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

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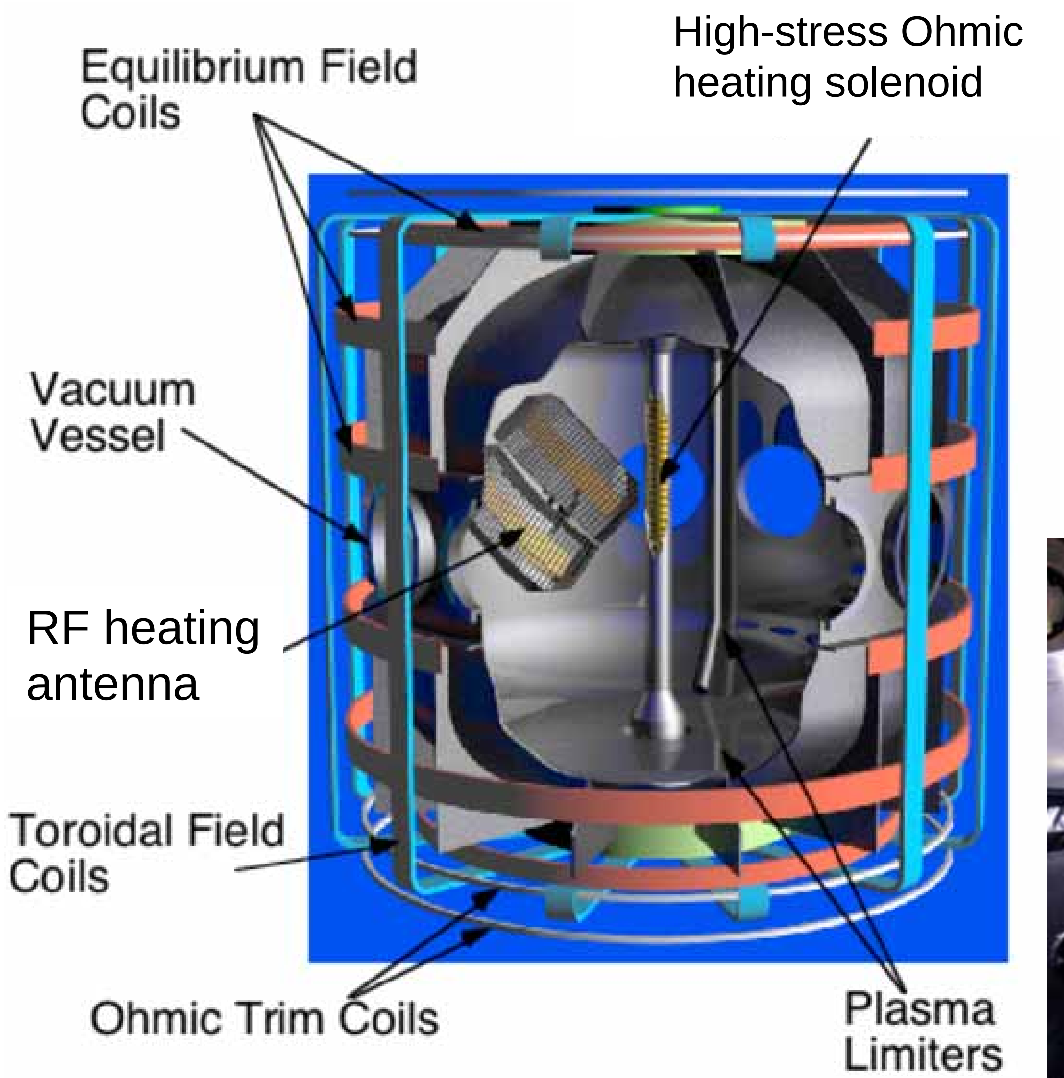
University of Wisconsin-Madison

PEGASUS Toroidal Experiment

PEGASUS is a Compact Ultralow-A ST

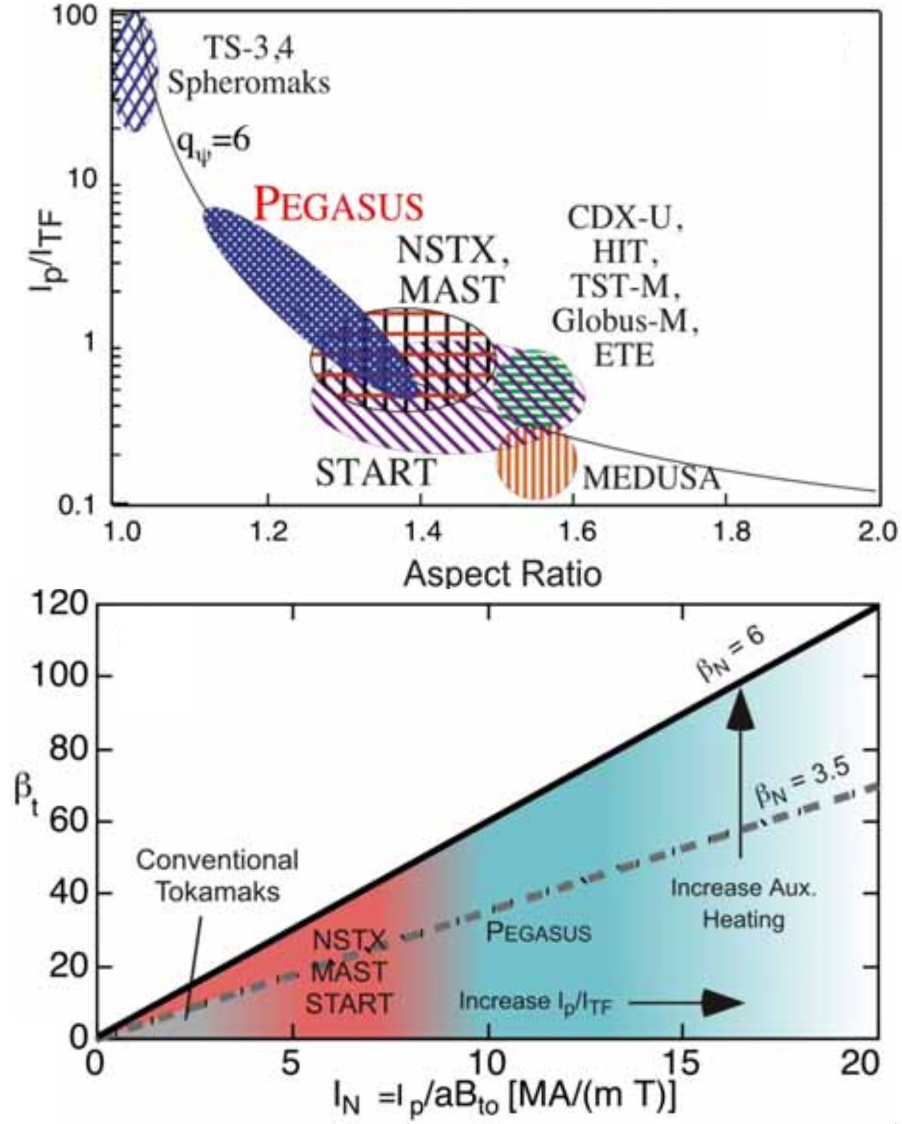


Experimental Parameters

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

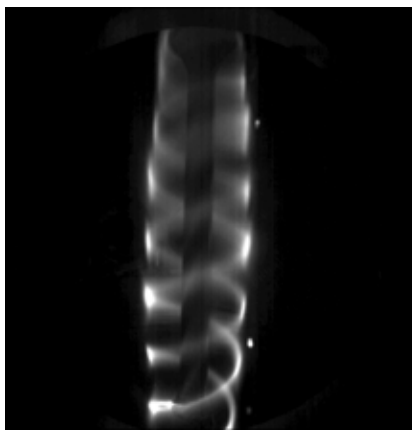
PEGASUS Mission: Physics of Low A → 1

- 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 β_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)



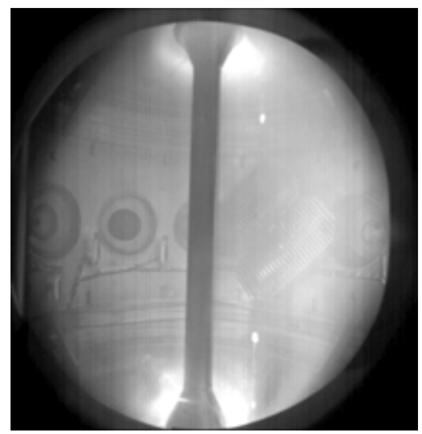
Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- 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_θ overwhelms vacuum B_z
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication



Current filaments

Reduced B_z



Relaxed tokamak

- Technical attractiveness: can remove sources and anode after startup

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

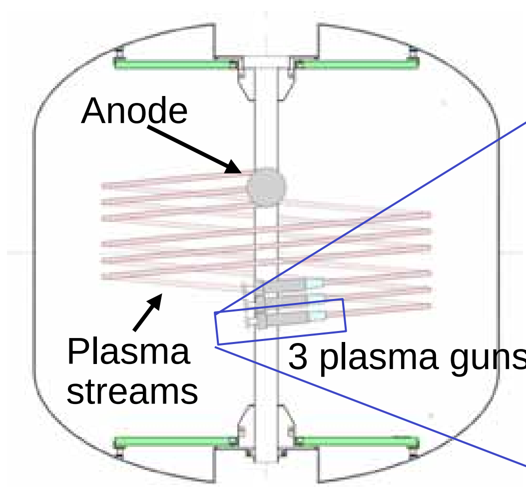
- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

