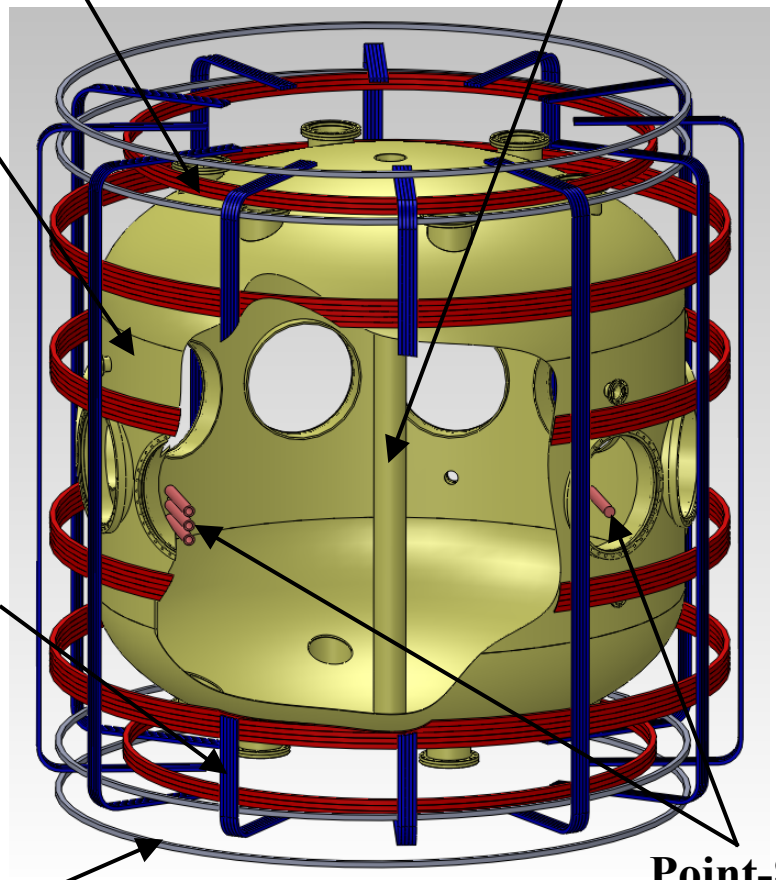
Motivation

- Design and install a coil at the top and bottom of the machine:
  - *Ability to fully divert an $I_p \geq 300kA$ Ohmic plasma*
  - *~100 kA-turns indicating the need for a 26 turn coil based on the 4kA limit of the available power supplies*
- Advanced helicity injection
  - *Expanded flux surfaces offers path to higher helicity injection and higher Taylor relaxation limit.*
- H-mode related studies
  - *Access to H-mode allows for MHD analysis of current-driven peeling modes and pressure-driven ballooning modes.*
  - *H-mode confinement enhancement may aid the path to high-β operation*

Pegasus is a compact ultralow-A ST



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)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 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*

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Diverted Operation Allows for Greater DC Helicity Injection

- Helicity balance equation:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot\mathbf{B}\, d^3x - 2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot d\mathbf{s} \qquad I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

  - I_p scales with the confinement time inside η

- Helicity injection rate of Pegasus point sources:
  - V_{inj} = injector voltage
  - B_N = normal field at gun aperture
  - A_{inj} = area of injector surface

$$V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi_T}V_{bias}$$

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

- Divertor topology provides a larger injection area between flux surfaces.

