Introduction

- Helicity injection research on Pegasus motivates a set of facility upgrades

  – Improved toroidal field strength and injector bias system can increase plasma current from helicity injection

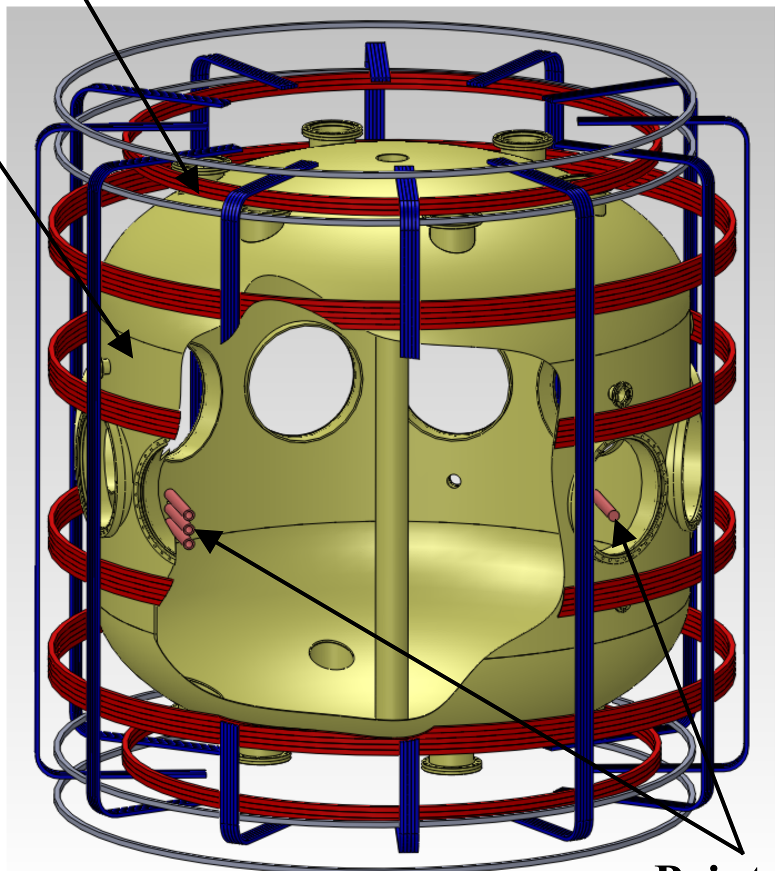
  – Increased position and shaping control can improve coupling of plasma to helicity injectors

  – Increasing complexity of power supply systems demands improved feedback control and fault handling

PEGASUS: A University Scale, Ultralow-A ST

Equilibrium Field Coils

Vacuum Vessel



Point-Source Helicity Injectors

Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	$\leq$ .21	$\leq$ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β stability limits*
  - *ELM-relevant edge MHD activity*

Helicity Injector Physics Motivates Facility Upgrades

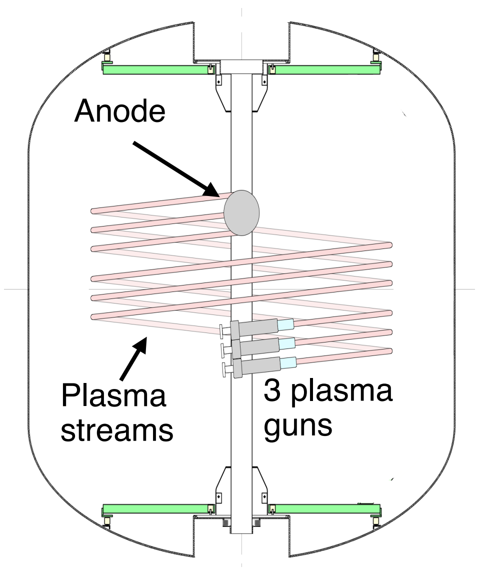
- Taylor Limit – maximum I_p from HI:
  - Depends on injector current, toroidal field current, injector width

$$I_{p,\max} \propto \sqrt{\frac{I_{inj} \bullet I_{TF}}{w}}$$

- Helicity injection loop voltage:
  - Proportional to B normal to injector surface, injector area, injector bias voltage

$$V_{eff} \propto \frac{B_{inj} \bullet A_{inj} \bullet V_{bias}}{\psi_T}$$

- Motivates increases in I_{inj}, I_{TF} through facility upgrades
  - Upgraded TF power supplies
  - Upgraded injector bias system



- Ref: D.J. Battaglia, Tokamak Startup Using Outboard Current Injection on the Pegasus Toroidal Experiment *Nuclear Fusion* **51**, 073029 (2011)

Compact Plasma Arc Sources Provide Dense Plasma for Electron Current Extraction

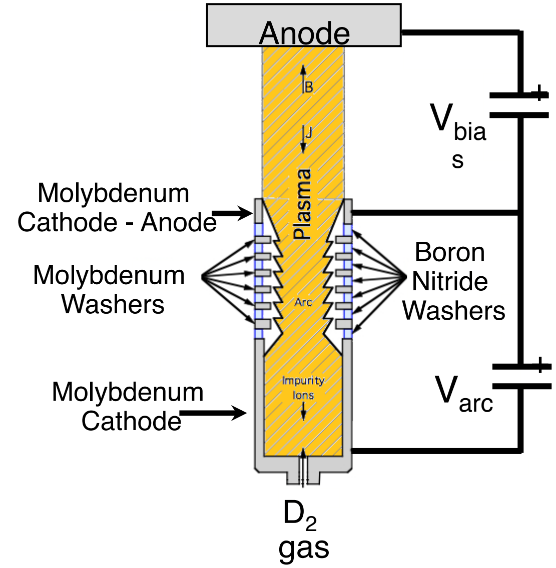
- Plasma arc(s) biased relative to anode:
  - Helicity injection rate:

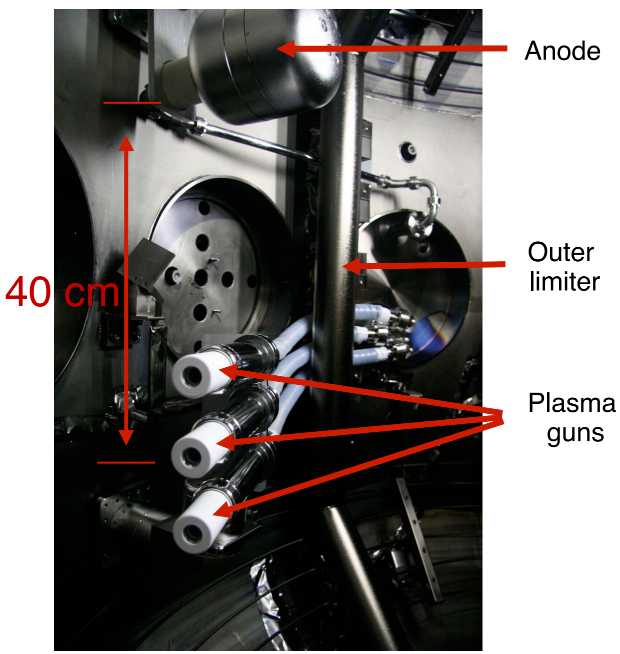
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

V_{inj} - injector voltage

B_N - normal B field at gun aperture

A_{inj} - injector area





- Arc plasma fully ionized
  - $N_e \sim 10^{20}\ m^{-3}$
  - $T_e \sim 10$ eV
  - Dia = 1.6 cm
  - $I_{arc} \sim 2$ kA

1 Fiksel, G, et. al., Plasma Sources Sci. & Tech. **5** (1996) 78.

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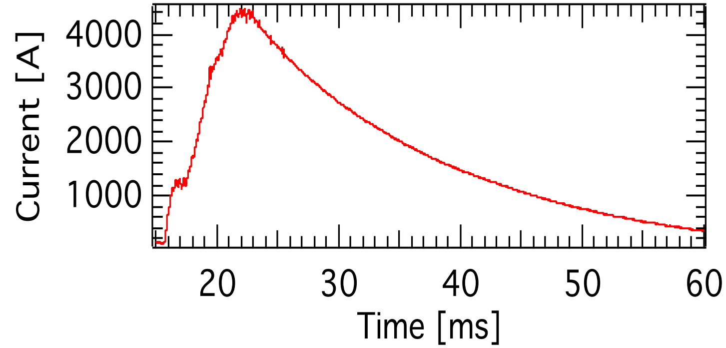
Pegasus Employs Modular Switching Power Supplies

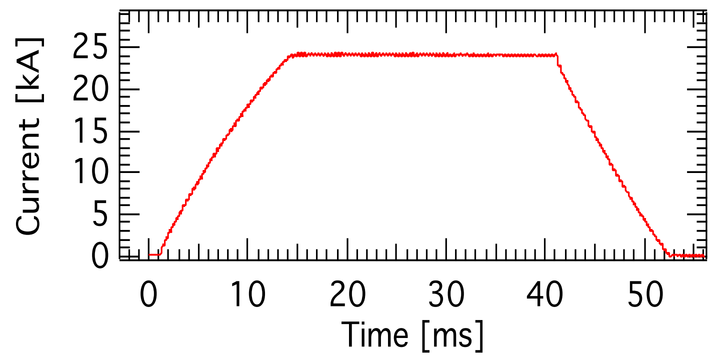
- Two banks of switching power supplies on Pegasus
  - Bank A: 12 x 2700V IGCT Bridges
    - Ohmic
    - New high voltage injector bias
  - Bank B: 28 x 900V IGBT Bridges
    - Toroidal Field Coils
    - Poloidal Fields Coils
    - Divertor Coils
    - Low voltage injector bias
- Power supplies are modular and reconfigurable
  - Allows reassignment of bridges between systems as needed

Systems Powered by Three Types of Bridges

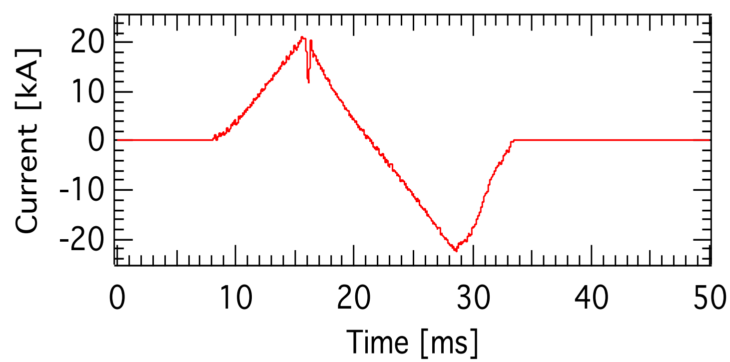
- One Quadrant Bridges
  - Unipolar drive / coast
  - e.g., – injector bias system



- Two Quadrant Bridges
  - Unipolar drive / regen
  - e.g., – toroidal field coils



- Four Quadrant Bridges
  - Bipolar drive / regen
  - e.g., – ohmic



New Bridge Technology Enables Doubling of Toroidal Field

- Improved IGBT technology supports TF increase from 0.15T to 0.3T
  - 6 4-kA IGBT bridges replaced by 8 6-kA IGBT bridges
    - 288 kA-turns → 576 kA-turns
  - Improved performance enables
    - Switching for twice the duration at same current
    - Switching for same duration at 50% higher current
- Original TF bridges now free for other use
  - PF upgrade / divertor coils

