Development of a Laser Timing Controller for the High Time-Resolution Nd:YAG Thomson Scattering System in Heliotron J*)

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A new laser timing controller for the high time-resolution Nd:YAG Thomson scattering system with two Nd:YAG lasers has been developed to study improved confinement physics in Heliotron J. A PIC-based timing controller synchronizes the timings of laser oscillations with plasma discharges and enables the measurement of plasma profiles with a precision of <1 μs. The timing controller is used for the "soft start" of the system, which protects the optical components against initial unstable laser oscillations. The timing controller is designed to precisely control the delay time of the laser pulse from one laser to another, and to investigate the profile change of electron temperature and density within a short time span (> 80 ns), which is crucial for transport physics studies including spontaneous transitions.

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1. Introduction

Temporal measurements of plasma profiles provide indispensable information of the physics of transport barrier formation relating to improved confinement modes in magnetically confined plasmas. In a helical-axis heliotron device, Heliotron J, spontaneous transition phenomena to an improved confinement mode, which are similar to the H-mode in a tokamak, have been experimentally observed [1]. However, the formation of transport barriers in this transition has not been confirmed yet because of the lack of detailed measurements of electron density and temperature profiles.

Thomson scattering diagnostic is an established method for measuring the electron temperature and density profiles in magnetically confined plasmas. A Thomson scattering system with Nd:YAG lasers has been developed to obtain high-resolution profile data with respect to time and space in Heliotron J [2]. The system has 25 measurement points with a nominal spatial resolution of ∼10 mm. Two Nd:YAG lasers of 550 mJ were selected to obtain adequate signal intensity in the profile measurements by considering the typical electron densities of Heliotron J plasmas ($\overline{n_e} = 0.5\times10^{19}$ to $3\times10^{19}\,\mathrm{m^{-3}}$). Polychromators with a set of interference filters are used to analyze the scattered light spectra.

Transport barriers usually form within several hundreds of microseconds, as observed in CHS [3]. Precisely time-controlled measurements are necessary to obtain the profile change during a short time span, which is expected in transition phenomena. A timing controller that rapidly and precisely controls the laser oscillation timings is required for this type of measurements.

To measure the profiles just before and after an L–H transition, the timings of laser injection have to be synchronized with that of the transition. The timing controller is required to detect and identify precursory phenomena in the L–H transition. In addition, it must be expandable and adjustable to newly validated precursory phenomena through experiments. Trigger controllers for a Nd:YAG Thomson scattering system have been developed on DIII-D using a VMEbus [4,5] and on MAST using an FPGA [6].

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The VME system requires using ready-made functions for its modules and operating system developments. Consequently, the system is large, expensive, and takes considerable time to expand its functions. The FPGA system needs processes for designing and implementing logical circuits, and for validating functions and timings during development. The system extension also requires all these processes, which makes rapid expansion of its functions difficult.

On the other hand, the functions of a PIC microcontroller can easily and rapidly change by program modifications on the CPU. The rapid development of a timing controller with more complex functions than the above two systems can be compactly and inexpensively realized with a PIC. Thus, we have developed a timing controller using a PIC to precisely and independently control the oscillation of two lasers.

In this study, we describe in detail the design of the timing controller in Section 2 and the conclusions are given in Section 3.

