Design of Stray Radiation Sensor for ITER ECE Diagnostic

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Abstract. 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 tens of watts, and therefore, the protection of millimetre wave components is one of the design challenges of ITER ECE diagnostic. This 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 positioned along the ECE transmission line, and shall be used for real-time power monitoring of the stray radiation. Here, we describe a novel design of a sensor for monitoring the stray radiation power. This sensor is a Schottky Diode rectenna, known for high-power and high-speed millimetre wave detection capability. It consists of a 2x2 microstrip patch antenna array, a matching circuit, a diode, and a low pass filter. The antenna array is designed analytically and optimized in CST Microwave Studio, for wide reception angle, high gain, and low side lobe levels. Furthermore, the rectifying circuit is optimized using Agilent Advanced Design System (ADS) software to get better rectification and impedance matching of the signal, thereby improving its detection sensitivity. The ADS simulation results show that the detection sensitivity is about 1000V/W for input power of -30 dBm at 170 GHz, thereby achieving the required performance of the sensor.

1 Introduction

The Electron Cyclotron Emission (ECE) diagnostic has a primary role in the measurement of electron temperature profile and electron temperature fluctuations in ITER. The supplementary roles of this diagnostic are the measurement of plasma energy, radiated power, run away electron behaviour and edge electron temperature profile. This diagnostic is also

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used as a back-up measurement of the ELM temperature transient [1]. The ECE measurement system consists of a front-end radiation collector, high temperature black body calibration sources, transmission lines (TLs), and the radiation measurement instruments (Radiometer and Fourier Transform Spectrometer). The ECE radiation emerges out through primary window and enters into the ex-vessel transmission line system in the port interspace region of Equatorial port plug (EPP) 09. This diagnostic shall be exposed to significant stray radiation power due to unabsorbed Electron Cyclotron Heating (ECH) power in the plasma. Per the latest design of the Diagnostic First Wall aperture (DFW) for 55.F1, the opening area is 0.024 m^2. Therefore, for the background power during the plasma start-up, it is approximately 6 kW for 5.5 s. For the non-optimal absorption during plasma flat-top, the power entering the 55.F1 DFW is ~ 48 watts [2]. Therefore, the protection of millimetre wave components is one of the design challenges of ITER ECE diagnostic [3].

The protection system shall include sensors, a band stop notch filter, and a shutter to stop the RF stray radiation from being incident on the sensitive components. Monitoring of the stray radiation at various locations is an important aspect of the stray radiation protection system. The objective of this sensor is to detect the expected ECH loads ~ 48 watts, being coupled into the ECE TL & receiver system, with a fast response time. From the experiences on other machines, the response time should be less than a few milliseconds. Further, it is to be noted that the stray radiation during plasma start-up is higher, so the shutter shall be kept closed in order to protect the ECE diagnostic. These sensors will be positioned along the ECE transmission line, and shall be used for real-time power monitoring of the stray radiation. One location that is being considered to mount the first such sensor, is inside the enclosure of Polarization splitter unit within the ECE beam path. However, work is in progress to finalize the position of first sensor and also number of sensors required and their respective positions along the transmission line.

In this paper, a novel design of a sensor is described for monitoring of stray radiation power. In Section 2, design of various components of sensor is described in detail. The ADS simulation results of the designed sensor are discussed in Section 3. In Section 4, summary and conclusion is given. Section 5 lists some future work anticipated in order to demonstrate the performance of this sensor to satisfy ITER ECE requirements.

2 Design of sensor

The sensor is a rectenna based system, known for high-power and high- speed millimetre wave detection capability [4], [5]. A rectenna is a device that captures the RF signal and converts it into DC voltage. A typical rectenna consists of four main components: a microstrip antenna, a matching circuit, a diode, and a low pass filter as shown in Figure 1. The antenna works as a receiver to capture the RF signals. A low-pass filter does the function of harmonic rejection to eliminate power loss due to harmonics. A rectifier is used to rectify the signals by using rectifying diode.

