Abstract

The Pegasus Toroidal Experiment is an ultralow aspect ratio ST with a mission to study the limits of magnetohydrodynamic stability at extremely low aspect ratio and high toroidal beta and to explore the transition region between the tokamak and spheromak configurations. The program is now completing a complete redesign of all the coil power systems and supporting infrastructure, and is entering a new operation phase. These upgrades include arbitrary, programmable waveform control for 8 independent coil currents, a factor of 3 increase in toroidal field, a factor of 2 increase in available ohmic flux, divertor coils, and improved pumping and conditioning. Results from earlier campaigns with the original facility showed that persistent low m/n tearing modes were responsible for limiting toroidal field utilization (I_p/I_tf) and toroidal beta. The first phase of operations of the next campaign will involve the development of startup scenarios that suppress the tearing modes. This will be accomplished by lowering the plasma current ramp rate and controlling the growth of the plasma size in order to decrease resistivity, and if necessary startup at transiently high toroidal field. The next phase of experiments will focus on establishing operating points at high toroidal field utilization and high toroidal beta, including limited and diverted configurations. With these operating points established, experiments will be conducted to determine the boundaries of the external kink mode at very low A. Earlier results from Pegasus showed an unstable point at q_95=5, albeit with significant edge currents. Studies will focus on the effects of aspect ratio, elongation, and I_i on the kink stability boundary.

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Outline

• Pegasus is a mid-size ST built to explore A

• Experimental results from phase I operations
  
  - Plasmas exhibit low-A characteristics
    - High $t, I_N, N$ via OH heating
    - High $I_p/I_{tf}$
    - low $\ell_i$
  
  - Characteristics of High $I_p/I_{tf}$ Operation
    - Large scale internal MHD limit on $I_p/I_{tf}$
    - External Kink at $q_{95}=5$

• Present phase of operations focusing on accessing high $I_p/I_{tf}$, $t$ regimes
  
  - Recent modeling has demonstrated existence and accessibility to this regime
    - DCON and local G-S solver for stability and equilibrium
    - TSC for shot simulations
  
  - Upgrades complete to increase access to this regime
    - Increased V-sec.; position and shape control; $B_{TF}$ versus time
    - Limited Operations have begun
PEGASUS Facility

E.A. Unterberg, ICC, Madison, WI, May 2004
Mission: Explore plasma limits as A\textasciitilde1

Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

- Stability and confinement at high $I_p/I_{TF}$
  - Extension of tokamak studies

- Limits on $q$ and $I_p/I_{TF}$ (kink) as $A\textasciitilde1$
  - Overlap between the tokamak and the spheromak

$\frac{I_p}{I_{tf}}$ figure of merit for access to low-A physics

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TS-3,4
Spheromaks

$ q =6$

PEGASUS

NSTX, MAST

CDX-U, HIT, TST-M, Globus-M, ETE

START

MEDUSA

“tokamak-spheromak overlap region”

Aspect Ratio

$1.0$ $1.2$ $1.4$ $1.6$ $1.8$ $2.0$

E.A. Unterberg, ICC, Madison, WI, May 2004
**E. A. Unterberg, ICC, Madison, WI, May 2004**

**PEGASUS is University-Scale, Mid-Sized ST**

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**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Phase II 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>0.2-0.38</td>
<td>0.2-0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤0.16</td>
<td>≤0.30</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6-8</td>
<td>15-20</td>
</tr>
<tr>
<td>RB_t (T-m)</td>
<td>≤0.03</td>
<td>≤0.1</td>
</tr>
<tr>
<td>shot (s)</td>
<td>≤0.02</td>
<td>≤0.05</td>
</tr>
<tr>
<td>n_e (10^{19} \text{ m}^{-3})</td>
<td>1-5</td>
<td>≤10</td>
</tr>
<tr>
<td>(%)</td>
<td>≤20</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>P_{HHFW} (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>
PEGASUS has complete set of magnetic diagnostics

Composite Photograph of Vessel Interior

Schematic of Magnetic Diagnostics

- EBW antenna
- HHFW antenna
- Outboard limiter
- Centerstack
- Extensive magnetic diagnostics
- Segmented divertor plates

