

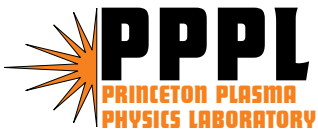
PPPL-4092

PPPL-4092

Status of the Control System on the National Spherical Torus Experiment (NSTX)

D.A. Gates, J.R. Ferron, M. Bell, T. Gibney, R. Johnson,
R.J. Marsala, D. Mastrovito, J.E. Menard, D. Mueller,
B. Penaflor, and T. Stevenson

August 2005



PPPL Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2005. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

Office of Scientific and Technical Information (OSTI):

Available electronically at: <http://www.osti.gov/bridge>.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Fax: (865) 576-5728
E-mail: reports@adonis.osti.gov

National Technical Information Service (NTIS):

This report is available for sale to the general public from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Fax: (703) 605-6900
Email: orders@ntis.fedworld.gov
Online ordering: <http://www.ntis.gov/ordering.htm>

Status of the Control System on the National Spherical Torus Experiment (NSTX)

D. A. Gates^a, J. R. Ferron^b, M. Bell^a, T. Gibney^a, R. Johnson^b, R. J. Marsala^a, D. Mastrovito^a, J. E. Menard^a, D. Mueller^a, B. Penaflo^b, T. Stevenson^a

^a Plasma Physics Laboratory, Princeton University, P.O.Box 451, Princeton, New Jersey 08543 USA
^b General Atomics, La Jolla, California 92186 USA

Abstract

In 2003, the NSTX plasma control system was used for plasma shape control using real-time equilibrium reconstruction (using the rtEFIT code - [J. Ferron, et al., Nucl. Fusion **38** 1055 (1998)]. rtEFIT is now in routine use for plasma boundary control [D. A. Gates, et al., submitted to Nuclear Fusion (2005)]. More recently, the system has been upgraded to support feedback control of the resistive wall mode (RWM). This paper describes the hardware and software improvements that were made in support of these physics requirements. The real-time data acquisition system now acquires 352 channels of data at 5kHz for each NSTX plasma discharge. The latency for the data acquisition, which uses the FPDP (Front Panel Data Port) protocol, is measured to be ~8microseconds. A Stand-Alone digitizer (SAD), designed at PPPL, along with an FPDP Input multiplexing module (FIMM) allows for simple modular upgrades. An interface module was built to interface between the FPDP output of the NSTX control system and the legacy Power Conversion link (PCLINK) used for communicating with the PPPL power supplies (first used for TFTR). Additionally a module has been built for communicating with the switching power amplifiers (SPA) recently installed on NSTX. In addition to the hardware developments, the control software [D. Mastrovito, Fusion Eng. And Design **71** **65** (2004)] on the NSTX control system has been upgraded. The control computer is an eight processor (8x333MHz G4) built by Sky Computers (Helmsford, MA). The device driver software for the hardware described above will be discussed, as well as the new control algorithms that have been developed to control the switching power supplies for RWM control. An important initial task in RWM feedback is to develop a reliable mode detection algorithm.

Keywords: Plasma control, hardware, software

1. Introduction

The National Spherical Torus Experiment, which began operations in 1999, has been operated with

purely digital plasma control system from the first plasma onwards. The initial development plan for this system, which was originally described in Reference [1], has now been completed. The system hardware