The design of sensor is based on microstrip technology, due to its various advantages over the conventional techniques. The advantages include: compact size, low cost, high integration, and high conversion efficiency. Also, the microstrip patch antennas are versatile in terms of resonant frequency, polarization, impedance, and are omnidirectional. These features are lacking in traditional systems, which are therefore not suitable for our application.

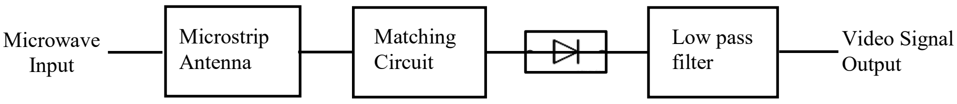


Figure 1: Schematic of proposed Stray radiation sensor

Details of various components of rectenna are described below.

2.1 Microstrip Antenna

The antenna is a crucial element of the sensor design as it must sense all the stray radiation power entering through the port. The desired characteristics for antenna design are wide reception angle, high gain, large bandwidth, low side-lobe-level and good power handling capability. Fig. 2 shows CST model of a 2×2 patch antenna array designed for the resonant frequency of 170 GHz. The microstrip patch antenna is a single-layer design consisting of four main parts: (i) Patch; (ii) Substrate; (iii) ground plane; (iv) feeding part. The details of antenna design can be found in [6]. The substrate chosen is RO3003 substrate with dimensions 3.55×3.0×0.254 mm^3. The substrate thickness is kept small to get higher bandwidth. A symmetric corporate feeding network is used to feed different patches of the antenna array with 50-ohm microstrip lines. The quarter-wave transformer is used to match impedance between the feeding line and the patch to reduce reflection losses. The array provides a large aperture, which makes it capable of detecting extremely weak signals from distant sources with improved gain and radiation pattern compared to a single patch antenna. The antenna array also offers better power handling capabilities than a single antenna element. The characteristics of designed antenna are given in Table 1.

Table 1: 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%

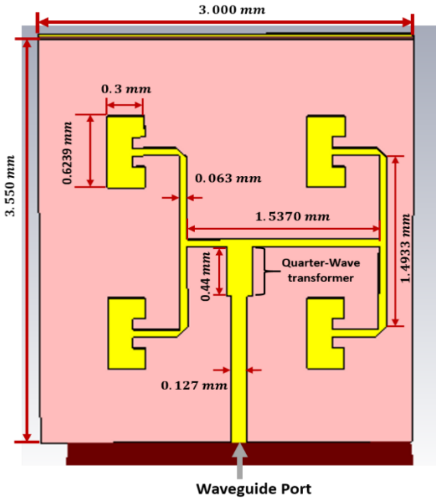
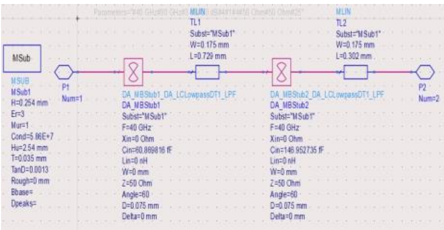


Figure 2: CST model of inset-fed directional microstrip patch antenna 2×2 array for 170 GHz resonant frequency.

2.2 Low Pass filter

The nonlinear components of rectifying circuits, such as diodes, generate harmonics of the fundamental frequency. These harmonics are reradiated back to the antenna which result in low total efficiency due to the loss in power. To eliminate harmonics reradiating back, filter is adopted. Filter is used to suppress the harmonics and maximize the total conversion efficiency. A low pass filter is designed using ADS software as shown in the Fig. 3. Here, the fourth-order maximum flattening filter passband (3 dB) with an upper frequency limit of

40 GHz and a 20 dB cut-off frequency of 80 GHz is used in designing. The substrate material RO3003 with dielectric constant 3.0 is chosen for the microstrip circuit. The dielectric thickness is $0.254\,mm$, the microstrip line material is copper, and the microstrip line thickness is $35\mu m$. The microstrip layout of the low pass filter is shown in Fig. 4.



