NSTX-U plasma control system

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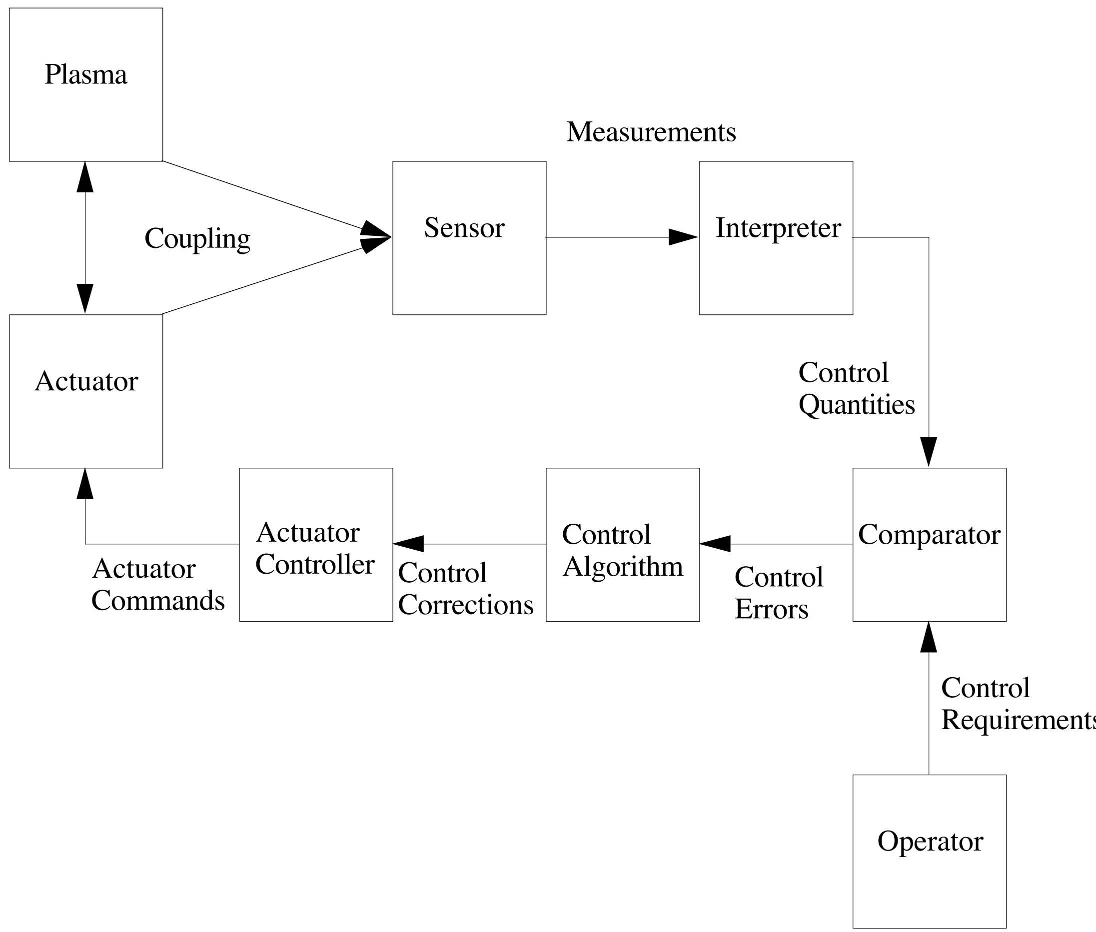
Outline

- Intro
  - System goals
  - Control basics
- Software
  - Control logic and algorithm heirarchy
  - Control examples
  - rtEFIT and isoflux
  - Other
- Summary

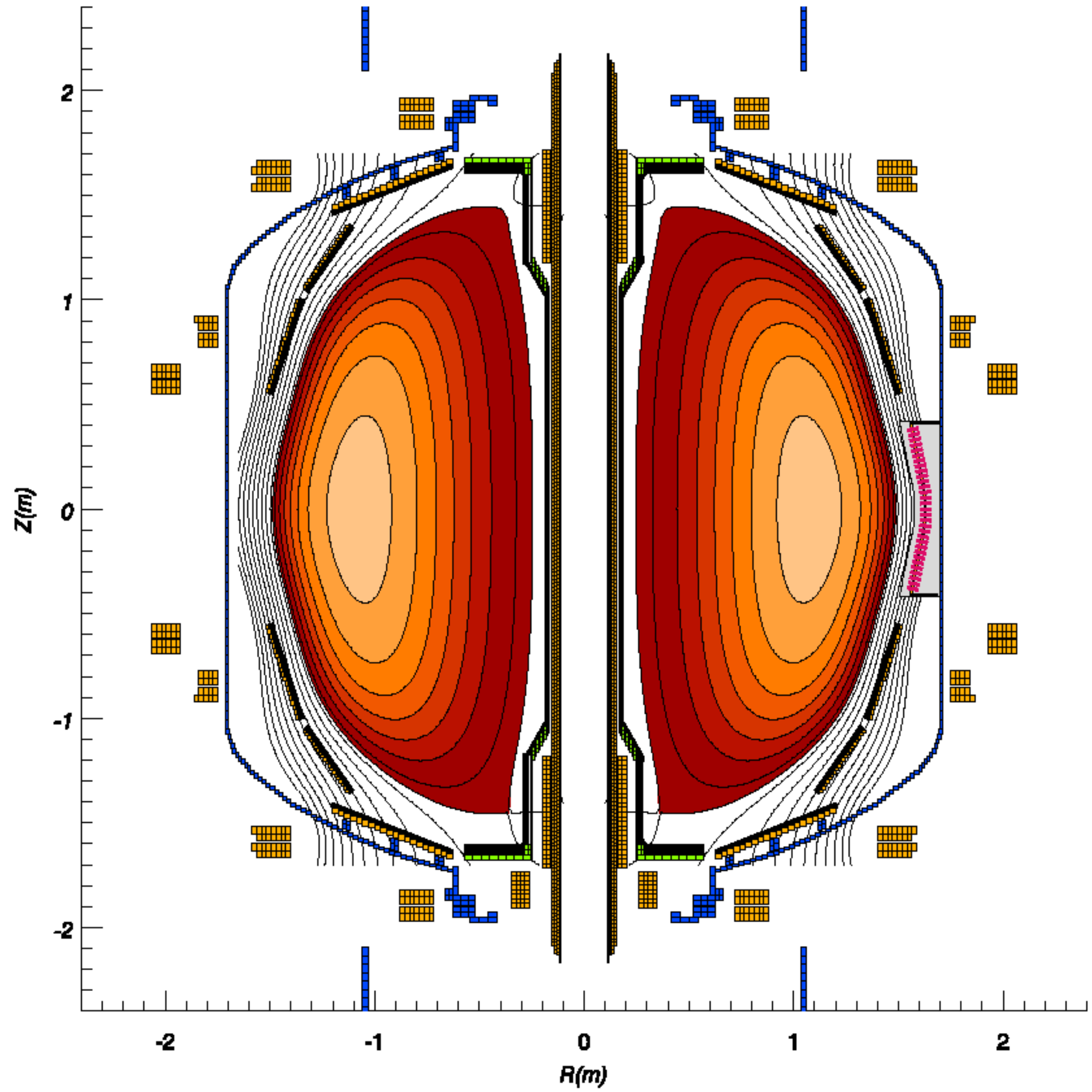
Control System Basics

- General control loop has many stages
- Physics has input via the interpretation of measurements and the control algorithm

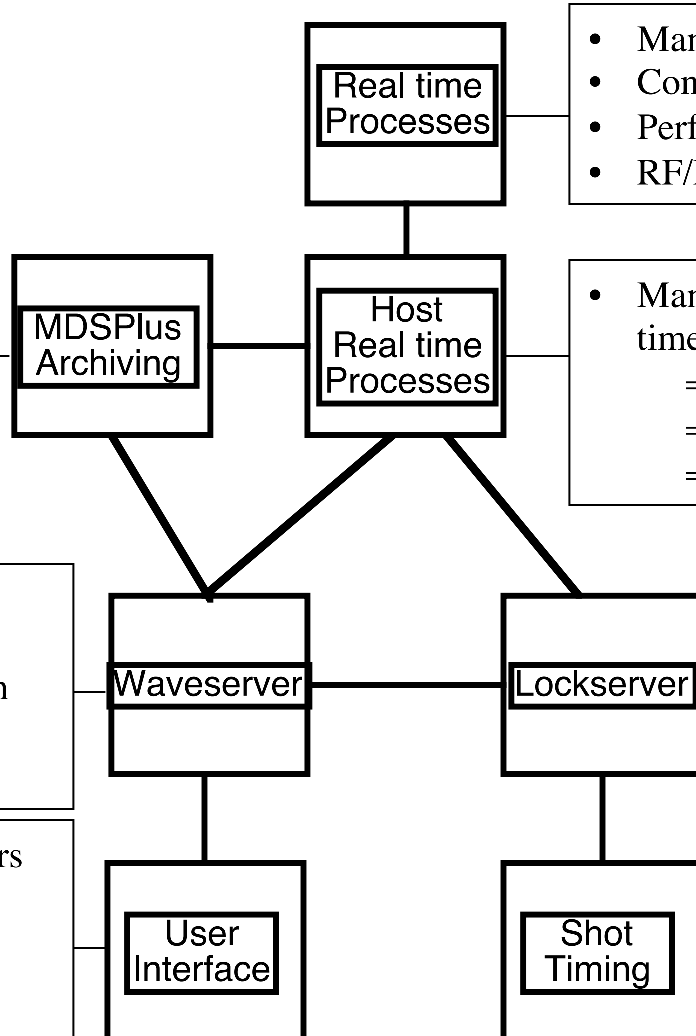


Control system goals

- Maintain plasma parameters in steady state
  - High triangularity high elongation plasma with high non-inductive current fraction at high toroidal β to demonstrate viability of spherical torus concept
    - ➢ Integrated scenario development tool
- Support physics experiments