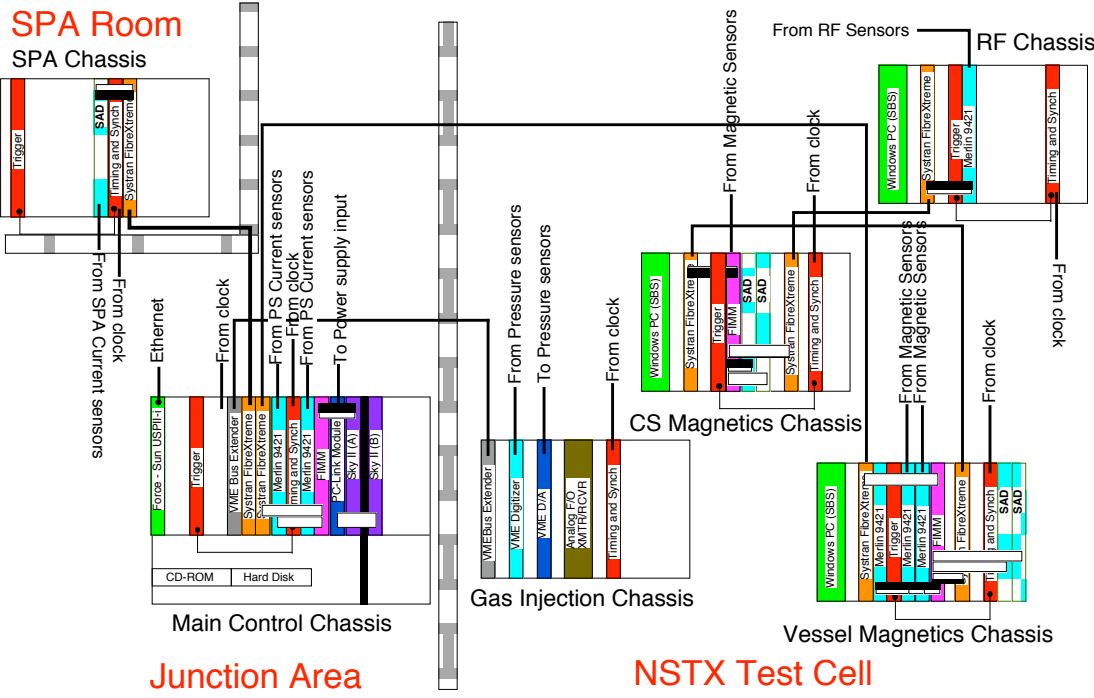


Fig. 1. The NSTX control system hardware block diagram.

status, which is evolving continuously, is described in Section 2. The hardware description is divided into subsections according to device function. The software for the NSTX control system, which has been developed in close collaboration with General Atomics in San Diego, will be described in Section 3. As with the hardware discussion, the software components section is subdivided into sections by function.

2. Hardware

2.1. Real-time computer

The NSTX plasma control system computer consists of 8 333MHz processors in a shared memory architecture. The processor cards are built by Sky Computers (Helmsford, MA). Each processor motherboard contains 4 G4 processors (Motorola) and one Front Panel Data Port (FPDP - ANSI/VITA 17) high speed low-latency direct memory access i/o port. The two motherboard are connected together by a

VME P2 backplane known as "Skychannel" (ANSI/VITA 10-1995). The real-time computer is not available for interactive processes, but is instead accessed over the VME backplane from a single-board workstation built by Force Computers (Fremont, CA). The Force computer runs the Solaris operating system written by SUN computers (Stanford, CA) and also acts as the VME Slot 0 controller. A block diagram showing the layout of the NSTX control system is shown in Figure 1.

2.2. Data acquisition

Data is acquired in real-time at 5kHz over a distributed network of point-to-point connections from VME crates that contain one or more 9421 (12bit) or 9422 (16bit) FPDP digitizers (Merlin Electronics, Memphis, TN). There are currently 352 channels of data being acquired in four different locations. The data consists of magnetic field and flux measurements, power supply currents and voltages for shape control.

Gas control data and current, voltage, and phase data for the antenna elements of the RF heating system [2] are also acquired in real time, but are not yet used in the shape control system. The distributed data acquisition system is required due to the rather complex grounding scheme on NSTX needed for the coaxial helicity injection system [3] which biases a large fraction of the NSTX vacuum vessel to $\sim 1\text{kV}$ potentials.

