Attainment of High Normalized Current by J(r) Manipulation in the Pegasus Toroidal Experiment


University of Wisconsin-Madison

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Abstract

The operating space defined by the external kink mode boundary in a near-unity aspect ratio ST allows access to very high toroidal beta and $I_N$. Normalized current can be equivalently expressed as the toroidal field utilization factor $I_p/I_{tf}$, where $I_{tf}$ is the current flowing in the centerpost. Values of $I_p/I_{tf} > 2$ ($I_N > 12$ MA/m-T) are expected to be stable to ideal MHD modes in the ultra-low-A Pegasus Toroidal Experiment. Simple inductively-driven plasmas on Pegasus had exhibited an operational limit of $I_p/I_{tf} \sim 1$, which was attributed to the early onset of large-scale low-order tearing modes in the plasma core. The use of point-helicity sources has greatly broadened the operating space of the device in the direction of low toroidal field. These sources can be employed as a preionization technique that facilitates ohmic startup and allows attainment of $I_p/I_{tf} \approx 1.5$ at low $I_p$ (\(\sim 50\) kA). Using these sources for non-inductive startup via helicity injection provides access to $I_p/I_{tf} > 2$, again at low $I_p$ and at very low field (0.01 T). In both cases, no large-scale tearing modes are evident. These observations, coupled with magnetic reconstructions indicating hollow J(R) with possible reverse shear, suggest that these sources provide significant modifications to the J(R) profile to allow stable discharge evolution. In addition, experiments conducted with strong toroidal field ramps indicate a positive plasma current drive and rapid increase in $I_p/I_{tf}$ above unity until plasma confinement is degraded. Finally, exploitation of the new programmable ohmic current drive system provides more useful V-s and allows much finer control of Vloop than was previously available. This supports a broad startup operating space, enabling control of J(r) during the current ramp. Experimental studies are focusing on extending these techniques to higher $I_p$, and probing the external kink stability limits at $A \approx 1$.

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G.D. Garstka, ICC 2007, College Park
Pegasus Mission: Exploit unique properties of A→1 ST

- Stability and confinement at high $I_p/I_{TF}$ and high $I_p$
  - Extension of tokamak studies
- Limits on $\beta_t$ and $I_p/I_{TF}$ (kink) as A→1
  - High kink-stable $\beta_t$ achievable
  - Overlap between the tokamak and the spheromak
- Noninductive current drive and sustainment
  - Key for success of ST and tokamak in general

$\beta_t$ vs. $I_p/I_{TF}$ figure of merit for access to low-A physics

Stability space for wide range of A

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Phase I: Low-order tearing modes limit plasma current

- Maximum \( I_p \approx I_{tf} \) limit
- Low-shear ST q-profile of ST \( \Rightarrow \) tearing mode instability
  - large region of low magnetic shear near axis \( \Rightarrow \) large island widths
  - low TF operations \( \Rightarrow q<2 \) when highly resistivity

- Crude manipulation of q(r) reduced mode amplitude
  - Increased shear, \( q_0 \) \( \Rightarrow \) delay tearing mode onset
  \( \Rightarrow \) Access higher \( I_p/I_{TF} \) via higher \( q_0 \), \( T_e \), shear

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Phase-I: External kink observed at highest $I_p$

- Highest Phase-I $I_p$ often disrupt
- $q_{95} = 5$ observed preceding disruption
  - $\ell_i = 0.5$ at this time
- DCON analysis $\Rightarrow$ unstable to $n=1$
  external kink
  - $m=5$ most unstable mode
- Consistent with theory expectation & high edge current
Expanded capabilities broaden access to high $I_N$

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
</table>
| - Limited current profile control  
  - coils controlled with simple LRC resonant circuits  
- Low-order rationals appear early  
  - large low magnetic shear regions  
- TF: steady state compared to discharge  
  - high $L_{tf}$ from 60 turn coil set |  
- Manipulate current profile  
  - $V_{loop}$ & position/shape control, $B_f(t)$, Electrostatic current sources  
  - Reduce $\eta$ before low-order rationals appear  
  - $V_{loop}$ & position/shape control, $B_f(t)$  
  - Transiently increase $q$ during startup  
  - $B_f(t)$, $V_{loop}$ control |