Flexible 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

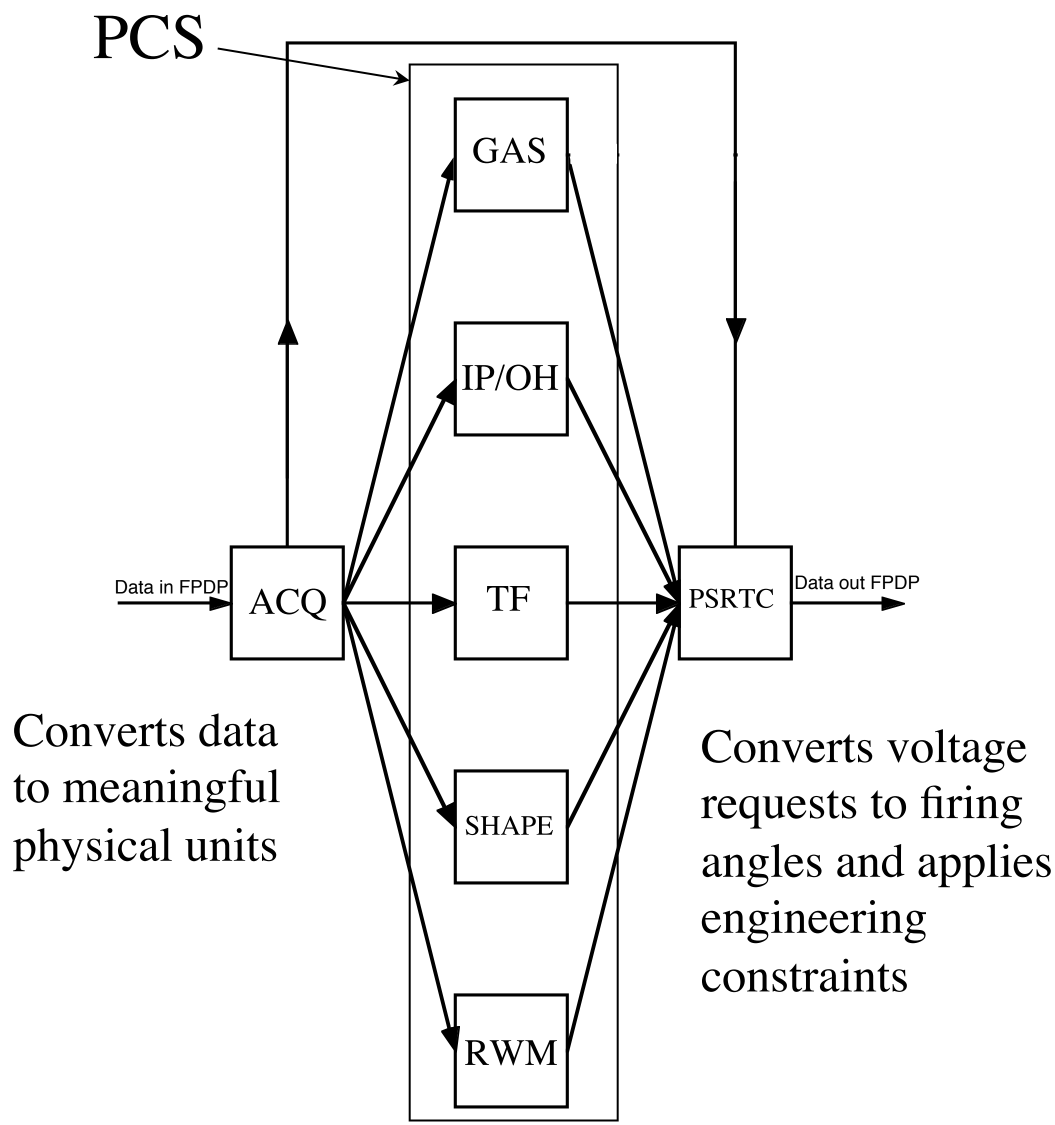
- Controls shot sequence

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

- Provides synchronized shot start/end events

Real time information flow

- NSTX control stream is (nearly) centralized through the PCS via the FPDP data stream
- Addition of new SPA requires modification of the software in the ACQ-RWM-PSRTC branch of control



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

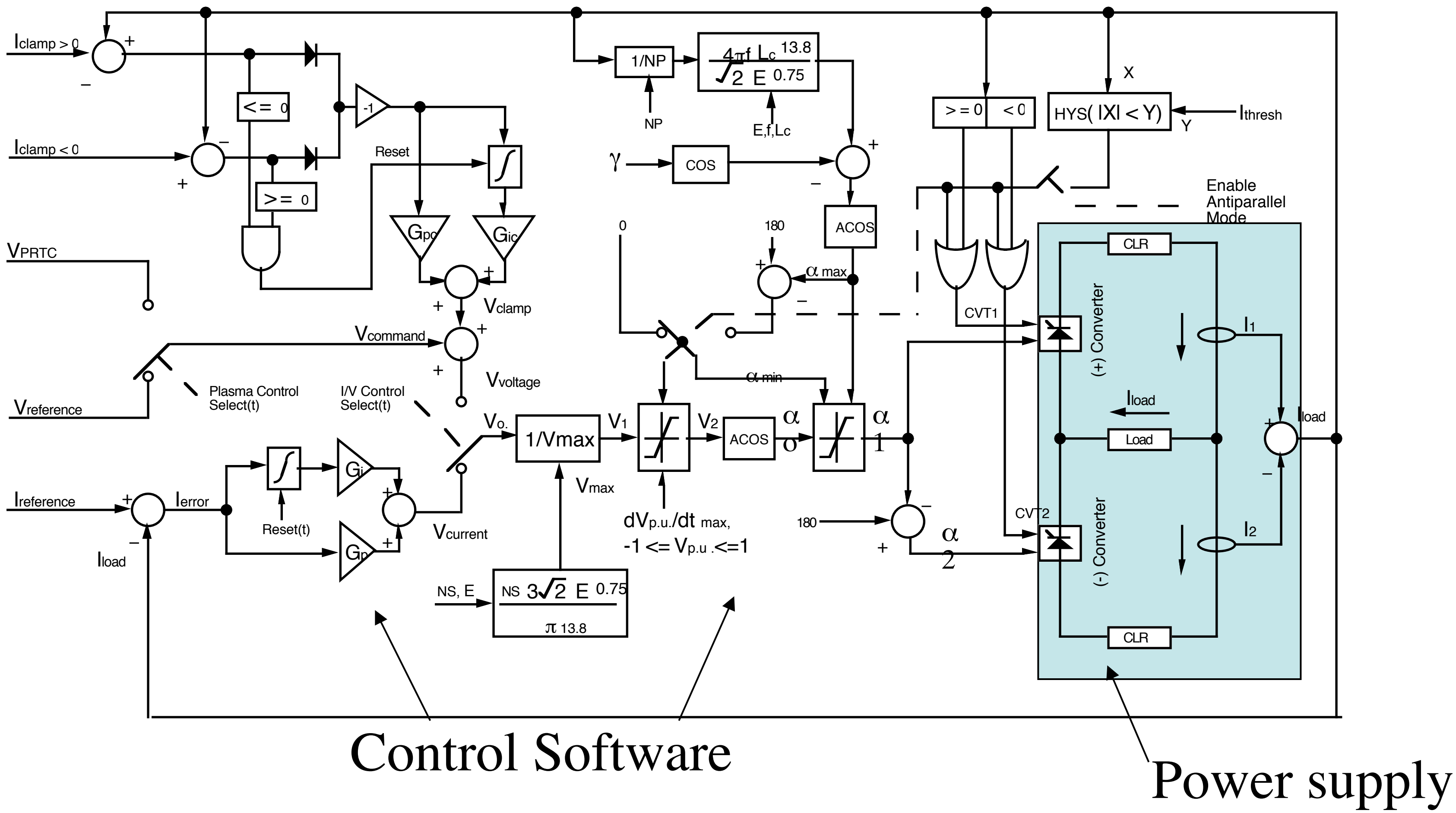
Plasma Control System

Category	
Ip/OH Control	Controls OH current (pre/post shot) or Ip (during shot)
TF Control	Controls Toroidal field current
Gas Injection	Controls gas flow either pre-programmed neutral pressure feedback (prefill) or ne feedback {future}
Discharge 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
Data Acquisition	Controls data flow and the operational mode of the PCS
Mode ID	Calculates RWM mode amplitude and phase using RWM sensors
RWM Control	Controls SPA power supplies
NBI	Modulates neutral beam sources

