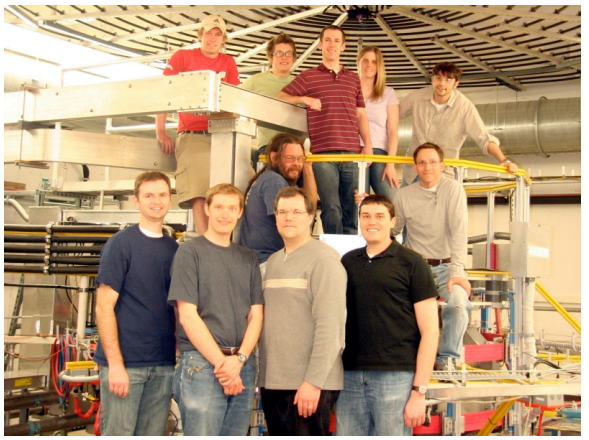
# Non-Solenoidal Plasma Startup in the Pegasus Toroidal Experiment

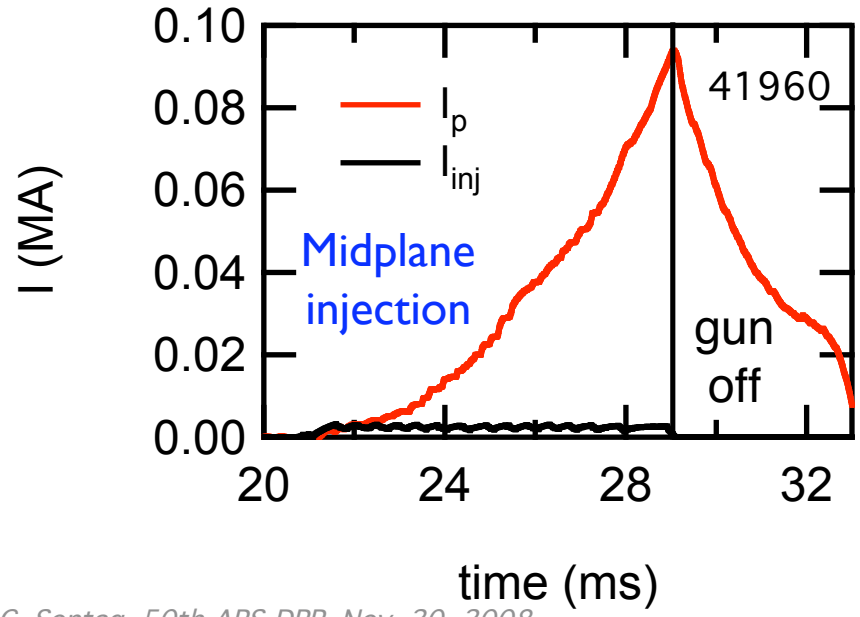
A.C. Sontag

for the Pegasus Research Team

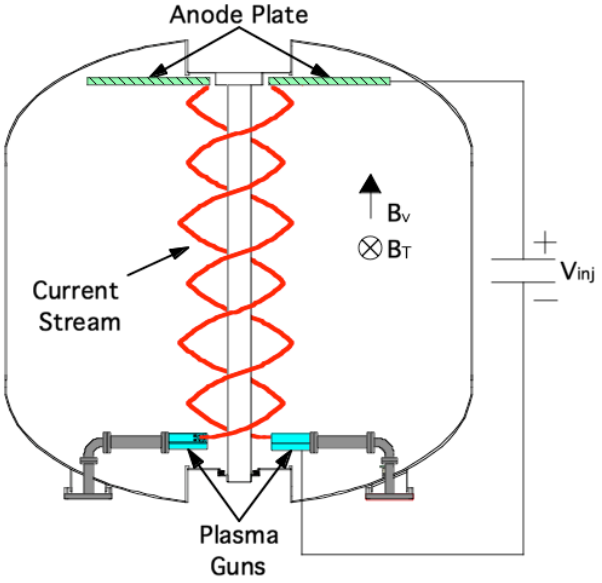


# Point-Source DC Helicity Injection Provides Viable Non-Solenoidal Startup Technique

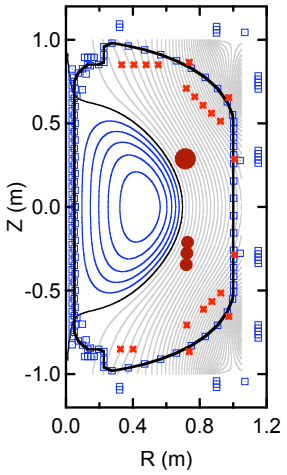
- Plasma guns provide localized, point-current source at plasma edge
- Technique appears to be flexible & scalable to larger currents & devices
- Up to 0.1 MA plasma current to date




Divertor injection




Midplane injection

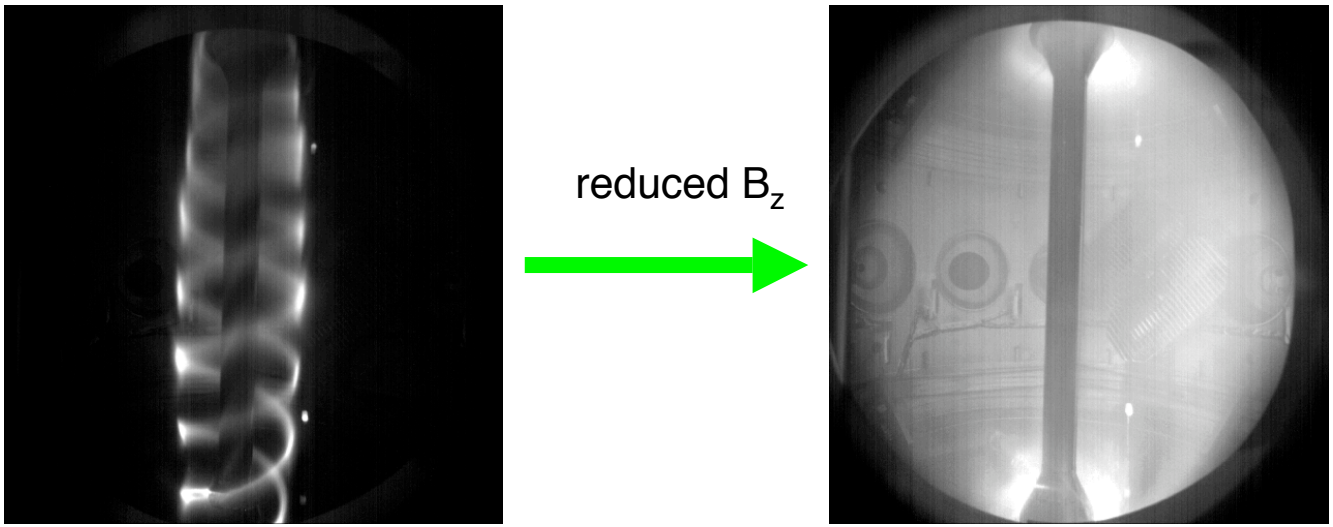



At gun shut-off:

$I_p$ = 94 kA
$R_0$ = 0.45 m
$\ell_i$ = 0.35
$\kappa$ = 1.6
$\beta_p$ = 0.22
$W_{tot}$ = 350 J

# Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme*

- Inject current into existing helical magnetic field
  - high $I_{inj}$ & modest B ⇒ current filaments follow field lines
    - *toroidal current = $I_{inj}$*geometric windup*
  - high $I_{inj}$ & low B ⇒ current-driven $B_\theta$ overwhelms vac. $B_z$
    - *relaxation via MHD to tokamak-like Taylor state w/ poloidal flux amplification*




*M. Ono, et *al.*, Phys. Rev. Lett. 59, 2165-2168 (1987)

# Pegasus is Studying Physics of Plasma Gun Startup & Using Technique to Access High-$I_N$

- Critical ST issue: plasma startup and ramp-up (FESAC TAP report)
- Relaxation through simultaneous satisfaction of multiple constraints
- Plasma gun startup readily coupled to other current drive
- Edge current drive allows access to high-$I_N$ via j(R) manipulation
- Goal: develop understanding to project to fully non-solenoidal operation with RF growth & sustainment of plasma gun target

# Point-Current Source Injection Allows Geometric Flexibility

- **Operation:**
  - Guns biased relative to anode
  - DC helicity injection rate:

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

$V_{inj}$ - injector voltage

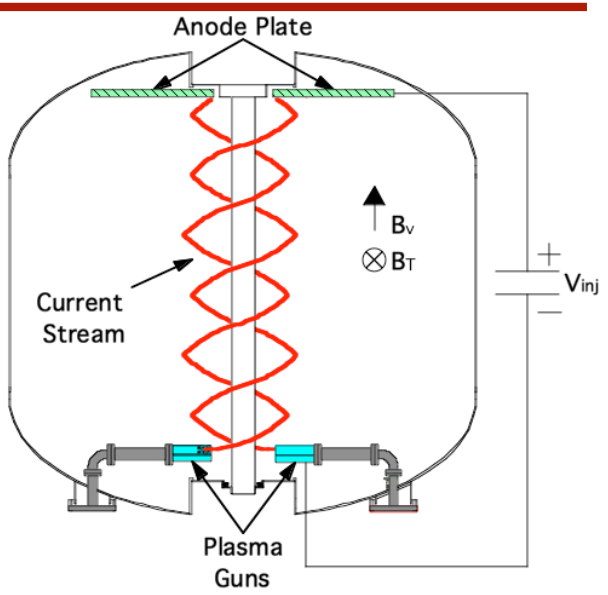
$B_N$ - normal B field at gun aperture

$A_{inj}$ - injector area

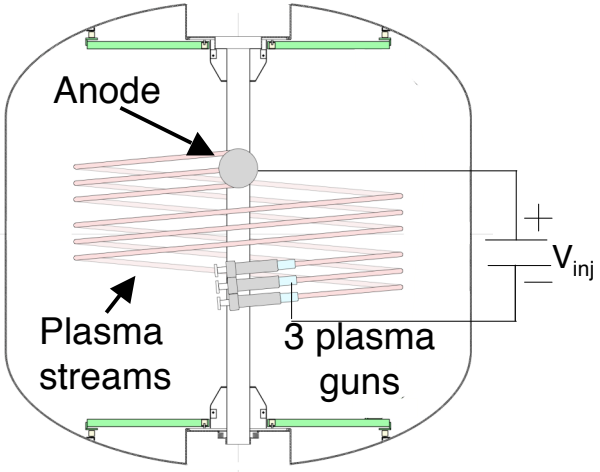
⇒ maximize helicity by increasing $B$, $A_{inj}$ & $V_{inj}$

- **Advantages of plasma gun system:**
  1. Potentially scalable to large facilities
  2. Flexible geometry possible
  3. Clean operation
     - *High-Z impurities trapped inside gun*

