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ABSTRACT

This paper will discuss alterations and enhancements of the real-time digital plasma control system (PCS) which were recently developed at DIII-D. These enhancements greatly increased the performance and scope of the control system after a successful upgrade from the previous VME-based version. A specific goal of these enhancements was to incorporate the charge exchange recombination spectrometry diagnostic for plasma rotation control. Enlargement of the PCS includes additional motional Stark effect channels for improved current profile control and a series of real-time data displays. Performance improvements include increased computing resources, multi-threaded parallel processing, and 11 μ s cycle times for the resistive wall mode component feedback.

1. INTRODUCTION

Over the last 15 years, monitoring and controlling the various DIII-D tokamak systems during a plasma discharge was largely dependent upon the DIII-D real-time digital plasma control system (PCS). Approximately five years ago, the PCS underwent an extensive upgrade from a Solaris/I860-based first generation to a Linux/Intel-based second generation [1]. The initial efforts of this upgrade were to maintain complete functionality of the previous version and provide modest enhancements. Now after validation and several years of experience, efforts shifted to increased functionality and better performance. This paper will discuss recent activities at DIII-D to these ends.

2. MOTIVATION FOR ENHANCEMENTS

A central concept of upgrading the PCS was to provide a relatively inexpensive and easily maintained hardware platform while adhering to the software model of the first generation [2]. This was achieved and validated approximately four years ago. The resulting PCS consists of a modular set of computing resources interconnected by a dedicated high speed network [1]. This design allows for easy enlargement and dynamic reconfiguration. It also gives the PCS the ability to reach out and more easily obtain data sets that were cumbersome to import into the PCS. With an increase in data access, the goal shifted to using these data sets for better real-time control of the plasma discharge.

An additional key benefit of the upgraded hardware platform is the capability of the PCS to take full advantage of the quantum leap in processor performance over the previous Intel I860 processors. This encouraged implementation of many improvements that in the first generation were inconceivable because computation and analysis would have pushed the feedback cycle beyond what was considered effective for control.

3. CURRENT PCS LAYOUT AND HARDWARE

Over the last couple of years, the PCS migrated to a homogeneous set of computing hardware centered around Intel Xeon processors running a custom UNIX flavor operating system (Linux), connected by a high speed 2 Gbit network by Myricom Inc., referred to as the Myrinet [3]. Most real-time nodes are nearly identical in components; utilizing the same series motherboard, with PCI bus and dual-Xeon processors. Slight variations are needed only to interface with differing peripheral hardware. The second generation PCS more than doubled the number of real-time central processing units (CPUs) originally conceived and made operational when the PCS was validated early in the upgrade. To some extent, this was quickly accomplished by converting the initial set of PCS nodes from single CPU systems to dual processor units. Dual processor computers not only add efficiency by allowing two real-time CPUs the ability to share peripheral resources but they give the PCS additional avenues for parallel processing compared to the previous smaller set of single processor computers. Implementation was enhanced even greater by multi-threaded execution of real-time processes upon a single node where an individual thread is dedicated to a specific CPU. In the past, individual PCS processes were confined to a corresponding real-time node. Related real-time processes communicated across the Myrinet to the alternate processes, sharing much needed information. When related processes are grouped upon the same node using threaded execution, they need not travel across the Myrinet to communicate with each other. Individual threads are assigned execution upon a defined CPU thereby being assured uninterrupted execution, but sharing access to common memory and I/O devices with the alternate threaded real-time process upon the other CPU. Perhaps the greatest hurdle to this implementation is the need for each thread to access the resources of the PCS node without colliding with the other threaded process.

Along with upgrades in CPUs, a major change in individual node configuration was the elimination of system hard disks. Each node of the early second generation PCS was dependent upon a single IDE hard disk for OS and Myrinet software. It was found that disk drive failure was a large factor in the down time of the PCS. To remove the dependence upon a system hard disk, normally network booting would be used. Because of the proprietary nature of the Myricom network, this was not possible. Instead, each node is now equipped with a stripped down file system installed upon a Compact memory card; basic enough to allow for primary boot-up. The standard Linux boot-up procedures were reorganized to allow for establishing the Myrinet and then mounting the remaining file systems needed for full operation via network file sharing (NFS).

As of the writing of this paper, the PCS consists largely of dual Xeon nodes. A smaller set of Intel-based systems, three in total, are single CPU systems with VME access. These

serve an important purpose in allowing the PCS to maintain interaction with older PCS components as well as allow the PCS to interface with other DIII-D sub-systems. In total, the PCS currently consists of 19 CPUs spread across 11 nodes. Table 1 shows the complete PCS configuration with assigned responsibilities.

