

Noninductive startup and attainment of high I_N on Pegasus

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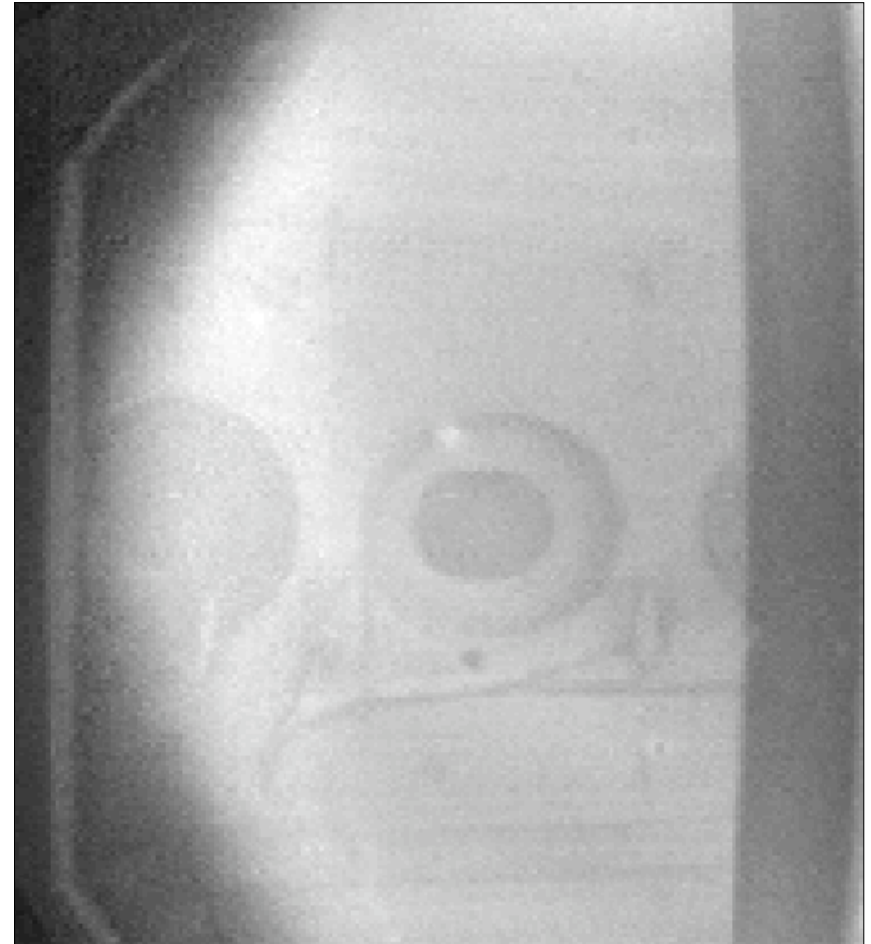
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Overview

- Plasma washer gun sources installed in lower divertor region
- In certain conditions, ST-like plasmas are formed
 - driven by helicity injection
- Plasmas with high I_p/I_{tf} produced
 - $I_p/I_{tf} = 2$
 - $I_N = 12$
- Guns used for seed plasma for PF induction experiments





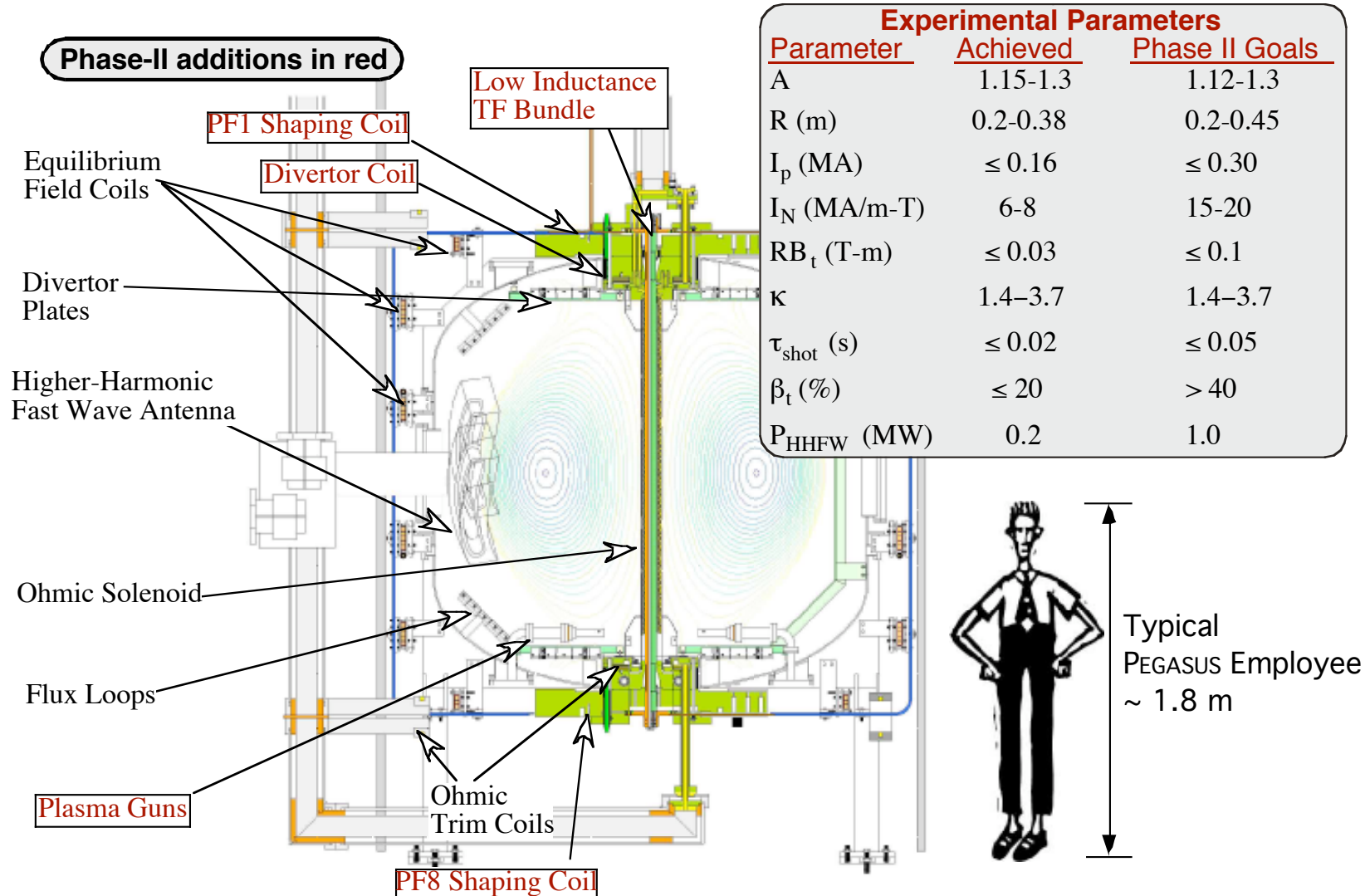
Exploration of $A \rightarrow 1$ regime limited by current drive considerations

- Shortage of ohmic current drive: longstanding ST issue
 - Especially problematic in Pegasus
- Experimental focus: explore high I_N , high β_t space
 - External kink stability should diverge from standard tokamak as $A \rightarrow 1$
 - 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





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

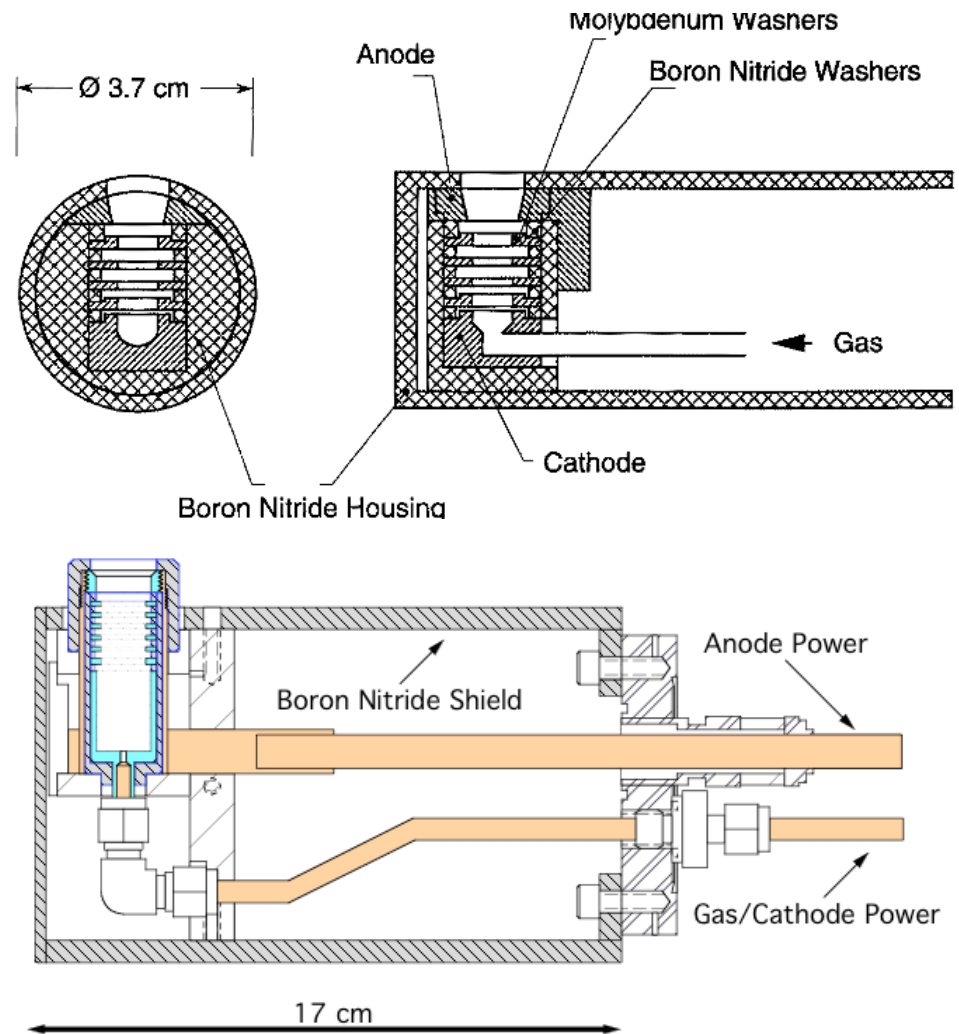
- Plasma guns have advantages as helicity injection technique
 - Low impurity content
 - Scalable to larger size
 - Controllable by current feedback
 - Integratable into existing Pegasus facility
 - Significant power per device (1-2 MW)





