# Non-Solenoidal Startup via Local Helicity Injection and Edge Stability Studies in the Pegasus Toroidal Experiment

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on behalf of the Pegasus Team

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University of Wisconsin-Madison

PEGASUS Toroidal Experiment

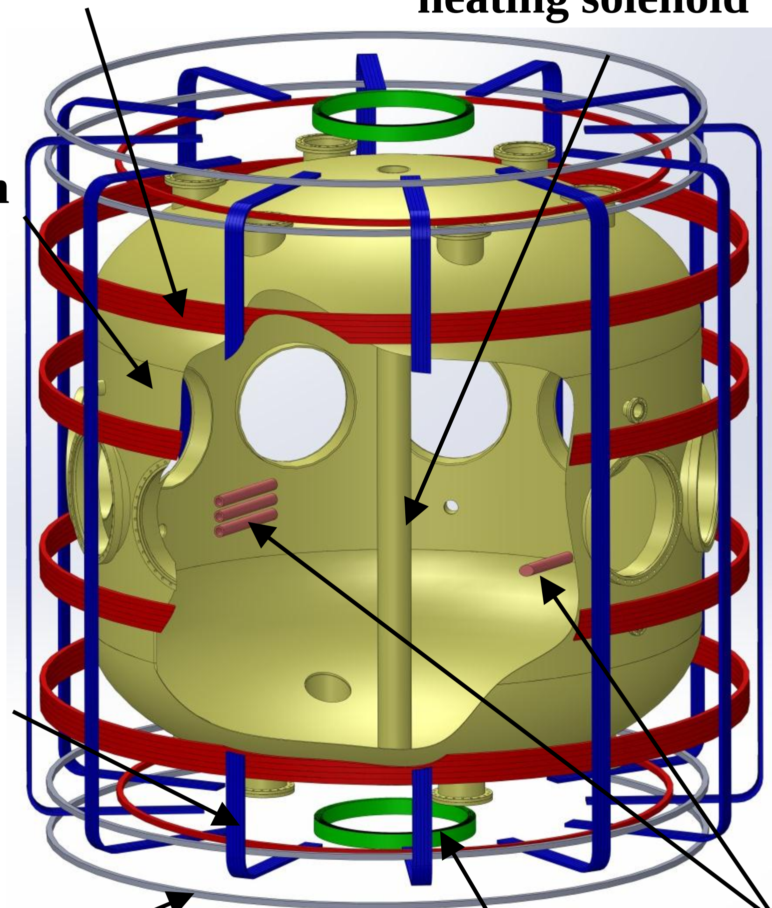
# Exploiting Unique Aspects of the ST to Improve Fusion Energy Science

- Non-solenoidal startup: Increasing reactor attractiveness
  - Local Helicity Injection produces tokamak plasmas using edge current drive
    - Predictive understanding through helicity conservation, Taylor relaxation constraints
  - Reduces cost, complexity of device
  - Technique applicable to any tokamak, not just ST

- Edge physics: Detailed measurements of pedestal, ELM dynamics
  - Low-A naturally provides access to peeling instability underlying ELMs
    - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
  - Extension to ITER-relevant peeling-ballooning physics via H-mode operation

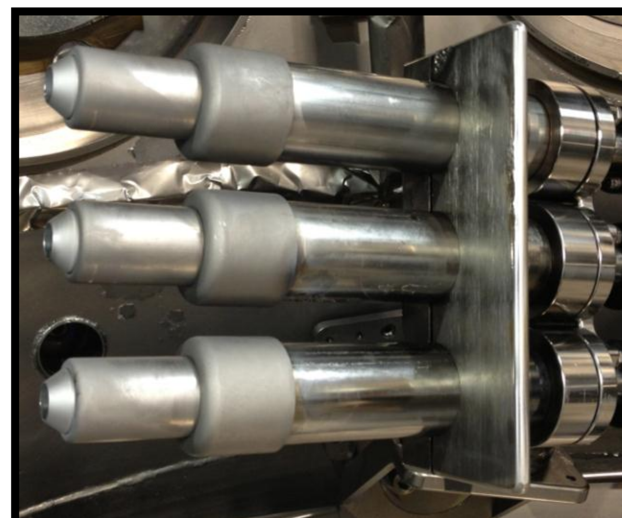
- Testing boundaries of tokamak stability at ultimate geometric limit
  - High $\beta_T$, toroidal field utilization $I_p/I_{TF}$ as $A \rightarrow 1$

# Pegasus is a Compact, Ultralow-A ST

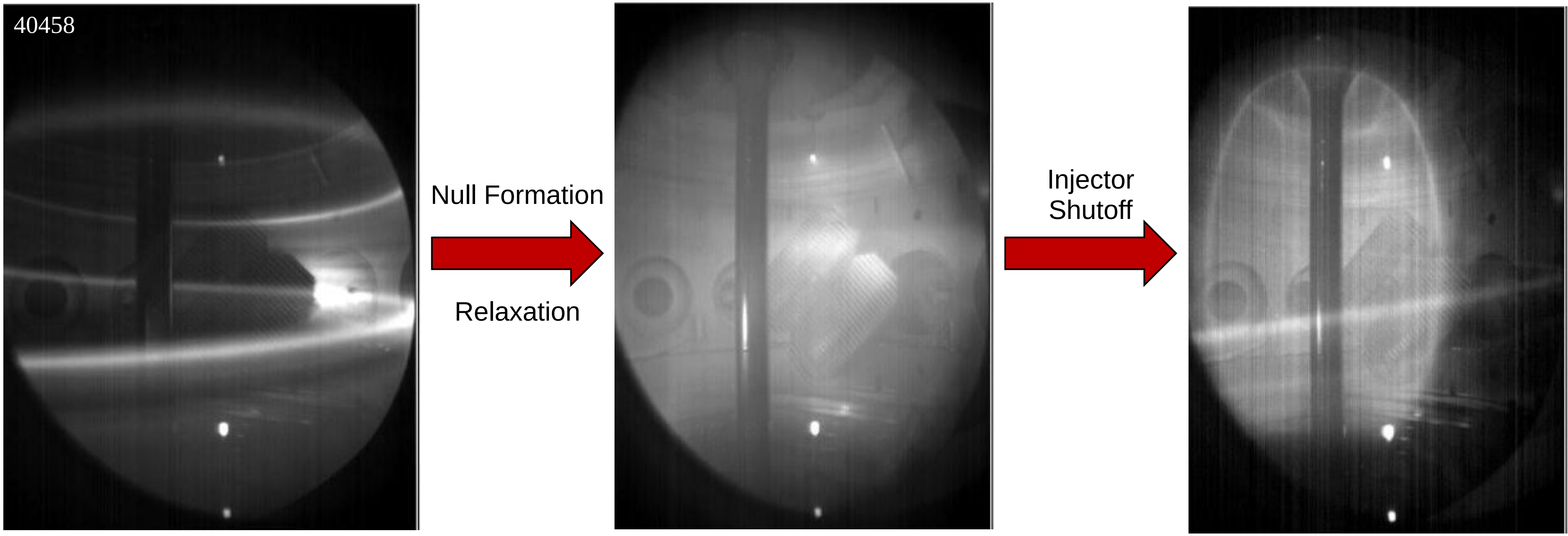



## Experimental Parameters

| 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) | $\leq$ .23 | $\leq$ 0.30 |
| $I_N$ (MA/m-T) | 6 – 14 | 6 – 20 |
| $RB_t$ (T-m) | $\leq$ 0.06 | $\leq$ 0.1 |
| $\kappa$ | 1.4 – 3.7 | 1.4 – 3.7 |
| $\tau_{shot}$ (s) | $\leq$ 0.025 | $\leq$ 0.05 |
| $\beta_t$ (%) | $\leq$ 25 | > 40 |



# Local Helicity Injection Offers Scalable Non-Solenoidal Startup




- Current injected along helical vacuum field
  - Local, active current sources
- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

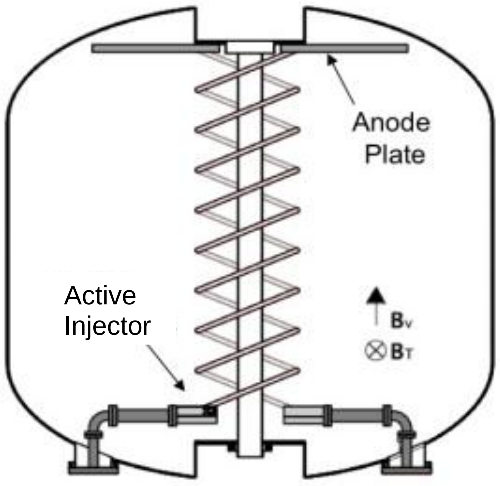


Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

# Helicity Input Provided by Edge-Localized Sources

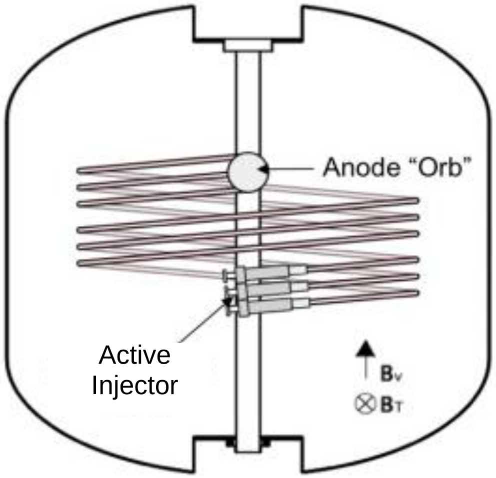
- Flexible injector geometry
- Active arc 'gun' injectors provide initial current windup, relaxation
- Either active guns or separate electrodes can provide further growth, sustainment

