Abstract

Developing non-inductive startup and efficient fueling techniques is important for the ultralow-A PEGASUS ST experiment, and the ST concept in general. Two low impurity, high I (~1 kA) plasma guns[1] have been installed in the divertor region of Pegasus to test auxiliary plasma injection and toroidal current drive during plasma startup. This is effectively a form of helicity injection. Direct plasma fueling reduces ionization losses during startup, and combined with a current multiplication factor of ~15-25, the guns provide a significant target Ip (~ 10 kA) at the beginning of an ohmic discharge. This significantly eases Pegasus plasma startup, allows access to a much wider range of plasma currents and shapes than current volt-second limitations allow, and provides critical tests for a future multiple-gun array. Experimental results from single gun and double gun tests are reported, as well as preliminary results from EF induction startup tests.

1. G. Fiksel, A.F. Almagri, D. Craig, M. Lida, S.C. Prager, J.S. Sarff, Plasma Sources Sci. Technol. **5**, 78 (1996).

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Motivation

- Non-inductive current drive source for ST plasma initiation
  - Multiple gun array could create significant target plasma before any other current drive utilized

- Plasma guns immediately aid PEGASUS plasma operations
  - Enhance ohmic V-s utilization via gun-to-ohmic hand off
  - Eliminate need to establish null field at startup

Outline

1. Pegasus Plasma Gun Experiment
2. Single Plasma Gun Results
3. Double Plasma Gun Results
4. Plasma Guns to Ohmic Handoff
5. Non-ohmic startup via EF Induction
6. Summary
7. Future Work

Plasma Gun as Helicity Injection Source

- For DC helicity injection in *steady state*, the helicity evolution equation can be reduced to[2]

$$I_p = V_{cath} A_{cath} B_{cath} / 2\pi R \overline{\eta} B_T$$

This suggests plasma gun driven Ip should scale with:

1) Bias voltage applied between gun and vessel
2) Plasma gun aperture area (or # of guns)
3) Alignment with vacuum field

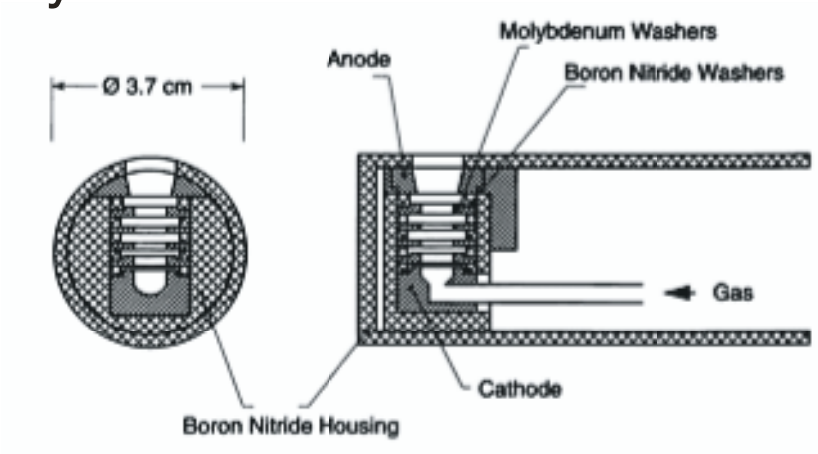
- Creation & maintenance of tokamak plasma by electron beam DC helicity injection demonstrated on CDX[3]

- Plasma guns are an ideal source for PEGASUS
  - Low impurity content compared to other current sources
  - Easy to integrate with current Pegasus systems and hardware

2. Darrow, D.S. et al., Phys. Fluids B, 2, 6 (1990)
3. Ono, M., Greene, G.J., Darrow, D., Forest, C., Park, H. Stix, T.H., Phys. Rev. Lett., 59, 19 (1987).

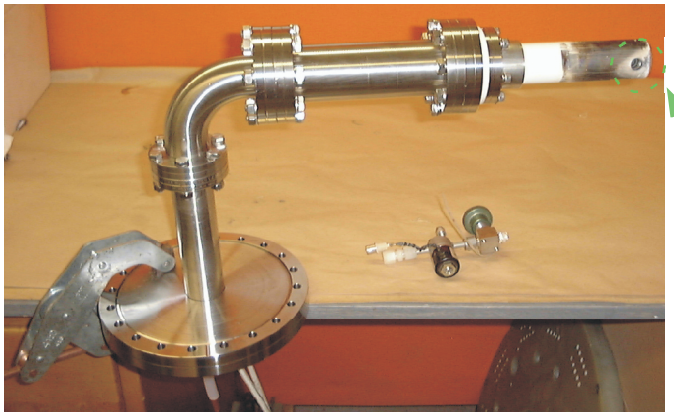
Plasma Gun Design

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



Schematic diagram of the plasma current injector[1]

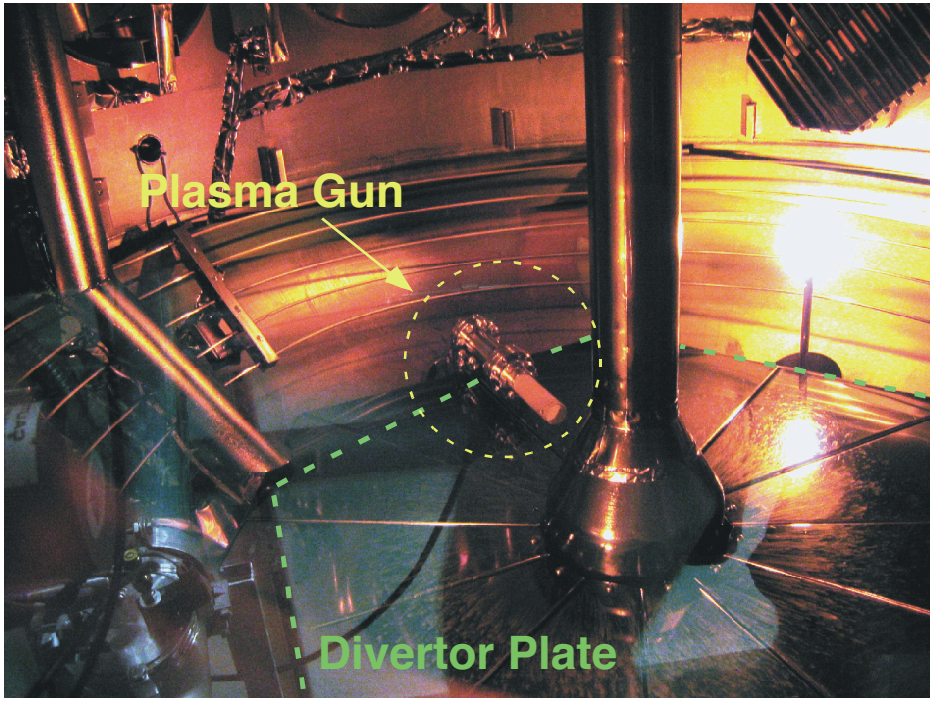
- SS armor added to allow reentrant insertion into PEGASUS vessel

