The NSTX Plasma Control System Operating Experience

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Outline

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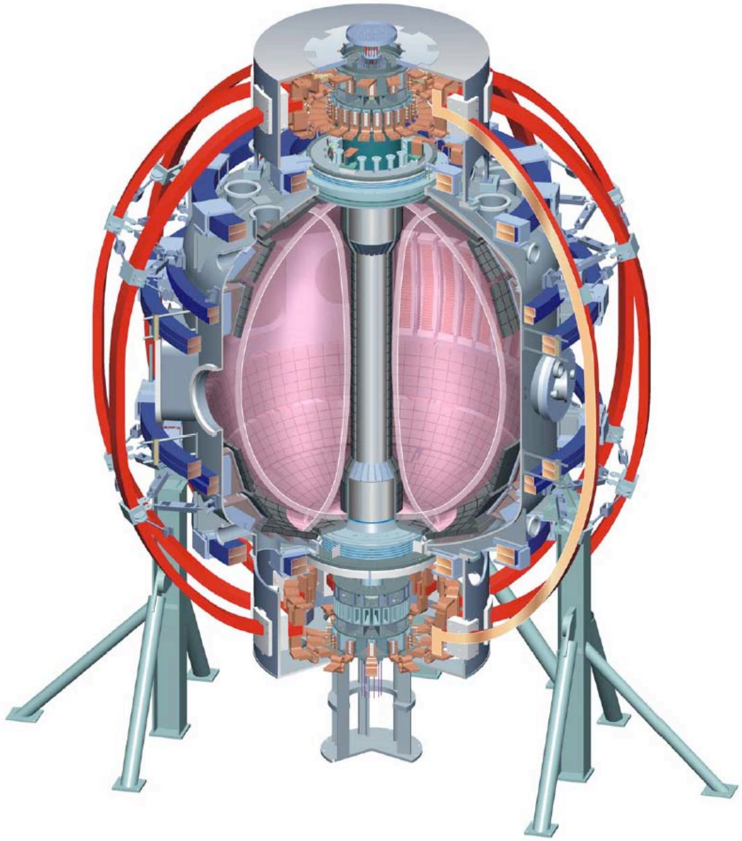
- PCS Overview
- Hardware
- Software
- rtEFIT/Isoflux control
- Operating Experience
- High elongation (kappa)
- Shape Comparisons
- Recent Progress
- Resistive Wall Mode Stabilization
- Error Field Correction
- Planned improvements - PCS Upgrade
- Summary



Background

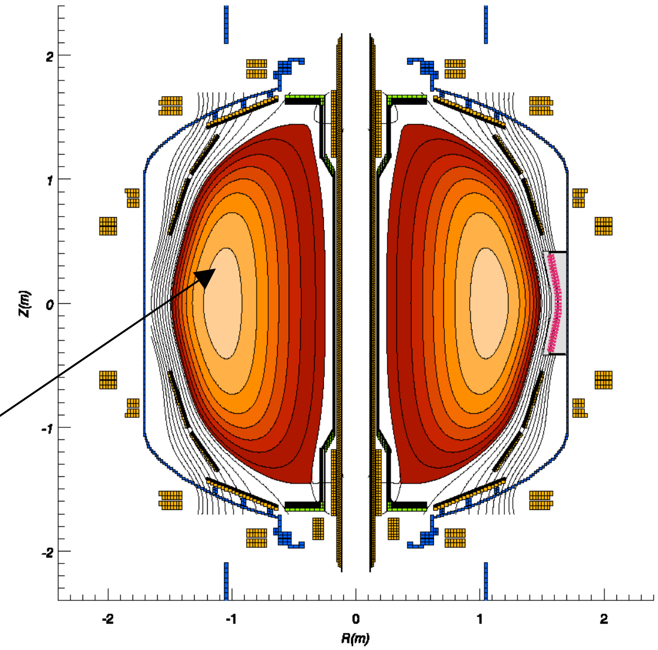
- National Spherical Torus Experiment explores plasma physics as it pertains to high current high Beta plasmas in a nearly spherical magnetic toroidal configuration
- The NSTX Plasma Control System uses magnetic field and flux measurements and power supply voltages and currents to initialize, grow, and maintain plasmas lasting on order of 1 second per shot for physics study
- The PCS consists of real time input computing, data acquisition, input and output hardware, fiber optic telemetry, software, and the power supply real time computer to control an array of power supplies and gas systems to produce and control plasmas.
- NSTX PCS came from the DIII-D PCS effort with appropriate adaptations. The PCS has been upgraded to rtEFIT control in recent years and optimized for most single and double null experiments.
- The NSTX Physics Operator uses PCS capabilities to set up a new shot or to restore an archived shot. NSTX Experimental Proposals often require extensive modifications to existing shots to explore new territory in the NSTX operating parameter space.
- Given thermal limits and certain glow discharge time allotments, NSTX has demonstrated the ability to run 20-30 plasma shots per normal operating day.

PCS Overview

- Maintain plasma in steady state
- Support physics experiments by controlling
  - Plasma current
  - Plasma position
  - Plasma shape
  - *And now plasma rotating modes*

Target $\beta_{t} = 40\%$

High bootstrap fraction plasma (from NSTX 5 year plan)