**Inboard Injection***

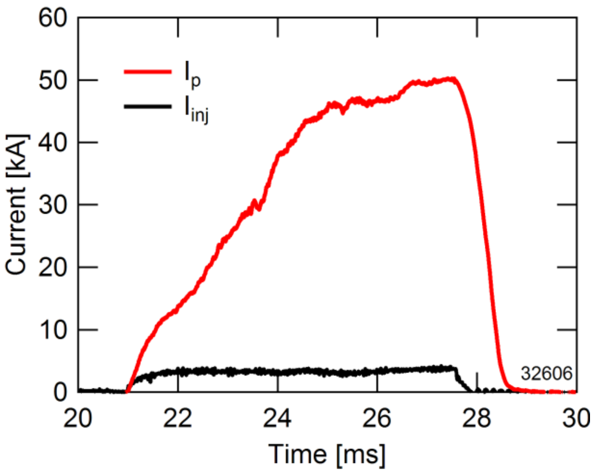


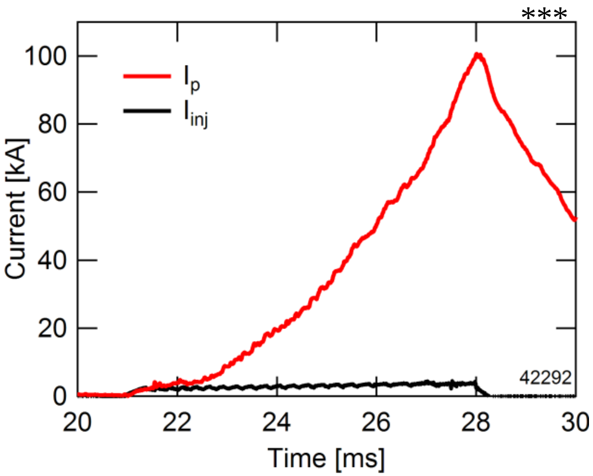

$R_{inj}$ = 16 cm, $Z_{inj}$ = -75 cm

**Outboard Injection****




$R_{inj}$ = 70 cm, $Z_{inj}$ = -20 cm




*: Eidietis *et al.*, J. Fusion Energ. **26**, 43 (2007)
**: Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)
***: Battaglia *et al.*, Phys. Rev. Lett. **102**, 225003 (2009)



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# Helicity Balance, Taylor Relaxation Criteria Determines Maximum Achievable $I_p$ from LHI

## Helicity balance in a tokamak geometry:

$$\frac{dK}{dt} = -2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}\, d^3x - 2\frac{d\psi}{dt}\Psi - 2\int_A \Phi\boldsymbol{B}\cdot d\boldsymbol{s} \;\Rightarrow\; I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

- Helicity injection can be expressed as an effective loop voltage
- $I_p$ limit depends on plasma confinement via resistivity $\eta$

$$V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj}$$

## Taylor relaxation of a force-free equilibrium:

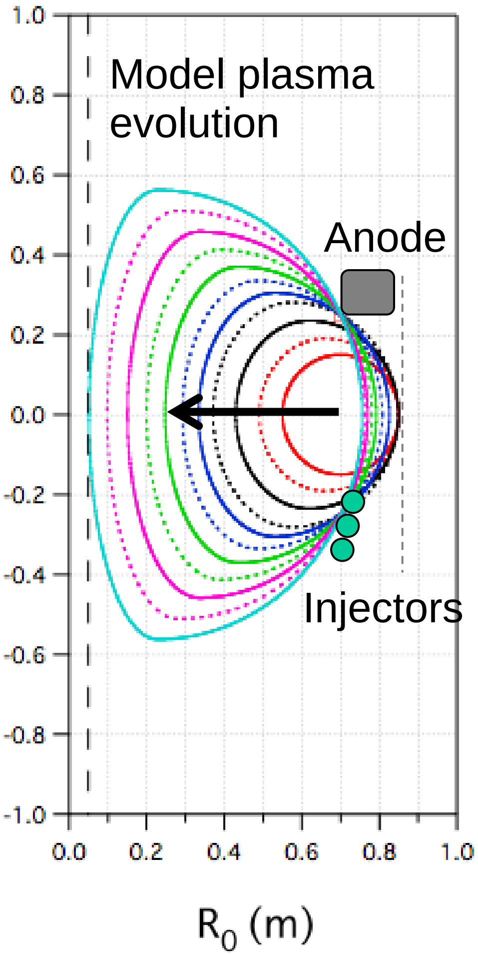
$$\nabla\times\boldsymbol{B} = \mu_0\boldsymbol{J} = \lambda\boldsymbol{B} \qquad \lambda_p \le \lambda_{inj} \rightarrow \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \;\Rightarrow\; I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2}$$

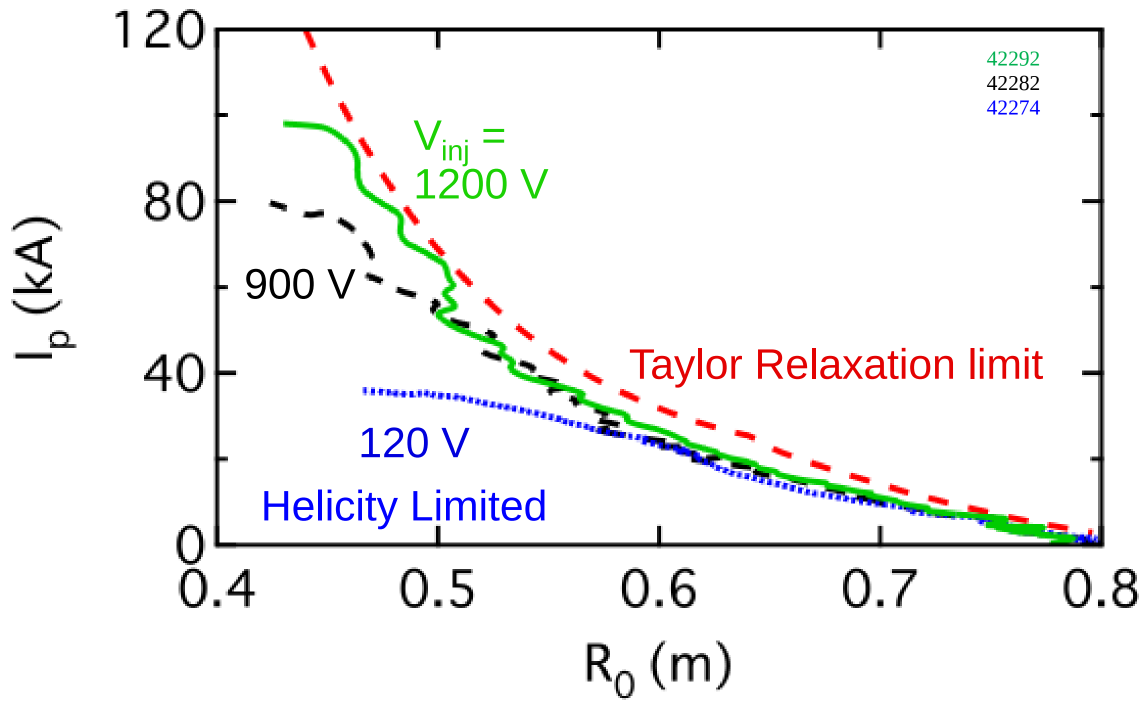
Assumptions:

- Driven edge current mixes uniformly
- Edge fields average to tokamak-like structure

$A_p$, $A_{inj}$ : Plasma, injector area
$C_p$ : Plasma circumference
$\Psi$ : Plasma toroidal flux
$w$ : Edge current channel width

