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PROGRESS ON THE MULTIPULSE THOMSON SCATTERING DIAGNOSTIC ON DIII-D

by
R.E. STOCKDALE, T.N. CARLSTROM, C.L. HSIEH,
and C.C. MAKARIOU

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ABSTRACT

The DIII-D Thomson scattering diagnostic, operational since 1990, uses 8 Nd:YAG 20 Hz lasers to measure electron temperature and density profiles (40 spatial points) throughout the plasma discharge. Recent progress has enabled a new set of operating modes to better fulfill varying plasma physics requirements. Custom circuitry for laser control (programmable with 1 μ s precision) has successfully replaced a previous scheme which used real-time 68030 software. Two new modes of operation have been demonstrated. Burst Mode is useful to study a transient plasma event: a series of laser pulses are fired at a rate ≤ 10 kHz after an external asynchronous event trigger. Burst Mode is also useful to synchronize the Thomson lasers with other systems, such as an asynchronous Michelson ECE diagnostic scanning near 40 Hz. Group Mode allows a programmed set of lasers to fire simultaneously into the same (65 nanosecond) data acquisition gate. Improved signal/noise then yields smaller statistical errors in the profile results. This provides profile data for lower density plasmas, such as those anticipated during fast wave current drive experiments. Plans for a new CCD-based laser alignment system for position monitoring and feedback control will also be presented.

INTRODUCTION

The use of rapidly pulsing lasers in Thomson Scattering diagnostics on tokamaks has become widespread.¹⁻³ At DIII-D, about 800 electron density and temperature profiles, measured at 6 to 10 ms intervals throughout the discharge, are analyzed and available for inspection within minutes of the plasma shot firing. Experimental physicists use this information between shots to help optimize plasma performance. The detailed time evolution of the Thomson data is later used for extensive analysis of selected shots. The data is also used by one or two secondary experiments that may be scheduled to run in the same discharge, after the primary experiment, and it is used by the dozens of specialized diagnostics that exist on the DIII-D machine. The multipulse Thomson diagnostic is now considered essential for plasma physics operation at DIII-D.

This paper describes improvements to the DIII-D Thomson Scattering diagnostic that have been completed since the previous paper that described the design and operation of the diagnostic.¹ The primary goal in this work was to improve the reliability and dependability of the diagnostic, so as to maximize the physics productivity of the DIII-D tokamak. New capabilities and improved precision in controlling the laser firing times were also desired. In addition, the systematic and statistical components of the measurement error have been studied. Small errors in laser alignment cause a large part of the systematic error in the electron density measurement. To reduce this error, a new laser position monitoring and feedback control scheme has been designed.

LASER CONTROL CIRCUITRY

The initial operation of the DIII-D Thomson diagnostic used micro-processor based real-time software to control the Nd:YAG lasers and the acquisition of digitized data.⁴ The VME bus in the system carried interrupts, incoming detector data and outgoing laser control commands. A considerable effort was needed to maintain and debug the software involved. In addition, there were recurring problems with data loss and system operation failure.

A decision was made to replace the laser control function of the real-time software with digital electronic circuits.⁵ This greatly reduced the interrupts and other traffic on the VME bus, and significantly reduced the problems and failures of the real-time VME system. It also allowed greater timing precision ($1\ \mu\text{s}$) than was observed with software (about 1 ms). The hardware solution was implemented more rapidly than seemed probable for a software only approach to the problems.

The new laser control circuits perform all of the functions previously implemented in software on the VME system. One microsecond precision in timing control is easily obtained with programmable counters and CAMAC programmable time sequence modules. One master circuit generates a (DIII-D synchronized) 20 Hz pulse sequence. Separate and identical circuits control the routine charging, holding and firing cycle for each laser. These basic circuits provide a robust and trouble-free engine at the core of the new laser control scheme.

After implementation of the basic laser control cycle, it was possible to add new capabilities with additional circuits. For example, laser fire delay circuits were added to compensate for the differing laser response times from fire command to the actual

laser pulse. This variation (up to 100 μ s) became a problem as the data acquisition rates increased above 1 kHz. More notable additions include asynchronous firing (Burst Mode) and synchronized laser firing (Group Mode) control circuits, which are described in later sections of this paper.

Circuits were developed to control the laser firing time at the nanosecond time scale. These use programmable delay chips with a 0.5 nanosecond step size. Synchronized laser firing into a single 65 nanosecond data acquisition gate (Group Mode) is controllable from software (without wiring changes). Another useful circuit was added to the data acquisition trigger, which creates a fixed nanosecond scale delay time between the laser pulse and the digitizer data gate. This circuit can scan the delay time during calibration, and digitally reproduce the optimal delay time.

BURST MODE

In addition to precise computer-programmable scheduling of the routine 20 Hz firing of each laser, a method was developed to allow asynchronous firing of lasers in response to an external trigger [Fig. 1(a)]. A series of one or more lasers is fired with a programmable period following the external trigger. This Burst Mode series is useful for studying transient and unpredictable plasma events, such as sawteeth, ELMs, L-mode to H-mode transitions and plasma disruptions.

