DEVELOPMENT OF A HIGH TEMPERATURE BLACK BODY SOURCE FOR ITER ECE DIAGNOSTIC

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Abstract

For ITER Electron Cyclotron Emission (ECE) diagnostic, there is a requirement of high-temperature black body radiation source operating at atmospheric pressure. This source needs to be operated at high temperature (~ 500 ^{0}C) having a microwave emissivity > 0.95 in the frequency band 100-500 GHz, and > 0.75 for 500-1000 GHz. Moreover, the radiation surface should have temperature uniformity within ±10 ^{0}C. This source will be utilized for characterizing the ITER ECE measuring instruments like Michelson Interferometer and radiometer. For this purpose, a radiation source has been designed and developed. The radiation source consists of a heater and an emissive surface. The emissive surface is made of silicon carbide (SiC), as it has high thermal conductivity, low thermal coefficient of expansion, excellent machinability, and high emissivity in the mm-wave region. The developed source emissive surface diameter is 200 mm.The suitable heating element has been used having high resistivity and good oxidation resistance nature.This paper deals with the design, analysis, and characterization of the developed high-temperature black body radiation source in the frequency range 100 to 1000 GHz. The Finite Element Method based software, "COMSOL", has been used to analyze and optimise the heating coil design to get desired temperature uniformity of the emissive surface. Experimentally, the temperature uniformity is measured by an IR camera and microwave emissivity is measured by the Michelson interferometer. The operating temperature of 500 ^{0}C is achieved in the developed source with temperature uniformity within ±10 ^{0}C. The short and long-term temperature stability up to ± 2 ^{0}C and ± 10 ^{0}C respectively has also been achieved. Further, the microwave emissivity of ~0.8 - 0.9 has been observed over wideband 100-1000 GHz. The above measured values are in compliance with ITER measurement requirement.

1. INTRODUCTION

The ITER Electron Cyclotron Emission (ECE) Diagnostic will be used to provide important information like electron temperature profile, magneto-hydrodynamic (MHD) fluctuation spectra, non-thermal behaviour and the ECE radiated power loss. The ECE system consists of front end optics, broadband transmission line system, ECE measurement equipment's with instrumentation & control and high temperature black body calibration sources. The calibration source plays a very important role to measure the absolute temperature of plasma within the accuracy of 10%.

For ITER ECE Diagnostic [1], there is a requirement of high-temperature black body radiation source operating at atmospheric pressure. Considering the ITER requirements, this broadband source is successfully developed by ITER-India. The high temperature radiation source is required to be operated at high temperature (~ 500 ^{0}C) and desired microwave emissivity > 0.95 in the frequency range of 100-500 GHz, and > 0.75 for 500-1000 GHz. Moreover, the emissive surface should have the temperature uniformity within ±10 ^{0}C. This source will be used to ensure the stability and performance of the ITER ECE measuring instruments like Michelson Interferometer and radiometer.

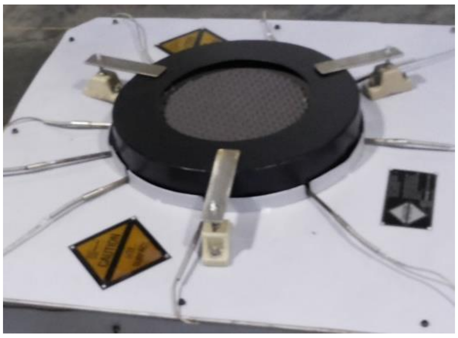

FIG.1. Broadband high-temperature blackbody calibration source

For this purpose, a high-temperature radiation source has been designed and developed. The radiation source consists of a heater and an emissive surface. The emissive surface is made of Silicon Carbide (SiC), as it has high thermal conductivity, low thermal coefficient of expansion, excellent machinability, and high emissivity in the mm-wave region [2]. Further to improve the absorptivity/emissivity, the surface of the source is grooved so that radiation incident on the surface will encounter multiple reflections and eventually gets absorbed by trapping the radiation. To cover the main lobe of the antenna radiation pattern, the optimized emissive surface size is 200 mm.The suitable heating element has been used, having high resistivity and good oxidation resistance nature.

