The PEGASUS Toroidal Experiment Program


2010 Annual Meeting of the APS Division of Plasma Physics

Chicago, Illinois

November 8-12, 2010
The PEGASUS program is developing nonsolenoidal startup and growth techniques for tokamaks, and exploring plasma stability at near-unity aspect ratio.

Helicity injection from localized current sources (plasma guns) in the plasma periphery have produced $I_p > 0.17$ MA to date, consistent with helicity balance and Taylor relaxation constraints. Compact passive electrodes can also be used for helicity injection and $I_p$ growth, given a tokamak discharge already formed by the plasma guns.

During helicity injection, the plasma edge exhibits bursty low-$n$ MHD activity and ion spectroscopy shows strong ion heating, consistent with turbulent magnetic relaxation processes.

After gun shutoff, the plasmas are MHD quiescent, and $I_p$ can be grown and sustained above 0.20 MA, due to formation of sheared magnetic profiles in the core region. Efficient handoff from helicity injection to inductive drive requires relatively slow $I_p$ rampup during helicity injection, to build up significant core current density.

Plasma stability is dominated by peeling-like modes at large $j_{\text{edge}}/B$, and large-scale low-$m$/$n=1$ core activity. Probe-measured edge profiles constrain equilibrium fits, and allow direct tests of peeling-ballooning theory.

Work supported by U.S. DOE Grant DE-FG02-96ER54375

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Main Physics Points

• Point-Source Helicity Injection Holds Promise as a Scalable Non-Inductive Startup Technique for STs and Tokamaks
  – Achievable $I_p$ governed by helicity input rate and Taylor relaxation constraints
  – Measurements on PEGASUS confirm predicted scalings of maximum achievable $I_p$
  – Recent development suggests simpler more powerful injection system using plasma gun – passive electrode combination

• The Helicity Injection Non-Inductive Startup Technique Allows $j(R,t)$ Control to Enable Access to high $I_N$, $\beta_T$

• High $j_{\text{edge}}$, low $B_T$ at $A \sim 1$ Provides Opportunity for Detailed Peeling Mode Studies
Pegasus is a Compact Ultralow-A ST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>To Date</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>≤ .22</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 12</td>
</tr>
<tr>
<td>l_i</td>
<td>0.2 – 0.5</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_shot (s)</td>
<td>≤ 0.025</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
</tr>
<tr>
<td>P_{HHFW} (MW)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Equilibrium Field Coils
High-stress Ohmic heating solenoid

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

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Plasma gun(s) biased relative to anode:

- Helicity injection rate:

\[
\dot{K}_{inj} = 2V_{inj}B_NA_{inj}
\]

- \(V_{inj}\) - injector voltage
- \(B_N\) - normal B field at gun aperture
- \(A_{inj}\) - injector area
Evolution of midplane-gun-driven plasma

PEGASUS shot #40458: two midplane guns, mild outer-PF ramp

- $t=21.1 \text{ ms, } I_p=2-3 \text{ kA}$
  - Filaments only

- $t=28.8 \text{ ms, } I_p=42 \text{ kA}$
  - Driven diffuse plasma

- $t=30.6 \text{ ms, } I_p=37 \text{ kA}$
  - Guns off, Decaying

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Achieving the Taylor-Limit Maximum $I_p$ Requires Sufficient Helicity Injection Input Rate

- Helicity input rate, and effective net volt-seconds, increases as $V_{inj}$ increases
- Sufficient net V-sec needed to reach Taylor relaxation limit

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Driven helical filaments can relax to an axisymmetric tokamak-like state

- Driven helical filaments are strongly unstable
- Tokamak-like equilibrium satisfies a set of conditions
  - Radial force balance, helicity/power balance, kink stability (edge $q > 3$), and a Taylor relaxation current limit
- Max $I_p$ determined by Taylor relaxation limit:

$$I_p \leq f_G \left[ \frac{\varepsilon A_p I_{TF} I_{inj}}{2\pi R_{\text{edge}} w} \right]^{1/2}$$

Where: $\varepsilon$ is the inverse aspect ratio, $A_p$ is the plasma cross-sectional area, $I_{TF}$ is the TF coil current, $I_{inj}$ is the gun bias current, $R_{\text{edge}}$ is the radial location of the gun(s), $w$ is the width of the driven plasma region, and $f_G$ is a scalar function ranging from 1 to 3, depending upon geometry.