A laser is eligible to participate in a Burst Mode series if it is fully charged, but not yet fired. The nominal charging time for each laser is about 20 ms, while the average firing period is 50 ms (to maintain the desired constant temperature in the laser components). To maximize the laser eligibility for Burst Mode, each laser spends nearly 30 ms holding in the fully charged state, before it receives the pre-programmed (synchronous) fire command. Thus, each laser is eligible to participate in a Burst Mode series about 60% of the time. For eight lasers scheduled to fire at equal intervals (6.25 ms apart) there are always four or five lasers eligible for a Burst series.

The charging command for each laser is always issued at regular intervals of 50 ms. Thus, a laser fired in Burst Mode must wait until its regular charging time to re-charge. This is a hardware safety feature to prevent the lasers from firing too often and over-heating.

A custom CAMAC module serves as an interface between the laser controller and the three external Burst Mode trigger sources. This Burst Generator module can prioritize the external triggers by their source, and can inhibit triggers during

Fig. 1. (a) Timing diagram showing typical laser operation and Burst Mode operation. Command pulses are generated by the new laser control circuitry: C = Charge, F = Fire (flash), B = Burst Fire. EOC = End of Charge pulse generated by laser. (b) Expanded view of laser flash lamp and Q-switch timing: PD = Programmable Delay, LS = Laser internal Setup, FLD = Flash Lamp Discharge, Q = laser cavity Q-switch (timing accuracy is $\pm 1 \mu$ s for single laser, ± 2 ns for Group Mode synchronized lasers).

desired intervals (inhibit gates). When a trigger is accepted, a burst series of laser fire commands is generated. This series of (up to eight) fire commands is issued at the pre-programmed frequency corresponding to the trigger's source. Typical frequencies might be 10 kHz, 5 kHz and 2 kHz, for the three external burst trigger sources.

Another custom module receives the laser fire commands from the Burst Generator module. This Burst Sequencer module monitors the state of each laser, and maintains a pointer to the laser which has been fully charged for the longest time. The Burst Sequencer directs the first laser fire command in the burst series to this laser, and then searches for the next available fully-charged laser. The Burst Sequencer continues to pass fire commands along to charged lasers until no more are available; any remaining fire commands are then discarded.

The first laser in a Burst Mode series is fired as quickly as possible after the Burst trigger is received. This latency interval is currently 400 μ s and determined by control logic internal to the laser itself [Fig. 1(b)]. By modifying this logic, it should be possible to reduce this interval to 200 μ s, or less. This will be attempted at some future time.

The minimum time between any two separate lasers firing (either in a synchronous programmed cycle or an asynchronous Burst) is limited by the data acquisition electronics. Currently, about 80 μ s are needed to digitize and transfer the raw signal data for one laser pulse to a buffer memory module. The minimum interval between any two data triggers is set to 100 μ s. Data acquired with trigger rates between 1 kHz and 10 kHz is accumulated in the buffer memory module, which can hold data for (many) more than eight laser pulses. This data is transferred to a slower, large capacity on-line memory when the Burst series ends.

Burst mode has been successfully used for several applications in DIII-D plasma discharges. In the simplest case, pre-programmed (scheduled) burst triggers have been generated internally by a Thomson CAMAC module. These provide a convenient

means to temporarily escape from the normal laser firing sequence in order to take data for some scheduled DIII-D event (such as a plasma shape change, pellet injection or start of rf power injection). These scheduled bursts were used to demonstrate successful data acquisition with plasma at burst frequencies between 0.5 kHz and 10 kHz.

Burst mode was used to study asynchronous DIII-D plasma events, such as the L- to H-mode transition. The Thomson system responded properly to the external burst trigger in each case. However, it was difficult to obtain the desired trigger timing from the analog signals available. Work to improve this situation is underway. Burst mode has also been tested (with similar outcome) in plasma disruption studies. As the external trigger becomes more accurate, the usefulness of Burst mode data will increase substantially.

Burst mode has been used to synchronize the Thomson lasers with asynchronous (non-plasma) events. An asynchronous Michelson ECE diagnostic on DIII-D scans the electron temperature profile with a frequency near 40 Hz. To obtain simultaneous Thomson and ECE data, a scan-start pulse from the ECE diagnostic was used as a Thomson burst trigger. Each of these triggers caused a burst sequence with half of the available Thomson lasers. Thus, burst mode data was obtained throughout the shot with a burst trigger rate near 40 Hz.

GROUP MODE

It is sometimes desirable to fire two or more lasers simultaneously into the same (65 nanosecond) data acquisition gate (Fig. 2). This Group Mode technique allows improved signal-to-noise when compared with firing into separate data acquisition gates, because the fluctuations due to background (non-laser) light and detector dark current are the same no matter how many lasers are used to generate the scattered light signal within a single data acquisition gate. Group Mode can be used to reduce statistical error in the data results (at the expense of the greater time resolution possible when lasers are fired separately). It is particularly useful for the study of low density plasmas, such as in the edge region, or target plasmas for fast wave current drive studies.

