Real-time equilibrium reconstruction and isoflux control of plasma shape and position in the National Spherical Torus Experiment (NSTX)*

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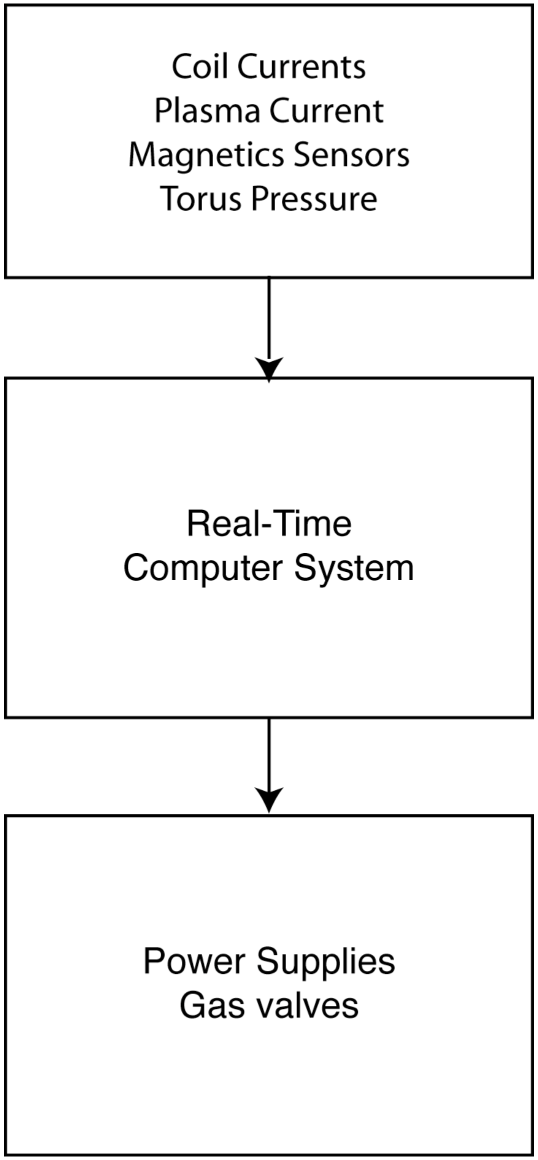
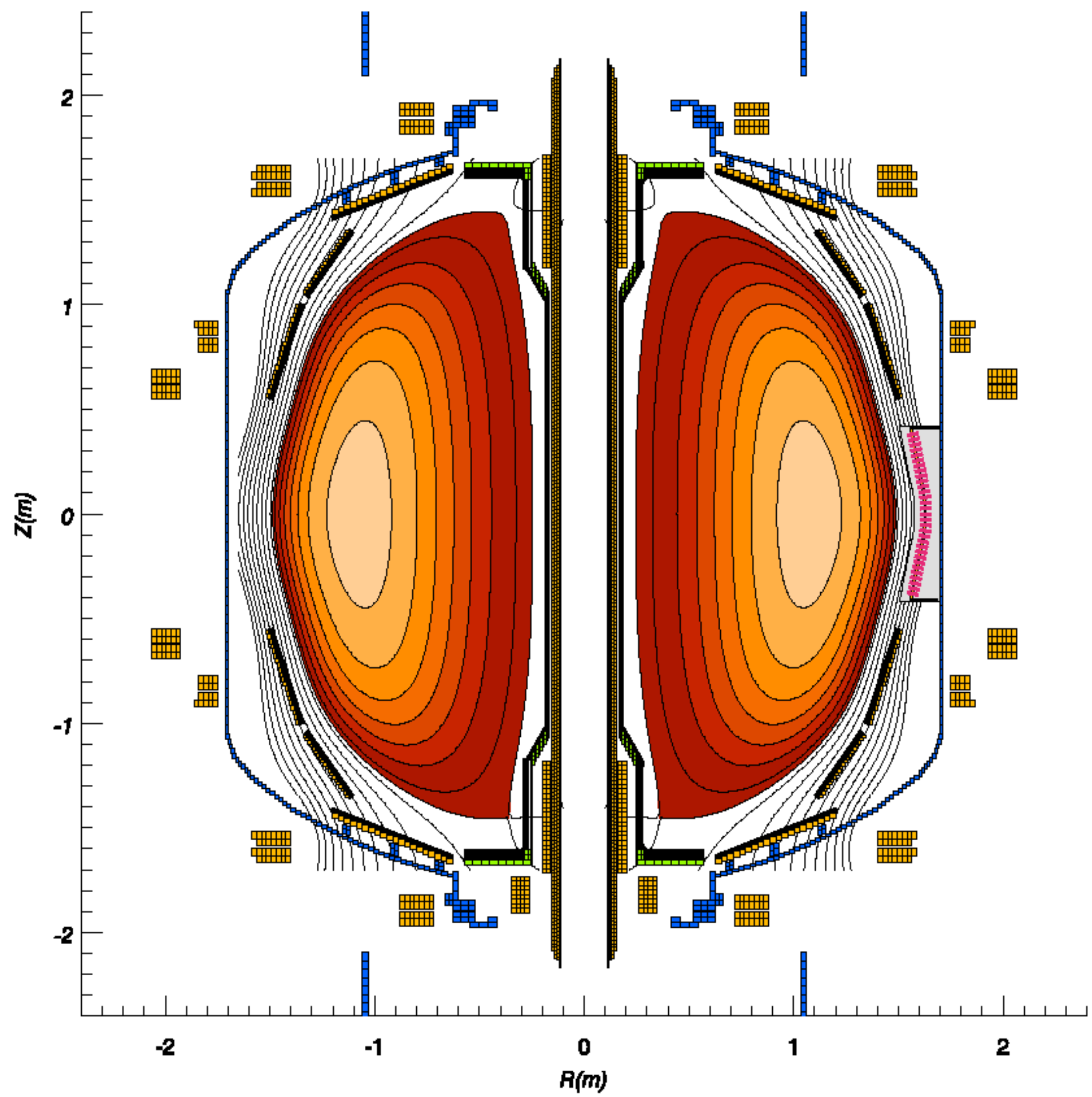
Outline

- Background
  - Control system goals
  - NSTX control system hardware
  - Control system software
- Status of rtEFIT/isoflux control
- Vertical position control
  - Hardware upgrades
  - Improved operating regime
- Summary



