Non-inductive Startup Using Localized Washer Gun Current Sources on the PEGASUS Toroidal Experiment

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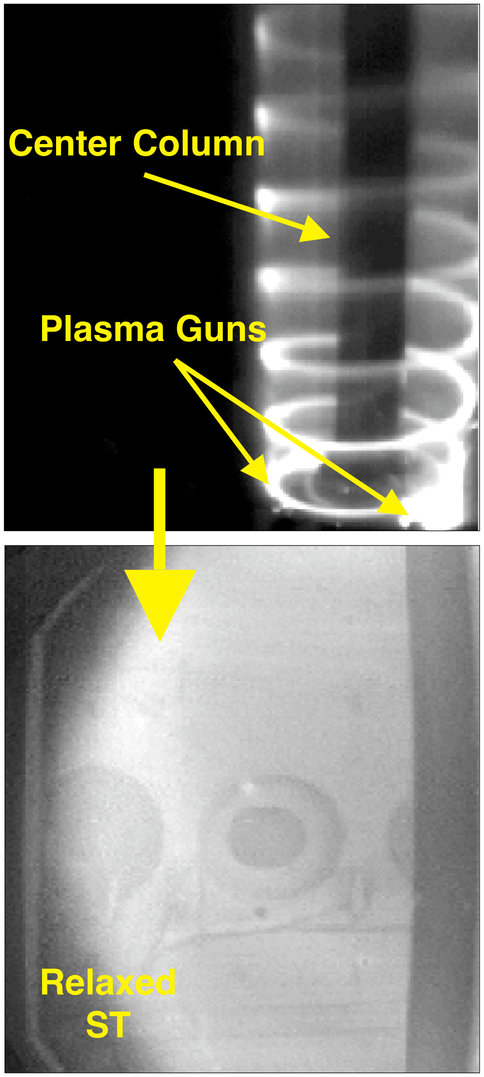
Overview: Localized Current Sources Provide Non-Inductive Tokamak Startup

- Non-inductive startup desired for tokamaks
  - ST's: Limited ohmic drive capability
  - Tokamak Reactor: Removing solenoid eases design
- Washer gun current sources installed in lower divertor region for DC helicity injection
- Injected current relaxes to ST-like plasma
  - $I_p \leq 50$ kA driven by $I_{Inj} \leq 4$kA
  - Consistent w/ helicity conservation
- Guns modify j(r): Allow access to $I_p/I_{TF} > 2$
  - I_{TF} = TF rod current
  - $I_N > 12$ MA/m-T



Conditions for Non-Inductive Formation of Tokamak Plasma

- Tokamak plasma formation must satisfy 3 constraints
  - Helicity conservation
  - Tokamak confinement scaling
  - Consistency with magnetic geometry and equilibrium

- Helicity and confinement requirements interconnected (next slide)
  - Both place requirements on source

- 3 magnetic constraints
  - Local field structure avoids current streams hitting other guns
  - PF weak enough to allow flux surface closure of plasma gun injected current
  - PF strong enough to maintain MHD equilibrium

Helicity Conservation, Confinement Properties Should be Self-Consistent

- Time derivative of helicity[1]:

$$\dot{K}_{Tok} = -2\int_V \mathbf{E}\cdot\mathbf{B}\,d^3x + 2V_{loop}\Phi_T - 2\int_A V_{Inj}\mathbf{B}\cdot d\mathbf{a}$$

Resistive Dissipation — AC Injection — DC Injection

- Equating AC & DC source terms gives "Effective Loop Voltage"[2]

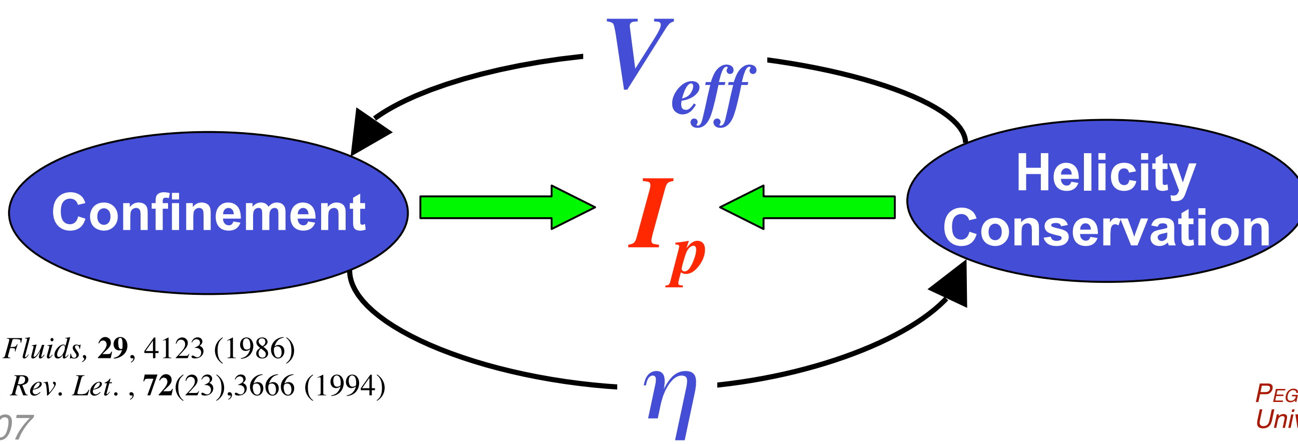
$$V_{eff} = V_{Inj}\frac{\psi_{Inj}}{\Phi_T}$$

← Injector Flux (ψ_{Inj})

← Plasma Toroidal Flux (Φ_T)

