Non-Solenoidal Startup of the Ultra-Low Aspect Ratio PEGASUS ST

Presented by

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APS DPP 2007
Orlando, FL
November 12, 2007
PEGASUS non-inductive startup utilizes washer-gun current sources for DC helicity injection

**Motivation**

1. **Near-term:** Augment limited ST V-s
2. **Long-term:** Eliminate CS entirely

- **Advantages of washer-gun design:**
  1. Small
  2. Simple installation
  3. Clean: high Z impurities stay in aperture

- **Current filaments injected along B**
  - Guns biased relative anode plate
  - 1-2 kA per gun

- **Relaxation to tokamak-like plasma @ low B** ($B_T \approx 0.01, B_Z \approx 0.005T$)
  - Filaments overwhelm B, reconnect
  - Simulations indicate not true closed flux during electrostatic injection

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Conditions for non-inductive tokamak-like formation & sustainment via DC helicity injection

1. Magnetic constraints on formation
   - Low $B_Z$ to allow filament reconnection, “closed flux” formation
   - $B_Z$ consistent with MHD equilibrium

2. Helicity constraint on sustainment
   - Equating AC (inductive) & DC helicity injection terms:
     \[ V_{loop} \Psi_t = V_{inj} \Psi_{inj} \rightarrow V_{eff} = V_{inj} \frac{\Psi_{inj}}{\Psi_t} \]
   - $V_{eff}$ must be sufficient to sustain plasma against helicity dissipation
   - Assumes all injected helicity dissipated in plasma, not open field lines

3. Power constraint on sustainment (Helicity balance assumed)
   - Input power sufficient to sustain plasma at efficiency
     \[ \varepsilon = \frac{P_{dis}}{P_{inj}} = \frac{I_{\varphi}}{I_{inj}} \frac{V_{eff}}{V_{inj}} = \frac{\Psi_{inj}}{\Psi_t} \frac{I_{\varphi}}{I_{inj}} \]
Relaxation significantly enhances non-inductive current drive capability

- $I_\phi > 50 \text{ kA}$ driven by $I_{\text{inj}} \leq 4 \text{ kA}$

- **Center column flux reversal $\Rightarrow$ relaxation**
  - Indicates filaments have overwhelmed $B_Z$

- **Current multiplication ($I_\phi/I_{\text{inj}}$) > geometric**
  - Not constrained by vacuum windup

- $\tau_{\text{plasma}}, \tau_{\text{gun}}$ decoupled
  - $I_\phi > 40 \text{ kA}$ after $I_{\text{inj}} = 0$
  - Relaxed $I_\phi$ not “windup” current
Maximum current drive limited by helicity injection rate

- Max $I_\phi$ offset linear to injected $dK/dt$

- $dK/dt$ limiting $I_\phi$?
  - Compare $V_{\text{eff}}$ & decay $V_{\text{loop}}$

- Decay $V_{\text{loop}}$ estimated by $V_{\text{surf}}$
  - Center column limited plasmas
  - Measured by center column flux loop

- $V_{\text{eff}} \approx V_{\text{surf}}$ indicates:
  1. Current drive limit due to $dK/dt$ limit
  2. Helicity efficiently transported into plasma
    - Primarily available for current drive, not dissipated on open field lines

\[ \text{Toroidal Current [kA]} \]
\[ \text{Average } (dK/dt)_{\text{inj}}/I_{TF} \text{ [Wb}^2\text{s}^{-1}\text{A}^{-1}] \]

\[ \text{Selected for } V_{\text{eff}} \text{ study} \]

\[ \text{--- } V_{\text{eff}} = V_{\text{surf}} \]
Plasma gun current drive expands PEGASUS operating space to $I_N > 12$ MA/m-T

- **Ohmic ops: $I_N \approx 6$ “soft-limit”**
  - Low order tearing modes limiting
  - Minimal shear stabilization
  - $I_N > 6$ achieved transiently

- **Gun ops: $I_\phi/I_{TF} > 2$ ($I_N > 12$)**
  - Edge current drive may enable increased $q_0$, shear stabilization,
  - *External magnetics only - profile not constrained*

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Midplane gun geometry scales to larger experiments

- **Prototype midplane gun tested on PEGASUS**
  - Transferable to any machine w/ midplane port access

- **Successfully formed relaxed plasmas**
  - \( I_{\text{inj}} = 0.75 \text{ kA} \Rightarrow I_\phi > 20 \text{ kA} \)
  - High windup not necessary: 2-3 transits max

![Graph of Toroidal Current vs. Injected Current over time](image-url)

### Graph Details
- **Toroidal Current**
- **Injected Current**
- **Time [ms]**: 20 to 32
- **kA**: 0 to 25
- **gun off** indicator
- **gun/collector assembly** markers
- **collector anode**
- **gun cathode**
- **3 transits = flux closure**

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Relaxed midplane target plasma handed off to PF-only and OH induction

**PF induction only:**
- Outboard PF coils only:
  - $V_{\text{loop}} \propto dB_Z/dt$
- Before gun shut-off: $I_p \uparrow 50$
- After shut-off, necessary $V_{\text{loop}}$ ($B_Z$) not compatible w/ force balance
  - Plasma driven into core
- More robust target required

**OH induction:**
- Additional $V_{\text{loop}}$ w/o strong radial force
- Steady growth if $V_{\text{loop}}$ after shutoff
  - Possibly indicates transition from tokamak-like to true tokamak after guns shut-off
  - Plasma compresses radially, but slowly
Pegasus is poised to pursue high-power non-solenoidal discharges

Summary

• Plasma gun DC helicity injection is effective startup technique
• Current drive limited by helicity injection rate
• Plasma gun startup enables high $I_N$ operation
• Midplane array shows promise for startup on any device w/ midplane port access
  • Readily coupled to OH induction

Future Work

• 3-gun midplane array installation underway
  • Improved power supplies ⇒ more helicity injection
  • Should provide > 100 kA relaxed plasma w/ static PF
  • Initial operation 12/07
Related Posters

**Tuesday Morning**

- GP8.00134  Nonlinear MHD simulation of DC helicity injection in spherical tokamaks - R.A. Bayliss

**Thursday Morning**

- TP8.00108  Overview of the PEGASUS Experimental Program - A.C. Sontag
- TP8.00109  Operations at High $I_N$ in the PEGASUS Toroidal Experiment - E.A. Unterberg
- TP8.00110  Non-solenoidal startup of PEGASUS plasmas using DC helicity injection and poloidal field induction - B.J. Squires
- TP8.00111  Global energy confinement studies on the PEGASUS Toroidal Experiment - D.J. Battaglia
- TP8.00112  Initial Edge Stability Observations in the PEGASUS Toroidal Experiment - M.W. Bongard
- TP8.00113  An Upgraded Soft X-ray Pinhole Camera for Current Profile Measurements on the PEGASUS Toroidal Experiment - M.B. McGarry