In addition to the Merlin digitizers, a Stand-Alone digitizer (SAD), shown in Figure 2 has been designed and built for use at PPPL. This module, which is intended for use in combination with a multiplexing module (see below) has a VME form factor, but uses the VME crate only for power. The digitizer is clocked externally and data is sent out via an FPDP port on the front panel. The unit requires no setup, and is an elegantly simple solution for real-time data acquisition.

Data for the gas system is still taken via the VME bus using VME based digitizers. The acquisition latency for this system is higher, and it is planned to replace the VME system with FPDP based i/o in the near future.



Figure 2 Shown on the left is the Stand Alone Digitizer (SAD) developed at PPPL is a simple 32 channel FPDP digitizer. Shown on the right is the Front Panel Data Port Input Multiplexing Module (FIMM) developed at PPPL combines multiple FPDP streams.

2.3. Telemetry

The data is transmitted over a fiber optic serial link known as Serial FPDP (ANSI/VITA 17.1-2003) built by Systran Corporation (Dayton, OH). Each module is capable of converting the parallel FPDP data stream to a serial FPDP (1 Gbit fiber optic) stream or vice-versa. The independent point-to-point data streams are multi-plexed into a single data stream by a module, shown in Figure 2, which is known as a FIMM (or FPDP Input Multiplexing Module, developed at PPPL) which does a simple concatenation of the individual streams into a single stream after FIFO (First-In-First-Out) buffering. The data is then streamed into the FPDP port on one of the Sky computer boards (which will be referred to as the input computer). The measured end-to-end latency of the data acquisition system is $\sim 8\mu\text{s}$.

2.4 Output hardware

Power supply commands are output through the second FPDP i/o card to a module, shown in Figure 3, which was developed at PPPL and is known as a PCLIM (PC-Link Interface Module). This module converts data into the digital format of the PCLink

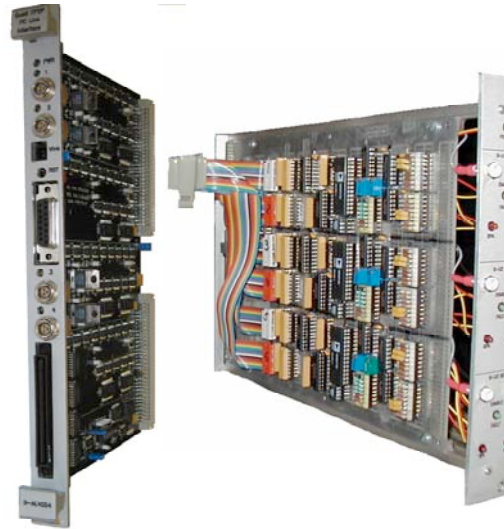


Figure 3 The PCLIM module (left) interfaces the FPDP output stream with the legacy PCLink interface that was inherited from TFTR while the SPAIM (right) interfaces FPDP to a switching power amplifier with analog inputs.

(Power Conversion Link) which was developed for use on TFTR (Tokamak Fusion Test Reactor) in the early 1980's. Each 32 bit FPDP word written from the output computer consists of both data and routing information. The digital commands are converted to rectifier pulses in firing generators inside the individual rectifier supplies after the routing information is stripped out.

A new high speed switching power amplifier (SPA) has recently been added to NSTX in order to power the resistive wall mode (RWM) feedback system. Unlike the legacy TFTR power supplies, which accept a digital firing angle as input, the SPA accepts either an analog current or an analog voltage request. This required designing an interface module that was compatible with the existing PCLIM. A module, also shown in Figure 3, referred to as a SPA interface module (SPAIM) was designed to create the required analog signal. The SPAIM was designed with front panel analog outputs for testing purposes.

3. Software

3.1 Infrastructure software

The basic infrastructure for the NSTX plasma control software is borrowed in large part from the Plasma Control System (PCS) developed at General Atomics for use on DIII-D, and has been described in detail previously [4]. For reference purposes, a block diagram showing the basic services provided by the PCS are shown in Figure 4. The system was modified to operate with the MDSplus archiving system in use on NSTX and to be compatible with the Sky real-time operating system.

