

# NSTX plasma control system

D. A. Gates

Presented at the NSTX operator  
training

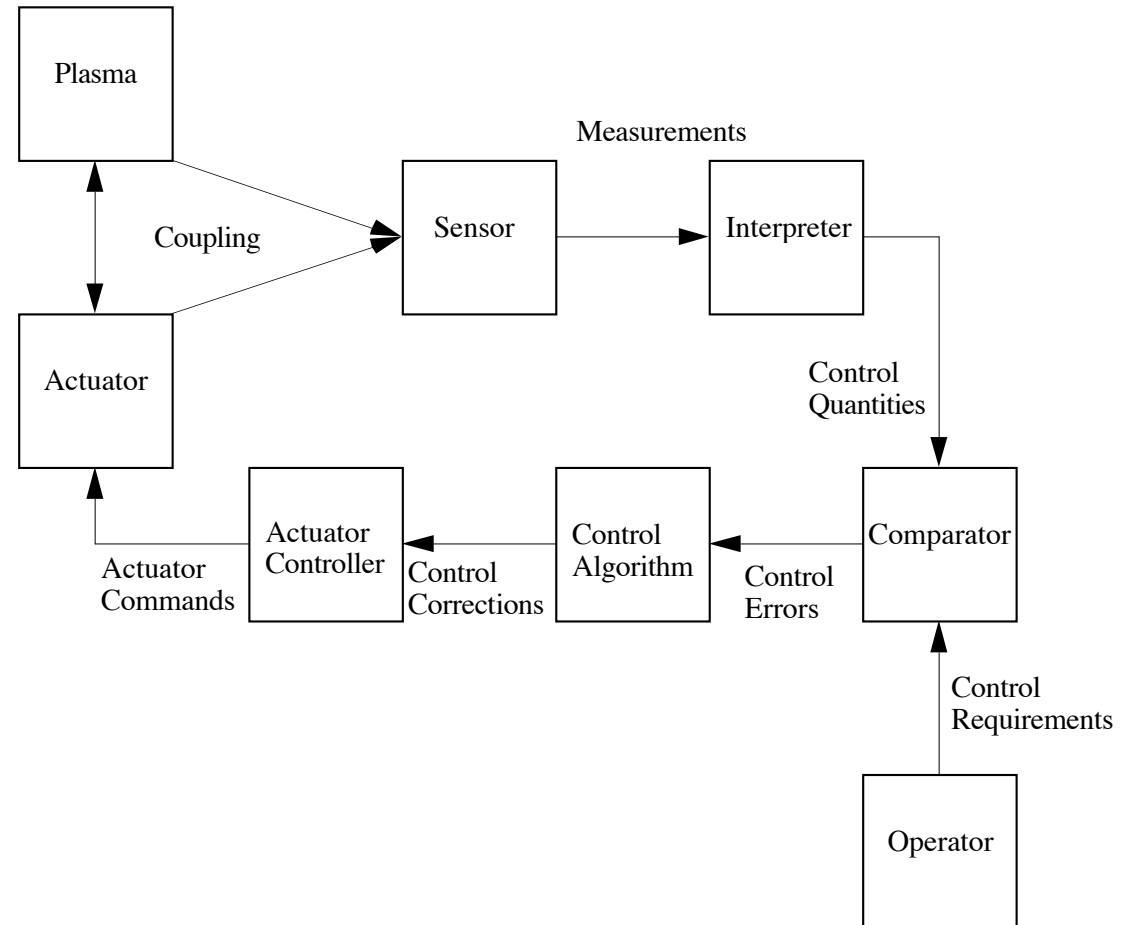
2/9/10

# Outline

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

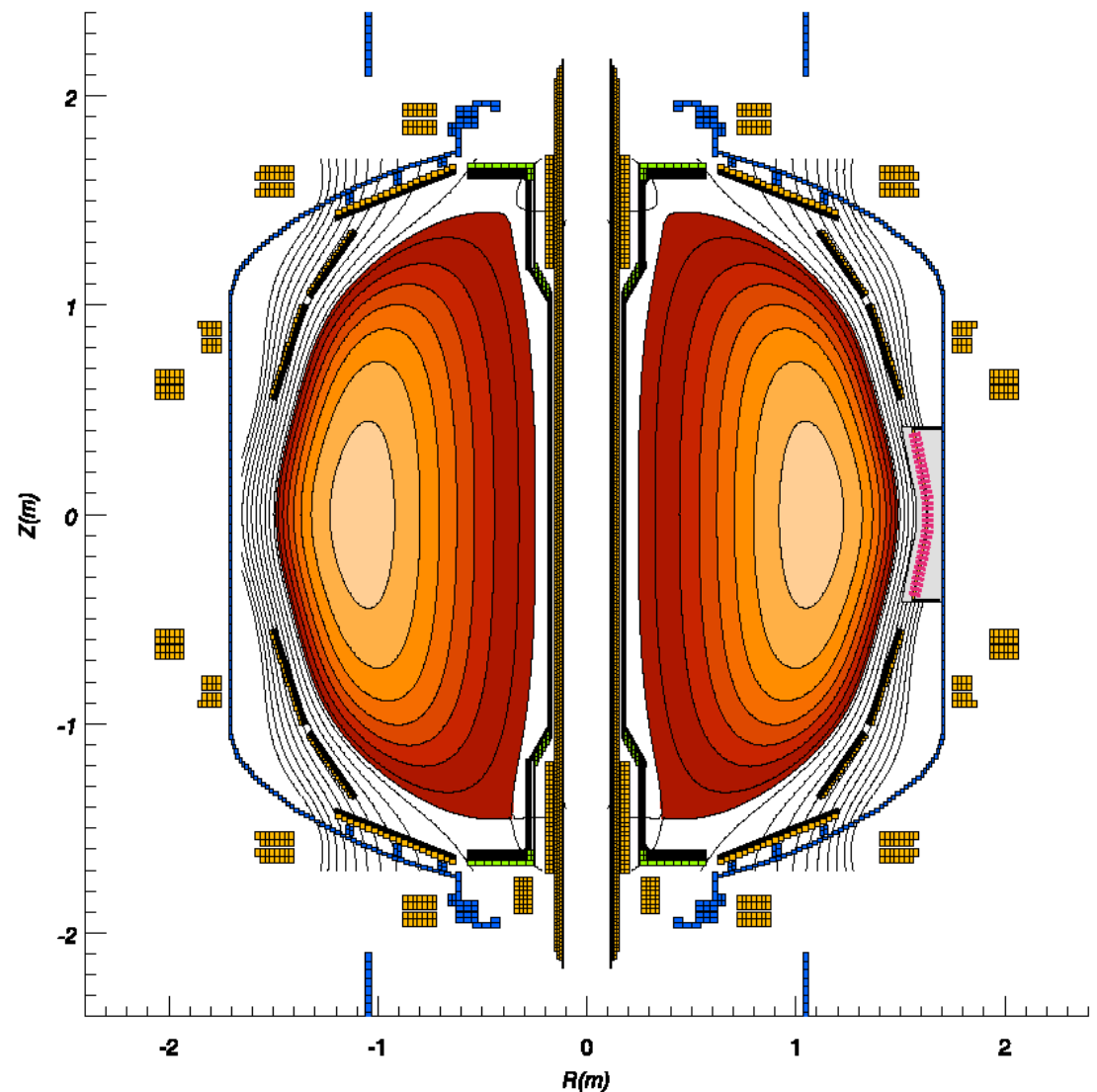
# Control System Basics

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



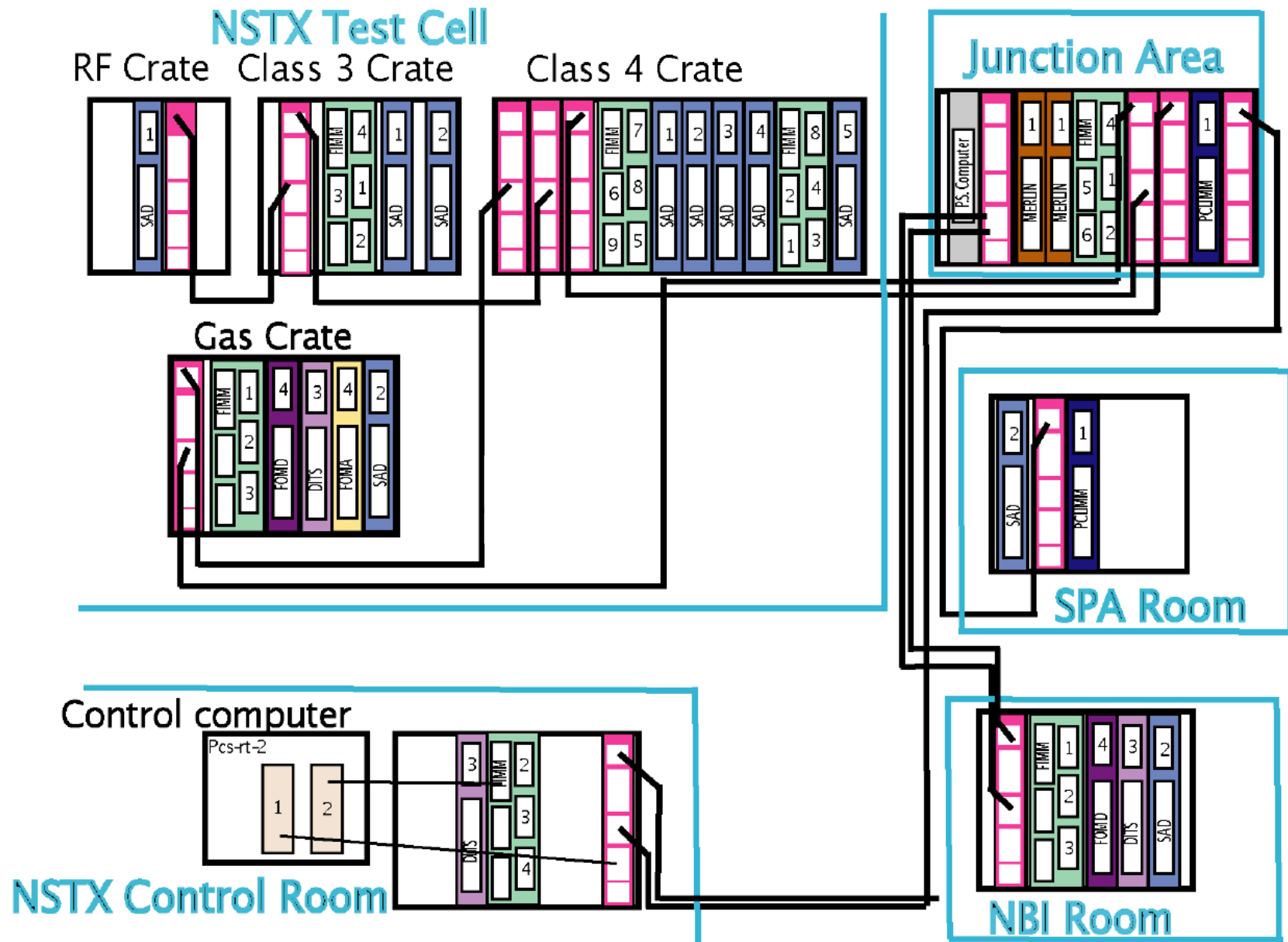
# Control system goals

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





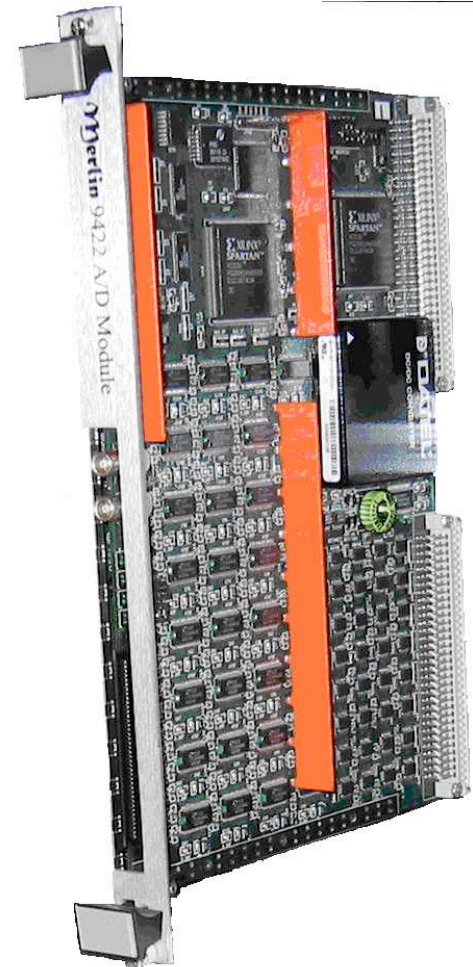
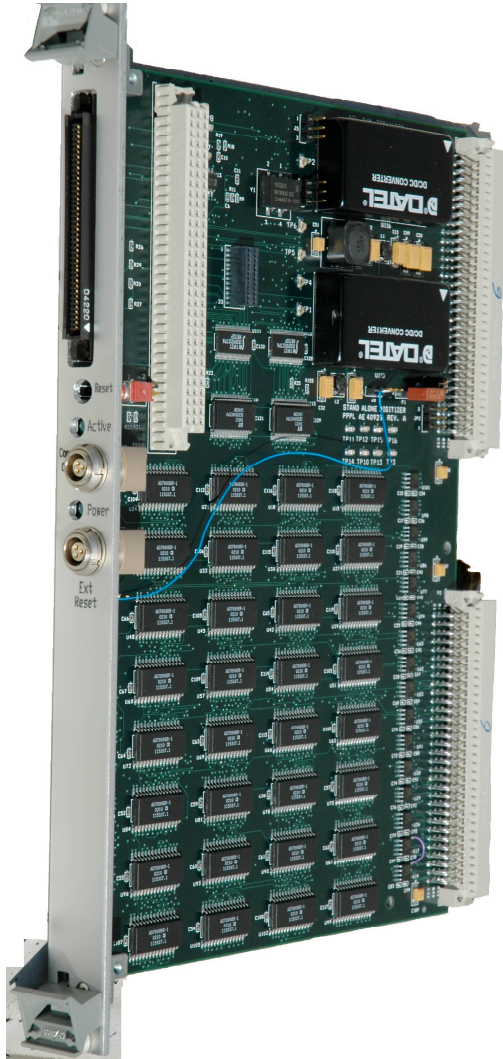
# Control system block diagram



# Digitizers

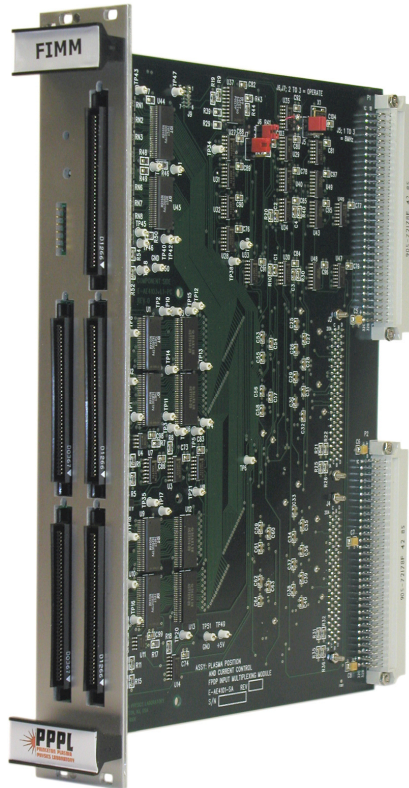