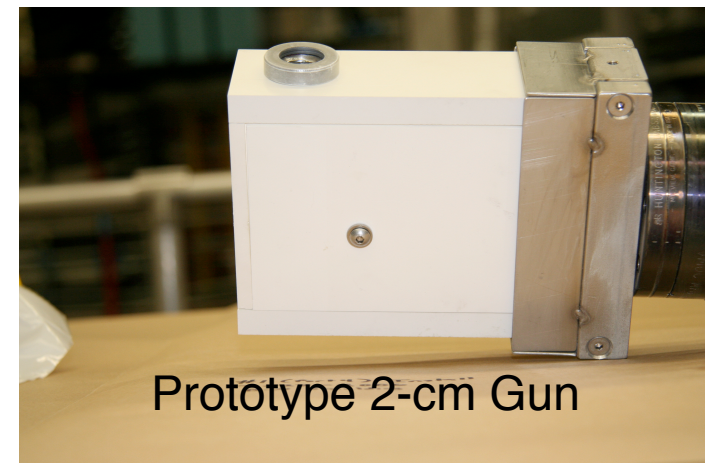
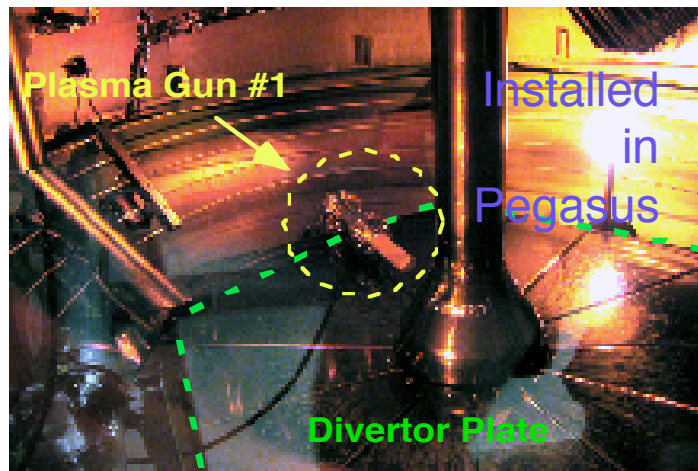
Gun construction

- Mo anode & cathode separated by Mo & BN washers
- D₂ fed independently via dual gas/cathode line
- BN housing
- Relatively clean plasma source
 - Internal arc formed
 - Anode of arc is cathode of electron source
 - Small aperture area
- Typical parameters:
 - $I_{\text{arc}} = 1\text{-}2 \text{ kA}$
 - $I_{\text{inj}} = 1\text{-}2 \text{ kA}$
 - $V_{\text{inj}} < 900 \text{ V}$
 - $\delta t_{\text{arc}} = 0.01 \text{ s}$ (set by heating)





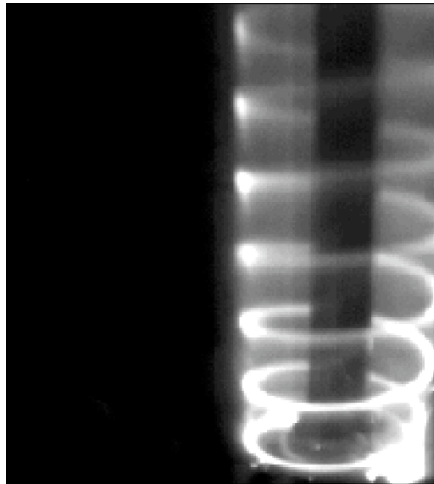
Gun photos





Relaxed plasmas can be formed

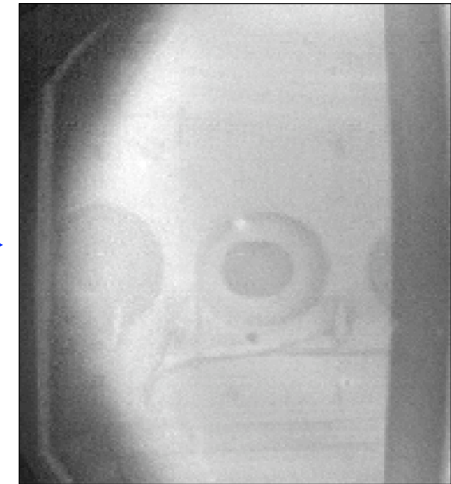
- At low I_{inj} and/or high pitch angle, helical current filaments form
 - $M = I_p/I_{inj} = \text{Geometric stacking}$
- Filaments merge into cylindrical sheet as I_{inj} increased, pitch decreased
 - $M > \text{Geometric stacking}$
- At low fields ($B_\phi \approx 0.01 \text{ T}$, $B_\theta \approx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



Filaments



Reconnected Sheet

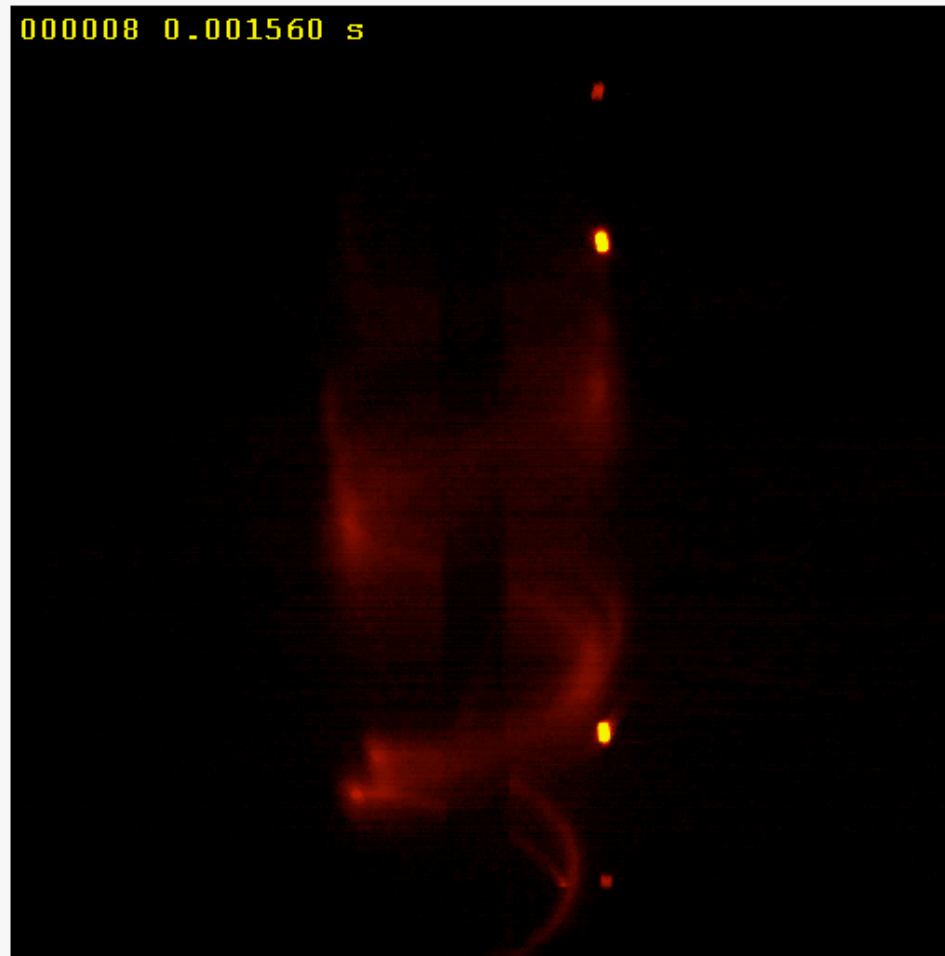


Relaxed





Formation of tokamak-like plasma



Shot 34769 $t = 19.559 \text{ ms}$





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: $I_p = V_{bias} A_{inj} / 2\pi R \eta$*
 - 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