New TF silicon

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Advantages of New IGBT Technology

Present System:

Eupec FZ2400R17KE3 IGBT

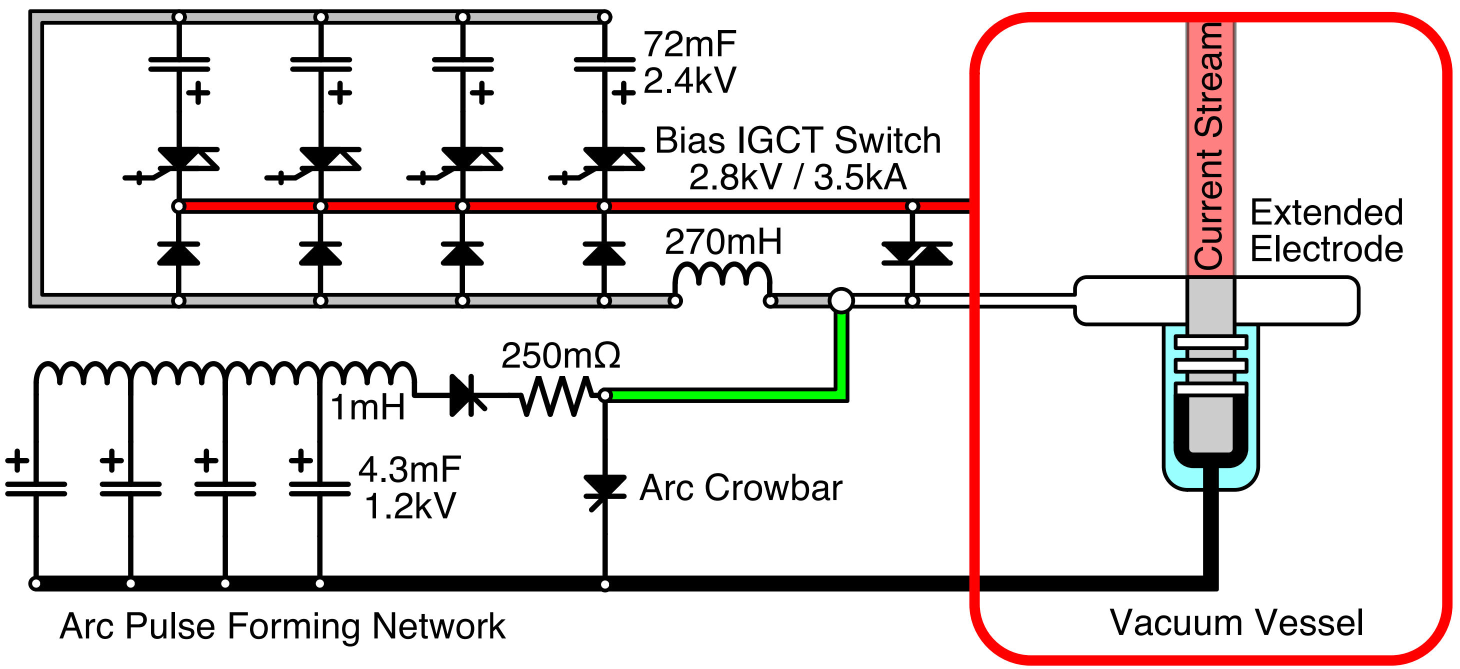
- Steady state voltage rating: 1200V, 2.4kA
- Pulsed rating: 900V, 2.4kA at 1kHz - Switching Frequency
- Repeated operation at 2x switch rating (4.8kA)
- Voltage switching up to 3kHz, dependent on switch topology, controller
- Heat sink: traditional copper base plate

Augmented System:

Eupec FZ3600R17HP4-B2 IGBT

- Steady state voltage rating: 1700V, 3.6kA
- Pulsed rating: 900V, 3.6kA at 1kHz switching frequency
- Repeated operation at 2x switch rating (7.2kA)
- Voltage switching up to 10+ kHz, dependent on controller
- Heat sink: AlSiC base plate for increased thermal cycling capability (better pulsed power performance)