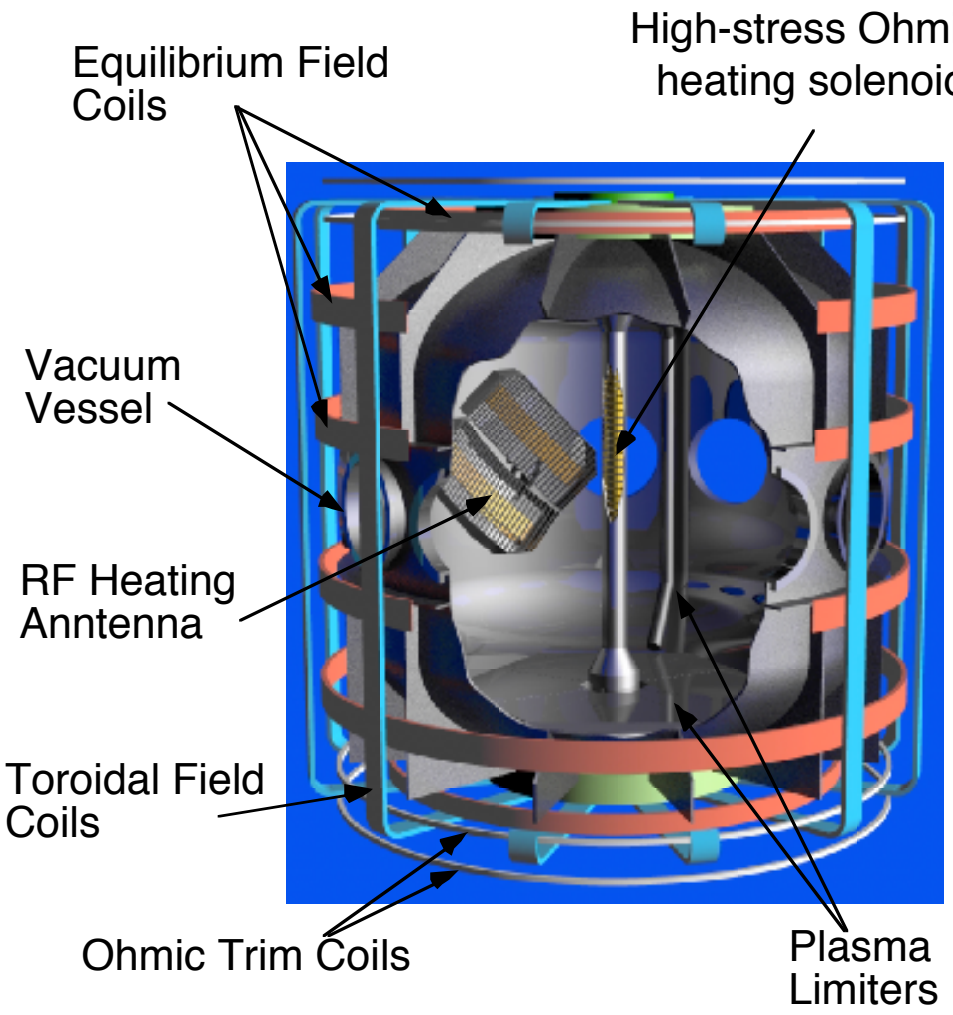
Divertor injection




Midplane injecton

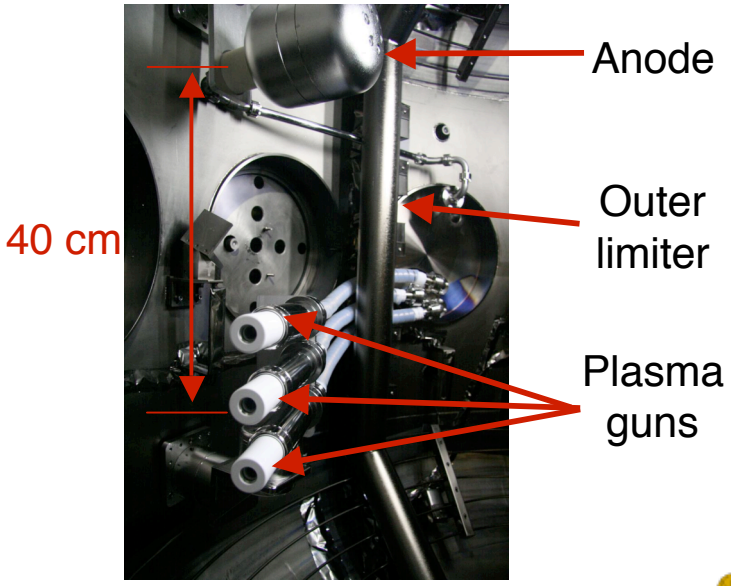


# Pegasus Operates at Near-Unity A to Study High-$I_N$, $\beta_t$ ST Regime




**Experimental Parameters**

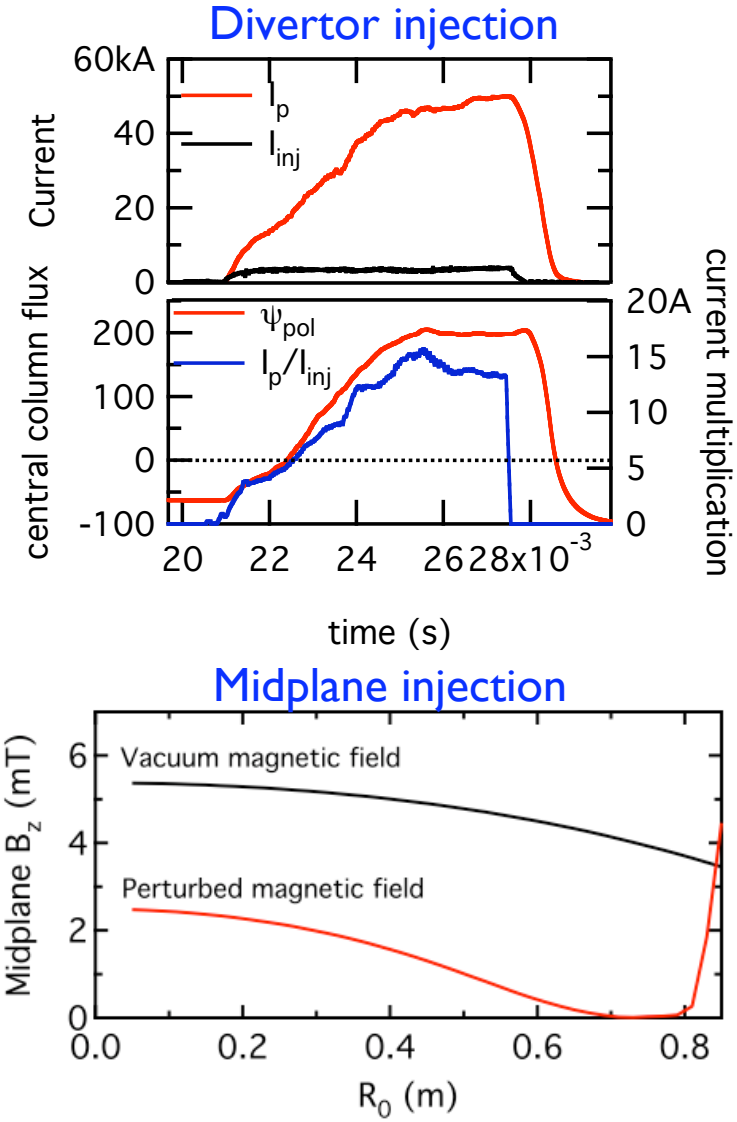
| Parameter | Achieved | Goals |
|---|---|---|
| A | 1.15-1.3 | 1.12-1.3 |
| R (m) | 0.2-0.45 | 0.2-0.45 |
| $I_p$ (MA) | ≤ 0.18 | ≤ 0.30 |
| $I_N$ (MA/m-T) | 6-12 | 6-20 |
| $RB_t$ (T-m) | ≤ 0.06 | ≤ 0.1 |
| $\kappa$ | 1.4–3.7 | 1.4–3.7 |
| $\tau_{shot}$ (s) | ≤ 0.02 | ≤ 0.05 |
| $\beta_t$ (%) | ≤ 25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



# Several Constraints Must Be Satisfied for Relaxation to a Tokamak-Like State

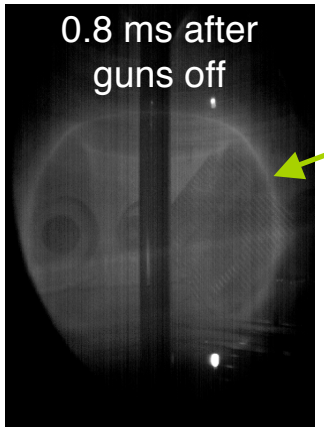
- Conditions for relaxation to occur:
  - $B_v$: low to allow null formation
  - $B_{TF}$: high to increase helicity injection
  - $B_v$, $B_{TF}$: tokamak equilibrium - force balance, $q_a$
  - $B_v/B_{TF}$: avoid collision with injector hardware