= Flux Loops
= Mirnov Coils

E.A. Unterberg, ICC, Madison, WI, May 2004
HHFW system tested in Phase-I OPS

- Two-strap HHFW system installed and heating tests run
  - \( P_{RF} = 1-2 \) MW available; sufficient to access high \( t \) regime
    - Up to 200 kW injected into plasmas - some evidence of heating observed
    - Forward power limited in Phase I by plasma shape and position control

- HHFW Startup and CD applications:
  - Startup assist via preheating and/or current profile “freezing”
    - Startup plasma phase: 40% single pass absorption
    - High plasma phase: 100% single pass absorption
  - Current Drive possible with present power supply and new antenna
$A < 1.3$  Ready Ohmic Access to High $t$

- $t$ up to 25% and $I_N$ up to 6.5 achieved ohmically
- Low field high $I_N$ and $t$

![Graph showing ohmic access to high values of $t$ and $I_N$.](image-url)
Equilibrium reconstructions show low-A characteristics

**Low-A Characteristics**

- High-\( t \) (Ohmic): \( t > 20\% \)
- High-\( N \) (Ohmic): \( N > 4 \)
- Large \( I_p/I_{TF} \): \( I_p/I_{TF} \sim 1 \)
- Natural: \( > 2 \)
- High field windup: high \( q \) at low TF
- Paramagnetism: \( F/F_{vac} \leq 1.5 \) on axis (\( p < 1 \))

**Sample Reconstruction**

[Flux Plot]

<table>
<thead>
<tr>
<th>( Z (m) )</th>
<th>-1.0</th>
<th>-0.5</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R (m) )</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- \( I_p \) 154 kA
- \( R_0 \) 0.34 m
- \( a \) 0.29 m
- \( A \) 1.15
- \( A \) 1.33
- \( F_0 \) 0.03 T-m
- \( t \) 18%
- \( W \) 570 J
- \( \ell_i \) 0.54
- \( q_0 \) 1.0
- \( q_{95} \) 4.3
Toroidal field utilization exhibits a “soft limit” around unity

- Maximum \( I_p \approx I_{TF} \)
- Limit not disruptive or abrupt
  - \( I_p \) saturates or rolls over

![Graph showing relationship between plasma current and TF rod current]
Two factors contribute to the $I_p/I_{TF} \approx 1$ soft limit

Large resistive MHD instabilities degrade plasma as TF

- low $B_t$ and fast $dI_p/dt$ early appearance of low-order $q=m/n$
  - *fixed* sine-wave loop voltage
- high resistivity early
- ultra-low $A$ low central shear

Result: rapid growth of tearing modes and large saturated island widths

- *Most common modes:* $m/n=2/1$, $3/2$
- *Leads to decreased* $C_E$, $I_p$

- $I_p/I_{TF} \approx 1$ $q_0 \approx 1.5 - 2$

Reduced effective Volt-seconds as TF

- reduced toroidal field delayed startup
- delayed startup + fixed sine $V_{\text{loop}}$ waveform reduced effective $V$-s
MHD Effected by q-profile Tailoring and TF Strength

- **q-profile tailoring increases plasma performance**
  - Discharge tailoring plasmas with reduced MHD activity, increase \( W \) and \( I_p \)
  - Increased shear, increased \( q_0 \) delay tearing onset
  - MHD amplitude decreases with increasing shear

- **Increased toroidal field strength also reduces MHD activity**
  - Along \( I_p=I_{tf} \) contour: \( B \neq \) as TF
  - At high TF effect of MHD minimal
    - \( C_E = 0.4 \)
  - At lower TF MHD amplitude increases
    - \( C_E \) increases
    - Stored energy decreases

Access higher \( \frac{I_p}{I_{TF}} \), \( t \) via increased \( q_0 \), \( T_e \), shear

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![Graph](image.png)
PEGASUS operates in low-$\ell_i$, high-density space

Visible light image

Generally low $\ell_i$

START Data
(Hender PoP ‘99)

High $N > 4\ell_i$

E.A. Unterberg, ICC, Madison, WI, May 2004
High $q_{95}$ external kink limit observed

- High $I_p$ plasmas often disrupt

- $q_{95} = 5$ observed preceding disruption
  - $\ell_i = 0.5$ at this time

- DCON analysis unstable to $n=1$ external kink
  - $m=5$ most unstable mode

- Consistent with theory expectation

![Graph showing Poloidal mode eigenfunctions via DCON with m=1, m=2, m=3, m=4.

