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Modifications to the Synthetic Aperture Microwave Imaging diagnostic

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The Synthetic Aperture Microwave Imaging diagnostic (SAMI) 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 (FPGAs) to conduct its work. Recent successes and newly gained experience with the diagnostic has 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.

I. INTRODUCTION

The edge of a Tokamak plasma is believed to be one of the primary factors defining the overall plasma performance. In particular the improvement of confinement in H-mode is largely related to the edge forming a strong density gradient due to the suppression of turbulence as a result of increased flow shear[1]. However, the onset of H-mode is not yet fully understood and thus still subject to intensive studies. As such diagnostics, which can provide detailed measurements of the plasma edge are of great interest.

The Synthetic Aperture Microwave Imaging diagnostic (SAMI) is a first of its kind diagnostic imaging the edge of a Tokamak plasma in the range of 10-35.5GHz 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[2]. Both of these modes hope to measure the pitch angle in the plasma edge.

Gaining 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), would strongly benefit from the knowledge of this parameter[3]. The measurement of magnetic pitch angle has been difficult. To the best of the authors knowledge the only diagnostic capable of measuring pitch angle to date is the Motional Stark Effect diagnostic[4].

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[5]. As a result of this work significant changes to the diagnostic hardware have been undertaken to enable the measurement of pitch angle profiles, which was not possible in the previous setup. Due to the current upgrades conducted at the MAST-U experiment the diagnostic has been moved to the NSTX-U to make use of its unique Li-conditioning capabilities. This also provides a good opportunity to evaluate the new changes and conduct further studies into various aspects of the diagnostic.

The current status of the development work is presented in this paper. First an overview of the diagnostic in general will be given. This is followed by a presentation of the modifications undertaken in order to improve the diagnostic and make it compatible with the NSTX-U setup. Lastly initial results from the NSTX-U will be presented and an outlook to further plans given.

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[6].

Fig. 1 shows a schematic of the hardware setup used. SAMI images the plasma at 16 discrete frequencies from 10-35.5GHz. The signal picked up by the antennas is sent through a set of hybrid couplers to generate the I and Q components. This is important as the subsequent down-conversion of the signals would destroy the phase information[6]. The probing frequency is selected using a fast RF switch and down-converted using 2nd harmonic mixers. The signals are digitized using two Xilinx

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Virtex-6 ML605 boards each equipped with an 8 channel 250MS/s 14bit digitizer. 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, i.e. one board supplying synchroneous trigger and clock for both boards. The data is directly streamed into a DDR3 SODIMM module on the FPGAs at a rate of 4GB/s enabling a total of just over 500ms of raw data acquisition. Previously this data was downloaded in between shots using a UDP protocol via Ethernet[7].

A. Firmware modifications

SAMI's new 2D DBS pitch angle measurement technique currently requires 10ms averaging windows for acceptable accuracy. However, the diagnostic's maximum time on one frequency was limited to about 350μs preventing the measurement of pitch angle profiles. In addition the diagnostic was incapable of separating O and X-mode, which led to additional errors for both the active and passive acquisition mode. To improve on these shortcomings significant redevelopment of the FPGA firmware was conducted.

To make more use of the long shot lengths available at the NSTX-U and MAST-U the firmware was modified to allow the acquisition of multiple arbitrarily spaced windows at the full sampling rate. In addition the channel switching time limit has now been lifted. In this context the clocking infrastructure on the FPGA chip was also redesigned to compensate for a probing frequency drift and enable an additional data streaming infrastructure.

As mentioned before SAMI's inability to separate O and X mode induces uncertainties in the measurements in both its passive and active acquisition mode. While the current hardware is unable to acquire both polarizations at the same time it is possible to get enough information

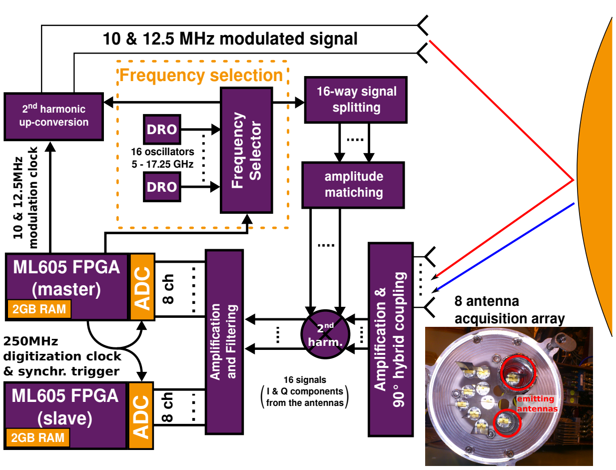

FIG. 1. Top level schematic of the diagnostic hardware.