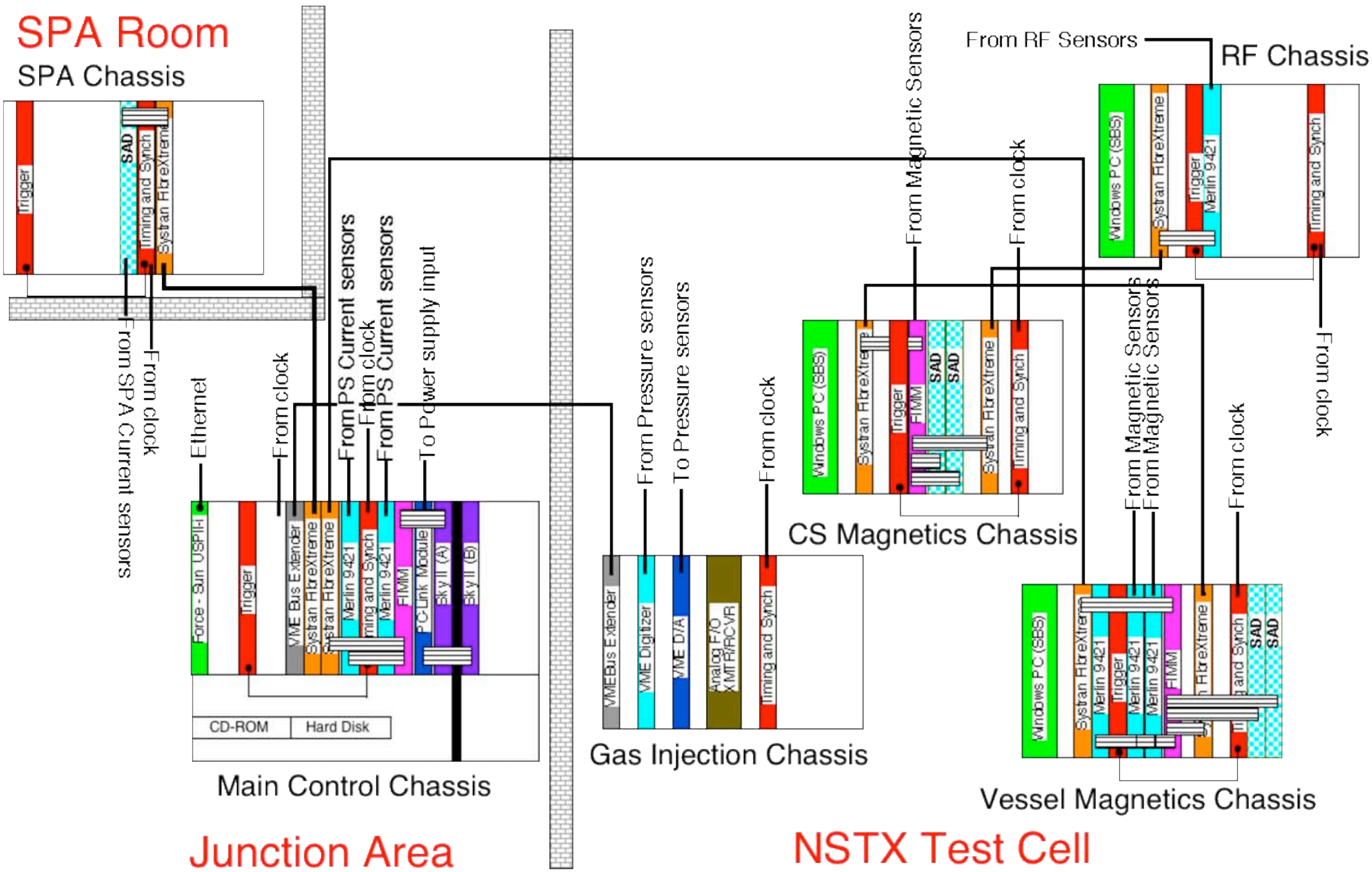


Sky II computer w/ FPDP Direct Memory Access

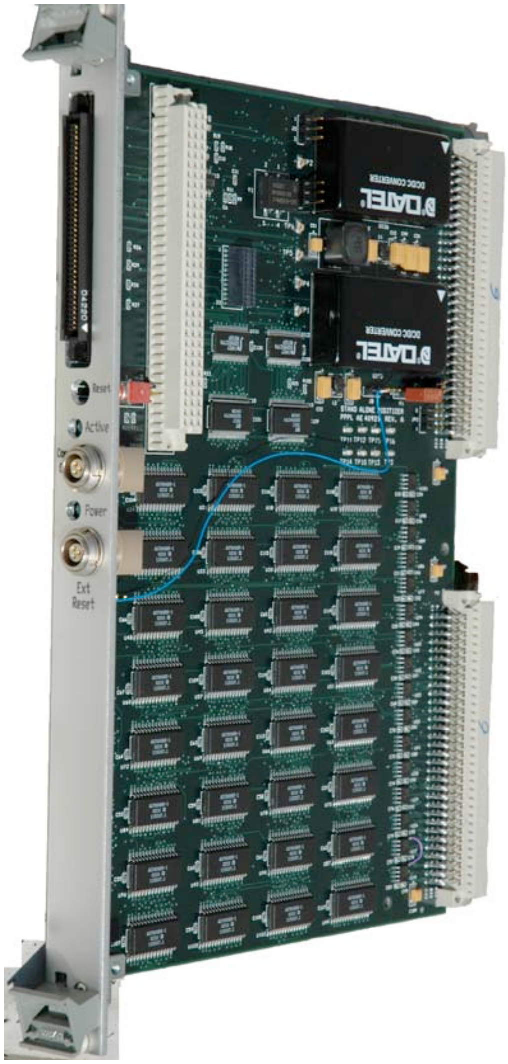
FPDP Input Multiplexing Module (PPPL) - combines Signals from four FPDP sources
(can be daisy chained)

(FPDP = Front Panel Data Port)

Control system block diagram



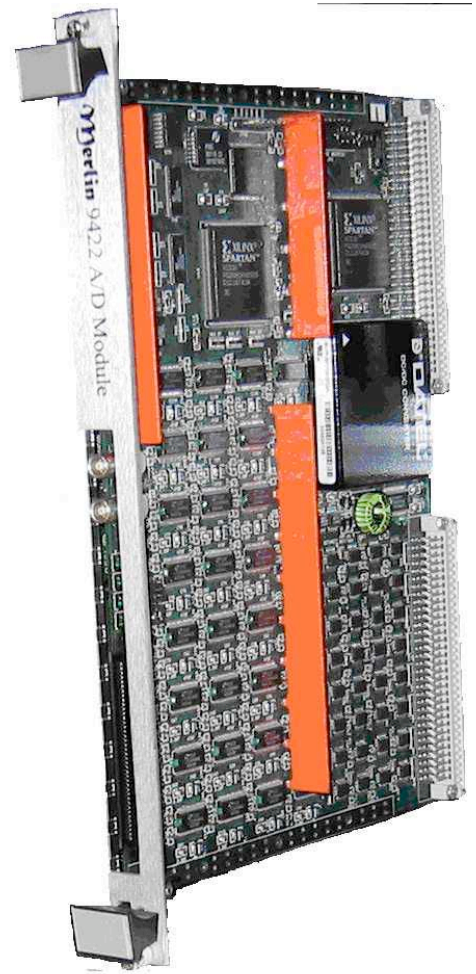
Digitizers



Input modules

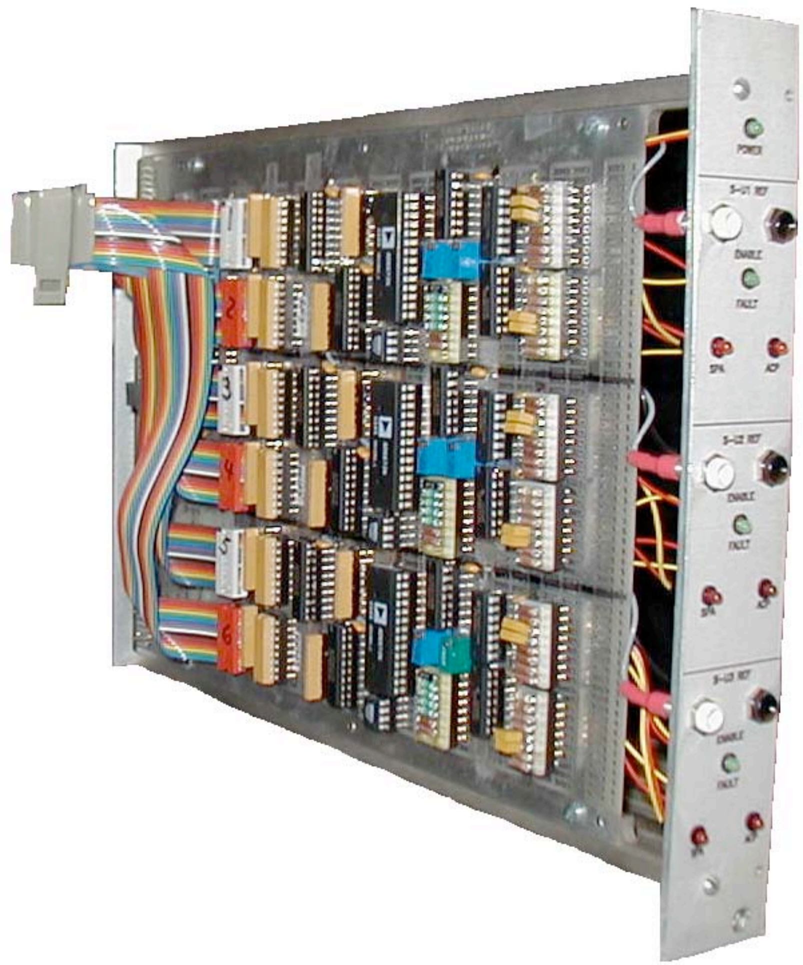
Merlin 9421/9422 12/16-bit digitizer w/ FPDP 1μsec latency
(can be daisy chained)

PPPL digitizer Stand Alone Digitizer (SAD)
Designed to be used in conjunction with the FIMM module

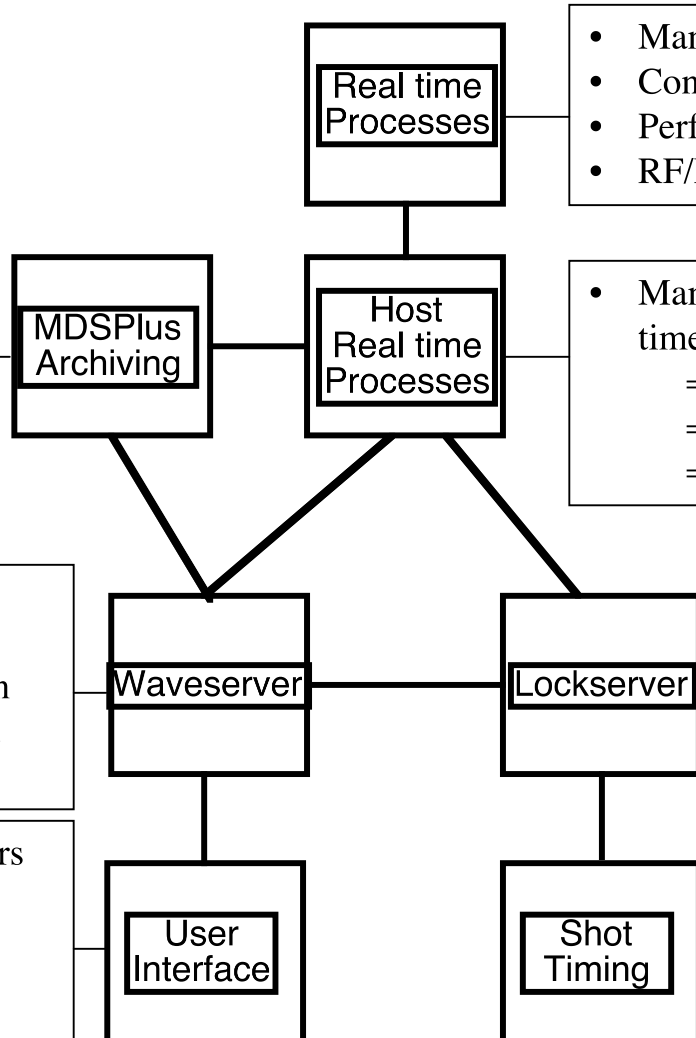


Outputs

- PCLIM output module developed at PPPL interfaces 1Gbit/s FPDP to the Power Conversion Link (PCLink) (34 bit communication protocol developed at PPPL in 1974)
- Split the serial link into 4 parallel links to reduce transmission latency to supplies



Flexible PCS Software Infrastructure



- Manages real-time data i/o (FPDP)
- Controls NSTX power supplies
- Performs all plasma control functions
- RF/NBI control (future)

- Centralized storage of shot setup information
- Also archives real-time data after shot for analysis
- Provides calibration information for real-time data

- Manages data exchange between real-time processes and “outside” world
  - ⇒ Shot data from waveserver
  - ⇒ Calibrations from MDSPlus
  - ⇒ Gas Valve configuration (EPICS)

- Handles multiple user inputs
- Stores data until next shot
- Coordinates communication between archiving/restore, user interface, and host real-time processes

- Controls shot sequence

- Accepts input from multiple operators
- Graphical user interface
- Shot “construction” from multiple archived shots
- Interface to EFIT database

- Provides synchronized shot start/clock/end events

PCS Categories

- Toroidal field
- I_p - current profile
- Poloidal field (shape and position)
- Plasma fueling (bulk and impurities)
- New categories - IMF and RWM

