Thermal Drift Study on the Bolometer Diagnostic for Steady-State Fusion Plasmas

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1. Introduction

For future quasi-steady-state fusion devices such as W7-X, WEST and ITER, bolometer diagnostics based on temperature changes of metal resistive detectors[1] are affected by thermal loads from long term plasma radiation. The detector holder behind the aperture, acting also as a heat sink for the detectors, warms up during long pulse experiments due to its limited heat capacity. This warming is partially due to the inherent ohmic heating of the meander resistors building the Wheatstone-bridge of each detector, which are usually connected to an AC-voltage supply. The detector holder temperature rise leads to offset drifts and thus measurement uncertainties as the detectors consist of measurement- and reference parts whose resistances, heat capacities and cooling time constants are not exactly equal due to production tolerances. Thermal drifts of ~100μV/K have been measured using two kinds of metal resistive bolometers (Au/Kapton type and Pt/SiN type). Simulations are performed on a bolometer camera with a similar geometry as that designed for the W7-X stellarator[2] aiming to demonstrate the non-negligible signal offset drift associated with the temperature rise of the detector holder if the designed water cooling in the holder is absent. This confirms the necessity of cooling the bolometer for steady state operation. Further, these simulations demonstrate the relationship between the offset voltage, U_{offset}, and the bridge current, I_d, as a function of the holder temperature. This demonstrates an alternative way to perform real-time offset correction besides suppressing the offset drift by cooling. This alternative is particularly suitable for bolometers without any possibility for cooling due to lack of space (e.g. the bolometers in ITER).

2. Simulation of the bolometer offset and its thermal drift

Bolometer offset The four meander resistors building the Wheatstone-bridge, M1 and M2 on the rear side of the measurement foil and R1 and R2 on the rear side of the reference foil (see Fig. 1), are produced with small tolerances (<2%). The other foil parameters, the cooling time coefficient, τ, the heat capacity, C, and the relative sensitivity, κ, defined as $C/\alpha\tau$ (α is the thermal coefficient of the resistance), have also individual variations. The foil parameters, hereafter using subscripts m and r for distinguishing those of the measurement and reference foil respectively, can be determined using the ohmic heating calibration method[3]. The τ values (~100-200 ms in vacuum) usually vary less than 5% and show only small temperature dependence. The relative sensitivities vary by as much as 10% and show stronger temperature dependence. Switching on the voltage supply, U_0, the meander resistors will warm up by ohmic heating. This process stabilizes within several cooling times when the foils reach thermal equilibrium. The bridge output, i.e. the offset, is given by:

$$U_{offset}=U_0\frac{1+\alpha\Delta T_m-\eta(1+\alpha\Delta T_r)}{1+\alpha\Delta T_m+\eta(1+\alpha\Delta T_r)},$$

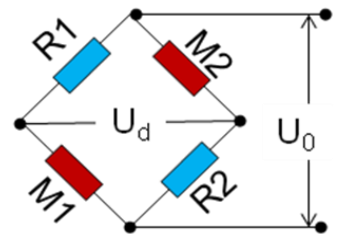

Fig. 1 The bolometer bridge consisting of two measuring resistors, M1 and M2, and two reference resistors, R1 and R2.

whith $\Delta T_r\approx\Delta T_0(1-\alpha\Delta T_0)$ and $\Delta T_m=\Delta T_r/[\beta(1+\alpha\Delta T_r)-\alpha\Delta T_r]$ being the foil temperature increments by ohmic heating, $\beta=(R_0/M_0)\cdot(\tau_r/\tau_m)/(C_r/C_m)$, $\eta=R_0/M_0$ and assuming $R1=R2=R_0$ and $M1=M2=M_0$ at room temperature for simplicity. For low heating power ($\alpha\Delta T$<<1), they are rewritten as $\Delta T_r\approx\Delta T_0=\frac{2U_0^2R_0}{(M_0+R_0)^2}\cdot\frac{\tau_r}{C_r}$ and $\Delta T_m\approx\Delta T_0/\beta$. β can be rewritten as $\beta=\eta\kappa_m/\kappa_r$. For $\beta\neq1$, this describes the total variations of the sensitivities and the resistances of the two foils. These variations are the major cause of the difference between ΔT_m and ΔT_r, and therefore the voltage offset. Using laser-trim technology the resistance differences of the measurement and reference meanders can be reduced and η close to 1 is obtainable[4].

