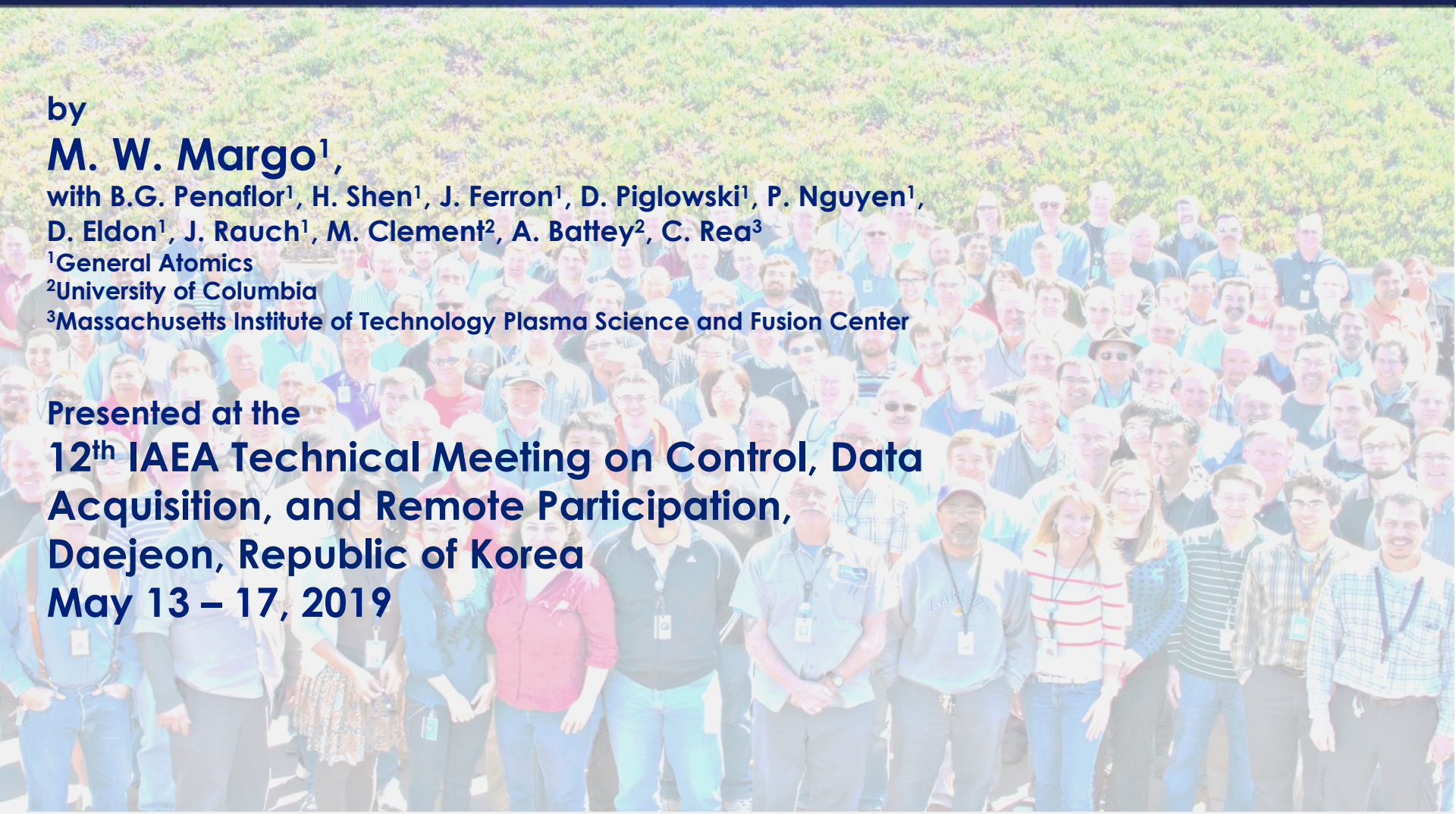
Current State of DIII-D Plasma Control System ID: 497