Experiments Confirm Relaxation Limit Scalings with $I_{TF}$ and $I_{inj}$

- The relaxation limit $I_p$ scales with: $I_p \propto \left[ \frac{I_{TF}I_{inj}}{w} \right]^{1/2}$

- Maximum achieved $I_p$ support these scalings:

![Graphs showing TF and inj scalings](image)

The addition of Ohmic drive did not raise $I_p$ beyond the Taylor limit

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Gun array was realigned to reduce $w$, which increased the relaxation limit

- Gun array was nearly vertical (in red):
  - Driven width $w$ scaled with # of guns
  - Red contour is approximate LCFS for best gun-driven $I_p$ of 0.11 MA.

- Changed the gun array tilt (in green):
  - Green contour is reconstructed LCFS for best gun-driven $I_p$ of 0.17 MA.
  - Maximum observed $I_p$ has increased by a factor of 1.5-1.7, implying a factor-of-3 change in $w$, consistent with changing the projected width at midplane.

- Gun array has been moved away from midplane and tilted further (in blue):
  - Blue contour corresponds to a projected full-size PEGASUS discharge

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Gun array tilt change increased Taylor limit and allowed higher gun-driven $I_p$

Experimental $I_p$ vs R Trajectories:
- Shot 45736 (retilted)
- Shot 42403 (old alignment)

Calculated Taylor Limits:
- For Shot 42403
- Multiplied by $\sqrt{3}$

Evolution in time
Gun array tilt change increased Taylor limit and allowed higher gun-driven $I_p$.

Experimental $I_p$ vs R Trajectories:
- Green: Shot 45736 (retilted)
- Red: Shot 42403 (old alignment)

Calculated Taylor Limits:
- Dashed red: For Shot 42403
- Dashed green: Multiplied by sqrt(3)
- Solid green: For Shot 45736

Evolution in time
Poloidal flux generated by HI startup is equivalent to Ohmic flux generation

- Compare two scenarios:
  1. Handoff of 80 kA gun-driven target to single-swing Ohmic
  2. Pure-Ohmic double-swing

- Handoff discharge reaches same peak $I_p$ using half the Ohmic flux
  - Implies ~ 50% flux savings

- Will assess the efficiency of helicity injection combined with other CD techniques
  - e.g., 0.8 MW PEGASUS HHFW
Slowly-evolved Gun-driven Plasmas
Hand Off Most Efficiently to Ohmic Drive

- Efficient handoff requires careful tailoring of gas fuelling, bias current, and outer-PF ramping
- Typical slowly evolving case (black $J_T$ curve, below left):
  - Smooth handoff to Ohmic inductive drive; handoffs shown in other slides (current density profiles from external-only equilibrium reconstructions)
- Typical rapidly evolving case (red $J_T$ curve, below left):
  - Does not hand off efficiently to Ohmic drive (below right)
Active Gun / Passive Electrode Assembly Points to Simpler, Higher $I_p$ Operation

- Potential for much higher $I_{\text{inj}}$ without need for either more plasma guns or larger guns.

- Helicity injection physics is agnostic to the exact source of the edge charge carriers.

- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) and the Taylor limit on $I_p$ (narrow in radial direction)

Plasma Guns with Integrated Slotted Electrodes

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Initial Tests of Gun/Electrode Helicity Injection System Are Promising

- **Operations use two steps:**
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger $I_p$ with passive electrodes fed by charge carriers in tokamak edge region.

- **First tests are promising**
  - Arc current off after relaxation and formation of tokamak-like state
  - $I_p$ rise is virtually the same, whether arc discharge or tokamak edge losses provide the charge carriers

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PEEGASUS Mission: Physics of Low A → 1

- **University-scale, Low-A ST**
  - $R_0 \leq 0.45$ m, $a \sim 0.40$ m

- **Physics of High $I_p/I_{TF}$**
  - Expand operating space of the ST
  - Study high $\beta_T$ plasmas as $A \rightarrow 1$

- **Non-solenoidal startup**
  - Point-source DC helicity injection
  - Helicity injection discharges couple to other current drive methods

- **Peeling-mode studies**
  - Experimental tests of peeling-balloonning theory

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Initial Phase of Operations had $I_p/I_{tf} \sim 1$, $I_N \sim 5$ Limit

- OH discharges experienced large tearing modes
  - Low-order rational $q$-surfaces in regions of low magnetic shear

