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## **A real-time digital control, data acquisition and analysis system for the DIII-D multipulse Thomson scattering diagnostic**

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A VME-based real-time computer system for laser control, data acquisition and analysis for the DIII-D multipulse Thomson scattering diagnostic is described. The laser control task requires precise timing of up to 8 Nd:YAG lasers, each with an average firing rate of 20 Hz. A cpu module in a real-time multiprocessing computer system will operate the lasers with evenly staggered laser pulses or in a "burst mode", where all available (fully charged) lasers can be fired at 50-100  $\mu$ sec intervals upon receipt of an external event trigger signal. One or more cpu modules, along with a LeCroy FERA (Fast Encoding and Readout ADC) system, will perform real-time data acquisition and analysis. Partial electron temperature and density profiles will be available for plasma feedback control within 1 msec following each laser pulse. The VME-based computer system consists of 2 or more target processor modules (25 MHz Motorola 68030) running the VMEexec real-time operating system connected to a Unix based host system (also a 68030). All real-time software is fully interrupt driven to maximize system efficiency. Operator interaction and (non real-time) data analysis takes place on a MicroVAX 3400 connected via DECnet.

## INTRODUCTION

Previous experiments on DIII-D relied on a single-pulse ruby laser Thomson scattering diagnostic<sup>1</sup> for accurate profiles of electron temperature and density. Although effective, the single-pulse nature of this diagnostic severely limited profile information per discharge.

We are building a multipulse Thomson scattering diagnostic,<sup>2,3,4</sup> incorporating up to eight Nd:YAG lasers, each capable of operating at 20 Hz. This instrument will make the same measurements as the previous system, but is predicted to have improved accuracy and will operate at rates as high as 160 Hz continuously (with the full complement of eight lasers) with bursts at rates exceeding 10 kHz for short periods of time.

In this paper, we describe the real-time techniques and hardware used for the laser control and data acquisition systems. We also discuss a method of data analysis developed to take full advantage of our new capabilities, while compensating for the time constraints involved in calculating several hundred profiles per shot.

## I. HARDWARE

### A. Computer systems

Real-time processing is done on a system with two or more Motorola 68030<sup>5</sup> microprocessors running under the VMEexec<sup>6</sup> real-time operating system. The system is controlled from a single host processor (a Unix-based 68030), which communicates with the DIII-D computer system via MicroDNET<sup>6</sup> (the Unix implementation of DECnet). The entire system (Fig. 1) resides in a pair of VME<sup>7</sup> backplanes connected

