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

Presented by

Nicholas Eidietis (ORAU)

On behalf of the members of the PEGASUS Toroidal Experiment

University of Wisconsin - Madison

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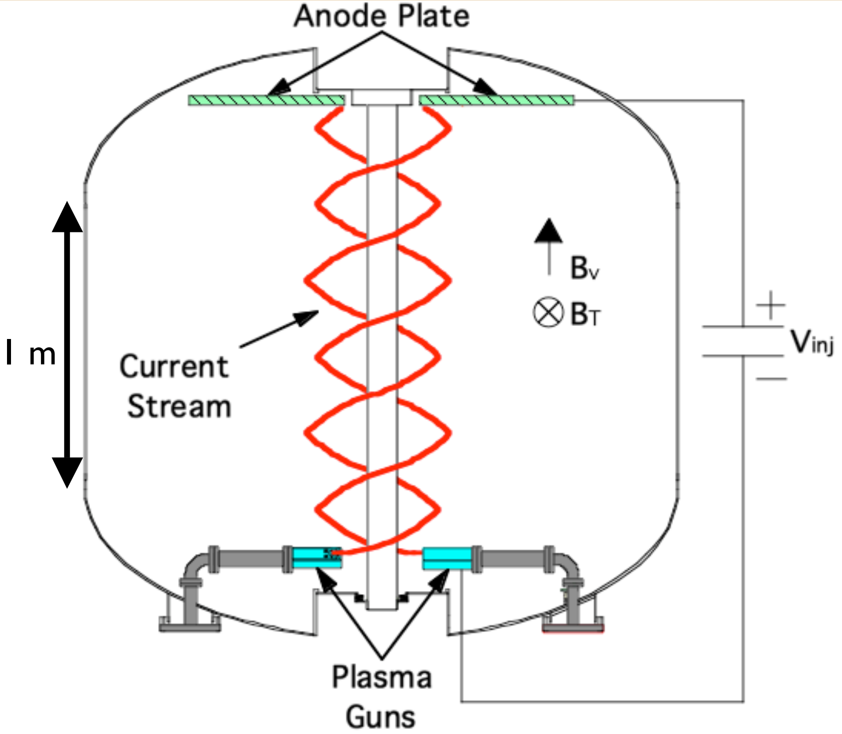
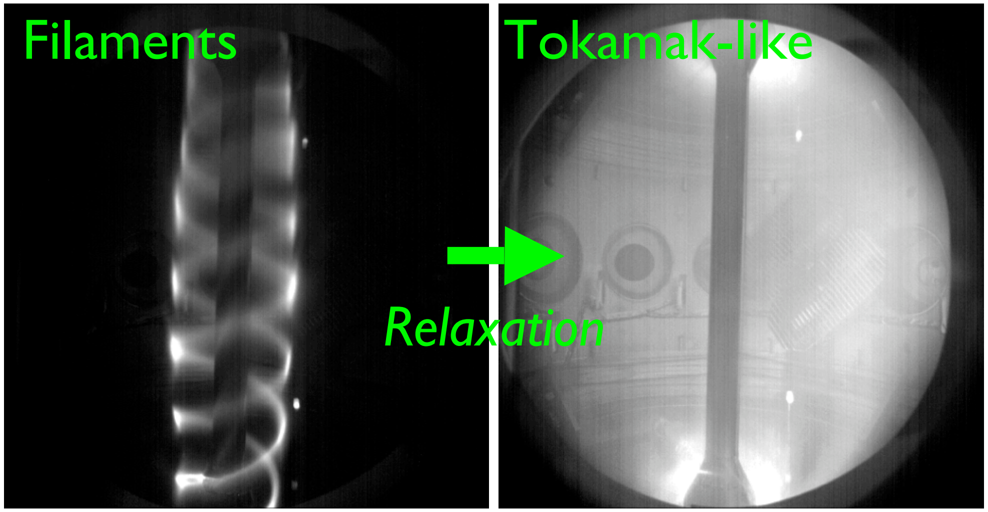
PEGASUS non-inductive startup utilizes washer-gun current sources for DC helicity injection

