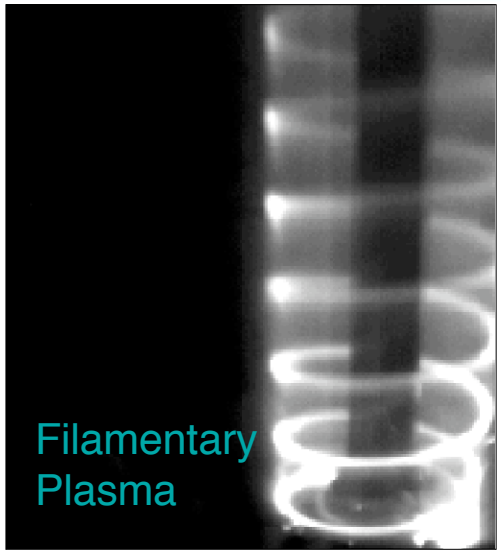
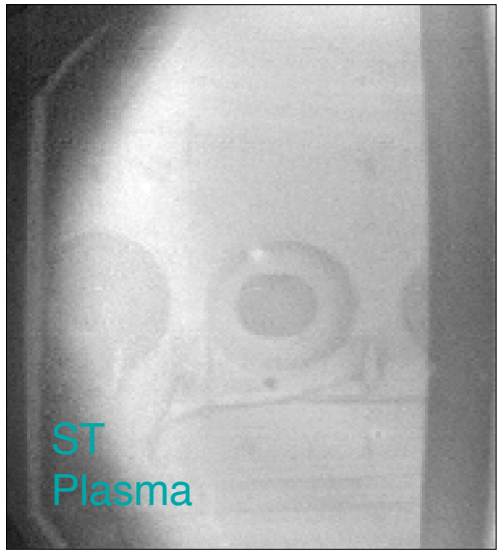
Overview

- Plasma washer gun sources installed in lower divertor region
- In certain conditions, ST-like plasmas are formed
  - Driven by DC helicity injection
- Plasmas with high I_p/I_{tf} produced
  - $I_p/I_{tf} = 2$ ($I_N = 12$)
  - Hollow J(r) profile
    - *Stable to tearing modes*
- Guns used for seed plasma for PF induction experiments

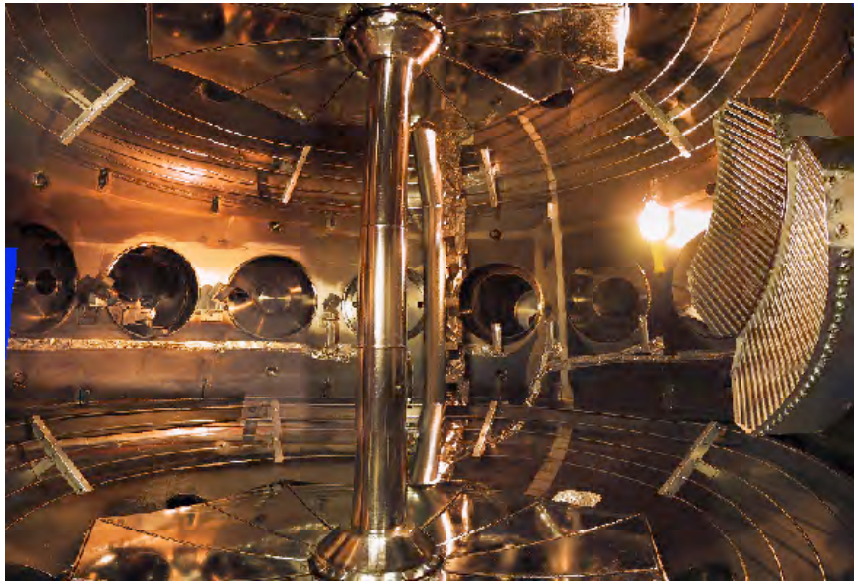




Exploration of A →1 regime limited by current drive considerations

- Shortage of ohmic current drive: longstanding ST issue
  - Especially important on ultra-low A Pegasus
- Pegasus experimental focus: explore high I_N, high β_t space
  - External kink stability should diverge from standard tokamak as A → 1
  - Very high stable β_t should be accessible at high I_N
  - Limited CD makes high I_N difficult to achieve
    - *Center column: 11 cm diameter*
- Plasma gun helicity injection fits into Pegasus program
  - Provides ready access to high I_N without OH
  - Assists OH operations at low field
  - Possible candidate for noninductive current drive tool in future

Pegasus is a mid-sized, ultra-low A ST



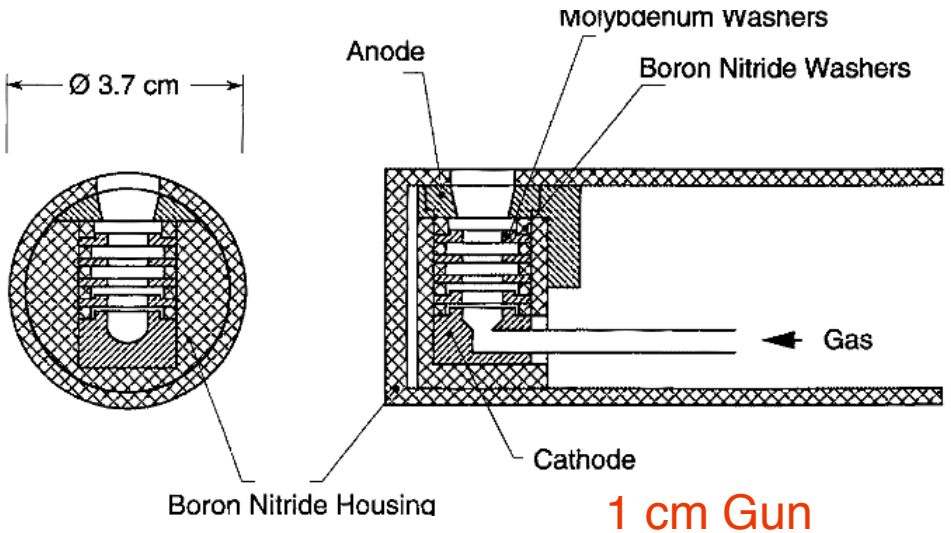


Experimental Parameters

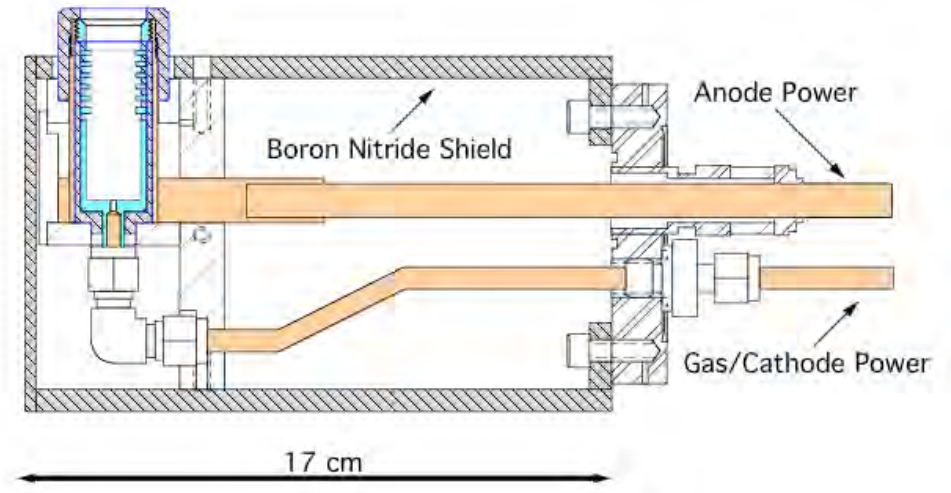
Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	≤ 0.18	≤ 0.30
I_N (MA/m-T)	6-12	15-20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

Gun construction

- Mo anode & cathode separated by Mo & BN washers
- D_2 fed independently via dual gas/cathode line
- BN housing
- Relatively clean plasma source
  - Small aperture area
  - Nitrogen sometimes observed
- Typical parameters:
  - $I_{arc} = 1\text{-}2$ kA
  - $I_{inj} = 1\text{-}2$ kA
  - $V_{inj} < 900$ V
  - $\delta t_{arc} = 0.01$ s (set by heating)
- G. Fiksel et al., Plasma Sources Sci. Technol. **5** (1996) 78.



