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Progress Towards Achieving Profile Control in the Recently Upgraded DIII–D Plasma Control System

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Abstract. This paper describes the improvements being made in the capabilities of the DIII–D Plasma Control System (PCS) towards achieving optimization of current and pressure profiles in advanced tokamak discharges. Key improvements have been increased processing power and the ability to include profile diagnostic data. The recently completed upgrade of the PCS to Linux based Intel computers connected with 2 Gigabit/sec Myrinet networking technology has been successful in achieving the goals of increasing the overall performance and flexibility of the system. The new Intel computing system has increased processing power by a factor 30 over the older i860 based systems. The Myrinet fiber based network has allowed the inclusion of data in real-time from DIII–D diagnostics situated in remote locations within the DIII–D research facility. The PCS now collects 32 channels of Motional Stark Effect (MSE) data and uses these data for real-time computation of the safety factor (q) profile. Electron temperature and density profile data from the Thomson Scattering diagnostic and electron temperature profile data from the Electron Cyclotron Emission (ECE) diagnostic are presently being added. Addition of ion temperature and toroidal rotation profile data from the charge exchange recombination diagnostic is planned. Feedback control by the PCS of the electron temperature at two points has been demonstrated using either ECH or neutral beam power. This has been used to modify current profile evolution during plasma current ramp up. Specifics of the latest improvements to the DIII–D PCS are detailed here.

1. Introduction

Optimization of the current and pressure profiles in advanced tokamak discharges [1] is considered to be highly important to obtaining steady state operation in a tokamak at high beta. Much of the most recent work in improving the DIII–D digital Plasma Control System has been directed towards achieving this through PCS feedback control.

The digital system for controlling plasmas at DIII–D has been in place for over a decade. The fundamental PCS software design [2] has remained intact through much of this time. It consists of multiple user interface clients coordinating changes to discharge parameters through a central waveform server process which in turn transfers information to real-time computer processes responsible for data acquisition and feedback control. This design has proven to be very robust and flexible over the years, allowing for a continual stream of improvements in keeping up with the needs of the DIII–D fusion research program. In addition to DIII–D, the PCS has also been adapted for use in a number of other tokamak experiments including NSTX in Princeton, the MAST experiment in Culham UK, and the KSTAR tokamak in South Korea. Work is also currently underway to develop versions of the PCS for China's new EAST tokamak and a version has been developed for analysis of ITER control. A solid yet flexible software system provides the foundation for making the improvements which will be needed in support of the goal of achieving current and profile control.

2. Status of the DIII–D PCS Upgrade

The most significant improvement to the PCS made in recent years has come as a result of the successful completion of the PCS computing and acquisition hardware upgrade project. The old system utilizing decade old Intel i860 VME based computing hardware has been completely replaced by a Myrinet [3] based cluster of rack mounted PCI Intel Xeon computers. The previous real-time acquisition system utilizing CAMAC Form TRAQ digitizers has been successfully replaced with PCI Form "ACQ32" digitizers from D-TACQ systems [4].

Details of this upgrade were first presented at the 2000 SOFT Conference held in Madrid [5]. At the time, the plans involved an upgrade to Alpha based computing hardware and the utilization of Front Panel Data Port (FPDP) digitizers. Rising concerns over the long term viability of the Alpha processors coupled with significant improvements in Intel CPU processing power brought about the modification to the original plan for CPUs.

The decision to make use of D-TACQ PCI based digitizers in place of FPDP digitizers was influenced by several factors. These included performance and capabilities of the ACQ32, ease of integration into the PCI based systems, vendor support, availability of hardware and relative low cost per channel. The specific needs for PCS real-time data acquisition were all met in the 16 bit D-TACQ ACQ32 digitizers which provided a large number of data channels (32) on a single board, 250 KHz sampling performance and support for low latency real-time data acquisition. Real-time data acquisition was accomplished by vendor modifications to both the digitizer firmware and Linux based device driver software. These modifications take advantage of the Direct Memory Access capabilities of the digitizer to post and make immediately available each sample set into the memory of a PCS real-time CPU process as it is acquired. The integration of the ACQ32s into the new PCI based computing systems proved to be fairly straightforward. The rack mount computing enclosures chosen for the upgrade were equipped with enough PCI slots and room to accommodate up to four long PCI ACQ32 cards each, in addition to providing sufficient cooling for the digitizers housed within. Support from the vendor for their product was exceptional. Numerous updates to the firmware and driver software were supplied and all hardware was delivered on schedule. The cost for each board was approximately $7000.

The remaining components of the upgrade have remained essentially intact since the last presentation. These include the use of Myrinet for the high speed real-time computing system interconnect, an in-house customized Linux kernel to achieve real-time computing performance, and the preservation of the VME based Datel D/A output cards as the primary means for sending commands from the PCS to the tokamak.

