Abstract

Developing a non-inductive startup technique is important for the ultralow-A Pegasus ST experiment, and the ST concept in general. Two low impurity, high I (~1 kA) plasma guns have been installed in the lower divertor region of Pegasus to test toroidal current drive via DC helicity injection during plasma startup. Aided by a high magnetic stacking factor, the dual gun array provides a toroidal current of 15-20 kA. A transition from discrete helical current streams to a uniform reconnected plasma is observed, with a doubling of the net toroidal current. Relaxation to a tokamak-like plasma state was not observed at this low current, but is expected as the net current is raised to provide a poloidal field greater than the vacuum vertical field. Experimental attempts to attain a relaxed tokamak-like configuration are concentrating on optimizing a 2-3 gun assembly at very low field strengths. Design requirements are presented for a 12 gun array to be installed in Pegasus next year, which is projected to provide Ip > 0.1 MA.

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Motivation for Non-Inductive Startup

• ST requires non-ohmic startup & current sustainment
  · Small center-column minimizes solenoidal induction in future experiments
  · ST startup & current drive may also apply to conventional tokamak geometries

• Non-ohmic startup greatly expands PEGASUS capability
  · Enhance ohmic V-s utilization via gun-to-ohmic hand off
  · Enable low-TF startup scenarios
3 Stages of Tokamak-like Discharge Formation

1. Initial Injection
   - Simple geometric stacking
   - Current filaments follow field lines

2. Filament Reconnection
   - Uniform shell plasma formation
   - Dynamically determined max $I_\psi$

3. Relaxation to tokamak-like state

Present Study

Future Goal
Outline

1. Desire > 0.1 MA non-ohmic tokamak target plasma
   - Requirements specified for forming non-ohmic tokamak:
     1) Helicity conservation
     2) Consistency with power scaling laws
     3) Magnetic equilibrium

2. Plasma guns provide good source for DC helicity injection
   - Low impurity injection
   - Integrate easily with current hardware

3. Initial experiments with 2 guns
   - Max $I_\phi \sim 16$ kA
   - In reconnected plasmas, $I_\phi / I_{Gun} \geq$ geometric stacking factor
   - Developed active feedback control of $I_{Gun}$
   - Max $I_\phi$ in reconnected plasmas correlates with helicity injection rate & power
   - Low $B_V$ flux closure may require $V_{Bias} >$ currently available 900V

4. Expanded 12 gun array predicted to provide > 0.1 MA $I_p$
   - Dramatically increased helicity & power input
   - Expected implementation in Fall 2006
Conditions for Non-inductive Formation of Tokamak Plasma

• Tokamak plasma formation must satisfy 3 constraints:
  1) Helicity conservation
  2) Power scaling laws
  3) Consistency with magnetic geometry & equilibrium

• Helicity and power requirements interconnected (see next)
  • Both place requirements on non-inductive source

• 3 magnetic constraints:
  1) Local field structure to match multi-gun geometry
  2) EF weak enough for flux surface closure of plasma gun injected current:

\[ B_{pol} > B_{Vac} \]
  3) EF strong enough to maintain MHD equilibrium
Helicity Conservation

- Helicity measures flux linkededness of a volume:

\[ K = \int \mathbf{A} \cdot \mathbf{B} \ dV \]

- Helicity conservation states\(^2\)

\[ \dot{K} = 2V\dot{\Psi} - 2\int \mathbf{E} \cdot \mathbf{B} \ dV - 2\int \Phi \mathbf{B} \cdot \mathbf{d}a \]

- For steady state DC helicity injection, reduces to\(^3\)

\[ I_p = V_{Bias} A_{Inj} / 2\pi RB_\phi \]  
[Eq. 1]

Helicity & Power Interconnection

- Eq. 1 above allows effective loop voltage to be defined:

\[ V_{\text{eff}} = V_{\text{Bias}} \frac{\Psi_{\text{INJ}}}{\Phi_0} = V_{\text{Bias}} \frac{A_{\text{Inj}} B_{\text{Inj}}}{\pi a^2 \kappa B_0} \]

\[ = V_{\text{Bias}} \frac{N_{\text{Inj}} A_{\text{Inj}} R_0}{\pi a^2 \kappa R_{\text{Inj}}} \]

