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.

[1] G. Fiksel, A.F. Almagri, D. Craig, M. Lida, S.C. Prager, J.S. Sarff, Plasma Sources Sci. Technol. **5**, 78 (1996).
* Supported by U.S. D.O.E. Grant DE-FG02-96ER54375
** The research was performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.

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_ϕ

→ Present Study

3. Relaxation to tokamak-like state → 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_ϕ 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 linkedness of a volume:

$$K = \int \mathbf{A} \cdot \mathbf{B}\, dV$$

- Helicity conservation states[2]

$$\dot{K} = 2V\Psi - 2\int \mathbf{E} \cdot \mathbf{B}\, dV - 2\int \Phi \mathbf{B} \cdot \mathrm{d}\mathbf{a}$$

Induction & AC injection

Resistive Dissipation

DC Injection

- For *steady state* DC helicity injection, reduces to[3]

$$I_p = V_{Bias} A_{Inj} / 2\pi R B_\phi \qquad \text{[Eq. 1]}$$

[2] *Boozer, A.H., Phys. Fluids,* ***29****,12 (1986)*
[3] *Darrow, D.S. et al., Phys. Fluids B,* ***2****, 6 (1990)*

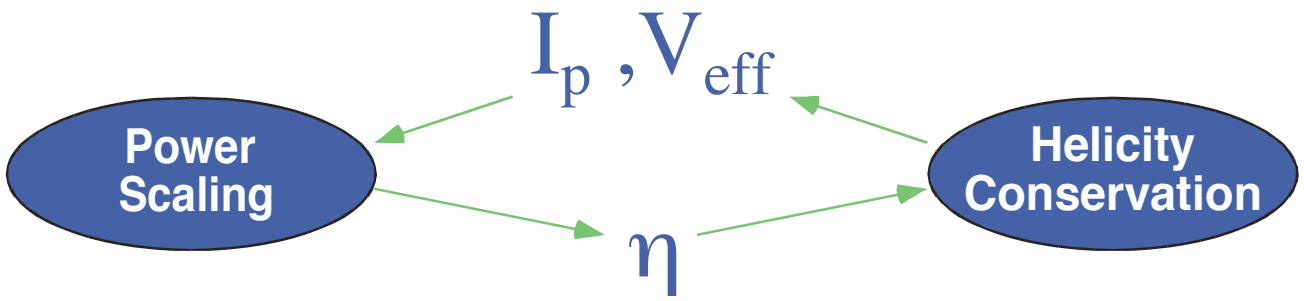
Helicity & Power Interconnection

- Eq. 1 above allows effective loop voltage to be defined[4]:

$$V_{eff} = V_{Bias}\frac{\Psi_{INJ}}{\Phi_{\phi}} = V_{Bias}\frac{A_{Inj}B_{Inj}}{\pi a^2 \kappa B_0}$$

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

- Power scaling laws give self-consistent I_p:



[4] *Nelson, B.A.Phys. Rev. Let. , **72**(23):3666 - 9, 1994*

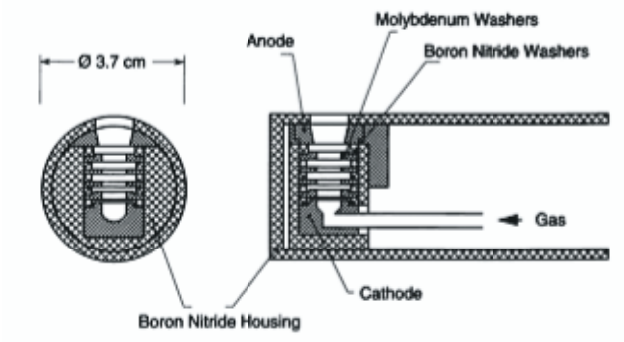
Plasma Gun as Helicity Injection Source

- 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

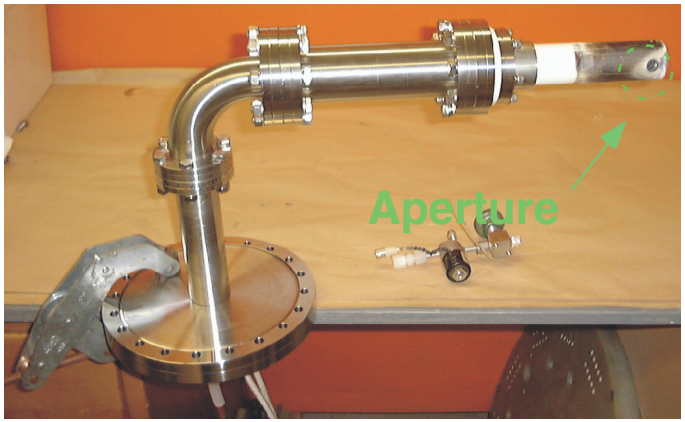
[5] *Ono, M., Greene, G.J., Darrow, D., Forest, C., Park, H. Stix, T.H., Phys. Rev. Lett.*, ***59****, 19 (1987).*
[6] D.J. Den Hartog, D.J. Craig, G. Fiksel, and J.S. Sarff. ,*Plasma Sources Science and Technology*, **6**(4):492 – 498, 1997