This paper deals with the design, analysis, and characterization of the developed high-temperature black body radiation source in the frequency range 100 to 1000 GHz. The Finite Element Method based software, "COMSOL" [3], has been used to simulate and optimise the heating coil design and its orientation to achieve desired temperature uniformity of the emissive surface. For characterization, the developed source has been heated up to 500 degree Celsius and temperature uniformity is checked. Also, temperature stability for long term uses has been done at different time intervals. Experimentally, the temperature uniformity is measured by an IR camera and microwave emissivity is measured by Michelson interferometer by comparing the radiation spectrum of SiC and liquid nitrogen (Eccosorb kept at liquid nitrogen temperature). The microwave absorber, Eccosorb at Liquid Nitrogen (LN2) is a good approximation of a black body in millimetre and sub-millimeter waves [3]. The radiation spectrum is measured using Martin-Puplett based Fourier transform spectrometer (i.e. Michelson interferometer) [4].

2. DESIGN REQUIREMENT OF HIGH TEMPERATURE BLACK BODY SOURCE

A prototype high temperature blackbody radiation source is developed for testing the functionality of the millimetre wave instruments like Michelson interferometer and radiometer. The emissive plate of the source is Silicon Carbide (SiC) disk and emissive surface of this is contoured in pyramidal shape. The pyramidal contouring of the SiC surface is created to produce multiple internal reflections of the emissions. The dimension drawing of the SiC emissive surface and photograph of the actual emissive surface are shown in Fig 2.

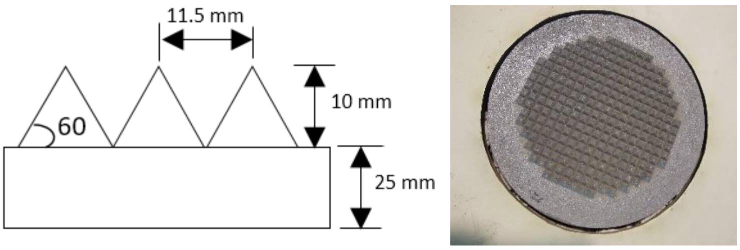

FIG.2. Schematic of the pyramid pattern and actual view of developed source SiC emissive surface

In the design of the emissive surface, two parameters play an important role; one is spacing between the pyramids and another is angle of the pyramids. In order to minimize the diffraction effects, the spacing (11.5 mm) in between the pyramids are kept larger than the maximum wavelength of interested frequency range. Our frequency range of interest is 70-1000GHz. The angle of the pyramids is kept around 60 degree to increase the number of internal reflections. The main design requirements of the calibration source are (a) the aperture of the calibration source should be large enough to cover the main lobe of the antenna radiation pattern, (b) The desired temperature of source (i.e. 500 ºC) should be as high as possible, (c) The emissivity of the source should be close to unity in the frequency range 70-1000 GHz, (d) the surface temperature of the source should be uniform across the emissive surface, (e) The temporal stability of the high temperature calibration source should be good. The required short and long term temporal stability of the source is ± 2 ºC and ± 10 ºC respectively.

3. DESIGN OF HIGH TEMPERATURE BLACK BODY SOURCE

The high temperature black body radiation source consists of heater plate, an emissive plate and surface temperature measurement arrangement with temperature controller. The heater plate is made of stainless steel (SS) plate of diameter is 285mm and 25 mm thickness. The heating elements are wound over the ceramic tubes in spiral form. These tubes are supported by the thermal shield made of ceramic material. Fig 3 shows the schematic diagram of heating elements and contoured silicon carbide plate. Ferritic iron-chromium-aluminium alloy (FeCrAl) is chosen as the material for heating elements as it has good oxidation resistance and high resistivity. The emissive surface of the source is made of Silicon carbide material. We used this material on account of its high thermal conductivity (~ 100 W/m-K), high emissivity in the mm wave region, and low thermal coefficient expansions. It is also having excellent machinability.

