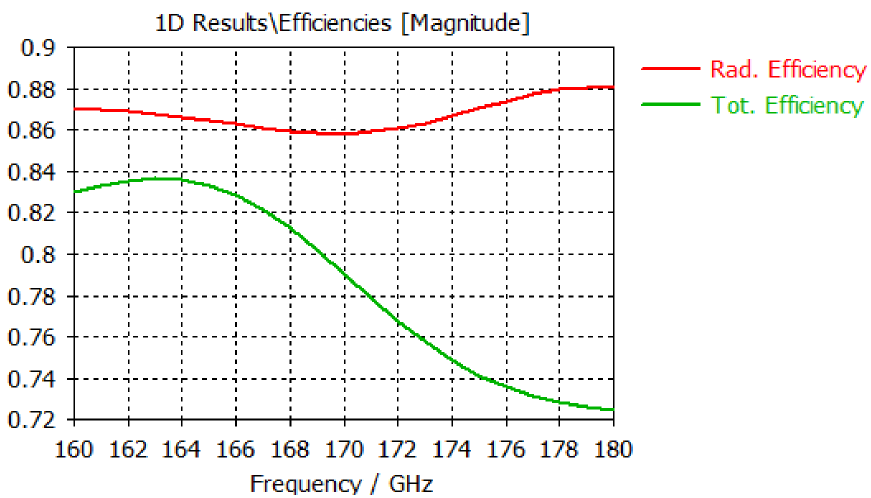


Figure 7: Variation of efficiency of antenna array with the frequency

Power Calculations

- **Power collected by receiving antenna**

Using the Friis-Transmission equation, the power collected by the receiving antenna is calculated

$$\frac{P_r}{P_t} = \frac{A_{em}G_{0t}}{4\pi R^2} = \left(\frac{\lambda_0}{4\pi R}\right)^2 G_{0r}G_{0t}$$

Wide aperture of an antenna array endorses higher gain, and hence, higher power collection than a single antenna element.

- **Average power handling capability(APHC)**

The rise in temperature determines the average power handling capability (APHC) of a system as

$$P_{av} = (T_{max} - T_{amb})/\Delta T$$

Temperature gradient (ΔT) is the total density of heat flow associated with conductor (αc) and dielectric αd losses

For, ambient temperature 25^0C and operating temperature 150^0C, APHC value for single antenna element is 79.5W and for antenna array 0.76kW.

Design of Rectifying Circuit

LOW PASS FILTER (LPF)

- The function of LPF is to suppress the fundamental wave and harmonics as only low-frequency signal is required, proportional to the wave power.

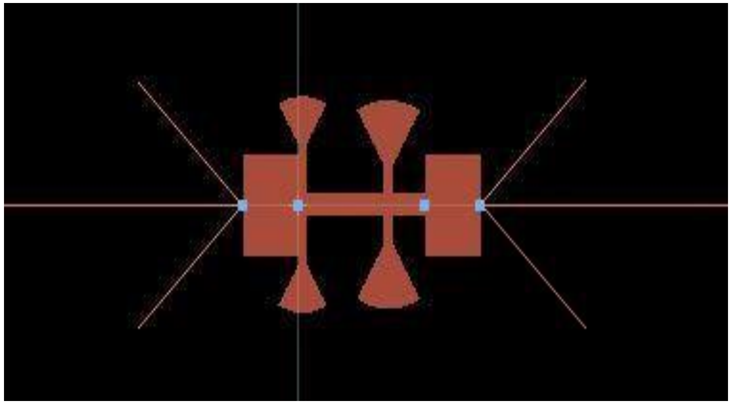
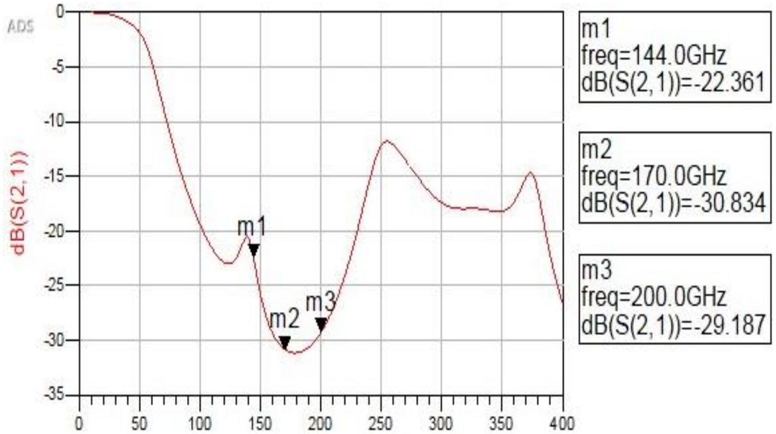