Physics Operator Inputs not in PCS

- Power (NBI and RF)
- GDC and vacuum system

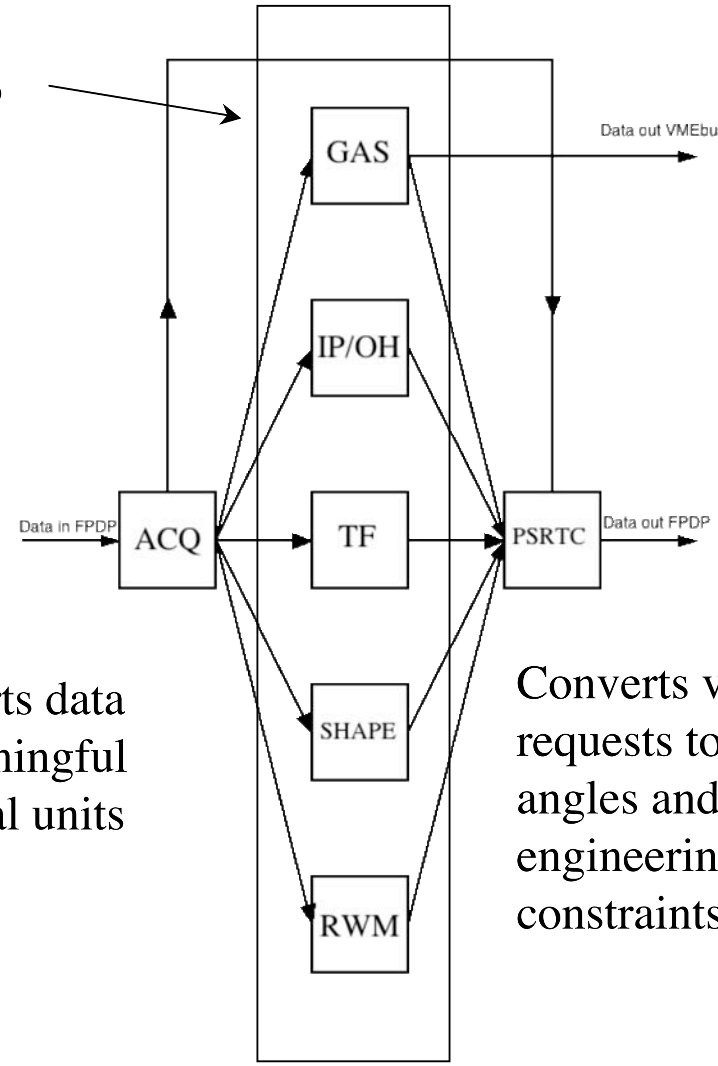
Each category can have several phases

- User defined (can be varied shot to shot)
- Each phase has one (real-time) algorithm (but an algorithm can be used in several phases)
- Can have alternate phase sequences (handles faults)

Real time information flow

- NSTX control stream is (nearly) centralized through the PCS via the FPDP data stream
  - Plan to eliminate remaining VME hardware in 2006 creating single input single output system
- Interprocessor communication uses shared memory and semaphores on “Skychannel” backplane

PCS



Converts data to meaningful physical units

Converts voltage requests to firing angles and applies engineering constraints

Real Time Processes

Data Acquisition and Conversion

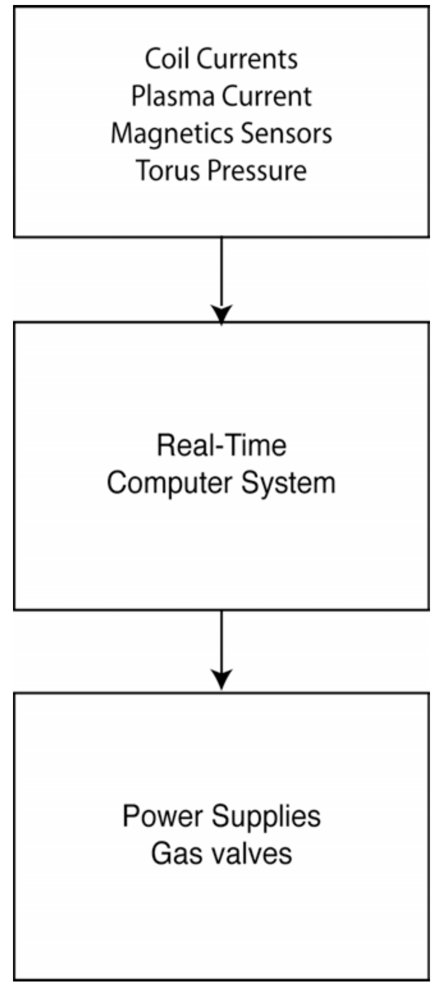
ACQ	Acquires real-time data, converts to meaningful physical quantities (fluxes, fields, currents, pressures, flow rates) and distributes data to other real-time processes

Plasma Control System

Category	
Ip/OH	Controls OH current (pre/post shot) or Ip (during shot)
TF	Controls Toroidal field current
GIS	Controls gas flow either pre-programmed neutral pressure feedback (prefill) or ne feedback {future}
Shape	Controls PF coil currents (pre/post shot) plasma shape with flux projection (current ramp up/down)
Equil	Calculates plasma boundary flux by inverting Grad-Shafranov equation
Isoflux	Controls PF coil currents during flat-top
System	Controls whether PF control comes from Isoflux or Shape category
IMF	Controls resonant field correction input to SPA power supplies
RWM	Controls SPA currents, phase, gain, feedback

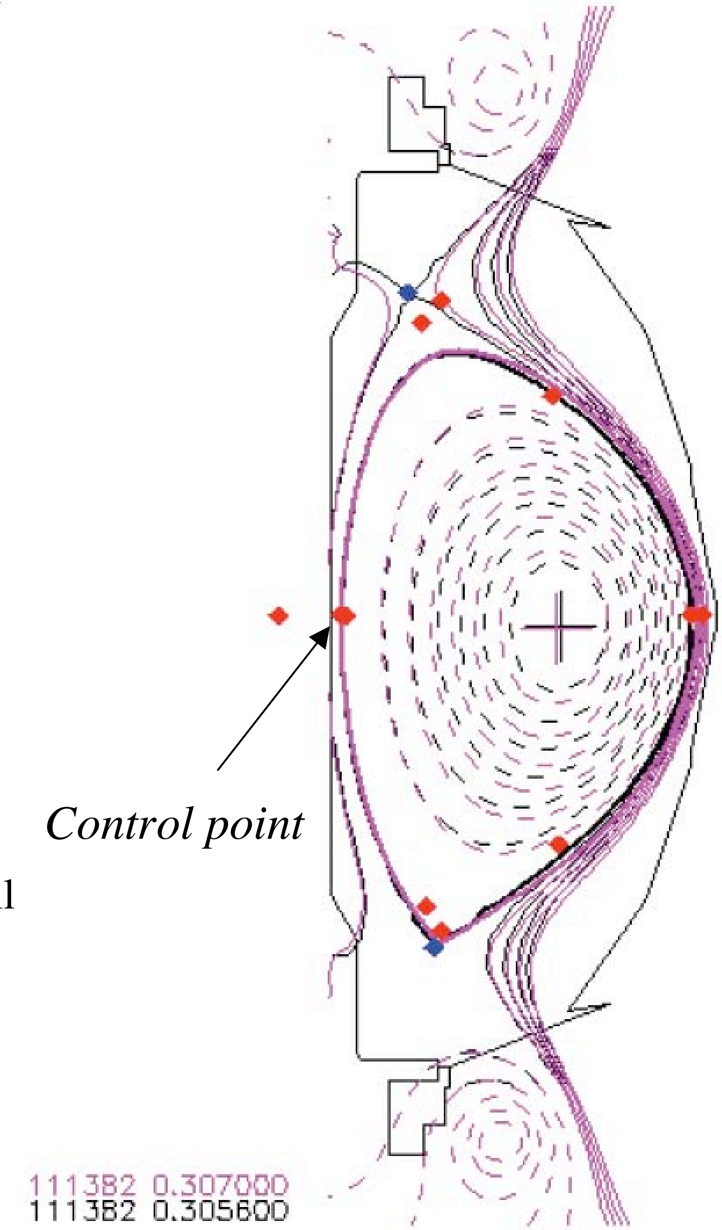
Power Supply Real-Time Control

psrtc	Chooses source of power supply control data (enables engineering test shots and plasma control shots). Converts requested voltage to thyristor firing angle (pulse width modulation). Enables bipolar power supply operation.



rtEFIT/isoflux control

- Real-time analysis on 8 333MHz G4 processors
- Data acquisition at 5 kHz - 352 channels
  - 62 magnetic data inputs,
  - 11 coil currents,
  - 9 loop voltages ($\Rightarrow$ vessel eddy currents)
- Reconstruction every 12ms (slow loop)
- Currents calculated on grid every 0.4ms (fast loop)
- Control boundary at up to 7 points using all PF coil currents

