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IMAGING BOLOMETRY DEVELOPMENT FOR LARGE FUSION DEVICES

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INTRODUCTION

As magnetic fusion experiments progress towards longer time-scales, more intense neutron and gamma backgrounds, larger physical dimensions, and use of diagnostics for real-time control, the measurement of total radiated power (including total neutral particle fluxes) becomes more challenging. The use of thin foils that absorb and convert the radiation and particle fluxes into a measurable temperature rise, is a standard tool for the plasma diagnostician. Both wide-angle, and tightly collimated foil detector arrays have been used on nearly every tokamak or alternative concept device. The temperature readout is usually accomplished via a DC or AC bridge circuits, to recover the millivolt-level signals, and then differentiated to get power from the time-integrated heat load on the foil and substructures. The challenge lies in making fast bolometers, responsive over the expected range in incident energies, which are also robust, reliable, compact, convenient to calibrate, and cheap enough to afford hundreds of channels for good spatial resolution using tomographic techniques. So-called "ASDEX" or JET-style bolometers manufactured by PTS GmbH, represent the present standard of performance. A new imaging bolometer[1], using infrared readout of hundreds of mini-foils in an actively cooled mask, has been built by LANL, and is presently being tested on the CHS and LHD plasmas in Japan. We describe work in progress towards a radically different approach to obtaining bolometer signals, which has many advantages (and a few disadvantages) over present conventional bolometer systems. We explore a system using technology available today, which simultaneously allows for a cheaper per/channel cost, a high degree of radiation-hardening, no wiring-harnesses in the vessel, no pre-amplifiers, good noise immunity, compatibility with long-pulse operation and real-time readout, and hundreds of channels to form a bolometric image. The drawbacks are the requirement for an optical path to the backside of the detector array, and some sacrifice of sensitivity. *

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BACKGROUND

Numerous review articles have been written over the years on the topic of bolometry in fusion plasma devices[2,3,4]. The general theme is one of trading off various sensor types to achieve sufficient time and spatial resolution in measuring the radiation losses from the plasma. The most sensitive detectors (semiconductors, thermopiles, pyroelectrics, and thermistors) are all unacceptably sensitive to gamma and neutron damage as well. For this reason, metal foil bolometers, which are more radiation-hard and high temperature compatible, have been chosen by most large fusion devices in recent years (TFTR, JET, ASDEX, JT-60U, Tore Supra, etc.). A resistive element is bonded to the radiation absorber, and then wire leads (2 to 4 per unit, including a matched (blind) reference detector) are brought out of the vacuum vessel. Unfortunately, this resistive element is also subject to nuclear radiation-induced changes, in its temperature/resistance coefficient. The signal levels are very small, necessitating a pre-amplifier as close as is practical in the signal pathway. An AC bridge circuit is often used in the readout. With these techniques, sensitivity levels down to 1 μwatt/cm^2 using 10 millisecond averaging, have been achieved in the lab. Noise due to magnetic pickup or auxiliary heating typically raises this lower-bound number by several orders of magnitude. Arrays of 30 – 100 detectors have been employed to reconstruct the spatial profiles of the plasma radiation.

The next generation plasma fusion machines (LHD, W7X, KSTAR, and ITER), will offer a new (or at least more difficult) set of problems for implementing bolometry. The major difficulty will have to do with the issue of survivability in the face of neutron and gamma bombardment of all elements of the bolometer, including sensor, insulators, cabling, or any other close-in components. Furthermore, due to the fact that they will be capable of long-pulse (> 10 second) operation, bolometers which have up to now been inertially cooled, will need active cooling as part of their basic design. Although present-day analysis typically take into account the cooling of the sensor element, usually the cooling time is long compared to the desired time response, and the bolometer temperature rise is differentiated to yield the radiated power, with minor corrections for thermal losses.