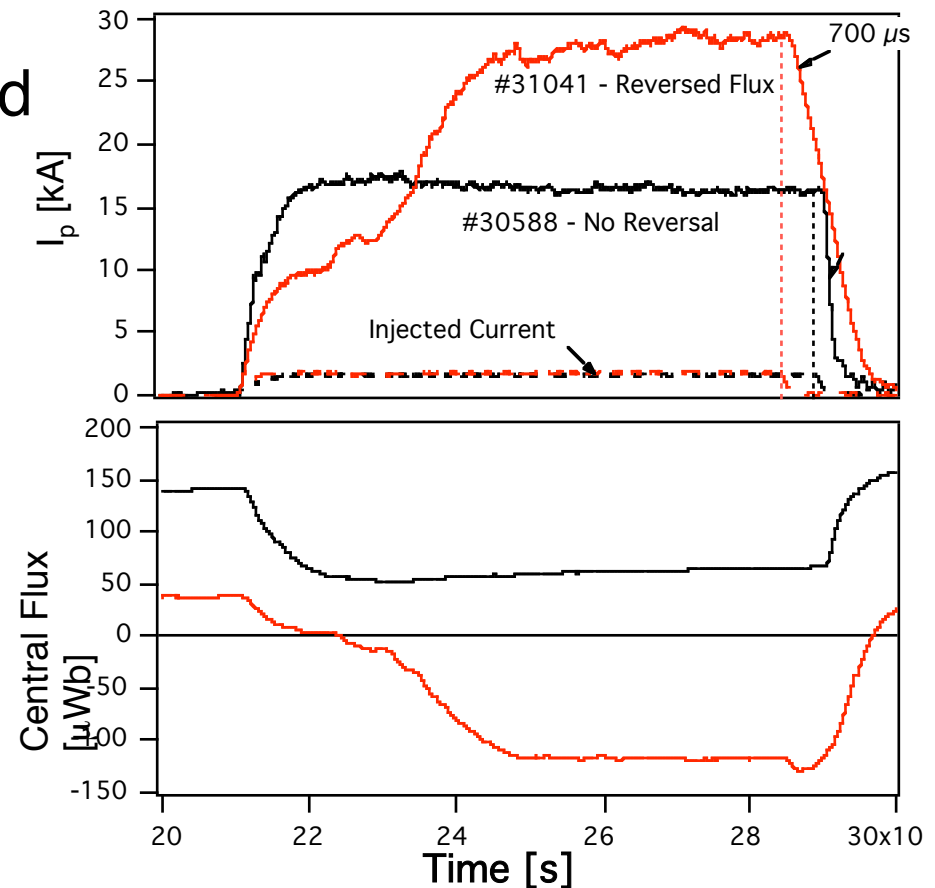
- Rapid increase in plasma current
- Reversal of core flux
- Increased plasma L/R decay time
- Appearance of $n=1$ MHD mode
- Increased core heating observed in VUV and SXR
- Consistency of vertical field with tokamak radial force balance





Central flux reverses sign and plasma decay time increases

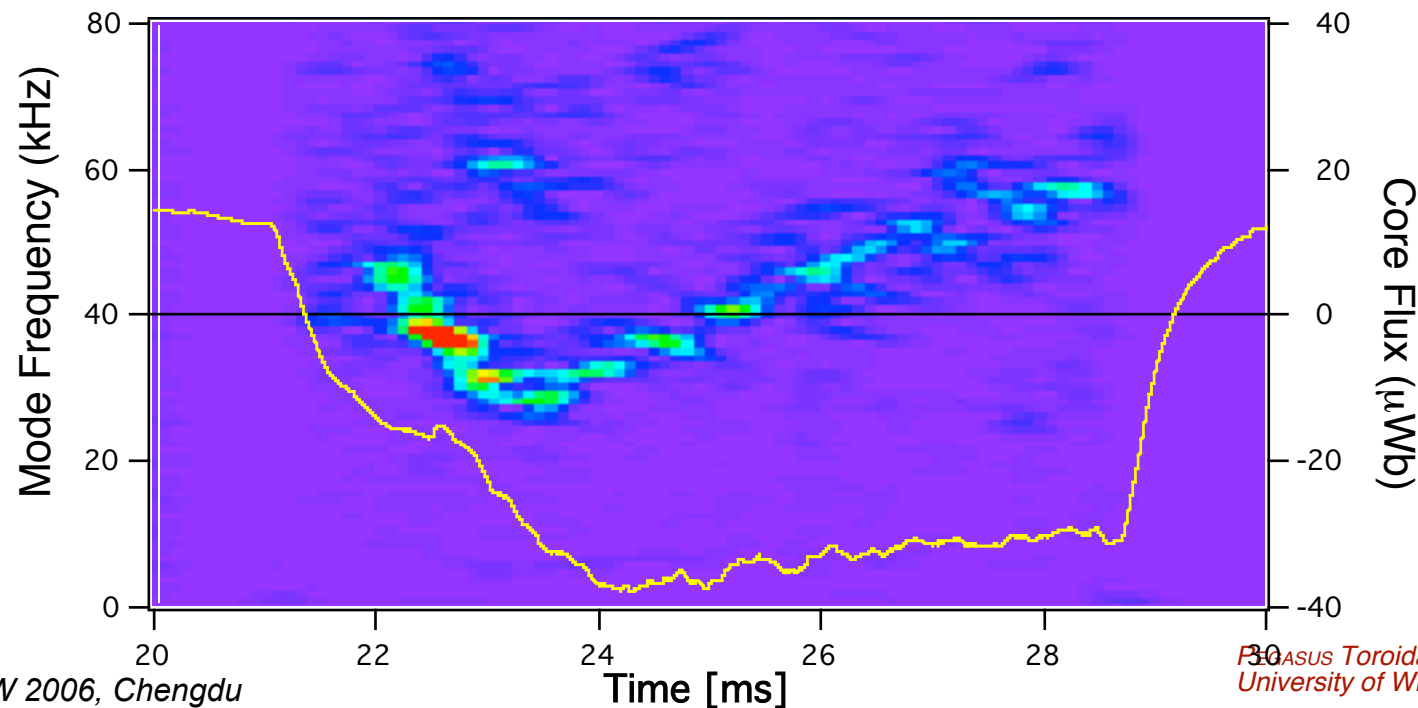
- Flux-reversed plasma observed during low field injection
 - > 4x flux reversal
 - Necessary for tokamak formation
- I_ϕ increase > 50 %
 - Increased current drive efficiency
 - Maximum observed $I_\phi < 50$ kA
- τ_{Decay} increase > 400 %
 - Decay w/o reversal $\approx 160 \mu\text{s}$
w/ reversal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





$n=1$ mode observed

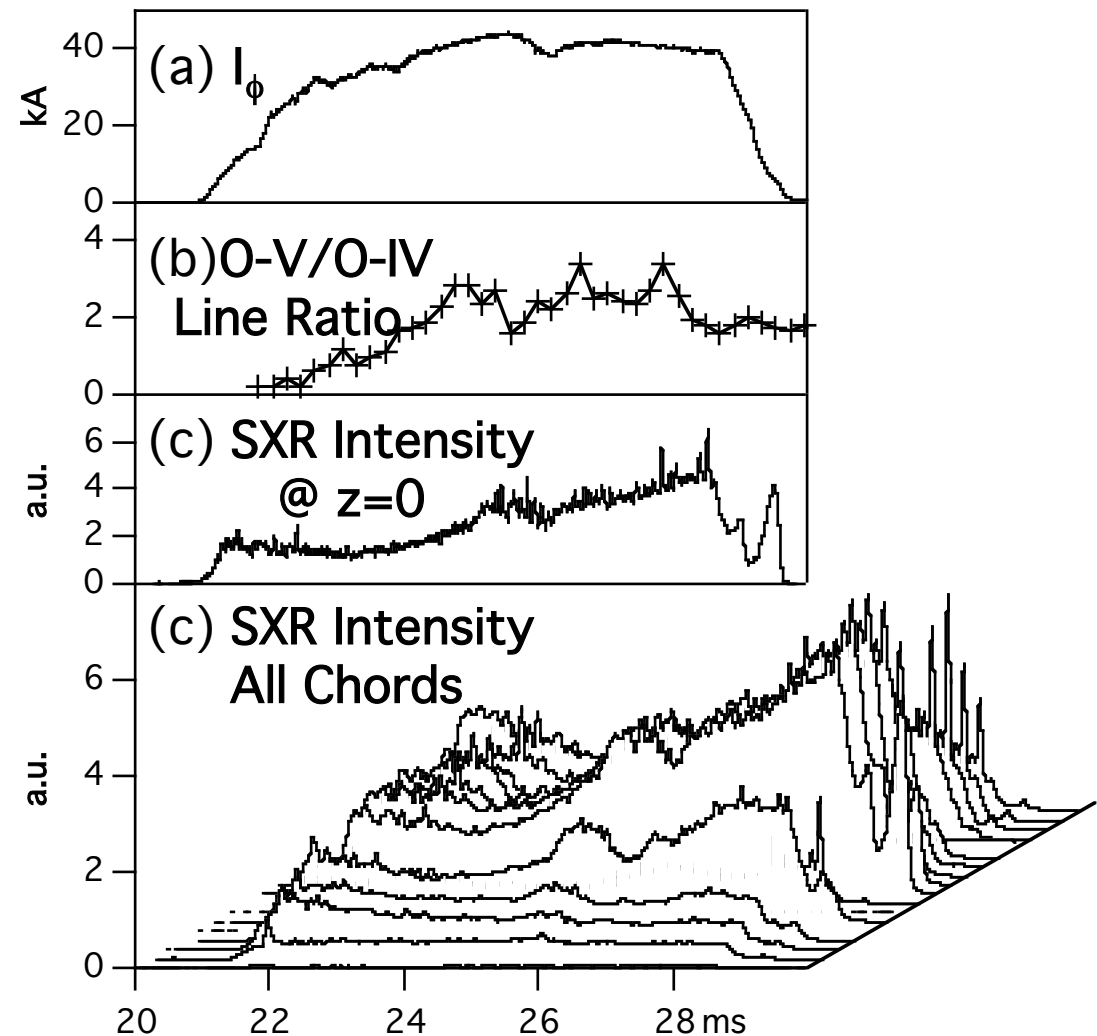
- 20-60 kHz $n=1$ mode observed soon after flux reversal
- Understood to be crucial to CHI current drive
- Dynamo action of $n=1$ line-tied kink believed to provide loop voltage for closed-flux current drive
- Higher order modes ($n=2,3$) also observed
 - At the time of flux reversal
 - Later in the discharge (> 1 skin time)





