Preliminary Design of O-mode Radiometer for ITER ECE Diagnostic

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Abstract: The ITER Electron Cyclotron Emission (ECE) diagnostic system will provide information about plasma electron temperature and its fluctuations and other important plasma parameters which are required for plasma control and physics studies. The temperature profile measurement in the first harmonic ECE frequency range from 122-230 GHz (for $B_T = 5.3$ T) is obtained by using an O-mode heterodyne radiometer. It is difficult to cover this wide frequency band by one radiometer, due to technological challenges in achieving wide bandwidth for the mixers. So, the present radiometer design has been optimized by considering four receivers, each of bandwidth ~ 30 GHz which can provide reliable temperature measurements. The splitting of frequency band into four receiver bands is efficiently achieved by considering a combination of quasi-optical and waveguide diplexers, optimizing power loss and cross-talk between the channels. The target spatial resolution of *a*/30, where "*a*" is the minor radius of the plasma cross section, is achieved by choosing Radiometer IF filter bandwidth of 1-2 GHz. Further, the radiometer is designed to achieve noise temperature < 10 eV. In this paper, the preliminary design and performance of O-mode Radiometer has been discussed.

1. Introduction

The Electron Cyclotron Emission (ECE) diagnostic system in ITER provides essential information for plasma control and for evaluating the plasma performance. It measures the electron temperature profile (edge/core), electron temperature fluctuations and radiated power in electron cyclotron frequency range from the plasma. These measurements yield information about important parameters such as NTM and TAE δT/Te, βp, ELM associated temperature perturbations and runaway electrons and are vital for understanding the evolution of plasma, thereby contributing significantly to transport studies and plasma confinement [1]. The ECE detection instruments include two Michelson interferometers (Ordinary, O-mode and eXtraordinary, X- mode) over a broad spectral range from 70 GHz to 1 THz, O-mode radiometer covering 122-230 GHz and X-mode radiometer covering 220-340 GHz. For full-field operation of ITER (5.3T), the O-mode radiometer will be used to measure the 1st harmonic O-mode ECE while the X-mode radiometer will measure the 2nd harmonic X-mode radiation. During ITER early operational stage, it is expected to run at half-field. In this case the O-mode radiometer will have to be used for 2nd harmonic X-mode measurements.

The primary role of O-mode Radiometer is core electron temperature radial profile measurement and NTM temperature fluctuation ($\delta T/T_e$) measurement in the frequency band 122-230 GHz. From the ITER measurement requirements, the electron temperature profile needs to be measured with a spatial

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resolution of $a/30$ which is ~ 6.7 cm for plasma minor radius of $a = 200$ cm, temporal resolution of 10 ms and accuracy of 10% in the plasma core, for the temperature range 0.5 – 40 keV [2]. The principal measurement limitations of the system are restricted radial region of observation due to harmonic overlap and degraded spatial resolution due to the relativistic broadening [3,4].

The O-mode radiometer has been designed and optimized to meet the ITER requirements. The paper discusses the requirements, challenges and the design of O-mode Radiometer.

2. Design Requirements and Challenges of O-mode Radiometer

The following design requirements for O-mode radiometer are considered:

2.1. Frequency Bandwidth

For ITER operation at toroidal magnetic field $B_T(0)$ ~ 5.3 T, the 1st harmonic ECE frequencies extend from 122-230 GHz. Therefore the O-mode radiometer should provide measurement of plasma electron temperature profile by measuring 1st harmonic frequency range 122-230 GHz for the full B_T operation.

A set of four receivers with different frequency bandwidths is chosen to cover this wide bandwidth of ~110 GHz. A frequency splitter unit is needed to split the frequency range 122-230 GHz into four receiver bandwidths. The design requirement of the splitter unit is that it should have low insertion loss and a sharp frequency roll-off. As the frequency band is very wide, a hybrid approach of splitting has been adopted: first the power will be split optically and then waveguide diplexer will be used to get the desired four frequency bands.

2.2. Spatial Resolution

The spatial resolution of ECE measured Electron temperature depends on the ITER plasma parameters, the front-end radiation collection system and the instrument frequency resolution. However the radial resolution is restricted by ECE frequency broadening effects, primarily due to the relativistic broadening. In Ref [3], the effects of relativistic broadening were investigated for Scenario 2 plasma with a central electron temperature of 25 keV.