Sources of Noise and Pickup

For the metal foil bolometer, the electrical bridge circuit which measures a change in resistance (of the resistor bonded to the metal absorber) is sensitive to a number of noise sources. At a very basic level, there is 1/f and shot-noise in the resistor. By using an AC bridge circuit measurement, at a carrier frequency of 100 kHz to several megahertz, the 1/f noise can be avoided. Although twisted pair or even coaxial leads are used, there still can be additional electrical pickup introduced in the relatively long leads coming from the diagnostic to the location of the discrete amplifiers. This pickup can include effects from magnetic field coils, RF Heating, and other auxiliary systems around the machine. In the case of ECH, it is even possible for actual thermal (resistive) heating of the foil to occur due to absorption of the microwave radiation itself. Consequently, the laboratory lab bench noise level limit of a working bolometer system is often much lower than the effective noise limit of the bolometer when used on a plasma device. The use of "blind" reference detectors, co-located with the plasma facing detectors is one way to "null out" a significant part of the magnetic pickup and nuclear radiation induced effects.

Sensitivity of Historical Metal Foil Bolometers

Metal foil bolometers have been the bolometer of choice for the present generation of large magnetic fusion plasmas, due to their moderately good radiation resistance, vacuum and bakeout compatibility, good time response (~10 msec) and reasonable sensitivity. The TFTR metal foil bolometers (derivatives which are also used on DIII-D) have an equivalent sensitivity of 60 mW/cm^2 with a 10 millisecond time resolution, and were packaged individually. The Physikalisch-Technische Studien GmbH (or PTS for short), Freiborg, Germany, has successfully developed a bolometer head with 2x4 sensors (four that are active, and four that are reference). The detectors are in a compact (33 mm x 20 mm x 15 mm) frame, which is bakeable to 300°C, and have a claimed sensitivity of 1 $microwatt/cm^2$ with a time resolution of 10 milliseconds, while responding to photon energies of up to 5 keV. These units have been sold to JET (England), RFX (Italy), ASDEX-UG (Germany), JT-60U and LHD (Japan), where they are employed in a pinhole/slit camera arrangement to form 1-D arrays.

At JET, the kapton substrate/gold resistor versions[5] (in the KB1 camera) have an equivalent noise level of 70 $microwatt/cm^2$ at 20 Hz, with a comparable level of magnetic pickup. Careful matching with blind detectors reduces both thermal drift and magnetic pickup noise problems. More recently, the new KB3D and KB4 cameras[6], employ a mica substrate/gold resistor, and a much smaller thermal capacity, leading to improved signals. A noise level of 20 $microwatts/cm^2$ is reported, but with substantially larger magnetic interference problems due to more demanding mounting locations, at 400 microwatts/ cm^2.

PTS units purchased for eventual use on LHD[7], are also measured at NIFS to have a 2 $microwatt/cm^2$ equivalent noise level on a lab test stand. On the CHS plasma, due to residual magnetic pickup and ECH interference, this number is also about 10x higher.

IMAGING BOLOMETER DEVELOPMENT

A new type of bolometer for magnetic fusion research is under development[1] at Los Alamos, using a state-of-the art infrared imaging video camera to image the temperature rise on a segmented foil, thereby making hundreds to thousands of "channels" of bolometry possible without wire leads to each foil element. In the late 1970's and early 1980's, single-channel, single detector infrared bolometers were first used on plasma experiments (TFR[8] and ZT-40M[9]). In the intervening 15-20 years, infrared detector technology has progressed to the point where 10's of thousands of detectors are available in one camera chip. Advantages of using an IR imaging bolometer for ITER were pointed out two years ago.[10] The sensitivity achievable by IR readout techniques (rather than resistive electrical measurements) will be a key tradeoff. Indeed, previous authors[2] have dismissed so-called "thermographic bolometers" because of sensitivity limitations (real or perceived) at that time. On the other hand, present specialists point out the need for 3000-4000 channels[6] for adequate reconstruction of ITER radiation profiles, and then dismiss this out of hand as too expensive. We hope to demonstrate that the IR bolometer can indeed answer these issues, and at the same time obtain unprecedented imagery of the plasma radiation profiles.

