# Plasma Startup via Local Helicity Injection and Stability Studies at Near-Unity Aspect Ratio in the Pegasus Experiment

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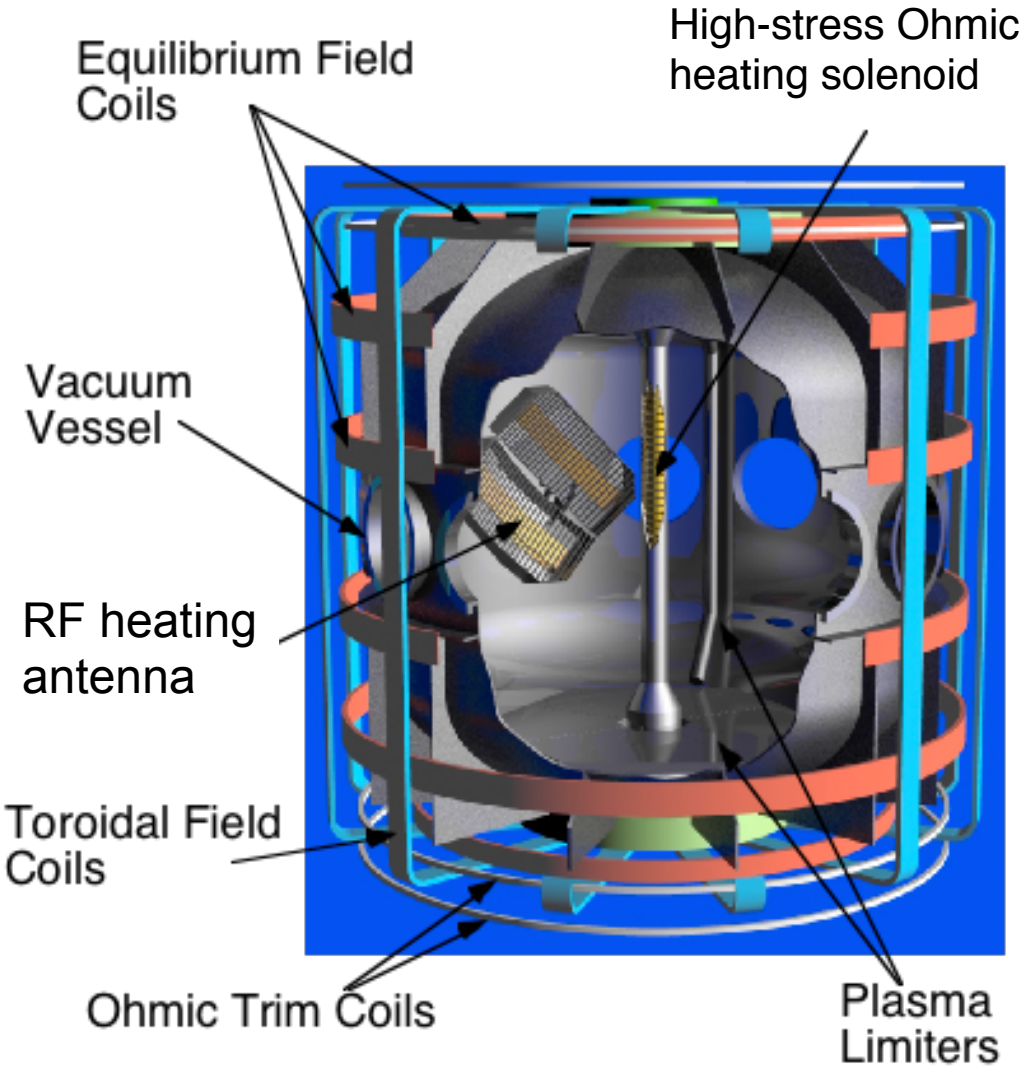


University of Wisconsin-Madison



PEGASUS Toroidal Experiment

# PEGASUS is a Compact Ultralow-A ST




**Experimental Parameters**

| Parameter | To Date |
|---|---|
| A | 1.15 – 1.3 |
| R(m) | 0.2 – 0.45 |
| $I_p$ (MA) | ≤ .22 |
| $I_N$ (MA/m-T) | 6 – 12 |
| $l_i$ | 0.2 – 0.5 |
| $\kappa$ | 1.4 – 3.0 |
| $\tau_{shot}$ (s) | ≤ 0.025 |
| $\beta_T$ (%) | ≤ 25 |
| $P_{HHFW}$ (MW) | 0.2 |

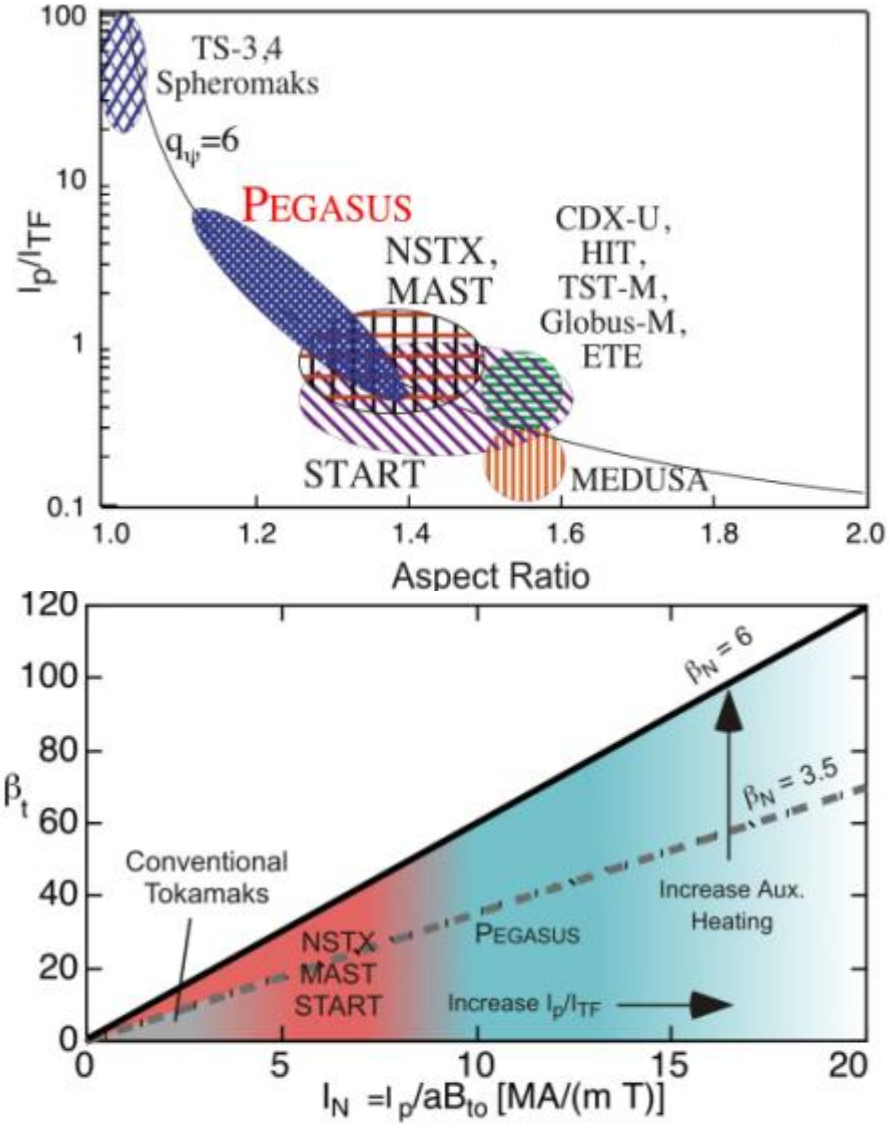




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# PEGASUS Mission: Physics of Low A → 1

- University-scale, Low-A ST
  - $R_0 \leq 0.45$ m, a ~ 0.40 m
- Physics of High $I_p/I_{TF}$
  - Expand operating space of the ST
  - Study high $\beta_T$ plasmas as A→1
- Non-solenoidal startup
  - Point-source helicity injection
  - Helicity injection discharges couple to other current drive methods
- Peeling-mode studies
  - Experimental tests of peeling-ballooning theory (ELM, ITER)

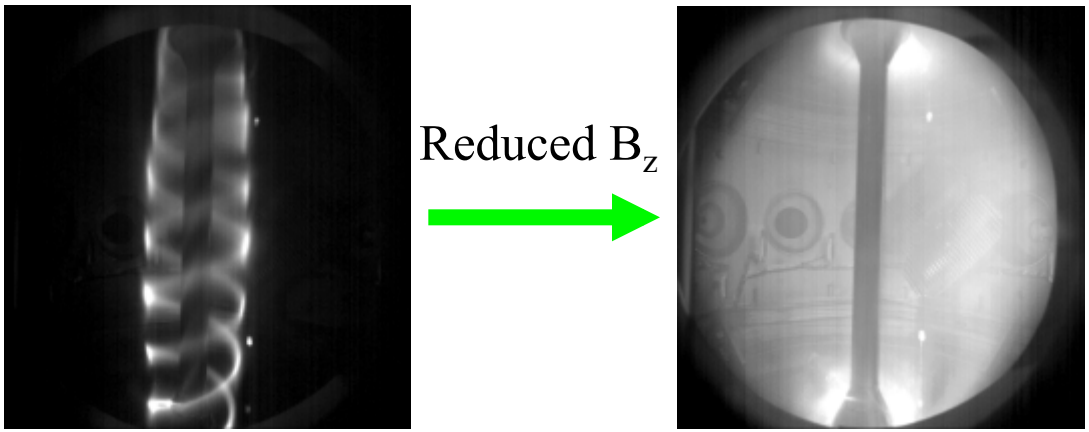





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# Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- Current is injected into the existing helical magnetic field
- High $I_{inj}$ & modest B $\Rightarrow$ filaments merge into current sheet
- High $I_{inj}$ & low B $\Rightarrow$ current-driven $B_\theta$ overwhelms vacuum $B_z$
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication




Current filaments  Relaxed tokamak

- Technical attractiveness: can remove sources and anode after startup



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# DC Helicity Injection Startup on PEGASUS Utilizes Localized Washer-Gun Current Sources

- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

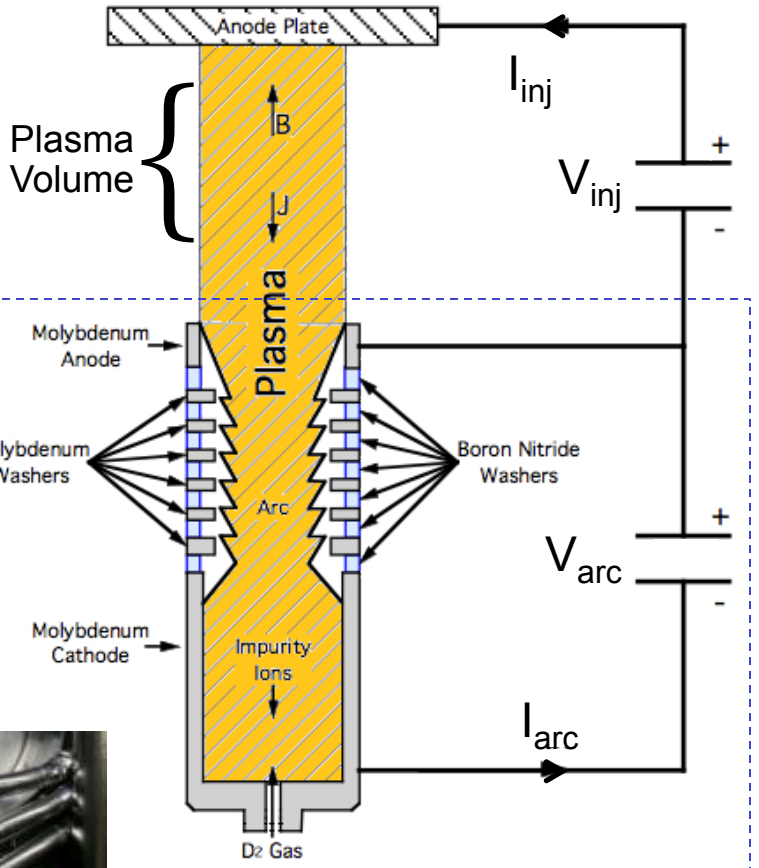
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

