Abstract

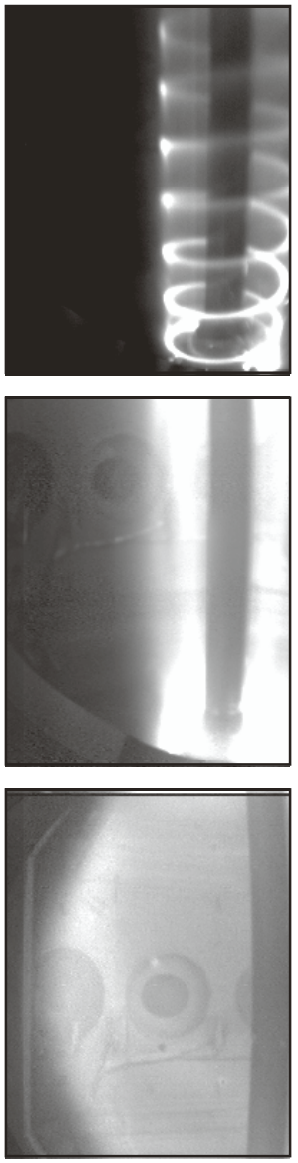
Developing non-inductive startup and efficient fueling techniques is important for the ST and for current-carrying toroidal devices in general. This need is especially acute on the very-low-A Pegasus toroidal experiment due to its limited volt-second capability. Experiments are being conducted to test auxiliary plasma injection and toroidal current drive via DC helicity injection. Dual low-impurity, high-current (1 kA) plasma washer guns[1] have been installed in the lower divertor region of the Pegasus vacuum vessel. These guns act both as helicity and fueling sources. The sources are biased up to –900 V relative to the vessel and initially drive current along helical field lines produced by the toroidal and vertical fields. At high current density, the helical current streams reconnect to form a continuous cylindrical plasma with a net toroidal current. At sufficiently low values of externally applied poloidal field, the toroidal current causes a reversal of the poloidal flux and the plasma relaxes to a tokamak-like configuration. Discharges with toroidal current greater than 25 kA are routinely produced with less than 2 kA of injected current. These high-current plasmas exhibit features indicative of closed flux surfaces, including strong reversal of poloidal flux at the center column, a well-defined edge, significantly increased L/R decay times (> 0.7 ms), observed peaking of the SXR emission at the center of the plasma, significant gas fuelling requirements, and the characteristic n = 1 mode (f=20-60 kHz) which is observed in other helicity-injection-driven toroidal devices. The design of a larger array to be installed in Pegasus next year, projected to provide Ip > 100 kA, is also presented.

* Supported by U.S. D.O.E. Grant DE-FG02-96ER54375

[1] G. Fiksel, A.F. Almagri, D. Craig, M. Lida, S.C. Prager, J.S. Sarff, Plasma Sources Sci. Technol. 5, 78 (1996)

Plasma Gun DC Helicity Injection Yields Tokamak-like Plasma Formation

- Washer gun plasma current sources placed in lower divertor region of PEGASUS
- In crossed B_V & B_ϕ, injected plasma current follows helical fields lines in discrete filaments
  - Low current density and/or high pitch angle
- As current density increases, discrete filaments reconnect into cylindrical plasma
- Under proper conditions, relaxation into tokamak-like plasma observed



Provides path to novel non-ohmic startup technique for ST's

Outline

1. Requirements specified for forming non-ohmic tokamak
   - Requirements specified for forming non-ohmic tokamak:
     1) Helicity conservation
     2) Consistency with power scaling laws
     3) Magnetic equilibrium

2. Plasma guns provide good source for DC helicity injection
   - Low impurity injection
   - Minimally invasive to vessel

3. Evidence of Tokamak-Like Discharges
   - Strong core flux reversal
   - Increased current drive capability
   - Increased L/R decay times
   - Massive deformation of poloidal field structure
   - n = 1 modes
   - Increased heating
   - Consistency with tokamak radial force balance
   - Consistency with helicity conservation

4. Plans for larger gun array capable of $I_\phi > 0.1$ MA

Conditions for Non-inductive Formation of Tokamak Plasma

- Tokamak plasma formation must satisfy 3 constraints:
  1) Helicity conservation
  2) Power scaling laws
  3) Consistency with magnetic geometry & equilibrium
- Helicity and power requirements interconnected (see next)
  - Both place requirements on non-inductive source
- 3 magnetic constraints:
  1) Local field structure to match multi-gun geometry
  2) EF weak enough for flux surface closure of plasma gun injected current:

$$B_{pol} > 3B_{Vac}$$

  3) EF strong enough to maintain MHD equilibrium

Helicity Conservation

- Helicity measures flux linkage of a volume:

$$K = \int \mathbf{A} \cdot \mathbf{B}\, dV$$

- Helicity conservation states[2]

$$\dot{K} = 2V\Psi - 2\int \mathbf{E} \cdot \mathbf{B}\, dV - 2\int \Phi \mathbf{B} \cdot \mathrm{d}\mathbf{a}$$

