# Abstract

The Phase II PEGASUS ST experiment includes fully programmable power supplies for all magnet coils. These will be integrated with a digital feedback plasma control system (PCS), based on the PCS in use on DIII-D, to provide active feedback control of the plasma evolution. The initial goal is to control $I_p(t)$, R(t), and Z(t). The feedback cycle consists of: 1) sampling magnetic diagnostics, 2) applying a response matrix derived from equilibrium reconstructions, 3) accounting for induced vessel currents and power supply frequency responses, and 4) adjusting the current demand, all on a timescale that is fast compared to the shot duration of ~25 ms. Data is sampled via a 500 kHz, 96-channel CPCI digitizer from D-TACQ Solutions, Ltd. The power supply control signals are generated by 16 analog waveform generators, with the option to utilize 32 digital I/O lines in the future. The PCS digitizer is controlled via a system of Linux-based computers that perform requisite computation-intensive tasks and interface to the existing LabVIEW control codes via a TCP/IP network link.

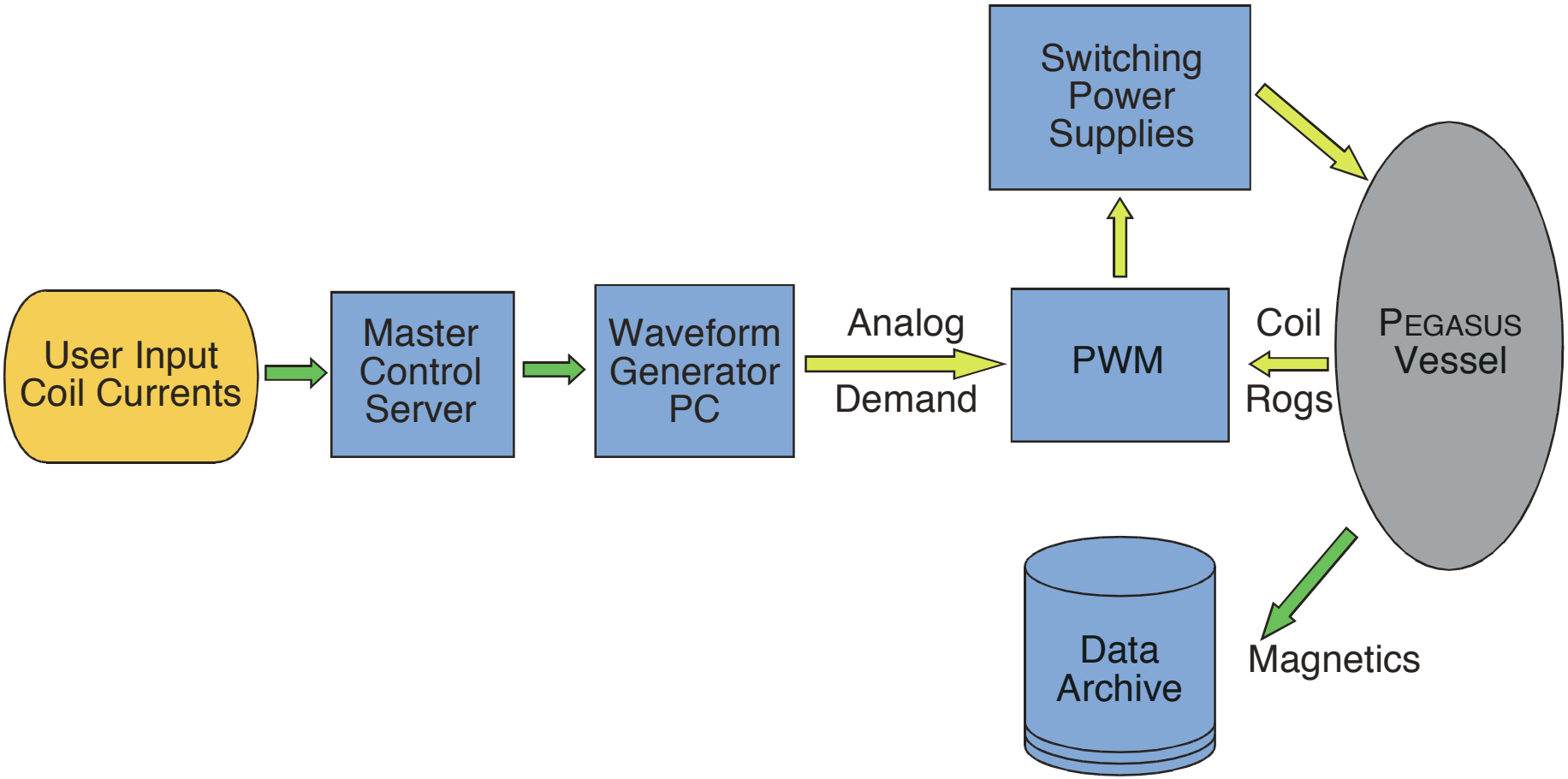
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# Motivation