In order to achieve the spatial resolution of $a/30$, the radiometer is designed with frequency resolution of 1 and 2 GHz across the frequency band. For the low-field side edge region of the plasma, in and near the pedestal, the temperature gradient is sharp, so frequency resolution of 1 GHz is required for the lowest frequency band. Towards the core region, temperature gradient is flatter, so frequency resolution of 2 GHz is sufficient. This is achieved by proper selection of cavity filters in the IF section of the radiometer.

2.3. Temporal Resolution

For the core electron temperature measurement, the time resolution requirement is 10 ms (100 Hz) and for the high frequency instability measurement, it is 100 μs (10 kHz). For ECE electron temperature measurement by a radiometer, the time resolution depends on time response of the radiometer IF detectors, video amplifier bandwidth, signal to noise ratio, and sampling rate of digitizer. With the current technology, the time response of commercially available IF detectors is 1 μs and the video amplifier bandwidth can be adjusted between 100 Hz to 10 kHz according to measurement requirement.

By choosing the appropriate video bandwidth (~10 kHz), required temporal resolution is achieved.

2.4. Accuracy

The stated measurement accuracy for the electron temperature profile is typically 10%. The uncertainty in ECE measured electron temperature depends on the absolute calibration accuracy and stability of the radiometer.

To achieve good stability in the measurements, the RF and IF parts of the radiometer with active components shall be temperature-controlled to keep the temperature fixed within their instrumentation enclosures.

2.5. Protection from the High power ECRH stray radiation of frequency 170 GHz
The stray radiation level due to ECH is of the order of few kilowatts and it can damage the sensitive ECE Radiometer components. Two protection measures have been taken: (1) the splitting of the frequency band into four receiver bands has been done in such a way that 170 GHz radiation does not fall in the four frequency bands as mentioned in section 3. This is ensured by choosing appropriate band pass filters at the input of the mixers. (2) A quasi-optical or a waveguide band stop notch filter at 170 GHz may be used in case of requirement. This will be in addition to the protection provided by the fast shutter that is in front of the polarization splitter.

3. Preliminary Design of O-mode Radiometer

Based on the above design considerations, radiometer design is developed as shown in figure 1. The O-mode Radiometer consists of a set of four receivers with IF bandwidth between 16-30 GHz. as shown in figure 1:

a) Receiver 1: 122 - 138 GHz bandwidth with sixteen channels of 1 GHz bandwidth
b) Receiver 2: 141 - 168 GHz bandwidth with fourteen channels of 2 GHz bandwidth
c) Receiver 3: 172 - 200 GHz bandwidth with fifteen channels of 2 GHz bandwidth
d) Receiver 4: 205 - 230 GHz bandwidth with thirteen channels 2 GHz bandwidth
e) Frequency splitter unit which will split the ECE radiation 122-230 GHz into above four receiver bands

