An FPGA-based bolometer for the MAST-U Super-X Divertor

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Abstract

A new resistive bolometer system is being developed for MAST-Upgrade. It will measure radiated power in the new Super-X divertor, with millisecond resolution, along 16 vertical and 16 horizontal lines of sight. The system will use a Xilinx Zynq-7000 series FPGA in the D-TACQ ACQ2106 carrier to perform real-time data acquisition and signal processing. The FPGA enables AC-synchronous detection using high performance digital filtering to achieve a high signal-to-noise ratio, and will be able to output processed data with millisecond latency. The number and arrangement of the lines of sight will allow for studying the effectiveness of the new Super-X divertor design. The system is currently being prepared for installation on JET, until MAST-U is operational.

1. The MAST-Upgrade Bolometer

The bolometer system will actually be made up of 2 units, each containing 16 bolometer sensors (Figure 1). Each bolometer is comprised of a pinhole camera which "images" onto platinum foil. The radiation incident on the foil heats up the platinum and changes its resistance. This in turn affects the voltage across the foil (Figure 2), so by measuring this voltage we can calculate the temperature rise and hence the power incident on the foil.

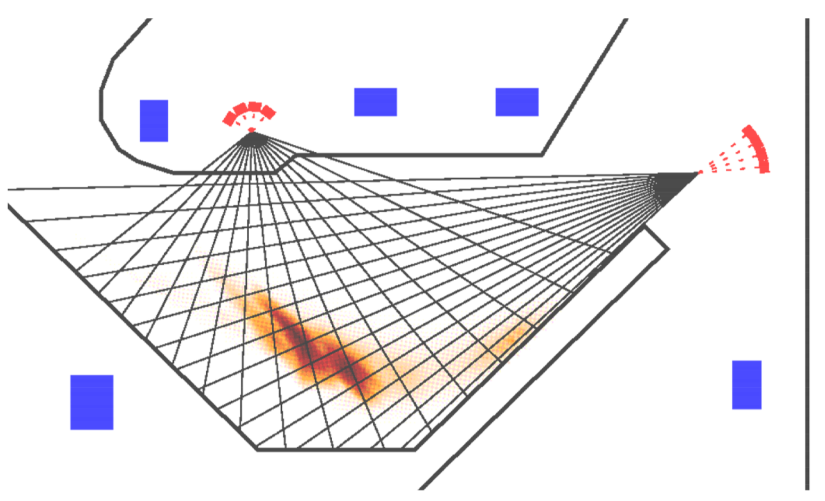

Figure 1: Diagram showing the location of the bolometer within the divertor region. The bolometer cameras are indicated in red, and the black lines are the lines of sight. The heat map in the centre of the chamber is a simulation of plasma emission. [1]

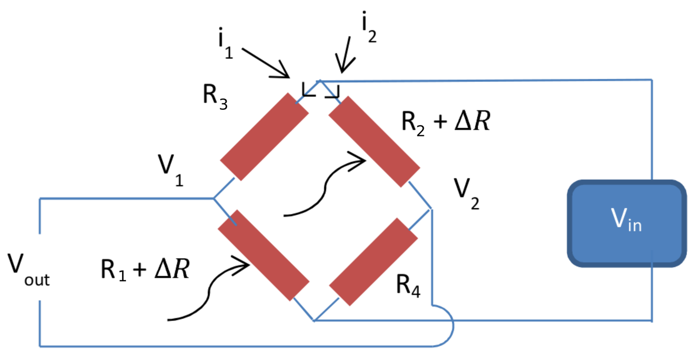

Figure 2: Schematic of a bolometer sensor, in the form of a Wheatstone bridge. Resistors R1 and R2 are heated by the plasma. This increases their resistance relative to R3 and R4, which are shielded. The bridge is unbalanced, and a voltage Vout is detected when Vin is applied. The ratio Vout/Vin tells us how much the resistance changed by, and hence how much the plasma power and divertor tiles heated the resistors.

To minimise electrical noise, we employ AC synchronous detection. We apply a 20kHz sine wave as Vin, and measure the amplitude of the 20kHz component of the output Vout. This involves mixing the signal with sine and cosine waves of the same frequency, filtering and then rotating these signals to compensate for phase delays in the cabling to get the amplitude.