Tokamak-like plasmas exhibit evidence of heating

- O-V (114 eV) to O-IV (77 eV) line ratio indicates increased T_e
 - $T_e > 50$ eV
- SXR array indicates formation of hot core
 - Emission peaks at midplane
 - Midplane signals decay slower at shut-off



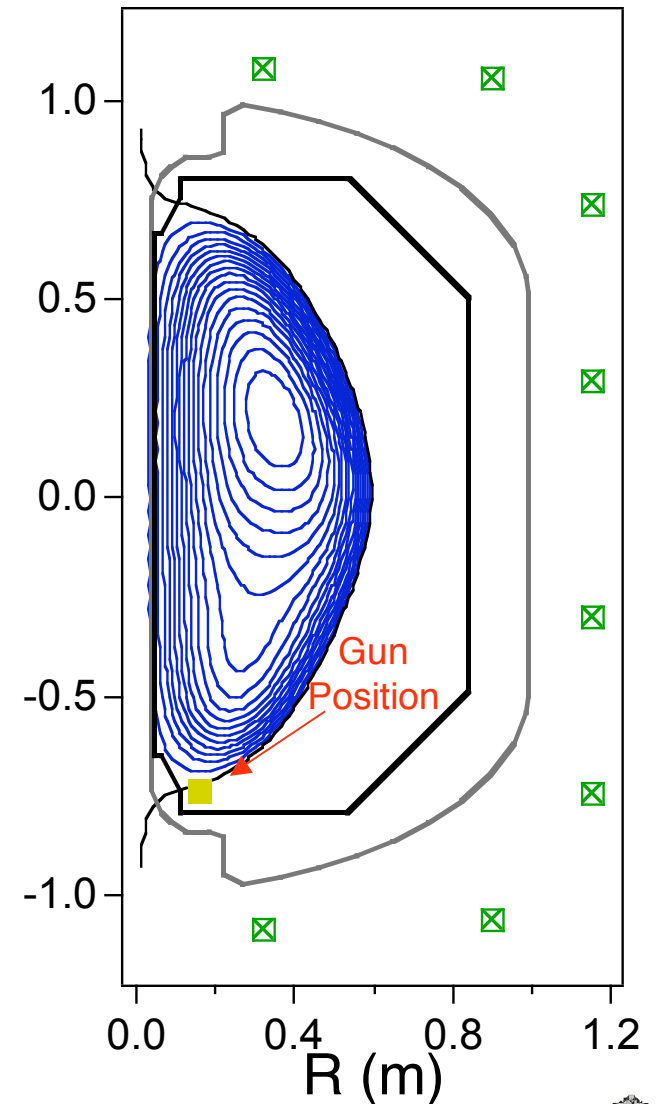


Radial force balance satisfied

- Sample case: 30 kA, $R=0.4$ m
 - B_v required by standard expression:
 - $\ell_i = 0.5$: 0.0072 T
 - $\ell_i = 0.0$: 0.0054 T
 - Applied vacuum B_v : 0.005 T
 - *Fair agreement*
- Equilibria have been reconstructed
 - Vertically asymmetric
 - Difficulties of reconstruction:
 - *Open field-line currents*
 - *Non axisymmetric currents near gun*

Sample Equilibrium Reconstruction

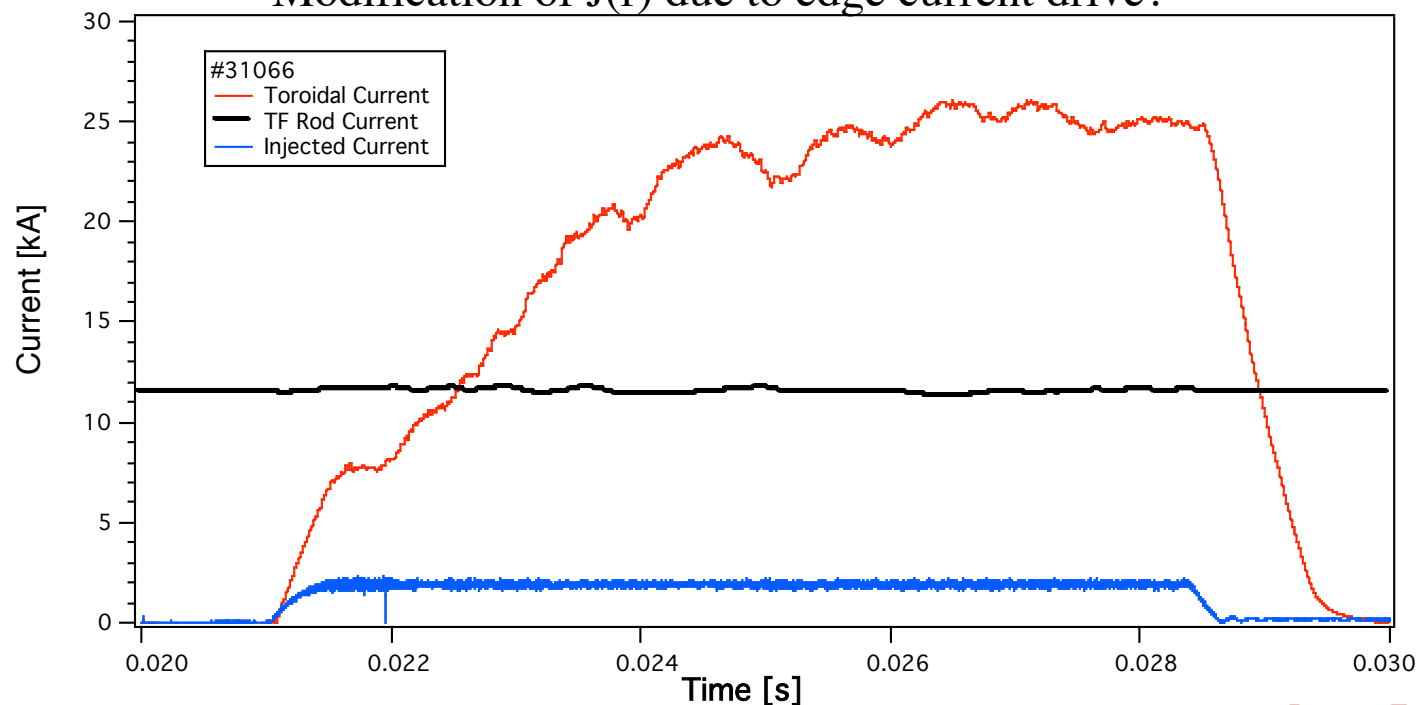
- | | |
|-------------------|---------------------|
| • I_p : 46.9 kA | • ℓ_i : 0.22 |
| • R_0 : 0.35 m | • Z_0 : 0.2 m |
| • q_{99} : 8.0 | • β_t : 11.4% |