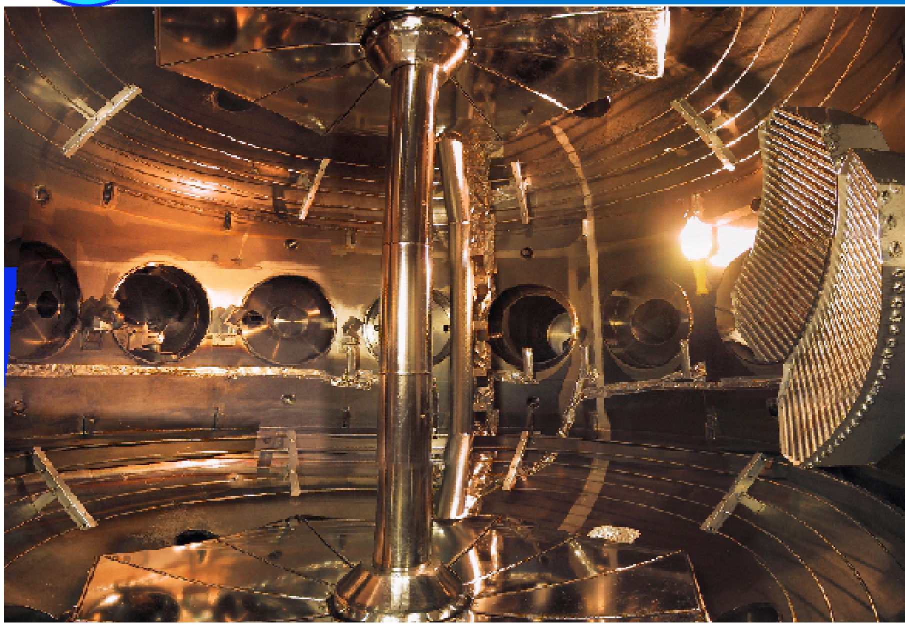
Bias Voltage (V_{Inj})

- Confinement scaling, helicity conservation should yield consistent I_p



[1] A.H. Boozer, *Physics of Fluids*, **29**, 4123 (1986)
[2] Nelson, B.A. *et al*, *Phys. Rev. Let.* , **72**(23),3666 (1994)