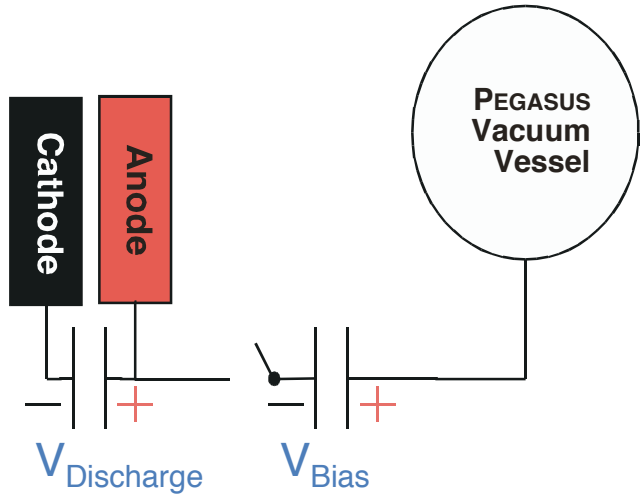


1. G. Fiksel, A.F. Almagri, D. Craig, M. Lida, S.C. Prager, J.S. Sarff, Plasma Sources Sci. Technol. 5, 78 (1996).

PEGASUS Plasma Gun Experimental Setup

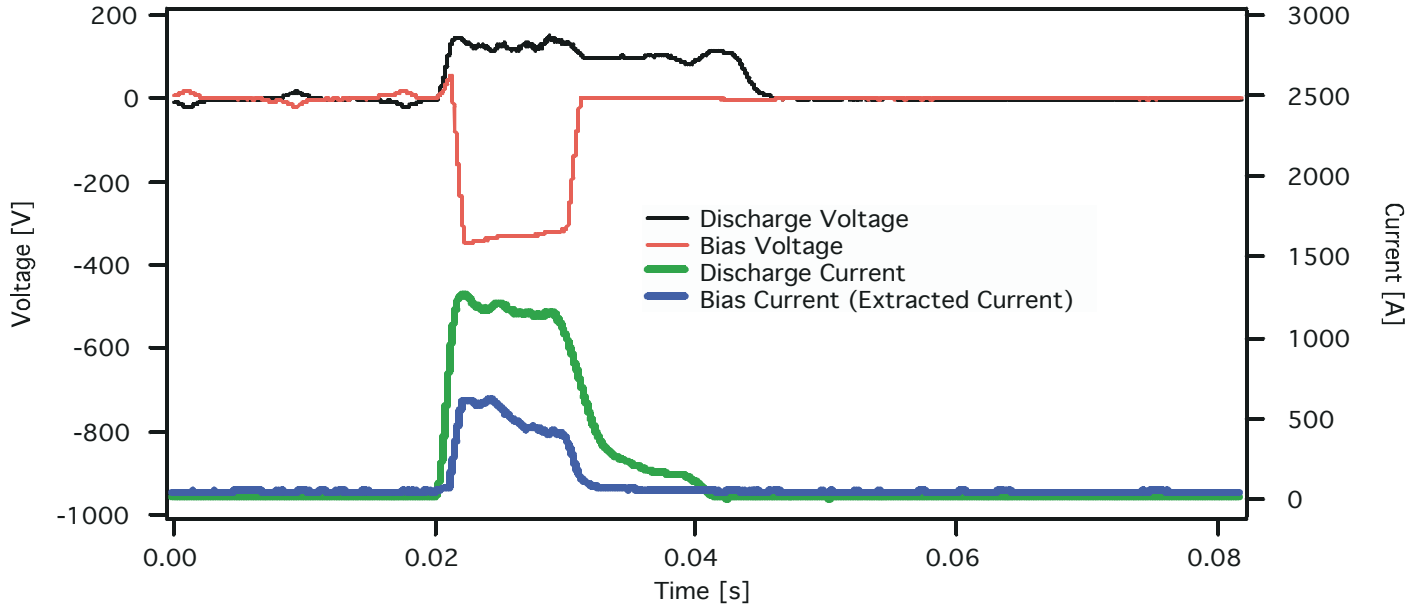
- Guns installed just above lower divertor plate
  - $R_0 \sim 27$ cm
- 180° separation between guns
- Aperature angled 10-20° above horizontal.
- Anode biased 100-400V relative to PEGASUS vacuum vessel
- Arc discharge shaped by PFN



