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Modifications to the synthetic aperture microwave imaging diagnostic

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The synthetic aperture microwave imaging diagnostic has been operating on the MAST experiment since 2011. It has provided the first 2D images of B-X-O mode conversion windows and showed the feasibility of conducting 2D Doppler back-scattering experiments. The diagnostic heavily relies on field programmable gate arrays to conduct its work. Recent successes and newly gained experience with the diagnostic have led us to modify it. The enhancements will enable pitch angle profile measurements, O and X mode separation, and the continuous acquisition of 2D DBS data. The diagnostic has also been installed on the NSTX-U and is acquiring data since May 2016. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4961283]

I. INTRODUCTION

The Synthetic Aperture Microwave Imaging (SAMI) diagnostic is a first of its kind diagnostic imaging the edge of a tokamak plasma in the range of 10-35.5 GHz using a synthetic aperture approach commonly found in radio astronomy. Its originally intended purpose is the study of B-X-O mode conversion windows, but it is also capable of simultaneously conducting active probing measurements by launching an omni-directional modulated RF signal.[1,2] Both of these modes can be used to measure the pitch angle in the plasma edge.

The magnetic pitch angle—and in particular profiles of the magnetic pitch angle—is a key measurement to obtain the edge current density, which is understood to be a central quantity in understanding edge stability. In particular, the study of peeling-ballooning stability criterion, which is important in understanding the onset and evolution of edge localized modes (ELMs), will strongly benefit from the knowledge of this parameter.[3] The measurement of magnetic pitch angle has been difficult. Diagnostics that have been able to measure edge current density are lithium-pellet ablation,[4] Zeeman polarimetry on lithium beams,[5] and Motional Stark Effect (MSE) diagnostic.[6] However, MSE is the only one routinely employed and its reliance on neutral beams is often unavailable in L-mode shots, which has been particularly true for MAST.

The SAMI diagnostic has recently shown the ability to conduct 2D Doppler back-scattering (DBS) measurements as the first of its kind. This technique yielded the magnetic pitch angle at fixed frequencies in the MAST plasma edge for both L and H-mode plasmas.[2] As a result of this work, significant changes to the diagnostic hardware have been undertaken to enable the measurement of continuous pitch angle profiles, which was not possible previously. Recently SAMI has been moved to the NSTX-U. Its Li conditioning capabilities are of particular interest to Bernstein wave physics.[7] SAMI's 2D capabilities will enable more thorough investigations in this field.

The current status of the development work is presented in this paper. First, a short review of the diagnostic will be given. For a more thorough description, the reader is referred to the already published literature.[1,2,8–10] This is followed by a presentation of the diagnostic modifications, which mainly concern the FPGA firmware. The initial data acquired will be presented in a separate paper as part of these proceedings.[11]

II. DIAGNOSTIC HARDWARE SETUP

The SAMI diagnostic images the plasma using a synthetic aperture approach. This utilizes the fact that the signal emitted by a localized source and picked up by an array of antennas will arrive at each of the antennas at a different time depending on the direction of the source. Hence, by preserving the phase information of the antenna signals the direction of the signal's source can be reconstructed.[1]

SAMI images the plasma at 16 discrete frequencies from 10-35.5 GHz. The signal is picked up by an array of 8 antennas and sent through a set of hybrid couplers to generate the I and Q components. The probing frequency is selected using a fast RF switch and down-converted using 2nd harmonic mixers. The signals are digitized using two Xilinx Virtex-6 ML605 boards each equipped with an 8 channel 250 MS/s 14 bit digitizer. The FPGAs also act as controllers. Because well known phase information across the channels is critical, the FPGA firmware is identical on each board and uses a master slave approach to synchronize the acquisition.[8] The data are directly streamed into a DDR3 SODIMM module on the FPGAs at a rate of

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4 GB/s. This provides just over 500 ms of raw data acquisition. Previously these data were downloaded in between shots using a UDP protocol via Ethernet.[8]