- Active feedback control of discharges is highly desirable
  - Position, $I_p$ control required for access to high $l_N$ regime
  - Stable plasma targets required for HHFW and EBW experiments
- Programmable power supplies provide flexible control capability
  - Present control system employs pre-programmed coil currents
  - Limited position, $I_p$ control possible but very time consuming
- Versatile DIII-D plasma control system (PCS) adaptable to other devices
  - NSTX, MAST, KSTAR, EAST employ customized versions of PCS
  - PEGASUS has the ability to benefit from such a customization
- Provides relatively unique capabilities for a university-scale fusion experiment

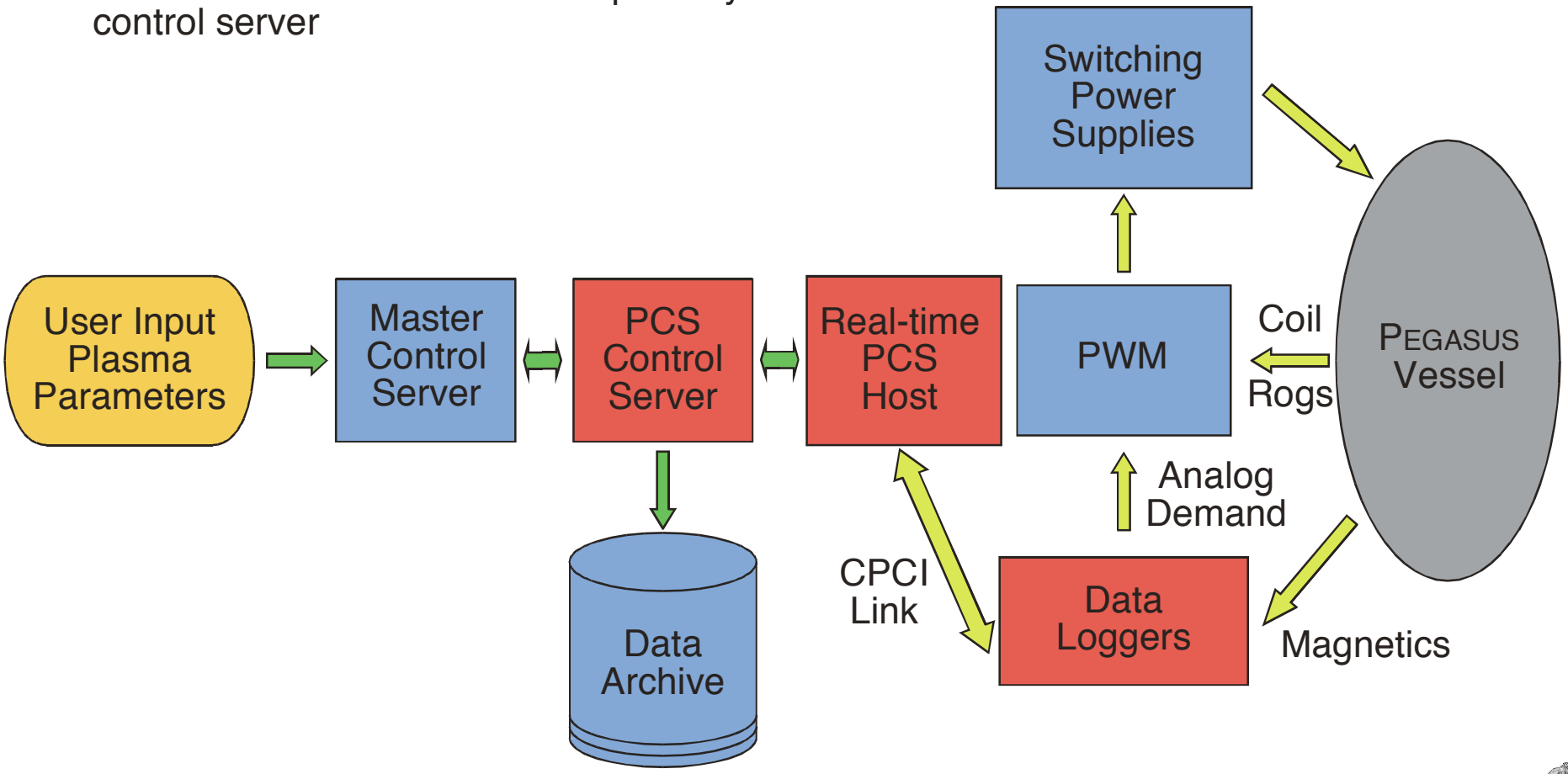
# Existing Control System

- Pre-programmed coil current demand provided as analog input during shot cycle
- Analog PWM circuitry commands power supplies to match coil currents to demand
- Magnetics information recorded for offline analysis



# Active Feedback System Design

- User inputs desired plasma parameters (R, $I_p$, Z) as function of time
- Magnetics actively sampled and analyzed throughout shot
- PCS actively generates analog demand waveform
- Data archived after shot is complete by PCS control server