Large values of I_N achieved at very low toroidal field

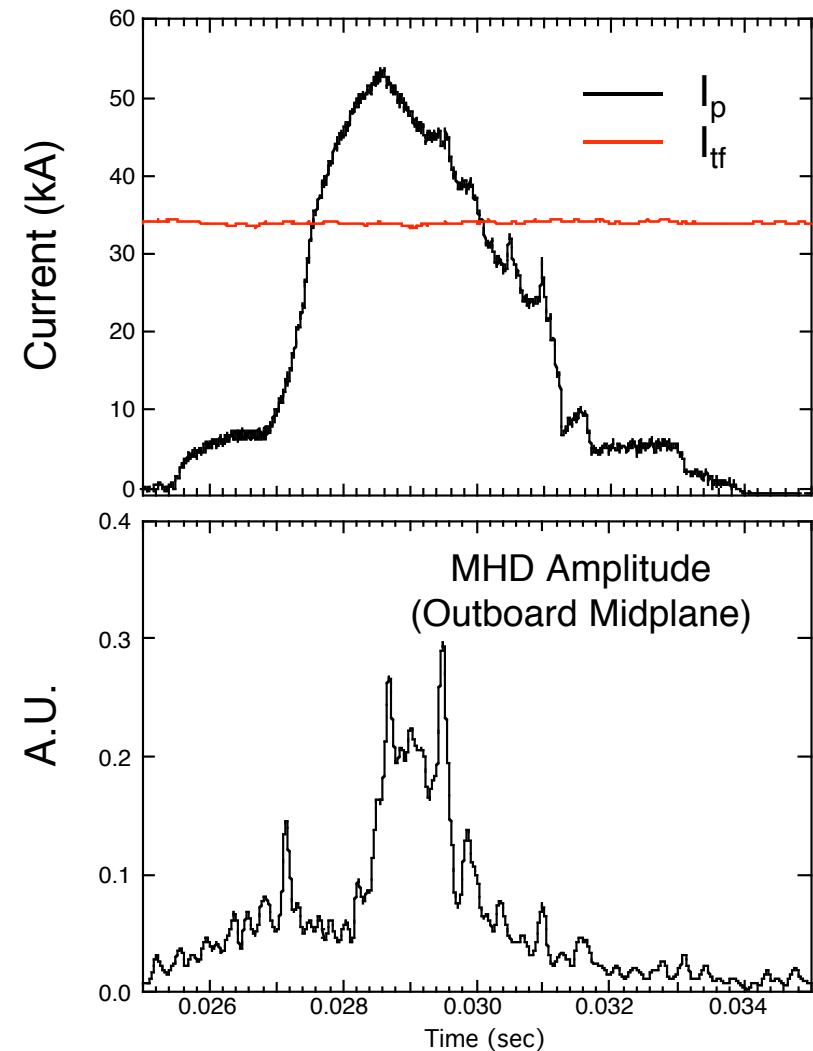
- Ohmic plasmas have been limited to $I_p < I_{tf}$
 - Due primarily to low-order tearing modes
- Gun plasmas routinely produce $I_p/I_{tf} \sim 2$ ($I_N \leq 12$)
 - $B_t < 60$ Gauss
 - Low frequency tearing modes not observed
 - Modification of $J(r)$ due to edge current drive?





High I_N in ohmic plasmas produced with gun preionization

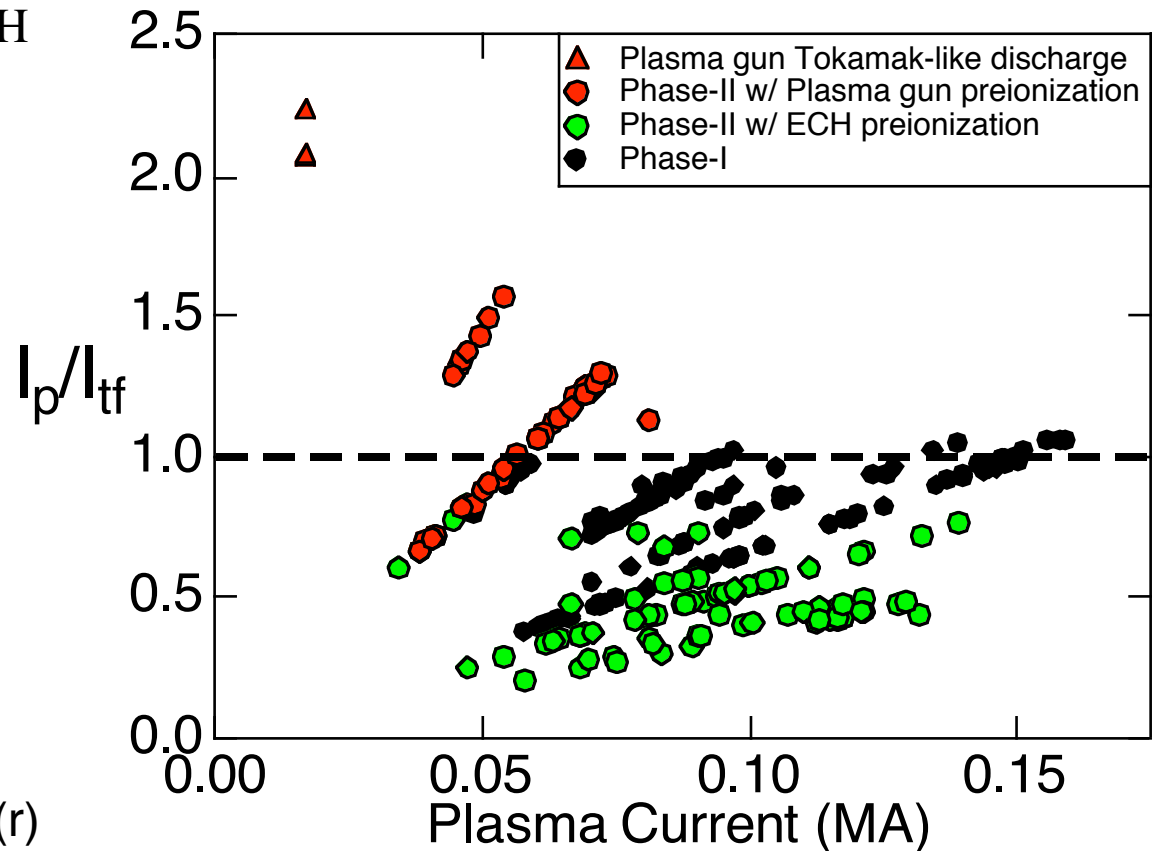
- Sheet gun plasma \rightarrow preionization at low B_t
 - $0.02 \text{ T} < B_t < 0.04 \text{ T}$
 - No resonant surface for ECH PI
- $I_p/I_{tf} = 1.5$ achieved using this technique
 - With low power OH system ($V_{loop} < 4 \text{ V}$)
- Tearing modes observed as I_p increases
 - $I_p = I_{tf}$ not intrinsic limit
- Future experiments: repeat at higher power
 - Increased gun power
 - Full OH system now operational





Guns have greatly expanded I_p/I_{tf} operating space

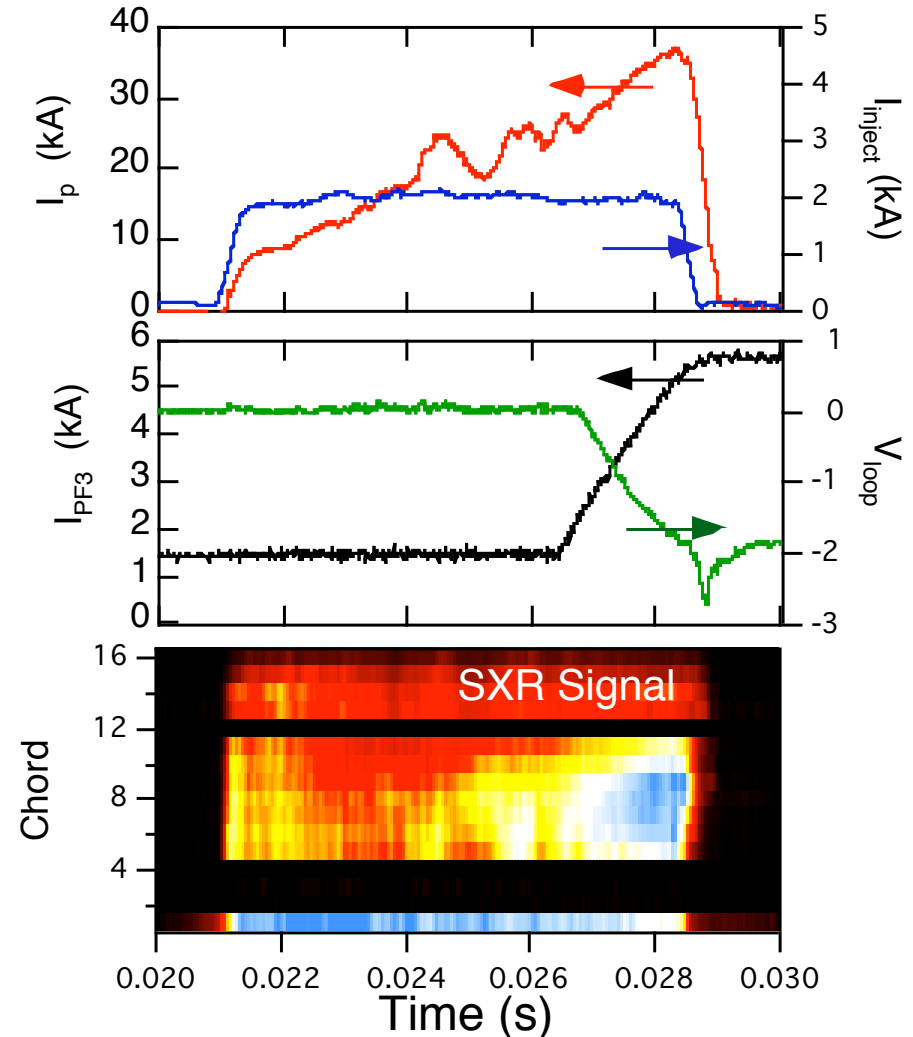
- $I_p/I_{tf} > 2$ achieved at low TF
 - No external kink
 - Tearing modes only with OH
- Helicity injection vs OH \Rightarrow fundamentally different CD mechanisms
 - OH CD at low η
 - HI: CD at edge
- Substantial $J(r)$ modification
 - Broad/hollow profile
 - q possibly reverse shear
- Guns provide possible tool to routinely access high I_N via $J(r)$ modification