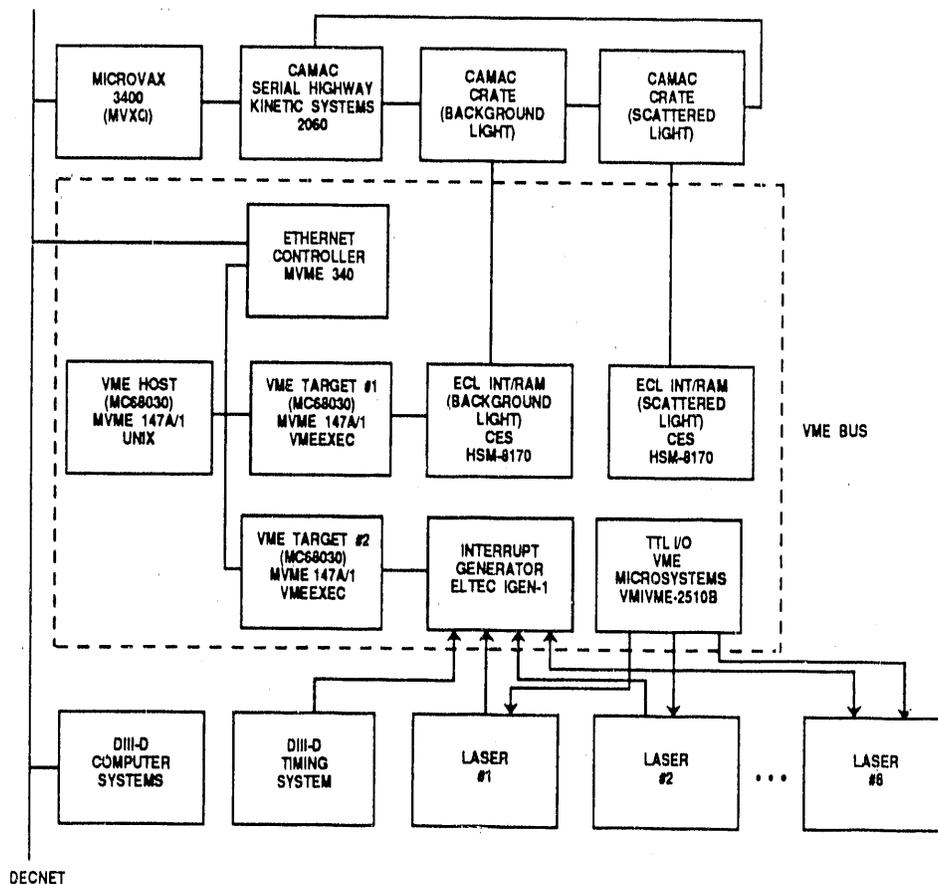


Fig. 1. Block diagram of DIII-D multipulse Thomson profile diagnostic control and data acquisition systems.

together through a bus repeater,<sup>8</sup> allowing for very fast (16 MHz) communication between processors and I/O devices.

The VME system also contains several modules used to interface the micro-processors with the laser and data acquisition hardware. These include a TTL I/O (input/output) module<sup>9</sup> to send commands to the laser, and an interrupt generator<sup>10</sup> to receive status signals from the laser. Data from the acquisition hardware is received and stored in an ECL interface/high-speed RAM module.<sup>11</sup> Use of these devices will be discussed in more detail below.

A MicroVAX 3400<sup>12</sup> is used for most tasks not requiring real-time processing. Operator control of VME computer tasks is accomplished via the MicroD-NET/DECnet interface. This connection is also used to transport all data obtained by the VME computer to the MicroVAX between shots for archival and full analysis. Some data acquisition functions are also performed by the MicroVAX. These include pre-shot setup of the polychromator data acquisition hardware, as well as acquisition of time base, laser divergence and other information not required in real-time. As discussed above, polychromator data readout is performed through means external to the serial highway, and does not directly involve the MicroVAX.

#### **B. Data acquisition hardware**

Data acquisition is performed using standard modules in a set of CAMAC crates located on a MicroVAX-based serial highway.<sup>13</sup> Data acquired directly by the VAX is read using standard CAMAC calls.

Polychromator data is acquired by a FERA (Fast Encoding and Readout ADC) system<sup>14</sup> (two such systems are required, one each for the background and scattered signals<sup>2</sup>). The FERA controller can transfer digitized data directly to the VME system through a front-panel ECL bus connected to the ECL interface/high-speed RAM module<sup>11</sup> located in the VME cage. This data transfer takes place at 10 MWords/sec; fast enough to transfer all data from 28 polychromators in less than 25  $\mu$ sec.

## II. REAL-TIME OPERATIONS

### A. The need for real-time computer operations

Although it is possible to build a multipulse Thomson diagnostic without using real-time control or data acquisition, such a system would have severely limited capabilities. Using a microprocessor controlled, interrupt driven laser control system allows us to modify the timing temporarily during an interesting plasma event in order to acquire data at a much faster rate than the usual 20 Hz/laser. In such a "burst mode", all available (*i.e.* fully charged) lasers can be fired in sequence at the maximum rate allowed by the data acquisition hardware in response to a physical event such as an ELM. After the burst ends, the system immediately returns to its normal mode, where the lasers are spaced at regular intervals.

Also, this system will be capable of limited real-time analysis. When the data becomes available (within microseconds after a laser pulse), it can be analyzed with partial profiles of electron density and temperature becoming available in less than 1 msec. The results of this analysis can be converted to analog signals for use in feedback control of the DIII-D discharge.

### B. Laser control system

The laser(s) must be carefully and precisely controlled for proper operation. A diagram of the laser control system is shown in Fig. 2.

