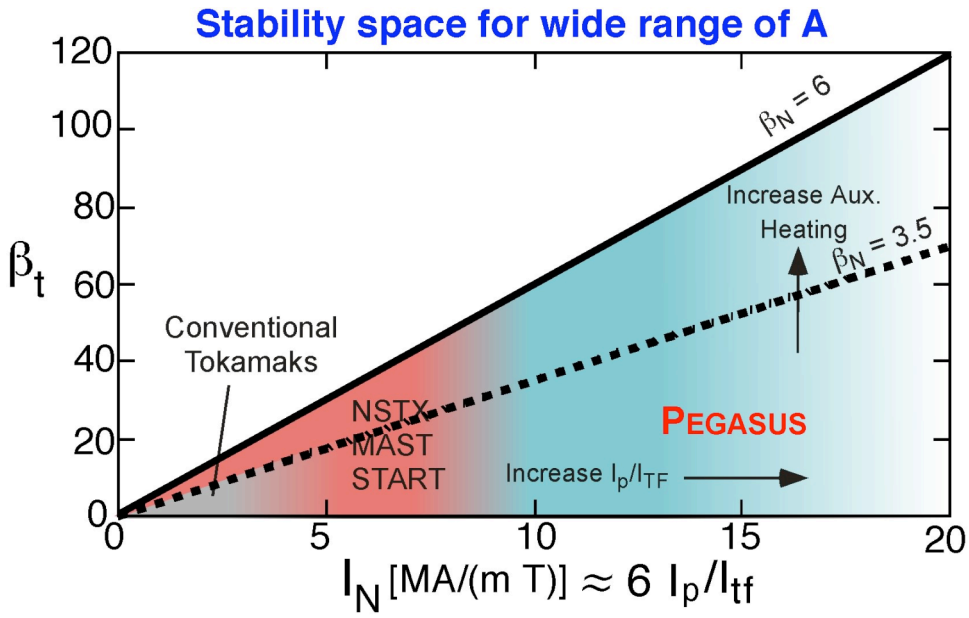
# Abstract

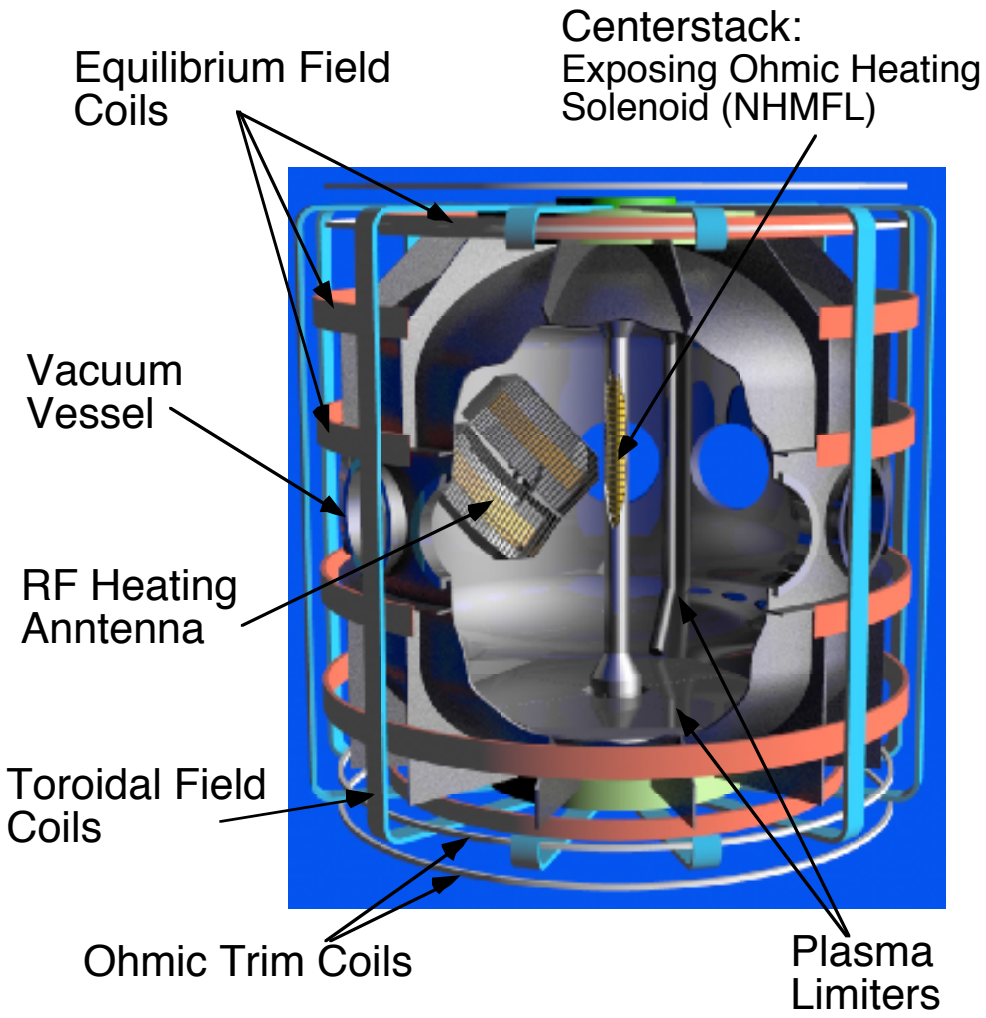
The Pegasus Toroidal Experiment is exploring plasma stability at near-unity A and developing non-solenoidal startup tools. Several techniques have been developed to suppress deleterious tearing modes by modifying the current profile, including toroidal field ramps and non-inductive current drive via washer-stack current sources. These techniques have allowed access to $I_N$ = 14 MA/m-T without the appearance of performance-limiting instabilities. Filamentary structures have recently been observed near the edge of almost all Ohmic discharges; large values of $j_{||}/B$ in this region suggest that these may be the result of peeling modes. Non-inductive startup via washer-stack current sources has produced plasmas with toroidal currents up to 50 kA. Plasmas have been produced using two geometries: with sources in the lower divertor region, and with a source on the outboard midplane producing moderate-A targets intended for PF induction. Plasmas produced with both geometries have been successfully coupled to Ohmic drive.

# Pegasus is Studying MHD as A → 1 & Developing Non-Solenoidal Startup Techniques

- Determining limits to $I_N$
  - high $I_N$ accessed through j(R) manipulation, fast TF ramps
- Edge filamentary structures observed which may be peeling modes
  - possibly due to high $(j_{||}/B)_{edge}$
- DC helicity injection via point current sources used to create non-inductive discharges
  - targets coupled to PF induction & OH drive



# Pegasus is a Mid-Sized, University-Scale ST

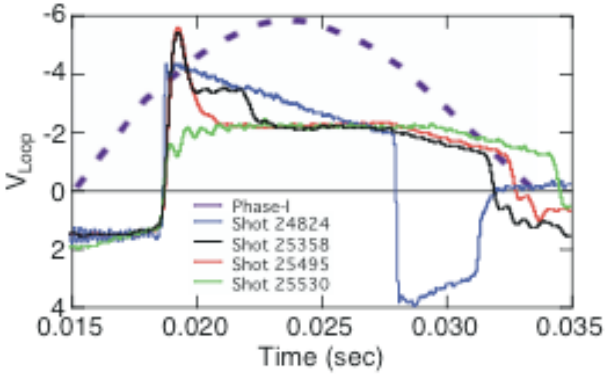


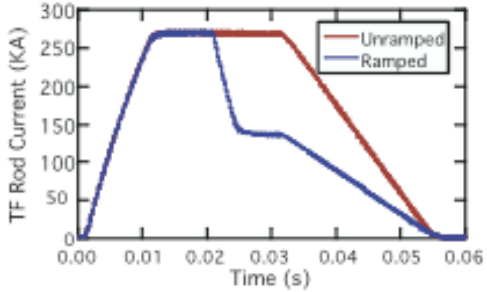

**Experimental Parameters**

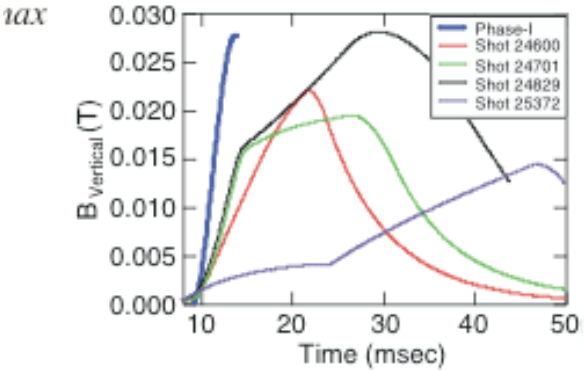
| Parameter | Achieved | Goals |
|---|---|---|
| A | 1.15-1.3 | 1.12-1.3 |
| R (m) | 0.2-0.45 | 0.2-0.45 |
| $I_p$ (MA) | $\leq 0.18$ | $\leq 0.30$ |
| $I_N$ (MA/m-T) | 6-12 | 6-20 |
| $RB_t$ (T-m) | $\leq 0.06$ | $\leq 0.1$ |
| $\kappa$ | 1.4–3.7 | 1.4–3.7 |
| $\tau_{shot}$ (s) | $\leq 0.02$ | $\leq 0.05$ |
| $\beta_t$ (%) | $\leq 25$ | $> 40$ |
| $P_{HHFW}$ (MW) | 0.2 | 1.0 |