Induction & AC injection

Resistive Dissipation

DC Injection

- For *steady state* DC helicity injection, reduces to[3]

$$I_p = V_{Bias} A_{Inj} / 2\pi R\eta \qquad \text{[Eq. 1]}$$

[2] *Boozer, A.H., Phys. Fluids,* ***29****,12 (1986)*
[3] *Darrow, D.S. et al., Phys. Fluids B,* ***2****, 6 (1990)*

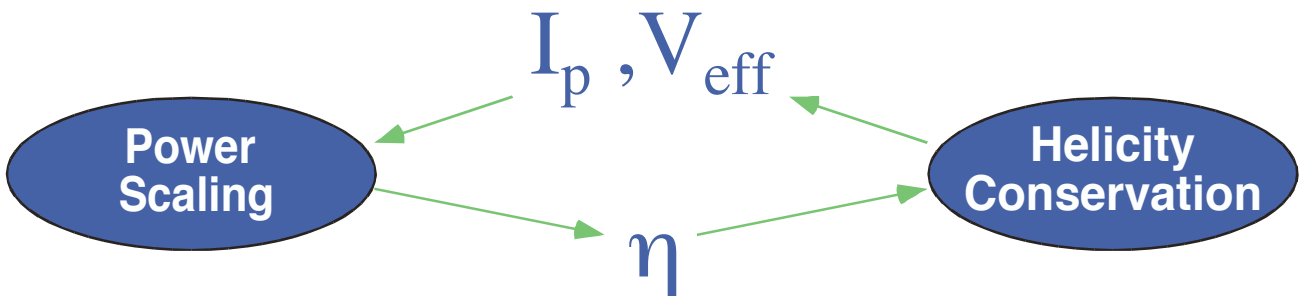
Helicity & Power Interconnection

- Eq. 1 above allows effective loop voltage to be defined[4]:

$$V_{eff} = V_{Bias}\frac{\Psi_{INJ}}{\Phi_{\phi}} = V_{Bias}\frac{A_{Inj}B_{Inj}}{\pi a^2 \kappa B_0}$$

$$= V_{Bias}\frac{N_{Inj}A_{Inj}R_0}{\pi a^2 \kappa R_{Inj}}$$

- Power scaling laws give self-consistent I_p:



[4] *Nelson, B.A.Phys. Rev. Let. , **72**(23):3666 - 9, 1994*

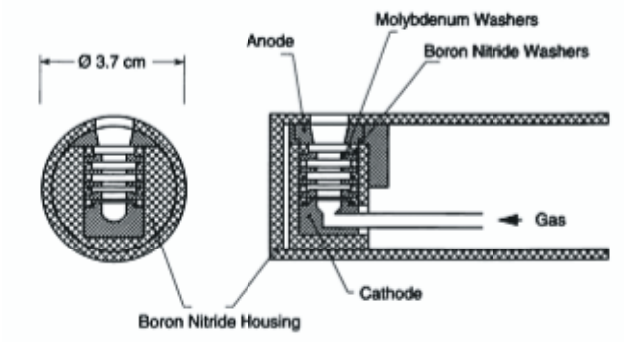
Washer Gun Current Sources for Localized DC Helicity Injection

- Creation & maintenance of tokamak plasma by electron beam DC helicity injection demonstrated on CDX[5]
- Washer guns are good DC helicity source for PEGASUS
  - Low impurity content compared to conventional emissive electrodes[6]
    - Impurity ions trapped in gun aperture
  - Easy to integrate with current PEGASUS systems and hardware
  - Scalable
  - Robust
- However, there are disadvantages
  - Small aperture area per gun limits helicity injection
  - Independent control of multiple guns adds complexity

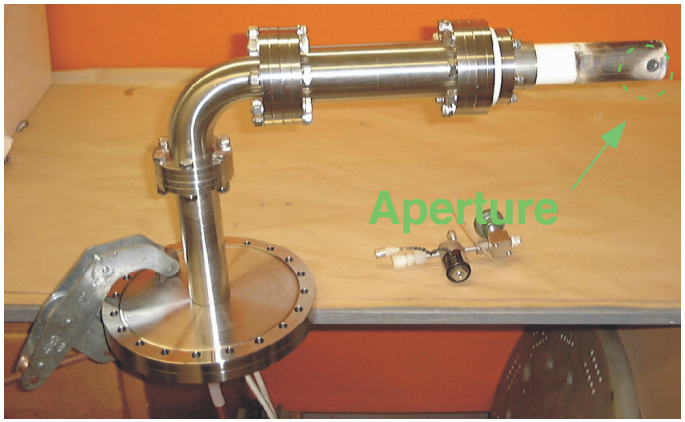
[5] *Ono, M., Greene, G.J., Darrow, D., Forest, C., Park, H. Stix, T.H., Phys. Rev. Lett.*, ***59****, 19 (1987).*
[6] D.J. Den Hartog, D.J. Craig, G. Fiksel, and J.S. Sarff. ,*Plasma Sources Science and Technology*, **6**(4):492 – 498, 1997