The TTL I/O module<sup>9</sup> consists of a single 64 bit parallel interface in which any single bit can be independently turned on or off. Also, each bit can be connected to a separate destination, so that 64 completely independent devices or functions can be

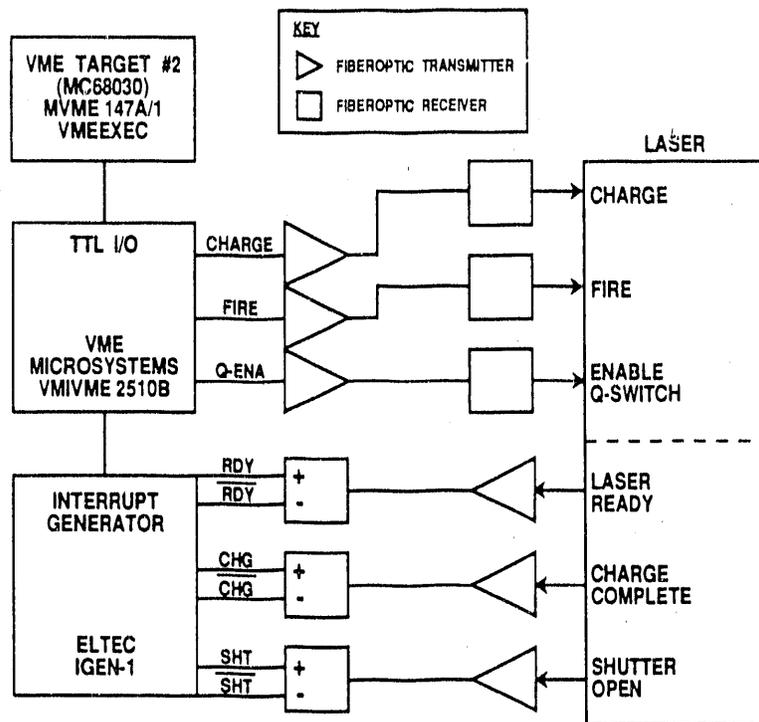


Fig. 2. Details of the laser control system.

controlled. In this system, each laser has three inputs from the VME computer: a charge command, a fire command, and a Q-switch enable gate. The two commands require single pulses approximately 30  $\mu$ sec wide to trigger their actions. This is done by turning on the bit, waiting the appropriate length of time, and then turning it off again. The Q-switch enable gate is turned on and left on for the duration of time that Q-switching is to be allowed.

The interrupt generator<sup>10</sup> is a 32 bit parallel interface in which receipt of a signal on any of the bits can generate a VME interrupt, causing the control program's internal laser status table to be updated. The status table consists of RDY (laser ready), CHG (end of charge) and SHT (shutter open). Any laser which has both

RDY and CHG set is eligible to fire (when its turn comes up). Also, the Q-switch will only be operated if SHT is set (the shutter is inside the laser oscillator cavity and would prevent Q-switched operation). In the normal operations mode, an interrupting clock within the IGEN-1 is used to fire each laser at 50 msec intervals, with the lasers interleaved. In "burst mode", all eligible lasers are fired in sequence immediately upon receipt of an event interrupt (also interfaced through the IGEN-1), with the time spacing between lasers determined by the limitations of the data acquisition system. In order to maintain proper operation, the lasers must be operated at an average rate of 20 Hz.<sup>4</sup> Therefore, after a burst, the system will experience a dead time to let the lasers catch up (*i.e.* if a laser has been fired with only a 30 msec interval, its next pulse will not come for another 70 msec).

### C. Data acquisition and real-time analysis

As described above, data acquisition is performed using the LeCroy 4301/4300B FERA system<sup>14</sup> located in a CAMAC crate. Several 4300B ADC's can be combined with a single 4301 controller to constitute an entire data acquisition system. While CAMAC serial highway operations initiated by the MicroVAX are used to set up these modules, data is read out through a fast ECL bus located on the front panels of the modules to the ECL interface modules located on the VME bus.<sup>11</sup> These modules each contain enough memory to buffer data from several hundred laser pulses, and can be configured to generate an interrupt upon receipt of new data from the FERA system. A microprocessor in the VME system can then asynchronously transfer the

data from this buffer to its own memory for real-time data analysis and storage until after the shot.

Two such systems are used. The first measures the background light level alone. The second measures the scattered light during a laser pulse, with the background subtracted electronically. For more details on the two separate measurements, see Ref. 2.

Real-time data analysis is performed using the method described in the next section. The speed of the method can be increased by calculating only the temperature and density and not the error bars (which are of limited usefulness in plasma feedback control and add significant extra computational overhead, including a square-root calculation). Also, we do not plan on analyzing complete  $r$  profiles in real-time; it would be difficult to use the data from more than two or three spatial points in any reasonable feedback scheme. At this time, we have not yet performed timing tests of the method on the real-time computer system. On the MicroVAX 3400, we find that single point analysis times vary between 20 and 150  $\mu$ sec depending on the number of polychromator channels used and whether error bars are calculated. We believe the VME computer system will be able to perform these functions somewhat faster, so that it is reasonable to assume analysis of several spatial points can be made available within 1 msec following a laser pulse.