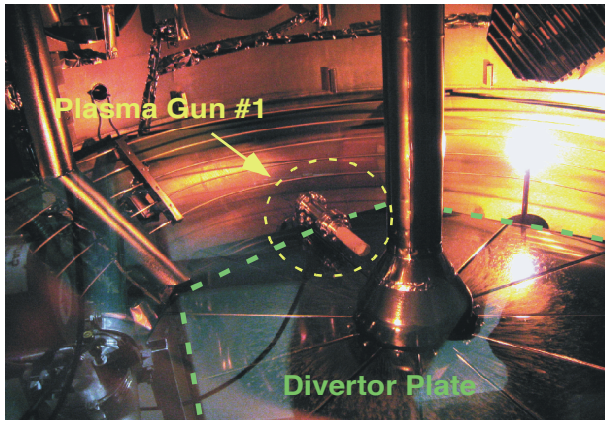
Plasma Gun Design

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



- SS armor added to allow reentrant insertion into vessel

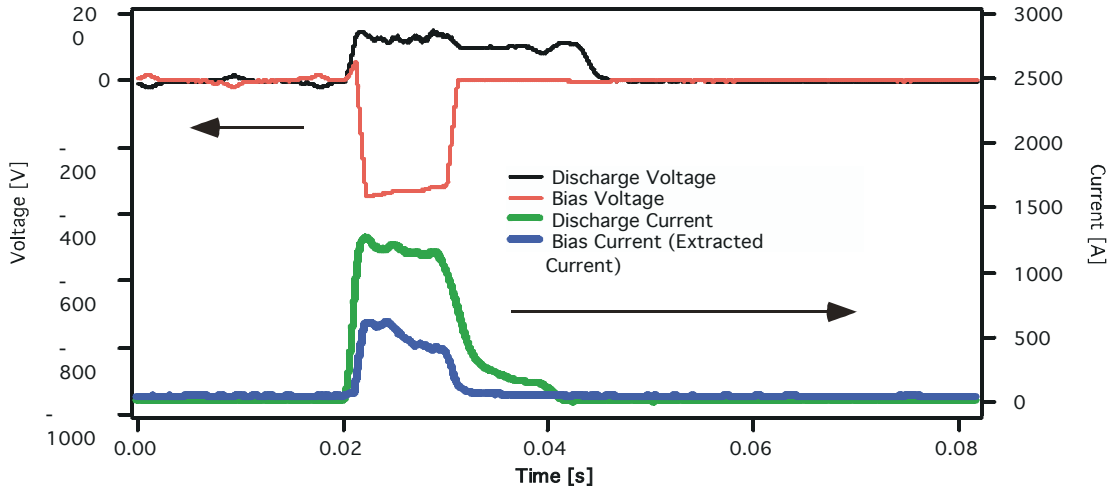




- Placed above lower divertor
  - $R_0 \approx 27$ cm