## Input modules

- Data is converted into digital signals and transmitted by a point to point Gigabit data transmission standard called FPDP (Front panel data port)

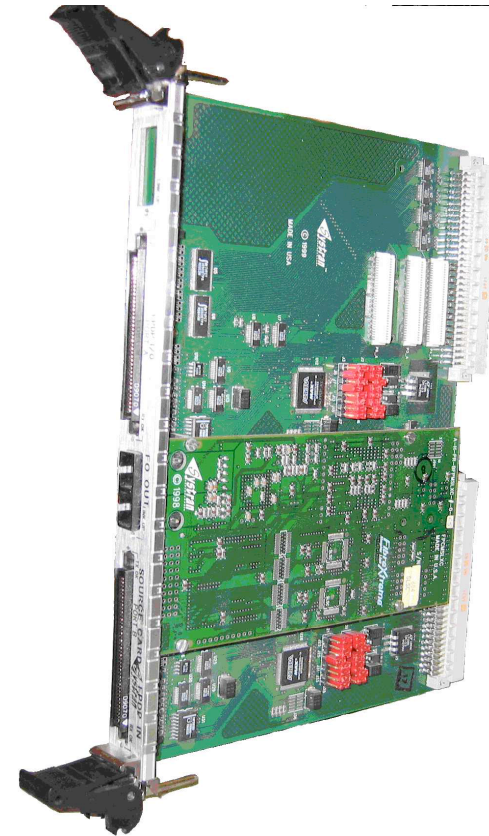


# Telemetry

Data can be combined and transmitted from anywhere in the laboratory complex with 4  $\mu$ second delay

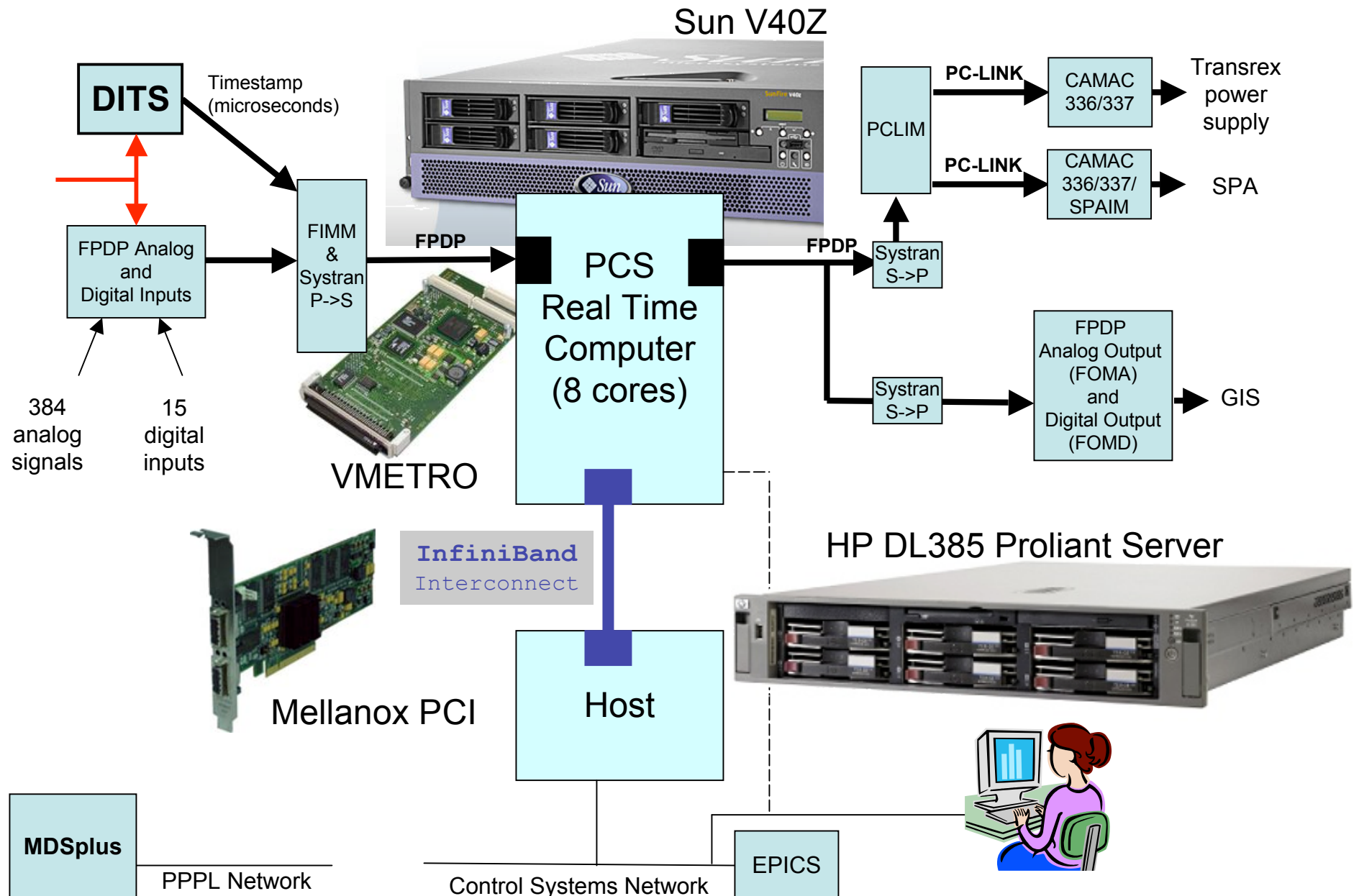


FPDP Input Multiplexing Module (PPPL) - combines Signals from four FPDP sources  
(can be daisy chained)



Systran FiberXtreme converts parallel FPDP to/from Serial FPDP  
F/O transmitter/receiver  
1Gbit/s 5 km transmission