Group Mode is entirely controlled by software. When desired, two or more lasers are scheduled to fire simultaneously by assigning to each the same charging (and thus firing) time in the cycle. (Group Mode is not available for use with asynchronous triggers, as in Burst Mode). A special circuit board detects the coincidence of two or more firing commands within the same 1 microsecond master clock tick. A single delayed fire command is emitted for each laser in the group. This pulse is further delayed by an individual (0.5 nanosecond step size, eight bit programmable) delay chip for each laser. This programmable delay is adjusted so that the scattered light signal from every laser arrives within a single data acquisition gate. This compensates for differences in the lasers' Q-switching response times and optical path lengths.

Group mode operation was recently demonstrated with two synchronized lasers in a DIII-D plasma discharge (79938). Signal to noise improved more than expected

Fig. 2. Timing diagram showing typical Group Mode laser operation: (a) Q-switch request and latch ($1 \mu\text{s}$ resolution by software); (b) Q-switch common master trigger for all lasers in group; (c) Adjustable delay (0.5 ns steps) before individual Q-switch commands are sent to each laser; (d) Laser light pulse ($\sim 10 \text{ ns}$ FWHM) synchronized $\pm 2 \text{ ns}$ along the common laser beam optical path; (e) Laser light pulse detection; (f) Adjustable delay (0.5 ns steps) before a single data acquisition trigger; (g) Fixed delay before 65 ns background signal digitizer data gate; (h) Additional 30 ns delay before 65 ns pulsed signal (background subtracted) digitizer data gate; (i) Fixed delay (due to optical path length) before synchronized Thomson scattering laser light pulses arrive (during the pulsed signal digitizer data gate).

from the scattered photon fluctuations alone because the (constant) background light also contributed significant photon fluctuations to the total signal variance.⁶

ALIGNMENT SUBSYSTEM

The laser pulses used in the DIII-D Thomson Scattering diagnostic travel about 30 meters, with eight mirrors and one lens along the way, to the target scattering volume in the plasma. There the diameter of the vertical laser beam is about 3 mm, and the width (toroidally) of the viewing volume is about 6 mm.⁷ The position of the lasers must be maintained accurately during both calibration (Rayleigh scattering in argon) and operation with plasma in order to obtain accurate electron density profile data. (The electron temperature result is unaffected by a constant fractional loss of scattered signal at all wavelengths, such as that caused by laser misalignment.)

A new scheme for laser position monitoring and feedback control is being implemented to improve the alignment accuracy (Fig. 3). In the first phase of this scheme, 2-dimensional position sensors have been replaced with CCD cameras. Each CCD camera views leakage light through one of the last two mirrors along the laser beam path. These cameras operate at normal video rates (30 frames/second) and so track the position of only one laser at a time. Usually, this is a reference HeNe laser that defines the beam path center for all YAG lasers. However, it could also be a single YAG laser firing at 20 Hz (during the idle time between plasma shots).

A dedicated computer (486 PC) was obtained to collect laser position data and issue corrective stepping motor commands to the appropriate mirrors. This computer controls the CCD video input to a commercially available laser cross-section analyzer ("BeamView Analyzer Plus" by Big Sky Software Corp.). The analyzer receives commands and returns position data via its built-in GPIB (IEEE 488) interface. The control computer collects position data periodically from both CCDs through the analyzer. It issues commands via a serial port to a low-level computer which

Fig. 3. Block diagram of new laser alignment subsystem. CCD = camera viewing mirror leakage light from HeNe or YAG laser, V = normal video (30 frames/s), VS = computer controlled video switch, LBA = laser beam cross-section analyzer, GPIB = IEEE 488 bus (commands and laser position data), 486 PC = dedicated 486 computer, S = serial data path (video selection, stepping motor commands), SMC = stepping motor controller for mirrors, XY = 2D mirror stepping motors (SMC A: 2 steering mirrors, SMC B: 8 YAG packing mirrors), DI = digital image data (200 frames/s), VME = 68030 VME-based host computer with image processing hardware, E = Ethernet, MV3400 = MicroVax 3400 (data archival), HP730 = Hewlett Packard 730 workstation (data analysis).

in turn operates the stepping motors on the adjustable mirrors. This feedback loop will normally run continuously to maintain correct alignment of the reference HeNe laser. It can also be run between plasma shots to check and correct the alignment of individual YAG lasers.

The second phase of the alignment monitoring scheme involves directly measuring the position of all YAG lasers during the DIII-D plasma shot. A high speed digital CCD camera (200 frames/second) and image processing hardware has been obtained for this purpose. A beam-splitter shares the view of the last mirror in the beam path between the fast camera and one of the slower cameras. This fast camera will be triggered to store an image whenever a YAG laser is fired. At 5 ms per image, the

camera can handle evenly spaced laser firing times, but not closely spaced or Burst Mode firing rates. (In this case, the image may be integrated over several lasers, and checked for an incorrect position of any laser.)

The fast camera will provide valuable 2-dimensional position information for almost all YAG laser pulses during DIII-D plasma. Profile data for each pulse can then be accepted or rejected depending upon the alignment quality implied by the recorded laser position.

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