MSub
MSUB
MSub1
H=0.254 mm
Er=3
Mur=1
Cond=5.86E+7
Hu=2.54 mm
T=0.035 mm
TanD=0.0013
Rough=0 mm
Bbase=
Dpeaks=

P1
Num=1

DA_MBStub1_DA_LCLowpassDT1_LPF
DA_MBStub1
Subst="MSub1"
F=40 GHz
Xin=0 Ohm
Cin=60.869816 fF
Lin=0 nH
W=0 mm
Z=50 Ohm
Angle=60
D=0.075 mm
Delta=0 mm

MLIN
TL1
Subst="MSub1"
W=0.175 mm
L=0.729 mm

DA_MBStub2_DA_LCLowpassDT1_LPF
DA_MBStub2
Subst="MSub1"
F=40 GHz
Xin=0 Ohm
Cin=146.952735 fF
Lin=0 nH
W=0 mm
Z=50 Ohm
Angle=60
D=0.075 mm
Delta=0 mm

MLIN
TL2
Subst="MSub1"
W=0.175 mm
L=0.302 mm

P2
Num=2

Figure 3 : Microstrip model with two radial stubs of low-pass filter

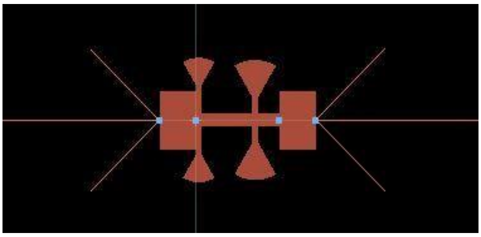


Figure 4 : Microstrip circuit of the low pass filter

The ADS simulation results for insertion loss and input impedance of low pas filter are shown in Fig. 5(a) and (b) respectively. The insertion loss is 30.8 dB and 29.1 dB at 170 GHz and 200 GHz respectively, and the harmonic signals are suppressed. Since the diode output port will be connected to the low-pass filter, the input impedance of the designed low-pass filter is first analysed, and is 19.5-j*20.7 Ohm at 170 GHz.

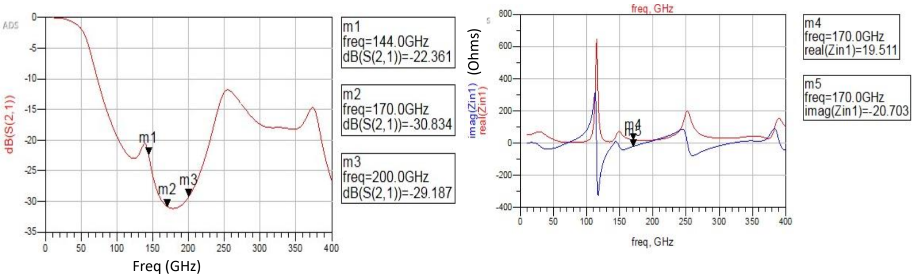


Figure 5 : The ADS Simulation result at 170 GHz (a) for transmission coefficient (S21) where the minima depicts the maximum power transfer, and (b) for input impedance of the low pass filter where its minimum value signifies its easy passage from source to load.

2.3 Schottky Diode

Diode converts the AC power collected by the antenna to DC. A G-band (110-300GHz) ZBD produced by VDI is used for our application, due to its high cut-off frequency and better I-V characteristics. The response time of detector is 1 µs, which is sufficient for detection of stray radiation power. The minimum chip dimensions are 255×88×43 µm. The diode simulation model for VDI G-Band ZBD in ADS is shown in Fig. 6.