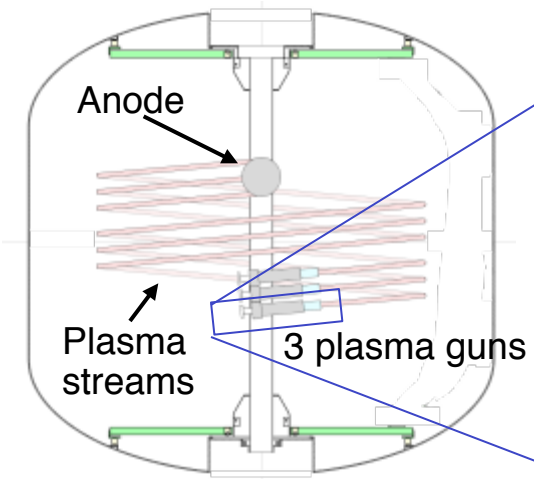
$V_{inj}$ - injector voltage

$B_N$ - normal B field at gun aperture

$A_{inj}$ - injector area

Simplified illustration of a plasma gun for helicity injection *(not to scale)*




Midplane Injection

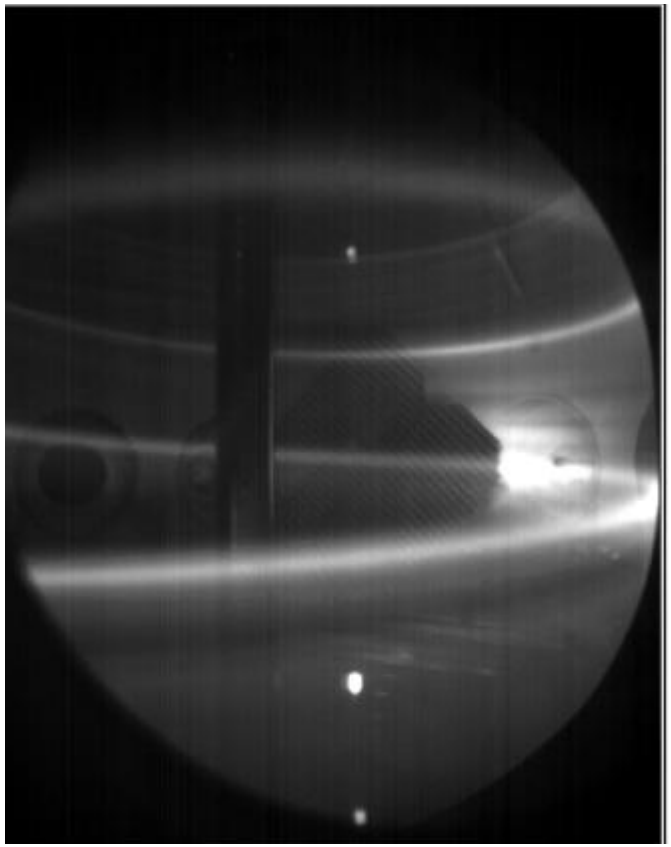




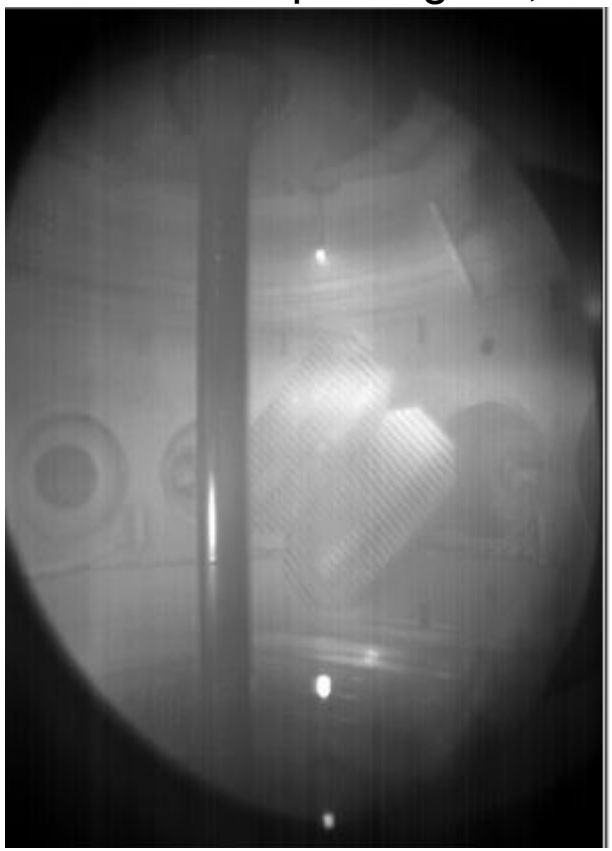
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# Evolution of midplane-gun-driven plasma

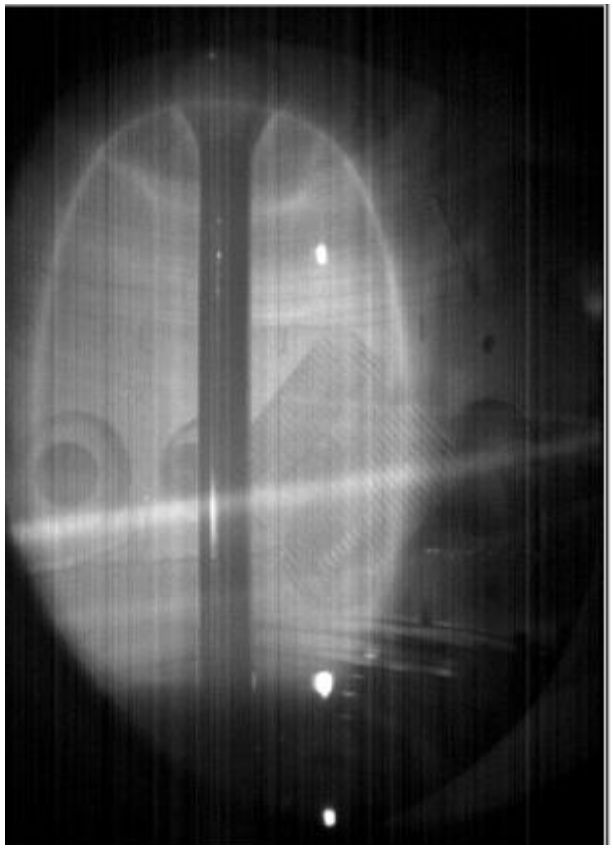
PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



t=21.1 ms, $I_p$=2-3 kA
Filaments only



t=28.8 ms, $I_p$=42 kA
Driven diffuse plasma



t=30.6 ms, $I_p$=37 kA
Guns off, Decaying



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# Taylor Relaxation Criteria Sets the Maximum $I_p$ for a Given Magnetic Geometry

## Helicity balance in a tokamak geometry:

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

- *Helicity injection can be expressed as an effective loop voltage*
- $I_p$ limit depends on the scaling of plasma confinement via the $\eta$ term

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

## Taylor relaxation of a force-free equilibrium:

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

Assumptions:

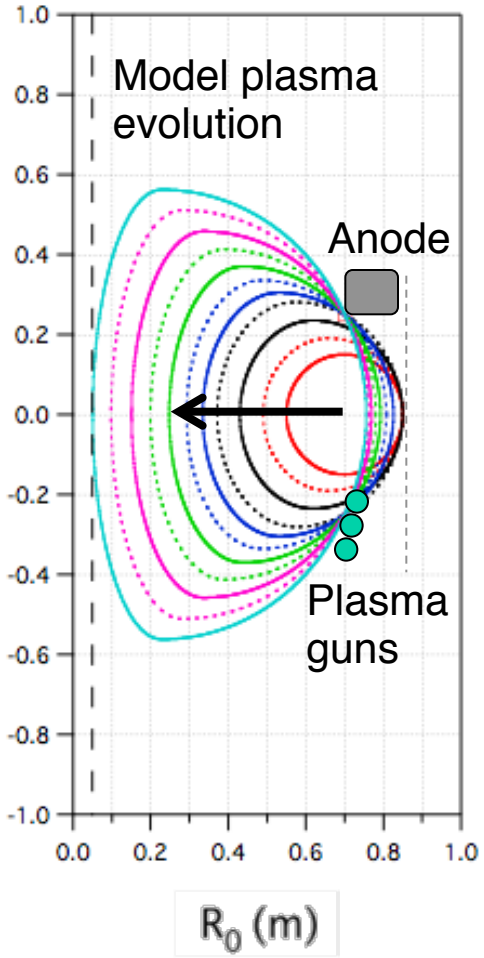
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

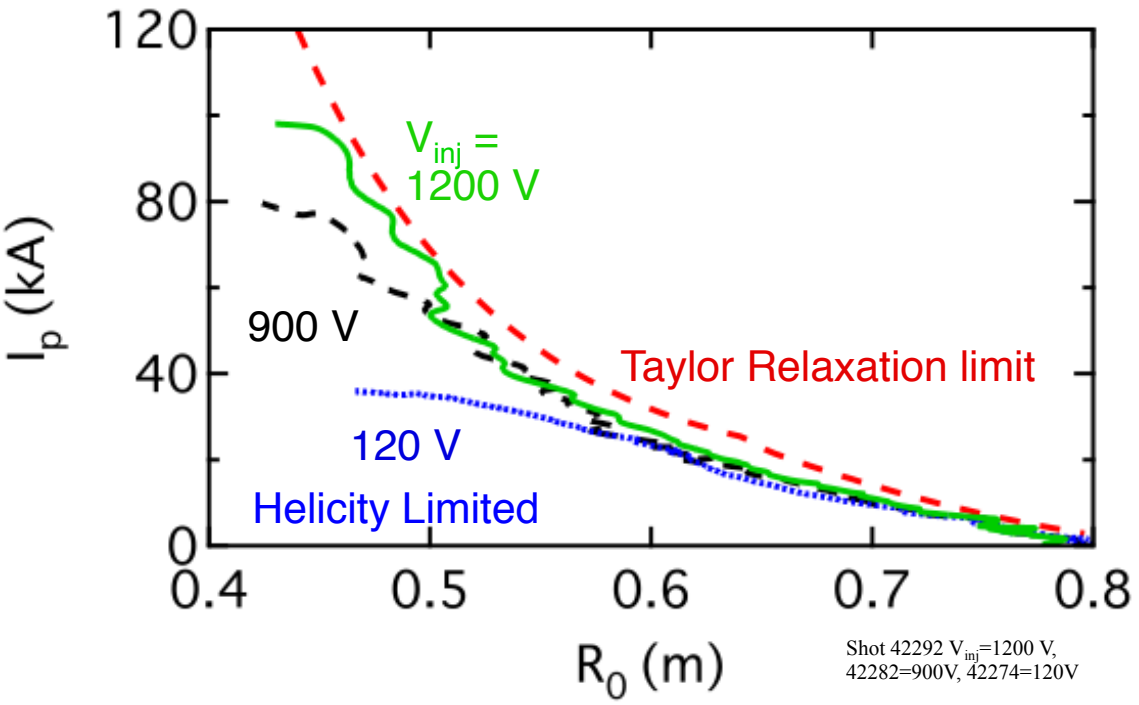
$A_p$ Plasma area
$C_p$ Plasma circumference
$\Psi_T$ Plasma toroidal flux
$w$ Edge current channel width



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




- Helicity input rate, and effective net volt-seconds, increases as $V_{inj}$ increases
- Sufficient net V-sec needed to reach Taylor relaxation limit