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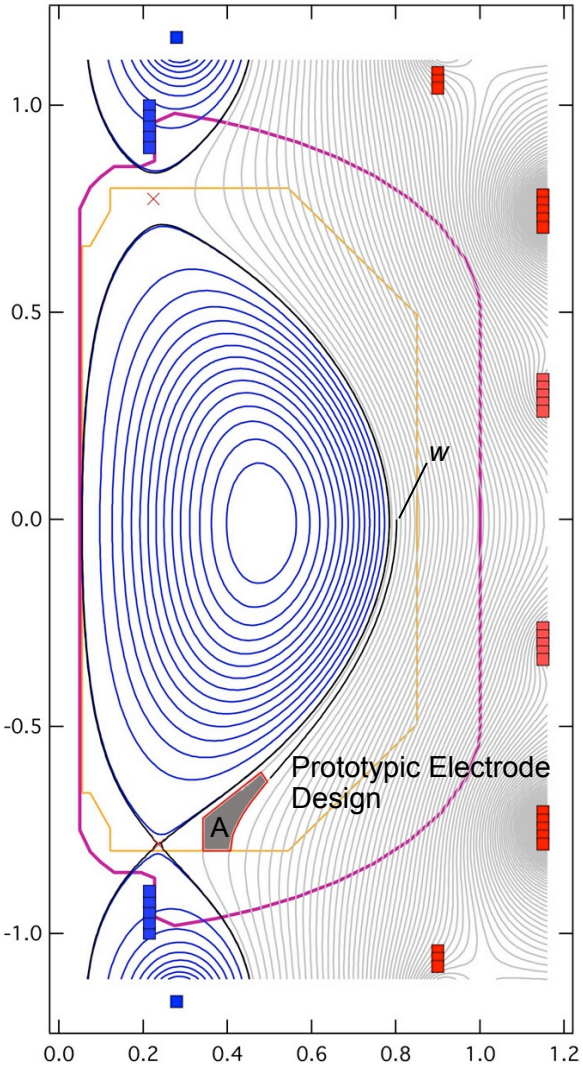
Flux Surface Expansion in Diverted Topology Offers Higher Current Drive

- Taylor relaxation limit on I_p:

$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$

  - I_{TF} = toroidal field current
  - I_{inj} = injected current
  - W = effective current channel width at outboard midplane

- Expansion of flux surfaces near the separatrix creates a larger A_{inj} while decreasing w creating higher dK/dt and I_p limit



A ≈ 120 cm^2 w ≈ 1.6 cm

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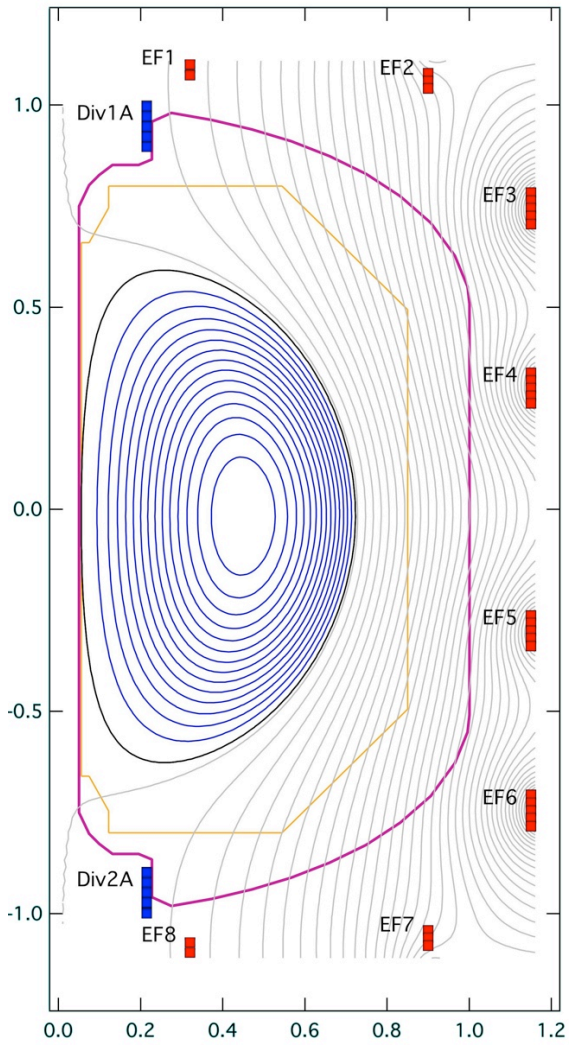
Grad Shavfranov Solver Used to Create Equilibrium Models for Divertor Design

- GS solver used to create design points for kA-turn requirement under desired plasma conditions
  - Additional coils were designed to augment the existing system which was intended to run under different power supplies
  - Equilibrium field coils are operated in groups:
    - i) EF Coils 1, 2, & 3
    - ii)EF Coils 6, 7, & 8
    - iii) EF Coils 4 & 5

Coil Currents:

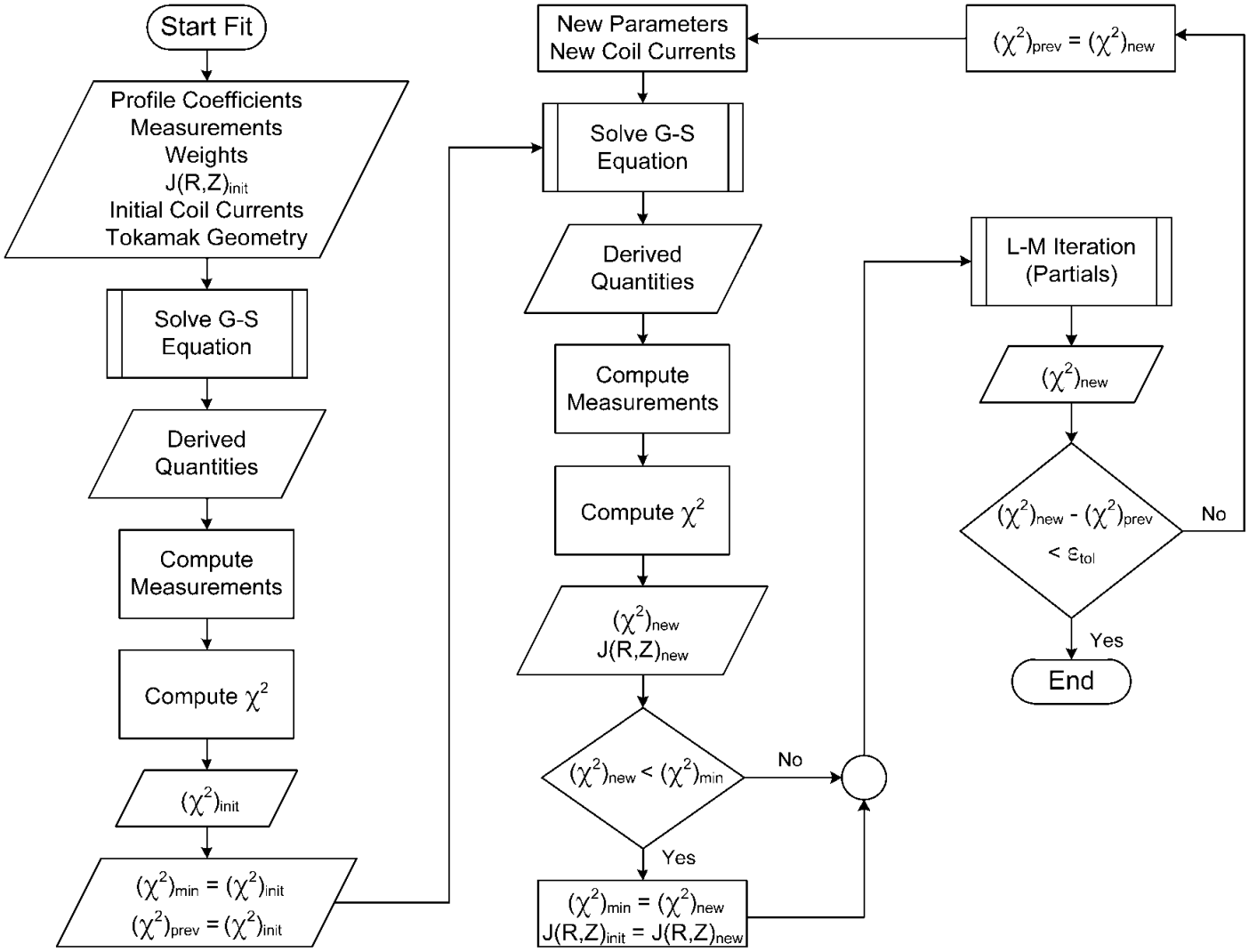
- co-I_p
- counter-I_p

Existing PF System



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KFIT Solution Flowchart



A target plasma with I_p=300kA was modeled in divertor design

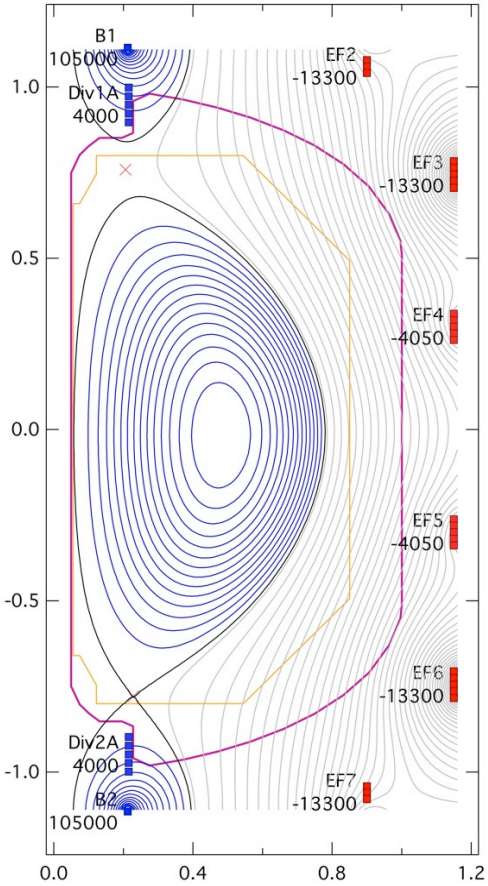
- Following parameters were used to describe the target plasma for equilibria:

Parameter	Range	Code Input	Std. Dev. (%)	Coil Design Point
I_p	~300kA	300kA	5	316.9kA
q_o	>1.5	1.5	20	1.56
β_p	$0.05 < \beta_p < 0.5$	0.275	80	0.13
li	0.3 < li < 0.5	0.4	25	0.49
R_o	~0.4 m	40 cm	10	37 cm
X_{mag}	~0.4 m	40 cm	10	48 cm

B_{To}=0.17 T

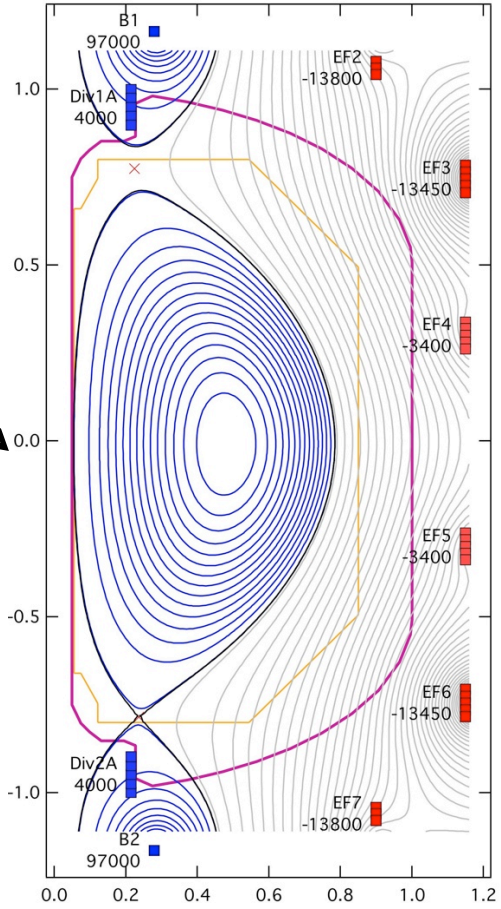
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New Coil Location Significantly Influences Power Requirements



Inboard Divertor Augmentation:
105kA-turns

Outboard Divertor Augmentation:
97kA-turns despite increased distance from the plasma



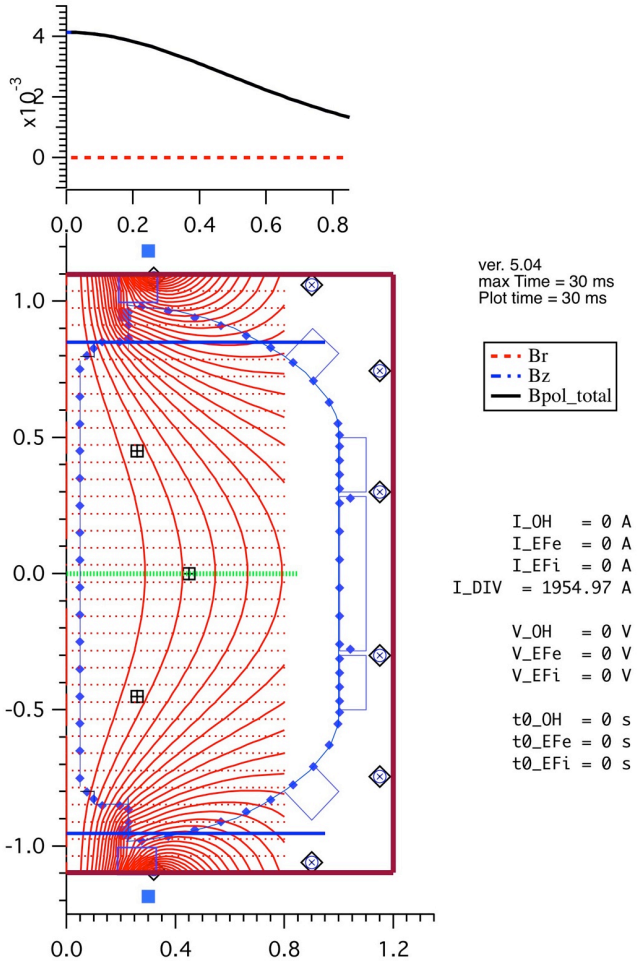
Coil Currents:
- co-I_p
- counter-I_p

- Dipole between coils is more efficient in an outboard location
- Additional coil has greater influence on x-points in this position