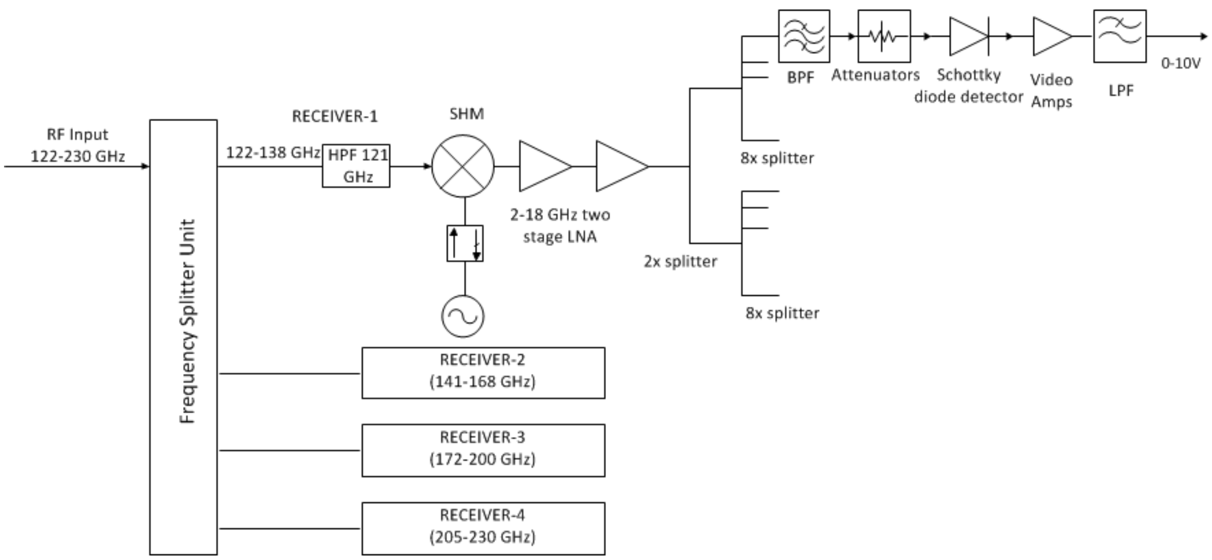

Figure 1. Schematic diagram of O-mode Radiometer (122-230 GHz)

3.1. Frequency splitter unit
The input frequency band 122-230 GHz needs to be split efficiently into four frequency bands corresponding to the four receiver bandwidths. Conventionally, directional couplers are used but the loss is high, and also the applicable frequency regime is limited due to the waveguide size. So, splitting needs to be done quasi-optically, but the roll-off is high in that case. A hybrid splitting mechanism is therefore adopted, making use of both quasi-optical splitter and waveguide diplexer as shown in figure 2.

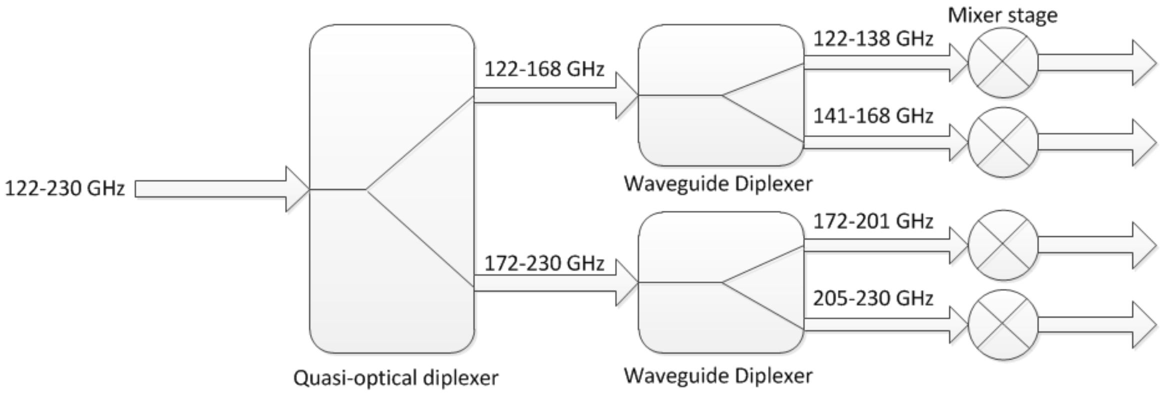

Figure 2. Frequency splitter unit for Radiometer

The quasi-optical diplexer unit consists of a Gaussian beam telescope and a dichroic filter (frequency selective surface). The analysis of the Gaussian beam telescope system has been done using 3D Gaussian Beam mode analysis software known as GBM CAD package [5,6] and summarized in Table 2. Gaussian beam propagation through the Gaussian Telescope System in GBM has been represented in Figure 3.

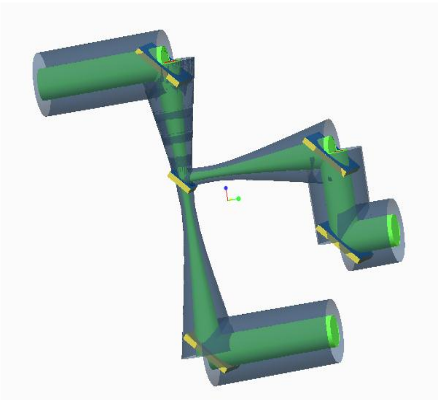

Figure 3. Representation of Gaussian bea propagation through the Gaussian telescop system in GBM software