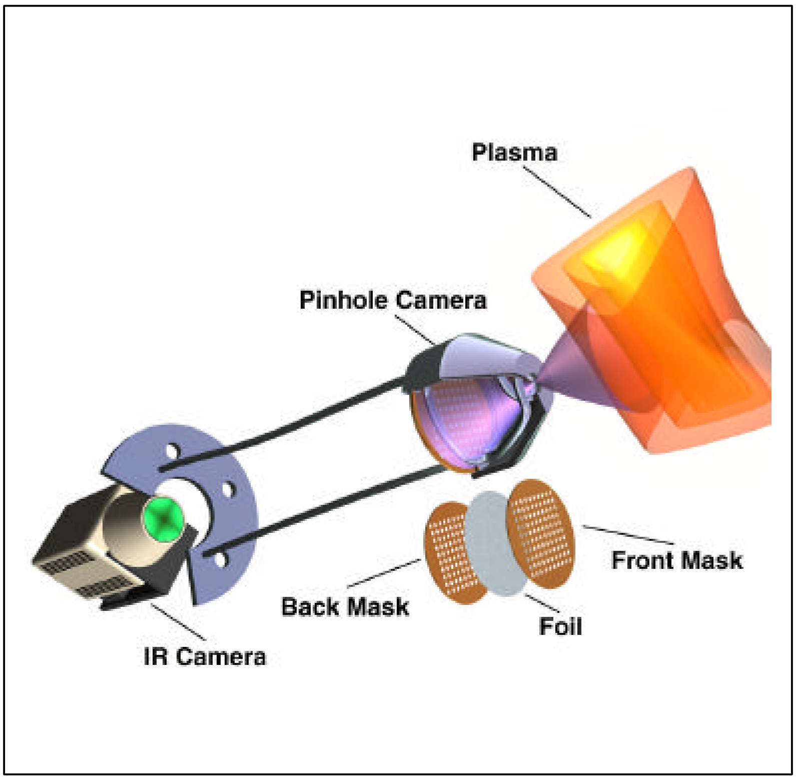

Figure 1: Artist's view of imaging bolometer concept for LHD. The pinhole-camera arrangement which holds the masks, is water-cooled.

The bolometer is very simple (as shown as an artist's concept in Figure 1, and in a CAD wire-frame in Figure 2, and actually realized in Figure 3). It uses an IR camera to view a segmented foil created by sandwiching a thin foil in-between heat sink material (copper) which has a suitable pixel pattern drilled into it. The pixel array views the plasma through a water-cooled pinhole camera. The plasma radiation heats the individual pixel elements on the foil, each of which is thermally isolated from its neighbor by the "thick" copper mask.

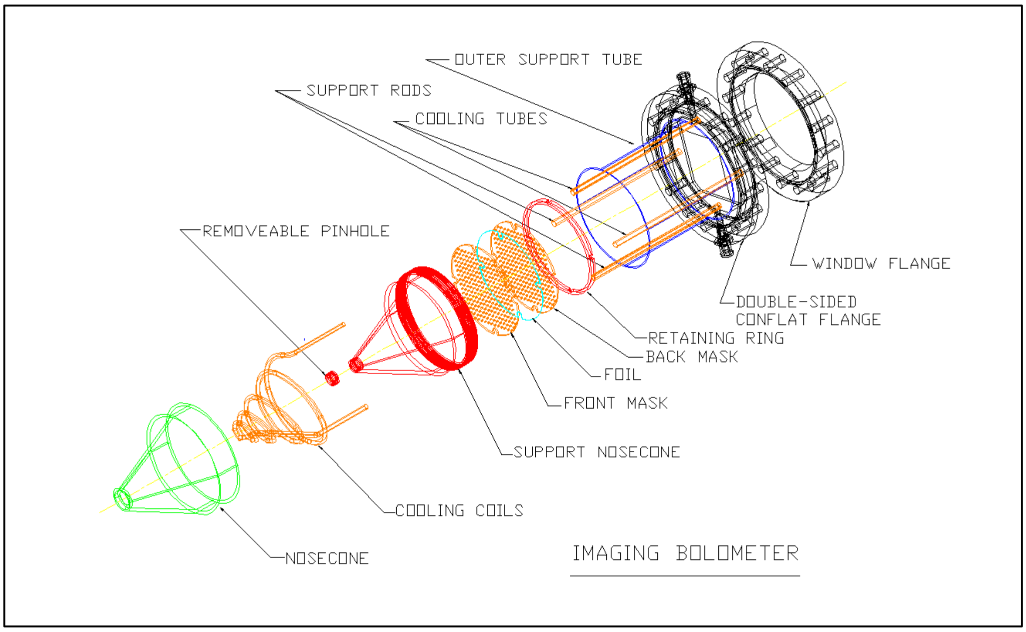

Figure 2: Wire frame schematic of imaging bolometer re-entrant head.