Offset drift The detector holder hosting multi-channel detectors acts additionally as a heat sink for the detector foils. A good thermal contact between the detector front plates and the holder is required. If the holder temperature increases with ΔT_h, the temperature changes of the two foils will be $\Delta T_m+\Delta T_h$ and $T_r+\Delta T_h$, giving rise to offset change, i.e. offset drift. The drift amplitude for small ΔT_h is derived as $U'_{offset}=\frac{2U_0\alpha^2(\Delta T_r-\Delta T_m)}{\eta+\eta^{-1}+2\alpha(\Delta T_r+\Delta T_m+\Delta T_r\eta+\Delta T_m/\eta)}$. For η =1 it can be simplified as $U'_{offset}=U_0\alpha^2(\Delta T_r-\Delta T_m)/(1+2\alpha(\Delta T_r+\Delta T_m))$. Estimation of U'_{offset} is done using typical values of Au/Kapton foil, R_0=1200Ω, η=1.02, α=0.0034 K^{-1}, C_r=135μJ/K, β=5% and U_0=10V. An offset drift around 120μV/K is obtained. Generally, U'_{offset} lies between 50-150μV/K for both Au/Kapton- and Pt/SiN-detectors (keeping U_0 at 10V), depending mainly on the β-value. These results are consistent with the experimental results.

Numerical simulations have been made based on one of the designed W7-X bolometer cameras assuming a deactivated cooling system in the holder. Three coupled power balance equations concerning the temperatures of the foils, T_m and T_r, and the detector holder, T_h, are established taking the ohmic heating and the plasma radiation as heat sources. Power losses are the heat transfer from the foils to the holder and grey body radiations of the foils as well as of the holder (in vacuum). The holder has dimensions of 140×45×7mm^3 and structures to install a 24-channel-detector array; the plasma radiation flux density for 30 min. discharges onto the aperture (5×10mm^2) is taken as 100 kW/m^2. The power flux density onto the detectors and the holder is reduced by a factor of around 600 due to the small viewing angles. Numerical solutions of the equations, i.e. time evolutions of T_m, T_r and T_h are obtained. The voltage signals, U_d, and the resistance differences of the resistors are accordingly calculated. They are shown in Fig. 2. The rapid changes of the parameters for t<1s after turning-on U_0 (at t=0s) are associated with the cooling time coefficients of the foils (τ_r=0.15s and τ_r/τ_m=1.04). During a 30 min. discharge the net temperature rise of the measurement foil induced by the plasma radiation is around 0.3°C, which is superimposed by the holder temperature rise of around 10°C. The pure voltage signal amplitude is 3.0 mV and the offset drift amplitude is comparable to it. The non-negligible offset drift affects the channel signal to be used for real-time performance, e.g. providing feedback control in case of deliberate impurity seeding. Enhancing data accuracy by suppressing the offset drift or by performing real-time offset correction is thus essential for steady-state bolometer diagnostics. The results showed in Fig. 2 are for Pt/SiN type detectors. Similar results have been obtained for the Au/Kapton type.

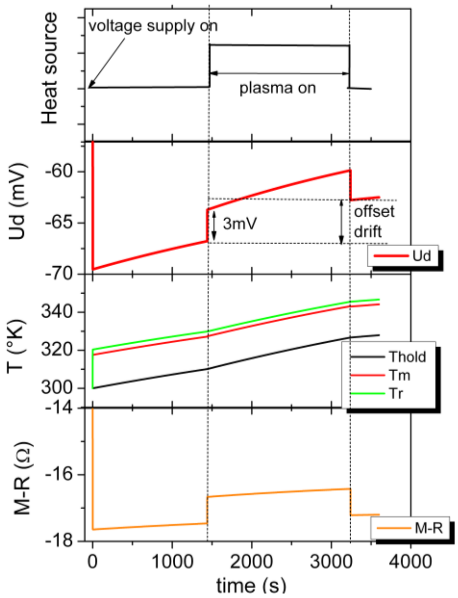

Fig. 2 Simulations of the signal thermal drift for a bolometer with Pt/SiN detectors (time step=10ms, β=1.10, η=1.005 and U_0=10V).