# Programmable Power Supplies Give Operational Flexibility

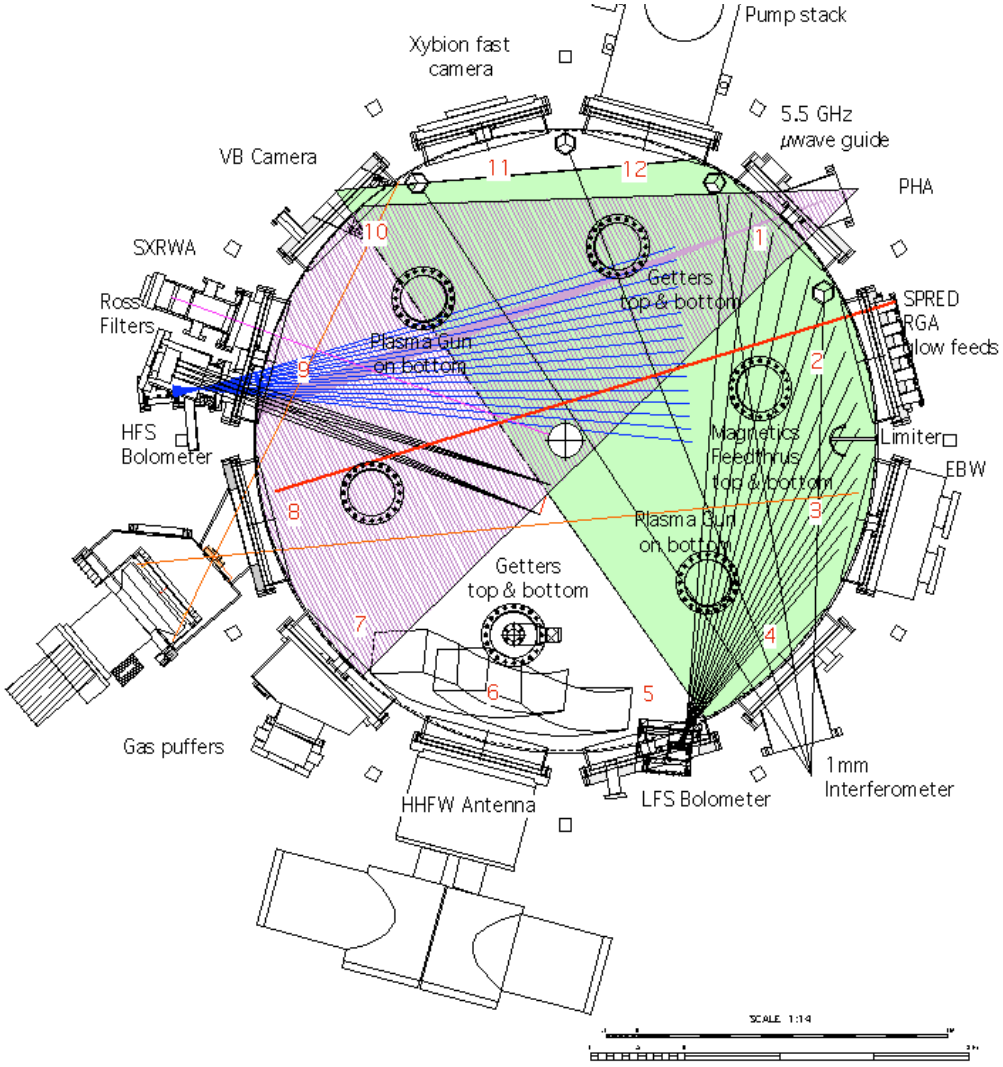
- Current feedback controlled fully controllable thyristor switches
  - IGCT system for high voltage OH (2800 v)
  - IGBT system for PF & TF (900 v)
- Tools to achieve high $I_p/I_{TF}$
  - detailed $v_{loop}$ control
  - fast TF ramps
- Allows active feedback control
  - GA PCS successfully used for open-loop pre-programmed control



# Pegasus Diagnostic Layout

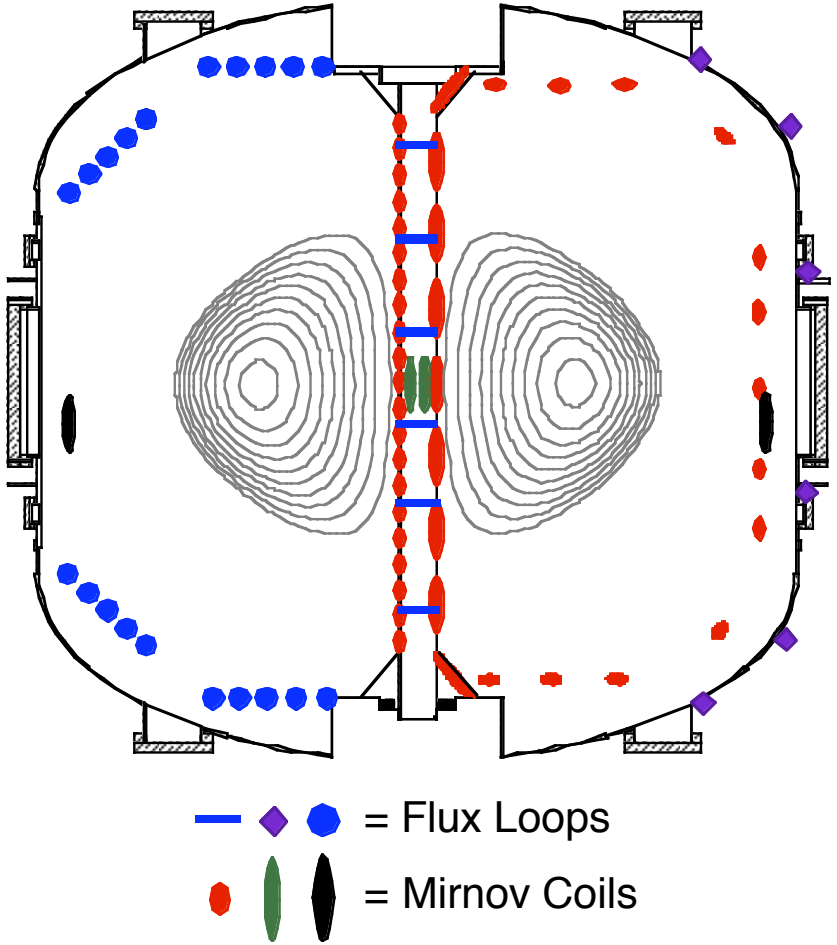



- SPRED
  - VUV impurity spectroscopy
- 1mm μ-wave interferometer
  - $n_e \ell$
- High resolution camera
  - plasma shape/position
- 2-D SXR PHC
  - j(R) constraint via flux surface imaging
- Poloidal SXR diode array
  - MHD - 19 channels
- Tangential PHA
  - $T_e(t)$
- Tangential bolometer array
  - $P_{rad}$ - 32 chords
- Filterscopes
  - $D_\alpha$, O, C, VB

# Magnetics Diagnostics Used for MHD Equilibrium & Stability Analysis

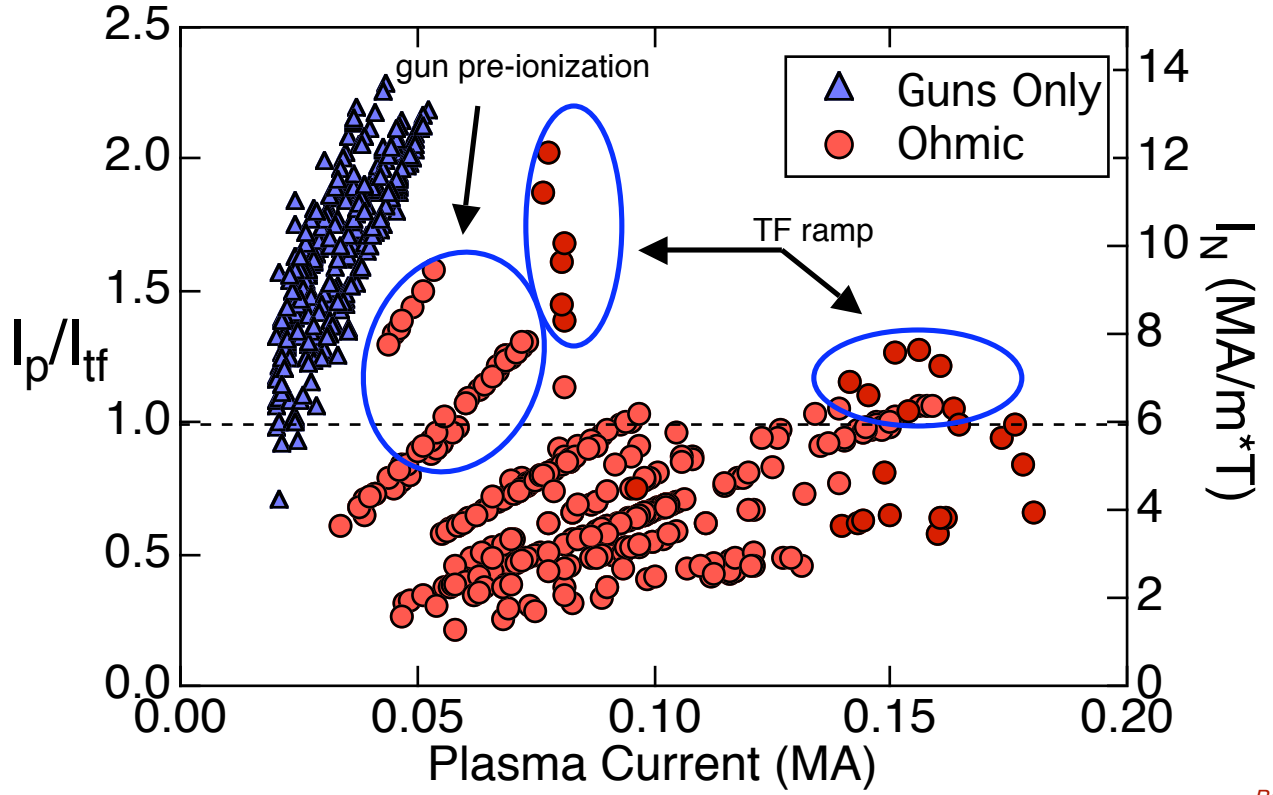
- 90 individual magnetics available for analysis
  - 43 poloidal Mirnov coils
  - 13 toroidal Mirnov coils
  - 32 poloidal flux loops
  - diamagnetic loop
  - plasma Rogowski
- Equilibrium reconstruction with local code
  - EFIT being implemented
- DCON for ideal MHD stability
- MHD mode analysis with Mirnov arrays