Figure 8: Microstrip circuit of low pass filter in ADS

Substrate material is RO3003 (ϵ=3, h=0.254 mm)

Microstrip line material is copper

Microstrip line thickness is 35µm



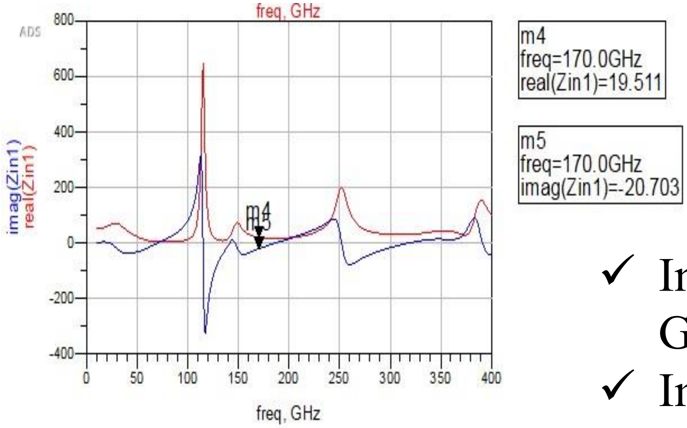


Figure 9: The ADS Simulation result (a) S_{21} (b) input impedance of the low pass filter.

- ✓ Insertion loss is 30.8 dB and 29.1 dB at 170 GHz & 200 GHz, respectively, and the harmonic signals are suppressed.
- ✓ Impedance is 19.5-j*20.7 at 170 GHz.

SCHOTTKY DIODE

- G-band (110-300GHz) ZBD produced by VDI due to its high cut-off frequency and better I-V characteristics.
- The diode simulation model for VDI G-Band ZBD in ADS is designed.

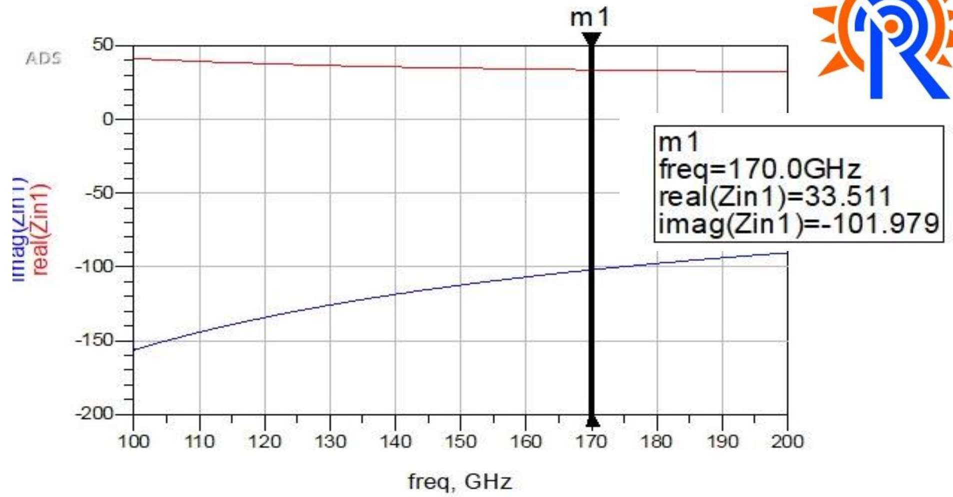


Figure 10: Diode input impedance simulation results at 170GHz.

MATCHING CIRCUIT

- The matching circuit is used to match the input impedance of the detector to a 50 Ω impedance to reduce the reflection, so that the microwave power enters the diode as much as possible, improving the detection sensitivity