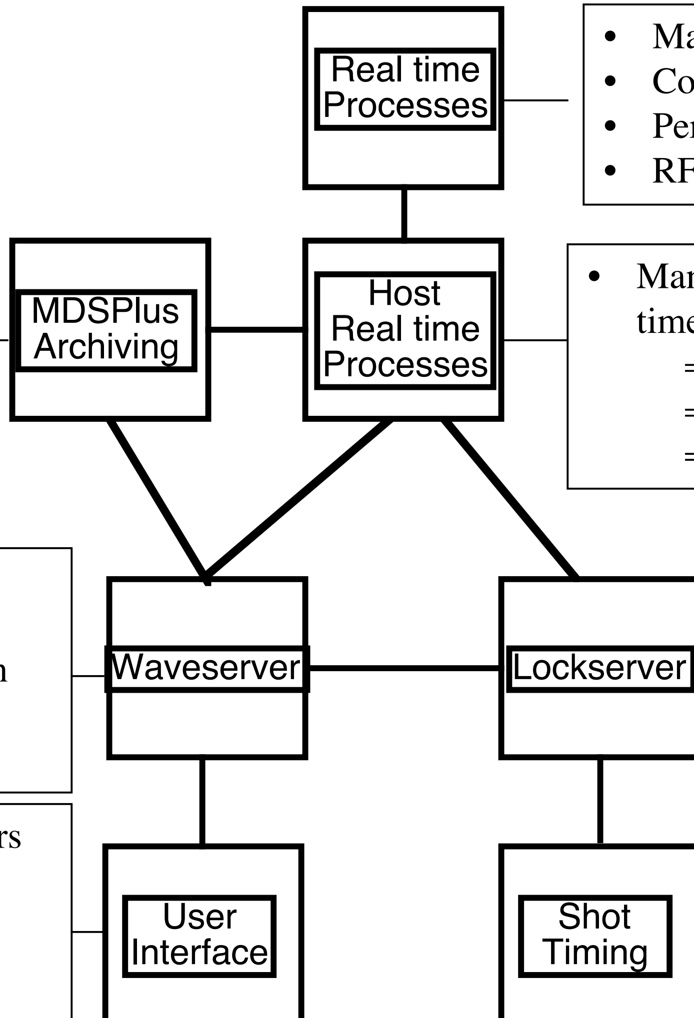
Control system goals

- Maintain plasma parameters in steady state
- Support physics experiments, tool for control of
  - Plasma current
  - Plasma position
  - Plasma shape



Plasma Control System (PCS) is a Flexible Software Infrastructure

NSTX



- 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/end events

Categories correspond to controllable parameters

- Toroidal field
- I_p - current profile
- Poloidal field (shape and position)
- Plasma fuelling (bulk and impurities)

- Power (NBI and RF)
- Momentum input….

Each category can have several phases

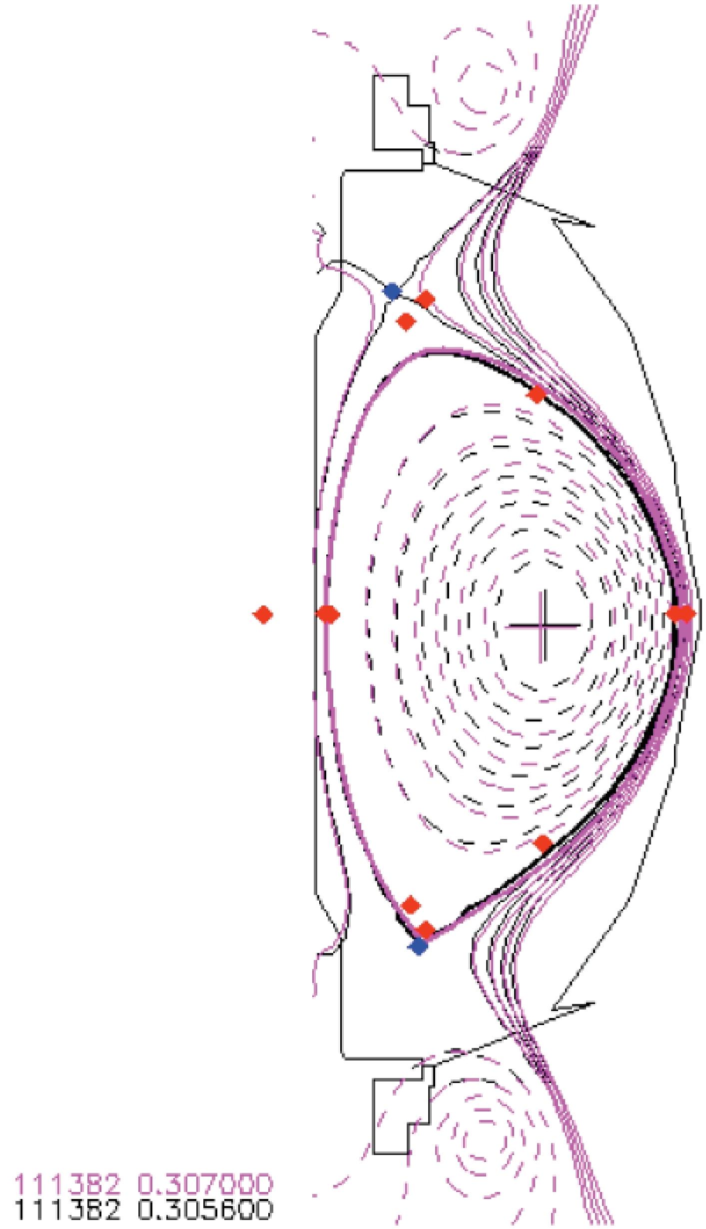
- User defined (can be varied shot to shot)
- Each phase has one (real-time) algorithm (but an algorithm can be used in several phases)
- Can have alternate phase sequences (handles faults)

Shape control

- 3 stage shape control development plan now complete
  - coil current control (1999)
  - Ip and position control - preprogrammed shape control (2000 - 2002)
  - rtEFIT/isoflux shape control (2003 - 2004)
- rtEFIT/isoflux control now functional and has been used successfully for several XPs

rtEFIT/isoflux control

- Real-time analysis on 8 333MHz G4 processors
  - Data acquisition at 5 kHz
    - 65 magnetic data inputs,
    - 11 coil currents,
    - 9 loop voltages (⇒ 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