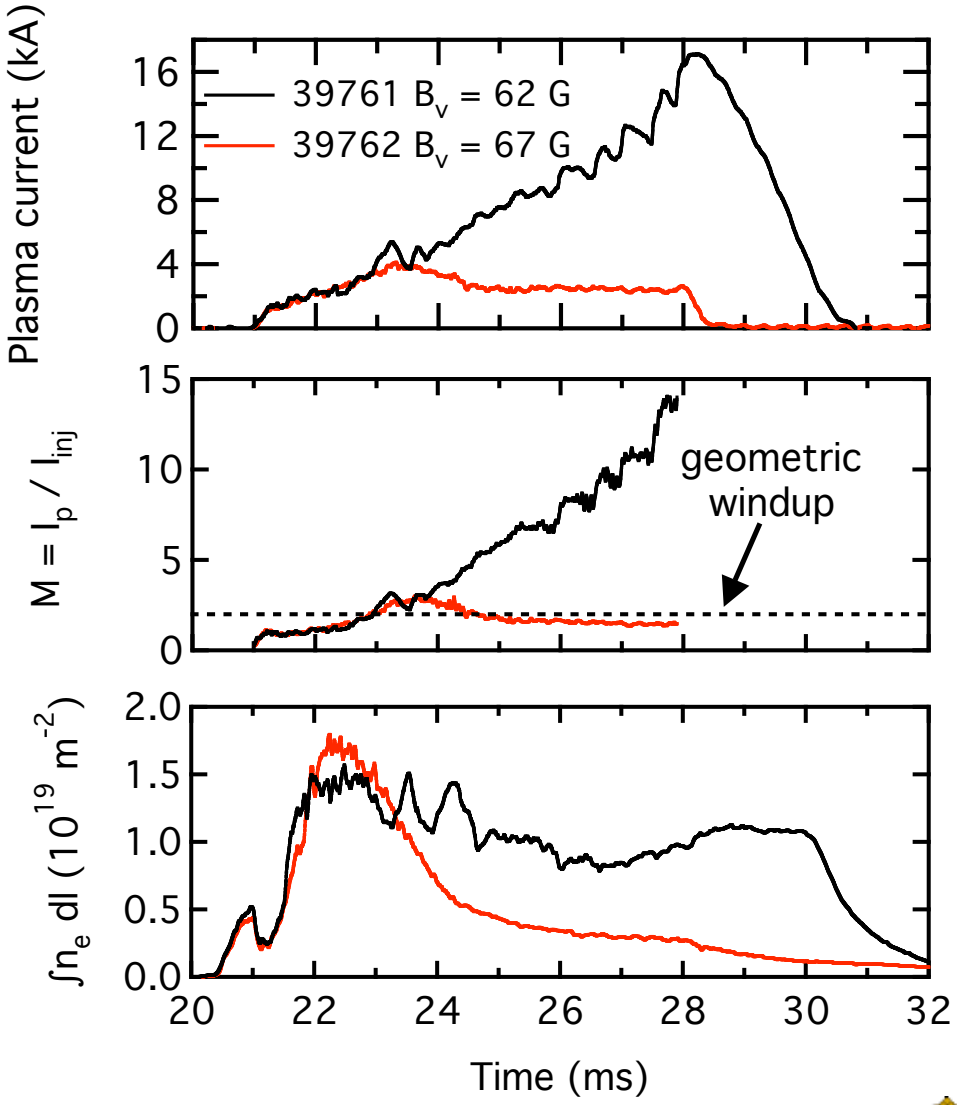
- Consistent with experimental observations
  - divertor injection:
    - *center-post limited discharges*
    - *relaxation coincides with reversal of central poloidal flux*
  - midplane injection:
    - *plasma modeled as set of axisymmetric filaments*
    - *perturbed magnetic field shows null in relaxed cases*



# Relaxation to a Tokamak-Like State Leads to Particle Confinement & Heating

- Relaxation to tokamak-like state very sensitive to applied $B_v$
  - consistent with null formation
- Relaxed state appears tokamak-like
  - current multiplication
  - particle confinement
  - increased decay time
  - suggestion of higher $T_e$
  - subject to radial force balance



# The Maximum $I_p$ is Determined by the Balance Between Helicity Injection and Resistive Dissipation

Total helicity injection rate in tokamak geometry:

$$\frac{dK}{dt} = \underbrace{-2\int_V \eta \mathbf{J}\cdot\mathbf{B}\,\mathrm{d}^3x}_{\text{resistive dissipation}} \underbrace{-2\frac{\partial\psi}{\partial t}\Psi}_{\text{AC injection (inductive drive)}} \underbrace{-2\int_A \Phi\mathbf{B}\cdot\mathrm{d}\mathbf{s}}_{\text{DC injection}}$$

$$\dot{K}_{AC} = -2\frac{\partial\psi}{\partial t}\Psi = 2V_{loop}\Psi \qquad \dot{K}_{DC} = -2\int_A \Phi\mathbf{B}\cdot\mathrm{d}\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$$

DC term is recast as effective $V_{loop}$ :

$$V_{eff} = \frac{N_{inj}A_{inj}B_{\phi,inj}}{\Psi}V_{bias}$$

- $I_p$ given by self-consistent confinement modeling with $V_{loop} \sim V_{eff} + V_{ind}$
  - *standard tokamak scaling is useful in regime where perpendicular losses dominate*

# Taylor Relaxation Criteria Also Limits the Total Sustainable $I_p$ for a Given Plasma Geometry

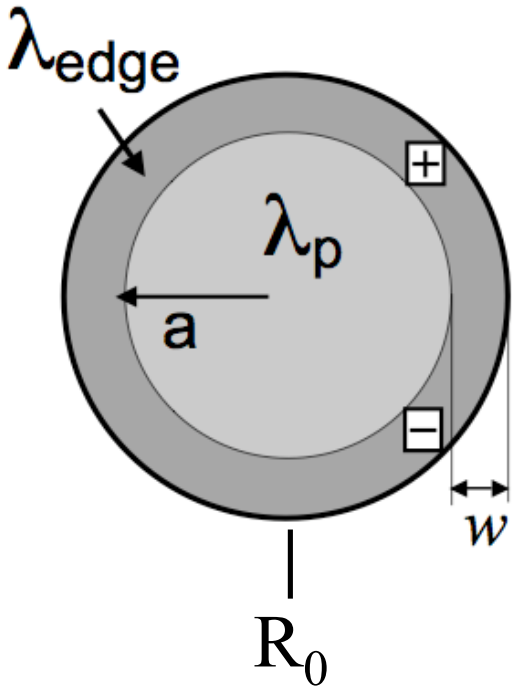
Considering force-free equilibrium:

$$\nabla \times B = \mu_0 J = \lambda B$$

Current penetration via Taylor relaxation gives:

$$\overline{\lambda}_{plasma} < \overline{\lambda}_{edge} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi} \leq \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}}$$

$$\Rightarrow \quad I_p \leq \left[ \frac{C_p}{2\pi R_{inj} \mu_0} \frac{\Psi I_{inj}}{w} \right]^{1/2}$$