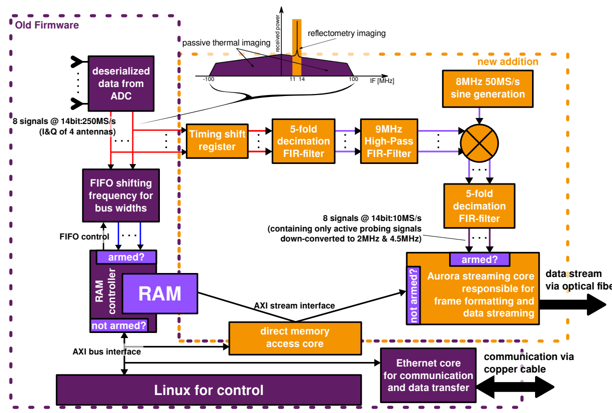

FIG. 2. Modifications to the SAMI FPGA firmware.

to do a partial separation of the polarization components by acquiring them intermittently. 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, which will be placed in a more symmetric array configuration to minimize the distortion of image features due to the array geometry.

One of the benefits of the 2D DBS System is that it's signal only requires a small portion of the overall SAMI bandwidth as indicated in fig. 2. The active probing modulation signal is located at +10MHz and +12.5MHz in the SAMI signal spectrum. On NSTX-U the information for the 2D DBS image reconstruction is contained in about ±1.5MHz around each center frequency. SAMI's raw acquisition is limited to 500ms, yet machines like NSTX-U and MAST-U intend to have several seconds long pulses, the firmware has been changed to stream the active probing section of the data continuously off the FPGA. This is done by forking the raw data stream before it is streamed to the RAM (see fig. 2). The 12.5MHz signal is isolated, downconverted and decimated using phase linear FIR filters and digitially generated mix-signals. This places the central probing signal at about 2MHz with a decimated sampling rate of 10MS/s. The reduction in data rate is enough to stream it off the FPGAs via a 2.5Gb/s fiber optic link based on the Xilinx Aurora protocol. This enables the continuous monitoring of the magnetic pitch angle profiles using this diagnostic.

As indicated in fig. 2 the same link can also be used to transfer the passive imaging data in between shots. This is beneficial for multiple reasons. For one the UDP approach previously used depended heavily on very specific hardware and for that reason was very unreliable if conditions changed slightly. The now employed fiber optic approach has so far proven to be more reliable at transferring the data. In addition the link provides much higher bandwidth than the Ethernet connection and allows the transfer of the 2GB of raw data stored on the FPGA within 12s. This in combination with the recently developed GPU code[8] enables to get results of the SAMI diagnostic within 1min of the shot finishing.

B. Aurora to PCIe bridge

The streamed data, whether during a shot or in between a shot, is directly captured by a linux PC using a self-designed FPGA based Aurora-to-PCIe interface card. The card is based on a Xilinx Spartan-6 SP605 board and in addition to the Xilinx Aurora core uses Xillybus as a PCIe interface. This firmware has proven to be very versatile and is used in other diagnostic setups[9]. There are also developments in progress to use the card as part of the MAST-U machine protection system.

Two of these cards with quasi-identical firmware are operating in parallel on a Linux host to capture the streamed data during a shot. The diagnostic control is still conducted using a webinterface running on the FPGA's Linux system[7], although the card is capable of transmitting data to the FPGAs.

III. INSTALLATION ON NSTX-U & OUTLOOK

Due to the MAST upgrade being under way SAMI has recently been installed on the NSTX-U . The experiment provides several interesting changes to the plasma environment, although being a spherical Tokamak of similar proportions to MAST. One of the main goals of operating on the NSTX-U will be to investigate the effect of Lithium conditioning. This has been found to have a significant impact on the location and efficiency of the B-X-O mode conversion windows by reducing collisional damping[10]. SAMI as a 2D diagnostic is ideally suited to conduct further studies on this matter. In addition the NSTX-U plasma is significantly closer to the SAMI acquisition array. In consequence a field of study will be the development of near-field image inversion techniques suited to reconstruct the image. Lastly we hope to use the new modifications to the diagnostic to deliver the first pitch angle profile measurements using the newly developed 2D Doppler back-scattering technique.

The initial measurements will be conducted using the old Vivaldi antenna array to benchmark the results against the data obtained on MAST. The results of the initial measurements taken on the NSTX-U already show several significant differences in the diagnostic behaviour[11]. Most notably the DBS power is significantly higher than expected potentially allowing us to look into k-spectra studies, which has previously been impossible due to the limited DBS power available to the system.

After the initial conditioning with the old Vivaldi array is finished it will be exchanged for a dual-polarized sinuous antenna system to separate polarization if desired. The respective array has already been built so that the swap-over will only require a short period of manual work and calibration. The necessary FPGA controlled RF switches selecting the polarization will be installed directly behind the antennas to minimize attenuation.

IV. SUMMARY

Significant development has been undertaken on the Synthetic Aperture Microwave Imaging diagnostic (SAMI). The improvements will raw acquisition in arbitrarily spaced windows and provide continuous 2D DBS data making more use of long shot lengths. The diagnostic has also been prepared for dual-polarization acquisition, which will make the interpretation of the obtained results easier. Lastly SAMI has been installed at the NSTX-U experiment to conduct investigations into the influence on Lithium conditioning on B-X-O mode conversion windows.

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