1 cm Gun



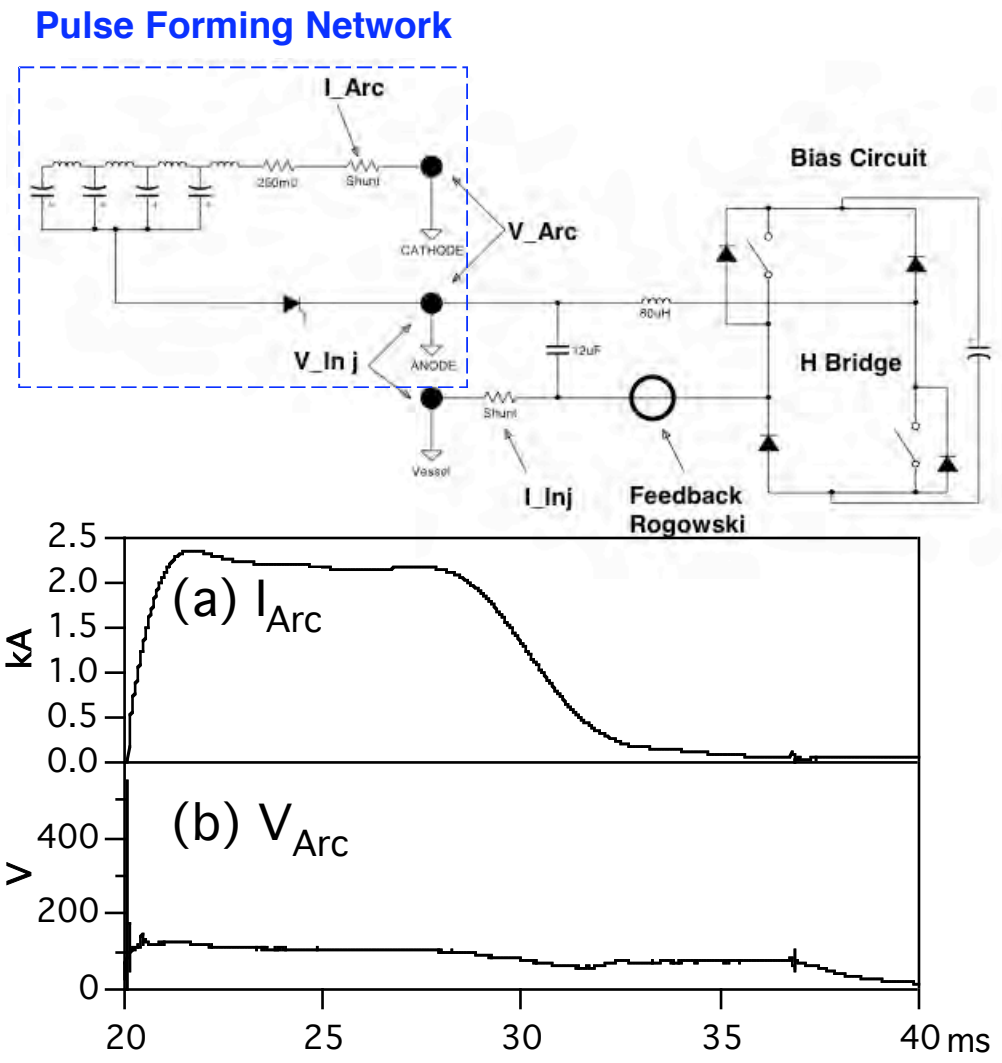
Prototype 2-cm Gun

Plasma arc is formed inside the gun

- After gas puff, PFN initiates
  ≈ 10 ms arc
  - Thermal limits on duration

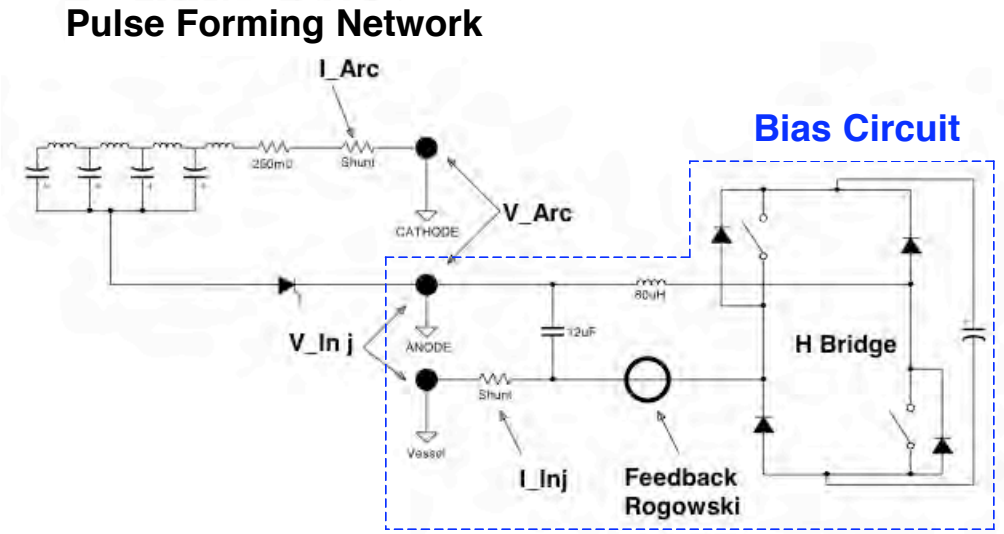
- I_{Arc} determined by V_{PFN}
  - $I_{Arc} \approx 1$ kA, $V_{PFN} = 0.7$ kV (1 cm)
  - $I_{Arc} \approx 2$ kA, $V_{PFN} = 1.4$ kV (2 cm prototype)