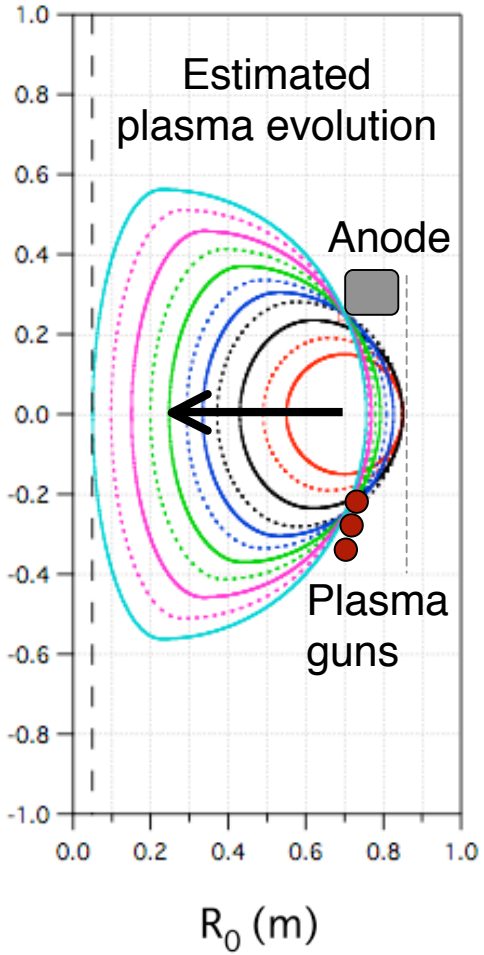


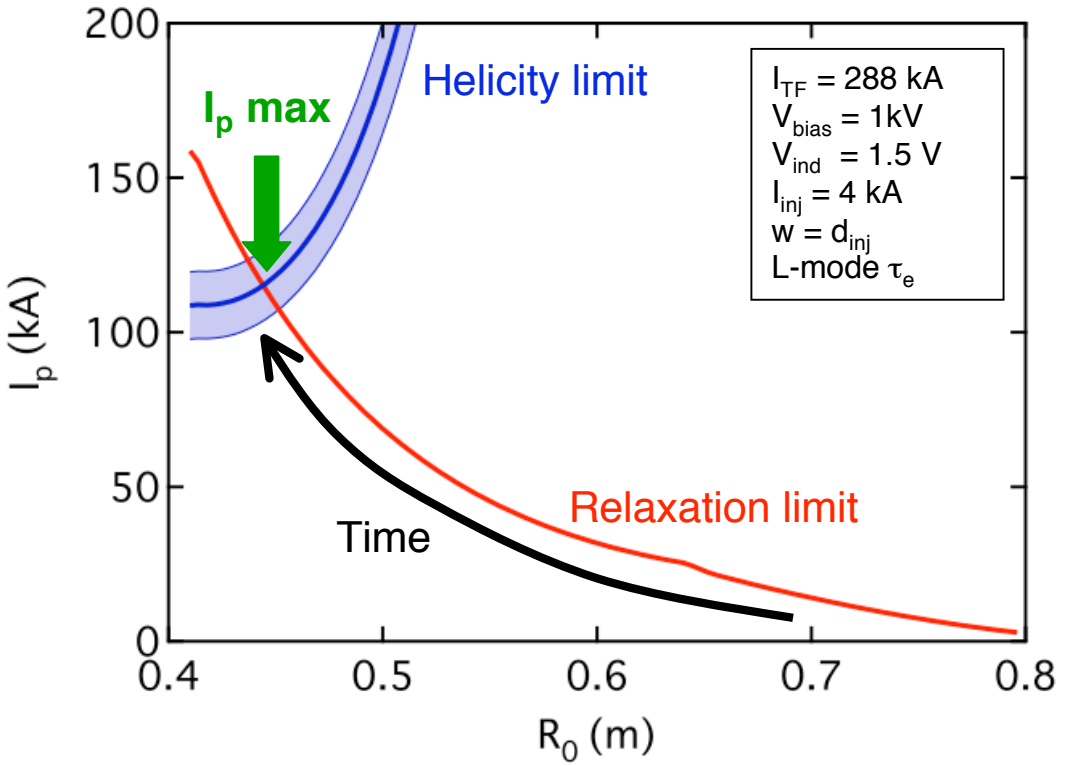

Assumptions:

- Force-free equilibrium:
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

$A_p$ Plasma area
$C_p$ Plasma circumference
$\Psi$ Plasma toroidal flux
$w$ SOL width w/ j≠ 0

# Max $I_p$ Achieved When Helicity and Relaxation Criteria are Simultaneously Satisfied




- Requires $B_v$ ramp for radial force balance & $V_{ind}$

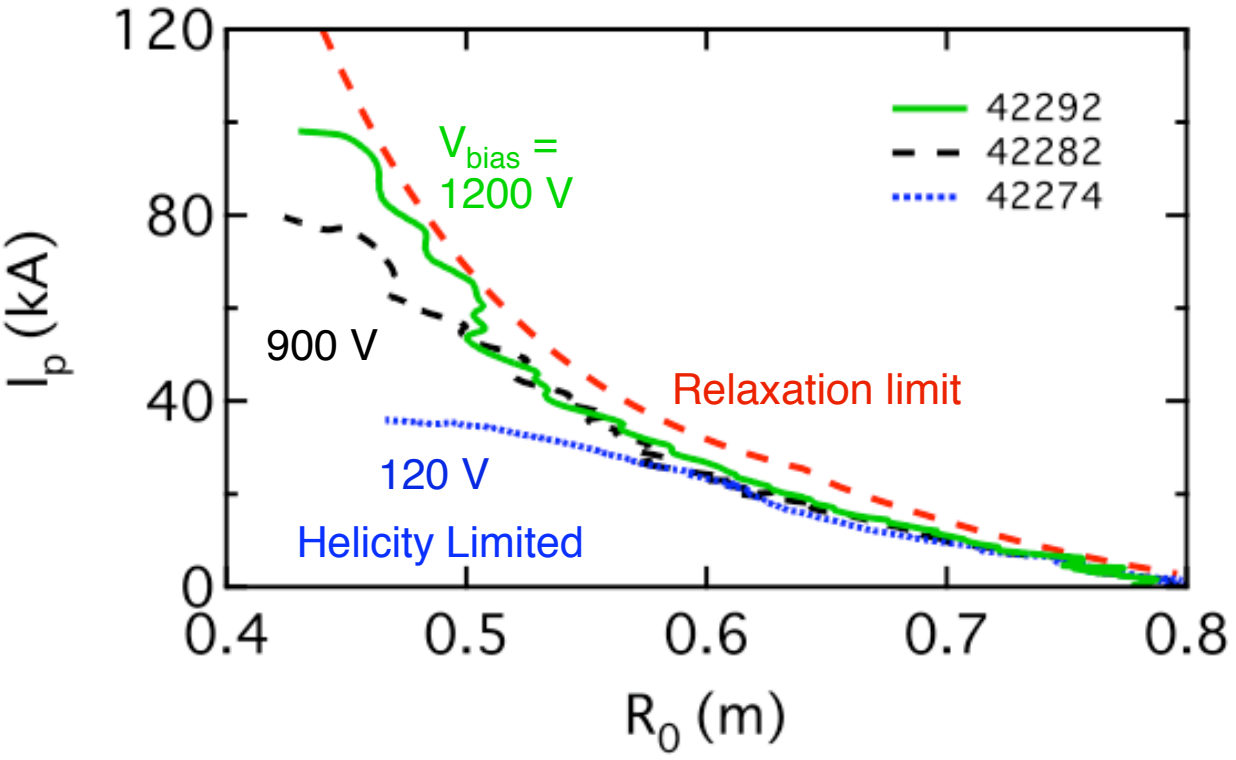
# Sufficient Helicity Injection is Required to Drive Plasma to the Relaxation Limit