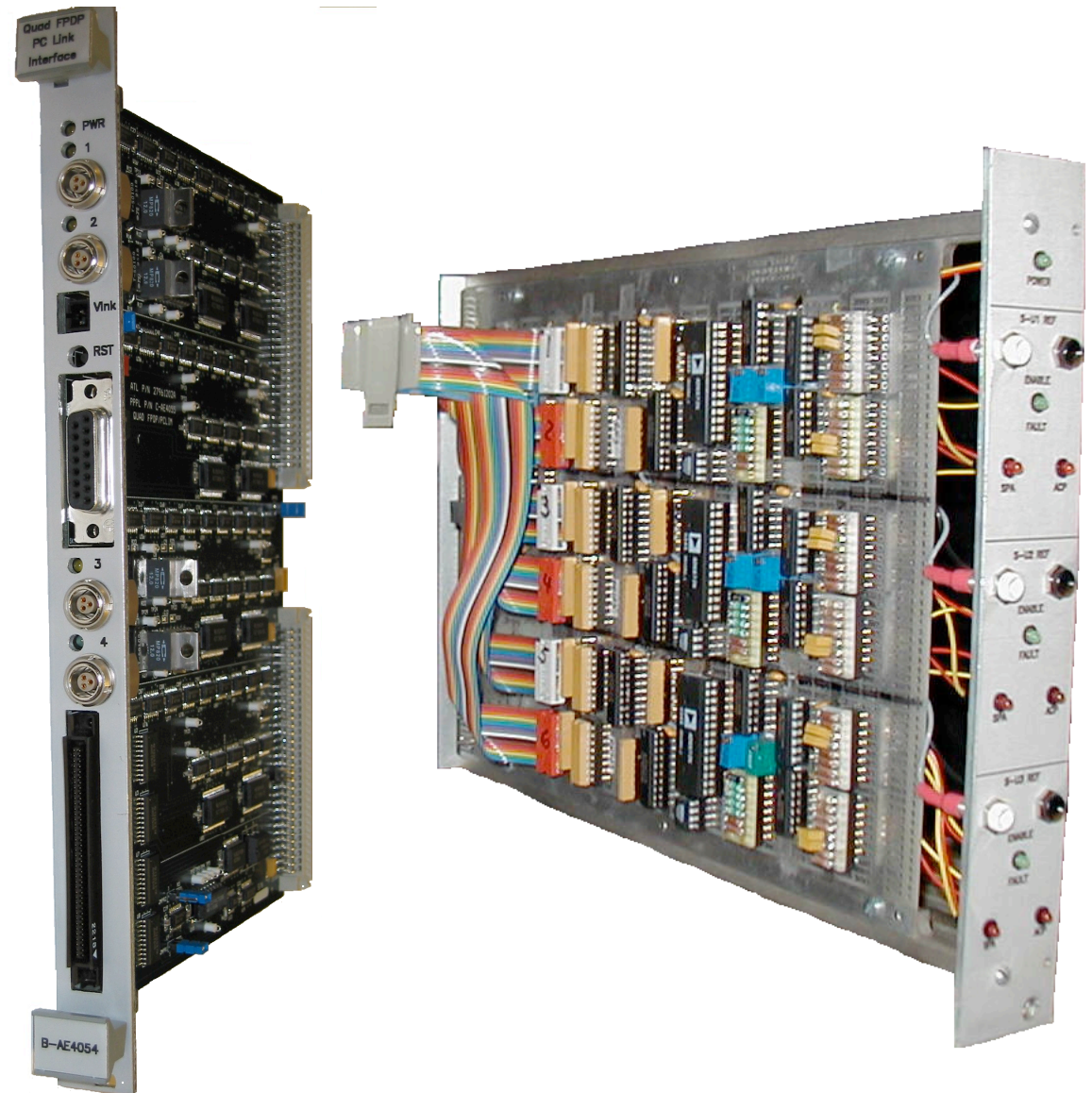
# Computers



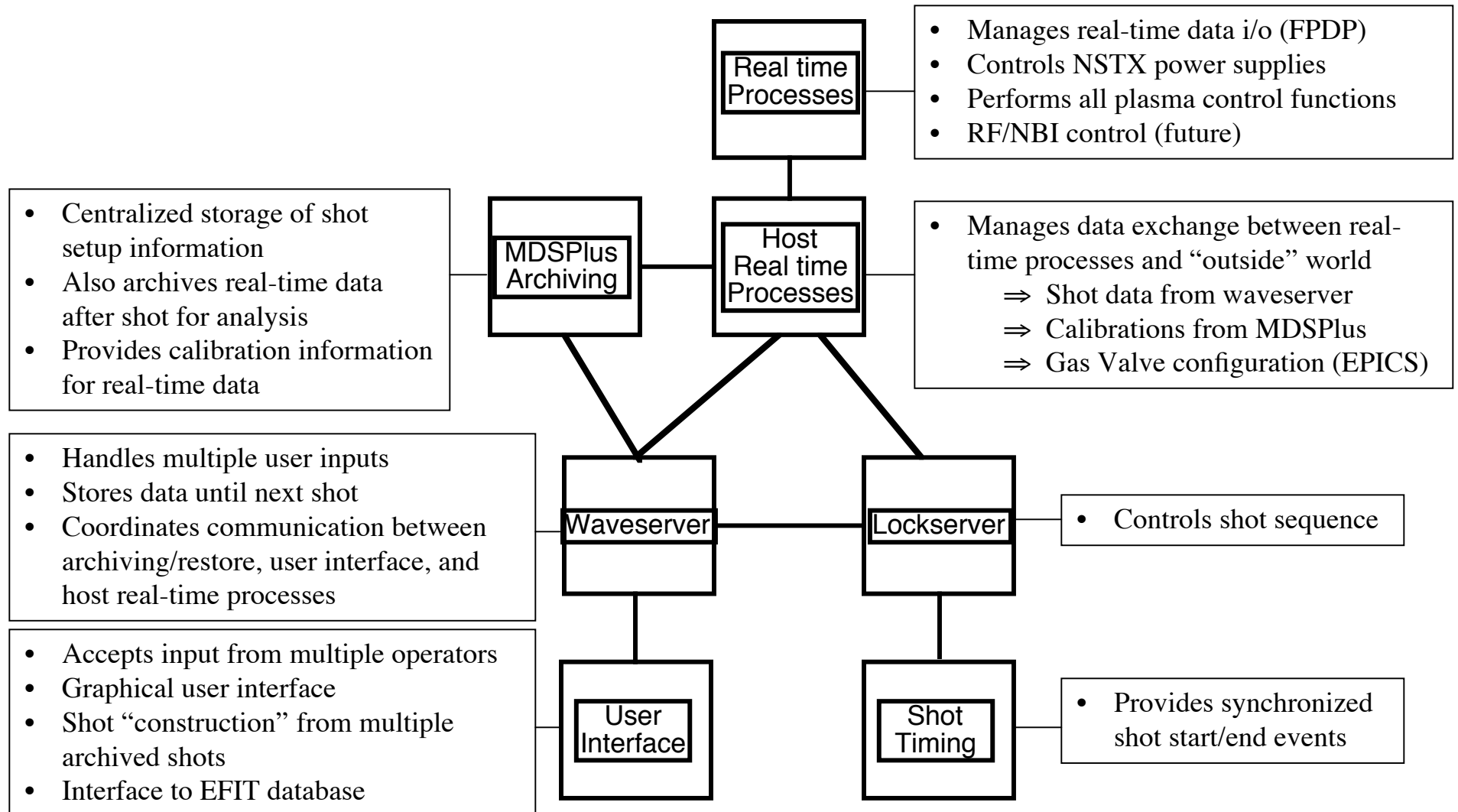


# Outputs

- 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

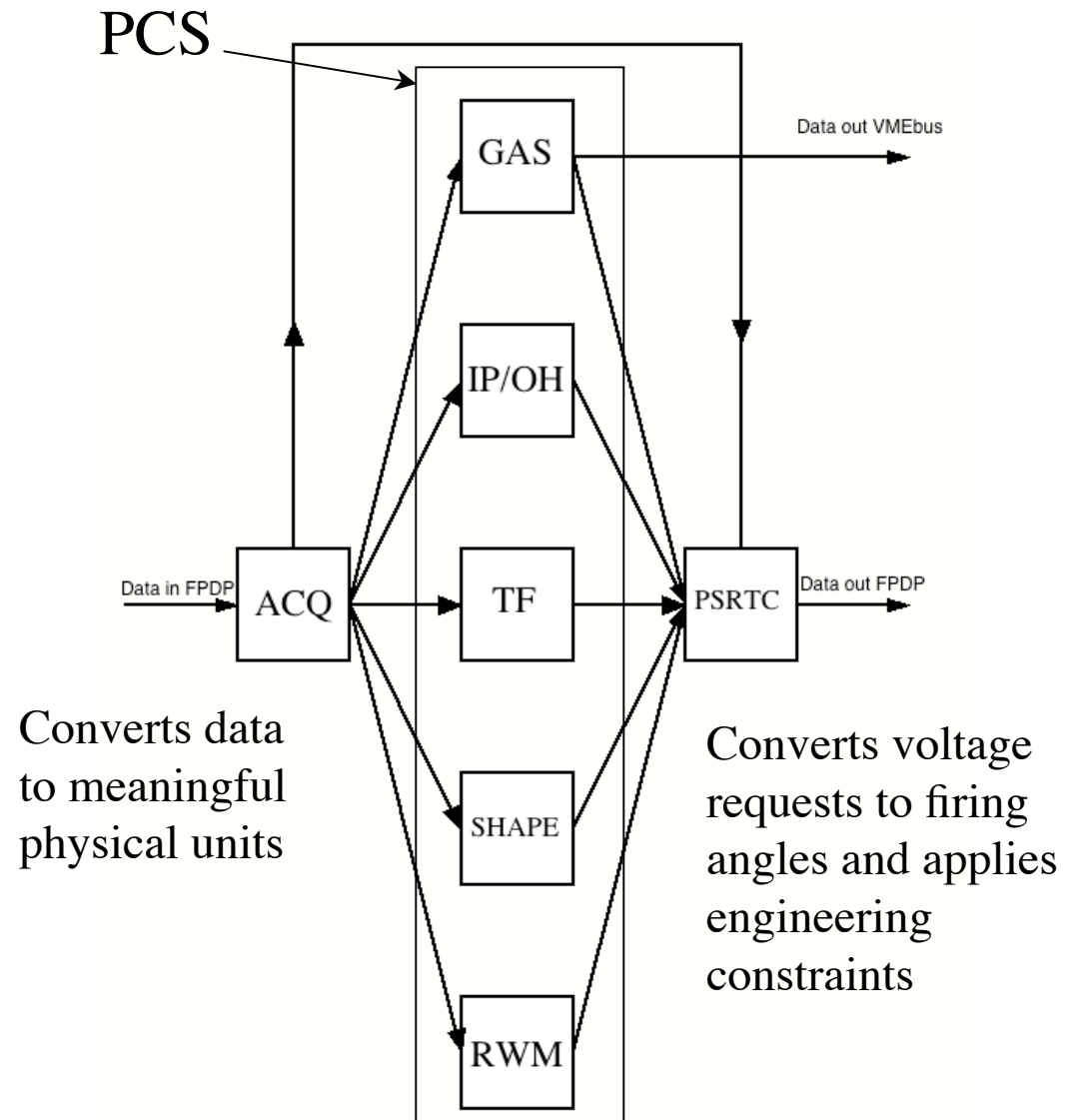


# Flexible Software Infrastructure



# 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

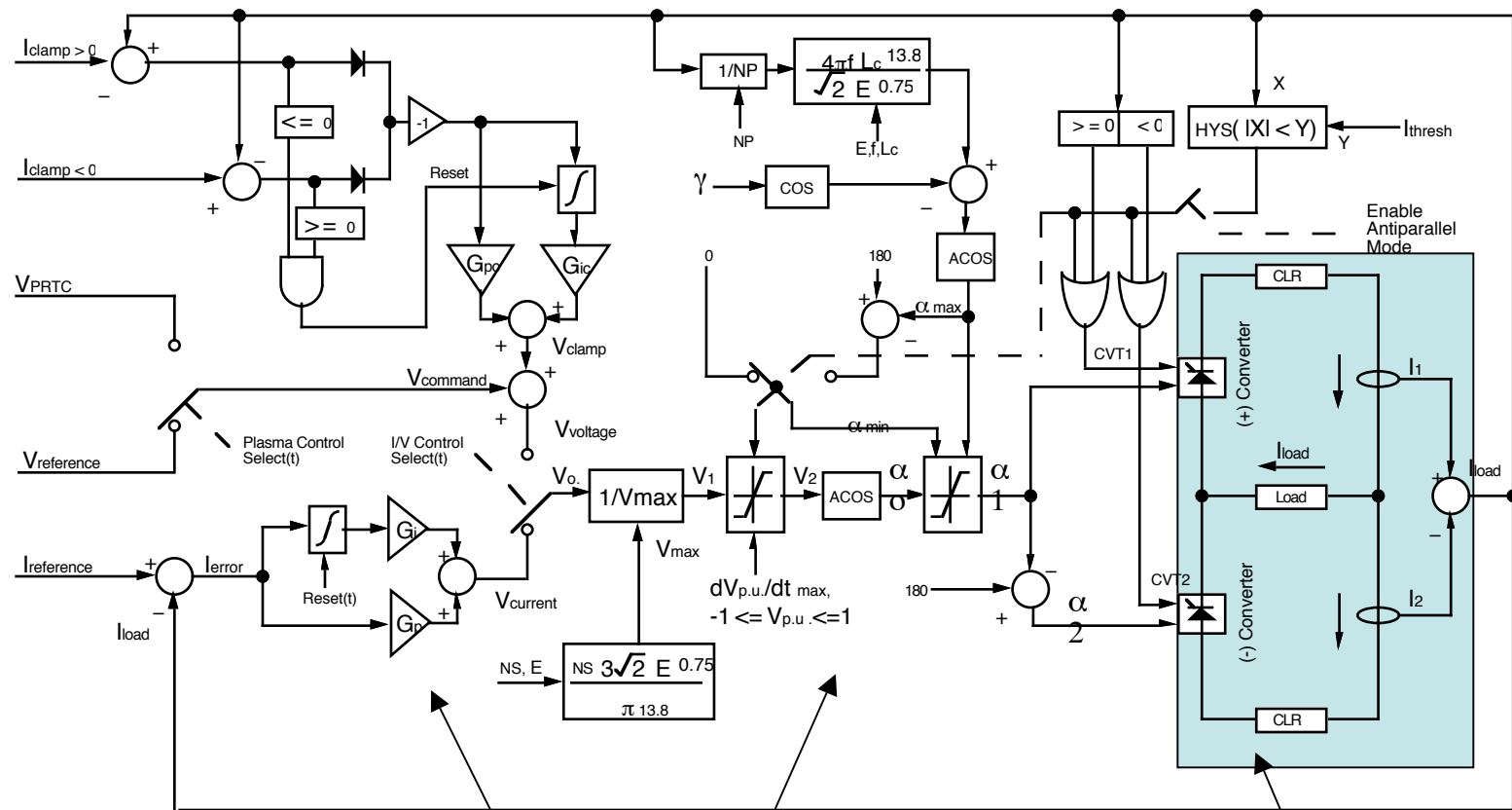
Ip/OH Control	Controls OH current (pre/post shot) or Ip (during shot)
TF Control	Controls Toroidal field current
Gas Injection	Controls gas flow either pre-programmed neutral pressure feedback (prefill) or ne feedback {future}