- Modes saturated $I_p$, $W$
  - Inefficient use of available power

- Need better control over discharge evolution and additional source of current!
  - All ST’s need non-solenoidal startup; Tokamaks could use it too
  - Approach: Point-source DC helicity injection for current startup

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• After helicity injection, OH phase of discharges are *stable* to low-n tearing modes
  - In contrast to most OH-driven startup plasmas
Current Drive Tools Providing Access to High Field Utilization Regime

- Helicity injection startup and Ohmic sustainment provides MHD-stable profiles at $I_p/I_{TF} < 1$
- Need to extend to higher $I_p$, then to low $I_{TF}$ for high $I_N$ and high $\beta_T$ as $A \approx 1$

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**PEGASUS: ELM-like Structures Observed**

- ELMs take form of filamentary, field-aligned structures
  - Peeling-ballooning theory: trigger mechanism
- **PEGASUS**: L-mode edge assumed
  - Peeling instability candidate mechanism

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Near-unity A Enhances Peeling Drive

<table>
<thead>
<tr>
<th>Device</th>
<th>$J_{\text{edge}}$ (MA/m²)</th>
<th>$B_{\varphi,0}$ (T)</th>
<th>$J_{\text{edge}}/B$</th>
<th>$R_0$ (m)</th>
<th>$q_{95}$</th>
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</thead>
<tbody>
<tr>
<td>PEGASUS</td>
<td>~ 0.1 – 0.2</td>
<td>0.1</td>
<td>~ 1</td>
<td>~ 0.45</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>DIII-D</td>
<td>1 – 2*</td>
<td>2</td>
<td>0.5 – 1</td>
<td>~ 1.50</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

*: Thomas, Phys. Plasmas 12, 056123 2005

- **PEGASUS operations at** $A \rightarrow 1$ **lead to naturally high** $J_{\text{edge}}/B$

- **However, source of** $J_{\text{edge}}$ **differs**
  - Large machines: H-mode $p' \rightarrow J_{BS}$
  - PEGASUS: Large $dI_p/dt \leq 50$ MA/s $\rightarrow$ transient skin current

- **Additional geometric effects: modest drive from** $R_{q_a}$ **possible**
  - Increased edge shear competes with this effect
J(R) Structure Strongly Influenced by $dI_p/dt$

- Data supports hypothesis of skin current drive

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Edge Dynamics Consistent with ELM models

- Tracking $J_{\text{max}}(R,t)$ allows determination of filament velocity, acceleration

- This particular filament has
  - $v_{r,0} \sim 600 \text{ m/s}$, $a_r \sim 1.7 \times 10^7 \text{ m/s}^2$
  - Fast imaging results comparable

- Filament / Hole creation, propagation qualitatively consistent with ELM dynamics models*
  - Current-carrying ELM filaments repelled by magnetostatic forces


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**J_{edge} Dynamics Resolved on ELM Timescales**

- J(R) evolution tracked over filament burst
- Filament carries |J_{edge}| prior to instability outward
- Outboard δJ acceleration, radial localization

*Figures and data from A.J. Redd et al, 2010 APS-DPP Annual Meeting, Chicago, IL, Nov 8-12, 2010*
• Significant progress with non-solenoidal startup of ST
  - Maximum achievable $I_p$ is determined by helicity input and Taylor limit
  - Observed scalings of Taylor limit consistent with simple theory-based model
  - Have achieved $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Demonstrated helicity injection with passive electrodes instead of plasma guns
    • Possibility of a simpler, more powerful helicity injection startup system
  - Goal $\approx 0.3-0.4$ MA non-solenoidal $I_p$ to extrapolate to next level/NSTX
    • Outstanding physics questions: $\lambda_{\text{edge}}$, $Z_{\text{inj}}$, confinement, etc.

• Exploration of high $I_N$, $\beta_T$ space facilitated by $j(r)$ tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high $I_p$, $n_e$ for high $\beta_t$

• Possibility of tests of Peeling / Peeling-Ballooning theory
  - Can compare stability calculations to experimental observations

A Reprint of this poster will be available at http://pegasus.ep.wisc.edu/
Long-Term PEGASUS Physics Studies Will Be Enabled by Medium-Term Upgrades

- **Power/Heating Upgrades**
  - Dedicated helicity injection power supplies and control
  - Double TF current
  - Commission 800 kW HHFW system

- **Expanded PF Coil Set**
  - New external divertor coils
  - Internal coils for radial position control

