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Calibration parameter drift compensation of metal resistive bolometers operating in a thermal varying environment

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HIGHLIGHTS

- ITER bolometers will have to provide measurements in a varying thermal environment of up to 250 °C.
- Heat capacity and thermal time constant of bolometers are affected by thermal drifts.
- ITER bolometer vacuum test facility is used simulate ITER-relevant environment.
- Different methods are demonstrated compensating in real-time the changing calibration values.

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ABSTRACT

The ITER bolometer diagnostic will have to provide accurate measurements of the plasma radiation in a varying thermal environment of up to 250 °C. Current fusion experiments perform regular in situ calibration of the sensor properties, assuming stable calibration parameters within short discharge times, e.g. 10 s on ASDEX Upgrade. For long-pulse fusion experiments, e.g. W7-X, the diagnostic is operated with water cooling for achieving a stable temperature environment. However, ITER will be equipped with about seventy bolometer cameras and is planned to have discharge times of up to 1 h. Due to space restrictions, active cooling is not available for all locations. Thus, an alternative approach is required to allow for compensation of the changing calibration values due to thermal drifts. This paper demonstrates a method using the Wheatstone bridge current of the sensor to calculate in real-time the changing calibration values, such as the heat capacity and the thermal time constant. It is shown, that the thermal calibration parameter drift can be calculated by either extrapolating from the initial values or using a previously determined look-up table. Measurements in the ITER bolometer vacuum test facility (IBOVAC), used to simulate ITER-relevant thermal and vacuum environment, show that the change of the calibration values can be predicted during repeated thermal cycles over a duration sufficient for ITER discharges and even longer. Confidence intervals for the typical in situ calibration method are determined and compared with the proposed extrapolation and look-up method for ITER, showing that these methods provide an equivalent quality of the measurement results.

1. Introduction

The metal resistive bolometer is the most commonly used concept in tokamak and stellarator fusion experiments to provide spatially resolved measurements of the radiated power from the plasma. The sensors are based on a metallic and ceramic microstructure which is used as a broadband radiation absorber and temperature transducer [1]. The change of resistance of an integrated Wheatstone bridge is measured and used to calculate the absorbed power of the sensor.

The sensor is described as a thermal first-order linear time-invariant (LTI) system characterized by its thermal time constant τ and its heat capacity κ [2]. These two values are then referred to as the calibration values of the sensor. They can be measured by heating the sensor with a known power and observing its temperature step-response shortly before the discharge phase. However, the calibration values are only valid for a certain temperature range because they depend upon the thermal conductivity and the thermal contact conductance which again depend on the ambient temperature of the sensor.

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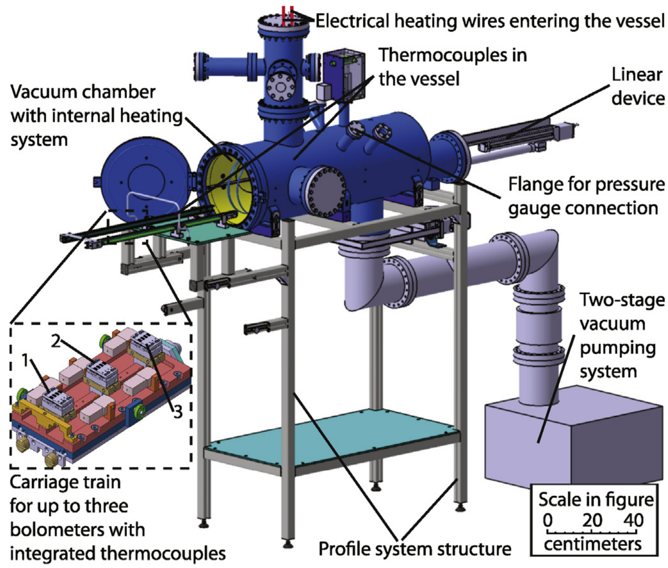

Fig. 1. Perspective CAD image of the IBOVAC test facility with a description of the relevant components.

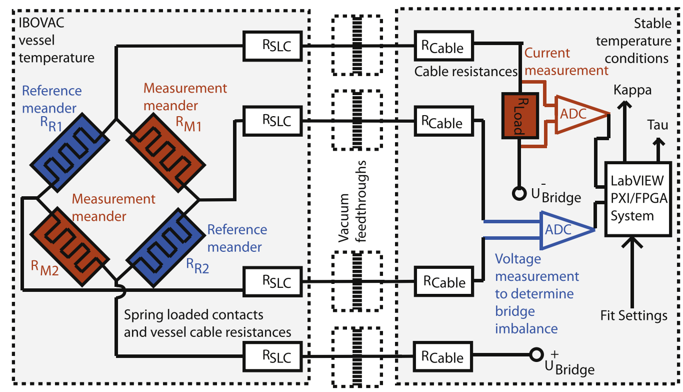

Fig. 2. Simplified equivalent circuit of IBOVAC showing the relevant temperature dependent resistances.