For a 1 μm-thick gold foil, coupled with a 25 m°K IR camera sensitivity, the imaging bolometer would have a 250 μwatt/cm^2 equivalent noise level at a 60 Hz image rate. Tests in the lab with actual windows, emissivity, and camera geometries suggest an actual sensitivity somewhat worse, at ~0.5 mW/cm^2 . If the foil is 10x thicker to stop higher energy photons, then the sensitivity will be correspondingly reduced.

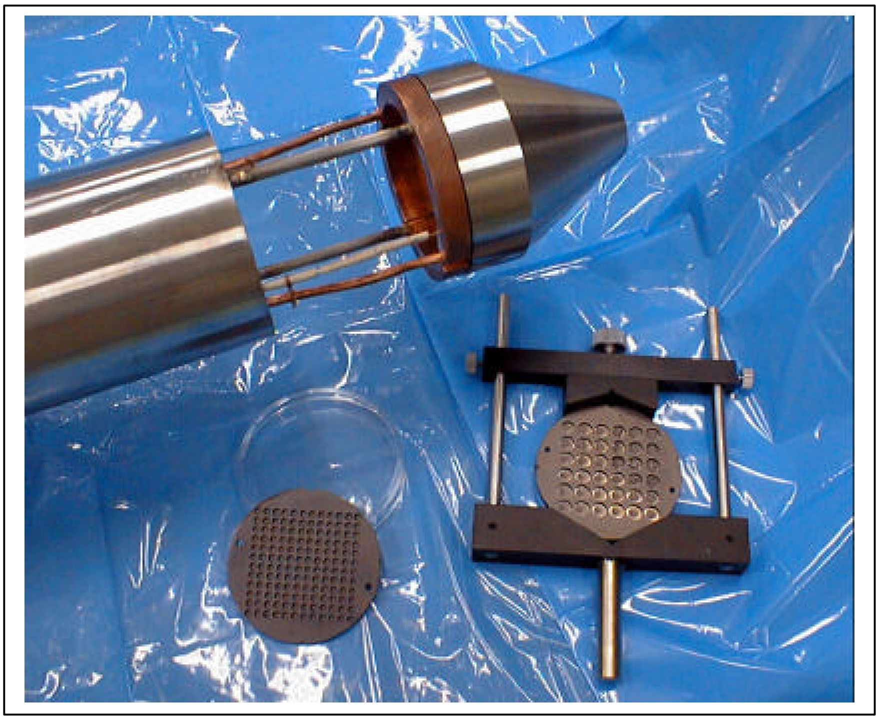

Figure 3: Front assembly of LHD imaging bolometer prototype, with two mask/foil assemblies shown. A mask/foil assembly is placed at the back of the water-cooled pinhole camera nosecone. Two (copper-constantan) thermocouples, and tubes carrying water, are also attached to the copper housing.