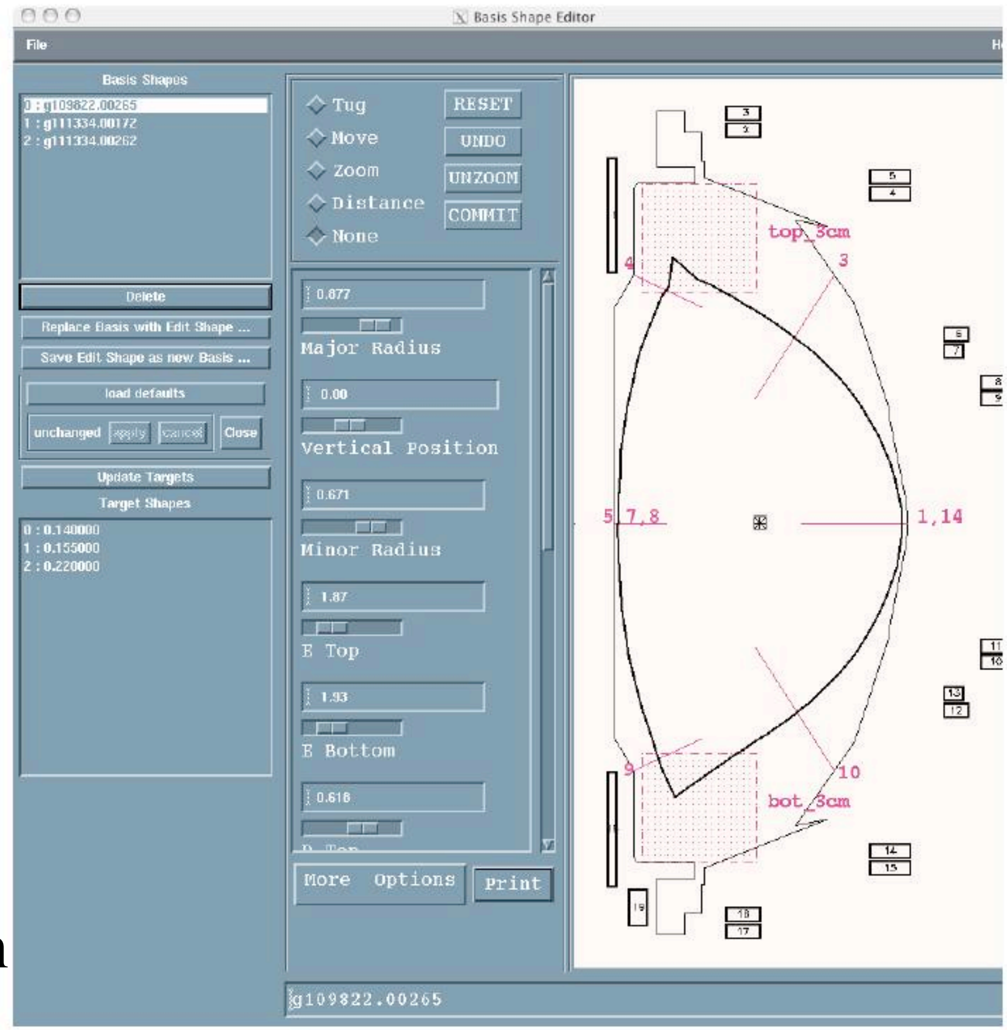
NSTX

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)

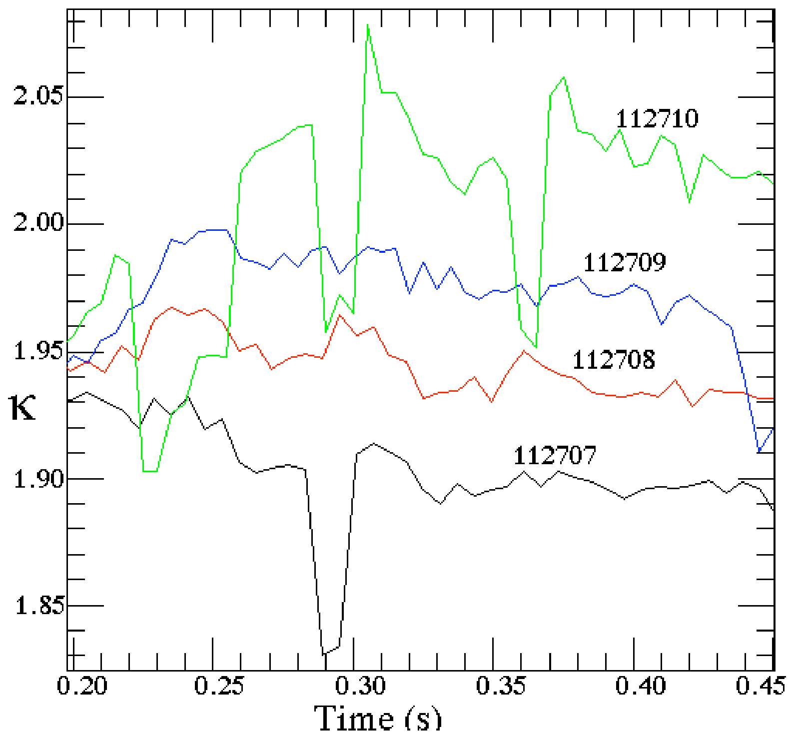
$$V_i = PID(M_{ij}\Delta\psi_j)$$

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



Elongation (κ) control

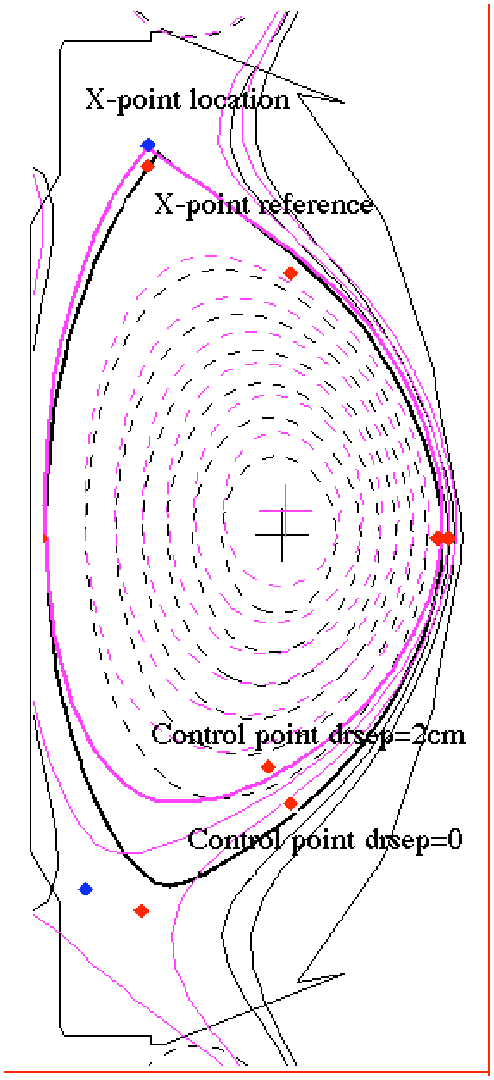
- High l_i (~1.5)double-null RF heated plasma
- κ was increased by increasing the requested height of the X-points after 0.2 s from shot-to-shot