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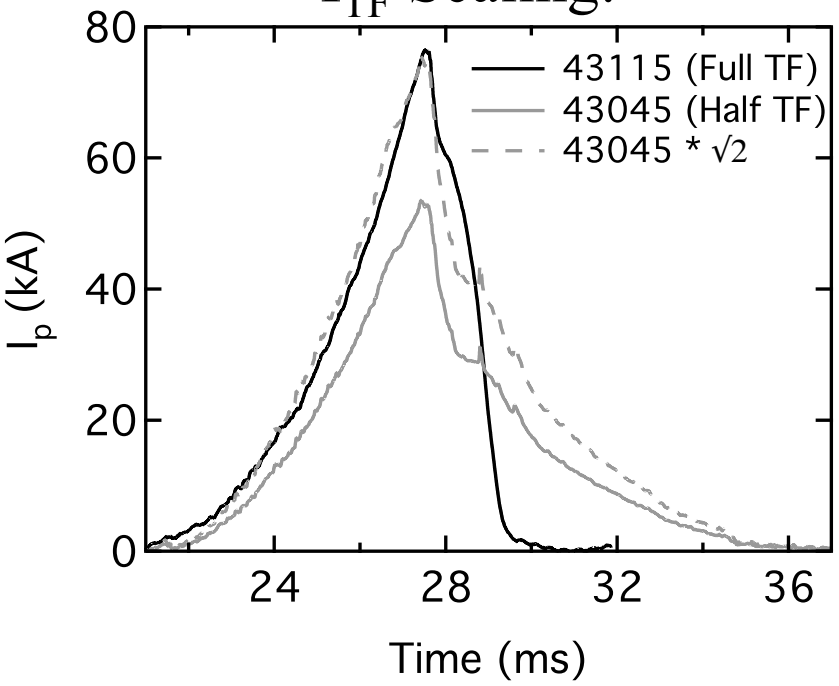
# Experiments Confirm Relaxation Limit Scalings with $I_{TF}$ and $I_{inj}$

- The relaxation limit $I_p$ scales with:

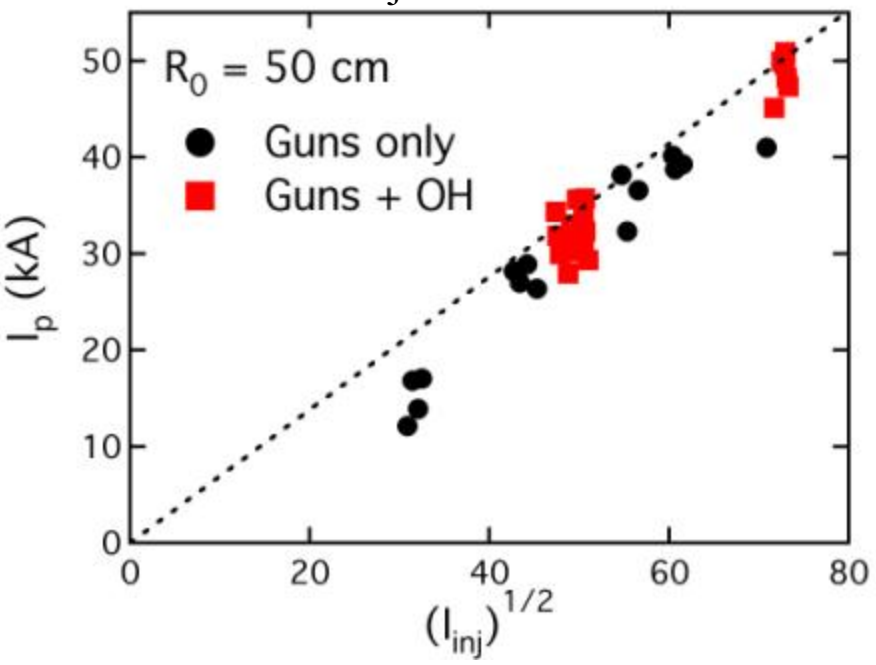
$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$

- Experimental plasma current limits follow these scalings:

$I_{TF}$ Scaling:




$I_{inj}$ Scaling:

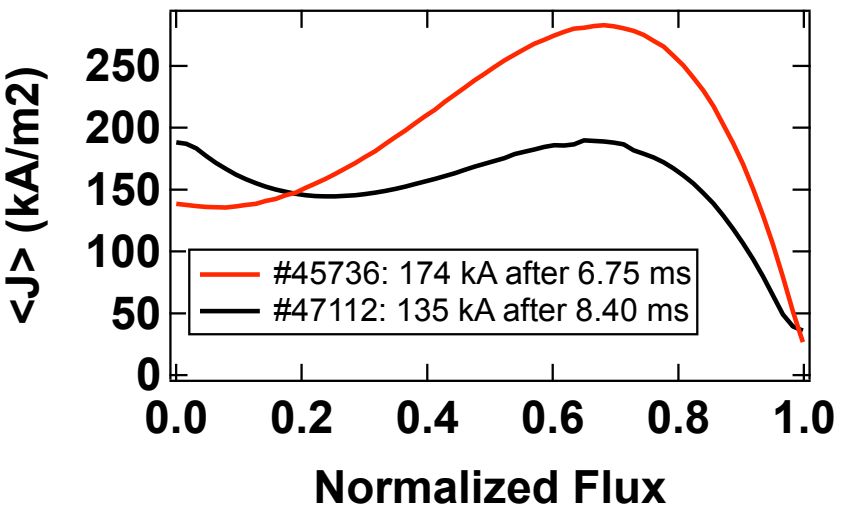


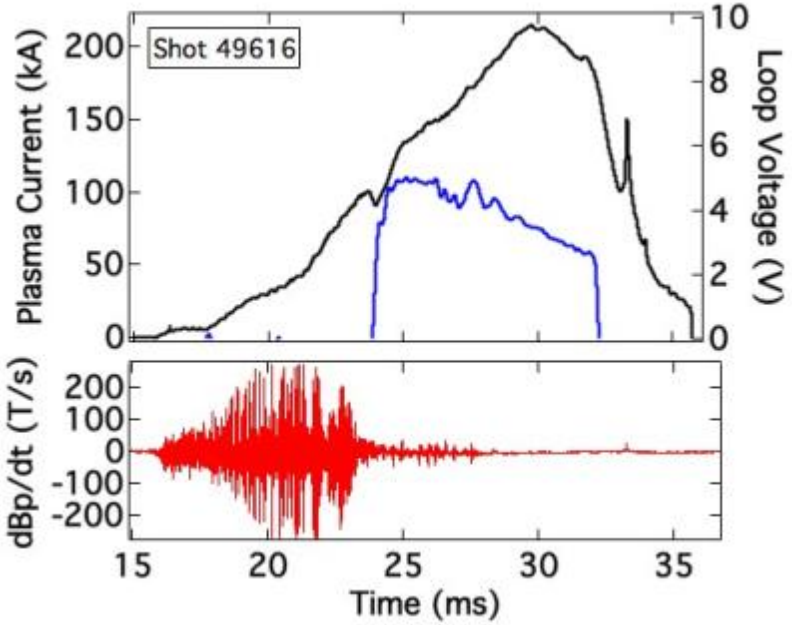



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# Slowly-evolving Gun-driven Plasmas Hand Off Most Efficiently to Ohmic Drive

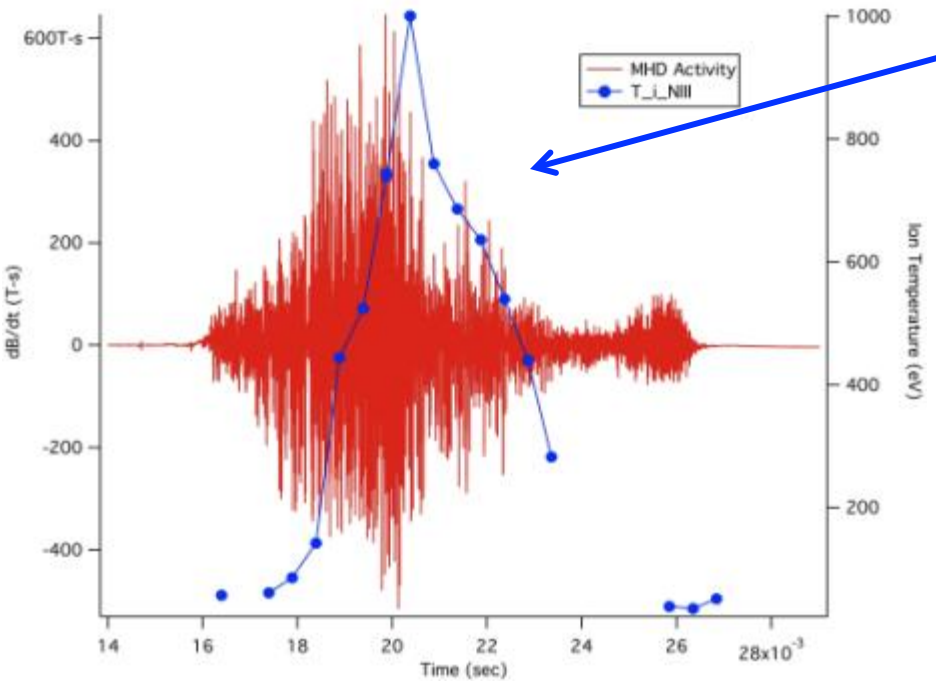
- Poloidal flux generated by helicity injection is equivalent to that generated by Ohmic Drive
  - $I_{total} = I_{HI} + I_{OH}$
- Excessive skin current => poor coupling to OH drive
- Slowly evolving: ~ flat j(r) (black)
  - Smooth handoff to Ohmic inductive drive (j(R) profiles from external-only equilibrium reconstructions; $l_i < 0.3$)
- Rapidly evolving: ~ hollow, strong skin j(r) (red)
  - Does not hand off efficiently to Ohmic drive



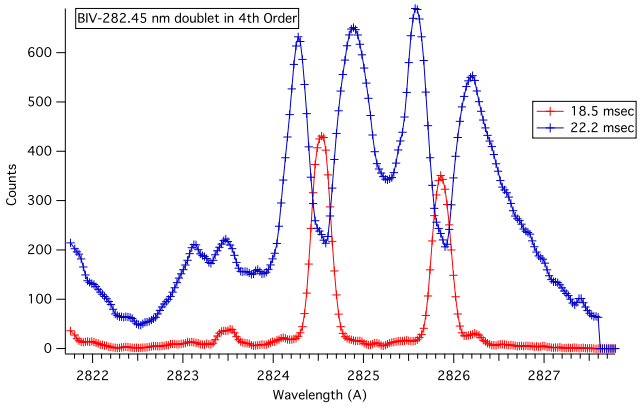
# Initial Spectroscopy Measurements Suggest Energetic Ions

- Spectroscopic $T_i$ suggest high ion energies during reconnection period




Doppler $T_i$ from radial view

Complex multi-line structures from tangential view




- However, situation is much more complex if viewed toroidally
  - Need improved time-resolution and spatial scans



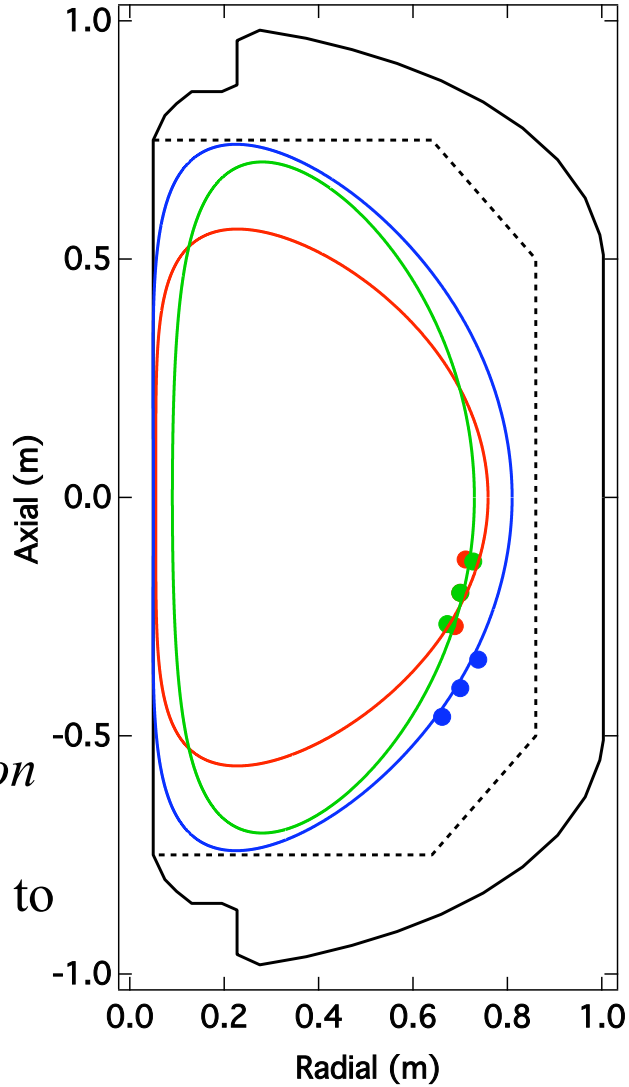
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# Several Issues to Address for a Predictive Model