# Achieving the Maximum $I_p$ at the Taylor Limit Requires Sufficient Helicity Injection Input Rate



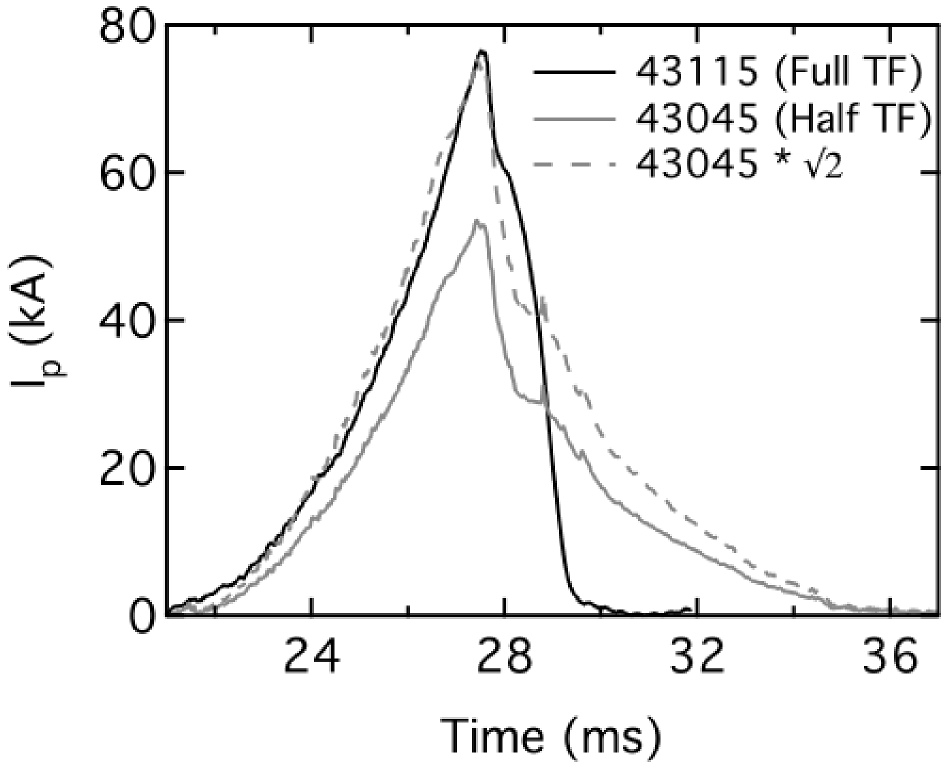



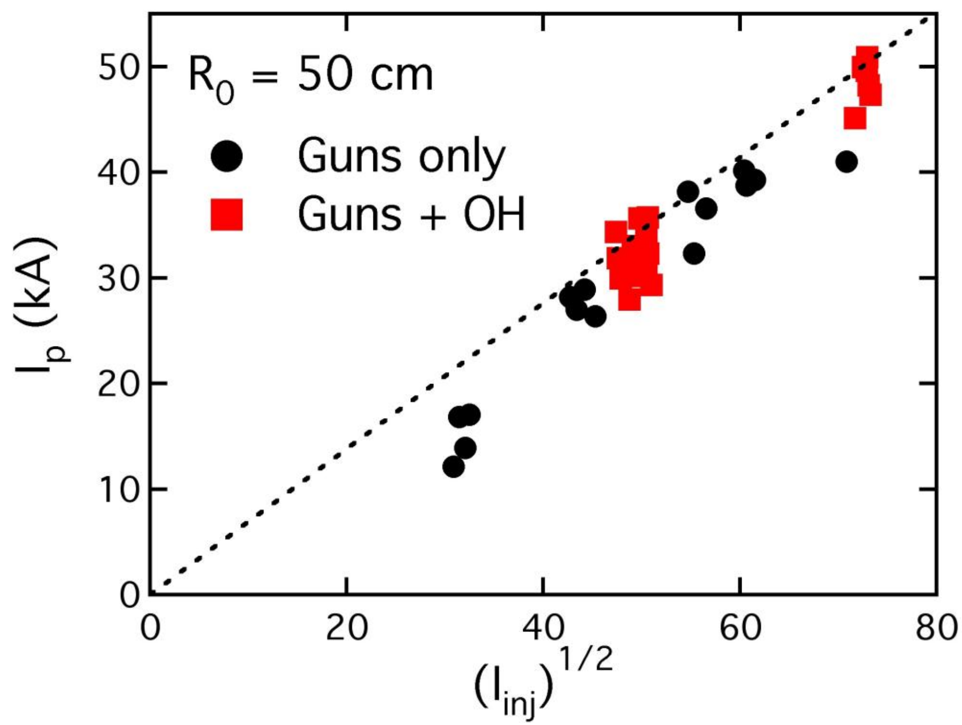

$$V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj}$$



Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

# Experimental Plasma Currents Follow Taylor Limit Scalings



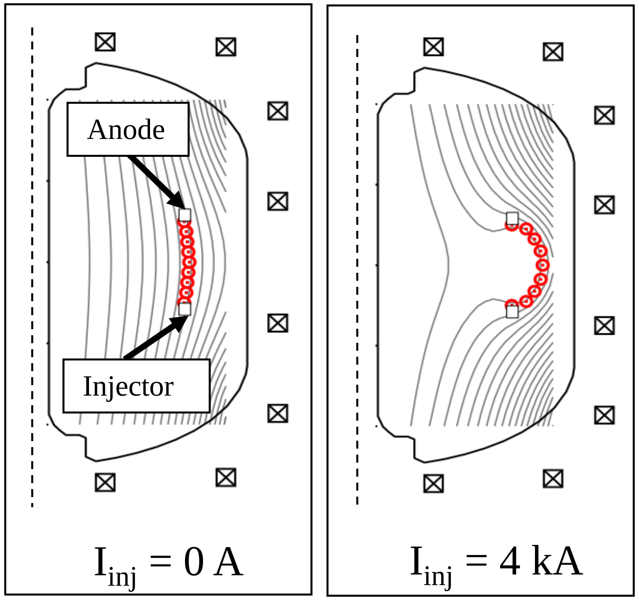

- Taylor limit: $I_{p,max} \propto \sqrt{I_{TF} I_{inj}}$
- Limit appears absolute
  - Additional OH $V_{loop}$ cannot raise $I_p$ during LHI

*M.W. Bongard, EPR Workshop, Fort Worth, TX Feb. 2013*

Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

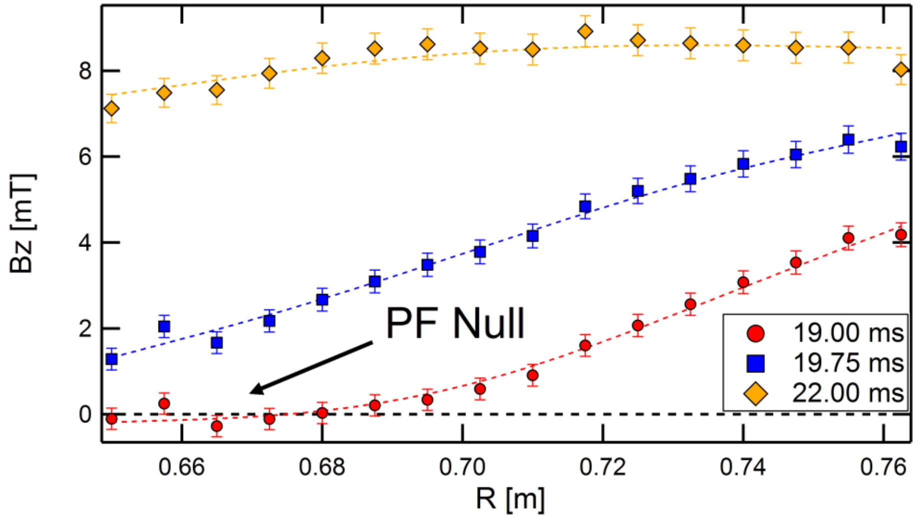
# Internal Measurements Show Null Formation, J(R,t) Throughout LHI Discharge Evolution

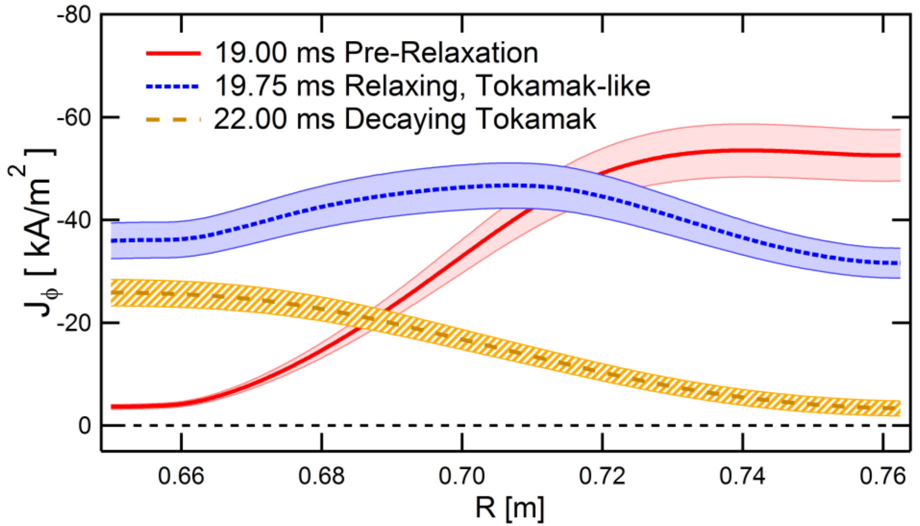
- Initial relaxation to tokamak-like topology coincident with inboard null formation
  - Injected current filaments perturb vacuum **B**
  - $B_z$ must be sufficiently low and/or $I_{inj}$ sufficiently high for null to form
- Hall probe* $B_Z(R)$ provides $J_\phi(R)$ evolution
  - Predicted field null observed




*2-D force free current model*

*: Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)



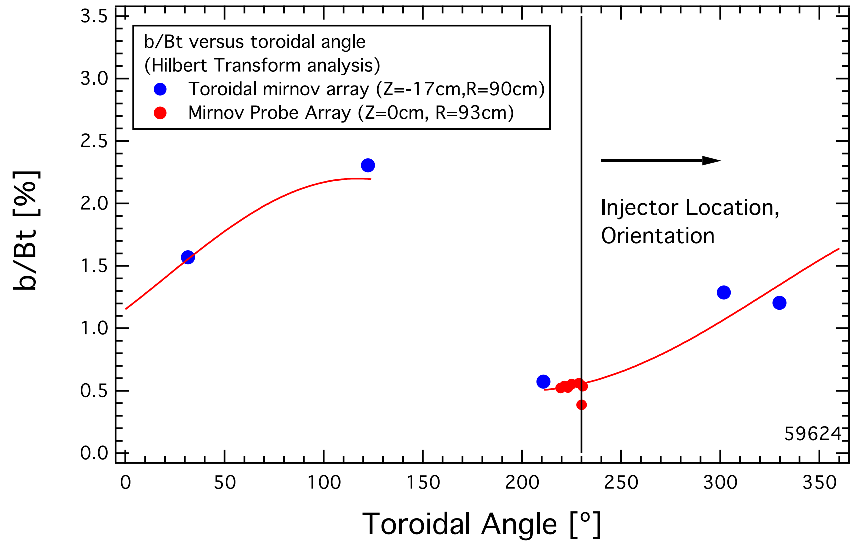
# Current Multiplication During LHI Accompanied by n = 1 Line-Tied Kink Activity

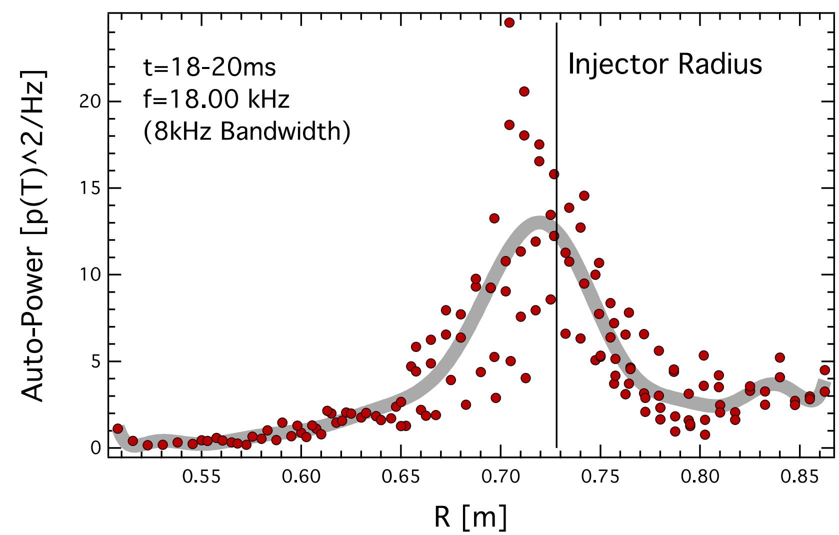
- Current multiplication, transport accompanied by MHD activity