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

V_{inj} - injector voltage

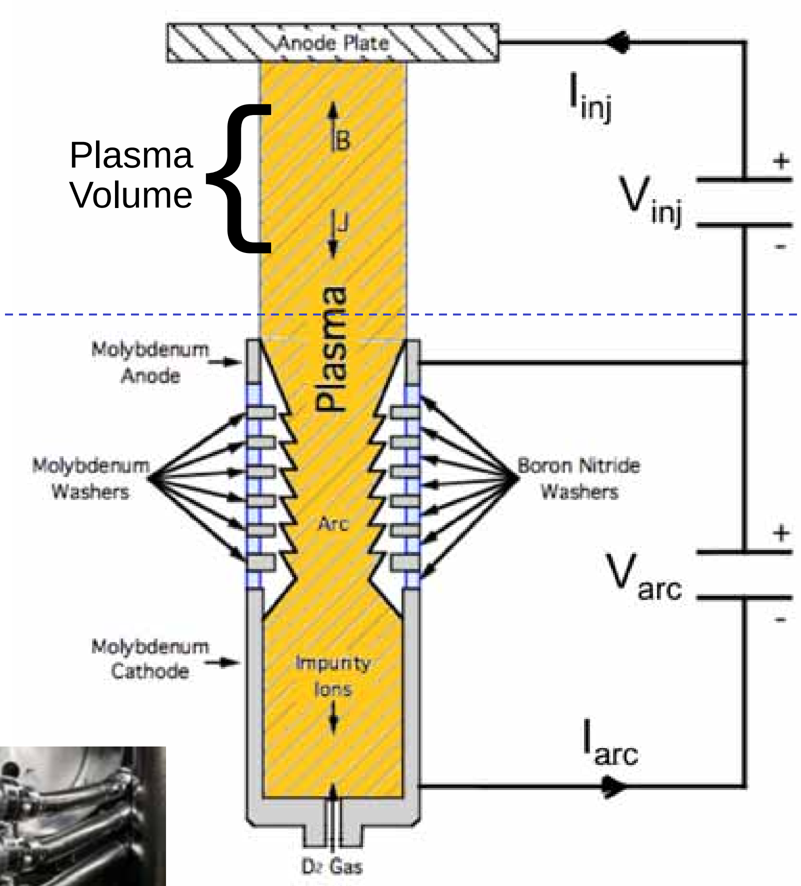
B_N - normal B field at gun aperture

A_{inj} - injector area



Midplane Injection

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



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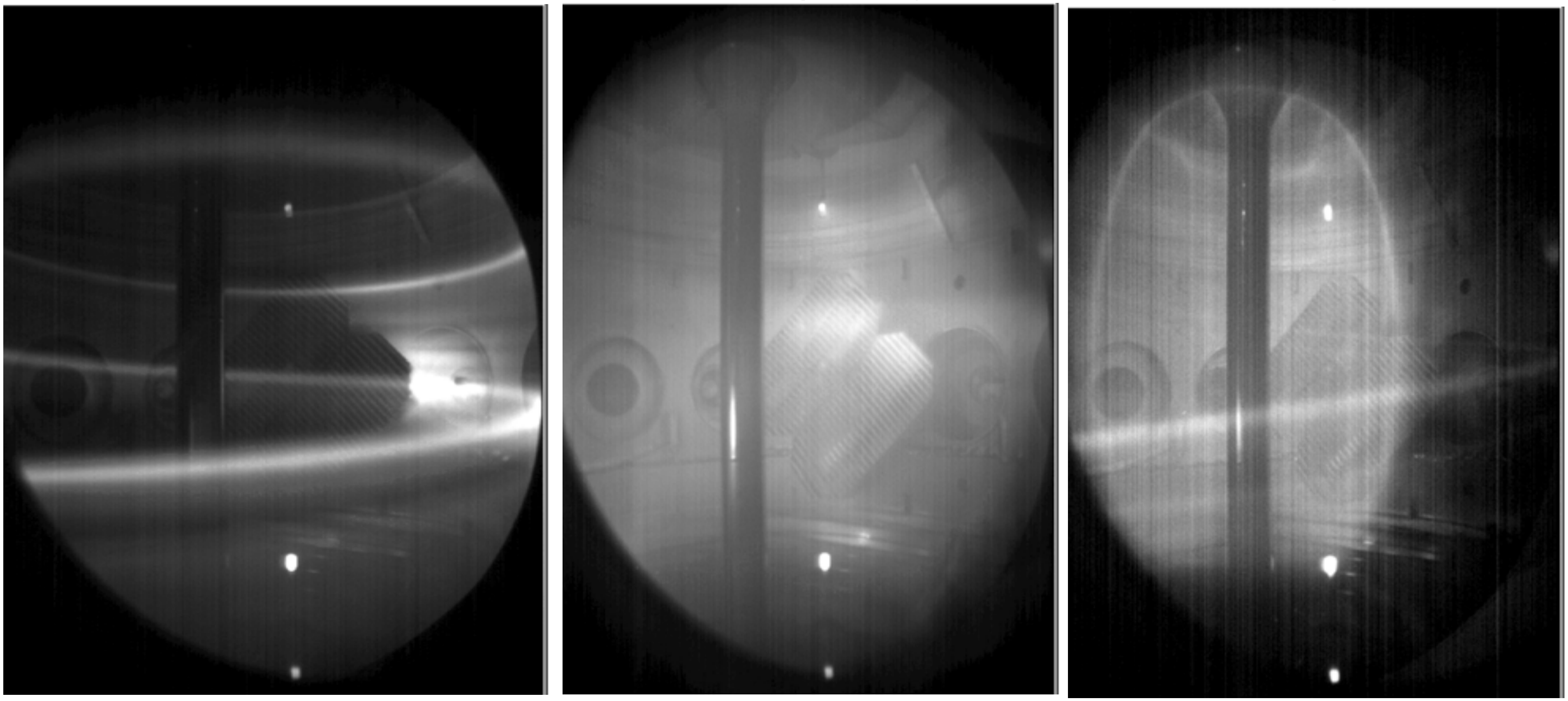
Evolution of midplane-gun-driven plasma

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

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

Helicity balance in a tokamak geometry:

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

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

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

Taylor relaxation of a force-free equilibrium:

$$\nabla\times B = \mu_0 J = \lambda B$$

$$\lambda_p \le \lambda_{edge}$$

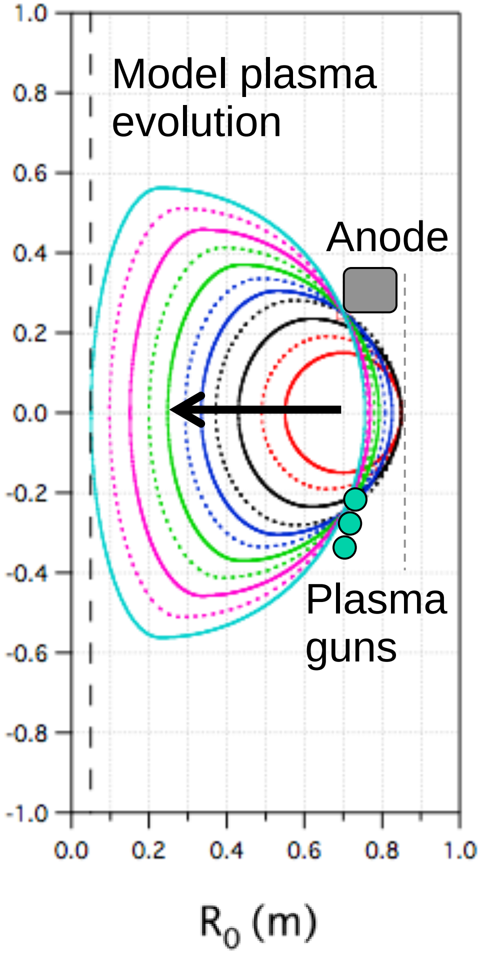
$$\Longrightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Longrightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

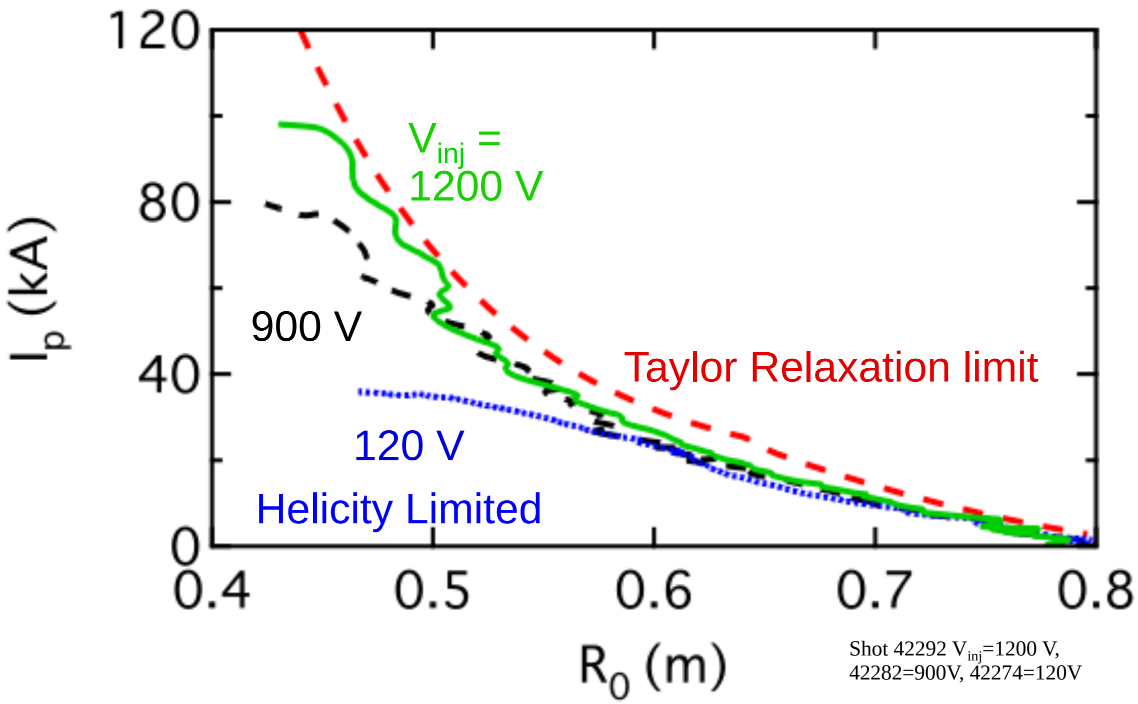
Assumptions:

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

A_p	Plasma area
C_p	Plasma circumference
Ψ_T	Plasma toroidal flux
w	Edge current channel width

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





Shot 42292 V_{inj}=1200 V, 42282=900V, 42274=120V

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

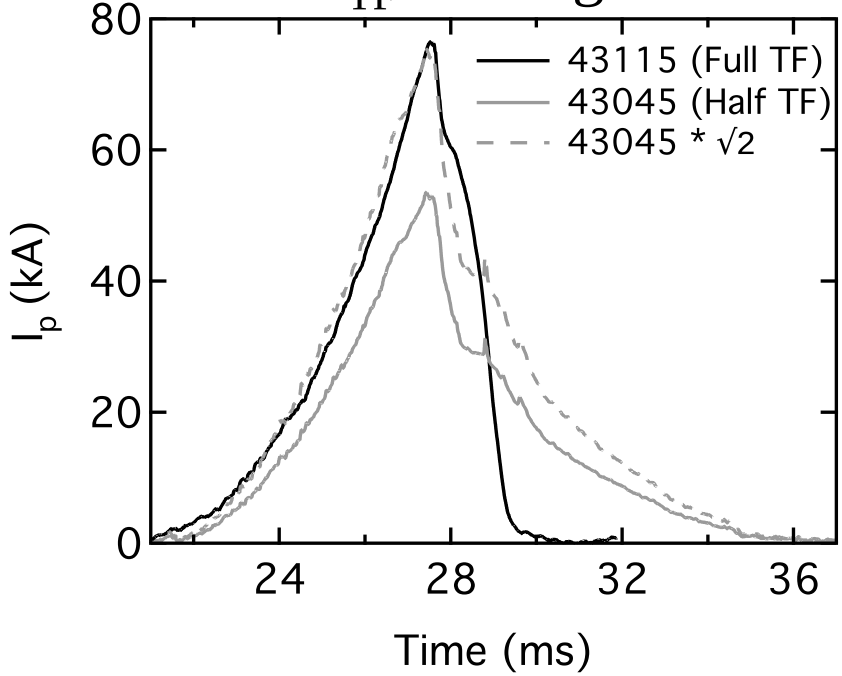
Experiments Confirm Relaxation Limit Scalings with I_{TF} and I_{inj}

- The relaxation limit I_p scales with:

