Fusion Engineering and Design 89 (2014) 693–697

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Timing and triggering of the Thomson scattering diagnostics on the COMPASS tokamak

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HIGHLIGHTS

- New timing and synchronization unit (TSU) for the Thomson scattering diagnostic (TS) on the COMPASS tokamak is presented.
- Construction of the TSU, including hardware design based on FPGA is shown.
- Operation regimes of TS and corresponding TSU operation flow are described.
- FPGA firmware and control software are introduced.

ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form 7 March 2014
Accepted 10 March 2014
Available online 31 March 2014

PACS:
52.55.Fa
42.55.-f
42.60.Gd
52.70.Kz

Keywords:
Tokamak
Timing and triggering
FPGA
Real-time control
Diagnostics control
Thomson scattering

ABSTRACT

The Thomson scattering diagnostics (TS) at the COMPASS tokamak (operated in the Institute of Plasma Physics ASCR, Prague, Czech Republic) is based on two high-power Nd:YAG lasers, which have a pulse energy of 1.5 J and repetition rate of 30 Hz each.

A new timing and synchronization unit (TSU) based on a Field Programmable Gate Array (FPGA) was designed and constructed in order to assure reliable and synchronized control of flash lamps and Q-switches of both lasers. Correct delay between laser pulses is necessary to obtain the highest possible laser energy and to prevent the active medium, the Nd:YAG rod, from thermal damage.

An FPGA development kit was chosen as core hardware for the TSU and dedicated input and output circuits were manufactured to adapt the kit interfaces for COMPASS TS needs. In addition, the FPGA firmware, the control software, and the graphical user interface were developed to control the TSU hardware.

This paper describes the TS regimes that are addressed by the new TSU. Further, the TSU design, the operation flow, and the firmware and software development are presented. Finally, the results of commissioning are shown.

1. Introduction

The Thomson scattering diagnostics (TS) is an important tool for determining profiles of electron density and temperature in tokamaks. The TS on the COMPASS tokamak [1] is based on two high-power Nd:YAG lasers, each of them having a pulse energy of 1.5 J and repetition rate 30 Hz. The system offers a high spatial resolution of 10 mm in the plasma centre and up to 3 mm at the edge [2]. However, the high-power lasers have a limited repetition rate which gives low temporal resolution. More samples and better results can be obtained by use of several properly synchronized lasers. For this purpose a new TS timing and synchronization unit (TSU) has been built.

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http://dx.doi.org/10.1016/j.fusengdes.2014.03.031
0920-3796/

The timing and synchronization unit is based on a Field Programmable Gate Array (FPGA) and was inspired by the MAST control unit [3]. Moreover, dedicated in-house designed electronic circuits were built to drive optical receivers/transmitters and electric inputs/outputs. The output signals are fed back to the FPGA and checked for logical and electrical integrity. Reliability is guaranteed by few independent safety features, both in firmware and hardware.

A single laser can be controlled using an embedded system provided by the manufacturer. However, no off-the-shelf system can trigger several lasers at once and provide a complex control scheme. For this purpose, the lasers contain necessary control inputs and hence can be connected to a custom-made unit, which meets all specific demands. The lasers at COMPASS were previously managed by a microprocessor accompanied by a separate system for output frequency checking and with a device for data acquisition triggering. This system was working well, but it was limited in its functionalities and further development was not possible. Three main drawbacks were found:

1. Microprocessor unit cannot trigger according to fast events.
2. A limited safety features.
3. A low computational speed.

Therefore, the new TSU based on FPGA was designed and replaces the previous device.

In this paper, the timing and synchronization unit design, principles and implementation are presented. In Section 2, the general information about TS on COMPASS and the envisaged regimes of its operation are addressed. In Section 3, the TSU hardware design is presented. Further, Section 4 is focussed on the actions of TSU from the user point of view. Section 5 addresses both the firmware and software development. Finally, Section 6 is devoted to results from testing and commissioning of the new TSU.