- Two common spectral features
  - High-frequency 10–20 kHz n = 1
  - Low-frequency < 5 kHz n = 0

- n = 1 mode consistent with line tying
  - Activity localized near injector radius
  - Toroidal asymmetry in $\tilde{b}/B$

- n = 0 localized to plasma interior
  - Inward radial motion




*M.W. Bongard, EPR Workshop, Fort Worth, TX Feb. 2013*

Barr *et al.*, APS-DPP 2012

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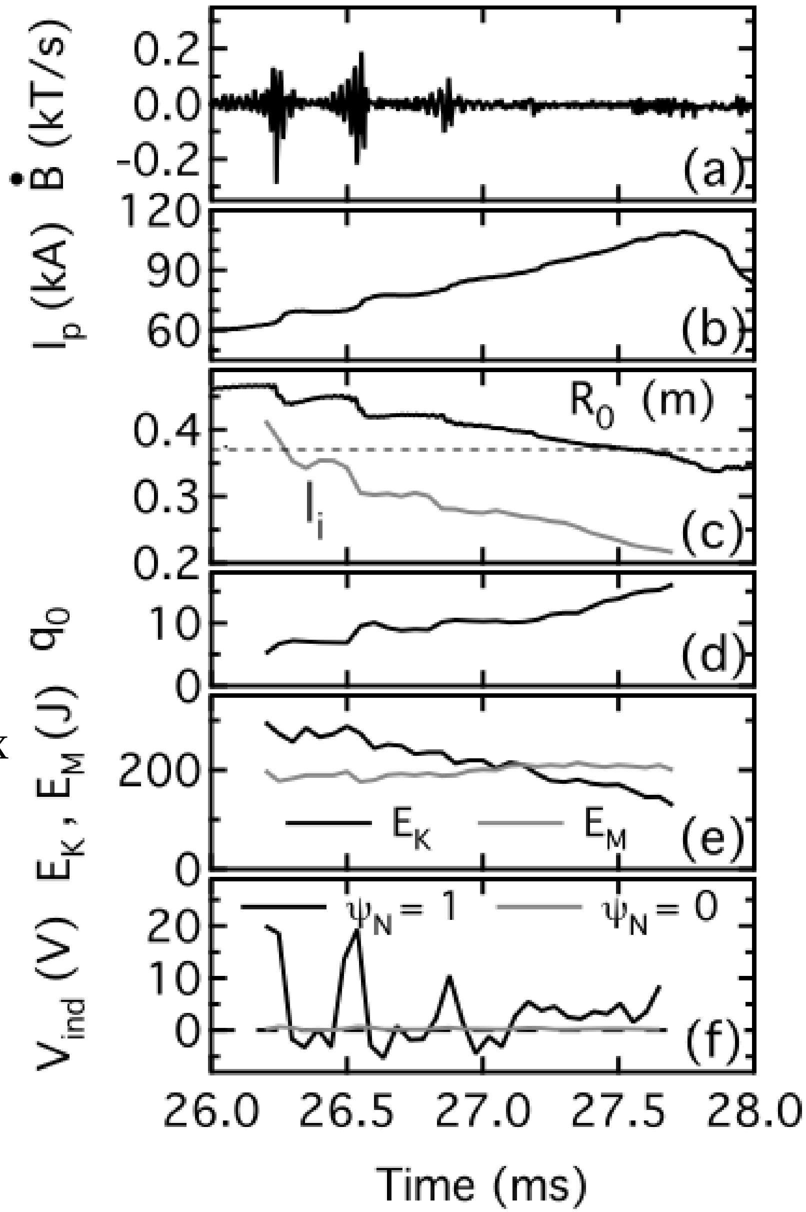
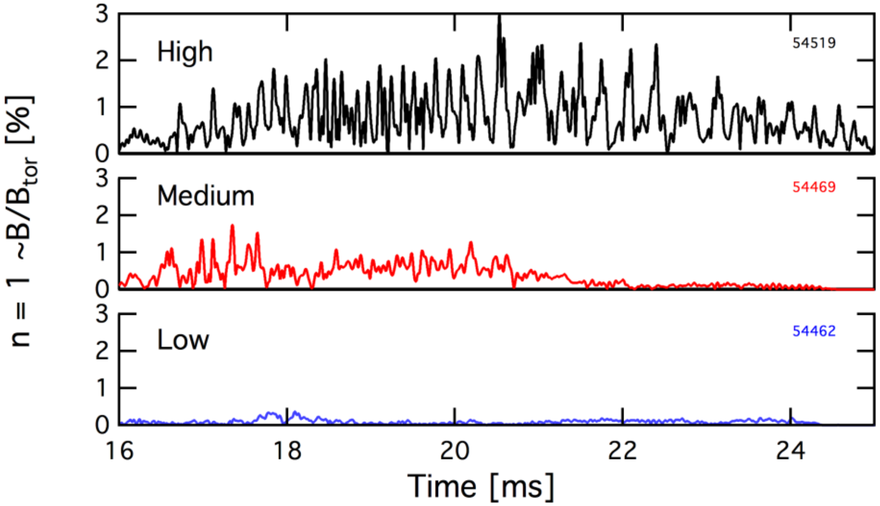
# Magnetic Topology Rapidly Changes with Bursts of MHD Activity During Helicity Injection

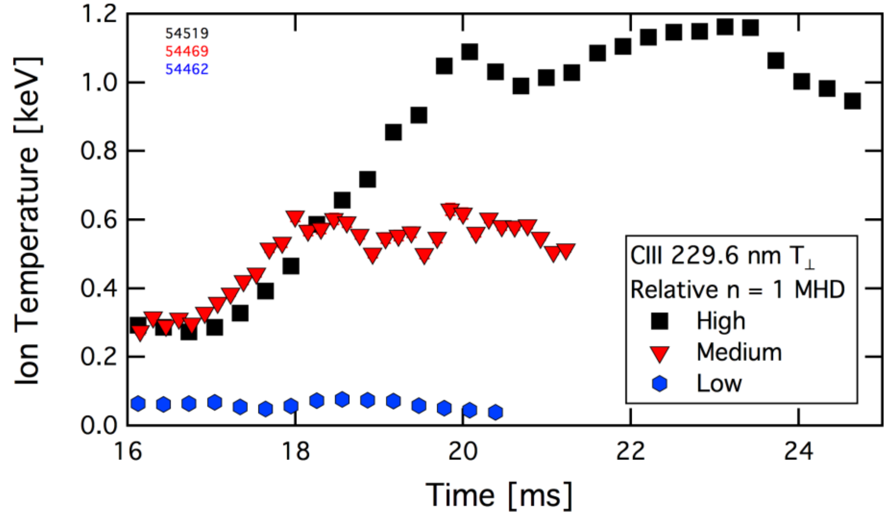
- Each burst typically ~ 0.1 ms
- With each burst…
  - $\ell_i$ decreases → $I_p$ increases
  - $R_0$ decreases → plasma expands
  - $B_{\phi,0}$ increases → $q_0$ increases
  - Slight drop in $E_k$ and $E_m$
  - Little change in poloidal flux at plasma edge
  - Rapid decrease in the total trapped poloidal flux
- Temporally and spatially averaged $V_{ind}$ ~ 1.5 V




Battaglia *et al*., Nucl. Fusion **51**, 073029 (2011)

# Strong, Anisotropic Ion Heating Observed During Helicity Injection




- Strong ion heating correlated with n = 1 burst activity on multiple line species
- Ion $T_{\perp} > 2\ T_{\parallel}$ is often observed
  - Similar phenomenon observed in MST** during magnetic reconnection



*: Burke *et al.*, Rev. Sci. Instrum. **83**, 10D512 (2012)
**: Magee, *et al*. Phys. Rev. Let. **107,** 065005 (2011)

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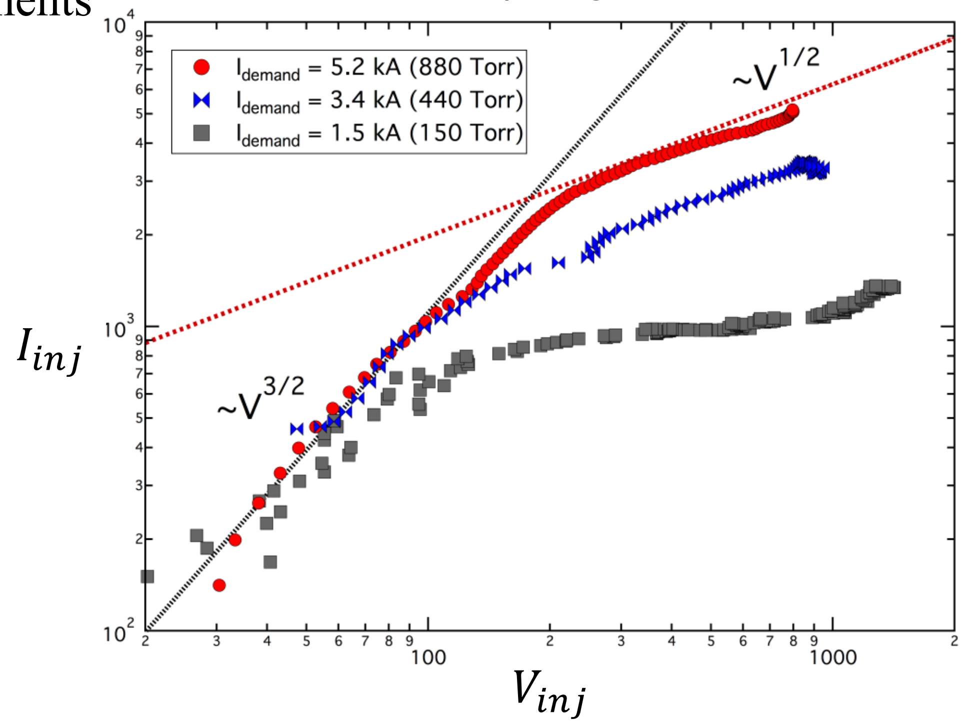
# Source Impedance Governed by Space Charge and Magnetic Current Limits

