Abstract

The Pegasus Toroidal Experiment is an ultra-low aspect ratio ($A < 1.2$) spherical tokamak (ST) capable of operating in the high $I_N$ regime ($I_N > 12$). Access to this regime requires a small center-post cross-section that consequently reduces the available inductive current drive from the central ohmic (OH) solenoid. Non-solenoidal plasma startup allows for more efficient use of the OH current drive and may possibly eliminate the need for a solenoid in future STs. Recent experiments on Pegasus use a single washer gun current source located near the outboard midplane to establish and sustain a tokamak-like plasma via DC helicity injection. A new gun head design permits high current (2 kA) injection with minimal impurity production and improved neutral fueling control. The washer gun and a biased anode are mounted at the same toroidal location, 20 cm below and above the mid-plane. The vacuum toroidal and vertical fields are chosen so the initial injected current follows a helical field line that connects the gun aperture to the anode. For a sufficiently large current density and small vertical field strength, the plasma relaxes into a tokamak-like configuration. With less than 2 kA of injected current, tokamak-like discharges with $I_p \approx 20$ kA are produced. Line-averaged densities near the Greenwald density limit of $1.0 \times 10^{19}$ m$^{-3}$ indicate improved particle confinement. The formation of a current channel within the vacuum region separate from the gun injection region is verified using magnetic field measurements. Substantially longer current decay times (2 - 3 ms) indicate the buildup of stored energy. The length of the decay time is suitable for coupling to other current drive techniques. Discharges of 80 kA were obtained by applying < 10 mWb of OH flux to a 20 kA seed plasma. These results are compared to discharges initiated with two 1 kA washer guns mounted in the lower divertor region. Future experiments with multiple injectors are also described.
ST startup and current drive using plasma gun
DC helicity injection on Pegasus

• Solenoid-free startup would extend the efficiency of inductive OH drive
  – Especially important for the low aspect ratio spherical tokamak (ST)

• Plasma gun point-source DC helicity injection on the Pegasus Toroidal Experiment
  – Plasma guns $\rightarrow$ low impurity, high $J_{\text{inj}}$ source
  – Plasma guns mounted in lower divertor
  – Available current drive described using concepts of DC helicity injection and Taylor relaxation

• New midplane plasma gun system installed on Pegasus
  – Identify dependence on point-source location
The Pegasus Toroidal Experiment is well suited for point-source DC helicity injection studies

- Ultra-low aspect ratio ($A < 1.3$)
  - Span large range of $R_0/R_{\text{inj}}$

- Flexible configuration
  - Independent PF & Div coils
  - Good port availability

<table>
<thead>
<tr>
<th>Experimental Parameters</th>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1.15-1.3</td>
<td>1.12-1.3</td>
<td></td>
</tr>
<tr>
<td>$R$ (m)</td>
<td>0.2-0.45</td>
<td>0.2-0.45</td>
<td></td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq 0.18$</td>
<td>$\leq 0.30$</td>
<td></td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6-12</td>
<td>6-20</td>
<td></td>
</tr>
<tr>
<td>$R_B$ (T-m)</td>
<td>$\leq 0.06$</td>
<td>$\leq 0.1$</td>
<td></td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.4–3.7</td>
<td>1.4–3.7</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>$\leq 0.02$</td>
<td>$\leq 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>$\leq 25$</td>
<td>&gt; 40</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{HHFW}}$ (MW)</td>
<td>0.2</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
Current drive in a tokamak is described using the concept of magnetic helicity

Total helicity in a tokamak geometry:

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

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

- 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:
  \[ K_{AC} = -2 \frac{\partial \psi}{\partial t} \Psi = 2V_{loop} \Psi \]

- DC Helicity Injection:
  \[ K_{DC} = -2 \int_A \Phi B \cdot ds = 2V_{inj} B_{\perp} \cdot A_{inj} \]
Electrostatic DC helicity injection has been demonstrated on a number of tokamak devices

- DC helicity injection is related to inductive current drive using:
  \[ V_{\text{eff}} \approx \frac{N_{\text{inj}} V_{\text{inj}} A_{\text{inj}} R_0}{A_p R_{\text{inj}}} \]