- Extension to higher current, longer pulse
  - Verify limit scalings
  - Discharge evolution for long growth phase
  - Test confinement properties, especially $T_e(r,t)$
    - Helicity dissipation scaling model
- Optimal gun-electrode configuration
- Increased helicity injection rate
  - Test regime where helicity drive dominates PF induction for growth
  - Active guns vs. passive electrode approach for long-pulse growth
- Injected current source impedance model
  - What sets helicity injection rate?
- Edge j(r) measurements and $\lambda(\psi,t)$
  - Physics of ultimate relaxation limits
  - Current transport: MHD behavior
- Impurity assessment and control

# Gun-Electrode Geometry: PF Induction, Plasma Size, and Null Formation

- Original: array was nearly vertical (red):
  - $J_{edge}$ width *w* scaled with # of guns
  - Maximum $I_p$ = 0.11 MA.
- Aligned gun array tilt (green):
  - Maximum $I_p$ = 0.17 MA.
  - 3-fold reduction in *w*., consistent with changing the projected width at midplane.
- Maximize plasma size: array moved further away from midplane (blue):
  - Maximum $I_p$ ~ 0.13 MA
  - Larger startup plasma = *reduced PF induction*
  - *Poorer poloidal field null* formed by current streams = more difficult to induce relaxation to tokamak state
- Tight gun-anode geometry preferred

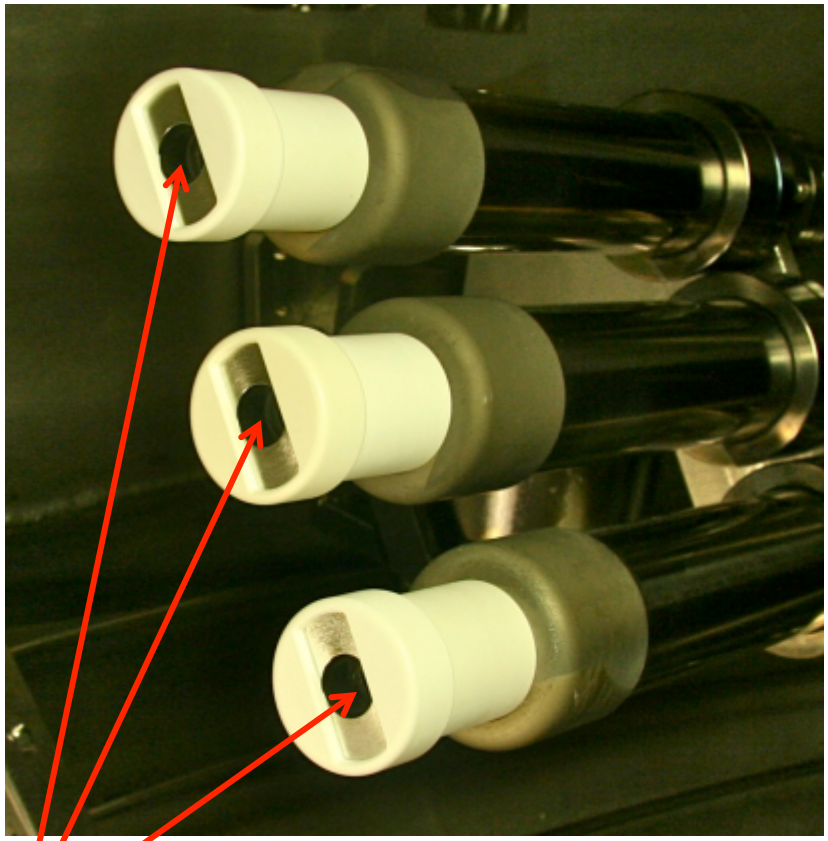





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# Active Gun / Passive Electrode Assembly Points to Simpler, Higher $I_p$ Operation

- Potential for much higher $I_{inj}$ without need for either more plasma guns or larger guns.
- Helicity injection physics is agnostic to the exact source of the edge charge carriers.
- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) *and* the Taylor limit on $I_p$ (narrow in radial direction)



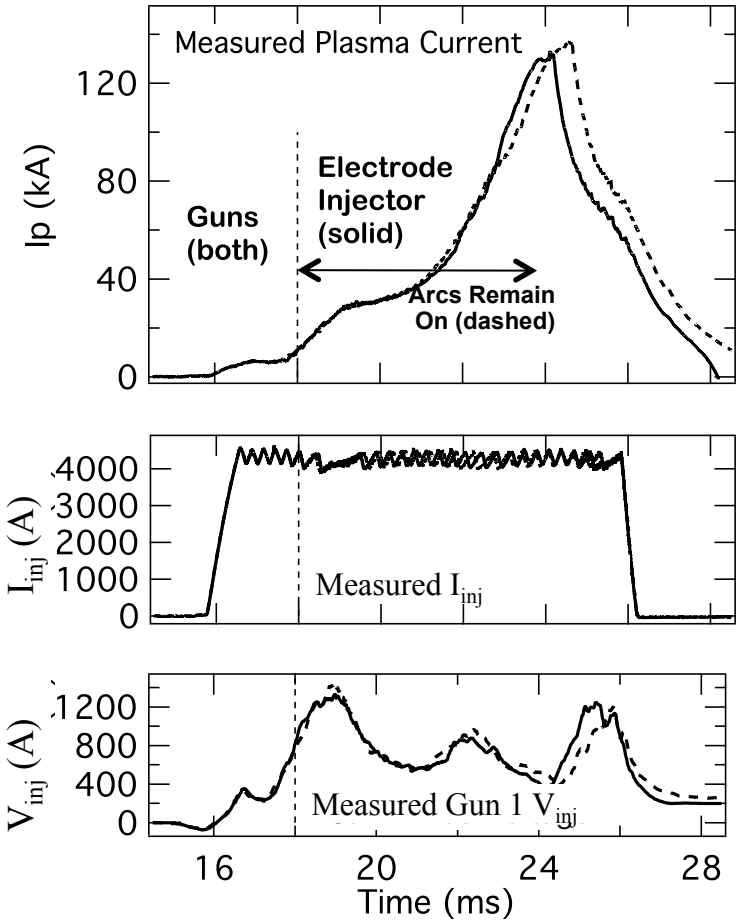
Plasma Guns with Integrated Slotted Electrodes



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# Initial Tests of Gun/Electrode Helicity Injection System Are Promising

- Operations use two steps:
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger $I_p$ with passive electrodes fed by electrode charge carriers induced and moderated by tokamak edge plasma.
- First tests are promising
  - Arc current off after relaxation and formation of tokamak-like state
  - $I_p$ rise is virtually the *same,* whether arc discharge or passive electrode provide the charge carriers



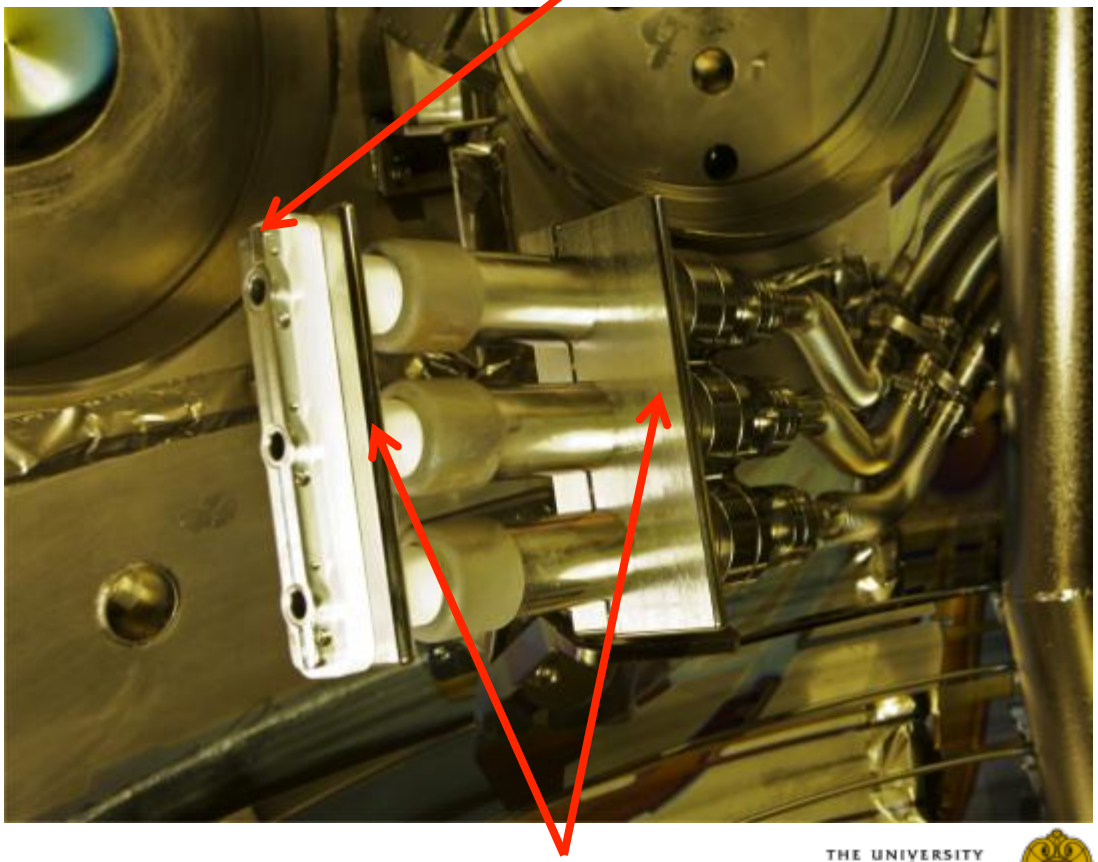



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# Integrated Arc Gun – Passive Electrode Experiments Begun

- New gun-electrode assembly has has extended electrode coupled to arc gun exit cathodes
  - Offers 5-times increase in helicity injection rate

- Integrated scraper limiters to protect assembly and control local edge density
  - Gas-puff control of $V_{bias} \sim V_{loop,\ effective}$