Discharge Shape	Controls PF coil currents (pre/post shot) plasma shape with 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

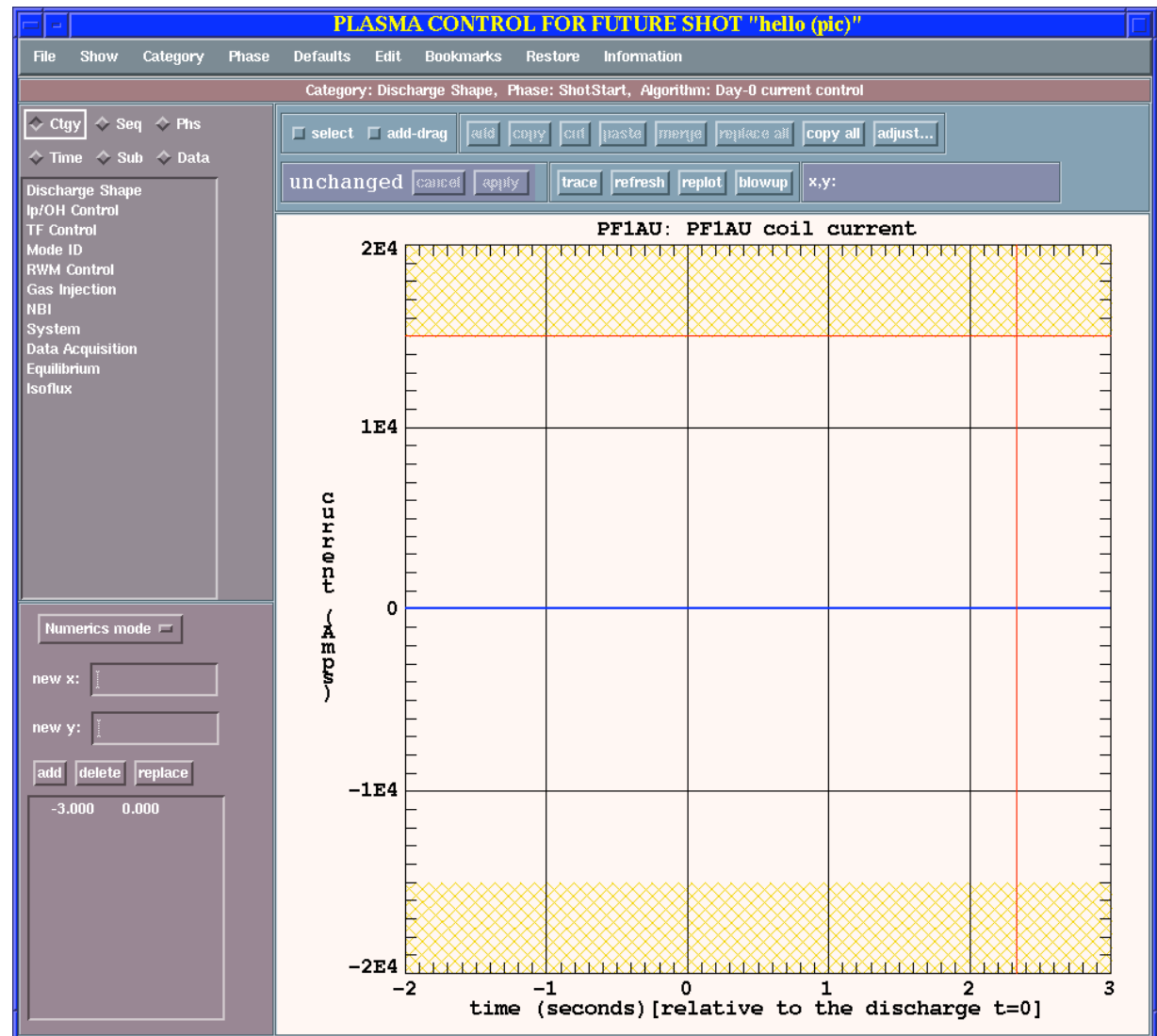


# Control Software

## Power supply

# 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....

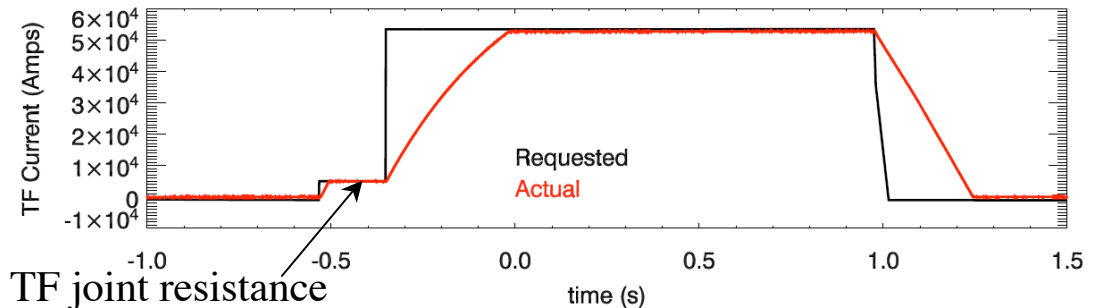
## Each category can have several phases

- 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)

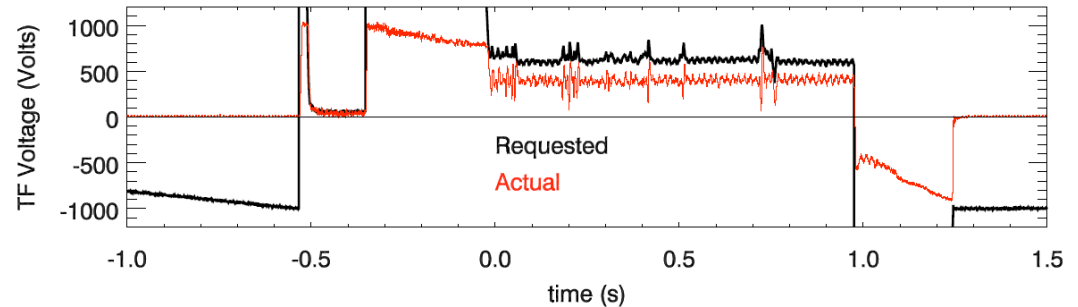
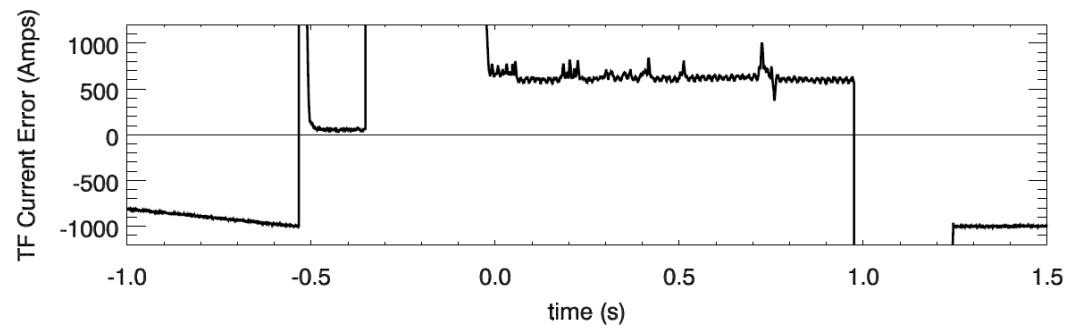
# TF control