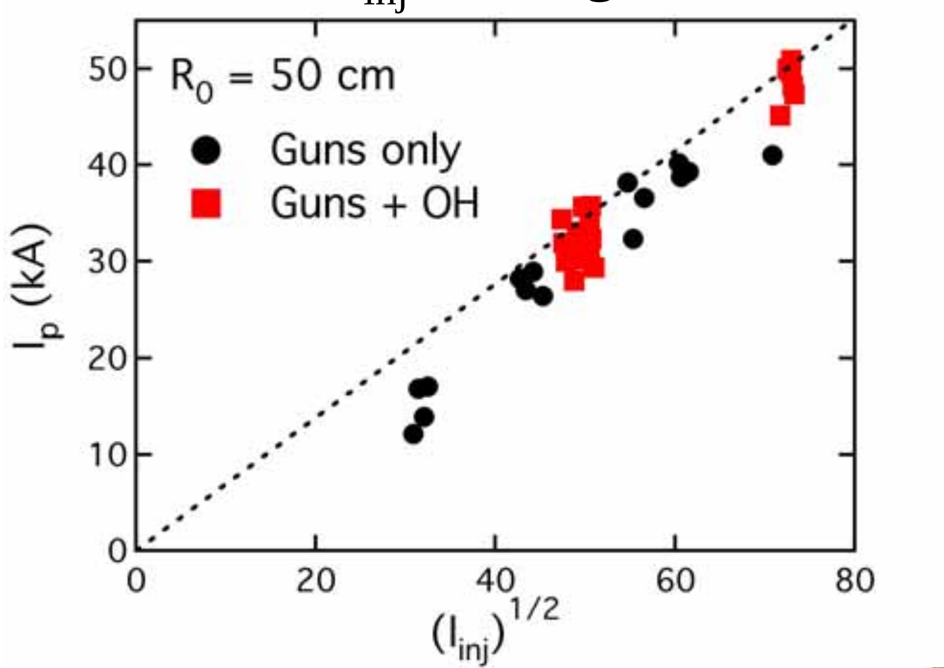
$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$

- Experimental plasma current limits follow these scalings:

I_{TF} Scaling:



I_{inj} Scaling:



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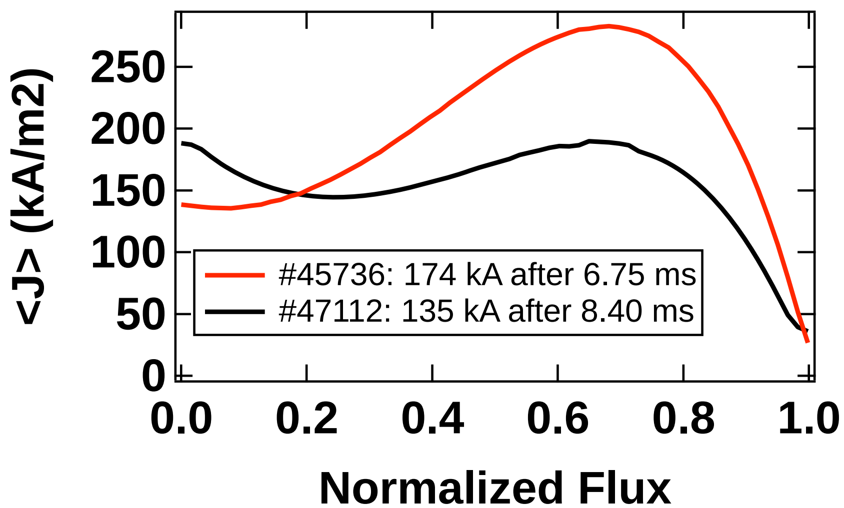
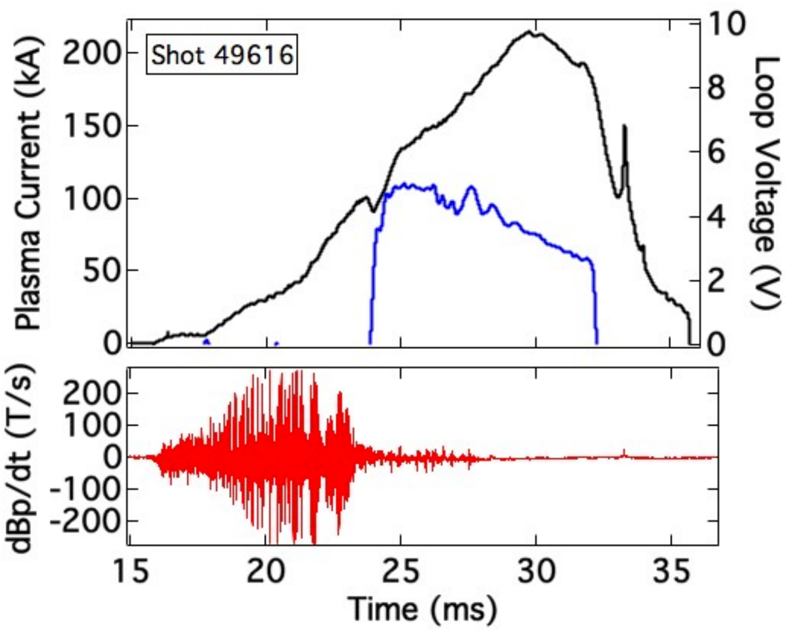
Slowly-evolving Gun-driven Plasmas Hand Off Most Efficiently to Ohmic Drive

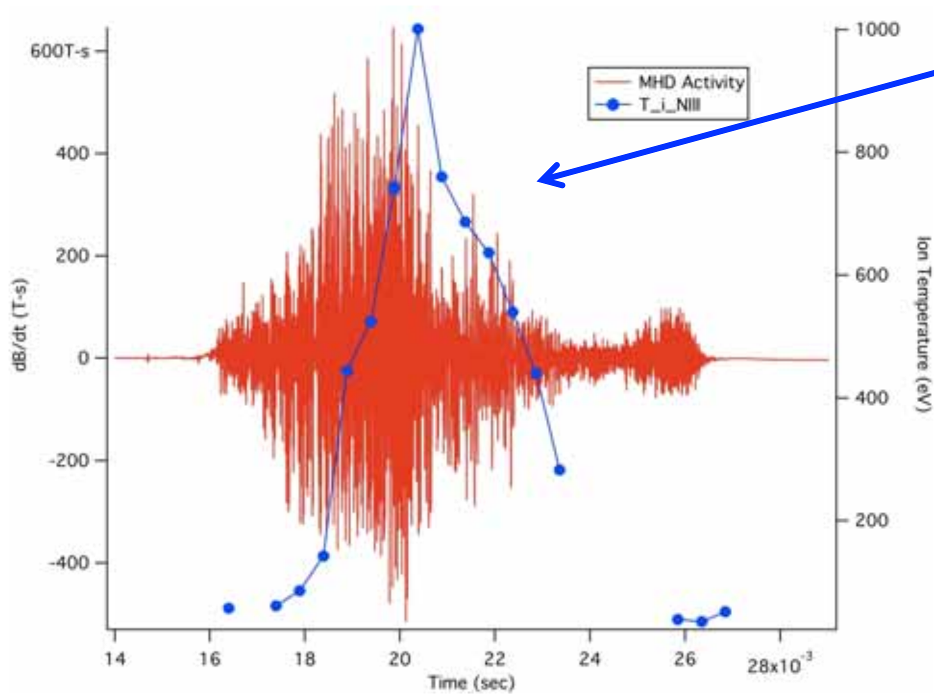
- Poloidal flux generated by helicity injection is equivalent to that generated by Ohmic Drive
  - $I_{total} = I_{HI} + I_{OH}$
- Excessive skin current => poor coupling to OH drive
- Slowly evolving: ~ flat j(r) (black)
  - Smooth handoff to Ohmic inductive drive (j(R) profiles from external-only equilibrium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





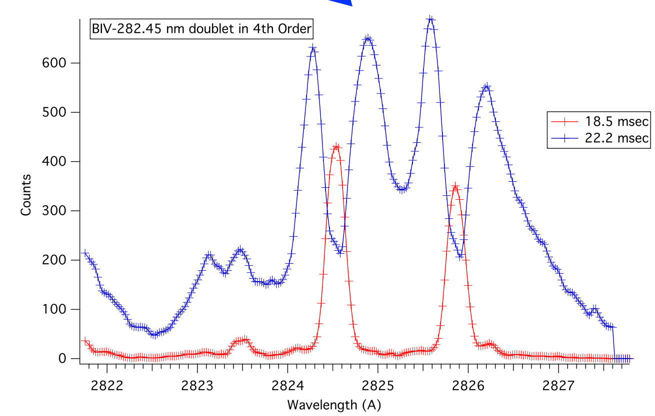
Initial Spectroscopy Measurements Suggest Energetic Ions

- Spectroscopic T_i suggest high ion energies during reconnection period



Doppler T_i from radial view

Complex multi-line structures from tangential view



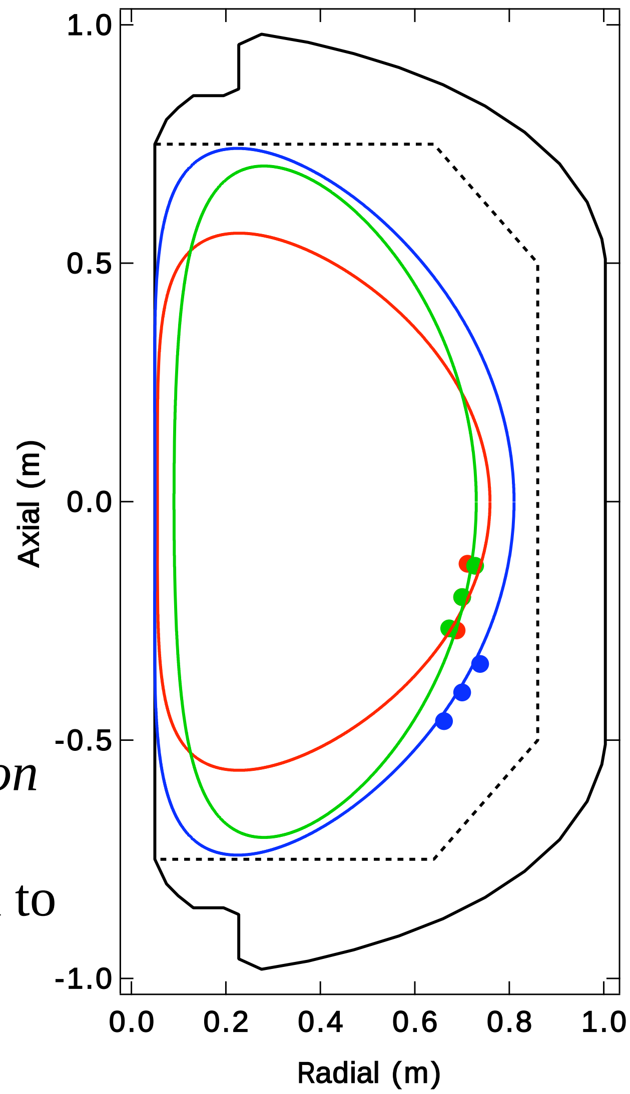
- However, situation is much more complex if viewed toroidally
  - Need improved time-resolution and spatial scans

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

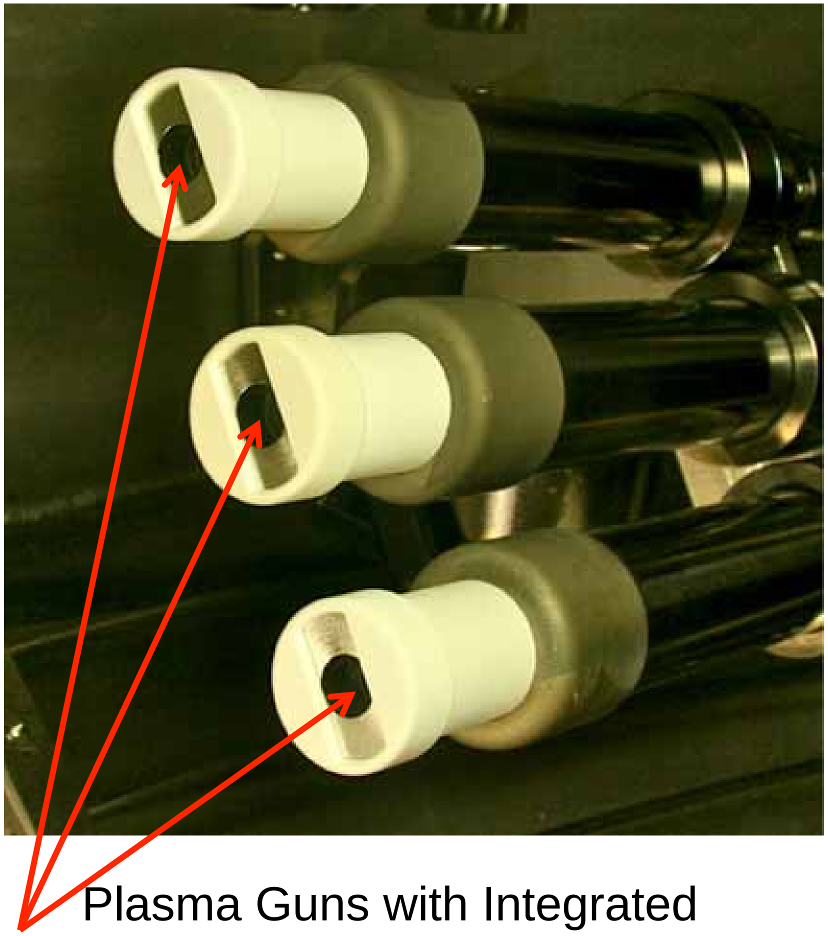
Gun-Electrode Geometry: PF Induction, Plasma Size, and Null Formation

