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Control and data acquisition upgrades for NSTX-U

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HIGHLIGHTS

- The NSTX-U upgrade is nearing completion, and various control and data acquisition upgrades are needed.
- The Digital Coil Protection System is a major addition which provides hardware and software to protect the magnetic coils from the complex, increased, stresses added from the upgrade.
- The increased computational requirements for the upgrade have largely followed Moore's Law, and enhancements to the infrastructure and computer hardware should maintain or exceed the previous functionality.
- Data requirements for Fast 2-D cameras have exceeded those of "conventional" time-varying signals. There has been a particular emphasis and increase in data from IR cameras.

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ABSTRACT

The extensive NSTX Upgrade (NSTX-U) Project includes major components which allow a doubling of the toroidal field strength to 1 T, of the Neutral Beam heating power to 12 MW, and the plasma current to 2 MA, and substantial structural enhancements to withstand the increased electromagnetic loads. The maximum pulse length will go from 1.5 to 5 s. The larger and more complex forces on the coils will be protected by a Digital Coil Protection System, which requires demanding real-time data input rates, calculations and responses. The amount of conventional digitized data for a given pulse is expected to increase from 2.5 to 5 GB per second of pulse. 2-D Fast Camera data is expected to go from 2.5 GB/pulse to 10, and another 2 GB/pulse is expected from new IR cameras. Our network capacity will be increased by a factor of 10, with 10 Gb/s fibers used for the major trunks. 32-core Linux systems will be used for several functions, including between-shot data processing, MDSplus data serving, between-shot EFIT analysis, real-time processing, and for a new capability, between-shot TRANSP. Improvements to the MDSplus events subsystem will be made through the use of both UDP and TCP/IP based methods and the addition of a dedicated "event server".

1. Introduction

The National Spherical Torus Experiment (NSTX) [1,2] is a medium-sized, magnetically-confined, fusion experiment (plasma major radius up to 85 cm, minor radius up to 68 cm) at the Princeton Plasma Physics Laboratory (PPPL) in Princeton, NJ, USA. After operating from 1999 to 2011, NSTX has undergone a US$94 M multi-year upgrade (NSTX-U) to double the toroidal magnetic field (to 1T), the plasma current (to 2MA), and the neutral beam heating power (to 12MW) and increase the pulse length from 1.5 s to 5 s. The spherical tokamak (ST) is a leading candidate for a Fusion Nuclear Science Facility (FNSF) due to its compact size and modular configuration and NSTX-U should be able to make important contributions to developing the physics basis for an ST-based FNSF [3]. Access to low collisionality plasmas in the ST configuration is particularly important to more fully understand transport, stability and non-inductive start-up and sustainment in the ST [3].

The US Department of Energy (DoE) is funding the NSTX Upgrade with Princeton University as the management and operating (M&O) contractor. Such capital asset projects in DoE are managed through various Critical Decision (CD) Stages, and CD-4, "Approval for the Start of Operations or Project Completion" is scheduled for the spring of 2015. This is when the project moves from the construction phase to the operations phase. The computer requirements for

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Table 1
Overview table of IT requirements for the NSTX-U Upgrade.

- Support increased data amounts
  - ○ More digitizer memory to support longer pulses
  - ○ More disk capacity to keep all data online
  - ○ Faster networks so increased data sets, especially from Fast Cameras, can be accessed by the users in a few minutes
- Intelligent Coil Protection
  - ○ Hardware and Software real-time calculations of the increased, complex, forces on the coils
  - ○ Thorough testing and configuration control of the systems used for protection
- Increase reliability
  - ○ Enhance and "harden" the event messaging used to coordinate post-processing
  - ○ Automatically alert users when specified signals are missing or out-of-range
- Increase computational capabilities
  - ○ Increase time and spatial resolution in EFITs [12]
  - ○ Have transport analysis available between shots (TRANSP [12,13])

CD-4 just involve activating and controlling the magnetic coils, and recording the glow of a 50KA plasma on a Fast 2-D Camera. To minimize the risk of unnecessary complications, changes to software and computer hardware used to operate NSTX-U have been minimized until this critical milestone is reached. There would then be about a 2-month period before relevant physics experiments can be carried out. By that time, additional computer hardware and software upgrades will need to be operational.

2. System requirements

The key, additional IT requirements for the upgrade to NSTX are summarized in Table 1.