**Schematic of Magnetic Diagnostics**



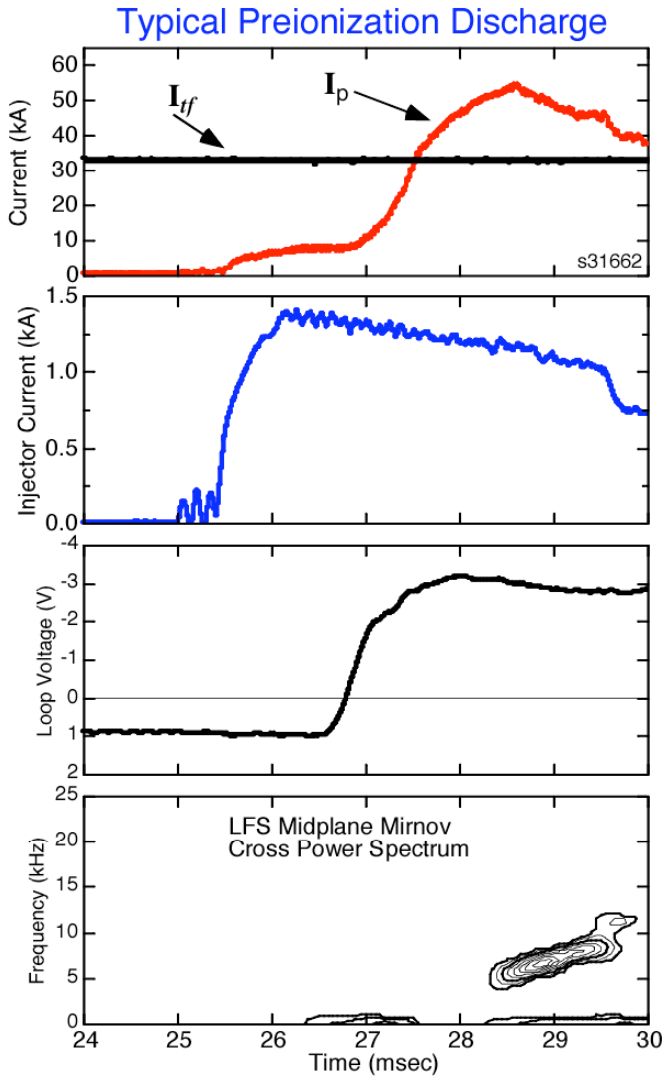
# Experimental Flexibility Provides Access to High $I_N$

- 3 techniques used to achieve high $I_N$ ($I_p/I_{TF} \approx I_N/6$)
  - OH drive at low TF via gun pre-ionization
  - Non-inductive discharge formation at low TF
  - Fast TF ramp-down during OH operation



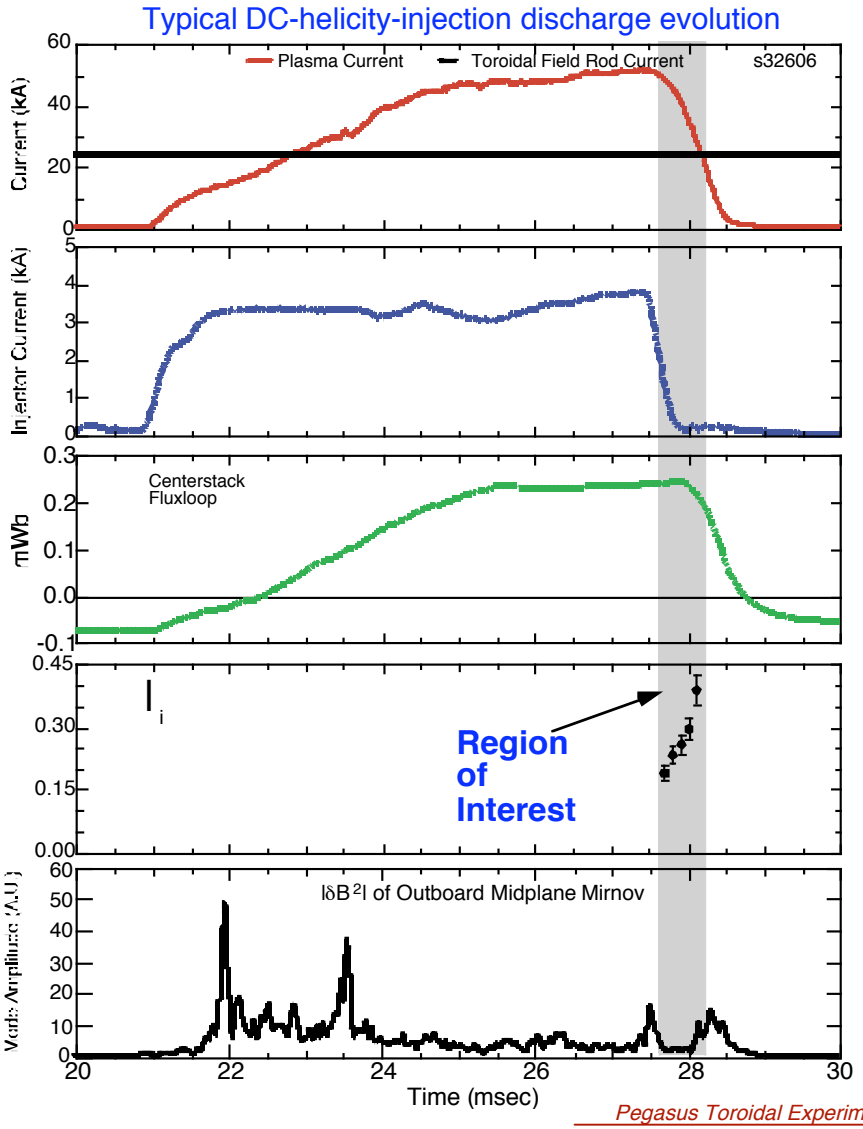
# High $I_p/I_{TF}$ via OH Inductive Drive

- Gun pre-ionization allows OH operation at low-TF
  - ECH resonance outside vessel at low-TF
  - no PF null required
- Better v-sec utilization
  - no OH flux required for breakdown
- $I_p/I_{TF}$ ~ 1.5 achieved
  - low TF limits max. $I_p$



# High $I_p/I_{TF}$ via Non-Inductive Drive

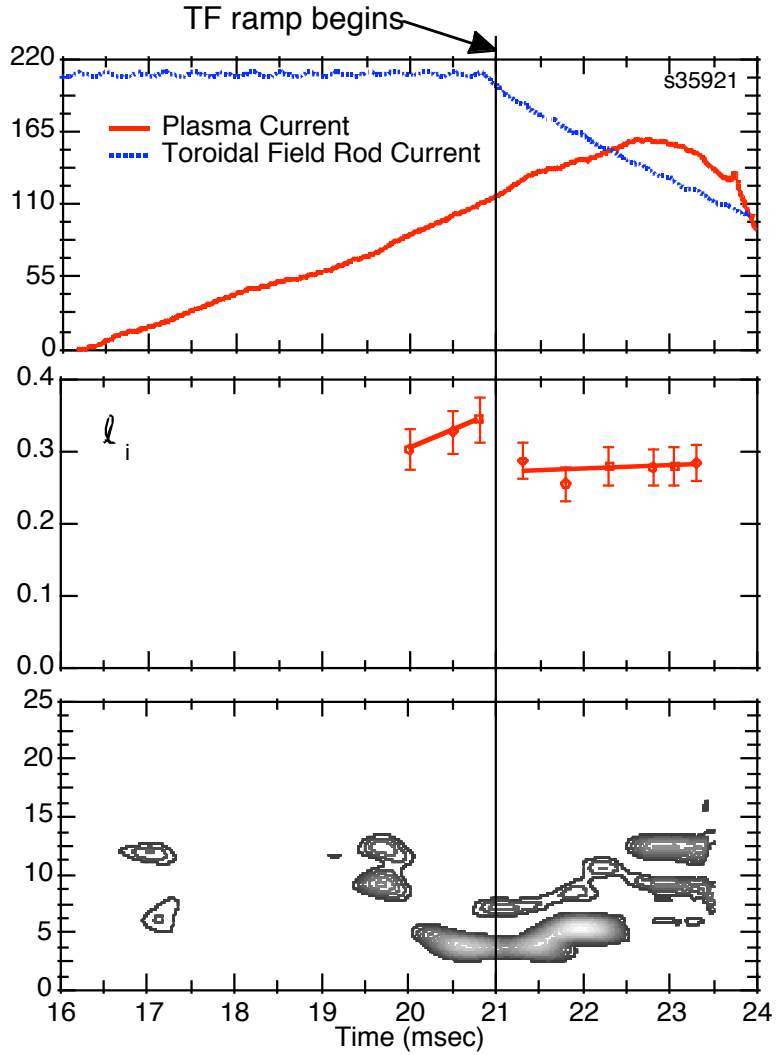
- Plasma guns used to create closed flux surface tokamak discharges
  - $I_p > 2I_{TF}$ achieved
  - agrees with helicity balance
- Current injection at edge leads to hollow j(R)
  - $\ell_i < 0.3$ at gun turn off
- Transient TM suppression after guns off
- TM return after current profile becomes less hollow