Power Supply Real-Time Control

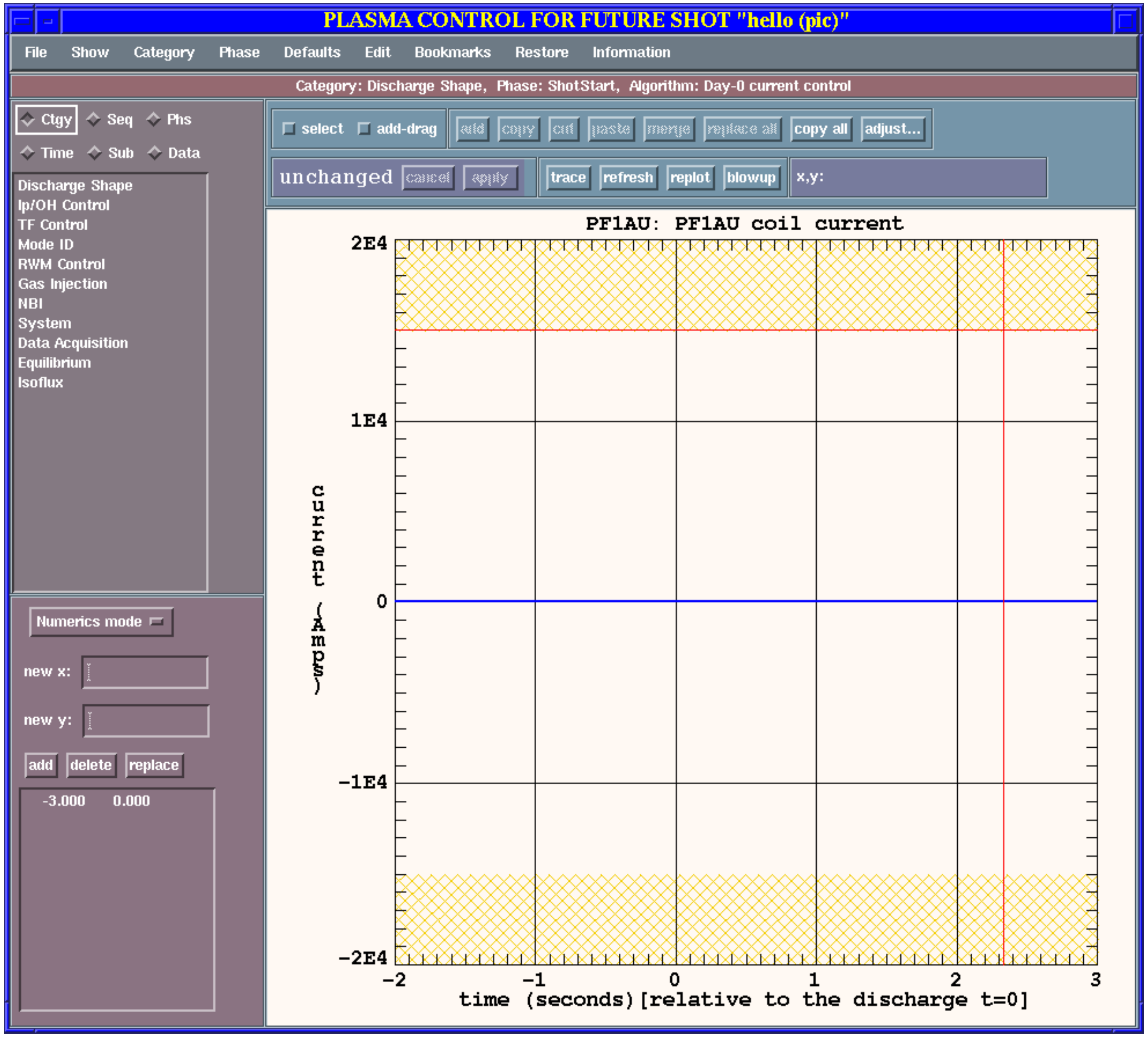
psrtc	Chooses source of power supply control data (enables engineering test shots and plasma control shots). Converts requested voltage to thyristor firing angle (pulse width modulation). Enables bipolar power supply operation.

Software based power supply control



Control categories

- The highest level of organization within the control system is called a category
- Categories cover either a control actuator or a meaningful intermediate control concept (e.g. equilibrium, modeID)
- Algorithms run within categories
  - Multiple algorithms can run in a category (one at a time)
  - Algorithm order determined by phase sequence



Categories correspond to controllable parameters

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

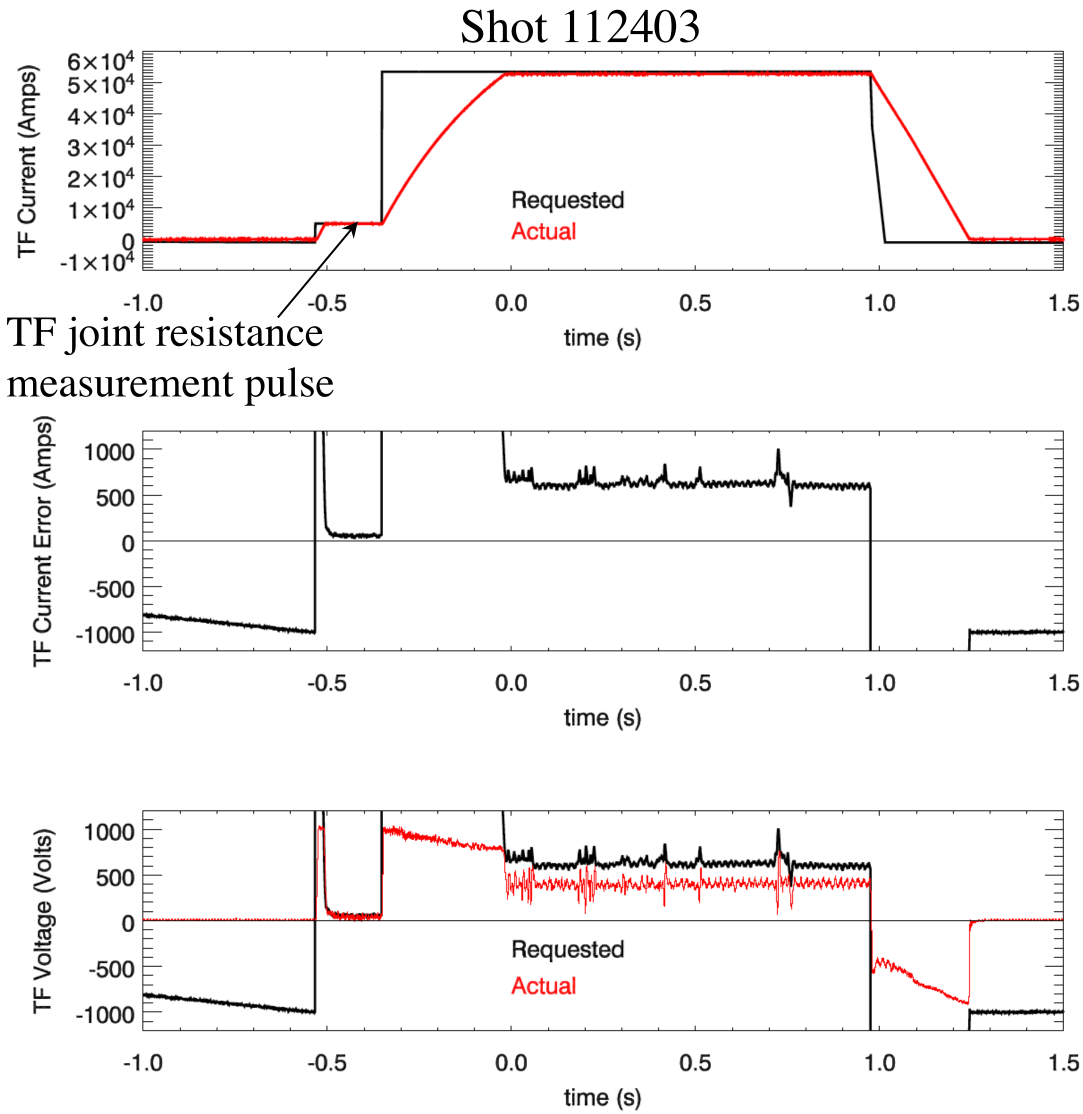
- Power (NBI and RF)
- Momentum input….