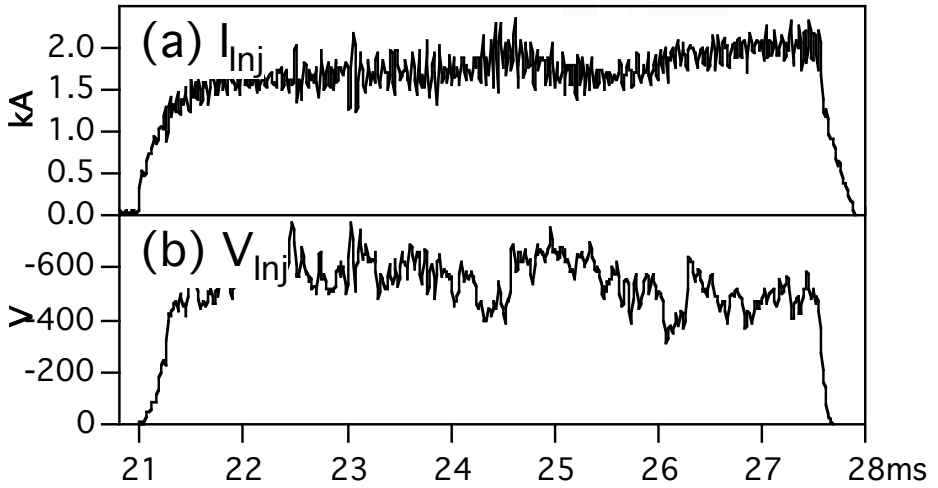
- PFN provides flat arc current waveform



Gun biased independently of arc

- Switched H-bridge biases gun anode negatively wrt vessel
  - Extracts electrons
  - Ionizes bulk plasma
- Impurity ions trapped in aperture
- PWM current-feedback control maintains $I_{inj} \leq I_{Arc}$
  - Important for confining ions
  - LC filter stabilizes current from switching power supply

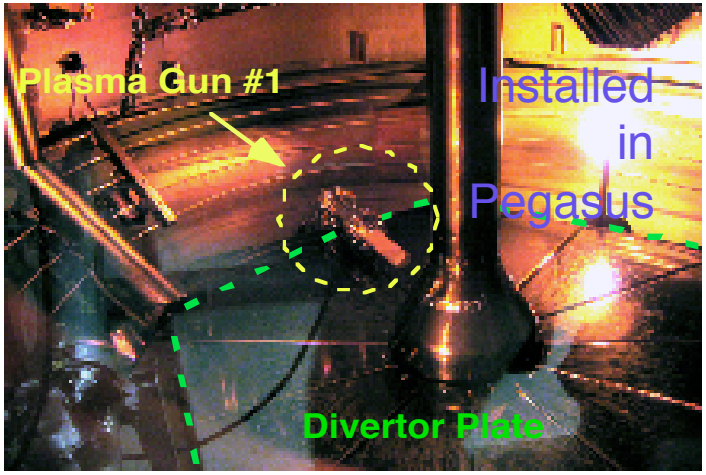


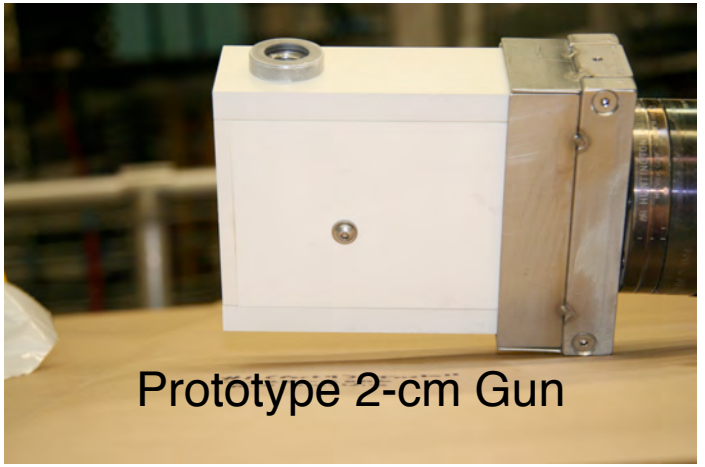


Gun photos


Without Vacuum Hardware


Mock-Up Assembly


Plasma Gun #1
Installed in Pegasus
Divertor Plate


Prototype 2-cm Gun

Biased electrodes can be used as helicity sources

- This technique can form tokamak-like plasmas
  - Demonstrated on CDX and CCT

- Helicity injection rate, assuming constant B across electrode area:

$$\dot{K}_{Inj} = 2\int_A \Phi \mathbf{B} \cdot d\mathbf{a} = 2V_{Inj}B_nA_{Inj}$$

where

V_{Inj} = Bias potential applied to electrode

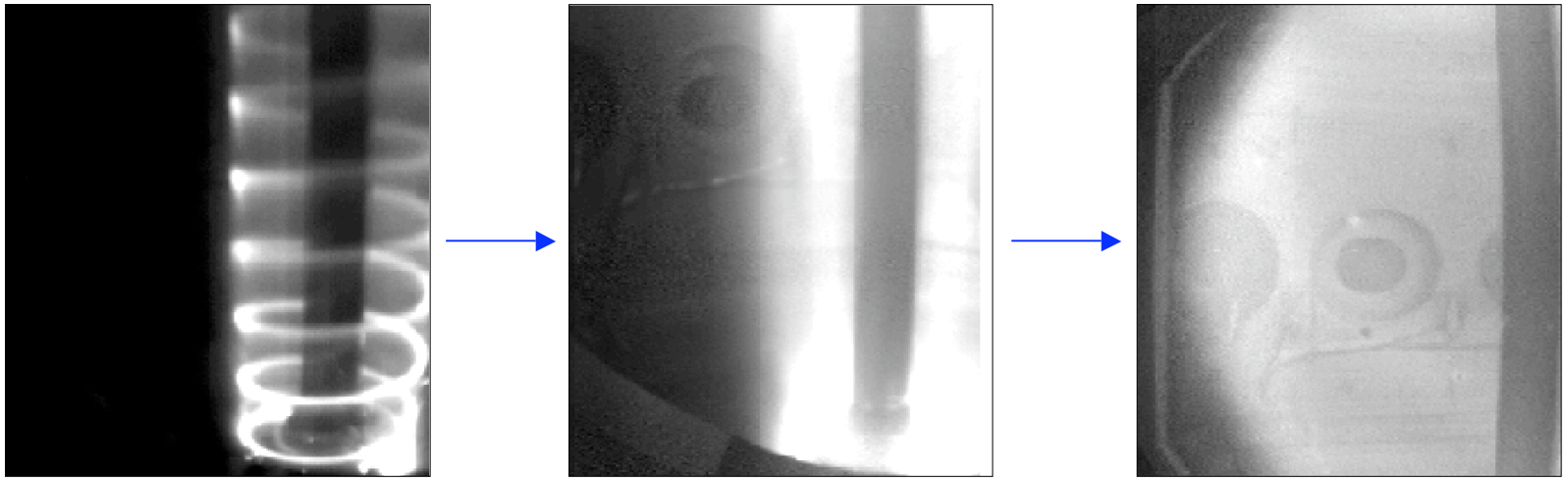
B_n = Magnetic field normal to electrode surface

A_{Inj} = Electrode area

- Plasma guns have advantages as helicity injection technique
  - Small high-Z impurity content
  - Scalable to larger size
  - Controllable by current feedback
  - Integratable into existing Pegasus facility
  - Significant power per device (1-2 MW)

Relaxed ST plasmas are formed

- At low I_{Inj} and/or high pitch angle, helical current filaments form
  - $M = I_p/I_{inj}$ = Geometric stacking
- Filaments merge into cylindrical sheet as I_{Inj} increased, pitch decreased
  - M > Geometric stacking
  - I_p set by helicity injection rate
- At low fields ($B_\phi \approx 0.01$ T, $B_\theta \approx 0.005$ T), relaxation to tokamak-like plasma
  - M >> Geometric stacking