By having 2 arrays of pinhole cameras we can build up a 2D map of the radiated power within the chamber. This will enable us to test how effective the new design is at cooling the plasma before it strikes the divertor plates.

2. The role of the FPGA

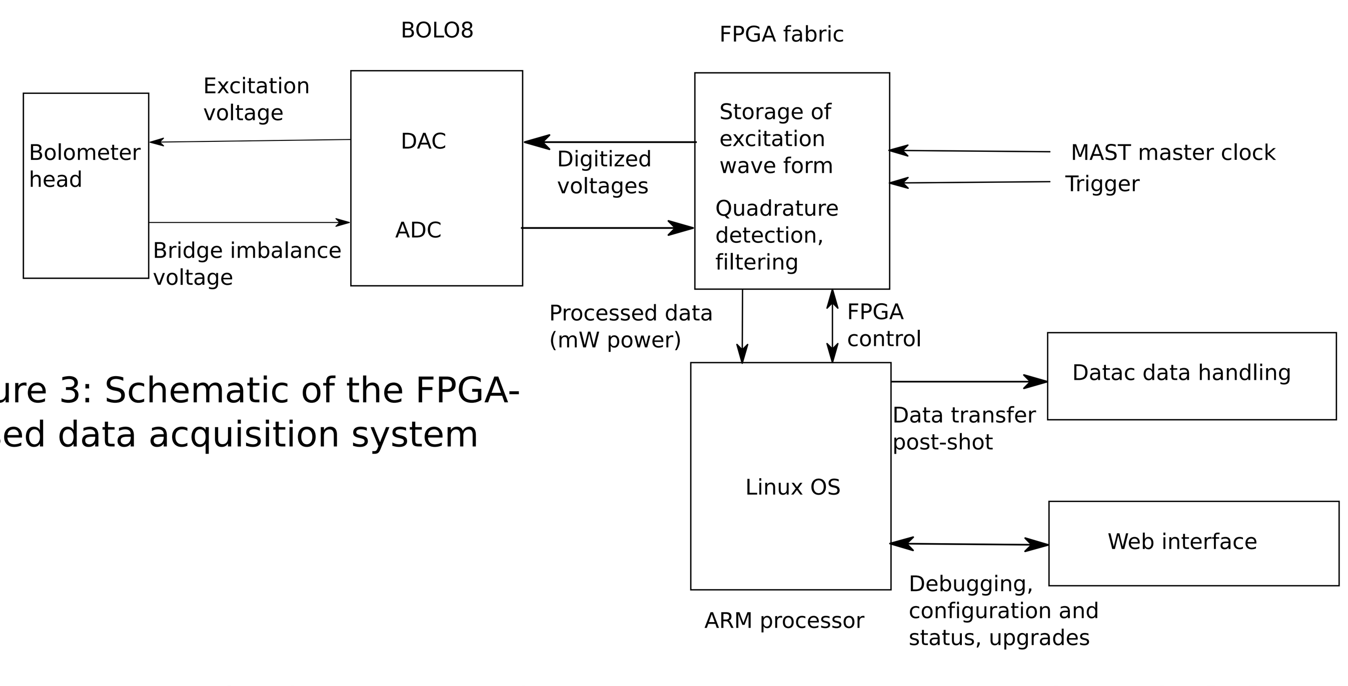

Figure 3: Schematic of the FPGA-based data acquisition system

The FPGA controls the DAC and ADCs on D-TACQ BOLO8 boards [2] to generate V_{in} and digitize V_{out} (see Figure 2). We also leverage the FPGA's digital signal processing (DSP) capabilities to perform the filtering of the digitised signal:
- A low pass FIR filter (cutoff frequency ~ 1kHz) is used in the quadrature detection, which has the effect of averaging over multiple periods of the excitation wave. This is how the voltage amplitude at 20kHz is calculated.
- By balancing the temperature rise with the cooling rate of the foil, we can calculate the incident power P from the voltage amplitude A [3]:

$$P = \frac{2R\kappa}{V_{in}}\left(A + \tau_c \frac{\mathrm{d}A}{\mathrm{d}t}\right) \qquad (1)$$

Here, τ_c and κ are the cooling time constant and normalised heat capacity of the foil respectively, and R is the foil resistance. The derivative of our filter function is applied to the signal to differentiate it. Both the filtered amplitude and power calculated from this process are then read from the FPGA logic by the ARM CPU and stored in RAM.