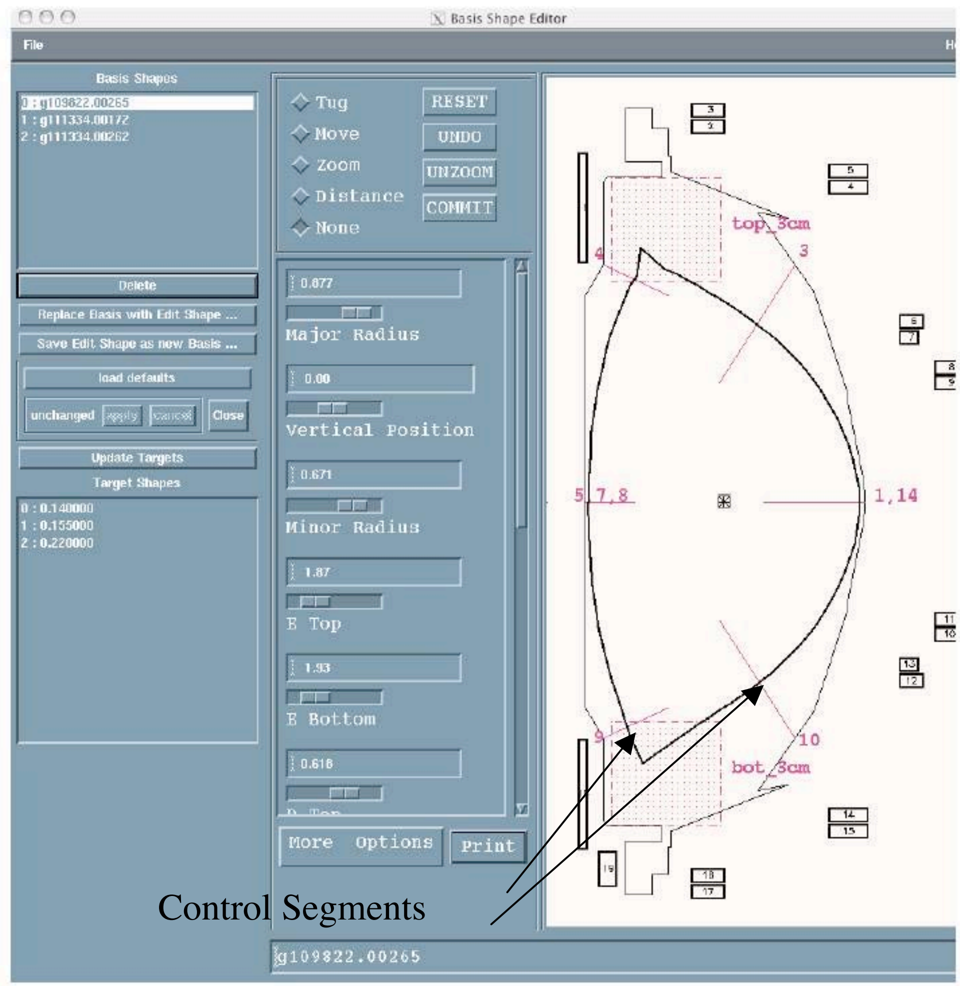


Isoflux control algorithm

- Calculate error between reference flux and flux at control point
- Use these errors to determine coil voltages (errors related to voltages by PID matrix)

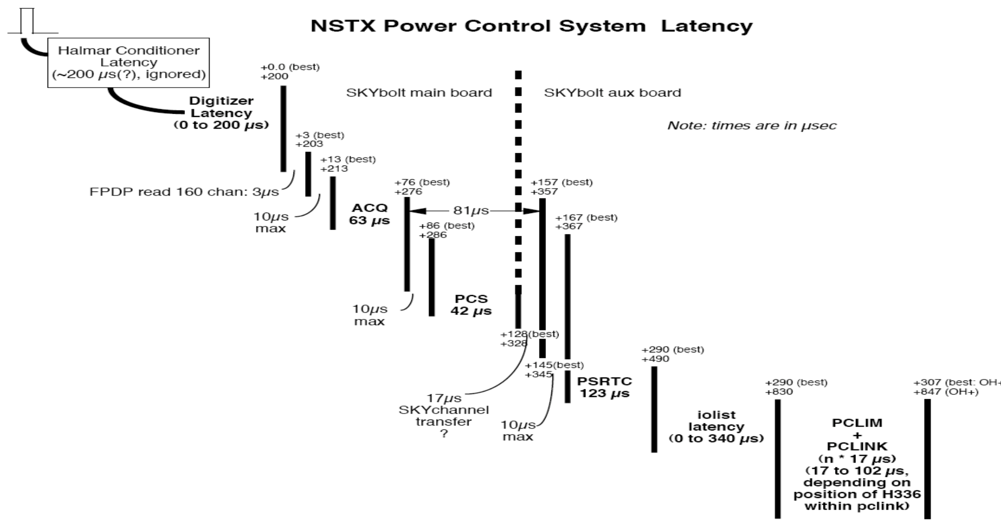
$$V_i = PID(M_{ij}\Delta\psi_j)$$

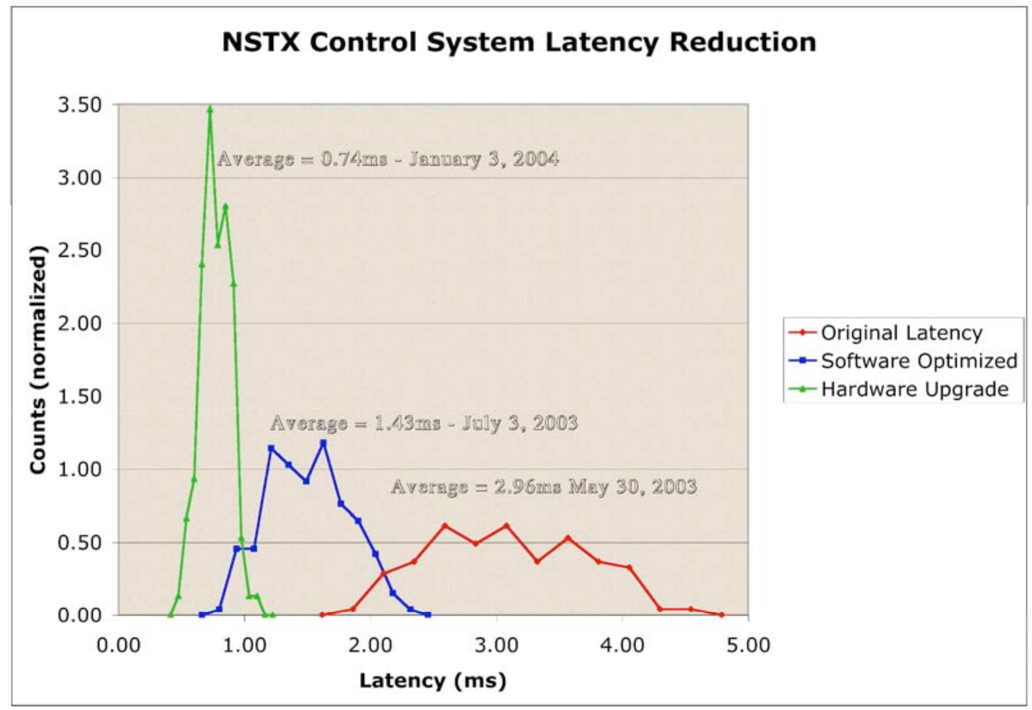
- Dynamic shape variations possible by allowing control points to move along control "segments"
- Segments defined by user (can be changed shot-to shot)



Control latency reduction

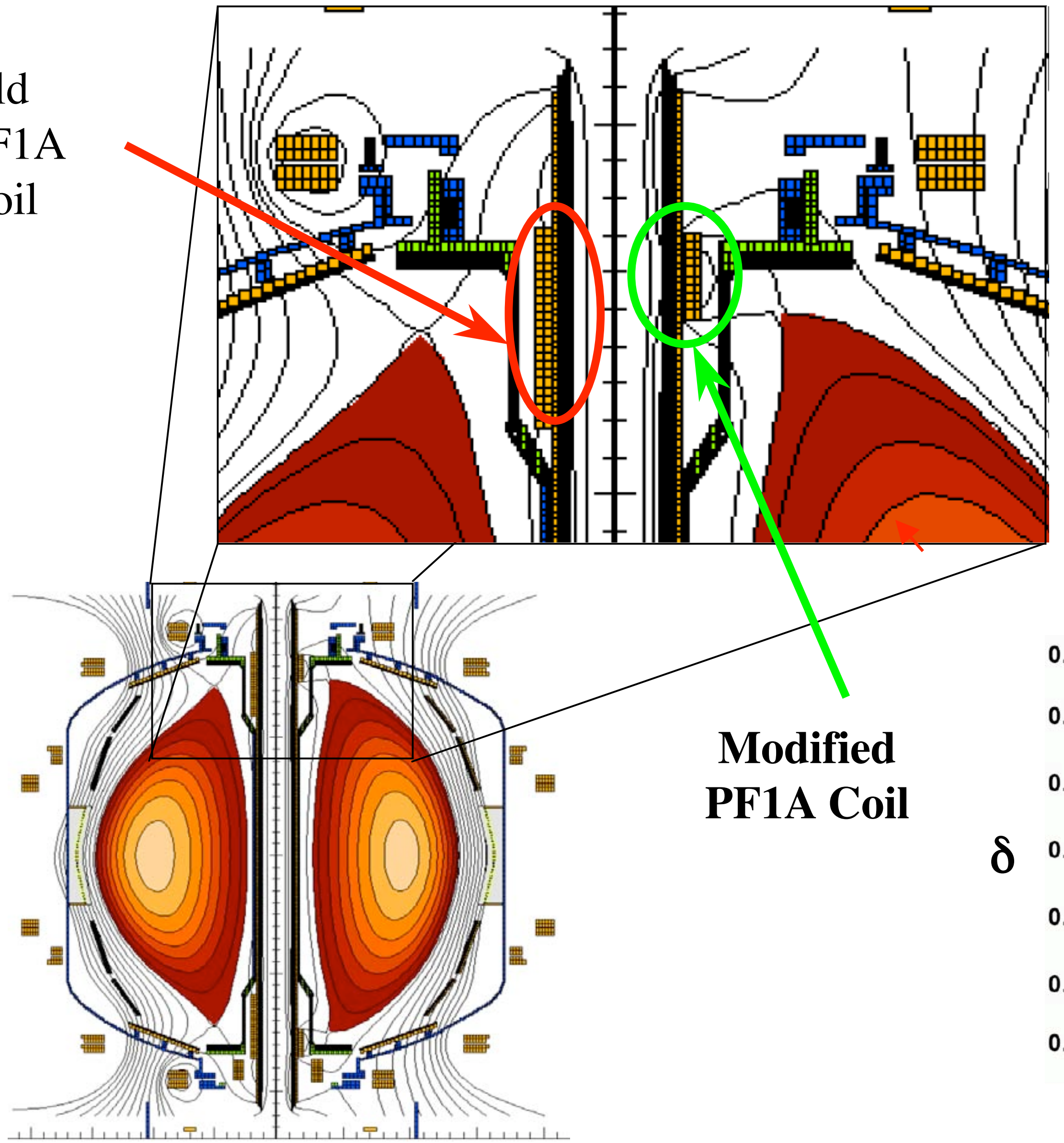
- Latency is the time from a change in an input signal until the system makes a response
- Identified system latency as primary source of vertical stabilization limits
- Systematically identified latencies and removed them
- Latency now ~1/4 value in 2003
- Also added analog vertical voltage difference measurement for dz/dt term in control algorithm
- Additional desired improvement will require upgrade to computer and architecture