Filaments | Reconnected Sheet | Relaxed ST

ST plasma formation requires satisfaction of multiple constraints

- Magnetic considerations
  - Flux closure: Vacuum field < plasma poloidal field
  - Radial equilibrium: Vacuum field must match relaxed I_p
  - Gun Geometry: Initial field windup must clear guns
    - $2\pi R(B_v B_t) > N_{gun}\delta_{gun}$

- Conservation considerations
  - Helicity conservation
    - *No flux conserver*
    - *For steady-state:* $I_p = V_{bias} A_{inj} / 2\pi R\eta$
      - Darrow, D.S. et al., Phys. Fluids B, **2**, 6 (1990)
  - Power balance
    - $P_{inj} = V_{bias} I_{bias}$

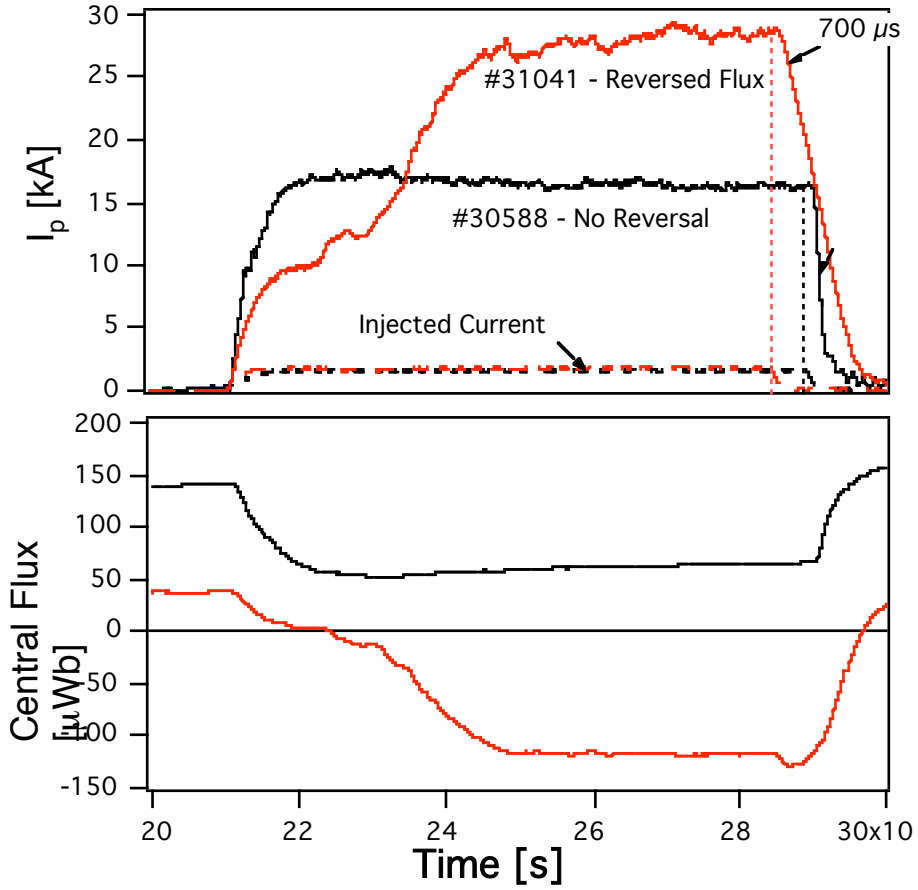
- Net result: for 1-2 injectors, $I_p \leq 50$ kA and B_t (0.4 m) ≤ 0.01 T

Independent measurements confirm formation of closed flux-surface plasmas

- Rapid increase in plasma current
- Reversal of poloidal flux at center column
- Increased plasma L/R decay time
- Appearance of n=1 MHD mode
- Increased core heating observed in VUV and SXR
- Consistency of vertical field with tokamak radial force balance
  - Equilibria can be reconstructed

Flux at centerpost reverses sign and plasma decay time increases

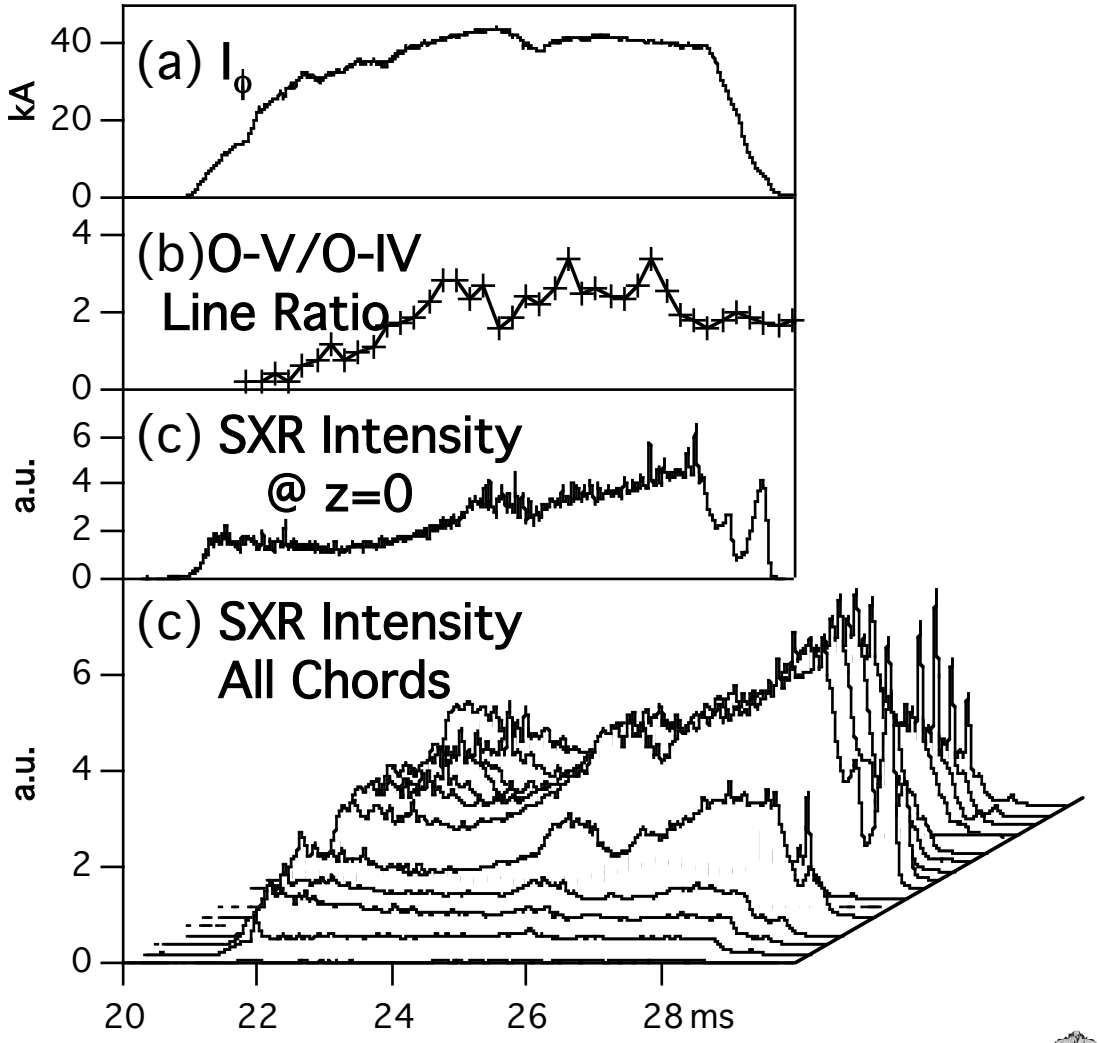
- Flux-reversed plasma observed during low field injection
  - > 4x flux reversal
  - Necessary for tokamak formation
- I_ϕ increase > 50 %
  - Increased current drive efficiency
  - Maximum observed I_ϕ < 50 kA
- τ_{Decay} increase > 400 %
  - Decay w/o reversal ≈ 160 μs
    w/ reversal > 700 μs
  - Significant change in L/R