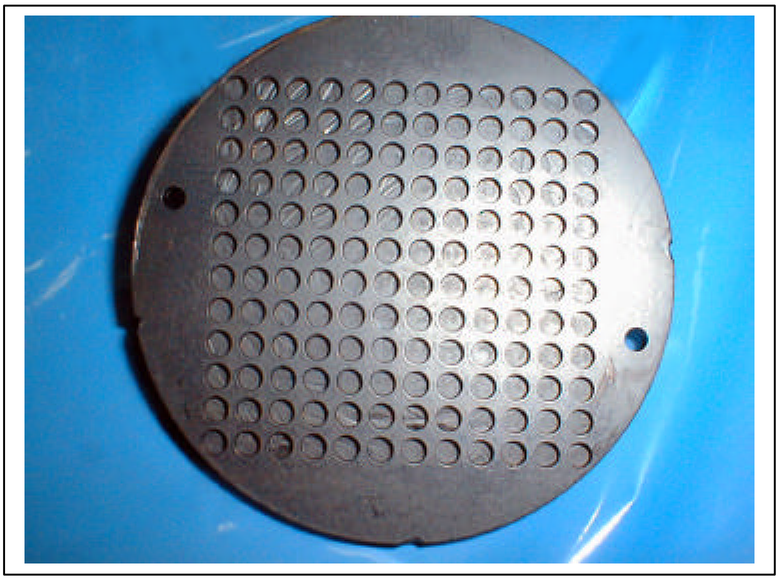

Figure 4: 12 x 12 copper mask, with gold foil which has been blackened with graphite spray.

For the small and relatively cold CHS plasma[11], we expect radiation ranging from 50 kW to 1 Megawatt levels. Thin foils (0.5 - 2.0 microns of gold) are sufficient to absorb the radiation of interest. In hotter (10-30 keV) plasmas, thicker foils are required (~10 microns gold). Even the most sensitive IR camera has only 10 milliKelvin sensitivity limit, at 30 frames/second near room temperature (the Amber Engineering Model 5128 research camera can do 1000 frames/sec but with only 128x128 pixel resolution). The infrared camera shown in Figure 5 costs approximately $100k as configured, including remote computer control and long lens. Consequently thicker foils will mean a loss of sensitivity for the bolometer measurement as well. Dynamic range of these camera systems is 12-bit in the infrared flux, which must then be converted to a temperature via Planck's Law for blackbody emission. Fortunately, ITER makes up for the need for thicker foils, by giving off more total radiated power (up to ~600 Megawatts during normal operation). However, it has been pointed out[12] that nuclear heating of the foils will compete with the desired plasma radiation signal. Blind pixels will be needed for compensation.

Figure 5: 3-5 micron band, 12-bit, infrared video camera, "Radiance 1" from Amber Engineering, with SiGe 75-250 mm f2.3 telephoto lens and internal filter wheel, all controlled by an RS-232 port. Standard 50 mm f2.3 lens is next to some of the filters.

Limitations on Sensitivity of IR Bolometer Systems

The sensitivity limitations come from several intrinsic issues: The noise equivalent power of the thermal imager in the IR wavelength band of interest sets a lower bound. Secondly, background object radiation (due to reflections or stray background thermal radiation) onto the foil of interest will contribute heat or IR emission in competition to that from the plasma radiated power deposited in the foil. Thirdly, IR photon statistics: You need to collect enough photons per desired observation time interval. That is to say, you can’t determine a temperature change, if you don’t have adequate IR photon statistics. Consequently, the optical throughput of the IR optics will effect the minimum ΔT that can be resolved. Next, in order to get the largest ΔT, for a given power flux, you want the lowest heat capacity for your absorber. This is in direct contrast to the requirement that the foil be thick enough to absorb a significant fraction of the soft x-ray flux that hits it. So, the hotter the plasma, the thicker the minimum thickness foil will need to be. This means that (strength issues aside) you can't make an arbitrarily thin foil, (in order to minimize the heat capacity of the target) and thereby boost up the ΔT for a given radiation flux onto the foil. Finally, the bolometer sensor must be shielded against microwaves, in a microwave-heated plasma, such as on CHS or LHD. A free-standing metal mesh must be placed over the entrance pinhole to preclude heating of the foil by microwaves. Cooling for this mesh must come from the boundary of the pinhole camera pinhole.

Calibration Tests (on the bench and with a plasma)

The imaging bolometer prototype, which employs a water-cooled copper pinhole-camera, shielded by a stainless-steel nose-cone, has been vacuum tested in the lab at the National Institute for Fusion Science, in Toki, Japan. A simplified (non-cooled) imaging bolometer has been installed on the CHS plasma in August 1997. To facilitate visible light He-Ne laser calibration, both gold and aluminum foils have been blackened with "Aerodag-G", commercially available micron-sized graphite spray from Acheson Corporation. Typical temperature rises are no more than 1°C for expected plasma sources. Response to a calibration laser is shown in Figure 6.