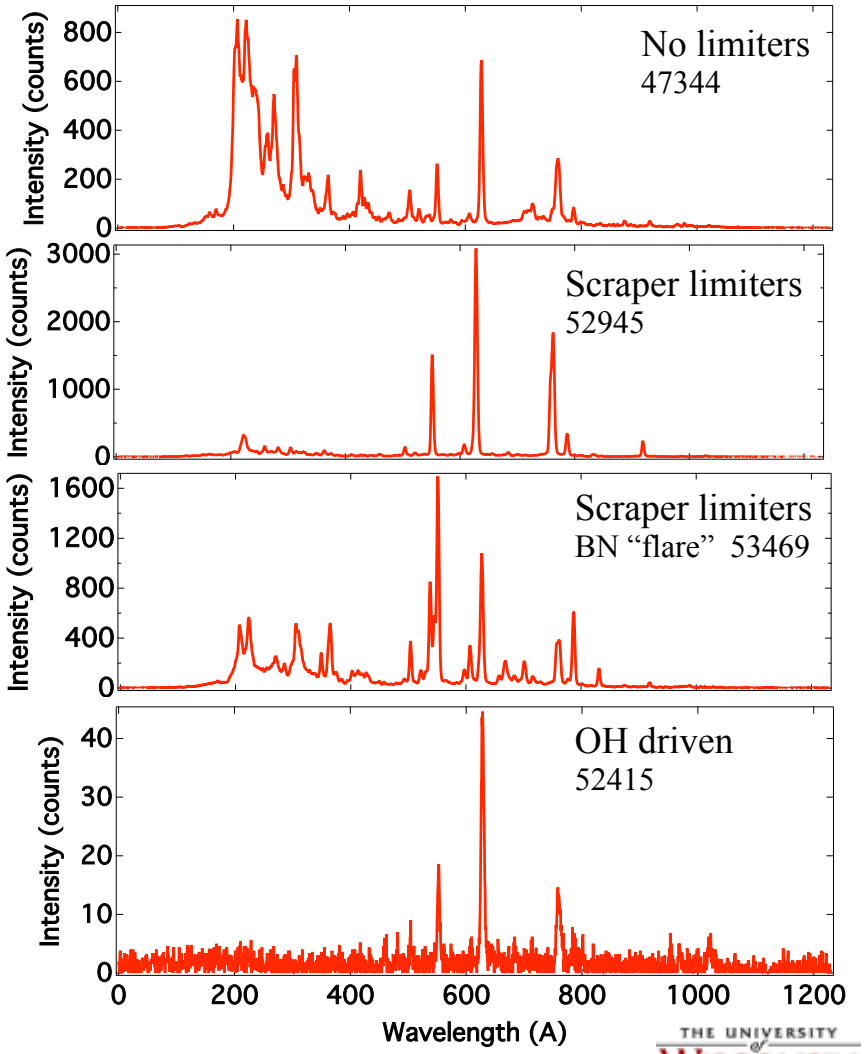
*Local limiters*



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# Local Limiters Reduce N to Negligible Levels in Well-behaved Injection Cases

- N dominant impurity with unprotected gun assembly
  - 1st *estimates* of impurity content via bolometer measures
    - $Z_{eff} \sim 2.2. +/- 0.8$ during injection; $\leq 1.4$ after injection
    - Mainly N; $n_e \sim 5 \times 10^{18}$ m$^{-3}$ to $2 \times 10^{19}$ m$^{-3}$
- Local scraper limiters much reduce N, O remains
- Bursts of N still evident with flare at BN surface
- Ohmic-only reference plasma very clean
  - Zeff ≤ 1.2

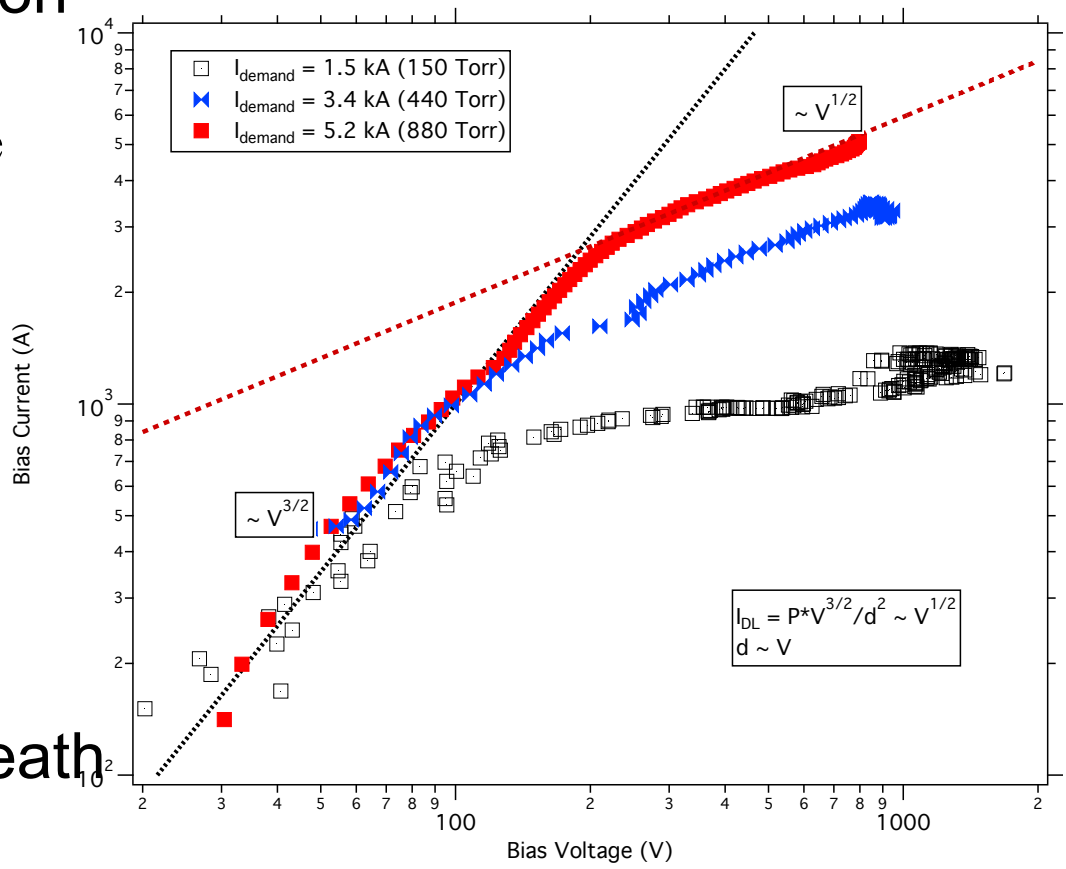





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# Source Impedance Appears to be Governed by Sheath Physics

- Model evolving for source impedance ~ helicity injection rate
  - Predicative model requires edge density measurements
- Initiation phase: vacuum space charge limitation
  - $I_{bias} \sim V^{3/2} / d^2$
- High $I_{bias}$ drive phase: expanding double layer sheath
  - $d^2 \sim V \Rightarrow I_{bias} \sim V^{1/2}$

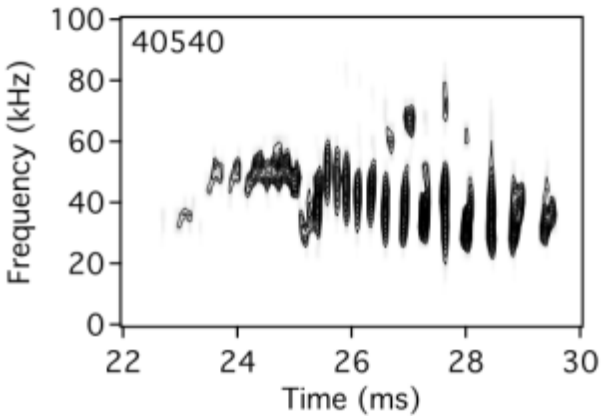


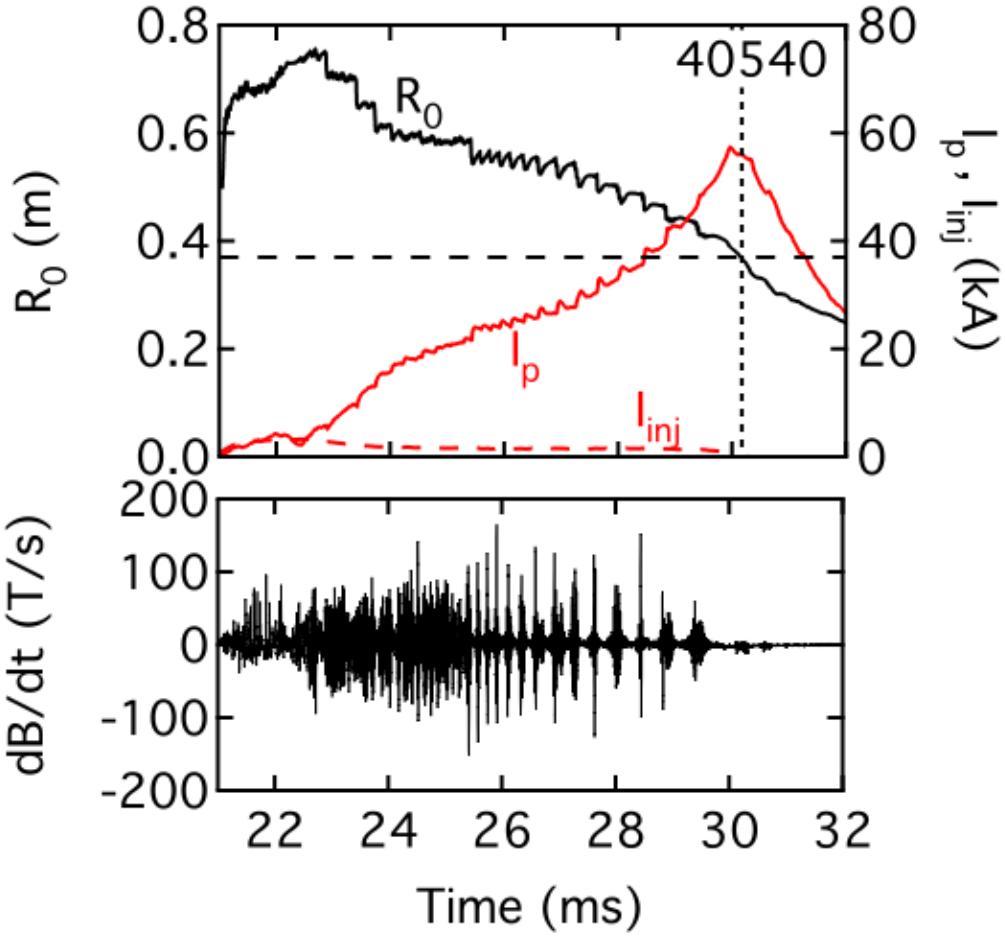



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# Intermittent 20 - 60 kHz n = 1 mode observed with strong edge current drive

- Bursts of *n* = 1 magnetic oscillations
  - Observed when plasma is coupled to edge current drive
  - Different in nature from inboard current injection experiments



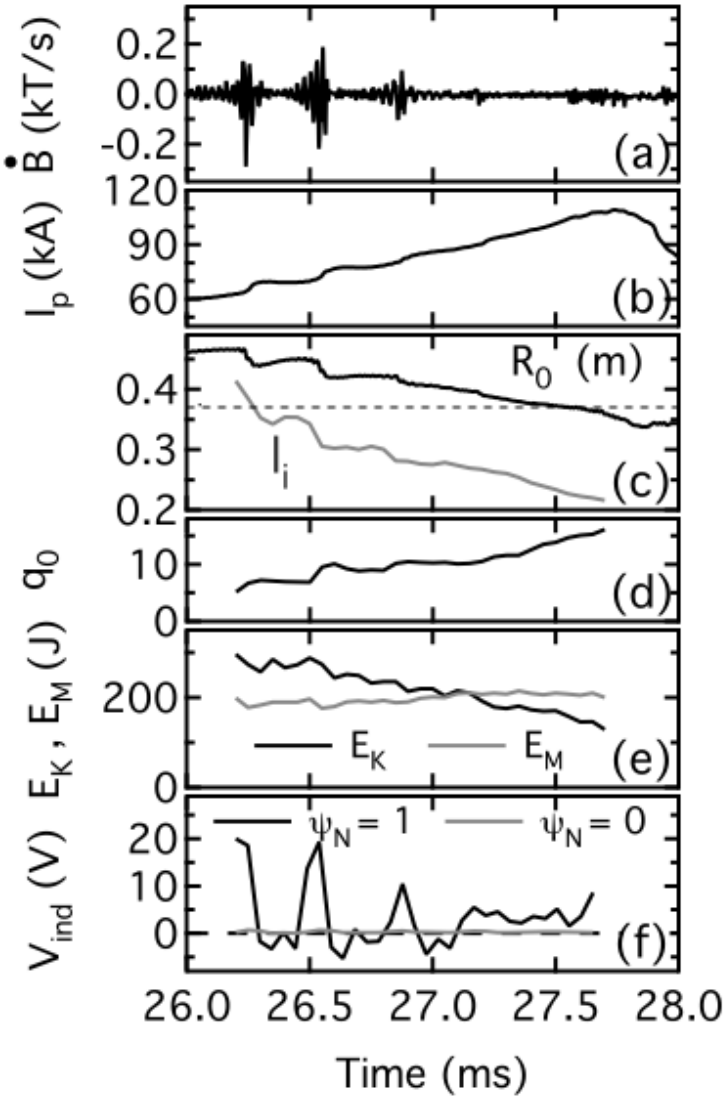






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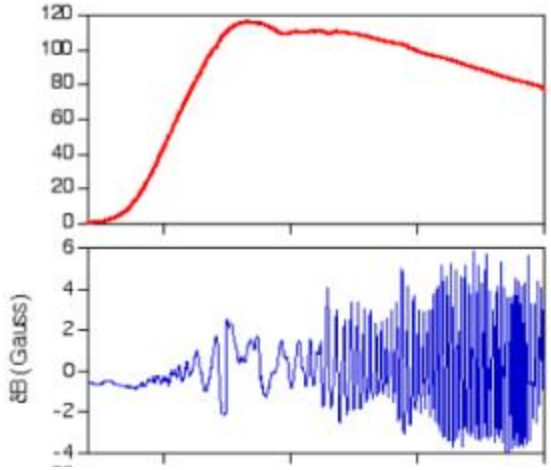
# The magnetic topology quickly changes with each burst of MHD activity

