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Comparison of Au and Pt foils for an imaging bolometer

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The imaging bolometer is a fusion reactor relevant diagnostic for the measurement of radiated power. Essential to its ability to make accurate temporally and spatially resolved measurements of radiated power is the detailed calibration of the thin metal foil that converts the radiated power to infrared radiation measured by an infrared camera. The choice of the foil material is critical to optimizing the sensitivity of the imaging bolometer. Calibration of the foil provides information on the actual sensitivity of the foil which can help in selecting the best foil material. In this work thermal properties of the 0.63 micron thick Au and 0.87 micron thick Pt foils are investigated by heating the foils with a chopped 25 mW HeNe laser and observing the temperature change, ΔT, of the foil and the rise/decay times, $\tau_{rise/decay}$, of the foil temperature. For a foil in which the cooling is dominated by diffusion, since the sensitivity of the foils is proportional to the ratio of the thermal diffusivity to the thermal conductivity of the foil, κ/k, which is proportional $\Delta T/\tau$, where τ is the average of the decay and rise times, we can compare the relative sensitivities of the foils by comparing these ratios for Pt and Au foils. The results surprisingly indicate that Pt is more than 9 times more sensitive than Au even though standard thermal properties indicate that Au should be 14% more sensitive than Pt. This inconsistency is largely due to a slightly smaller decay time, τ, which is inconsistent with a 5 times smaller κ, in the case of the Pt compared to Au. While the 5 -6 times larger temperature rise, ΔT, is somewhat consistent with 3.2 times smaller kt for the Pt foil compared to Au foil. This inconsistency in the thermal times, along with observed differences between the rise and decay times, indicate that the IR radiation is dominant over diffusion in the cooling of the foil. In that case the sensitivity should be evaluated by $1/k \sim \Delta T$ which indicates that Pt is 8 times more sensitive than Au, while the ratio of thermal conductivities indicates that it should be only 4 times more sensitive.

Keywords: bolometer, diagnostics, infrared, imaging, calibration,

1. Introduction

Bolometer diagnostics are essential for the measurement of radiated power loss from fusion devices [1]. The InfraRed imaging Video Bolometer (IRVB) has been under development for application to a fusion reactor due to its durability vis-à-vis neutrons and gammas and its lack of in-vessel wires and the numerous vacuum feedthroughs which plague conventional resistive bolometers [2,3,4]. Also it provides an image of the radiation from the plasma which can be useful for steady-state reactor operation [5].

An IRVB consists of a thin metal foil mounted in a copper frame which absorbs the radiation from the plasma through an aperture. Viewing the foil from the opposite side is an IR camera which is used to measure the change in the foil temperature due to the absorbed radiation. The radiation profile on the foil is obtained by solving the two-dimensional heat diffusion equation for the foil. In order to do so the thermal characteristics of the foil including the product of the thermal conductivity , k, and the foil thickness, t_f, the thermal diffusivity, κ, and the blackbody emissivity, ε, must be determined. Since the foil is blackened with a graphite coating for good IR emissivity, and due to non-uniformity in the manufacturing of the foils, these properties can vary considerably across the foil and from the standard values found in reference handbooks [6]. Therefore it is important to measure these properties carefully to insure the calibration of the diagnostic and to evaluate which foil material is the most sensitive.

The noise equivalent power density, S_{IRVB}, of the IRVB is given by the following equation [7]

$$S_{IRVB} = \frac{\sqrt{2}kt_f\sigma_{IR}}{\sqrt{f_{IR}N_{IR}}}\sqrt{\frac{5N_{bol}^3 f_{bol}}{A_f^2} + \frac{N_{bol} f_{bol}^3}{\kappa^2}} \quad (1)$$

in terms of the IR camera parameters: sensitivity, σ_{IR}, frame rate, f_{IR}, and number of pixels, N_{IR}, the foil properties: area, A_f, thickness, t_f, thermal conductivity, k, and thermal diffusivity, κ, and the IRVB parameters: frame rate, f_{bol} and number of channels, N_{bol}. The blackbody

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radiation term is not included since it is negligible for background temperatures below 1000 K. In normal applications the term on the right side under the radical dominates, therefore we can write $S_{IRVB} \propto kt_f / \kappa$. This should be as small as possible for high sensitivity, therefore we can write the sensitivity of the IRVB in terms of the foil parameters as κ/kt_f.

