Synchronization of Thomson scattering measurements on MAST using an FPGA based "Smart" trigger unit[a]

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The MAST Thomson scattering diagnostic has recently been upgraded to make electron density and temperature measurements at 130 points across the 1.5 m diameter of the plasma. The new system is able to take 240 measurements per second using eight Nd:YAG lasers, each running at 30 Hz. The exact firing time of these lasers is adjusted with 100 ns precision using a field programmable gate array based trigger unit. Trigger pulses are produced to fire the lamps of all lasers and the Q switches with the appropriate delay depending on the warm-up status. The lasers may be fired in rapid bursts so as to achieve a high temporal resolution over eight points separated down to the microsecond level. This trigger unit receives optical trigger events and signals from external sources, allowing the trigger sequences to be resynchronized to the start of the plasma pulse and further events during the shot such as the entry of a fuelling pellet or randomly occurring plasma events. This resynchronization of the laser firing sequence allows accurate and reproducible measurements of fast plasma phenomena. [doi:10.1063/1.3479120]

I. INTRODUCTION

The timing of Thomson scattering (TS) measurements of electron density and temperature profiles is determined by the arrival time of Q-switched YAG laser pulses as well as a Ruby laser in the Mega Ampere Spherical Tokamak (MAST) plasma. The laser pulses are fairly short (~12 ns) compared to evolution time periods of the plasma and so can be considered as snapshots of the plasma profile. A single laser pulse determines the temperature and density at 130 points across the midplane of MAST defined by the path of the laser beam. Eight lasers, each running at 30 Hz with adjustable time separation, enable burst mode operation and the tracking of fast processes within the plasma: edge localized modes,[1] neoclassical tearing modes (NTMs),[2] pellet ablation,[3] snakes, low to high confinement transition, sawteeth, etc. A recent improvement is described in this paper, which concerns the synchronization of these bursts of measurements to the timing of the shot and to randomly occurring events during the shot.

II. LAYOUT

The layout of the MAST TS system is shown in Fig. 1. The Smart trigger unit is located in the YAG laser room and provides the flash lamp and Q-switch trigger pulses independently to the eight YAG lasers and via optical fibers to the ruby laser in the MAST area. The Smart trigger unit also provides acquisition enable pulses to the YAG spectrometer room, which are then resynchronized to optical pulses from the YAG lasers.

III. DESIGN

The Smart trigger unit is based around a Nexys II Field Programmable Gate Array (FPGA) development board from Digilent Inc. This board uses a Spartan 3E FPGA from Xilinx. Development, simulation, and bit generation of the firmware used on the FPGA systems was performed using the toolbox System Generator™ from Xilinx[4] running in Simulink™ (The Mathworks[5]).

This device can be programed to perform an arbitrary logical function and read from and control a large number of electrical ports. Such FPGAs are therefore well suited to performing real time operations on digital trigger or analog inputs and outputting trigger signals to control the various lasers. The connections between the Smart trigger unit and external devices/systems are shown in Fig. 2. All electrical trigger signals are terminated with 50 Ω to ensure lower jitter performance. The FPGA receives a 10 MHz reference clock which is used to provide absolute timing of events with respect to other diagnostic acquisition systems. Trigger pulses are provided at a 30 Hz rate to each laser in order to synchronize lamp and Q-switch firing of the eight YAG lasers as well as a single lamp and Q-switch pulse for the ruby laser. During the warm-up phase of the Nd:YAG lasers, no Q-switch pulses are provided for 2 min, after which a Q-switch delay of about 600 μs is provided (at which little laser energy is produced) and the delay is gradually reduced to the nominal operating delay (just less than 300 μs) ready for the start of the shot. The settings of the laser timings including the relative timing in burst mode are set from a

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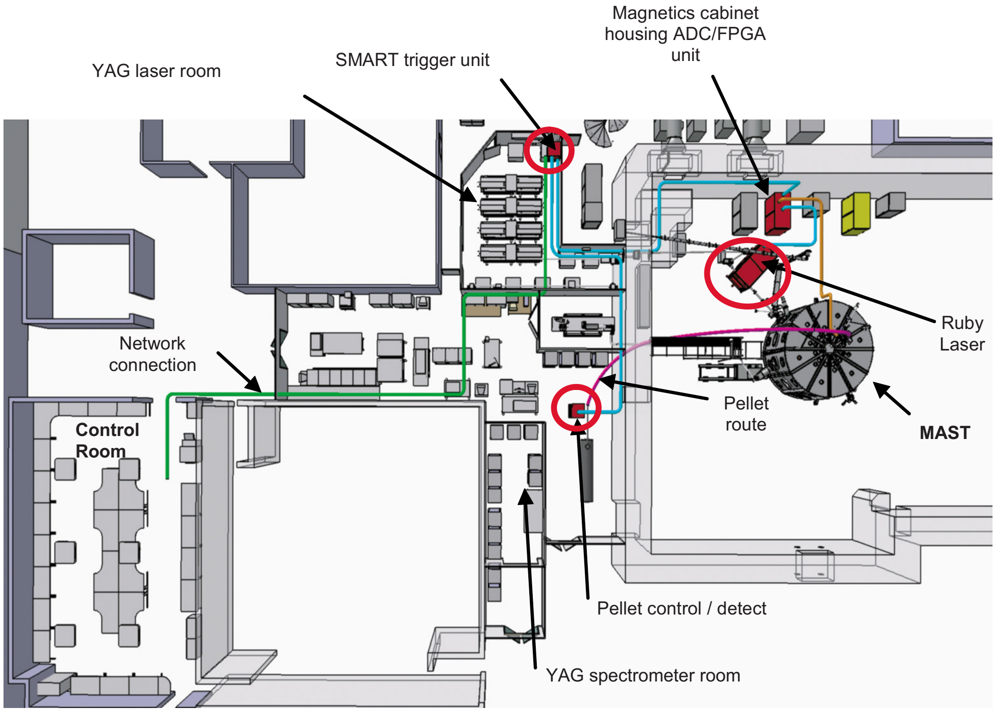