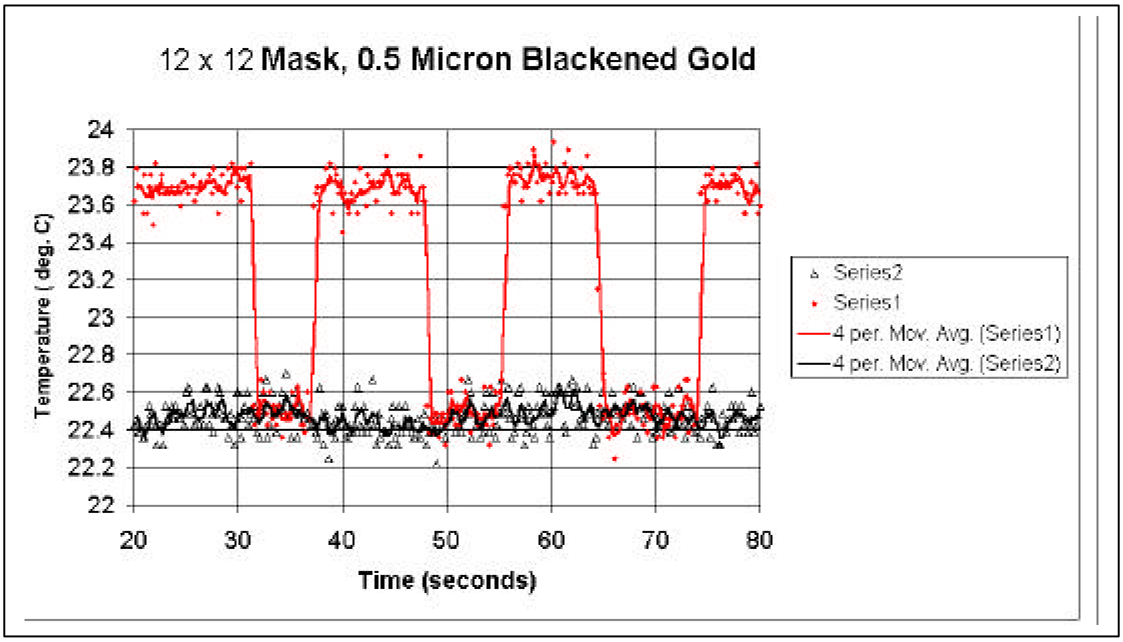

Figure 6: Point temperature measurement made by Agema 9600 IR camera of a foil pixel being illuminated by a 1.5 mW calibration laser (in air).

1). Difference between in-air, and in-vacuum response. The bolometer is observed to be approximately a factor of *2x* more sensitive to radiation in vacuum than it is in air, due to the additional cooling pathway represented by the air hitting the foil. This pathway is absent in vacuum below 100 milliTorr. The magnitude of observed signals in vacuum is at the same time a factor of ~2x larger than our simple model of a cylindrical absorber of conducting material surrounded by a perfectly clamped temperature boundary condition would predict. The peak to average temperature ratio across each pixel, is also observed to be different in air than in vacuum, due to the edge-cooling dominating in vacuum, but with surface-cooling also contributing in air.

2). Degree of thermal cross-talk observed between nearest-pixel neighbors. First generation masks and foil assemblies are observed to have approximately 10% crosstalk levels between nearest neighbor pixels. This is most likely due to imperfect bonding (or no bonding in some cases) between the thick cold mask, and the very thin foil laid across it. The mask must be very flat, and the foils smooth, for good thermal contact. In principle, the foil/mask assembly should be done in a clean room, to keep dust from getting between the surfaces.

3). Decay time of signal. The decay times have not yet been systematically compared to theoretical predictions. Some of the initial foils have an additional complication of a comparable thickness mylar backing film (for strength), which undoubtedly alters the thermal properties of the foil. For these foils, the decay times appear to be somewhat longer (~2-3 *x*) than initial simple design estimates, which don't include mylar.

4). Observation of air-currents across surface of the mask. When a mask/foil is heated by several degrees, and then allowed to cool, it is possible to see "waves of cooling" roll over the mask, which is the signature associated with air-currents. Similarly, spatial isolation of the signals from two ~1mW laser spots onto the array (in air) is easily achieved, as shown in Figure 7.

