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Preparing the Alcator C Bolometer System for Use on MTX

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ABSTRACT

The Alcator C bolometer array has been modified to be compatible with electron cyclotron heating on the Microwave Tokamak Experiment. Fine wire mesh screens are mounted on the front of the bolometer collimator tubes to attenuate microwave heating of the bolometers. Structural changes eliminate openings in the seams of the bolometer housing, which represent pathways for microwaves to enter the system. This paper outlines the operational principles of the bolometer system, discusses the measured and predicted performance characteristics of the bolometer array, and includes a concise guide to the operation of the bolometer controller.

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I. INTRODUCTION

Bolometers are used to measure the total power radiated from a fusion plasma. On MTX we use the Alcator C bolometer system, comprised of an array of 16 bolometers with collimator tubes that allow viewing of different radial segments of the plasma. The array must be mounted on a top port, preferably as far away from the free electron laser (FEL) as possible. The Alcator C bolometer system was not designed to be compatible with microwave heating schemes. The 1.2-mm waves from the FEL would heat the bolometers, giving false signals; the bolometer electronics might amplify microwave signals absorbed in the bolometer circuitry if corrective modifications are not made.

To shield the bolometers from microwave energy, we chose fine, electroformed copper meshes at a spacing equivalent to 750 wires/in. The copper meshes are mounted over the front of the bolometer collimator tubes. Tests on similar meshes indicate that they will attenuate the microwave signal penetrating into the bolometer tubes enough that FEL heating of the bolometers should be nearly indiscernible above the bolometer circuits' electronic noise. Tests on the system also indicate this amount of microwave energy inside the bolometer produces no measurable increase in noise in the bolometer circuitry. Other physical modifications made on the bolometer system prevent microwaves from entering through seams and openings in the structure.

The bolometer controller is the same device used on the bolometers on the Tandem Mirror Experiment. The controller was designed at Princeton to be used with 50- Ω platinum wire bolometer pairs and is completely compatible with the Alcator C bolometer array. Malfunctioning bolometer controller circuits are repaired and aligned with the individual bolometer cells.

II. BOLOMETER DESIGN

Observations of the MTX bolometers indicate that they are the most recent version developed for the tokamak fusion test reactor. The sensor consists of platinum wire sandwiched between layers of epoxy and platinum foil. The active sensor is cemented at the ends of a copper heat sink. A reference sensor is mounted on the back of the heat sink. Shielded from the plasma, its entire area is cemented to the heat sink to remain in thermal contact. The copper heat sink is covered with a film of insulating material, likely epoxy.

Platinum sensors are used because they can withstand temperatures of up to 200°C, are highly resistant to damage by neutron and gamma radiation, and have a minimal outgassing. In addition, the platinum has a nearly constant temperature resistance coefficient over the bolometer temperature operating range.

III. BOLOMETER MEASUREMENT AND CONTROL CIRCUITRY

The active and reference sensors and fixed resistors in the electronics chassis are connected to form a Wheatstone bridge. The bridge is excited with a square wave at 20 kHz to reject pick-up voltages induced by the changing electromagnetic fields of the tokamak. To eliminate the need for a reactance adjustment, the synchronous detector is gated off for a time after each reversal of the square wave. The control electronics establish a reference power input to the bolometer sensors.

Two modes of operations are possible. In the open loop (or temperature) mode, the bridge is balanced at the time of the "t-zero" pulse. Changes in the incident radiation intensity change the temperature of the active sensor. The resistance change induces a voltage across the bridge. To determine the absorbed power versus time in this mode, it is necessary to unfold a detector cooling curve from the measured sensor temperature versus time. On TMX this mode was used most often because electronic noise (likely from the neutral beams) was present in the bolometer circuit, and the operators felt they could discriminate the noise from the data better when there was minimum processing of the signal data between the input and output of the controller circuitry.

Another mode of operation is available, however, lacking some limitations of the conventional mode of operation. In this closed loop (or power) mode, the sensor is maintained at constant temperature by modulating the electrical power dissipated in the sensor. This provides a direct measure of the absorbed power from the plasma. In this mode there is an output proportional to absorbed power, and the result is independent of the sensor thermal capacitance and resistance for our bolometer system. Besides simplifying calibration and data analysis, this mode of operation has an inherently rapid time constant depending primarily on the ratio of the circuit gain to the sensor thermal capacitance.