by

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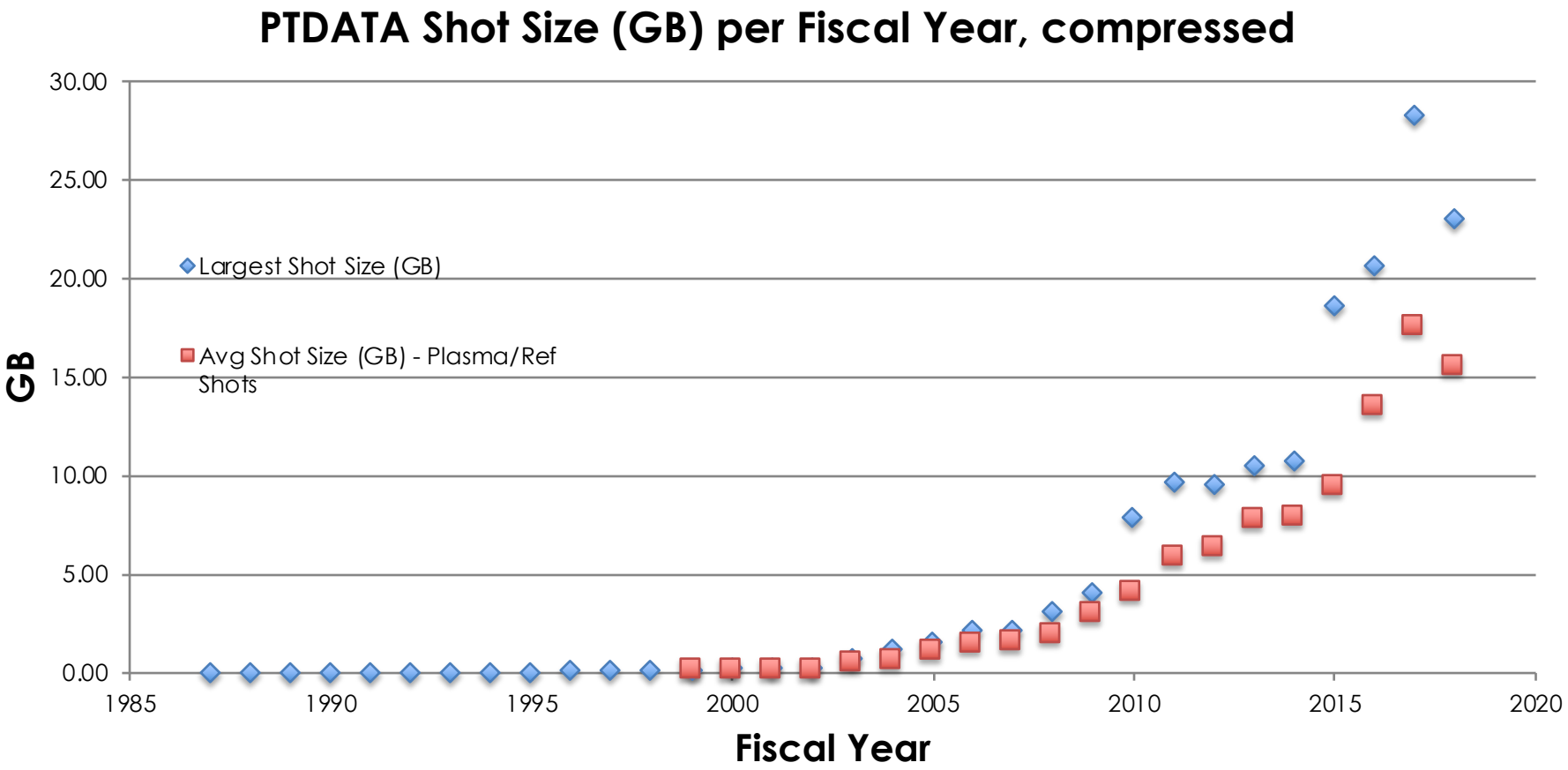
DIII-D Plasma Control System (PCS) Is Extensible

- **DIII-D PCS is a scalable software platform to create and control plasma in the tokamak**
- **PCS is operated at tokamaks worldwide: DIII-D, K-STAR, EAST, MAST, NSTX, HL-2M (future), Pegasus (U. of Wisconsin)**
- **Recent areas of enhancements**
  - Real time control algorithm
  - New diagnostics that feed real-time data to the PCS
  - Computing hardware and best practices