- Predictive impedance models required to design future startup systems
  - Taylor limit $\propto \sqrt{I_{inj}}$ ; Helicity input $\propto V_{inj}$
  - $Z_{inj}$ couples $I_{inj}, V_{inj}$ $\rightarrow$ power requirements
- Two distinct regimes evident in active source I-V characteristics
  - Double-sheath space-charge limit
    - Low $I_{inj}$, $V_{inj}$
    - $I_{inj} \propto V^{3/2}$
  - Alfvén-Lawson magnetic current limit
    - High $I_{inj}$, $V_{inj}$
    - $I_{inj} \propto V^{1/2}$
    - Sheath expansion may also contribute

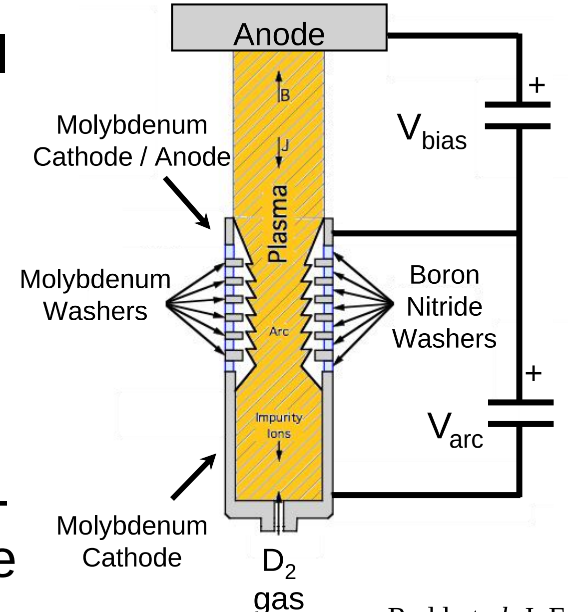
*I-V characteristics of arc plasma current injector for varied fueling rates.*

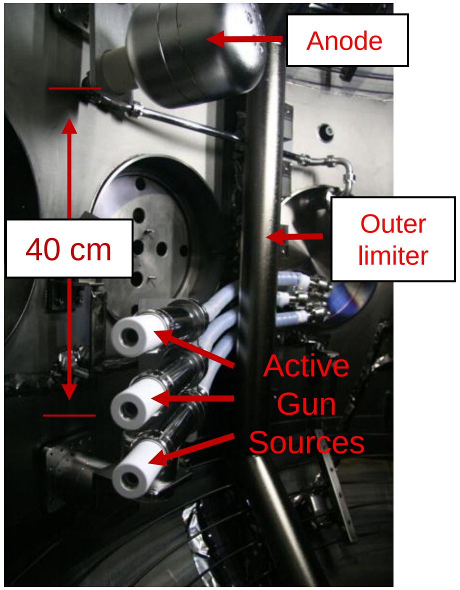



Hinson *et al.*, APS-DPP 2012

# Local Helicity Input Requires Increasingly Capable Electron Current Injectors

- Active gun sources used for initial relaxation, sustainment
  - Arc plasma created in coaxial washer gun
  - Electron current extracted from arc




Redd *et al*, J. Fusion Energy **28**, 203 (2009)

- Subsequent growth via electrode-based systems may offer scalable path forward
  - Goal: simultaneously optimize helicity injection, Taylor relaxation constraints
    - High $I_{inj}$ over extended area

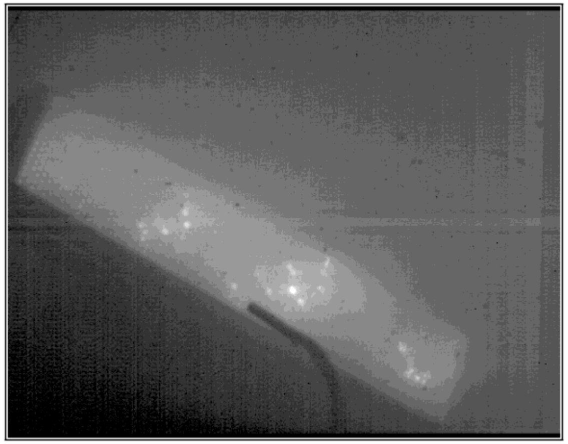
$A_{eff} \sim 6\ cm^2$

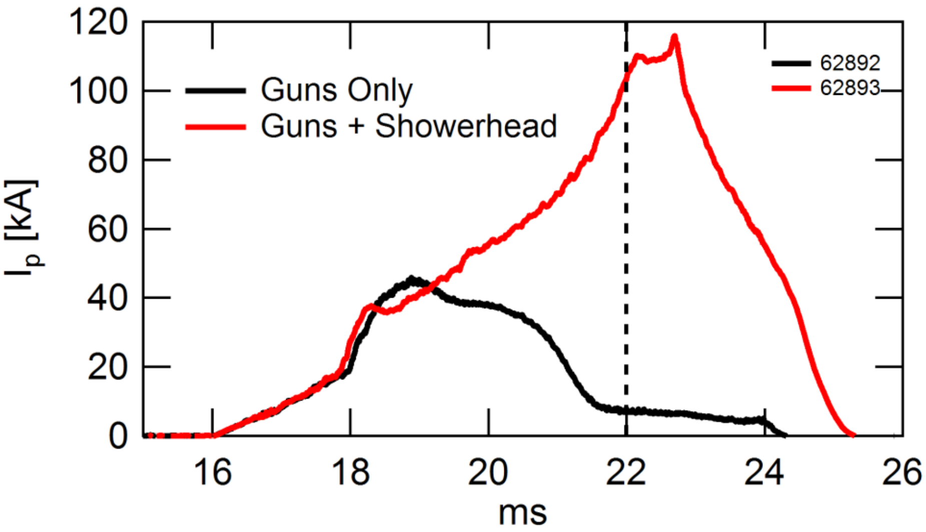
$A_{eff} \leq 50\ cm^2$

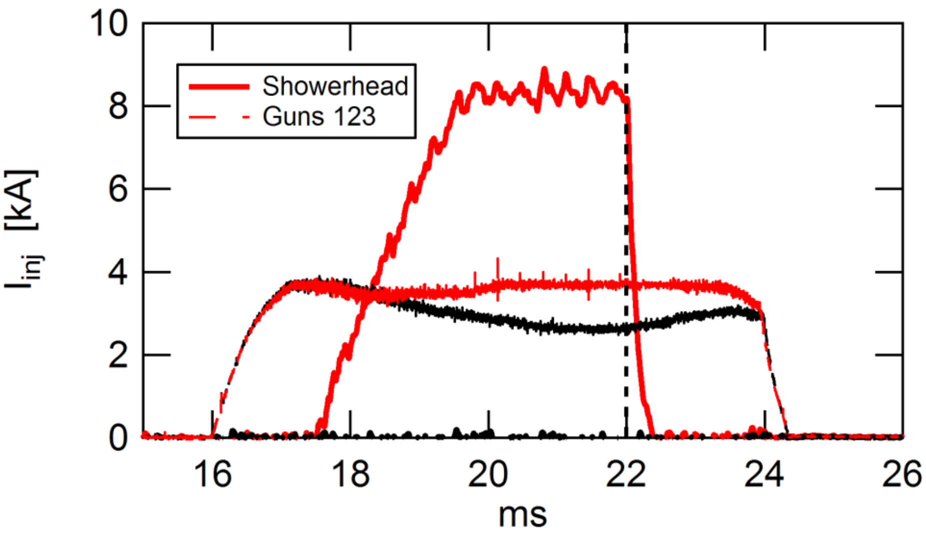
- Need to develop large $A_{inj}$ uniform current injector
  - Minimize gas load

# New 'Showerhead' Electrode Designed for Hollow-Cathode, High Area Helicity Injection

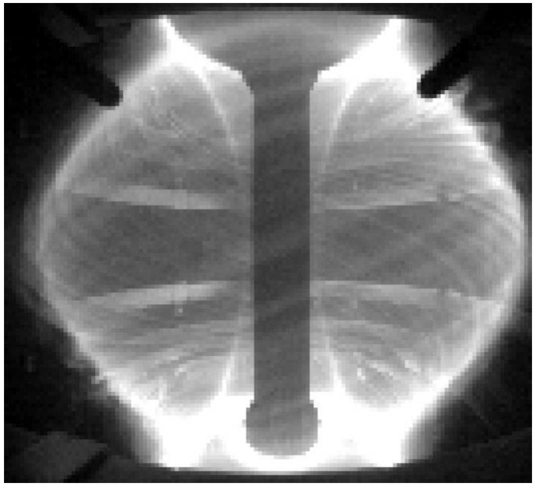
- Promising results from initial commissioning of new electrode
  - $I_p$ > 100 kA with showerhead assist; ≤ 45 kA without
  - Matched PF evolution, fueling
- Diffuse illumination of assembly, $I_p$ increase suggests high $A_{eff}$