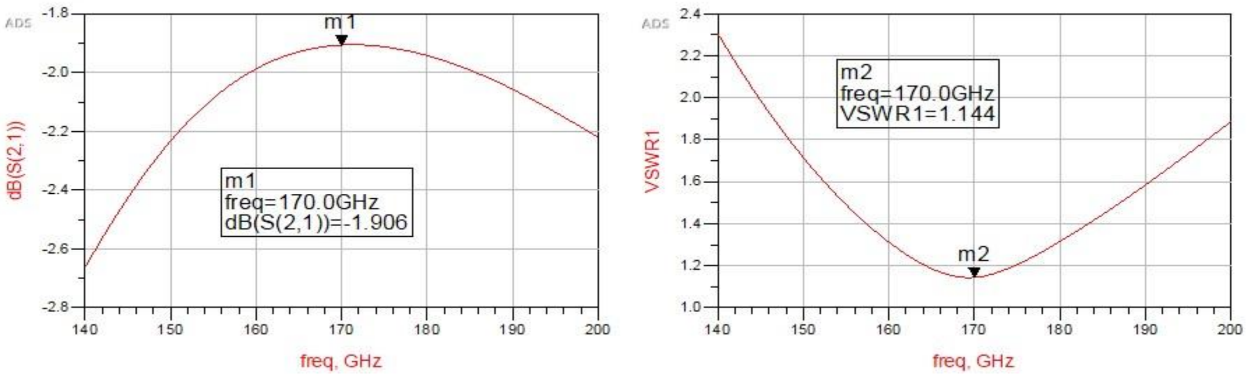


*Figure 11: Simulation result of matching circuit when load impedance is set to 33.5-j*101.9Ω.*

Table 4: Power delivered to the diode for different input power

RFpower	Pdel_Watts
10.000	0.006
15.000	0.020
20.000	0.064
25.000	0.204
30.000	0.645
35.000	2.039
40.000	6.447

ADS Simulation of Rectifying Circuit

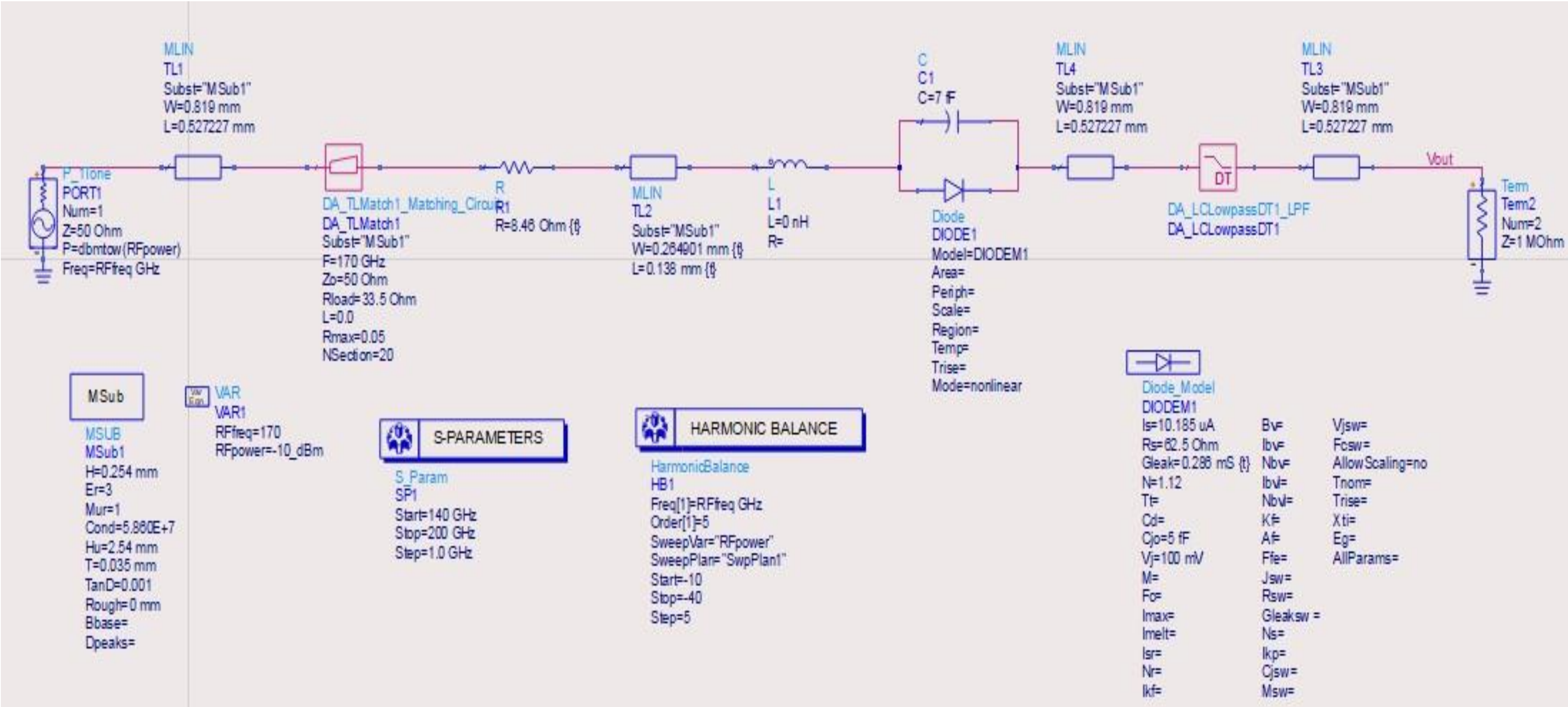


Figure 12: The detector circuit and harmonic balance simulation configuration.