ST-like plasmas exhibit evidence of heating

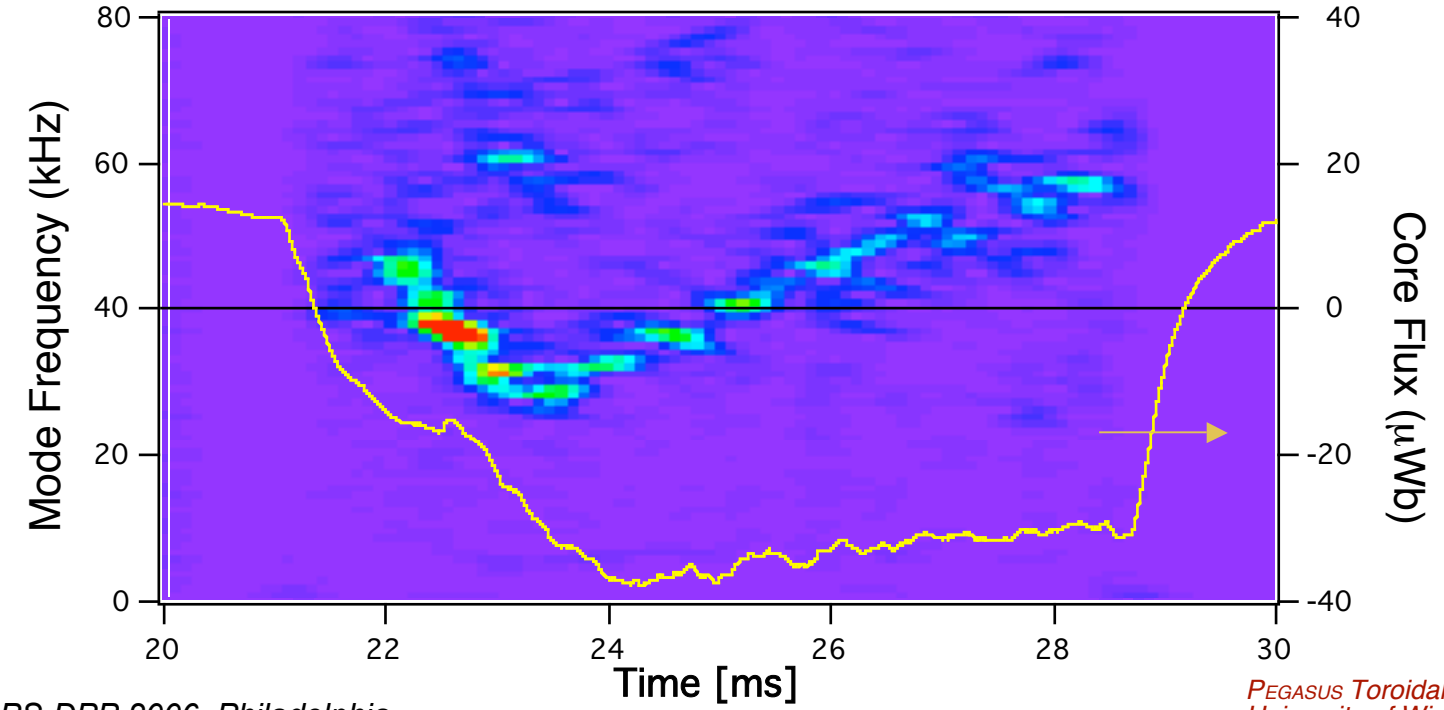
- O-V (114 eV) to O-IV (77eV) line ratio indicates increased T_e
  - Indicates $T_e > 50$ eV

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



n=1 mode observed

- 20-60 kHz n=1 mode observed soon after flux reversal
- Understood to be crucial to CHI current drive
- Dynamo action of n=1 line-tied kink believed to provide loop voltage for closed-flux current drive



Higher-n modes observed later in shot

- n=1 seen in every relaxed plasma studied
- Higher-order modes observed in highest-current discharges
  - n=2,3 observed
- Consistent with theory of open-field-line kink
  - Tang & Boozer, Phys. Plasmas **11** (2004) 2679

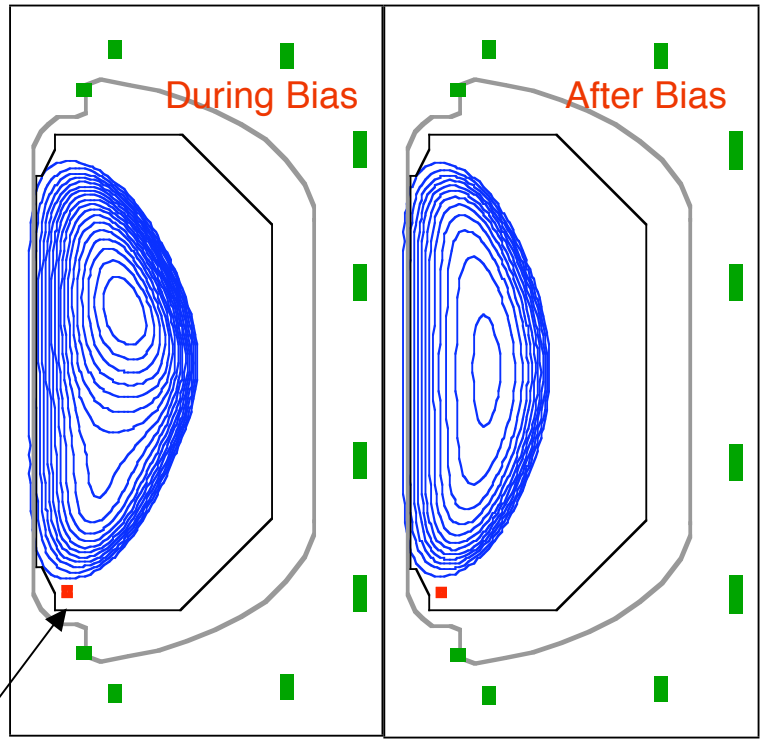
Flux (mWb)

Ip (kA)

Frequency (Hz)