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Current and Field Rise Time is Dependent on New Coil Location

- Code was used to determine the current rise time and field diffusion through the wall
- Wall and current modeling represents actual systems in place on Pegasus
- Current time response varies directly with radial position of the additional coil whereas the power requirement varies inversely

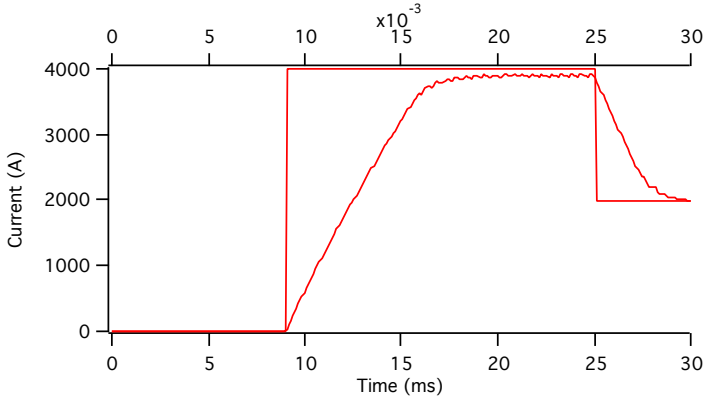


Divertor system fields after full diffusion through vessel wall.

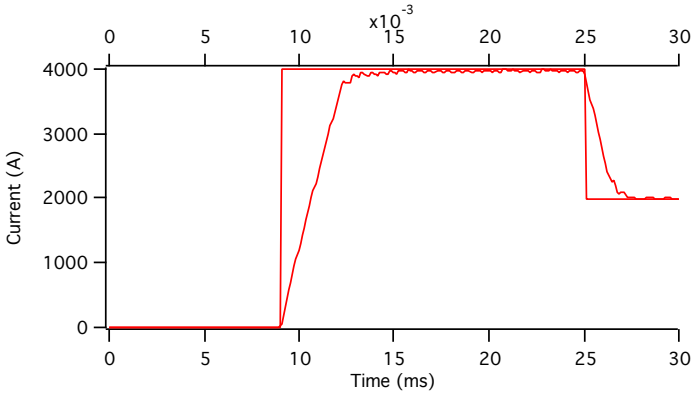
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Current Rise Time and Field Penetration Optimized with Wall Current Code

- A single IGBT power supply is sufficient for poloidal field penetration on the order of ~7ms.
- For higher coil performance the upper and lower sets will be run on independent power supplies.
  - 2 quad, IGBT bridges operating at 4kA, 900V
- In this configuration, current rise time (~2-3ms) is acceptable for field penetration.



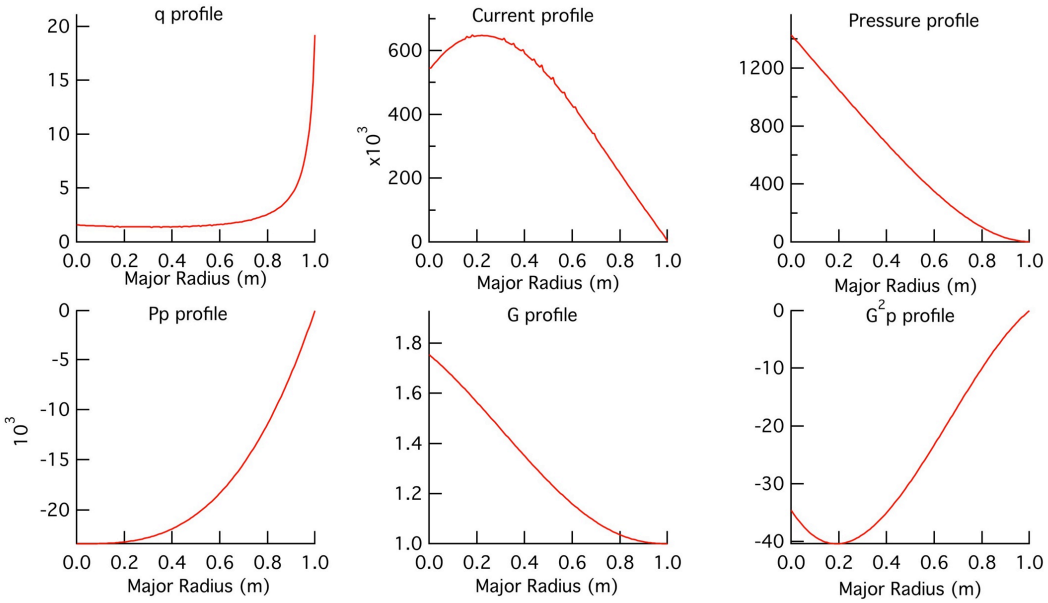
Coil Rise time under one IGBT power supply.