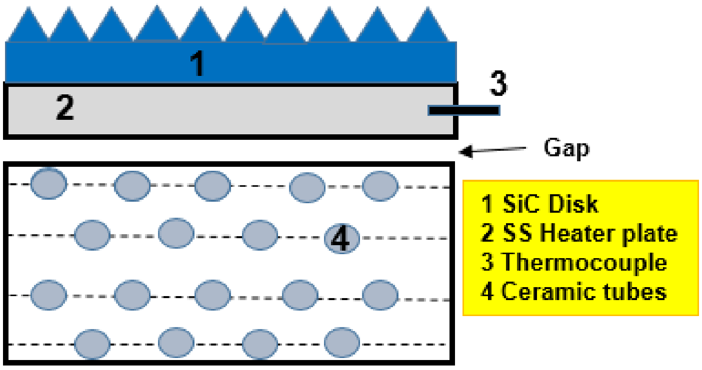

FIG.3. Cross section view of the developed source shows the arrangements of heating coils and other parts of the source

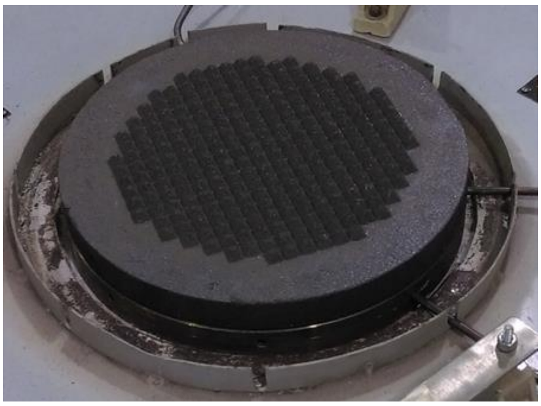

FIG.4. Emissive SiC surface integration with the source

The indirect heating option is adopted for heating the emissive surface of the source. The heater plate is kept just above the heating coils shown in Fig 4 and emissive plate is kept over the heater plate with good contact. The heating wires are heated resistively and the heat energy emitted from the coils is transferred to lower side of the heater plate via radiation and convection. Due to surface contact in between the heater plate and emissive plate, heat is conducted and required temperature is achieved over the emissive surface.

4. THERMAL ANALYSIS USING COMSOL SOFTWARE

The FEM based COMSOL Software [5] is used for simulating the temperature distribution in high temperature radiation source. Using this simulation tool, various orientation of the heating coils were modelled and their impact was studied on the temperature uniformity over the emissive surface which is one of the main design parameter of the source. Moreover, the pyramid size (Height, base cross section, and pyramid angle) was also optimized to get the desired temperature uniformity. The difference in temperature between the pyramid top and the bottom versus pyramid height is shown in Fig 5.

