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A Rad-Hard, Steady-State, Digital Imaging Bolometer System

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Abstract

The concept and design of a new type of bolometer system which can function with excellent spatial resolution and good time resolution in the next generation of long-pulse (or steady-state), harsh-neutron environment, fusion plasmas, is outlined. It uses a cooled pinhole camera design, employing a robust, passive, segmented radiation absorber, cooled from the back-side. Infrared emission from the absorber's front surface is relayed by metal mirror optics to a shielded, high-resolution IR video camera with ±0.01 C temperature resolution. The system is readily capable of making thousands of simultaneous "pixel" measurements at up to 50-60 Hz, with no wire leads through the vacuum interface.

1. Introduction

Classical bolometry[1] in a fusion plasma employs discrete thin-foils which are heated by the plasma radiation, and the temperature rise is detected by a metal resistor or thermistor bonded to the back side of the foil, often separated by an insulating film[2-5]. Sometimes a single-channel IR detector has been used to monitor the rise in temperature of the foil instead, so as to provide better electrical noise-immunity[6]. In cases of a short-pulse of plasma radiation, or when studying the energy deposited by by ion, neutral or electron beam, researchers have imaged (in the IR) the backside of a foil or plate target, in order to determine the "instantaneous" distribution of energy in the beam[7]. The problem with using this technique to observe a long-pulse plasma, is that the lateral heat flow in the foil or target plate would spoil the subsequent images, and confuse the measurement. In addition, a foil which is thin enough to have reasonable time response must be cooled over longer time intervals to prevent melting or radiative cooling damage or nonlinear effects from spoiling the measurement. Finally, the detectors must be radiation hardened, to survive the neutron and gamma fluences from a long-pulse DD or DT machine. So-called "silicon bolometers"[8] and pyroelectric detectors have an advantage in that they respond directly to the incident power, but they will not work in this environment. The plasmas may have a complex geometry, and multi-channel views (even tomography)[9] are desired for modeling analysis.

2. Design Concept

The solution to these issues is remarkably simple, and involves a pinhole imaging design, with the plasma radiation striking a compact, segmented, back-cooled "foil". Each segment of the “foil” corresponds to one imaging resolution element or “pixel”. Each pixel absorber is raised up from the back cooling block (which can be held at a constant reference temperature), and the height of the pixel (and the material thermal conductivity) is designed for rapid axial heat flow compared to the relatively longer lateral heat flow path over to the next adjacent pixel. The passive absorber matrix is imaged in the infrared, via two metal mirrors, which allow the (neutron-sensitive) state of the art, 12-bit digital video IR video camera to be positioned out of the line of sight of the neutron flux from the plasma. Some of the pixels may be positioned outside of the plasma field of view, to act as “background” pixels if necessary. The front surface of the absorbing matrix may be initially be a “blackened coating” (like any other bolometer design), but in the long term, this may change somewhat due to plasma contamination of the surfaces. No wires are required to come out of the vacuum interface, which is a tremendous advantage for thousands of channels compared to discrete classical bolometer arrays.

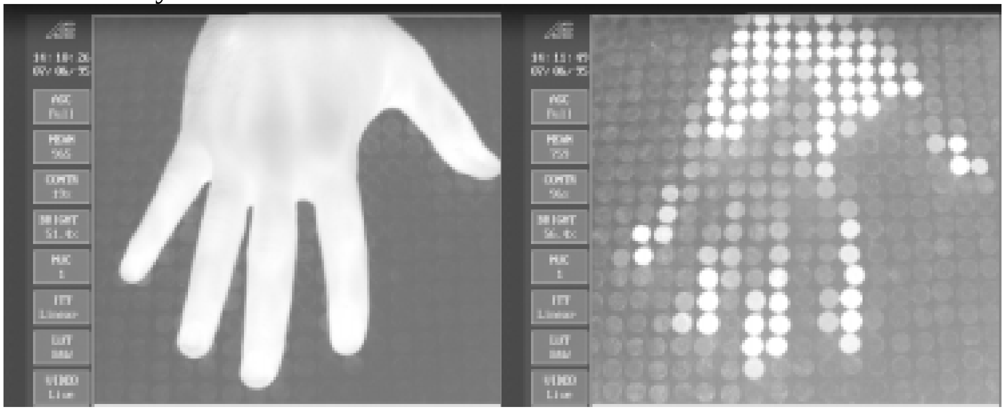

Figure 1: A test matrix (of blackened nails) holds the warmth from a hand, without lateral heat flow degradation.

Tests of a segmented matrix (20x20 array of blackened, galvanized roofing nails) are shown in Figure 1, where the warmth from a human hand held on the matrix for a few seconds is easily detected 30 seconds later. The matrix of nails was heat-sinked into a pool of water, although the heat decay time is much too long in this prototype to be used for plasma imaging. The images in the 3-5 micron band were taken with a 256x256 element InSb focal plane array (Radiance 1) commercially available 12-bit digital IR video camera from Amber.