The expected growth in data amounts and other quantities related to supporting NSTX-U is shown in Table 2. During the last experimental campaign in 2010, an average of 5 GB of data was taken and stored for a 1 s pulse (also called a "shot"). About half of this was fast camera data and half was signal data from digitizers. There were typically 40 pulses per run day, and 100 run days in a year. For the 2015 campaign we expect the per-pulse signal data to double and the camera data to quadruple, totaling 17 GB/pulse. During most of this first year of operation, NSTX-U will operate with a pulse length of 1 s, or so, but within the next few years, the pulse length will increase to 5 s as the increased capabilities of the upgrade are utilized, and the data amounts are expected to increase proportionally.

On a typical run day in 2010, there were 40 engineers and scientists in the NSTX Control Room and an additional 10–20 participating remotely. We expect the number of participants to be ~20% higher in 2015 on NSTX-U.

The number of "pulses of interest" for years in which NSTX-U will be run at full operating capacity are expected to be somewhat lower (e.g. 2025 in 2018 vs. 3000 in 2015) because the magnetic coils will need more time to cool between pulses.

Fast 2-D Camera data [4,5] will continue to be an important source of understanding the plasma behavior in NSTX-U, both macroscopically and for edge turbulence. A key issue in tokamak and ST studies is the understanding of the transport of heat from the main plasma to the plasma material interface (PMI) — especially the divertor [6]. As such, there will be a substantial increase in the amount of IR camera data [7] taken during the next run. As shown in Table 2, the amount of camera data is increasing more quickly than signal data. Table 3 shows the types of cameras used on NSTX-U that will contribute the most data.

The Phantom cameras and the Miro 4, manufactured by Vision Research, will view the lower and upper divertors in NSTX-U. The Miro 2 color camera will view the full vessel interior during a discharge. The Santa Barbara Focalplane SBF 161 cameras will record IR data from the lower and upper divertors. The FLIR Tau 2 cameras will record IR data from the lower divertor (wide angle view) and the RF Antenna tangentially. The IDS UI-5240CP-NIR GigE Camera will be used for the Multi-Point Thomson Scattering diagnostic. The 8 Dalsa GigE Vision Spyder 3 cameras record 1D CCD arrays. The Princeton Instruments ProEM GigE cameras are used for a Divertor VUV spectrometer and a Divertor Control Spectrometer. The Princeton Instruments CCD w/PCI Spec-10 is used for an ultraviolet-visible survey spectrometer.

A major upgrade for NSTX-U in terms of manpower, capital equipment, and computing infrastructure is the Digital Coil Protection System (DCPS) [8,9]. The increased heating power and magnetic coil field strength for the upgrade have contributed to an increased need for protection of the coils and vessel hardware. The DCPS will protect NSTX-U during a plasma pulse by running a collection of algorithms involving 1200 calculations every 200 μs using real-time measurements of the plasma current and the 16 magnetic coil currents [10]. If the calculations from any algorithm exceeds a pre-programmed minimum or maximum limit, the power supplies are shut down before damage or unnecessary fatigue occurs. Significant improvements were made to the Power Supply Real Time Control (PSRTC) and the Plasma Control System (PCS) infrastructure, as well [9]. The pre-operational testing with DCPS has gone much more quickly, and been more reliable, than similar power testing on NSTX in the past. This can be attributed to good design and development methodologies and to the use of the AutoTester [11], where electrical signals are generated to simulate actual operations.

The equilibrium fitting code EFIT has always been integral to NSTX operations [12], calculating the location of the magnetic flux surfaces within the vacuum vessel as a function of time. A version that only uses magnetics [10] (called EFIT01) is computed quickly (~2.5 min) after a pulse and a more accurate version (called EFIT02) that uses magnetics, diamagnetic loop, and Thomson electron density and temperature data is available ~10min after the shot. Having EFIT data available more quickly allows other key NSTX-U calculations to be started earlier. EFIT is easily parallelized, so more dedicated processing power can also increase the time and spatial resolution of the EFIT data available between shots.

TRANSP [12,13] is a widely-used time dependent transport analysis code for tokamak experiments. Software optimizations and new computer hardware have reduced the time needed for a TRANSP analysis on an NSTX-U pulse from 90 min to less than 5 min. Having this information available between shots will help the Physics Operator know what control adjustments to make before the next pulse.

The time requirement for all the data to be acquired and sufficiently analyzed to inform the settings for the next shot is "soft." Naturally, the sooner results are available to the physics operators, the more time they have to consider their next steps. Circumstances vary, but generally speaking, if the physics operators have a minute or two to digest results before starting the next cycle, there are no complaints. Machine operating requirements, such as time needed to cool the magnetic coils, or to spin up the motor generators, will typically limit between-shot times on NSTX-U to 15–30 min.

