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An FPGA-Based Bolometer for the MAST-U Super-X Divertor[a)]

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A new resistive bolometer system has been developed for MAST-Upgrade. It will measure radiated power in the new Super-X divertor, with millisecond time resolution, along 16 vertical and 16 horizontal lines of sight. The system uses 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 in real time with millisecond latency. The system has been installed on 8 previously unused channels of the JET vertical bolometer system. Initial results suggest good agreement with data from existing vertical channels but with higher bandwidth and signal-to-noise ratio.

I. INTRODUCTION

Bolometers are widely used for radiation measurements in fusion devices. Bolometer measurements are important for power balance studies, and arrays of detectors can be used to make spatially-resolved measurements of plasma radiation, enabling an improved understanding of radiative losses.

The MAST spherical tokamak at Culham Centre for Fusion Energy (CCFE) is currently undergoing a major upgrade. A significant feature of the upgraded device (MAST-U) is the new “Super-X” divertor (SXD) configuration, which aims to reduce heat load on the divertor target plates[1]. However, this is one of the first fusion devices to use this particular divertor configuration, so a thorough and high-quality diagnosis of the SXD is imperative. The large number of divertor magnetic field coils, and gas injection valves, in the MAST-U tokamak allow the possibility of real-time control applications to optimize divertor operation. It is therefore advantageous to have diagnostics which can not only make high quality measurements, but also produce low-latency real time data to be used in control and feedback systems.

The new bolometer system which has been developed for MAST-U has already been introduced in a previous paper[2]. In this paper, we describe in more detail the capabilities of the system. We then go on to demonstrate operation of the system on the JET tokamak, and compare the results obtained with those of the existing JET bolometer system.

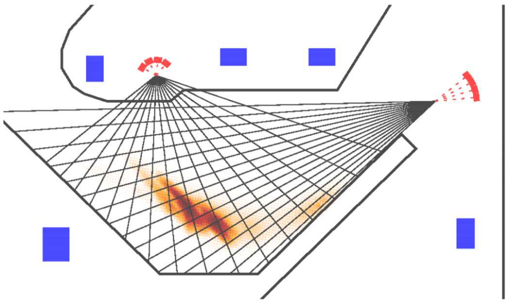

FIG. 1. Illustration of the lines of sight of the SXD bolometer system on MAST-U

II. CAPABILITIES OF THE NEW SYSTEM

The system as developed for MAST-U comprises 32 bolometer sensors with lines of sight in the divertor. These sensors are of the same design as is to be used in ITER[3]. 16 sensors view the chamber vertically and 16 horizontally. Figure 1 shows these lines of sight, with a simulated emissivity profile as calculated from the SOLPS code[4]. The configuration allows us to reconstruct the 2D emissivity profile from integral line of sight measurements using tomography.

The new bolometer electronics use FPGA technology. A Xilinx Zynq System-on-chip (SOC), combining a dual core ARM CPU running Linux and FPGA programmable logic, is used to control the excitation of the bolometer sensor, digitisation of the sensor output voltage and processing of the signal. The electronics hardware is built by D-TACQ Solutions[5], with the digital signal processing to be performed on the FPGA being designed by Durham University and CCFE.

In common with previous resistive bolometer systems, which consist of a Wheatstone bridge with two resistors heated by plasma radiation and two resistors shielded,

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[c)] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia the detector signals are measured using AC synchronous detection[6]. An AC excitation voltage in the form of a sine wave, at a frequency of around 20kHz, is applied to one diagonal of the bridge, and from the output voltage across the other diagonal of the bridge we measure the amplitude only at the excitation frequency. This technique allows us to extract the small bolometer signal from the noisy environment of a tokamak. It involves mixing the bolometer output signal with a reference signal of the correct frequency and phase, and low-pass filtering the mixed signal to remove the mixing harmonics and out-of-band noise. Traditionally, this has been done using analogue electronics, which are susceptible to deterioration over time and to manufacturing tolerances.

In the new system, all of this processing is done digitally. The bridge voltage is digitised, then multiplied by in-phase and quadrature-phase copies of the excitation voltage, and the results are filtered using digital finite impulse response (FIR) filters. This produces I and Q components, which can be considered as real and imaginary parts of the signal, and so can be converted to polar representation to extract the voltage amplitude. This process has the additional benefit of being phase sensitive: the true amplitude is produced whatever the phase of the bridge signal relative to the reference signal, meaning that it is not necessary to manually compensate for any phase delays in the system.

The excitation frequency is configurable. This allows the system to be run at a frequency away from other sources of noise on the tokamak, such as switching power supplies. Additionally, the filter bandwidth is configurable up to 2kHz. Higher bandwidth is suitable for measuring large transient events, whereas lower bandwidth filters will allow measurement of very small but slowly evolving signals.

Once the amplitude A has been measured, the power incident on the bolometer sensor can be calculated using:

$$P = \frac{1}{S}\left(A + \tau\frac{\mathrm{d}A}{\mathrm{d}t}\right) \tag{1}$$

This is a simplified form of the more complete expression derived by Giannone et al[7]. This form has the advantage of only depending on the measured voltage amplitude and two calibration constants: the sensitivity S (V/W) and cooling time constant τ. The calibration procedure is described in detail in Section 5 of the previous paper on this system[2]. It can be performed for every sensor simultaneously, is fully automated and takes only a few seconds, meaning it can be performed before every shot if desired.