### III. DATA ANALYSIS METHOD

In order to calculate electron temperature and density from the measured Thomson spectrum, we fit the spectral data to Selden's formula for the relativistic Thomson

scattering spectrum.<sup>15</sup> Previously, in the single-pulse system, this was done with a least-squares fit technique.<sup>16</sup> This method, however, is very inefficient. With a full complement of eight lasers, we estimate that it would take as much as two to three hours on the MicroVAX 3400 to analyze the data from a single DIII-D shot. This is unacceptable; we would like to be able to present a complete analysis within a few minutes following a shot.

One possibility is to employ the method used by ASDEX.<sup>17</sup> They use a three channel polychromator, taking a ratio  $V$  of the signals in two channels (or the ratio of the third channel to the sum of the first two). The ratio is used in an analytical expression for  $T_e(V)$  which has been generated from the polychromator calibration, thus giving the electron temperature. The density is calculated using a similar technique. Although this method is fast enough, it does not lend itself to use with a polychromator with many more than two channels since it effectively uses only two channels to calculate the temperature.

We have chosen to use an error-weighted multiple lookup table method. We can define a set of ratios

$$R^{ij} \equiv \frac{S_i}{S_j}, \quad (1)$$

where  $S_i$  is the signal from the  $i^{\text{th}}$  polychromator channel. For six usable channels (the seventh is located at the laser wavelength and is used for Rayleigh scattering calibration of the system), there are fifteen such ratios. We can calculate the electron

temperature  $T_e^{ij}$  and its error  $(\sigma_T^2)^{ij}$  as a function of each ratio and its measured error  $(\sigma_R^2)^{ij}$ :

$$T_e^{ij} \equiv T_e(R^{ij}) \quad (2)$$

$$(\sigma_T^2)^{ij} = \left( \frac{dT_e^{ij}}{dR^{ij}} \right)^2 (\sigma_R^2)^{ij} \quad (3)$$

Using a calculated correspondance between  $T_e^{ij}$  and  $R^{ij}$ , we define the functions  $C_1^{ij}$  and  $C_2^{ij}$ , and build tables of them vs.  $R^{ij}$ :

$$C_1^{ij} \equiv \frac{T_e^{ij}}{(dT_e^{ij}/dR^{ij})^2} \quad (4)$$

$$C_2^{ij} \equiv \frac{1}{(dT_e^{ij}/dR^{ij})^2} \quad (5)$$

Rather than having a single table, we now have a full set of tables, one for each ratio  $R^{ij}$ . For a given  $T_e$ , some of these ratios will be more appropriate than others. The temperature calculated from an inappropriate ratio will have a large calculated error  $\sigma_T^2$ . Using Eq. 6, we average the results from all tables in such a way as to minimize the effect of ratios with large errors:

$$T_e = \frac{\sum_{i,j} \frac{C_1^{ij}}{(\sigma_R^2)^{ij}}}{\sum_{i,j} \frac{C_2^{ij}}{(\sigma_R^2)^{ij}}} \quad (6)$$

We can also calculate the error in  $T_e$  from the tables:

$$\sigma_T^2 = \frac{1}{\sum_{i,j} \frac{C_{ij}}{\sigma_R^2}} \quad (7)$$

The total number of scattered photons integrated over the entire spectrum is proportional to the electron density  $n_e$  and the laser energy, but we do not measure the entire spectrum. We build another set of tables  $C_3$  to calculate the density such that

$$n_e = C_3(T_e) \sum_{i=1}^n N_i, \quad (8)$$

where  $n$  polychromator channels are used and  $N_i$  is proportional to the number of photons detected by the  $i^{\text{th}}$  polychromator channel normalized by the laser energy. In this application,  $C_3(T_e)$  is proportional to the ratio of the number of scattered photons visible to the polychromator to the total number of scattered photons in the spectrum.

Using this method, we are able to perform a full analysis very quickly on the MicroVAX. Preliminary estimates predict that we should be able to analyze all data from a shot within about 1 minute after the shot. Also, after detailed comparisons of the two methods, it appears that this method can be as accurate as the least squares fit, with a 2-3 order of magnitude speed improvement.

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