3. Proposed IT hardware

Much of the IT equipment used during the last NSTX campaign needed to be updated for NSTX-U. For our primary MDSplus [14,15] data server the following hardware was ordered:

HP DL380 Gen9 24SFF CTO Server with x2 2.6 GHz-10-core- 20 threads

Table 2
Increasing quantities of data, users, and computer resources from NSTX to NSTX-U.

	2010 run	2015 est.	2018 est.
Max pulse length (s)	1.5	3.5	5
Fast Camera data/sec (GB)	2.5	10	40
IR Camera data/sec (GB)	0.1	2	8
Conventional signal data/sec (GB)	2.5	5	20
Total GB for typical pulse	5	17	68
Total GB for max pulse	8	60	340
run days/year	100	75	75
pulses of interest	4000	3000	2025
Concurrent users	50	60	80
Diagnostic systems	45	52	65
Linux CPU cores for between shot processing	58	194	776
Cores for Real-time processing	8	96	

Table 3
Fast 2-D and IR cameras that will contribute the most data on NSTX-U.

Camera Type	Typical MB/pulse	Max MB/pulse	Mega Pix/sec	Max. Resol.	Bits/pixel
Phantom 7.3 (2@)	1000	4000	3000	800 × 600	14
Phantom 710 (2@)	1000	10000	7000	1280 × 800	12
Phantom v1211	2000	12000	12000	1280 × 800	12
Miro 4	350	1000	600	800 × 600	12
Miro 2	50	2000	300	640 × 480	12
SBF 161 (2@)	500	750	26	128 × 128	14
FLIR Tau 2 (2@)	110	110	20	640 × 512	14
IDS UI-5240CP-NIR	43	43	60	1280 × 1024	10
Dalsa GigE Vision Spyder 3 (8@)	75	75	40	1024	12
Princeton Instruments ProEM GigE 1600 × 400	28	28	380	1600 × 400	16
Princeton Instruments ProEM GigE 1600 × 200	20	20	370	1600 × 200	16
Princeton Instruments CCD w/PCI Spec-10	27	27	130	1340 × 100	16

- 4 × 400GB SSD disks (for newly acquired shots)
- P840 4GB Caching RAID controller
- 2 × 120GB SATA SSD System disks.
- 32GB RAM
- QLogic 2562, Dual Port 8Gb Optical Fibre Channel HBA
- 4 PCIe × 16 ports on riser
- 2 port 10GB SFP network interface
- 4 port 1GB network interface

For the EFIT processing for the upcoming run, two 32-core systems have been added to the 10-core EFIT computing cluster, nearly quadrupling the processing power.

300 TB on our Hitachi SAN array will be dedicated to the raw and analyzed data from NSTX-U and NSTX in 2015.

Since the last NSTX campaign most of our networking infrastructure has been upgraded from 1 Gb/s to 10 Gb/s. We plan to put "low-risk systems" (those NOT involved with machine protection, personnel safety, Personally Identifiable Information, etc.) on an "iScience" virtual local area network (VLAN) and use a layer 3 switch as a gateway.

Traffic between these "science" systems will not need to go through a firewall, and will have the capability to communicate directly with one another via the iScience switch at a full 10 Gb/s. This will result in increased bandwidth, lower latency, and substantially improved performance. Other traffic that does need to go through the Internal Firewall will have less contention. The iScience VLAN will be configured to support multicasting, so UDP events can be used in MDSplus.

NSTX-U will continue to rely on EPICS [16] for plant-monitoring functions. Four servers (Dell PowerEdge R520) have been purchased to replace old EPICS servers as we move into operations. Fig. 1

The 53 seats in the NSTX-U Control Room will be expanded to 60 for the 2015 run, and another 7 will be added in 2016. 22 Macintosh-based configurations have been ordered to upgrade Control Room stations. Most of these will have two 24 or 27" displays. 10 PC-based configurations have been or will be upgraded, as well. We expect around 10 seats to be used by visiting collaborators or on-site scientists with their own laptops. External monitors will be provided at these stations.

4. Planned S/W changes

A number of software changes are planned to modernize and prepare for the increased demands of NSTX-U. Our primary Linux-based data serving infrastructure will be upgraded from older versions of Red Hat Enterprise Linux (RHEL) to newer ones. After extensive testing, our data serving software, MDSplus will be upgraded from version 2 to 7 to add additional features and fix existing bugs. Given the number of changes being made for NSTX-U a conservative phased approach was adopted to gently upgrade our systems without causing undue failures or loss of functionality. Multiple versions of MDSplus have been made available on a port by port basis with control over port utilization managed manually. In this manner we are able to steer legacy devices and systems that utilize MDSplus towards the version they are most compatible with. Over time, as these systems are upgraded or replaced, the older version will be disabled. A similar approach will be taken to explore and potentially fully utilize MDSplus UDP events.