- Power scaling laws give self-consistent \( I_p \):

\[ I_p , V_{\text{eff}} \]

\[ \eta \]

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N.W. Eidietis, APS-DPP, Denver, CO, October 2005
Plasma Gun as Helicity Injection Source

• Creation & maintenance of tokamak plasma by electron beam DC helicity injection demonstrated on CDX$^5$

• Plasma guns are good DC helicity plasma source for PEGASUS
  • Low impurity content compared to conventional emissive electrodes$^6$
    - Impurity ions trapped in gun aperture
  • Easy to integrate with current PEGASUS systems and hardware
  • Scalable
  • Robust

• However, there are disadvantages
  • Small aperture area per gun
  • Independent control of multiple guns adds complexity

Plasma Gun Design

- High current, low impurity design by Fiksel et al.\(^1\)
  - Up to 1 kA extracted current
  - \(T_e \sim 10-20\) eV
  - \(n_e \sim (1-3) \times 10^{20}\) m\(^{-3}\)

- SS armor added to allow reentrant insertion into vessel

- Placed above lower divertor
  - \(R_0 \approx 27\) cm
  - 180° apart

\(^1\) N.W. Eidietis, APS-DPP, Denver, CO, October 2005
Typical Plasma Gun Discharge

- PFN forms arc discharge within gun
- Current extracted by vessel-anode $V_{\text{Bias}}$

![](image)

- Extracted current initially follows magnetic field lines

$\tau_{\text{Pulse}} \approx 10 \text{ ms}$

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Anatomy of a Plasma Gun Discharge

- Max observed $I_\phi \approx 16$ kA

- Plasma gun current multiplication $\sim 15$-20 routinely achieved

- Toroidal current evolution displays two distinct phases:
  1) Simple stacking of current stream due to magnetic geometry
  2) Increased multiplication as current streams reconnect

![Graph showing toroidal current, extracted gun bias current, current multiplication factor, discrete filaments, gun shutoff, and reconnection over time.](image-url)
Visual Comparison of Standard and Reconnecting Discharges

100V Bias... No Reconnection

400V Bias... Reconnection

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Active Control Developed to Match Evolving Plasma

- High $V_{Bias}$ operation highly desirable
  1) Maximizing gun helicity & power input $\Rightarrow$ increasing $V_{Bias}$

$$P = VI$$
$$dK/dt = -2V\Psi$$

2) Integration with available 900V coil supplies
3) Exploration of helicity/power scaling of gun-driven toroidal current

- Caution required: $I_{Bias}$ cannot safely exceed gun arc current
  - Overbiasing causes electrode damage & vessel contamination

- Extracted current is nonlinear function of voltage
  - Linear/Nonlinear threshold occurs well before 100% current extraction
  - Linear/Nonlinear threshold is a function of:
    1) Bias voltage
    2) Current stream path length (determined by magnetic geometry)
    3) Plasma resistance (determined by gassing, temperature)

- These variables are not static in PEGASUS environment:
  Safe operation requires active bias current control

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Actively Controlled Bias Power Supply

- Bias current control via active current feedback
  - PWM controls 2-quad IGBT H-bridge
  - 5 kHz LC filter smooths 27 kHz switching

- Runaway bias current controlled, avoiding gun damage

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I_\phi Scales with dK/dt, Power

- Empirical I_\phi scaling desired to aid multi-gun array design

- Tests undertaken to determine primary factors controlling I_\phi
  - Data includes 1 & 2 gun tests @ 400, 650, & 900 V_{Bias}; 0.053, 0.10, 0.18 T B_\phi & numerous gas programs

- I_\phi correlates to average injected dK/dt & power
Flexible Coil Systems Enable Low $B_V$ Flux Closure Experiments

- Initial gun experiments utilized simple magnetic configuration
  - Fairly uniform $B_z$, magnitude set to avoid current stream hitting opposite gun

