Magnetics and Power System Upgrades for the Pegasus-U Experiment

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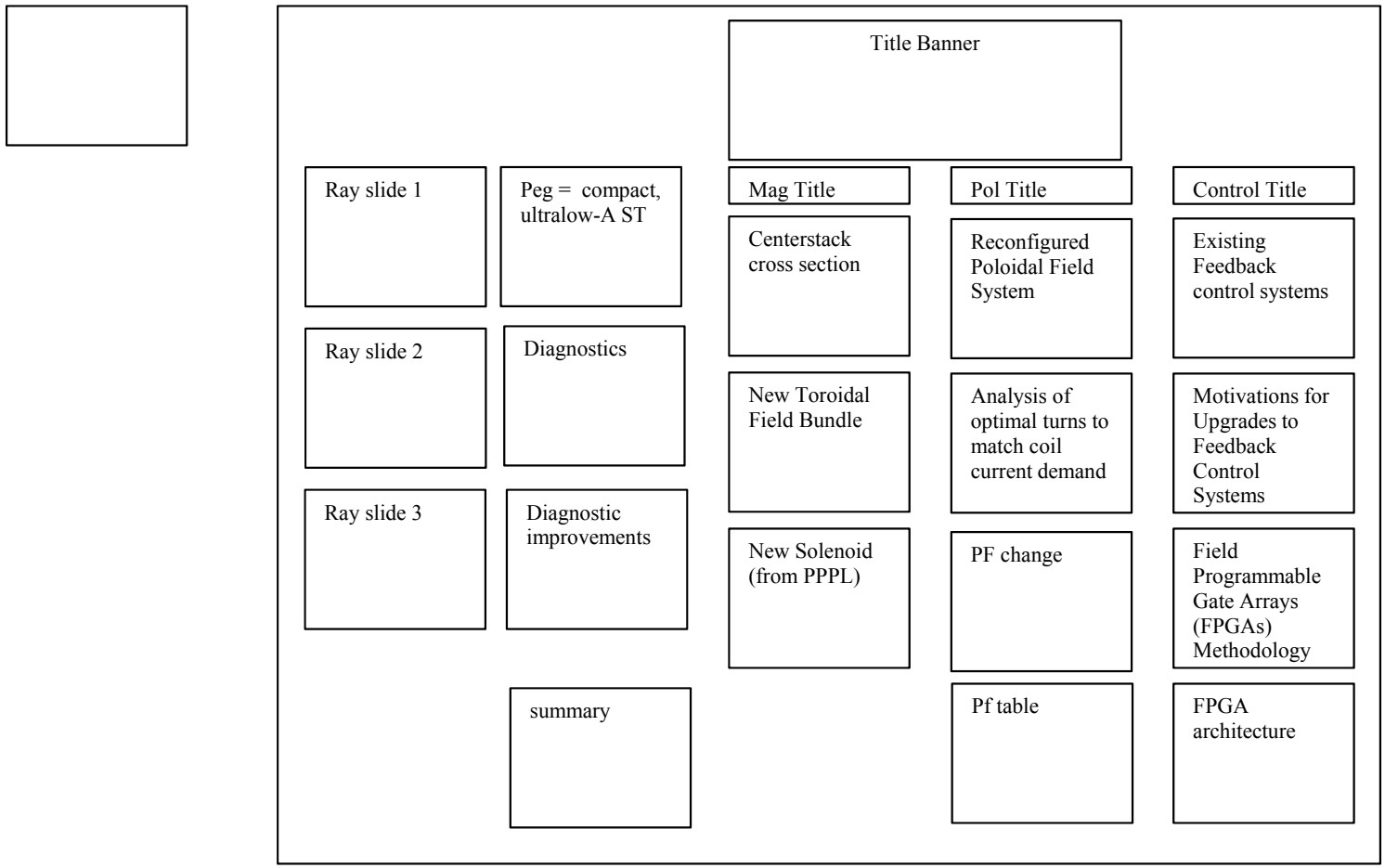
University of Wisconsin-Madison

56th Annual Meeting of the APS Division of Plasma Physics

New Orleans, LA
October 29, 2014

PEGASUS Toroidal Experiment

Layout

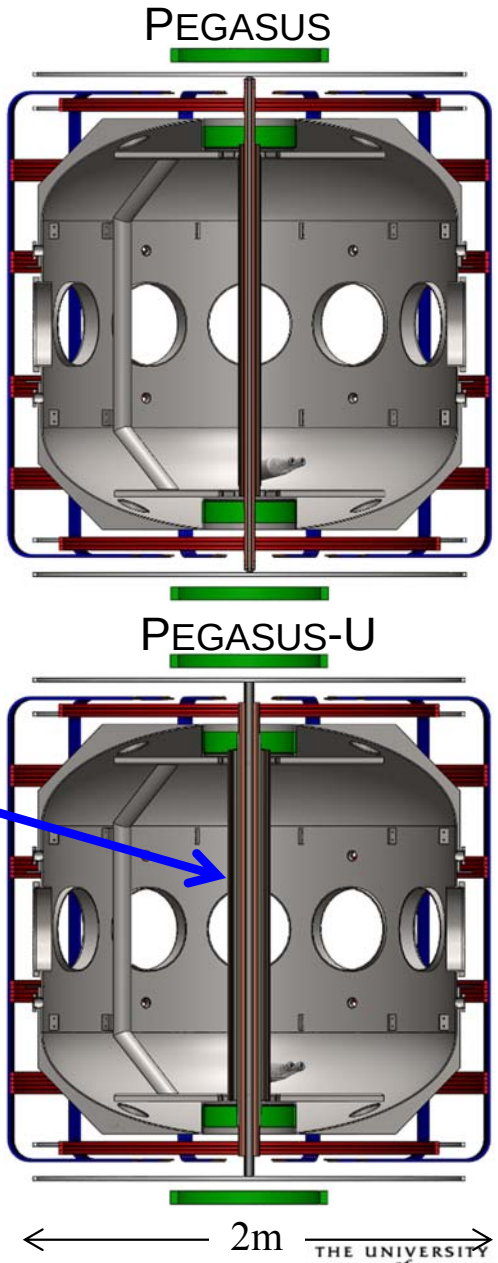


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PEGASUS-U Proposal: Advancing Non-Solenoidal Startup and AT Physics

- Mission
  - Physics and technology of LHI
    - For NSTX-U and beyond (FNSF)
  - Nonlinear ELM dynamics, H-mode physics
  - Tokamak stability limits: A~1 high β_T regime

- Facility enhancements
  - New centerstack assembly
    - B_{TF} increases 5x
    - Δt_{pulse} ~ 100 msec
    - V-sec increases 6x (PPPL)
    - Improved separatrix operation
  - NSTX-U relevant LHI injector arrays
    - Helicity input rate increases 2x
  - Diagnostics: multipoint TS; CHERS via DNB
  - Upgraded power systems