Table 1
Individual PCS Node Configuration

RT Index	Node Name	CPU Index	Functions
1	pcsr1	1	Non-shape
2	pcsr4	2	Vertical Position, error field
3	pcsr3	1	Discharge Shape (fastloop)
4	pcsr4	1	Resistive Wall Mode
5	pcsr5	1	Discharge Shape (slowloop)
6	pcsr6	1	Resistive Wall Mode (ID)
7	pcsr7	1	MSE 2 data collection and MSE (slowloop)
8	pcsr8	1	ECE data collection and 65x65 RTEFIT (fastloop)
9	pcsr9	1	Thomson Scattering Analysis
10	pcsr9	2	CER Analysis
11	pcsr11	1	MSE 3 data collection
12	pcsr12	1	MSE 4 data collection
13	pcsr13	1	shape 65x65 slowloop
14	pcsr14	1	MSE 1 data collection and MSE 65x65 (slowloop)
15	pcsr15	1	RTEFIT New spec
16	pcsr16	1	CER VME data collection
17	pcsr17	1	Thomson Scattering VME data collection
18	rtscope	1	Real-time Display
19	pcsr19	1	VME I/O

The increase in the number of real-time nodes from the initial eight used to validate the second generation PCS extended the reach of the PCS to incorporate the Thomson scattering and charge exchange recombination (CER) spectrometry diagnostics. Additional nodes also increased, by two fold, the amount of motional Stark effect (MSE) data collected and analyzed during a DIII-D discharge. Four more CPUs doubled the computational resources for the real-time EFIT.

Along with upgrades to computational hardware a new series of I/O devices from D-tacq Solutions Inc. (the sole manufacture of PCS digitizers) was implemented. This new series has both A/D input and analog and/or digital output. The combination of both made more efficient the feedback cycle of the real-time nodes utilizing these devices. In the case of the node assigned to resistive wall mode (RWM), the new devices greatly reduced the cycle times from $50 \mu\text{s}$ to $\sim 11 \mu\text{s}$. This cycle includes data acquisition, analysis and output of command set-points. The reduction was accomplished with a large effort at streamlining the RWM process logic and with an equally large effort upon D-tacq's side to optimize the input and output of data.

4. REAL-TIME ACQUISITION OF CER DATA FROM THE PCS

The CER diagnostic is an important diagnostic system for determining the plasma performance in DIII-D discharges, most importantly measuring ion temperature and plasma rotation. The rotation is important for studying and controlling RWMs or neoclassical tearing modes (NTMs). The DIII-D PCS recently added the capability of acquiring and analyzing data from the CER diagnostic in real-time. This includes spectral line amplitudes, ion temperatures, rotation values and χ^2 errors from eight CER chords. This information is used in feedback control of plasma rotation by adjusting the mix of co- and counter-injected neutral beam power.

The implementation into the PCS follows the same model as the real-time acquisition and analysis of Thomson Scattering data which was made available for the 2005 run period [1]. Several similar factors exist between the two systems in terms of PCS inclusion. The input for the existing CER diagnostic is VME based as is the Thomson Scattering data. In addition, CER data collection occurs during the discharge with analysis performed both in real time and post-shot on an auxiliary set of UNIX computers also as with Thomson Scattering. These similarities eased the implementation as did the familiarity with Intel I860 computers/coding used for CER acquisition and also used in the first generation PCS. Eight chords of CER data are provided by two I860 computers. The connection from the CER acquisition system to the PCS was accomplished by installing an Intel single CPU VME computer into the CER VME crate. This computer is a fully capable PCS real-time node, running the standard DIII-D real-time Linux kernel and equipped with a PMC slot Myrinet card enabling it to communicate directly to the rest of the PCS. Data is extracted directly from the memory of the I860, transmitted to an alternate PCS node for analysis and then made available to the real-time PCS process that is responsible for neutral beam control, Fig. 1. Analysis of CER chord data was further aided by jointly using many of the post-shot CER analysis codes. The PCS real-time analysis takes full advantage of common standard C library functions created and maintained for post-shot CER analysis.