PEGASUS is Mid-sized, Ultra-low A ST

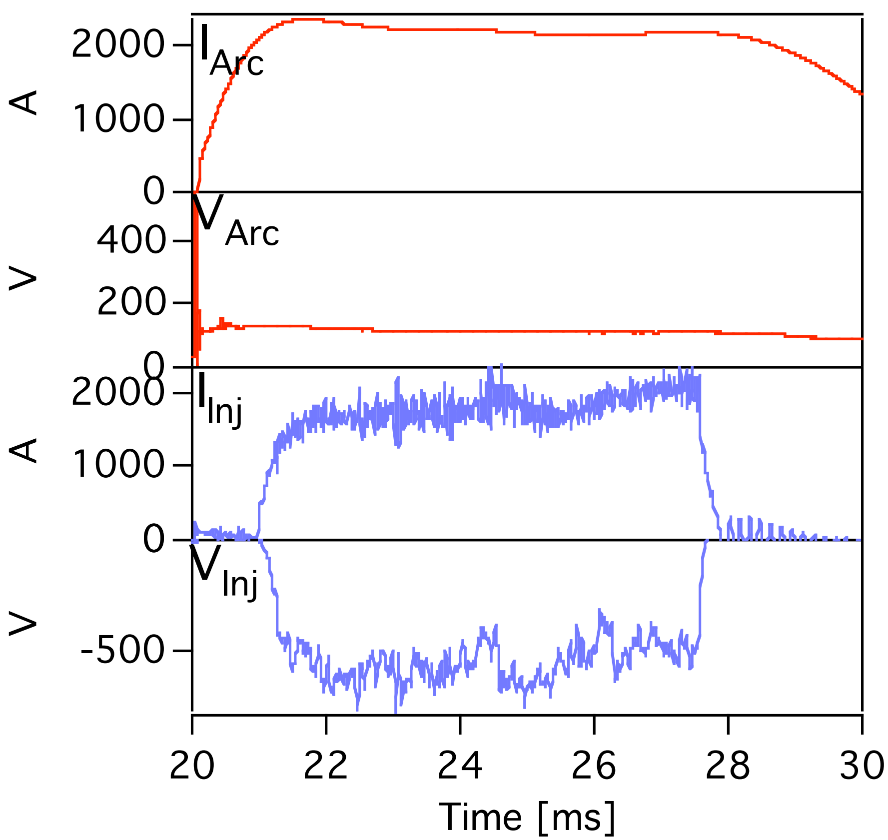


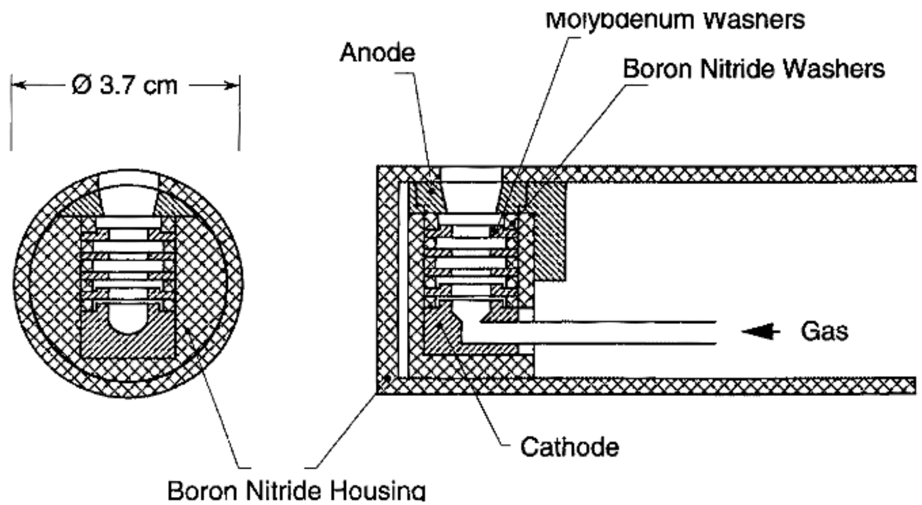
Experimental Parameters

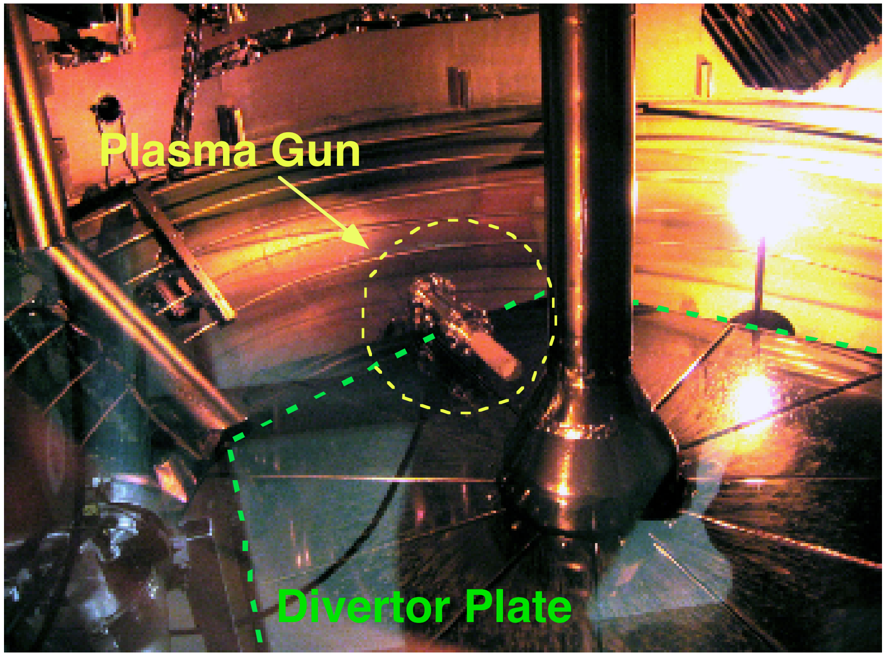
Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	≤ 0.18	≤ 0.30
I_N (MA/m-T)	6-12	6-20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Current Injectors[4] Inserted Above Lower Divertor, Biased Relative Vessel

- Gen1: 10 ms, 1-2 kA arc in gun
- Bias extracts e-, plasma into vessel along field lines







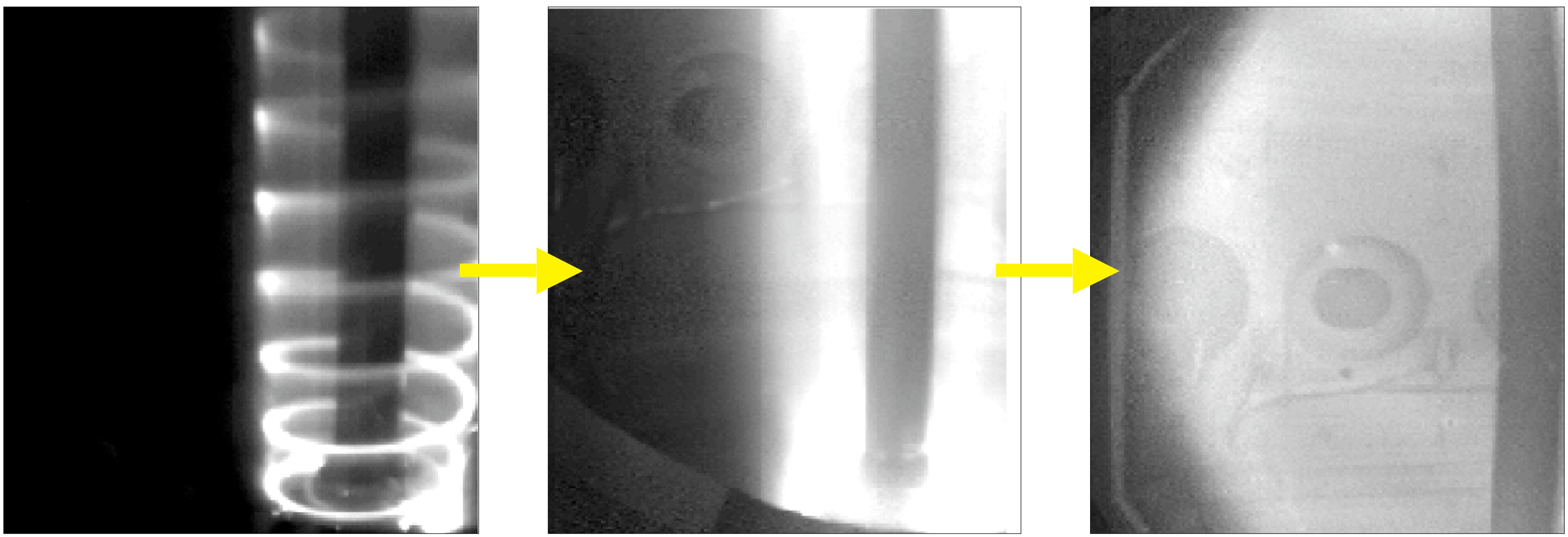
[4] Fiksel *et al*, Plasma Sources Science and Technology, **5**(1), 1996