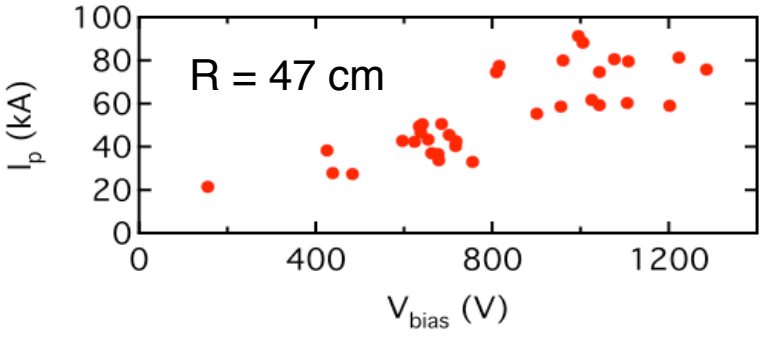
- Helicity injection rate varied by changing $V_{bias}$

$$\dot{K}_{DC} \propto V_{bias} \propto Z_{inj}$$

  - Injector impedance controlled by neutral fueling

- $I_p$ increases with $V_{bias}$, helicity injection rate

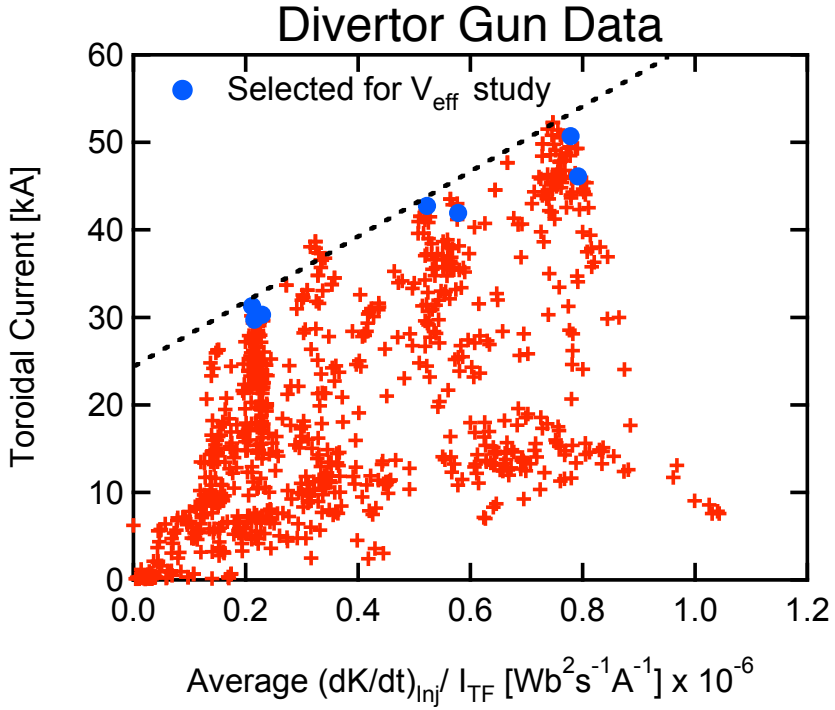


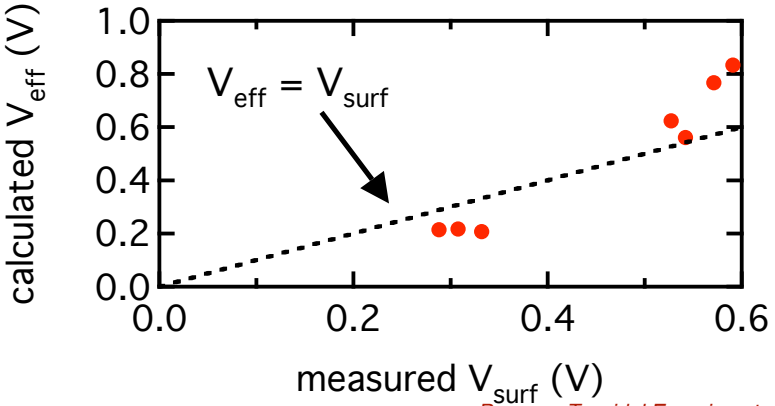



# Helicity Balance Provides One Limit on Current

- Max $I_p$ appears limited by injected helicity for divertor gun data
  - all cases with static external fields
    $\Rightarrow$ *no inductive* $V_{loop}$

- $V_{eff} \approx V_{surf}$ supports helicity conservation:
  - $V_{loop} \approx V_{surf}$ at gun shut-off
  - measured by center column flux loop
  - helicity efficiently transported into plasma
  - current drive limited by helicity injection rate