- 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



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

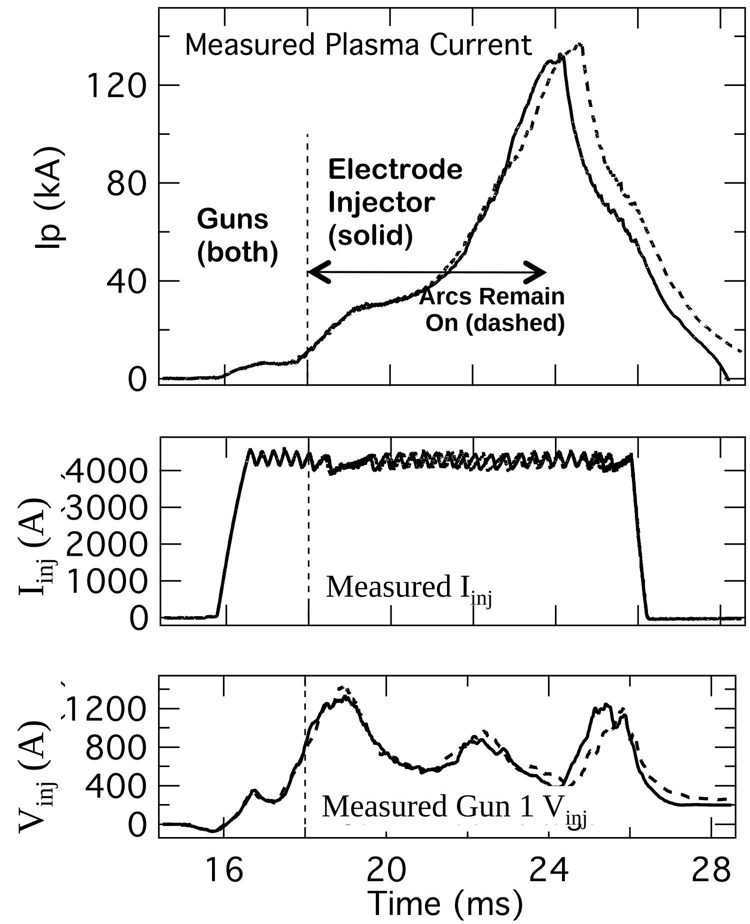
- Potential for much higher I_{inj} without need for either more plasma guns or larger guns.
- Helicity injection physics is agnostic to the exact source of the edge charge carriers.
- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) *and*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



Plasma Guns with Integrated Slotted Electrodes

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.

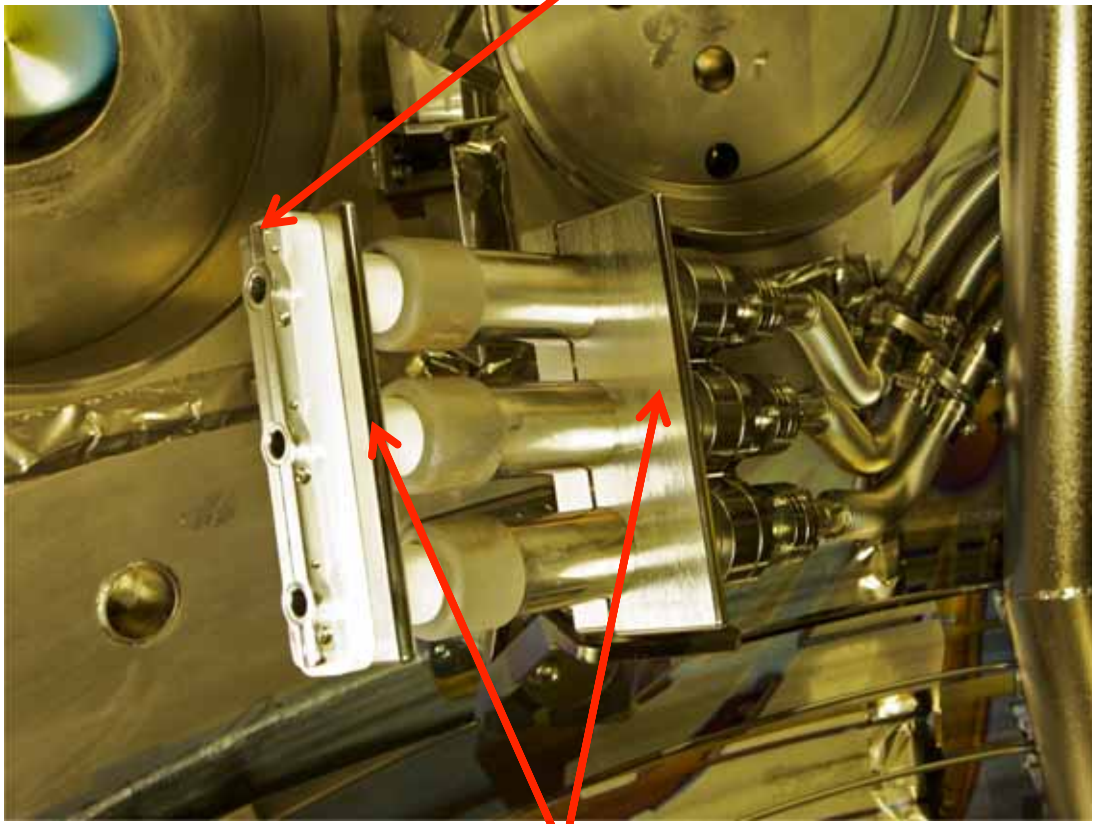


- First tests are promising
  - Arc current off after relaxation and formation of tokamak-like state
  - I_p rise is virtually the *same*, whether arc discharge or passive electrode provide the charge carriers

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

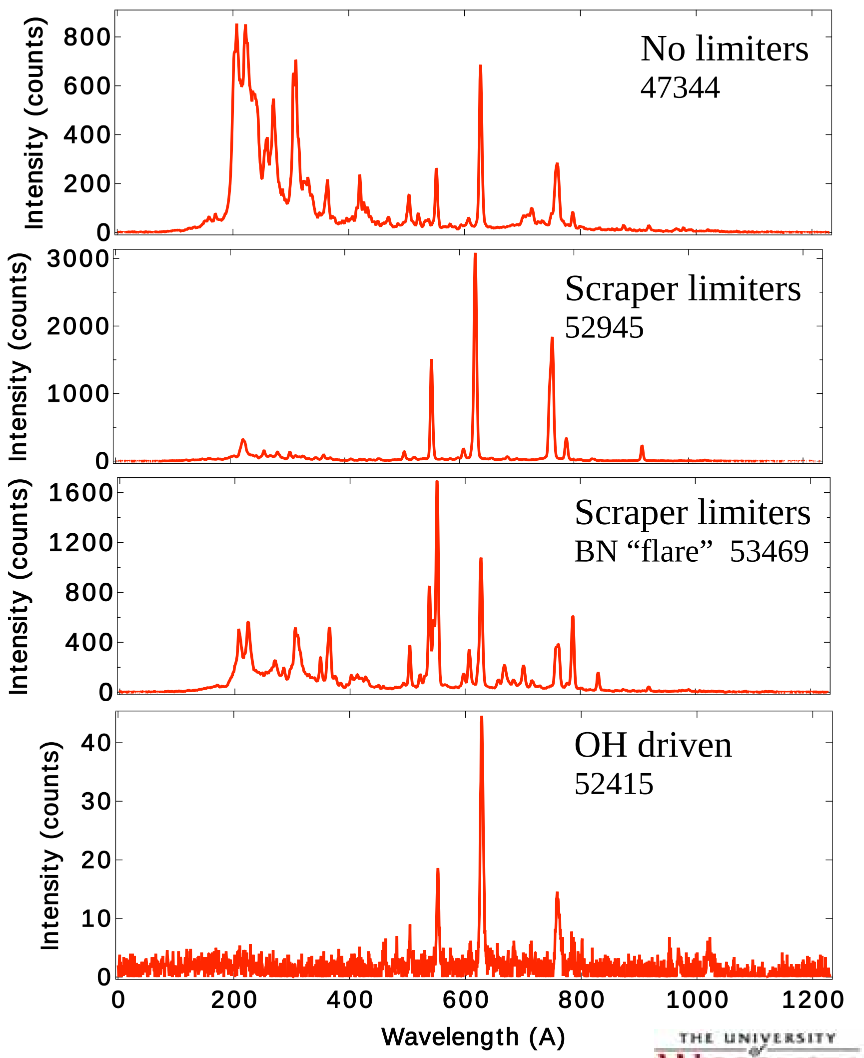
- Integrated scraper limiters to protect assembly and control local edge density
  - Gas-puff control of $V_{bias} \sim V_{loop,\ effective}$



Local limiters

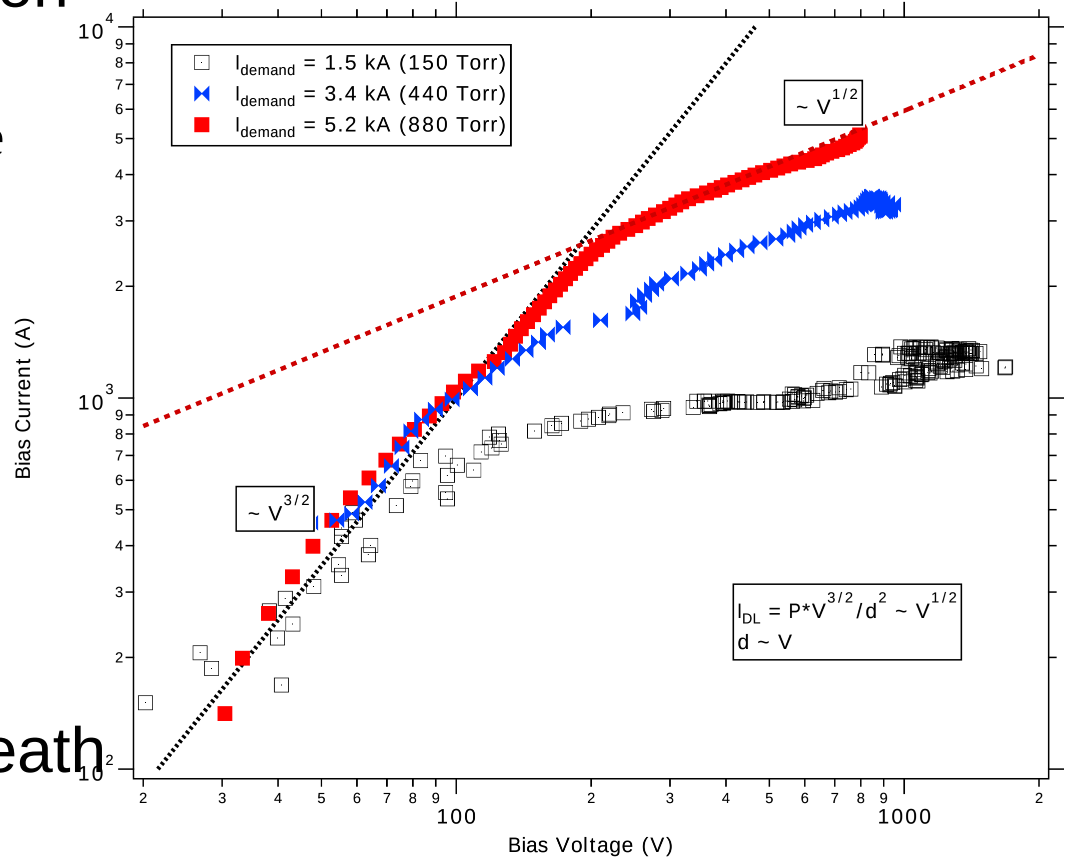
Local Limiters Reduce N to Negligible Levels in Well-behaved Injection Cases

