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ABSTRACT

A photomultiplier (PMT)-based diagnostic system for monitoring spectral lines along multiple viewchords, named the "Filterscope" [R.J. Colchin, et al., Rev. Sci. Instrum. **74**, 2068 (2003)], is currently in use at the DIII-D, NSTX, and CDX-U fusion plasma devices in the US, and has been installed at the KSTAR device in Korea. This diagnostic has recently been upgraded for application to long pulse devices, such as KSTAR, EAST in China, and the future ITER in France. A new data acquisition system, employing the PXI instrumentation platform with an embedded Windows microprocessor controller, can simultaneously record up to 72 channels at 100 kHz sampling rates for plasma periods lasting up to 20 minutes. Based on the average signal level during an adjustable time interval (100 ms in the present DIII-D implementation), the controller digitally adjusts PMT dynode voltage throughout the course of a discharge, thereby maintaining the output signals at a level where they are neither saturated, nor dominated by digitizer noise. The new system's ability to accommodate large variations in source strength, discharge to discharge and within a single discharge, has proved particularly valuable during DIII-D operations, since changes between top, bottom and double-null divertor magnetic configurations lead to large temporal variations in signal brightness.

I. INTRODUCTION

Line intensity measurements with spectrally filtered photomultipliers (PMTs) provide line radiation measurements at high sensitivity and with high temporal resolution. These advantageous features have led to widespread use of filtered PMT monitors on fusion devices worldwide. The compact, 4-channel, modular detection systems in use on the DIII-D and NSTX tokamaks are called filterscopes. Their electrical design and associated light collection systems have been reported previously [1]. The filterscope diagnostic has been used for precise temporal measurements of edge localized mode (ELM) behavior [2] and for studying the physics of L-H transitions [3]. It has also been employed to characterize the spatial distribution of neutral recycling in the plasma edge and divertor [4] and to benchmark fluid-flow models of the edge plasma against quantitative intensity measurements of hydrogen and low charge state impurities [5]. Because filterscopes can be absolutely calibrated, they can be used for day-to-day and year-to-year comparison of similar discharges.

A desire to make this diagnostic more suitable for long-pulse devices motivated the design of a new control and data acquisition system capable of taking and storing data at high sampling rates for time periods of many minutes, instead of a few seconds. The new feedback control system maintains good signal-to-noise ratios during large changes in source brightness without operator intervention, and acts to prevent signal dropout caused by high light levels which trigger the filterscope's anode over-current protection circuit. Section II describes the specific hardware used to implement the control system; section III provides insight into its operating logic; and section IV contains some examples which illustrate the performance attained. Section V is a summary.

II. FILTERSCOPE HARDWARE

A compact control and data acquisition (DAQ) unit has been developed for the filterscope diagnostic, employing a Windows-based [6] dual-core Intel central processing unit (CPU) and a high capacity hard disk drive in a PXI crate — PXI is an industry standard for a modular electronic instrumentation platform, developed by a consortium led by National Instruments (NI) [7]. The PXI crate also contains a parallel interface and signal digitizers from NI: a PXI 6508 digital I/O module and six National Instrument PXI 6250 16-ch A/D modules. Figure 1 is a photograph taken during laboratory tests, showing the PXI crate on the left, and an instrumentation bin with three filterscope modules on the right. In each filterscope module, the four red plastic caps mark the position of the four PMTs; each red cap covers a fiber optic bulkhead connector, behind which lies a collimating lens and spectral bandpass filter. In actual use, fiber optic cables convey plasma light from the tokamak to the filterscope modules as detailed in Ref. [1].

Fig. 1. Filterscope electronics under test. The PXI crate is on the left and the filterscope bin with three modules on the right. The black boxes under the filterscope bin accommodate cabling. The PXI crate contains an Intel CPU, a parallel interface, and two digitizers.

