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A field programmable gate array unit for the diagnosis and control of neoclassical tearing modes on MAST[a)]

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A real-time system has been developed to trigger both the MAST Thomson scattering (TS) system and the plasma control system on the phase and amplitude of neoclassical tearing modes (NTMs), extending the capabilities of the original system. This triggering system determines the phase and amplitude of a given NTM using magnetic coils at different toroidal locations. Real-time processing of the raw magnetic data occurs on a low cost field programmable gate array (FPGA) based unit which permits triggering of the TS lasers on specific amplitudes and phases of NTM evolution. The MAST plasma control system can receive a separate trigger from the FPGA unit that initiates a vertical shift of the MAST magnetic axis. Such shifts have fully removed $m/n = 2/1$ NTMs instabilities on a number of MAST discharges. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4732057]

I. INTRODUCTION

Neoclassical tearing modes (NTMs) limit performance and stability on tokamaks and are predicted to be one of the principal performance limiting instabilities on next step devices. Further understanding and methods to control these instabilities are therefore needed.

A new event generator unit has been built on MAST to generate triggering events on NTM amplitude and phase using the Thomson scattering (TS) system. The unit permits useful data to be collected for NTM studies and also provides a novel method of NTM control, using vertical shifts of the magnetic axis. Initial results show vertical shifts to stabilize $m/n = 2/1$ NTMs and prevent NTM-driven disruptions for a number of MAST shots and thus extend H-mode duration.

II. DESIGN

The event generator unit consists of a Nexys II FPGA board from Digilent Inc, built around a Xilinx Spartan-3E FPGA. It is programmed to receive and process signals from the magnetic coils and use these to calculate the amplitude and phase of a given NTM (Fig. 1). Triggering events are sent to the TS triggering unit[1] when these values match a set of user-defined input criteria and this in turn triggers the lasers. Triggers are also sent to the MAST plasma control system which can generate vertical shifts of the magnetic axis. The event generator unit has been programmed using both the Xilinx Software Development Kit (version 12.4) (Ref. 2) and the Mathworks Simulink System Generator Toolbox.[3] The FPGA firmware design, which consists of six principal subsystem blocks (Fig. 2), will now be described.

The analogue-to-digital converter (ADC) block converts the analogue signal from each Mirnov coil to a 12 bits, 1 MHz signal which is sent to the FIR (finite impulse response) block. By combining the digital signals from each Mirnov coil, the FIR block determines the $n = 1$ the signal of a 2/1 NTM. The contribution of each coil to the $n = 1$ signal is given by the complex number $e^{ni\theta}$, where θ is the toroidal phase difference between the Mirnov coils and n is the toroidal mode number and is equal to 1. The real and imaginary components for each coil are determined using bandpass and Hilbert FIR filters, respectively. The amplitude and phase of the $n = 1$ signal is then determined by taking the Cartesian-to-polar transform of its real and imaginary components using a CORDIC algorithm. NTM frequency is then calculated from the finite difference of the phase and, finally, the NTM period is determined using a zero crossing algorithm.

Both FIR filters need an identical high frequency response over the observed 2/1 NTM frequency range (typically, 2-10 kHz for MAST) as differences would cause errors in the NTM amplitude and phase calculations. A number of FIR filter design methods have been tested and the least squared method[4] was found to give superior results, producing FIR filters with similar high frequency responses in the desired range whilst only requiring 180 FIR coefficients. This is important the greater the number of FIR coefficients the longer the event generator unit processing delay.

The 2/1 NTM amplitude and phase signals are sent from the FIR block to the triggering logic subsystem. In the current version of the firmware, both TS lasers and vertical shifts can be triggered on either the rising or falling edge of the $n = 1$ amplitude. The phase at which the lasers are triggered is adjusted to compensate for the delays incurred by both event generator unit processing and laser lamp triggering.