- N dominant impurity with unprotected gun assembly
  - 1st *estimates* of impurity content via bolometer measures
    - Z_{eff} ~ 2.2. +/- 0.8 during injection; ≤ 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



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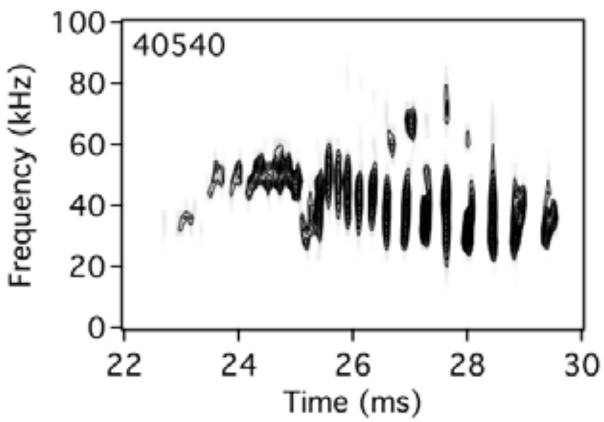
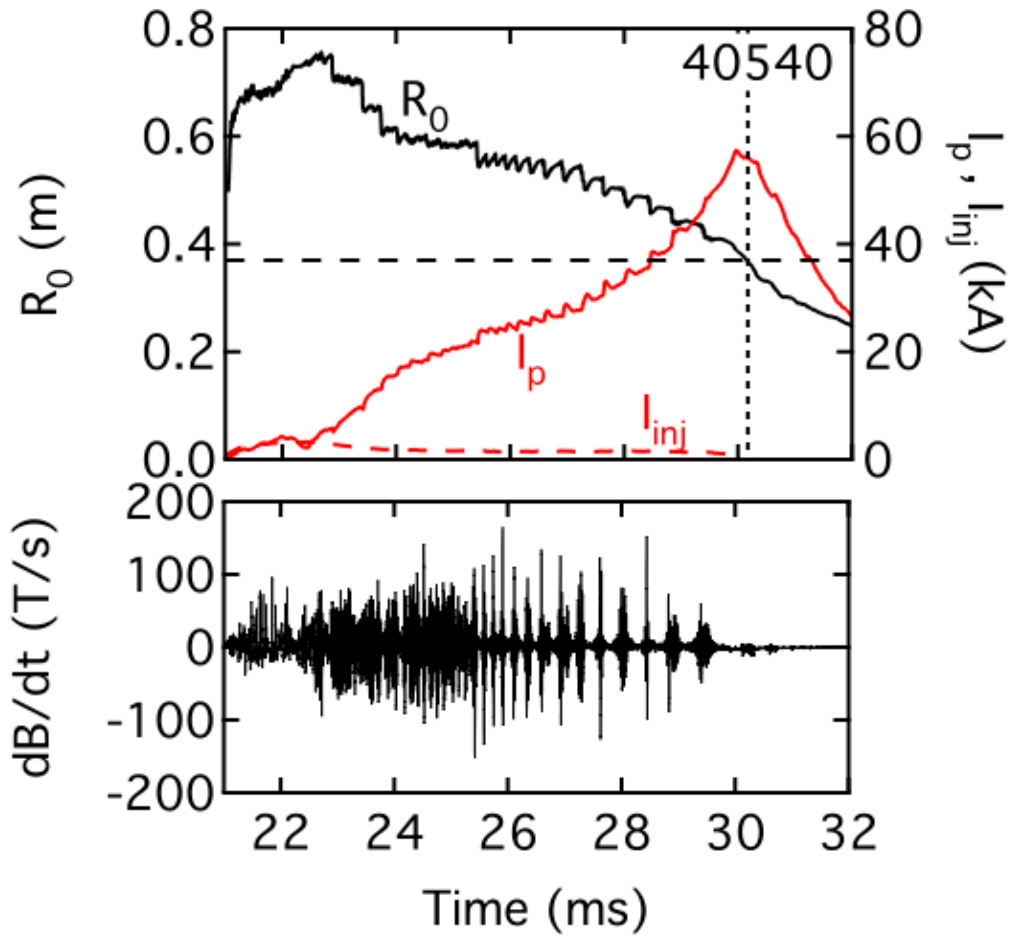
Intermittent 20 - 60 kHz n = 1 mode observed with strong edge current drive

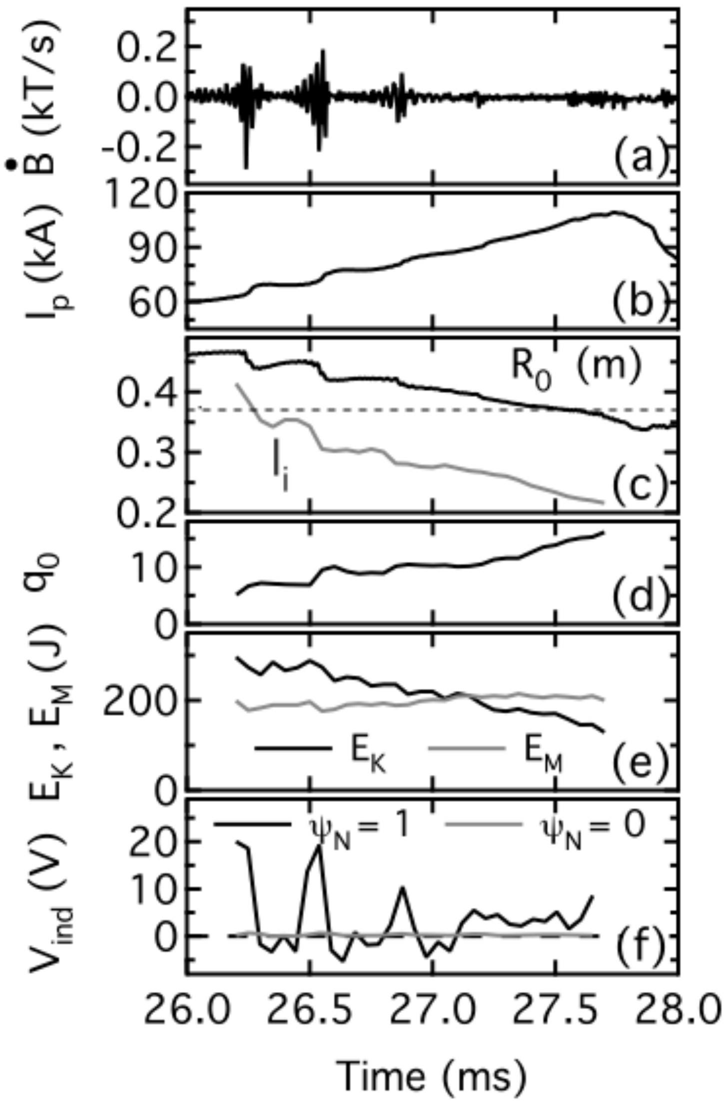
- Bursts of $n = 1$ magnetic oscillations
  - Observed when plasma is coupled to edge current drive
  - Different in nature from inboard current injection experiments





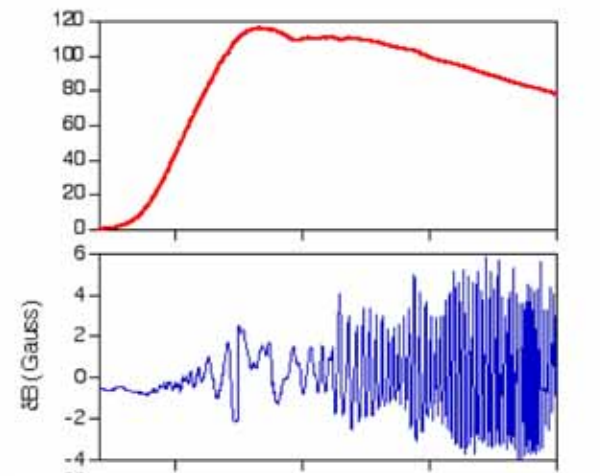
The magnetic topology quickly changes with each burst of MHD activity

- Each burst typically ~ 0.1 ms
- With each burst…
  - l_i decreases → I_p increases
  - R_0 decreases → plasma expands
  - $B_{\phi 0}$ increases → q_0 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

