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Fission Chamber Data Acquisition system for Neutron Flux Measurements on the Mega-Amp Spherical Tokamak Upgrade

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Neutron flux measurements are important in fusion devices for both safety requirements and physics studies. A new system has been built for the Mega Amp Spherical Tokamak Upgrade (MAST Upgrade) that provides neutron count, DC and Campbell mode measurements for a 1 μs period at 1 MHz. The acquisition system uses a Red Pitaya board to sample current from two fission chambers mounted on the side of the MAST-U vessel. The system-on-chip design of the Zynq-7020 on the Red Pitaya also allows a web server implementation using Flask for data retrieval and diagnostic configuration over the MAST Upgrade network.

Keywords: Fusion, Plasma, Fission Chamber, FPGA, Neutron Flux, Koheron, Red Pitaya, Flask, MAST Upgrade, Tokamak

I. INTRODUCTION

The Mega Amp Spherical Tokamak Upgrade (MAST Upgrade) is a new UK operated fusion experiment located at Culham Centre for Fusion Energy in South Oxfordshire[12]. MAST Upgrade has been designed to explore novel divertor geometries with the installation of the super-X divertor[3]. One of the many new diagnostics designed for implementation on MAST Upgrade are two new fission chambers for neutron flux measurements. Not only is there a safety case for measuring neutron flux to ensure the facility operates within its neutron budget, but as half of deuterium fusion reactions produces a neutron[4] there is also a physics case in measuring the fusion rate to determine power produced and correlate fusion power to different plasma effects.

The previous fission chamber system implemented on MAST used commercial-off-the-shelf signal conditioning electronics to produce the Campbell mode, DC and pulse counting signals[5]. For MAST Upgrade the decision was made to replace the fission chamber used on MAST for a more up-to-date system. A digital electronics based real-time analysis and data acquisition system to be built in house was selected for the upgrade. This decision was made to improve the maintainability and redundancy of the fission chamber system, and by bringing development in-house future upgrades and added functionality will be easier and more cost effective to integrate.

It is worth noting that while fission chambers are widely used with both fission and fusion reactors to monitor total neutrons[6789], fission chambers are not the only neutron measurement diagnostic implemented on MAST Upgrade. A neutron camera is used to look at the neutron spectrum where the on-axis neutral beam interacts with the plasma. Radiation badges are also placed around the experimental hall to monitor total radiation levels.

This paper will discuss the use of a Red Pitaya STEMlab board[10] and the open source Koheron Software Development Kit (SDK) to implement a data acquisition and real-time processing system for two simultaneously operating fission chambers. Implementation of the Campbell mode, a measurement technique to reduce the impact of gamma rays[11], in programmable logic as well as verification of the hardware will also be covered.

II. BACKGROUND

A. Neutron Flux

The predominant fusion reaction in the MAST Upgrade tokamak is between two deuterium atoms. This produces a Helium nucleus and a neutron at 2.45 MeV 50% of the time. The neutron flux of a tokamak is therefore a measurement of the number of fusion reactions occurring over an amount of time. High energy neutrons are also capable of causing damage to components by creating atomic displacements or transmutations which can weaken structural materials and reduce the transmittance of windows and mirrors. Transmutation products can also be radioactive causing harm to people working with the materials. Finally, there are also neutron budgets imposed by government legislation when operating nuclear devices and these must be adhered to.

For all the reasons above it is therefore necessary to measure the total neutrons emitted by the MAST Upgrade tokamak. As previously mentioned a neutron camera to measure the neutron spectrum and spatial distribution will also be in operation. However, the proximity of the camera to the plasma means that the measured flux cannot be assumed to be representative of the isotropic flux. The fission chambers are mounted far from the vessel and in two separate locations,

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so that the total flux of the experiment can be measured after calibration.

B. The Fission Chambers

The fission chambers selected for operation on MAST Upgrade are Centronic FC765 units. These are sealed aluminium cylinders containing two uranium oxide coated electrodes and an argon-nitrogen gas mix.

When neutrons are incident on the uranium coated electrodes a fission reaction occurs. The high energy fission products ionise the fill gas which is drawn to the electrodes. This registers as a current pulse which is then measured by the data acquisition system.

Both neutrons and gamma rays entering the device can cause fission events to occur and so the fission chambers are shielded with a 45 mm thick lead layer to reduce the likelihood of gamma ray penetration. The cross-section of neutrons with the uranium coating is also higher at thermal energies than the 2.45 MeV of the fusion neutrons and so a polyethylene layer of 50 mm is included in the the shielding to thermalise incoming neutrons. Finally, a thin Cadmium layer of 0.5 mm is used to filter out neutrons with very low energies as this would reduce the temporal resolution. The neutron transport modelling code MCNP[12] was used to simulate the appropriate material and thickness of shielding layers.