Gun Plasmas Exhibit 3 Distinct Phases: Relaxation to ST Observed at Low B

1. At low I_{inj}, high pitch angle & B_V, helical current filaments form

2. Filaments merge into cylindrical sheet as I_{Inj} increased, B_V decreased

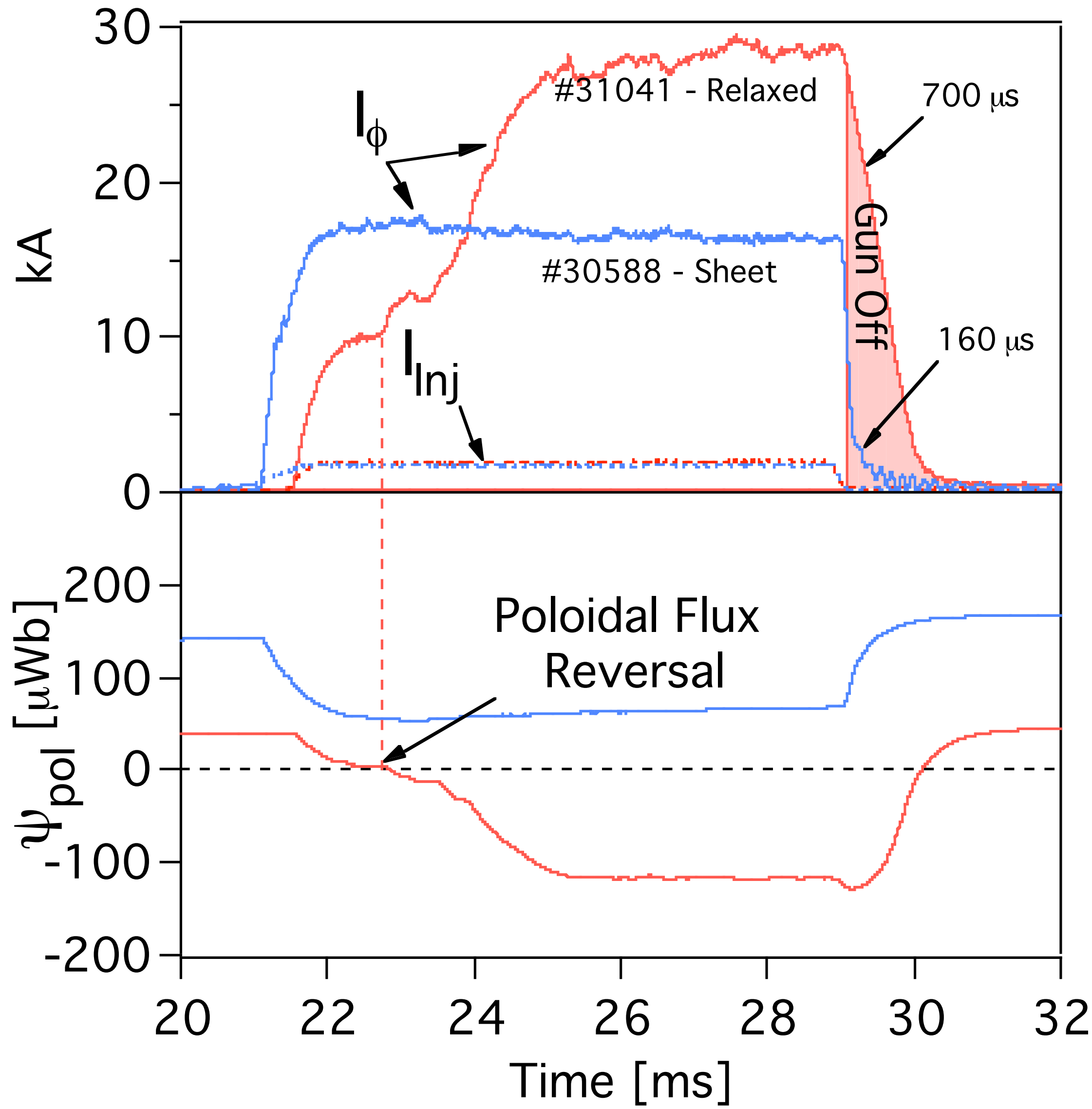
3. At low fields ($B_T \approx 0.01$ T, $B_V \approx 0.005$ T), relaxation to ST-like plasma



(1) Filaments (2) Sheet (3) Relaxed ST

Relaxed Plasmas Exhibit Central Flux Reversal, Increased Current Drive & τ_{decay}

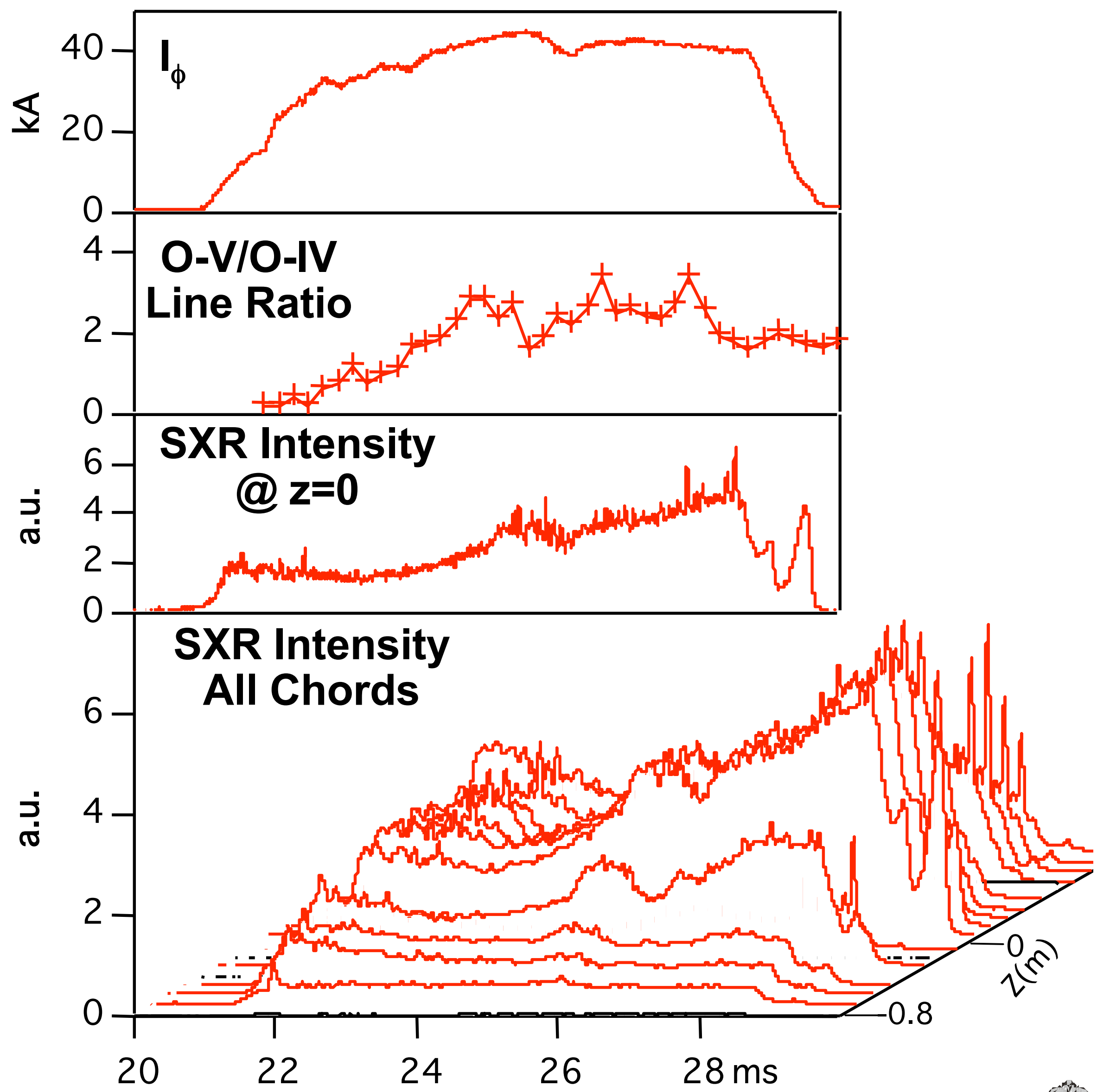
- Flux-reversed plasma observed during low field injection
  - $>$ 4x flux reversal
  - Indicates separatrix formation
- I_ϕ increase > 50 %
  - Increased current drive efficiency
  - Max observed $I_\phi \approx 50$ kA
- τ_{Decay} increase > 400 %
  - Decay w/o reversal $\approx 160\ \mu s$
    w/ reversal $> 700\ \mu s$
  - Significant change in L/R