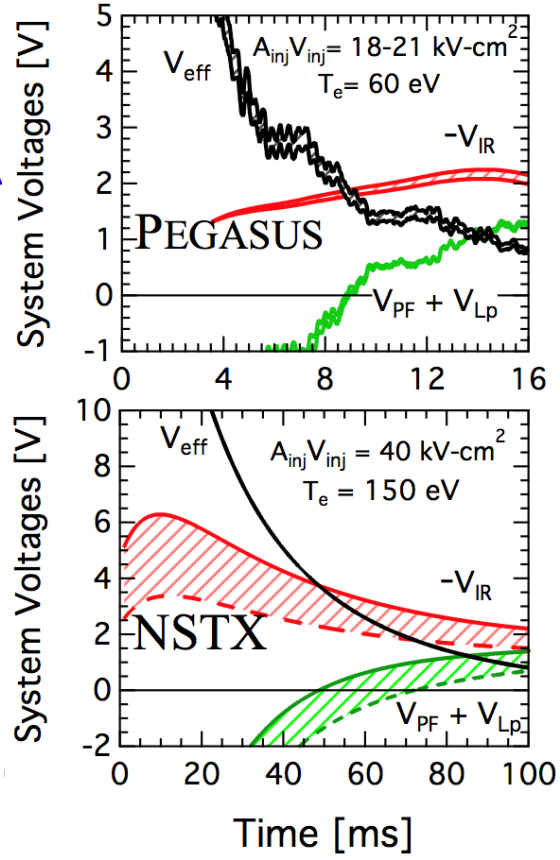


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PEGASUS-U Proposal: Develop & Validate LHI-Startup for NSTX-U and Beyond

- Critical physics issues
  - Confinement behavior and helicity dissipation
  - Edge λ=J/B, J penetration processes
  - Injector geometry optimization
- Technology development
  - Long-pulse, large-area injectors in high B_{TF}
- Models & predictive understanding
  - 0-D Power Balance $I_p(t)$ model
  - NIMROD
  - TSC

PEGASUS @ 0.3 MA = same regime as NSTX-U @ 1MA:





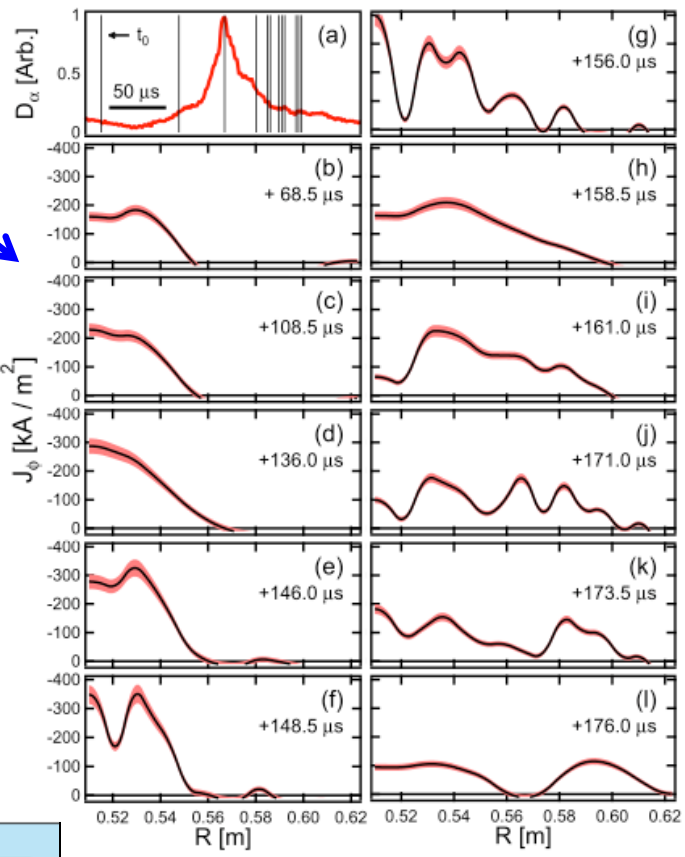
"Pagoda-style" injectors sustain $V_{inj} \leq 1.5$ kV, $I_{inj} \sim 2$ kA with no PMI effects within 1-2 cm of LCFS

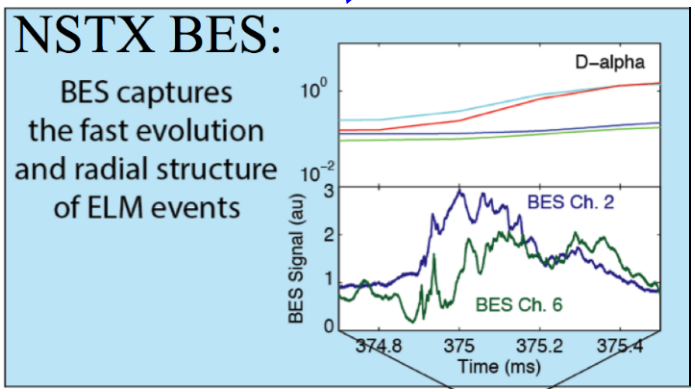
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PEGASUS-U Proposal: Nonlinear ELM Studies and H-mode Physics

- P(r,t), J(r,t), v_ϕ(r,t) through ELM cycles
  - Nonlinear evolution of magnetic structures
- ELM, H-mode modification and mitigation
  - Vary J_{edge}(r), modify edge v_ϕ and shear via LHI
- Synergistic studies with BES on NSTX-U, DIII-D
- Models to test
  - NIMROD
  - BOUT++
  - EPED

Edge J(r,t) through an ELM cycle on PEGASUS

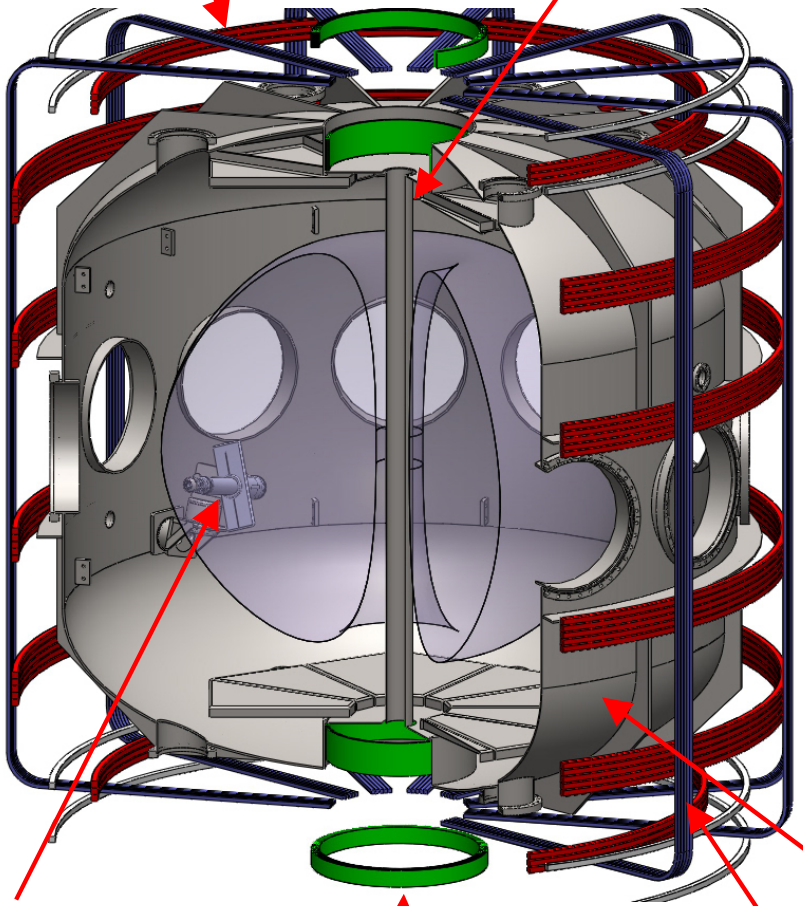




Comparison of J(r,t), N_e(r,t), T_e (r,t) on Pegasus to detailed N_e(r,t) on NSTX-U will aid interpretation of BES ELM studies on NSTX-U