New IGCT Bias System Increases Injector Current and Voltage



- Four 1-quad IGCT bridges supply up to 14kA injector current at up to 2kV

- Helicity rate ~ V_{bias}
- Taylor Limit ~ $\sqrt{I_{inj}}$

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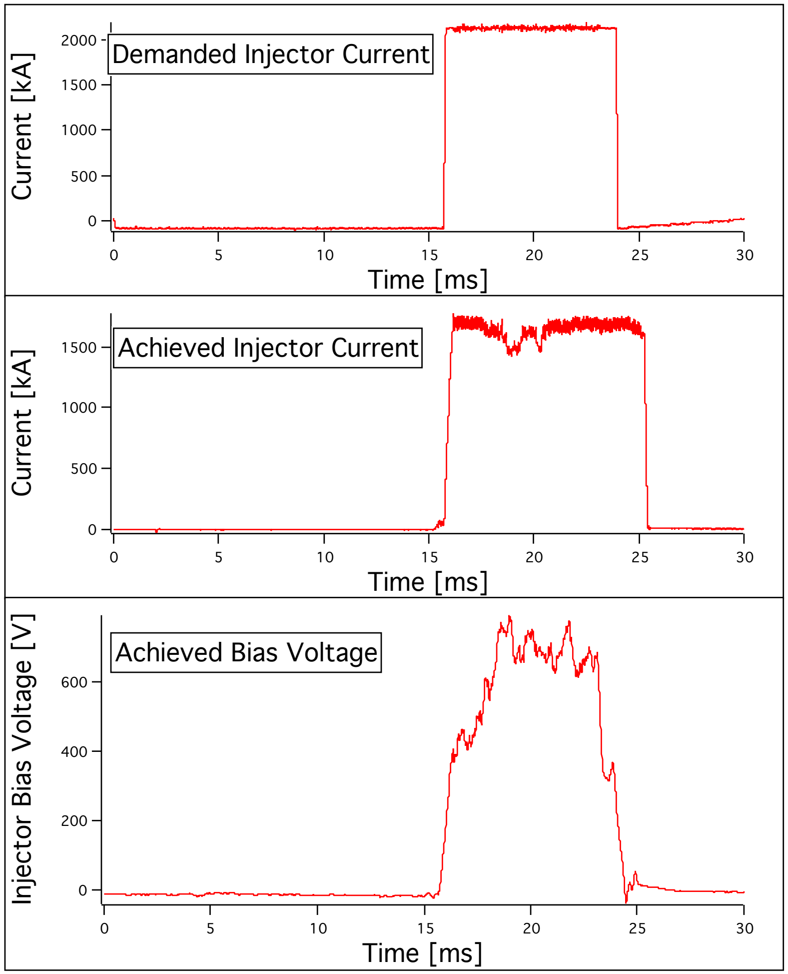
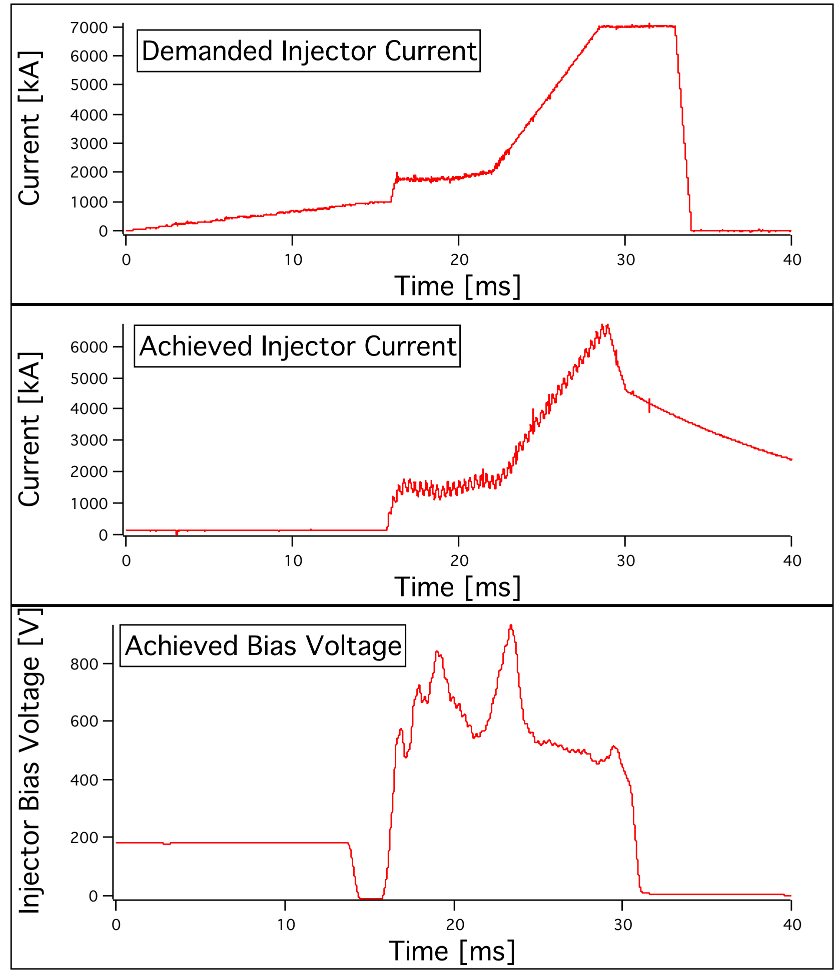
Increased Injector Current for Helicity Drive