3.2 Real-time information flow

The flow of information during a pulse sequence is represented by the block diagram in Figure 5. Data is acquired in real-time from the direct memory access (DMA) services provided by the Sky operating system and is converted to meaningful physical units by the acquisition program running on one of the processors on the input board. It is then distributed to each processor across the Skychannel bus. The PCS and power supply real-time control (PSRTC) software receive and process this data. The PCS generates voltage requests for the plasma control actuators and

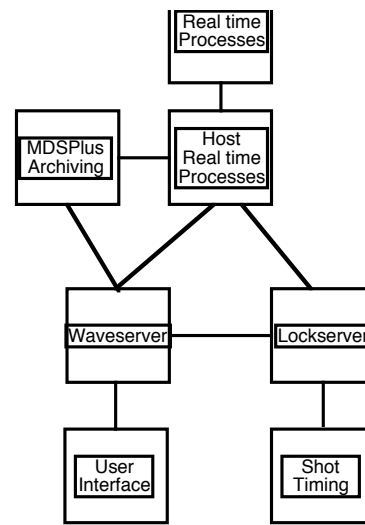


Figure 4 Block diagram showing the relationship of the major components of the PCS, developed at General Atomics

sends them to PSRTC, which applies engineering constraints to the requests. After constraining the data the voltage requests are converted to the appropriate output units and sent out through the FPDP output port. The gas system is handled separately, with out puts being sent out through the VME port without passing through PSRTC.

3.3 Control algorithms

The PCS infrastructure supports modular control algorithm development. Different categories of control on the NSTX PCS are currently:

1. Toroidal Field
2. Plasma current/transformer control
3. Discharge Shape
4. Equilibrium
5. Isoflux
6. System
7. Data Acquisition
8. Gas Injection
9. Error Fields and Resistive Wall Modes

Category 1 controls the toroidal field coil current with a simple PID algorithm. Category 2 consists of three different phases of control; 1) control of the ohmic heating coil current through PID control up until the point of plasma breakdown, 2) Control of the plasma current up until the point of the end of the plasma current (determined by $I_p < I_p^{\min} = 60\text{kA}$), and 3) control of the ohmic heating coil current back down to zero after the discharge ends. Categories 3 through 6 correspond to plasma shape control. The Discharge Shape category contains a rudimentary control

algorithm which controls the plasma radial and vertical position with preprogrammed control of the other coil currents. The Equilibrium category inverts the Grad-Shafranov equation using the rtEFIT code; the resulting equilibrium solution provides input to the isoflux category. The isoflux category uses the errors between the flux at the requested boundary and the real-time calculation of the plasma boundary flux as input to a PID type controller that determines the poloidal field coil voltages. The various isoflux algorithms in use in the isoflux category are described in Reference [5]. The system category is used to choose between the Discharge Shape category and the Isoflux category as a source for the poloidal field coil voltage commands. The System category has been recently upgraded to allow for a continuous hand-off from one category to the other using "fuzzy" logic, which has been beneficial for avoiding jumps in the plasma position and shape at the category transition. Reference [6] has more detail on plasma shape control on NSTX. The Data acquisition category has no explicit real-time algorithm, but rather controls parameters of the data acquisition functions of the PCS. The Gas Injection category controls 1) the pre-fill pressure using measurements of the torus pressure from ion gauges, 2) The gas injection flow rate from the low field side gas injectors on NSTX, and 3) the status of several solenoid valves which control pulsed gas flow from the high field side and divertor gas injectors on NSTX. The final category, Resistive Wall mode control is the newest control category. Currently this category controls the SPA current using PID. Algorithms are being developed to implement error field feedback control and resistive wall mode feedback control.