Recently several candidate foils materials have been suggested for an IRVB. These include Au, Pt and Ta. Au is not a good choice for a reactor since it has a high neutron cross-section which has been observed to lead to transmutation to Hg [8]. Calibration work with Ta showed that its value of kt_f was two times larger than the standard values indicating a halving of its sensitivity [6]. In this paper we consider Pt for the first time and compare it to Au with which we have much experience. The objective of this study is to determine which foil material would be most sensitive for future use on LHD and KSTAR, two large experiments without sizable amounts of neutrons.

2. Experimental technique

In order to evaluate the relative merits of gold and platinum foils we use a laser calibration technique to evaluate the sensitivity of the two foils. Foils with a nominal thickness of 2.5 microns are selected since the target is applications to LHD or KSTAR for which that thickness is sufficient to stop energetic photons. However when samples of the foil material were measured with a microbalance the average thicknesses were calculated to be 0.87 microns for the Pt foil and 0.63 microns for the Au foil. The foils are mounted in copper frames to expose an area of 7 cm x 9 cm then sprayed on both sides with graphite as shown in Figure 1and then mounted in a vacuum flange with a ZnSe IR window. Then the flange is mounted on a vacuum chamber as shown in Figure 2. A chopped HeNe laser (~20 mW) is used to heat the foil at each of twenty positions on the foil starting in the center of the foil and moving step by step in 1 cm increments in both dimensions to cover one quadrant of the foil. A FLIR SC500 IR camera (microbolometer, 8 – 12 microns, 60 fps, 256 x 320 pixels with a close up lens) is used to measure the foil temperature. At each laser position the IR camera data is taken as a series of four 200 frame captures. The first is without the laser to provide a background image, the second is during the temperature rise after the laser shutter is opened, the third records the steady-state temperature profile due to the laser heating of the foil and the fourth records the decay of the foil temperature after the shutter is closed. The background temperature measurement is averaged over the 200 frames and subtracted from the remaining 600 frames. The steady state series is then averaged over the 200 frames and the

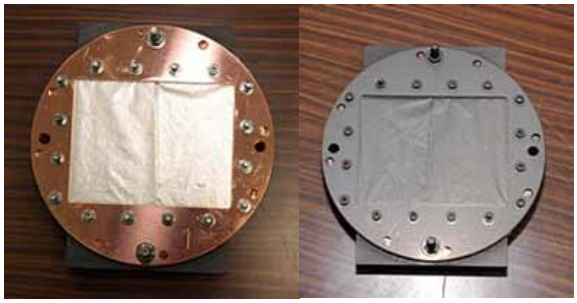

Fig.1 Platinum foil mounted in copper frame before (left) and after (right) blackening with graphite.

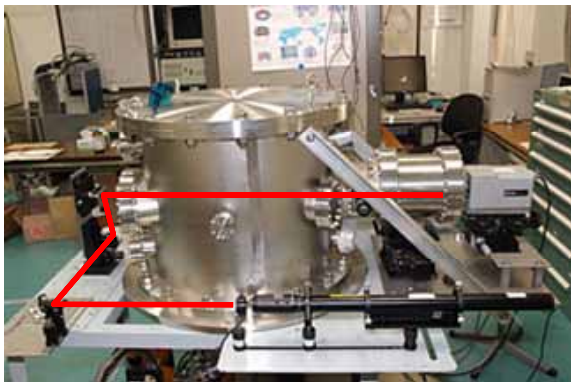

Fig.2 Test stand showing laser path (red).

peak of the temperature profile, ΔT, is found and measured. The temperature rise and decay are fit to a modified Gaussian [4] to find the rise and decay times, respectively, which are averaged to give an effective thermal time, τ, in order to partially remove the effect of the IR radiation. If we neglect the blackbody radiation from the foil then $\tau \propto 1/\kappa$ and $\Delta T \propto 1/kt_f$ and therefore the sensitivity can be written as

$$\kappa / k_f \propto \Delta T\, t / \tau S \quad (2)$$

where S is the laser power density. By comparing these parameters we can evaluate the relative sensitivity of the Au and Pt foils.