  - 180° apart

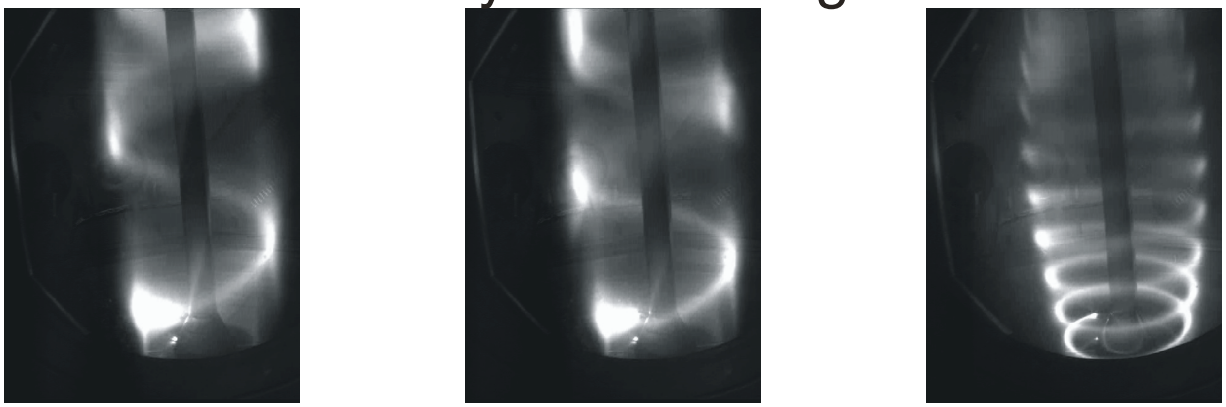
Typical Plasma Gun Discharge

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



$\tau_{Pulse} \approx 10$ ms

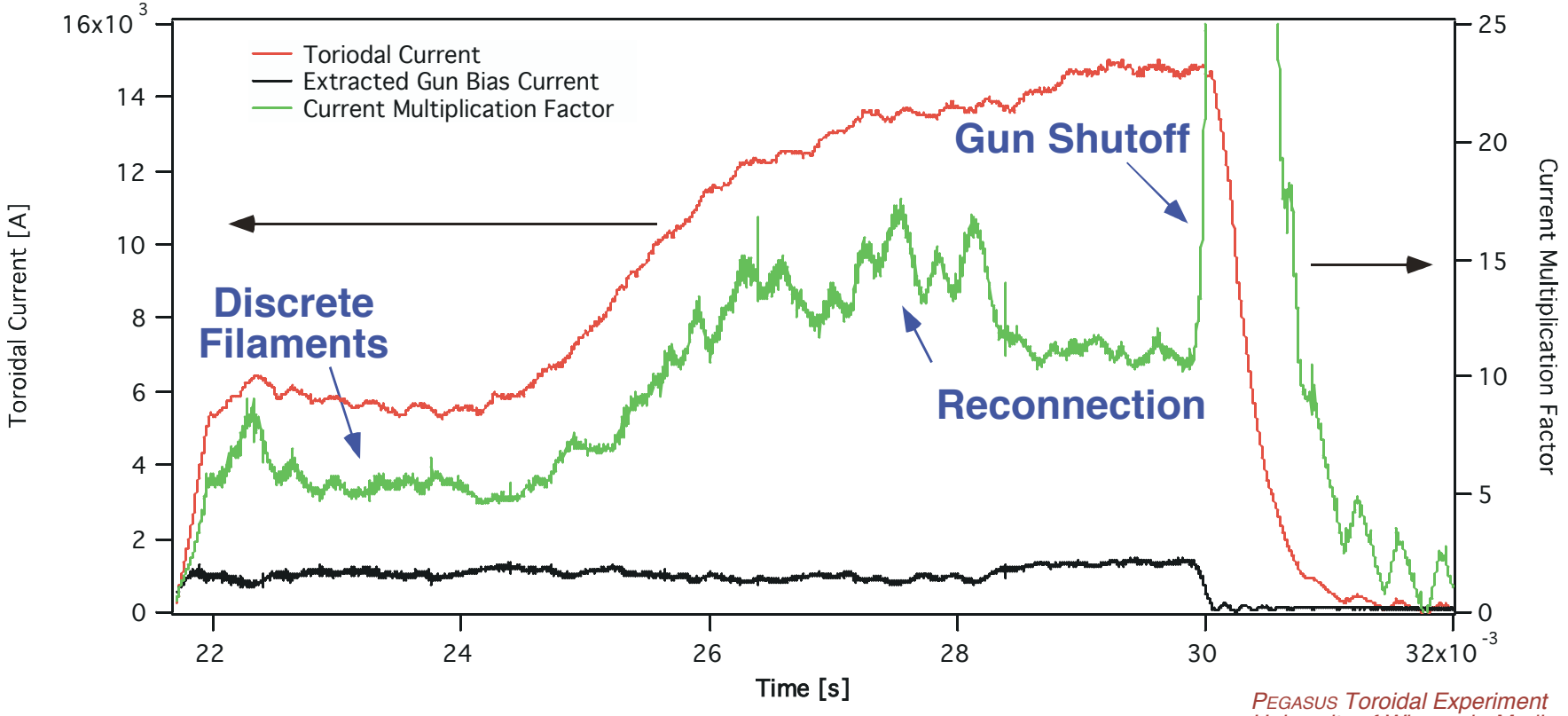
- Extracted current initially follows magnetic field lines