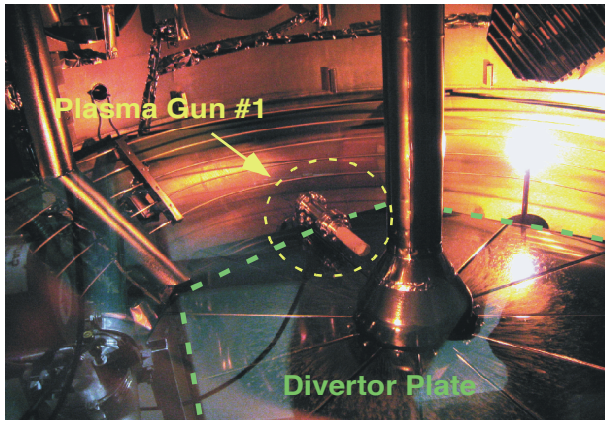
Washer Gun Current Source Design

- High current, low impurity design by *Fiksel et al.*[1]
  - Up to 1 kA extracted current
  - $T_e \sim 10\text{-}20$ eV
  - $n_e \sim (1\text{-}3) \times 10^{20}$ m^{-3}



- SS armor added to allow reentrant insertion into vessel

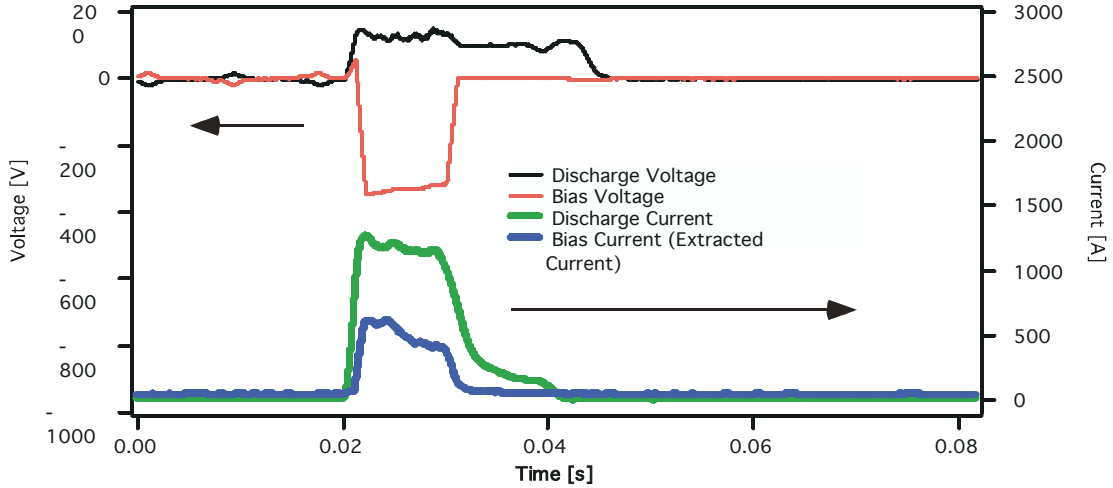




- Placed above lower divertor
  - $R_0 \approx 16$ cm
  - 180° apart

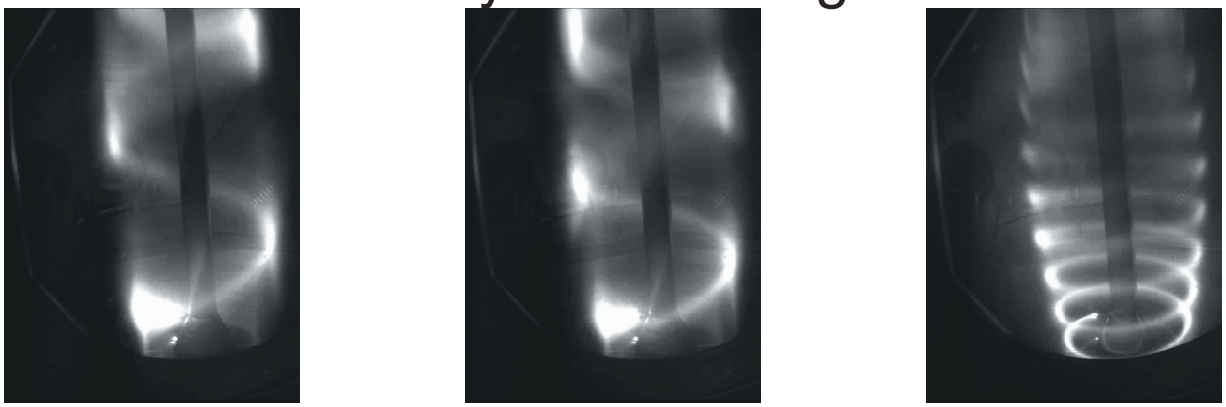
Typical Washer Gun Discharge

- Pulse Forming Network forms arc discharge within gun
- Current extracted by vessel-anode V_{Bias}



