Non-inductive Startup Using Localized Washer Gun Current Sources on the PEGASUS Toroidal Experiment

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Overview: Localized Current Sources Provide Non-Inductive Tokamak Startup

- Non-inductive startup desired for tokamaks
  - ST’s: Limited ohmic drive capability
  - Tokamak Reactor: Removing solenoid eases design

- Washer gun current sources installed in lower divertor region for DC helicity injection

- Injected current relaxes to ST-like plasma
  - \( I_p \leq 50 \text{ kA} \) driven by \( I_{\text{Inj}} \leq 4 \text{kA} \)
  - Consistent w/ helicity conservation

- Guns modify \( j(r) \): Allow access to \( I_p/I_{\text{TF}} > 2 \)
  - \( I_{\text{TF}} = \text{TF rod current} \)
  - \( I_N > 12 \text{ MA/m-T} \)
Conditions for Non-Inductive Formation of Tokamak Plasma

- Tokamak plasma formation must satisfy 3 constraints
  - Helicity conservation
  - Tokamak confinement scaling
  - Consistency with magnetic geometry and equilibrium

- Helicity and confinement requirements interconnected (next slide)
  - Both place requirements on source

- 3 magnetic constraints
  - Local field structure avoids current streams hitting other guns
  - PF weak enough to allow flux surface closure of plasma gun injected current
  - PF strong enough to maintain MHD equilibrium
Helicity Conservation, Confinement Properties Should be Self-Consistent

- Time derivative of helicity:\[1:\]
  \[ \dot{K}_{Tok} = -2 \int_V \mathbf{E} \cdot \mathbf{B} \, d^3x + 2V_{loop} \Phi_T - 2 \int_A V_{Inj} \mathbf{B} \cdot d\mathbf{a} \]
  
  - Resistive Dissipation
  - AC Injection
  - DC Injection

- Equating AC & DC source terms gives “Effective Loop Voltage”:\[2:\]
  \[ V_{eff} = V_{Inj} \frac{\Psi_{Inj}}{\Phi_T} \]

  - Injector Flux
  - Plasma Toroidal Flux
  - Bias Voltage

- Confinement scaling, helicity conservation should yield consistent \( I_p \)

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**PEGASUS is Mid-sized, Ultra-low A ST**

<table>
<thead>
<tr>
<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>
</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(t) (T-m)</td>
<td>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>κ</td>
<td>1.4–3.7</td>
<td>1.4–3.7</td>
</tr>
<tr>
<td>t_shot (s)</td>
<td>≤ 0.02</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>β_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>

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Current Injectors\(^4\) Inserted Above Lower Divertor, Biased Relative Vessel

- Gen1: 10 ms, 1-2 kA arc in gun

- Bias extracts e-, plasma into vessel along field lines

![Graph showing current and voltage over time](image)

\[^4\] Fiksel et al, Plasma Sources Science and Technology, 5(1), 1996
Gun Plasmas Exhibit 3 Distinct Phases: Relaxation to ST Observed at Low B

1. At low $I_{\text{inj}}$, high pitch angle & $B_V$, helical current filaments form

2. Filaments merge into cylindrical sheet as $I_{\text{inj}}$ increased, $B_V$ decreased

3. At low fields ($B_T \approx 0.01$ T, $B_V \approx 0.005$ T), relaxation to ST-like plasma
Relaxed Plasmas Exhibit Central Flux Reversal, Increased Current Drive & $\tau_{\text{decay}}$

- Flux-reversed plasma observed during low field injection
  - $> 4x$ flux reversal
  - Indicates separatrix formation

- $I_\phi$ increase $> 50\%$
  - Increased current drive efficiency
  - Max observed $I_\phi \approx 50$ kA

- $\tau_{\text{decay}}$ increase $> 400\%$
  - Decay w/o reversal $\approx 160 \mu s$
  - w/ reversal $> 700 \mu s$
  - Significant change in L/R
Relaxed Plasmas Exhibit Core Heating

- O-V (114 eV) to O-IV (77 eV) line ratio indicates increasing $T_e$

- SXR array indicates formation of hot core
  - SXR emission increases throughout shot
  - Emission peaks at midplane
  - Midplane signals decay more slowly than edge at shut-off

![Graph showing O-V/O-IV line ratio, SXR intensity at z=0, and SXR intensity for all chords.](image-url)
n=1 MHD Activity Observed During Current Drive

- CHI & Spheromaks: n =1 activity associated w/ current drive\(^5,6\)

- Line tied kink provides axisymmetric \(V_{\text{loop}}\)\(^7\)

- Mode strong during current ramp, attenuates at flattop

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Equilibria Reliably Reconstructed during Decay Phase

• $B_z$ consistent with radial force balance

• During current injection phase:
  - Vertically asymmetric
  - Significant difficulties in reconstruction
    - large open field-line currents
    - non-axisymmetric currents near gun
    - possible field line stochasticity

• After injector shut-off:
  - Vertically symmetric
  - Axisymmetric currents

\begin{align*}
\text{Gun} & \quad \begin{array}{c}
\text{During Bias} \\
\text{After Bias}
\end{array} \\
I_p (kA) & \quad 48.1 \quad 47.4 \\
I_i & \quad 0.21 \quad 0.19 \\
q_{99} & \quad 8.2 \quad 9.9 \\
R_{axis} (m) & \quad 0.36 \quad 0.31
\end{align*}