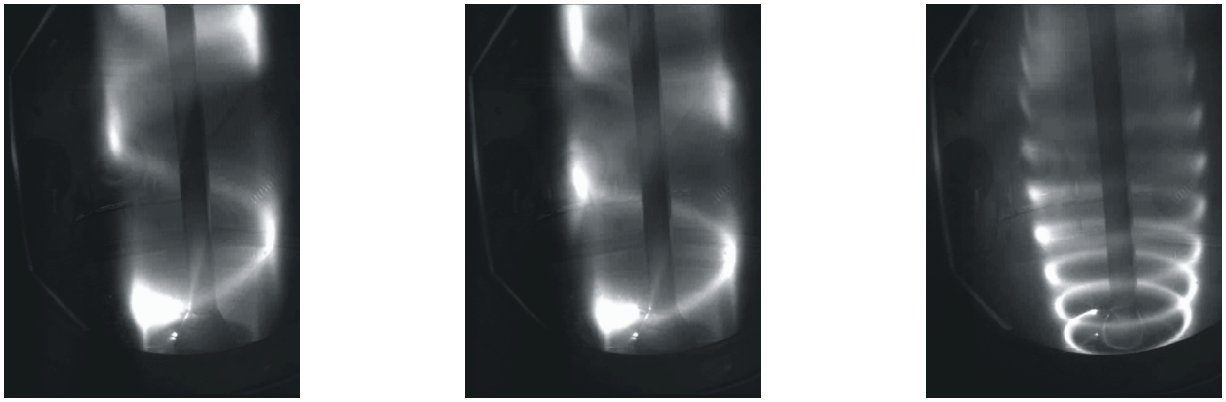


Typical Plasma Gun Discharge

- Current injection for ~ 10 ms



- Extracted current follows magnetic field lines



Decreasing Field Pitch

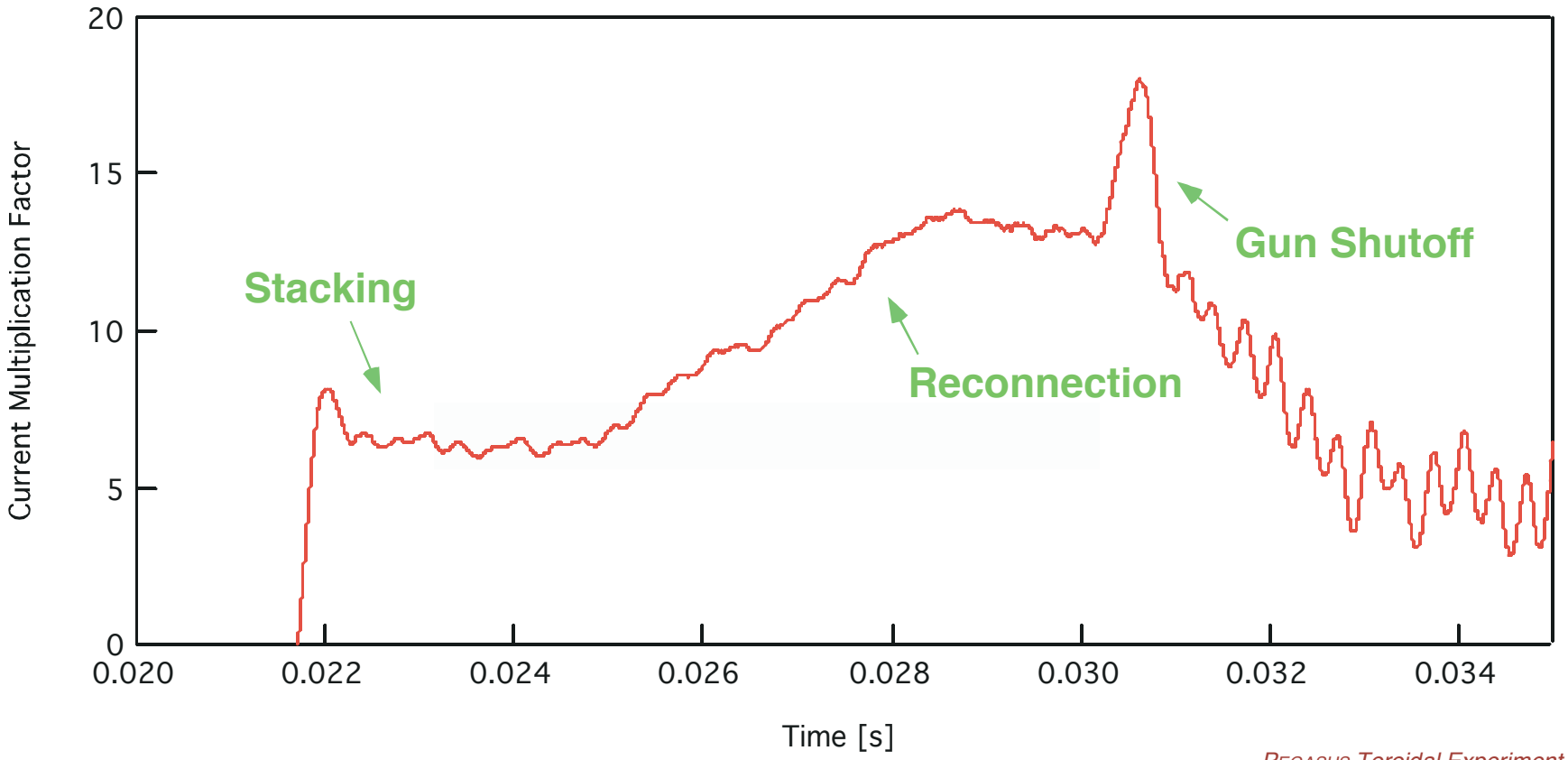


Single Plasma Gun Results

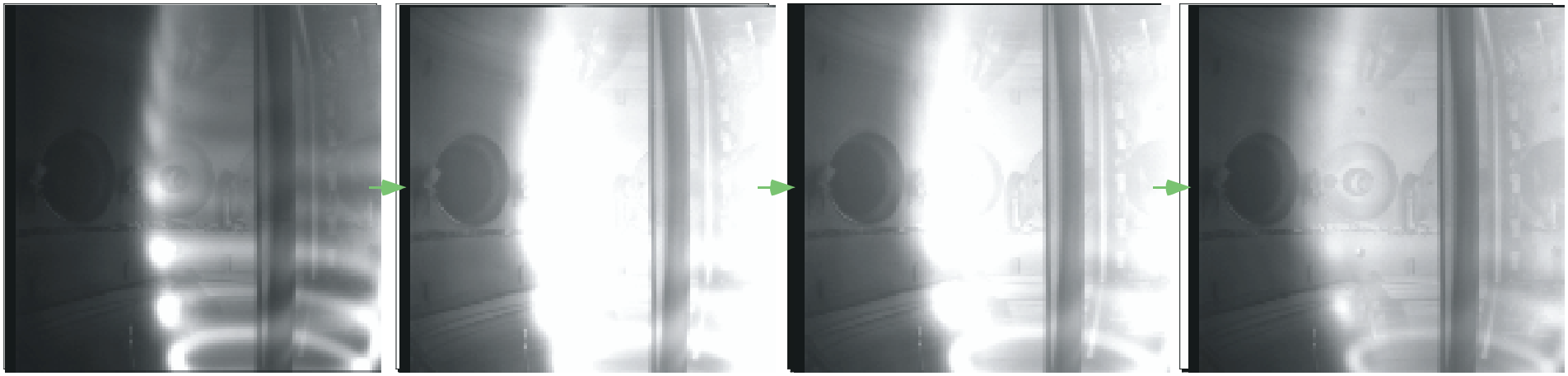


Windup & Reconnection Effects on Ip

- Plasma gun current amplification ~ 15-25 routinely achieved
- Current evolution display two distinct phases:
  1) Initial rapid flattop due to helical stacking of plasma stream
  2) Gradual rise during reconnection of stream lines