During its lifetime NSTX relied heavily on MDSplus, and features of that software package were taxed up to, and possibly beyond, its limits. An example of this is the MDSplus event system, which is used to communicate post-processing steps, relay small amounts of data (like the NSTX shot number) and provide information to monitoring tools. Two underlying transport protocols may be used with MDSplus events, one using the UDP Multicast protocol and the other a more mature TCP/IP based approach. Thousands of events [17] are sent and received during a 15-min shot cycle. During NSTX operations, event handling could become unreliable after many days of heavy use. The MDSplus experts suggested we use the lighter-weight UDP communication protocol for events. More testing is needed, but we may have our main MDSplus server,

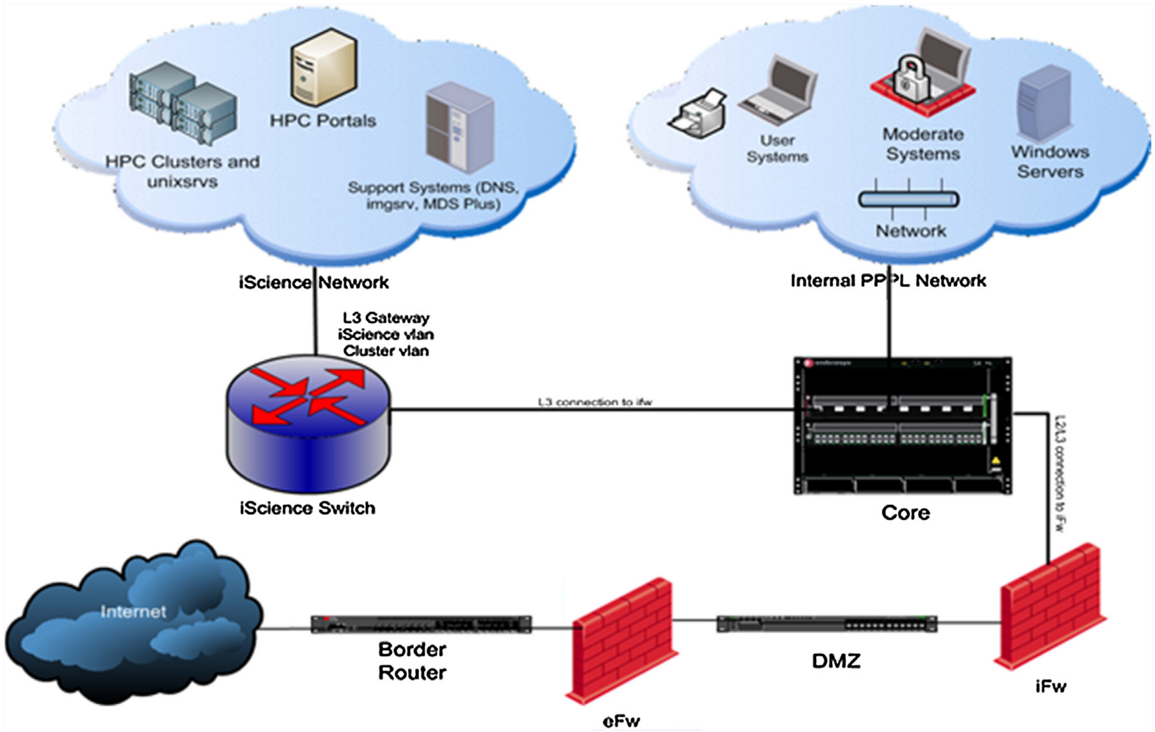

Fig. 1. Consolidating scientific processing on our network will reduce latency.