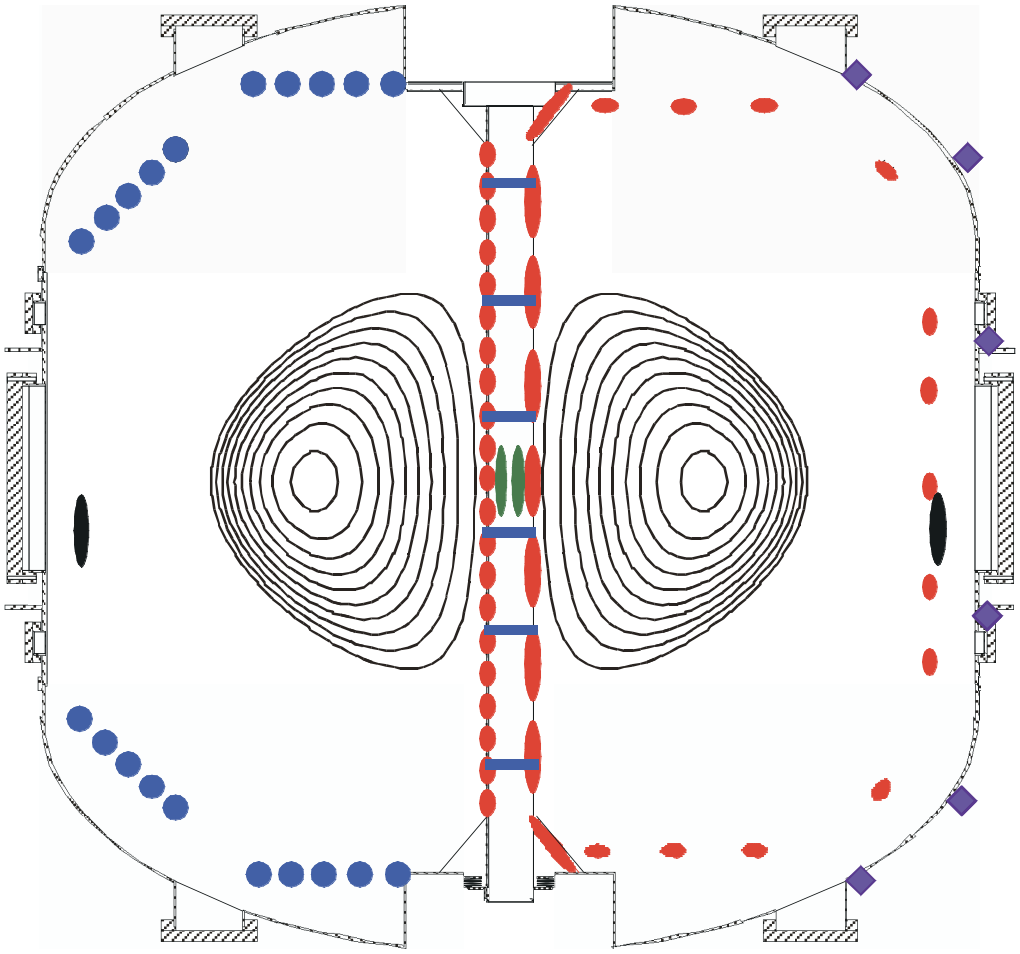


# Extensive Magnetics Diagnostics Available

- Flux Loops (26)
- Poloidal Mirnov Coils (22 + 21)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)
- External Wall Loops (6)

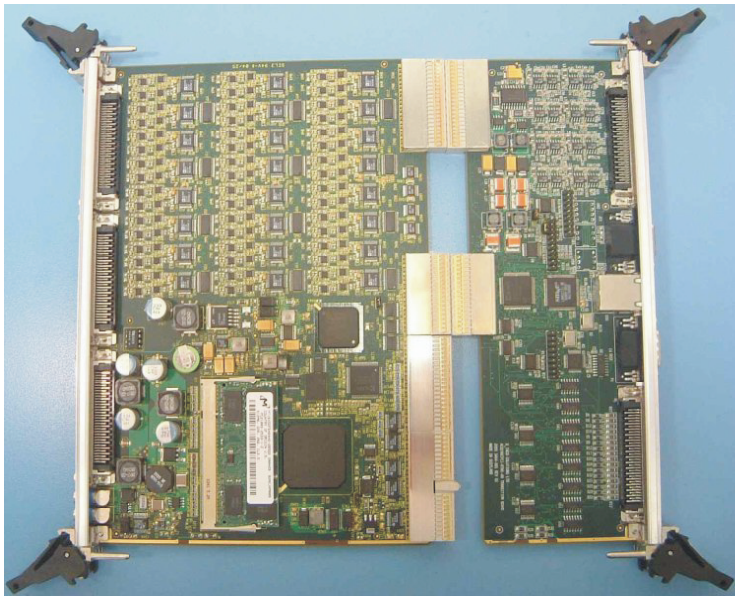
*Not shown:*

*Internal Plasma Rogowski Coils (2)*
*Internal Diamagnetic Loops (2)*
*Diamagnetic Compensation Loop*

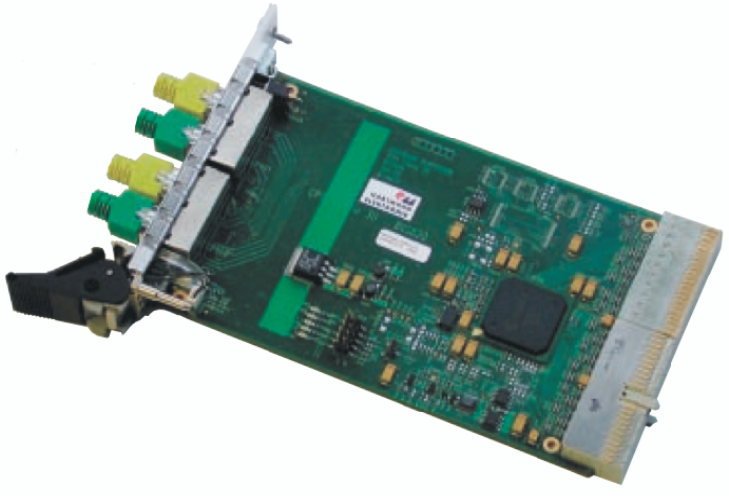


# PCS Hardware Enables Rapid Control

- D-TACQ Solutions, Ltd. ACQ196CPCI digitizer
  - 96 channels analog input, simultaneously sampled with 500 kHz, 16-bit ADC
  - Onboard or remote CPU data storage
  - 16 analog output channels, updated with 500 kHz DAC
  - 32 high-speed digital I/O lines available for future use
  - Runs embedded Linux
  - Open source drivers provide operating transparency



- StarFabric bus extender technology
  - Links digitizer compact PCI (CPCI) bus to host CPU PCI bus at full 64 bit, 66 MHz bandwidth
  - Data present in host memory no more than 10 μs following sample clock