3. Results

The vertical and horizontal ΔT profiles when the laser is located at the center of the foil are shown in Figure 3 for the Au and Pt foils. One notes that the temperature rise on the Pt foil is 38.5C while that of the Au foil is 7.65C or 5 times lower. When averaged over 20 points on the foil the average is 44.2C for Pt and 7.15C for Au giving a difference of a factor of 6. In Figure 4 the foil temperature decays are shown for the peak ΔT position with the central laser position for the Pt

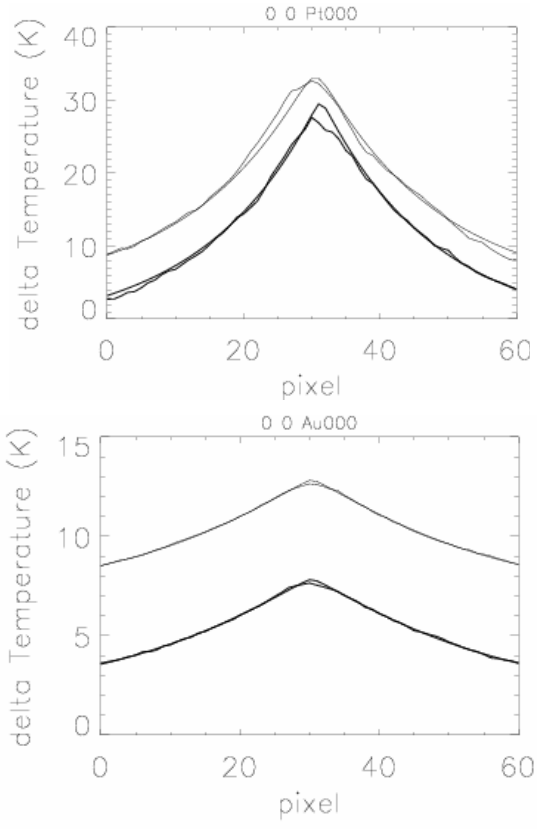

Fig.3 Temperature profiles for Pt (upper) and Au (lower) foils. In each plot upper profile is vertical profile and is offset by 5 C and lower profile is horizontal profile. Fits to a modified two-dimensional Gaussian are also shown.

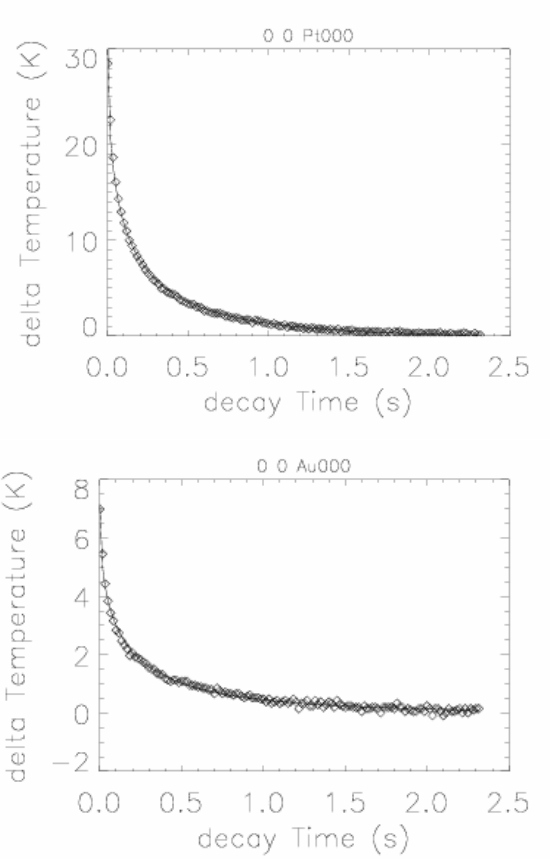

Fig.4 Temperature decays (symbols) for Pt (upper) and Au (lower) foils and modified exponential fits (lines).

