Abstract (1): HICD in PEGASUS

- Plasma startup and steady-state sustainment without using an Ohmic solenoid is a general problem facing tokamaks. This problem is most acute in small aspect ratio tokamaks, in which the relatively small center stack assembly does not allow the luxury of a significant Ohmic solenoid.

- The PEGASUS Toroidal Experiment is an ultra-low aspect ratio tokamak (A~1.15), dedicated to exploring the physics of low-A tokamaks and the boundary between typical tokamak and spheromak operating spaces.

- PEGASUS uses compact plasma sources (“washer guns”) as point-source magnetic helicity injectors to form tokamak discharges.

- This non-solenoidal startup technique has produced up to 100 kA of toroidal current in published studies [Battaglia et al, Phys. Rev. Lett. v.102, p.225003 (2009)], and after recent hardware modifications has produced up to 174 kA.

- The maximum toroidal current during helicity injection is limited by helicity balance and a relaxation limit, with this limit corresponding to the usual lowest-energy Taylor state. This theoretical current limit scales with the TF coil current, the gun-injected current, and the injection geometry, and these predicted scalings are consistent with the results from experimental scans over those parameters.
• Addition of Ohmic solenoid drive during the gun injection period enhances the helicity injection rate, but the maximum current cannot exceed the relaxation limit, demonstrating that this is a hard limit on the plasma current.

• Conversely, Ohmic solenoid drive can be used to sustain and enhance the gun-generated plasma, if the Ohmic drive is applied after the gun injection ceases.

• The current-profile relaxation associated with this helicity injection technique correlates with bursts of low-n MHD activity on the outboard side of the discharge.

• Planned near-term physics studies include the direct observation of the current-profile relaxation using an internal Hall-effect magnetic probe array and enhancement of the gun drive with shaped electrodes.

• In the longer term, the relaxation limit model is guiding the enhancement of the gun injection and TF coil power supplies, with the goal of reaching 300-400 kA of gun-driven toroidal plasma current.

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### Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>To Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (m)</td>
<td>1.15 – 1.3</td>
</tr>
<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
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<tr>
<td>I_p (MA)</td>
<td>≤ .22</td>
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<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 12</td>
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<tr>
<td>l_i</td>
<td>0.2 – 0.5</td>
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<tr>
<td>k</td>
<td>1.4 – 3.0</td>
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<tr>
<td>(\tau_{\text{shot}}) (s)</td>
<td>≤ 0.025</td>
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<tr>
<td>(\beta_T) (%)</td>
<td>≤ 25</td>
</tr>
<tr>
<td>(P_{\text{HHFW}}) (MW)</td>
<td>0.2</td>
</tr>
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</table>
• Using DC helicity injection for solenoid-free startup
  – $I_p$ up to 174 kA using helicity injection and outer-PF rampup
  – Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
  – $I_p$ up to 135 kA smoothly “handed off” to Ohmic, then driven to 218 kA

• High-$I_p$ non-solenoidal startup enables exploration of high $I_N$, $\beta_T$ operating space
  – $I_p/I_{TF} > 2$, $I_N > 14$ achieved
  – Extend to high $I_p$, $n_e$ for high $\beta_T$
Helicity Injection Startup Provides a Path to High-$I_N$, High-$\beta_T$ Noninductive Ops

- Previously achieved $I_N > 12$ using helicity injection alone
- No evidence of $\beta$ stability limits at high $I_N$
  - PEGASUS discharges have been limited by available current drive
- Gun startup and Ohmic handoff are extending PEGASUS operational space to higher $I_p$
- Future: Use RF heating (HHFW, EBW) to reduce dissipation. Also, explore handoff to RF current drive

$$\beta_t = \beta_N I_N \quad I_N = \frac{I_P}{aB_\phi}$$

$$\beta_t = \frac{2\mu_0 \langle p \rangle}{B_{\phi 0}^2}$$
Magnetic helicity in tokamak plasmas

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 \( I_p \).
Current drive in a tokamak is equivalent to magnetic 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:
  $$K_{AC} = -2 \frac{\partial \psi}{\partial t} \Psi = 2V_{loop} \Psi$$
  - $\Psi$ is toroidal flux, $\psi$ is poloidal flux