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

Shot 112403

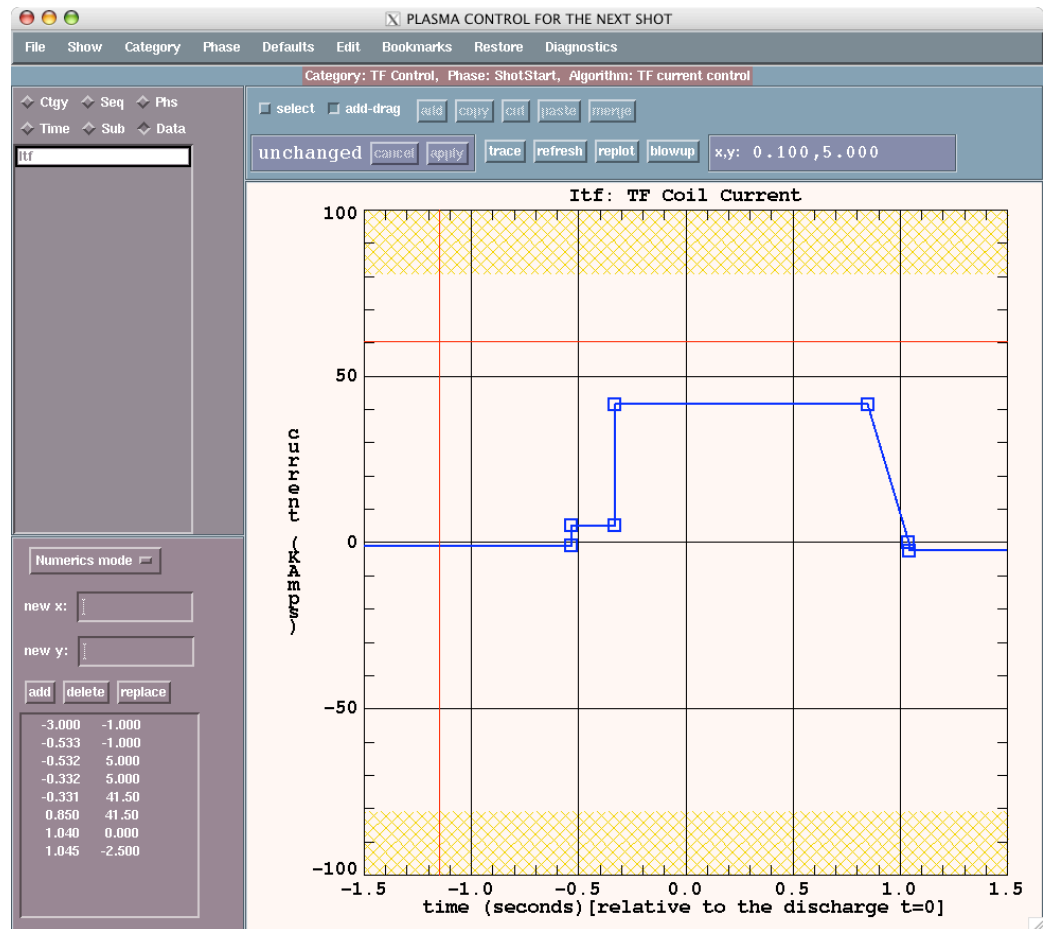


TF joint resistance measurement pulse



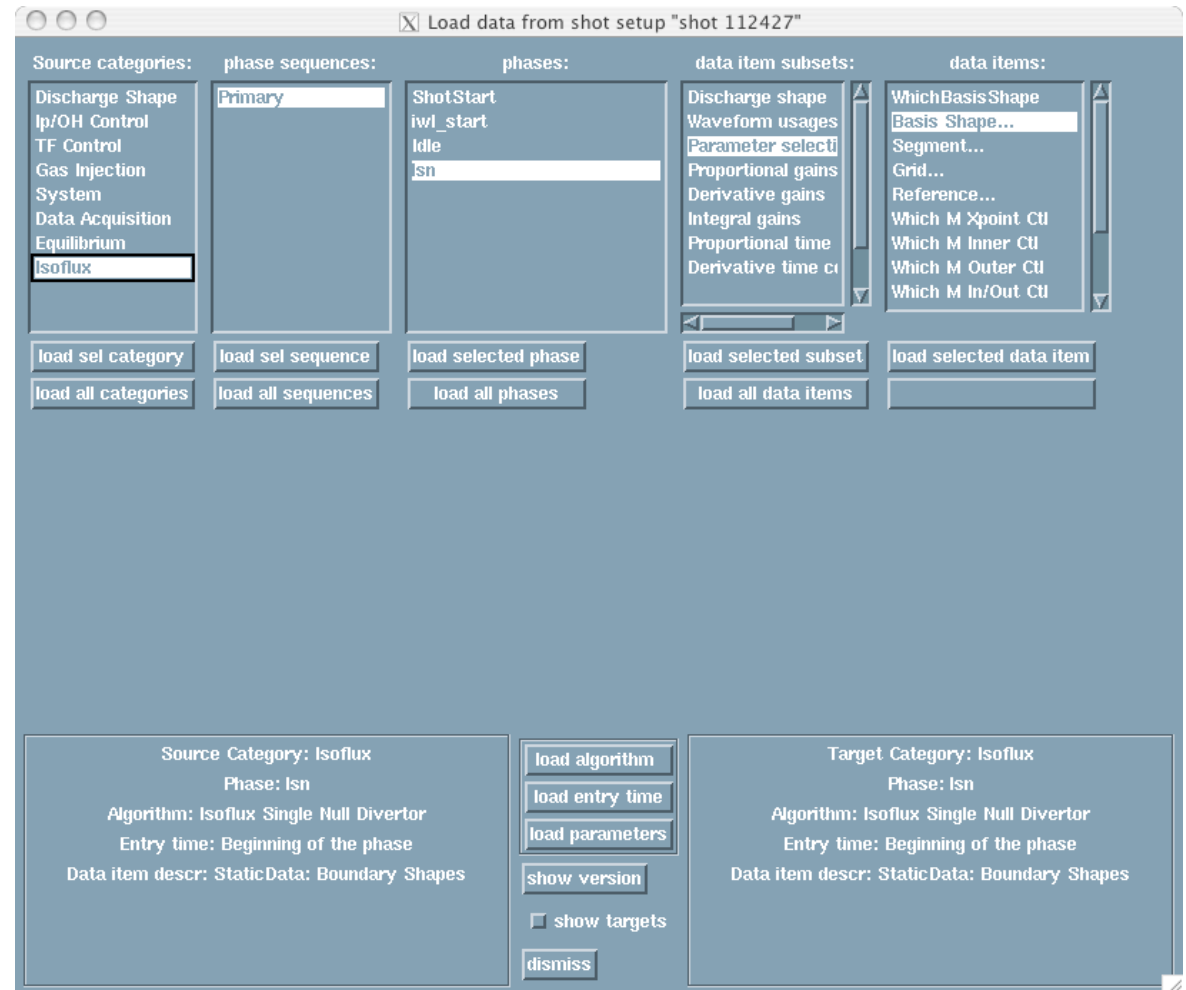
# TF control (cont.)

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



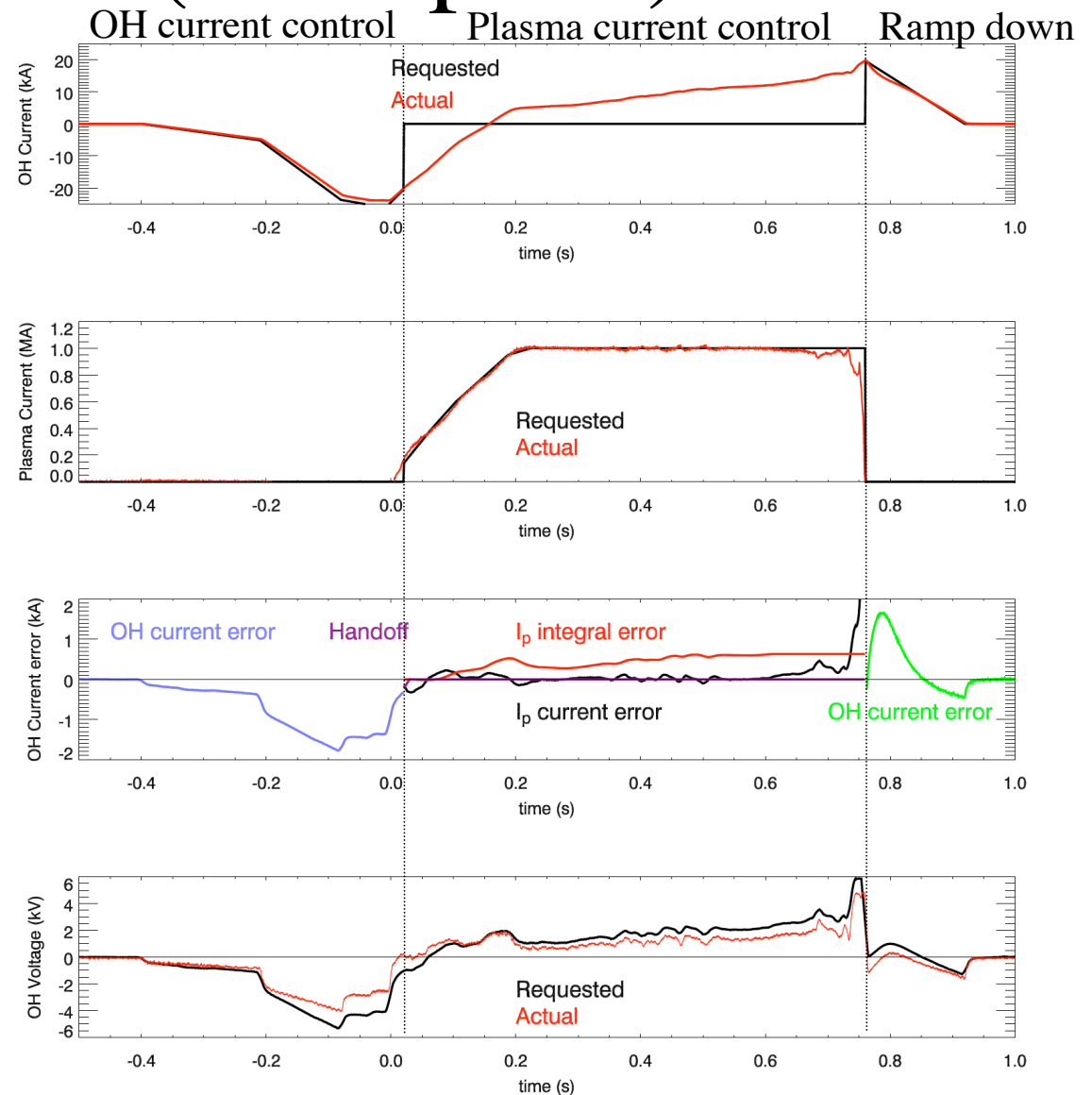
# Shot restore function

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



# $I_p$ 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

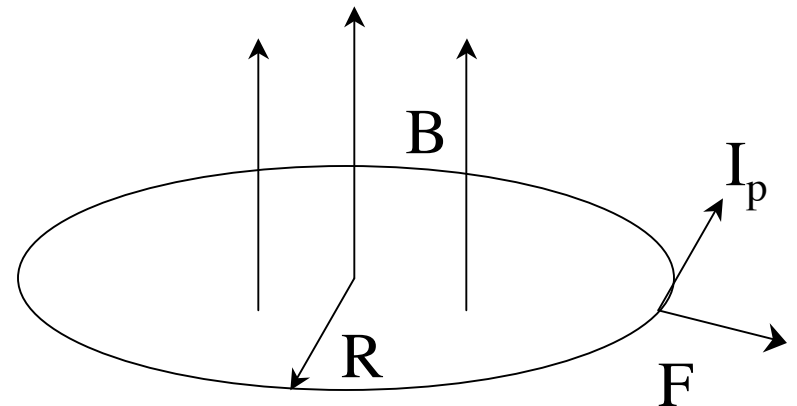
$$J \times B = \nabla P \quad \Rightarrow \quad R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial z^2} = \mu_0 R^2 \frac{dP}{d\psi} - F \frac{dF}{d\psi}$$