- **Activate feedback PCS**
  - GA Plasma Control System technology

- **Diagnostic Additions**
  - Multipoint Thomson Scattering
  - Poloidal SXR Arrays
Near-Term Helicity Injection goal is $I_p = 0.3-0.4$ MA to address relaxation physics issues:
- What sets the bias impedance $Z_{inj}$?
- Confirm Taylor-limit parametric scalings
- Is the confinement/dissipation stochastic? (What physical processes determine $T_e(R,t)$?)
- What sets the width $w$ of the driven region?
- Confidently extrapolate to NSTX parameters

Sustained high $I_N$ operations requires HI high-$I_p$ startup, double-swing Ohmic sustainment, at low $I_{TF}$
- High $\beta_T$ accessible at $I_p/I_{TF} > 2$

Hardware upgrades may enable H-mode access
- Diverted operation and auxiliary heating to reach power threshold
- Edge instabilities will more closely resemble ELMs in larger devices
• Current is injected along helical vacuum magnetic field
• High $I_{\text{inj}}$ & modest $B \Rightarrow$ filaments merge into current sheet
• High $I_{\text{inj}}$ & low $B \Rightarrow$ current-driven $B_\theta$ overwhelms vacuum $B_z$
  – Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication

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Magnetic helicity is a measure of the linkage between magnetic fluxes (or, equivalently, the currents that generate those fluxes). The general definition of magnetic helicity is an integral over a volume that encompasses the linked fluxes:

\[ K \equiv \int A \cdot B \, dV \]

Magnetic helicity is the best-conserved constant of motion in magnetized plasma, decaying on resistive timescales.

In the case of two linked but distinct fluxes \( \phi \) and \( \psi \), similar to the rings shown, the total magnetic helicity of the volume is \( K=2\phi\psi \).

In a tokamak, the magnetic helicity \( K \) is proportional to the product \( I_{TF}I_p \), with \( I_{TF} \) determined by the TF coil power supply. Increases in the helicity \( K \) correspond to increases in the toroidal plasma current \( I_p \).
Tokamak Current Drive is Helicity Injection

Total helicity $K$ in a tokamak geometry:

$$K = \int_V (A + A_{vac}) \cdot (B - B_{vac}) \, d^3x$$

$$\frac{dK}{dt} = -2 \int_V \eta J \cdot B \, d^3x - 2 \frac{\partial \Psi}{\partial t} \Psi - 2 \int_A \Phi B \cdot ds$$

- **Resistive Helicity Dissipation**
  - $E = \eta J \rightarrow$ much slower than energy dissipation ($\eta J^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity

- **AC Helicity Injection:**
  - $\Psi$ is toroidal flux, $\psi$ is poloidal flux
  - (e.g., current drive through solenoid induction)

- **DC Helicity Injection**
  - $\Phi$ is electrostatic potential

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Taylor Relaxation Criteria Sets the Maximum $I_p$ for a Given Magnetic Geometry

Helicity balance in a tokamak geometry:

$$\frac{dK}{dt} = -2 \int_V \eta \mathbf{J} \cdot \mathbf{B} \, d^3x - 2 \frac{\partial \Psi}{\partial t} \Psi - 2 \int_A \Phi \mathbf{B} \cdot ds \quad \Rightarrow \quad I_p \leq \frac{A_p}{2\pi R_0 \langle \eta \rangle} \left( V_{ind} + V_{eff} \right)$$

- Helicity injection can be expressed as an effective loop voltage
- $I_p$ limit depends on the scaling of plasma confinement via the $\eta$ term

Taylor relaxation of a force-free equilibrium:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = \lambda \mathbf{B} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \leq \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta, inj}} \quad \Rightarrow \quad I_p \leq \left[ \frac{C_p}{2\pi R_{inj} \mu_0 w} \frac{\Psi_T I_{inj}}{\Psi_T w} \right]^{1/2}$$

Assumptions:
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

$A_p$ Plasma area
$C_p$ Plasma circumference
$\Psi_T$ Plasma toroidal flux
$w$ Edge current channel width

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Electrode-driven discharges have been coupled to Ohmic double-swing

- **Double-swing ramp:**
  - Longer Ohmic drive duration
  - Demonstrates feasibility for high-bT scenario development

- **This particular shot had:**
  - Only two guns: low handoff $I_p$
  - Non-optimal handoff target: best available electrode-driven target plasma at the time.
  During helicity injection phase, the limiter material and location has a profound effect on plasma performance. This is an area of active research.
  - Ohmic-phase plasma fills the PEGASUS confinement region.

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