# High $I_p/I_{TF}$ via Fast TF Ramps

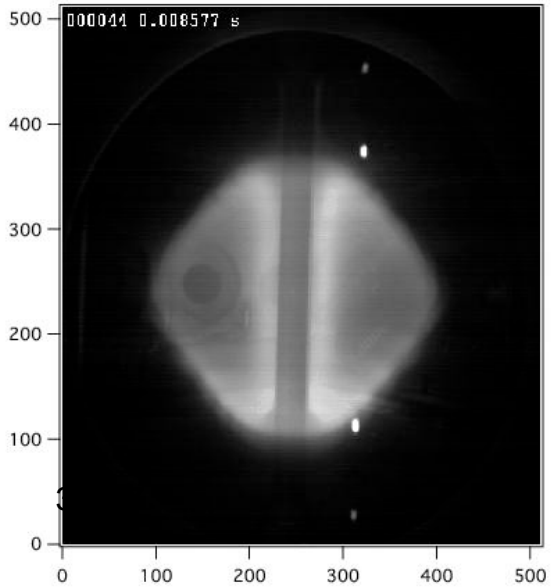
- Low inductance TF coil set allows fast current ramps
  - discharge formed with high TF to avoid early TM
- Poloidal induction drives edge current
  - gives hollow j(R)
  - $\ell_i$ drops by ~ 20%
- $I_p/I_{TF}$ ~ 1.3 achieved

Discharge evolution for strong TF ramp

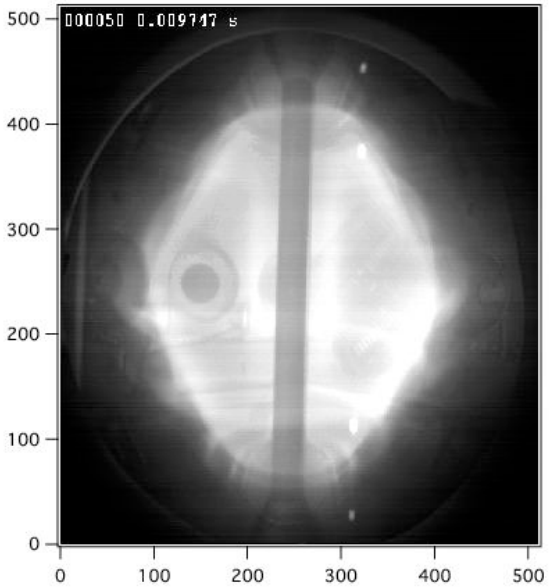


# Edge Filaments Observed in Most Discharges

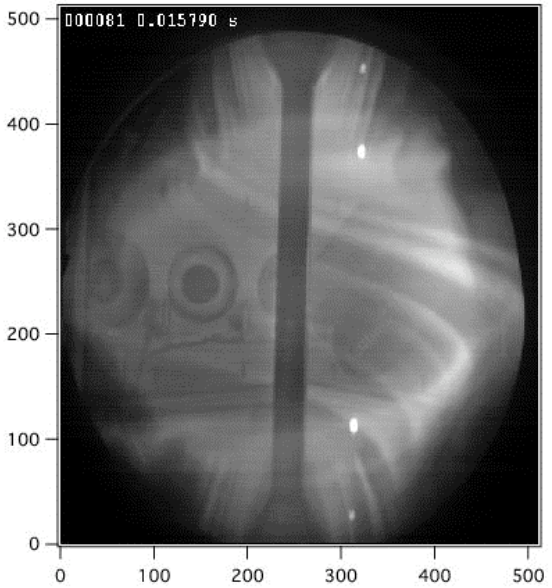
- Localized to edge
  - large tearing modes also observed which cause entire plasma to wobble
- Appear early in discharge & persist throughout shot
  - not bursty or transient
- Uncorrelated with $I_p$ saturation




15.577 ms



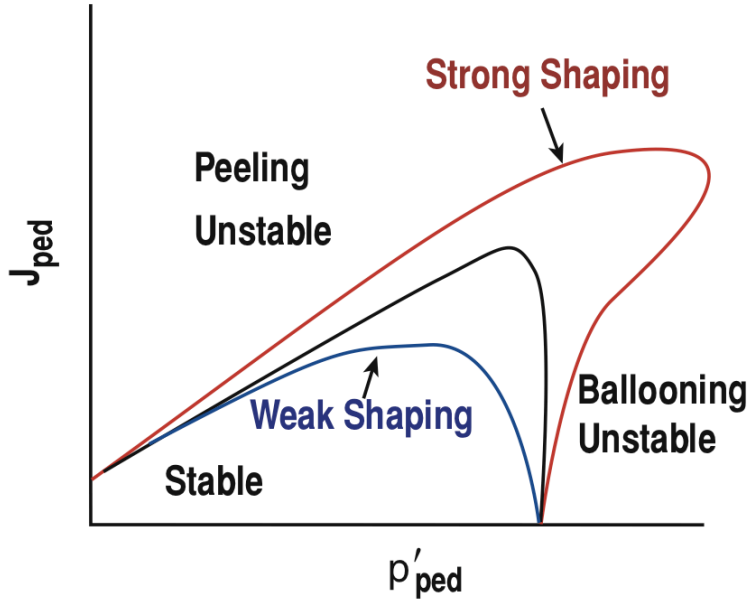

18.747 ms




24.789 ms

# Filaments Possibly Related to Peeling/Ballooning Instability

- Proposed mechanism for ELMs
- Localized edge instability
- Peeling
  - Edge current, current gradient drive
  - Stabilized by pressure gradient
- Ballooning
  - Normal pressure gradient drive
  - Stabilized by shear
- Strong stabilizing influence of shaping
  - Decouples current, shear




Snyder, Phys. Plasmas **12**, 056115, 2005

# Peeling Mode Destabilized by High Edge $j_{||}$

- Necessary peeling stability criterion: (Connor, PoP 5, 1998)

$$2\sqrt{-D_I} = \sqrt{1-4D_M} > 1 + \frac{2}{2\pi q'}\oint \frac{j_{||}B}{R^2 B_p^3}\,dl \sim \frac{j_{||}}{B}$$

where

- $D_M \propto p'$ = Mercier coefficient ($< 0$)
- $q'$ = Magnetic shear
- $j_{||}$ = Parallel edge current density

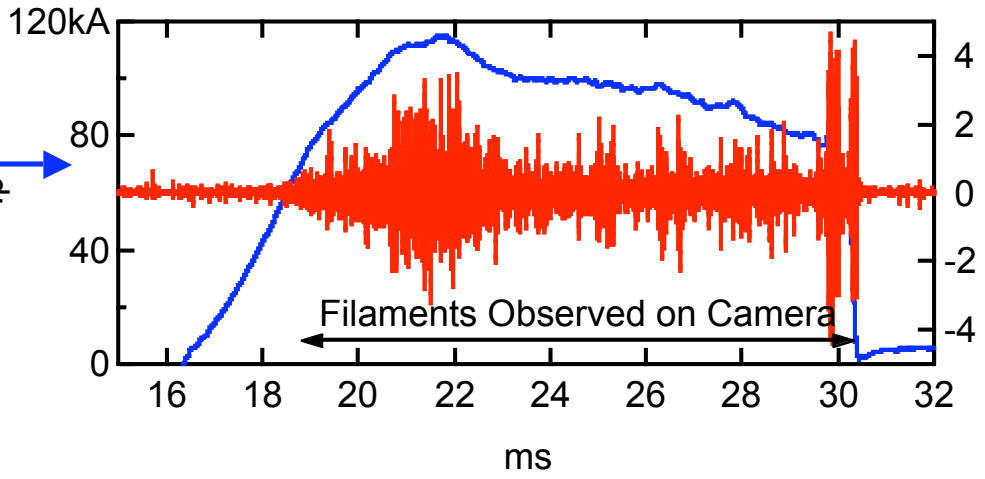
- Stability in high A, low-$\beta$, low $\nu$, weak shaping limit:

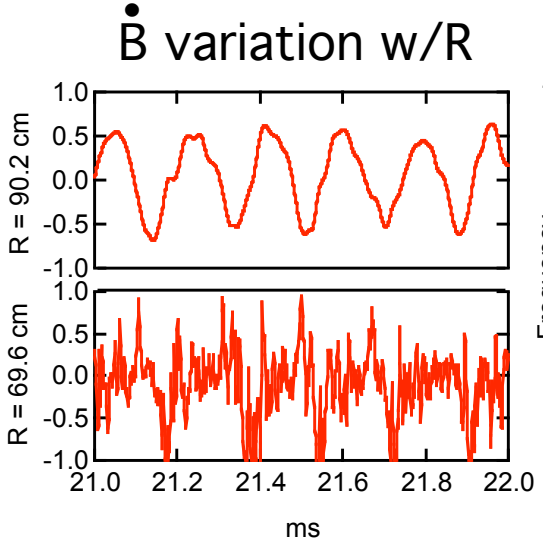
$$-D_R > \frac{Rq}{s}\left(\frac{j_{||}}{B}\right)_{edge} \qquad s \equiv \frac{r}{q}\frac{dq}{dr}$$