C. Red Pitaya and the Koheron SDK

We have used a Red Pitaya STEMlab board used for the data acquisition and real-time processing. This board uses a Zynq 7000 System-on-Chip (SoC) with two 125 MHz Analogue-to-Digital converters (ADC) and two 125 MHz Digital-to-Analogue converters (DAC). The Zynq 7000 SoC incorporates a dual core ARM processor and a Xilinx Field Programmable Gate Array (FPGA) on a single chip with Xilinx providing standardised work flows for passing data between the two platforms. In this application the FPGA is designed to collect and process data from from the on-board ADCs as well as generate test signals that are passed through the pre-amplifier with the DAC. To send data to the MAST Upgrade data system the ARM processor is configured to run a web server using the python library Flask[13]. The web server handles data and configuration requests, using HTTP GET and POST, from the MAST Upgrade DATAC system.

The Koheron Software Development Kit (SDK) is a useful open-source development fit for a variety of Xilinx SoCs. It facilitates quick set-up of custom Zynq based instrumentation by providing a standardised Linux system and an open source Programmable Logic to Processing System infrastructure. It has been successfully used before in other instrumentation for plasma physics applications[14][15].

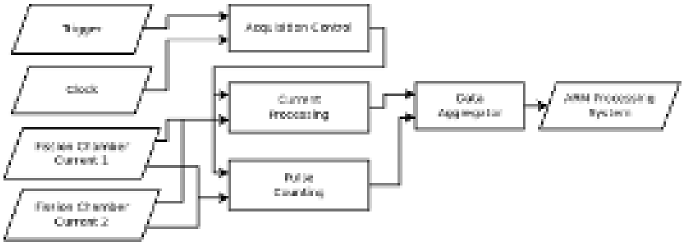

FIG. 1: Block diagram of the programmable logic used for the fission chamber data acquisition system. The acquisition control and pulse counting blocks are fairly simple, the former being a clock sync and the latter a current threshold check, the current processing block has been expanded in figure 3.

D. Pre-Amplifier Electronics

To ensure that the full dynamic range of the STEMlab board ADCs is used a built in-house pre-amplifier stages takes the current from the fission chambers and amplifies it by a factor of ten. The pre-amplifier also has a loop-back capbility that takes a signal from one of the on-board DACs and feeds it back to the ADC's. This signal can then be used to test design changes to the Programmable Logic (PL) without having access to a neutron source. The amplifier input is controlled through a relay that connects to a pin on the Red Pitaya so that switching between the real and test signal can be done remotely.

III. MEASUREMENT METHODS

The STEMlab board is designed to sample the fission chamber output current at 125 MHz and deliver a processed output at a rate of 1 MHz. In each 1 MHz packet is a timestamp, pulse mode count, DC current, and current variance measurement. Figure 1 shows the block diagram of the PL design implemented for the fission chamber data acquisition system.

A. Pulse mode

When in pulse operating mode the data acquisition system detects single pulses above a user defined threshold. This pulse detection system is simple and does not record any pulse statistics such as average frequency, or shape. A flow chart of the pulse detection algorithm is shown in figure 2 While this is a suitable method for measurement of low neutron flux each pulse has a finite width, so as the neutron rate increases the current pulses begin to overlap. This causes saturation of the pulse counter and eventually, when multiple pulses are arriving simultaneously, the signal current gains a DC offset relative to the neutron flux.

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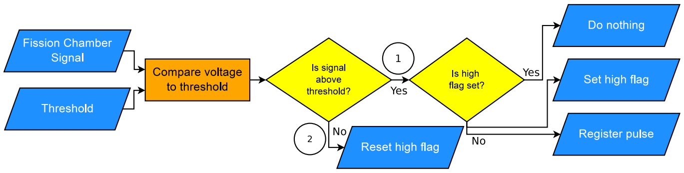

FIG. 2: Flow chart of the pulse detection algorithm.

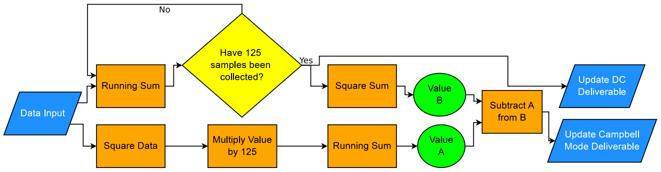

FIG. 3: Flow chart of the statics module that calculates the DC and Campbelling measurement modes.

B. Average Current (DC) output

The Campbell mean theorem shows that the mean signal from a random pulse sequence is proportional to the mean pulse rate[5]. The PL design must calculate the DC current of the fission chamber current from the 125 MHz sampled signal with low latency. To achieve this, as divisions in FPGA fabric are logic and clock cycle expensive, the DC current measurement is a sum of the 125 samples over the 1 μs sampling period. As the number of samples per 1 μs period is the same, this is functionally similar to the mean current. However, clock jitter may cause between 124 and 126 samples to occur in a 1 μs period so two bits per data packet are dedicated to registering how many samples were used to calculate the sum.