- Facility modifications for expanded capability
  - Power Supplies  
    - OH: effective $V$-s $\uparrow$ w/ increased waveform control  
  - Coil Sets  
    - Lower inductance TF set: 60 turns $\Rightarrow$ 12 turns  
    - PF Set: monolithic set $\Rightarrow$ 8 independent sets  
    - Divertor coil set installed  
  - Electrostatic Current Sources in Lower Divertor Region

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Pegasus is a university scale, mid-sized ST

### Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A</th>
<th>R (m)</th>
<th>(I_p) (MA)</th>
<th>(I_p/I_{tf})</th>
<th>(I_N) (MA/m-T)</th>
<th>(\kappa)</th>
<th>(\tau_{\text{shot}}) (s)</th>
<th>(P_{\text{HHFW}}) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved</td>
<td>1.15-1.3</td>
<td>0.2-0.38</td>
<td>(\leq 0.175)</td>
<td>(\leq 2.2)</td>
<td>6-12</td>
<td>1.4-3.7</td>
<td>(\leq 0.02)</td>
<td>0.2</td>
</tr>
<tr>
<td>Proposed Goals</td>
<td>1.12-1.3</td>
<td>0.2-0.45</td>
<td>(\leq 0.30)</td>
<td>(\leq 3)</td>
<td>6-20</td>
<td>1.4-3.7</td>
<td>(\leq 0.05)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Equilibria comparison**

- Equilibrium Field Coils
- Low Inductance TF Bundle
- Limiters
- High Stress Ohmic Solenoid
- Higher-Harmonic Fast Wave Antenna
- Divertor Coil
- Plasma Guns

**Typical PEGASUS Employee**

\[ \approx 1.8 \text{ m} \]
Modeling indicates access to high $I_N$

- **0-D confinement scaling calculations:**
  $I_p/I_{tf} = 2 \Rightarrow \beta_t = 40-70\%$
  - Enables access to pressure stability boundaries
  - Consistent with initial data set

- **TSC: Full ohmic flux (90 mV-s)**
  - $I_p \sim 300$ kA attainable
  - Simulations corroborate:
    - $I_p/I_{tf} = 2$; $I_N \sim 12$ MA/m-T

- **DCON stability modeling:**
  - Found $I_p/I_{tf} = 2$ stable with $q_{95} > 4$
    - Consistent with known theory
  - Suggests $I_p/I_{tf} = 3$ kink stable boundary
  - Pressure profile affects under investigation
Modeling of stability boundaries to guide experiment

- **Goal:** To determine optimal parameters for external kink stability at high $I_p/I_{tf}$

- **Base cases with** $I_p/I_{tf} = 2$ and 3 used as starting points for further study
  - Variety of profiles and shapes studied to determine possible stability boundaries

- **Studies ongoing to determine possible stability boundaries; key parameters for high $I_p/I_{tf}$ operations**
  - Initial indications show need for broad current profiles & high elongation for stability

![External kink stability from DCON](image-url)
3 Unique Paths to high $I_p > I_{tf}$

• **Fast TF rampdown, $\tau_{ramp} < \tau_{skin}$**
  - Simultaneously high $I_p$ & high $I_p/I_{tf}$
  - Allows access to high $I_N$, $\beta_t$ plasmas
  - Adds edge current $\Rightarrow$ develop hollow current profile during ramp

• **Non-inductive startup with electrostatic current injection**
  - Gives highest $I_p/I_{tf}$ (~2.2)
  - MHD activity characteristically different from OH driven discharges
  - Adds $J(r)$ relaxes from hollow profile $\Rightarrow$ reverse shear early