- \( V_{\text{eff}} \) increases with \( A_{\text{inj}} \)
  - \( A_{\text{inj}} \) maximized with CHI system
  - CHI demonstrated on HIT, HIT-II, NSTX
  - CHI not easily retrofitted onto Pegasus

- Point-source injection requires large \( V_{\text{inj}} \) as \( A_{\text{inj}} \) is reduced
  - Studied on CDX, CCT using emissive electrodes
    - Demonstrated tokamak-like plasma formation
    - Limited to low \( J_{\text{inj}} \) by impurity sputtering
Plasma guns provide a low impurity, point-source DC helicity injection scheme

- Arc discharge sustained in washer stack cavity
  - Washers stabilize arc while limiting surface contact \(^1\)
  - Sputtered high-Z impurities mostly trapped in gun cavity

- Plasma column supports large \(J_{\text{inj}}\) without space charge limitations \(^2\)

- Requires constant current arc and bias power supplies
  - \(I_{\text{arc}} = 2\) kA using a pulse forming network
  - \(V_{\text{arc}} = 100 - 500\) V
  - \(I_{\text{bias}} < I_{\text{arc}}\) for impurity sputtering
  - \(I_{\text{arc}} < 2\) kA using current feedback control
  - \(V_{\text{bias}} < 800\) V (before near-term upgrade)

---

1 Den Hartog, D.J., Plasma Sources Sci. & Tech. 6 (1997)
The maximum sustained $I_p$ is determined by the balance between helicity injection and dissipation

- For $B_\phi >> B_\theta$: $\dot{K}_{diss} \approx 4\pi R_0 I_p B_\phi \langle \eta \rangle$

- Solving for $\dot{K}_{diss} = \dot{K}_{DC}$ gives

$$I_p = \left( \frac{N_{inj} V_{inj} A_{inj}}{R_{inj}} \right) \frac{1}{2\pi \langle \eta \rangle}$$

Maximum $I_p$ related to plasma geometry and magnetic field strength through $\eta$ term

- Use Spitzer resistivity as an approximation:

$$\eta \approx 5.2 \times 10^{-5} Z_{eff} \ln \Lambda / T_{e0}^{3/2} (\Omega \cdot m)$$

Maximum $I_p$ related to $T_{e0}$

- Reworking the helicity balance expression gives:

$$\bar{T}_e \approx \left[ 10^6 \pi I_p Z_{eff} \ln \Lambda \left( \frac{R_{inj}}{N_{inj} V_{inj} A_{inj}} \right)^{2/3} \right]^{2/3}$$

Assuming nearly flat temperature profile
Initial experiments on Pegasus mounted the plasma guns near the lower divertor

- Anode plate hung from upper divertor
- Crossed $B_v$ and $B_\phi$ vacuum field
- Low current plasma follows helical field line connecting gun & anode
  - Inboard injection
    - Maximize $V_{\text{eff}}$ for given $R_0$, $A_p$ and $V_{\text{inj}}$
      \[ V_{\text{eff}} \propto \frac{R_0}{R_{\text{inj}}} \]
    - Typical centerstack limited plasma startup
    - Capture sub-ms dynamics with fast camera
- Easily retrofitted into Pegasus

Zero current plasma filaments in vacuum magnetic field
Magnetic topology relaxes into a tokamak-like configuration at sufficiently high $I_{\text{inj}}$ and low $B_v$

Current filaments

“Current sheet”

Tokamak-like plasma

Small $G I_{\text{inj}} / B_v$

Large $G I_{\text{inj}} / B_v$

$M = G$

$M > G$

Toroidal current multiplication factor:

$M = I_\phi / I_{\text{inj}}$

Geometric stacking factor:

$G \approx \frac{\mu_0 I_{TF} \Delta z}{\left(2\pi R_{\text{inj}}\right)^2 B_v}$

Gun - anode separation

$B_\phi \sim 10\text{mT}$

$B_v \sim 5\text{mT}$

$I_{\text{inj}} \sim 2\text{kA}$
The onset of flux amplification correlates with inboard poloidal magnetic flux reversal

- $I_p > 50 \text{ kA}$ driven by $I_{\text{inj}} \leq 4 \text{ kA}$
  - Static B fields (no inductive drive)
  - Two plasma guns
    - $A_{\text{inj}} = 3 \text{ cm}^2$, $R_{\text{inj}} = 16 \text{ cm}$