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PEGASUS is a Compact, Ultralow-*A* ST



Experimental Parameters

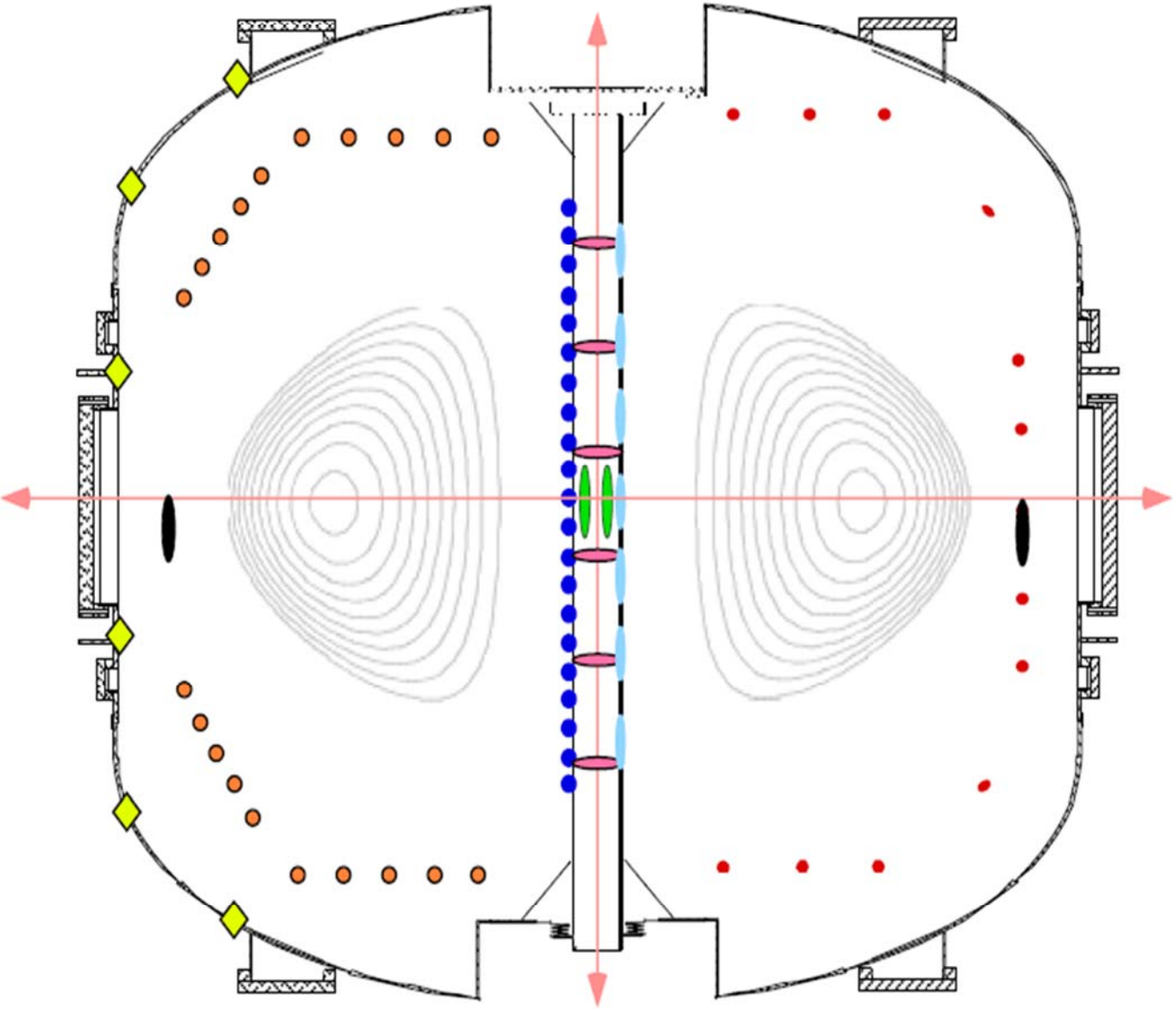
Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .25
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25

Major research thrusts:

- Tokamak physics at small aspect ratio
- Non-inductive startup and growth

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Magnetic Diagnostics Layout for PEGASUS



Current Magnetics Arrangement

Inboard Measurements

- Core Flux Loops (6)
- High Resolution Mirnovs (21)
- Low Resolution Mirnovs (7)
- HFS Toriodal Mirnovs (7)

Outboard Measurements

- Flux Loops (20)
- Poloidal Mirnovs (13)
- LFS Toroidal Mirnovs (6)
- Ext Wall Loops (6)

Not Shown

- Plasma Rogowski Coils (2)
- Diamagnetic Loops (2)
- Diamagnetic Compensation Loop