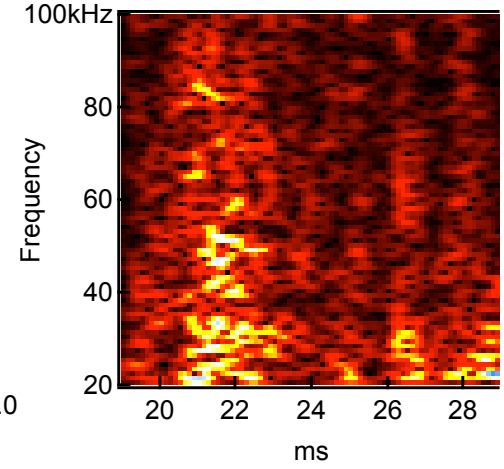
with $D_R$ ($< 0$) = GGJ resistive interchange coefficient

# Initial Magnetic Probe Data Shows Magnetic Signature of Filaments

- Visual observation of filaments correlates with high-freq. signal
  - 20-300 kHz fluctuations
- Probe must be at plasma edge to observe filament signatures
  - outboard limiter probes only see tearing mode
  - probe at scrape-off sees additional high-freq. components
- High-frequency spectrum shows broadband activity
  - intermediate n consistent with peeling mode
- Future probe arrays for more detailed measurements
  - multiple toroidal locations ⇒ n ID
  - triple probes ⇒ $n_e$, $T_e$
  - radial B-probe array ⇒ $j(R)_{edge}$



# DC helicity injection startup on PEGASUS utilizes localized washer-gun current sources (plasma guns)

- **Operation:**
  - Guns biased relative anode plate
  - $I_{inj}$ initially follows helical field lines
  - DC helicity injection rate:

$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

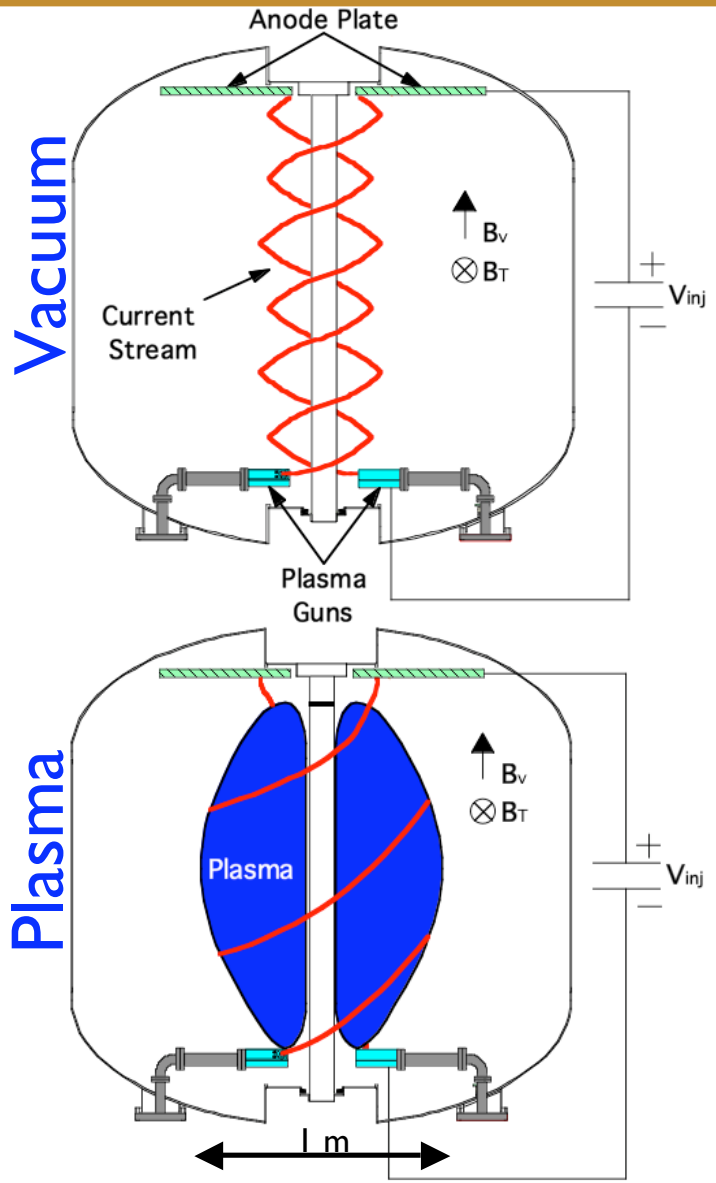
$V_{inj}$ - injector voltage

$B_N$ - normal B field at gun aperture

$A_{inj}$ - injector area

⇒ maximize helicity by increasing $A_{inj}$ & $V_{inj}$

- **Advantages of plasma gun system:**
  1. Small size = Ease of installation
  2. High current/power density
     - *~ 1 kA/cm², 1 MW/cm²*
  3. Clean operation
     - *High-Z impurities trapped in gun aperture*



# Conditions for Non-Inductive Tokamak Formation & Sustainment via DC Helicity Injection

1. Magnetic Constraints
   - $B_Z$ weak enough to allow closed flux formation
   - $B_Z$ strong enough to maintain MHD equilibrium
2. Helicity Constraint
   - Equating AC (inductive) & DC helicity injection terms:

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

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 (Helicity balance assumed)
   - Input power sufficient to sustain plasma at efficiency

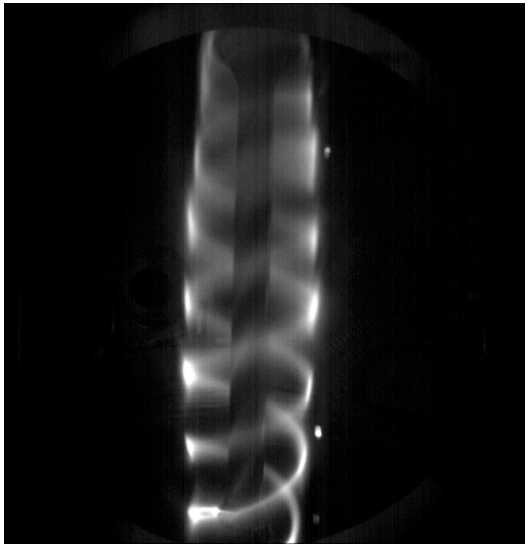
$$\varepsilon = \frac{P_{dis}}{P_{inj}} = \frac{I_\varphi}{I_{inj}}\frac{V_{eff}}{V_{inj}} = \frac{\Psi_{inj}}{\chi}\frac{I_\varphi}{I_{inj}}$$

Toroidal Current

Injected Current

# Gun Plasmas Exhibit Two Distinct Phases: Helical & Relaxed

1. High B ⇒ Current filaments follow helical vacuum field
   - Visuals: Discrete filaments or continuous sheet (due to curvature, grad-B drift)
   - Current multiplication ($M = I_\phi / I_{inj}$) determined by vacuum geometric stacking (G)
2. Low B ($B_T \approx 0.01$ T, $B_Z \approx 0.005$ T) ⇒ Relaxation to tokamak-like plasma
   - M not limited by G