IGBT Bias System



IGCT Bias System



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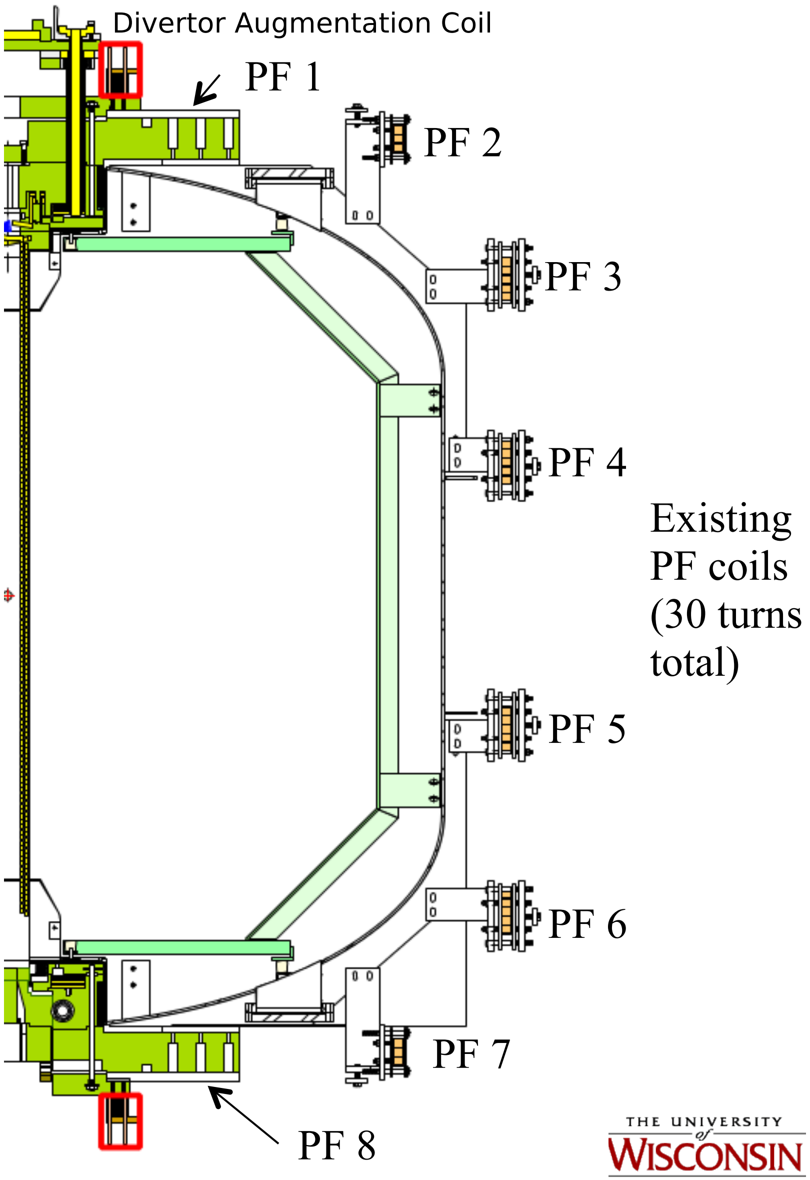
Planned Expansion of Poloidal Field Coils

- Presently poloidal field is driven by 8 coils sets with a total of 30 turns
- PF time response important for position control, poloidal induction
  - Limited by coil rise time (L/R), penetration of vacuum vessel
- Modifications chosen to improve time response:
  - Decrease turns per coil set
  - Increase number of independent coil sets, using former TF power supplies



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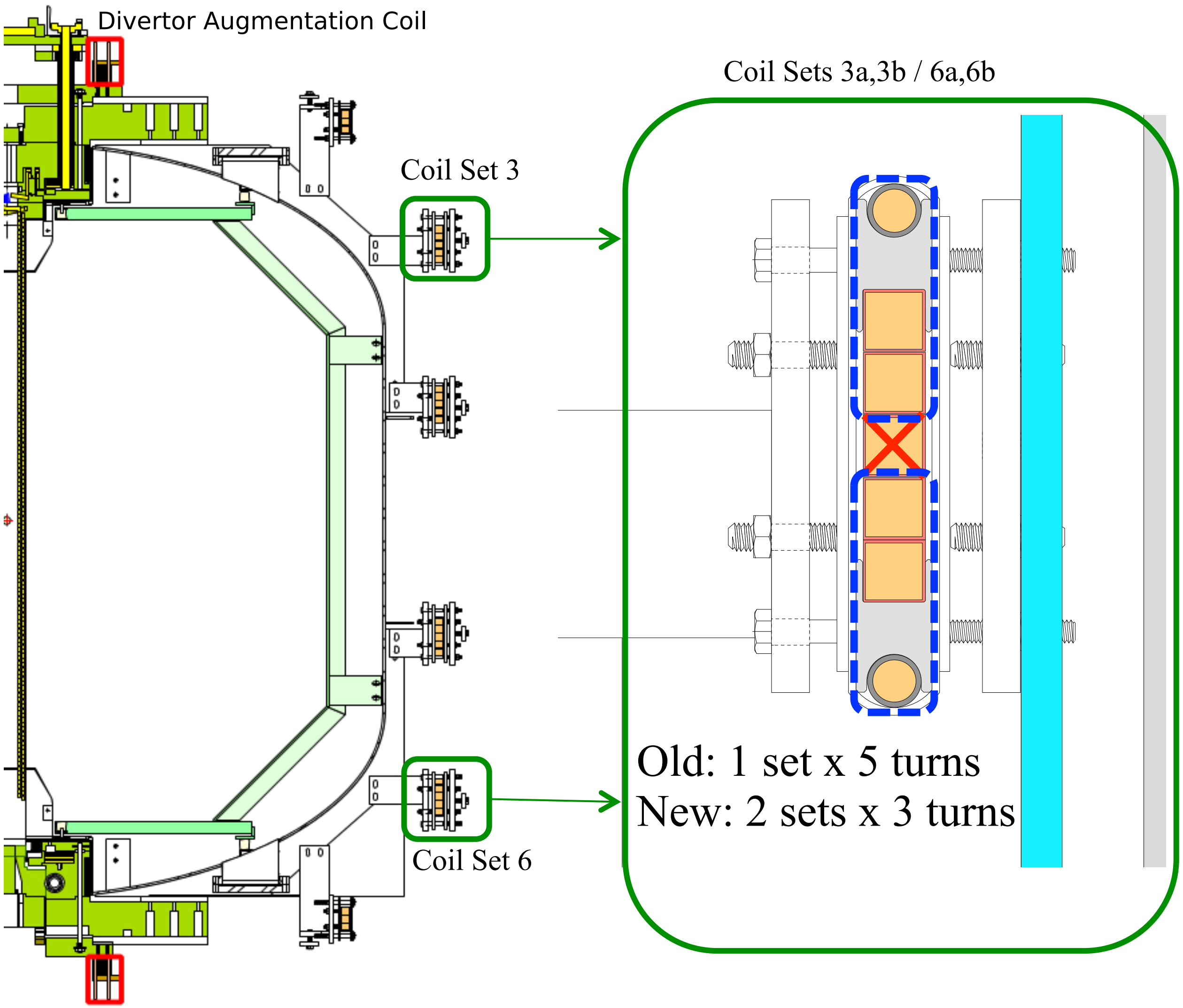
More Independently Driven PF Coil Sets