Control of drsep

(the separation at the outboard midplane between the flux surfaces on which the X-points lie)

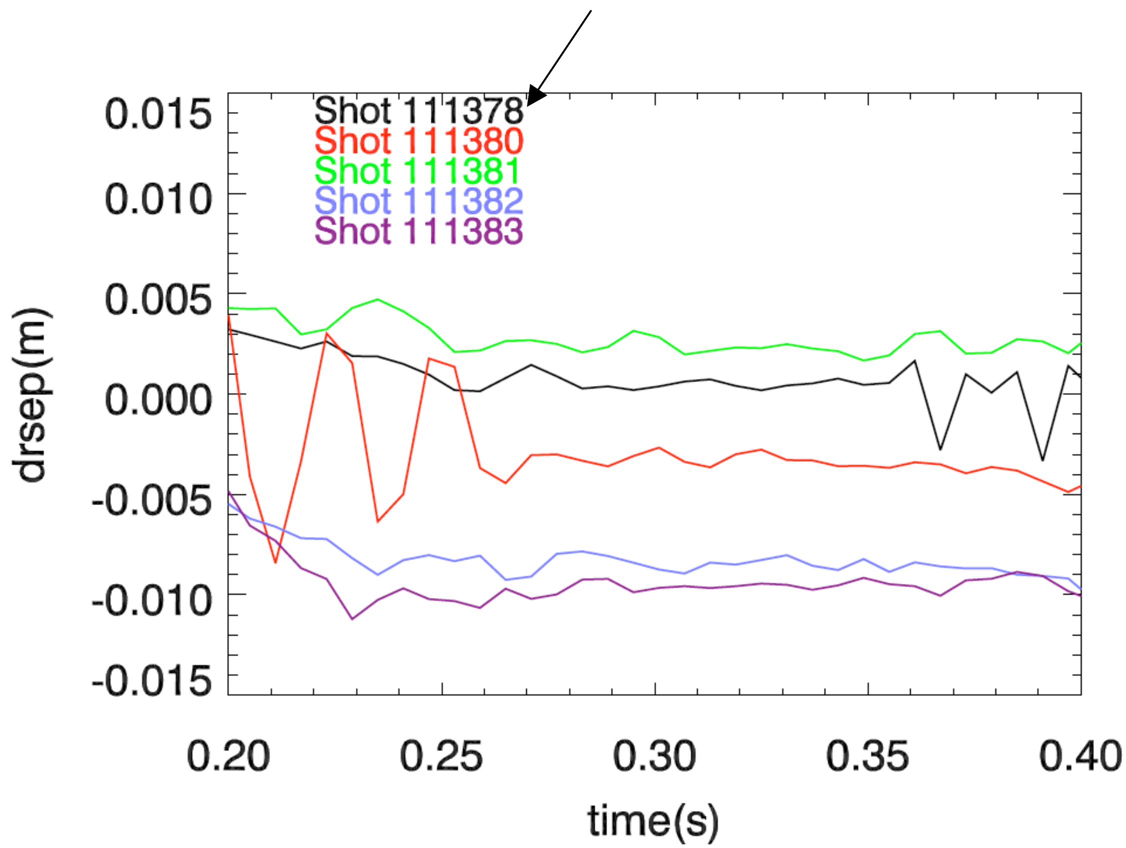
- Control of drsep is achieved by adjusting the control point for PF3L (for positive drsep) to be further inside the plasma than for drsep = 0 and by using a symmetry term to control the fluxes at the two control locations at the outer midplane
- The X-point references are unchanged, but the actual location of the lower X-point moves.



Isoflux control examples

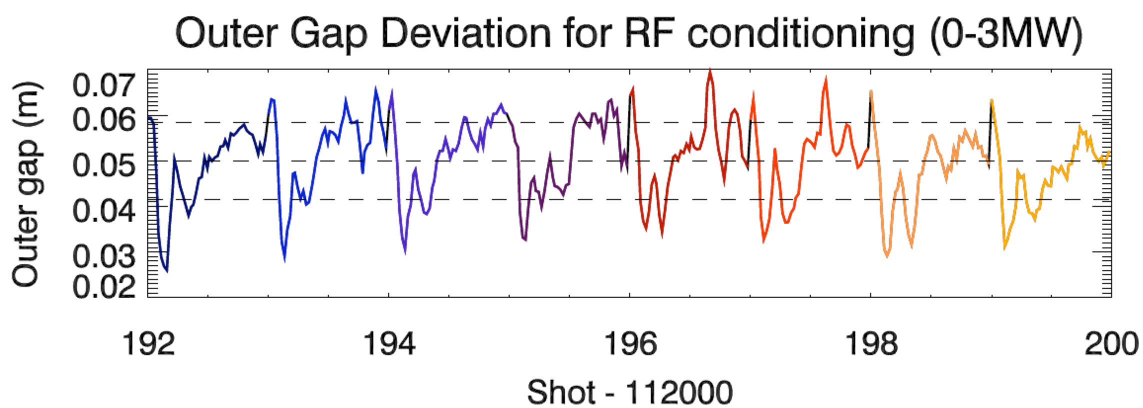
- XP 418 (MAST/NSTX H-mode comparison) used isoflux control to vary drsep
- Also required specified ramp up shape evolution and current ramp to match MAST scenario