Processing delays in the event generator unit consist of the group delay of the preamp (11.6 μs), the group delay of the FIR filter (90 μs), the 12 FPGA clock

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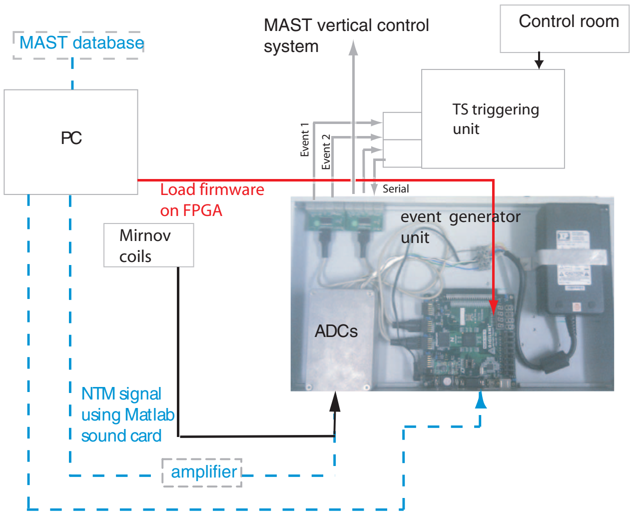

FIG. 1. Schematic diagram showing the event generator unit and its interface with the control PC, TS triggering unit, Mirnov coils, and MAST plasma control system. Blue dotted lines represent the PC test signal and black solid lines represent the input signal during operation.

cycles (0.25 μs), and also the transit time delays over the fibers and the laser flight line (~0.2 μs). The laser lamp triggering delay is ~300 μs for the Nd:YAG lasers and 1250 μs for the ruby laser. The range of the phase is scaled to between −128 and 128 units in the FPGA unit. Thus, if a NTM period is k μs and a trigger at phase p is required, then the lamp triggers must be sent at $k - (300 + 102) \times \frac{256}{p}$ μs (Nd:YAG lasers) and $k - (1250 + 102) \times \frac{256}{p}$ μs (ruby laser). The Q-switch triggers are issued at $k - 102 \times \frac{256}{p}$ μs for both systems.

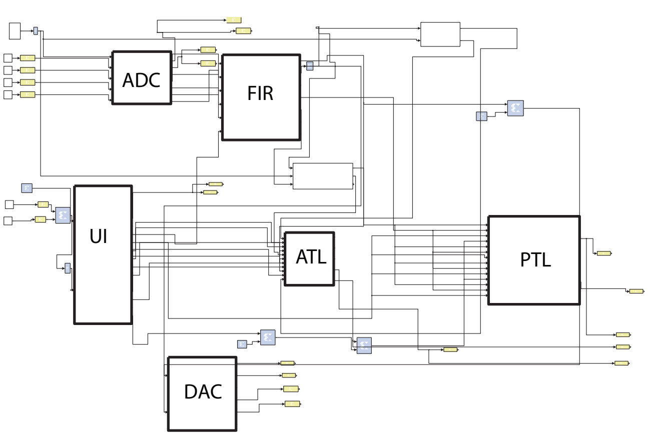

FIG. 2. Simulink block model of the event generator unit firmware. The principle blocks are labelled and the links between them represent data channels. The input signal from the magnetic coils enters the ADC block and is then sent to the FIR block , which calculates the NTM phase and amplitude. These data are sent to the amplitude triggering logic (ATL) block and phase triggering logic (PTL) block. Desired NTM amplitude and phase are set by the user and interpreted by the user interface (UI) block, which sends the signal to the triggering logic blocks. When NTM phase and amplitude match user requirements in the triggering logic blocks, the laser Q-switch and lamp triggers are generated by the phase triggering logic block and these are sent to the TS triggering unit. The digital-to-analogue converter (DAC) block contains the logic to convert FPGA signals to analogue for monitoring the unit.

The Nd:YAG (Event 1) and ruby (Event 2) outputs (Fig. 1) are sent to the TS triggering unit. The rising and falling edges of these outputs provide the respective triggers for the laser lamp(s) and Q-switches. A hold-off period can be introduced to ensure all lasers are available for triggering when a NTM event occurs.