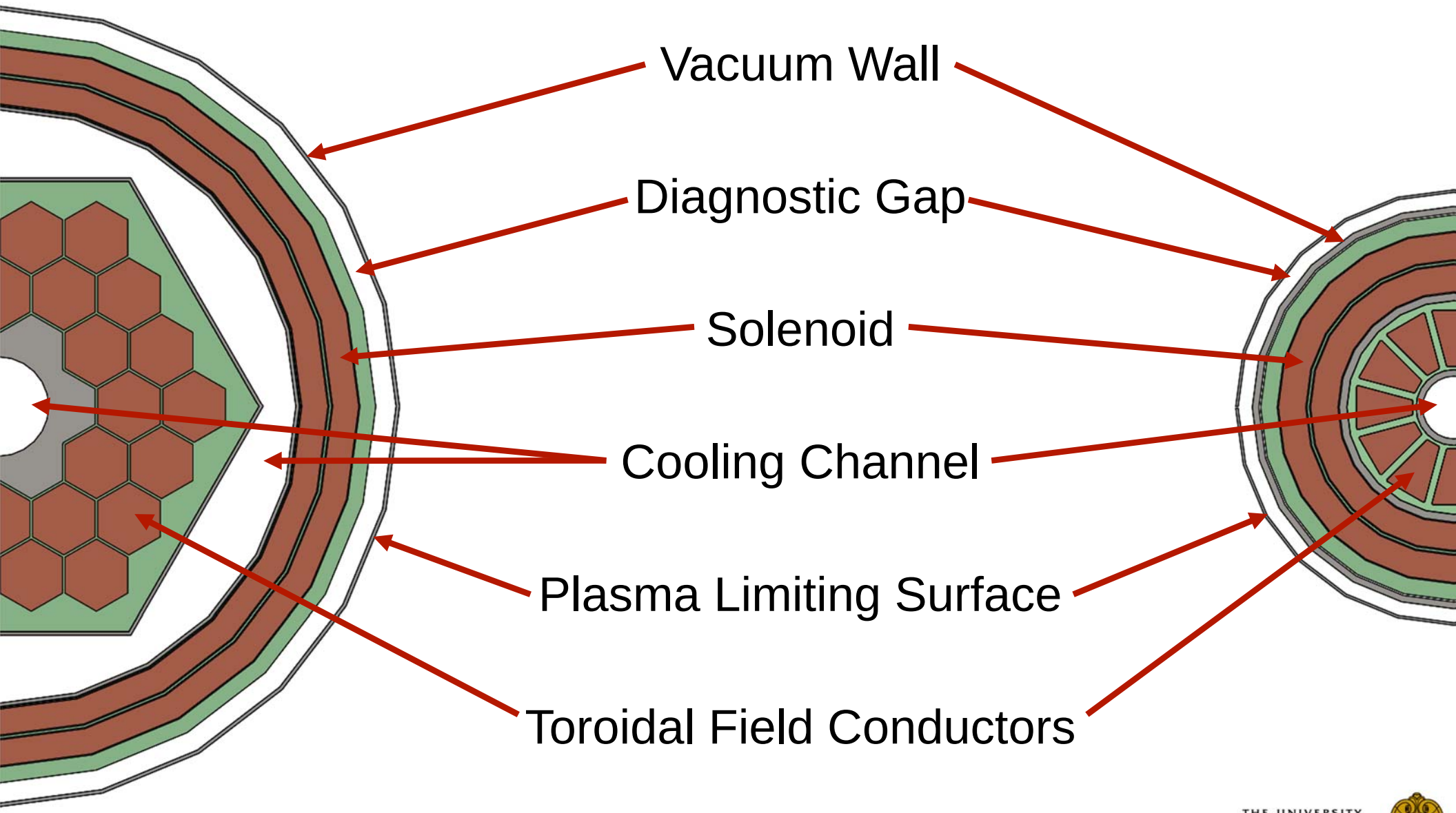
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Magnetic Diagnostics Improvements

- New centerstack requires a new diagnostic suite
- Design improvements are
  - Fully shielded
  - Differential routing
  - In atmosphere
  - Local buffers and/or data acquisition

New Centerstack Assembly

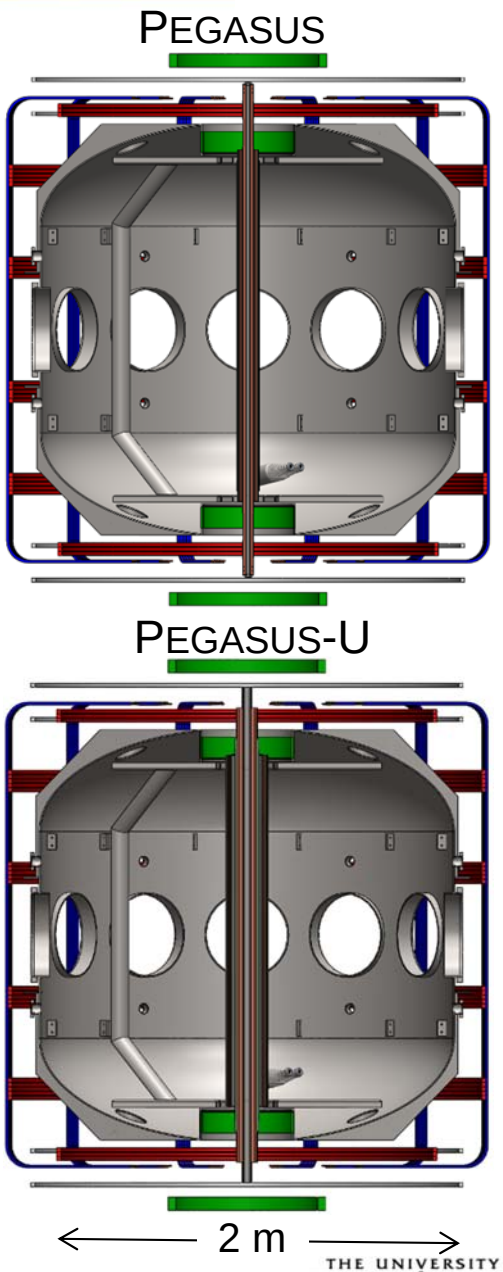
Centerstack Cross Section Comparison



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New Toroidal Field Center Rod & Power Supply

Parameter	Present	New
Field strength	0.15 T	1 T
Bridge current	4 kA	6 kA
Single turn current	24 kA	72 kA
Number of bridges	6	12
Coil turns	12	30
Rod current	0.288 MA-t	2.16 MA-t
Control	Analog	Digital
Pulse length	25 ms	50-100 ms
Stored energy	0.5 MJ	1-1.5 MJ