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)

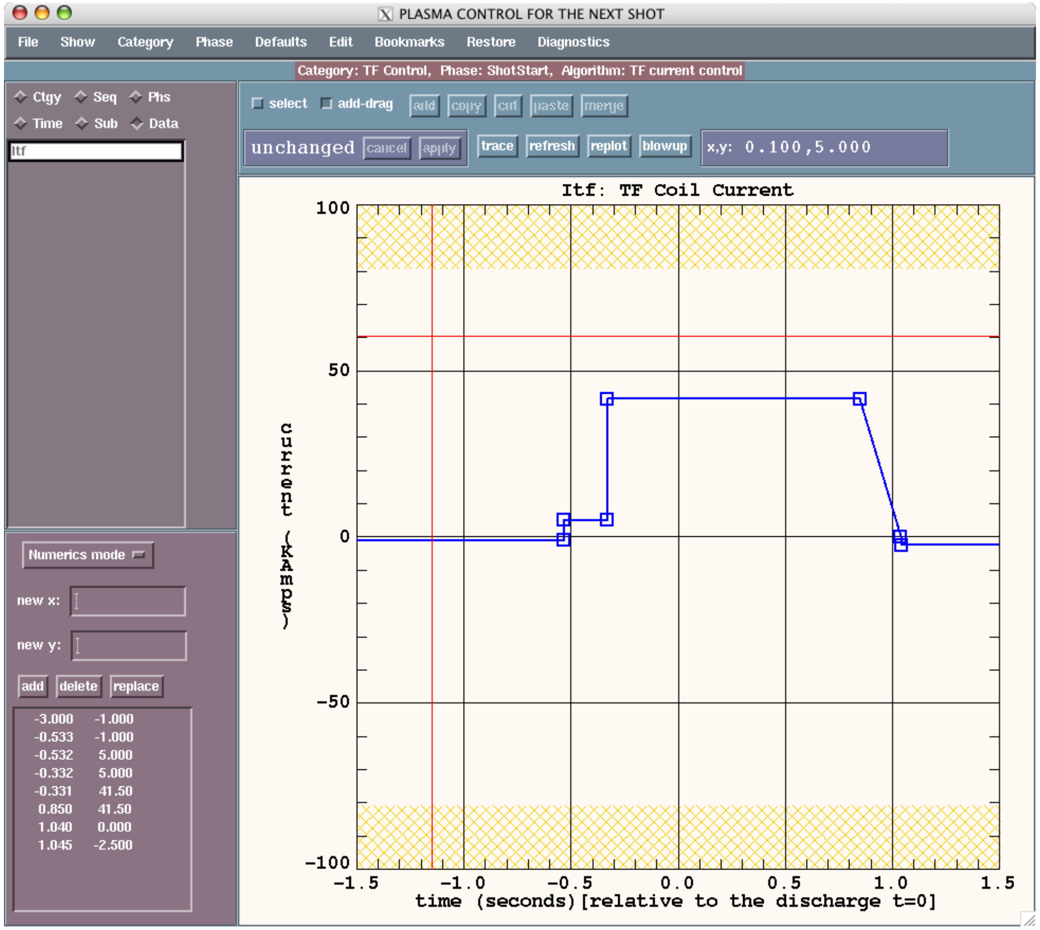
TF control

- Simplest proportional control $V = G_p(I_{ref} - I_{meas})$ {with $G_p = 1$}
- Category contains one phase with one algorithm
- Programmable current waveform



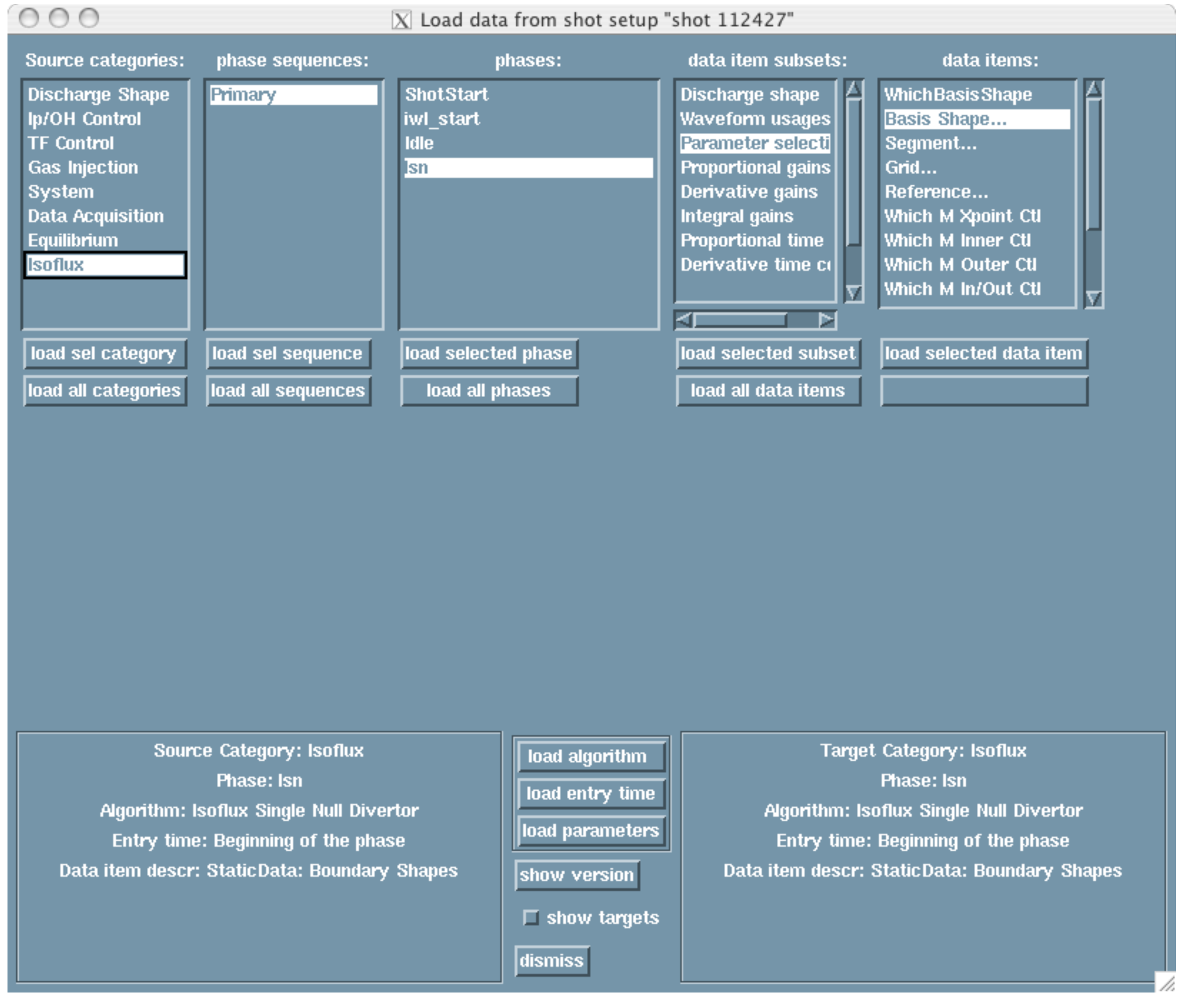
TF control (cont.)

- Waveform editor (point-and-click IDL based interface)
- Data points can also be typed in by hand
- Easiest to simply restore from MDSplus



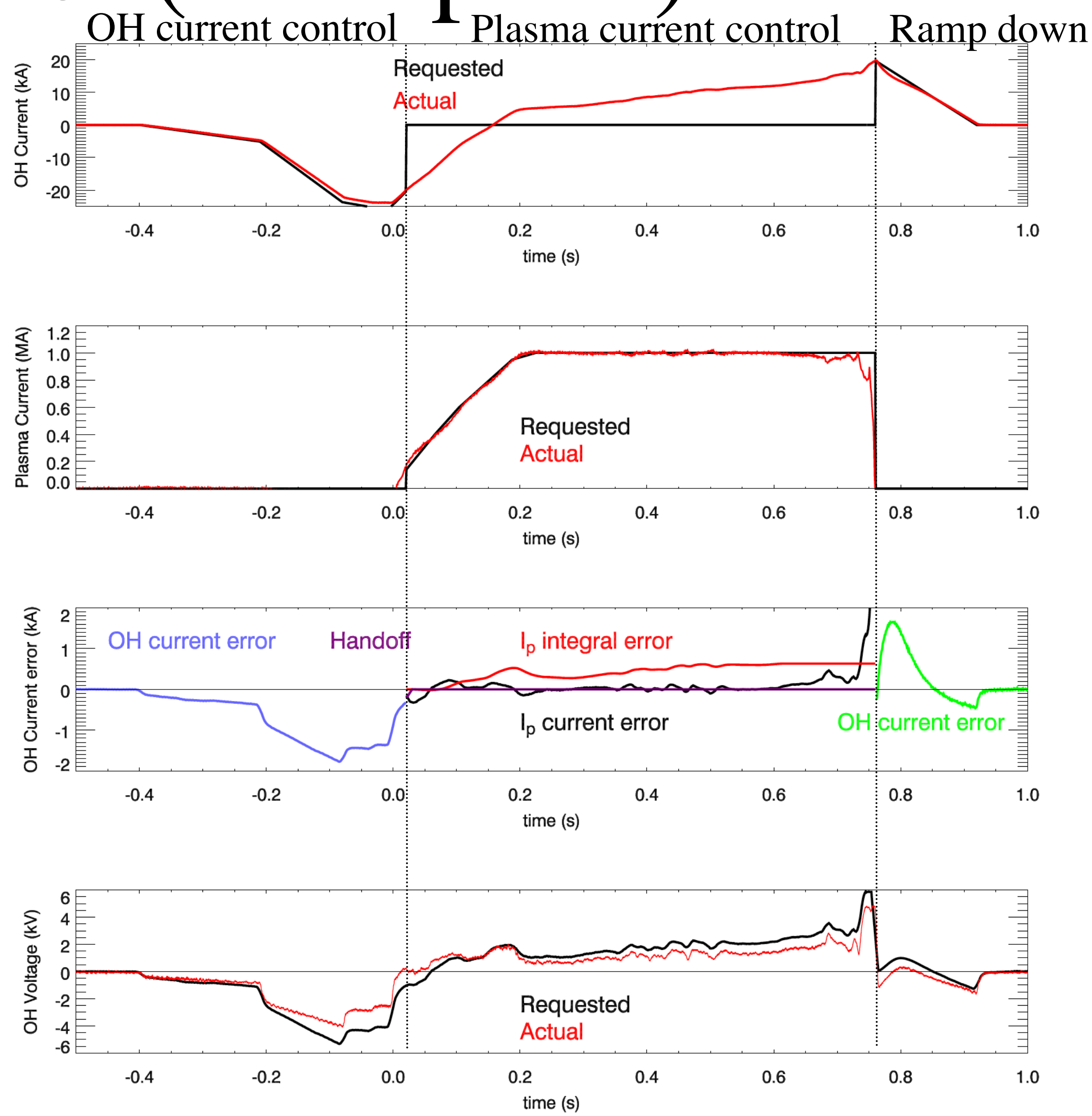
Shot restore function

- One button click for complete shot restore
- Can also load individual waveforms from multiple shots (to any destination waveform)



