Magnetics and Power System Upgrades for the Pegasus-U Experiment

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New Orleans, LA
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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: $A \sim 1$ high $\beta_T$ regime

• Facility enhancements
  – New centerstack assembly
    • $B_{TF}$ increases 5x
    • $\Delta t_{\text{pulse}} \sim 100$ 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
PEGASUS-U Proposal: Develop & Validate LHI-Startup for NSTX-U and Beyond

• Critical physics issues
  – Confinement behavior and helicity dissipation
  – Edge $\lambda = J/B$, $J$ 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

“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

- \( P(r,t), J(r,t), v_\phi(r,t) \) through ELM cycles
  - Nonlinear evolution of magnetic structures

- ELM, H-mode modification and mitigation
  - Vary \( J_{\text{edge}}(r) \), modify edge \( v_\phi \) and shear via LHI

- Synergistic studies with BES on NSTX-U, DIII-D

- Models to test
  - NIMROD
  - BOUT++
  - EPED

NSTX BES:
BES captures the fast evolution and radial structure of ELM events

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

**Major research thrusts:**
- Tokamak physics at small aspect ratio
- Non-inductive startup and growth

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**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$1.15 - 1.3$</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>$0.2 - 0.45$</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq 0.25$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1.4 - 3.7$</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>$\leq 0.025$</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>$\leq 25$</td>
</tr>
</tbody>
</table>

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**Diagram Details**
- Equilibrium Field Coils
- High-stress Ohmic heating solenoid
- Local DC Helicity Injectors
- Divertor Coils
- Vacuum Vessel
- Toroidal Field Coils

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Magnetic Diagnostics
Layout for PEGASUS

Inboard Measurements
- Core Flux Loops (6)
- High Resolution Mirnovs (21)
- Low Resolution Mirnovs (7)
- HFS Toroidal 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

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Centerstack Cross Section Comparison

New Centerstack

Old Centerstack

- Vacuum Wall
- Diagnostic Gap
- Solenoid
- Cooling Channel
- Plasma Limiting Surface
- Toroidal Field Conductors

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### New Toroidal Field Center Rod & Power Supply

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

- **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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turns</td>
<td>260 turns</td>
<td>250 turns</td>
</tr>
<tr>
<td>Length</td>
<td>170 cm</td>
<td>180 cm</td>
</tr>
<tr>
<td>Peak current/turn</td>
<td>24 kA</td>
<td>48 kA</td>
</tr>
<tr>
<td>Flux increase</td>
<td>5-10x</td>
<td></td>
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</tbody>
</table>
Poloidal Field Reconfiguration

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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 ($\tau_w \approx 10 \text{ ms}$)

- 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

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

Old: 1 set x 5 turns
New: 2 sets x 3 turns

Coil Sets 3a,3b / 6a,6b

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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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>New</th>
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</thead>
<tbody>
<tr>
<td>Number of bridges</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Controlled sets</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Control type</td>
<td>Analog</td>
<td>Digital</td>
</tr>
<tr>
<td>Volts per turn</td>
<td>110</td>
<td>300</td>
</tr>
<tr>
<td>kA-turn per set</td>
<td>80 kA-turns</td>
<td>72 kA-turns</td>
</tr>
<tr>
<td>kA per turn</td>
<td>16 kA</td>
<td>12 kA</td>
</tr>
</tbody>
</table>
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)
Coil current controlled via switching power supplies
  - IGBT: 900V EF, TF
  - IGCT: 2100V OH (noise/fault limited)

Proportional analog PWM control
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
FPGA I/O Block

National Instruments 7852R PXI FPGA Unit

RMIO
8 x 750kHz AI
8 x 1 MHz AO
16 x 40 MHz DIO

RDIO
40 x 40 MHz DIO

Interface card to FPGA crate

All modular cards connect here

Easily replaceable power connection

Shielded case

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• 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