DIII-D Average Data Size Per Shot Reaches 17 GB in 2017



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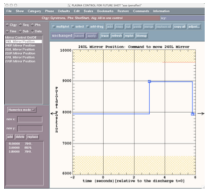
PCS Receives Distributed Signals From Diagnostics And Controls Actuators

PCS Real-Time System



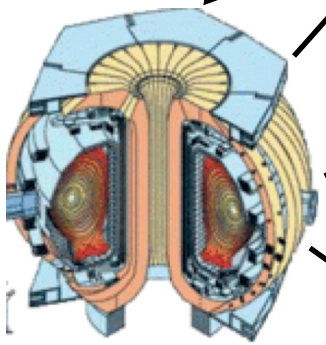
PCS 40 Gb/s InfiniBand Fiber Network

PCS Real-Time Cluster

UDP ethernet

RT Control CPU

RT Control CPU with D-TACQ I/O



DIII-D Tokamak

Fiber

RT Control CPU linked to External Diagnostic Systems

External Actuator Control

ECH Mirror Controllers

ECH Computer

CER Data Acquisition

Windows PC with Cameralink card connecting Sarnoff Cameras

Mirnov Probe Data Acquisition used for Real-time magnetic field fluctuation analysis

Thomson Scattering

RWM and ECE

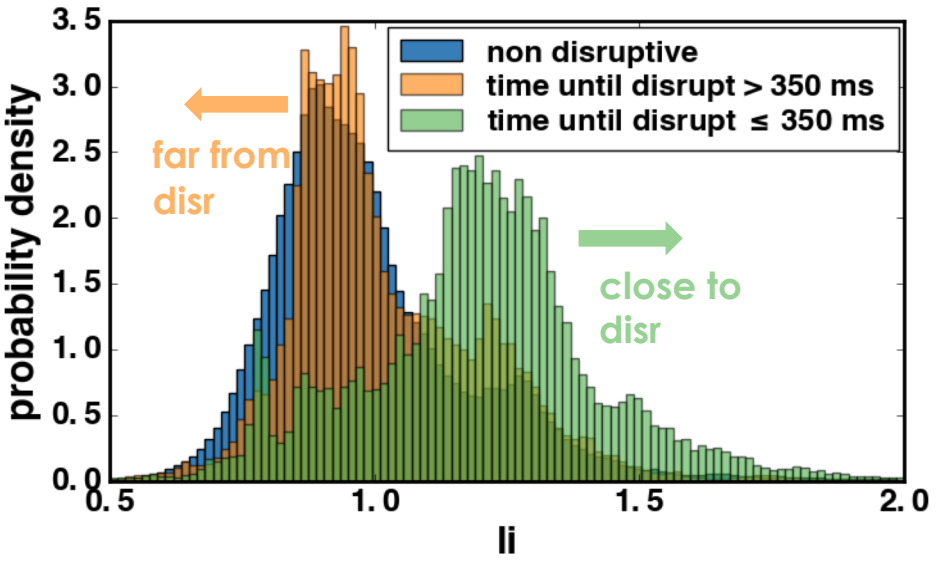
Recent Enhancements to Real Time PCS Has Increased Capability

RT diagnostic	Enhancement	Benefit
Thomson Scattering (TS)	New 960 channel ACQ196 digitizer over fiber	High number of channels can be streamed in block-mode
Resistive Wall Mode (RWM)	ACQ2106 in low latency mode	100 kHz acquisition, low latency10 µsec of 96 channels
Electron Cyclotron Emission (ECE)	New ACQ2106 digitizer over fiber	96 channel , 500 kHz sample, 1 kHz stream
Mirnov probe	Upgraded ACQ196/RTM-T	160 channel, 4 kHz
Charge Exchange Recombination (CER)	In-house camera acquisition using point-to-point UDP	Real time acquisition
Electron Cyclotron Heating (ECH)	In-house mirror control using point-to-point UDP	Real time control and feedback

850 Real-time signals are available

Disruption Prediction Via Random Forests (DPRF) Algorithm[1] Gives Explainable Predictions