Ip control (example 2)

- Three phases of control with 3 different algorithms
- Proportional and integral gain on I_p as well as "handoff" term
- 2 alternate phase sequences (Load overcurrent and Insufficient I_p)



Force balance in an axisymmetric device

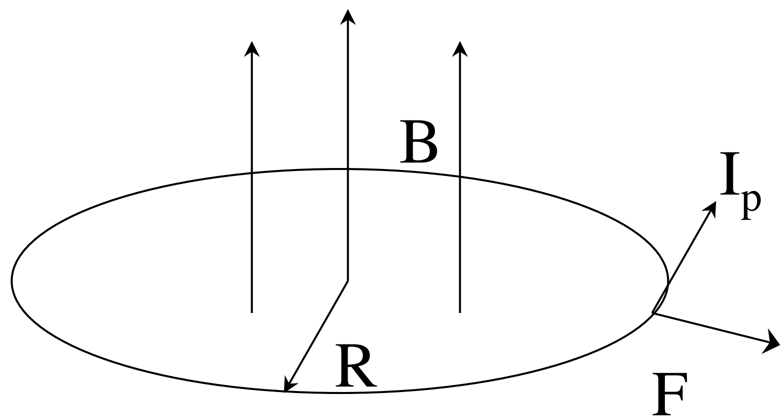
- In equilibrium plasma obeys the Grad-Shafranov equation

$$JxB = \nabla P \quad \Rightarrow \quad R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \psi}{\partial R}\right) + \frac{\partial^2 \psi}{\partial z^2} = \mu_0 R^2 \frac{dP}{d\psi} - F\frac{dF}{d\psi}$$

- Ideal method to control plasma position is to solve the Grad-Shafranov equation in real-time and use the result for feedback control!

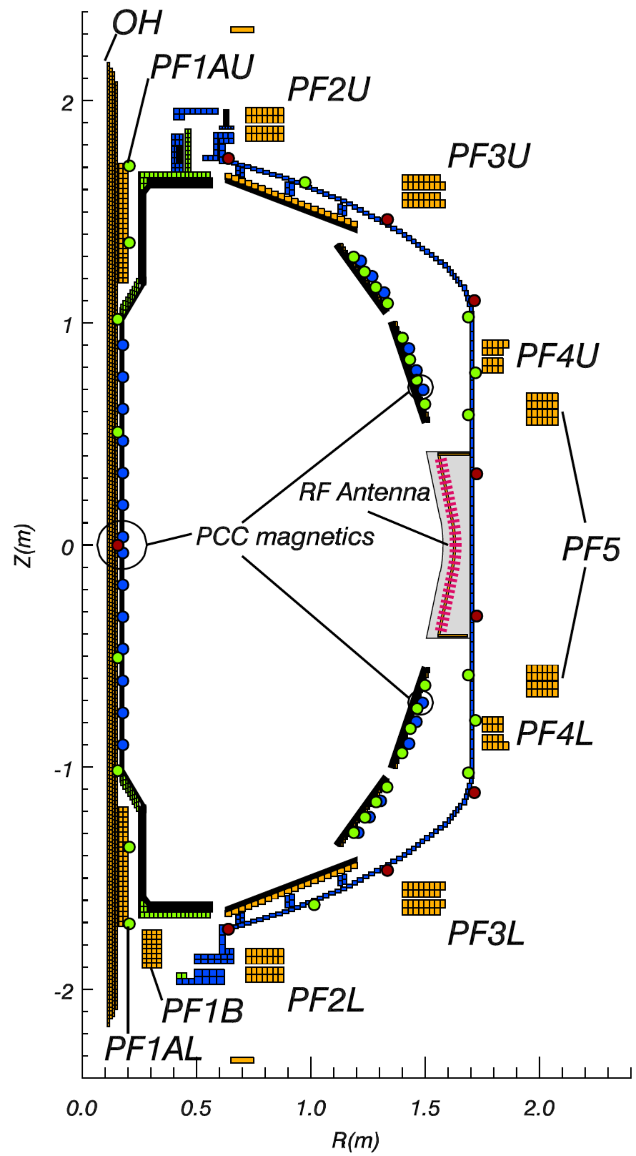
Plasma force balance

- For a plasma current of 1MA at a radius of 1m the self generated field is about $\mu_0 I/2\pi R$ ~ 0.2T
- $F \sim 2\pi R I_p B$ ~ 1.2x10^{6}N ~ 200,000lbs ~ 100tons!
- Plasma mass ~ 3mg
  - n = N/V = 1x10^{20}m^{-3}
  - V = 10m^3 of plasma
  - m_D = 3.2x10^{-27}kg
- Plasma with unbalanced forces will leave the vacuum vessel in
  - t ~ (2*1m*3x10^{-6}kg/1.2x10^{6}N)$^{1/2}$ ~ 1μs
- Good force balance is important!



rtEFIT boundary value problem

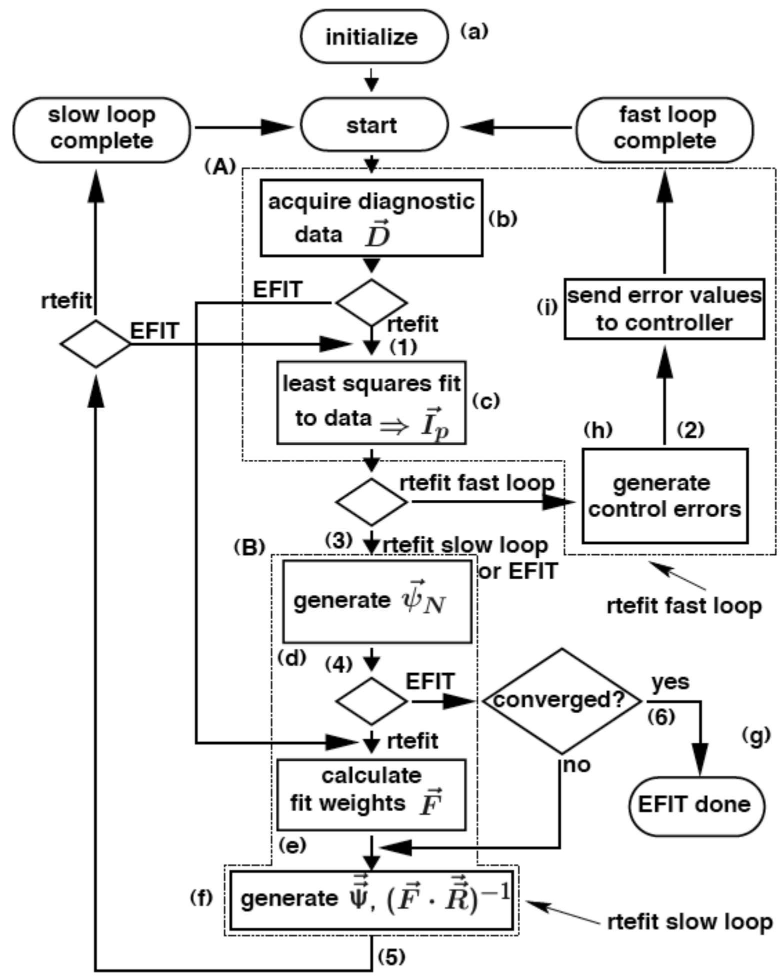
- Measure the magnetic fluxes and fields on the vessel boundary (70 measurements)
- Measure the coil and vessel currents (31 measurements)
- Assume a functional form for the current and pressure profiles
- Solve GS equation iteratively



Picture showing the location of magnetic field coils and measurements used in real time reconstruction