FIG. 1. (Color online) MAST TS system layout.

parameter file by a server control program running on a Linux personal computer (PC) over the network via an Ethernet to RS232 converter. This master PC also downloads the event data from the Smart trigger after the shot which includes information on each trigger pulse delivered (including time stamping to 100 ns precision, laser energy, reference of laser trigger, event type, etc.). Trigger signals are also provided for the fast acquisition units (500 channels) which record the scattered signals from the YAG TS system and the charge coupled device (CCD) trigger of the ruby TS system. The timing of the lasers can be adjusted, provided an average repetition frequency of close to 30 Hz is maintained (averaged over 1 s) and that subsequent laser pulses from one unit do not lie outside the range 30–100 ms. The 1 s time constraint is given by the thermal time constant of the YAG amplifier rods. The profile of the laser output in the far field of a laser after being interrupted for 100 ms was measured and shown to have very similar collimation to a beam with a regular pulse train. Separate watch dogs implemented on the FPGA ensure that the pulses provided to each laser satisfy the constraints indicated above in order to avoid damage to optics and to the lasers themselves.

A shot start signal at −2.5 s is used to ensure that laser number 1 is always fired at t=0. Once this command is received, the laser clock is interrupted and restarted at a fixed delay (so as to respect the constraints indicated above).

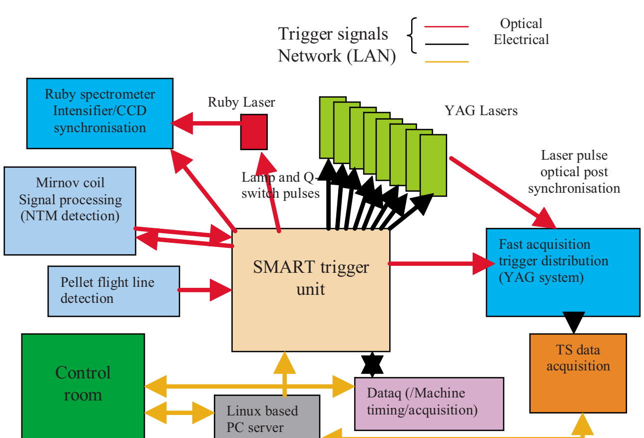

FIG. 2. (Color online) Connections of the Smart trigger unit.

IV. APPLICATIONS

A. Pellet ablation

A pellet launch signal is used to interrupt the laser triggering sequence. If this is received during a laser burst, this will continue until laser 8 is fired, after which the sequence is put on hold until a pellet arrive signal is received (about 40 ms later). Once the pellet arrive signal is received (light curtain above the tokamak), the burst restarts after a preset delay in order to allow time for the pellet to reach the plasma (see Fig. 3).

B. Neoclassical tearing modes

At a preconfigured delay during the shot, the laser sequence will be interrupted in anticipation of a magneto hydro-dynamics (MHD) event. A FPGA based signal processing device in the MAST area receives signals from several Mirnov coils located on the MAST center column, which are processed in real time in order to determine in real time the amplitude and phase of particular NTM modes.

The second FPGA device is connected to four 12 bit analog to digital convertor (ADC)s sampling at 1 MHz and processes real time signals from magnetic pick-ups. It calculates the NTM period, calculates the time of the trigger tak-