The CPU runs Ubuntu Linux 12.04LTS, and communicates with the MAST-U data acquisition systems via HTTP, enabling remote configuration, monitoring and retrieval of data from the diagnostic.

3. Results of preliminary testing

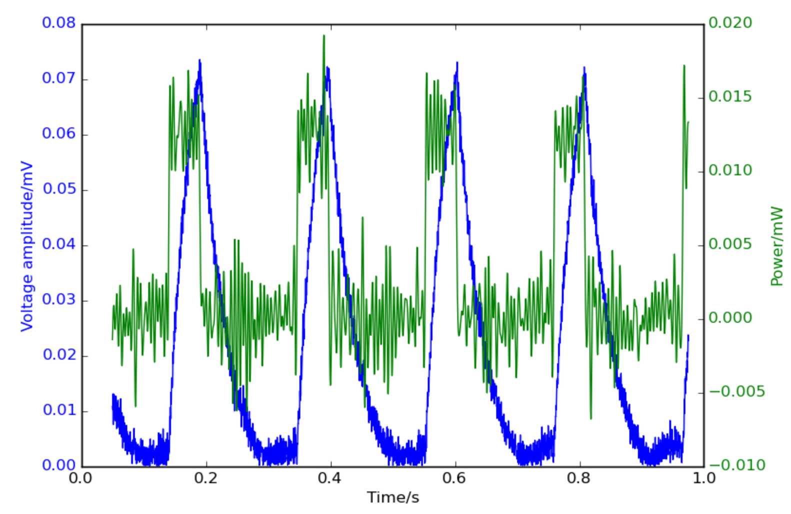

Figure 4: A plot of the bolometer output and calculated power when driven by a red LED in 5Hz flash mode

To test the data acquisition and signal processing systems, the light from two different LEDs was used to excite a spare gold-foil sensor, and the resulting output voltage was digitised and filtered on the FPGA to calculate the bridge amplitude. Once the amplitude had been recorded, software-based post processing was used to calculate the incident power on the sensor, using knowledge of τ_c and κ (see Equation 1) calculated from a calibration procedure. All tests were done at atmospheric pressure.

Figure 4 shows the result from a red LED, set to flash at 5Hz. Due to the high reflectivity of gold at red-light wavelengths, the detected signal was extremely small. Nevertheless, the heating and cooling of the bridge can be clearly seen in the amplitude signal. The power trace was calculated using Equation 1, and smoothed with a 200Hz bandwidth filter. The reconstructed power trace shows that even tiny power levels are easily measured. This demonstrates that the new diagnostic is capable of resolving extremely small signals at moderate time resolutions.

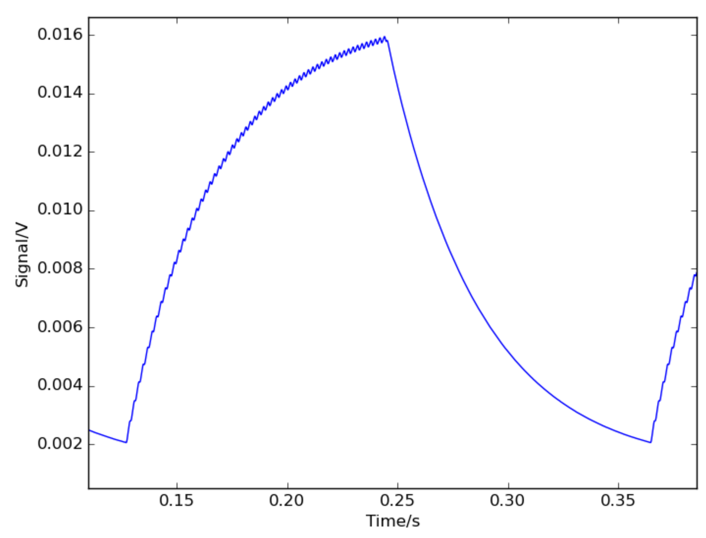

Figure 4: A plot of the bolometer output voltage when driven by a bright white LED, also in 5Hz flash mode.