Motivation

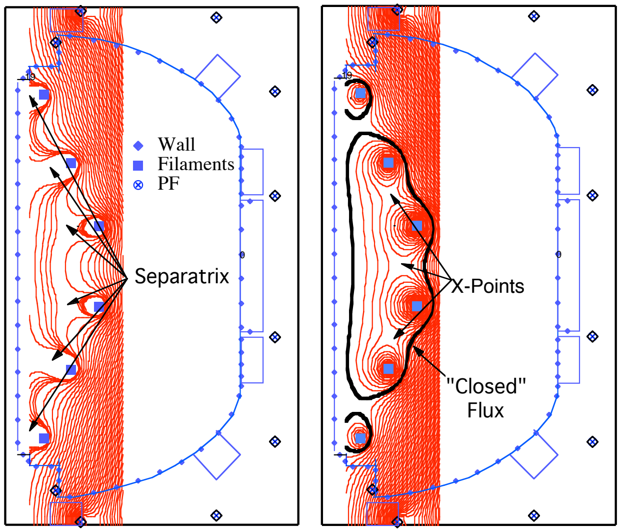
1. **Near-term:** Augment limited ST V-s
2. **Long-term:** Eliminate CS entirely

- 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





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



Filaments

Relaxed

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:

$$V_{loop}\Psi_t = V_{inj}\Psi_{inj} \rightarrow V_{eff} = V_{inj}\frac{\Psi_{inj}}{\Psi_t}$$

Injector Flux

Toroidal Flux

- 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

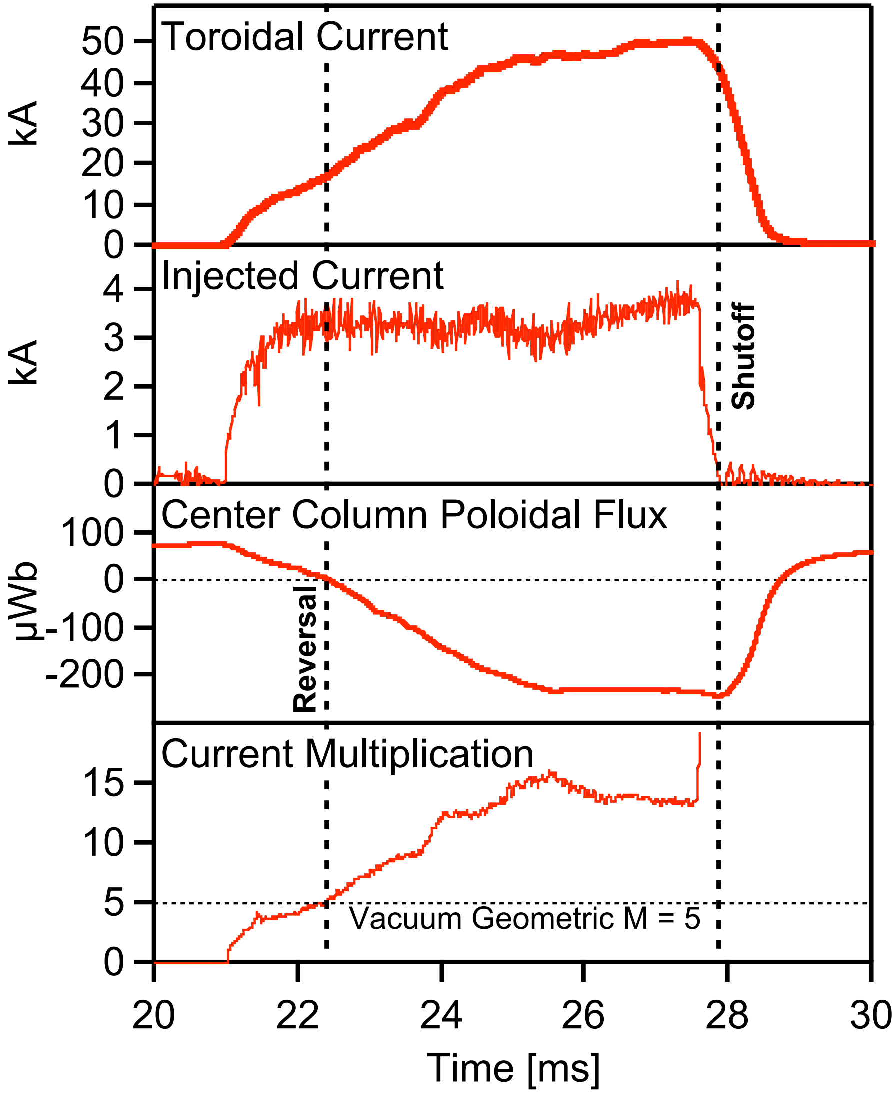
$$\varepsilon = \frac{P_{dis}}{P_{inj}} = \frac{I_\varphi}{I_{inj}}\frac{V_{eff}}{V_{inj}} = \frac{\Psi_{inj}}{\Psi_t}\frac{I_\varphi}{I_{inj}}$$