A built-in feature of the circuit is an electrical power pulse to calibrate the detector. A dc offset is added to the square wave applied to the bridge. Only the active sensor sustains a significant resistance increase due to the increased power. This electrical calibration can be used in either mode.

IV. MAGNETIC FIELD INTERACTION

Platinum wires function as strain gauges. The alternating $\vec{I} \times \vec{B}$ force on the strands of the sensor grid can excite vibrations which would produce noise in the output signal. The bolometer grids are cemented to a backing of kapton and platinum in order to reduce this effect. Furthermore, all bolometers are mounted so that strands are parallel to the toroidal field.

V. ASSESSMENT OF THE CONTRIBUTIONS TO BOLOMETER HEATING

The majority of the radiation is expected to be in the far ultraviolet and soft x ray. The bolometer collimator tubes have a threaded, blackened inner surface, which improves collimation of visible light and actually helps 1.2-mm microwaves to propagate down the tube. Measurements of the angular discrimination of the bolometer collimator tubes show that they have a steep cutoff with a half maximum value when the incident line radiation is at 2° to the axis of the tube (Fig. 1). The platinum foil covering the bolometers is somewhat reflecting in the ultraviolet region and about 50% reflecting in the visible region. The copper meshes to be placed at the front of the collimator tubes should transmit 55% of the incident visible and ultraviolet radiation at normal incidence. When mounted on the bolometer, the mesh will be deliberately slackened to allow it to fit over the collimator tubes. These meshes are easily torn and thus cannot withstand much tension. One should avoid touching them and take suitable care when installing the bolometer in its port. The wire mesh screens have a negligible effect on the angular discrimination of the collimating tubes (Fig. 2a,b). X rays of energies greater than 3 keV will pass through the wires in the mesh to some extent. For a copper mesh 6 μm thick, x rays with an energy of 4.51 keV will pass through the fraction of screen area occupied by the wires at a rate of 18.6% for wires with a rectangular cross section such as ours. For these screens

the transmission of x rays of energy less than 3 keV through the wires is negligible; the attenuation of the lower-energy x rays by the screens is the same as that for visible light.

The reflectivity of platinum to various wavelengths is listed in Table 1 and shown in Fig. 3. The platinum foil covering the sensor is excellent for absorbing x radiation. All soft x rays incident upon the sensor are absorbed by it. The mean-free path of x rays in platinum becomes comparable to the foil thickness at an energy of approximately 16 keV. A compilation of the sensitivity of the bolometers to electromagnetic radiation at different energies is given in Fig. 4. This takes into account the reflectivity of platinum and the mass absorption coefficients of copper and platinum for photons of various energies. Observation of the screens with a microscope at 1000X magnification reveals that the wires are flat on one side and slightly rounded on the other, giving them a nearly uniform depth across. According to the manufacturer, the wire depth is nominally 1.5×10^{-4} in. The platinum foil across the top of the bolometer is nominally 3.5×10^{-4} cm thick. The latter numbers were used to generate Fig. 4.

In addition to electromagnetic radiation from visible through x ray, which we intend this instrument to measure, there will be contributions to bolometer-measured energy from FEL radiation, synchrotron radiation, infrared radiation (from the limiters), neutron and gamma radiation, and neutral atoms. The center collimator tubes will be nearly flush with the edge of the tokamak outer wall. The flux of charged particles into the bolometer tubes should be negligible because the bolometers are far enough behind the limiters.

A. HEATING BY NEUTRAL PARTICLES

The heating of the collimator tubes by neutral particles should be negligible. The solid angle viewed by the bolometers is 3.8 mSr. For a flux of 1.0×10^{14} neutrals/cm² s at 1 keV, the bolometer would see 13 μ W of power, including attenuation by the screens. This would be difficult to distinguish from circuit noise. It is felt that the estimate of 1.0×10^{14} neutrals/cm² s is rather conservative.

B. NEUTRON HEATING

For D-D (deuterium) shots the neutron heating of the bolometers should be at least an order of magnitude lower than the impurity radiation. To separate the neutron and gamma flux contributions to bolometer heating, one could cover a bolometer to allow only neutrons and gammas to pass through.