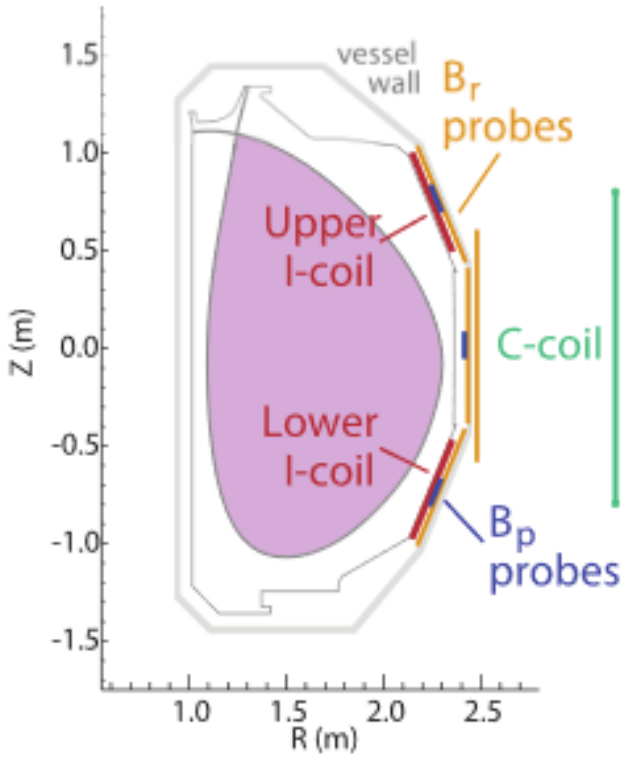
- Trained machine learning (ML) model on ~5300 DIII-D plasma discharges (both disrupted and non-disrupted)
- DPRF reads historical DIII-D data from GA's Toksearch[2] data mining platform
- Routinely used during DIII-D FY18 campaign
- Use supervised binary classifier techniques



[1]C. Rea and R.S. Granetz, Fus. Science Tech. (2018)
[2]B. Sammuli et al. TokSearch: A Search Engine for Fusion Experimental Data (2017)

GPU-based Resistive Wall Mode (RWM) Control[1] Reduces Response Time By 32%

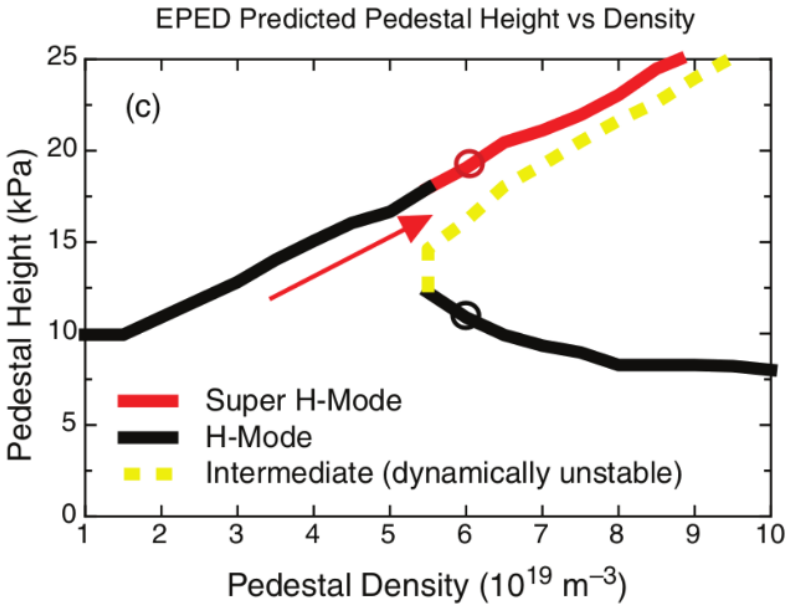
- NVIDIA Tesla P40 GPGPU is installed in PCS RT computer with 61k cores
- RWM uses Linear Quadratic Gaussian (LQG) control of I-coils and amplifiers (SPAs)
- Software library to perform fast CPU to GPU memory transfer and archiving has been implemented and can be reused



[1]Clement, M. D, GPU-Based Optimal Control for RWM Feedback in Tokamaks (2017)

PCS Dynamic Target For β[1] Control Yielded in Tighter Control of Pedestal Evolution Trajectory

- Dynamic β target setting is useful for linking evolution of β with evolution of density and trying to steer up the channel to super H-mode
- Generate new target control using inputs from CO_2 inferometer or Thomson Scattering
- The control allows tighter control of pedestal evolution trajectory (super H-mode)