The overall system will tradeoff sensitivity, speed, and spatial resolution; with the ultimate speed being limited by cooling rates (to erase the previous image) or camera framing rates (which can range from 1 Hz to 1000 Hz with today’s technology). If a chopper interupts the pinhole aperature, then the heating and cooling timescales of the matrix can be different. For use without a chopper, then some amount of integration of the heat from one frame to the next will occur, and it will be necessary to differentiate subsequent frames (in analogy with normal single-channel bolometers), while taking into account pixel cooling, in order to have time resolution limited by the video system . The only vacuum window in this system can be positioned behind neutron shielding, and is essentially the IR interface to the camera and its (non-vacuum compatible) electronics.

3. Point Designs for TPX, LHD, or ITER

Depending on the radiated power density, the desired temporal and spatial resolution, and the plasma access available for diagnostics, one can design a conceptual layout of an imaging bolometer package. A sketch (not to scale) is shown in Fig. 2 below:

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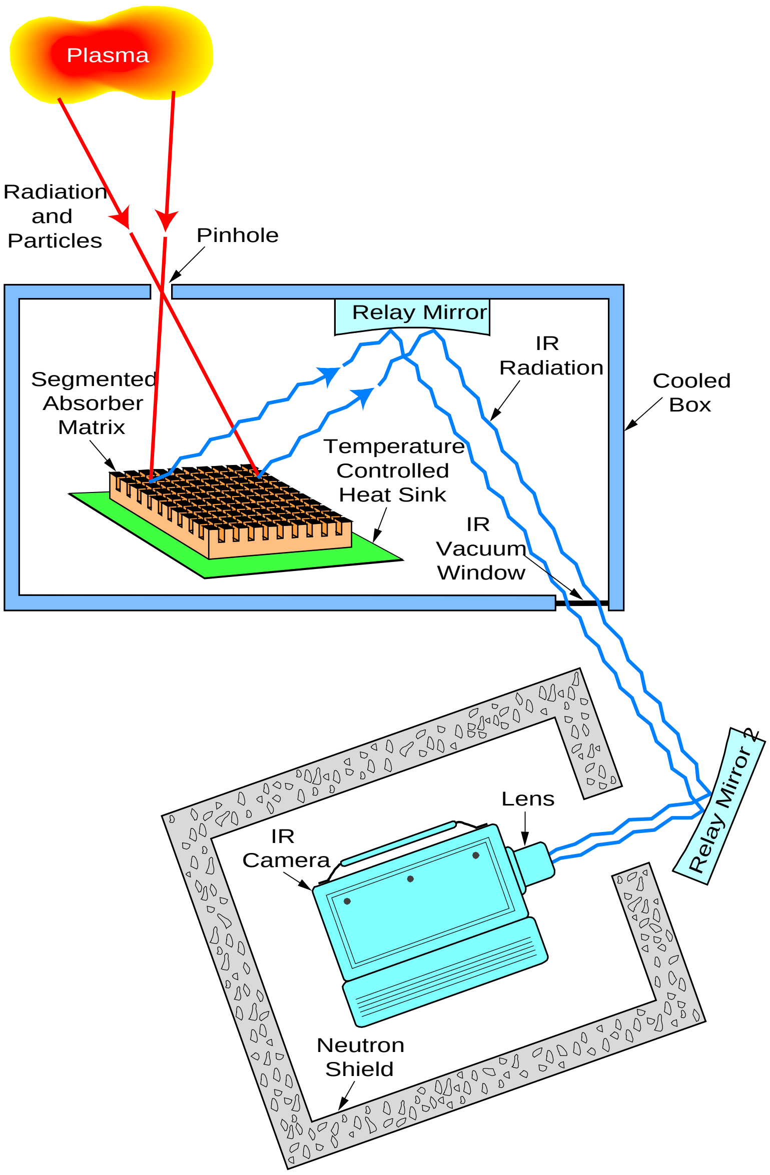

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Figure 2: Components of the rad-hard, steady-state, digital imaging bolometer system.

Design choices for pinhole size, demagnification (radial or tangential viewing), target matrix size and number of pixels, distance to IR imager and amount of neutron shielding, must all be made. Sample design points are shown in Table 1 , assuming an aluminum matrix, and a pixel spacing 1.1 times the pixel diameter.

Plasma Device:	***TPX***	***LHD***	***ITER***	***Comments***
Plasma Volume	50 m^3	30 m^3	2500 m^3	
Radiated Power	20 MW	1.5 MW (cw)	500 MW	assuming ~50% radiation
Plasma distance	1 m	0.5 m	5 m	(average)
Pinhole aperature	1 mm	1 mm	1 cm	ITER is larger scale size
Demagnification	10x	10x	20x	
Distance to back plane (matrix)	0.1 m	0.05 m	.25 m	
Pixel size	1.1 mm	1.1 mm		
Number of resolution elements	50x50	25x25	50x50	
Radiated power at each pixel				depends on sight line
Temperature decay time desired	30 ms	10 ms	100 ms	LHD needs the speed
Height of each pixel				
Max temperature rise	1 ^{o}C	0.5 ^{o}C	10 ^{o}C	

Table 1: Possible design points for an imaging bolometer on long-pulse plasma devices.

4. Summary

A new type of imaging bolometer is presented, which can operate in the steady-state (long-pulse) and harsh radiation conditions expected to be encountered in the next generation magnetic fusion devices. Point designs for the TPX, LHD, and ITER plasmas are discussed.

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