The embedded CPU controls the gain of the individual filterscope channels and supervises the processing and storage of the digitized data. Control commands from the CPU to the PMTs, to change high voltage or on-board, amplifier gain, are routed through the 24-bit programmable, PXI 6508 parallel interface module using the PMT addresses encoded in DIP switches on the printed circuit board in each filterscope module. Because of the strong, non-linear dependence of PMT gain on dynode voltage, highly accurate, 12-bit digital-to-analog converters (DACs) in each filterscope module are used to input the voltage commands to the Cockroft-Walton voltage multiplier, which is potted into each photomultiplier assembly.

The high frequency, analog signal data from the PMTs are recorded by the 16-bit bipolar, analog-to-digital converter (A/D) modules and then passed in digital form over the PXI data bus to the CPU. Although the A/D modules contain 16 channels rated at 100 kHz, the 1.25 Msample/s speed of the multiplexed A/D converter chip limits channel usage at 100 kHz sampling rate to 12 channels per module. Use of the commercial software program Timbukto [8] to control the CPU from offsite computers located anywhere on the internet enables the software system engineer to update the commercial system software and custom filterscope application software as needed.

III. FILTERSCOPE CONTROL

The feedback control scheme implemented in the CPU software is simple in concept. If the signal averaged over the “cycle” period (100 ms) lies outside the window defined by the user-specified lower and upper limits, the dynode high voltage is raised or lowered, respectively, by a fixed step of 50 V. The success of this algorithm can be attributed to the restricted design goals chosen at the outset. Avoiding saturation during sudden intensity spikes associated with ELMs was not considered a realizable objective. These rapid magneto-hydrodynamic relaxation phenomena typically occur with a rise time of tens of microseconds, whereas the Cockcroft Walton voltage multiplier has a response time of tens of milliseconds. Consequently, PMT voltage changes are implemented based on the average value of the PMT signal over a 100 ms cycle period, rather than instantaneous value of the PMT signal. The feedback system permits the filterscope system to cope with the slow evolution in plasma brightness associated with changes in MHD topology, with varying levels of auxiliary input power, and with secular changes in plasma density. It does not prevent the detector from saturating at the peak intensity of an ELM event.

Protection against excessive current to the PMT’s dynode structure during the light spikes produced by ELMs is provided by a comparator circuit on the printed circuit board within each filterscope module. If the PMT signal seen by the comparator exceeds a hardware-specified limit, the high voltage output of the Cockcroft-Walton power supply is turned off, and remains off until reset by the CPU at the trigger for the next plasma discharge. A 20 ms RC smoothing constant built into the comparator circuit prevents individual ELM spikes from causing the PMTs to trip off. Hard-wiring of the over-current protection into the PMT electronics has prevented operator oversights, greatly contributing to the long-life the PMTs have experienced since installation of the filterscope system on DIII-D.

A latency, or lag, exists between the acquisition of data for a cycle period and the actual gain change. One part of that delay is introduced by the PXI-based control system. Though decision-making by the CPU is near simultaneous for all 64 tubes, the serial manner of communicating with the 64 tubes adds a variable element to this lag time, the magnitude of which depends on the number PMTs which must be addressed in each cycle. With the current PXI-based system controlling 64 tubes, the average lag is about 40 ms.

The other part of the latency arise from the reaction time of the Cockcroft Walton multiplier to a voltage change request. Since the command from the CPU for a 50 V increment causes the Cockcroft-Walton power supply to ring for approximately 200 ms, the corners of these square steps were rounded by means of a 30 ms RC time constant inserted between the DAC and the PMT assembly. The result of the Cockcroft-Walton and CPU latencies limit the minimum time between voltage adjustments to about 100 ms.

A graphical user interface (GUI) has been designed to control other functions of the filterscopes, such as the frequency of data sampling (up to 100 kHz) and the duration of the data acquisition period (up to 20 minutes). Data acquisition can either be initiated by an external trigger pulse (for tokamak discharges), or via software for hardware testing.