Equilibria can be reconstructed

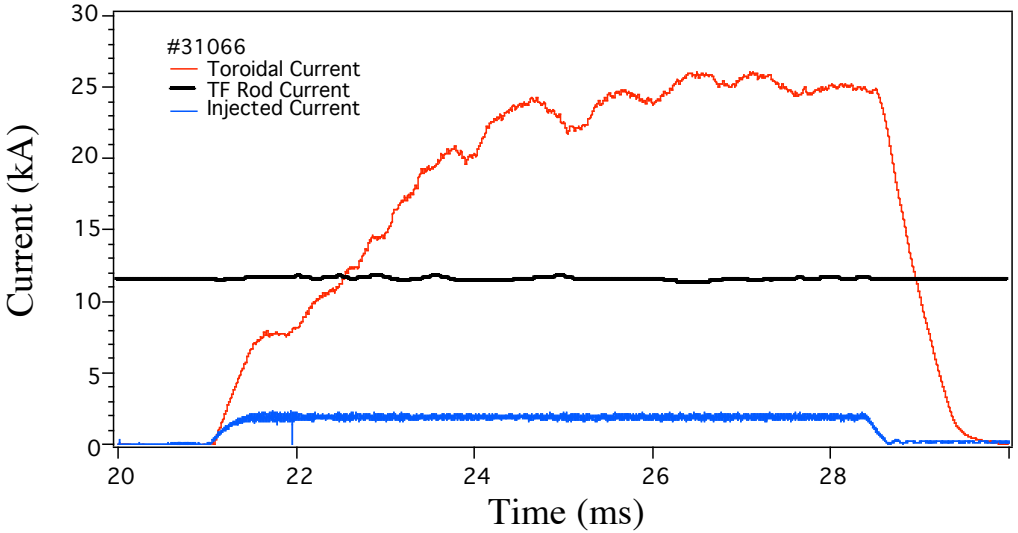
- B_v consistent with radial force balance
- During gun bias phase:
  - Vertically asymmetric
  - Significant difficulties in reconstruction
    - *large open field-line currents*
    - *non-axisymmetric currents near gun*
    - *possible field line stochasticity*
- After bias shut-off:
  - Vertically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



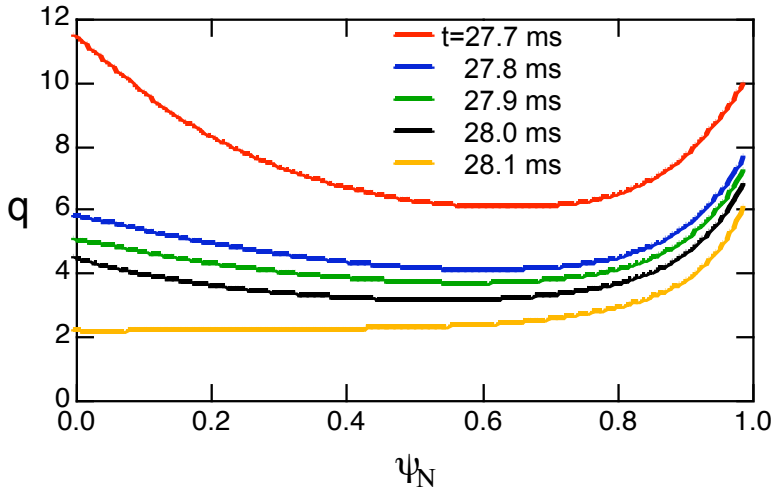
48.1	I_p (kA)	47.4
0.21	l_i	0.19
8.2	q_{99}	9.9
0.36	R_{axis} (m)	0.31

Large values of I_N achieved at very low toroidal field

- Ohmic plasmas have been limited to $I_p \sim I_{tf}$
  - Due primarily to low-order tearing modes
- Gun plasmas routinely produce $I_p/I_{tf} \sim 2$ ($I_N \leq 12$)
  - $B_t < 60$ Gauss
  - Low frequency tearing modes not observed
  - Possible modification of J(r) due to edge current drive
    - *Stabilizing to tearing modes*
    - *Equilibria exhibit hollow J(r), NCS profiles*