Toroidal Current

Injected Current

Relaxation significantly enhances non-inductive current drive capability

- I_ϕ > 50 kA driven by I_{inj} ≤ 4 kA
- Center column flux reversal ⇒ relaxation
  - Indicates filaments have overwhelmed B_Z
- Current multiplication (I_ϕ/I_{inj}) > geometric
  - Not constrained by vacuum windup
- τ_{plasma}, τ_{gun} decoupled
  - I_ϕ > 40 kA after $I_{inj} = 0$
  - Relaxed I_ϕ not "windup" current



Maximum current drive limited by helicity injection rate

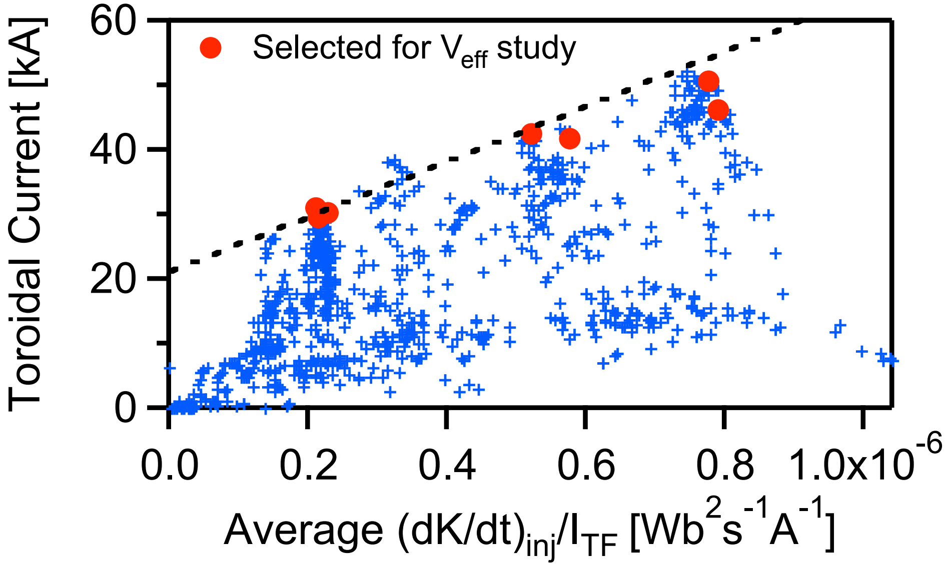
- Max I_ϕ offset linear to injected dK/dt

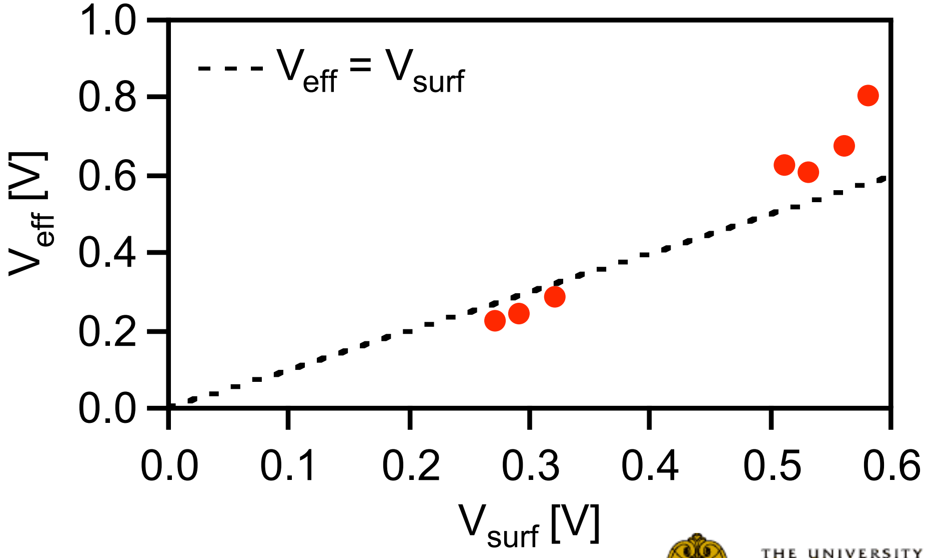
- dK/dt limiting I_φ?
  - Compare V_{eff} & decay V_{loop}

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

- $V_{eff} \approx V_{surf}$ 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*