C. INFRARED AND MICROWAVE HEATING

The bolometer has been located at the top F port to minimize the microwave energy flux and infrared radiation flux incident upon it. The theory for a thin, inductive mesh predicts that our 750 lines/in. screens should attenuate normally incident microwave radiation by more than 35 dB. Microwave transmission tests were performed on two nickel meshes of 250 and 400 LPI at a frequency of 140 GHz. For the 250-LPI screen, the measured ratio of transmitted to incident-normal radiation was -16.9 dB. When the mesh was allowed to hang wrinkled on the mounting frame (as our final screens will), the ratio dropped to -21.4 dB. This drop is thought to be partially due to the greater reflectivity of the mesh when the radiation is incident at an angle with the normal and partially due to scattering of transmitted microwaves out of the path between the source and receiver horns used in the test. With the 400-LPI screen, the attenuation at normal incidence was measured at -19.1 dB. With a "wrinkled" screen the attenuation was measured at -22.7 dB. There is a large difference between the measured performance of these screens and the prediction of the theory for thin, nonresistive screens. The large difference between the predicted and measured screen performance is due partly to the surface resistivity of the metal but mostly due to the nonnegligible thickness of these wire mesh screens. Thin meshes made of perfectly conducting material obey the relations:

$$\tau = 1 + \Gamma$$

$$|\tau|^2 + |\Gamma|^2 = 1,$$

where τ and Γ are the transmission and reflection coefficients. For an incident wave of unit amplitude, $|\Gamma|$ is the magnitude of the scattered wave.

The points satisfying these relations form a circle (Fig. 4). The resistivity of the screen would cause a shift in the locus of these points in the direction of the real axis. The magnitude of the effect of resistivity can account for only a tiny fraction of the discrepancy observed. A theoretical treatment by Marcuvitz¹ predicts that the finite thickness of the mesh shifts the Γ curve in the negative imaginary direction and the $1 - \tau$ curve equally in the positive imaginary direction. Experimental observations by Ulrich² and others confirm this shift. The absolute magnitude of the shift is, however, considerably larger than the theory predicts. This might be an inherent difference between two-dimensional and one-dimensional meshes. In all theories covering inductive and capacitive meshes, the parameters of interest are the ratios of mesh spacing to wavelength, wire/plate width to spacing, and wire/plate thickness to spacing. The 400-LPI mesh was chosen to simulate at 140 GHz as closely as possible the performance of a 750-LPI mesh at 250 GHz. Published experimental results indicate that copper meshes are better attenuators of millimeter microwaves than nickel meshes, by more than the difference for which bulk resistivities alone would account. Therefore, with the method of mounting planned, we can expect to achieve 22.7 dB of attenuation for the 1.2-mm waves with 750-LPI copper screens.

A test was conducted on the bolometer to measure the sensor absorption of microwaves. All openings out of the bolometer were covered, and power reflected into the waveguide horn was measured. When a directional horn was used to launch power into a tube 0.9% of the net input energy (at 140 GHz) was absorbed by the sensor. When an open-ended waveguide was used 0.6-0.7% was absorbed. Microwaves launched from a directional horn outside the tube normally incident were absorbed at a rate of 0.4-0.5%.

Based on preliminary data from the measurement of the Q of the Alcator C cavity at 140 GHz, one expects that for a power input of 2 MW of microwaves into the empty cavity one would measure an average power flux of 400 W/cm^2 at the cavity outer wall. Including a factor for the attenuation of the microwave flux by plasma absorption, one can estimate the FEL heating of a bolometer sensor:

$$(1.17 \text{ cm}^2)(400 \text{ W/cm}^2)(A_{\text{plasma}})(10^{-2.27})(0.01) < 10^{-4} \text{ W } A_{\text{plasma}} < 0.004 .$$

Estimates of the fraction of power absorbed by the plasma on a single perpendicular pass range from 0.5 to 0.98, the lower figure due to nonlinear absorption on the first pass. Linear absorption predicts 80% absorption during startup and 98% absorption when the electron temperature reaches 1.8 keV. If 80% is absorbed per pass on the average, the number of such passes needed to attenuate the microwave flux to 0.004 of the initial magnitude is

$$\frac{\log(0.004)}{\log(0.2)} = 3.4 .$$

One can expect such attenuation to occur by the time microwaves have traveled to the opposite side of the torus. A signal resulting from 100 μ W of power should be much smaller than the impurity/line radiation. If the microwaves made just one more pass through the plasma, effectively attenuating the intensity by another order of magnitude, the signal magnitude would be buried in the noise in the closed loop mode. Because the synchrotron radiation will be much less intense, it won't contribute significantly to bolometer heating. The wire mesh screen's transmittance goes, very roughly, as the ratio of mesh spacing to radiation wavelength, so that harmonics radiated by the plasma will be effectively shielded by the screen. Thus, the screens improve the bolometer's capability to exclude microwave power from the measured power.