- Flux closure experiments require more complex fields
  - Strong $B_V$ at gun to avoid hitting opposite gun
  - Minimal midplane $B_V$ to facilitate flux closure

- Coil systems reconfigured to facilitate flux closure
  - Divertor, PF1,8 shaping coils provide strong local & low midplane $B_V$

![Basic Configuration](image1)

![Low Midplane $B_V$ Configuration](image2)

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Initial Attempts for Flux Closure via Low $B_V$ Scenario

- For 8 kA single gun $I_\phi$, $B_{pol}$ elliptical estimate is:

$$B_{pol} = \frac{\mu_0 I_\phi}{2 \pi a \sqrt{1 + \kappa^2}} \kappa = \frac{b}{a}$$

$a \sim 0.2\text{m}, \ k \sim 4 \Rightarrow B_{pol} \sim 0.0025\text{T}$

- Coil reconfiguration $\Rightarrow$ opportunity for flux closure
  - Midplane $B_V \leq 0.001\text{T}$

- Data displays signs of impedance mismatch with 900 V bias system
  - Low extracted current: $I_{\text{Gun}} \leq 200\text{A}$
  - $I_\phi \leq 3\text{kA}$

- Flux closure with current gun array may require reconfiguration to $V_{\text{Bias}} > 900\text{V}$

- Active research ongoing
Design of Expanded Plasma Gun Array

- Expected 6x power & 12x helicity gain
- 12 apertures on 6 gun stalks
  - Double aperture guns require fabrication
- Full insertion to R ~ 15 cm
  - Gives ~ 2x gain in $B_\Phi$, helicity
  - Requires raising lower divertor plate
- Radial port insertion
  - Allows easy adjustment of radius & angle
  - Requires drilling new ports in PEGASUS vessel

Maximum Capability @ $V_{Bias} = 900$V:

- Power $= 10.8$ MW
- Energy $= 108$ kJ
- $dK / dT = 4.5$ Wb$^2$s$^{-1}$
- $K = .045$ Wb$^2$
First Order Model
Scenario for Achieving $> 0.1$ MA $I_p$

- **Magnetics:**
  - Utilizes divertor for strong $B_v$ local to gun, weak midplane
  - Estimated $I_\phi$: $1kA \times 12 \times 20 = 240$ kA

- **Flux Closure:**
  - Use elliptical model to estimate $B_{pol}$:
    
    $a \sim 0.2m$, $k \sim 4 \Rightarrow B_{pol} \sim 0.08$ T $>$ $B_v \sim 0.025$T

- **Equilibrium:**
  - $B_v$ compatible with $0.1$MA plasma @ $R=0.45$ m

- **Helicity/Power Conservation:**
  - Self-consistent solution found to helicity & 1-D power balance model
  - $0.1$-$0.3$ MA $I_p$ sustainable, depending on chosen $<N_e>$ $(1-6 \times 10^{19}$ m$^{-3}$)
Conclusions

1. Evaluated constraints governing non-ohmic startup
   1) Helicity conservation
   2) Consistency with power scaling laws
   3) Magnetic consistency

2. Plasma guns candidate for DC helicity injection source for non-ohmic startup
   · Low impurity injection
   · Integrate easily with current hardware
   · Robust
   · Scalable

3. Initial 2 gun experiments provided valuable data
   · In reconnected plasmas, $I_\phi / I_{Gun} \geq$ geometric stacking factor
   · Developed active feedback control of $I_{Gun}$
   · Max $I_\phi$ in reconnected plasmas correlates with helicity injection rate & power
   · Low $B_V$ flux closure may require $V_{Bias} >$ currently available 900V

4. 12 gun array shows great promise for providing $> 0.1$MA Ip
   · First order models confirm the viability of this design
Future Work

1. Continue low $B_y$ flux closure experiments with 2 gun array

2. Construct & implement 12 gun array
   - Completion projected for Fall 2006

3. Characterize & Optimize gun-driven $I_p$

4. Perfect Gun-OH hand-off to extend PEGASUS capability

5. Explore PF induction for increased non-ohmic drive