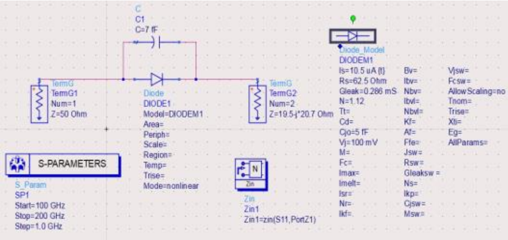


Figure 6: Diode model of VDI G-band ZBD

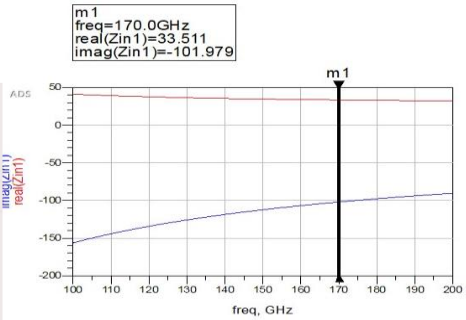


Figure 7: Diode input impedance simulation results

The variation of input impedance of the diode with frequency is shown in Fig. 7. Since the gyrotron output frequency in the ECE system is 170 GHz, the input impedance of the diode should be matched to 33.5-j*101.9Ω.

2.4 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 maximum microwave power enters the diode, thus improving the detection sensitivity. An impedance matching method combining a tapered-line match and a series resistor match is proposed in order to attain maximum sensitivity of detector at 170 GHz. The simulation results of the matching circuit when load impedance is set to 33.5-j*101.9 Ω are shown in Fig. 8. The VSWR is 1.1 at 170 GHz. The power delivered to the diode for different input powers is shown in Table 2.

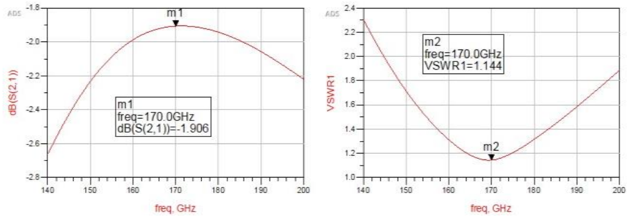


*Figure 8: Simulation result of matching circuit when load impedance is set to 33.5-j*101.9Ω*

Table 2: Power delivered to the diode for different input power

RF Power (dBm)	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

3 Simulation Results

The rectifying circuit, consisting of the matching circuit, low pass filter and the diode, is then simulated and optimized in ADS and is shown in Fig. 9. The harmonic balance simulation of the detector is carried out.

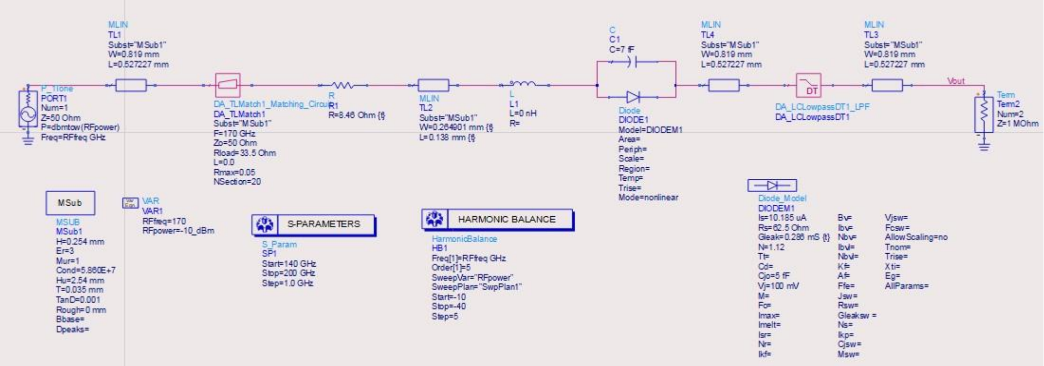


Figure 9 : The detector circuit and harmonic balance simulation configuration.

Simulation is done for different input RF power. When the input power is -10 dBm, the output voltage is about 0.07 V, and the detection sensitivity is about 700 V/W. When the input power is -20 dBm, the output voltage is about 0.01V, the detection sensitivity is about 1000V/W; when the input power is -30dBm, the output voltage is about 0.001V, and the detection sensitivity is about 1000V/W. The simulation results when $L = 0$ are similar to the simulation results when $L = 0.05nH$. The simulation results show that the detector has good linearity for a frequency of 170 GHz as shown in Fig. 10.