The use of digital FIR filters allows for more complex signal processing than analogue filters. Using knowledge of the sensitivity and cooling time constants, it is possible to design a filter kernel that will simultaneously differentiate the voltage signals, multiply by the cooling time and add this time-derivatitive to the original signals, in addition to low-pass filtering the signals. This means we can actually calculate P for each sensor using Equation 1 on the FPGA in real time, and this data is available to send over a fibre-optic network to a control system for use in a feedback loop. The signal latency is determined by the time taken for samples to pass through the filter system, and is of order 1ms.

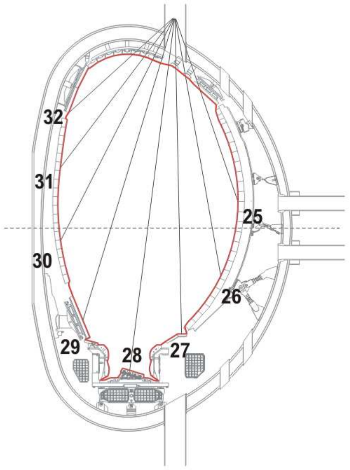

FIG. 2. Lines of sight of bolometer system, as installed on JET

By combining the real-time calculated power values described in the previous paragraph with knowledge of the geometry of the sensors, it is possible to calculate moments of the emissivity profile, without having to do a full tomographic inversion. The 0th and 1st order moments give the average position and the size of the emission respectively. This is particularly useful for the MAST-U divertor, since optimising the size and location of the emitting region will cool the plasma exhaust and help to reduce the heat load on the divertor target. Some work on an FPGA implementation of this processing has already been done[8], though it has yet to be integrated into the bolometer system.

III. INSTALLATION ON JET

The new electronics has been installed on the JET tokamak, on 8 previously unused channels of the existing vertical bolometer system. The lines of sight are shown in Figure 2. Although represented by lines, each channel actually views a finite solid angle, extending half way to the neighbouring channel, giving complete coverage of the plasma. The same is true of the channels on the existing JET system, though there are more of these (24 vertical and 28 horizontal) with closer spacing and hence narrower viewing angles. Some lines of sight are shared between the existing system and the new system, meaning it is possible to directly compare measurements from the two systems, as long as the different viewing areas are taken into account.

Figure 3 shows a comparison between two channels with similar lines of sight. The new system does not have

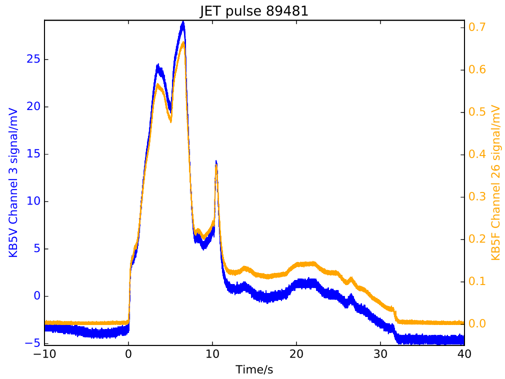

FIG. 3. Comparison of channel 3 of the existing JET system (KB5V, dark blue) and channel 26 of the new system (KB5F, light orange). Note that the zero point on the KB5F axis has been shifted to avoid the two traces overlapping too closely.

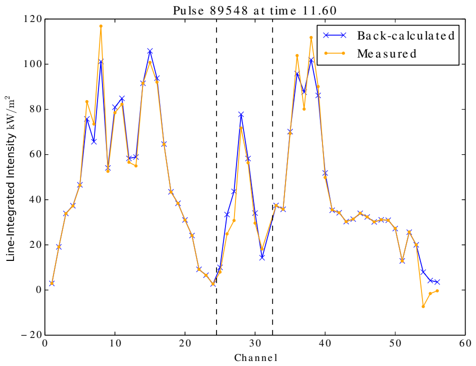

FIG. 4. Comparison of measured intensity and expected intensity, back calculated from the emissivity profile. The channels belonging to the new system (KB5F) are inside the dashed lines. The vertical channels of the existing system are on the left of the plot, and the horizontal channels are on the right.

a high gain amplifier like the old system, so the voltage measurements are much smaller. However, it can clearly be seen that the new system is in qualitative agreement with the existing system. Furthermore, there is a higher signal-to-noise ratio, despite the filters in the new system being set to 1kHz bandwidth in this pulse, compared to 200Hz for the existing system. This demonstrates that we can make higher bandwidth measurements without compromising on signal quality.

To perform a quantitative validation of the new system's data, the measured voltage was used to calculate the line-integrated intensity for each channel, $I = 4\pi P/E$, where P is calculated using Equation 1 and E is the étendue of the sensor. The expected intensity measurement can be obtained by integrating a tomographic reconstruction of the emissivity profile along the channel's line of sight. The tomographic reconstruction was performed using only data from the existing JET system, and the back-calculation was done additionally for the new system. Figure 4 shows the result of this for JET pulse 89548 at one of the time slices for which a valid reconstruction was available. Channel 32 has been omitted, since it was discovered upon installation of the electronics that the in-vessel sensor for this channel is broken. The measured and expected intensities are in good agreement, with deviations in the new system comparable to those of the existing system. The agreement of the new system with calculations using the existing system's data demonstrates that the new system has accuracy comparable to that of the existing system.

IV. SUMMARY AND CONCLUSIONS

The new bolometer system which has been developed for the MAST-U Super-X divertor has been described. Improvements over existing bolometer systems include the use of an FPGA to perform digital signal processing, a fast and automated calibration procedure and the ability to calculate the power incident on the bolometer sensors in real time. Future real time control applications have been discussed. The electronics have been installed on the JET tokamak on 8 previously unused vertical channels, and the system has been shown to produce data in good agreement with the existing JET bolometer system, but with a better signal-to-noise ratio, even at higher bandwidth.

ACKNOWLEDGMENTS

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