[1]P.B. Snyder et al. "Super H-mode: theoretical prediction and initial observations of a new high performance regime for tokamak operation". Nucl. Fusion 55, 083026 (2015) doi:10.1088/0029-5515/55/8/083026

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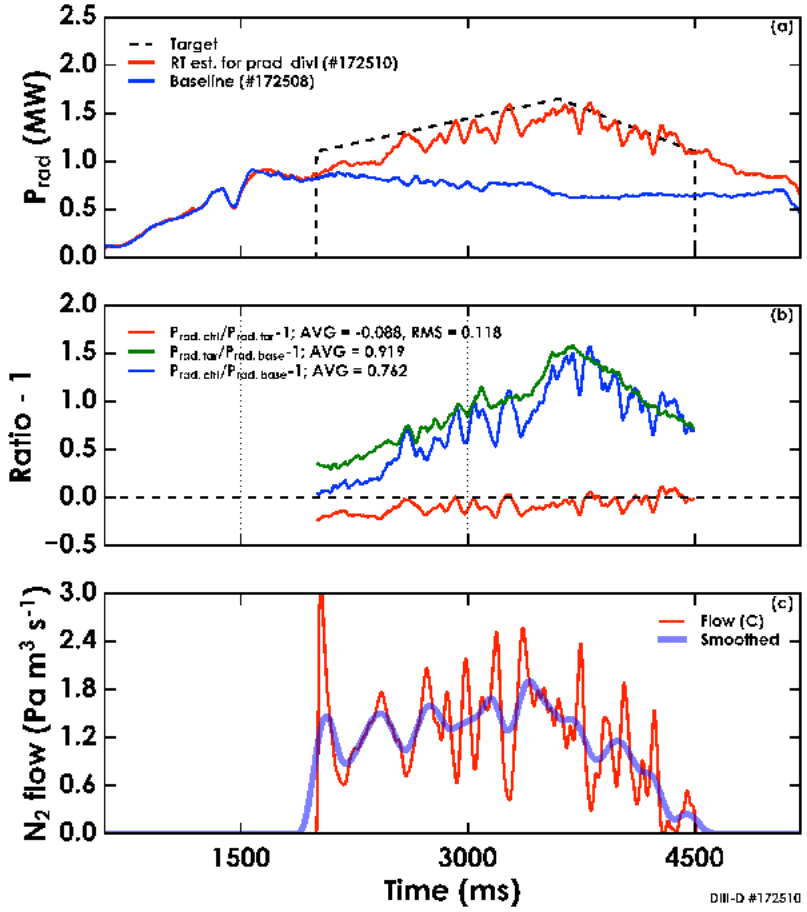
Radiated Power (P_{rad})[1] Control Dissipates Power From Scrape Off Layer (SOL)



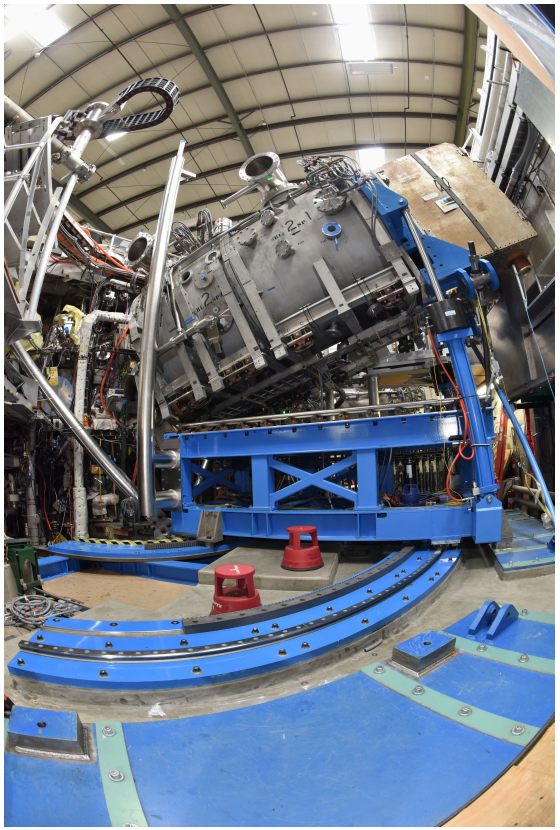
- **ITER must mitigate divertor heat load by radiating ~70% power**
- **DIII-D bolometers used to measure real time P_{rad} from lower divertor**
- **Measurement is compared to target value and error is fed back into gas control system to set flow rate for impurity seeding, which will promote power radiation and detachment**