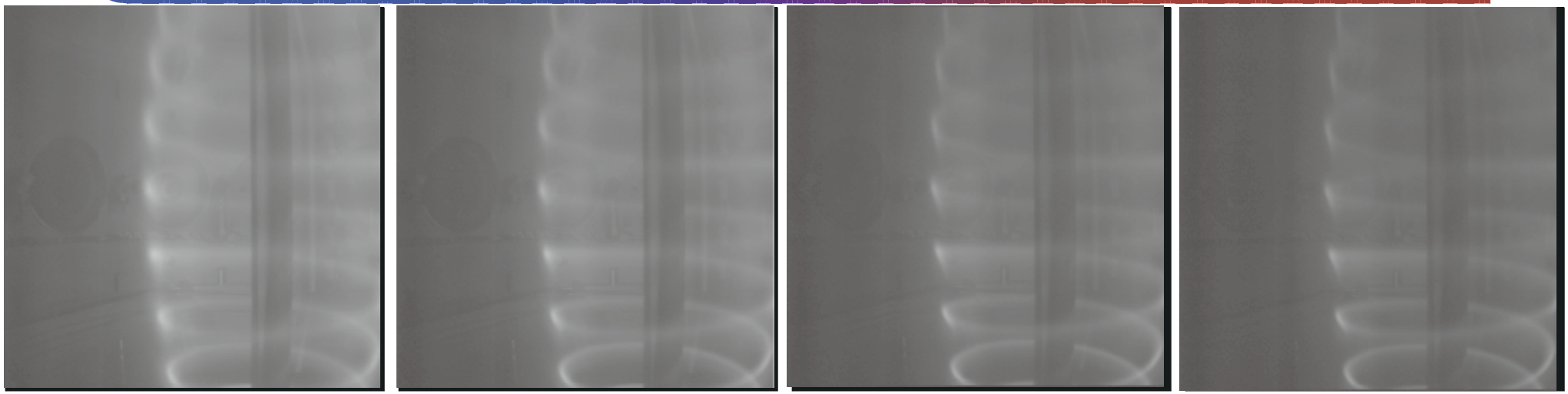
Decreasing Field Pitch

Anatomy of a Plasma Gun Discharge

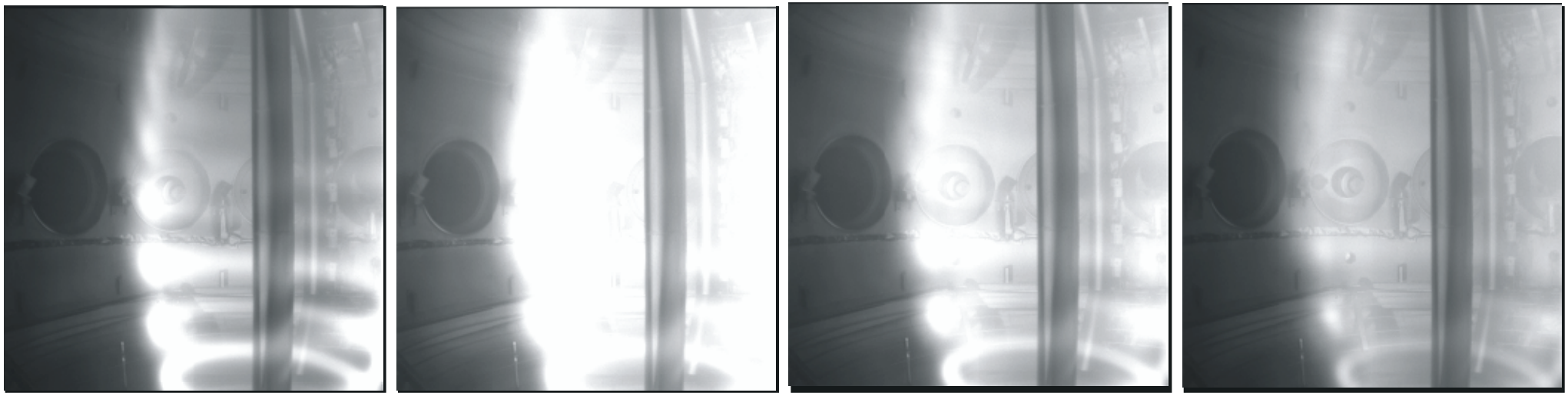
- Max observed $I_\phi \approx 16$ kA
- Plasma gun current multiplication ~ 15-20 routinely achieved
- Toroidal current evolution displays two distinct phases:
  1) Simple stacking of current stream due to magnetic geometry
  2) Increased multiplication as current streams reconnect