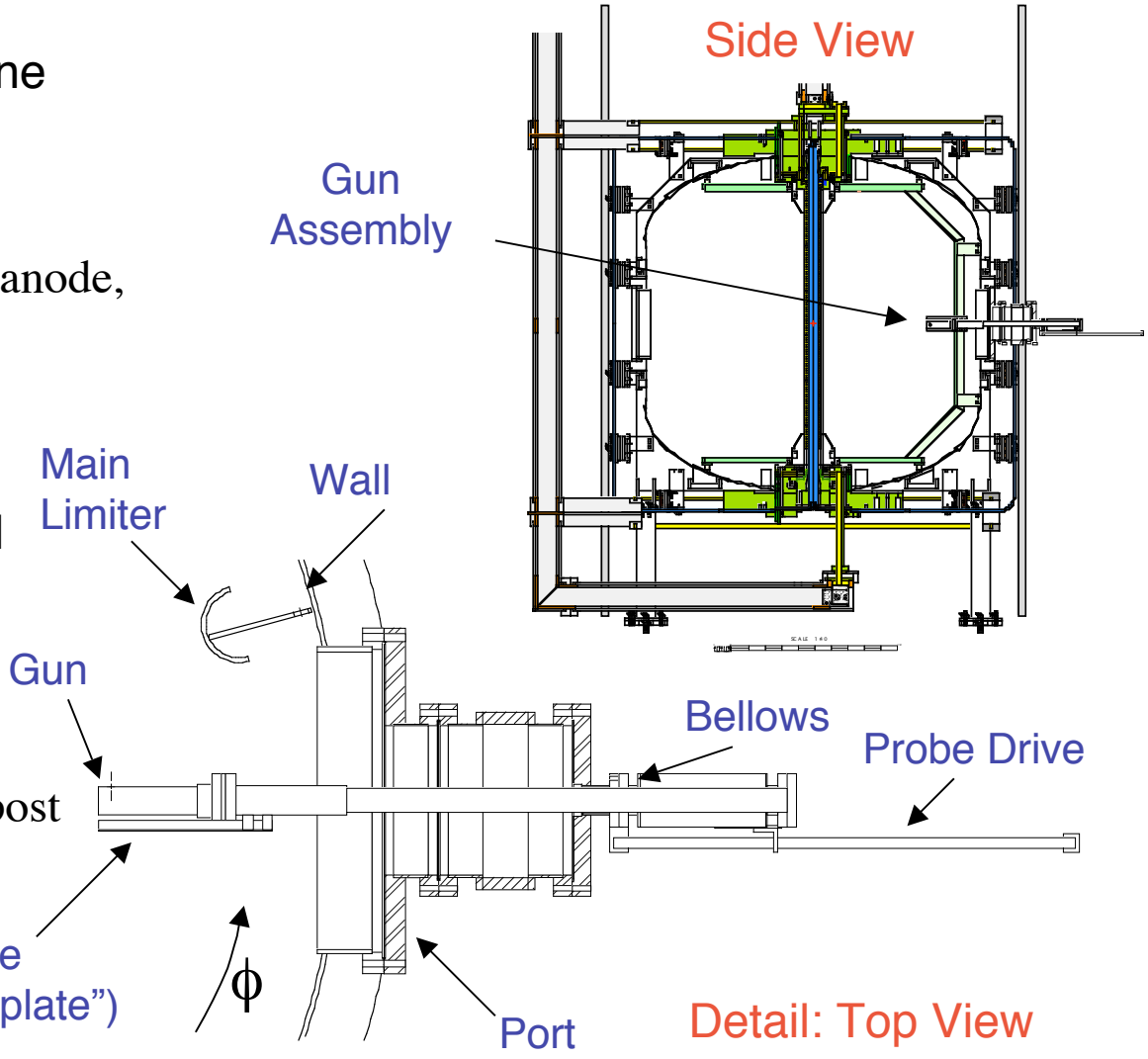


q-Profile evolution following gun shutoff

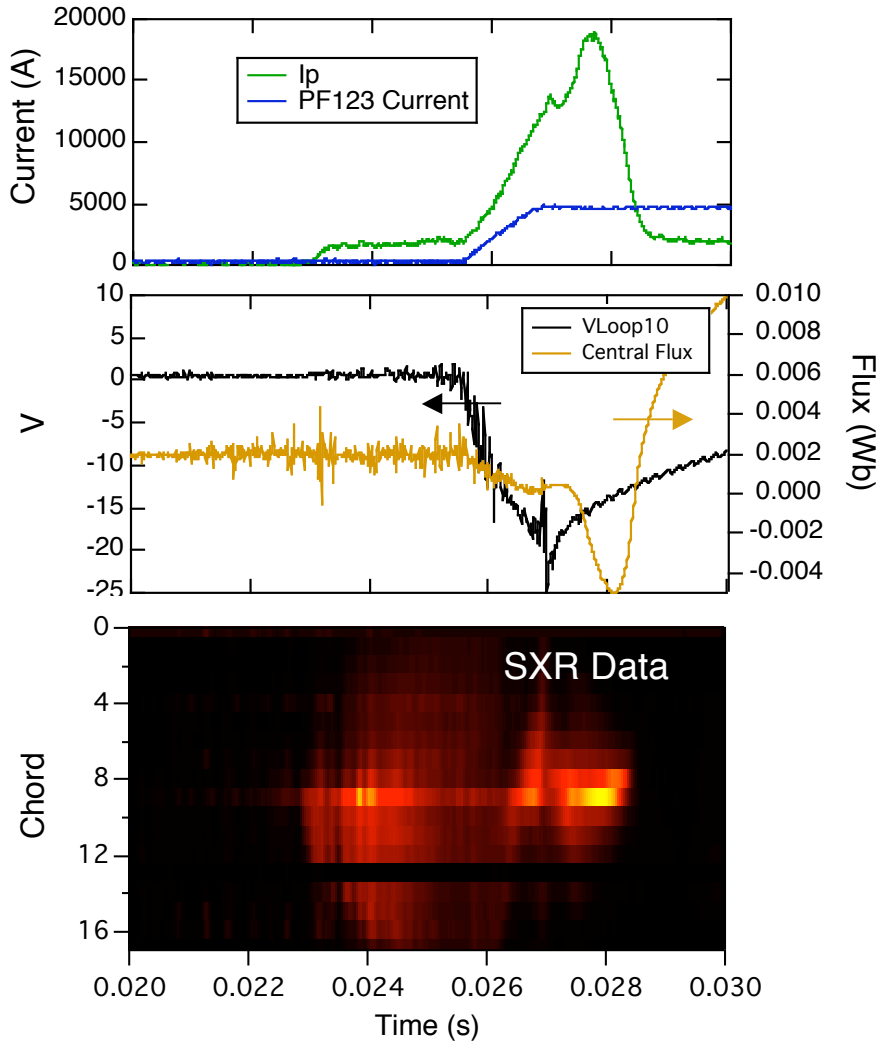


New poloidal field induction experiments assisted by midplane gun

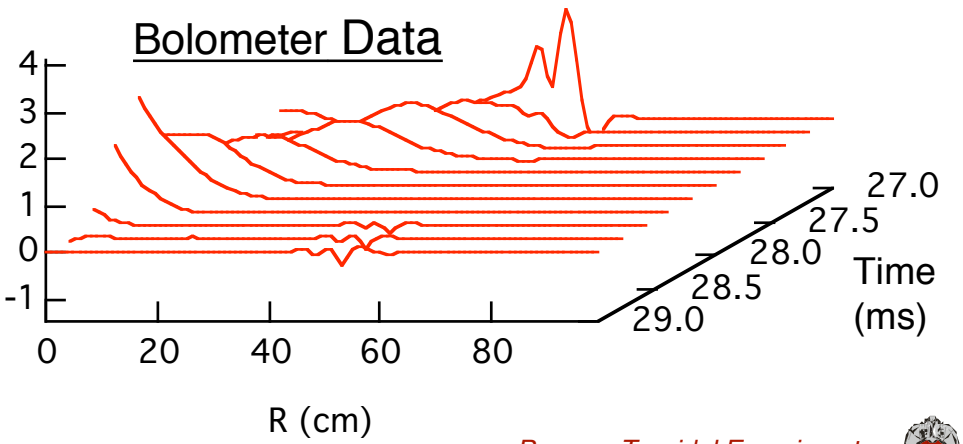
- 1 kA gun installed on midplane
  - R=0.7 m
  - Oriented toroidally
  - Current returns to separate anode, not vessel
    - *Anode biased positively*
- Single turn plasma produced
- Poloidal fields ramped in
  - OH-free PF induction
  - Plasma moves in to centerpost