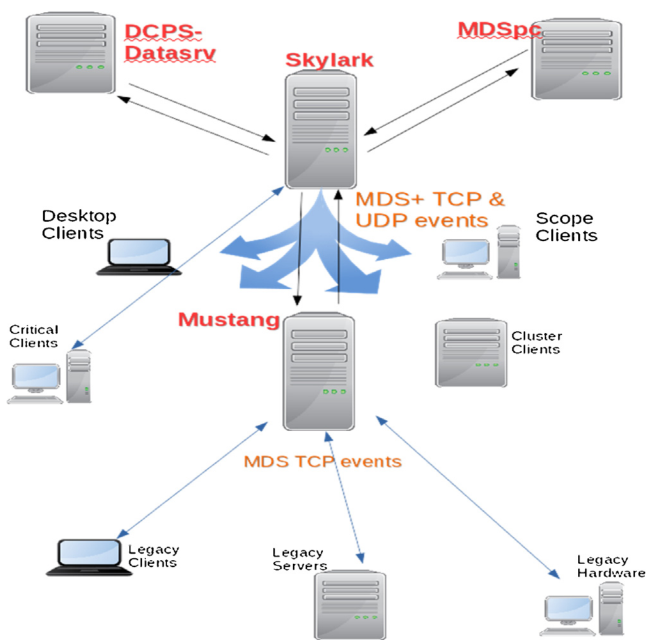

Fig. 2. A new server, labelled Mustang, will be used to relay UDP-based MDSplus events to TCP/IP-based events.

Skylark, use UDP events, and use another server for TCP/IP-based events, as illustrated in Fig. 2. This relaying of events might be necessary for older, legacy, systems that cannot use UDP, or for some systems that need the “guaranteed” delivery of TCP/IP. For reasons mentioned in the Introduction, above, these changes will be made after the CD-4 milestone.

Hardware and software failures can result in some data signals being wrong or not being acquired. We will continue to use the EPICS Alarm Handler to monitor and present a hierarchy of statuses of the plant systems. For NSTX-U we will also have a process, called SigAlert, which runs after a shot, and emails designated users, and optionally writes to EPICS variables, when important signals are missing or out of prescribed bounds. The Digital Coil Protection System, mentioned above, is a new requirement for NSTX-U with extensive software associated with it, but it is necessary for the CD-4 milestone.

5. Evaluating the upgrades

Of course the ultimate test comes when NSTX-U restarts, but meaningful load and timing tests can be run before full operations. Transfers of fast camera data from the Test Cell at D-site, where the cameras and host PCs are located to the central servers showed substantial increase due to the use of the 10-Gb/s Ethernet as well to the use of Globus. The new DCPS software was tested using the AutoTester [9] to simulate inputs, so many, many logic and timing problems could be identified before needing the actual power supplies, machine coils, etc. A lead Electrical Engineer or an Experimental Physicist was paired with a Software Engineer, who had not written any of the code, to go through a 20-page test plan that exercised all of the critical parts of the system. Before use in actual operations, an Integrated System Test Plan, which typically takes several days, is run to very that all components are working together and meeting requirements. Past experience proves that unexpected requirements continue to arise up to the beginning of operations and afterwards, and a graded approach to testing will be applied when any changes are required for critical software. Strict configuration control and administrative reviews will be required for changes to any of the systems involved in protecting the machine. When operating, total acquisition time and disk space usage will be carefully monitored, so necessary adjustments can be made as soon as possible.

6. Future possibilities

With the increasing pulse length of NSTX-U over its lifetime and the expectation that data loads will increase with new diagnostics and experimental requirements, we plan to explore the use of a Red Hat High Availability (HA) cluster as a potential way to scale infrastructure to meet the anticipated ever-increasing demands. If the current computing infrastructure becomes a limiting factor on the time between shots, and diagnosticians have to wait too long for high-quality plasma surface reconstructions, for example, an HA Cluster would allow Controls and Data Acquisition (CODAC) to quickly deploy new servers without jeopardizing existing server functionality. Additionally, it provides an infrastructure for immediate fail-over and load balancing. An important part of this evolving technology will be the utilization of UDP based events. By eliminating a persistent TCP/IP connection to the MDSplus server and allowing the network infrastructure to manage subscriptions and delivery of events, the ability to add or subtract HA servers as needed becomes less invasive and even more attractive.

7. Summary

Data-handling requirements have naturally grown in the 4 years since NSTX operated, with conventional signal data increasing by a factor of 2, and fast camera data increasing by a factor of 4. Fortunately, computer technology has kept pace, so we fully expect to maintain and continually extend the capabilities of our computing infrastructure to support the mission of NSTX-U and the Princeton Plasma Physics Laboratory. Additional software capabilities, such as between-shot TRANSP and faster availability of camera data will also facilitate the more efficient and effective operation of the experiment. The new Digital Coil Protection System will help protect NSTX-U from the increased, more complex forces on the magnetic coils. Last, but not least, increased reliability and diagnostic tools in the Controls and Data Acquisition software will reduce downtime and enhance experimental productivity.

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