Relaxed Plasmas Exhibit Core Heating

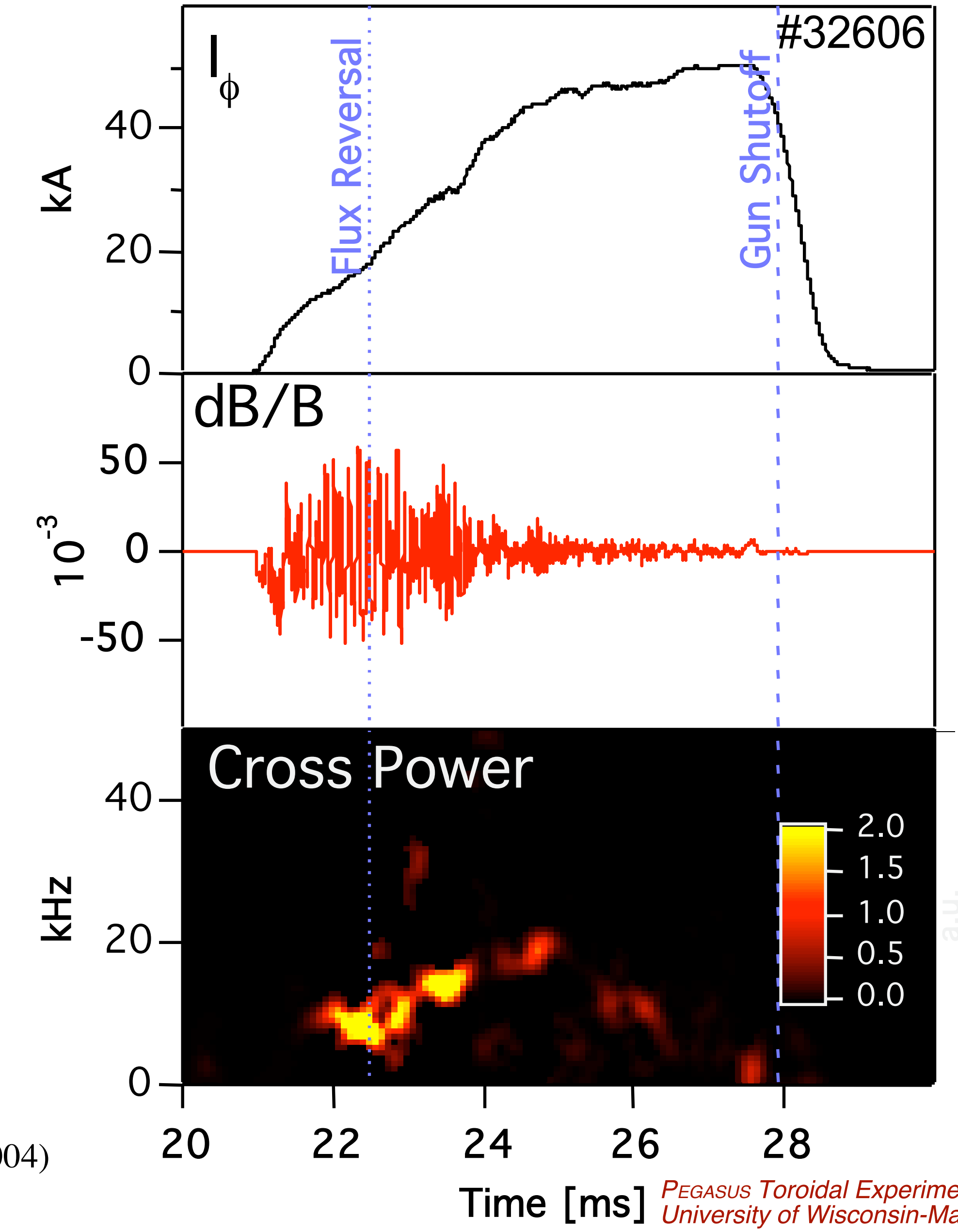
- O-V (114 eV) to O-IV (77eV) line ratio indicates increasing T_e

- SXR array indicates formation of hot core
  - SXR emission increases throughout shot
  - Emission peaks at midplane
  - Midplane signals decay more slowly than edge at shut-off



n=1 MHD Activity Observed During Current Drive

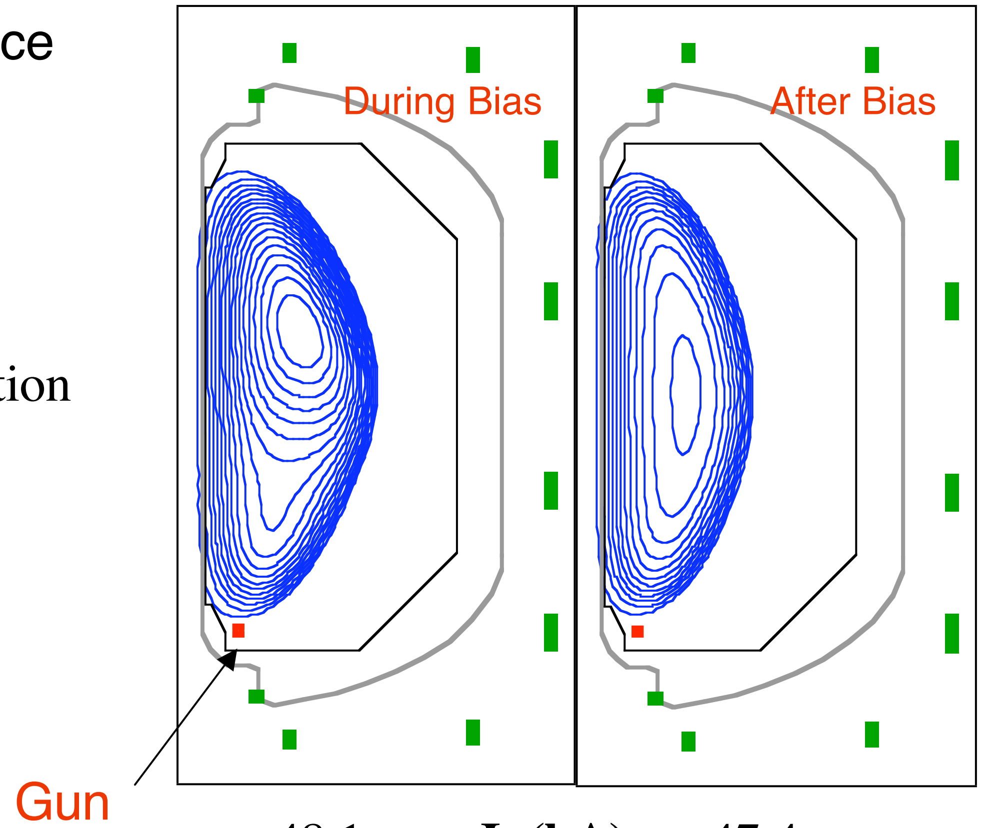
- CHI & Spheromaks: n =1 activity associated w/ current drive[5,6]
- Line tied kink provides axisymmetric V_{loop}[7]
- Mode strong during current ramp, attenuates at flattop