The successful completion of the PCS upgrade project has brought about numerous important improvements to the overall performance and capabilities of the PCS. The processing performance has been dramatically improved by the incorporation of the Intel Xeon processors into the system. The acquisition capabilities have been improved both in terms of number of overall channels acquired and also in the resolution of the data. The Myrinet interconnect continues to simplify the inclusion of new computers and diagnostic systems into the PCS.

3. Description of the Current DIII–D PCS

The PCS computing system [6] is now comprised of twelve computers connected in a 2.0 gigabit per second Myrinet network. Eleven real-time computers running a customized version of the Linux operating system work in parallel to acquire data and control the DIII–D plasma discharges. These include nine rack mounted PCI form Intel Xeon computers ranging in speeds from 1.7 to 3.0 GHz, and two VME form Intel computers from Dynatem Corporation. A single non-real-time host computer provides the platform from which the PCS user interfaces and from which coordinating server processes are run.

A single Myrinet 16 port switch containing a mix of Fiber optic and SAN ports connects the real-time computing hardware. Each real-time computer in the network is equipped with a Myrinet network interface card and is capable of sending and receiving messages from any other real-time computer in the Myrinet network.

The real-time customizations to Linux first described in the 2000 SOFT Conference are now installed and routinely being used by each of the PCS real-time computers. These customizations help provide the PCS with the ability to perform the low latency real-time control needed for DIII–D plasma discharges. The Redhat 9 version of the Linux operating system utilizing a customized 2.4.20 revision of the Linux kernel has been adapted for use. The means of obtaining real-time responsiveness using Linux is achieved through GA developed custom routines which provide each PCS real-time computer process with the ability to obtain complete command of the CPU during a discharge. The specific method for doing so involves the execution of routines before and after every plasma discharge to lock the real-time CPU process and all of the dependent resources into memory, switch off all hardware and software interrupts, and then switch the interrupts back on when done. A method for re-enabling interrupts via the console keyboard has recently been implemented to provide a means of recovering access to a real-time CPU in the event a CPU process which has toggled off all interrupts becomes unresponsive.

4. Improvements to PCS Diagnostic and Processing Capabilities

Several improvements continue to be made in the diagnostic capabilities and processing performance of the PCS. These improvements are critical to obtaining pressure and current profiles in the PCS in real-time.

The successful addition of data from the DIII–D Motional Stark Effect (MSE) [7] diagnostic coupled with the real-time equilibrium reconstruction (RTEFIT) codes [8] implemented in the PCS have made current profile information now available in the PCS. Motional Stark Effect data is now being routinely acquired by a pair of dedicated real-time computers each fitted with a single D-TACQ digitizer and situated remotely in the MSE Diagnostic lab. The MSE PCS computer is connected to the rest of the PCS Myrinet network through a 100 meter fiber optic line.

The availability of pressure profile information in the PCS will be dependent upon the recently added Electron Cyclotron Emission (ECE) data [9] measuring electron temperature (Te), and the successful completion of tasks to incorporate data from the existing DIII–D Thomson (Te,ne) and charge exchange recombination (Ti,v) data acquisition systems.

A new real-time computer has been setup to acquire 32 channels from the Electron Cyclotron Emission diagnostic. The DIII–D ECE radiometer is a multi-channel heterodyne system providing $T_e(r,t)$ from measurements of optically thick second harmonic (X-mode) electron cyclotron emission.

Inclusion of temperatures and densities from the Thomson diagnostic system [10] has required more effort and is still in the implementation stages. The present Thomson spectral diagnostic utilizes a set of polychromators to measure laser light scattering from 44 points in plasma space. Raw data from these measurements is collected by a set of FERA digitizers and written into VME based CES memory modules. In order to integrate this information into the PCS two new PCS real-time computers are required. A single Intel VME CPU with a Myrinet network connection has been installed in the Thomson VME crate containing the CES memory modules. This computer provides the access to the Thomson light scattering measurements in real-time to the rest of the PCS. A second real-time computer is being added to process the raw data obtained from the Thomson system and generate the temperature and density profile results critical in obtaining accurate pressure profiles.

The addition of ion temperature and toroidal rotation profile data from the CER diagnostic [11] is planned. This will depend on the ability to integrate raw data from the CER acquisition system into the PCS and compute useful results in real-time. This diagnostic presents more of a challenge to integrate into the PCS Linux based system since it presently utilizes a set of eight Microsoft Windows based computers in order to control the Pixelvision CCD cameras. These will have to be connected in some manner to the PCS real-time system in order to pass raw CER data to a PCS real-time computer which would then be responsible for analyzing spectral lines from CER and pass them to other PCS CPUs.

The processing power of the PCS has been further enhanced by the recent implementation of codes enabling a PCS real-time process running on a dual processor equipped computer to spawn a threaded portion of itself on a second CPU. This new feature takes advantage of a set of CPU affinity routines now available in Redhat 9 Linux systems which allow processes or threads to be bound to specific CPUs in multi-CPU computer systems. It has been particularly effective for applications such as the real-time equilibrium reconstruction code which contain subroutines which can be run in parallel with one another to produce results, significantly reducing processing time. At present, two PCS real-time computer systems have been equipped to run as dual CPU systems. Future plans include the creation of more dual CPU systems and development of codes which would allow a single PCS real-time process to run on each of the CPUs of a dual CPU equipped computer.