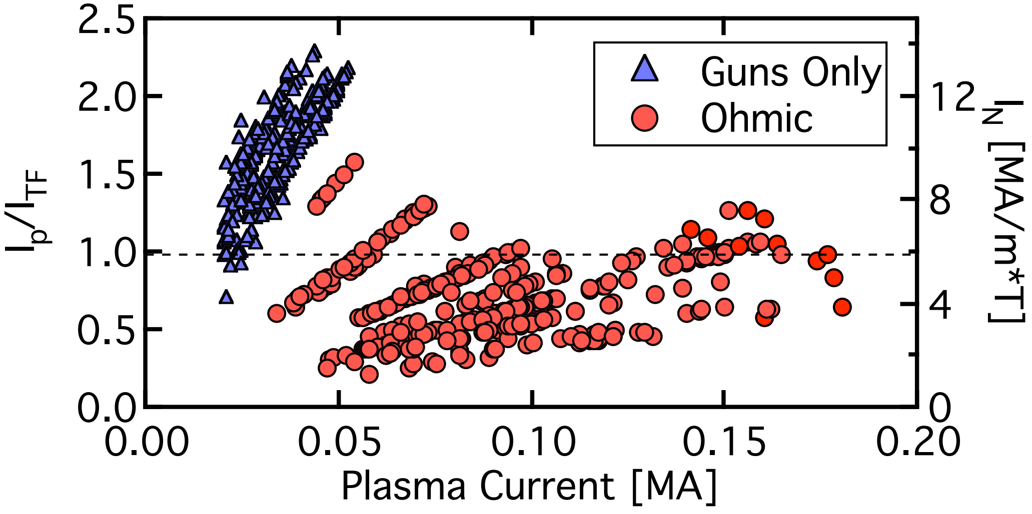


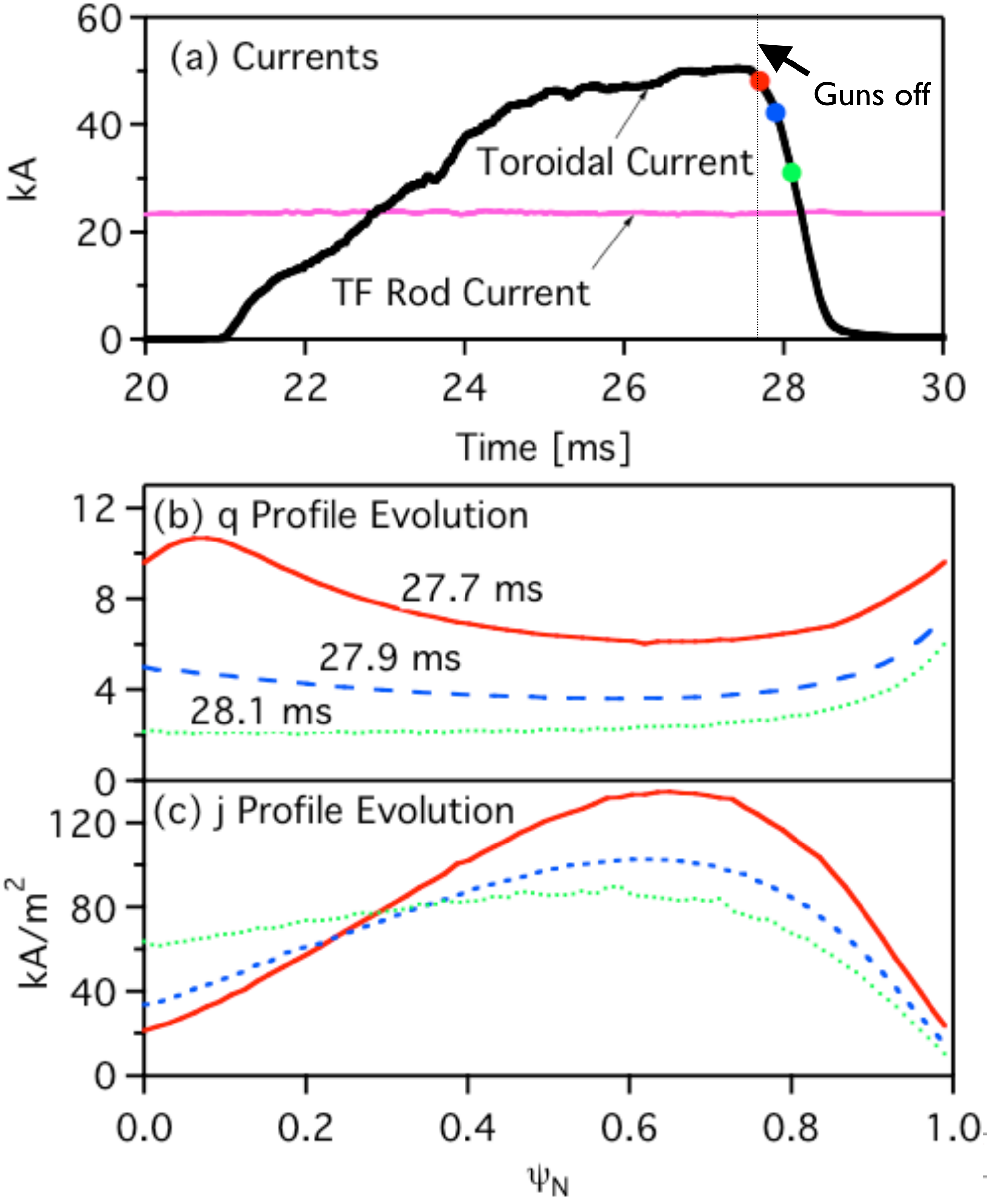


Plasma gun current drive expands PEGASUS operating space to $I_N > 12$ MA/m-T

- **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*

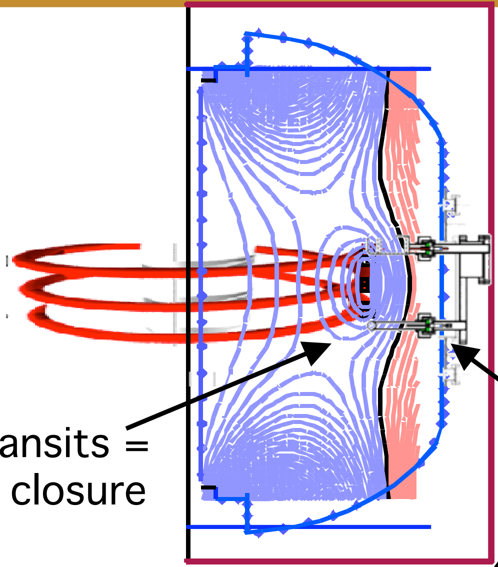


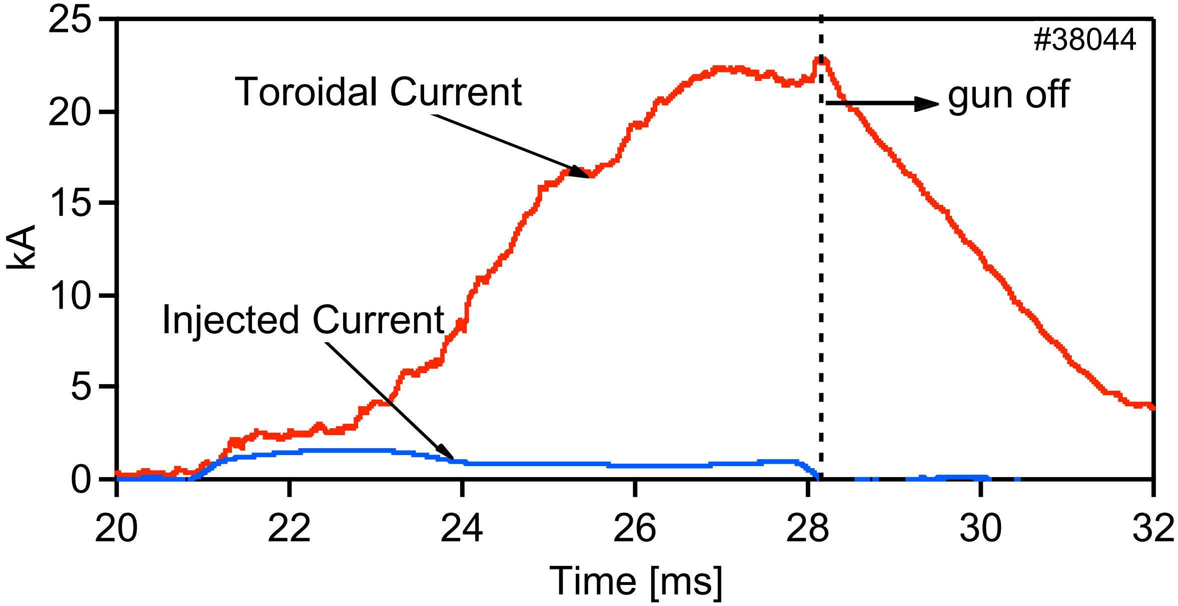