In addition to the above named categories of control, a new category, tentatively named real-time mode detection, is under development which will be used in conjunction with the resistive wall mode feedback system. Its primary function will be to attempt to sense the presence of a resistive wall mode as input to the feedback algorithm.

4. Recent upgrades and results.

4.1 Latency reduction

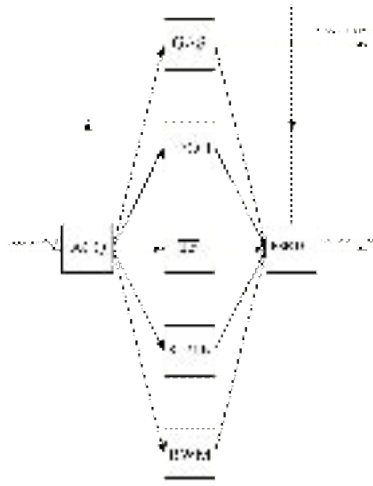


Figure 5 Real-time informationflow in the NSTX control computer

In addition to the RWM category mentioned above, the PCS was recently upgraded in order to reduce the system latency. This was achieved by purchasing a more recent implementation of the Sky FPDP i/o board and by optimizing the processor to processor communications on the Skychannel bus.

The optimization resulted in a substantial reduction in the latency of the NSTX control system. The overall latency was measured to be almost 3ms before the upgrades, and was reduced to 750 μ s afterwards. These optimizations led to a marked improvement in plasma performance on NSTX. In particular, the vertical position control was improved so that plasmas with elongations up to ~ 2.8 have been achieved. Plasma theory indicates high elongation is very important for plasma performance.

4.2 Data acquisition upgrade

The number of real-time data acquisition channels was recently increased from 192 to 352 in order to support more accurate shape reconstructions and to support the planned development of an RWM mode detection algorithm. All new channels are acquired using the SAD and FIMM modules developed at PPPL (described above).

5. Summary

The NSTX plasma control system has been upgraded to support the physics requirements of the device. These upgrades have been central to the achievement of recent performance records for the spherical torus concept, which include high elongation and high plasma pressure.

Acknowledgements

This work was supported by the U.S. Department of

Energy Grant under contract number DE-AC02-76CH03073. The authors would like to dedicate this work to the memory of Tom Gibney, whose work made this effort possible.

References

- [1] D. A. Gates, D. Mueller, C. Neumeyer, J. R. Ferron, IEEE TRANSACTIONS ON NUCLEAR SCIENCE **47** (2000) 222-224, Part 1
- [2] J. R. Wilson, R. E. Bell, S. Bernabei, et al., Phys. Plasmas **10**, Part 2 (2003) 1733
- [3] R. Raman, T. R. Jarboe, D. Mueller, et al., Plasma Phys. Cont. Fusion. **43** 305 (2001)
- [4] B. G. Penaflo, D. A. Piglowski, J. R. Ferron, M. L. Walker, IEEE Trans. Nucl. Science **47** 201 (2000)
- [5] J. R. Ferron, M. L. Walker, L. L. Lao, et al., Nucl. Fusion **38** 1055 (1998)
- [6] D. A. Gates, et al., to be published in Nucl. Fusion (2005)

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Science Center, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research
Institute for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Dr. Pandji Triadyaksa, Fakultas MIPA Universitas Diponegoro, Indonesia
Professor Sami Cuperman, Plasma Physics Group, Tel Aviv University, Israel
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Istituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study,
Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Professor Toshitaka Idehara, Director, Research Center for Development of Far-Infrared Region,
Fukui University, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Mr. Adefila Olumide, Ilorin, Kwara State, Nigeria
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences, People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Kazi Firoz, UPJS, Kosice, Slovakia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita,
SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Dr. Rasulkhozha S. Sharafiddinov, Theoretical Physics Division, Institute of Nuclear Physics, Uzbekistan
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Director, Research Division, OFES, Washington, D.C. 20585-1290

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: <http://www.pppl.gov>