• **Ultra-low TF with guns as preionization source**
  - Efficient OH driven discharges; $V_{loop} < 4$ V
  - MHD activity similar to high TF discharges
  - Expands operating space; Ultra-low TF = no ECH resonance for breakdown assist
Separate experimental paths allow access to $I_p > I_{tf}$

- Current significantly above Phase-I $I_p \approx I_{tf}$ “soft-limit”
- New tools used to access new operating space
  - DC helicity injection $\Rightarrow$ lowest $I_p$ yet highest $I_p/I_{tf}$
  - Gun assisted startup $\Rightarrow$ transient $I_p/I_{tf}>1$ w/ OH drive
  - TF ramps $\Rightarrow$ highest $I_p$
- $I_p \leq I_{tf}$ is not an intrinsic limit
Fast TF rampdown effective technique to increase $I_p/I_{tf}$

- **New TF coil set allows fast ramprates**
  - Phase-I $\rightarrow$ 60 turn, high inductance set
  - Phase-II $\rightarrow$ 12 turn, $dI_f/dt \sim 50$ MA/sec

- **Current amplification seen during ramp**
  - $dI_p/dt \sim 25$ MA/sec before ramp
  - $dI_p/dt \sim 35$ MA/sec after ramp
  - Attributable to non-zero poloidal resistivity

- **Fast ramp occurs at end of typical discharge**
  - Ramps begin after $\sim2$ msec of high TF flattop
  - Allows high $q$ in low resistance phase of discharge

![Example of TF rampdown](chart.png)
J(r) profile becomes more hollow during TF ramp

- **TF rampdown drives edge current**
  - *poloidal induction*
- **Edge current gives hollow J(r)**
  - $\ell_i$ drops $\sim 20\%$
- **q(r) modification affects mode activity**
- **Another tool for profile modification**

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Current profile before and after TF ramp

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$J(r)$ profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.3</td>
<td><img src="image1.png" alt="Current profile before TF ramp" /></td>
</tr>
<tr>
<td>20.8</td>
<td><img src="image2.png" alt="Current profile after TF ramp" /></td>
</tr>
</tbody>
</table>

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Tearing mode activity increases as q profile flattens

- Low level n=1 activity before ramp
- Instability grows during ramp
- q(r) modification via edge current drive possible mechanism
  - Equilibria suggest reduced dq/dr
TF rampdown produces high $I_N$, $\beta_t$

- **Uses only magnetic sensors**
  - Flux loops, Plasma
  - Rogowski, pickup coils
  - No diamagnetic signal or $T_e$ available for these discharges

- **$J(r)$ control different from Phase-I**
  - TF ramp drives edge current
  - OH power only $\sim 1/3$ power
  - Much opportunity to expand/explore

- **Experiments in high $I_N$, $\beta_t$ to continue**
  - Full V-sec & faster TF ramps

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**Reconstruction Parameter List**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p$ (A)</td>
<td>161000</td>
</tr>
<tr>
<td>$I_N$</td>
<td>6.5</td>
</tr>
<tr>
<td>$I_p/I_{tf}$</td>
<td>1.23</td>
</tr>
<tr>
<td>$\ell_i$</td>
<td>0.33</td>
</tr>
<tr>
<td>$q_0$</td>
<td>3.6</td>
</tr>
<tr>
<td>$R_0$ (m)</td>
<td>0.37</td>
</tr>
<tr>
<td>$a$ (m)</td>
<td>0.32</td>
</tr>
<tr>
<td>$A$</td>
<td>1.17</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>24</td>
</tr>
<tr>
<td>$K$</td>
<td>2.2</td>
</tr>
<tr>
<td>$q_{95}$</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Plasma gun injectors noninductively produce high $I_N$ plasmas

- $I_p > I_{tf}$ routinely observed
- Large-scale tearing modes not observed
  - some $n=1$ activity present
  - likely line-tied kink, not tearing mode

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Edge current drive produces high $I_N$ without low-order tearing modes

- Gun-produced plasmas readily achieve $I_p > 2ltf$
  - In agreement with helicity balance
  - Large-scale tearing modes not observed