IV. DATA NORMALIZATION UNDER REAL TIME CONTROL ON DIII-D

Raw filterscope data must be normalized for differing amplifier gains and tube voltage variations and converted to the corresponding photon flux emitted by the plasma. For each channel of the filterscope system the digitally recorded photomultiplier signal, designated PMT, and a synthetically generated control signal CTL are written, both with 100 kHz resolution, by the CPU as raw data files on the hard disk, in the format prescribed for PTDATA, DIII-D's raw data archival system. Then, the CPU prompts DIII-D's MDSplus [9] server that those data files are available for external access, causing the MDSplus server to initiate an interactive data language (IDL) [10] program which reads the data from the filterscope controller and processes it. The resulting normalized signal data and photon fluxes are then transferred into the MDSplus system of archival storage for analyzed data.

Gain normalization requires an accurate knowledge of the dependence of photomultiplier gain on dynode voltage over the useful range of the tubes. For each PMT, the relative gain was measured over the range from 250 to 900 V, at intervals of 50 V, using a calibrated light source with adjustable output intensity. The resulting data was fit to a power law, PMT = a * $\boldsymbol{CTL}^{b}$.

The precise times of voltage changes, which are different for each of the 64 PMTs, are obtained by digital differentiation of the CTL signal shown in figure 2. The PMT signal gain depends on the instantaneous dynode voltage which, due to the 30 ms RC time constant discussed in section III, is smoothed out relative to each stepwise digital input command from the PC. The time response of the dynode voltage, HV, is modeled as an exponential rise (or decay), whose start is delayed by a fixed interval relative to the step in the control voltage demand. For each time sample in this analytic approximation to the dynode voltage, the gain is calculated from the power law fit of gain to voltage. Lastly, the gain-normalized signal is converted to a photon flux using the absolute luminosity calibrations previously detailed [1].

The ability of the filterscope system to recover the photon flux correctly as control voltage varies in response to temporal changes in brightness is illustrated in figure 3, where the time history of the D_α and D_β photon fluxes are compared for the same viewchord. Under plasma conditions in which divertor recycling light is dominated by electron impact excitation, as was the case in this attached L-mode discharge with bursty MHD activity after 2500 ms, the emission from deuterium lines originating from successive n-levels must track one another in time, though their absolute intensities differ. Feedback control of dynode voltage was employed on the D_α detector, whereas fixed voltage was maintained on the D_β tube. Though the raw D_α signal looks very different from the D_β photon flux signal, the D_α photon flux recovered following gain normalization mimics D_β. Deviations between the two, on the order of 20%, are visible after dynode voltage changes; these errors in gain normalization result from the residual ringing of the Cockcroft Walton voltage multiplier, which is not modeled.

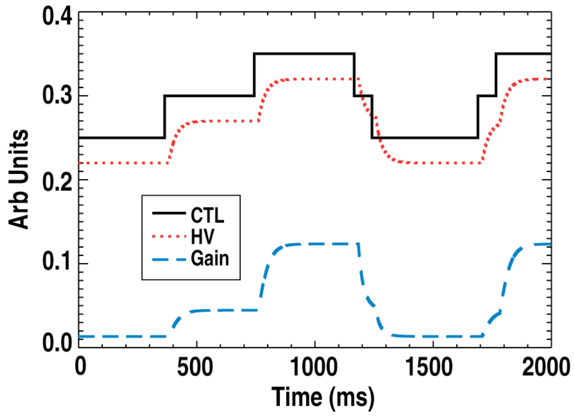

Fig. 2. Response to PMT voltage changes. The upper trace (solid black line) shows the voltage demands sent to the Cockcroft-Walton power supply, the middle trace (red dotted line) shows the voltage response of the supply, and the lower trace (blue dash line) shows the gain changes of the PMT.