Visual Comparison of Standard and Reconnecting Discharges



100V Bias. . . No Reconnection



400V Bias. . . Reconnection

Active Control Developed to Match Evolving Plasma

- High V_{Bias} operation highly desirable
  1) Maximizing gun helicity & power input ⇒ 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

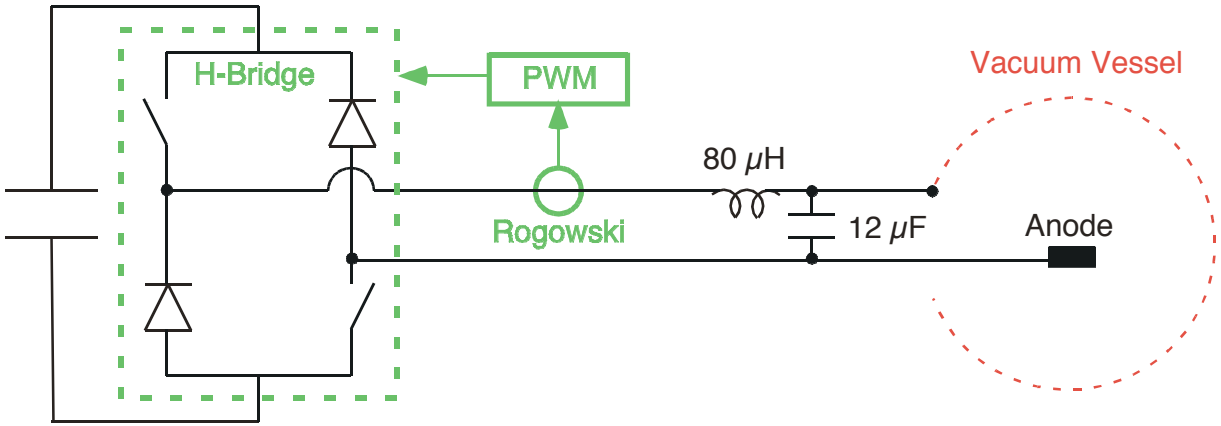
- Caution required: I_{Bias} cannot safely exceed gun arc current
  - Overbiasing causes electrode damage & vessel contamination

- 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)

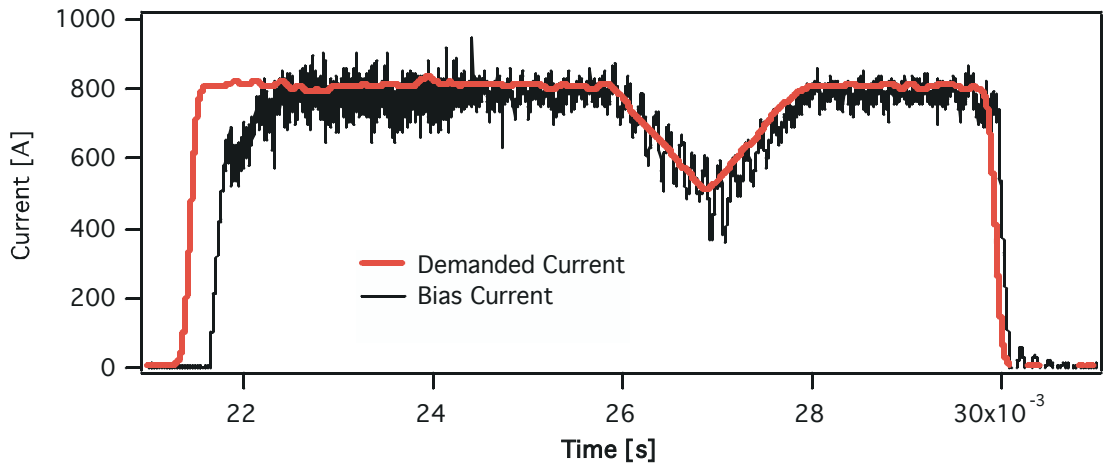
- These variables are not static in PEGASUS environment:
  Safe operation requires active bias current control