The MAST plasma control system[5] controls the position and shape of the plasma using real-time feedback from currents in the poloidal field coils and measurements from additional coils located around the vessel. This system has been modified to permit triggered vertical shifts of the magnetic axis. The Z_{ref} parameter is the system reference for the vertical (Z) position of the magnetic axis and can now be modified in real-time using an optical signal generated by the event generator unit. When this optical signal is on Z_{ref} is shifted by Z_{offset}, which can be set to a specific offset value before the shot begins. The duration and onset of a vertical shift are also controlled by the event generator unit and if the $n = 1$ signal amplitude is greater than an upper threshold, the vertical shift is triggered and remains on until the amplitude reaches a lower threshold. These thresholds can be set on a shot-by-shot basis.

III. TESTING AND IMPLEMENTATION

The frequency range at which NTMs occur is within that of PC sound cards and therefore previous shots from the MAST database can be replayed to the event generator unit from a PC. This provides a simple means of generating an input magnetic signal for testing this unit (blue dotted line in Fig. 1).

The design of the firmware and operation of the system can be tested using Chipscope pro software[2] which allows a logical analyzer to be inserted into the FPGA design. Using this tool, internal FPGA signals can be monitored and recorded during the FPGA operation. These tests reveal that the event generator unit could be falsely triggered by ELMs, as these result in a fast drop (~1 ms) in the amplitude and frequency of the magnetic signal. This is prevented by calculating derivatives of both the n = 1 amplitude and frequency and comparing these to specified control parameters. Triggering is prevented when calculated values are greater than the control parameters.

IV. RESULTS

The TS system can now be triggered on specific amplitudes and phases of a 2/1 NTM and, through adjustments to laser timings, permits different aspects of 2/1 NTMs to be investigated. Equal spacing of TS lasers (240 Hz) provides useful data for NTM evolution studies[6] and has been successfully demonstrated on a number of MAST shots (Fig. 3). The TS lasers can also be triggered in burst mode, with laser separation typically ~20 μs, and this permits detailed study of heat transport across NTMs.[6] The laser burst can be triggered on a specific amplitude, but at present cannot be triggered on the phase as laser separation is less than the laser lamp triggering delay. The event generator unit now also permits triggering of vertical shifts of the magnetic axis on NTM amplitudes.

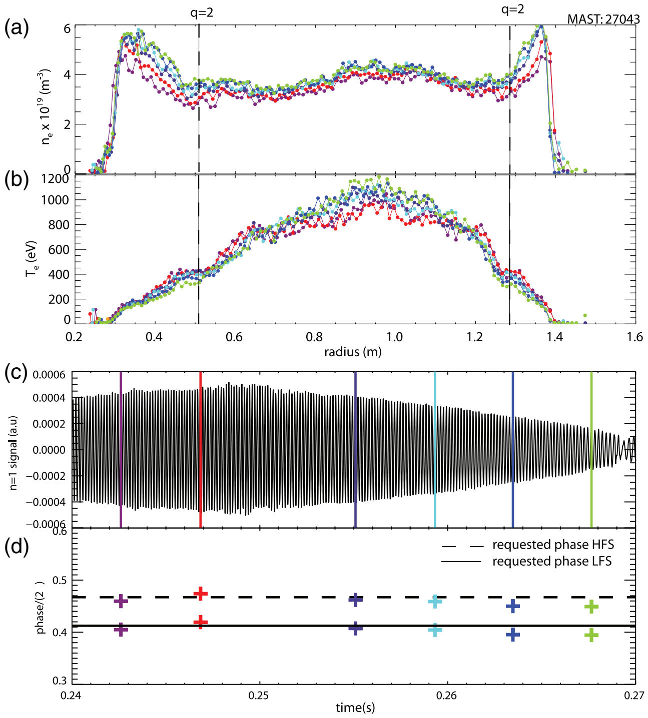

FIG. 3. (a, b) n_e and T_e measurements, respectively, at a number of NTM o-points (phase/2π ~ 0.5). An o-point is seen as a flattening of the T_e profile around the $q = 2$ surface. (c) The TS laser times (colored lines) are over plotted on the n = 1 signal (black line). (d) The phase at which each laser is triggered on the high field side (HFS, dotted line), and low field side (LFS, solid line) of MAST is over plotted on the requested phase. FIR filters introduce a small (~0.01) systematic offset as the frequency of the n = 1 signal decreases.