![Graph showing Plasma Current, Free-Boundary Energy (DCON), MHD Amplitude against Time (s).]
Measured q-profile indicates low central shear

• 2D soft x-ray camera gives q-profile
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

• Measured q-profile    low central shear

E.A. Unterberg, ICC, Madison, WI, May 2004
Island widths are on the order of plasma minor radius

- Island width estimates give $w > 10 \text{ cm}$

\[ w \approx 4 \sqrt{\frac{B q R}{B_t n \frac{dq}{dr}}} \sim \frac{a}{2} \]

- $B=4 \text{ Gauss at wall}$

- SXR large radial extent of mode

**Mode Spectrogram**

**SXR Chords**
Access to High $I_p/I_{tf}$, $t$ Operation

- **Suppression of large internal MHD modes**
  - Vary $q(\rho)$
  - Lower before $q(\rho)$ approaches low-order rational mode surfaces

- **Expand access to external kink modes studies**
  - Plasma time evolution, shape
  - Edge conditions and edge currents

- **Access to very high $t$ regime for stability analysis**
  - OH access and HHFW heating availability
Stable $I_p/I_{tf} > 1$ Equilibrium Found

- "zero"- Equilibria showing $I_p/I_{tf} = 1.93$

Flux Plot

Equil. Parameters

- $I_p = 290000$
- $I_N = 12$
- $I_p/I_{tf} = 1.93$
- $\epsilon_i = 0.59$
- $q_0 = 1.5$
- $R_0 = 0.39$
- $a = 0.34$
- Elongation 2.2
- $q_{95} = 4.8$

- Predicted Stable with DCON

D$I_i$D$R > 0$ => Unstable

ArcSinh $D_i (A.U.)$

ArcSinh $D_R (A.U.)$

Mercier Criterion

GGJ Resistive Criterion

Newcomb Criterion, $n=1$ (A.U.)
Plasma Limits Modeled at $I_p/I_{tf} \sim 3$

- **High-**$I_p/I_{tf}$, “zero”- Equilibria

**Flux Plot**

**Equilibria Parameters**

- $l_p = 296000$
- $l_{tf} = 90000$
- $l_N = 18.9$
- $l_i = 0.68$
- $q_0 = 0.91$
- $R_0 = 0.41$
- $a = 0.36$
- Elongation = 1.98
- $q_{95} = 2.3$

- **DCON Output**
  
  - $D_1, D_R > 0 \Rightarrow$ Unstable
  
  **Mercier Criterion**

  **GGJ Resistive Criterion**

  **Newcomb Criterion, $n=1$ (A.U.)**

- **Approaches Phase II Goals of PEGASUS**

- Conventional Tokamaks
  - Increase $I_p/I_{TF}$
  - Increase Aux. Heating

- PEGASUS

- Increase $I_p/I_{TF}$

E.A. Unterberg, ICC, Madison, WI, May 2004
TSC: Fast TF Rampdown is tool for $q(r)$ and manipulation

- Effect of fast ramp:
  - $t$ increases
  - $q_a$ drops as $B_t$, $q_0$ falls more slowly (on $R$ time scale)
  - Energy conservation:
    - $J$ driven, $l_i$ drops
    - $I_{ef}$ and $I_p$ increase

- Results of TSC PEGASUS simulation:
  - $RB_t$: 0.06 to 0.03 T-m in 2 ms
  - $I_p$: up from 90 kA to 140 kA
  - $t$ increases from 5% to 16%
  - up from 1 to 6 mWb
New tools to access $I_p > I_{tf}$

