Plasma Formation Studies and Plans for the PEGASUS Toroidal Experiment*

by T. A. Thorson
for the PEGASUS Group
University of Wisconsin–Madison U.S.A.

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.

• Explore the extreme limit of low-aspect ratio physics

*Supported by U.S. DoE grant No. DE-FG02-96ER54375
Role of the PEGASUS Experiment

- **Contribute to development of the Spherical Torus** (High $q_\psi$)
  - Extreme toroidicity ($A \rightarrow 1$)
  - Current limits and disruptivity
  - $\beta$ limit dependence on $A$, $\kappa$, etc.
  - Confinement with aux. heating at $A < 1.3$
  - New startup schemes (e.g., plasma gun current injection)

- **Address physics of $A \rightarrow 1$ as an Alternate Concept** (Low $q_\psi$)
  - Very high TF utilization ($I_p/I_{TF} > 3$);
  - Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation
  - MHD equilibrium and stability at very low TF ($\beta \approx 1$)
  - Explore RF heating and CD schemes (HHFW, EBW)

$A \rightarrow 1 \Rightarrow$ smaller centerstack, less recirculating power and waste

[Diagram showing aspect ratio vs. $I_{\text{plasma}}/I_{\text{TF}}$ with various experiments marked]
**PEGASUS Operates at Ultra-Low A via Reinforced, High-Stress Solenoid**

**PEGASUS Operational Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1.16 - 1.3</td>
<td>1.1 - 2.0</td>
</tr>
<tr>
<td>$R$</td>
<td>0.2 - 0.3 m</td>
<td>0.2 - 0.45 m</td>
</tr>
<tr>
<td>$I_p$</td>
<td>0.1 MA</td>
<td>0.1 - 0.3 MA</td>
</tr>
<tr>
<td>$B_t$</td>
<td>$\leq 0.1$ T</td>
<td>$\leq 0.15$ T</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$\sim 1.5 - 3.0$</td>
<td>$\sim 1.5 - 3.7$</td>
</tr>
<tr>
<td>$\Delta t_{\text{pulse}}$</td>
<td>3 - 8 msec</td>
<td>30 - 60 msec</td>
</tr>
<tr>
<td>$\beta_t$</td>
<td>0.03 - 0.2</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>1 - 5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>$I_N$</td>
<td>$\sim 2 - 6$</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

Heating and Sustainment

Inductive*  Inductive*+ RFCD (HHFW, EBW), Plasma Guns

* NHMFL: $B_{\text{solenoid}} = 10 - 14$ T
Goals of the PEGASUS Toroidal Experiment:

**Primary Goals:**
- Plasma stability limits at high $I_p/I_{TF}$, low $A$, high $\kappa$
- Operational limits (in terms of $q_\psi$, density, $\beta$, $\kappa$, $A$, etc.) for $A \to 1$
- Demonstrate access to high $\beta_t$ at extreme $I_N$ without a close-fitting conducting shell.

**Secondary Goals:**
- Test relaxation stability at tokamak/spheromak boundary
- Measure global confinement characteristics for varied $A$, $\kappa$, etc.
- Evaluate the need for external CD as $A \to 1$
- Evaluate plasma guns for startup and $j(R)$ modification
- Initial studies of startup, heating, and CD via EBW launch
First Campaign: Plasma Formation Studies

• Demonstrated efficient startup and startup at low $B_t$ in presence of conducting walls
  - Critical for low TF, high $\beta$ mission for Pegasus
  - Induced wall currents are reasonably understood and accounted for
  - Startup achieved at $B_{to} \sim 0.05$ T, startup at 2 V possible at full field

• Accessed a variety of plasma geometries

Geometric Plasma Properties Estimated from Visible Images

<table>
<thead>
<tr>
<th>R (m)</th>
<th>a (m)</th>
<th>A</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>0.29</td>
<td>1.17</td>
<td>1.8</td>
</tr>
<tr>
<td>0.2</td>
<td>0.15</td>
<td>1.3</td>
<td>$&gt;3$</td>
</tr>
</tbody>
</table>
Startup Plasmas Show ST Characteristics