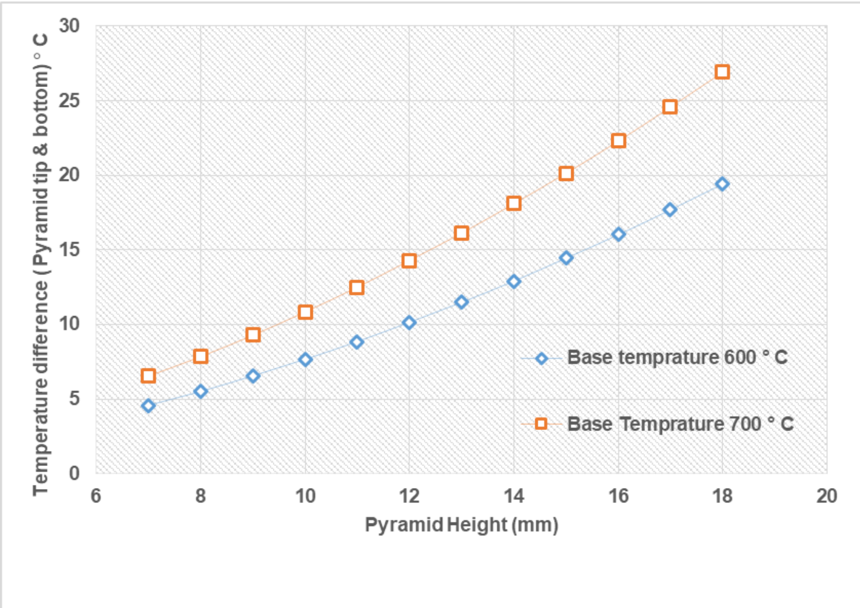

FIG.5. Temperature difference between pyramid tip & bottom versus pyramid height

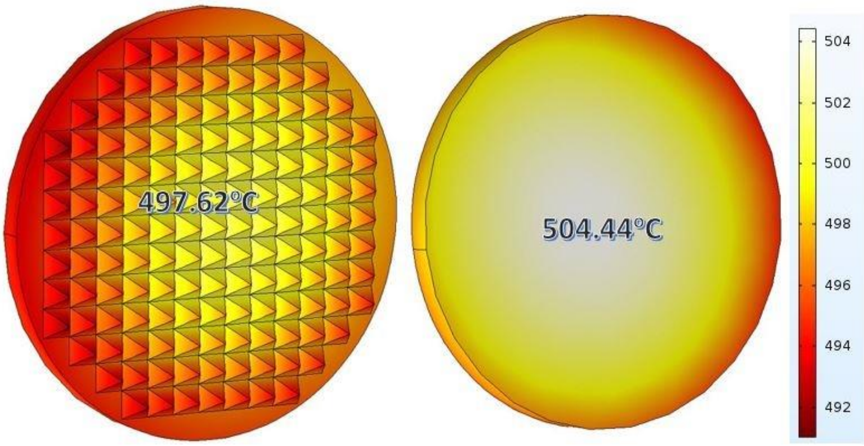

FIG.6. Temperature distribution in designed source front and rear surface of emitter plate

The simulation results of steady state analysis show that the design of the high temperature source can achieve the required emitter surface temperature of 500 degree Celsius with less than 10 degree Celsius surface temperature uniformity. The temperature distributions in the SiC emitter is shown in Fig 6.

5. MEASUREMENTS RESULTS

5.1 IR Measurement

An experimental set-up was developed for measuring the radiation temperature over the emissive surface of the source. The experimental setup consists of the high temperature radiation source and an IR camera which is fully controlled by PC. The IR camera is used to measure the temperature distribution of the emissive surface. The thermocouples are inserted into drilled holes inside of the heater plate at different location around the circumference and the center to monitor the temperature of the heater plate. These thermocouples are calibrated with temperature accuracy of ± 0.5 ºC. The IR imaging of high temperature black body source is carried by FLIR camera [6]. The IR camera is capable to measure the surface temperature of the material from where emitted radiation falls in the wavelength region of 7.5-14 micron. As emissivity of Silicon Carbide is not available in this wavelength region, therefore the IR camera was calibrated against the standard thermocouple with an uncertainty of ± 0.5 ºC. The Fig 7 is showing the temperature distribution over the emissive surface of black body radiation source. The temperature values (minimum, maximum and average) are measured over the drawn chords.

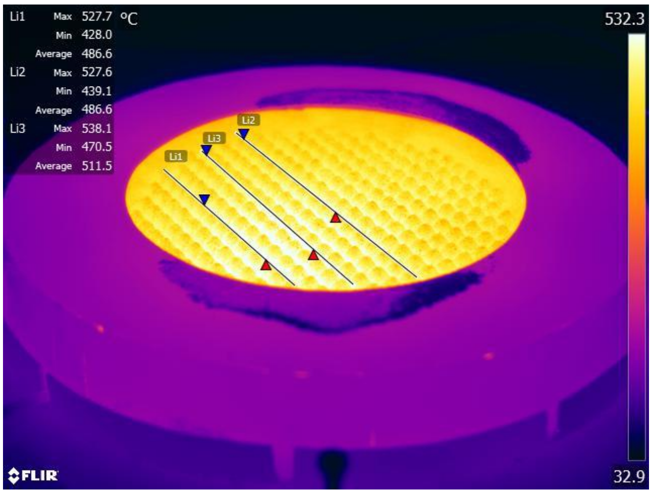

FIG.7. Emitted radiation distribution of the developed source captured using IR Camera