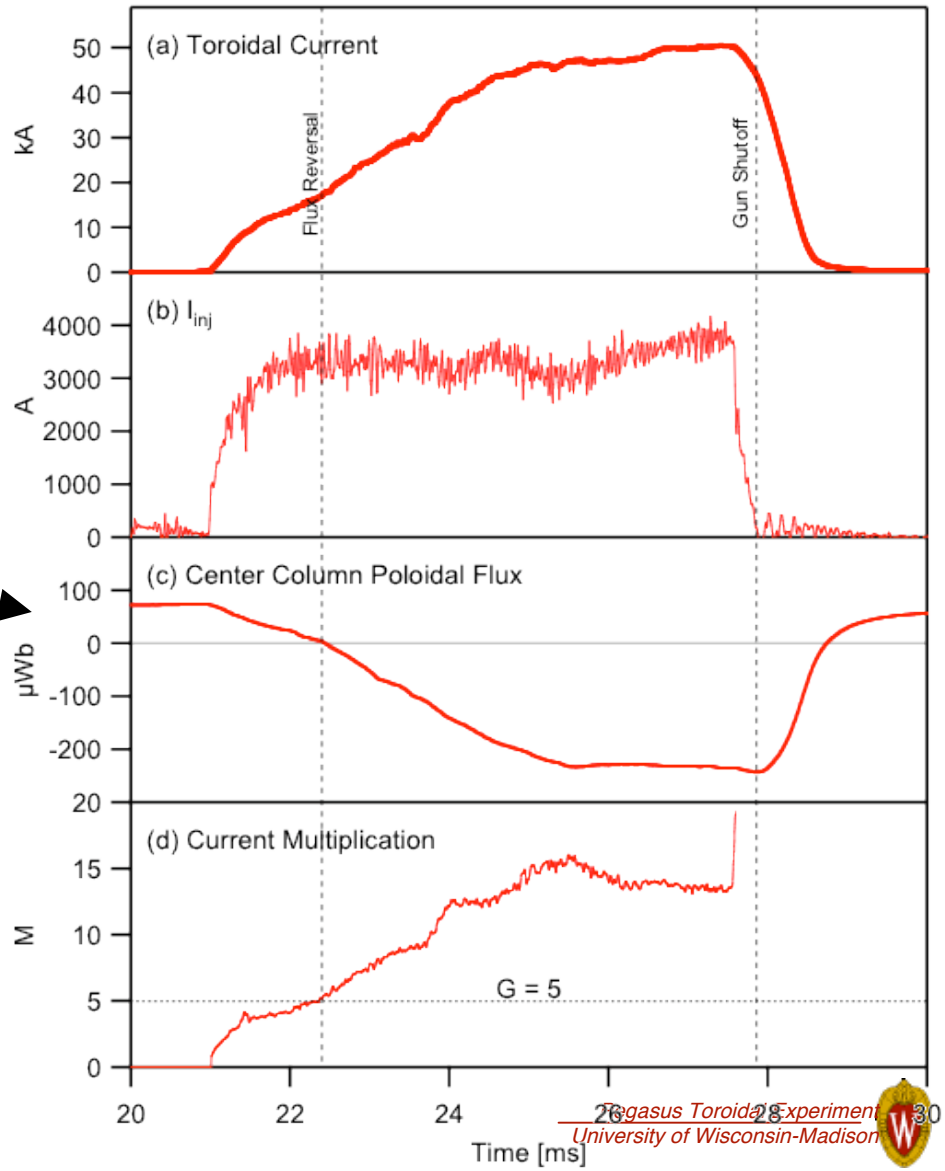
(1a) Filaments



(2) Relaxed

# Relaxation Enables Increased Current Drive

- $I_\phi$ > 50 kA driven by $I_{inj}$ ≤ 4 kA
- Static mid-vessel fields:
  - $B_V$= 0.007 T
  - $B_T$ = 0.011 T
- Poloidal flux reversal ⇒ relaxation
  - plasma $B_v$ > vac. $B_v$
- Maximum M = 15
  - M ≈ 3x G
- $\tau_{plasma}$, $\tau_{gun}$ decoupled
  - $I_\phi$ > 40 kA after $I_{inj}$ = 0



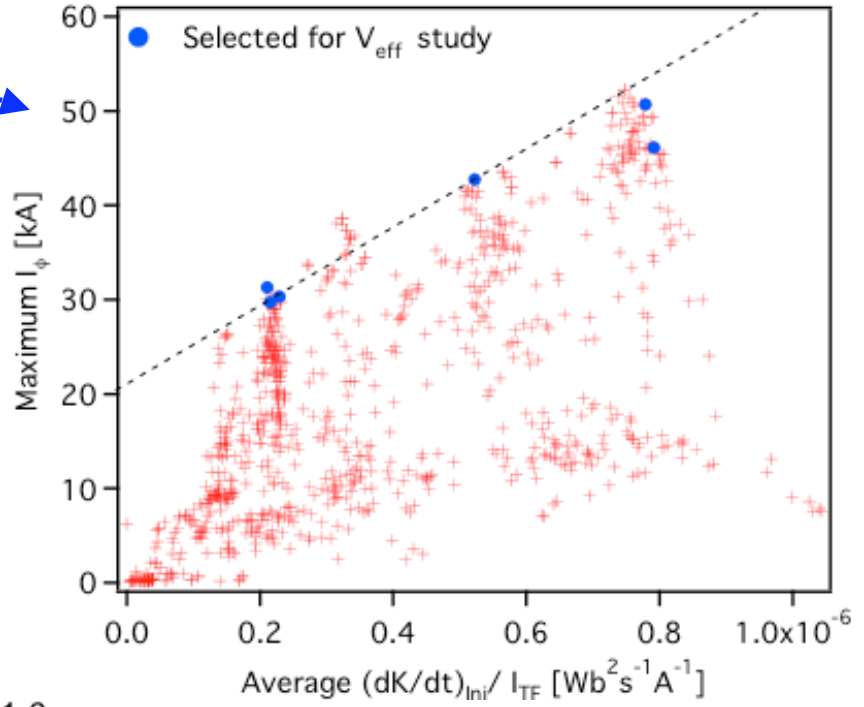
# Helicity Balance Determines Maximum Current

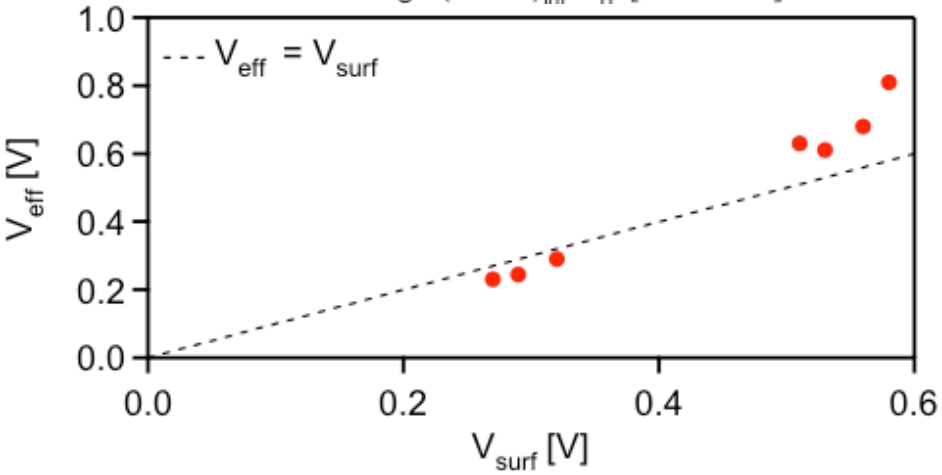
- Max $I_\phi$ offset linear to injected dK/dt

- Decay $V_{loop}$ estimated by $V_{surf}$
  - Measured by center column flux loop

$$V_{eff} \approx V_{inj} \frac{N_{inj} A_{inj} B_{Tinj}}{A_p B_{Tp}}$$

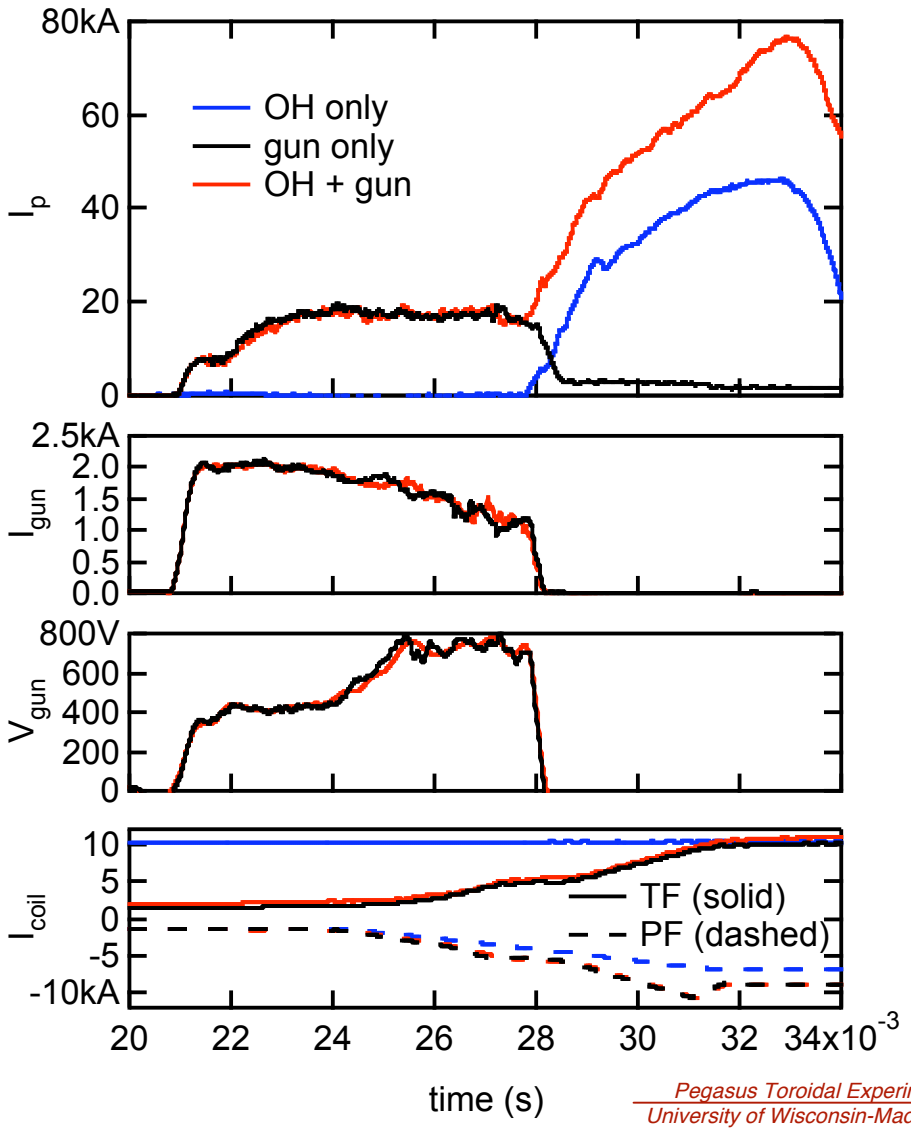
- $V_{eff} \approx V_{surf}$ indicates:
  1. Helicity efficiently transported into plasma
  2. Current drive limited by helicity injection rate