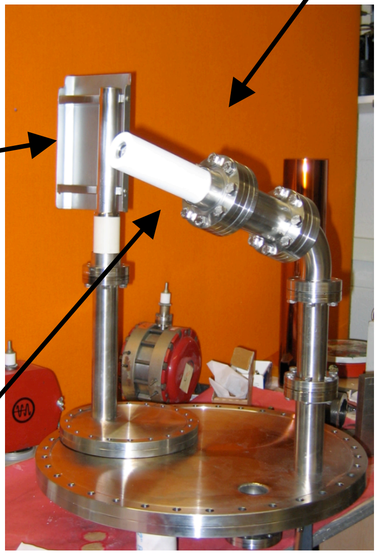
Midplane gun geometry scales to larger experiments

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

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



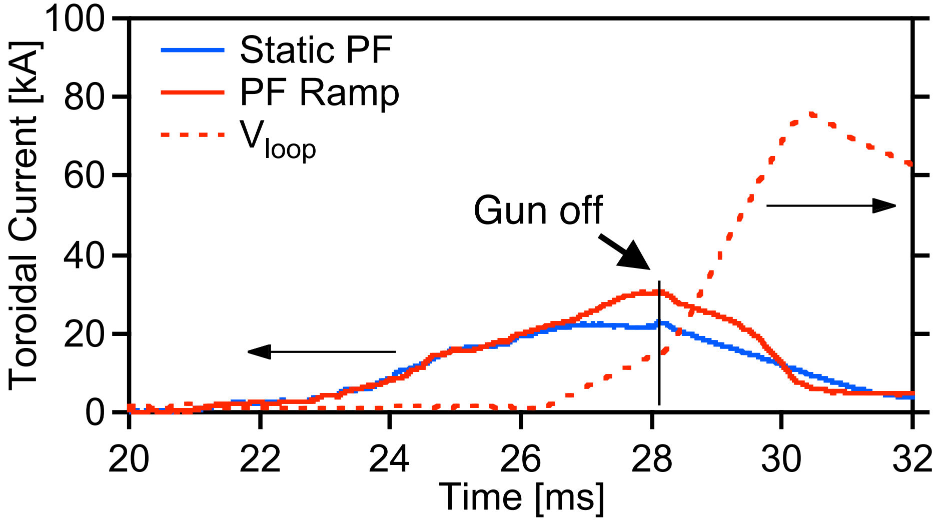