2. Laser Timing Controller

In our developed Nd:YAG Thomson scattering system, a timing controller has four significant functions in the laser system. First, it precisely controls the flash lamp, Q-switch, and shutter timings of the two lasers that are synchronous with the Heliotron J plasma discharges. Second, it protects the optical components against the thermal lens effect and safety start-up of the laser oscillation. Third, it controls the oscillation timings of the two lasers for profile measurements before and after the rapid transition during barrier formation. Finally, it provides the timing signals for YAG Thomson data acquisition system. Consequently, we developed a laser timing controller that independently controls the triggering of the flash lamps and Q-switches of the two Nd:YAG lasers (Powerlite DLS 8050: Continuum Inc.). The controller is based on a PIC18F2550 [7] and allows for (1) real-time processing regardless of the state in the main control program, (2) program modification and flexible control of the sequence, and (3) remote monitoring. The controller and circuit diagram are shown in Figs. 1 (a) and 1 (b), respectively. The connections between the timing controller and external devices, or systems, are shown in Fig. 2. The controller has two input ports for receiving triggers from the Heliotron J control system and two output sets for timing signals to the flash lamp and Q-switch of each laser. In addition, a D-sub port is used for sending open-collector TTL signals and open/close of shutters in front of each laser. A USB port is used for remote monitoring and a modular jack (6 poles) is used for program modifications. Q-switch signals are also provided for the YAG Thomson data acquisition system and used for gate signals. The acquired data are transferred to the Heliotron J Linux-based PC server via a LAN.

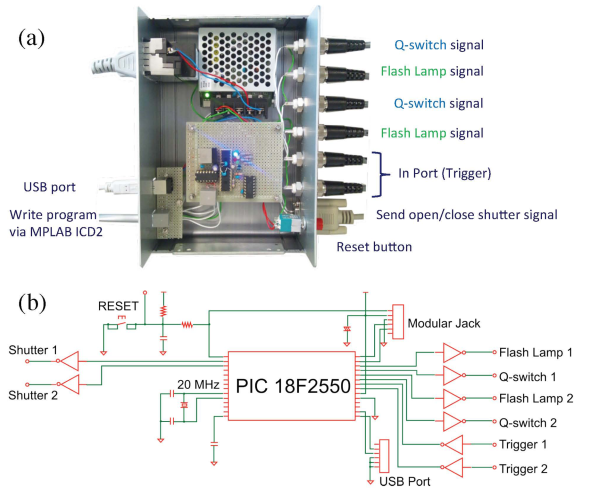

Fig. 1 (a) Top view of the timing controller and (b) its circuit diagram.

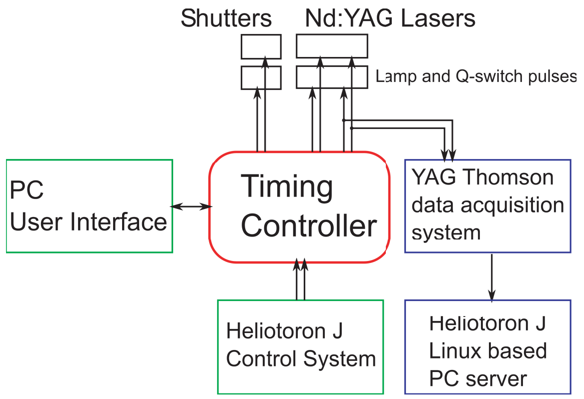

Fig. 2 Connections of the timing trigger.

2.1 Sequence control synchronized with plasma discharge

The laser pulse timing has to be exactly synchronized with the plasma discharge sequence. On the other hand, the warming-up operation of the laser system starts about 30 s before the plasma discharge. Therefore, the timing controller starts its control sequence after receiving the first trigger from Heliotron J about 60 s before the start of the excitation of the Heliotron J magnetic field. Once the second trigger is received from Heliotron J at $t = 0$ s (the start of plasma initiation), the timing controller clock is also reset to $t = 0$ s. We can control the output trigger timing with a resolution of 0.3 µs owing to the clock frequency of the PIC (20 MHz), and the firing timing of the lasers is synchronized with the second trigger with a precision of < 1 µs. These features allow measuring the profiles of the transition phenomena at precise timings. The first and second triggers are the contact outputs and TTL signals, respectively. The second trigger adopts an optical link, which insulates the Heliotron J control system from the