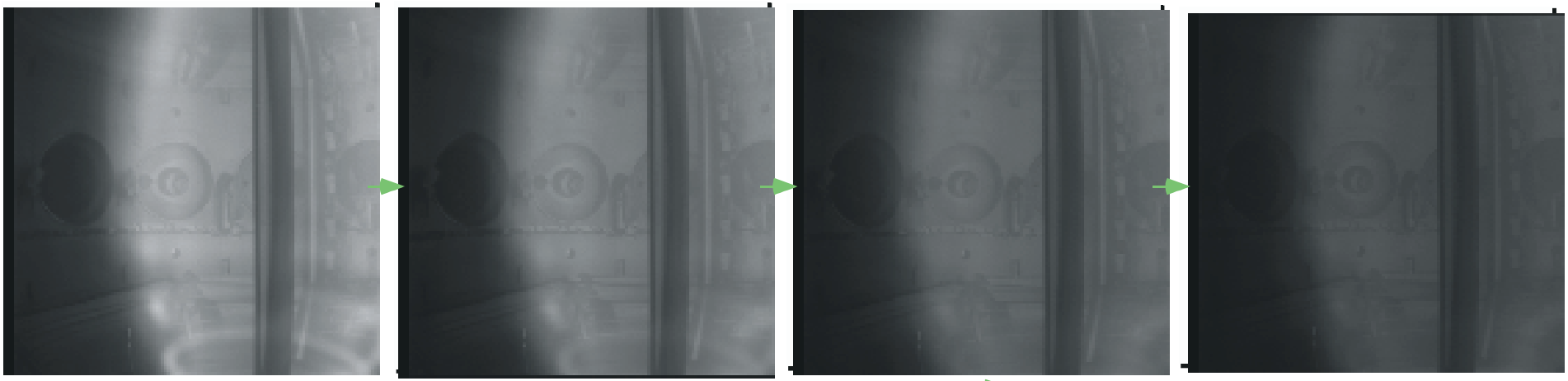


Visual Evidence of Reconnection



Start Discharge...
Streams well defined

Streams coalesce

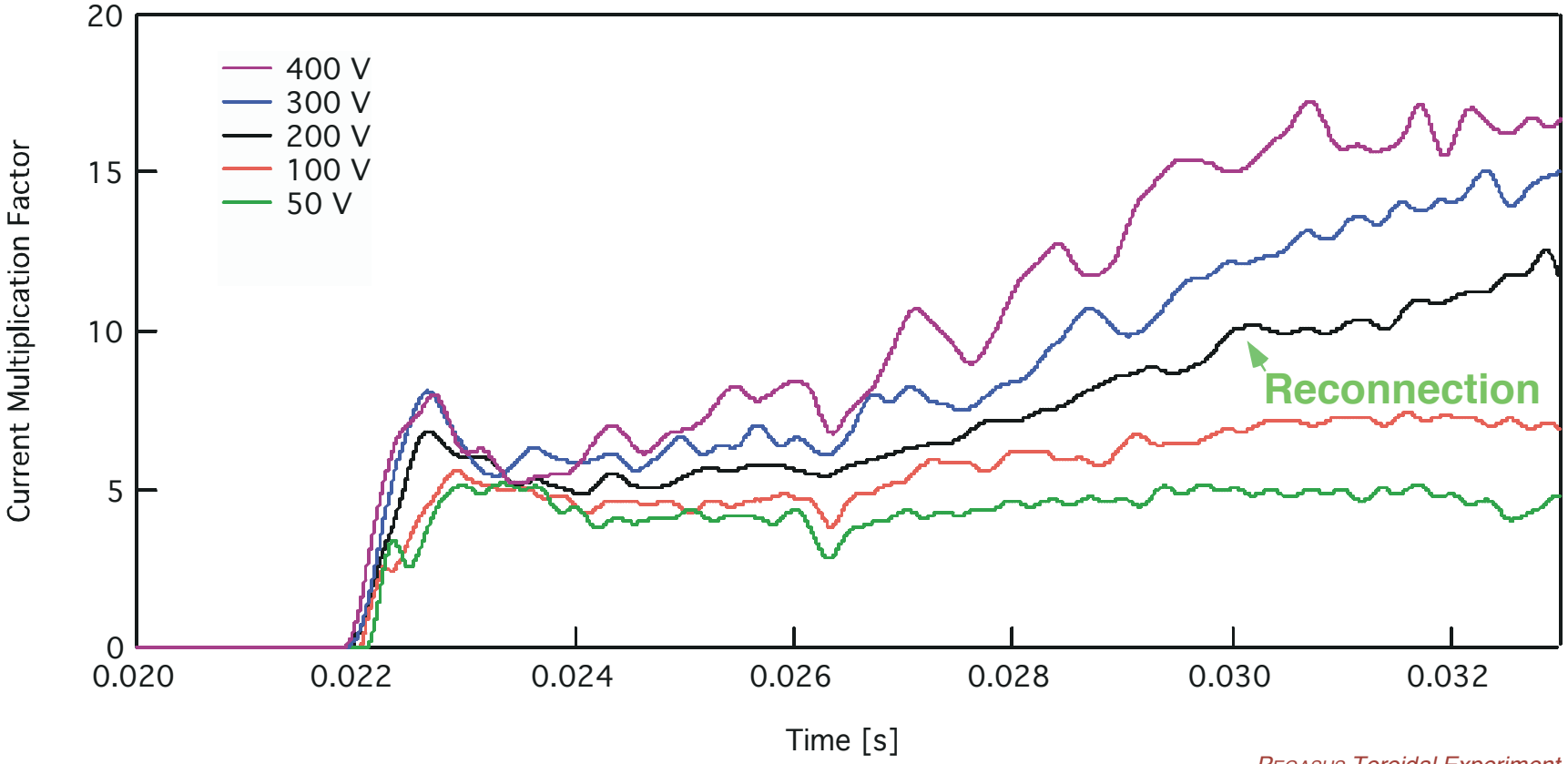


Reconnected plasma

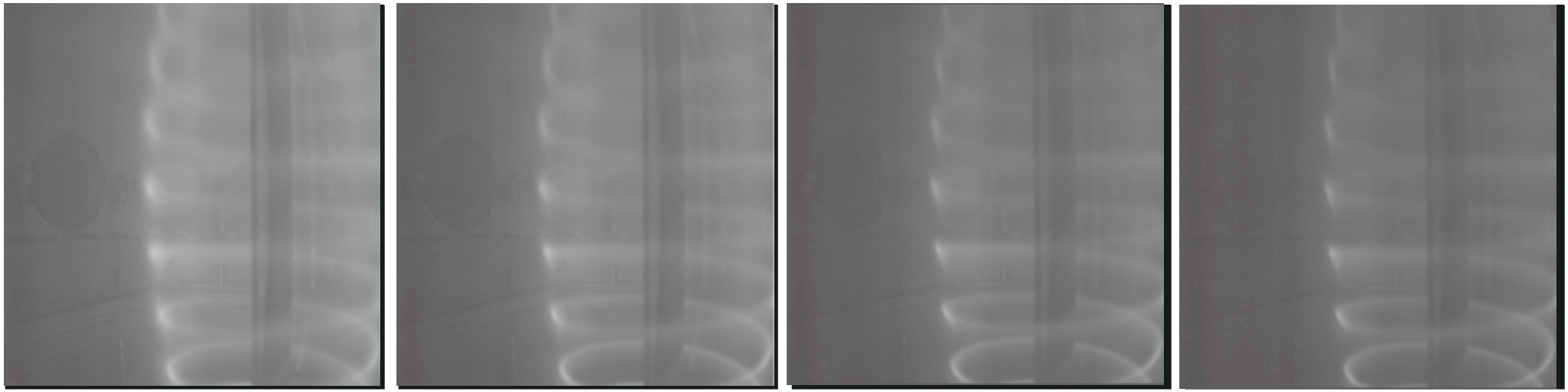
End Discharge

Effect of Bias Voltage on Ip

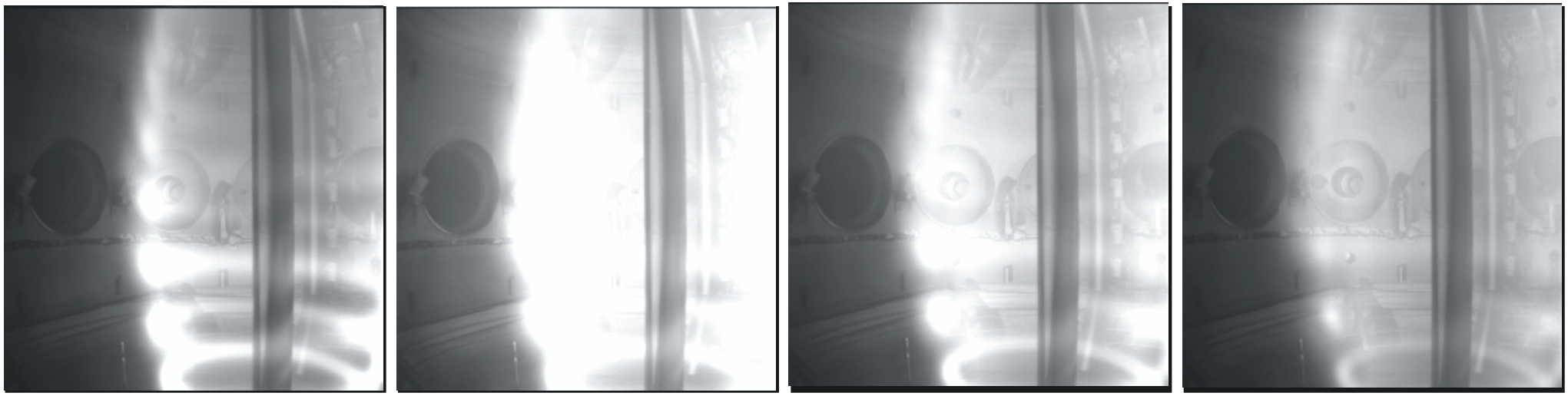
- Current multiplication & Ip scale roughly with bias voltage
  - Consistent with DC helicity injector model
- Reconnection bias threshold ~ 200 V