2. Thomson scattering operation regimes

Solid state Nd:YAG lasers like those on COMPASS have active medium (Nd:YAG rod) positioned between two mirrors and pumped by flash lamps. Q-switch blocks one mirror and prevents stimulated emission. As soon as the Q-switch is activated, the barrier is removed and the laser produces a high energy nanosecond pulse. Flash lamps and Q-switches operate according to control signals produced by TSU. Correct delay between pulses is necessary to obtain the highest possible laser energy and maintain the beam profile.

Before each experimental shot, the lasers are synchronized and warmed up. This period lasts approximately 2–3 min and the main aim of TSU is to provide a correct sequence of the control pulses, which is crucial for proper work of the lasers as mentioned before and to prevent the Nd:YAG rod from thermal damage. Afterwards, during the plasma discharge, each laser is firing with the 30 Hz repetition rate. The delay between the two lasers can be user defined utilizing the TSU. Thus, in principle, three regimes of operation can be achieved:

1. Maximum repetition rate of 60 Hz – the delay is set to half of the laser period.
2. Maximum power – both lasers synchronized to trigger at the same time (to maximize the scattered light intensity, achieve higher signal to noise ratio and minimize the error in determination of electron density and temperature).
3. General double pulse of the lasers with a delay between the pulses from 1 μs to several ms can be set to address particular physics studies. These double pulses are repeated with the natural laser frequency of 30 Hz in standard operation.

Moreover, the lasers can skip one pulse and wait for a trigger raised by an event. This is a feature allowing to obtain valuable data in selected snapshots of particular events (like the Edge Localized Modes (ELMs)) which can be recognized in the real-time control loop. The triggering unit is ready to handle these requests and to perform the event based triggering as well. However, it is obvious that the event detection itself has to be performed either by the superior system [4] or a real-time diagnostic.

3. Hardware construction

First step in the development process was selection of the computing platform. Field Programmable Gate Array (FPGA) was chosen as the most suitable candidate. The main advantage is that the FPGAs are inherently safer, more flexible and parallel processing systems, compared to the microprocessors. It should be noted that code for FPGA cannot be understood in the same manner as in the case of microprocessors. The code for FPGA is translated into a real hardware setup and physical connections. Thus, the result of the program is a description of the electrical circuits created on the chip. Development of our own board with FPGA would not be cost-effective in our case. Therefore, the so-called development kit Digilent Atlys [5] with Spartan 6 chip was chosen as optimal solution. Digilent Atlys has a mounted USB-UART converter enabling serial communication and 48 digital I/O pins on VHDCI connector for a general purpose. Easier access to signals on FPGA's pins offers the VmodMIB – VHDC Module Interface Board. Pmod connectors on VmodMIB were soldered out and replaced by Dubox connectors with locking mechanism. For board layout and connections in the TSU see Fig. 1.

The Digilent Atlys outputs can supply only 3.3 V and currents below 30 mA. The TSU is connected to lasers through a coaxial cable terminated by 50 Ω resistor. Laser inputs need TTL compatible control signals. It means that at terminating resistor should be optimally 5 V and 100 mA during logical one of control signal. A dedicated electronic board was designed to shift voltage amplitude to 5 V and amplify the current of FPGA signals. Moreover, the outputs are fed back to the FPGA through comparators. This circuit provides mechanisms for checking the voltage level and proper signal sequence. The TSU is also equipped with a second board containing optical inputs reserved for communication with, e.g., real-time system MARTe [6] or other COMPASS control systems [7,8]. Electronics with optical outputs are mounted above the previous board, controlling the shutters which open the laser path to tokamak hall and tokamak vacuum vessel.

Configuration of TSU can be done by several switches on its front panel or through a serial communication from a PC. The whole system is modular and can be simply extended or partially changed to execute new functions.

4. TSU operation flow

In Section 2, behaviour of the lasers which has to be ensured by TSU from the user point of view was described. Here, a more inside view of the triggering and synchronization is provided.

After start up, the TSU waits for configuration either from remote PC or by the TSU switches. Users then choose between the two modes of TSU operation:

1. Only pulses for flash lamps are generated in the first mode. It is done typically at the beginning of an experimental day and it is intended for the laser preparation. After 20 min, the lasers are