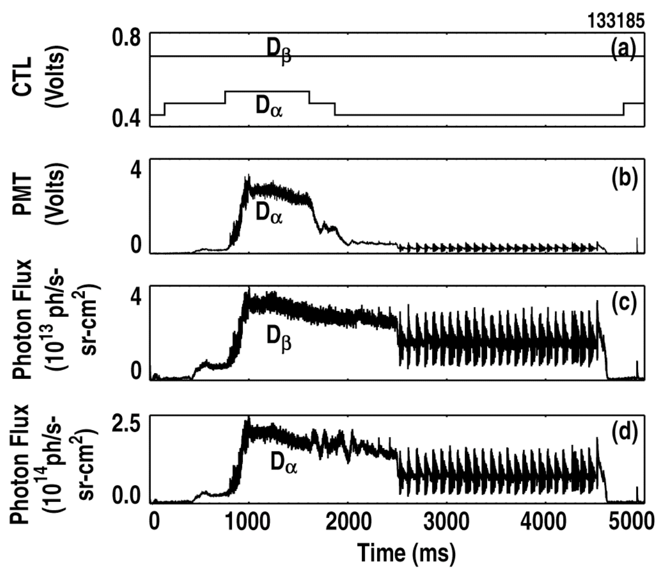

Fig. 3. Recovery of correct temporal behavior in the presence of automatic gain changes. The traces in box (a) shows the command voltages applied to the D_α and D_β detectors. Trace (b) is the raw D_α signal and trace (c) the D_β photon flux. Trace (d) shows the D_α photon flux following normalization by the time-varying gain.

Occasional clipping of the signal during the sudden intensity spikes associated with ELMs is unavoidable. Though auto-gain control dramatically increases the ability of the filterscopes to track secular changes in brightness during the course of a discharge, the instantaneous dynamic range of the PMT is unaltered on the time scale of a typical ELM. Therefore, ELMs can, and occasionally do saturate the linear output amplifier of the PMT. Though clipping of the raw signal is immediately obvious and unambiguous, its appearance in the calculated photon flux can be misinterpreted. As shown in figure 4, clipping causes a flat-topping of the PMT signal at the 10 V maximum output of the signal amplifier. Due to normalization of the raw signal by the PMT gain after each change in the CTL, the isolated occurrences of saturation map out an envelope in the photon flux signal with a shape corresponding to the inverse of the gain. It is important to recognize that this envelope has no physical significance; it is merely a clue that clipping has occurred. Imposing a limit on the number of saturated ELM events within a cycle period, as a second condition for lowering gain, has been found to reduce the occurrences of clipping significantly compared with the case shown in figure 4.

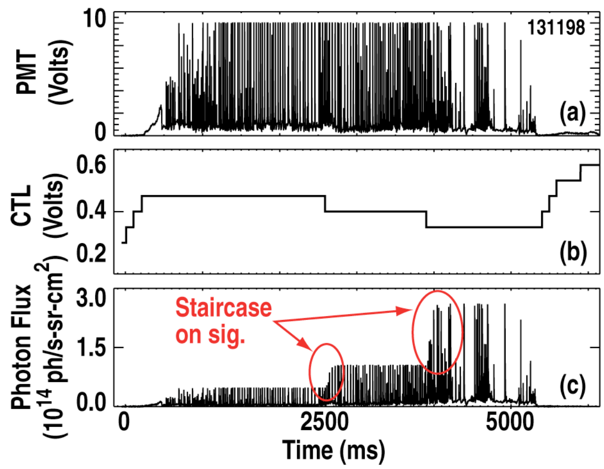

Fig. 4. Clipping of the raw signal can produce the non-physical, staircase like effect on the gain-normalized signal outlined in red circles. The top trace (a) shows a raw signal which saturates during ELM events; the middle trace (b), the CTL voltage demand; and the bottom trace (c), the signal normalized for the changes in applied dynode voltage.

V. SUMMARY

The advent of long-pulse tokamaks has created the need for diagnostics with the capability to record and store high frequency data over tens of minutes. Fortunately, these needs can be satisfied by taking advantage of the recent development of fast CPU controller systems with fast data busses and high-capacity hard-disc drives. We have developed a system capable of simultaneously handling 64 PMTs taking data at 100 kHz for 20 minutes. In addition to acquiring the data, the system controls the gain of the PMTs to optimize signal quality, protect the photomultipliers against excessive anode current, and minimize the need for operator control.

Operational experience on the DIII-D tokamak, with discharge lengths limited to about 8 s, has demonstrated that the new filterscope system provides faster, higher-quality data than was previously available. It is expected that future advances in electronic chip speed will enable even more capable filterscope systems.

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