- **Suppress tearing modes early in discharge evolution**
  - Transiently manipulate $q$ during discharge:
    - Increased TF at startup $\Rightarrow$ high $I_{tf}$, low inductance TF bundle
    - Variable $I_p$ and $R_0$ control $\Rightarrow$ coil-current-waveform control
  - Reduce resistivity before low-order rationals appear
    - Maximize $J$ $\Rightarrow$ $V_{loop}$ control, position & shape control
    - Increase ohmic flux $\Rightarrow$ new ohmic power supply
    - Use HHFW system $\Rightarrow$ position control, $V_{loop}$ control

- **Explore edge kink boundary at high field utilization**
  - Manipulate edge shear $\Rightarrow$ divertor coils & PF shape control
  - Decrease edge currents $\Rightarrow$ loop voltage control
  - Manipulate plasma shape $\Rightarrow$ shape control
  - Manipulate current profile $\Rightarrow$ $V_{loop}$ control, position control
# Upgrades Near Complete to All Coil Sets

<table>
<thead>
<tr>
<th>System</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field</td>
<td>• 60 turns</td>
<td>• 12 turns</td>
<td><img src="image1.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>• Quasi-DC</td>
<td>• Fast time-variable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 150 kA-t max</td>
<td>• 450 kA-t max</td>
<td></td>
</tr>
<tr>
<td>Ohmic Heating</td>
<td>• Half-sine Waveform</td>
<td>• Programmable Waveform</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• ±40 KA</td>
<td>• ±15 kA (available)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ±50 kA (full power)</td>
<td></td>
</tr>
<tr>
<td>Equilibrium</td>
<td>• Monolithic coil set</td>
<td>• 5 Independent coils</td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>Field</td>
<td>• 2 Resonant banks</td>
<td>• Programmability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Waveform constrained by startup concerns</td>
<td>• Evolution free from startup constraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No divertor</td>
<td>• Divertor installed</td>
<td></td>
</tr>
</tbody>
</table>

- All power now driven by solid-state IGBT and IGCT solid-state high power switches
  - Switches arranged in an H-bridge
  - Assistance from HIT Group @ U. of Washington
Modelled Equilibria Shows Flexibility of Phase-II PF

- $I_p = 315 \text{kA}, \quad k = 2.2, \quad d = 0.2$
- $I_p = 285 \text{kA}, \quad k = 1.7, \quad d = 0.56$
- $I_p = 280 \text{kA}, \quad k = 1.5, \quad d = 0.55$

$R_z$ = Coil Current Magnitude (~ kA-turns)

E.A. Unterberg, ICC, Madison, WI, May 2004
Current Status

- Power testing complete
- Cross field testing in progress; Plasma Ops to follow
- All coils tested to nominal operating currents
  - Waveform control demonstrated with EF coil set
  - OH tested to 900V; +/- 15 kA (design = 2700V; +/- 50 kA)
    - 30 mV-sec. manageable OH flux demonstrated vs. 40mV-sec. increasing flux in Phase-I Ops
Summary

• Pegasus is a mid-size ST built to explore $A = 1$

• Experimental results from phase I operations
  - Plasmas exhibit low-$A$ characteristics
    - $t \sim 20\%$, $I_N \sim 6$, $N > 4$ via OH heating
    - $I_p/I_{tf} \sim 1$
    - $\ell_1 \sim 0.4$
  - Characteristics of High $I_p/I_{tf}$ Operation
    - Large scale internal MHD limit on $I_p/I_{tf}$
    - External Kink at $q_{95} = 5$

• Next phase of operations will focus on accessing high $I_p/I_{tf}$, $\ell_1$ regimes
  - Recent modeling has demonstrated existence and accessibility to this regime
    - DCON and local G-S solver for stability and equilibrium $\Rightarrow$ found $I_p/I_{tf} \sim 2 - 3$
    - TSC for shot simulations
  - Upgrades to increase access to this regime
    - Increased V-sec.; position and shape control; $B_{TF}$ versus time
    - Power supply and cross-field testing in progress; limited plasma operation to follow