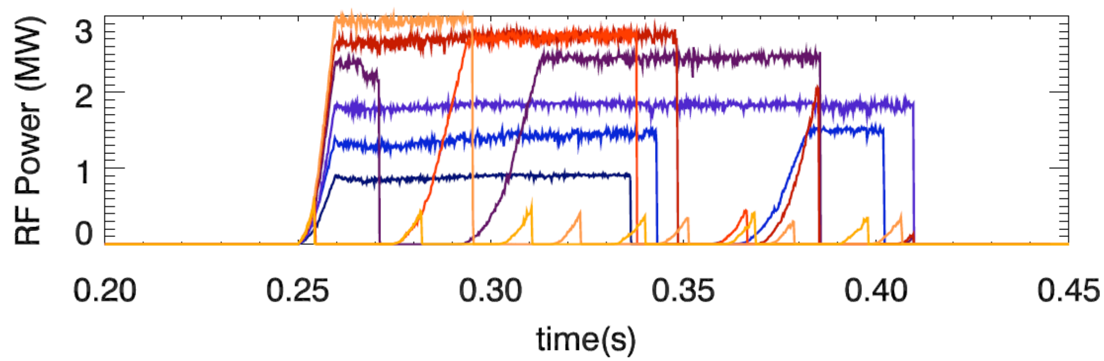
Note consecutive shot numbers



Gap control good to ~1cm

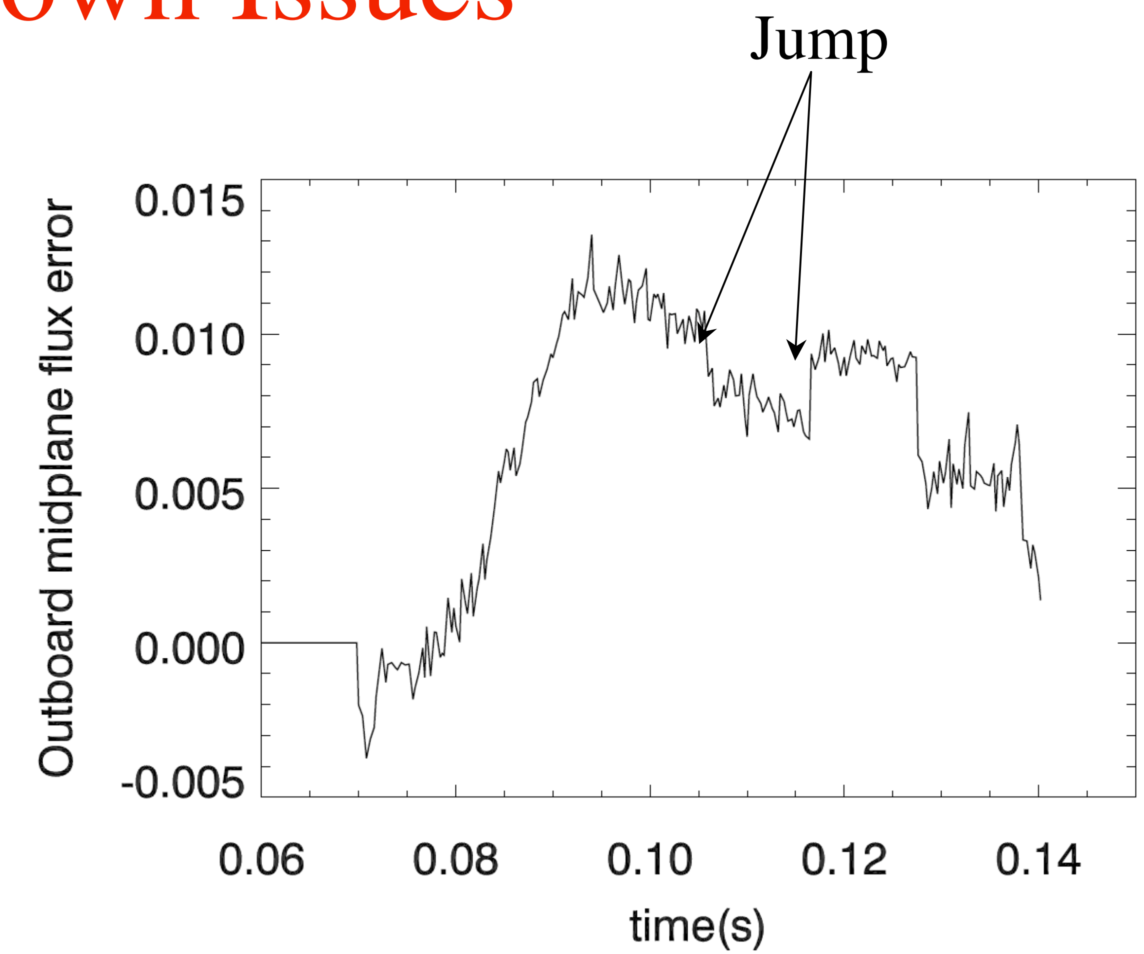
- Data taken during shots with large transient disturbances
- Handoff algorithm has reduced initial perturbation