Visual Comparison of Standard and Reconnecting Discharges



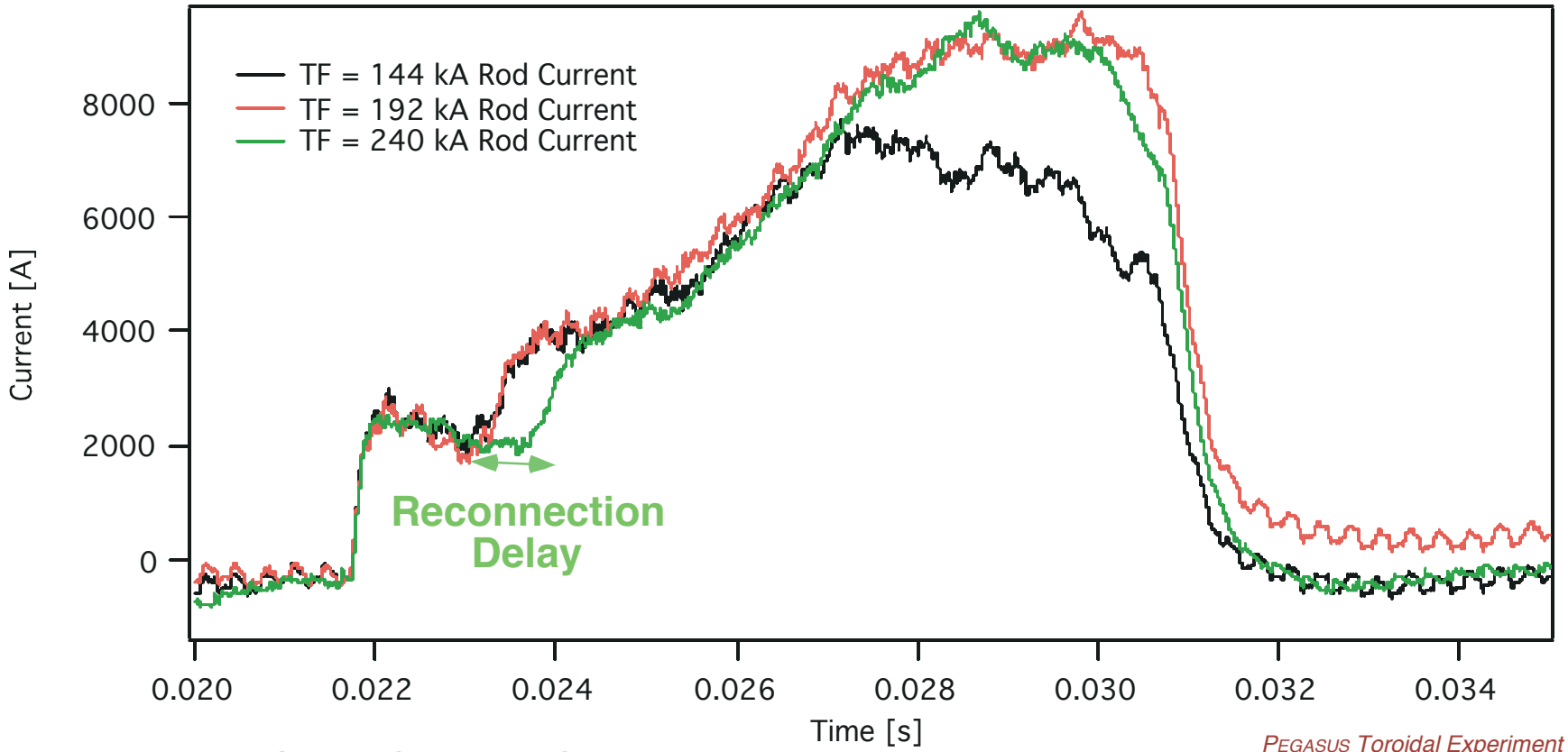
100V Bias. . . No Reconnection



400V Bias. . . Reconnection

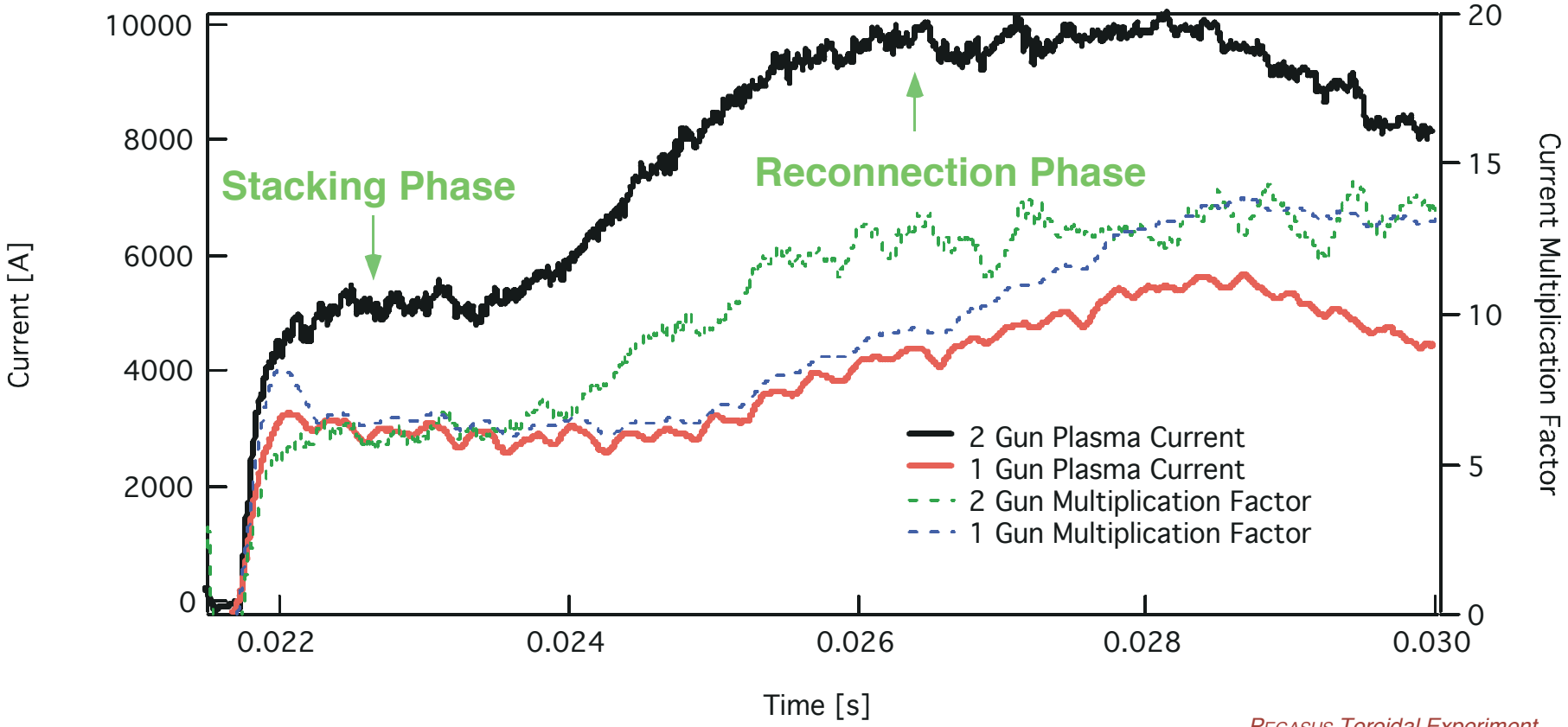
Effect of Field Strength on Ip

- Vacuum field strength increased, stacking factor held constant
- Increased field strength delays reconnection
  - Vacuum field more difficult for plasma streams to overcome
- Maximum Ip displays limit with increasing field strength