- $I_p$ persists after $I_{\text{inj}} = 0$
  - Suggests non-zero stored energy

- $B_\theta$ reversal observed at inboard midplane
  - Plasma is limiting on center column
  - Reversal correlates with $M > G = 5$
Evidence that the maximum $I_p$ is realized when the tokamak-like plasma achieves helicity balance

- Data set for static B fields
  - Each point represents one discharge
  - Includes one and two gun operations
  - Max $I_p$ for given conditions achieved at max $B_v$ that allowed flux reversal

- Steady-state helicity balance roughly approximates average $T_e$
  - Assume Spitzer $\eta$ & $Z_{eff} = 2.5$
  - Calculated average $T_e = 35 - 65$ eV from approximate resistive helicity dissipation

- $V_{surf} \approx V_{eff}$ suggests plasmas achieve helicity equilibrium
  - $V_{surf}$ estimated using a flux measurement at center column
  - G-S solver provides plasma geometry for $V_{eff}$ calculation
Outboard plasma gun system designed to explore point-source injection at the other geometric extreme

• High-field side injection
  – For fixed $I_{\text{inj}}$, $A_{\text{inj}}$ & $A_p$:
    \[ V_{\text{eff}} \propto Z_{\text{inj}} R_0 / R_{\text{inj}} \]
  – Sacrifice favorable $R_0/R_{\text{inj}}$ scaling
  – The effect on $Z_{\text{inj}}$ is unknown
    • Study dependence with injector geometry, plasma and injector parameters, etc.

• Outboard limited plasma
  – More dynamic evolution of EF required to maintain outboard position
  – Gain PF induction current drive

• Installation is straightforward
  – Outboard side of vessel is the most accessible
Three plasma guns were recently mounted near the outboard midplane on Pegasus.
A first-order model is being developed to estimate the maximum sustained $I_p$ with outboard injection

- Simplest operation scenario $\rightarrow$ static B field, single gun

- Use 2-D field model to calculate maximum $B_v$
  - Predicts magnetic field regimes that allow for field reversal
  - $B_v$ required for radial force balance in static field scenario

- Once a tokamak-like plasma has formed . . .
  - Estimate plasma shape vs $R_0$
  - Determine $I_{p,\text{max}}$ that satisfies these requirements

  (1) Force balance
  (2) Tokamak stability
  (3) Helicity balance
  (4) Taylor relaxation requirements
A 2-D current filament code is used to determine maximum $B_v$ that leads to inboard field reversal

- **Experimental observation:**
  - $M > G$ correlates with inboard B field reversal

- **Geometric windup = 2**
  - Treat the discrete filaments as a toroidally averaged current sheet tied to a flux surface

- **Max $B_v$ that allows field reversal when $I_{PF} \sim 1.2kA**
  - $B_v \sim 0$ at inboard edge

Force-free plasma filaments perturb the vacuum magnetic field

- $I_{inj} = 0 \ A$
- $I_{TF} = 300 \ kA$, $I_{PF} = 1.2 \ kA$ (PF1-3, 6-8)

- $I_{inj} = 2 \ kA$
The simple model assumes an outboard limited, large aspect ratio, circular cross-section plasma.

Plasma limiting surface: (A) Center column  
(B) Gun / anode  
(C) Outer limiter

Large-A radial force equilibrium

$$B_v = -\frac{\mu_0 I_p}{4\pi R_0} \left[ \ln\left(\frac{8R_0}{a}\right) + \Lambda - \frac{1}{2} \right]$$  

Fixing $B_v$ at the maximum value from the field reversal model gives $I_p(R_0)$

Assuming $\Lambda = \beta_p + \ell_i/2 - 1 \approx -1$

gives most optimistic $I_p$

Large-A cylindrical edge $q$

$$q_a \approx a^2 I_{TF} / R^2 I_p$$

Considered for edge kink stability
Find a self-consistent solution for $\tau_e$ approximated using empirical energy confinement relations:

- ITER97L: Tokamak L-mode\(^2\)
- ITPA - low A: ST & tokamak H-mode\(^3\)