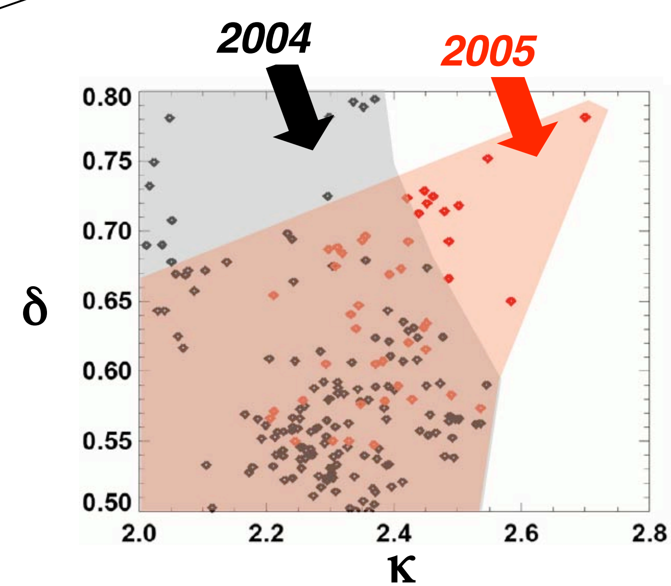
Inner divertor poloidal field coil modified

Old PF1A Coil



Modified PF1A Coil

- PF1A Control is the same in PCS with new limits
- Can now simultaneously achieve high κ and δ



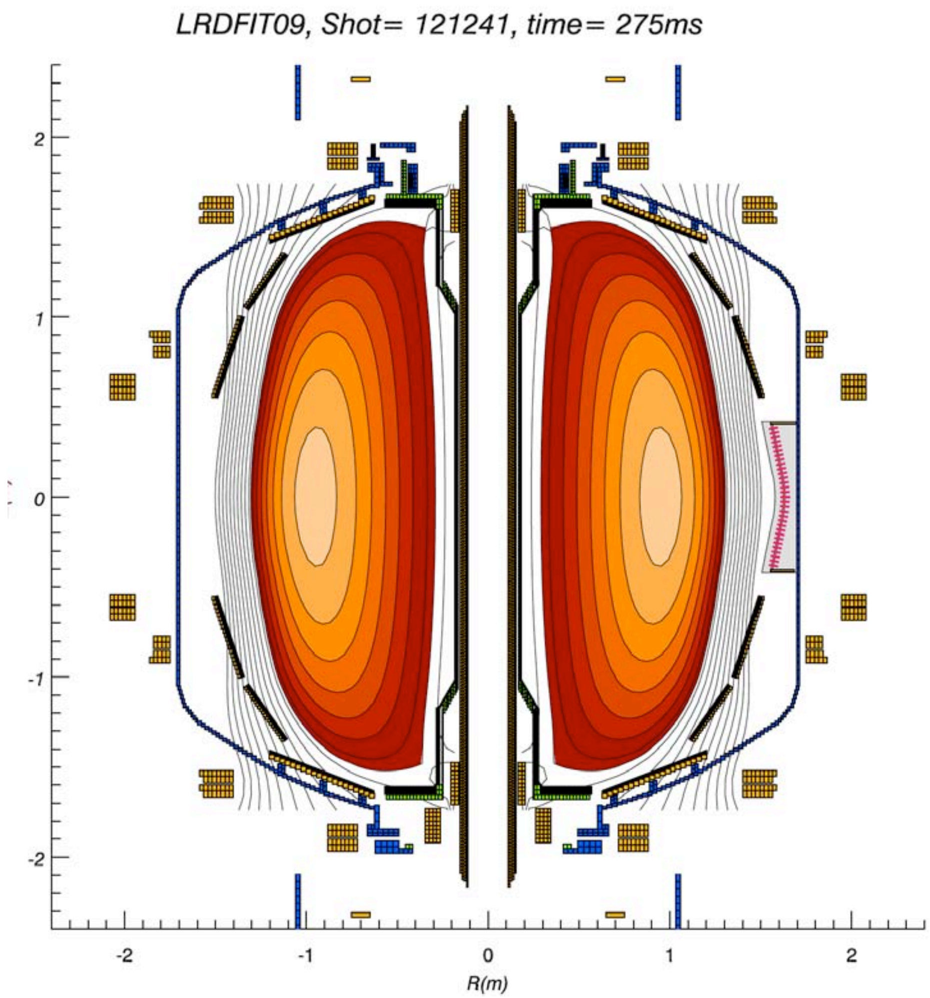
NSTX PCS Shape Operating Experience

- *12.6 run weeks in 2006 run period*
- *1617 shots on 1932 attempts for an efficiency of 84%*
- *Over 100 more shots than for 2005 after first 12.7 weeks of run time*
- *30 XPs and 5 XMPs*
- *rtEFIT used for about 2/3 of all shots*
- *NBI, HHFW heating*
- *Lithium evaporation, Pellets, EBW, full time MSE, high k scattering*
- *Extensive use of SPA/RWM for EFC and RWM stabilization*
- *Shape comparisons across several devices*
- *Record elongation (kappa) of 3.1*

Improvements enable record plasma shaping

- Plasma with elongation 3 achieved on NSTX ($\kappa >$ 2.8 for several growth times)
- Shape factor S ($q_{95}*(I_p/aB_t)$) ~ 41
- World record for both parameters in a controlled plasma
- $l_i \sim 0.35$, very encouraging for steady-state scenarios

MSE based reconstructions



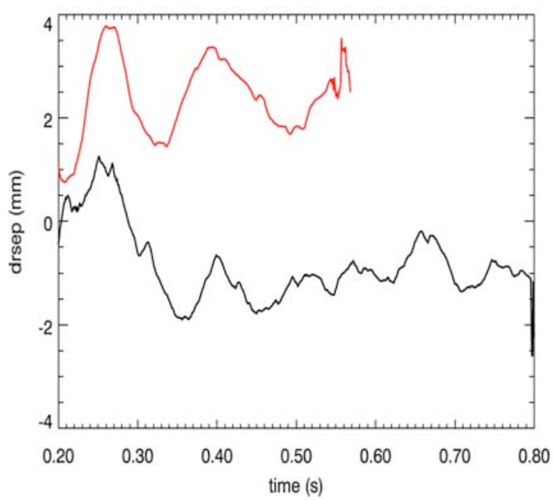
Shape comparisons using PCS shape control

- Introduced international investigation of pedestal characteristics across NSTX, MAST, and DIII-D in 2005
- Added investigation of small ELM regimes in NSTX, DIII-D, and C-MOD.
- Performed extensive shape development using PCS capability
- Evaluated key parameters
- Adjusting ∂rsep, outer gap, squareness, x point position, and other PCS adjustment features to achieve reproducible plasma types in a single device
- ∂rsep had a large influence on ELM behavior and is easily adjusted in PCS with some precision

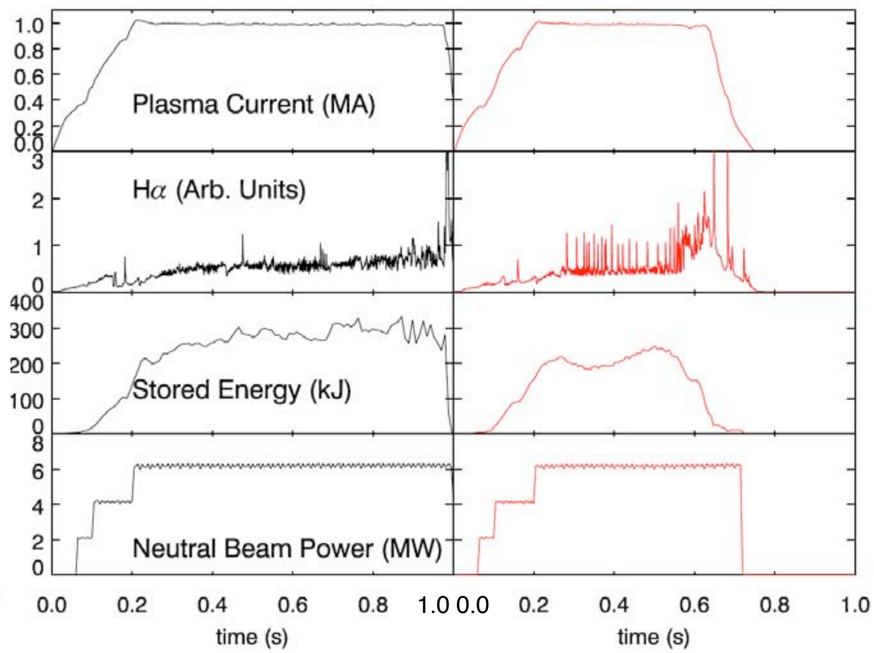
Changes in X-point balance affect ELM characteristics