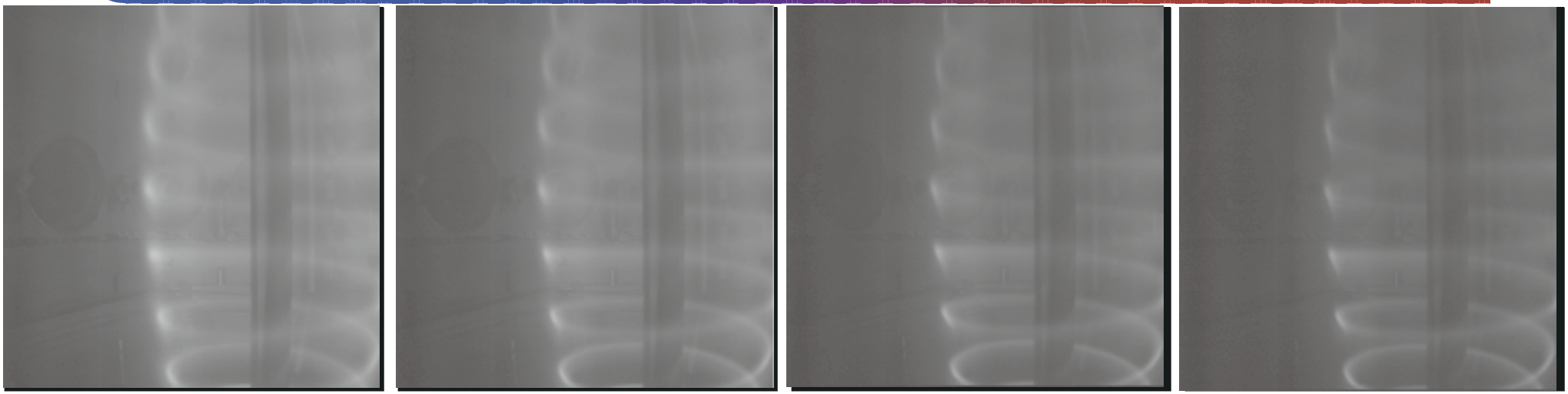
$\tau_{Pulse} \approx 10$ ms

- Extracted current initially follows magnetic field lines

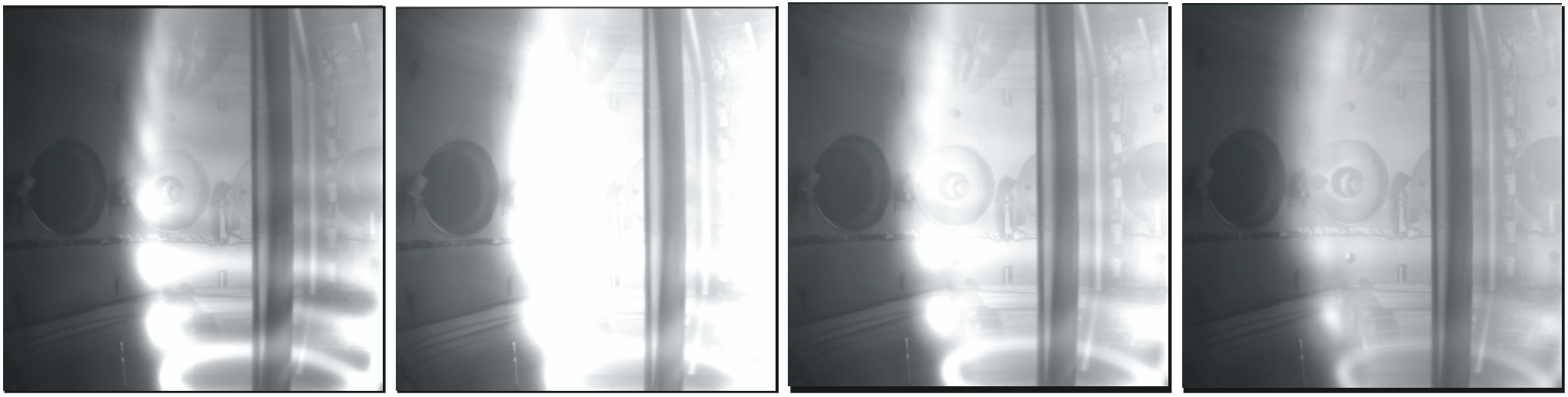


Decreasing Field Pitch

Visual Comparison of Standard and Reconnecting Discharges



Filament structure at low current density / high pitch angle →



Reconnection of filaments at higher current density →

Evidence of Tokamak-like Gun Discharge at Extremely Low Field

- Magnetic prerequisites for tokamak formation:

  1) Local field structure to match multi-gun geometry
  2) $B_\theta > 3B_{Vac}$

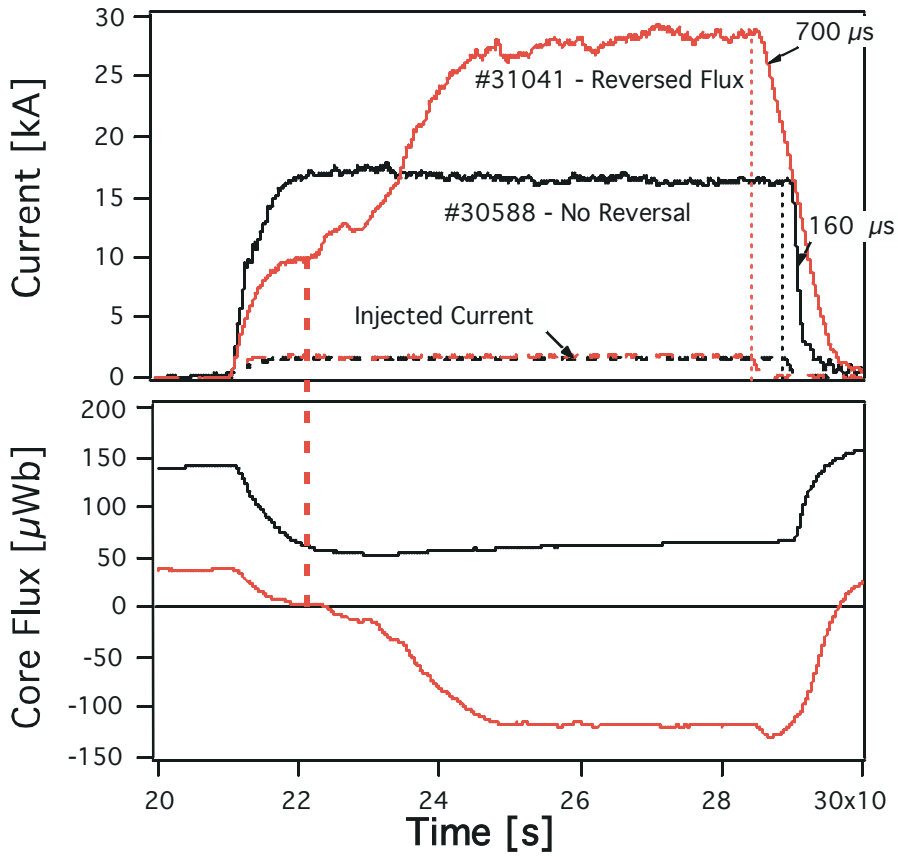
- Flexible PEGASUS power supplies allow low-field operation

- Experimental Conditions:
  - 2 Guns, R ≈ 0.16 m, 180° apart
  - PWM feedback controlled current extraction
  - **Mid-Vessel: $B_\phi \approx .01$ T, $B_V \approx .005$ T**

Observe tokamak-like plasmas with only 2 kA injected current

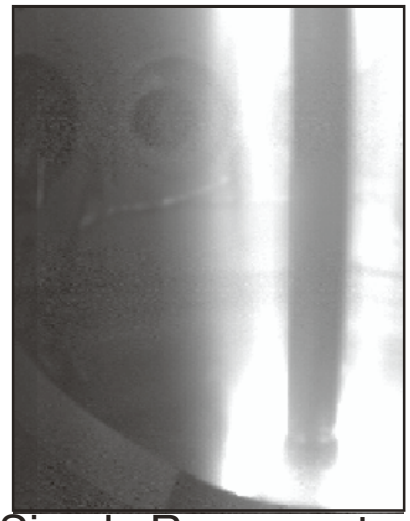
Flux Reversal, Increased I_ϕ & τ_{Decay}

- Flux-reversed gun plasma observed during low field injection
  - > 4x flux reversal
  - Necessary for tokamak formation
- I_ϕ increase > 50 %
  - Max I_ϕ w/o reversal ≈ 18 kA
    w/ reversal > 29 kA
  - Increased current drive efficiency
- τ_{Decay} increase > 400 %
  - Decay w/o reversal ≈ 160 μs
    w/ reversal > 700 μs
  - Significant change in L/R

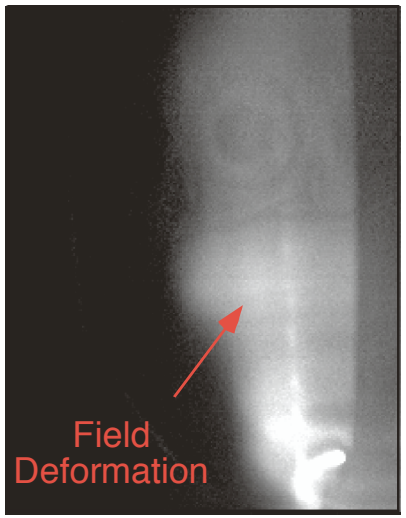


Strong Poloidal Field Deformation

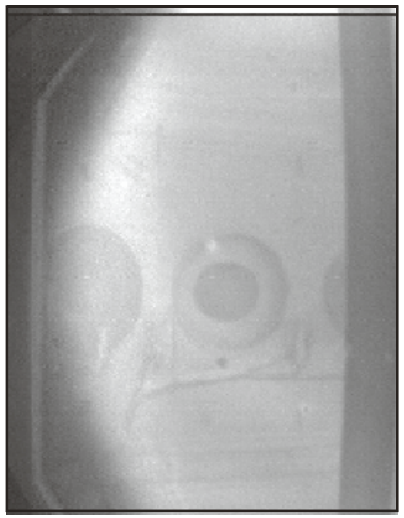
- Images exhibit significant differences between relaxed & simply reconnected plasma formation
- Typical simply reconnected plasmas maintain cylindrical geometry
- Relaxing plasmas exhibit dynamic formation & tokamak-like poloidal field structure