H-mode access and edge pedestal height are both sensitive to the vertical position of the magnetic axis (Z_{ref}).[7] Recent experiments performed using this unit have exploited these sensitivities in order to modify 2/1 NTM stability. A back transition to L-mode and a significant drop (~70%) of the local plasma pressure (principally, as a result of a drop in density) at the location of a NTM (Fig. 4) results from the vertical shift triggered by the presence of a NTM itself. This method has been shown to prevent 2/1 NTM disruptions on MAST for a number of discharges and also to extend the length of the H-mode by 100% in these same discharges. Typically, the H-mode phase is recovered and the NTM removed within 20 ms of its onset, with this time response at least partly due to delays in the interface with the existing plasma control system. Importantly, in the core of the plasma no significant drops in core plasma electron pressure (Fig. 4(c)) are observed as a result of vertical shifts.

V. FUTURE WORK

Future work on the TS triggering will focus on triggering from 3/2 to 4/3 NTMs. In addition, the system will be upgraded to allow phase triggering when the TS lasers are separated by less than laser lamp triggering time (300 μs).

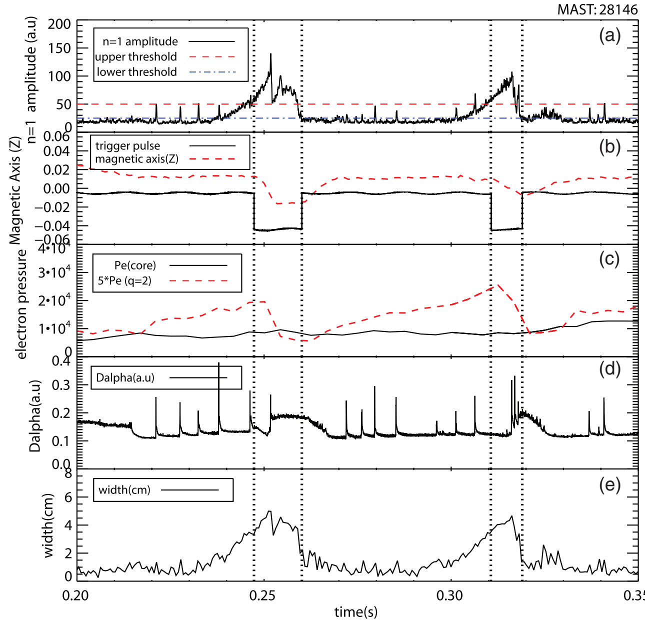

FIG. 4. The removal of a 2/1 NTM using two triggered vertical shifts. (a) The n = 1 amplitude calculated by the FPGA unit. (b) The trigger pulse (black line) and the resulting 1.5 cm shift of the vertical axis (red dashed line) are shown. (c, d) The effect of each shift is to drop from ELMy H-mode to L-mode, which can be seen as changes in electron pressure and D_{alpha}, respectively. (e) Evolution of NTM width, the NTM disappears at both 0.265 s and 0.33 s.

Triggered vertical shifts have been shown to remove 2/1 NTMs on a number of discharges and to prevent 2/1 NTM driven disruptions. Further work will involve improvements to the response time of the MAST plasma control system, in order to permit vertical shifts at smaller NTM sizes. This would reduce the perturbation to the plasma and thus the time required to stabilize the NTM.

ACKNOWLEDGMENTS

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[1] G. Naylor, Fusion Eng. Des. **85**, 280 (2010).
[2] Xilinx, "Xilinx software development kit," 2011.
[3] Mathworks, "Simulink: environment for multidomain simulation and model-based design," 2011.
[4] T. W. Parks and J. H. McClellan, IEEE Trans. Circuit Theory **CT-19**(2), 189–194 (1972).
[5] G. J. McArdle, J. Storrs, and J. Ferron, Fusion Eng. Des. **66–68**, 761 (2003).
[6] K. J. Gibson and the MAST team, Plasma Phys. Controlled Fusion **52**, 124041 (2010).
[7] H. Meyer, Y. Andrew, P. G. Carolan, G. Cunningham, E. Delchambre, A. R. Field, A. Kirk, P. Molchanov, V. Rozhansky, S. Voskoboynikov, and the MAST and NBI teams, Plasma Phys. Controlled Fusion **50**, 015005 (2008).