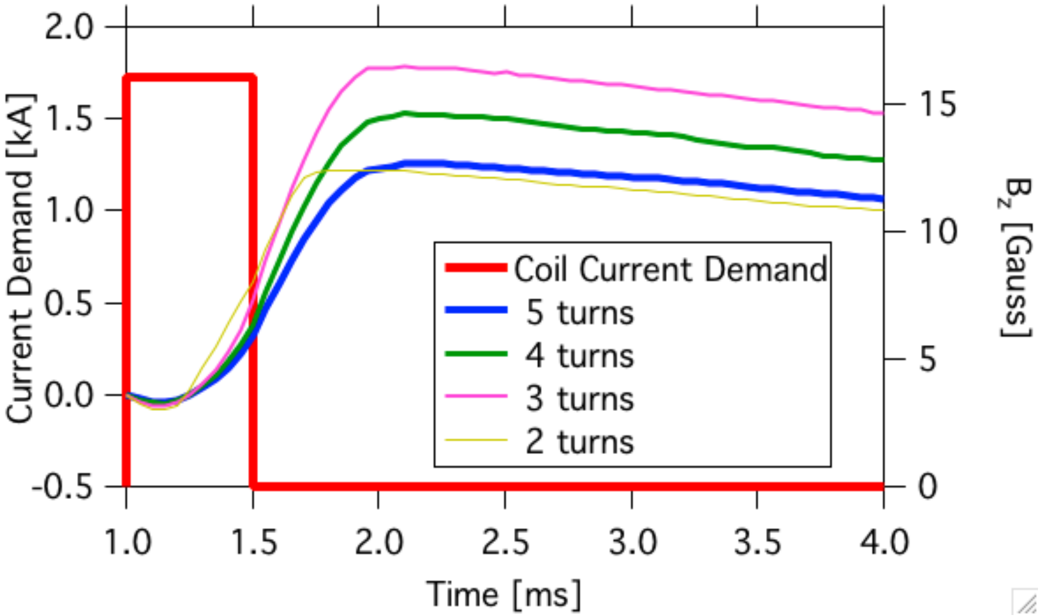


Modifications to coil sets 3 and 6:

- new turns added above and below
- Each set split into 2 sets of 3 turns

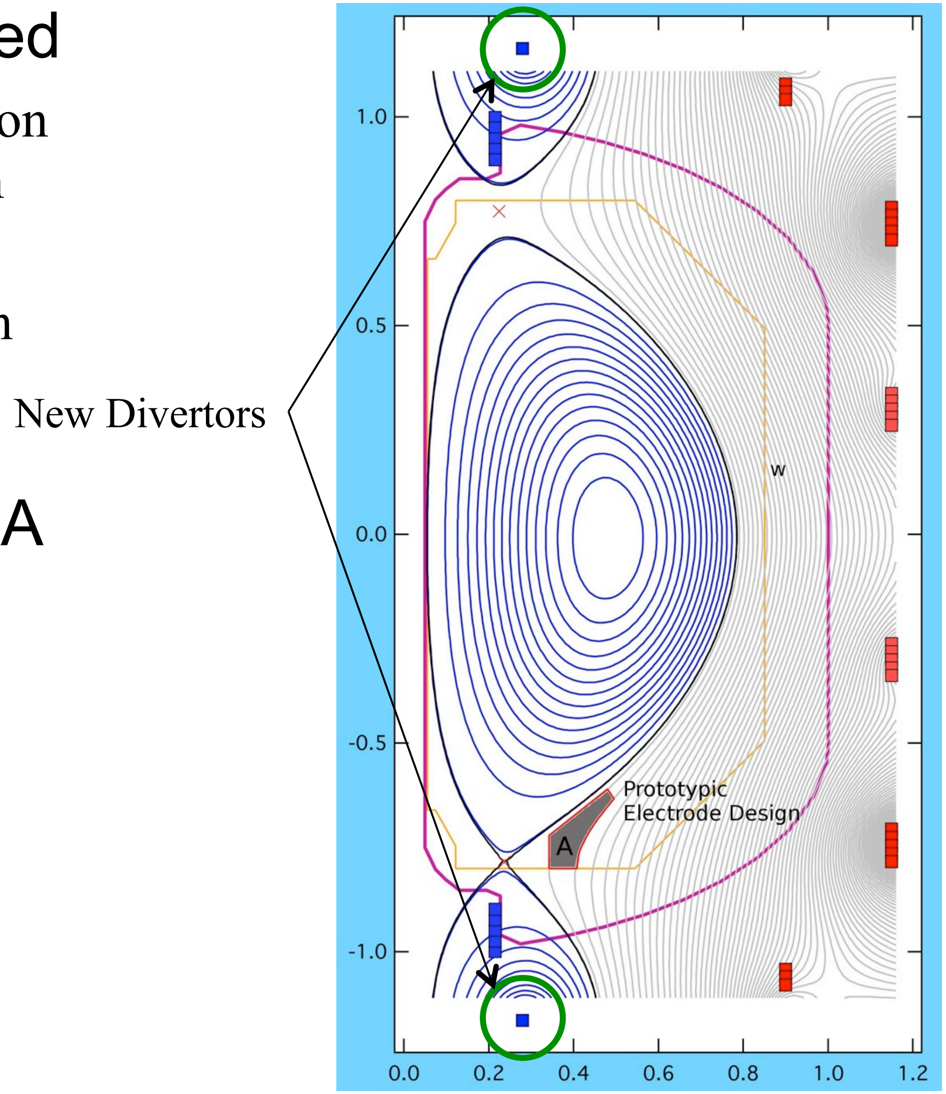
Number of Turns Drives PF Response Time

- Wall code simulations used to find optimal # turns / coil set in Pegasus
  - Balance of coil rise time vs. wall penetration time
- Response time characterized using 0.5ms square pulse
  - Figure of merit: $B_z(t)$ at R=0.4m
- 3 turns/set gives optimal response time for available power supplies