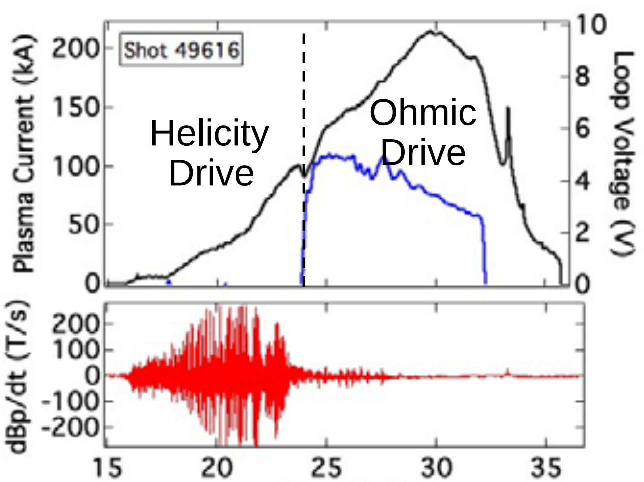


Current Drive Tools Providing Access to High Field Utilization Regime

OH only = large 2/1 modes limit I_p



HI startup = MHD quiescent



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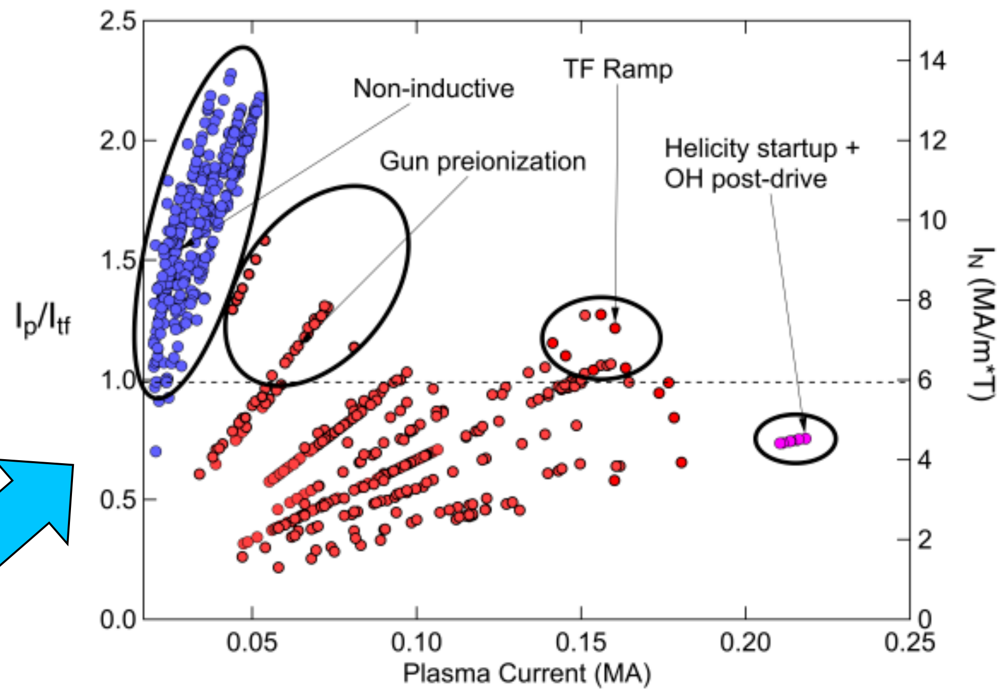
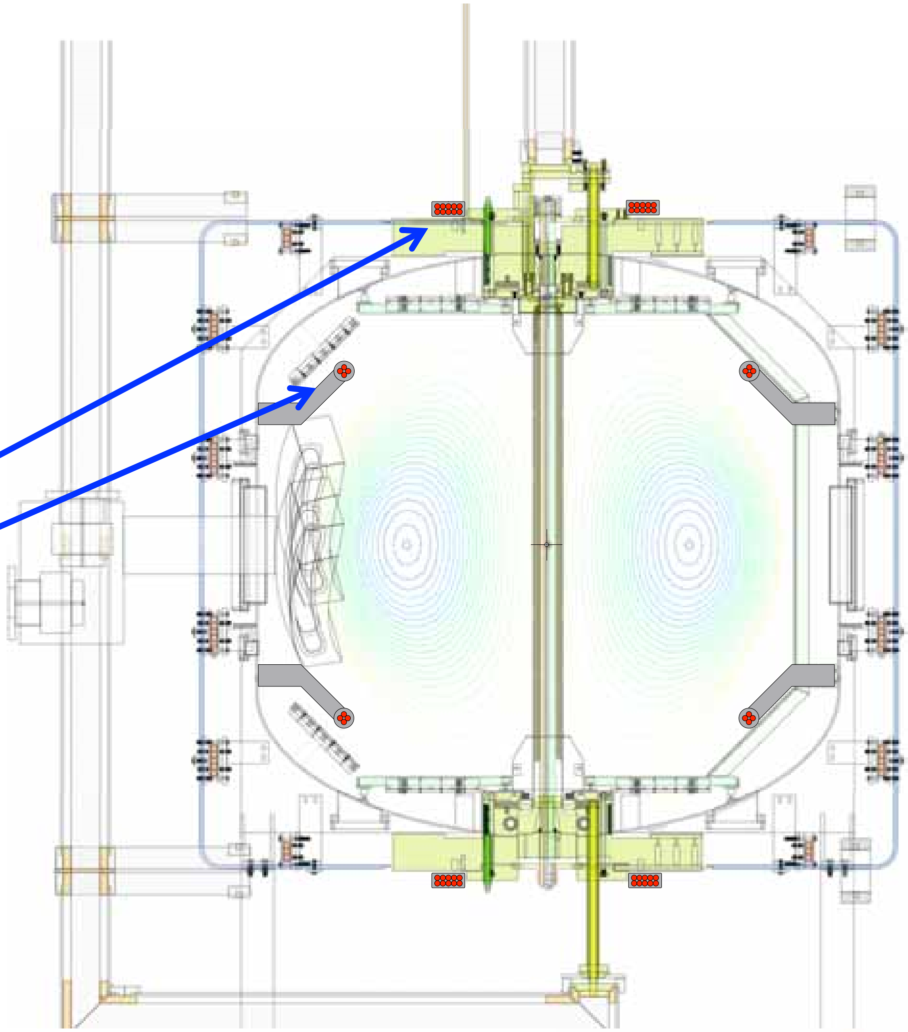


- Helicity injection startup and Ohmic sustainment provides MHD-stable profiles at $I_p/I_{TF} < 1$
- Need to extend to higher I_p, then to low I_{TF} for high I_N and high β_T as $A \approx 1$

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

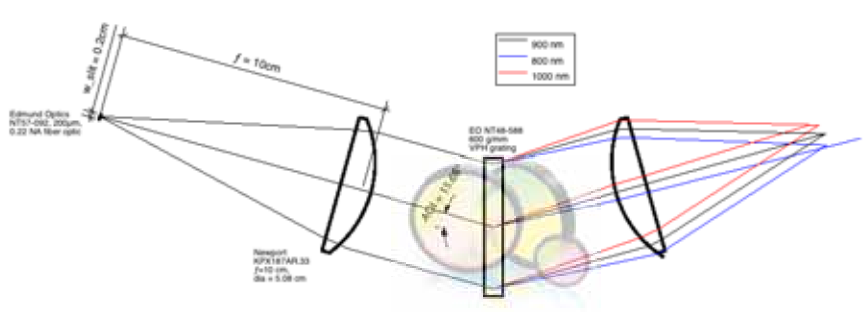
- Gun-electrode Evolution
  - Passive electrode material variations
    - C electrode being installed
  - Separate plasma gun and electrode
- Power Supplies, Heating
  - New helicity injection power: *2 kV, 15 kA*
  - Double TF current: *Taylor limit increase*
  - Commission HHFW system: *electron heating*
- 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*



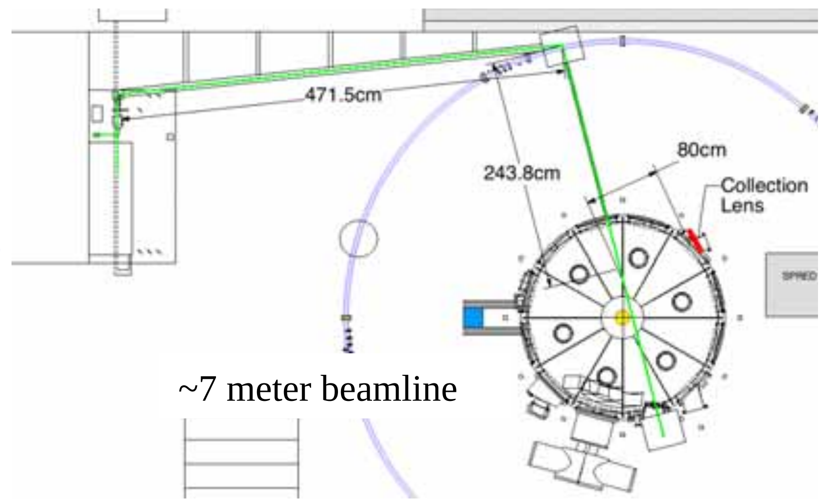
Thomson Scattering system uses new technologies for visible wavelength system

- Frequency doubled Nd:YAG laser provides ~10^{18} photons
- For typical PEGASUS plasma, $n_{scattered}$ ~ 10^4 photons
- VPH grating efficiency >85% for λ_{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



~7 meter beamline

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

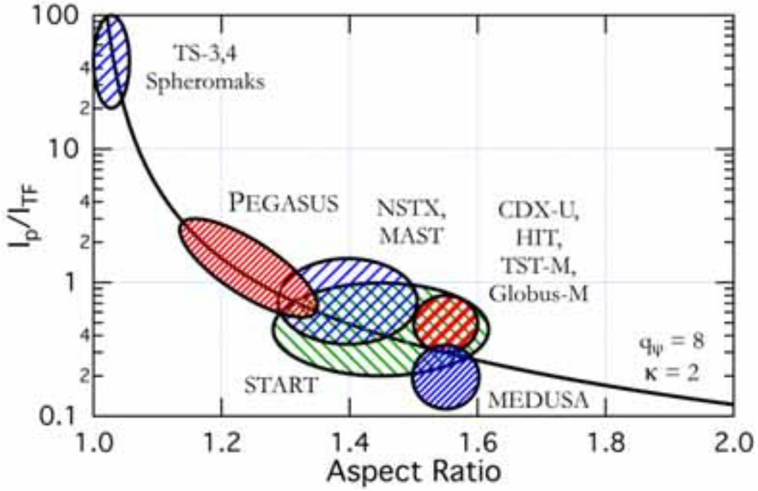
- Significant progress with non-solenoidal startup of ST
  - $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
    - So far, predicted scalings supported
  - Goal ≈ 0.3-0.4 MA non-solenoidal I_p to extrapolate to next level/NSTX
    - Outstanding physics questions: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Deploying plasma diagnostics to better understand properties

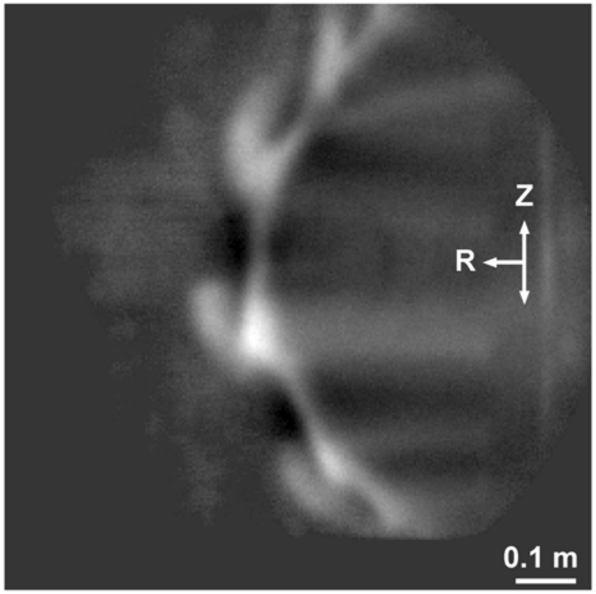
- Exploration of high I_N, β_t space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high I_p, n_e for high β_t

- Holds Promise as a Scalable Non-Inductive Startup Technique
  - Simpler injection system using plasma gun – passive electrode combination may be feasible

