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
  - $\sim 100 \text{ kA-turns}$ 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-$\beta$ operation
Pegasus is a compact ultralow-A ST

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$1.15 - 1.3$</td>
<td>$1.12 - 1.3$</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>$0.2 - 0.45$</td>
<td>$0.2 - 0.45$</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq .21$</td>
<td>$\leq 0.30$</td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>$6 - 12$</td>
<td>$6 - 20$</td>
</tr>
<tr>
<td>$R_B$ (T-m)</td>
<td>$\leq 0.06$</td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1.4 - 3.7$</td>
<td>$1.4 - 3.7$</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>$\leq 0.025$</td>
<td>$\leq 0.05$</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>$\leq 25$</td>
<td>$&gt; 40$</td>
</tr>
<tr>
<td>$P_{\text{HHFW}}$ (MW)</td>
<td>$0.2$</td>
<td>$1.0$</td>
</tr>
</tbody>
</table>

Major research thrusts include:

- Non-inductive startup and sustainment
- Tokamak physics in small aspect ratio:
  - High-$I_N$, high-$\beta$ stability limits
  - ELM-relevant edge MHD activity
Diverted Operation Allows for Greater DC Helicity Injection

- Helicity balance equation:

\[
\frac{dK}{dt} = -2 \int_{V} \eta J \cdot B \, d^{3}x - 2 \frac{\partial \psi}{\partial t} \Psi - 2 \int_{A} \Phi B \cdot ds
\]

\[I_{p} \leq \frac{A_{p}}{2\pi R_{0} \langle \eta \rangle} \left( V_{ind} + V_{eff} \right)\]

- \(I_{p}\) scales with the confinement time inside \(\eta\)

- 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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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

$$A \approx 120 \text{ cm}^2 \quad w \approx 1.6 \text{ cm}$$
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-$I_p$

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KFIT Solution Flowchart

Start Fit
- Profile Coefficients Measurements
  - Weights
  - $J(R,Z)_{\text{init}}$
  - Initial Coil Currents
  - Tokamak Geometry

Solve G-S Equation
- Derived Quantities
- Compute Measurements
- Compute $\chi^2$
- $\chi^2_{\text{init}}$
- $\chi^2_{\text{min}} = \chi^2_{\text{init}}$
- $\chi^2_{\text{prev}} = \chi^2_{\text{init}}$

New Parameters
- New Coil Currents

Solve G-S Equation
- Derived Quantities
- Compute Measurements
- Compute $\chi^2$
- $\chi^2_{\text{new}}$
- $J(R,Z)_{\text{new}}$
- $\chi^2_{\text{new}} < \chi^2_{\text{min}}$
- $\chi^2_{\text{prev}} = \chi^2_{\text{init}}$
- $J(R,Z)_{\text{init}} = J(R,Z)_{\text{new}}$

L-M Iteration (Partial)
- $\chi^2_{\text{prev}}$
- $\chi^2_{\text{new}}$
- $\chi^2_{\text{new}} - \chi^2_{\text{prev}} < \epsilon_{\text{tol}}$
- End

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Code Input</th>
<th>Std. Dev. (%)</th>
<th>Coil Design Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$</td>
<td>~300kA</td>
<td>300kA</td>
<td>5</td>
<td>316.9kA</td>
</tr>
<tr>
<td>$q_o$</td>
<td>&gt;1.5</td>
<td>1.5</td>
<td>20</td>
<td>1.56</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>$0.05 &lt; \beta_p &lt; 0.5$</td>
<td>0.275</td>
<td>80</td>
<td>0.13</td>
</tr>
<tr>
<td>$l_i$</td>
<td>$0.3 &lt; l_i &lt; 0.5$</td>
<td>0.4</td>
<td>25</td>
<td>0.49</td>
</tr>
<tr>
<td>$R_o$</td>
<td>~0.4 m</td>
<td>40 cm</td>
<td>10</td>
<td>37 cm</td>
</tr>
<tr>
<td>$X_{mag}$</td>
<td>~0.4 m</td>
<td>40 cm</td>
<td>10</td>
<td>48 cm</td>
</tr>
</tbody>
</table>

$B_{To} = 0.17$ T
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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• 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.
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.
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

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Divertor Augmentation is a Spiral-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

For a .pdf copy of this poster please visit:

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

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