# PCS Computing Architecture

- Control Server
  - Dual AMD Opteron 250 processors, 1 GB RAM
  - Runs Red Hat Enterprise Linux
  - Manages user input and all real-time host CPUs
  - Archives PCS data following shot cycle
- Real-time Host
  - Dual Intel Xeon processors, 1 GB RAM
  - Runs modified Red Hat Enterprise Linux kernel
  - Digitizer is a logical extension of PCI bus
  - Receives and analyzes real-time data during shot
  - Issues control commands to PWM systems via digitizer analog output

# Low-Latency Control Possible

- Magnetics data sampled by digitizer ADC units during shot
- Data stored directly in host computer via Direct Memory Access (DMA) transfer
  - Utilizes high-speed CPCI bus
  - Transfer latency much less than via network transmission
- Output commands similarly written directly to memory-mapped digitizer memory
- Low-latency cycle times $\sim 25\ \mu s$
  - Sample all inputs and store in host CPU
  - Write output command to change demand
- Digitizer firmware updates can decrease cycle time significantly

# Realtime Control via Modified Linux Kernel

- Linux is not a realtime-safe operating system
  - Sequential process execution not guaranteed due to scheduler interrupts
  - CPU, memory shared among many processes
- DIII-D kernel modifications allow PCS to disable interrupts
  - Enables realtime control of hardware
  - 100% CPU resources dedicated solely to PCS for shot duration
  - Dedicated mode may be aborted via special keyboard command

# Hardware Provides Growth Potential

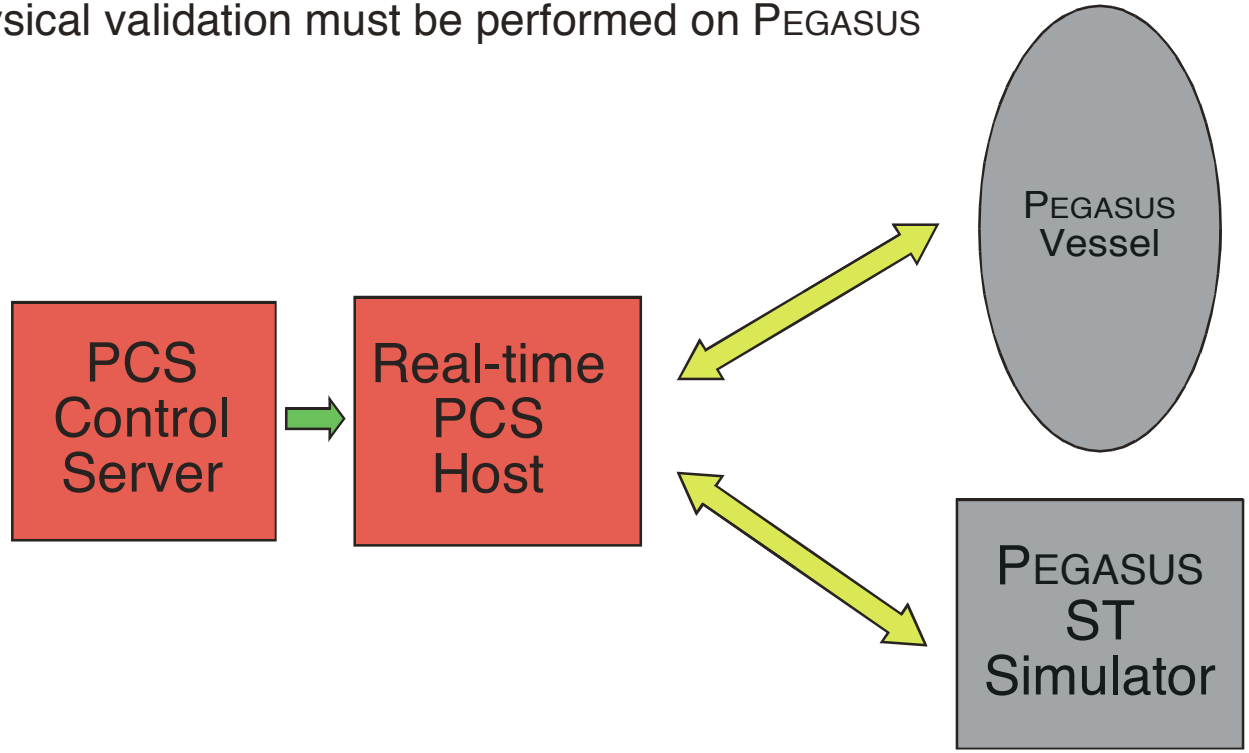
- Hardware sampling and analysis capabilities extremely well-suited for PEGASUS
  - Small subset of capacity initially utilized for active control
  - Surplus digitizer channels may record other diagnostic signals
- Master-Host architecture leaves room for expansion
  - PCS control software capable of handling arbitrary numbers of real-time CPUs
- Increasing sophistication in plasma control primarily reduced to implementation of control algorithms
  - Typically involves additional diagnostic measurements
- Digital I/O lines offer capability of direct, digital control of power supplies from PCS
  - Could eliminate analog component of power system