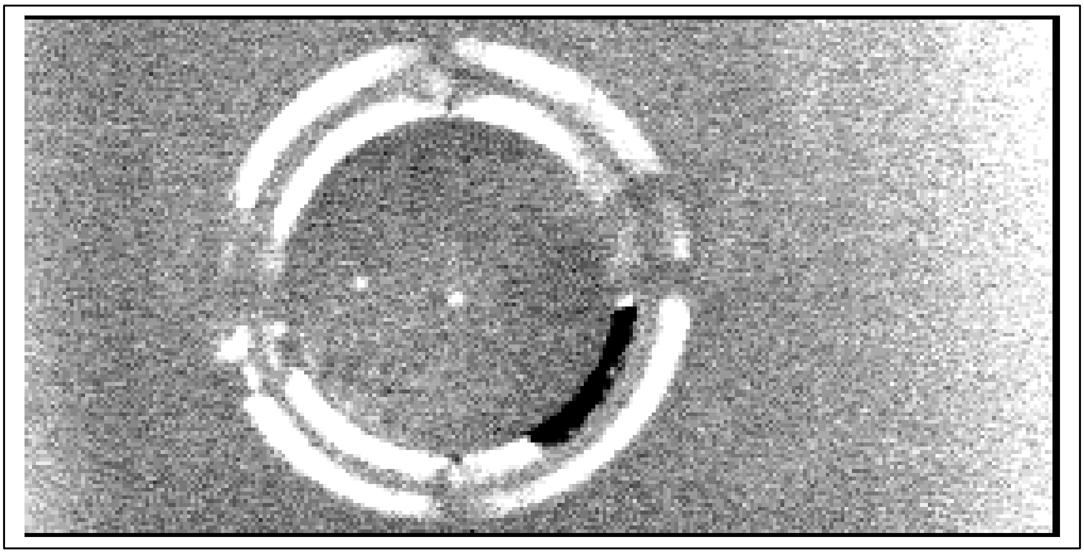

Figure7: Two laser spots illuminate the front surface of a 144-element array, and the IR image is taken from the back side of the foil/mask assembly. The two concentric bright rings are shiny copper and stainless sections of the 1.3 meter LHD prototype. An Agema 900 Thermovision 900 long wavelength series IR camera made the image.

6). Effect of a nearby hot filament ionization gauge: We installed a filament hot cathode ionization gauge about 20 cm to the side of the simple imaging bolometer for CHS. We could easily notice a several degree heating effect from this source. During plasma operations, the filament is off. We can report here that good signals have been seen during shots with from 50 to 400 kW of total radiation, although data is still being analyzed for possible ECH pickup. We use soft iron shielding to protect the IR camera from ~ 1 kG magnetic fields under the CHS machine.

7). Necessity to keep hot objects out of the optical IR field of view. The optical IR field of view between the backside of the mask, and the IR camera, should be isolated from objects hotter than the operating temperature of the mask, to prevent un-wanted IR reflections.

8). Problem of reflection of the cold camera dewar into the center of the field of view (FOV), for normal incidence alignment. This suggests the use of a background subtraction technique to allow for easier analysis.

9). The thermal emissivity of the backside of the foil (the side viewed by the IR camera) should be close to unity over the wavelength band being observed. Even though shiny gold is a good VUV and soft x-ray absorber, having a shiny gold on the backside of the same foil is bad, as this is an IR mirror!