Performance of the CER acquisition and analysis cycle was $\sim 638 \mu\text{s}$. Transfer of a single time slice of chord data from both I860 computers to the designated PCS node for analysis is $\sim 88 \mu\text{s}$ and the full analysis takes an additional $550 \mu\text{s}$. This total time is slightly slower than the CER can acquire a single time slice of data, $552 \mu\text{s}$. It is hoped that a future iteration, utilizing faster CPUs or paralleling analysis may achieve a one-to-one analysis to acquisition cycle. Figure 2 is a comparison of a typical calculated plasma parameter provided by CER real-time analysis in the PCS and by post-shot analysis.

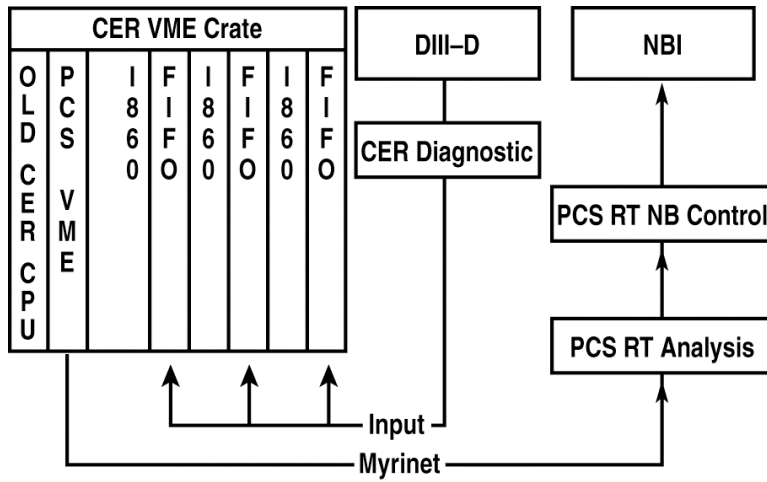


Fig. 1. CER to PCS hardware interface.

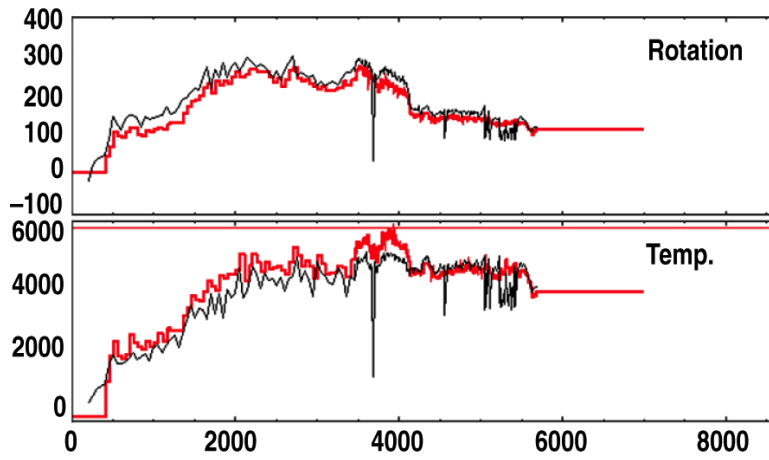


Fig. 2. Comparison of CER real-time to post shot analysis.

5. ADDITIONAL MSE DATA

As mentioned before, several new MSE channels were added to the PCS. Over the last year, the MSE system was expanded to view the newly rotated 210 deg neutral beam line. To accommodate the growth of the diagnostic and to acquire some previously existing but not connected MSE channels, two new real-time nodes were added to the PCS. Two nodes were required because of electrical isolation issues between sections of the MSE diagnostic. These new nodes are configured as the remaining other MSE specific nodes; dual Xeon CPU with single D-tacq 32-channel PCI digitizer. The PCS is the primary data acquisition system for MSE data of these channels. All of these MSE channels are available for use in real-time by rfit for calculations of the current profile and the safety factor profile [4].

6. ALGORITHM IMPROVEMENTS

Currently preparations for increasing the real-time EFIT computation grid size from 33 x 33 to 65 x 65 are under way. The benefit of increasing the grid dimensions are improved accuracy of the equilibrium reconstruction and improved agreement with off-line EFIT calculations which also use 65 x 65 grids. To implement the increased grid size, more memory and computation power are required over the current scheme. Memory is not an issue given the current configuration of PCS real-time nodes dedicated to the real-time EFIT. However the increase in computation would have exceeded the previous CPU resources if cycle times were to still remain practical for control. The main hardware restriction in the previous PCS for the grid expansion was CPU resources; resources which are needed for the several matrix multiplications included in the rfit calculation. With the increase in grid size, most of these calculations will take a factor of four longer and in one case a factor of eight. To meet this demand, CPUs were added to the PCS so that there could be four PCS CPUs assigned to each component of the rfit; the fast loop, slow loop, and the complete rfit with MSE. Plans are also underway to parallelize the matrix operations so that the cycle time for rfit will not increase when the grid size is increased.