Simply Reconnected



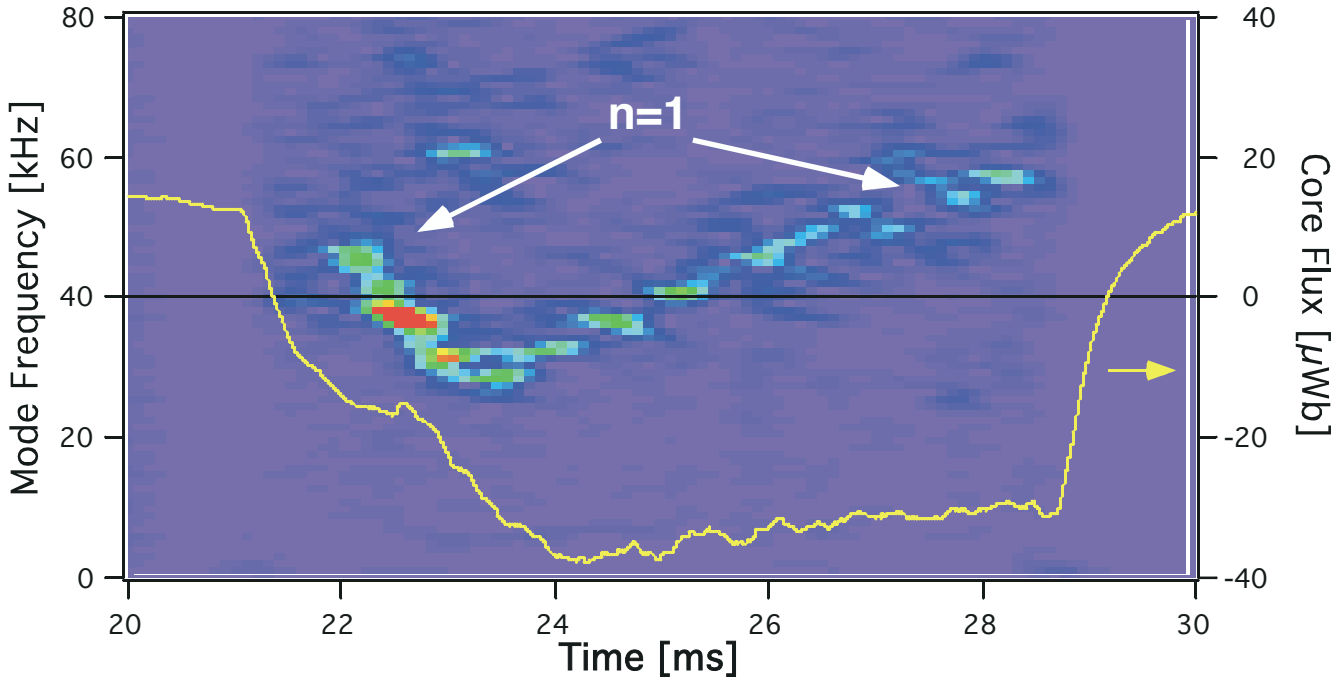
Start: 1 ms into shot



Middle: 5 ms into shot

n=1 Mode Observed during Relaxation

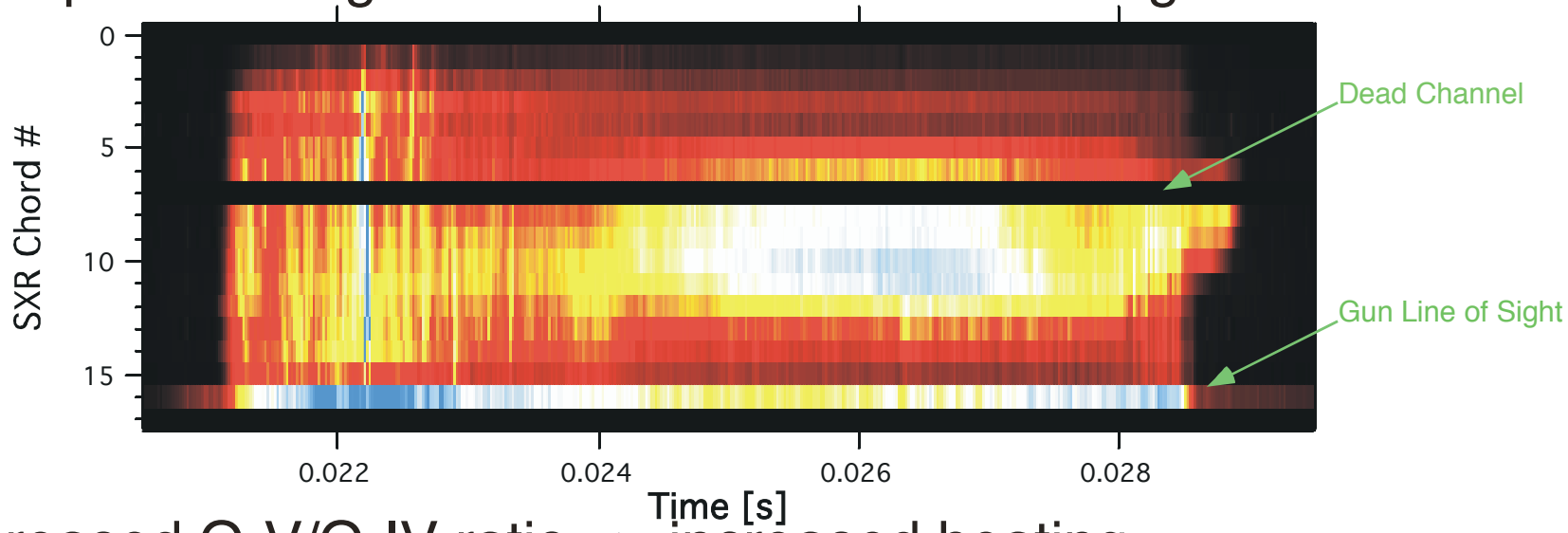
- 20-60 kHz n=1 mode observed soon after flux reversal
- ST's, spheromaks report mode crucial to CHI current drive[7,8]
- Dynamo action of n=1 line-tied kink believed to provide loop voltage for closed-flux current drive[9]