[1]Eldon D. et al. Advances in Radiated Power Control at DIII-D (2019)

DIII-D NATIONAL FUSION FACILITY

PCS RT Neutral Beam Injection (NBI) Control[1]

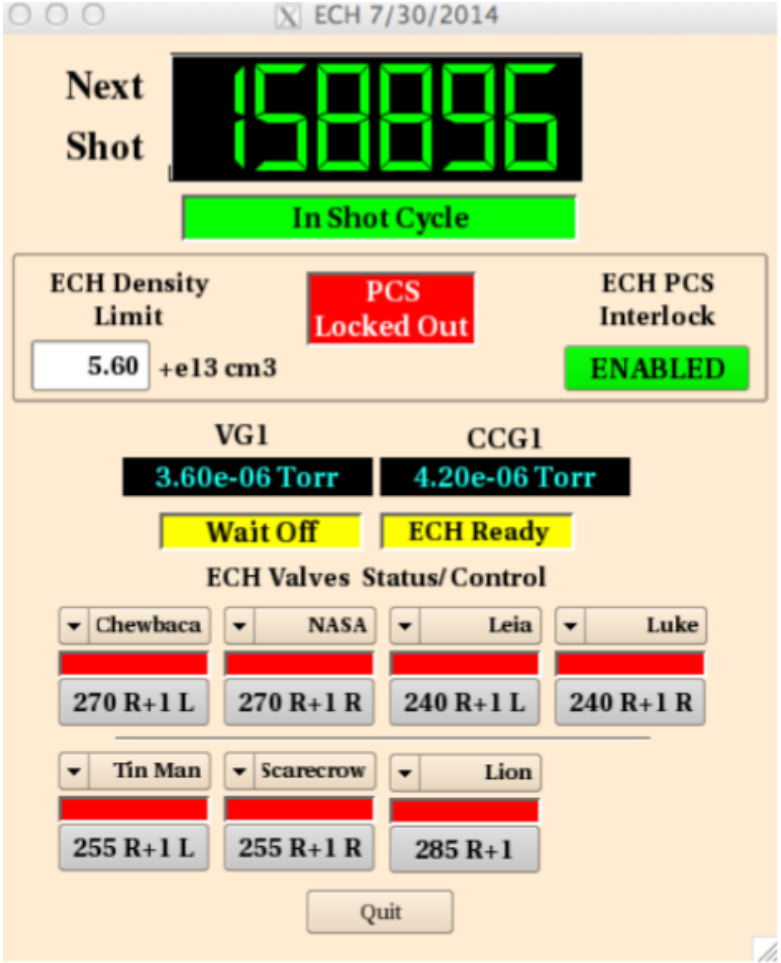
- DIII-D has 8 active NBI sources capable of supplying ~ 20 MW of injected power
- PCS regulates NBI beam energy and perveance (particle count) in real-time using input, one of which is injection angle (co-injection and counter injection)
- Control results in high performance plasma creation with maximum torque



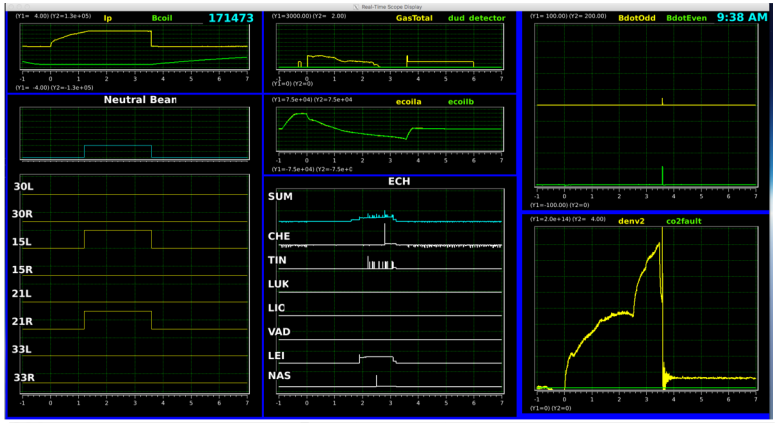
[1]J. Rauch, at el , "Upgrade to DIII-D National Fusion Facility PCS and Neutral Beam Systems: In-Shot Variation of Neutral Beam Particle Energy",. Journal Fusion Science and Technology, Volume 72, 2017 - Issue 3.

