Non-inductive plasma startup and current profile modification in Pegasus spherical torus discharges

Aaron J. Redd for the Pegasus Team
2008 Innovative Confinement Concepts Workshop
Reno, Nevada
June 24-27, 2008

University of Wisconsin-Madison

PEGASUS Toroidal Experiment
Talk Outline

• The Pegasus spherical torus device

• Non-inductive formation of tokamaks:
  — DC helicity injection using biased plasma guns
  — Divertor-region vs outboard midplane locations

• ELM-like MHD activity in Ohmic discharges:
  — Filamentary magnetic structures
  — Correlated with high edge current density

• Summary
Studying ST Science and Engineering

Centerstack: Exposing Ohmic Heating Solenoid (NHMFL)

Equilibrium Field Coils
Vacuum Vessel
RF Heating Antenna
Toroidal Field Coils
Ohmic Trim Coils
Plasma Limiters

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (m)</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>≤ 0.18</td>
<td>≤ 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>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>1.4–3.7</td>
<td>1.4–3.7</td>
</tr>
<tr>
<td>(\tau_{shot}) (s)</td>
<td>≤ 0.02</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>(\beta_t) (%)</td>
<td>≤ 25</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>(P_{HHFW}) (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Non-inductive startup/sustainment
- Tokamak physics in small aspect ratio:
  - High-\(I_N\), high-\(\beta\) operating regimes
  - ELM-like edge MHD activity
Biased Plasma Guns Can Be DC Helicity Sources

- Two divertor-mounted guns are shown.
- DC helicity injection rate is given by:
  \[ \dot{K}_{inj} = 2V_{inj}B_N A_{inj} \]
- The helical filaments can relax and form a tokamak if:
  1. Plasma-generated \( B_p \) greater than vacuum \( B_v \)
  2. Radial force balance is satisfied
  3. Sufficient input power
- Relaxed-plasma \( I_p \) is greater than \( I_{bias} \) multiplied by vacuum field windup.
Relaxation Enhances the Driven Current Beyond the Vacuum-Field Windup

- $I_p > 50 \text{ kA}$ driven by $I_{\text{bias}} \leq 4 \text{ kA}$:
  - Plasma current persists after $I_{\text{bias}} = 0$
  - Coil currents static (no ramps)
  - $B_T = 11 \text{ mT}$ at plasma magnetic axis
  - Vacuum vertical field is 7 mT

- Poloidal flux reversal on column is hallmark of significant relaxation:
  - Occurs when $I_p/I_{\text{bias}}$ exceeds windup

- Current multiplication ($I_p/I_{\text{bias}}$) up to 15:
  - Consistent with poloidal flux amplification
  - Vacuum-field windup of only 5

Maximum $I_p$ Set by Helicity Balance

• Maximum $I_p$ is consistent with the helicity injection rate:
  – Offset-linear relationship

• Maximum $I_p$ can be increased by
  – Increasing number of guns
  – Increasing gun aperture(s)
  – Increasing bias voltage

• At peak current $I_p$, helicity injection rate is equal to measured dissipation:
  – Dissipation voltage $V_{\text{surf}}$ measured with central-column flux loop
  – Effective drive voltage $V_{\text{eff}}$ is:
    \[ V_{\text{eff}} \approx V_{\text{inj}} \frac{N_{\text{inj}} A_{\text{inj}} B_{T\text{inj}}}{A_p B_T p} \]

See Eidietis et al., JFE 26, 43 (2007).
• Divertor-gun-driven tokamaks couple to Ohmic drive, but require significant coil-current ramps:
  – To maintain radial magnetic stability.
  – To reach typical Ohmic operating parameters (e.g., increased TF to maintain kink stability).

• Tokamaks formed by outboard midplane guns would:
  – Form with typical Ohmic parameters (relatively high TF).
  – More easily couple to outer-PF induction.
  – Be more accessible to diagnostics
  – Have longer L/R decay timescales

• Studies using these two extreme geometries can be used to determine the optimum injector configuration.
Outboard Midplane Gun Array Deployed

- Three guns, stacked as shown, below the Pegasus midplane.
- Single anode is at same major radius, above the midplane.
Evolution of Midplane-Gun-Driven Plasma

Pegasus shot #40458: Two midplane guns, outer-PF ramp

$t=21.1$ ms, $I_p=2-3$ kA
Filaments only

$t=28.8$ ms, $I_p=42$ kA
Driven diffuse plasma

$t=30.6$ ms, $I_p=37$ kA
Guns off, Decaying
• Single-gun discharge with no PF ramps.

• Current multiplication above 50 at gun shutoff.

• Sharp rises in $I_p$ during rampup may correspond to low-order rational values for the edge-$q$. 

Outer-PF Ramps Further Enhance $I_p$

- Current multiplication through relaxation and outer-PF ramp.

- $I_p$ evolves through three stages:
  1. Relaxation of gun-driven plasma + outer-PF ramp
  2. Radial compression of detached tokamak
  3. Tokamak decay, limited on the central-column
Gun-Driven Plasma Studies Ongoing

• Divertor-gun-driven plasma evolution is relatively simple:
  – Guns in high-field region sustained plasmas in low-field region.
  – Plasma current $I_p$ evolved relatively smoothly with time.
  – Maximum $I_p$ is primarily determined by the helicity injection rate.

• Plasma evolution for outboard guns is more dynamic:
  – Discharges must “grow” from the low-field region near the guns into the higher-field confinement region.
  – “Bursts” of MHD activity correspond to rapid increases in $I_p$; these “bursts” may also correlate with low-order rational edge-q.
  – Maximum $I_p$ is related to the helicity injection rate, radial force balance, and the Taylor relaxation condition ($\lambda_{inj} > \lambda_{tok}$).