[5] Redd et al., Phys. Plasmas, **9**, 2006 (2002)
[6] Brennan et.al, Phys. Plasmas, **6**, 4248 (1999)
[7] X.Z Tang and A.H Boozer, Phys. Plasmas, **11**, 2679 (2004)

Equilibria Reliably Reconstructed during Decay Phase

- B_v consistent with radial force balance
- During current injection phase:
  - Vertically asymmetric
  - Significant difficulties in reconstruction
    - *large open field-line currents*
    - *non-axisymmetric currents near gun*
    - *possible field line stochasticity*[8]
- After injector shut-off:
  - Vertically symmetric
  - Axisymmetric currents



During Bias		After Bias
48.1	I_p (kA)	47.4
0.21	l_i	0.19
8.2	q_{99}	9.9
0.36	R_{axis} (m)	0.31

[8] Sovinec *et al.*, Phys. Rev. Let., **94** (2002)

Current Drive Consistent with Helicity Conservation within Factor of 2

- Use magnetic reconstruction of fiducial 50 kA shot #32606

- Effective loop volts: $V_{eff} = 0.7$ V
  - 0-D Confinement Scaling (ITER98PBY2): V_{eff}, I_p consistent with $\langle T_e \rangle \approx 55$ eV
    - *Assumptions: parabolic profiles, 50% radiated power, $Z_{eff} = 2$*
  - $\langle T_e \rangle$ reasonable given increased O-V/O-IV, no burnout

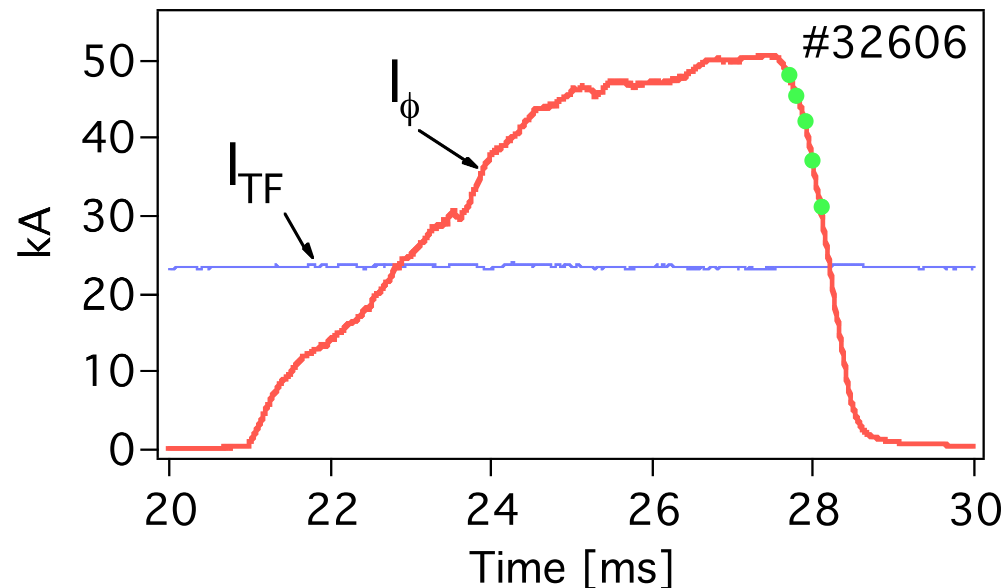
Helicity Injection Rate	Helicity Dissipation Rate
$2V_{Inj}A_{Inj}B_n$	$4\pi I_p \eta_s R_0 B_0$
1.8 x 10^{-2} Wb^2s^{-1}	**1.0 x 10^{-2} Wb^2s^{-1}**

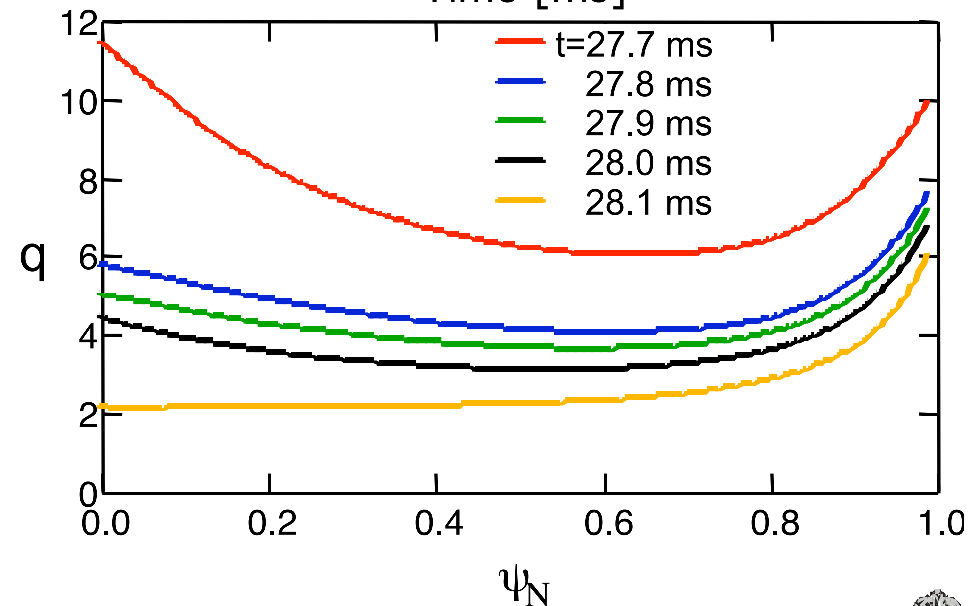
- Better plasma characterization required for more accurate comparison