Assume peaked $n_e$ and $T_e$ profiles

$$n_e(r) = n_{e0} \left( 1 - \left( \frac{r}{a} \right)^2 \right)^{\alpha_n} \quad T_e(r) = T_{e0} \left( 1 - \left( \frac{r}{a} \right)^2 \right)^{\alpha_T}$$

with Greenwald density scaling

$$n_{GR} \left( 10^{20} \text{ m}^{-3} \right) = I_p \text{ (MA)} / \pi a \text{ (m)}^2$$

Estimate of self-consistent $T_{e0}$ calculation provides maximum $I_p$ from helicity balance

$$V_{eff} I_p = W_k / \tau_e + dW / dt$$

Assume $dW / dt = 0$ at $I_{p,\text{max}}$

$$V_{eff} I_p = W_k / \tau_e + dW / dt = 0 \quad \text{at } I_{p,\text{max}}$$

Assume $n_e$ and $T_e$ profiles

$$n_e(r) = n_{e0} \left( 1 - \left( \frac{r}{a} \right)^2 \right)^{\alpha_n} \quad T_e(r) = T_{e0} \left( 1 - \left( \frac{r}{a} \right)^2 \right)^{\alpha_T}$$

with Greenwald density scaling

$$n_{GR} \left( 10^{20} \text{ m}^{-3} \right) = I_p \text{ (MA)} / \pi a \text{ (m)}^2$$

2 Kaye, S.M. et al., Nuc. Fusion 37, no. 9, 1997
Taylor relaxation criteria also limits the total sustainable $I_p$ for a given plasma geometry

Considering force-free equilibrium:

$$\nabla \times B = \mu_0 J = \lambda B$$

Current penetration via Taylor relaxation requires:

$$\bar{\lambda}_{\text{sheet}} > \bar{\lambda}_{\text{plasma}}$$

$$\bar{\lambda}_{\text{sheet}} = \frac{\mu_0 J_{\phi,\text{sheet}}}{B_{\phi,\text{sheet}}} \approx N_{\text{inj}} \frac{I_{\text{inj}}}{I_p} \frac{a}{R_L \delta}$$  (using $G = q_a$)

$$\bar{\lambda}_{\text{plasma}} = \frac{\mu_0 J_{\phi,\text{plasma}}}{B_{\phi,\text{plasma}}} \approx \frac{2R_0 I_p}{a^2 I_{TF}}$$  (for large $A$ and circular cross-section)

Averaging $\bar{\lambda}_{\text{sheet}}$ over the plasma surface area gives$^1$:

$$\frac{L}{2\pi a} \bar{\lambda}_{\text{sheet}} > \bar{\lambda}_{\text{plasma}}$$

which leads to

$$I_p < \varepsilon I_{TF} \left[ \frac{N_{\text{inj}} I_{\text{inj}} R_0}{I_{TF} R_L} \frac{L}{2\pi \delta} \right]^{1/2}$$

Maximum sustained plasma current achieved when plasma simultaneously satisfies four criteria

- $I_{\text{p,max}}$ realized when plasma is in force and helicity balance
  - Determined when black and blue lines cross
- Operation point satisfies tokamak stability and Taylor relaxation criteria
  - $I_{\text{p,max}}$ point is below red curve
  - $q_a > 3$ at $I_{\text{p,max}}$ point

$I_{\text{p,max}} \sim 19 \text{ kA}$

at $R_0 \sim 55 \text{ cm}$

Helicity balance calculated using ITER97L confinement scaling

Taylor relaxation limit calculated using $I_{\text{inj}} = 2 \text{ kA}$

$I_{\text{PF}} = 1.2 \text{ kA}$, $I_{\text{TF}} = 300 \text{ kA}$
Flux amplification is observed with outboard midplane plasma gun DC helicity injection

- Initial results suggest agreement with crude model
  - $I_{PF}$ field reversal threshold $\sim 1.2$ kA → agrees with 2-D filament model
  - $I_{p,max} \sim 17$ kA → correlates with helicity and force balance limit
  - $R_0 \sim 55$ cm at $I_{p,max}$ determined from midplane Mirnov measurements

- Evidence of flux amplification
  - $G \sim 2$, $M > 12$ achieved
  - Long $I_p$ decay after injector shutoff
  - $\int n_e \, dl$ suggests improved particle confinement with flux amplification
  - Line averaged density near Greenwald density limit

