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A field programmable gate array unit for the diagnosis and control of neoclassical tearing modes on MAST\textsuperscript{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\textsuperscript{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.\textsuperscript{3} The FPGA firmware design, which consists of six principal subsystem blocks (Fig. 2), will now be described.

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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 $k - (300 + 102) \times \frac{256}{p} \mu s$ (Nd:YAG lasers) and $k - (1250 + 102) \times \frac{256}{p} \mu s$ (ruby laser). The Q-switch triggers are issued at $k - 102 \times \frac{256}{p} \mu s$ for both systems.

The MAST plasma control system 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 $Z_{\text{ref}}$ 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 $Z_{\text{ref}}$ is shifted by $Z_{\text{offset}}$, 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 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 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. 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.
H-mode access and edge pedestal height are both sensitive to the vertical position of the magnetic axis ($Z_{\text{ref}}$). 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).

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