New Divertor Coils Will Enable Full Separatrix Operation

- New divertor coils designed
  - achieve higher helicity injection rate through flux expansion in divertor region
  - Conduct H-mode studies; path towards high-β
- 26 turns carrying up to 4kA support single null and double null topology with $I_p \leq 300$kA
- Full divertor design presented by P. Shriwise
  - Poster NP8.00067



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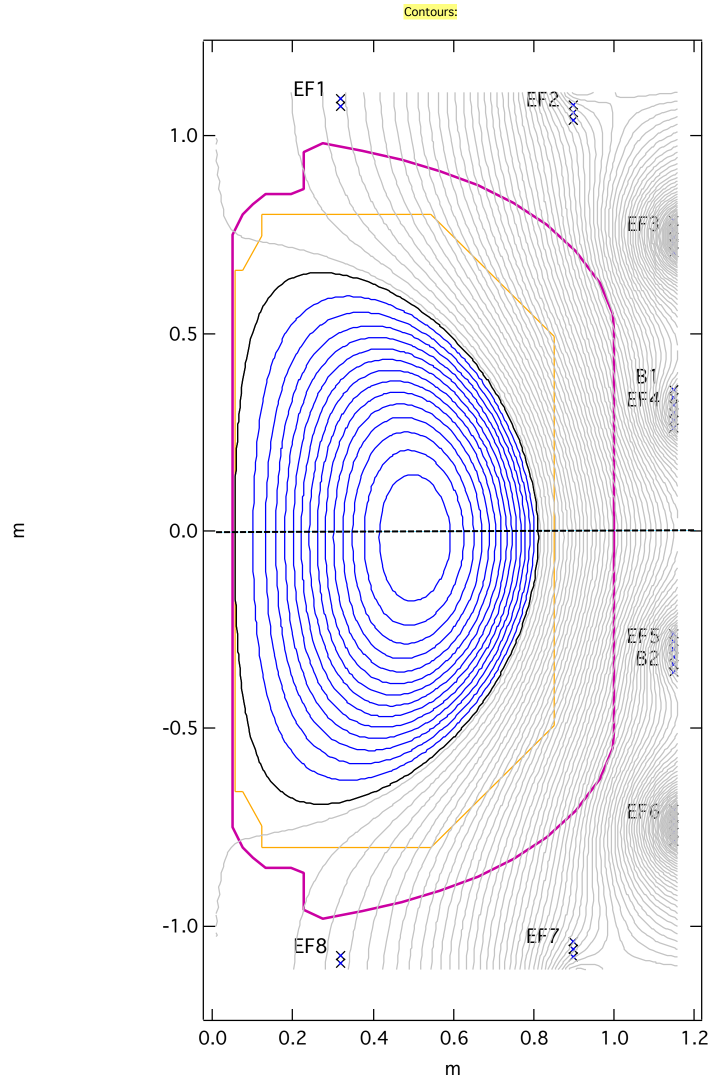
Exploration of Improved Vertical Position Control

- Plasma vertical position control desirable:
  - Compensates for magnetic field errors
  - Provides control flexibility
    - Optimize current coupling to helicity injector

- Three avenues under consideration:
  - Run top/bottom divertor coils in opposing directions (anti-series)
  - Additional turns to PF coils closest to midplane – running opposed current
  - Run main PF coils up-down assymetric



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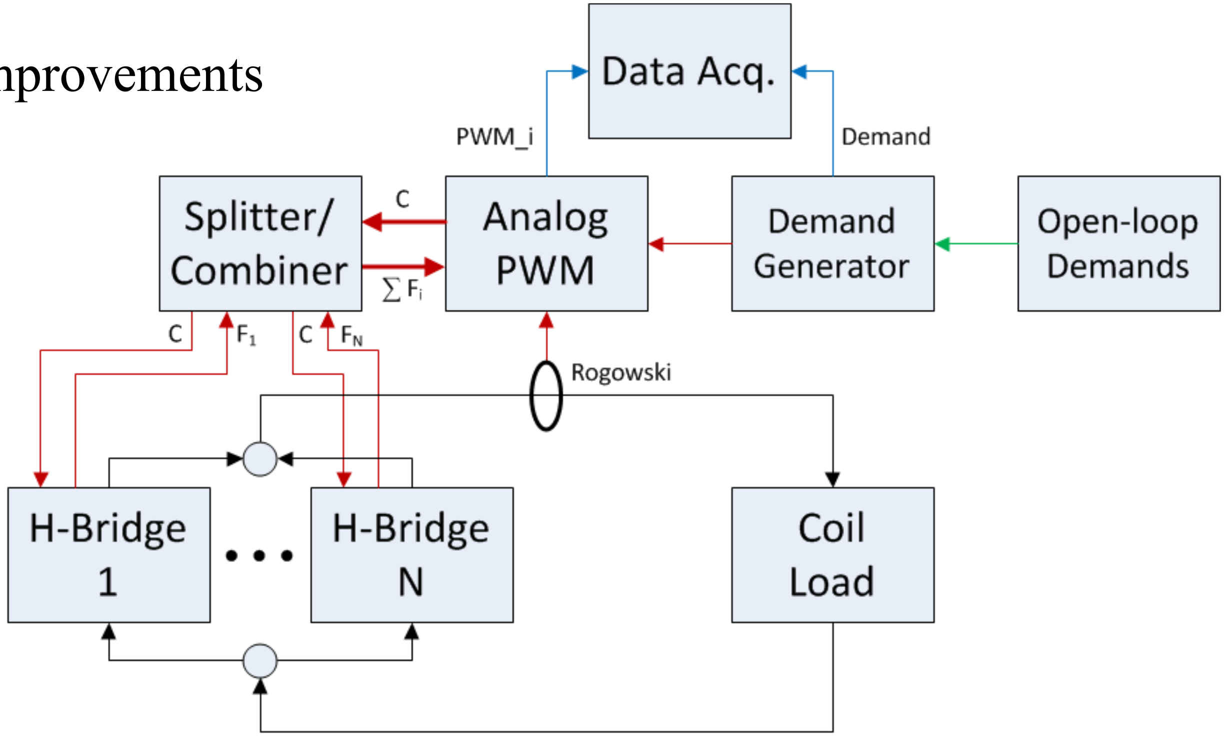
Control Enhancements Accompany Power Supply Upgrades