Table 2. Gaussian Beam Analysis: Mirror parameters and Distortion levels

	f (mm)	w (mm)	R_i (mm)	R_e (mm)	XP-loss (dB)	HM-loss (dB)
EM1	250	28.19	-4271.3	265.5	25	28
EM2	250	28.19	-265.5	4271.3	25	28
EM3	250	28.19	-265.5	4271.3	25	28

Here, f = focal length, w = beam size on the mirror, $R_i = R_1$ = Radius of curvature of the phase front of the incident beam, $R_e = R_2$ = Radius of curvature of the phase front of the reflected beam, XP-loss = Cross Polar loss, HM-loss = Higher order mode loss, EM = Ellipsoidal Mirror

From the Gaussian beam analysis results shown in Table 2, it can be seen that focal lengths of 250 mm give acceptable distortion levels of the order of ~ -25 dB or lower. The splitter unit has a 3 dB power loss.

3.2. O-mode Receivers

For ITER ECE radiometer, the wide band 122-230 GHz is measured using four receivers, details of which are described in Table 3. A receiver consists basically of a down-converter, IF amplifier, power divider and detection system with band pass filters. The IF bandwidths of these four receivers are respectively 16, 27, 28 and 25 GHz. Broadband mixers with frequency bandwidths of around 30-35 GHz have already been developed and used in tokamaks such as Alcator C-mod [7]. Also the noise temperature of < 10 eV is achievable with such broadband mixers. To determine, the noise temperature of the radiometer, the overall noise figure is estimated using the Friis' formulae [8] as given below

$$T_r \sim (T_m + L_c T_{if}) \tag{1}$$

where T_m = mixer noise temperature, L_c = mixer conversion loss, T_{if} = Noise temperature of IF amplifier.

Assuming $T_m \sim$ 4000 K, $L_c \sim$ 9 dB, T_{if}= 1000 K, results in T_r = 12000 K

Table 3. Main specifications of the Receivers

Parameters	Receiver-1	Receiver-2	Receiver-3	Receiver-4
Frequency covered (GHz)	122-138	141- 168	172-200	205-230
Bandwidth (GHz)	16	27	28	25
No. of mixer	1	1	1	1
Frequency resolution (GHz)	1	2	2	2
IF band pass filter bandwidth	0.5 GHz	1 GHz	1 GHz	1 GHz
No. of channels	16	14	15	13
Noise Temp	Less than plasma noise ~ 10 eV [7]			
Remarks	Total no. of channels = 58, Total no. of mixers/down converters = 4			

3.2.1. Channel details for Receivers:
This section describes the channel details of each of the four receivers. A 2-way and an 8-way power divider are used after the mixer and IF amplifier to obtain the required number of channels in each receiver. This is then followed by cavity filters. The channel separation of the cavity filters decides the frequency resolution and hence the spatial resolution in the plasma. The frequency resolution will be different in different receivers in order to achieve the spatial resolution requirement of ~6.7 cm. The number of channels will depend on the frequency resolution. For Receiver-1, the IF frequency bandwidth is 16 GHz and frequency resolution is 1 GHz, so number of channels would be 16. For receivers 2, 3 & 4, the IF frequency bandwidths are 27 GHz, 28 GHz and 25 GHz respectively and frequency resolution is 2 GHz. Thus number of channels is 14, 15 and 13 respectively.

3.2.2. I & C requirement for the Radiometer:
In order to meet the temporal resolution requirement for temperature measurement and Plasma control system for the radiometer having four receiver systems with a total of 58 channels, it is planned to use video amplifier with 3 dB bandwidth of 1 MHz and sampling at 100 Hz (slow sampling) and at 500 kHz (fast sampling). The data acquisition system will be based on 16 bit channel ADC modules.

4. Conclusion
The preliminary design of O-mode Radiometer for ITER ECE Diagnostic has been described in this paper. The Radiometer is designed considering the measurement requirements and present days' technical feasibility. The design has been optimized by considering four receivers, each of bandwidth ~ 30 GHz which can provide reliable temperature measurements. Splitting of the frequency band into four receiver bands is efficiently achieved by considering hybrid splitting mechanisms. The target spatial and temporal resolutions have been achieved by choosing appropriate IF and video bandwidths.

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