- The detector circuit consisting of a matching circuit, a diode, and a low-pass filter is simulated using ADS software.
- The harmonic balance simulation of the detector is carried out.

Results

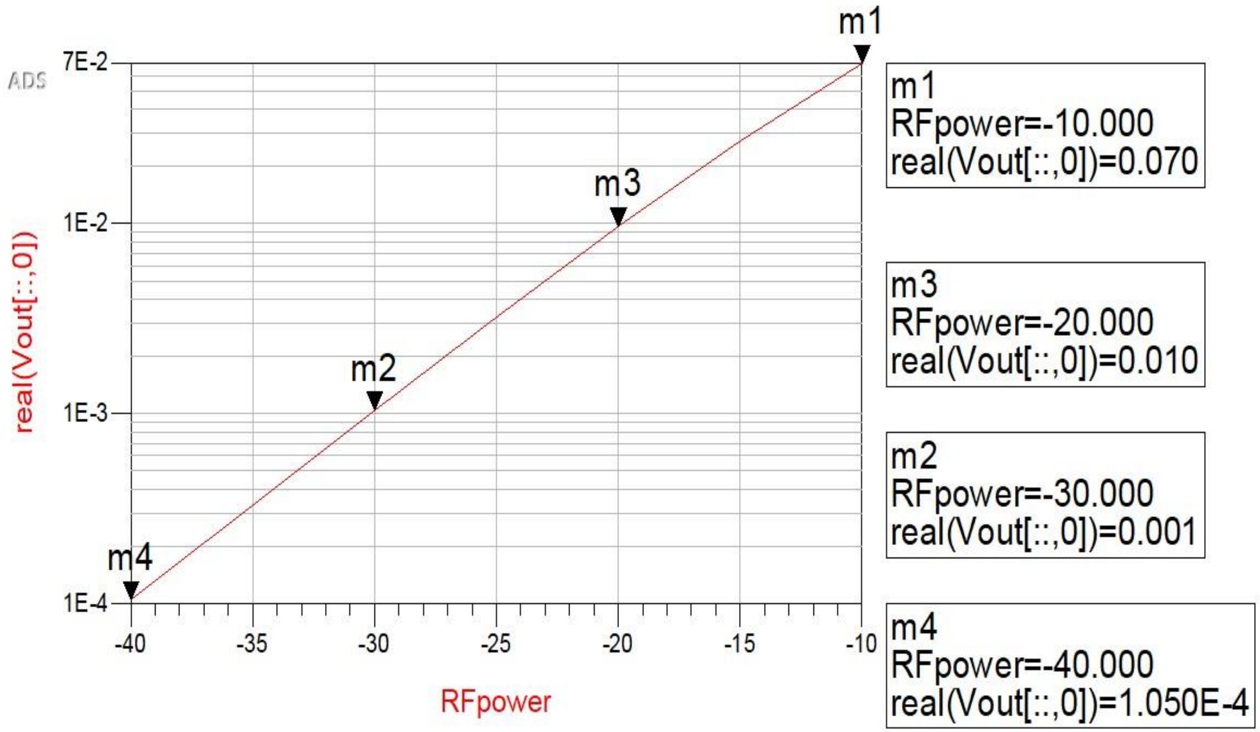


Figure 13: The harmonic balance simulation results at 170 GHz

- Simulation results show that the detector has good linearity for a frequency of 170 GHz.
- Detection sensitivity is ~1000V/W for input power of -30 dBm at 170 GHz.

Summary

- A novel design of a sensor for monitoring the stray radiation power is described.
- This sensor is a Schottky Diode rectenna, and consists of a 2x2 microstrip patch antenna array, a matching circuit, a diode, and a low pass filter.
- A 2×2 microstrip antenna array has been designed and simulated successfully for the resonant frequency of 170 GHz using CST Microwave Studio software.
- Increasing the number of array elements further enhances its directivity but decreases its angular width. Hence, the 2×2 antenna geometry reasonably satisfies our desired requirements.
- The rectifying circuit, consisting of the matching circuit, low pass filter and the diode, is simulated and optimized in ADS software.
- The ADS simulation results show that the detector has good linearity for a frequency of 170 GHz and the detection sensitivity is about 1000V/W for input power of -30 dBm.

The proposed design fulfills the requirement of Stray Radiation Sensor for ITER ECE Diagnostic.

Future Plans/Challenges

- To develop a prototype of the sensor and test it at ITER-India lab for its performance.

- To calibrate the sensor.

THANK YOU