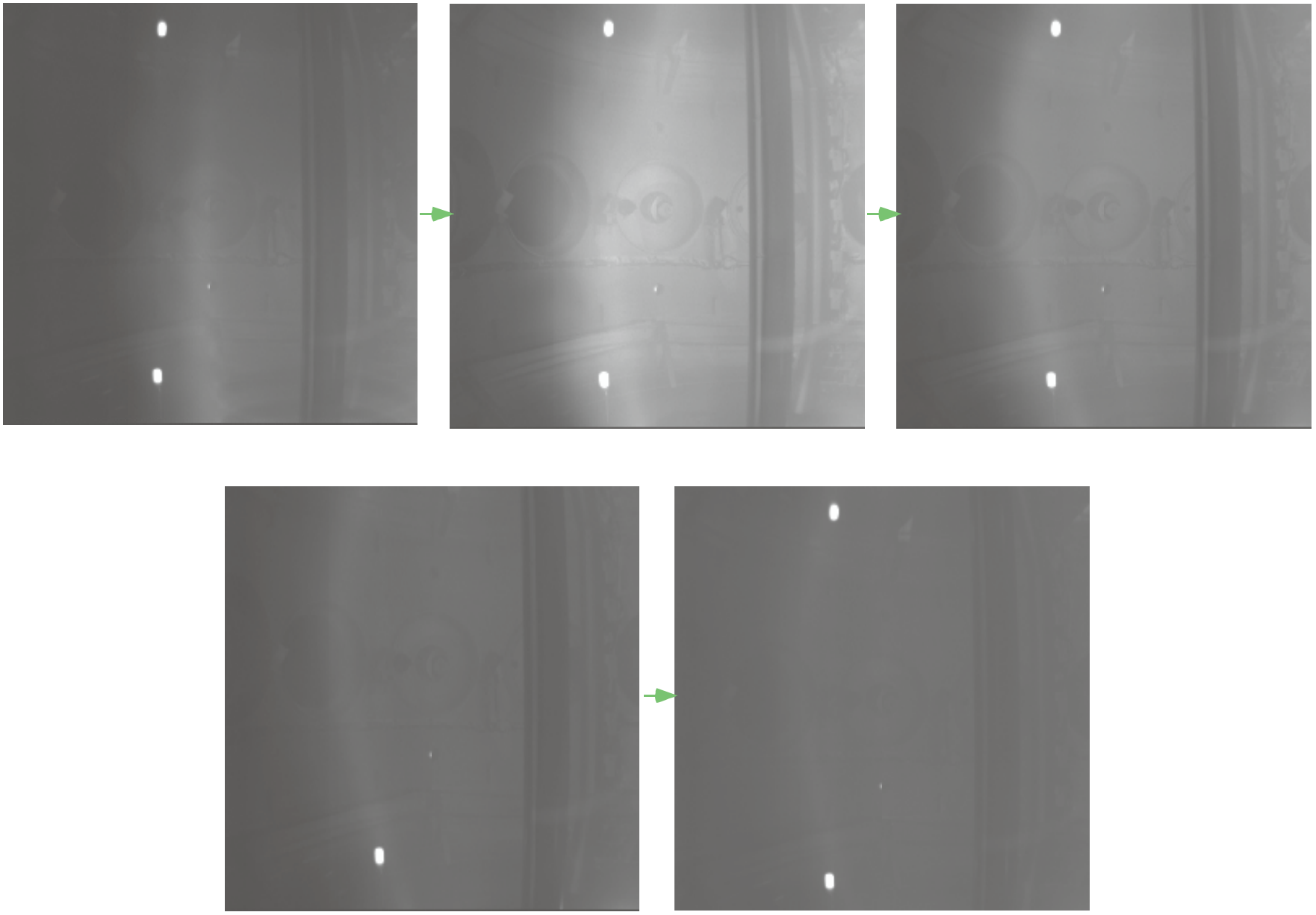


Ip Increases Linearly with # of Guns

- Consistent with DC helicity injector model
- Current multiplication factor remains constant with more guns
- Reconnection occurs more rapidly with two guns
  - Plasma streams are more densely packed