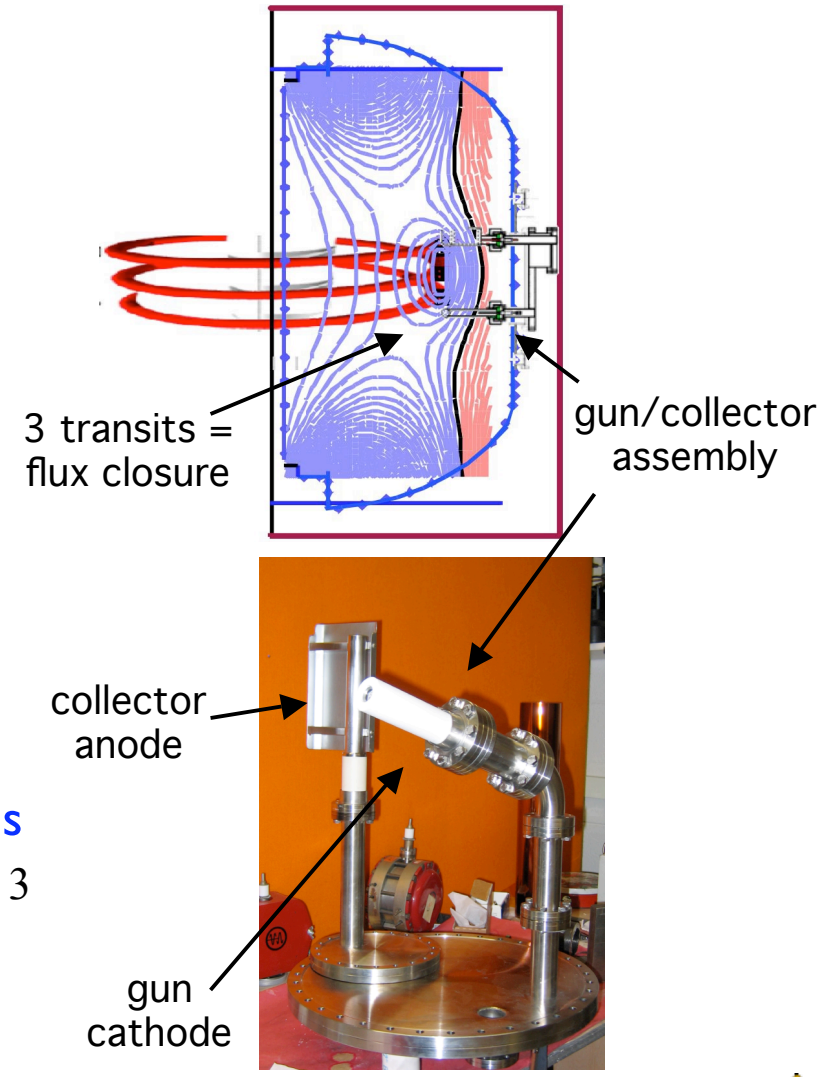
# Relaxed Gun Plasmas Coupled to Ohmic Drive

- Combined $I_\phi$ = gun only $I_\phi$ + OH only $I_\phi$
- Optimal hand-off at gun shut-off
  - early handoff ⇒ current driven on open field lines
- Field ramps required for OH compatibility



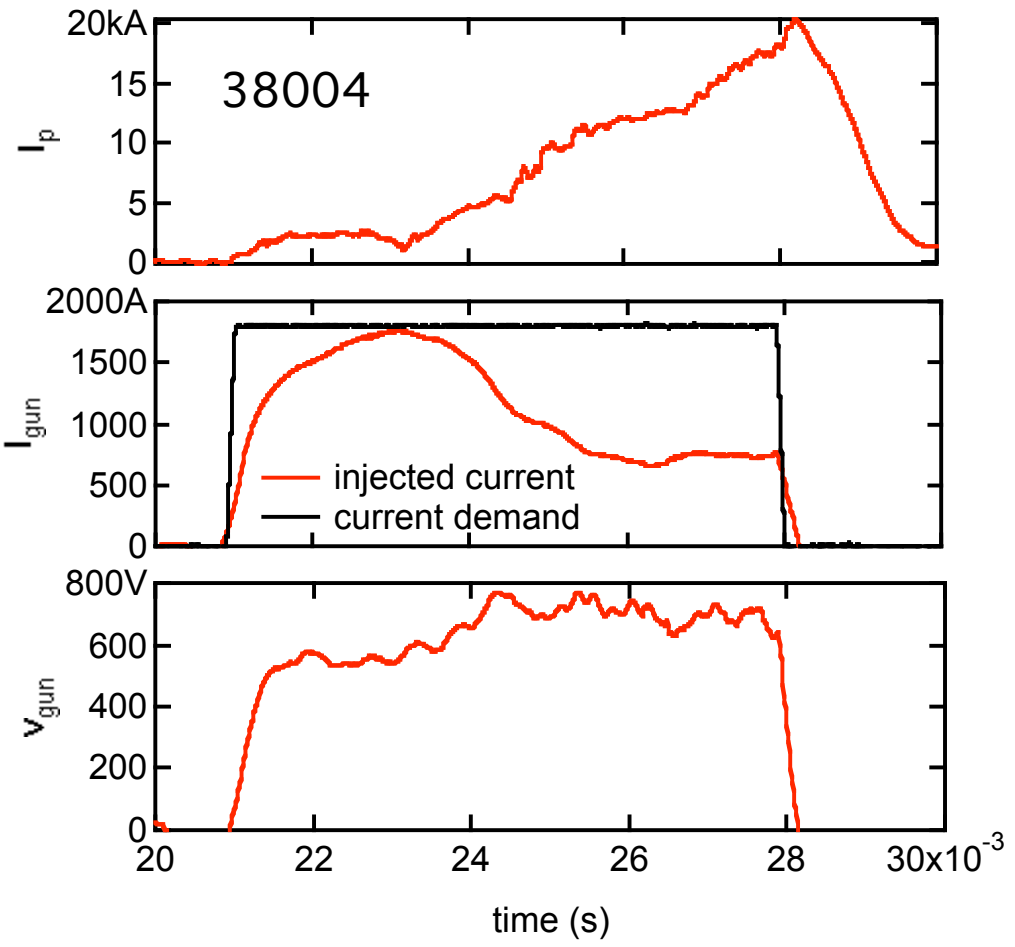
# Midplane Gun Geometry Scales to Larger Experiments

- Possible advantages of midplane guns:
  - Engineering
    - *midplane port access available for most machines*
    - *no high heat loads in diverted discharges*
  - Physics
    - *larger R plasma has longer L/R decay*
    - *low field pitch for relaxation allows for higher TF*
    - *longer path length/transit gives higher resistivity ⇒ higher injection voltage*
- Prototype midplane gun tested on Pegasus
  - single 2 kA gun should give flux closure with 3 toroidal transits
  - PF induction to ramp up $I_p$ further



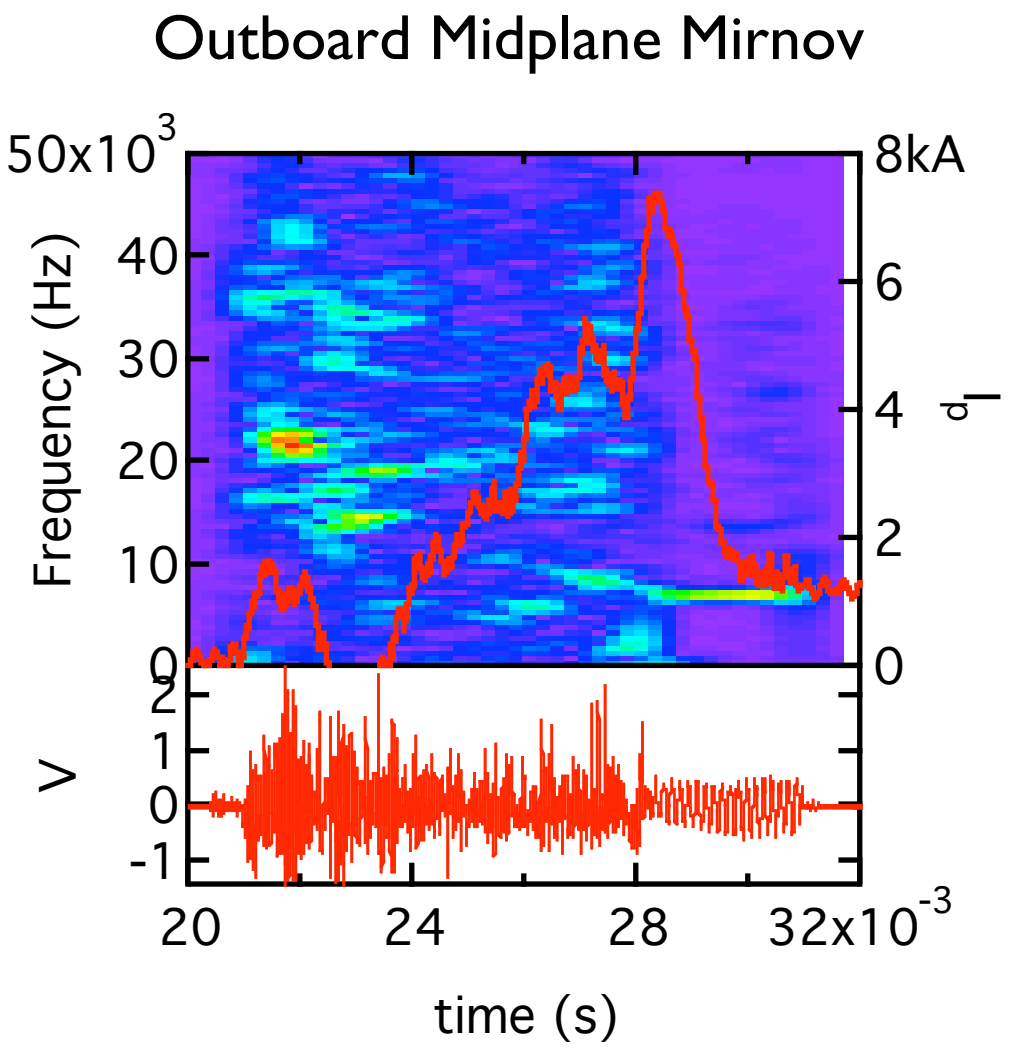
# Midplane Gun Used to Create Relaxed Discharges