TABLE.1 Temperature variations along the lines depicted in Fig.7

Cords	Temperature uniformity (%)
Li1	+ 8.4 /-12
Li2	+8.4/-9.8
Li3	+5.2/-8

Li1 Line passes through the peak of pyramids in edge of the silicon carbide (SiC) radiative source, Li2 Line passes through the peak of pyramids in center of the SiC source and Li3 Line passes through the variety of pyramids of the Silicon carbide radiative surface as shown in Fig 7.

5.2 Microwave emissivity measurement

The emissivity of Silicon carbide material at mm wave frequencies is very important for calibration source used for electron cyclotron emission measurements. ITER Prototype Michelson Interferometer [7] has been employed for measuring the emissivity of silicon carbide material. The Michelson Interferometer can cover a broadband frequency range 70-1000 GHz and also it is very sensitive due to low noise equivalent power (NEP) i.e. $\leq 2\times 10^{-12}$ W. Hz$^{-1/2}$. For measuring the emissivity, a very standard experimental set-up was prepared. This experimental set-up consists of the Michelson Interferometer, short section of transmission line for coupling the black body radiations from source to the Michelson interferometer input ports and LN2 source. The schematic of set-up is shown in Fig 8.

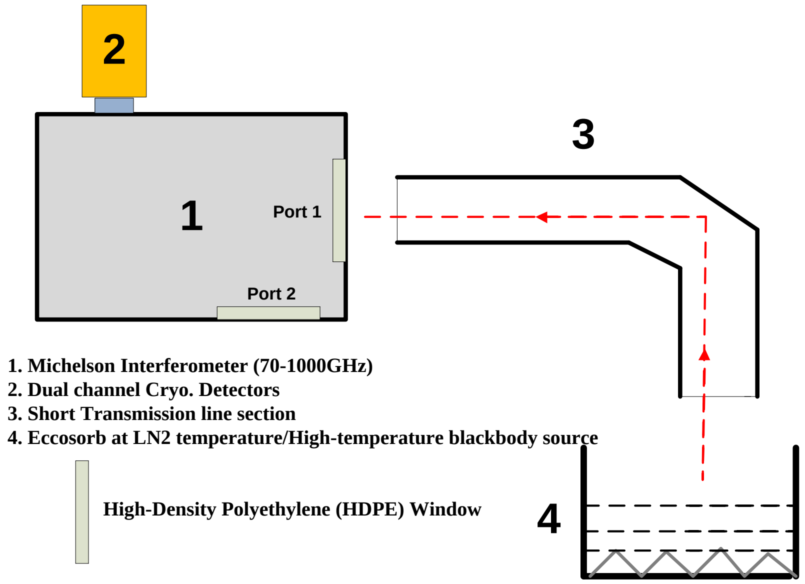

FIG.8. Schematic of an Experimental set-up

The radiation spectrum of the high temperature source and another source with known emissivity i.e. Eccosorb at LN2 temperature were measured separately using Michelson Interferometer. The strong absorption lines due to water vapour are seen at 552, 752, and 988 GHz. Eccosorb at LN2 temperature is used as an ideal black body in the millimeter and Sub-millimeter wavelengths. By comparing the spectrums shown in Fig. 9, the emissivity of the high temperature source is derived.