Manipulation of j(r) by Plasma Guns Allows Access to High I_p/I_{TF}, I_N

- Ohmic ops:
  - $I_p/I_{TF} = 1$ ($I_N \approx 6$) "soft-limit
  - 2/1 tearing mode limiting
    - Minimal shear stabilization
- Gun plasmas: $I_p/I_{TF} \sim 2$ ($I_N \approx 12$)
  - No limiting MHD
- Stability possibly due to edge j
  - Hollow j(r)
  - Negative core shear

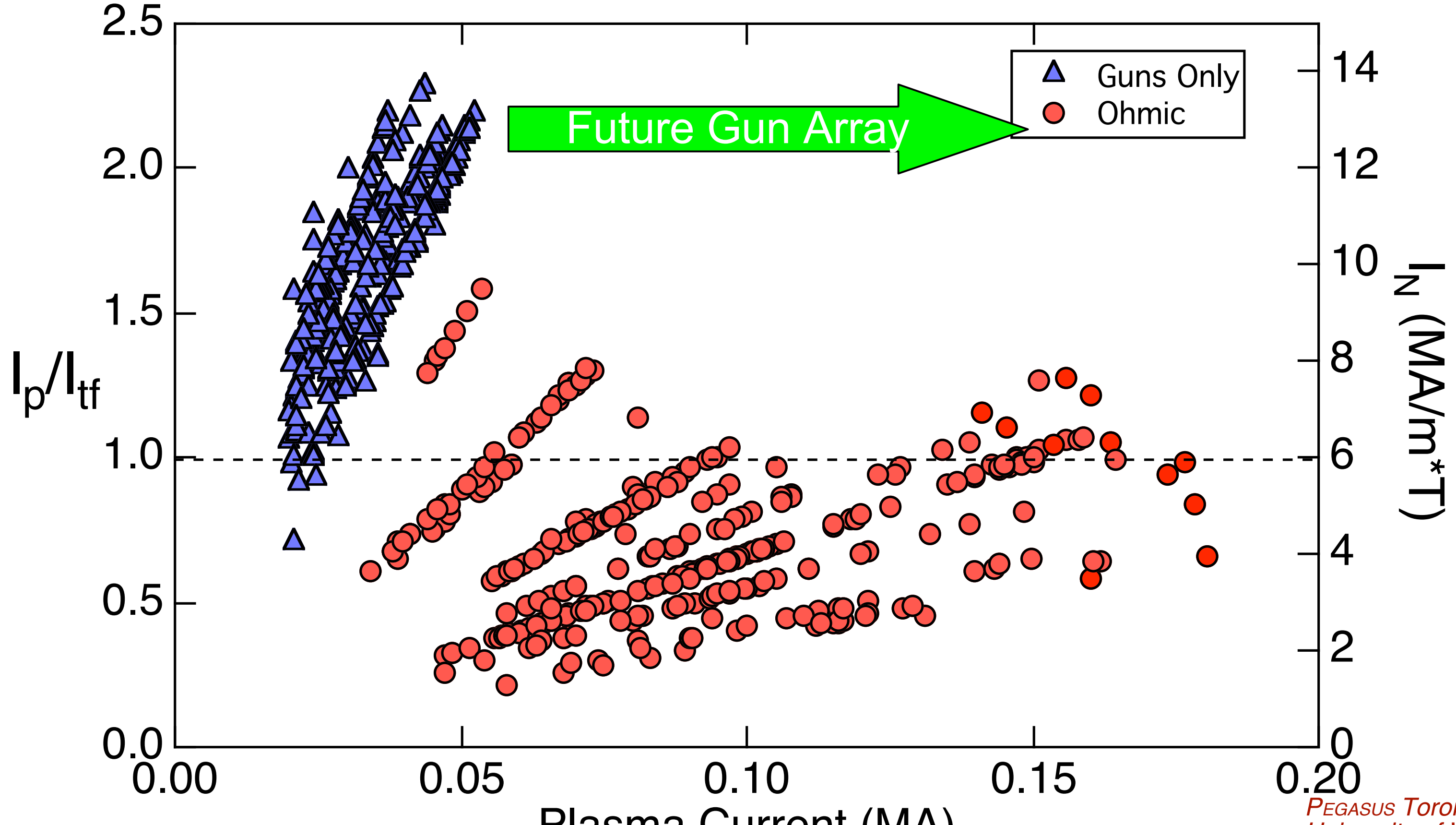
Note: Reconstruction constrained by external magnetics only





Plasma Guns Expand PEGASUS Operating Space

- Present system: Significantly expands access to high I_p/I_{TF} @ low I_p
- Future Plans: Upgrade gun array to access high I_p/I_{TF}, high I_p