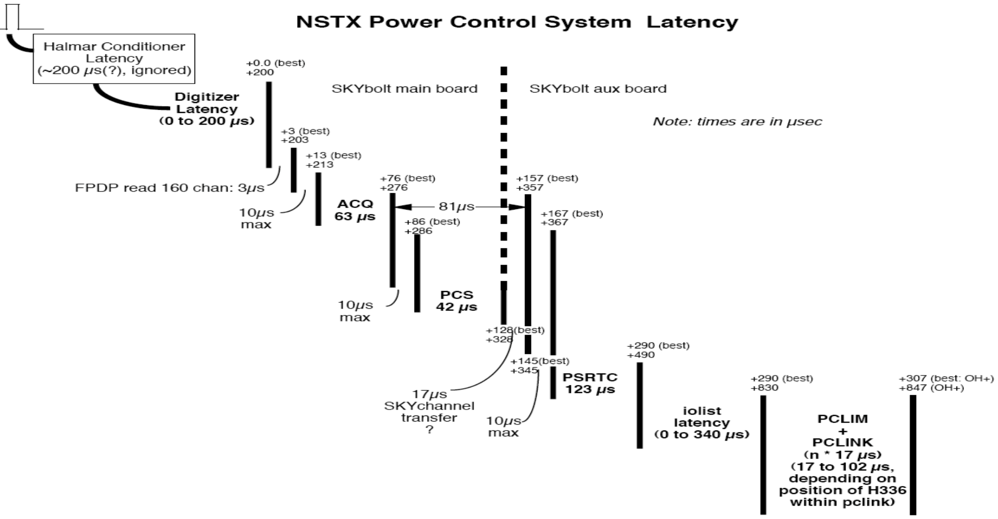
Known Issues

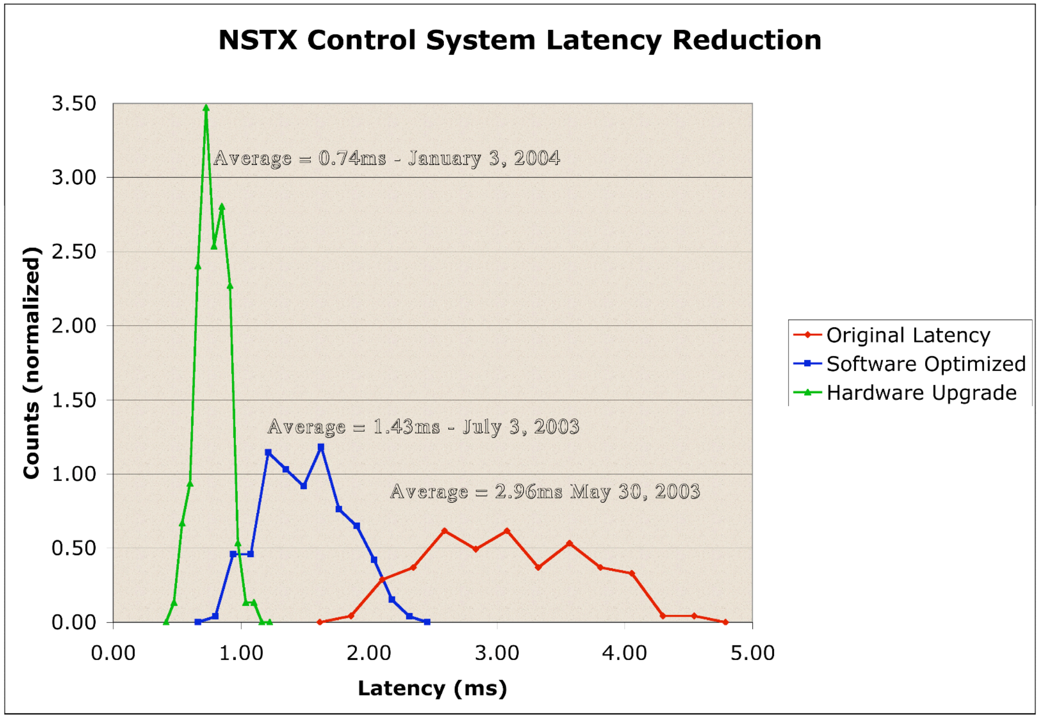
- During rapid current ramp rtEFIT sometimes jumps from one solution to another in the slow loop
  – Speeding up calculation should help
  – Improved vessel model may help



Control latency reduction

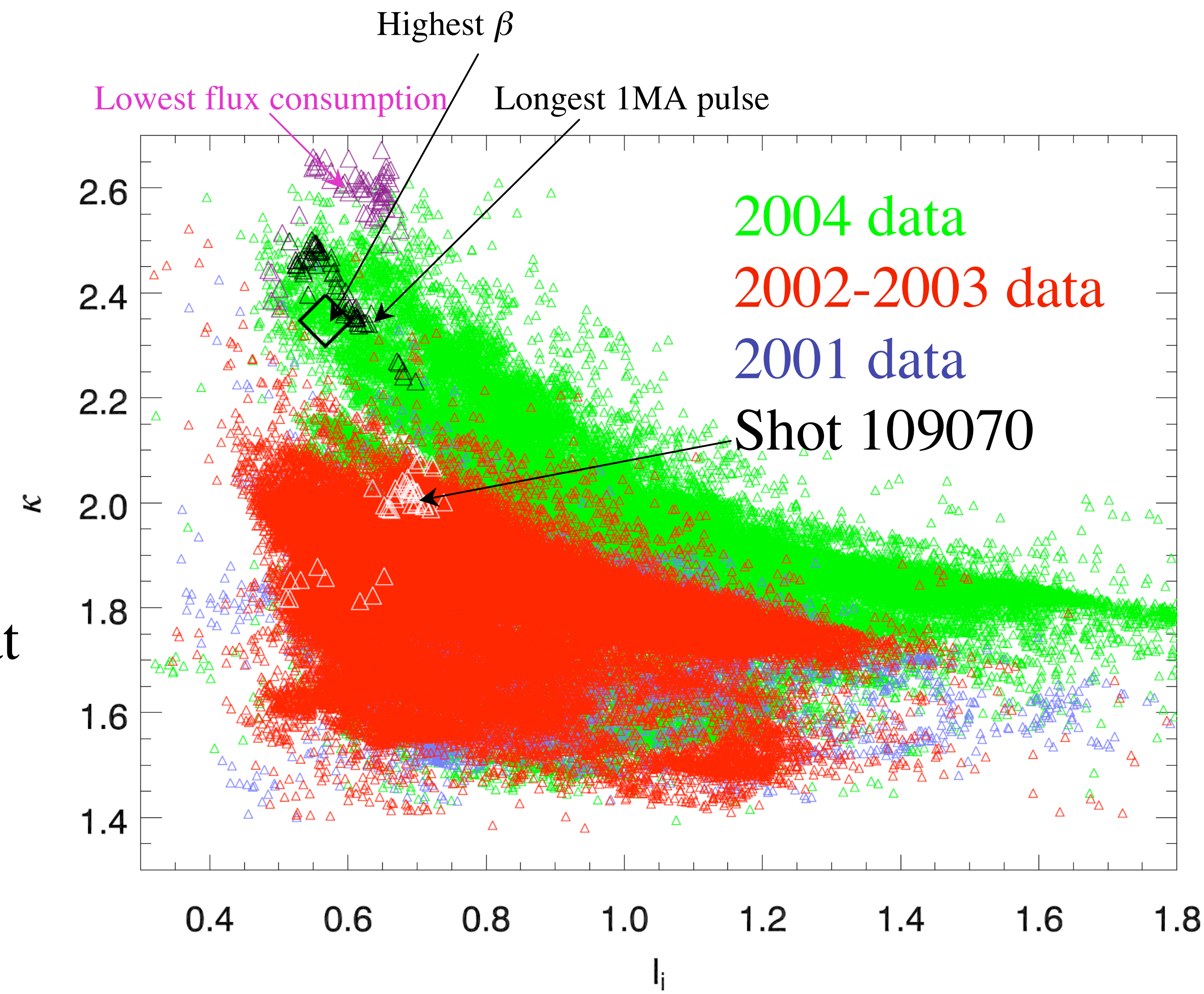
- Latency is the time from a change in an input signal until the system makes a response
- Identified system latency as primary source of vertical stabilization limits
- Systematically identified latencies and removed them
- Latency now ~1/4 value in 2003
- Also added analog vertical voltage difference measurement