- Very small changes in the plasma boundary reproducibly lead to large differences in ELM behavior
- ELMs have a major impact on plasma performance, controlling them is crucial
- Precise plasma control provides an important tool for controlling ELMs - highly ITER relevant

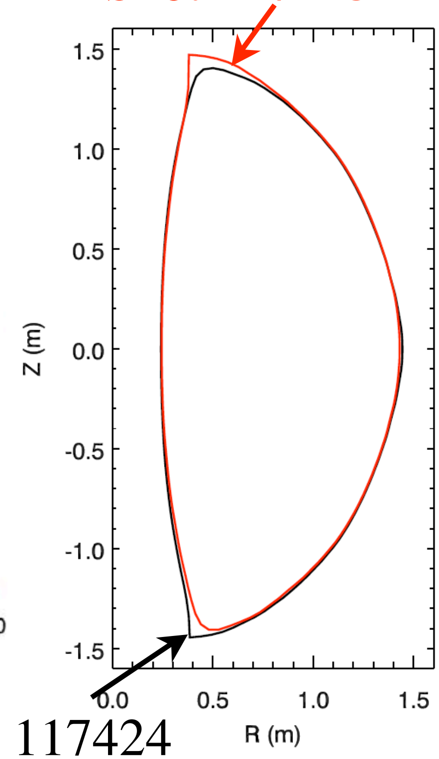
δr_{sep} (mm) for 117424 (black) and 117425 (red)



Shot 117424 Shot 117425



Shot 117425



Shot 117424

δr_{sep} is the radial separation of the flux surfaces which pass through the x-points measured at the outboard midplane

NSTX PCS PROGRESS FOR 2006

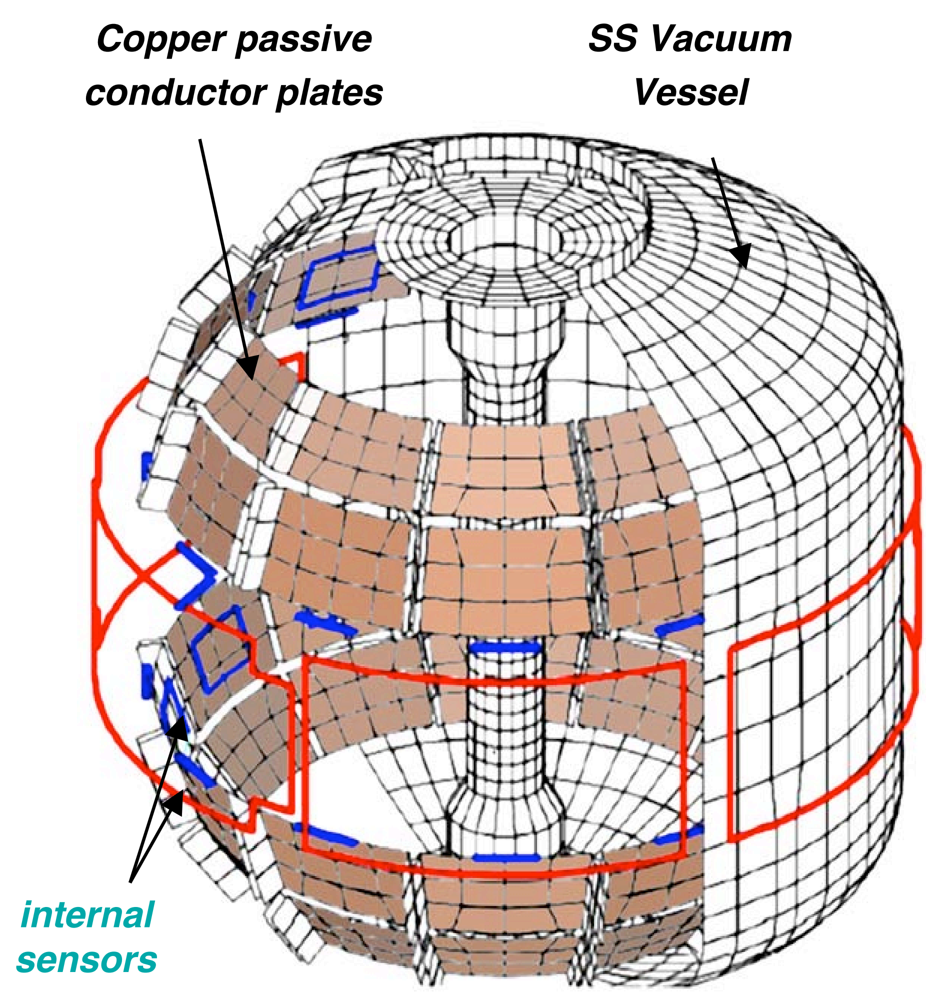
- *PCS computer moved to an electrically quieter and more convenient location within the Control Room complex prior to run period*
- *Software upgrades brought online during operations as they became ready*
- *New category software startup and testing in prime time with code development and solutions introduced off hours to meet experimental schedules*
- *RWM coils made extensive use of the Switching Power Amplifier supply upgrade (7 kHz switching for 3 independent coil pairs) to power an n=3 stabilizing field*
- *Error Field correction experiments were undertaken also using SPAs to pulse RWM coils to add n=1 correcting field*

Recent additions to PCS code to allow a new class of experiments on NSTX

- IMF category
  - Error Field Correction using n=1 field with preprogrammed currents, proportional currents to OHxTF or OHxTF^2, and dynamic feedback on RWMs
- RWM category
  - Preprogrammed currents (square, sinusoidal, stepped waves, etc.)
  - Phase and gain control
  - Feedback control (on/off and timing)
  - Dynamic Feedback using sensors to control SPA power supplies in real time
  - Performed experiments on RWM rotating modes to quench, brake, and stabilize modes using n=1, n=3 fields with adjustable gain and phase angle

Active n=1 control on NSTX

- NSTX has installed non-axisymmetric coil system with feedback sensors
  - 6 coils with 3 independent power supplies in n=odd arrangement
  - Capable of simultaneous n=1 and n=3 control
  - n=12 measurement capability
  - Closed loop digital control
- Can investigate physics of RWM stabilization and error field control ⇒ important for ITER
- Rotational stabilization for driven systems (CTF), but may need active stabilization for non-rotating ST reactors such as for ARIES-ST