Gun-OH handoff shows signs of heating

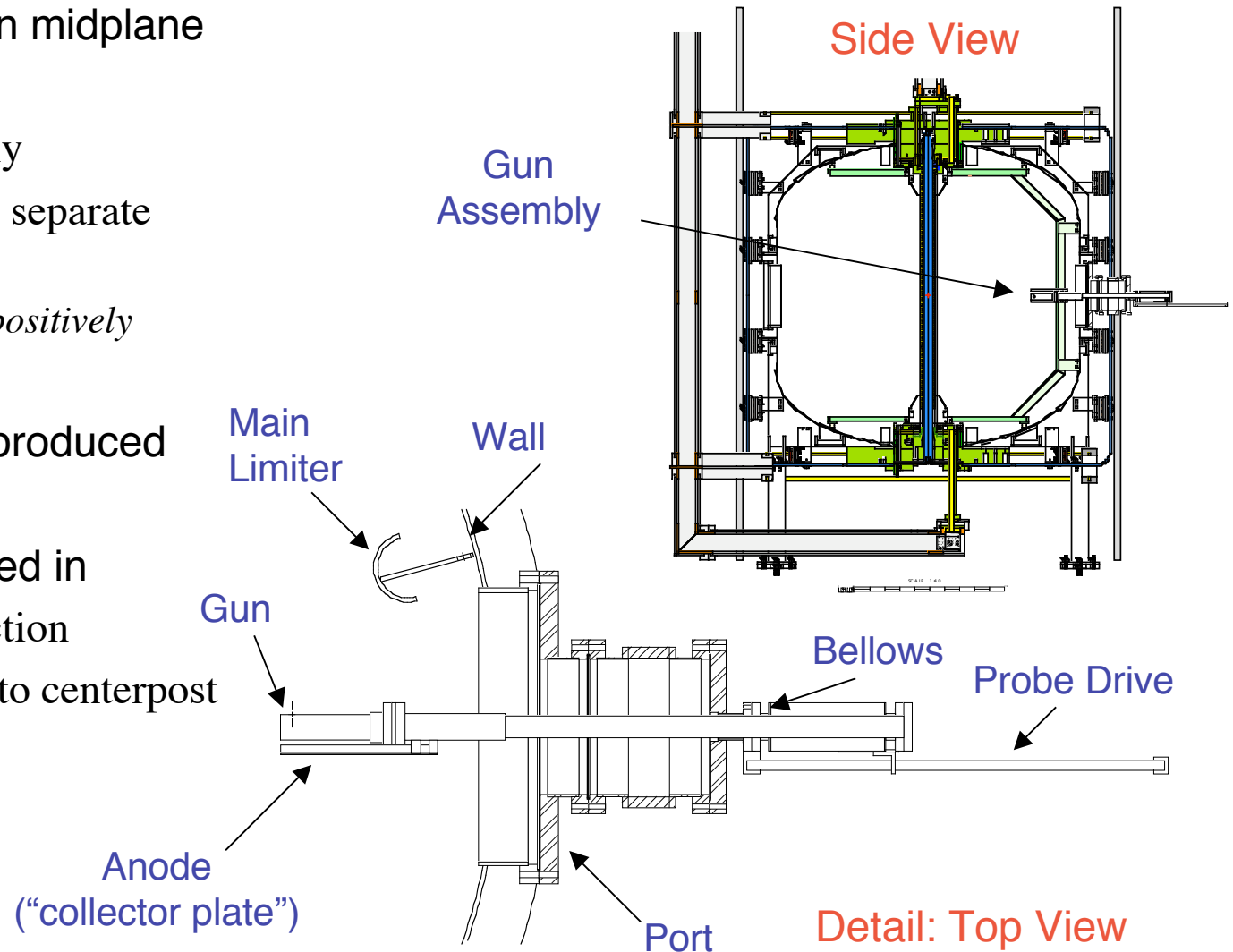
- Low V_{loop} added to end of gun discharges
 - Modest increase in I_p
 - Prototype guns: limited to very low TF
- SXR emission increases with V_{loop}
- Want full handoff: guns \rightarrow OH
 - low field \Rightarrow poor confinement
 - input power mismatch:
 - guns: 2 MW
 - OH: 80 kW
- Approach: increase gun helicity & power
 - allows higher field ops
 - better matching of applied field to equilibrium field
 - added flux, V_{loop} from full power OH