and Au foils. The decays are fit to a modified Gaussian as shown in the figure giving decay times of 0.341 s (Pt) and 0.368 s (Au). Not shown are the temperature rise data when the shutter is opened which when fit to the modified Gaussian give rise times of 0.367 s (Pt) and 0.459 s (Au). Taking the average of the rise and decay times for each point and averaging over the 20 points on the foil gives effective thermal times of 0.321 s (Pt) and 0.360 s (Au). If we combine τ, ΔT and slight variations in the laser power according to Equation 2 then we get relative sensitivities of 5.4 Cμm/smW (Pt) and 0.59 Cμm/smW (Au). Therefore Pt is considered to be 9.2 times more sensitive than Au.

4. Discussion

Several observations deserve comment and discussion. First of all, regarding the steady state temperature rise, ΔT, we observed that this is 5 to 6 times higher for Pt than for Au. Since $\Delta T \propto 1/kt_f$, this may be partially explained by the difference in kt, which for the Au foil is 3.2 times greater than that of the Pt foil since Pt has a thermal conductivity which is 4.4 times smaller than that of Au.

Secondly, regarding the rise and decay times, we observe that the rise time is longer than the decay time. This is presumably due to the radiative cooling of the foil by infrared radiation. We attempt to mitigate the effect of this on our comparison of the two foil sensitivities by averaging the decay and rise times. Although this is not the correct way to compensate for this effect, it should remove it partially. In the same sense the temperature rise, ΔT, should also be affected by the infrared cooling. The higher the temperature rise the greater the cooling, therefore we estimate that the Pt data should be more strongly affected by the IR cooling, hence we expect that the actual difference between the two sensitivities should be even larger. Also regarding the thermal times, τ, we note that Pt has a slightly shorter thermal time than that of Au. However, for cooling of the foil dominated by diffusion $\tau \propto 1/\kappa$, we expect that the thermal time for Pt should be 5 times greater than that for Au due to a five times smaller thermal diffusivity. This discrepancy, in addition to the previously described difference in the rise and decay times, indicates that blackbody (IR) radiation is more dominant than diffusion in the cooling of the foil.

This would explain also why the Pt foil cools faster than the Au foil since its temperature is higher due to smaller *k* and therefore the IR cooling effect is greater. This would also explain why Pt is more than 9 times more sensitive than Au even though a comparison of the ratio of their thermal diffusivity to thermal conductivities would suggest that Au should be slightly more sensitive than Pt.

This indicates that our criteria for evaluating the sensitivity given by Eq. 2 may not be correct since this is based on the assumption that diffusion is dominating the cooling of the foil and the experimental evidence that we have is to the contrary (especially the difference between the rise and decay times). Therefore we should consider another criteria for the sensitivity, namely

$$1/k_f \propto \Delta T\, t / P \quad (3)$$

where P is the laser power. When this is considered the experimental values show that Pt is 8.1 times more sensitive that Au while the ratio of the thermal conductivities is 4.4. Therefore based on this criteria the Pt is still 8 times more sensitive than Au while the standard thermal parameters indicate that it should be only 4 times more sensitive.

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We can conclude that Pt would be 8 or more times more sensitive than Au as long as the radiation dominates over the diffusion in the cooling of the foil. We should confirm at which power levels the IR radiation dominates over the diffusion in the foil and make sure that the balance of these two cooling channels is properly handled in the solution of the heat diffusion equation for the incident radiated power. Also this effect should be checked in a thicker foil such as the 2.5 microns we plan to use eventually in KSTAR and LHD and the 10 microns that would be necessary for ITER.

This result indicates that we can raise the sensitivity of the IRVB by a factor of 8 or more by using Pt instead of Au. This should be an advantage for the IRVB compared to resistive bolometers since the resistive bolometer thermal time is determined by the diffusion through the insulating layer to the metal grid and not by blackbody radiation.

By raising the temperature of the foil and frame above that of the surrounding background we should be able to insure that the IR radiation term dominates over the diffusion and thereby remove diffusion from the foil power balance. This will enable an instantaneous measurement of the radiated power that will no longer require solution of the heat diffusion equation. We plan to test this in the near future.

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