- Driven current is limited by power supply voltage
  - higher voltage may allow more injected helicity
- $I_p$ = 20 kA for $I_{gun}$ = 750 A
  - M = 26
  - static fields
  - very encouraging for low-power prototype test
- Tokamak-like discharge with R = 0.4 m observed after gun off
  - $I_p$ decay much longer than $I_{gun}$ decay



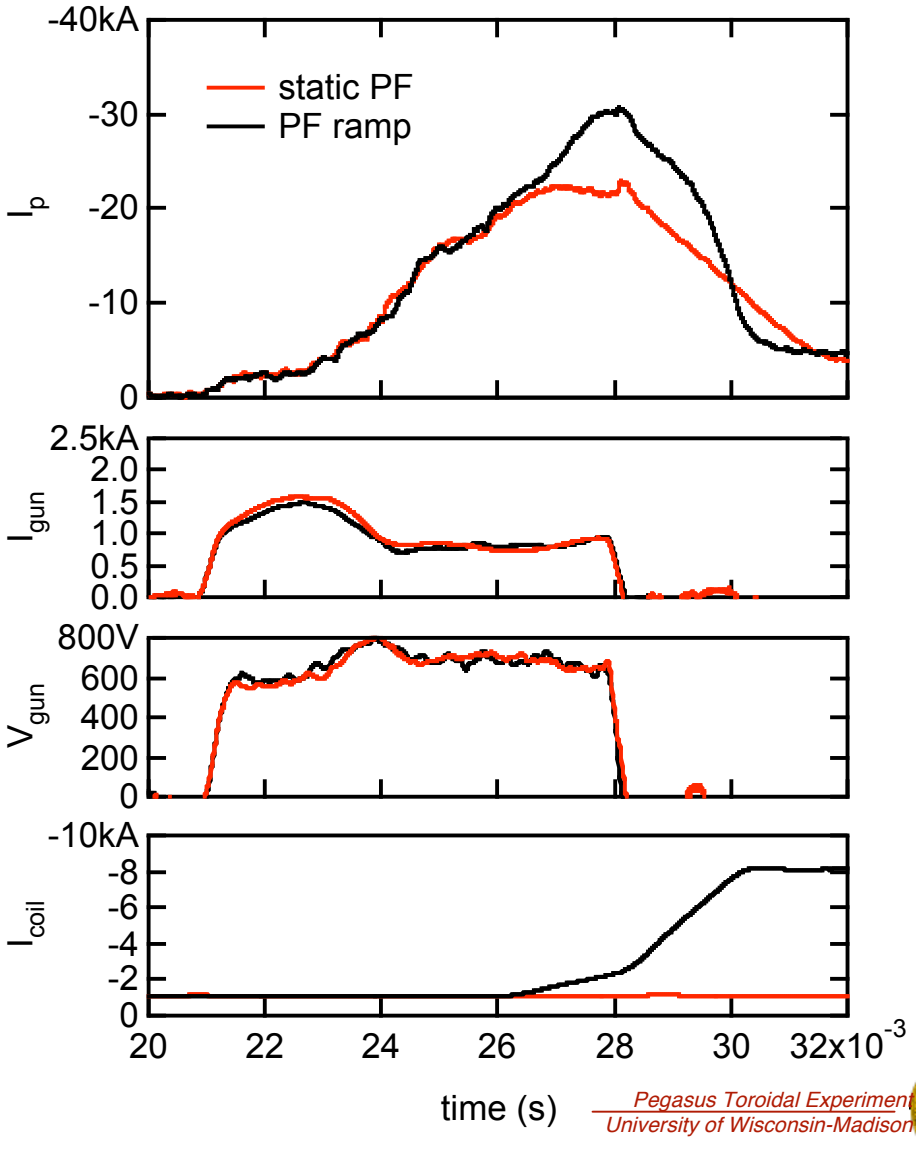
# Coherent MHD After Gun Shut-Off Indicates Flux Closure

- 22 kHz mode present during unrelaxed phase
  - less coherent activity during relaxation
- 7 kHz mode appears while plasma is in decay phase
  - similar frequency to typically observed TM in Pegasus
- Mode decreases in amplitude and duration with lower pre-fill pressure and higher $I_p$
  - hotter discharge?



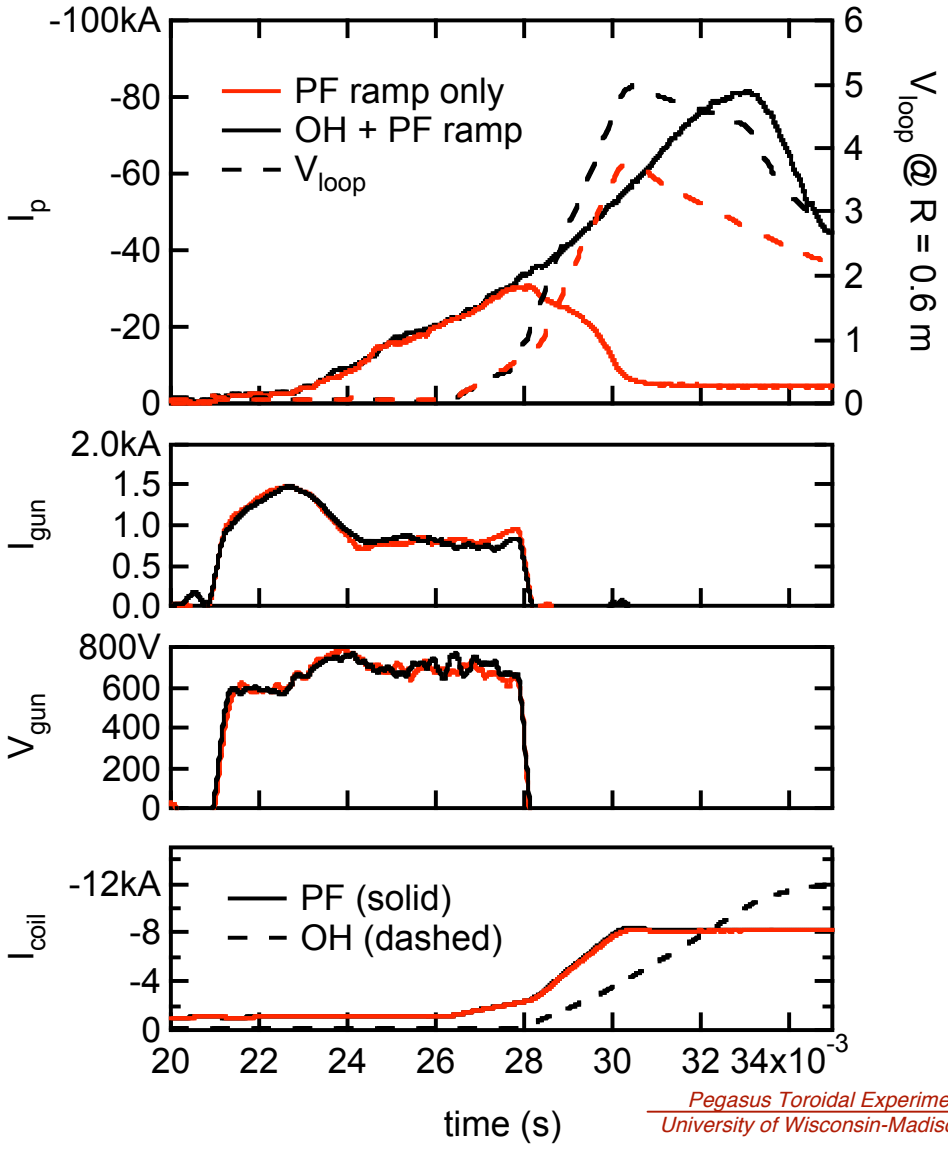
# PF Induction Enhances $I_p$

- PF induction before gun shut off increases $I_p$ by ~ 50%
  - limited by radial force balance
  - high $B_v$ during injection causes plasma detachment from gun
- Fast PF ramp after gun off drives plasma into core
- PF induction insufficient to sustain midplane gun discharge in this configuration
  - possibly more effective with higher target current
  - next generation, high-power gun array will give further test



# OH Induction Couples Readily to Midplane Gun Discharge

- Additional OH $v_{loop}$ does not affect radial force balance
- OH plasma still moves in radially, but much more slowly
- Handoff much easier than with divertor guns
  - larger R plasma has longer L/R decay
- Operations halted to install higher power guns
  - all results to date with simple prototype single gun
  - high power gun array being installed 11/07



# High Power Gun Array Being Installed

- 3-gun array at single toroidal location
  - 3x current of prototype
  - still use single anode
  - broad scrape-off should allow simultaneous injection
- High-voltage power supply in design
  - should allow more injected helicity
- Initial tests 12/07
  - existing power supplies
  - optimize gun configuration

⇒ New array & power supplies should easily give > 100 kA relaxed gun plasma



# Pegasus is Ready to Perform Detailed Studies of Edge Stability and Create High-Power Non-Solenoidal Discharges

- Exploration of high $I_N$ space continues
  - recent TF ramp-down experiments reach new OH record ($I_N \sim 12$)
- Capability to determine detailed stability characteristics of edge filaments is being developed
  - initial magnetic measurements show mode characteristics consistent with peeling mode
  - expanded probe array is in design stage
    - *j(R) at edge with insertable magnetic probes*
    - *Langmuir probe array for edge $n_e$, $T_e$*
- Outboard midplane gun startup results show great promise
  - initial work on divertor guns allowed for general understanding of gun startup
  - midplane gun able to surpass divertor gun performance
  - high-power midplane gun array being deployed
    - *hardware for 3-gun array currently being installed*
    - *higher voltage power supply in design stage*

# Reprints