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





PF induction: the movie

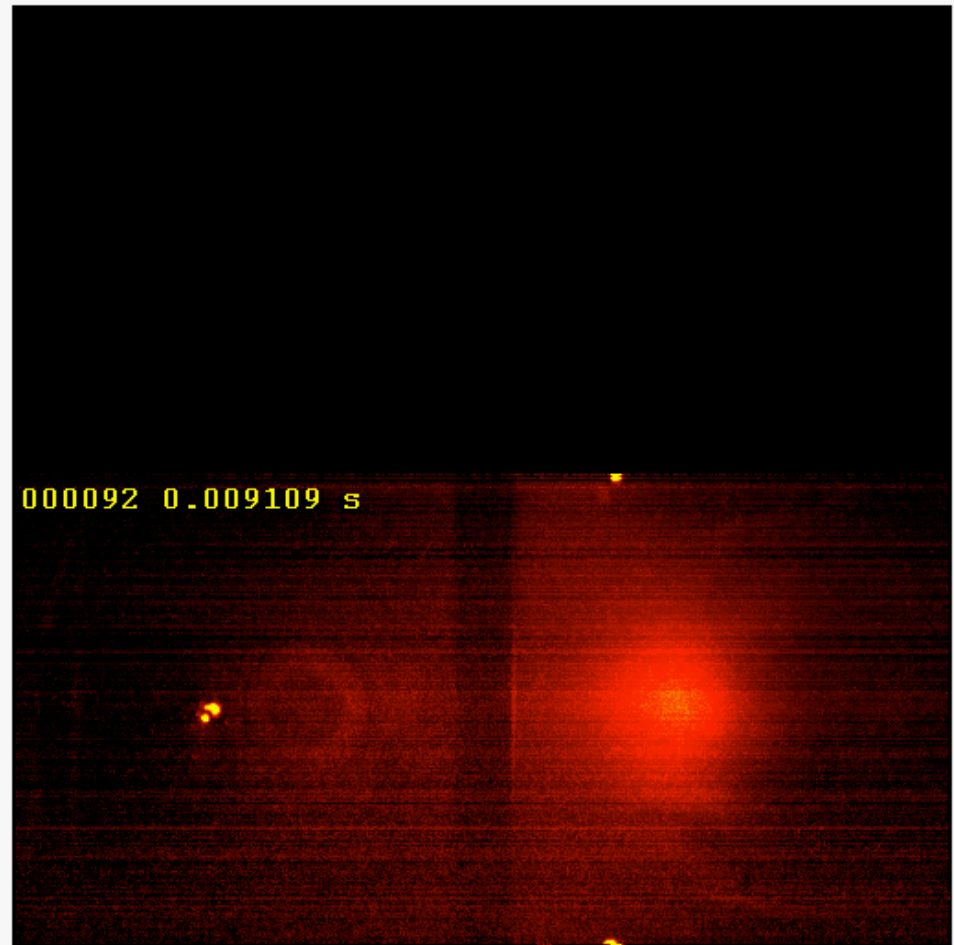
20 ms: Toroidal current starts

20.8 ms: Gas puff

23 ms: Plasma fades

26.7 ms: Induction begins

28 ms: Plasma fades

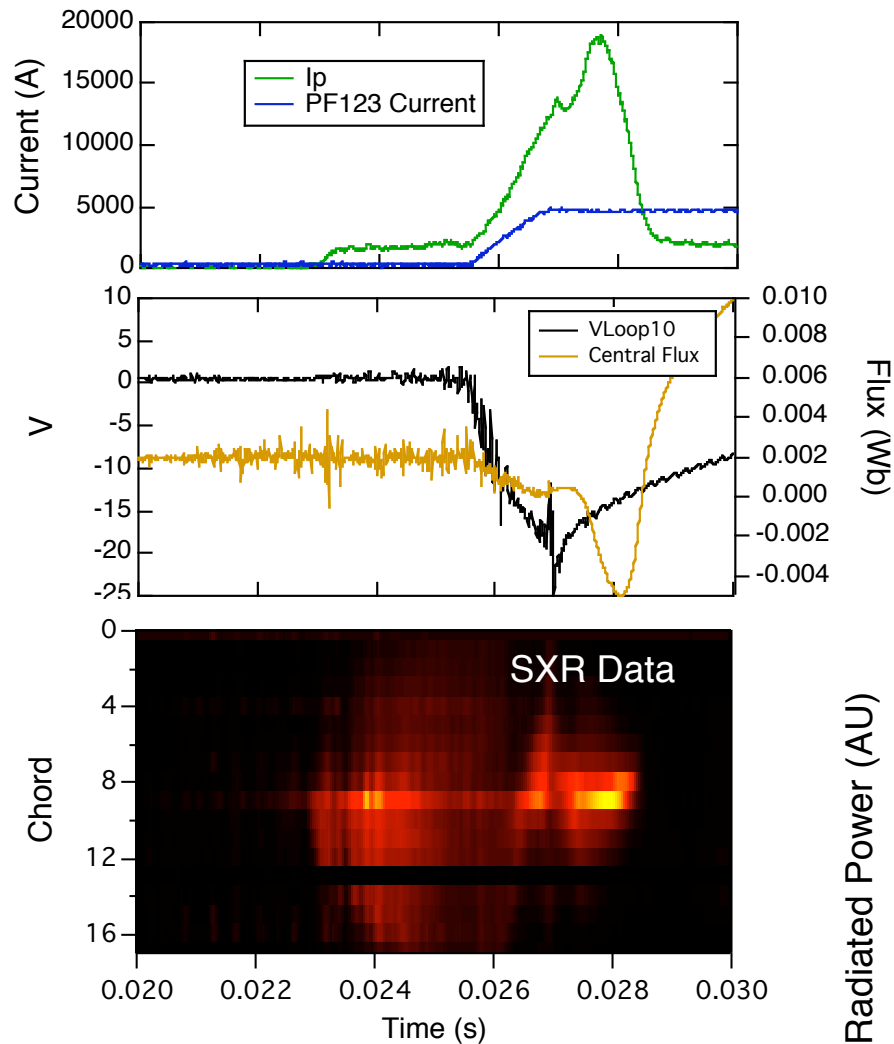


Shot 35657 t = 27.109 ms

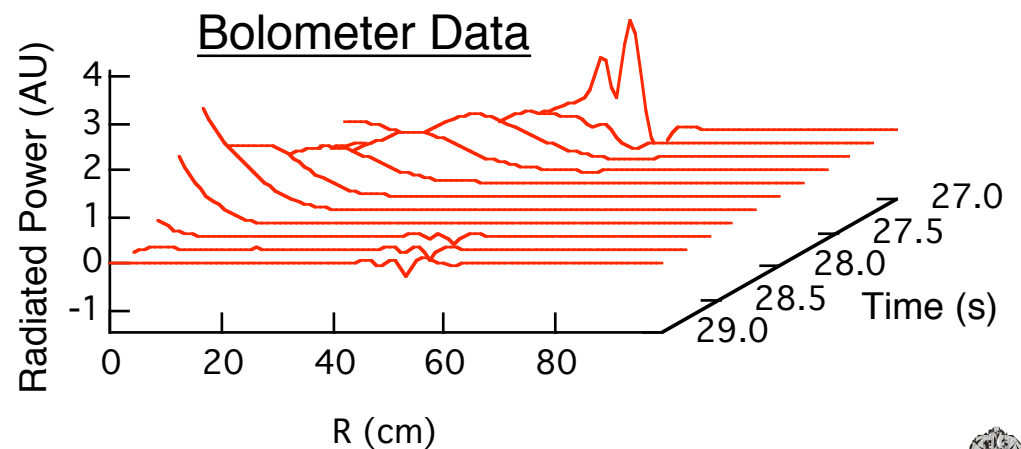




Midplane gun assists PF induction



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





Future plans

- Study plasmas with high I_N , β_t
 - Install upgraded high-current guns
 - *Array of guns for $I_p > 0.1$ MA (~ 10 MW system)*
 - *Redesign to minimize nitrogen production*
 - Couple high-power guns to full-power OH system
 - *Preionization vs fully relaxed gun plasmas*
 - *Study effects of $J(r)$ modification on MHD stability*
 - Implement upgraded midplane gun system (imminent)
 - *Multi-turn gun/collector system*
 - *Designed to produce 5-10 kA relaxed plasma as target for induction*
- Study physics of discrete-helicity-source current drive
 - Aided by installation of high-power gun array
 - Helicity & power scalings
 - Current profile measurements
 - Detailed mode activity studies





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
 - $T_{e,0} > 50$ eV
- 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*
 - Good technique for reliably accessing high I_N
- PF induction experiments conducted using gun source
 - Initial target plasma 1-2 kA
 - Induction produced $I_p \sim 18$ kA





SUPPORTING MATERIAL



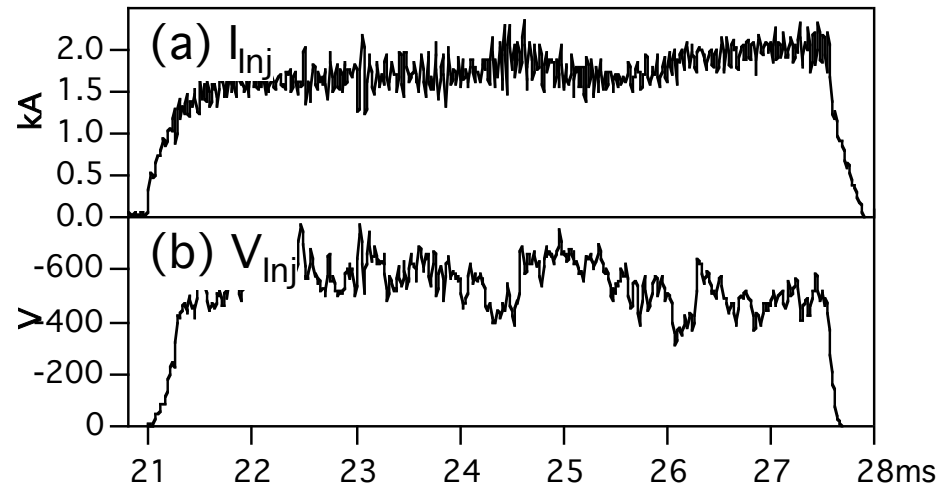


-
- The schematic diagram illustrates the Pulse Forming Network (PFN) and the Bias Circuit. The PFN consists of a series of capacitors and inductors, including a 250mΩ resistor and a shunt, connected to the CATHODE and ANODE of the vacuum tube. The ANODE is connected to the Vessel. The Bias Circuit includes an H Bridge and a Feedback Rogowski coil. The waveforms show the current I_{Arc} (a) and voltage V_{Arc} (b) over time, with the current peaking at approximately 2.2 kA and the voltage peaking at approximately 150 V.





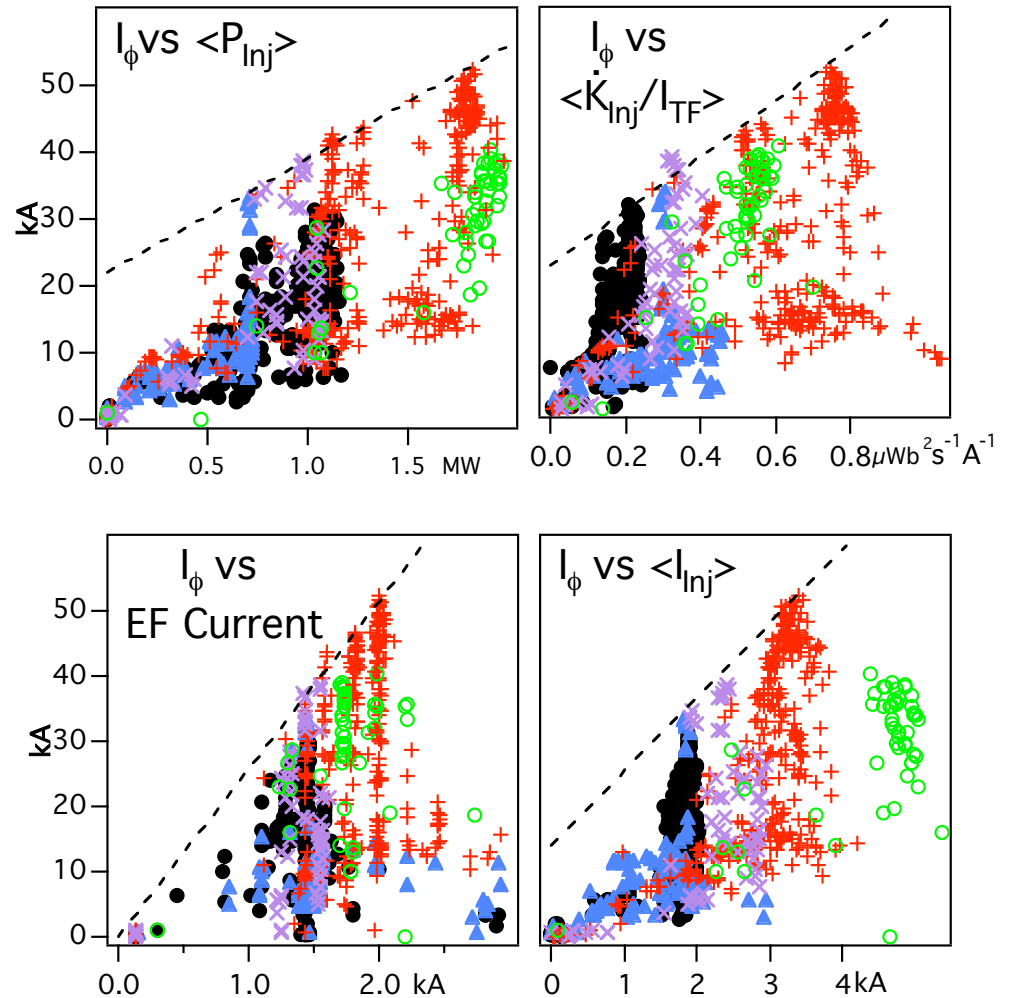
-
- Pulse Forming Network**
- I_{Arc}
- 250mΩ
- Shunt
- CATHODE
- V_{Arc}
- ANODE
- V_{Inj}
- 12μF
- Shunt
- Vessel
- I_{Inj}
- Feedback Rogowski
- Bias Circuit**
- 80μH
- H Bridge