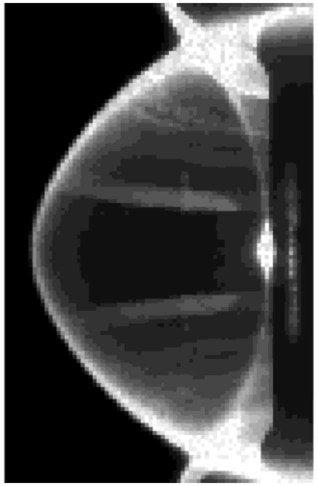


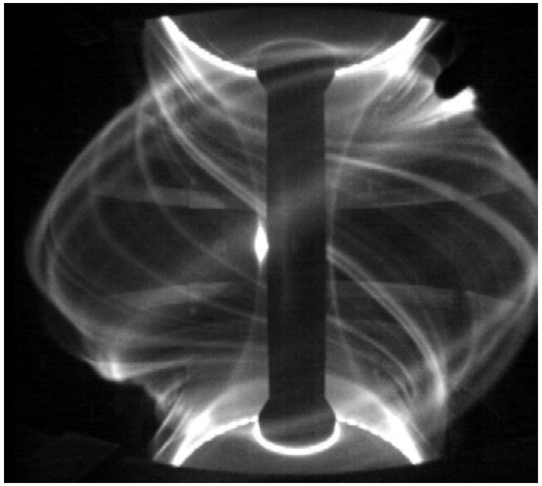


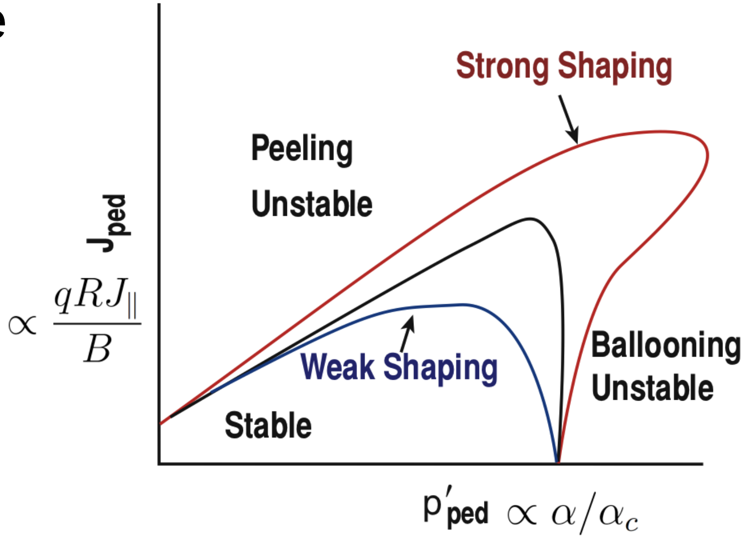
# Edge Stability Critical to Next-Step Fusion Devices


MAST L-Mode*


H-Mode*


ELM**

- Future fusion devices will operate in H-mode
  - Edge Localized Modes (ELMs) of concern
- Peeling-ballooning theory believed to underlie most damaging Type-I ELM
  - Pressure, current density gradients in edge drive ideal MHD instabilities
  - Detailed $J_{edge}$ measurements needed

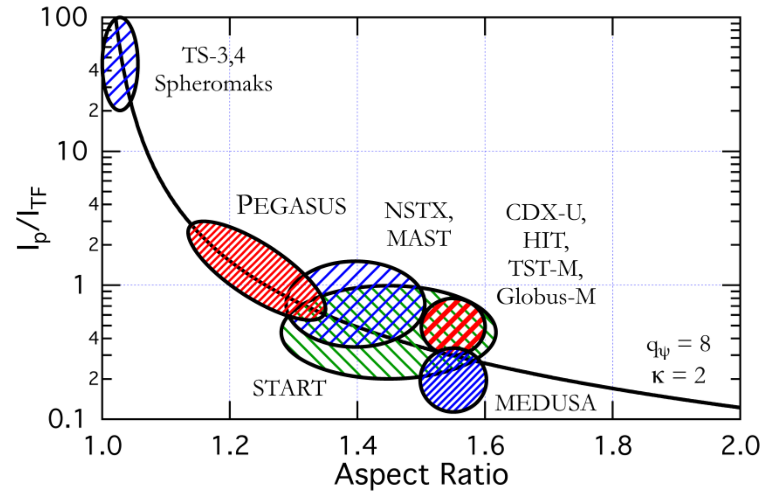


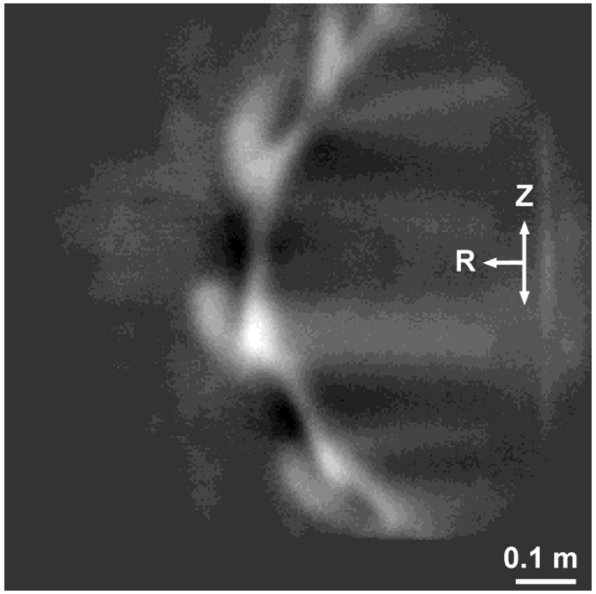
Stability Space***

*: Kirk *et al.*, Plasma Phys. Control. Fusion **48**, B433 (2006); **: Kirk *et al.*, Plasma Phys. Control. Fusion **49**, 1259 (2007)
***: Snyder, Phys. Plasmas **12**, 056115 (2005); Hegna, Phys. Plasmas **3**, 584 (1996)

# Low-A PEGASUS ST Provides Access to Peeling Instability and Conditions to Measure J

- Spherical tokamaks naturally provide strong peeling drive
  - Toroidal field utilization $I_p/I_{TF} \sim J_{\|}/B$
- PEGASUS accesses peeling modes
  - Strong $J_{\|}/B \sim 1$ MA/m$^2$-T at $A \leq 1.3$
  - Comparable to DIII-D in H-mode
- Machine parameters permit internal edge measurements
  - Short pulse lengths (< 50 ms)
  - Modest $T_e$ < 200 eV

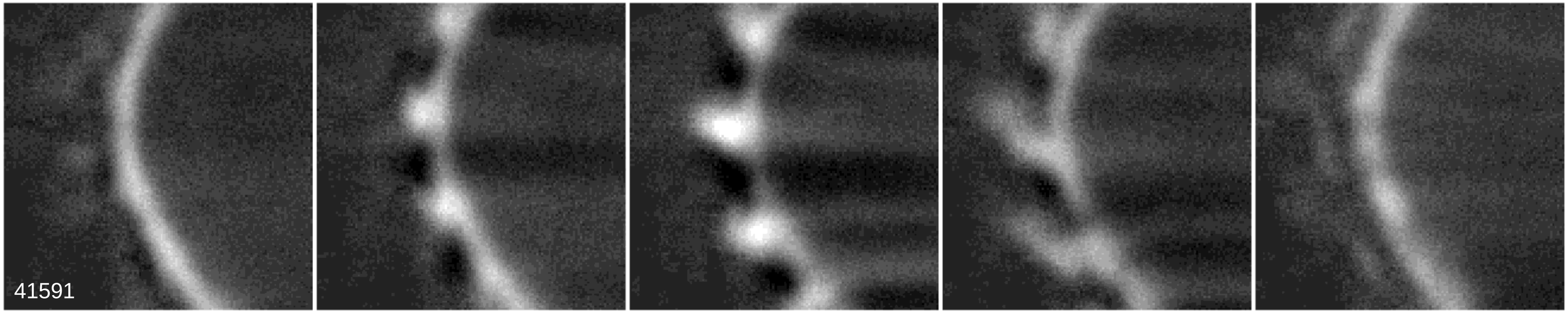




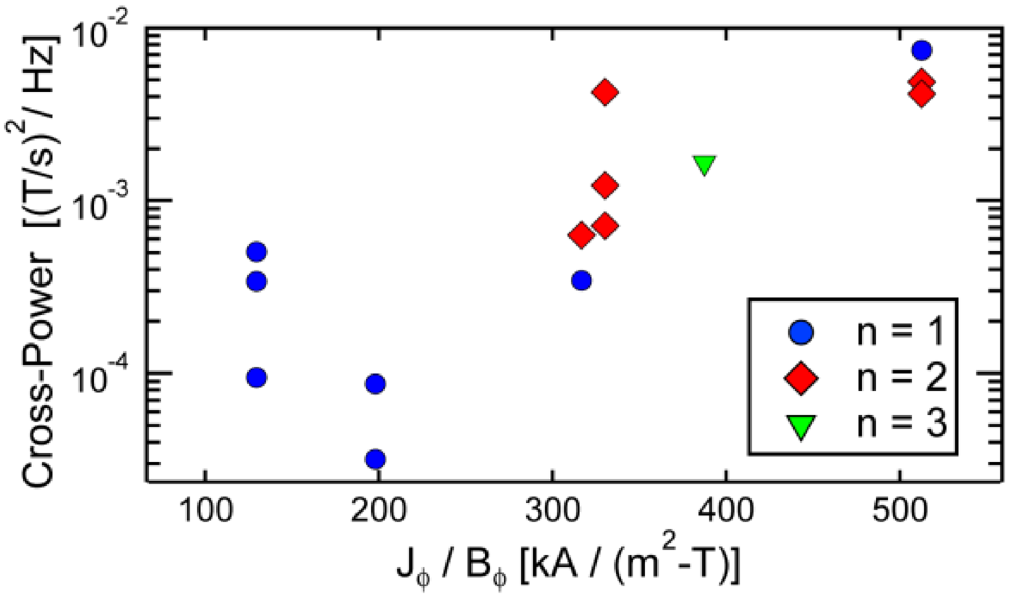

Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

# Pegasus Peeling Mode Features Match Empirical and Theoretical Expectations




0-9 μs | 11-20 μs | 22-31 μs | 33-42 μs | 44-53 μs

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with theoretical drive J/B

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Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