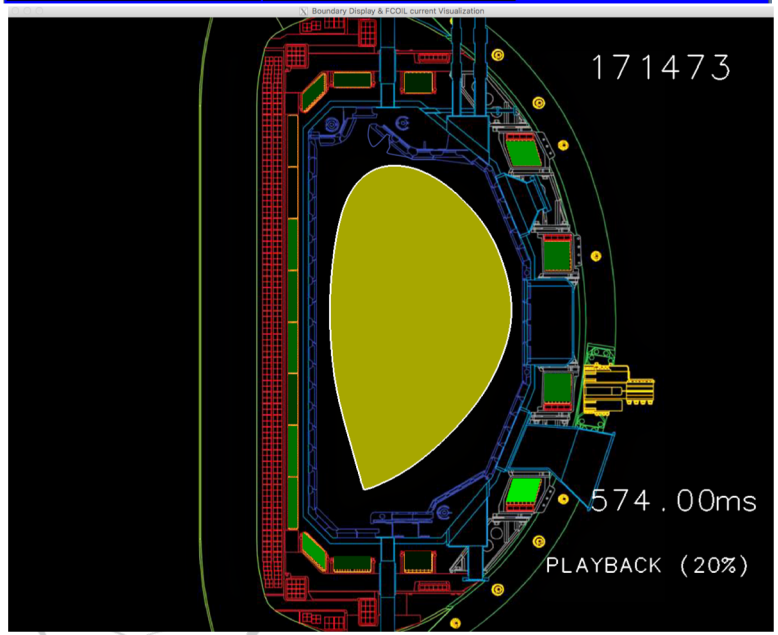
PCS Is Used To Protect Vessel From ECH Refraction

- Introduced in 2014, PCS would shutdown ECH when plasma density limit (maximum value) is reached
- Thomson and inferometer gives real-time density
- Prevent damage to diagnostic ports



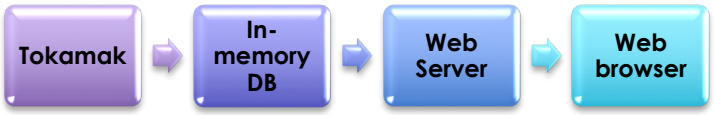
DIII-D PCS Has Expanded Visualization Capabilities





- ~96 PCS RT digitized and calculated quantities are available
- Custom remote display using UDP possible
- In-house QT visualization app is the main client
- Visualization tools include arrays of 2D plots and boundary display with equilibrium reconstruction

DIII-D PCS Streams RT Signal Data To Remote Web Clients



- Technology allows participation from remote location
- System will replace in-house QT visualization app
- Up to 10k RT signals can be streamed

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DIII-D PCS Takes Advantage Of Best Practices In Software Engineering

Feature	Implemented in	Benefit
Git source control	2017	Ability to track source code changes and revert to previous commits when failure occurs
Jenkins	2017	Early warning of new SW defects in source code
Nagios/Icinga2	2017	Early detection of SW faults and OS warnings, i.e. disk is getting full
ZFS shared file system and environment module	2018	Now possible to use non PCS computer to develop and debug control algorithm. Ensure software consistency for all
Network segmentation	2019	Better network security posture and better data transfer performance

Collaborations Is Crucial to Success of DIII-D PCS

- **DIII-D PCS has gained major capabilities over the years, which helps it to satisfy increasingly challenging DIII-D scientific mission**
  - New control algorithms: DPRF, RWM, P_{rad}, Dynamic Target for β
  - New real time diagnostic : P_{rad}, ACQ 2106
  - New Computer hardware and best practices: InfiniBand network, Git
- **This achievement would not have been possible without contributions from researchers and collaborators world-wide**
- **Work is supported by US Department of Energy under DE-FC02-04ER54698 and DE-SC0010685**

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