VI. ASSESSMENT OF THE LONGEVITY OF THE SCREENS

The wire mesh screens should be able to withstand constant heating resulting from steady-state operation of the FEL without any plasma. The sputtering from energetic neutral particles will degrade the screens only over a very long period of time. Sputtering and heating of the screens during Taylor discharges (cleaning) will be negligible. Other phenomena, such as unipolar arcs, may shorten the life of the screens. Thus, periodic inspection of the screen, using a microscope with a magnification in the range of 500X, is recommended.

VII. OPERATION OF THE BOLOMETER CONTROLLER

The MTX bolometer controller can be issued commands through the front panel when the REMOTE/LOCAL switch is in the LOCAL position. The remote setting allows it to be configured to various states by digital electronic commands through a connection on the rear panel. The entire system can be tested without the use of a computer. The channel selector, which operates in base 8, allows one to look at the output of a particular circuit through the TLM OUT outlet. The LIVE setting allows one to look at the instantaneous output of a circuit while the MEM setting locks into the 200-ms memory built into the unit.

Other controls function as follows:

- MEM SYNC Synchronizes an oscilloscope with the memory output.
- EXT SYNC IN Triggers the controller into the hold balance mode when it produces data. After about 5 s, the controller reverts to its original state.
- GAIN TEST In the open loop mode, it simulates a known temperature change in the sensor allowing calibration.
- WRT ENABLE Readies the memory to fill itself with new data at the time of the next trigger.
- PULSE ENABLE Enables the calibration electrical power pulse system.
- PWR PULSE Triggers a pulse. The HOLD BAL light is lit whenever the controller is producing data.
- POWER MAGNITUDE Selects the magnitude of the power pulse settings: low, med, and hi correspond to 0.8, 1.6, and 3.2 mW nominally. The actual value of the offset voltage can be monitored through channel 67.
- PULSE WIDTH Selects the duration of the power pulse. The settings narrow, med, and wide correspond to 10 ms, 100 ms, and 1 s.
- PULSE SYNC Sends a pulse to synchronize other equipment with the controller.
- ABS PWR Allows one to measure the reference power delivered to a sensor. The transfer function is 0.5 V/mW.

- NB FILTER In the wideband mode the controller output is passed through a 250-Hz low-pass filter. With the narrow band filter in, the output filter is 50 Hz. The filter is not simply a line filter but an active part of the bolometer circuitry.
- LOOP Open loop = temperature mode; closed loop = power mode.

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APPENDIX

Summary of Tests Closed Loop Measurements

Transfer functions	2.50 V/mW wideband 2.38 V/mW narrowband
	11.0 ms wideband 14.5 ms narrowband
Noise	20 mV rms = 8 μ W wideband 7 mV rms = 2.8 μ W narrowband
Auto balance hold drift test	2.8 μ W/s

Open Loop Measurements

Transfer function	20 V/°C
C	8.6×10^{-4} J/°C
R	168°C/W
Auto balance hold drift mode	280 μ °C/s
Noise (wideband)	115 μ °C/s rms

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Table 1. *Platinum reflectivity at normal incidence for visible wavelengths.*

450 nm	550 nm	750 nm
55%	60-65%	71%

Figure 1. (a) Angular discrimination of bolometer collimator tubes;
 (b) angular discrimination of bolometer collimator tube with
 respect to visible, ultraviolet, and x radiation.

Figure 2. Angular discrimination of bolometer collimator tubes: (a) wide 400-LPI mesh (nickel); (b) with respect to visible, ultraviolet, and x radiation with wire mesh screen in place.

Figure 3. Platinum reflectivity at normal incidence for ultraviolet wavelengths.

Figure 4. Relative bolometer detection efficiency.

Figure 5. The transmission and reflection vectors.