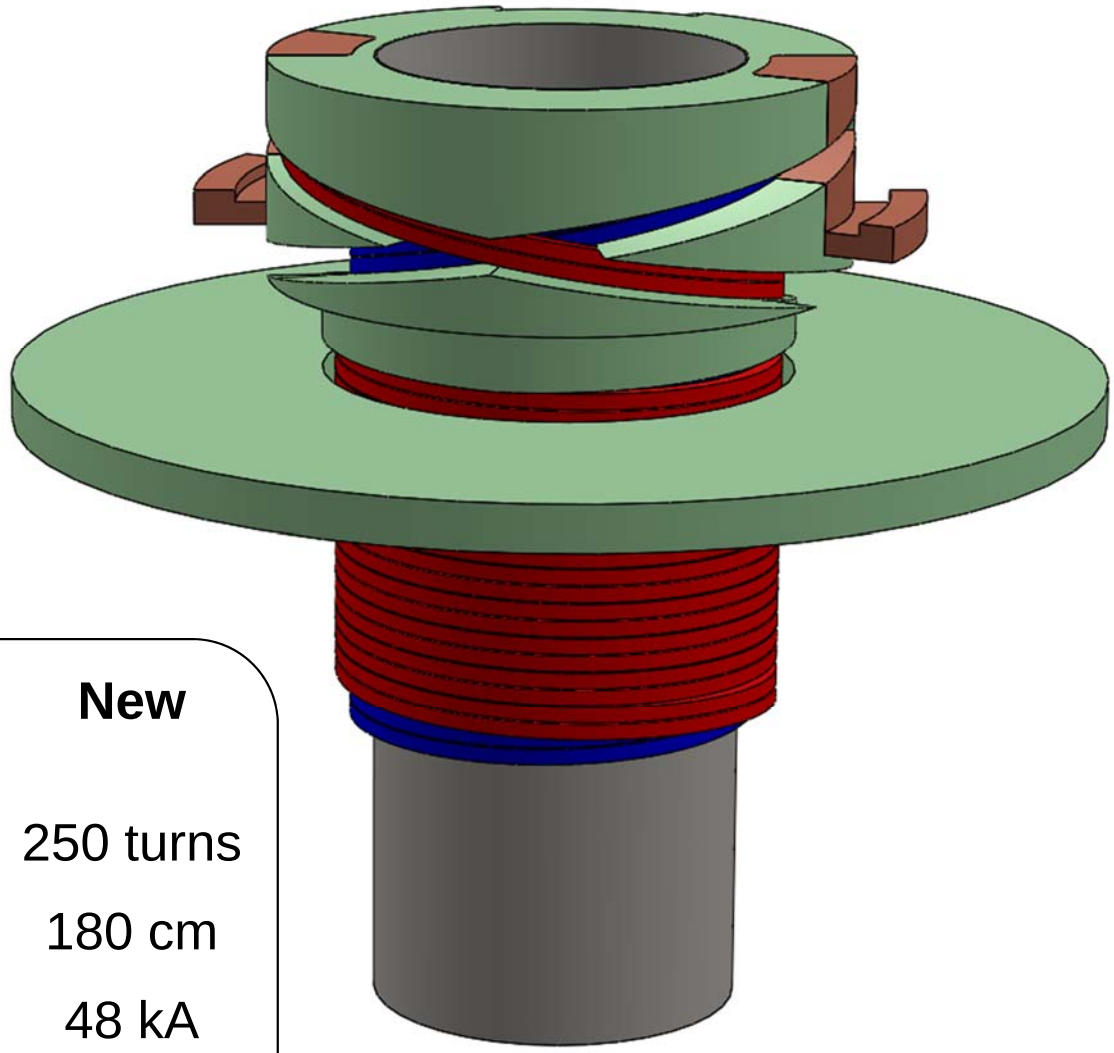


- New 6 kA IGBT bridge

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New Solenoid (From PPPL)

- Volt-seconds increased by five to ten times
  - 5x from solenoid geometry
  - 2x from power supply upgrade
- Low aspect ratio of ~1.2 maintained in PEGASUS-U

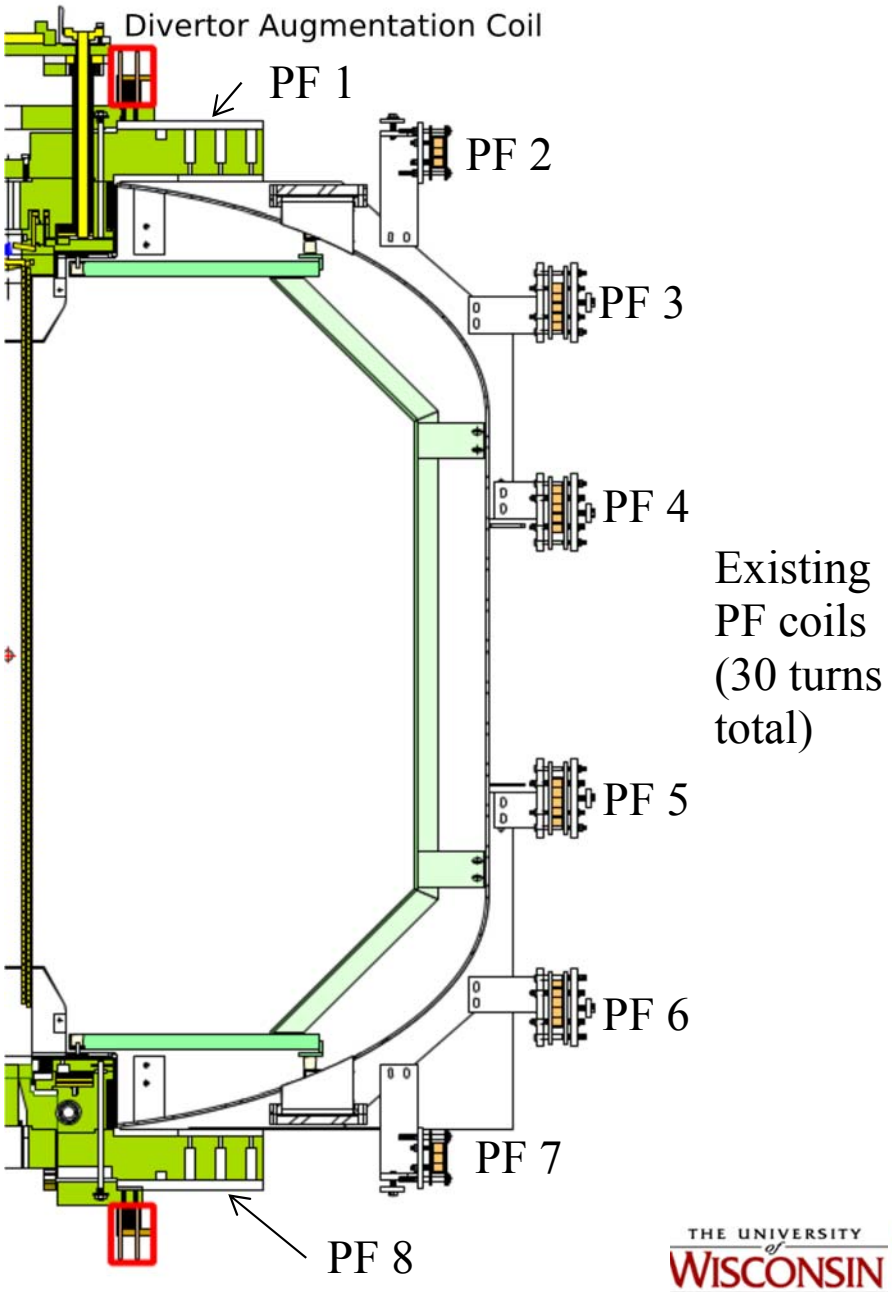


Parameter	Present	New
Turns	260 turns	250 turns
Length	170 cm	180 cm
Peak current/turn	24 kA	48 kA
Flux increase		5-10x