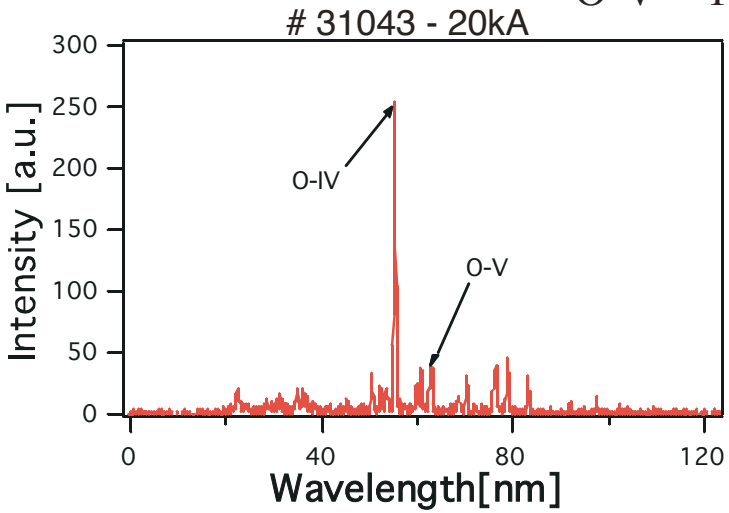
[7] Redd et al., Phys. Plasmas, 9, 2006 (2002)
[8] Brennan et.al, Phys. Plasmas, 6, 4248 (1999)
[9] X.Z Tang and A.H Boozer, Phys. Plasmas, **11**, 2679 (2004)

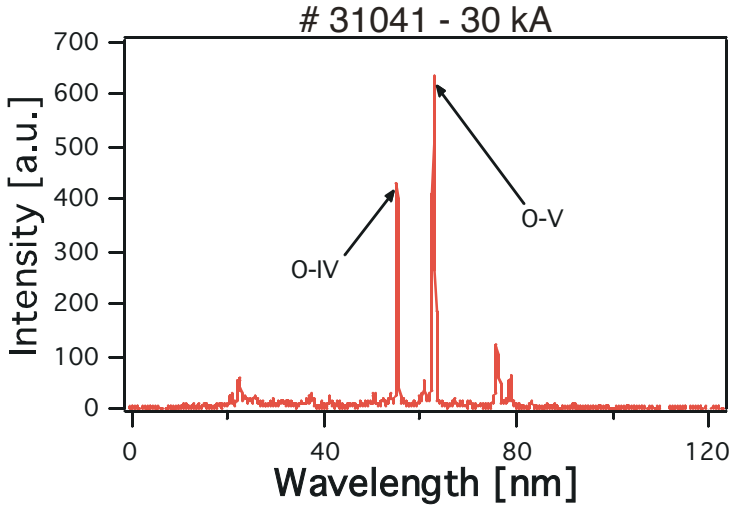
SXR & Spectral Evidence of Increased T_e and/or τ_E

- SXR peaks along central chords => core heating



- Increased O-V/O-IV ratio => increased heating
  - Ionization Potentials: O-IV = 77 eV
    O-V = 114 eV





Consistent with Tokamak Radial Force Balance

- Compare B_V required by radial force balance to applied B_V.
- Assuming:
  1) R = 40 cm, a = 35 cm (inferred from images)
  2) $\beta_p = 0$
  3) I_p = 30 kA (shot # 31041)

Required B_V = .0072 T (uniform J)
= .0055 T (hollow J, $q(a)/q_0 = 1/3$)

- Vacuum $B_V \approx$ .005 T @ magnetic axis
  - Calculated from simulation including wall currents