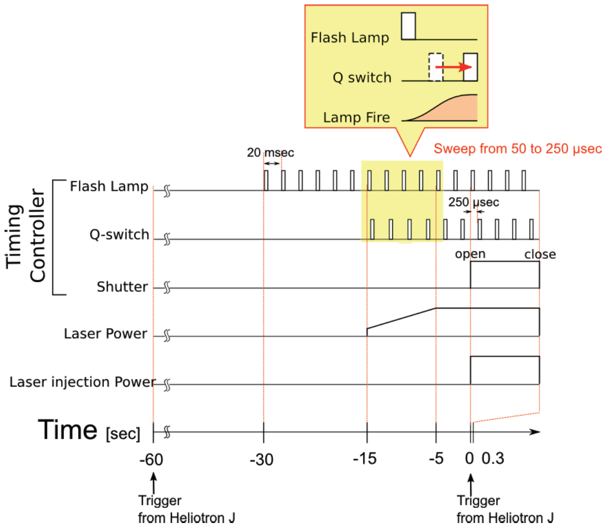

Fig. 3 Timing control sequence. The timing controller sends the triggers for the flash lamp, Q-switch, and control signal of the two shutters.

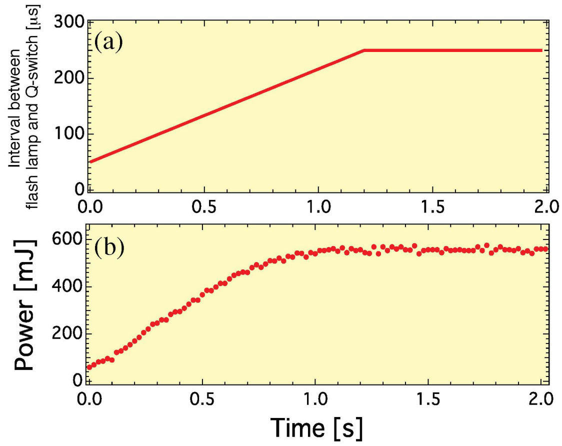

Fig. 4 (a) Example of time evolution of the interval between flash lamp and Q-switch and (b) laser power. A soft-start operation is realized by gradually increasing the interval time between the flash lamp and Q-switch from 50 μs to 250 μs (Time: 0 - 1.2 s).

timing controller to avoid the risk of inducing noises from the lasers to other devices connected to the control system.

Figure 3 shows the basic control sequence. After receiving the first trigger, the timing controller does not act for ~30 s. From approximately −30 s to −15 s, the timing controller generates the trigger signals only for the flash lamps for warming up the cavities of the lasers. From approximately −15 s to −5 s, the timing controller generates the trigger signals for the flash lamps and Q-switches, where the delay time of the Q-switch trigger from the flash-lamp trigger gradually increases from 50 μs to 250 μs to gradually increase the laser power (as illustrated in Fig. 3 inset). From about −5 s to 0.3 s, the delay time is fixed for steady-state operation. The base time of the sequence is resynchronized with the plasma discharge by using the second trigger. At the same time, the controller sends a command to open the shutters. The signals of the Q-switches, flash lamps, and shutters are TTL signals.

In addition, the timing controller can synchronize the measurement timing with the timing of target phenomenon by setting the laser pulse timing after receiving a signal from precursory phenomena. For this trigger signal, the timing controller can use not only simple high- or low-voltage signals but also calculated values of signals such as differentiated or integrated values, change of frequencies, and combinations of some signals. These functions can be easily and rapidly extended by program modifications of the timing controller whenever new precursory phenomena are identified, such as change in frequencies or magnitudes of Hα radiation, interferometer signals, soft X-ray signals, magnetic probe signals, ECE signals, radiation signals from plasma, power signals of heat sources, and combinations of them. Such flexibility and expandability are indispensable in experiments of magnetically confined plasmas of variable conditions and target phenomena.