One major improvement to the real-time EFIT software was made in the double-null discharge control. In this algorithm, the quantity, “dRsep,” is the separation at the outer midplane between the separatrix flux surface that passes through the upper X-point and the separatrix flux surface that passes through the lower X-point. A new method was implemented of controlling dRsep that involves calculating dRsep in real-time and controlling directly on the error in dRsep. The error in dRsep is used to specify the location of the control points on some of the control segments (particularly for the vertical position control coils) in order to adjust dRsep to the correct value. Small improvements were made to rfit to allow computation of gradients in flux at the proper locations in order to calculate dRsep and to calculate how much to move the control points for a given error in dRsep. This new method was tested in recent experiments with good success, providing more accuracy and reproducibility than previously achieved.

Continued improvements in neutral beam control were also implemented. A model-based PCS control algorithm was developed for simultaneous feedback control of plasma rotation and stored energy. This capability was made possible by the recent redirection of one of the four co-injection neutral beam systems, changing it to a counter-injection beam line. The PCS sends commands to all the beam systems for energy feedback control, while simultaneously changing the mix of co- and counter-injection beams to control the plasma rotation. Decoupling the injected momentum from the energy allows access to physics regimes that was not previously possible when using neutral beam heating [5].

7. REAL-TIME DISPLAY OF DATA

Perhaps the most visible and very useful part of the PCS is the real-time display. The display is a series of high-resolution graphical screens located throughout the DIII-D control room that show users a selectable subset of PCS data sets. Although not part of actual control, one PCS node was set aside to handle the collected data and near real-time graphical representations. The DIII-D PCS is a logical means to present such information to users since it acquires so many important plasma parameters before and during the discharge. The real-time display became an indispensable tool during operations. It instantly displays many of the parameters that were used in the actual plasma control. Many off-line diagnostics and acquired data may be gathered for up to several minutes after a shot. The PCS signals, although often not the same resolution as the actual off-line signals, are adequate to validate the off-line signals and, in some cases, aid in the debugging of problematic systems. Because this PCS node is not critical to plasma control, it is unique in that it not only has Myrinet access but also standard Ethernet access. This gives it the capability to output its graphics to any X window-equipped workstation with standard Ethernet connection, such as the Neutral Beam operators' screens.

One display was recently added to the primary set of six. During the plasma discharge, this display shows a cross section of the DIII-D vessel and the real-time boundary of the plasma shape as calculated by the real-time EFIT of the PCS, Fig. 3. Subtle shading also transmits important data to users such as plasma current and proximity of coil currents to their maximum value.

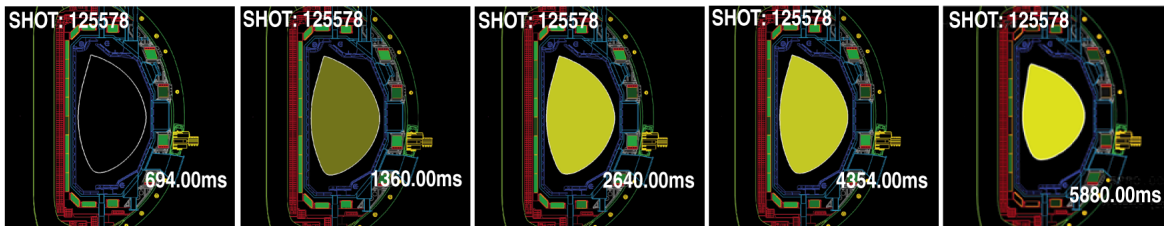


Fig. 3. Select real-time boundary frames.

8. SUMMARY

The recent alterations in the PCS are part of an ongoing effort to improve the PCS. The most significant of these alterations was the increase of CPU resources, the incorporation of data from the CER diagnostic, and additional MSE channels and algorithm development, particularly those which are directly influenced by the recent rotation of the 210-deg neural beam line.

The current evolution of the DIII-D digital PCS is proving to be a flexible and scalable system. Future enhancements may include further upgrades of computing technology, in particular Xeon quad processor real-time nodes. Of course, work will continue on the PCS to meet the experimental needs and accommodate physics demands.

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