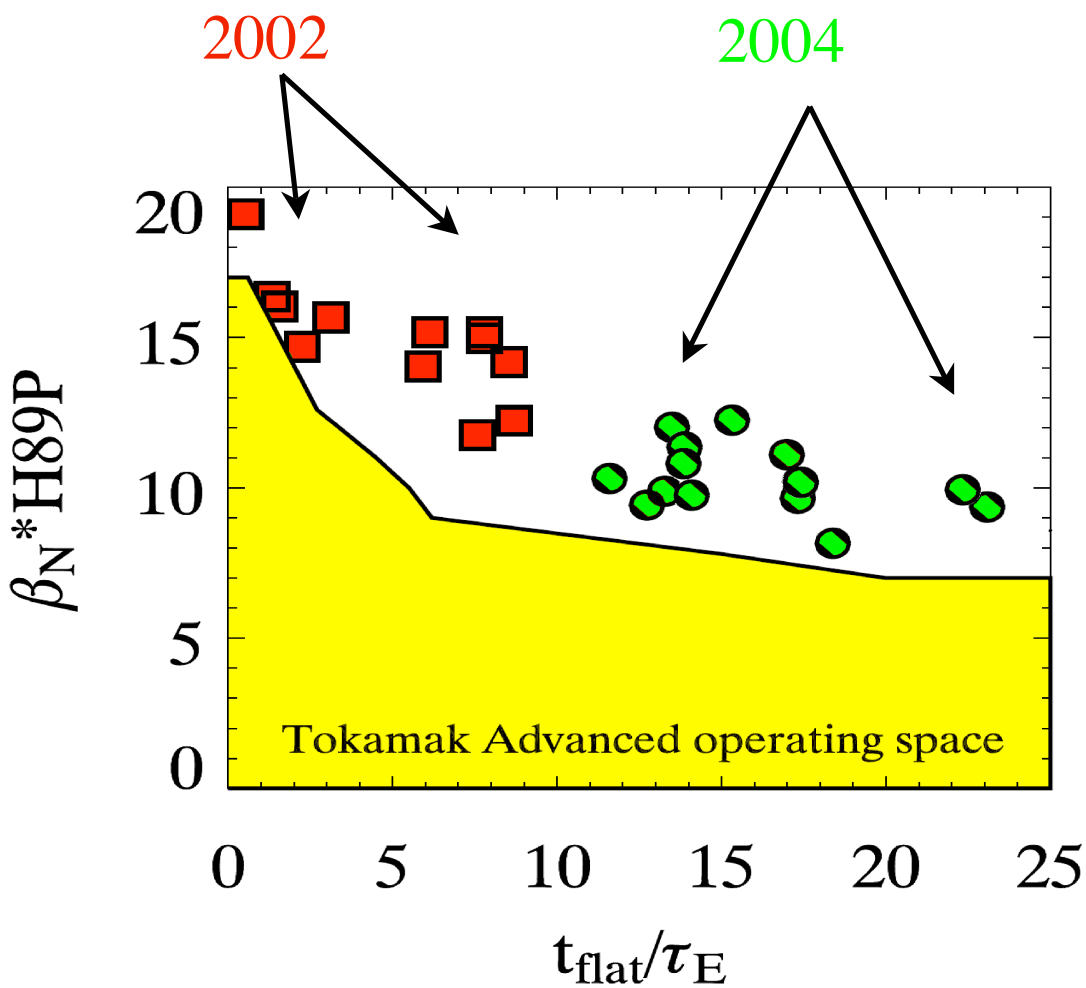
Increased operating space

- Maximum $\kappa \sim$ 2.4 (fills vessel)
- Has already led to improved results
  - higher β_t
  - higher β_p
  - Longest pulse at 1MA - 1second
- Higher κ only recently achieved - more to come



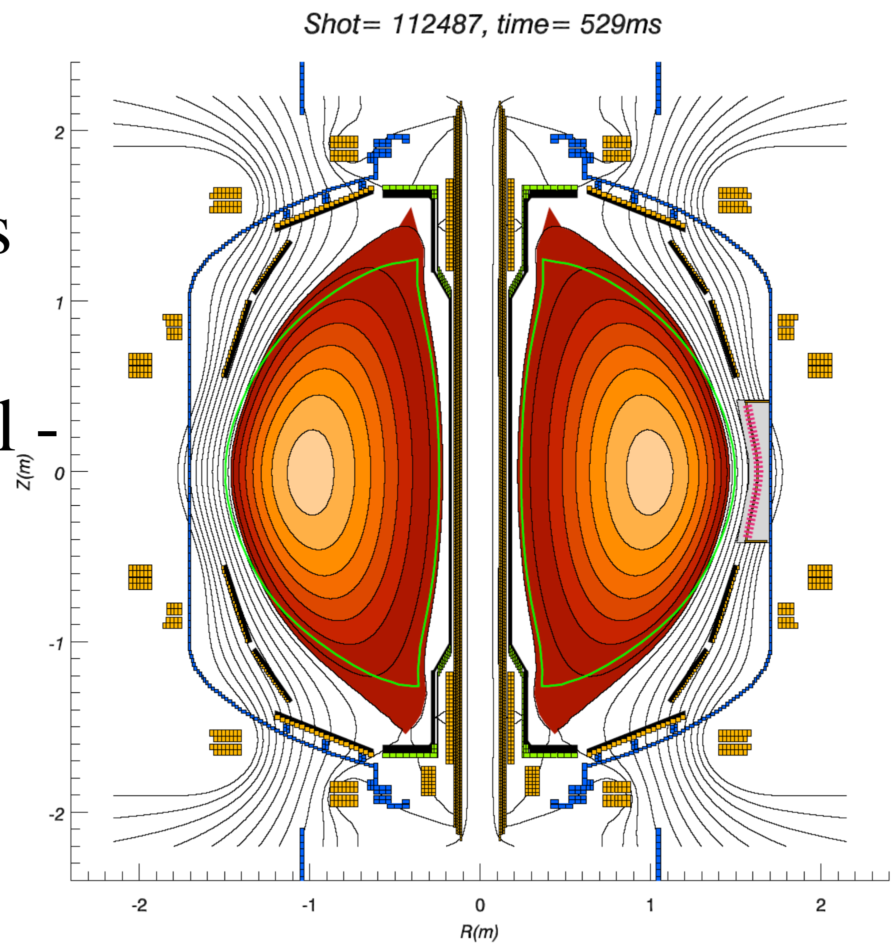
Pulse length extended at high performance

- First truly successful long pulse run this year
- Further shape optimizations likely
- Confinement degraded relative to peak performance
- All new long pulse data above $\kappa = 2.2$