C. Current Variance (Campbell mode)

The Campbell mode technique uses the AC component of the fission chamber current to measure the neutron flux[76]. This method of neutron flux measurement favours neutron pulses over gamma rays and is a standard output of fission chamber analysis.

Previous implementations of Campbell mode in FPGA fabric have used digital filtering[6] and variance approximation techniques[1611] to generate the Campbell mode signal. However, these methods require more samples to calculate the variance of the signal than are available within the 1 MHz delivery requirement specified for this system. It is also the intention to provide a real-time Campbell mode signal in the future so the calculation latency should be as small as possible.

The variance of a signal with discrete samples x_i is shown in equation 1.

$$Var(x) = \sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2 \tag{1}$$

Where μ is the mean of the discrete samples and n is the number of samples within the collection period. Direct expression of this calculation in FPGA fabric requires the storage of each sample, and the approximation of two divisions. This is both resource intensive and, depending on the accuracy of the division approximation, would increase latency on the order of the sample time.

Instead, equation 1 can be expressed in the form of equation 2 shown below.

$$n^2\sigma^2 = n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2 \tag{2}$$

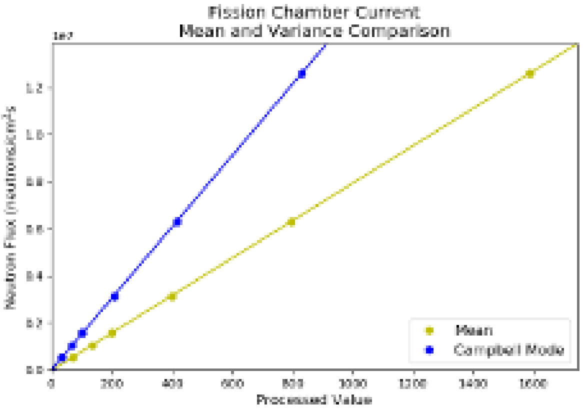

FIG. 4: Comparison of the real-time calculated mean and variance signal response to different neutron flux. Data has had the zero offset removed.

In this we can keep track of the sums through an aggregate of the samples over the collection period, with a calculation latency of less than five samples to calculate the final subtraction. A flow chart of how the DC and Campbelling measurement modes are simultaneously calculated is shown in figure 3.

IV. TESTS AT NATIONAL PHYSICS LABORATORY

Testing at the National Physical Laboratory was used to verify the system worked as expected and to perform an initial calibration of the system before implementation on MAST Upgrade. A van de Graaff generator produced charged deuteron particles which were then accelerated towards a beryllium target. Rotatable deflection plates were used to moderate the number of deuterons that hit the beryllium target and hence change the neutron flux incident on the fission chamber. Figure 4 compares the response of the mean and Campbelling measurements of neutron flux. Both the measurements are linear with respect to neutron flux as expected.

The different gradients are due to the different scales of response for each signal. This means that the Campbell and mean signals can be used for different neutron flux ranges, as well as cross-calibration with each other and the pulse counting mode to monitor gamma ray incidence on the fission chambers. Cross calibration is important for in-vessel calibration as it may not be possible to produce enough neutrons for detection with the Campbell mode using a laboratory neu-

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tron source. The cross-over between pulse counting and mean signals can then instead be used to calibrate the Campbell mode signal. However, comparisons to the crossover region between pulse counting and the DC current were not possible as the thermal neutron source could not be moderated to sufficiently low neutron flux.

A Finite Impulse Response (FIR) filter was used when testing at NPL to attempt to improve the dynamic range of the pulse counting mode. This filter was later removed from the design making the NPL calibration invalid. Due to the small amount of logic resources available on the Zynq 7010 SoC used in the STEMlab board only a filter of twenty taps was achievable. The filter had a poor frequency response which did not significantly reduce the effect of pile-up and also added significant latency to the system on the order of 20 percent of the 1 μs sampling time. The filter has therefore been removed for fission chamber operation on MAST Upgrade and comparisons with activation foils will be used for a future in-area calibration.

V. SUMMARY

A new data acquisition and real-time processing system for neutron flux measurement has been developed for MAST Upgrade. The new system implements a novel method for calculating fission chamber current variance to generate a 1 MHz measurement of neutron flux in pulse counting, DC current and Campbell mode simultaneously.

Functionality of the new system was verified using facilities at the National Physical Laboratory with the instrument showing a linear response to neutron flux as expected. In-area calibration of the instrument will be completed after the end of the first MAST Upgrade campaign. For the duration of the campaign an approximation of the total neutron flux has been calculated from the manufacturer supplied fission chamber documentation and MCNP simulations of neutron transmission and energy through the fission chamber shielding assembly.

VI. ACKNOWLEDGMENTS

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