Phenomenological Trends of I_ϕ

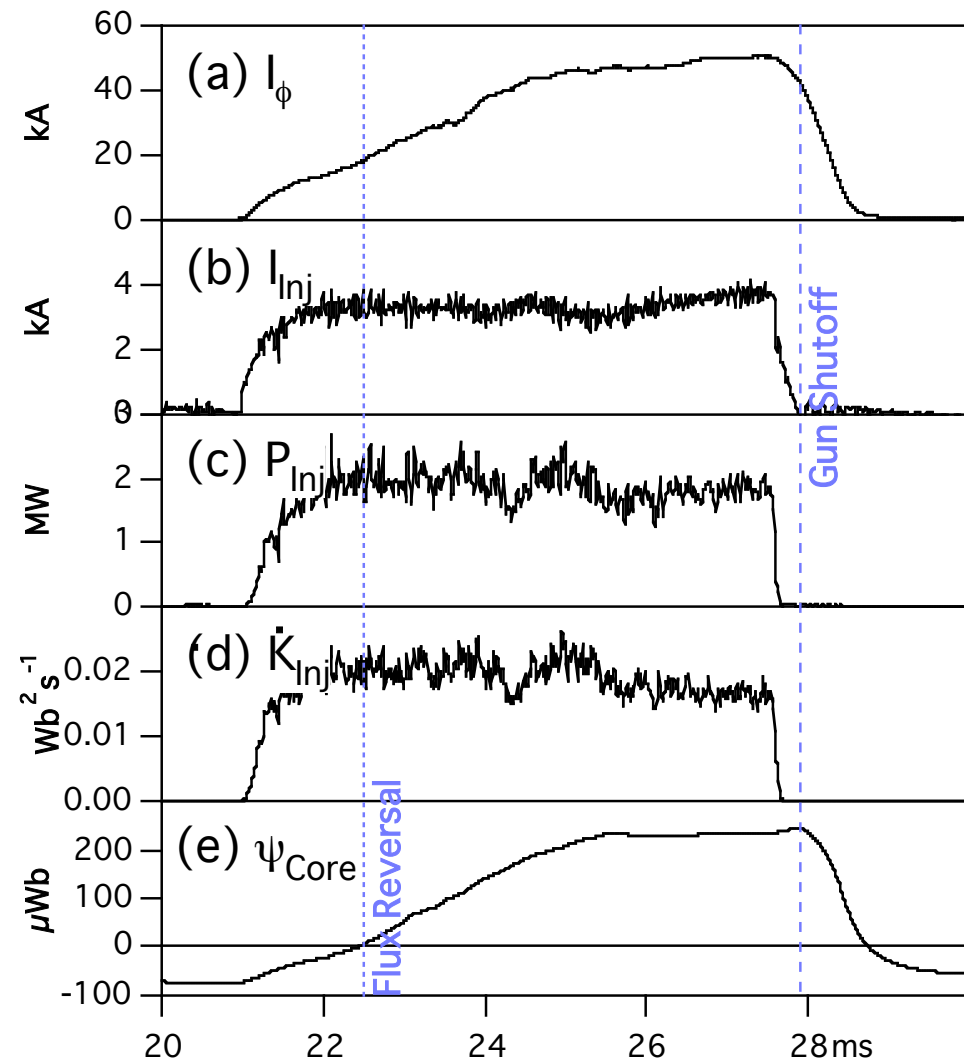
- I_ϕ transition from non-linear to offset-linear response to both P_{Inj} and
- Transition corresponds to transition from non-reversed to marginally reversed to fully relaxed plasmas
- Only response to B_v approximates 0-intercept





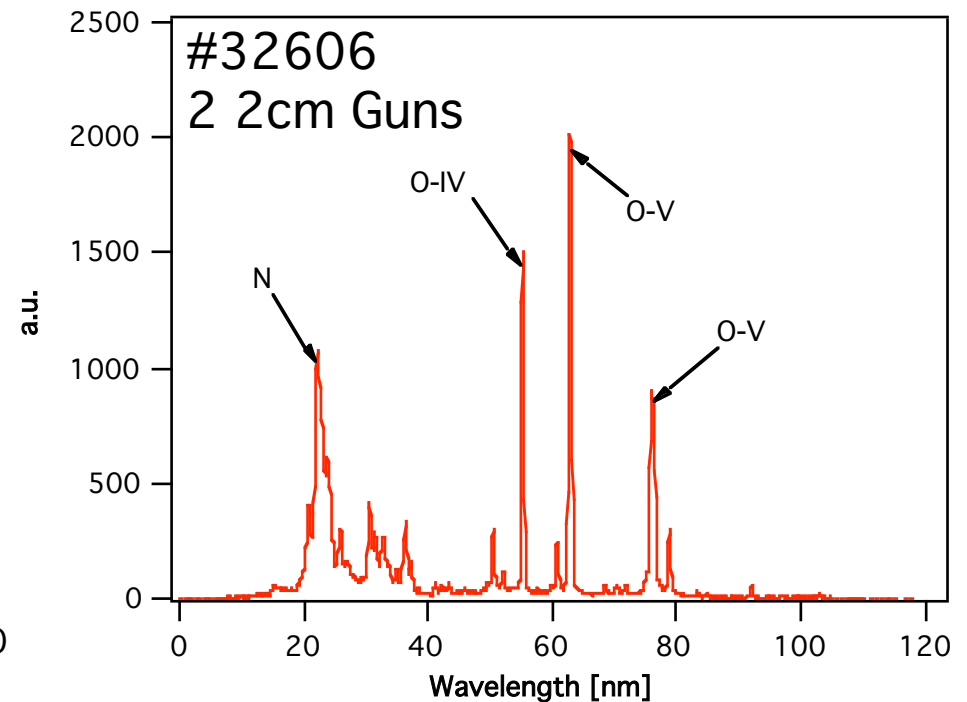
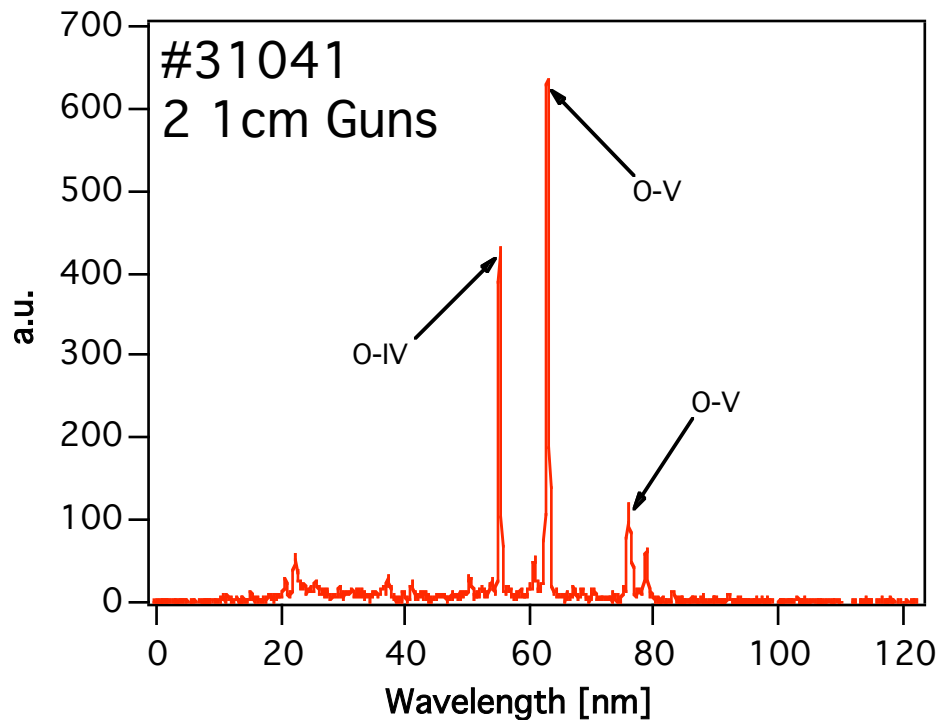
Characteristics of Fiducial Tokamak-like Gun Discharge

- $I_\phi > 50$ kA attained
- $I_{inj} \approx 4$ kA, $P_{inj} < 3$ MW
- I_ϕ rises until gun shut-off
- Roughly constant
– Calculated assuming $B_n = B_\phi$
- Deep flux reversal ($> 3x$)





Impurity Spectra





Consistent with Helicity Conservation

- Is measured I_p consistent with helicity input?
- Assuming:
 - 1) $R = 40$ cm, $a = 35$ cm (inferred from images)
 - 2) η_{Spitzer}
 - 3) $Z_{\text{eff}} = 2$
 - 4) Uniform J
 - 5) $B_\phi = 0.01$ T
 - 6) Injected $dK/dt \approx 4 \times 10^{-3}$ Wb²/s (calculated from experimental data)

$I_p = 25\text{-}35$ kA is consistent with $T_e = 50\text{-}70$ eV

- Given SXR and spectral data, 50-70 eV reasonable estimate
 - More quantitative analysis planned

Helicity conservation in general agreement with observed plasmas





Transition of sheet plasma to relaxed closed flux-surface plasma

- B_V reduced to allow flux reversal
 - B_ϕ reduced to maintain pitch
- As reversal approached, I_ϕ proportional to B_V
- I_ϕ regulation maintains near-reversal over large B_V variation
- Reversal at $B_V \approx 20\text{-}30$ gs matches expectation
 - Simple elliptical model: 3 gs / kA
- Behavior changes once reversal appears
 - I_ϕ not proportional to B_V
 - Poloidal structure changes dramatically
- Narrow optimal operating space
 - Very sensitive to fields, background gas