As a solution for this, long-pulse fusion experiments with significant heating systems, e.g. W7-X, are operating the bolometer diagnostic in vessel ports with water cooling [3] in order to achieve a stable temperature environment. ITER will be equipped with about seventy bolometer cameras. They will be distributed all around the vacuum vessel (VV), the divertor, two upper and one equatorial port. Due to space restrictions, in particular with the bolometer cameras mounted onto the VV, active cooling is not available for all locations. And exactly these cameras are considered particularly relevant for physics studies and used to monitor and improve the massive gas injections of the Disruption Mitigation System ensuring the safe operation of ITER. Implementing active cooling for a diagnostic inside a nuclear facility such as ITER will be challenging and costly, consequently should be avoided for other cameras as well.

Theoretical work undertaken in the past, demonstrated the relationship between the offset voltage and the bridge current being a function of the ambient sensor temperature [4]. In this paper, the concept is extended towards the thermal drift of the calibration values (κ and τ). It is shown in an experimental setup, that the drift can be calculated in real-time eliminating this source of error for the calculation of the radiated power. Confidence intervals for the typical in situ calibration method are determined and compared with the accuracy of the proposed extrapolation method for ITER showing that this method provides an equivalent quality of the measurement results.

2. Experimental set-up

The ITER bolometer vacuum test facility (IBOVAC), shown as a CAD image in Fig. 1, is used to examine the change of calibration parameters in a ITER-like thermal and vacuum environment.

Up to three (four-channel) bolometer sensors can be mounted on a carriage train, electrically contacted and then inserted in the center of the vessel controlled by a linear device. The vessel can be heated through thermal radiation from a heating drum with coils around the carriage train (operated at 230 V, 11 A) and through thermal conduction by a second heating circuit in the carriage train (operated at 24 V, 11 A). Both heating circuits are feedback controlled with an on/off controller having a deadband of 1 °C. Thermocouples of type K are distributed on several positions in the vessel including one being integrated in each one of the bolometer sensor holders to be as close as possible to the sensor itself. Internal temperatures of up to 450 °C can be reached and permanently kept in order to simulate ITER-like bake out temperature cycles or other needed temperature profiles. The outer surface of the heating drum and the inner surface of the vacuum-vessel are fitted with thermal shields to reduce heat transport by radiation. An additional thermal insulation on the outside of the vacuum-vessel reduces energy loss. The vacuum vessel is pumped in two stages by the dry roughing pump Adixen ACP28 and the turbo pump Adixen ATP400 enabling operation at pressures down to 10^{-8} mbar at 25 °C. The pressure inside IBOVAC is monitored using the compact full range gauge Pfeiffer PKR 251 and the baratron MKS type 120A. Temperature and pressure values can be acquired with a sample rate of up to 10 Hz.

Control and data acquisition of all components of the test facility IBOVAC is done using a dedicated software programmed in National Instruments LabVIEW, running on a PXI/FPGA system. The same calibration and measurement procedures in this software are currently in use at ASDEX Upgrade and W7-X bolometer systems [5]. This has the advantage that the methods shown in this paper will be easy to implement on these devices.

Fig. 2 shows the equivalent circuit (EC) of IBOVAC containing the relevant resistances: The reference meander resistances (R_{R1}, R_{R2}), the measurement meander resistances (R_{M1}, R_{M2}), the resistances due to the spring loaded contacts, the in vessel cable resistances ($4xR_{SLC}$) and the external cable resistances ($4xR_{Cable}$). Simplified symbols for the analog to digital converters (ADC) performing the current and voltage measurement of the bridge are shown as well. The special characteristic of the system here, is that each channel contains an additional ADC with load resistor allowing to measure the current through the entire bridge circuit. Intention of this EC is to show also which resistances are part of the varying thermal environment respectively which ones have to be taken into account when calculating the impact on the total current through the system.

Fig. 3 shows the thermal and pressure reference scenario (RSC) used for all results shown in this paper. The vacuum vessel is heated in three stages, 30 °C, 90 °C, 150 °C with a heat ramp of 1 °C/min. Then, it is left to cool down for about 2 days. Operation at >150 °C are possible but would exceed the specifications of the spring loaded contacts which electrically connect the bolometer sensors and could add uncertainties to the interpretation of the signals. Thus, this is avoided here, in particular for an experiment which focuses on the question of measurement quality. At the beginning of the run, the pressure is at the lowest achievable value of the pumping system. Due to the internal heating the pressure rises, but stays always $<10^{-5}$ mbar. Therefore, heat transfer via