Poloidal Field Reconfiguration

Reconfigured Poloidal Field System will Improve Shape Control and Response Time

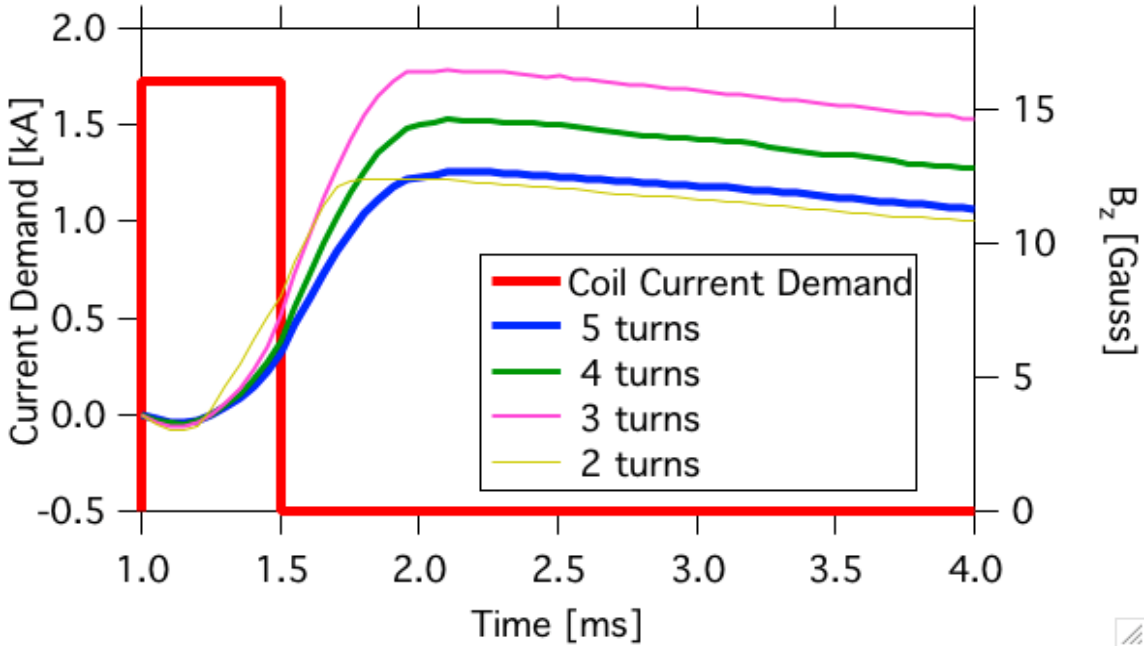
- Present poloidal fields are driven by 8 coil sets
- PF time response important for position control and poloidal field induction
  - Limited by coil rise time (L/R), penetration of vacuum vessel ($\tau_w \sim 10\ ms$)
- Reconfiguration of the poloidal field coil sets will allow for improved shape control
- New divertor coil set



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New Poloidal Field Set Optimized for Response Time

- Modifications chosen to improve time response:
  - Decrease turns per coil set
  - Increase number of independent coil sets, using former TF power supplies

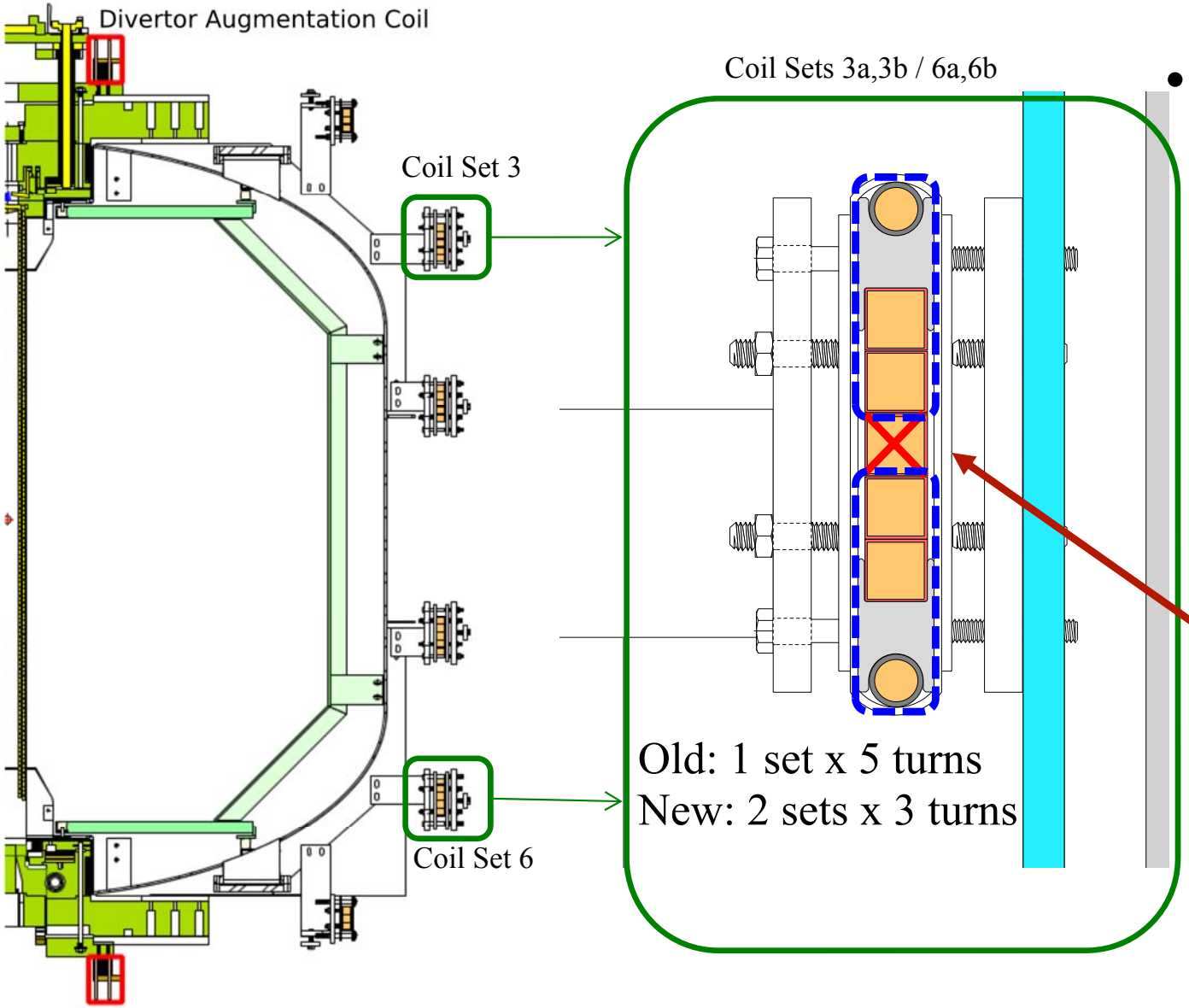


- Wall code simulations* to find best number of turns per coil set
  - Balance coil rise time vs. wall penetration time
- Response characterized using a square pulse
- Three turns per set gives an optimal response time for power supplies

R.C. Preston, 56th APS-DPP, New Orleans, LA, October 2014
**A.C. Sontag, Ph.D. Thesis, UW-Madison, 2002.*

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Poloidal Field Upgrade Splits Existing Coil Set



- Modifications to coil sets 3 and 6:
  - New turns added above and below
  - Each set split into 2 sets of 3 turns
  - Abandon single turn

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Present 4 kA TF Bridges Reassigned to Expand PF System

- Increased voltage improves time response of coil set with a marginal decrease in ultimate current

- Improved controls can optimize wall response to changing internal field parameters

Parameter	Present	New
Number of bridges	10	18
Controlled sets	3	6
Control type	Analog	Digital
Volts per turn	110	300
kA-turn per set	80 kA-turns	72 kA-turns
kA per turn	16 kA	12 kA