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



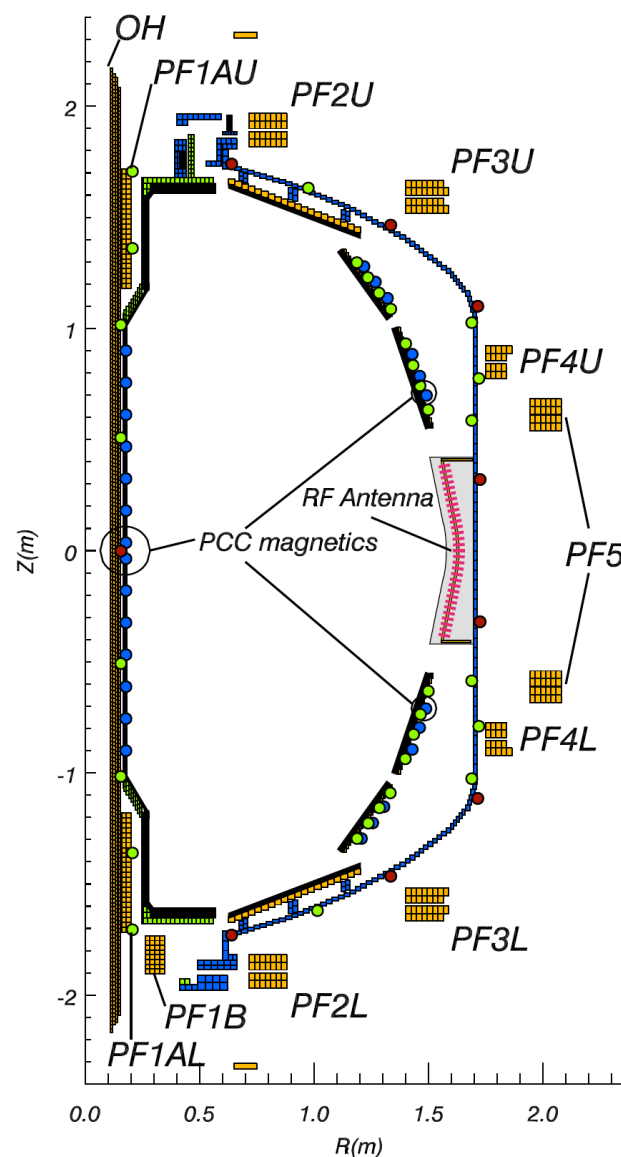
# Plasma force balance

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



# rtEFIT boundary value problem

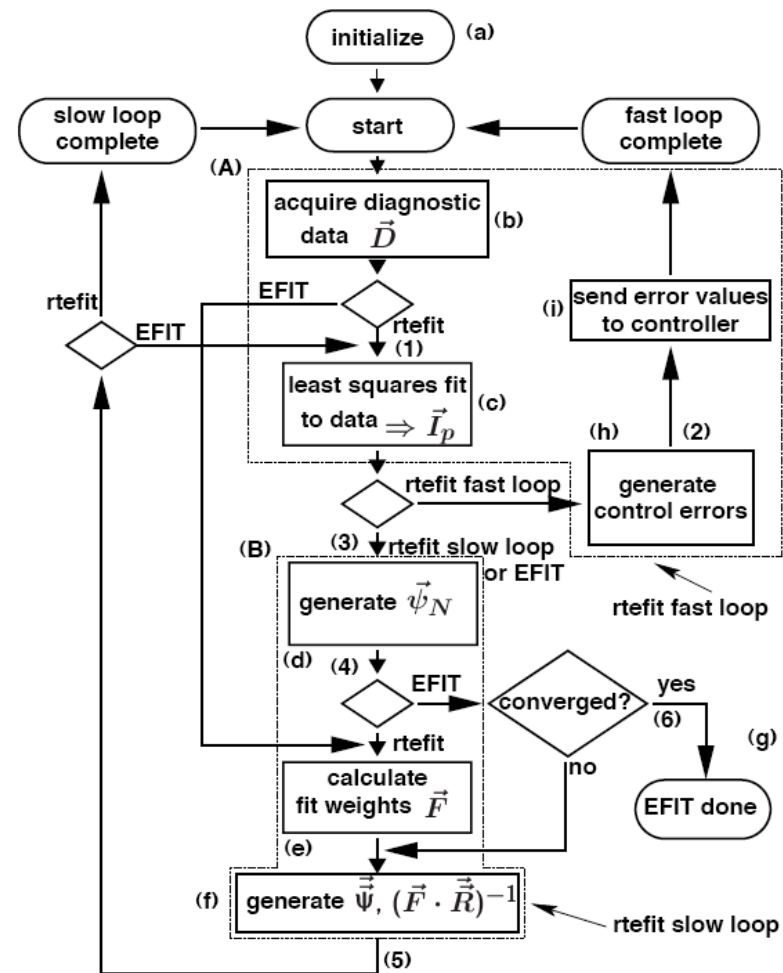
- Measure the magnetic fluxes and fields on the vessel boundary (70 measurements)
- Measure the coil and vessel currents (31 measurements)
- Assume a functional form for the current and pressure profiles
- Solve GS equation iteratively



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

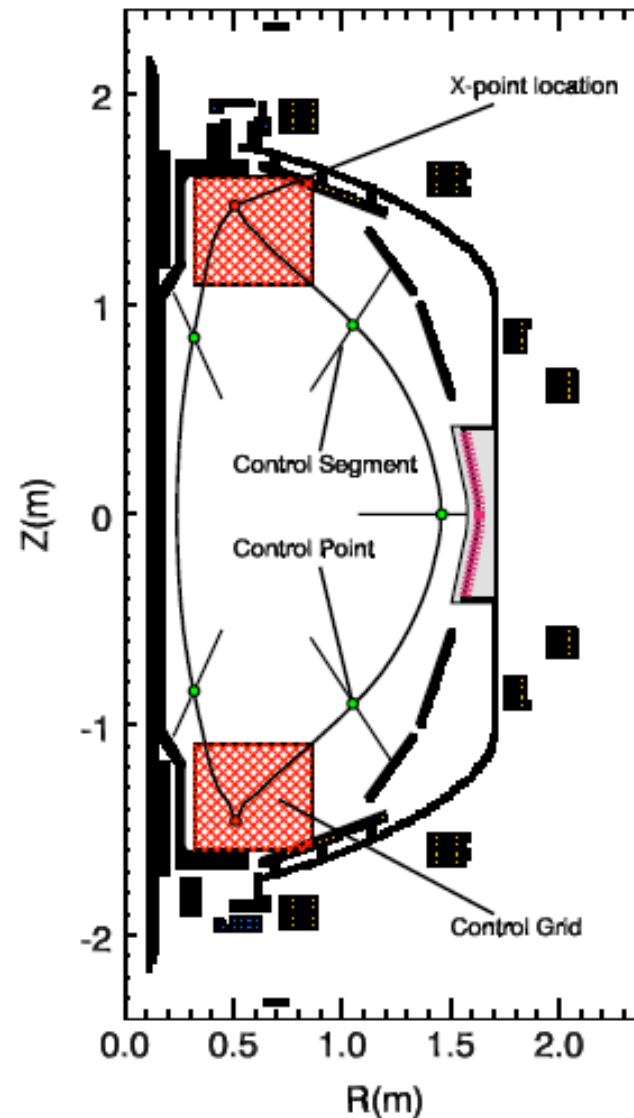
# rtEFIT has slow and fast loops

- rtEFIT does not mimic the offline efrit
  - No iteration to convergence
  - New data on each loop
  - Fast loop generates new control commands based on 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