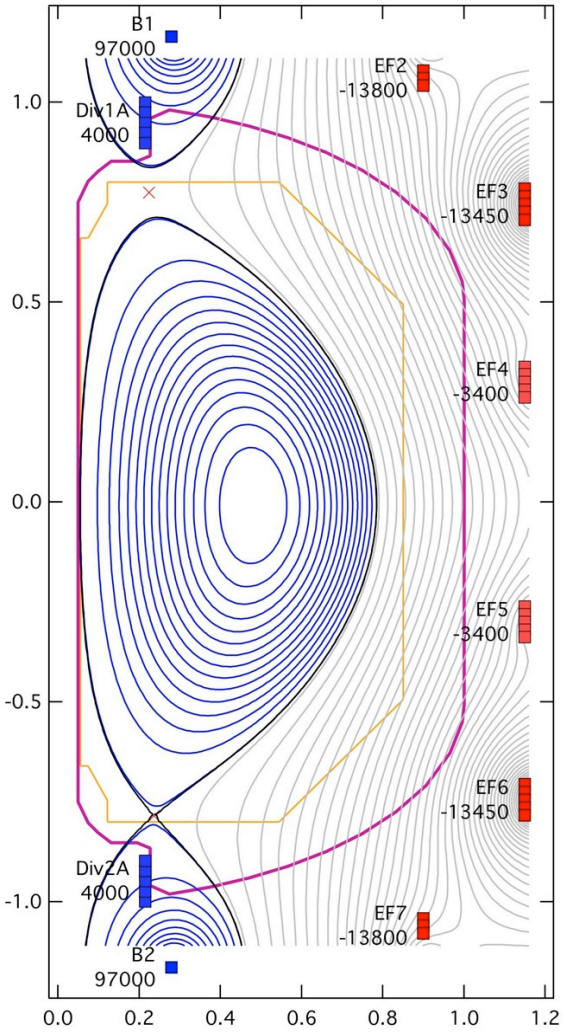


Coil Rise time under independent IGBT power supplies.

Final Design Point

- 97 kA turns are required for double-null diversion
- 26 turn coil operating at 4kA with the ability to divert a 300kA plasma.

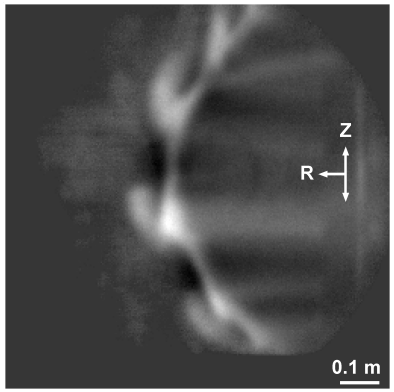


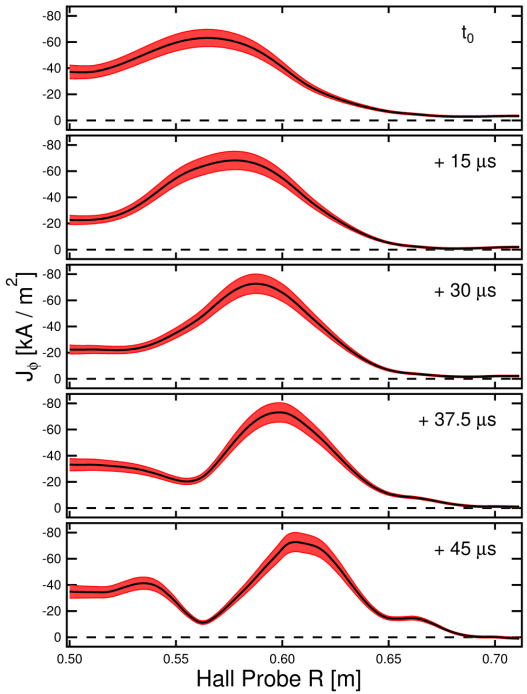


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Edge Stability Studies are Critical to Next-Step Fusion Devices