- Each burst typically ~ 0.1 ms
- With each burst…
  - $l_i$ decreases → $I_p$ increases
  - $R_o$ decreases → plasma expands
  - $B_{\phi o}$ increases → $q_o$ increases
  - Slight drop in $E_k$ and $E_m$
  - Very 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

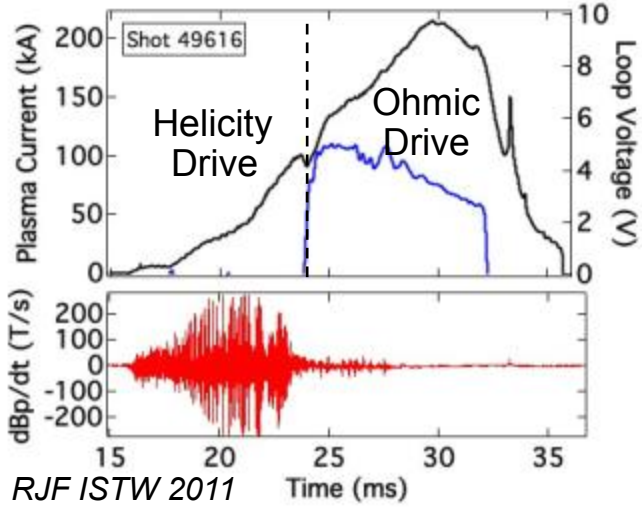


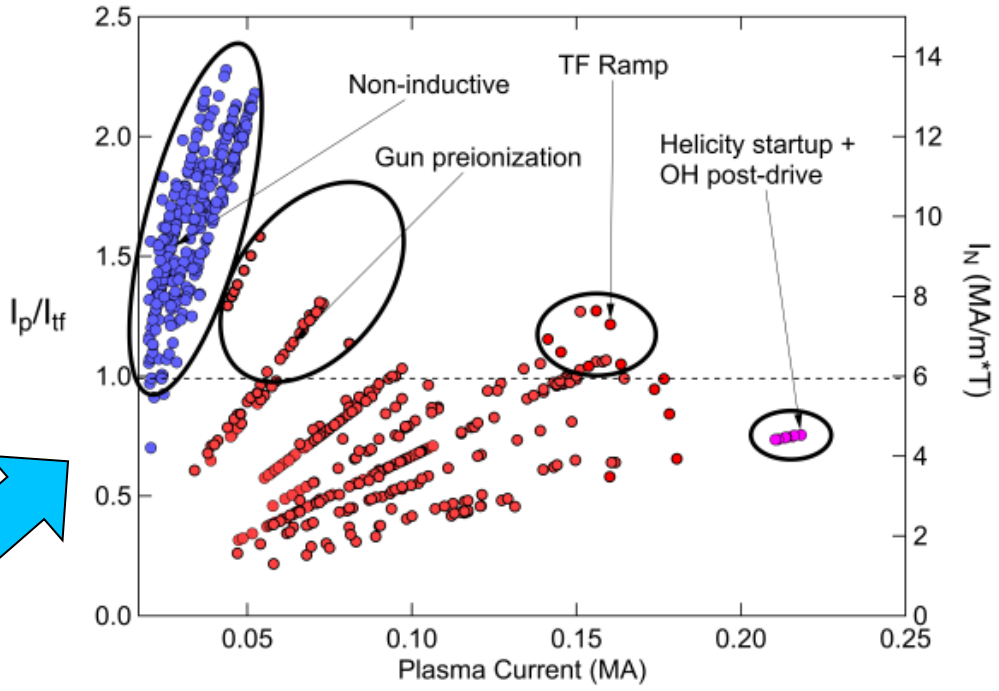
# Current Drive Tools Providing Access to High Field Utilization Regime

OH only = large 2/1 modes limit $I_p$




HI startup = MHD quiescent



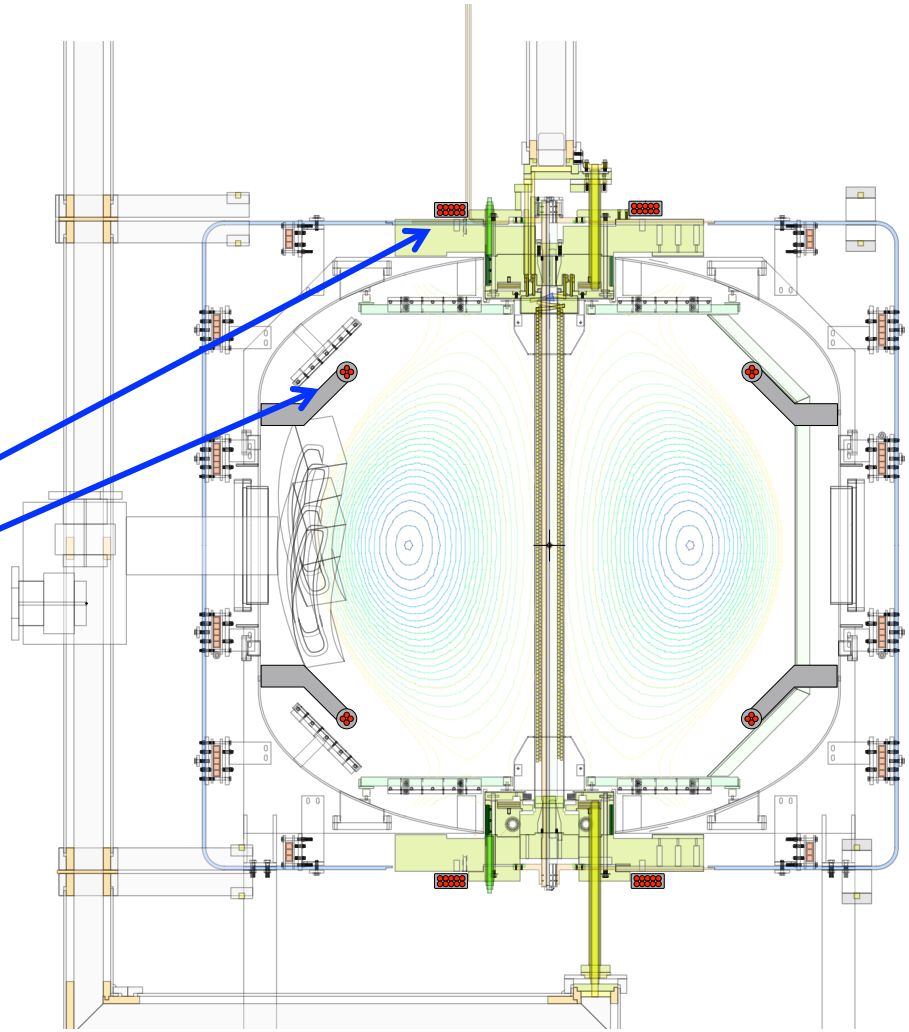

- Helicity injection startup and Ohmic sustainment provides MHD-stable profiles at $I_p/I_{TF} < 1$
- Need to extend to higher $I_p$, then to low $I_{TF}$ for high $I_N$ and high $\beta_T$ as A≈1



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# Medium-Term Upgrades Will Allow Further Tests of Point-Source Helicity Injection

- Gun-electrode Evolution
  - Passive electrode material variations
    - C electrode being installed
  - Separate plasma gun and electrode
- Power Supplies, Heating
  - New helicity injection power: *2 kV, 15 kA*
  - Double TF current: *Taylor limit increase*
  - Commission HHFW system: *electron heating*
- Expanded PF Coil Set and control
  - Internal coils for radial position control
  - New external divertor coils
  - Implement GA Plasma Control System
- Diagnostic Additions
  - Multipoint Thomson Scattering
  - High-speed $T_i(r,t)$
    - *Anomalous reconnection heating*



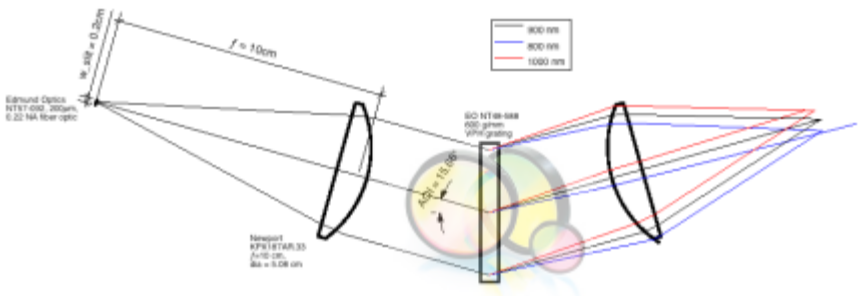


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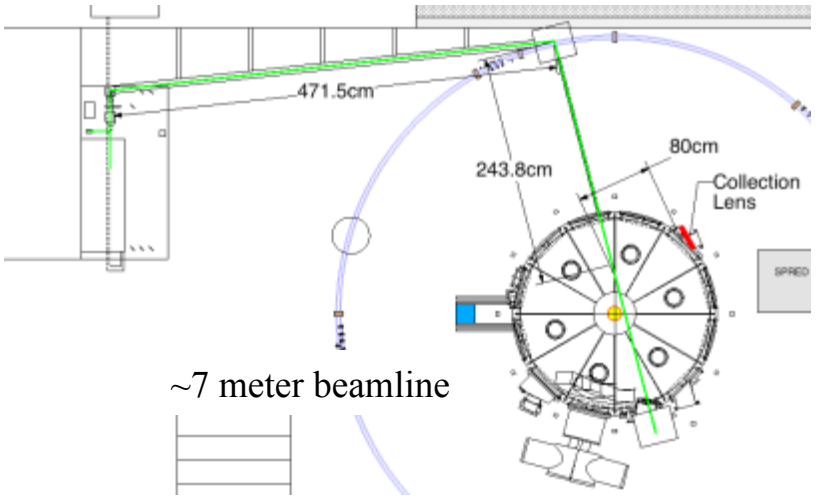
# Thomson Scattering system uses new technologies for visible wavelength system

- Frequency doubled Nd:YAG laser provides ~$10^{18}$ photons
- For typical PEGASUS plasma, $n_{scattered} \sim 10^4$ photons
- VPH grating efficiency >85% for $\lambda_{inc}$ = 532 - 632 nm
- Gen III image intensifiers ~50% efficient in visible region
- ~ 6 ns ICCD gating provides easy detector technology

| Laser Specifications | Value |
|---|---|
| Output Energy at 532 nm | ≥ 2000 mJ |
| Beam diameter at head | 12 mm |
| Beam diameter at waist | 3 mm |
| Pointing stability | ≤ 50 μrad |
| Divergence | ≤ 0.5 mrad |
| Repetition Rate | ≤ 10 Hz |
| Pulse length | ≥ 10 ns |



Volume Phase Holographic (VPH) Grating






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# HI Conclusion: High-$I_p$ Non-Solenoidal Startup via Point-Source Helicity Injection Looks Promising