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

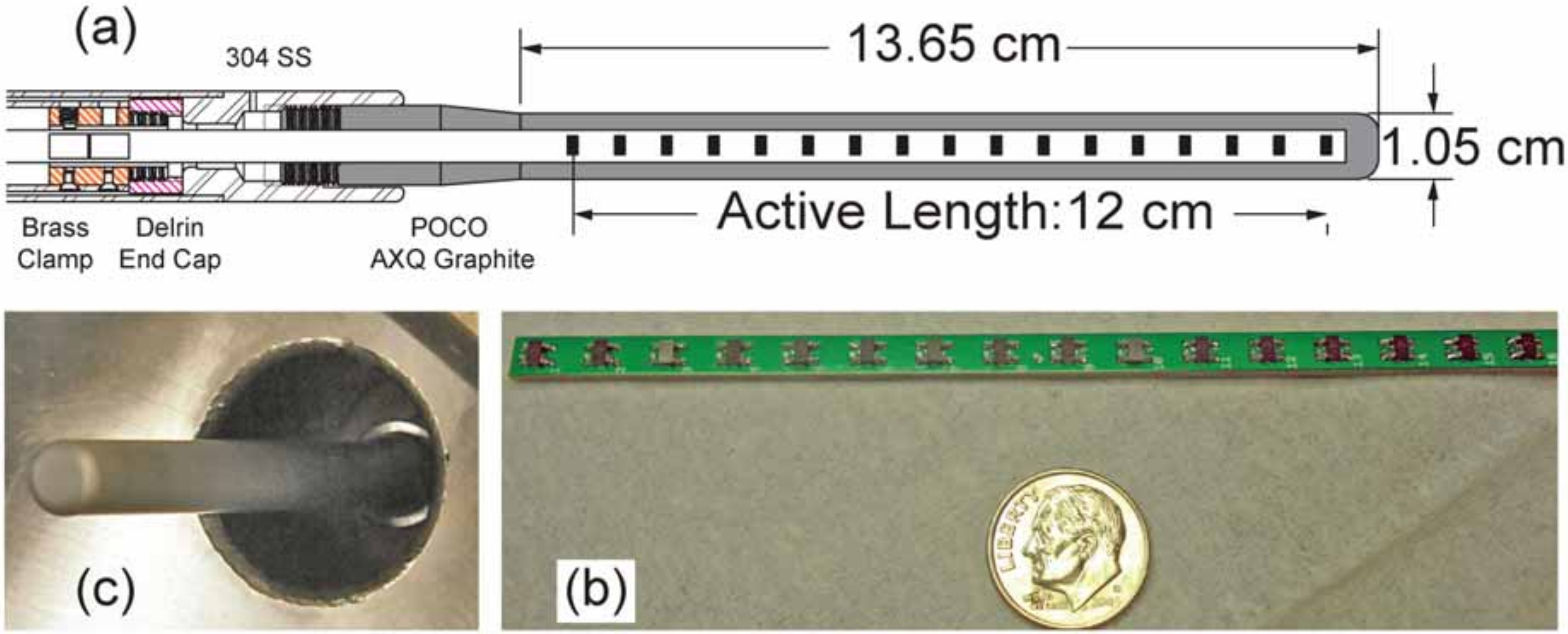
- Spherical tokamaks naturally provide strong peeling drive
  - Toroidal field utilization $I_p/I_{tf} \sim j_{||}/B$
- PEGASUS accesses peeling modes
  - Strong $j_{||}/B$ MA/m^2-T at
  - Comparable to DIII-D in H-mode
- Machine parameters permit internal edge measurements
  - Short pulse lengths (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





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

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:

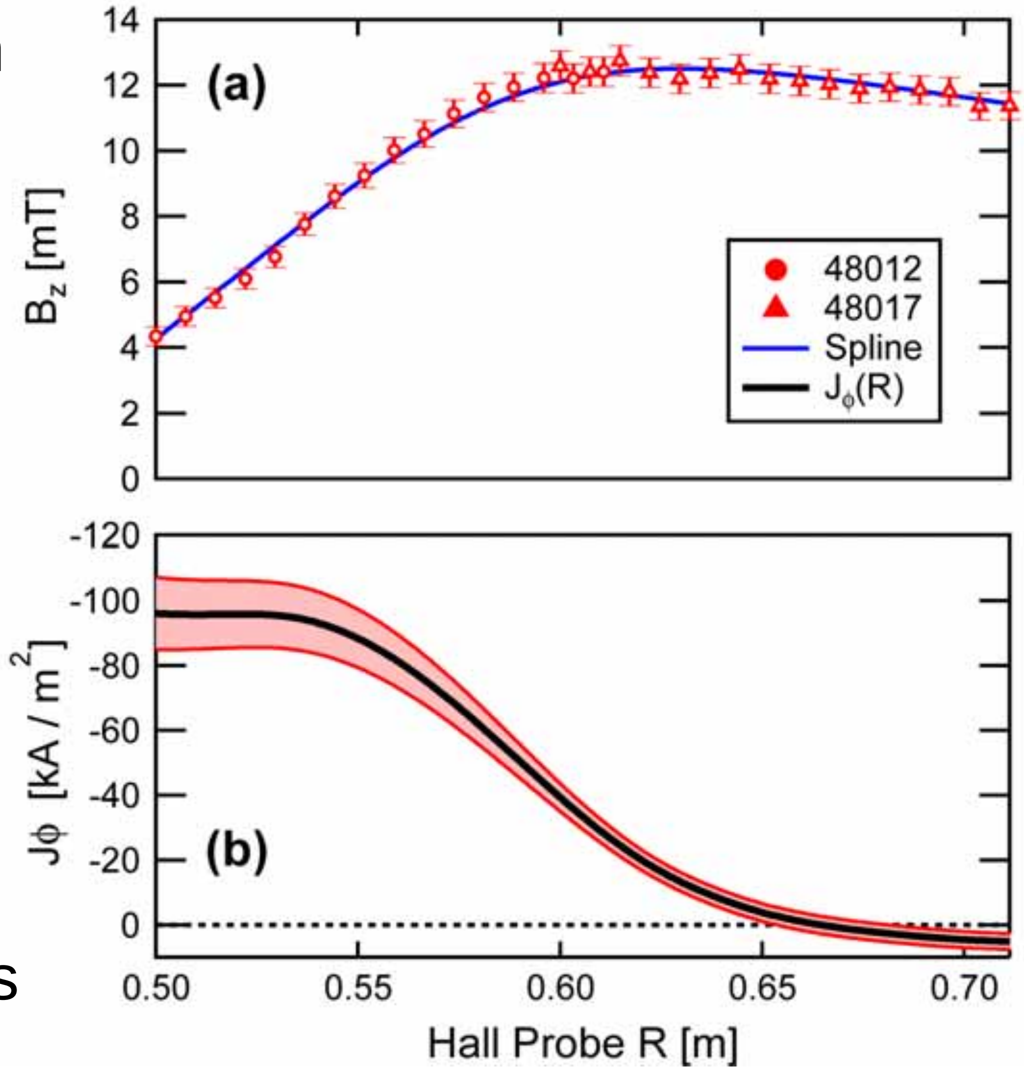
$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2}\right) - \frac{dB_Z}{dR} \left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2}\right)$$

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

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

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)

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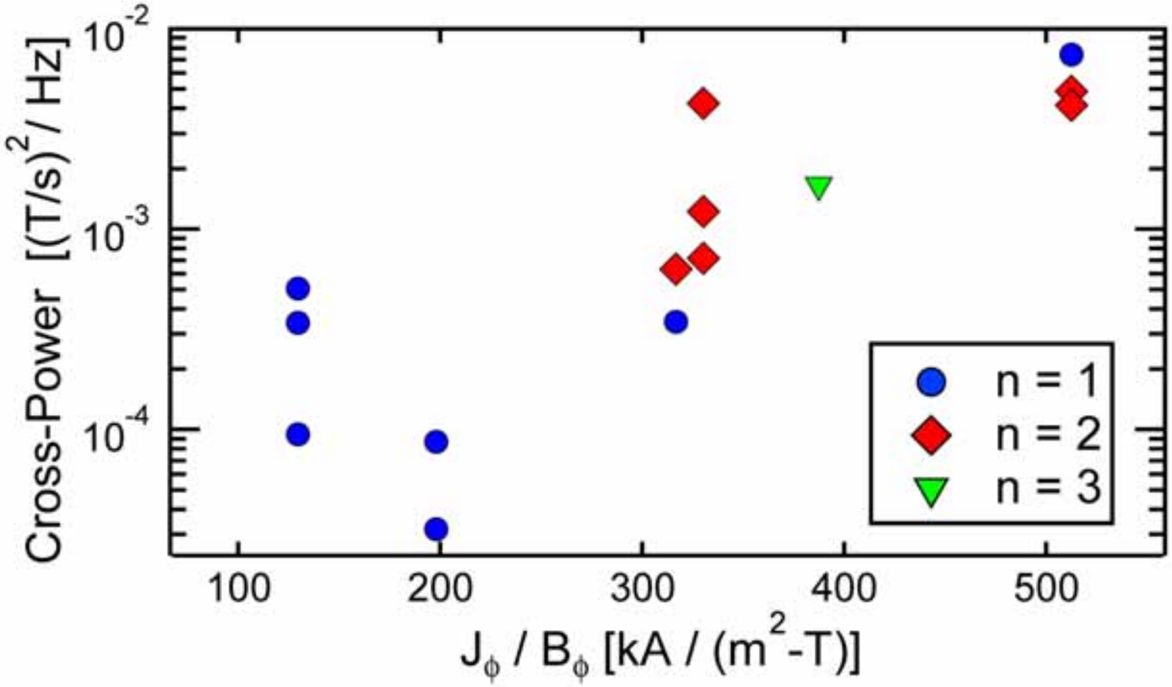
*: Reinsch, Numerische Mathematik **10**, 177 (1967)

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
  - $10 \leq m_{lab} / n \leq 30$ ($\psi_N > 0.9$)
- 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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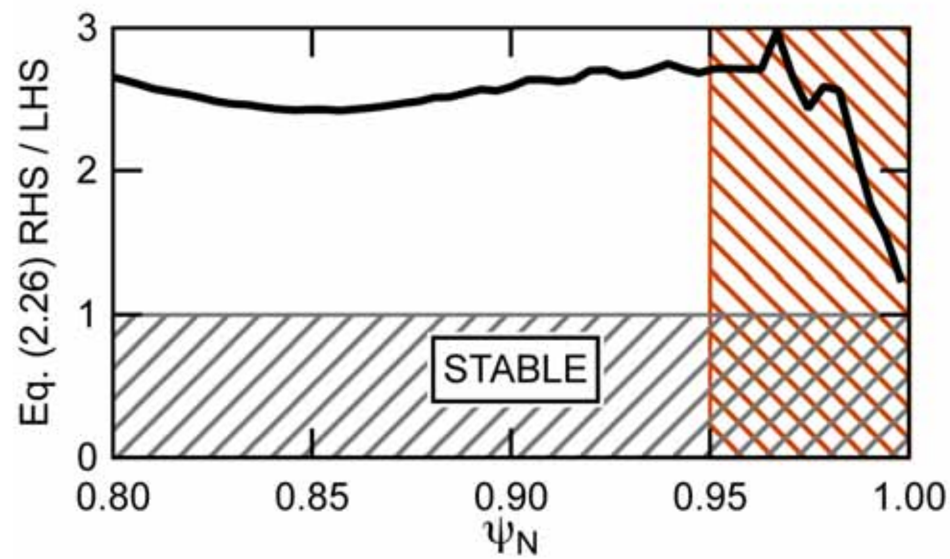
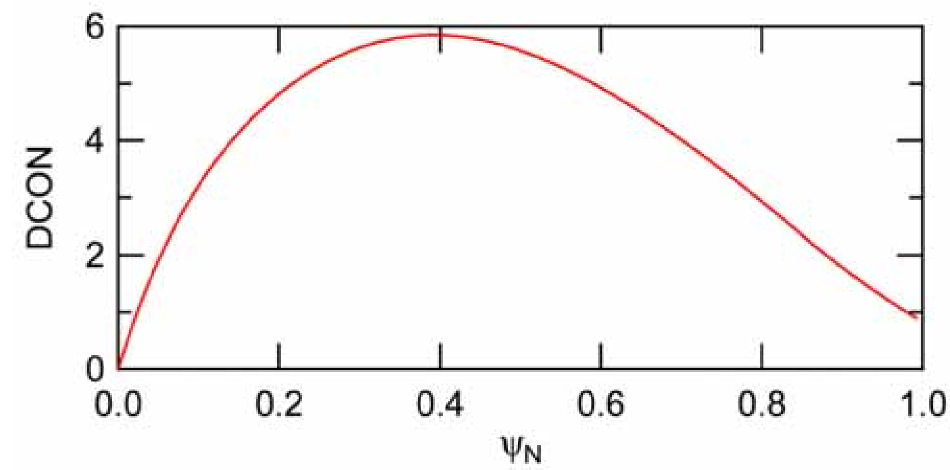
Stability Analysis Confirms Peeling Instability