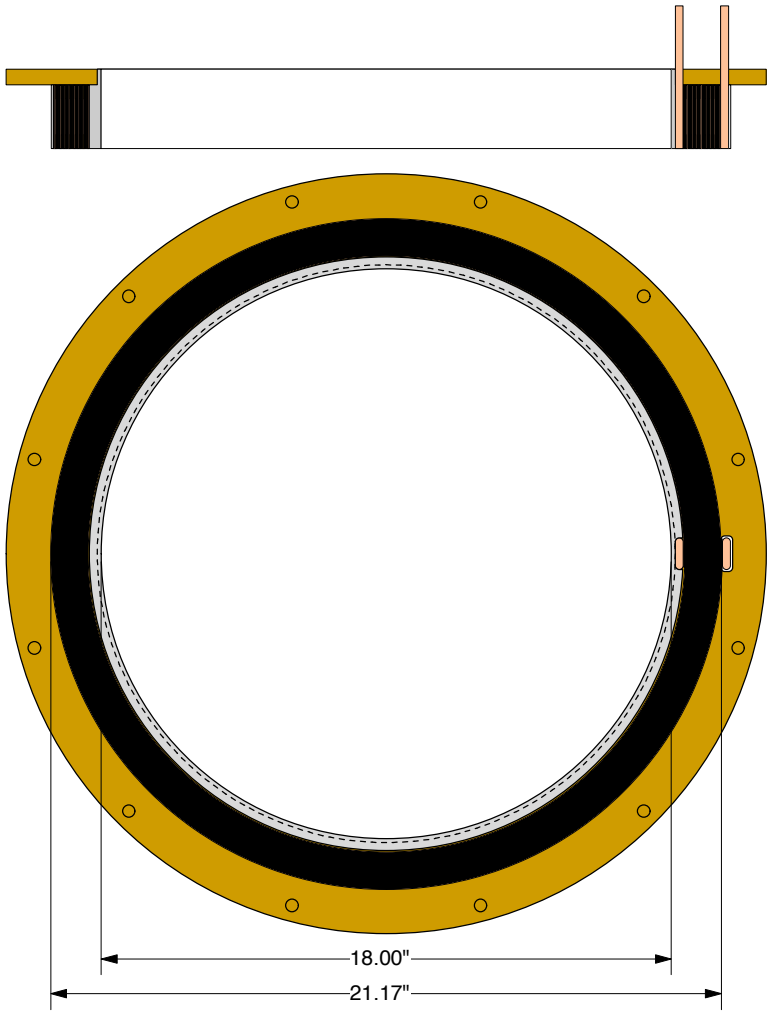
- Pressure, current density gradients drive MHD instabilities
  - Edge Localized Modes (ELMs): periodic, transient release of stored energy
- Validated theory needed for effective ELM mitigation/control
- J(r,t) has been measured on Pegasus through a peeling mode cycle at the plasma edge
- New coil will expand these studies to robust H-mode pedestal