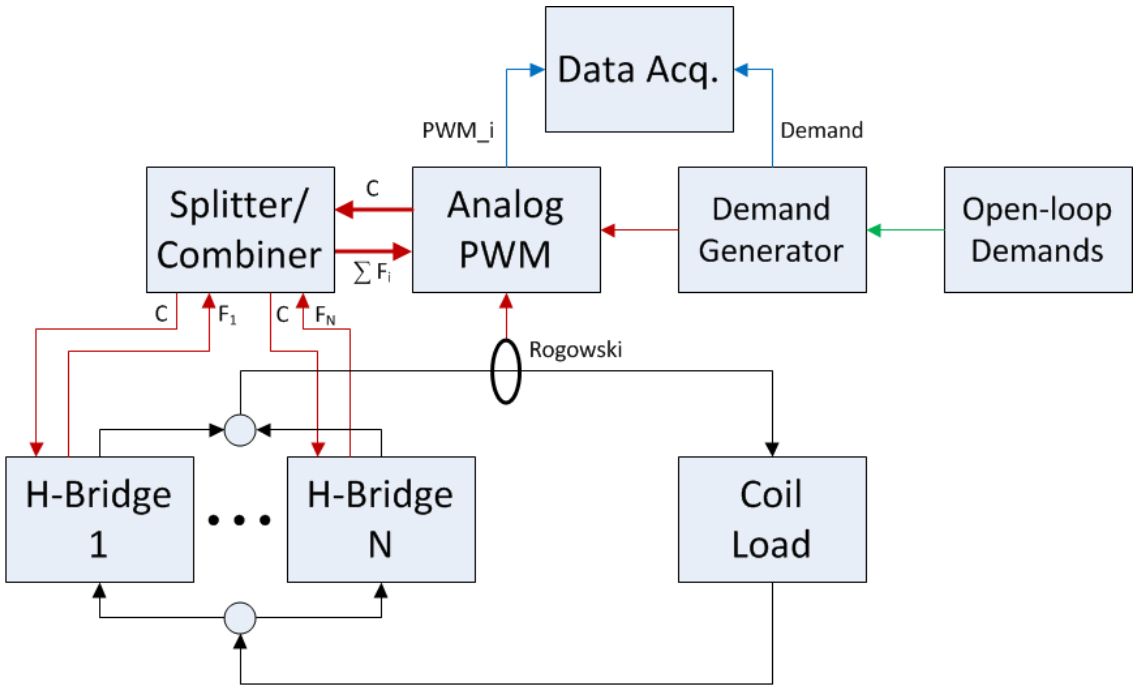
Power and Feedback Control System Upgrade

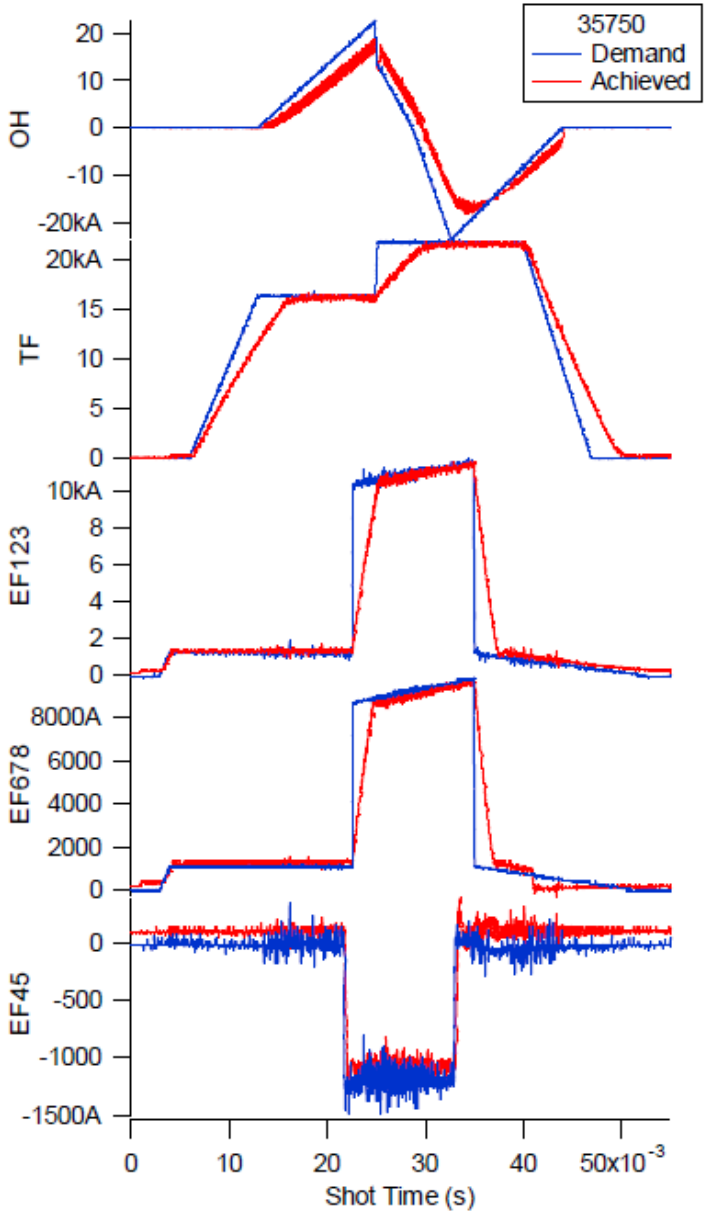
Motivation for Control System Upgrade

- More bridges requires additional control channels
  - Feedback control logic
  - Fan-out, fan-in optical communications to parallel bridge arrays
- Digital controllers based on Field Programmable Gate Array (FPGA)
  - More reliable than discreet analog PWM
  - Flexible and readily expandable
- Digital systems allows shift to programmable hardware
  - Allows for more than just proportional control
  - Higher order feedback control
  - Different control options for different run types
  - Integrates with DIII-D based Plasma Control System (PCS)

PEGASUS Power Systems Presently Employ Analog Feedback Control

- Coil current controlled via switching power supplies
  - IGBT: 900V EF, TF
  - IGCT: 2100V OH (noise/fault limited)
- Proportional analog PWM control