- DC Helicity Injection
  $$K_{DC} = -2 \int_A \Phi B \cdot ds = 2V_{inj} B_\perp A_{inj}$$
  - $\Phi$ is electrostatic potential
• Current is injected into the existing helical magnetic field
  – Superposition of vacuum toroidal and vertical fields

• 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

PEGSASUS Point-Source Helicity Injection Uses an Array of Three Plasma Guns

Anode
Plasma guns
Outer Limiter

Side view

Anode
3 plasma guns
Plasma streams

Top view (rotated)

Anode
Plasma guns
Limiter

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 $dK/dt$ and Taylor relaxation limit:

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

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, $R_{edge}$ is the gun location, $w$ is the width of the driven plasma region, and $f_G$ is a scalar function ranging from 1 to 3, depending upon geometry. See Battaglia et al., Phys. Rev. Lett. 102, 225003 (2009).
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
Maximum $I_p$ achieved when helicity input is sufficient to reach the relaxation limit.

- $I_{TF} = 288$ kA
- $V_{bias} = 1$ kV
- $V_{ind} = 1.5$ V
- $I_{inj} = 4$ kA
- $w = d_{inj}$
- L-mode $\tau_e$

Sufficient helicity injection is required to drive the plasma up to the relaxation limit.

Max $I_p$ increases with $V_{bias}$

$K_{DC} \propto V_{bias} \propto Z_{inj}$

High dK/dt with modest $I_{bias}$ requires high impedance $Z_{inj}$

• Single-gun discharge with no PF ramps.

• Current multiplication above 50 at gun shutoff.

• Discrepancy between demanded and actual bias current is due to insufficient bank voltage.
Empirical scalings with $I_{TF}$ and $I_{bias}$ are consistent with relaxation limit model

- Predicted relaxation limit $I_p$ scales with $(I_{TF}I_{bias})^{1/2}$
- Experimental $I_p$ observed to follow these scalings:

Note: adding solenoid induction during gun drive does not allow driven $I_p$ to exceed the Taylor relaxation limit

Experiments suggest strong dependence on the width of the driven current layer

- Relaxation current limit scales as $w^{1/2}$ in the model
- One-gun discharges have higher limits than corresponding three-gun cases, indicating gun array was misaligned:
Gun array was realigned to reduce $w$, significantly increasing relaxation limit

- Changing the tilt of the gun array increased the max $I_p$ by a factor of 1.5-1.7, implying a factor-of-3 change in $w$, consistent with changing the projected width at midplane.
- In this configuration, have achieved $I_p = 174$ kA.
Retilted gun array allows much higher maximum gun-driven $I_p$

Highest peak currents with old gun-array alignment were around 100 kA
Retilted gun array allows plasma currents of over 170 kA
• During helicity injection phase, bursty MHD activity appears:
  – Typically $n=1$, with frequencies varying from 20 kHz to 60 kHz
  – Can be either intermittent or continuous with “bursts” of large amplitude
  – Mode frequency and amplitude may vary with magnetic field

• “Bursts” correlate with rapid rises in $I_p$, density dumps, and inward radial shifts of the plasma.

• External kink mode ($n=1$) correlates with current-profile relaxation and poloidal flux amplification in CHI-driven spheromaks and STs:
  – Computational work by A.Bayliss, D.Brennan, and X.Tang each provide detailed studies of current-profile relaxation through low-$n$ modes
  – A similar mechanism may be responsible for relaxation in PEGASUS

• Presently under study: to understand the onset of the bursts and the detailed mechanism for the equilibrium shifts.
MHD activity bursts during gun drive correspond to rapid rises in $I_p$.

Rapid $I_p$ rises correspond to inward shifts of the current channel, as noted in D.J. Battaglia’s PhD dissertation (2009).
Shortly after gun shutoff, plasma currents are similar to those in PEGASUS Ohmic discharges, while equilibrium reconstructions indicate that the $q$-profiles are similar to Ohmic. But the handoff discharges remain quiescent, while the Ohmic discharges are unstable to low-$n$ tearing modes.
MHD activity “bursts” also can correlate with density dumps

Shot 46526: Gun-only Discharge

Line-Integrated ne (10^19/m^2), Halpha (arb)

Electron Density
H-Alpha Emission
Bp Fluctuations

Measured Fluctuations OTOR1 Bp (T)

Time (ms)

19.6 19.8 20.0 20.2 20.4 20.6
MHD activity “bursts” correlate with rapid inward radial shifts

Shot 46526: Gun-only Discharge
- Measured Plasma Current
- Outboard Field (OTOR1)
- Inboard Field (CTOR1)

• $dI_p/dt$ during gun phase is strongly affected by the applied bias current and voltage, outer-PF induction, and fuelling.