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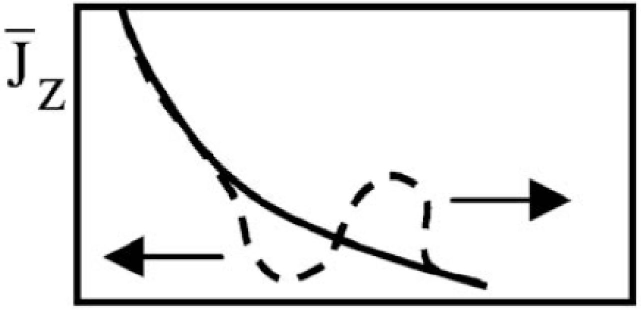
# $J_{edge}$ Dynamics Measured on ELM Timescales

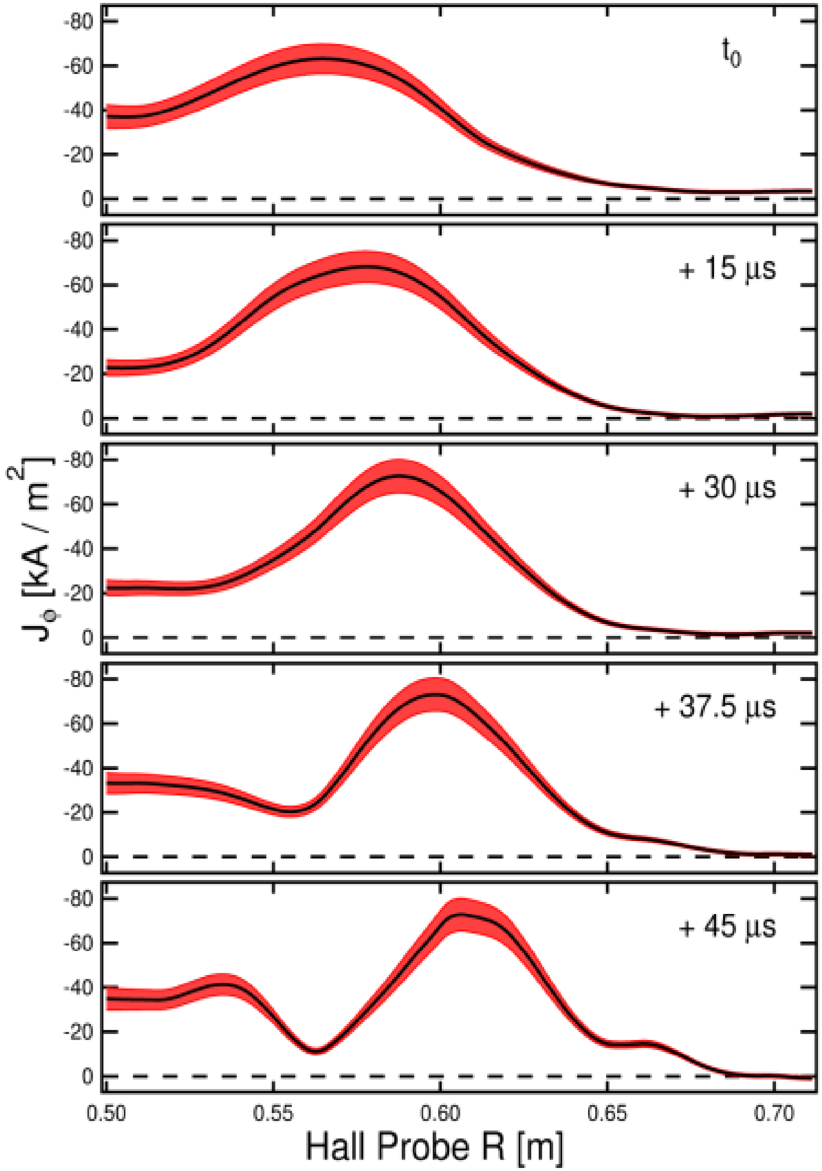
- Peeling mode filament forms from initial "current-hole" $J_{edge}$ perturbation*
  - Validates formation mechanism hypothesized by EM blob transport theory**

- Filaments carry current $I_f \sim$ 100-220 A
  - $I_f < 0.2$ % of $I_p$, similar to MAST ELMs

- Radial motion qualitatively consistent with transient magnetostatic repulsion
  - Measured $v_R$ consistent with available analytic models***



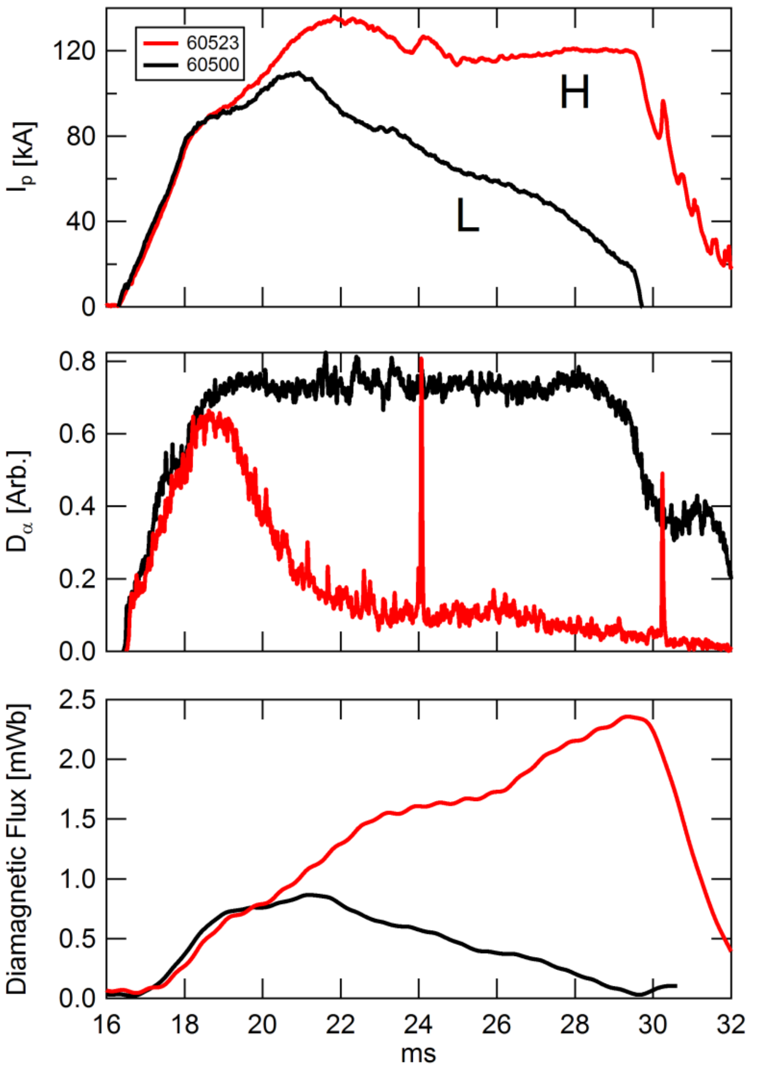

**: Myra, Phys. Plasmas **14**, 102314 (2007)
***: Myra *et al.*, Phys. Plasmas **12**, 092511 (2005)

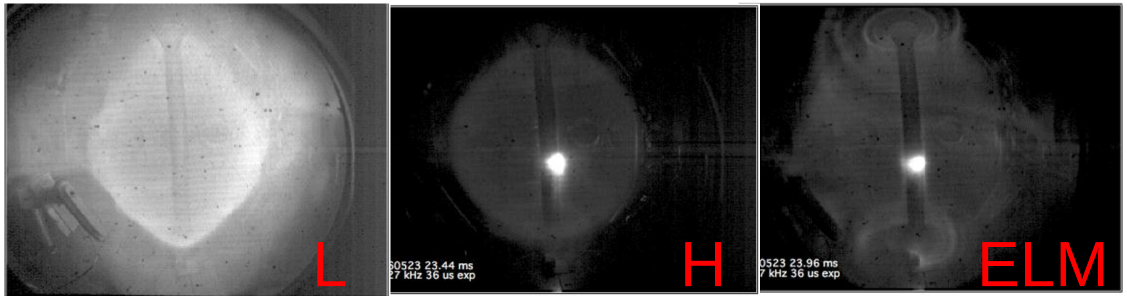



*: Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

# H-mode Access: More Detailed ELM Tests and Possible Post-HI Current Drive Enhancement

- Ohmic H-mode achieved with new central column (high-field-side) fueling system
  - Standard L-mode with strong low-field-side external fueling
- Standard H-mode signals seen
  - Reduced $D_\alpha$ emission
  - Quiescent edge between ELM events
  - Type I and III ELMs suggested
  - Improved confinement inferred



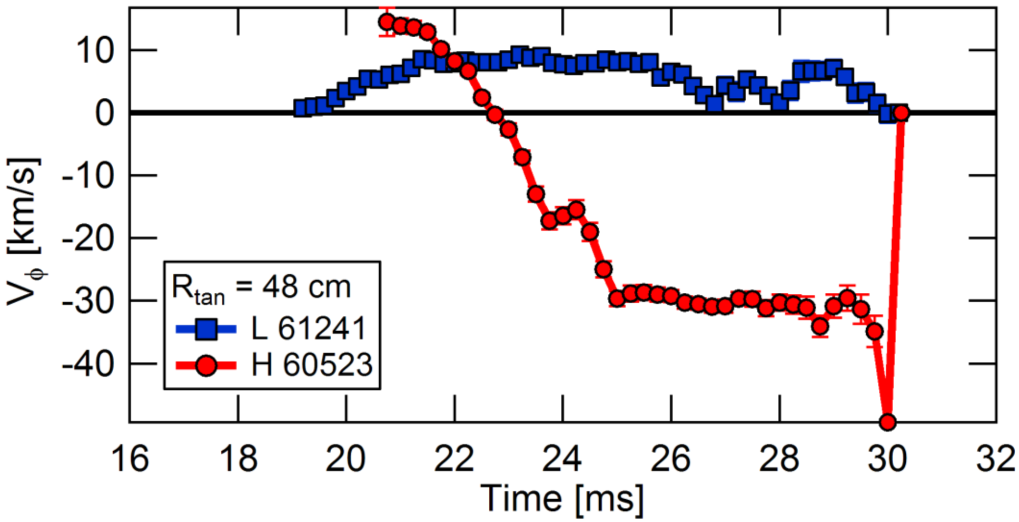






Thome *et al*. APS-DPP 2012
Redd *et al*., IAEA FEC 2012

# Toroidal Flow Reverses at L–H Transition

- Toroidal rotation measured via $T_i$ spectrometry* in L, Ohmic H-mode discharges
  - No external momentum input
- L-mode flows are in the counter-current direction
- H-mode shots reverse rotation at L → H transition
  - Effect seen on MAST** and NSTX during HFS fueling