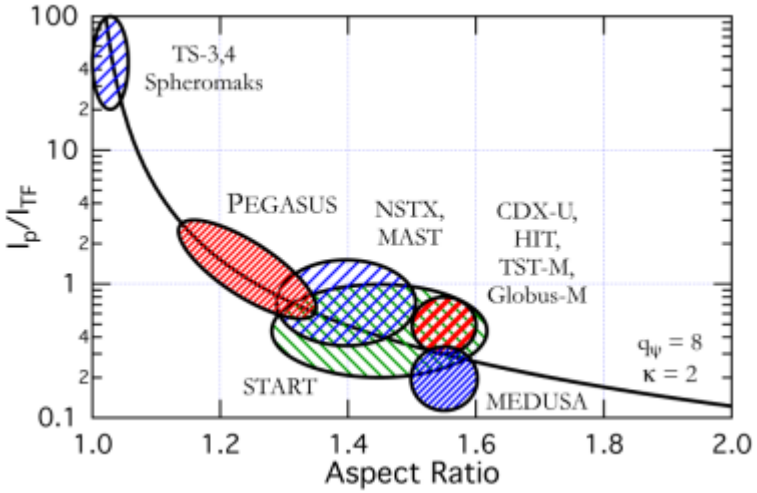
- Significant progress with non-solenoidal startup of ST
  - $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
    - So far, predicted scalings supported
  - Goal $\approx$ 0.3-0.4 MA non-solenoidal $I_p$ to extrapolate to next level/NSTX
    - Outstanding physics questions: $\lambda_{edge}$, $Z_{inj}$, confinement, *etc.*
  - Deploying plasma diagnostics to better understand properties
- Exploration of high $I_N$, $\beta_t$ space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high $I_p$, $n_e$ for high $\beta_t$
- Holds Promise as a Scalable Non-Inductive Startup Technique
  - Simpler injection system using plasma gun – passive electrode combination may be feasible

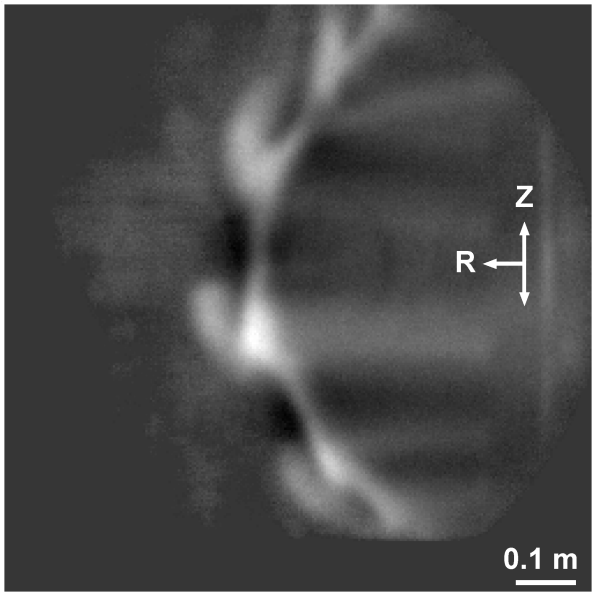


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# Some Low-A ST ITER-relevance: Access to Peeling Instability and Conditions to Measure J

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



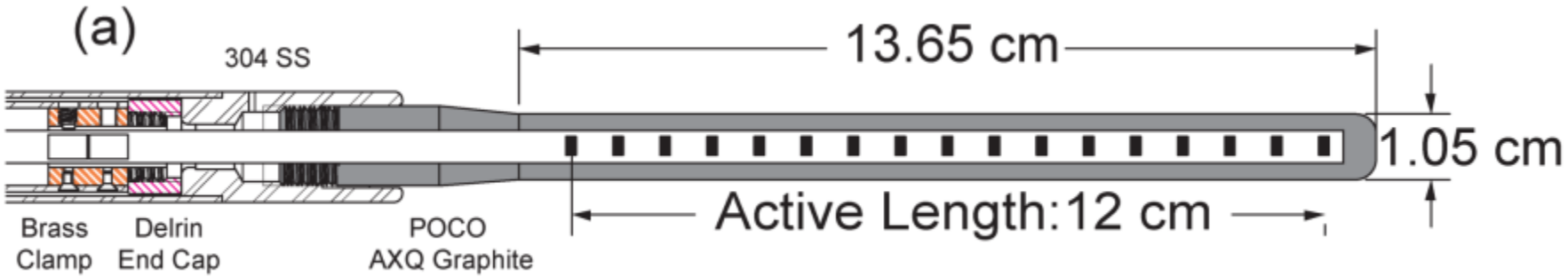



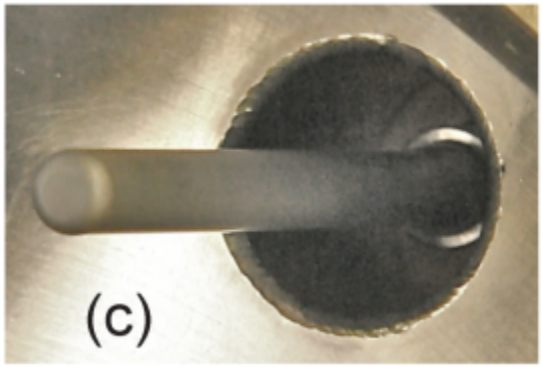

Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



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# PEGASUS Hall Probe Deployed to Measure J







- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth



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

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# $J_\phi(R,t)$ Calculable Directly from Ampère's Law

$$\mu_0 J_\phi = (\nabla \times \mathbf{B})_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R}$$

- Simplest test follows from $B_R(Z)$ or $B_Z(R)$ measurements
- Petty* solves for an off-midplane $B_Z(R)$ measurement set and an elliptical plasma cross-section:

$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2}\right) - \frac{dB_Z}{dR} \left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2}\right)$$

- Does not make assumptions on shape of J(R)

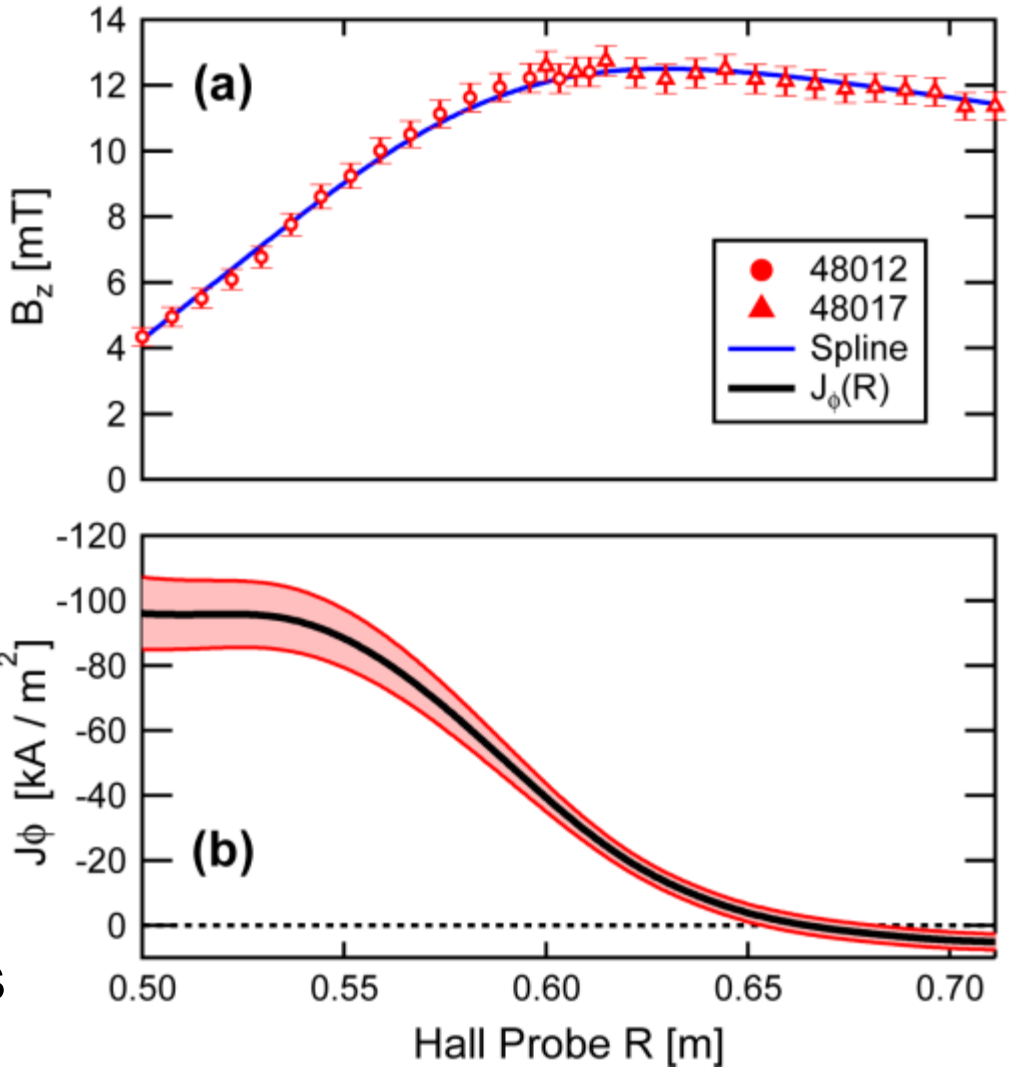


*: Petty, *et al.*, Nucl. Fusion **42**, 1124 (2002)

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# Direct $J_\phi(R)$ Profiles Obtained in PEGASUS

- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute $dB_Z/dR$ using interpolated smoothing spline*
  - Compute $J_\phi(R,t)$ given geometry
- Resultant $J_\phi(R,t)$ consistent with $I_p$, MHD evolution
- Radial span extendible with multi-shot averaging
- Higher-order shaping effects negligible within errors



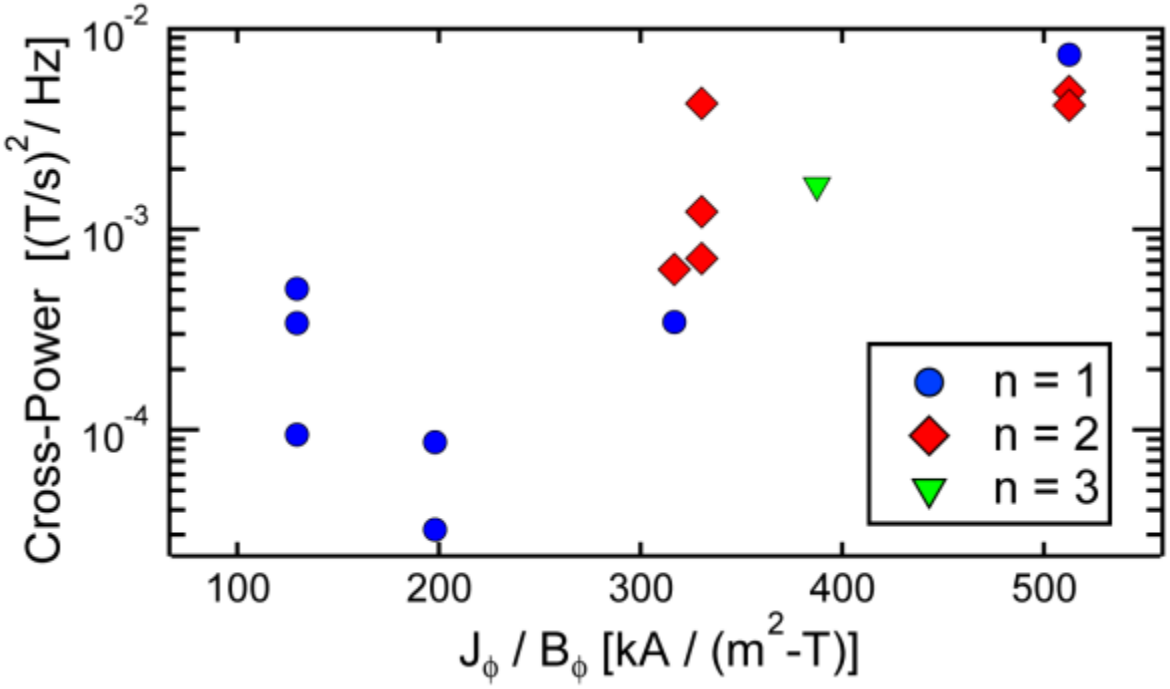

Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

*: Reinsch, Numerische Mathematik **10**, 177 (1967)