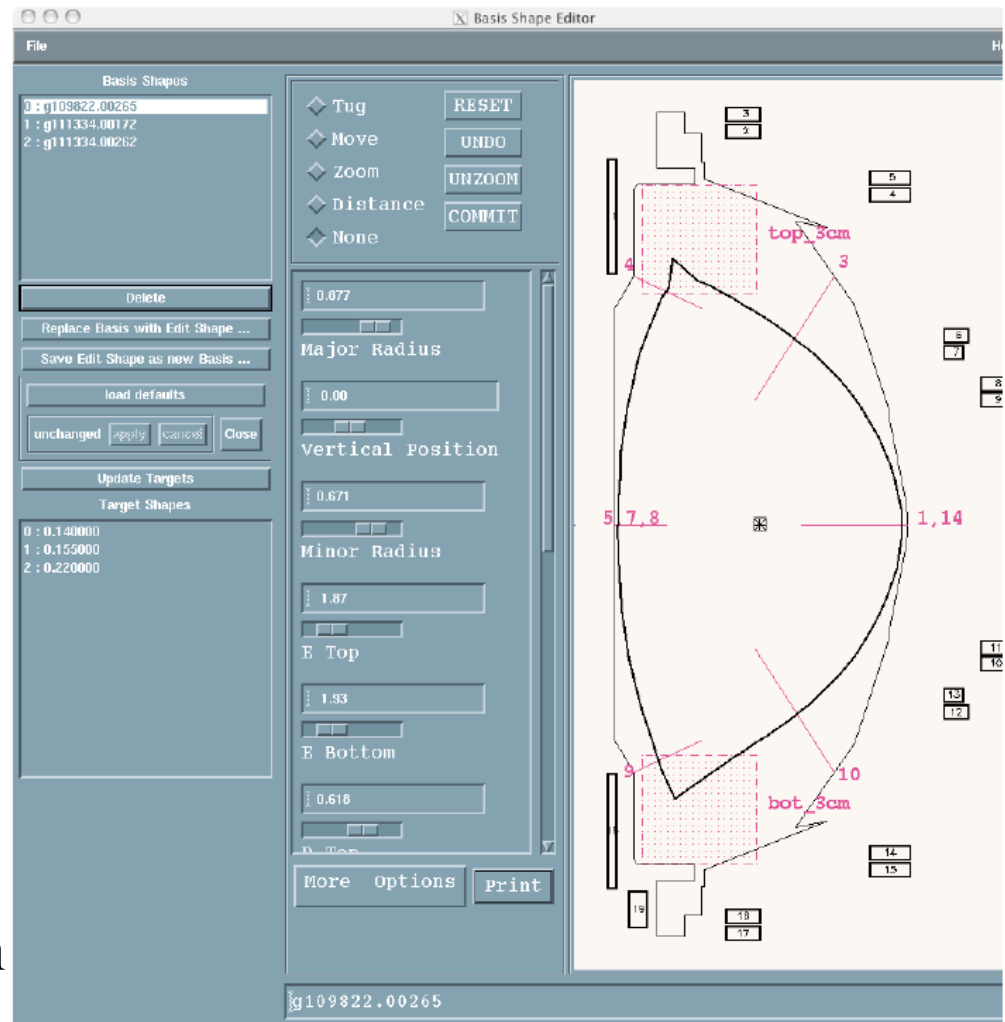


# Isoflux control algorithm

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

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

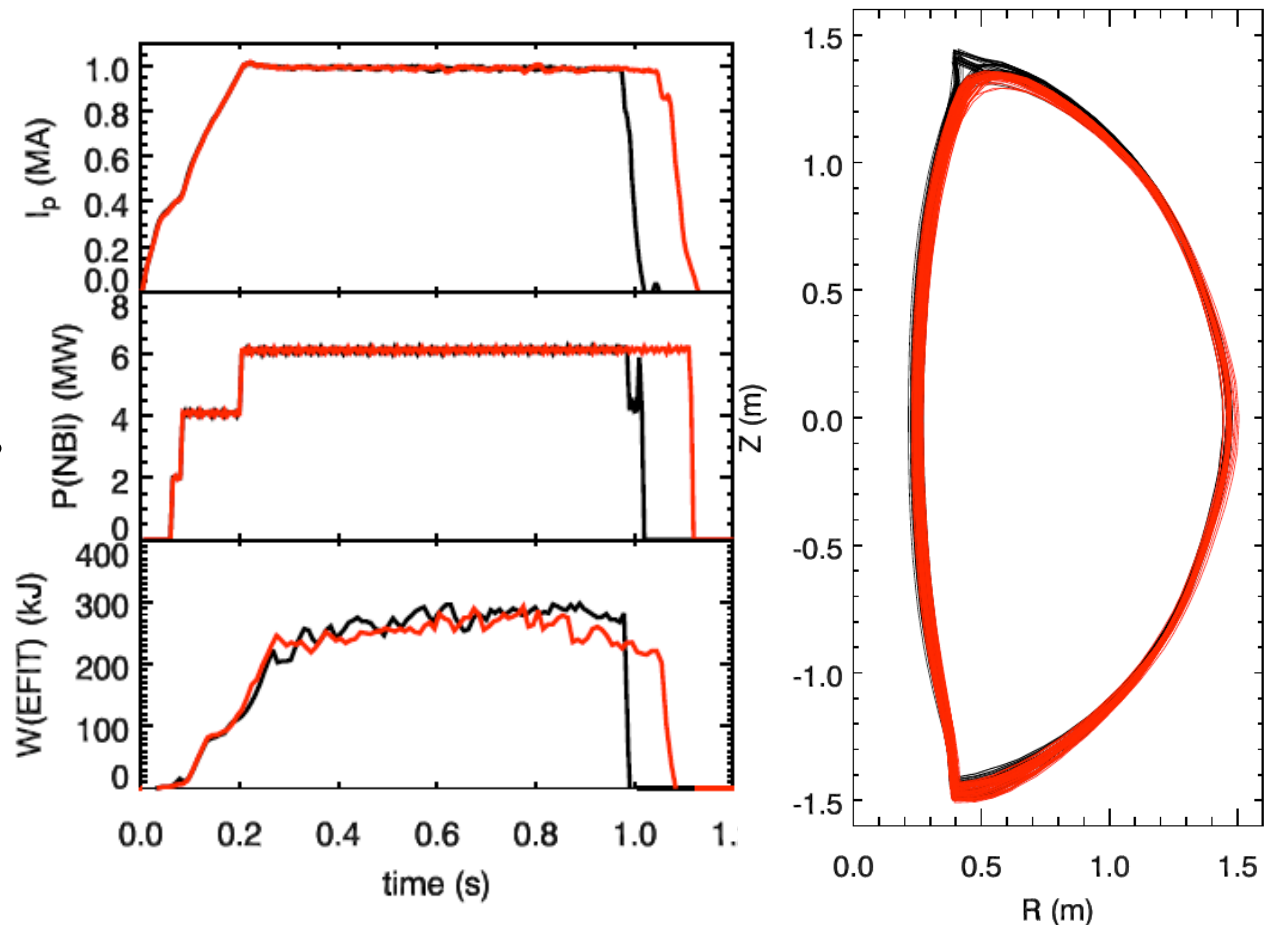
- Dynamic shape variations possible by allowing control points to move along control “segments”
- Segments defined by user (can be changed shot-to-shot)



# Real-time EFIT enables precise boundary control

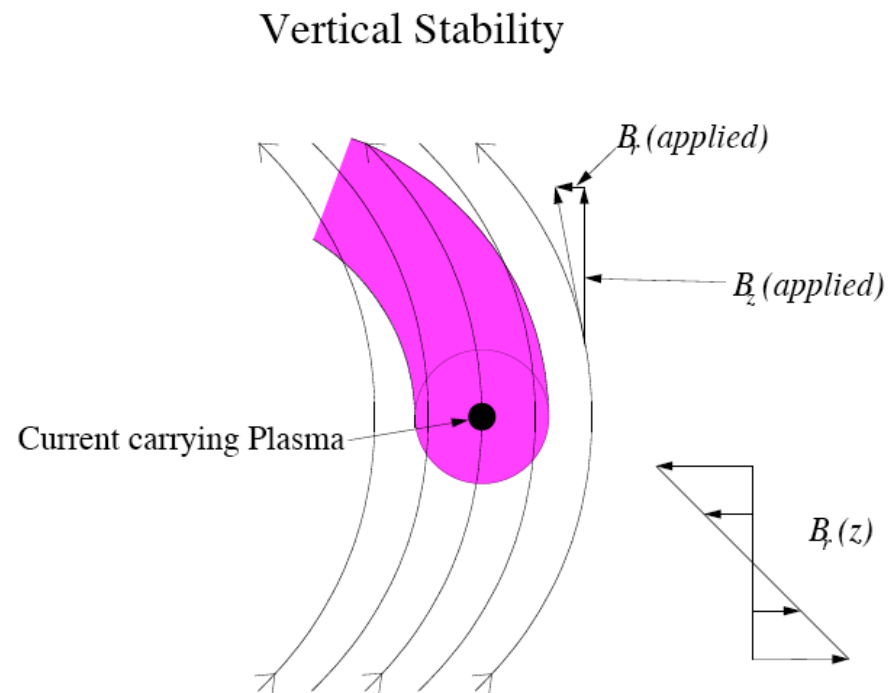
- Collaboration with General Atomics has brought real-time equilibrium calculations used for control to the ST
- Longest 1MA discharge on NSTX made using rtEFIT/isoflux control
- Precise control makes detailed shape variations possible - important research tool

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

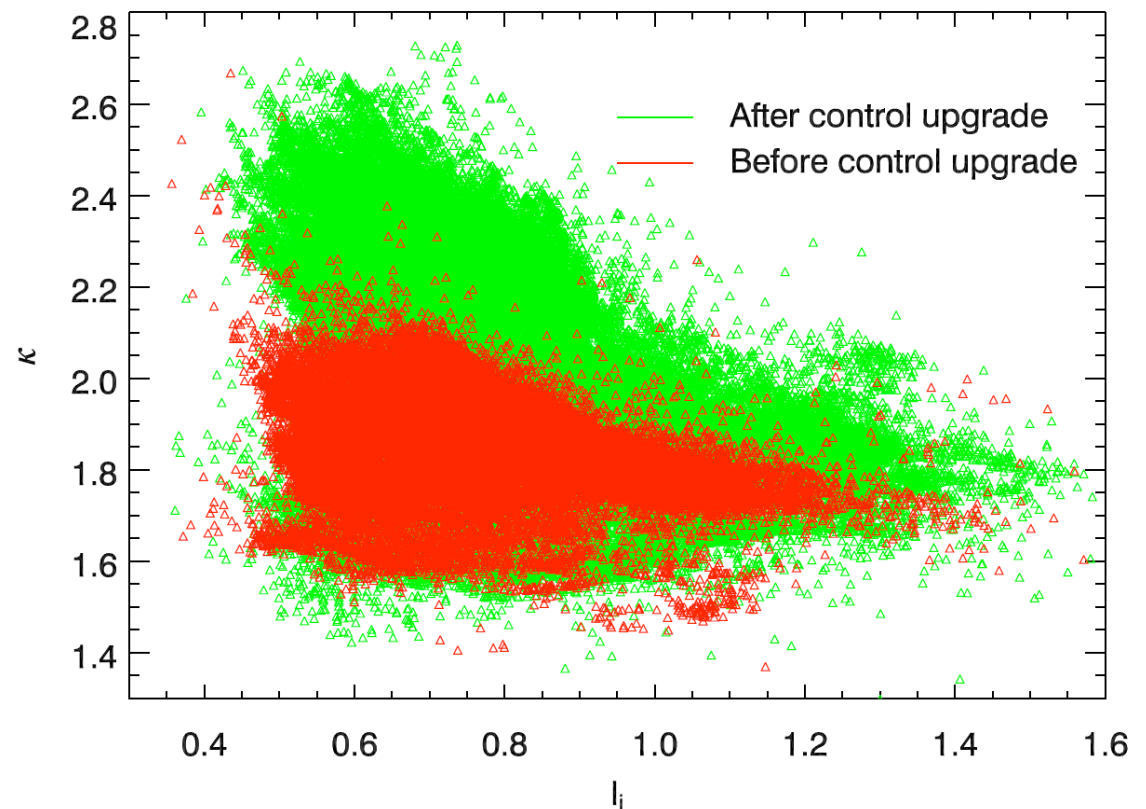


For a vertically stable plasma, as the plasma moves up, it encounters a radial field that pushes it down