The increases in PCS processing performance are of particular importance to the CPU intensive codes required for the analysis of raw diagnostic data obtained from systems such as Thomson and CER. In these cases greater CPU power can lead to improved results from the specialized fitting and analysis codes needed to convert the raw data into information which would be useful to the PCS in determining the pressure profiles in real-time. The PCS RTEFIT codes used in obtaining the current profile information from the MSE data also benefits from improvements in PCS processor performance.

5. Achieving Control of Profiles Within the PCS

The DIII-D PCS is responsible for sending commands to numerous tokamak actuators used in controlling plasma discharges. This includes both analog and digitally driven outputs controlling the DIII–D power supplies, magnetic field coils, gas puffing and more. For use in controlling the current and pressure profiles, the PCS has the capability of modifying injected power from DIII–D neutral beam [12] and Electron Cyclotron Current Drive (ECCD) [13] sources.

Control of the DIII–D neutral beam average power and pulse shape using the PCS has been available for a number of years. DIII–D has four neutral beam lines, each containing two ion sources in parallel focused through a common drift duct. Each ion source is capable of producing a 2.5 MW, 80 keV deuterium beam. PCS control over the neutral beams includes the ability to modulate any of the eight ion sources throughout the entire course of a plasma discharge with resolutions as fine as a quarter of a millisecond. Using PCS feedback control, neutral beam injection can be modified in real-time in response to asynchronous events.

PCS control of the DIII–D ECCD system is a recent improvement. DIII–D has five 1 MW class gyrotrons available for electron cyclotron heating (ECH) and current drive. The PCS has the ability to modulate injected power from each of these gyrotrons in response to selected feedback signals. This has been used to successfully control the electron temperature (T_e) profile with ECH. Figures 1 and 2 illustrate the successful control of two electron temperature points on a single discharge using four gyrotrons. The electron temperature at the first off-axis point exhibits good control using three gyrotrons up to the time the gyrotrons being used for control begin to saturate [fig 1]. Control of the second on-axis point using a single gyrotron displays better tracking [fig 2].

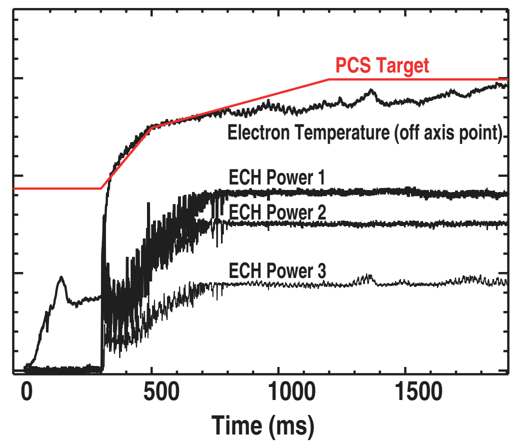

Fig 1. Electron temperature control at first off-axis point.

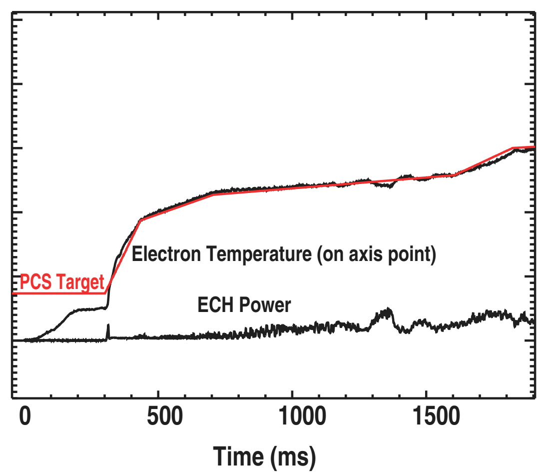

Fig 2. Electron temperature control at second on-axis point.

6. Summary

Important strides are being made towards achieving the goal of controlling current and pressure profiles in the DIII–D tokamak using the PCS. The successful completion of the upgrade of the PCS real-time computing and data acquisition systems has opened up several avenues for expansion. The recent addition of data from the MSE diagnostic coupled with the real-time equilibrium reconstruction codes have now made information about the current profile available in the PCS. Tasks to include new diagnostics from the ECE, Thomson and CER acquisition systems are moving closer to supplying the PCS with all the information it will need to obtain pressure profiles in real-time. Continuing improvements in PCS processing performance are benefiting the real-time analysis capabilities for codes used to obtain the current and pressure profile information from the raw diagnostic data. Improvements to the control capabilities of the PCS are demonstrating that certain aspects of the feedback control required for optimizing the current and pressure profiles are achievable.

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