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# Peeling MHD Strongly Scales with Theoretical Drive




- Mode helicities estimated from port 8 Mirnov array
  - $n < 3$ via cross-phase analysis
  - $m_{lab} \geq 10$ via radial decay rate
  - $10 \leq m_{lab} / n \leq 30$ ($\psi \downarrow N > 0.9$)
- MHD power spans two orders of magnitude with factor-of-five variation in J/B

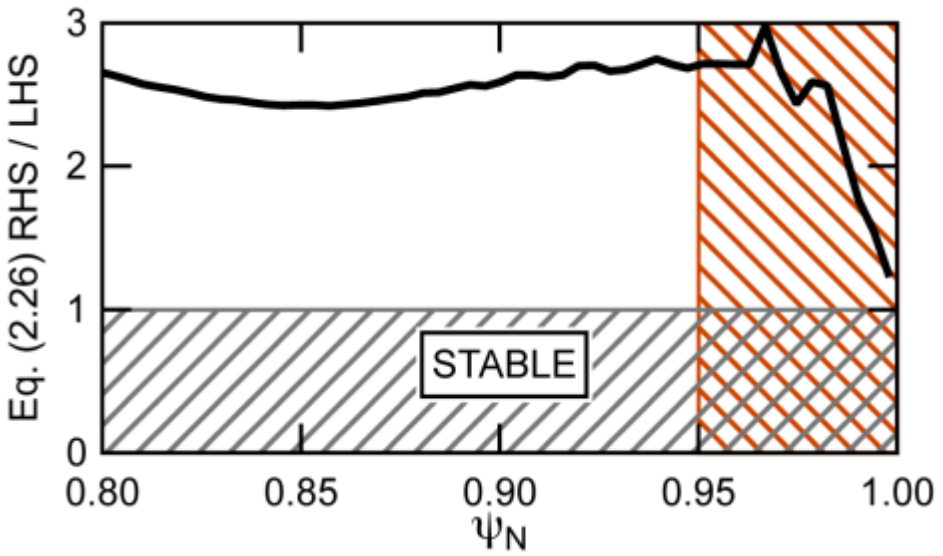


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

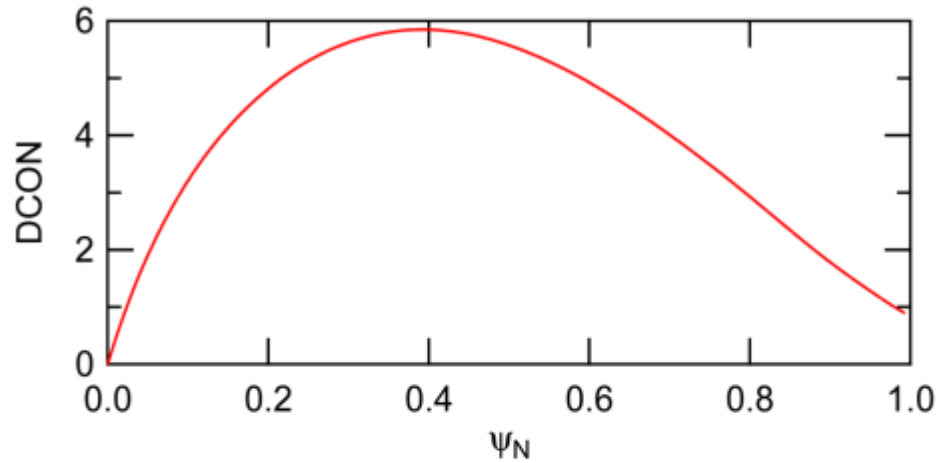
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# Stability Analysis Confirms Peeling Instability

- Analytic peeling criterion computed from Hall-constrained equilibrium indicates instability
  - More than factor of two in region of optimal $\langle J \cdot \nabla \phi \rangle$ constraint
- Free-boundary ideal stability analysis performed with DCON
  - Indicates instability to m/n = 19/1 external kink
- Both methods agree with experiment




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

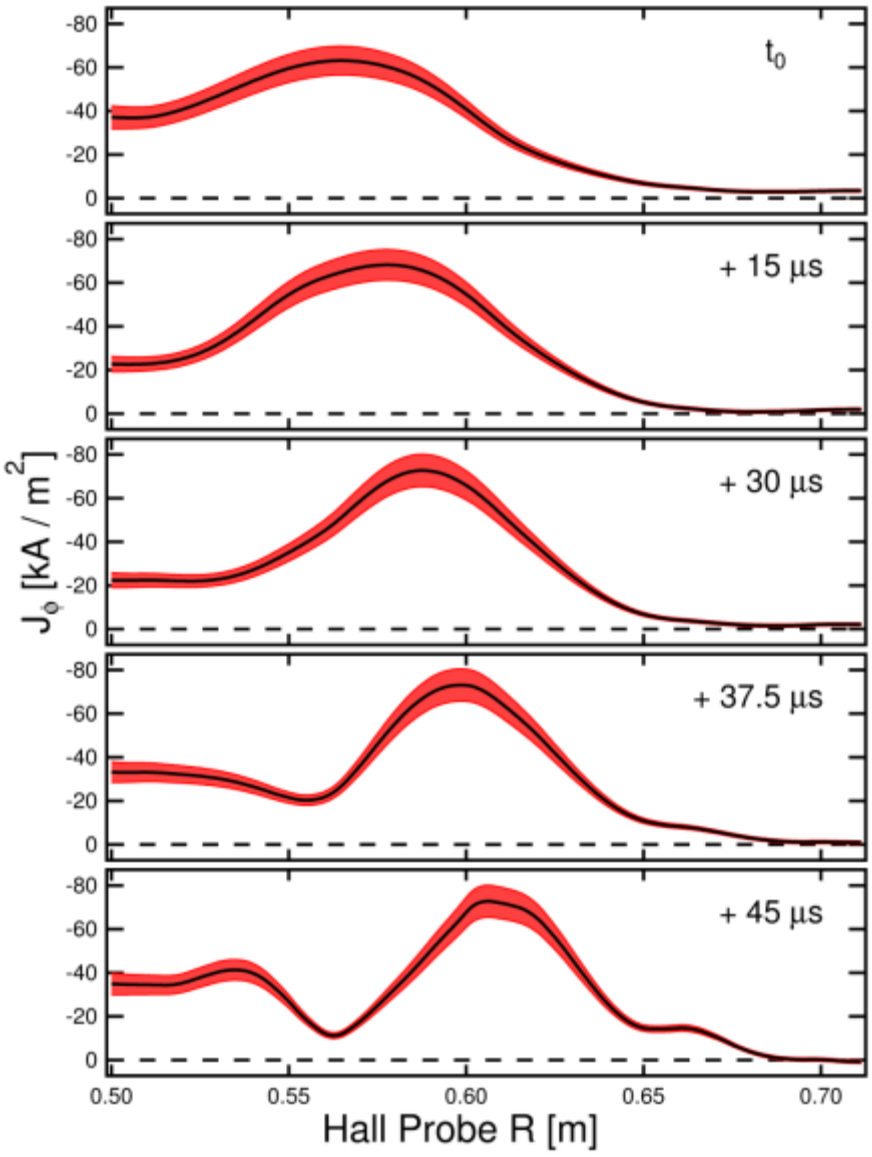





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# $J_{edge}$ Dynamics Measured on ELM Timescales

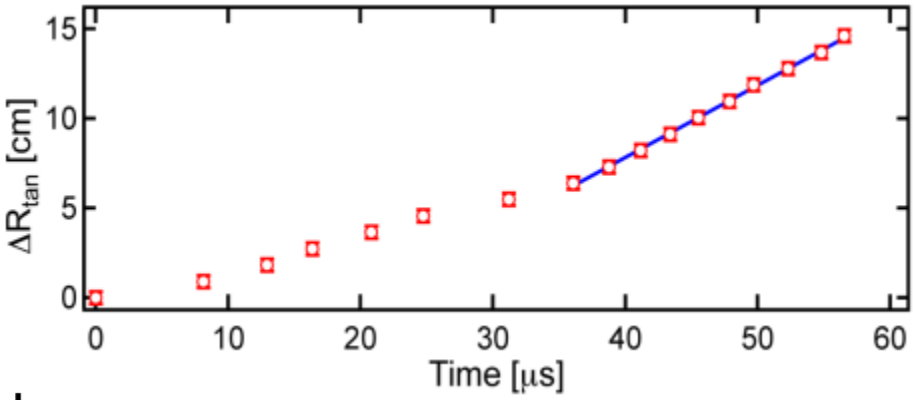
- $J_{edge}$ resolved during peeling filament generation
- Propagating filament forms from initial "current-hole" $J_{edge}$ perturbation
  - Validates formation mechanism hypothesized by EM blob transport theory
- Filament carries toroidal current $I_f$ ~ 100–220 A
  - Comparable to MAST ELM estimates
  - $I_f < 0.2$ % of $I_p$




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

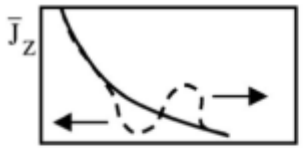
# Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

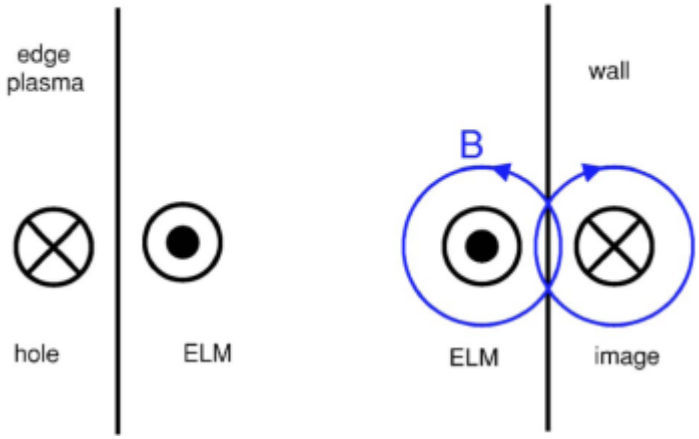
- Trajectory of detached filament tracked with 275 kHz imaging
  - Radially accelerates, followed by constant velocity motion




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

- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole $\boldsymbol{J}\times\boldsymbol{B}$ drives $aR$
  - Transition at ~ 35 μs comparable to healing time of current-hole




- Measured $VR$ comparable to available EM blob models**
  - $VR \sim 4$ km/s; $VR,IB \sim 8$ km/s
  - Agrees to O(1) accuracy of theory

*: Myra, Phys. Plasmas **14**, 102314 (2007)

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



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# Peeling Mode / ELM Conclusions

- Direct measurements of $J_{edge}$ conducted with Hall probe
  - Direct analysis, equilibrium reconstruction
  - $J_{edge}$ controllable with $dI_p/dt$
- Characteristics of Peeling Modes Consistent with Theory
  - Macroscopic features: Low-n, high-m external kink
  - Onset consistent with ideal MHD, analytic peeling stability theories
  - Observed MHD scales with measured J/B peeling drive
  - Coherent, propagating filaments
- $J_{edge}$ dynamics supports current-hole & EM blob hypotheses
  - Nonlinear filaments generated from current-hole $J_{edge}$ perturbation
  - Transient magnetostatic repulsion
  - Constant-$V_R$ propagation in agreement with available EM blob theory



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# HI Conclusion: High-$I_p$ Non-Solenoidal Startup via Point-Source Helicity Injection Looks Promising

- Significant progress with non-solenoidal startup of ST
  - $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
    - So far, predicted scalings supported
  - Goal $\approx$ 0.3-0.4 MA non-solenoidal $I_p$ to extrapolate to next level/NSTX
    - Outstanding physics questions: $\lambda_{edge}$, $Z_{inj}$, confinement, *etc.*
  - Deploying plasma diagnostics to better understand properties
- Exploration of high $I_N$, $\beta_t$ space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high $I_p$, $n_e$ for high $\beta_t$
- Holds Promise as a Scalable Non-Inductive Startup Technique
  - Simpler injection system using plasma gun – passive electrode combination may be feasible



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