Close agreement => **Measured I_ϕ dominated by closed flux I_p**

Consistent with Helicity Conservation

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

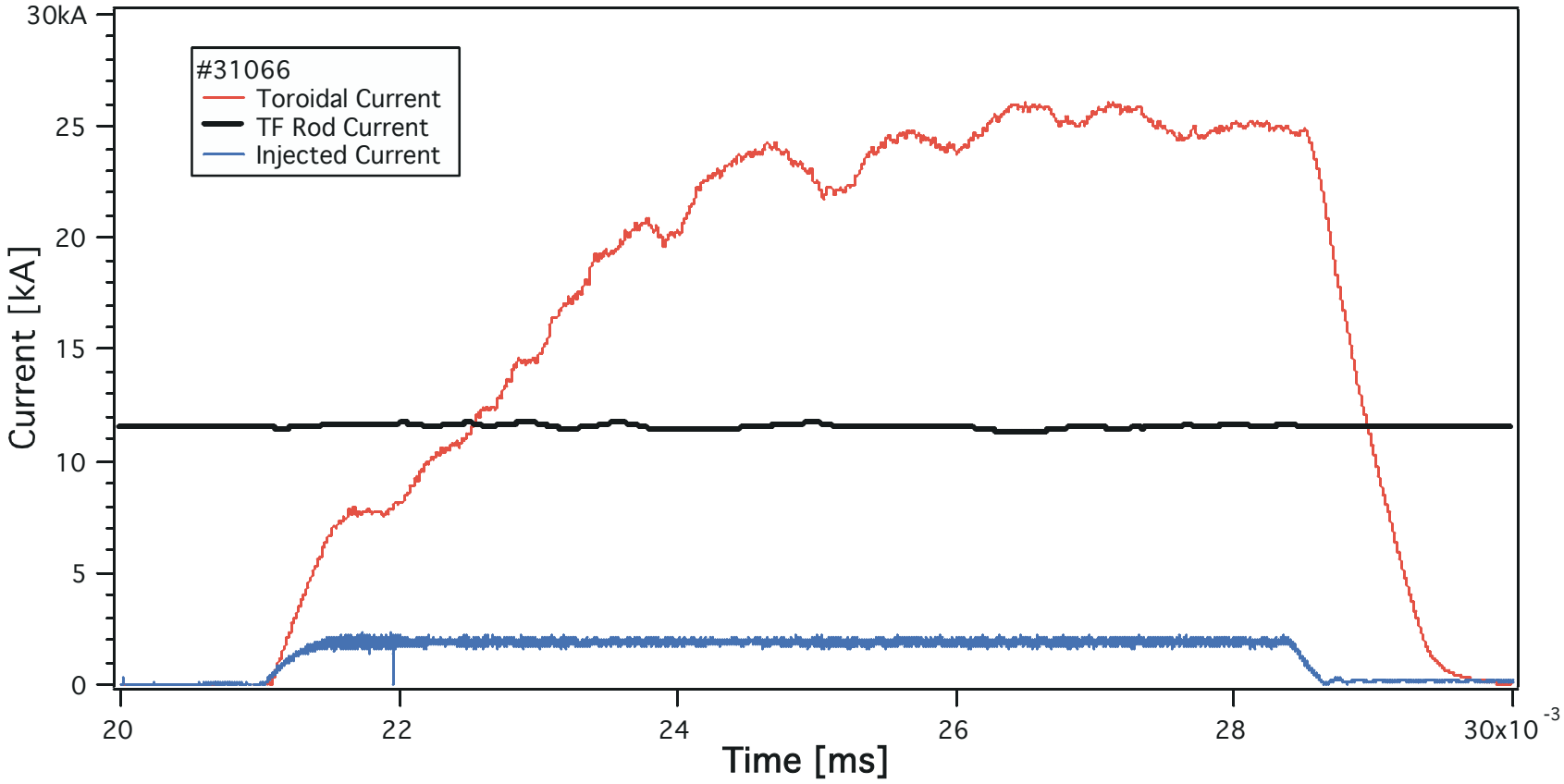
I_p = 25-35 kA is consistent with T_e = 50-70 eV

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

Helicity conservation in general agreement with observed plasmas

$I_p/I_{TF} \geq 2$ Achieved

- 12 kA TF rod current, 26 kA I_ϕ
- Entirely driven by DC helicity injection



Development of > 0.1 MA Gun Array

- Desire non-inductive current drive ~ PEGASUS OH capability
  - Allows direct comparison of OH and gun plasmas
  - Significantly enhance V-s utilization and shot length via gun-OH hand-off
  - Allows profile modification for access to higher I_N
- Recent data provides groundwork for enhanced array
  - Higher I_p requires higher field => more current injection required
  - Helicity conservation => I_p will scale with helicity input
- Prototyping gun designs for greater unit helicity & power input

Current Source Development

- Path to higher I_p in staged approach

Stage 1: Tokamak-like plasma with available washer guns

- ≈ 2kA injected current
- **COMPLETE**

Stage 2: Verify I_p scaling with larger washer guns

- Provide 400% more helicity injection, 200% ≤ power injection
- Allow separation of power and helicity effects
- **CURRENTLY BEING INSTALLED**

Stage 3: Implement extended array design to provide > 0.1 MA

- Stage 2 data will provide scaling data necessary for determining array parameters
- Future implementation

Conclusions

1. DC helicity injection with localized current sources produces tokamak-like plasmas, as evidenced by:
   1) Strong core flux reversal
   2) Increased current drive capability
   3) Increased L/R decay times
   4) Massive deformation of poloidal field structure
   5) Strong n = 1 modes
   6) Increased heating
   7) Consistency with tokamak radial force balance
   8) Consistency with helicity conservation

2. These results motivate building > 0.1 MA gun array
   - Will provide current drive ~ OH capability

3. Prototyping new guns to simplify array design

4. Diagnostics deployed to better diagnose plasmas & explore helicity - power relationship