- Equilibria suggest that current driven largely at edge
  - Hollow $J(r)$ ⇒ reversed shear $q$
  - Low-order rationals do not appear
  - Region of low shear small
  - Not susceptible to virulent modes

- After gun shutoff, profile relaxes
  - $I_p$ rampdown peaks current
  - Conventional ST $q$-profile observed late in discharge
Guns provide preionization for ohmic operation at low $B_t$

- Frees ohmic operations space from requirement of ECH resonance
  - Expands breakdown space
  - More PF control
  - Better V-s utilization

- $I_p \sim 1.5I_{tf}$ achieved to date
  - Transient discharges; limited by derated OH
  - Full OH; Increased $V_{loop}$, V-s $\Rightarrow$ further study

- Significance: No intrinsic limit in $I_p/I_{tf}$

- Further analysis in progress
  - Determine $I_p/I_{tf}$ limiting mechanism
  - Characterize MHD $\Rightarrow I_p > I_{tf}$
J(r) control techniques yield increased $I_N$

- $I_p/I_{tf} \sim 2.3$ ($I_N \sim 14$) to date ⇒ Target: $I_p/I_{tf} \sim 2-3$ ($I_N \sim 12-20$)
- Continue with integration of 3 paths ⇒ should allow routine access
- Near term: Characterize kink stability limit
- Challenge $\beta$-stability limit w/ highest $I_N$ & $P_{aux}$ (HHFW &/or EBW)

**Design ops space**

**Realized ops space to date**

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Pegasus Toroidal Experiment
University of Wisconsin-Madison
Edge instability observed in visible light

Edge Filaments on Pegasus

- Filamentary structures observed throughout discharge
  - Follow field lines
  - Appear to have moderate n (10-30)
  - Rotate in co-current direction
  - Sometimes appear to break away & propagate radially

- Visually similar to ELMs
  - Pegasus plasmas limited, likely L-mode

ELMs on MAST

B. Lloyd, 12th ST Workshop, Chengdu, 2006

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Filaments appear early in discharge

- Structures first observed about 1 ms into discharge 
  \( (I_p \sim 40 \text{ kA}) \)

- Appear ballooning/interchange-like
  - Concentrated on low-field side
  - Lead to mixing of plasma and vacuum
  - Low pressure, high-J limit: peeling modes

ELITE calculation of density perturbations preceding ELM on DIII-D  
(P. Snyder et al., PPCF 46 2004, A131)

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Resistive interchange calculation in DCon suggests peeling instability

- Resistive interchange:
  - $D_R < 0$ stable
  - Marginally stable at Pegasus edge

- Peeling mode:
  - For high $A$, low $\beta$ ordering:
    \[ D_R < -\frac{q R}{s} \left( \frac{J_\parallel}{B} \right)_{edge} \]
  - Less stable than resistive interchange
  - Unstable at edge?

GGJ Resistive Criterion, $D_R$

Parameter List
- $I_p$ (A) 164400
- $\ell_i$ 0.32
- $q_0$ 3.4
- $R_0$ (m) 0.30
- $a$ (m) 0.25
- $A$ 1.2
- $\beta_t$ (%) 2
- $\kappa$ 1.8
- $q_{99}$ 14

Current and q profile

Reconstruction Flux Plot
Summary

• In early experiments, MHD instabilities limited $I_N (I_p \sim I_{tf})$
  - Large-scale low-order tearing modes
  - External kink mode

• Upgrades to experiment enable new $J(r)$ manipulation techniques
  - Improved loop voltage control
  - High-current, low-inductance TF coil
  - Plasma gun helicity sources

• New techniques enable increased $I_p/I_{tf}$
  - Purely noninductive helicity injection
  - Plasma gun preionization at low $B_t$
  - Rapid $B_t$ rampdown during discharge

• Edge instabilities recently observed
  - Located mostly on low-field-side, moderate $n$, aligned with $B$
  - Possibly peeling modes