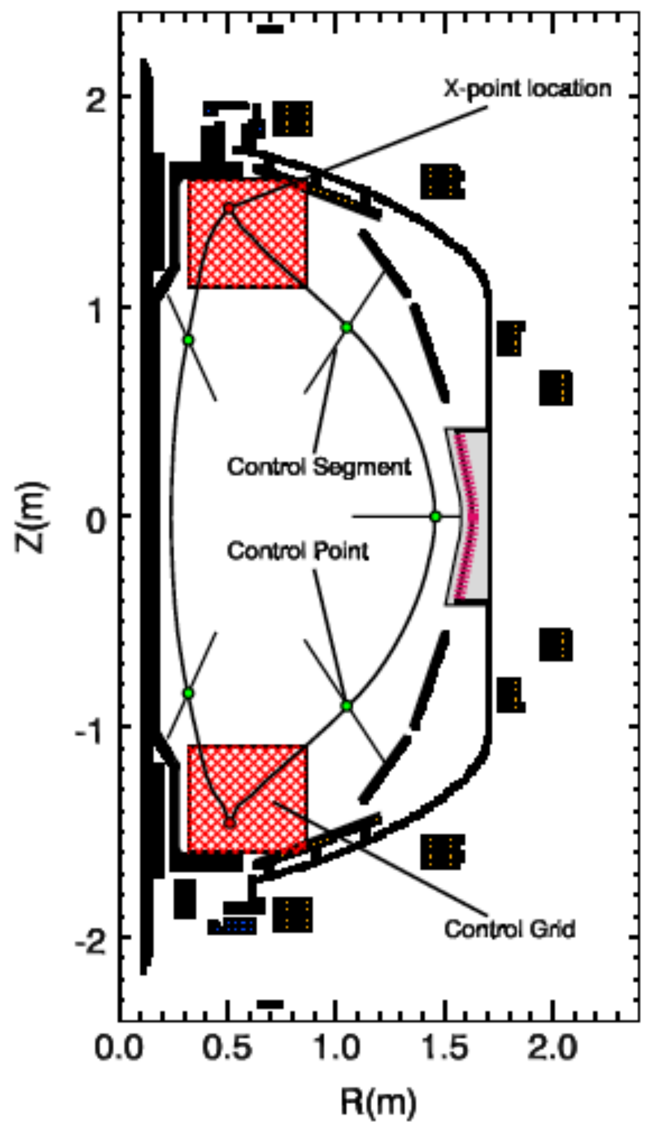
rtEFIT has slow and fast loops

- rtEFIT does not mimic th offline efit
  - No iteration to convergenc
  - New data on each loop
  - Fast loop generates new control commands based o new data on ~200microsecond rate
- Usually matches offline calculation well
  - Good control means small changes from time point to time point



Control scheme

- The user defines a desired plasma boundary
- We define a series of line segments chosen to intersect all desired plasma boundaries called control segments
- Define the intersection of the line segment and the desired boundary the control point

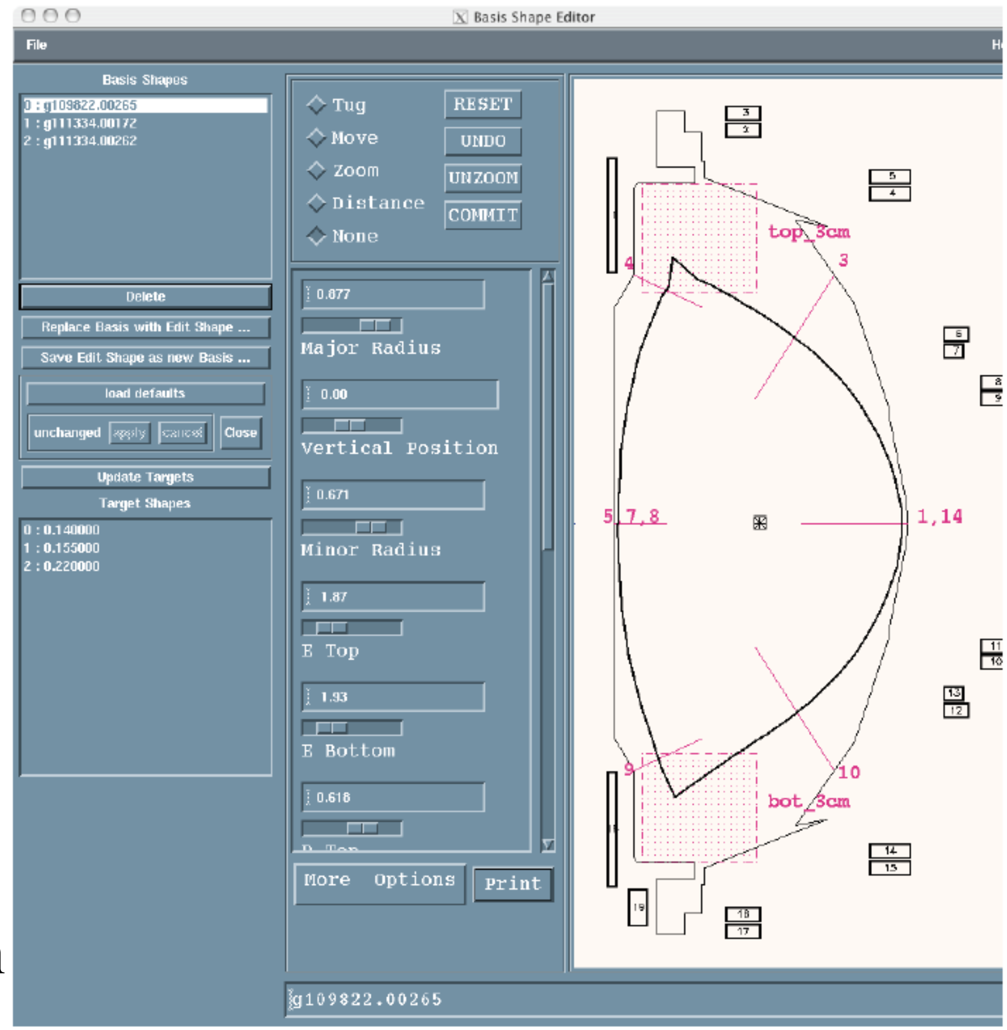


Isoflux control algorithm

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

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

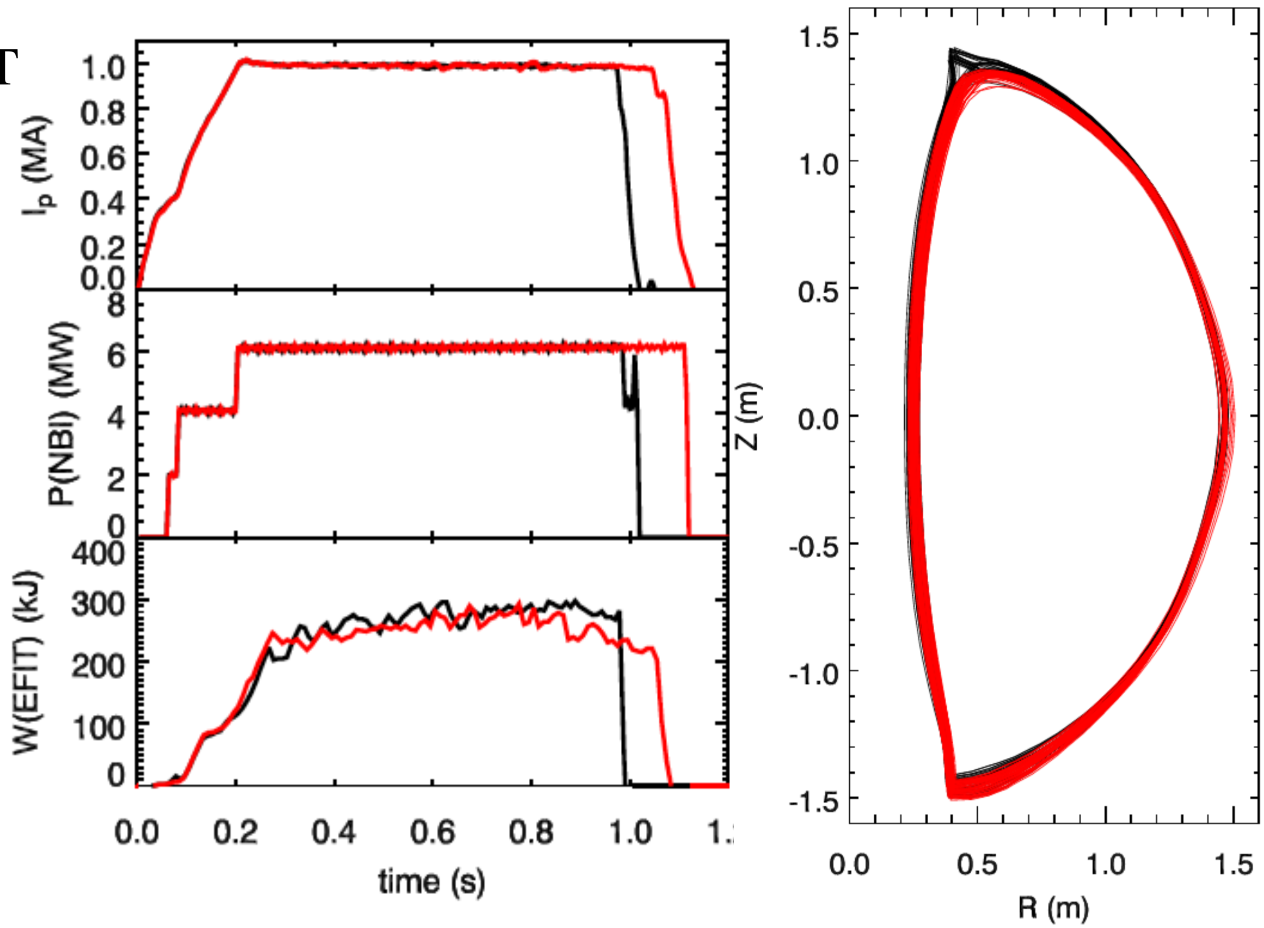
- Dynamic shape variations possible by allowing control points to move along control "segments"
- Segments defined by user (can be changed shot-to shot)