*: Burke, *et al.*, Rev. Sci. Instrum. **83**, 10D516 (2012)

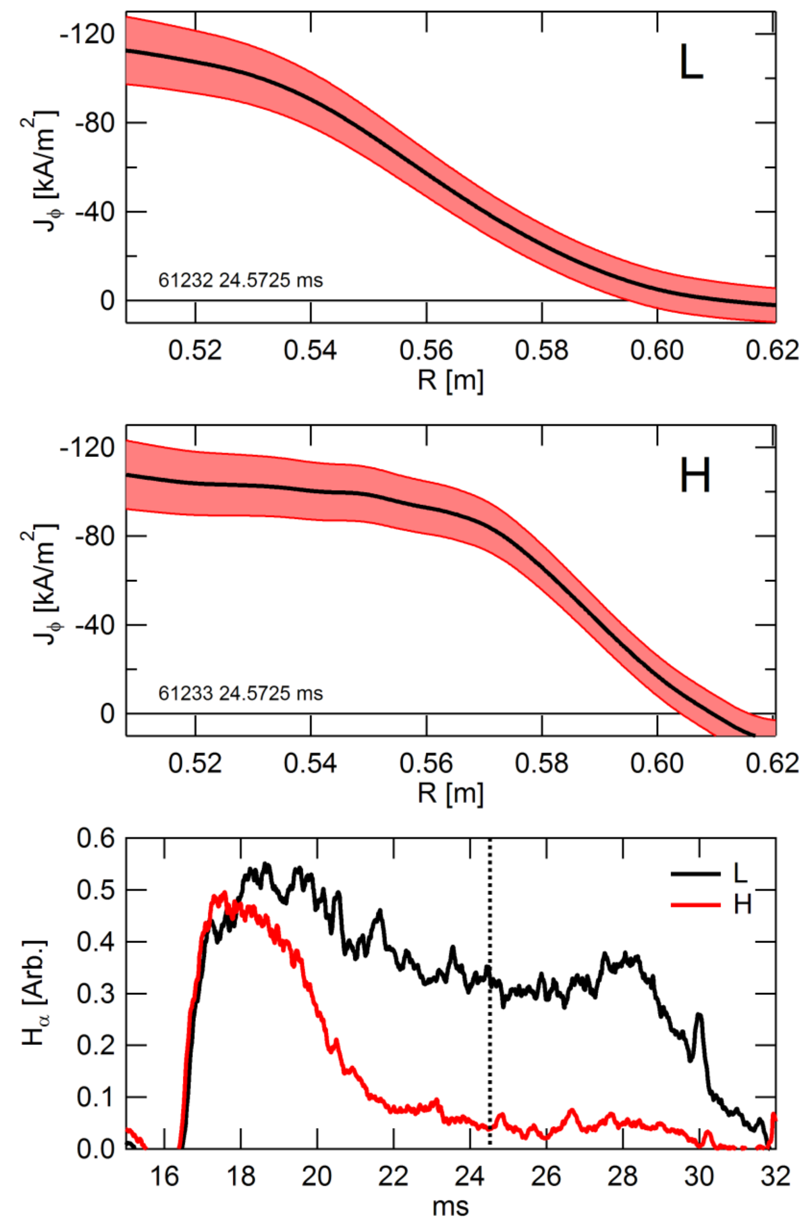
**: Meyer *et al.*, J. Phys.: Conf. Ser. **123,** 012005 (2008)



Burke *et al.*, APS-DPP 2012

# Edge Current Pedestal Observed in H-Mode

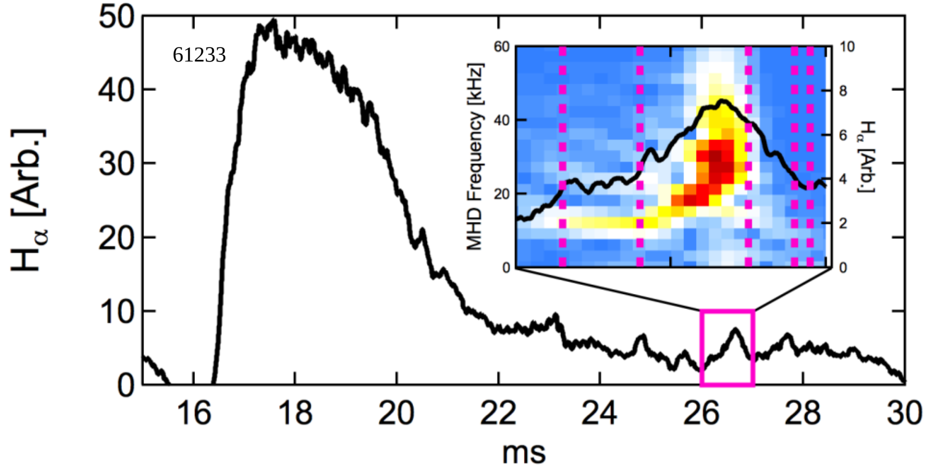
- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
- Current gradient scale length significantly reduced in H-mode
  - L → H: 6 → 2 cm



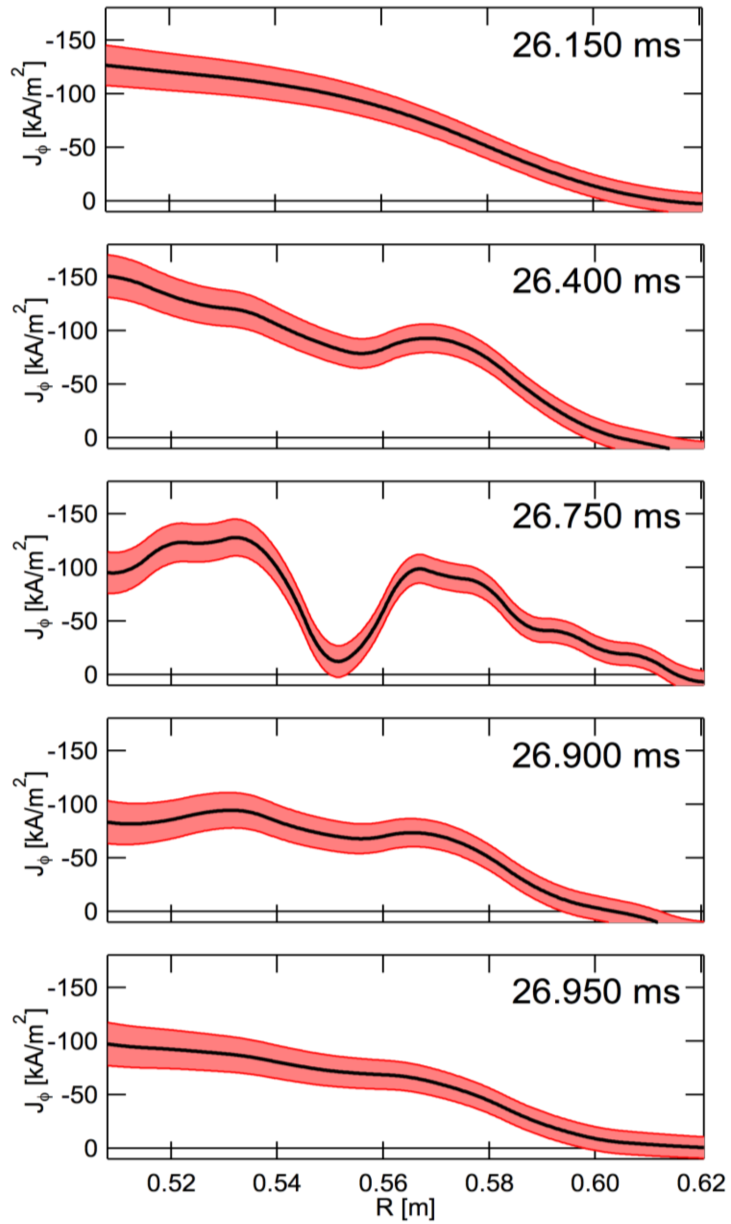

*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
**: C.C. Petty *et al.*, Nucl. Fusion **42**, 1124 ( 2002)


# $J_{edge}$ ELM Dynamics Observed

- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% $I_p$ loss, negligible $\Delta\Phi$
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in Pegasus
- Rapid recovery of H-mode pedestal




*M.W. Bongard, EPR Workshop, Fort Worth, TX Feb. 2013*



# Studies at Near-Unity Aspect Ratio Advance Fusion Energy Sciences

- Significant progress with non-solenoidal startup of ST
  - Increasing understanding of HI physics to project towards MA-class startup
    - Helicity balance, relaxation current limits determine ultimate $I_p$
    - Complex MHD drives J(R,t) and reconnection-driven ion heating
    - Sheath and magnetic current limits govern injector impedance
  - Developing advanced edge current sources for increased helicity injection

- Leveraging low-A regime to test edge stability theory
  - Peeling mode characteristics consistent with theory
    - Onset, spatial structure, MHD virulence consistent with ideal MHD
    - Nonlinear dynamics: filament creation / propagation from $J_{edge}$ current-hole
  - ITER-relevant ELM stability tests of peeling-ballooning modes

- LHI J(R,t) control and H-mode access support high-β studies of tokamak limits
  - Deploying enhanced divertor coils for separatrix operation