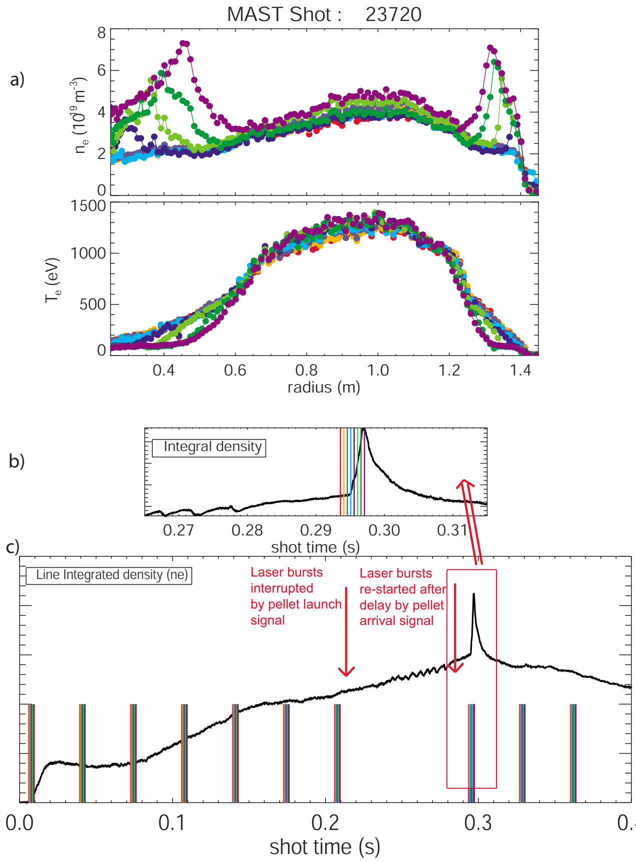

FIG. 3. (Color online) Resynchronization of TS laser bursts to pellet entering the tokamak. (a) T_e and n_e profiles (eight lasers). (b) Triggering on event (pellet). (c) Triggering before and after event.

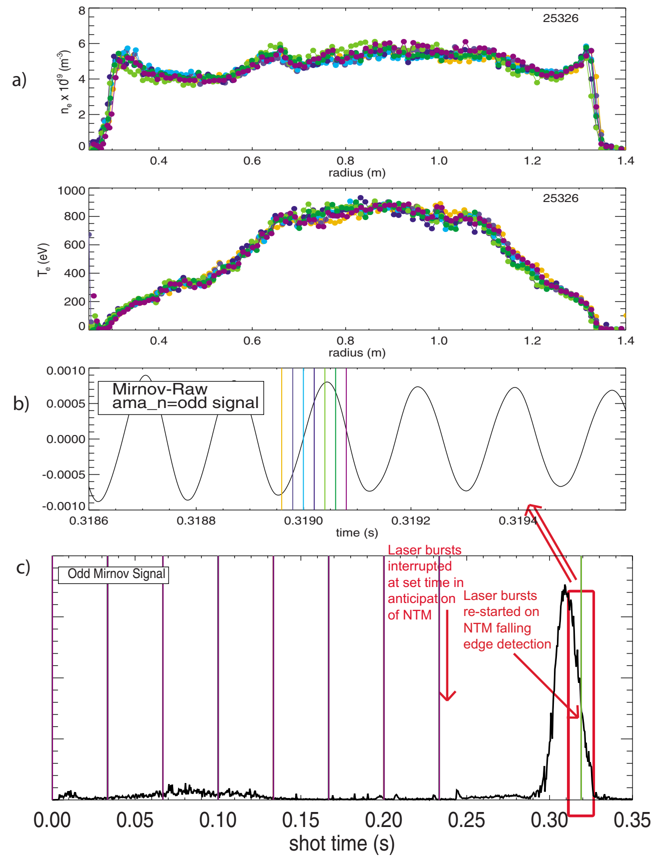

FIG. 4. (Color online) Resynchronization of TS laser bursts to falling edge of a NTM. (a) T_e and n_e profiles (eight lasers). (b) Triggering on event (NTM). (c) Triggering before and after event.

ing into account NTM filter delays, Q-switch delays, etc., and then issues the trigger. This device is controlled via the Smart trigger unit over a pair of fibers using universal aysynchronous receiver transmitter (UART) modules implemented in the FPGAs at each end. Configuration parameters such as trigger thresholds are sent from the master PC. Currently, the firmware enables trigger events on the falling edge of the NTM in order to catch a magnetic island just before it becomes subcritical again. Two trigger thresholds are set. One sets a minimum amplitude of NTM which will arm the triggering and triggering is then enabled once the amplitude falls below a second much smaller threshold. A second pair of fibers carries potential trigger points to the Smart trigger unit. The Smart trigger unit then selects which event is used to synchronize which laser depending on the sequencing of each laser (see Fig. 4). There is a minor bug to be corrected in the firmware, such that when the delay of the first laser is set to zero (as was the case in this shot) the first laser is missing.

V. CONCLUSIONS

A complex triggering architecture[6] to control many devices has been implemented using a flexible FPGA based system. Custom electronics housed in a single 2U crate provide all the input and output signals required to resynchronize Thomson scattering measurements to reproducible times during the MAST plasma shot and to randomly occurring events such as pellet entry and NTM decay. The possibility of reprograming the firmware allows the possibility of developing very complex triggering schemes.

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[4] See http://www.xilinx.com/tools/dsp.htm for a description of System Generator.
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