Relaxed midplane target plasma handed off to PF-only and OH induction

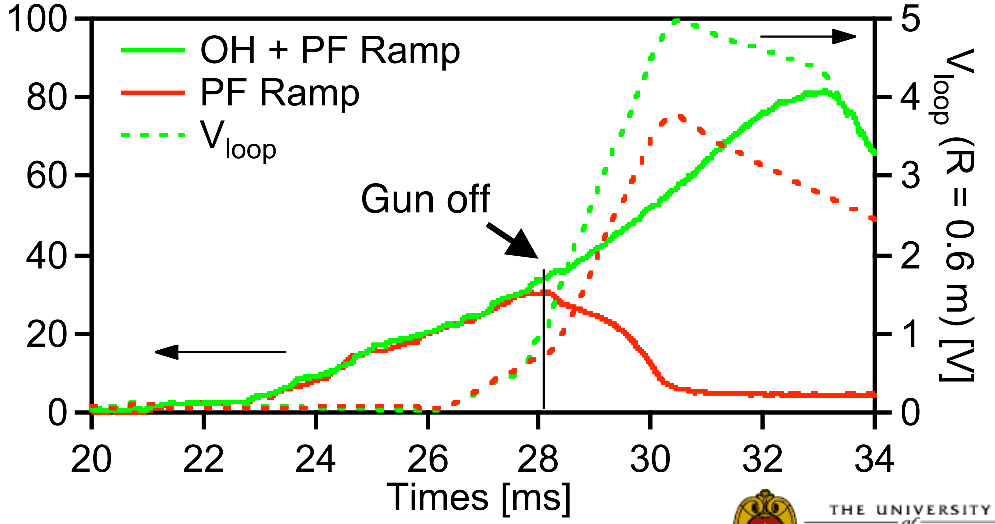
PF induction only:

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



OH induction:

- Additional V_{loop} w/o strong radial force
- Steady growth if V_{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