- Power supply control system improvements motivated by:
  - Increasing number of bridges require additional control channels
  - Need to handle and log hardware faults
  - Advanced feedback control of magnetic field coils and DC helicity injectors
  - Need for more independent feedback controllers and fault detectors
- Two approaches being pursued to implement these goals
  - Near-term: improvements to existing analog system
  - Medium-term: advanced digital control (FPGA)

Near Term Control System Modifications

- Stage 1: Improvements to present analog system
  - Improved bridge protection logic
  - Deployed more PWMs
  - CAMAC timing improvements



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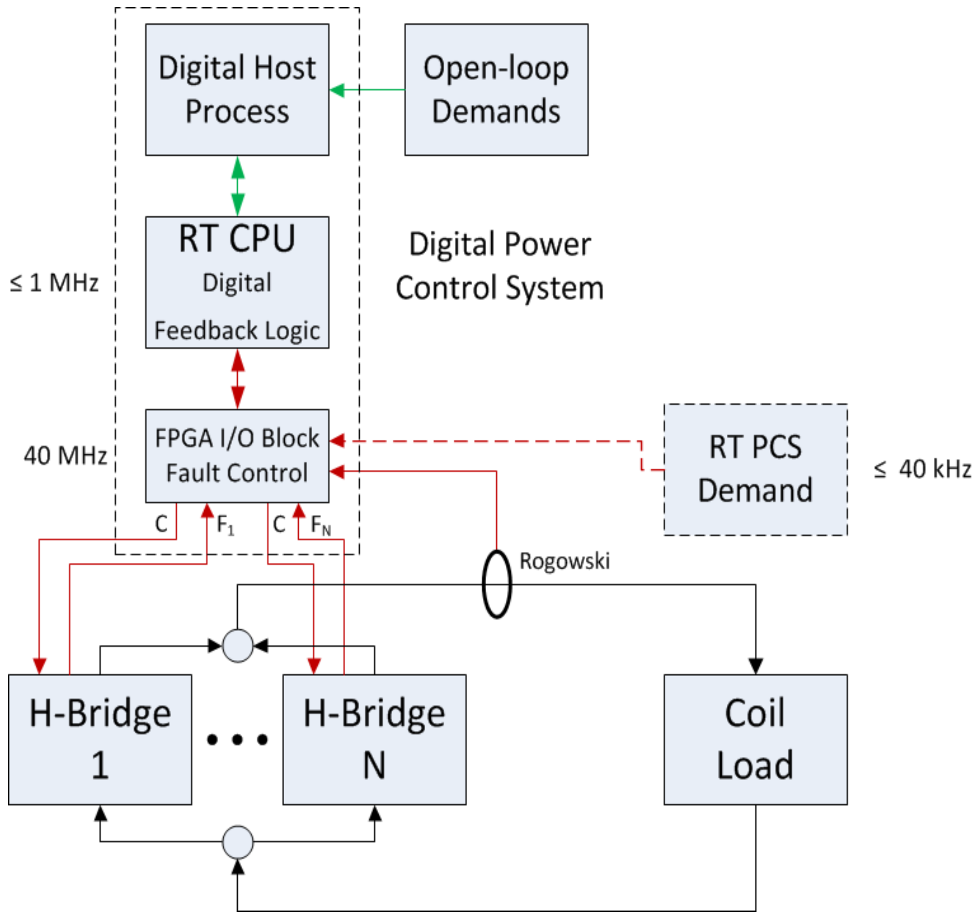
Digital Feedback Control

Stage 2: Digital control system

- based on NI FPGA technology
- Enables ~5MHz digital polling of bridge states
- FPGA level fault handling
- Realtime controller provides 5kHz feedback control
- Fully replaces analog PWM, splitter/combiner hardware



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Summary

A set of current and planned upgrades will improve the physics capability of Pegasus

- Power supply upgrades boost HI capabilites:
  - Toroidal field kA-turns doubled
  - High voltage, high current injector bias system
- Magnetic field coils enable increased position and shaping control
  - Expanded PF coils for faster time response
  - New divertor coils will allow improved helicity injection, H-mode studies
  - Vertical position control – options under consideration
- Control systems advanced to meet needs of new power systems
  - Near term: improvements to analog control systems
  - Medium term: advanced digital control