• For more details, see poster by D. Battaglia et al.
Midplane-Driven Plasmas Couple More Easily to Ohmic

- Both discharges had guns, outer-PF ramps, and applied OH drive.
- The midplane-driven discharge required less Ohmic flux and applied loop voltage to reach the same peak plasma current (90 kA).
ELM-like Edge FilamentsObserved

Pegasus

• Filaments follow field lines, and correlate with high edge current density.
• Pegasus filaments are continuous in time, unlike “bursty” strong ELM behavior:
  – Pegasus likely has an L-Mode edge
  – But, may be same physical mechanism as ELMs

High \((j_{\parallel}/B)_{\text{edge}}\) Typical in Pegasus

• Key parameter for peeling-mode stability is the ratio \(j_{\parallel}/B\), related to the usual magnetic inverse length scale \(\lambda\).

• Edge \(j_{\parallel}/B\) (or \(\lambda\)) in Pegasus Ohmic plasmas is comparable to that in larger devices, suggestive of strong peeling drive:
  - Pegasus: \(j_{\parallel}/B \sim 1 \times 10^6 \, \text{A/(m}^2\text{-T)}, \) or \(\lambda \sim 1.2 \, \text{m}^{-1}\)
  - DIII-D*: \(j_{\parallel}/B \sim (0.5-1) \times 10^6 \, \text{A/(m}^2\text{-T)}, \) or \(\lambda \sim 0.6-1.2 \, \text{m}^{-1}\)

• Pegasus edge \(j_{\parallel}/B\) can be manipulated with loop voltage variations in time, or by using the midplane plasma guns.

*: Thomas, Phys. Plasmas 12, 056123 2005
Fast camera images of Ohmic shot #40271 at:
- 17.5 ms: current rise, filament onset.
- 23.1 ms: near current peak, vigorous filaments.
- 30.6 ms: current flattop/decay, filaments strongly suppressed.
Determining the magnetic structure of these edge filaments requires diagnostics with good spatial and temporal resolution.

Pegasus DAS electronics have been upgraded: anti-aliasing up to 400 kHz; common-mode noise rejection.

Two internal magnetic probes are deployed, and a finely-spaced toroidal array will be installed.

Taking initial data, after completing Ohmic-bank upgrade.

Relative power radial structure for a low-frequency edge mode, for a series of identical shots. The relative power for this $n=1$ mode falls as $(R-R_{\text{edge}})^2$, as expected for the 2/1 tearing mode.

Similar scans for high-frequency modes are now possible for Pegasus.
Summary

• The Pegasus device is a valuable testbed for exploring tokamak- and ST-related physics and engineering:
  – Non-inductive startup, MHD studies, high-\(I_N\) high-\(\beta\) operations.
• Non-inductive Pegasus discharges (with \(I_p\) up to 80 kA) can be formed with biased point current sources:
  – DC helicity injection with point current sources (vs CHI electrodes).
  – Midplane-driven plasmas will be further optimized, including the optimum coupling to Ohmic or other current drive methods.
  – Gun startup + upgraded Ohmic may extend high-\(\beta\) operations.
  – Physical understanding of the relaxation and its geometric dependence will enable design of a future optimum source configuration.
• Ohmic Pegasus discharges have high edge \(\lambda\), and exhibit continuous instabilities similar to peeling modes:
  – Internal probes are being used to characterize these modes.
  – Control of these modes may be possible by manipulating the edge \(\lambda\).
PEGASUS Team and References

FACULTY/STAFF:
Chris C. Hegna (PI)         Benjamin Kujak-Ford         Paul Probert
Aaron J. Redd               Benjamin Lewicki            Pamela Wagner
Aaron C. Sontag             Greg Winz

GRADUATE STUDENTS:
Devon Battaglia             Michael Bongard            Edward Hinson

UNDERGRADUATES:
Jon Cole                    Alex Robinson              Amy Wiersma

REFERENCES:
• Garstka et al., Nuclear Fusion 46, S603 (2006).

Near-Term Plasma Gun Research

- Further optimize gun-driven plasma performance:
  - Three guns, higher bias voltage: peak $I_p$ well over 100 kA
- Couple gun-driven discharges to Ohmic drive:
  - Single-swing and double-swing ramps
  - Separate Ohmic upgrade: more flux, longer duration
  - Gun-driven startup may extend high-$I_N$, high-$\beta$ operations
- Edge probing: what is the relaxation mechanism?
- Development of a complete model, including:
  - Plasma current limits versus geometry and other parameters
  - Optimum gun-array design and running scenarios for Pegasus and other toroidal devices, such as NSTX or ITER
Candidate Instability: The Peeling-Ballooning Mode

- Proposed ELM mechanism, supported by experimental and computational studies:
  - Medium-n MHD instability
- Peeling-mode branch
  - Edge current, current gradient drive
  - Stabilized by increasing edge $p'$, for a range in edge current density
  - Weakly stabilized by strong shaping
- Ballooning-mode branch
  - Normal pressure gradient drive
  - Stabilized by increasing shear
  - Strongly stabilized by shaping

Snyder, Phys. Plasmas **12**, 056115, 2005
Is the Pegasus Edge Peeling-Unstable?

- Pegasus plasma edge is compatible with probes
  - Two midplane single-winding magnetic probes deployed
  - Midplane toroidal array being implemented
  - Triple langmuir probes being designed

- Internal probe analysis:
  - Confirm that the filaments have a magnetic signature
  - Correlation studies and mode analysis to determine structure
  - Measured internal fields improve equilibrium reconstructions, for stability analysis or comparison to theoretical models