An additional antenna, which is separate from the acquisition array, is used to send out a modulated signal. This probing signal is reflected by the plasma at the density cut-off. The reflected power is also picked-up by the antennas and is used for 2D DBS experiments.[1,2]

III. FIRMWARE MODIFICATIONS

One of the major issues for the SAMI diagnostic is its limited acquisition time of 500 ms, which is defined by the amount of RAM present on each FPGA. To make use of the long shot lengths found on modern machines, the FPGA firmware was enhanced to split the data acquisition into several arbitrarily long windows that can be spread across several minutes. Since synchronicity across the two FPGAs is of prime importance, the clock infrastructure had to be rewritten to ensure synchronous windowed detection.

Figure 1 shows the clock infrastructure present on the boards. The firmware is identical on both boards, hence synchronization is controlled by the clocks supplied to each board. However, one has to take into account that although the firmware is identical, there might be differences in the board's hardware, e.g., due to manufacturing accuracy. These differences will cause phase mismatches between the boards. Hence, all processes are synchronized via a set of carefully timed triggers resetting and synchronizing components across boards before the actual acquisition starts. This scheme extends through the entirety of the firmware design. Some of the phase mismatch between data lines from the ADC's cannot be corrected using triggers. To cope with the residual mismatch FIFO elements are used to shift all signals to the same clock-edge. The reworking of the clocking infrastructure, as shown in Fig. 1, also enables the diagnostic to switch frequencies at an

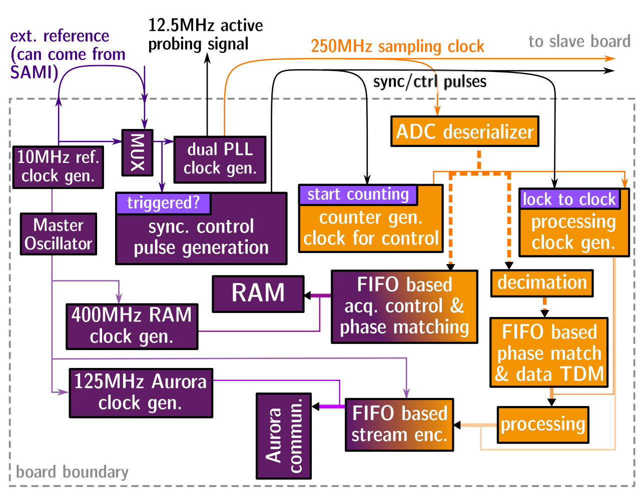

FIG. 1. The clocking infrastructure on the SAMI firmware. The identical firmware bitstream operates on both boards. Orange (bright) components are synchronous across boards. Purple (dark) components are driven from local non-synchronous clocks. Broken thick lines indicate non-phase matched data lines. Thin lines indicate clock nets. Different shades of the same color mark synchronous derived clocks.

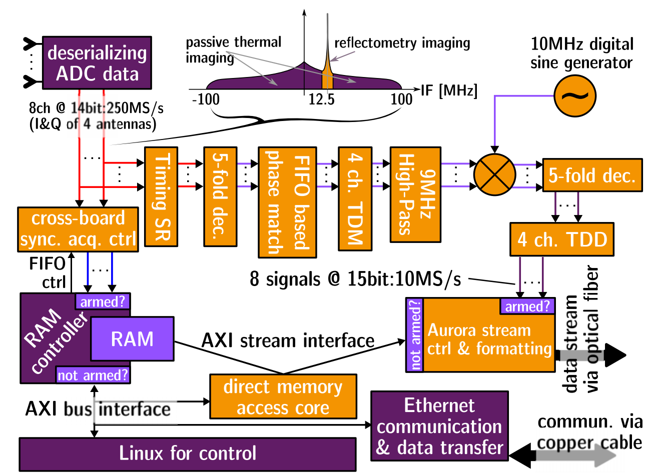

FIG. 2. Overview of the new SAMI FPGA firmware. The passive acquisition scheme is marked in purple (dark) and is the basis for the original diagnostic. The orange (light) components have been added and have the purpose of pre-processing the part of the spectrum responsible for 2D DBS. Filters are implemented as finite impulse response filters to maintain the phase relationship. The fiber optic link is also used to increase the speed of the passive data transfer.

arbitrary rate. Previously, the dwell time on a single acquisition channel was limited to 350 µs. During the development of the 2D DBS technique, this dwell time was found to be insufficient to measure pitch angle profiles due to the strong averaging required.