# PCS Software Based on DIII-D Framework

- DIII-D PCS being adapted to the PEGASUS Toroidal Experiment
  - Designed for use with currently deployed D-TACQ hardware, real-time CPUs
  - Implementation in C, IDL, with optimized assembly for critical segments
  - Integration with MDSPlus data acquisition system
- Modular design reduces development time
  - Device-specific models integrated into common computational framework
  - Wide latitude in operator choice for use of control algorithms
- PEGASUS-customized PCS model development underway through GA collaboration
  - Vacuum vessel
  - Power supply
  - Plasma response

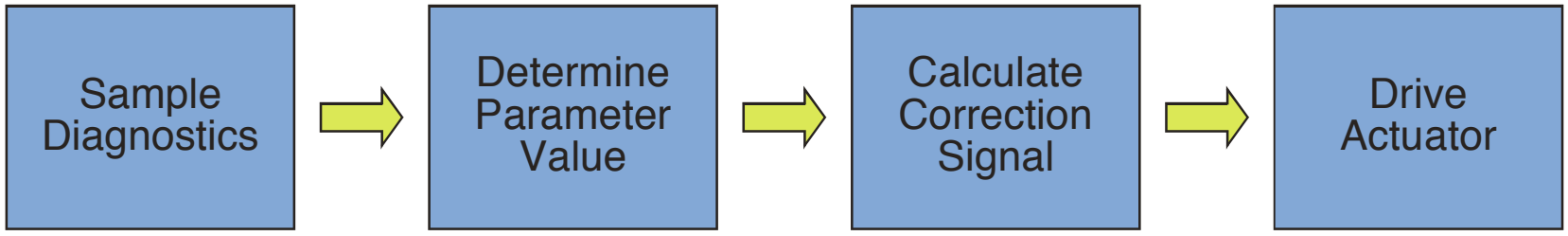
# DIII-D Tokamak Simulation Being Adapted

- Simulator computes plasma response to received PCS commands
  - Utilizes physical model of PEGASUS vacuum vessel and power supply system
  - Generates next set of magnetics 'signals' for the real-time host to 'sample'
- Simulation allows feedback control algorithm development without run time
  - Proven extremely useful on DIII-D
  - Physical validation must be performed on PEGASUS



# Typical Control Algorithm Cycle

- Controlled parameters (e.g. $I_p$) affected through changes to an *actuator*
  - PEGASUS actuators include coil currents and gas puffing
- Control algorithms constructed for each parameter of interest
- Cycle times must be completed on a timescale much shorter than the duration of a plasma discharge
  - For PEGASUS discharges ~ 25 ms, initial cycle time goals are ~ 25 μs
  - Reductions in cycle time possible via improved algorithm efficiency and digitizer firmware improvements