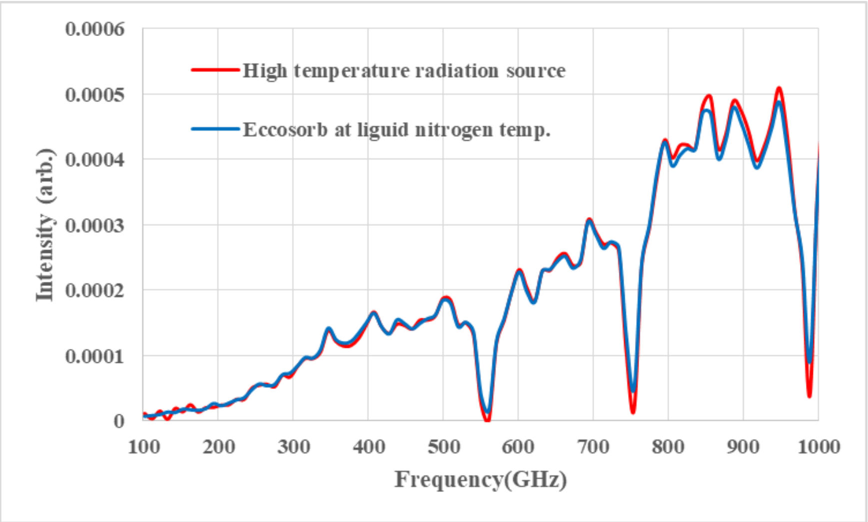

FIG.9. Spectra of High temperature source and Eccosorb at LN2 temperature using Michelson

The developed high temperature calibration source emissivity is measured using Michelson Interferometer. The source has good emissivity of 0.8 in the desired 100-1000 GHz frequency range, excluding water vapour lines, as shown in Fig 10

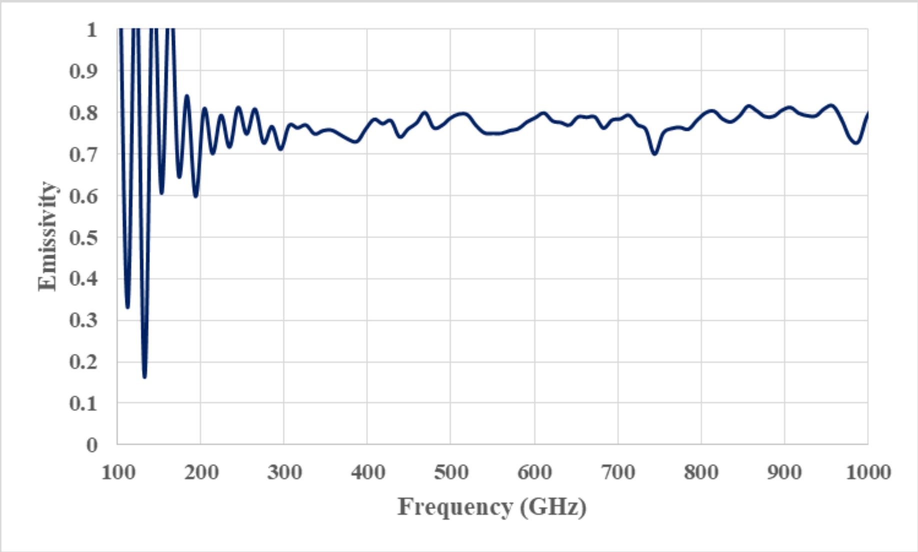

FIG.10. Measured emissivity of the high-temperature radiation source

6. CONCLUSION

This paper describes about the design, analysis and measurement of high temperature black body calibration source. The high temperature radiation source has been developed for testing the functionality and performance of the ECE instruments. The Thermal Model was developed using FEM based COMSOL Software for analysing the temperature uniformity of emissive surface and simulations results are meeting the ITER requirement. The IR camera was also used to measure the spatial temperature uniformity across the radiative surface which is +8.4 %/-12%. The temporal stability of the source is also good. Moreover, the emissivity of high temperature black body radiation source is determined which is 0.8 in 100-1000GHz using ITER Prototype Michelson Interferometer.

Note: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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