2.2 Soft-start control

In the initial phase of the laser oscillation sequence, the laser power profile might have some local "hotspots" because of the thermal lens effect. To protect the optical components of the system from such local hotspots, only flash lamp pulses are provided to warm up the cavities of the lasers at first. Thereafter, for warming up the other components installed on the outside of the cavities, the laser power should be gradually increased to the optimum level until the stabilization of the thermal lens effect. Moreover, the shutters are opened only during a plasma discharge to avoid damaging the optical components. The laser power is determined by the time interval between the start of the flash lamp and Q-switch timing. The maximum laser power is obtained when this interval is set at the optimum level. When the intervals are short (or long) compared with the optimum one, the laser power is low. By controlling the interval with the timing controller, we can realize a soft start of the laser system and take measurements with maximum laser power.

Figure 4 shows an example of such operation. In Fig. 4 (b), the time evolution of the laser power, which is measured with a GaAs detector and calibrated by a power meter, is plotted as a function of time from the start of the system operation. In this control scenario, the laser emits at a constant interval of 20 ms. The timing controller gradually increases the interval time from 50 μs (at $t = 0$ s) to 250 μs (at $t = 1.2$ s), as shown in Fig. 4 (a), and fixes the interval time at 250 μs, which is the value for maximum power. As shown in Fig. 4 (b), the laser power is gradually ramped up at a programmed rate and fixed at the maximum power.

2.3 Time interval control of two lasers

To measure the rapid profile change due to the transi-

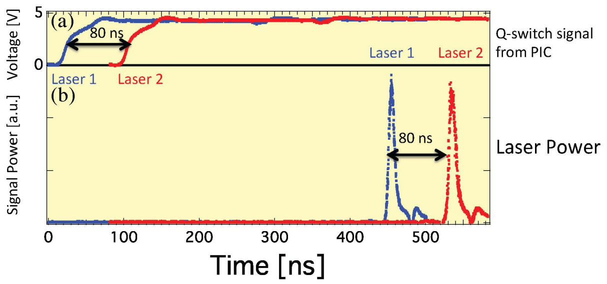

Fig. 5 (a) Q-switch signals from the timing controller and (b) laser power of the two lasers. The timing controller sends the Q-switch signals between 80 ns, and the lasers are oscillated between 80 ns.

tion, where the transport barriers are usually formed within ~100 µs, at least two laser pulses during this time span are necessary. For this purpose, our system uses two independently timing-controlled Nd:YAG lasers (> 500 mJ at 50 Hz). The maximum repetition frequency of the laser pulse is 50 Hz for the first laser, and the second laser is operated with a 10-ms delay; thus, we can realize routine profile measurements at time steps of 10 ms. When profile measurements at two timings within a shorter time span are required, the system changes the delay time to measure the profile at the two timings within the required short time span. The timing controller sets the timing of the laser oscillation and the intervals of the two lasers before discharge via a USB remote control with PC.

We designed the timing controller for controlling the delay time to more than 80 ns. Figure 5 (a) shows the Q-switch timings from the controller, and Fig. 5 (b) shows the power of the two lasers measured with the GaAs detector. Figure 5 (b) indicates that the two lasers are emitted at an interval of 80 ns with a jitter of only several ns. Therefore, we confirm that the timing controller can work as designed and the competent short (80 ns) laser emission interval is realized for measuring rapid (~100 µs) profile transitions.

The developed timing controller can adjust the measurement timings as long as the interval time of each laser is more than 20 ms. We can set high time-resolution points at any time and measure profiles at constant intervals for different times.

3. Summary

A new Thomson scattering system with two Nd:YAG lasers was developed to study the improved confinement physics in Heliotron J. A PIC-based timing controller was designed to precisely control the delay time of the laser pulse of two lasers and to investigate the profile change of the electron temperature and density within a short time span (≥80 ns), which is critical in transport physics studies including spontaneous transitions. The timing controller is also used for the “soft start” of the system, which can protect optical components against initial unstable laser oscillations. In addition, it synchronizes the timings of laser oscillations with the plasma discharges. The developed timing controller for high time-resolution profile measurements can help clarify the relevant transport barrier physics.

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