• Gun plasmas hand off most efficiently to Ohmic when the gun drive shuts off at the current peak.
  – Higher bias voltage, or more outer-PF induction, raises $dI_p/dt$
  – More fuelling lowers $dI_p/dt$
  – Gun-driven current can peak, and the plasma decouple from the guns, before the pre-programmed gun drive ends.

• Efficient handoff relies upon careful tailoring of fuelling, bias current, and outer-PF ramping, which is consistent with controlling the current profile evolution.
  – Good handoff requires a slowly evolving $I_p$, which would be consistent with a broader, less hollow current profile.
Early peaking of gun-driven $I_p$ reduces handoff current and impacts subsequent $I_p$.
Ohmic evolution is not optimized: plasma is being crushed into the centerstack, which probably causes the $I_p$ rollover.
Equilibrium reconstructions indicate that further optimization is possible.

KFIT equilibrium fit @ 25.0 ms in PEGASUS discharge #47112

Equilibrium Parameters:

\[ I_p = 151 \, \text{kA} \quad I_{TF} = 288 \, \text{kA} \]
\[ R_0 = 0.24 \, \text{m} \quad \beta_T = 5.4\% \]
\[ a = 0.195 \, \text{m} \quad \beta_p = 0.061 \]
\[ A = 1.2 \quad l_i = 0.27 \]

Approximately 1 ms after the shutoff of helicity injection, and the plasma has rapidly moved inward away from the guns (at approximately R=0.75m)
Gun-formed discharges have reasonable electron densities

Chord length: exact determination is difficult, but is approximately 1-2 meters

Summary: HICD in PEGASUS

- Point-source helicity injection current drive non-inductively generates high-$I_p$ (up to 174 kA) tokamak discharges
- An empirically-supported model for the maximum gun-driven $I_p$ has guided experiments
- Gun-formed plasmas exhibit bursty MHD activity during the gun drive, with the bursts corresponding to rapid equilibrium changes.
  - Studying onset of the bursts, and detailed mechanisms for the rapid changes
- Gun-formed discharges hand off most efficiently to Ohmic with a very slow $I_p$ rise during helicity injection, consistent with controlling the current-profile evolution toward a broad profile.
  - Have demonstrated handoff with 135 kA, driven with Ohmic up to 218 kA (for $I_p/I_{TF}=0.7$), which is a significant extension to the PEGASUS operating space
  - More optimization is possible with the present power supplies
- High-current gun-drive formation with handoff to other current drive techniques may lead to high-$I_N$, high-$\beta_T$ PEGASUS operations
Further development of gun startup needed for predictive understanding

• Test of working model requires access to 0.3-0.4 MA
  – Characterize confinement/dissipation in driven plasma
  – Develop efficient handoff scenarios, to Ohmic and/or RF current drive
  – Access high $I_p/I_{TF}$, high $\beta$ parameter regimes

• Outstanding physics issues include:
  – Is the confinement/dissipation stochastic?
  – What sets the bias impedance?
  – What sets the width $w$ of the driven region?
  – How well does the simple helicity injection model hold as $I_p$ increases?

• Addressing these issues requires facility modifications:
  – Increase capability of TF supplies: higher transient TF or long-pulse
  – Increase bias gun current and voltage and/or deploy larger guns
  – Augment the guns with shaped electrodes
Point-source helicity injection could be critical for PEGASUS and other ST devices

- Solenoid-free startup and ramp-up have been identified as critical ST issues (ReNeW report, FESAC TAP report)

- Solenoid-free startup with point-source helicity injection significantly extends the PEGASUS operating space
  - Formation of the startup plasma saves limited Ohmic transformer flux, and increases the current $I_p$ that can be achieved with the same Ohmic flux
  - May enable high-$I_N$, high-$\beta$ studies on PEGASUS
  - May enable completely solenoid-free operation with RF current drive

- Point-source helicity injection is flexible, and may provide solenoid-free startup in future toroidal devices
  - Gun assemblies can be placed at any experimentally convenient location
  - Point-source helicity injection science and technology is being developed

- The PEGASUS program is strongly focused on developing a deep physical understanding of this approach