Single gun, static B field discharges
Shot 39762: $I_{TF} = 300$ kA, $I_{PF} = 1.3$ kA
Shot 39761: $I_{TF} = 300$ kA, $I_{PF} = 1.2$ kA

\[ R_{tang} = 8 \text{ cm} \]
Poloidal field magnetic induction coupled to tokamak-like plasma during DC helicity injection

- AC helicity injection successfully coupled to DC helicity injection
  - Low $B_v$ required for field reversal
  - Larger $B_v$ required after field reversal to maintain radial force balance with larger $I_p$

- Demonstration of $B_v$ field ramp during gun injection
  - Two plasma guns in operation
  - Ramp begins after field reversal
  - Induction provides additional current drive

- $V_{total} \approx 1.5$ V
  - $V_{eff}$ calculated using $R_0$ and plasma shape estimation from magnetic measurements
  - $V_{PF}$ calculated using 2-D vacuum field model that includes wall effects

![Graph of plasma current and injection current with time (ms) and calculated magnetic field $B_z$ at R = 50 cm, z = 0 cm.]
The tokamak-like plasma can “detach” from the gun during rapid PF ramps.

Plasma detaches at 29.4 ms for a slower PF ramp.

Plasma detaches at 25.3 ms for a faster PF ramp.

After detachment, current drive is purely inductive and MHD activity is reduced.
Handoff from point-source DC helicity injection to OH induction has been demonstrated

- Data shown for single outboard plasma gun system
  - < 10 mWb of OH flux
  - Prototype system → OH handoff experiments with new 3 gun system are planned

- Demonstrated using both point-source geometries
  - OH drive is applied after DC helicity injection is terminated
  - Outboard limited plasmas have longer L/R decay → easier to “catch” plasma after injector termination
Non-inductive startup provides a path to high $\beta_t$ operations in the $I_N > 12$ regime on Pegasus

- Point-source edge current drive provides tool for modifying the current profile
- Access to $I_N > 12$ achieved using non-inductive startup
- No evidence of $\beta$ stability limits at high $I_N$
  - Discharges have been limited by available current drive
- Non-inductive startup with hand-off to OH drive will extend the operational space
- Hand-off to HHFW in future

\[ \beta_t = \beta_N I_N \quad I_N = \frac{I_p}{aB\phi} \]

\[ \beta_t = \frac{2\mu_0 \langle p \rangle}{B^2_{\phi_0}} \]
Summary

- ST startup and current drive via point-source DC helicity injection was demonstrated on the Pegasus Toroidal Experiment
  - Poloidal flux amplification observed and correlated with inboard field reversal
  - Maximum $I_p$ described by force and helicity balance
  - Observed increase in L/R decay and modest plasma heating

- A new midplane gun array provides a test of the geometric dependence of point-source DC helicity injection
  - A model is being developed based on early plasma gun work
  - Initial single gun, static B field results consistent with simple max $I_p$ model
  - Evidence such as flux amplification and increased particle confinement suggest a tokamak-like plasma is formed in the vacuum region using outboard injection

- Magnetic induction compatible with DC helicity injection
  - PF induction provides current drive and maintains radial force balance with larger $I_p$ plasma
  - Fast PF ramps can cause the tokamak-like plasma to detach from the gun
  - Handoff to OH induction also demonstrated
Future work

• Near term experimental plans
  – Planned hardware upgrades: Larger bias voltage supply, 20% higher TF fields
  – > 100 kA target plasmas using 3 guns + PF induction
  – Handoff > 100 kA target plasmas to OH induction

• Modeling and analysis
  – Develop and test more sophisticated model of \( I_p \) limits
  – Plasma geometry calculation using current filament code or G-S solver
  – PF induction/compression modeling using TSC

• Long term goals
  – Develop and test new plasma gun head designs to optimize current injection while maintaining low impurity injection
  – Gain a deeper understanding of the initial plasma relaxation into a tokamak-like configuration using internal probe measurements and simulations
  – Develop a complete predictive model for optimizing a plasma gun point-source system in an arbitrary tokamak geometry
  – Demonstrate high-power tokamak startup and handoff to HHFW current drive