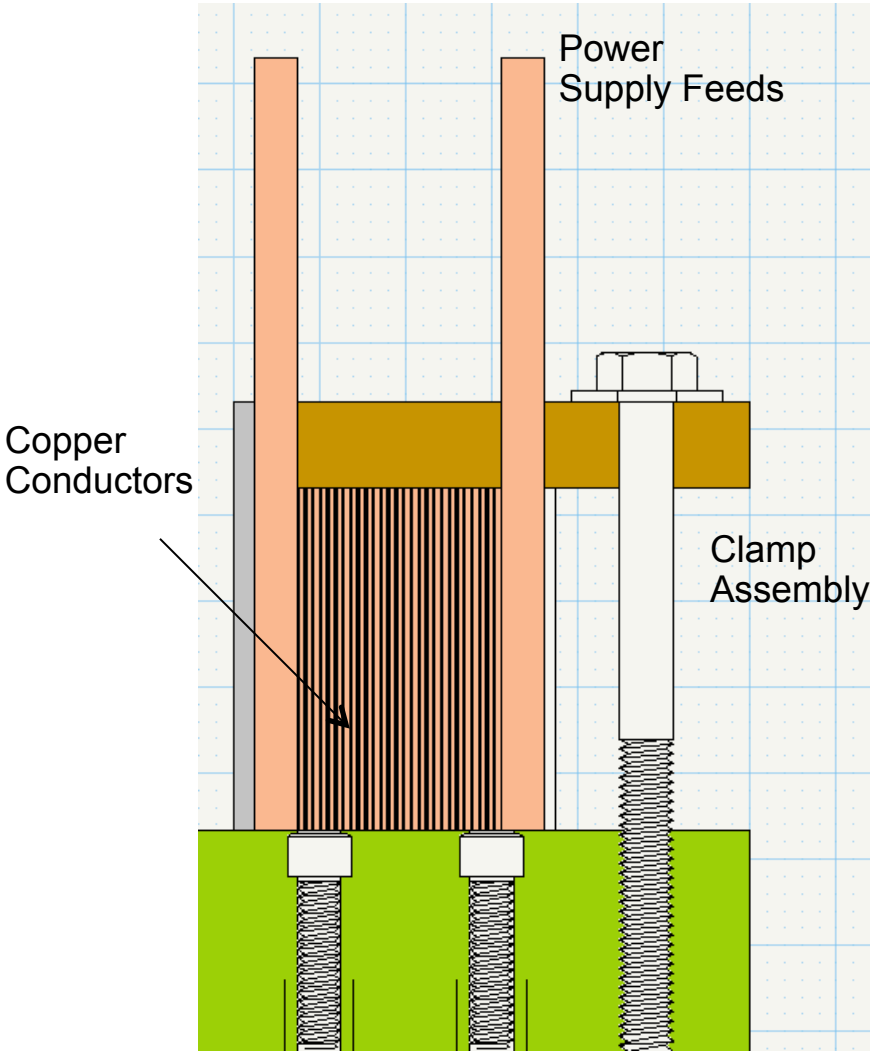




Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

Divertor Augmentation is a Sprial-Build ,Copper Conductor Coil

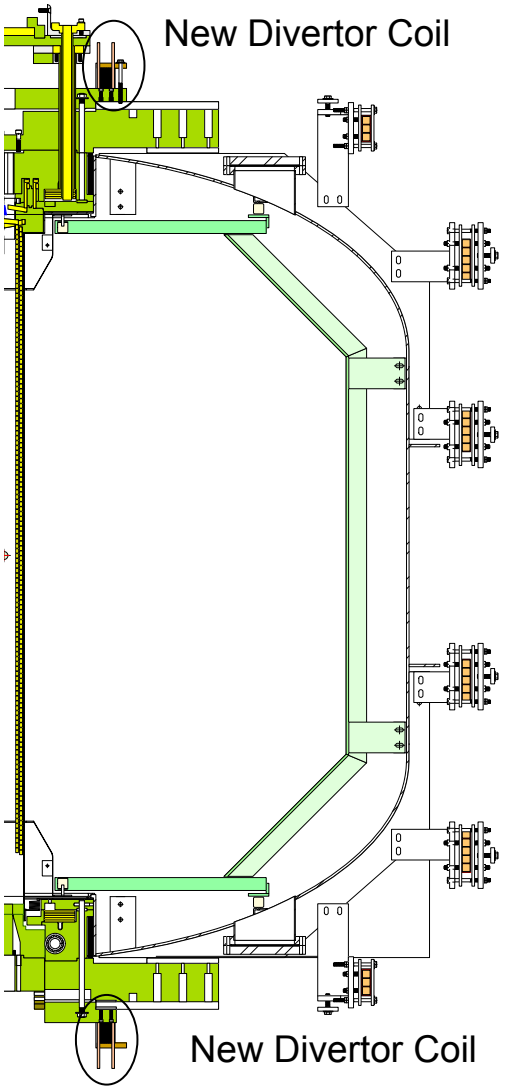




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Summary

- 26 turns of 1/32” x 2” copper conductor
- 4kA power supplies provide up to 104 kA –turns
- Designed to fully divert a 300kA plasma with double null topology



Acknowledgements

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http://pegasus.ep.wisc.edu/Technical_Reports/Conferences.htm

Or contact Patrick at shriwise@wisc.edu

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