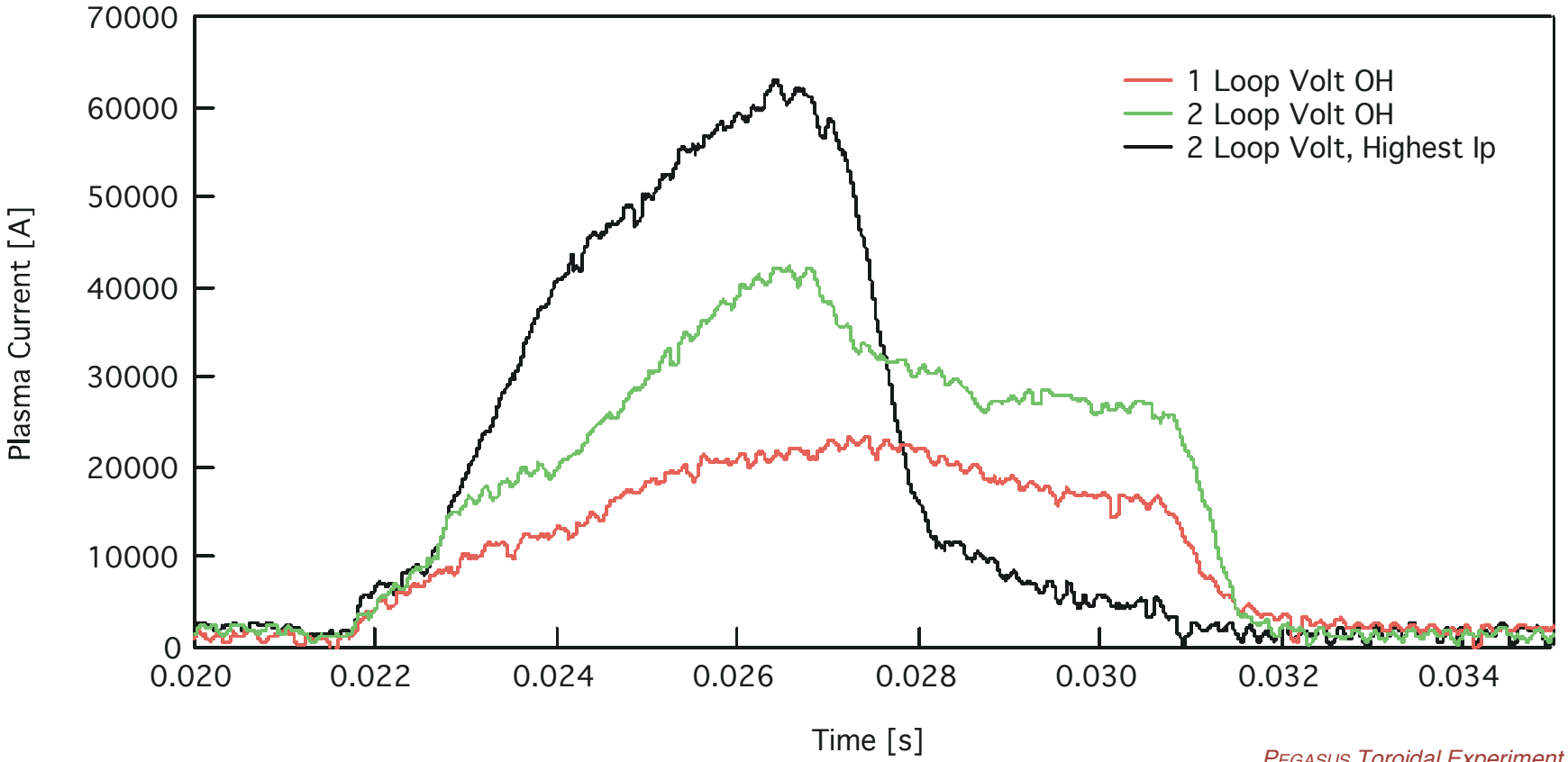


Visual Evolution of Double Gun Discharge



Initial Plasma Gun to OH Handoff Results

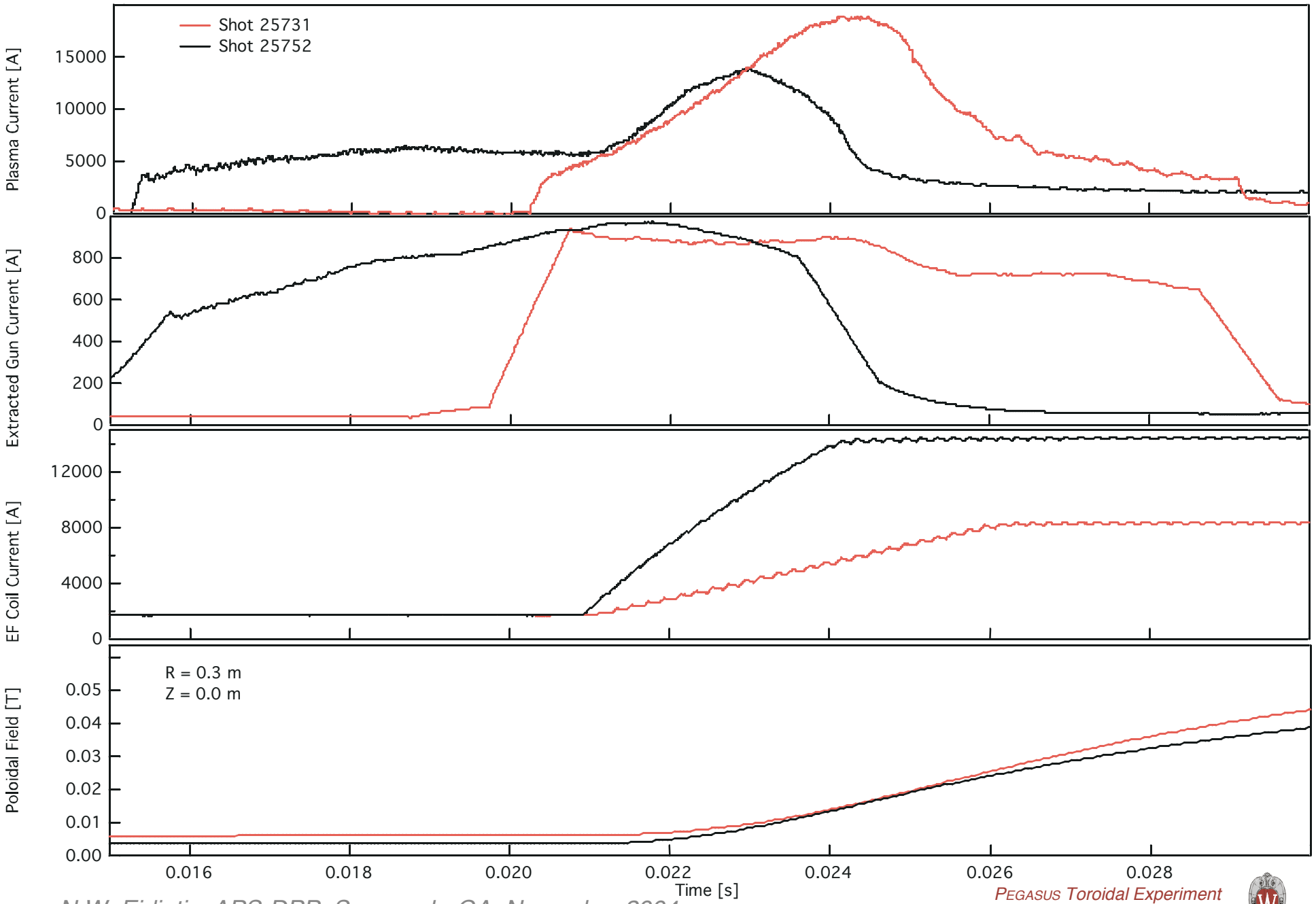
- Ohmic solenoid used to evolve gun plasma
  - No microwave plasma source or bias coils required
  - V_{Loop} = constant in time
- Ip ~ 60 kA achieved
- No evidence yet of closed flux surfaces



Preliminary EF Induction Startup Results

- EF induced loop voltage used to evolve gun plasma
  - No ohmic solenoid or microwave plasma source
- Ip ~ 20 kA achieved
  - Rising fields crunch plasma before larger Ip develops
- Closed flux surface formation not yet achieved
- Plasma current not yet surviving past gun shutoff

Preliminary EF Induction Startup Results



Paths to Plasma Gun Injected Current Flux Surface Closure

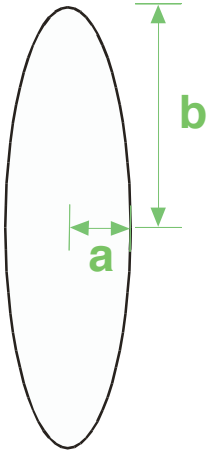
Flux surface closure of plasma gun injected current requires:

$$B_{pol} \approx B_{Vac}$$

Assuming an elliptical plasma,

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

$$\kappa = b/a$$



For the PEGASUS cases presented here,

$$B_{Vac} \approx 0.01T \quad a \approx 0.2\,m \quad \kappa \approx 4 \quad \Rightarrow \quad I_\phi \approx 29kA$$

This analysis presents two paths to flux surface closure:

1) Increase injected current by adding more guns
   - *Two gun scaling suggests 6 guns would provide ~ 30 kA*

2) Decrease B_{Vac} > 0.005 T
   - *Finite field required to enable gun current extraction*
   - *Minimum field dictated by error fields*

Summary

- Plasma guns exhibit additive behavior
  - Supports adding more plasma guns for increased current drive
- Injected current exhibits reconnection
  - Total Ip *is not* solely a function of helical stacking
- Plasma guns can aid ohmic operations
- Plasma gun plasmas provide a viable target for non-ohmic startup
- Simple DC helicity injection model is instructive but not sufficient to explain injected current behavior

Future Work

- Upgrade PEGASUS plasma gun array
  - PEGASUS vessel can support up to six plasma guns
  - Ip ~ 30-40 kA expected based on two gun current scaling
- Develop path to closed flux surface generation
- Continue to explore non-ohmic startup via EF coil induction
- Refine gun to ohmic handoff to aid present ohmic operations



Reprints