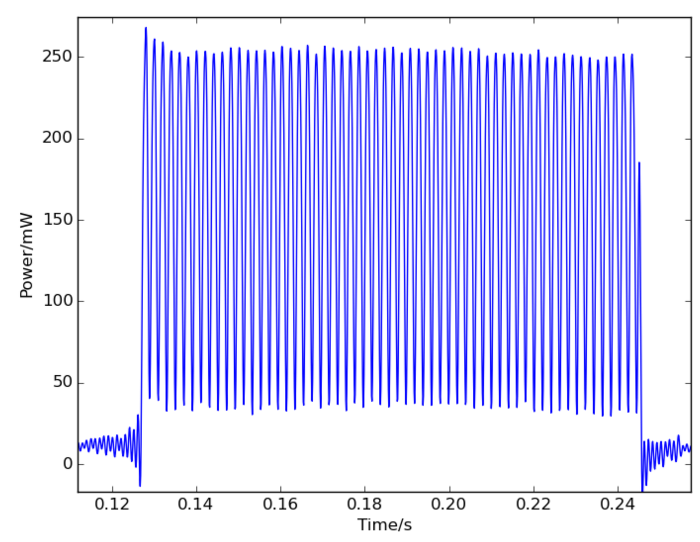

Figure 5: The resulting calculated power for the white LED, zoomed to show when the LED is illuminating the sensor.

To produce Figures 4 and 5, a much brighter, white light was used. The signal is much higher in this case, both because the LED is brighter and because it outputs much more light towards to blue end of the visible, where gold is a much better absorber. In Figure 4, a ripple can be seen in the heating curve, but not the cooling curve. This is actually due to 500Hz pulse width modulation (PWM) being used to reduce the LED brightness as it appears to the human eye. The PWM was verified by measuring the brightness with a fast photodiode. Upon calculating the incident power with smoothing at 1kHz, the PWM can clearly be seen from the bolometer measurements. A spectral analysis has shown that we can actually detect the first harmonic (at 1kHz) of the PWM with ease.

This result is highly encouraging, as higher time resolutions require less smoothing and are therefore more sensitive to noise. For sufficiently large signals (e.g. ELMs and disruptions) we expect to have kHz resolution from the new system.

The calibration constants were calculated by applying a DC bias voltage across Vout, and shifting Vin by the same DC voltage whilst still exciting with a 20kHz, 40Vpp sine wave.This ohmically heats the measurement resistors but not the reference resistors. The same synchronous detection process is used to determine the voltage amplitude, and from this an exponential function is fitted to determine sensitivity (V/W), time constant and bridge offset (the signal measured for zero input power). For the sensor in air, we measured a cooling time constant of 36ms, and a sensitivity of 7.5V/W. In vacuum, we expect a longer cooling time and smaller sensitivity, which will make high time resolution measurements more challenging.

4. Summary

- A bolometer system is being developed for the MAST-Upgrade divertor.
- It will measure the power radiated by the plasma using the Wheatstone bridge principle, and help to evaluate the effectiveness of the new divertor design.
- An FPGA will be used for data acquisition and signal processing, due to its flexibility and inherant parallelism, as well as dedicated hardware resources.
- The FPGA incorporates a CPU running Linux, for easy interfacing with MAST-U's data acquisition and diagnostic control systems.
- The device has been tested for functionality with an older gold foil sensor, and will soon be installed on JET for testing in a tokamak environment.

References:
[1] Schneider R, Bonnin X, Borrass K, Coster D P, Kastelewicz H, Reiter D, Rozhansky V A, Braams, B J 2006 *Plasma Edge Physics with B2-Eirene*, Contributions to Plasma Physics 46 WILEY-VCH Verlag 3-191
[2] http://www.d-tacq.com
[3] Mast K F, Vallet J C, Andelfinger C, Betzler P, Kraus H and Schramm G 1990, *A low noise highly integrated bolometer array for absolute measurement of VUV and soft x radiation*, Rev. Sci. Inst. 62 744-750.

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