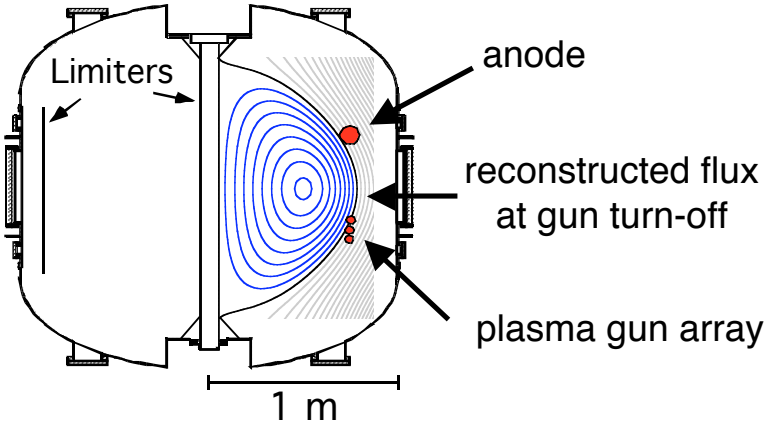



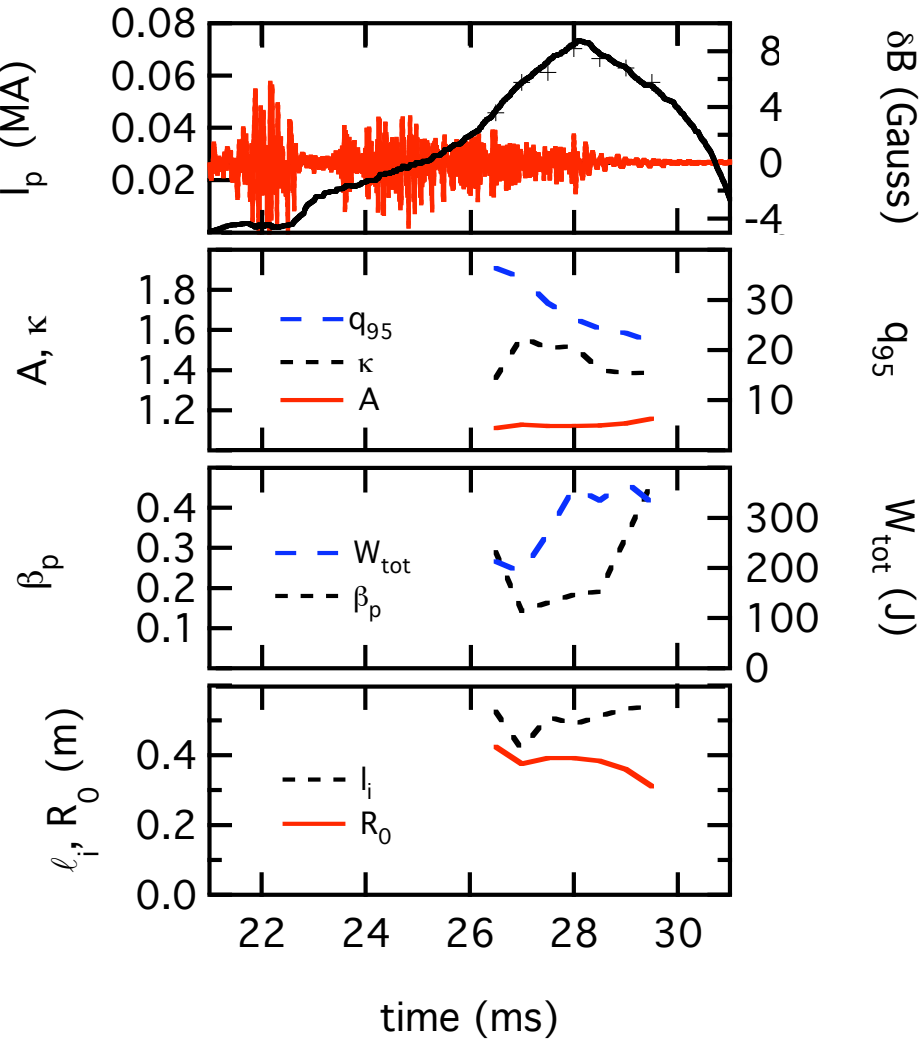


Pegasus Toroidal Experiment
University of Wisconsin-Madison

# Relaxed Gun Plasma Exhibits Increased Stored Energy and Confinement after Gun Turn-Off

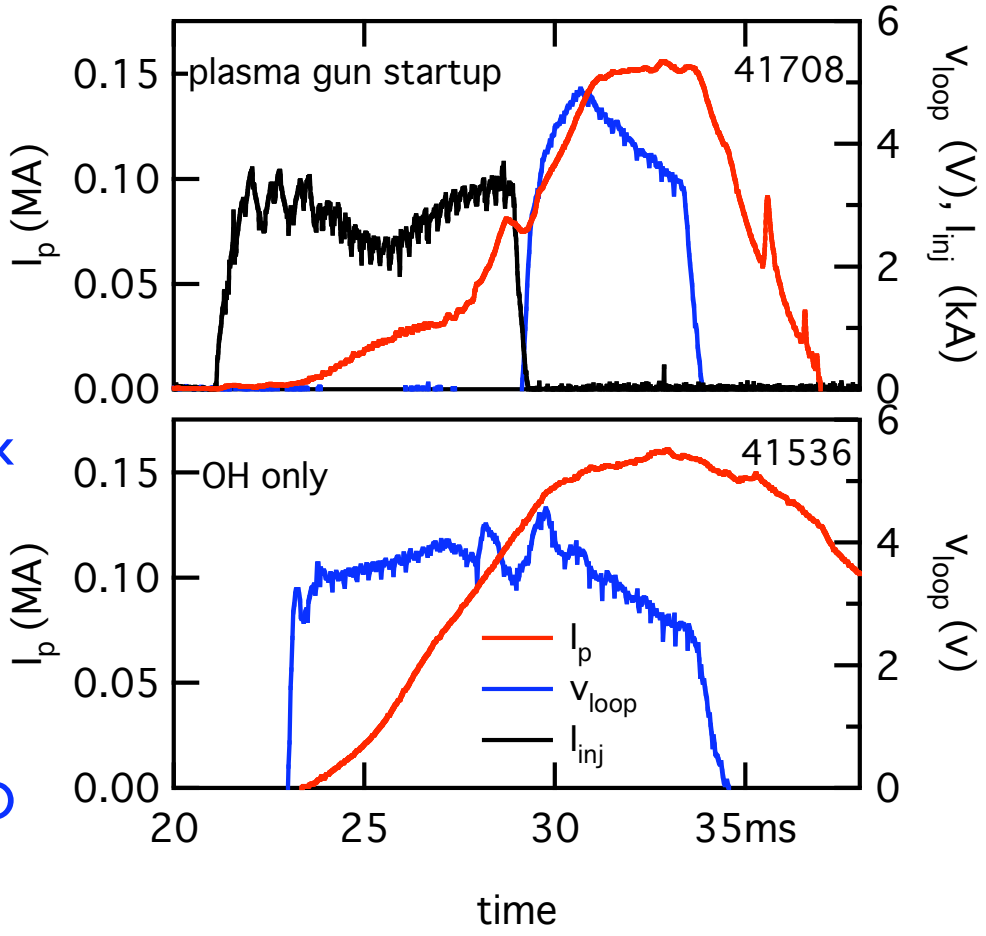
- 3-gun array: up to ~ 0.1 MA
  - PF induction adds AC helicity/CD
  - helicity input limited by power supply voltage
- Magnetic equilibrium reconstructions for plasma characteristics
  - stored energy steady during compression
  - maximum Ip when plasma fills vessel



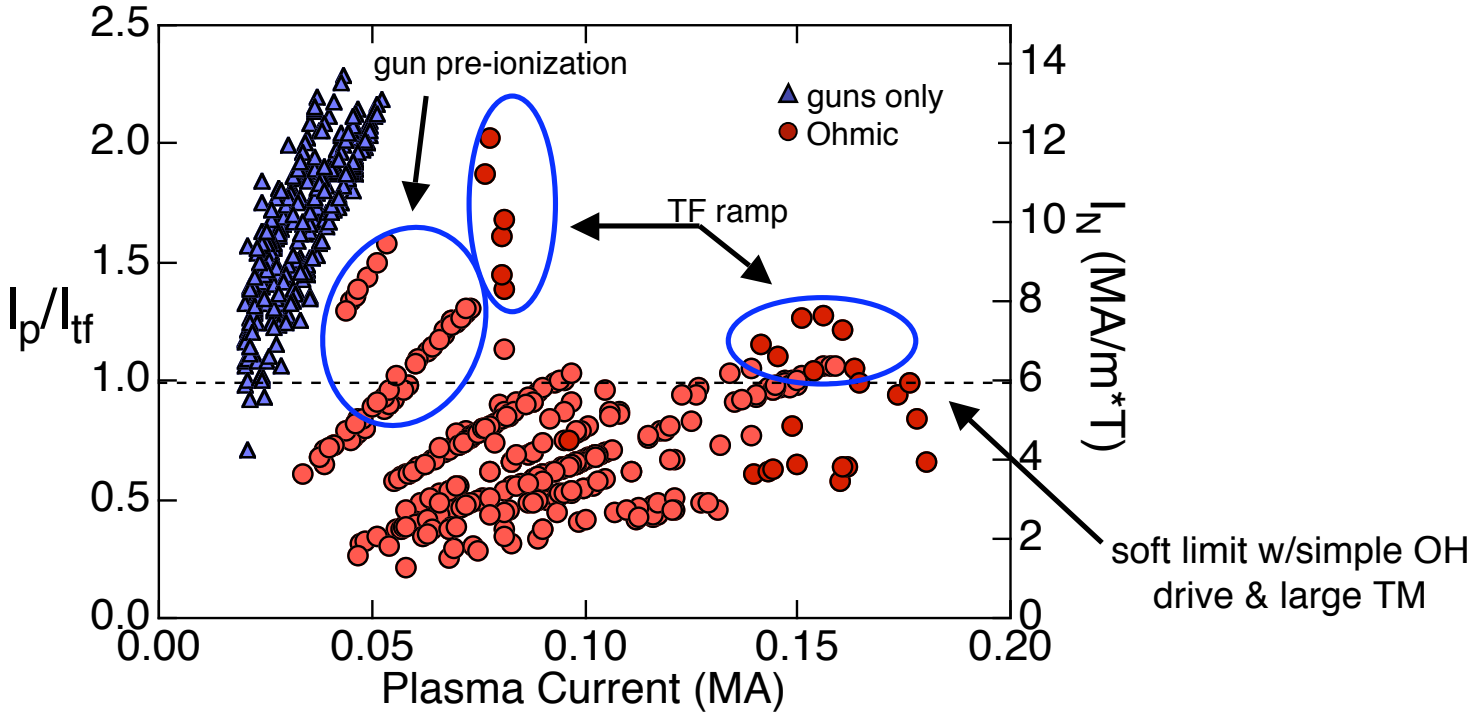
# Plasma Gun Startup Provides Robust Target Plasma for Consequent Ramp-Up and Sustainment