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Current Drive Consistent with Helicity Conservation within Factor of 2

- Use magnetic reconstruction of fiducial 50 kA shot #32606

- Effective loop volts: $V_{\text{eff}} = 0.7$ V
  - 0-D Confinement Scaling (ITER98PBY2): $V_{\text{eff}}$, $I_p$ consistent with $<T_e> \approx 55$ eV
    - Assumptions: parabolic profiles, 50% radiated power, $Z_{\text{eff}} = 2$
  - $<T_e>$ reasonable given increased O-V/O-IV, no burnout

<table>
<thead>
<tr>
<th>Helicity Injection Rate</th>
<th>Helicity Dissipation Rate</th>
</tr>
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<tbody>
<tr>
<td>$2V_{\text{Inj}}A_{\text{Inj}}B_n$</td>
<td>$4\pi I_p \eta_s R_0 B_0$</td>
</tr>
<tr>
<td>$1.8 \times 10^{-2}$ Wb$^2$s$^{-1}$</td>
<td>$1.0 \times 10^{-2}$ Wb$^2$s$^{-1}$</td>
</tr>
</tbody>
</table>

- Better plasma characterization required for more accurate comparison
Manipulation of j(r) by Plasma Guns Allows Access to High $I_p/I_{TF}$, $I_N$

- **Ohmic ops:**
  - $I_p/I_{TF} = 1$ ($I_N \approx 6$) “soft-limit
  - 2/1 tearing mode limiting
    - Minimal shear stabilization

- **Gun plasmas:** $I_p/I_{TF} \sim 2$ ($I_N \approx 12$)
  - No limiting MHD

- **Stability possibly due to edge j**
  - Hollow j(r)
  - Negative core shear

*Note: Reconstruction constrained by external magnetics only*
Plasma Guns Expand
PEGASUS Operating Space

- Present system: Significantly expands access to high $I_p/I_{TF}$ @ low $I_p$

- Future Plans: Upgrade gun array to access high $I_p/I_{TF}$, high $I_p$

![Graph showing plasma current and normalized plasma current](image)
Local Current Sources Provide DC Helicity for Startup of Tokamak Plasmas

- Non-inductive formation of ST demonstrated using plasma guns
  - $I_p \leq 50 \text{ kA}$ driven by $I_{\text{Inj}} \leq 4 \text{ kA}$
  - $B_T \approx .01 \text{ T}$

- Evidence of closed flux plasma formation:
  - Central flux reversal $\Rightarrow$ Formation of separatrix
  - $\tau_{\text{Plasma}}$ decoupled from $\tau_{\text{Gun}}$ $\Rightarrow$ Persistent $I_p$ after shutoff
  - Increased heating, formation of core $\Rightarrow$ better confinement
  - Strong $n=1$ mode correlated with current drive
  - Consistent with tokamak radial force balance

- Current drive consistent with helicity conservation within factor of 2
  - More detailed measurements needed

- Guns allow strong manipulation of $j(r)$
  - Significantly expands PEGASUS access to high $I_p/I_{TF}$ ($I_p/I_{TF}>2$, $I_N>12$)
Future Goal: 0.1-0.2 MA
Non-Solenoidal Startup

1. Larger gun array for access to high $I_p$
   - Divertor Array:
     - Implement local bias coil
   - Develop midplane gun system
     - Extrapolatable to fusion class devices
     - Compatible w/ PF field induction

2. $I_p \leq 50$ kA: Optimize prototype divertor gun pair
   - Install dedicated gun bias anode plate
     - Protect vessel, maintain impedance
   - Improve plasma characterization & expand operating space

3. Demonstrate handoff of non-inductive gun plasma to alternate current drive
   - Ohmic or RF
Outline

1. Conditions for non-inductive startup

2. Overview of PEGASUS experiment

3. Evidence for relaxation of gun plasmas into ST

4. Gun current drive roughly consistent with helicity conservation

5. Gun $j(r)$ manipulation allows access to $I_p/I_{TF} > 2$ ($I_N > 12$) discharges
   - Significantly expands PEGASUS operating space
**PEGASUS Studies ST Physics Limits as A → 1**

- 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 $A → 1$ ($A = R/a$)
  - Overlap between tokamaks and spheromaks

Both aided by non-inductive startup
Washer Gun Current Sources Provide Localized DC Helicity Injection

• Creation & maintenance of tokamak plasma by discrete electrodes demonstrated on CDX, CCT\textsuperscript{3}

• Advantages of washer guns as DC helicity injectors for PEGASUS
  - Low impurity content compared to conventional emissive electrodes
    - Impurity ions trapped in gun aperture
  - Easy to integrate w/ Pegasus hardware
  - Scalable

• Disadvantages
  - Small aperture per gun limits helicity injection rate
  - Independent control of multiple guns adds complexity

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Independent Measurements Indicate Formation of Relaxed, Closed Flux-surface Plasmas

- Increased current drive
- Reversal of poloidal flux at center column
- Increased plasma L/R decay time
- Core heating observed in VUV and SXR
- Appearance of n=1 MHD mode
- $B_v$ consistent with tokamak radial force balance