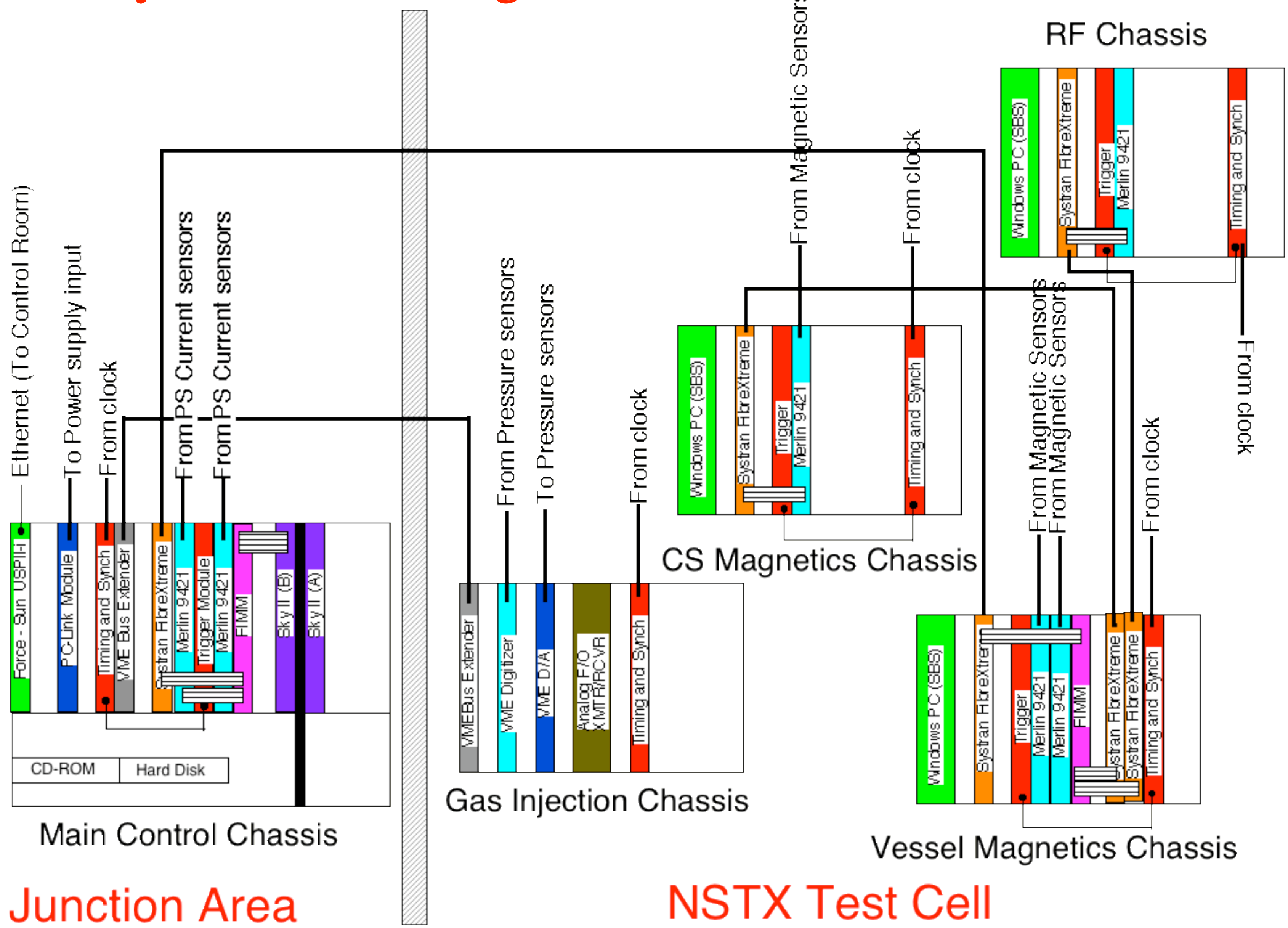


Summary

- PCS is a useful flexible tool
- rtEFIT/isoflux control works well
- Latency reduction successful - has led to a significant increase in accessible parameter space

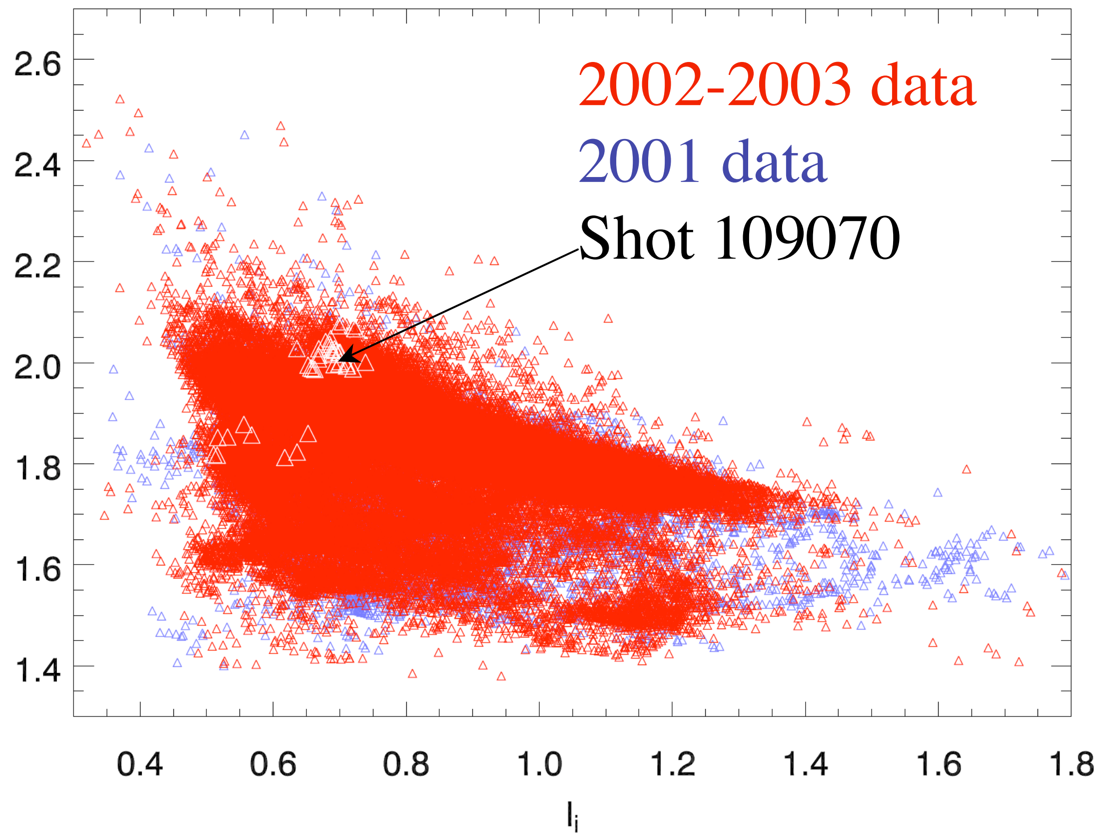


Control system block diagram



Vertical position control

- High performance associated with strong shaping
- 2002-2003 operating range limited to κ <2.1 in steady state



NSTX

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

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.