• **ST-like behavior observed:**
  - Fast plasma current ramps (20 - 100 MA/sec)
  - High natural elongation
  - MHD: IRE’s and tearing modes observed

• **Initial plasmas beginning to access low TF, high $\beta_t$ regime**
  - High $\beta_t$, normalized $\beta$ $\beta_t \sim 20\%$, $\beta_N \sim 5$
  - High density $n_e \sim n_G$
  - High TF utilization factor $I_p/I_{TF} \sim 1$
  - High normalized current $I_N \sim 6$

• **Full power, long pulse operation anticipated by OH completion**
  - Pulse extended from ~ 5 to 30 ms
  - $I_p$ raised from 0.1 to 0.3 MA
Moderately High $\beta_t$ Accessible in OH Plasmas

Shot 4699

- $R = 0.27$ m
- $I_P = 0.065$ MA
- $a = 0.22$ m
- $\beta_{pol} = 0.6$
- $A = 1.22$
- $\kappa = 2.1$
- $I_{TF} = 0.09$ MA
- $\kappa_t \approx 0.22$
- $\beta_N = 4.9$
- $q_a \approx 7$
- $q_0 \approx 1.5$

Equilibrium reconstruction using 6-8 $B_p$ coils & 4-6 fluxloops

Visible image used to constrain position and size

Density, spectroscopy and confinement consistent with fit pressure
First Results: Promising for Full-Power Operation

- Estimates of $\beta_t$ consistent with START scaling
  - Experiment $\beta_t$ estimated from magnetic equilibrium
    - Min. diagnostics, $P_{Rad}$, $Z_{eff}$, $\tau_{pulse}$, etc. $\rightarrow$ large uncertainties
    - 0-D confinement model with ITER98PBy1 $\tau_E$ scaling for expected $\beta_t$

- Interesting plasma regime appears accessible with OH only
  - Lower collisionality and challenge stability limits with more flexible shapes via auxiliary heating
Plasma Density Approaches Greenwald Limit

\[ n_G = \frac{I_p}{\pi a^2} \]

\[ n_e (x 10^{20} m^{-3}) \]

\[ I_p / \pi a^2 (MA/m^2) \]

\[ Shot 4117 \]

\[ Shot 4117 \]
$I_p/I_{TF} \rightarrow 1$ at Lowest TF Settings

- Present limits on $I_p/I_{TF}$: ramp rate and pulse length
- Tearing modes limit $I_p$ ramp rate → High $I_p/I_{TF}$ only at low TF

$B_{to} \sim 0.04$ T

Shot 5066:36 MA/s before knee, 8 MA/s after knee
Double Tearing Modes Limit Plasma Current Ramp Rate

Similar events on MEDUSA identified as DTM's with internal $j(r)$ measurements

Shot 5066: $m=2$ mode after "knee" in plasma current

$q$ profile flattens and current penetrates into the core after the DTM

$m = 2$ activity observed on Mirnovs and interferometer

- $I_p$ ramps up to 30 MA/sec are stable
PEGASUS Research Program Overview

• Low-q/low-TF stability studies in full power OH plasmas
  - Full power, large OH plasma development
  - Low-q limits @ A < 1.3
  - Limits of $I_p/I_{TF}$ operation
  - Loading and coupling tests for HHFW antenna
  - $j(R)$ via SXR imaging tests
  - Test separatrix/divertor operation
  - Tests of plasma gun injection

• High $\beta$ stability and high power RF auxiliary heating
  - MHD stability limits: shaping, profiles, configuration effects
  - $\beta_t$ limits with auxiliary heating and DC TF
  - Confinement evaluation

• Exploration of high $\beta$ stability at high and low edge q
  - Kink and ballooning stability limits
  - Tokamak/spheromak stability boundary with TF rampdown
  - Tests of EBW heating

• Status: Feb 2000
  - Ending maintenance period: OH power supply completion
  - Operations expected early March
Investigate Tokamak-Spheromak Transition

- **Determine limit of low TF operation**
  - As $TF \to 0$, a transition from a stable tokamak configuration to an unstable spheromak-like plasma is expected
  - This transition defines the lower limit of $B_t$
  - Explore transition behavior with geometry, $j(R)$, $\beta$, etc.