Real-time EFIT enables precise boundary control

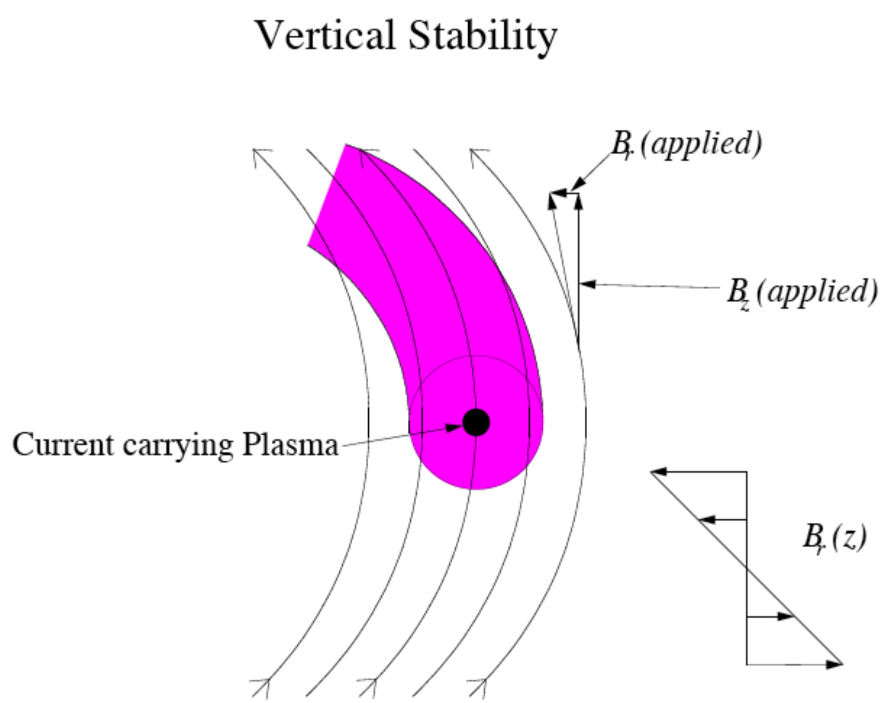
- Collaboration with General Atomics has brought real-time equilibrium calculations used for control to the ST
- Longest 1MA discharge on NSTX made using rtEFIT/isoflux control
- Precise control makes detailed shape variations possible - important research tool

Overlay of boundaries and waveforms from shots 117707 and 117814 1MA, 1s pulse length, nearly double null plasmas controlled with rtEFIT/isoflux control



Maximum plasma elongation is limited by axisymmetric vertical stability

- In order to elongate the plasma, decrease the curvature of the applied field
  - Reduce the radial component of the field
- As the curvature changes sign, the plasma becomes vertically unstable
- Can control the instability using a time vary radial field
  - Ability to control the vertical position depends on the growth rate and the available feedback power

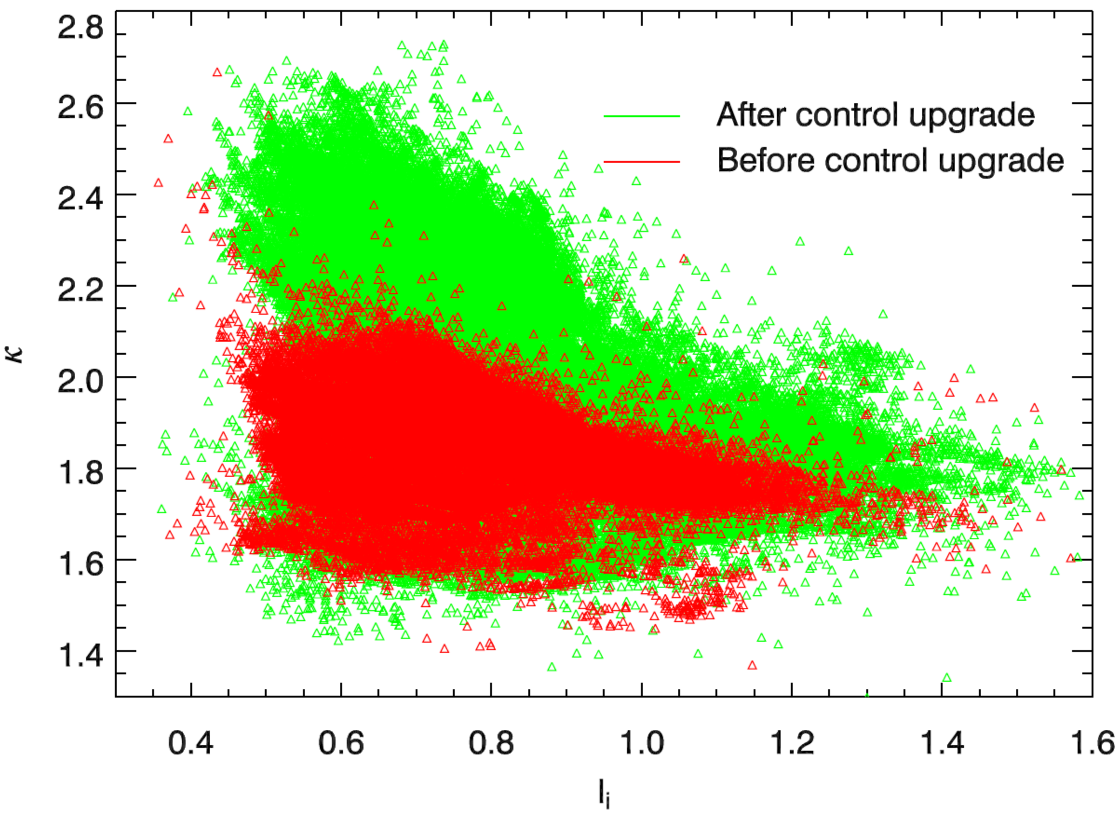


For a vertically stable plasma, as the plasma moves up, it encounters a radial field that pushes it down

NSTX control system has achieved high κ

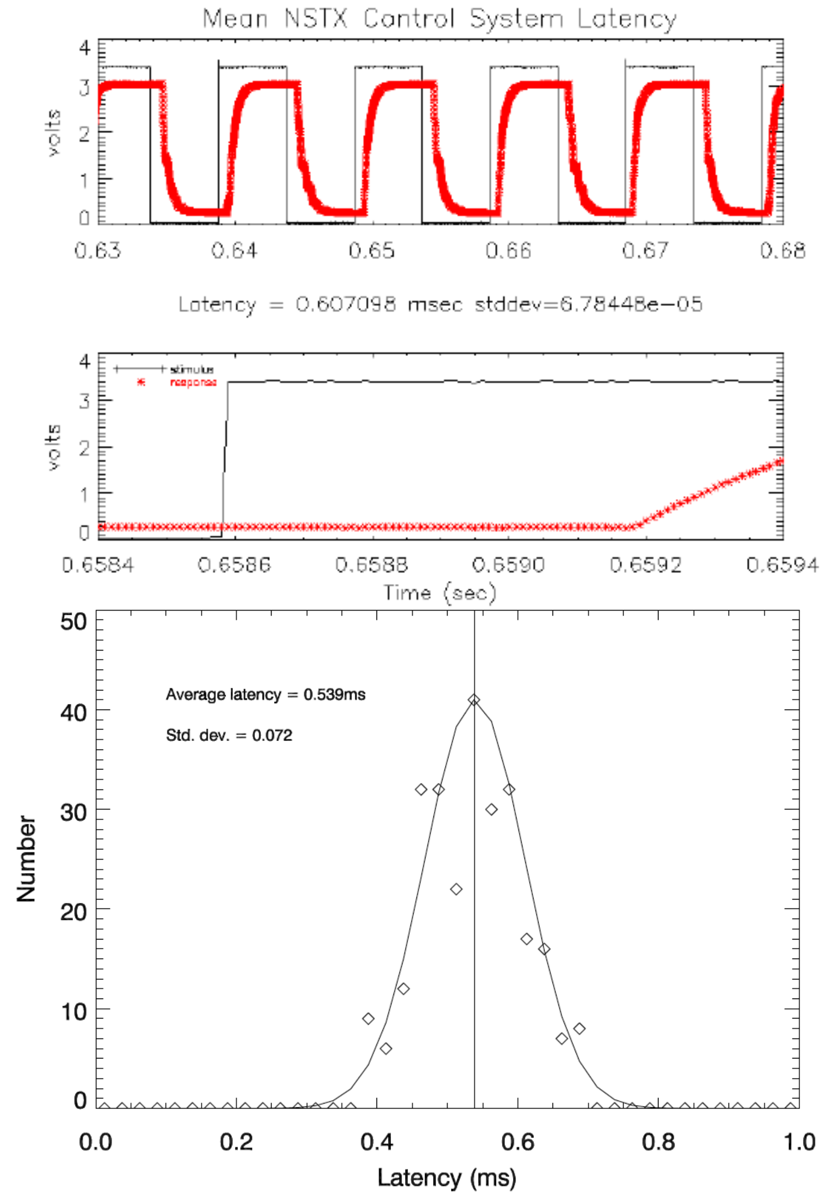
- Low latency key to achieving stability
- Have reached maximum $\kappa \sim 3$ world record
  - ⇒High κ achieved in NSTX without internal coils or sophisticated control optimization

Graph showing the vertical stability space for NSTX, $\kappa = b/a$ is the plasma elongation and l_i is the normalized internal inductance. The boundary of the data is roughly a curve of constant vertical growth rate.