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

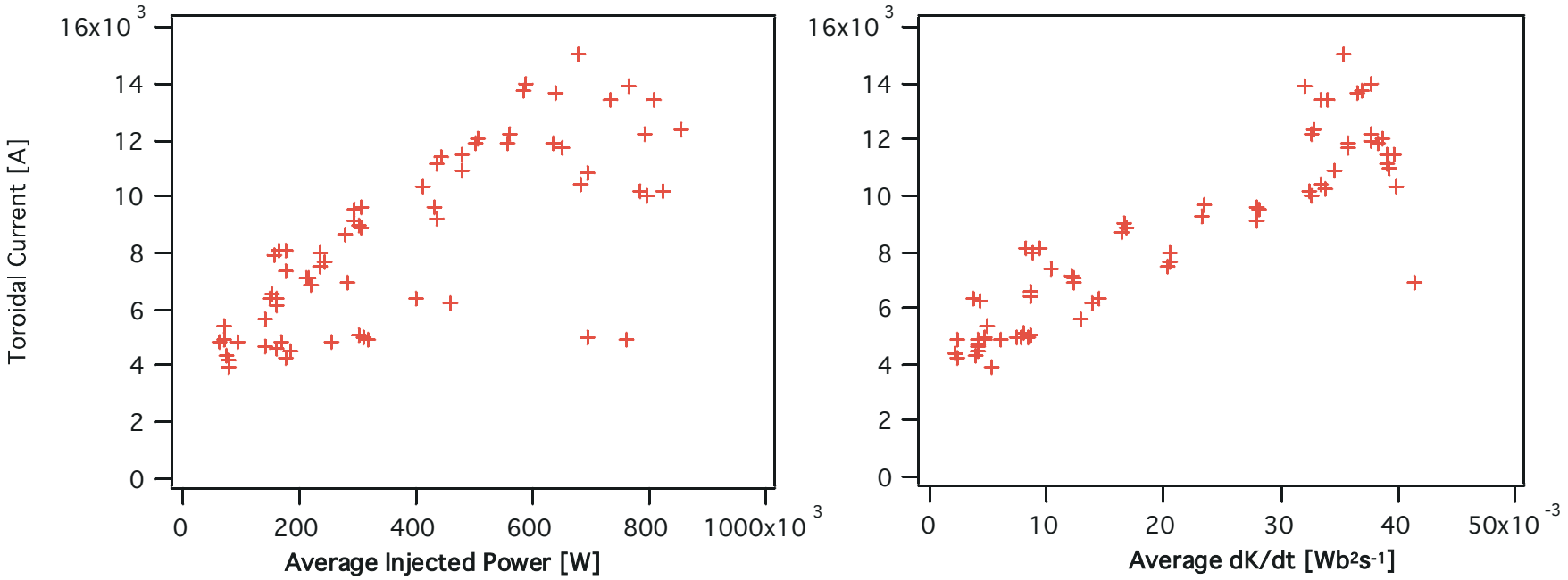


- Runaway bias current controlled, avoiding gun damage



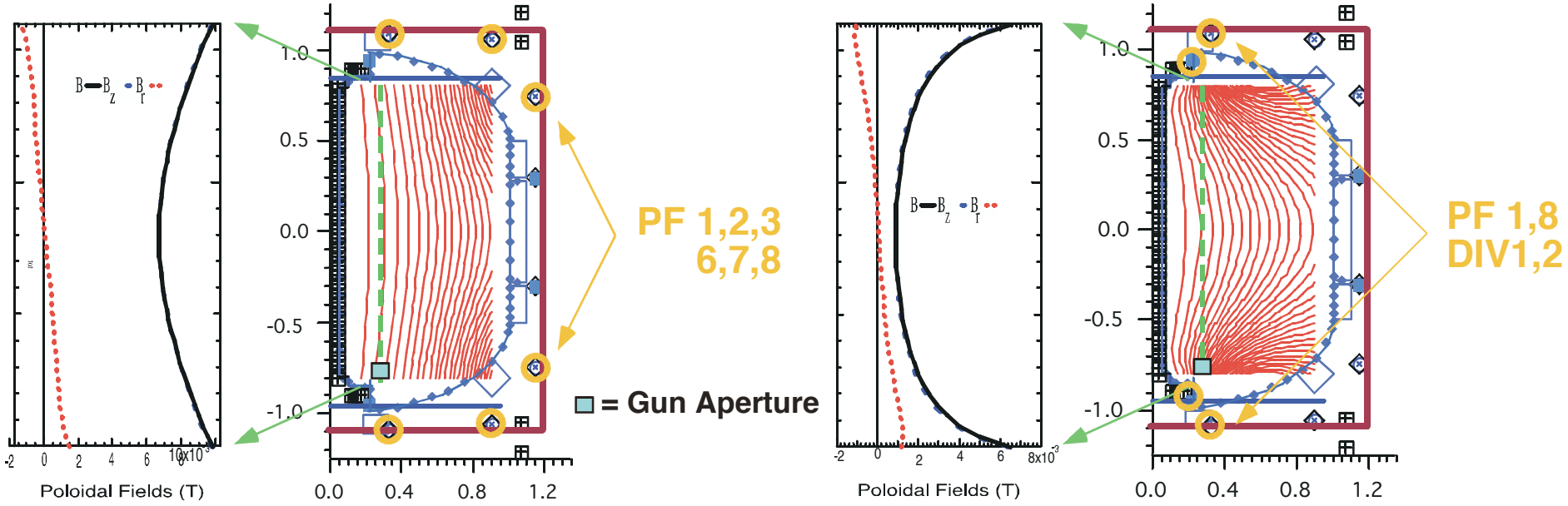
I_ϕ Scales with dK/dt, Power

- Empirical I_ϕ scaling desired to aid multi-gun array design
- Tests undertaken to determine primary factors controlling I_ϕ
  - Data includes 1 & 2 gun tests @ 400, 650, & 900 V_{Bias} ; 0.053, 0.10, 0.18 T B_ϕ & numerous gas programs
- I_ϕ 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

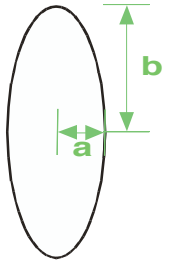


Basic Configuration **Low Midplane B_V Configuration**

Initial Attempts for Flux Closure via Low B_V Scenario

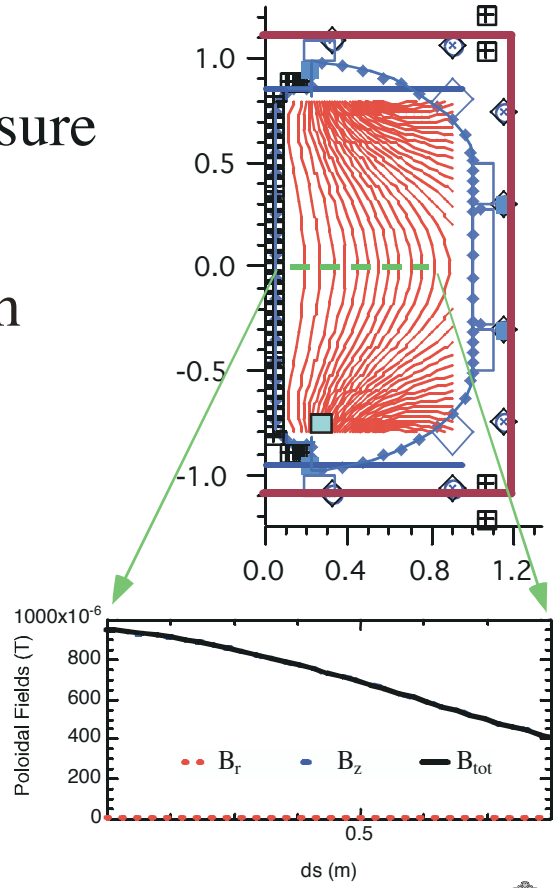
- For 8 kA single gun I_ϕ, B_{pol} elliptical estimate is:

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



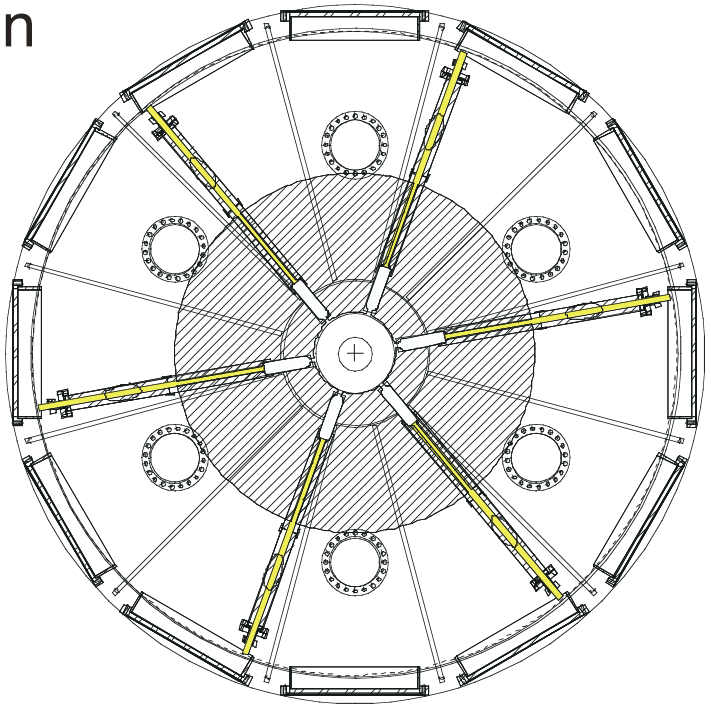
a ~ .2m, k ~ 4 ⇒ Bpol ~ 0.0025 T

- Coil reconfiguration ⇒ opportunity for flux closure
  - Midplane $B_V \leq 0.001$ T
- Data displays signs of impedance mismatch with 900 V bias system
  - Low extracted current: $I_{Gun} \leq 200$ A
  - $I_\phi \leq 3$ kA
- Flux closure with current gun array may require reconfiguration to $V_{Bias} > 900$ V
- Active research ongoing

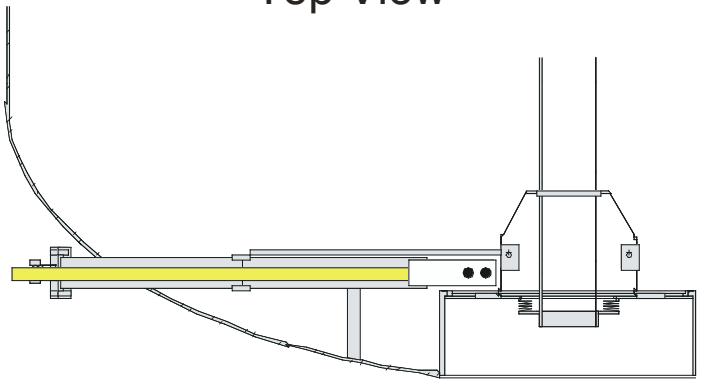


Design of Expanded Plasma Gun Array

- 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_ϕ, helicity
  - Requires raising lower divertor plate
- Radial port insertion
  - Allows easy adjustment of radius & angle
  - Requires drilling new ports in PEGASUS vessel



Top View



Side View

Maximum Capability @ V_{Bias} = 900V:

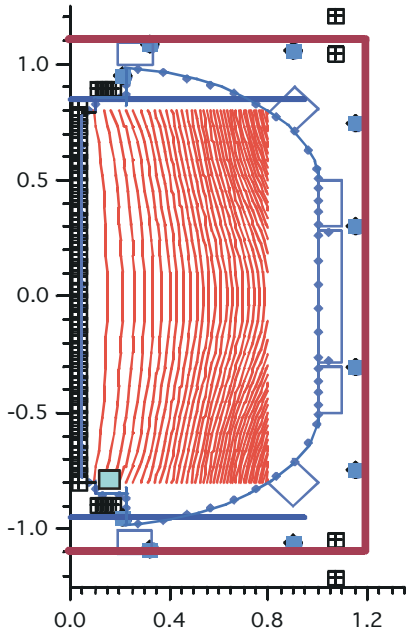
Power = 10.8 MW
Energy = 108 kJ
dK / dT = 4.5 Wb^2s^{-1}
K = .045 Wb^2

First Order Model
Scenario for Achieving > 0.1 MA Ip

- Magnetics:
  - Utilizes divertor for strong B_v local to gun, weak midplane
  - Estimated I_ϕ : 1kA * 12 * 20 = 240 kA

    # Guns

    Max Observed Multiplication



- Flux Closure:
  - Use elliptical model to estimate B_{pol}:

    $a \sim .2m, k \sim 4 \Rightarrow Bpol \sim 0.08\ T > Bv \sim 0.025T$

- Equlibrium:
  - B_v compatible with 0.1MA 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 $\langle N_e \rangle$ (1-6 x 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_ϕ / $I_{Gun} \geq$ geometric stacking factor
   - Developed active feedback control of I_{Gun}
   - Max I_ϕ 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 > 0.1MA Ip
   - First order models confirm the viability of this design

Future Work

1. Continue low B_V 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