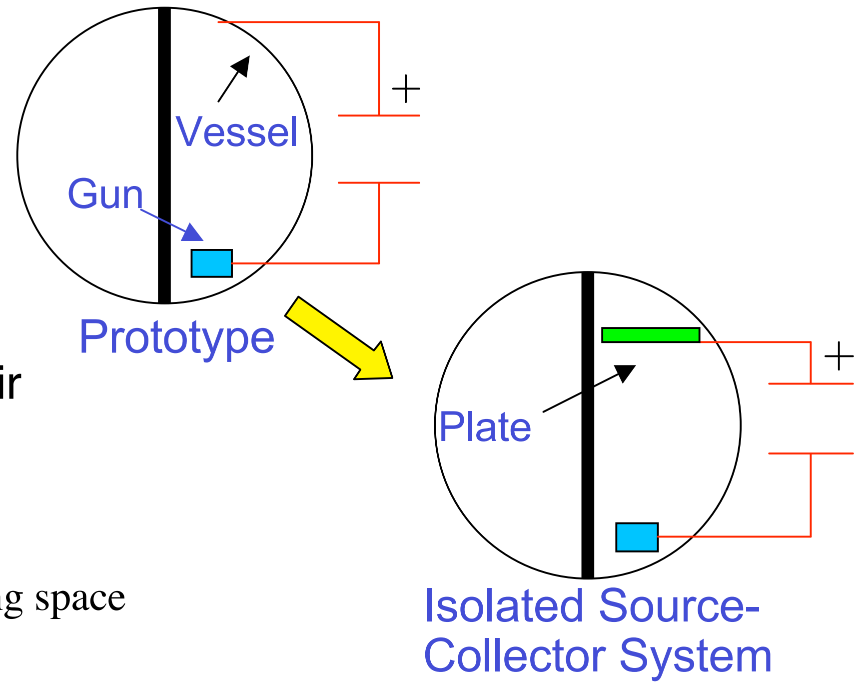


Local Current Sources Provide DC Helicity for Startup of Tokamak Plasmas

- Non-inductive formation of ST demonstrated using plasma guns
  - $I_p \leq 50$ kA driven by $I_{Inj} \leq 4$ kA
  - $B_T \approx .01$ T
- Evidence of closed flux plasma formation:
  - Central flux reversal ⇒ Formation of separatrix
  - τ_{Plasma} decoupled from τ_{Gun} ⇒ Persistent I_p after shutoff
  - Increased heating, formation of core ⇒ better confinement
  - Strong n=1 mode correlated with current drive
  - Consistent with tokamak radial force balance
- Current drive consistent with helicity conservation within factor of 2
  - More detailed measurements needed
- Guns allow strong manipulation of j(r)
  - Significantly expands PEGASUS access to high I_p/I_{TF} (I_p/I_{TF}>2 , I_N>12)

Future Goal: 0.1-0.2 MA Non-Solenoidal Startup

1. Larger gun array for access to high I_p
   - Divertor Array:
     - *Implement local bias coil*
   - Develop midplane gun system
     - *Extrapolatable to fusion class devices*
     - *Compatible w/ PF field induction*



2. Ip ≤ 50 kA: Optimize prototype divertor gun pair
   - Install dedicated gun bias anode plate
     - *Protect vessel, maintain impedance*
   - Improve plasma characterization & expand operating space

3. Demonstrate handoff of non-inductive gun plasma to alternate current drive
   - Ohmic or RF

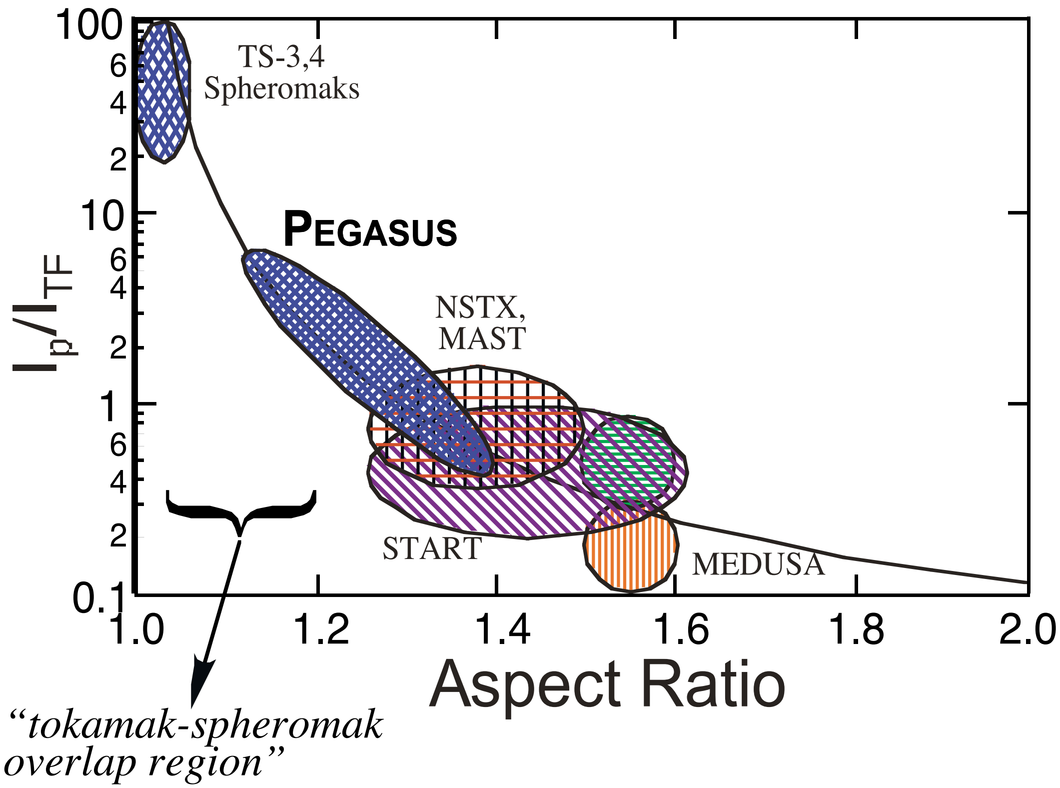
Outline

1. Conditions for non-inductive startup
2. Overview of PEGASUS experiment
3. Evidence for relaxation of gun plasmas into ST
4. Gun current drive roughly consistent with helicity conservation
5. Gun j(r) manipulation allows access to $I_p/I_{TF} > 2$ ($I_N > 12$) discharges
   - Significantly expands PEGASUS operating space

PEGASUS Studies ST Physics Limits as A →1

- Stability and confinement at high I_p/I_{TF} and high I_p
  - Extension of tokamak studies
- Limits on β_t and I_p/I_{TF} (kink) as A→1 (A = R/a)
  - Overlap between tokamaks and spheromaks

Both aided by non-inductive startup



Washer Gun Current Sources Provide Localized DC Helicity Injection

- Creation & maintenance of tokamak plasma by discrete electrodes demonstrated on CDX, CCT[3]

- Advantages of washer guns as DC helicity injectors for PEGASUS
  - Low impurity content compared to conventional emissive electrodes
    - *Impurity ions trapped in gun aperture*
  - Easy to integrate w/ Pegasus hardware
  - Scalable

- Disadvantages
  - Small aperture per gun limits helicity injection rate
  - Independent control of multiple guns adds complexity

[3] D.S. Darrow *et al*, *Physics of Fluids B*, **2**, 1415 (1990)

Independent Measurements Indicate Formation of Relaxed, Closed Flux-surface Plasmas

- Increased current drive
- Reversal of poloidal flux at center column
- Increased plasma L/R decay time
- Core heating observed in VUV and SXR
- Appearance of n=1 MHD mode
- B_V consistent with tokamak radial force balance