- e.g.: to OH CD
- 3-gun target then OH drive
  - pre-OH plasma ~80 kA
- Equivalent $I_p$ with 1/2 OH flux swing
  - ~ 50% flux savings
- Develop further to optimize target suitability for other CD



# $I_N > 12$, $I_p/I_{TF} > 2$ Readily Accessed at Low-A

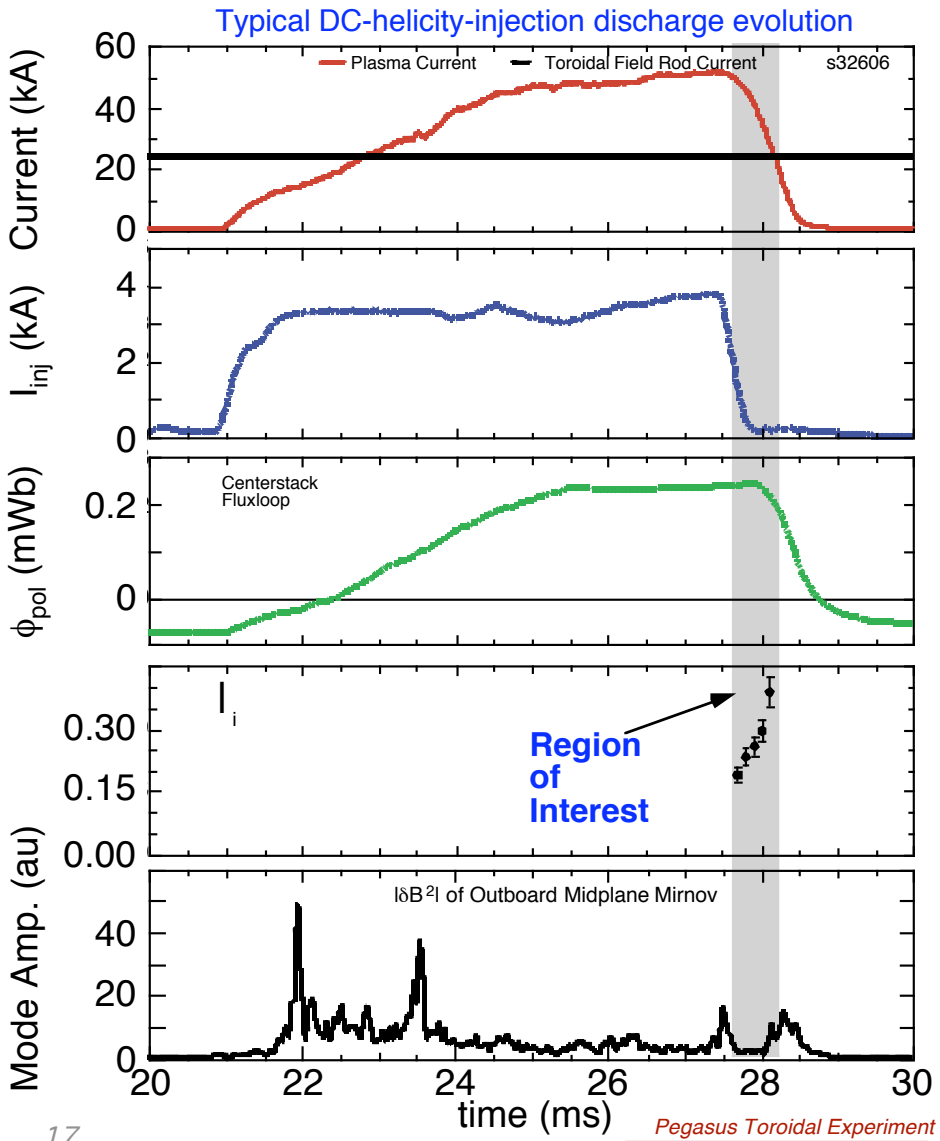
- 3 techniques used to achieve high $I_N$ ($I_p/I_{TF} \approx I_N/6$)
  - OH drive at low TF via plasma gun pre-ionization
  - Non-inductive discharge formation at low TF
  - Fast TF ramp-down during OH operation




*Plasma gun startup able to achieve highest $I_N$*

# Plasma Gun Startup Appears to Give Broad, Stabilizing Current Profiles

- Current injection at edge leads to hollow j(R)
  - $\ell_i \leq 0.35$ at gun turn off
- Transient TM suppression
  - TM returns after $\ell_i$ increase
- Create stable, full-current targets in future system
  - exploit hollow j(R) target with RF



# Near-Term Issues to be Addressed

- What determines $\lambda_{edge}$?
  - $J_{edge}$ broadening due to magnetic turbulence (edge & global)
  - magnetic shear
  - gun characteristics
  - physical geometry
- How does $T_e$ scale with $I_p$?
  - $\chi_\perp$ vs. $\chi_\parallel$ in the presence of magnetic turbulence
  - confinement depends of degree of stocasticity of magnetic field
- What determines injector impedance?
  - $V_{bias} = I_{inj}Z_{inj}$
  - neutral fueling
  - filament length
- What are plasma properties?
  - $T_e$, $n_e$, j(R), $P_{rad}$, etc.

# Point-Source Current Injection Potentially Provides an Attractive ST Startup & Growth Technique

- Point-source DC helicity injection appears to be viable startup technique
  - simple & scalable
- Tests today with small 3-gun system gives Ip up to ~0.1 MA
  - limited by present hardware configuration
- Helicity driven discharges governed by helicity balance and Taylor relaxation limits
  - many issues remain to be addressed (edge current profiles, gun impedance, field stocasticity, $\chi_{\perp}$ vs $\chi_{||}$, geometry, plasma characteristics, etc.)
- Pegasus moving towards high-current startup and sustainment without solenoid