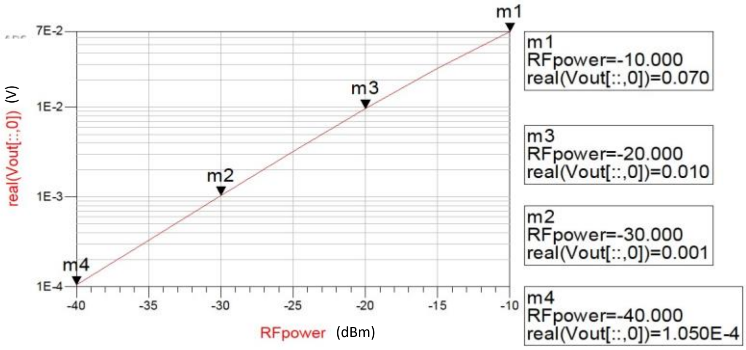


Figure 10 : The harmonic balance simulation results at 170 GHz

The effect of variation of RF frequency is also studied. When the input power is set to $-10\ dBm$, the simulation results show that the detection sensitivity is greater than $500V/W$ in the frequency range of $199\ GHz{\sim}157\ GHz$, which is shown in Fig. 11. The series inductance (0 or $0.05nH$) has little effect on the results. Hence, the detector designed is more suitable for use in the ECE system.

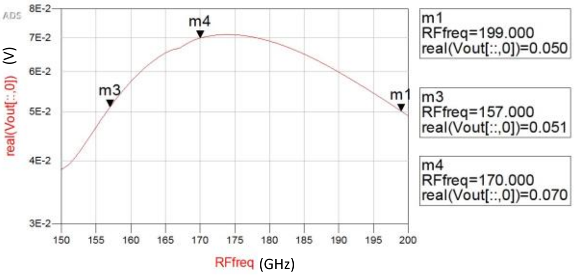


Figure 11 : The harmonic balance simulation results at -10 dBm.

4 Conclusion

A novel design of a sensor for monitoring the stray radiation power is described in this paper. This sensor is a Schottky Diode rectenna, known for high-power and high-speed millimetre wave detection capability. It 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 for the resonant frequency of 170 GHz using CST Microwave Studio software. At resonant frequency of 170 GHz, the return loss is -50 dB, angular width is 70.5^0 and the gain is 8.6 dBi, which meets desired antenna requirements reasonably well. The rectifying circuit, consisting of the matching circuit, low pass filter and the diode, is simulated and optimized in ADS software. The harmonic balance simulation of the detector shows 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. It is therefore concluded that the above design satisfies all the performance requirements of the sensor and seems to be a possible solution for monitoring of stray radiation power. However, a prototype of the designed sensor shall be developed and tested for its performance. Further optimization of sensor design shall be done if needed, based on the experimental results.

5 Future work

The future work involves development of a prototype of the designed sensor and test it for its performance. Also, the mounting position of the sensor inside the ex-vessel TL shall be finalized and a method for its calibration shall be developed.

6 References

1. Taylor et al, EPJ Web of Conferences 147, 02003 (2017)
2. Preliminary design proposal of stray radiation protection system, ITER IDM UID PKZCAZ.
3. Johan W. Oosterbeek. et al. “Loads due to stray microwave radiation in ITER”, Fusion Engineering and Design 96, 2015
4. A. Etinger et al. “Characterization of a Schottky Diode Rectenna for Millimeter Wave Power Beaming Using High Power Radiation Sources” ACTA PHYSICA POLONICA A Vol. 131 (2017)
5. Maho Matsukura et al. “Instantaneous measurement of high-power millimeter-wave beam for 28 GHz gyrotron”, Rev. Sci. Instrum. 90, 024703 (2019)
6. Sheetal Punia, et al “Design and Analysis of a 170 GHz Antenna for Millimeter-wave Applications” *http://arxiv.org/abs/2208.10075*