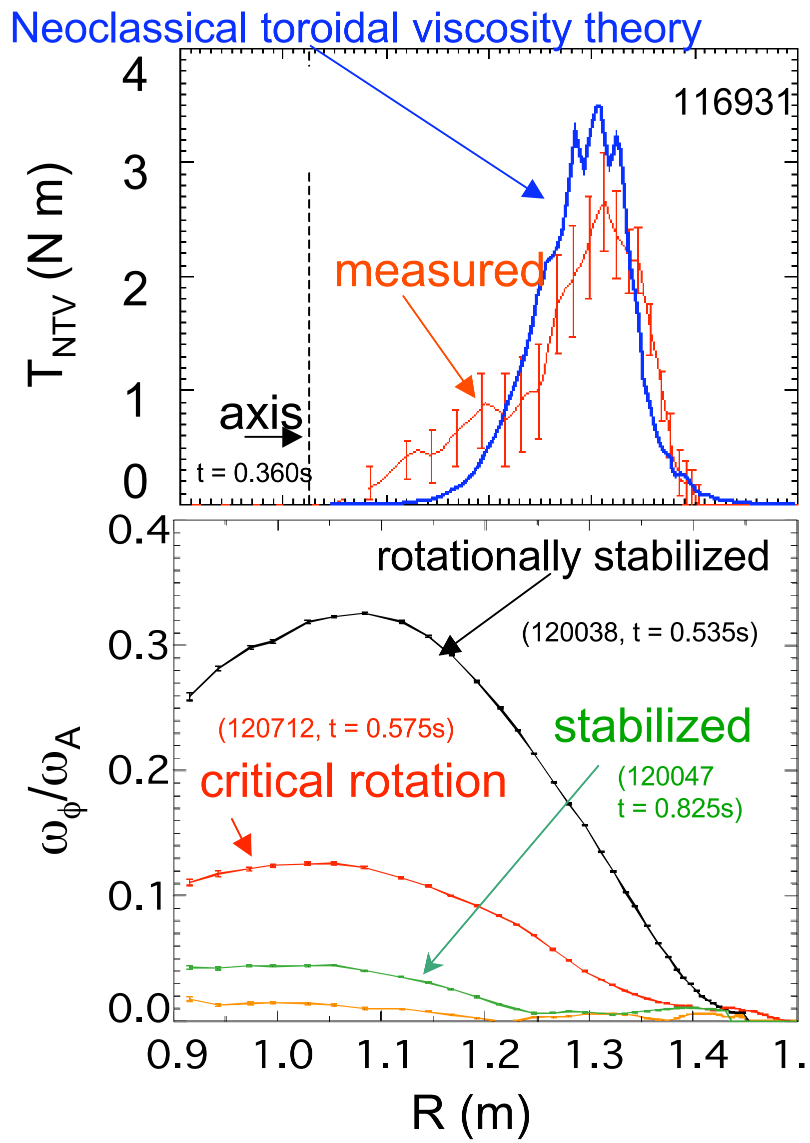


VALEN Model of NSTX

6 ex-vessel midplane control coils

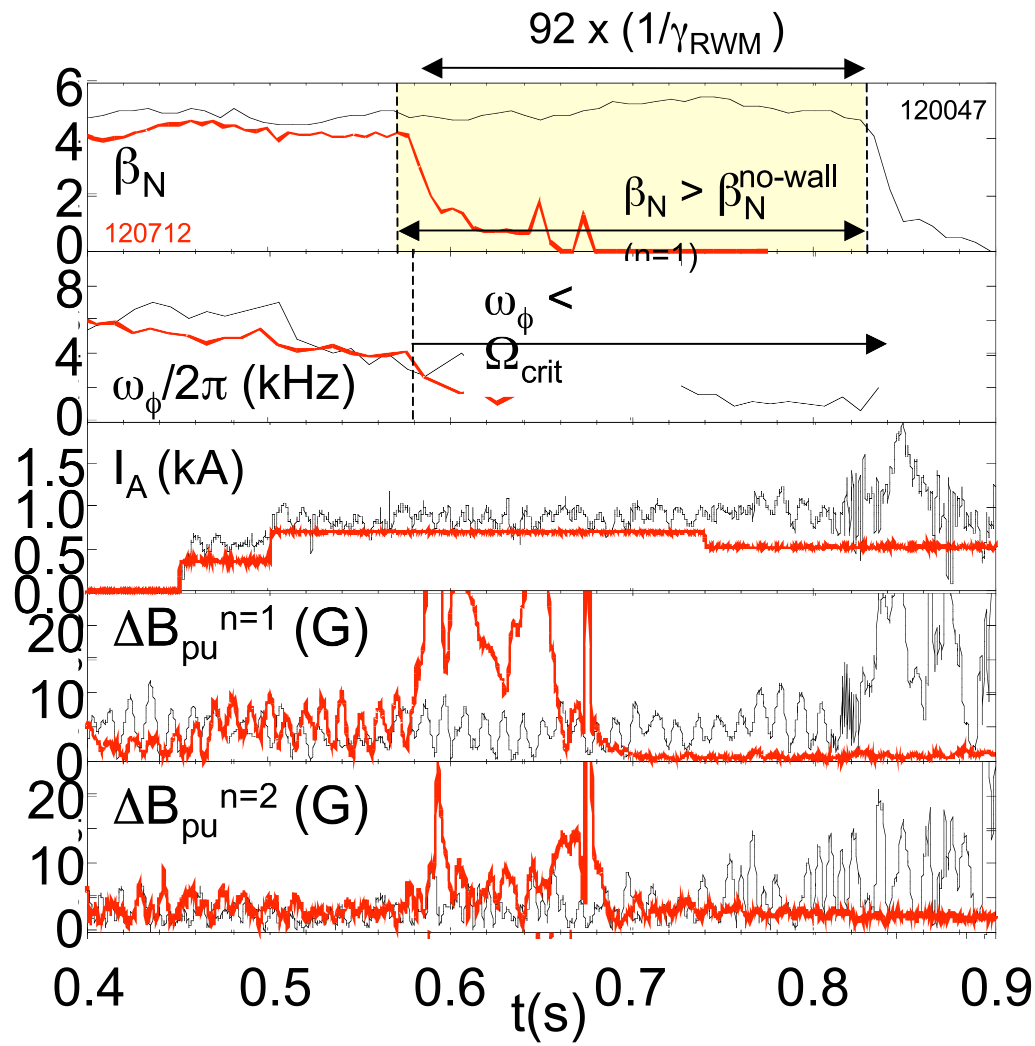
n=3 braking enables ITER relevant RWM physics

- n = 3 field applied which reduces plasma rotation
- Torque consistent with neoclassical toroidal viscosity theory
  - Torque measured using 51 channel CHERS rotation profile
- As rotation slows, plasma goes unstable to RWM at critical rotation velocity
- RWM is then stabilized using n=1 feedback



RWM stabilized

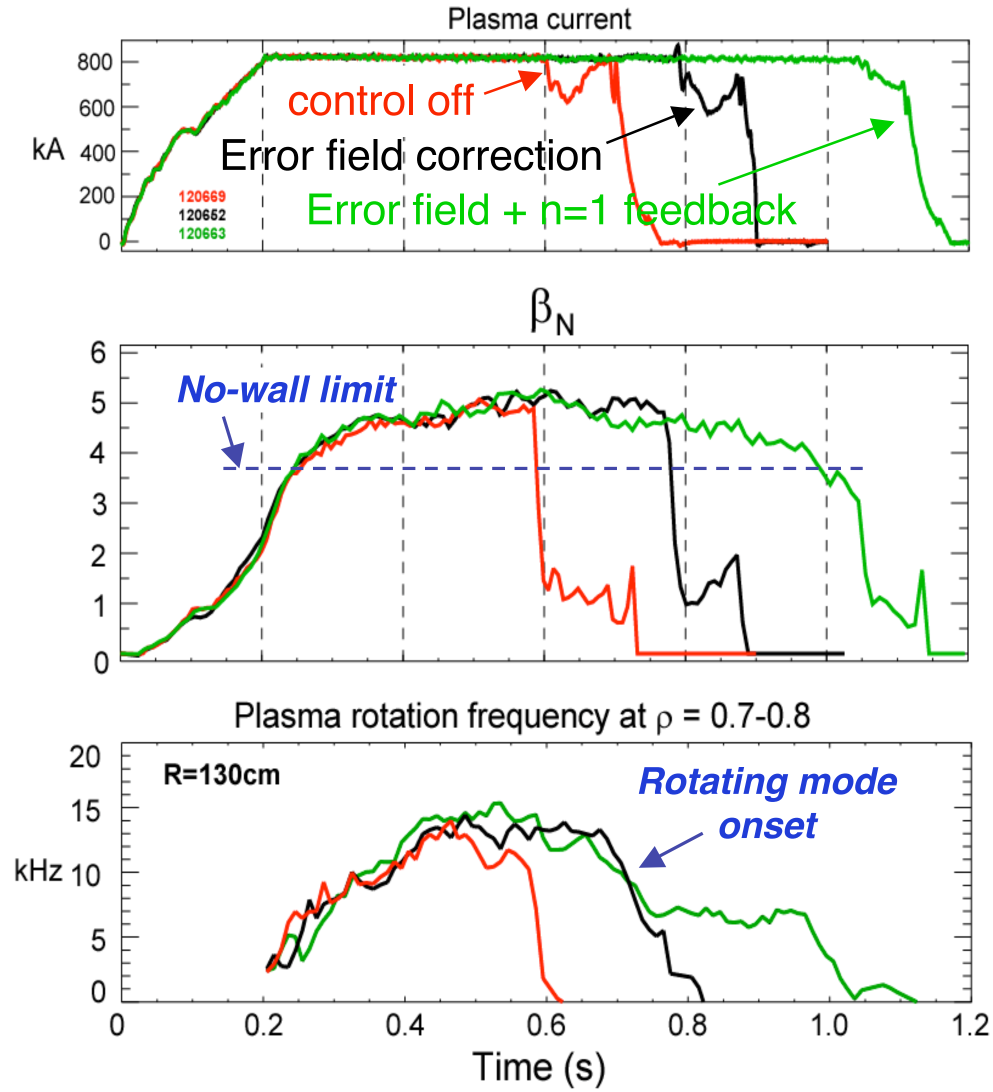
- Feedback system enabled during n=3 braking period
- High β maintained in low rotation target
- <u>First</u> such demonstration in low A tokamak
  - Exceeds $\beta_N^{\text{no-wall}}$ for n = 1 and n = 2 (calculated using DCON stability code
  - n = 2 RWM amplitude increases, mode remains stable while n = 1 stabilized
  - n = 2 internal plasma mode seen in some cases



(thanks to Sabbagh, et al., PRL **97** (2006) 045004.)