# Initial Pegasus Control Goals

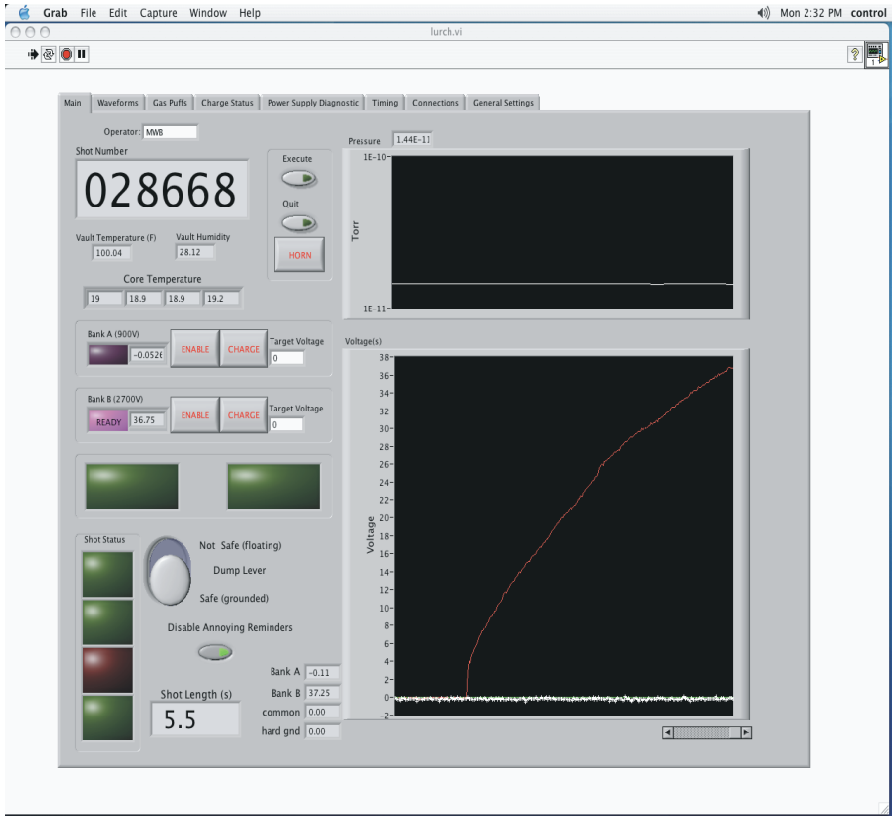
- Radial position R(t)
- Vertical position Z(t)
- Plasma current $I_p(t)$
- These algorithms should require relatively little computation
  - Efficient control cycle latency times
- Additional control algorithms will be implemented following demonstration of R, Z, $I_p$ control

# Data Archive System Requires Upgrades

- PCS integrates seamlessly with MDSPlus
  - DIII-D system capable of using arbitrary data storage/retrieval systems
  - Adapting current archive system for use with PCS difficult
- Existing archive system will be replaced with MDSPlus and integrated with PCS
- Benefits of upgrade include:
  - Network accessibility
  - Independence of analysis programs
  - Simplified data sharing with collaborators

# MDSPlus Integration at PEGASUS

- LabVIEW and Igor Pro are extensively used throughout PEGASUS in a mixed OS environment
- Unfortunately MDSPlus has limited support for LabVIEW on all platforms
- No Igor Pro support available
- MDSPlus compatibility layers under development for these programs
  - Built off existing C libraries
  - Results will be released to MDSPlus community when completed




*Main Control Code Panel*

# PCS Being Integrated Into Existing Codes

- Pegasus-tailored PCS system software successfully built
    - Standalone test operations underway
- Existing control system will be modified to yield control of actuators to PCS system when appropriate
- TCP/IP network structure of existing system will ease communications with PCS
- MDSPlus LabVIEW compatibility layer encourages re-use of existing reliable codes

# PCS Will Enhance Scientific Effort

- Plasma control marks a significant change to PEGASUS operations
- Active control of R(t), Z(t), $I_p(t)$ necessary to evolve plasma into high $I_N$ regime
- Staff will be able to think in terms of plasma parameters versus machine characteristics
- PCS control of plasma parameters decreases amount of time to achieve desired conditions
- Enhanced operator tools available from PCS integration
  - Simple shot reproduction from shot database
  - Multiple operators independently editing future shots

# Summary

- A digital feedback control system is being implemented on the PEGASUS Toroidal Experiment
- PCS hardware in place and operational
- DIII-D control software successfully built
- PCS being customized with PEGASUS-specific modeling
- Existing control and data archive systems being merged with PCS
- Initial control goals are R(t), $I_p(t)$, Z(t) to provide access to high $I_N$ regime

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