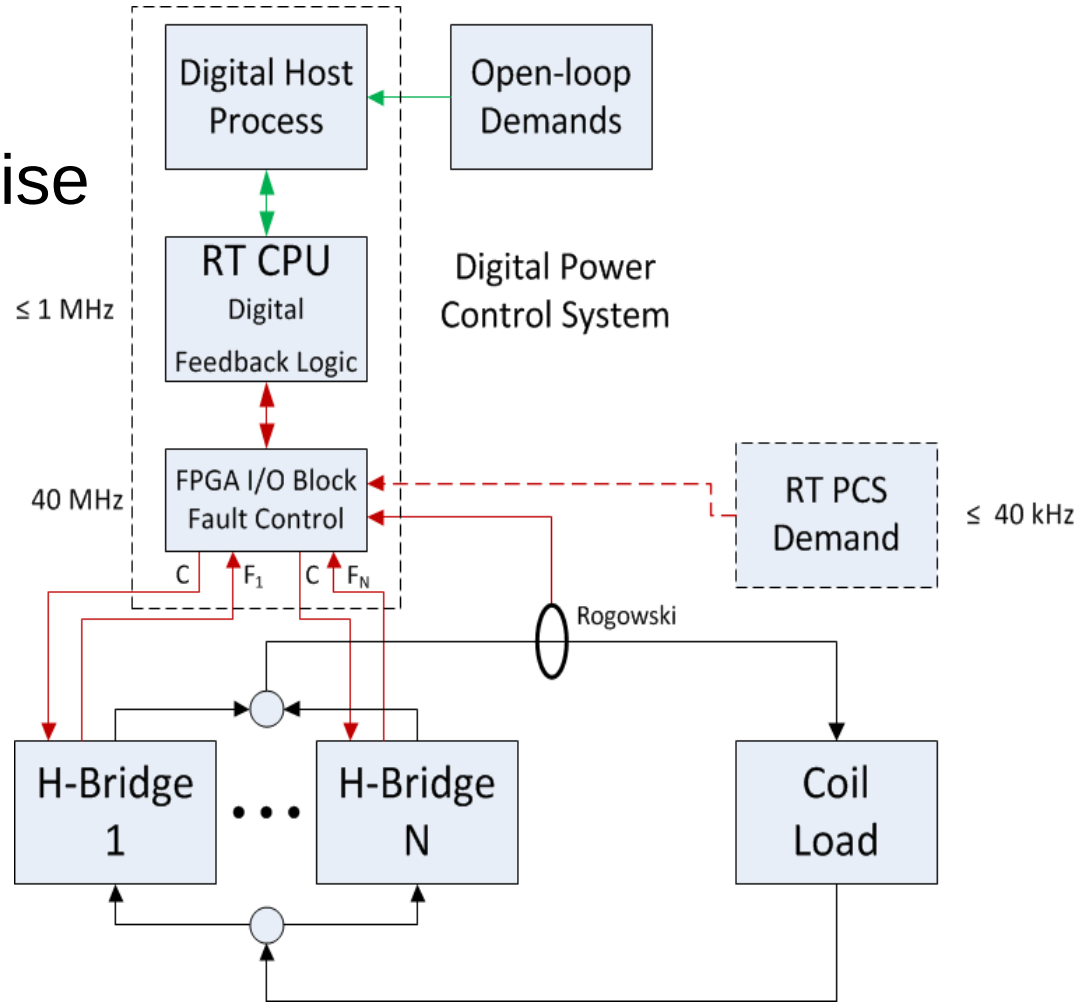




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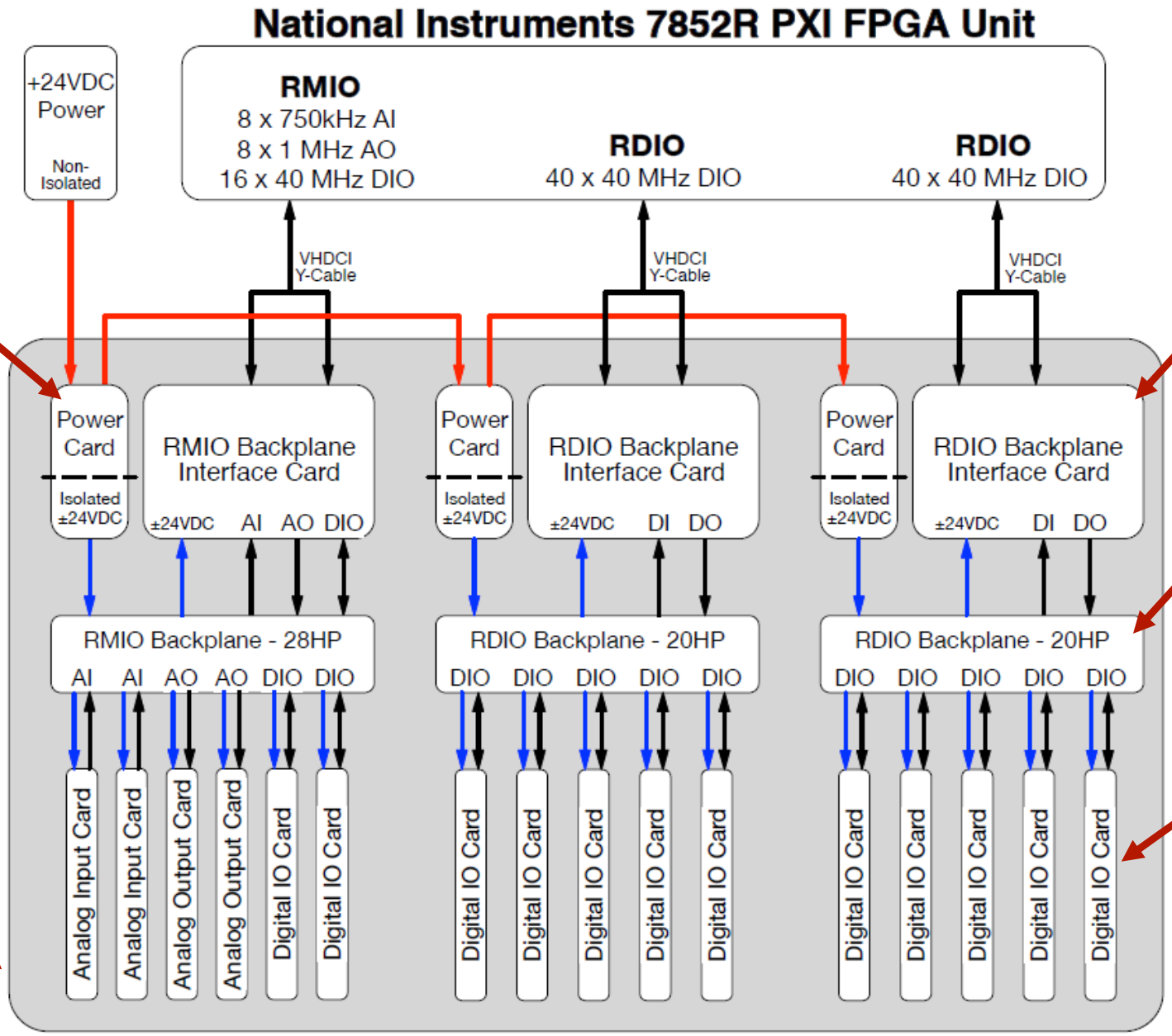
Digital Feedback Control Designed

- Shifting to fully digital system
- Modular PCB chassis with noise resistant design techniques
  - Pseudo differential traces
  - Floating systems
  - Local digitization
- Better fault protection
- Long term expandability



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FPGA I/O Block



Easily replaceable power connection

Interface card to FPGA crate

All modular cards connect here

Modular cards to connect to diagnostics

Shielded case

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Summary

- New solenoid being designed and fabricated by PPPL
- New TF power supply silicon (IGBTs) in house
- New TF stored energy (1 MJ) in house
- NI FPGA hardware in house and deployed for DNB testing
- FPGA interface electronics designed
- New centerstack assembly and installation awaits DOE approval and support