Error field control extends plasma pulse

- Error field correction based on field coil currents extends pulse
- Addition of n=1 measured plasma response improves performance further
- Extended pulse limited by onset of saturated n=1 mode



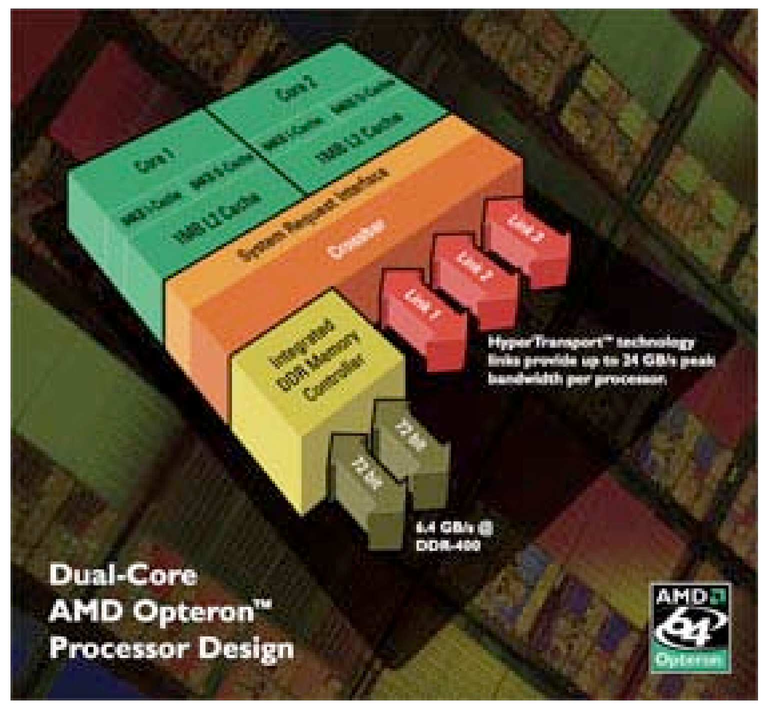
Coming soon…
PCS Upgrade in progress

- PCS upgrade to new computing platform with improved architecture and communication
- New architecture to reduce latency even further
- Change eliminates known problem that causes data acquisition fault - improved reliability is hoped for and expected
- Much higher speed in processing which is especially important for rtEFIT

AMD Opteron is fastest for rtEFIT

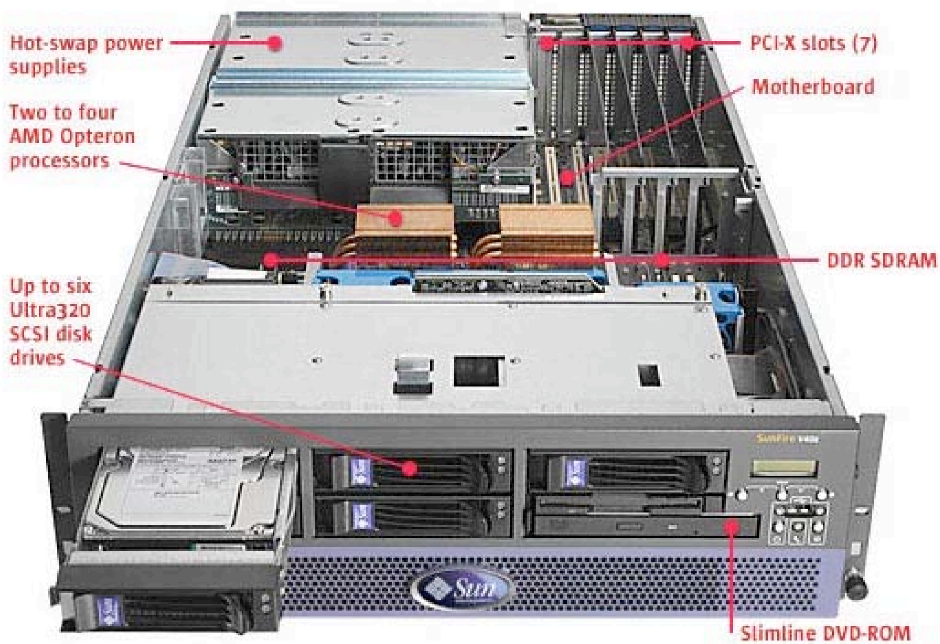
- Opteron benchmarked on rtEFIT reconstructions against Intel Xeon and Opteron is 30% faster at the same clock speed (J. Ferron GA)
- rtEFIT is the most compute intensive application in the PCS by a large factor

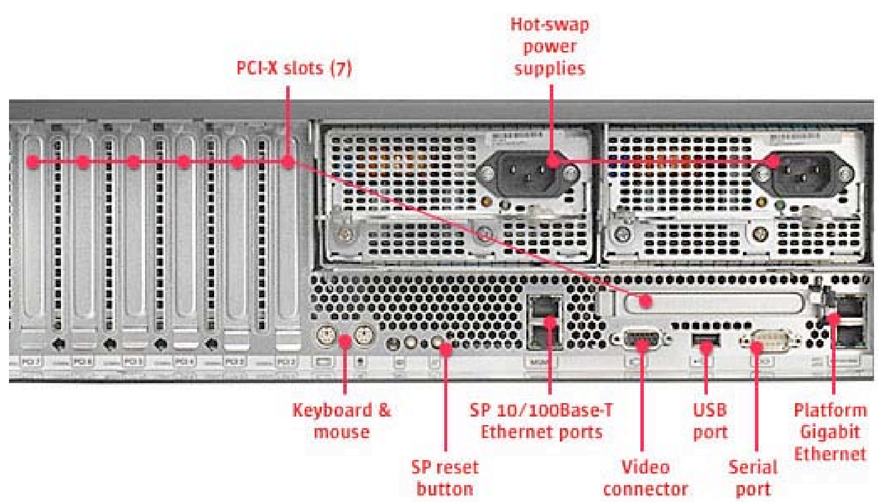
- Designed for multi-processor servers (4 dual core processors 8 cores)
- Available with educational discount
- 3 parallel on chip parallel buses (up to 24GB/s)



SUN V40z server

- 4 dual core Opteron processors running at 2.6GHz (total of 8 CPUs)
- 16 GB memory
- dual, mirrored, SCSI system disks (146GB)
- two additional 146 GB SCSI disks
- dual redundant, hot swappable power supplies, heavy duty fans
- 7 full height PCI-X slots
- price: $24,800 with 7x24 support for 3 years.





8 core layout

- Processors are directly connected on a single bus (Hypertransport 6.4GB/s per node)
- One box, one vendor for the entire real-time computer
- Single address space for all memory

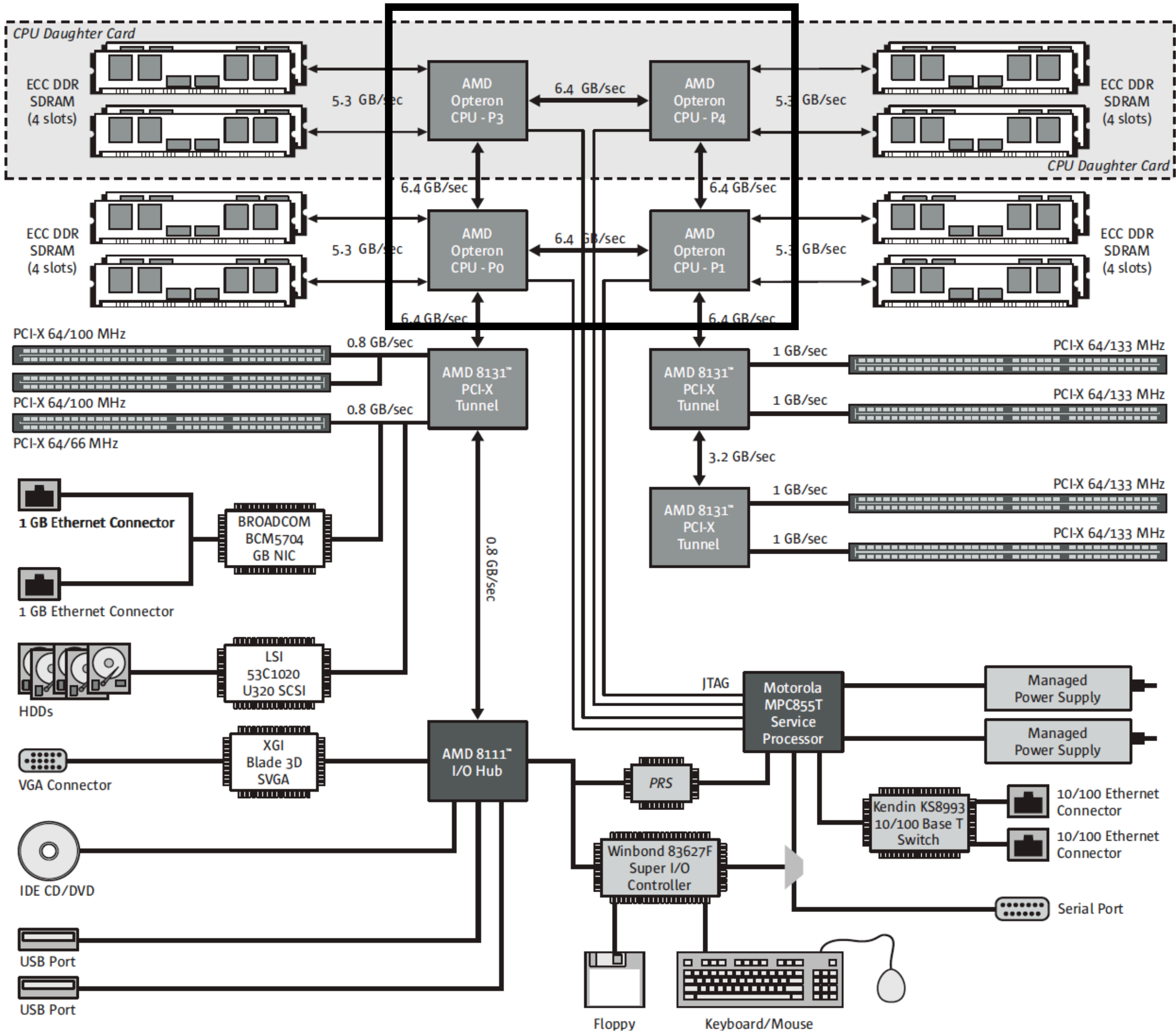


Figure 1-8. Sun Fire V40z server architecture block diagram

Summary

- PCS is a mature control system adequate to the task - improvements possible with updated control computing platform
- NSTX has been productive in novel experiments that relied heavily on all new PCS capability
- rtEFIT shot library grew and evolved to accommodate most XPs
- Fully integrated SPA control for RWM and EFC
- PCS will resume operations as is with a parallel effort to introduce the upgrade in the upcoming run period.

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