3. Offset drift suppression and real-time correction

To suppress the thermal drift effect, active water cooling systems are implemented both in the detector holders and apertures of the W7-X bolometers to minimize ΔT_h. Thermal analysis using ANSYS indicates that T_h can be kept close to the cooling water temperature during 30 min. discharges. This method is however not available for the bolometers in ITER due to limited cooling access. Here we demonstrate a way to deduce the offset and to compensate it in real-time.

The bridge current is given by $I_d=2U_0/\{(R_0+M_0)+\alpha\cdot[M_0(\Delta T_m+\Delta T_h+\Delta T_{rad}))+R_0\cdot(\Delta T_r+\Delta T_h)]\}$ with ΔT_{rad} being the plasma radiation induced measurement foil temperature change during discharges. Since $\Delta T_{rad} \ll \Delta T_h$ as demonstrated by the simulation results above, the contribution of ΔT_{rad} to I_d is negligible. The correlation of I_d with ΔT_h is therefore confirmed. Based on the definition of the bridge output, the relationship between the voltage offset, U_{offset}, and I_d can be derived. For the case of $R_0=M_0$ and small temperature changes of the foils, it is given by $U_{offset}=I_dU_0^2(\beta-1)/4\kappa_m$, where κ_m is the relative sensitivity of the measurement foil. Fig. 3 shows the total bridge signal, U_d, versus I_d, which are deduced from the simulated data in Fig. 2. A polynomial function is fitted to the data points without plasma radiation and noted as $U_{offset}(I_d)$. It differs only slightly from the linear function above. Using this function and measuring the I_d values during the discharges, the corresponding voltage offsets can be subtracted from U_d. The corrected data are shown in the inset. It is noteworthy that the corrected U_d decreases with time slightly. The reason is the increment of the bridge resistances with time. For further conversion of U_d to power fluxes the temperature dependences of the resistances and the sensitivities should be taken into account. Relative errors involved in this method, caused by ignoring I_d change due to ΔT_{rad} are estimated as ~0.2%. The relationship of $U_{offset}(I_d)$ for the actual bolometer system should be measured in advance in the laboratory.

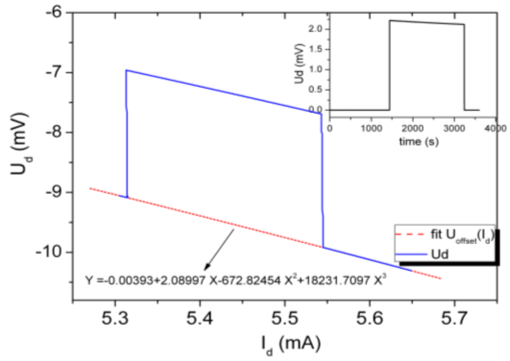

Fig. 3 The simulated bridge signal U_d versus the bridge current I_d for a bolometer with offset thermal drift and the correction of offset (in inset) based on the fit $U_{offset}(I_d)$ and the values I_d.

The simulation results confirm the advantage of implementation of cooling in the W7-X bolometers and provide guidelines for the design of other steady-state bolometers. Further technical aspects, such as selecting a good thermal conductor as holder material (e.g. CuCrZr) to reduce temperature gradients and the additional advantage of a shutter to measure the offset during long pulse experiments, could be implemented in the bolometer system at WEST.

Reference

[1] K.F. Mast, J.C. Vallet, C. Andelfinger, P. Betzler, H. Kraus and G. Schramm, Rev. Sci. Instrum. **62**, 744 (1991).
[2] D. Zhang et al., Rev. Sci. Instrum. **81,** 10, 134 (2010)
[3] L. Giannone et al., Review of Scientific Instruments **73**, 3205 (2002).
[4] H. Meister et al., Rev. Sci. Instrum. **81**, 10E132 (2010).