- **Taylor relaxation may occur at lower $I_p/I_{TF}$**
  - $\lambda a > 2.4$ ($\lambda = j||/B_{tot}$) suggests the onset of relaxation and/or increased MHD in PEGASUS for $I_p/I_{TF} \geq 2$
  - The above relation assumes a cylindrical geometry - torodicity may increase the $I_p/I_{TF}$ limit for PEGASUS

- **PEGASUS expected to be tilt/shift stable at relaxation threshold**

- **Takes advantage of new, low-inductance TF centerstack**

![Graph showing possible relaxation threshold with TS-3 Results and stability limit](image-url)
• **OH power supply development near completion**
  - Step-down transformer for impedance matching and double-swing
  - Longer pulse, more flexible waveform control

• **RF heating system development continuing**
  - 1-2 MW HHFW heating system
  - First-generation antenna fabricated; install Spring 2000
  - 0.5 MW tested into dummy load

• **Internal hardware upgrades due during RF install**
  - More complete centerstack protection and upper/lower limiters
  - Increased coverage with magnetics diagnostics

• **Next-generation centerstack in fabrication**
  - Low inductance TF circuit
  - Ramp down power supply in development

• **Advanced diagnostics in design**
  - \( j(R,t) \) from SXR 2-D imaging and Li pellet injection (PPPL help)
  - \( T_e(t) \) from EBW radiometer
  - \( N_e \) profiles from beam fluorescence
  - Tilt angle from Reflectometry (UCLA)
Summary

• Primary goal is to explore the $A \to 1$ regime
  - Geometry ($A$, $\kappa$, separatrix) and current profile ($I_p$, $q_o$, $q_\psi$) influence on the stability limits?
  - Tokamak/Spheromak Overlap: How close can $A \to 1$ and maintain good stability and confinement?
  - Tradeoffs between $A \approx 1$ and current drive requirements?

• Starting to access interesting low TF, ST regime
  - $I_p = 0.1$ MA
  - $n_e \sim n_G$
  - $\beta_t \sim 20\%$, $\beta_N \sim 5$
  - Startup up at 60 kA of TF rod current ($B_{10} \sim 0.05$ T)
  - $I_p/I_{TF} \approx 1$, $I_N \sim 6$
  - Completion of OH will allow for longer pulses, higher $I_p$

• Near-term goals concentrate on exploration of low-TF ohmic operation
  - High field utilization
  - Equilibrium and stability as $A \to 1$
  - Initial RF operation
PEGASUS has Benefited Greatly from Contributions from Members of the Fusion Science Community:

• Collaborations

  - NHMFL: Solenoid design, fab., tests
  - Stress Analyses; VV construction;
  - Theory (MHD, RF…); Future expts.
  - General Atomics
  - PPPL: RF; Power Engr.; DNB assistance
  - UCLA: µwave interferometer
  - MST: Engineering; diagnostics; e-gun j sources

• Contributions

  - NHMFL Magnets
  - General Atomics Vacuum Vessel, Iron core
  - PPPL Capacitors; diagnostics; CAMAC
  - LANL Caps; Ignitrons, RF systems
  - MST Ross diodes; iron core; caps, etc.
  - HSX EF cap bank
  - LLNL Caps; DNB power system
  - ORNL Thomson scattering
  - Westinghouse High-E cap bank
  - UW SC Lab: TF hex conductor