SAMI's total raw acquisition is limited to 500 ms, yet machines like NSTX-U and MAST-U intend to run multi-second pulses. SAMI's pitch angle measurements therefore cannot span the entire shot, but are at best intermittently spread across it using passive imaging windows. However, the 2D DBS signal only spans a small portion of the overall SAMI bandwidth as indicated in Fig. 2. The modulation signal is located at +12.5 MHz in the SAMI signal spectrum and the information needed to conduct 2D DBS is contained within a 3 MHz window surrounding the peak. The spectral constraints enable the use of data reduction techniques. The ML605 carrier board is equipped with a SFP cage for fiber optic data transmission, which was previously unused. Using the Xilinx Aurora 8b/10b protocol this link can be run at 2Gb/s, a limitation given by the SP605 Aurora-PCIe link used to transfer the data to PC memory. This bridge is based on an implementation used for the MAST-U interferometer.[12] Figure 2 shows the firmware changes implemented to reduce the data rate of the 2D DBS signal to the bandwidth limit. To reduce the demands on the subsequent processing, the raw digitized data are immediately 5-fold decimated. To this point, the data, although frequency synchronous, are not necessarily clock edge aligned. Hence, as indicated in Fig. 1, the data are phase matched using FIFOs and then time division multiplexed (TDM) to further reduce the resource constraints. The 12.5 MHz active probing signal is then down-converted to 2.5 MHz with a cross-board synchronized digital 10 MHz sine. The final 5-fold decimator brings the data rate down to 10 MS/s before time division de-multiplexing (TDD) the signals for transmission.

As indicated in Fig. 2, the same link can also be used to transfer the passive imaging data in between shots. This method of data transfer is more reliable than the previously employed UDP approach. In addition, the link provides much higher bandwidth than the Ethernet connection and allows the transfer of the 2 GB of raw data stored on the FPGA within 12 s. This improvement in download speed, in combination with the recently developed GPU code, provides imaging results within 1min of the shot finishing, instead of more than 20 min previously.[13]

As mentioned before, SAMI's inability to separate O and X mode induces uncertainties in the pitch angle measurements.[2] While the current hardware is unable to acquire both polarizations at the same time, it is possible to get enough information to do a partial separation of the polarization components by acquiring them intermittently. As part of the upgrades, the firmware has consequently been enhanced to enable an interleaved dual-polarization acquisition. The currently installed Vivaldi antennas will be replaced by dual-polarized sinuous antennas after the initial conditioning test. The new array will be placed in a more symmetric array configuration to minimize the distortion of image features due to the array geometry.

IV. SUMMARY AND OUTLOOK

Significant improvements to the SAMI diagnostic have been presented. The raw data acquisition can now be conducted in arbitrarily spaced windows. The diagnostic has also been changed to provide continuous 2D DBS data and allow the measurement of pitch angle profiles using 2D DBS. The presented data handling and processing techniques can be applied to other similar constraint scenarios. Modifications for dual-polarization acquisition have been implemented, which will make the interpretation of the obtained results easier.

The SAMI diagnostic has recently has been installed at the NSTX-U to conduct investigations into the influence on lithium conditioning on B-X-O mode conversion windows and test the changes described in this paper. Initial measurements have been conducted using an operation mode that is equivalent to the SAMI diagnostic as it has operated on MAST and are presented as part of this conference's proceedings.[11] The first measurements with the new modifications are expected as soon as the NSTX-U has been repaired and plasma operations commence.

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