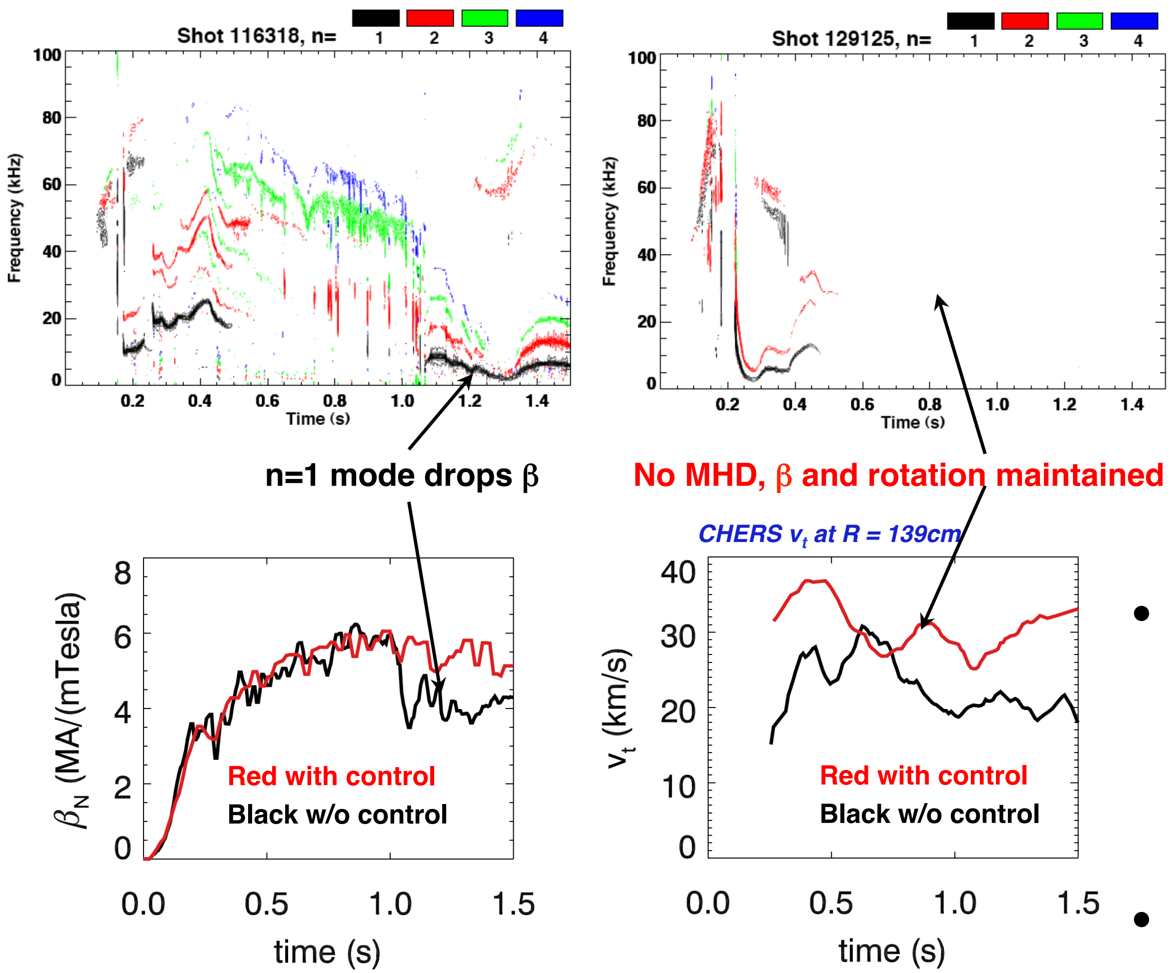
Latency measurements

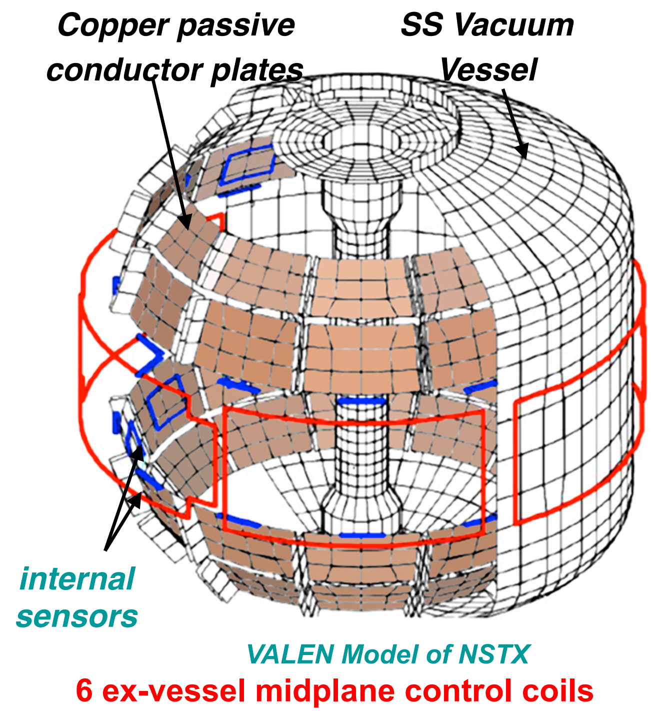
- One step latency measurement system installed
- Present latency measured at 0.54ms



RWM feedback controls instabilities

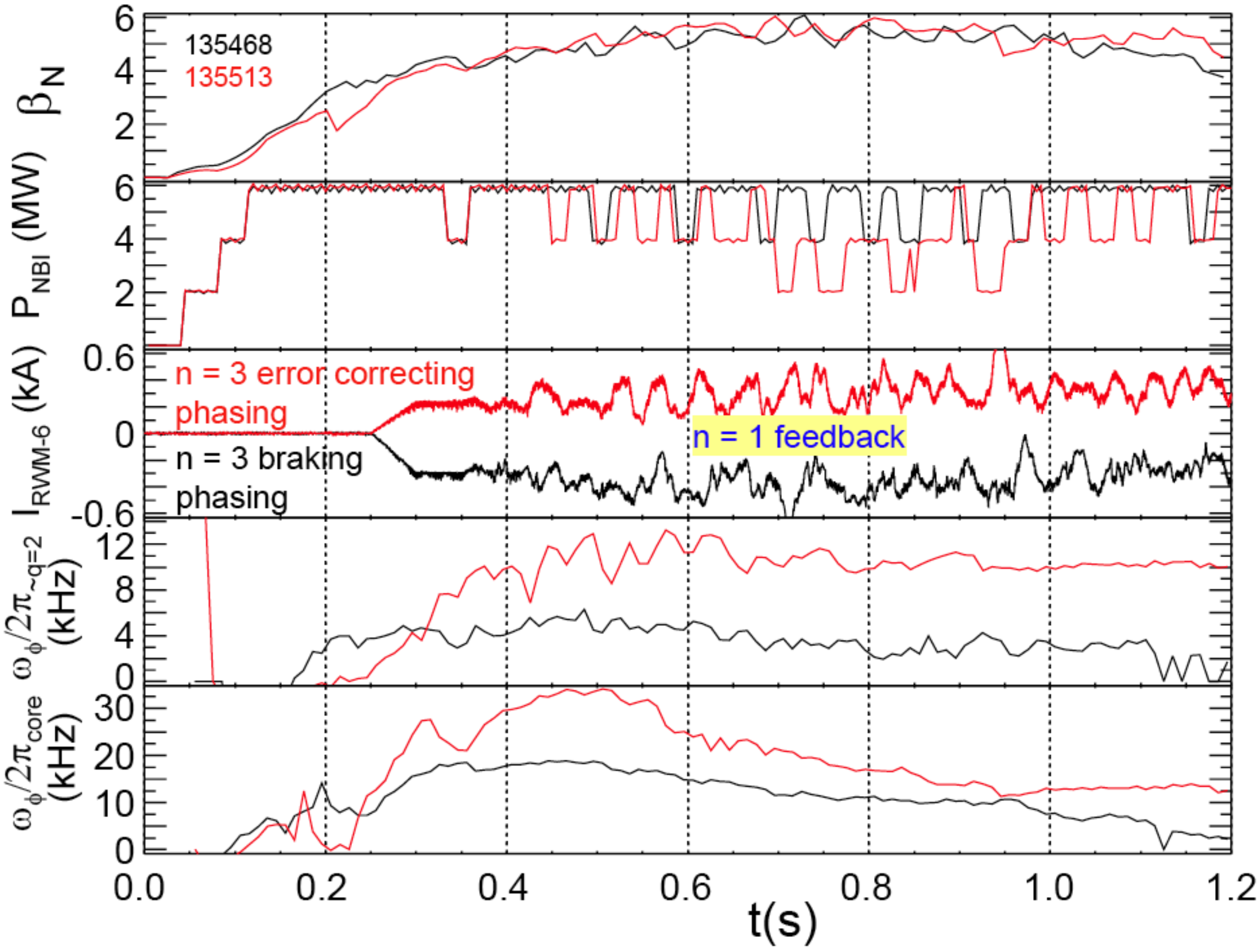
- ***MHD spectrogram w/o n=1 feedback and n=3 correction***
- ***MHD spectrogram with n=1 feedback and n=3 correction***





- Non-axisymmetric feedback algorithm
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Control statistically raises β and increase pulse length

β_N feedback combined with n = 1 RWM control to reduce β_N fluctuations at varied plasma rotation levels



- Prelude to ω_ϕ control
  - Reduced ω_ϕ by n = 3 braking does not defeat FB control
  - Increased P_{NBI} needed at lower ω_ϕ
- Steady β_N established over long pulse
  - independent of ω_ϕ over a large range

Summary

- NSTX control system is CPU based with a distributed serial data acquisition system
- Software is designed to have flexible components
  - Categories, phases, algorithms
- The system is well established
- New development is a continuous process