# NSTX control system has achieved high $\kappa$

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

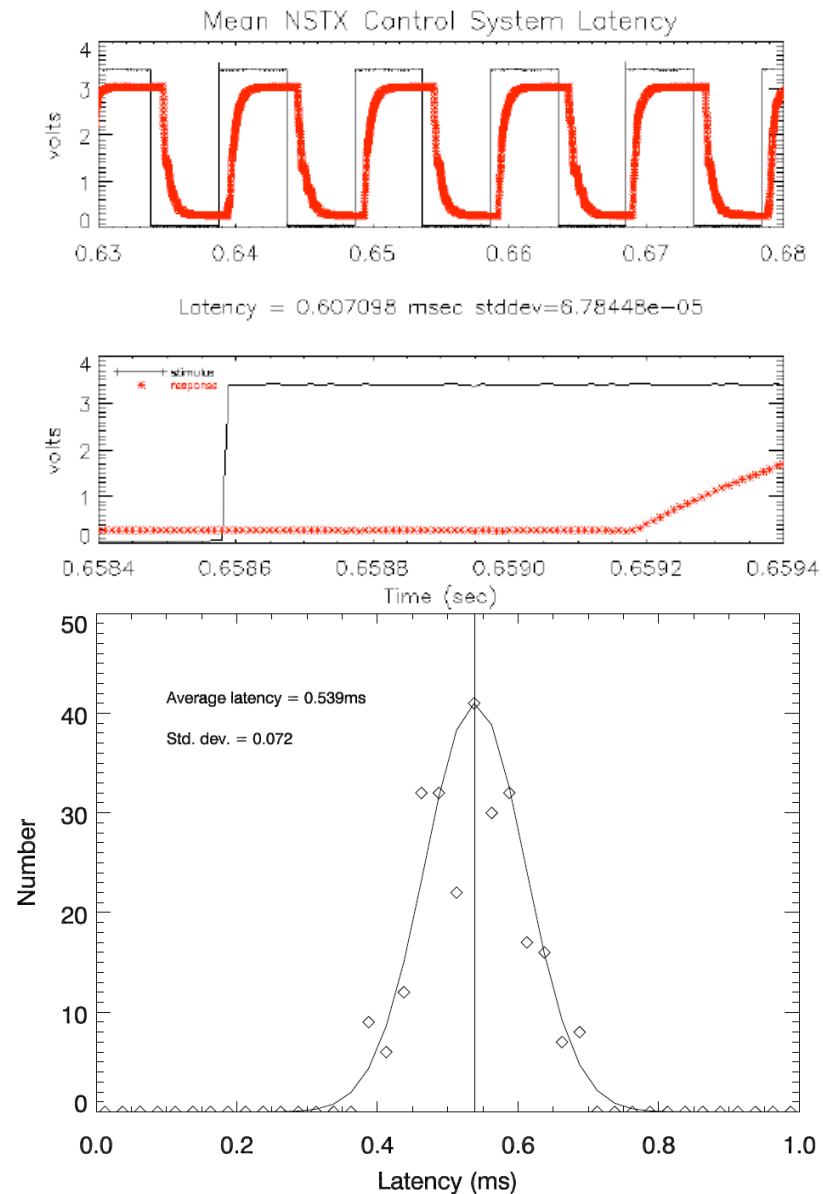
Graph showing the vertical stability space for NSTX,  $\kappa = b/a$  is the plasma elongation and  $l_i$  is the normalized internal inductance. The boundary of the data is roughly a curve of constant vertical growth rate.





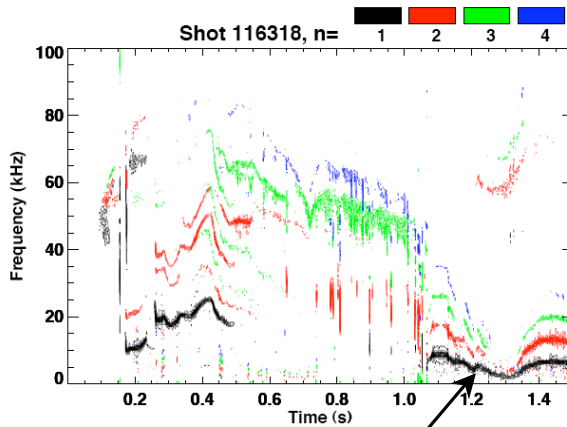
# Latency measurements

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

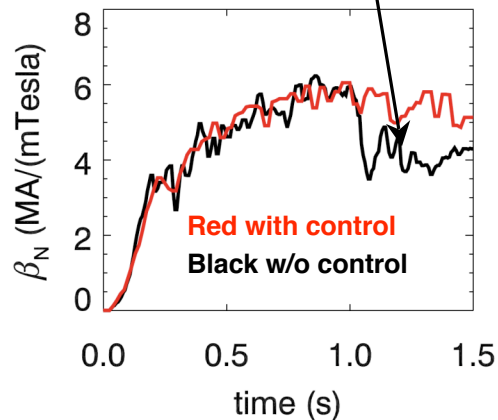


# RWM feedback shows promise

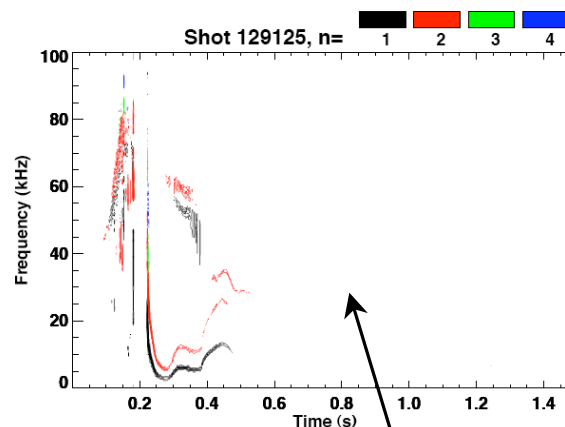
- MHD spectrogram w/o  $n=1$  feedback and  $n=3$  correction



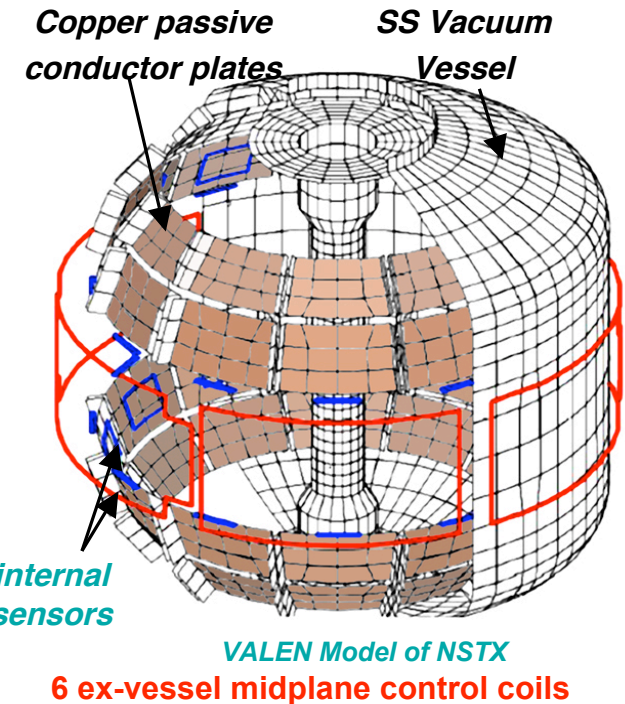
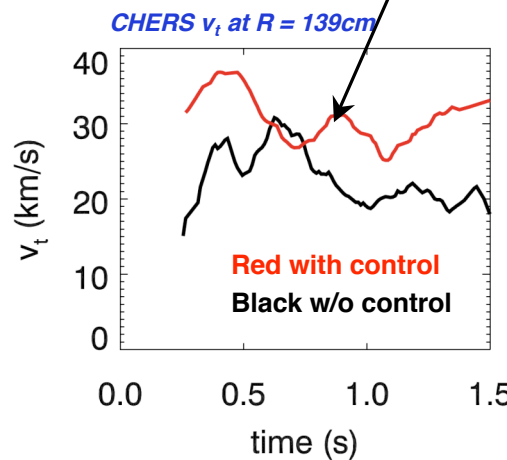
$n=1$  mode drops  $\beta$



- MHD spectrogram with  $n=1$  feedback and  $n=3$  correction

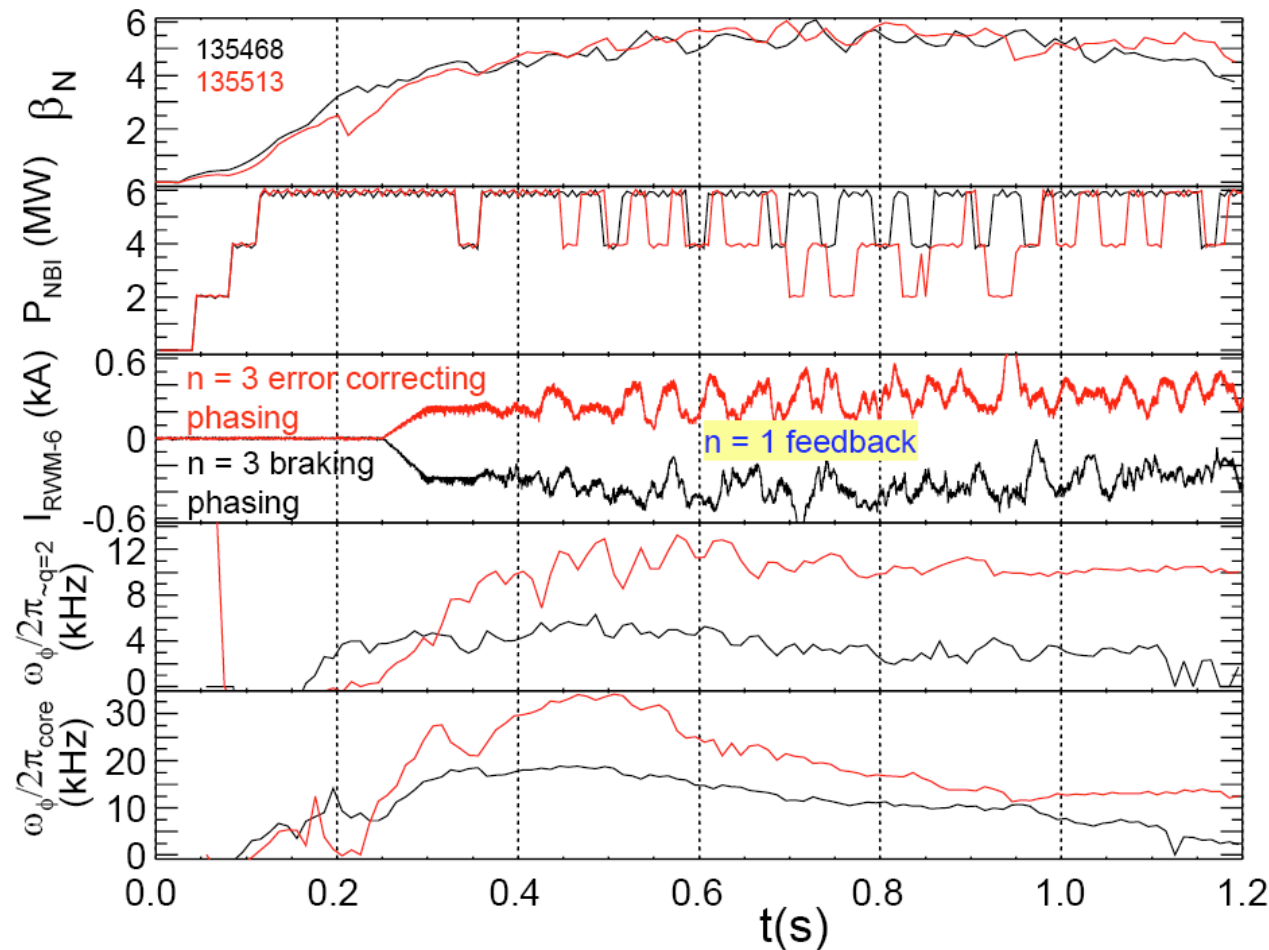


No MHD,  $\beta$  and rotation maintained



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

# $\beta_N$ feedback combined with $n = 1$ RWM control to reduce $\beta_N$ fluctuations at varied plasma rotation levels



- Prelude to  $\omega_\phi$  control
  - Reduced  $\omega_\phi$  by  $n = 3$  braking does not defeat FB control
  - Increased  $P_{\text{NBI}}$  needed at lower  $\omega_\phi$
- Steady  $\beta_N$  established over long pulse
  - independent of  $\omega_\phi$  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