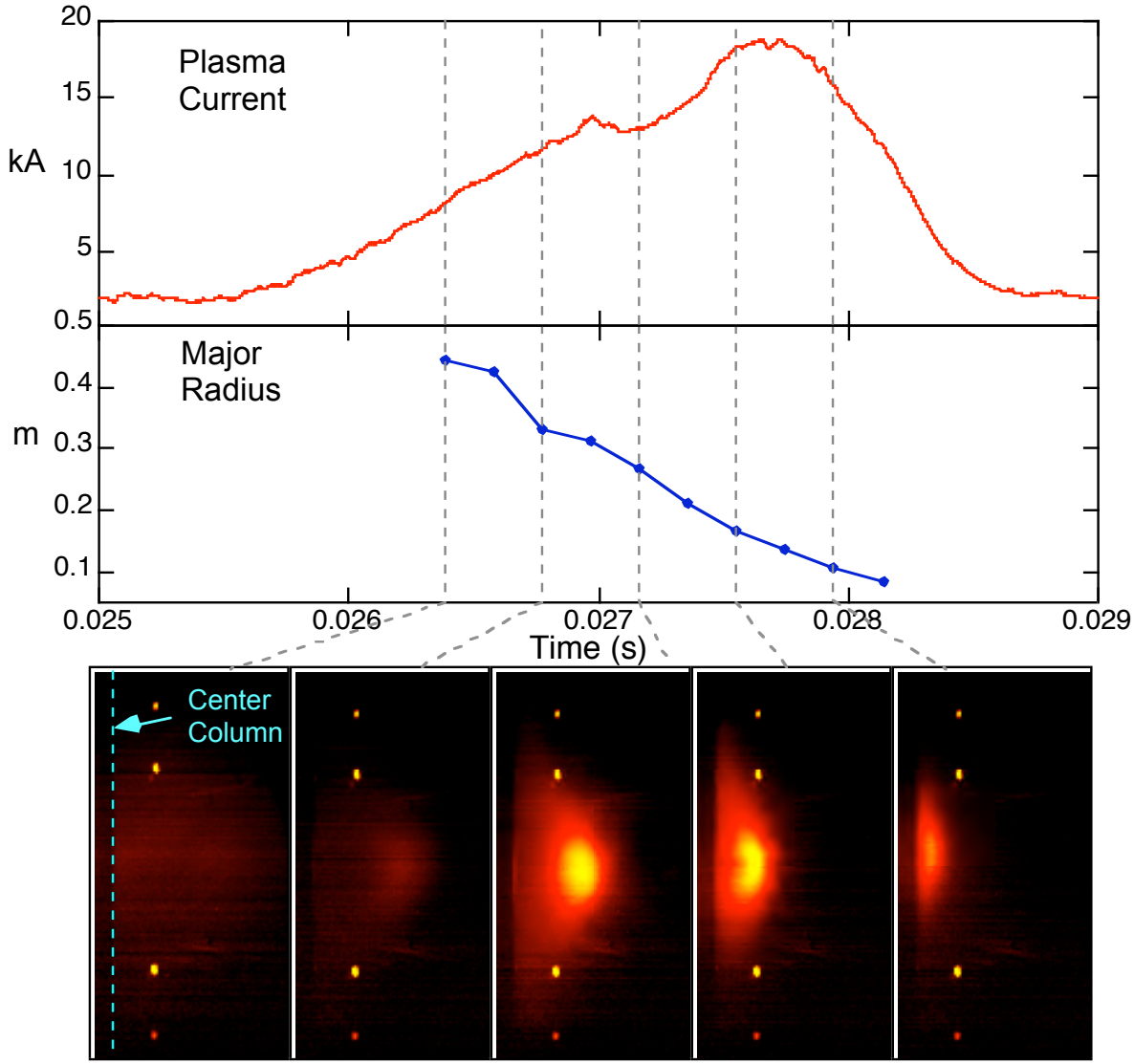
Midplane gun assists PF induction



- I_p up to 18 kA driven
  - Initial filament current = 1 kA
- Diagnostics indicate flux closure
  - SXR: increased signal
  - VUV: O-V > O-IV
  - Central flux: reversal observed
  - Bolometry: centrally-peaked radiation moving toward centerpost

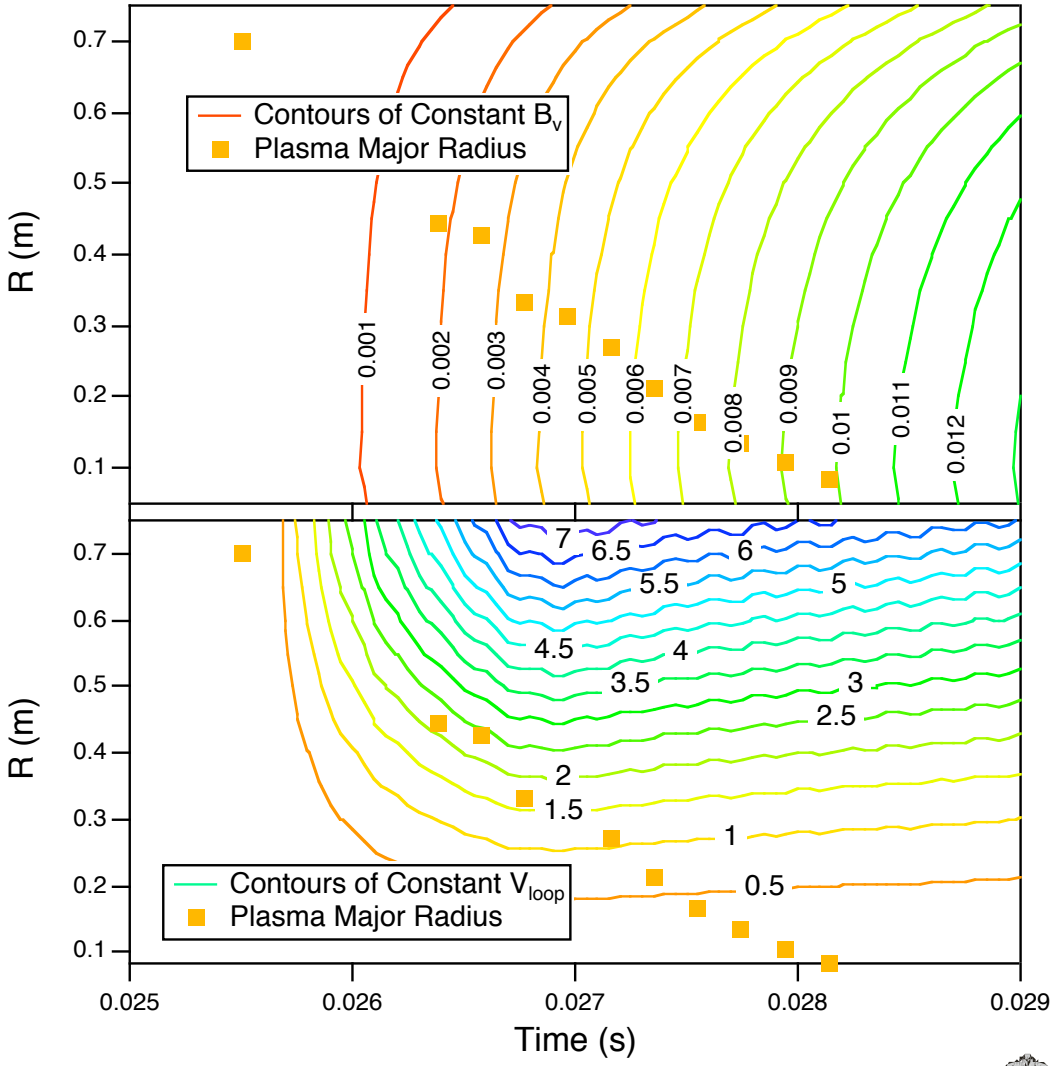


Plasma compressed by PF coil ramp



Outer PF coils ⇒ B_v - V_{loop} mismatch

- Outer PF coils used to provide B_v, V_{loop}
  - Wall L/R time ~ 2 ms
  - $V_{loop} > 7$ V @ gun
- As plasma compresses:
  - V_{loop} decreases
    - *V_{loop} at plasma < 2.5 V*
  - B_v increases
  - Net result: overcompression into center column
- Next experiments designed to address these issues
  - More robust target plasma
    - *Multi-turn gun system*
    - *Relaxed, MHD stable target*
  - Improved scenario
    - *Decoupling of V_{loop}, B_v*



Upcoming Work

- Gun Physics
  - Measure J(r) profiles
  - Study relaxation physics
  - Characterize helicity & power balance
  - Study associated MHD activity

- Hardware
  - Determine source(s) of nitrogen
  - Develop higher-power gun array
    - *More robust gun design*
    - *Possible modification of lower divertor region*
    - *New power supplies*

- PF Induction
  - Install higher-power midplane gun assembly
    - *Multiple-wrap configuration*
    - *Closed flux-surface large-A plasma target*
  - Improved coil configuration
    - *Partially separate effects of* B_v, V_{loop}

Summary

- Relaxed, ST-like plasmas ($I_p < 50$ kA) produced via helicity injection using arrays of discrete washer gun sources
  - Sources are clean but small
    - *Nitrogen observed with higher power guns*
  - Operating space set by requirements for field reversal, force balance

- Strong evidence for flux surface closure
  - $T_{e,0} > 50$ eV — Reversal of core flux
  - n = 1 mode — Increased L/R decay time
  - Radial force balance — Rapid increase in I_p

- Plasmas with $I_N \sim 12$ ($I_p/I_{tf} \sim 2$) produced with this technique
  - Kink and tearing mode stable
    - *Suppression of tearing modes via J(r) manipulation*

- PF induction experiments conducted using gun source
  - Initial target plasma 1-2 kA
  - Induction produces $I_p \sim 18$ kA