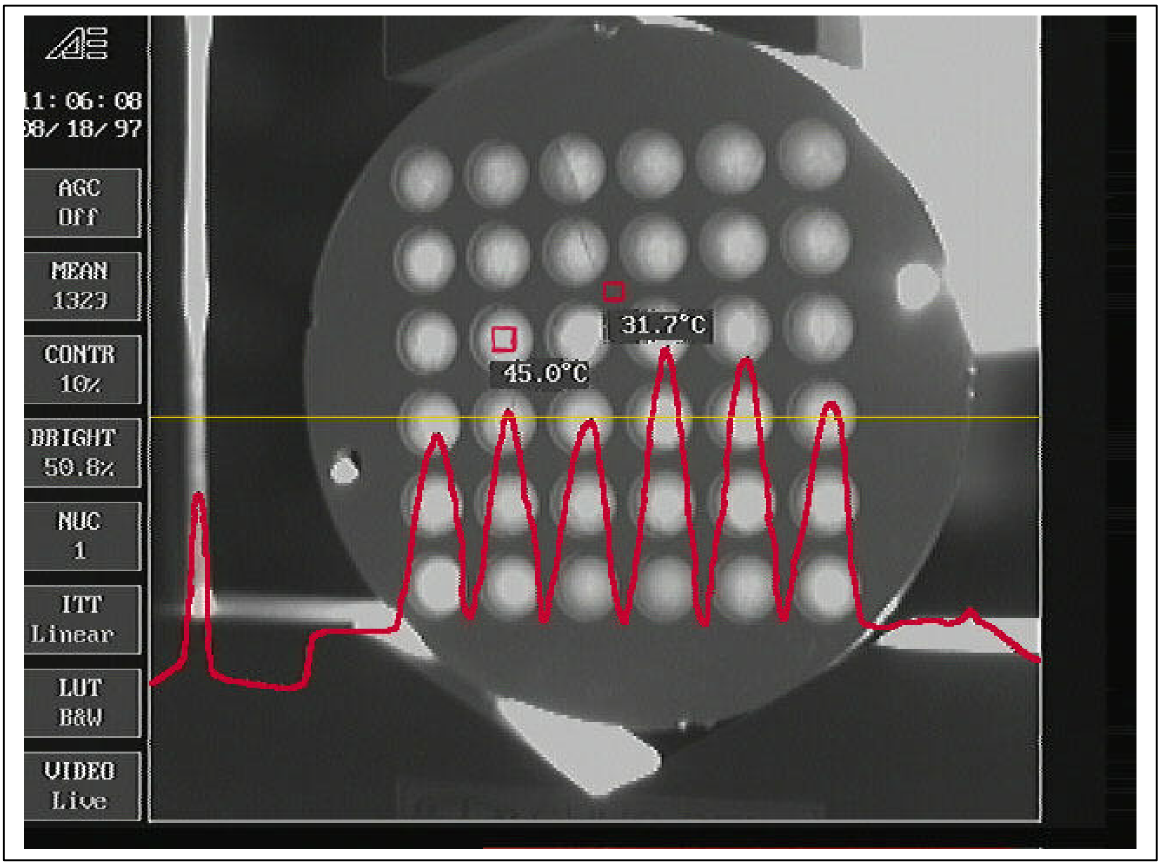

Figure 8: Heating of a masked 6x6 foil in air caused by a 100 watt heat lamp, 20 cm away from the mask, is easily seen by the Amber IR Video camera. The IR intensity profile on a line across the middle of the image, is graphically displayed near the bottom of the image. The temperature near the edge of each pixel is clamped by the thermal inertia of the thick copper mask.

SUMMARY

Testing of prototype infrared bolometers is in progress at NIFS in Japan, and preliminary indications are that there are no intrinsic problems to fielding such devices on the next generation of large fusion devices. At the cost of ~20x reduction in useful sensitivity (relative to standard metal foil bolometers), the IR imaging bolometer will eliminate all wiring harnesses inside the vacuum vessel, provide hundreds to thousands of channels (again, trading off sensitivity, spatial resolution, # of viewing positions) at a much lower cost per channel (<$1k). Furthermore, it will be immune to magnetic pickup, be compatible with steady-state data requirements, and be compatible with both high vacuum and high nuclear radiation environments. This assumes that the sensitive optical detector is shielded from magnetic and nuclear radiation fields. The transport optics will require metal mirrors, but they will not directly view the plasma. The penetrations through the ITER blanket will need to be of order ~1 cm, expanding quickly to ~ 30 cm diameter for the wide-angle "pinhole camera". A 20-meter stand-off distance to the IR video camera is assumed. Tangential views obtained with a bolometer head followed immediately by metal turning mirrors, may prove to be the most useful for real-time plasma position control during long-pulse operation. Unfortunately, we see no convenient way to position this type of system on the inner wall of ITER, although it may also be useful in a divertor port.

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