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

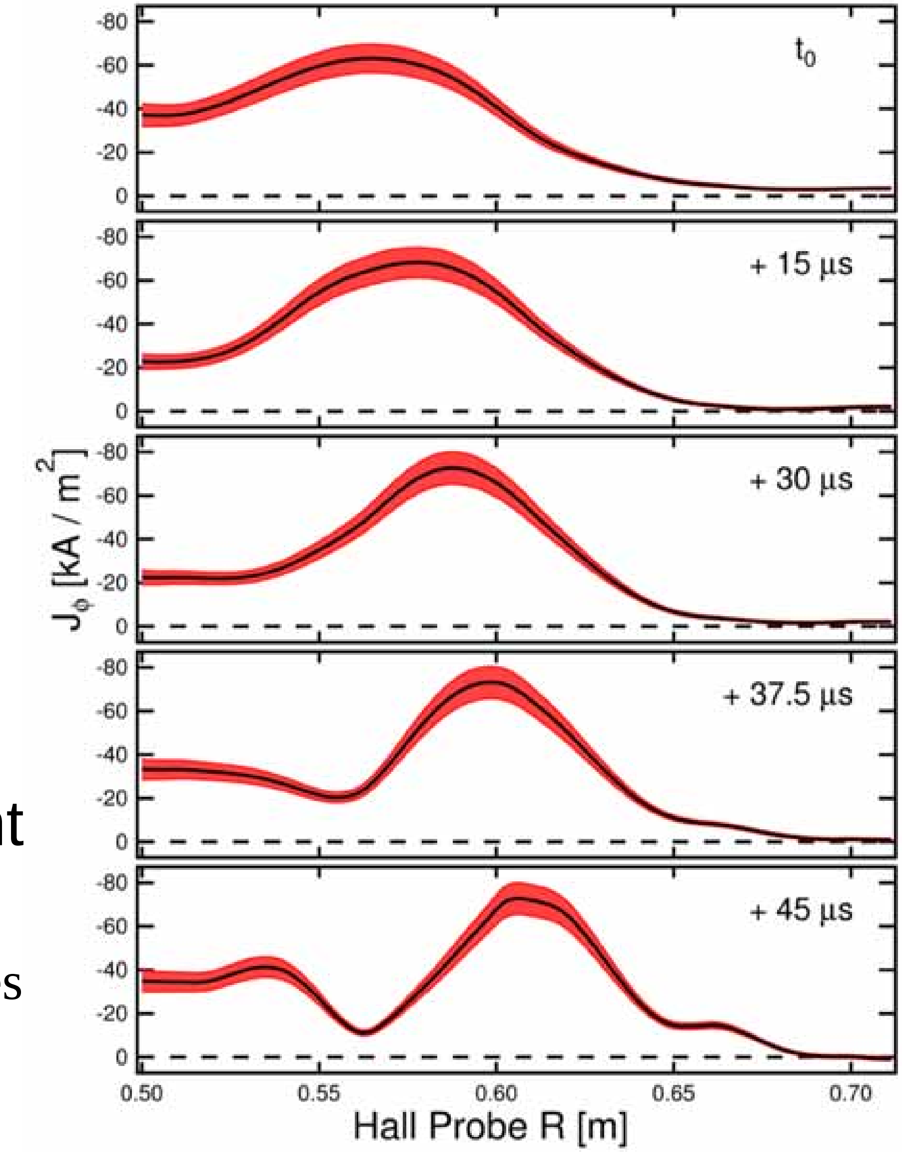


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



J_{edge} Dynamics Measured on ELM Timescales

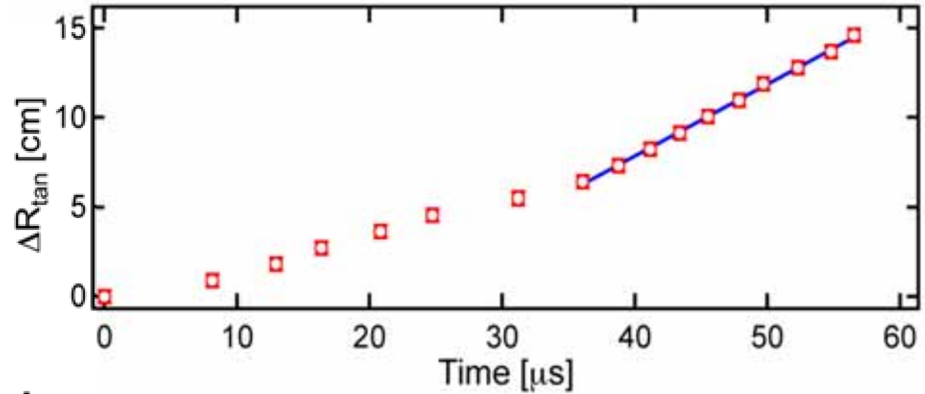
- J_{edge} resolved during peeling filament generation
- Propagating filament forms from initial "current-hole" J_{edge} perturbation
  – Validates formation mechanism hypothesized by EM blob transport theory
- Filament carries toroidal current $I_f \sim 100$–220 A
  – Comparable to MAST ELM estimates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



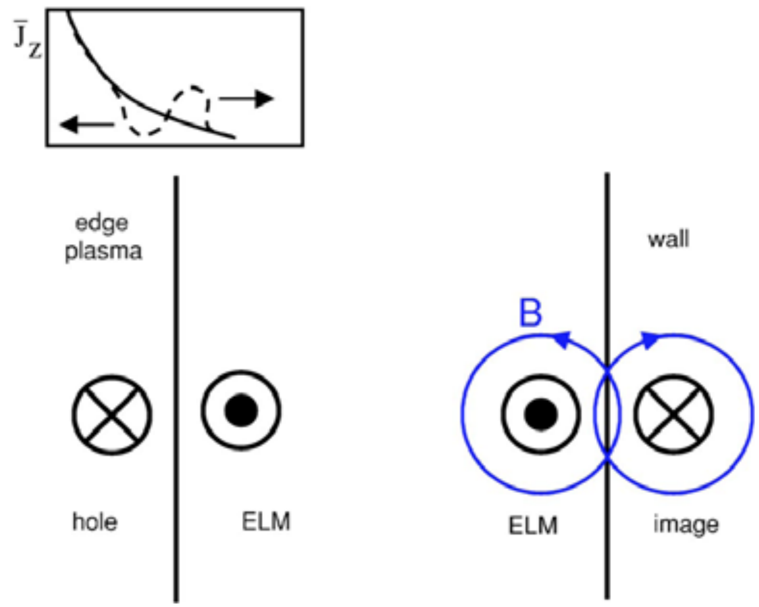
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

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
- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole ***J***×***B*** drives *aR*
  - Transition at ~ 35 μs comparable to healing time of current-hole
- Measured *VR* comparable to available EM blob models**
  - *VR* ~ 4 km/s; *VR,IB* ~ 8 km/s
  - Agrees to O(1) accuracy of theory



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



*: 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

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: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Deploying plasma diagnostics to better understand properties

- Exploration of high I_N, β_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 β_t

- Holds Promise as a Scalable Non-Inductive Startup Technique
  - Simpler injection system using plasma gun – passive electrode combination may be feasible

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

R.J. Fonck, J.L. Barr, M.W. Bongard, M.G. Burke,
E.T. Hinson, A.J. Redd, N. Schoenberg,
D.J. Schlossberg,K.E. Thome

The Joint Meeting of 5th IAEA Technical Meeting on Spherical Tori

16th International Workshop on Spherical Torus (ISTW2011)

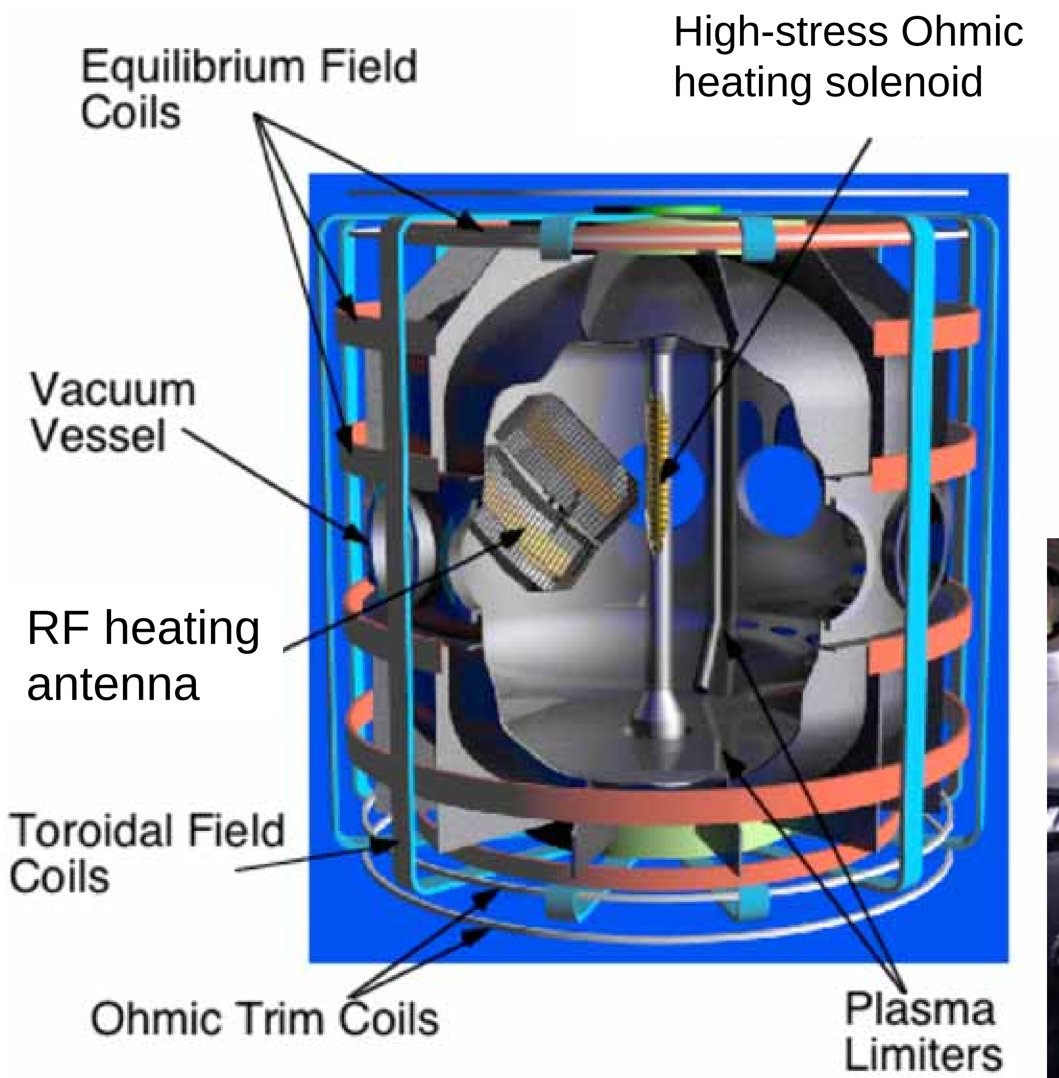
2011 US-Japan Workshop on ST Plasma

National Institute for Fusion Science, Toki, Japan September 27-30, 2011

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)	$\leq$ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.0
τ_{shot} (s)	$\leq$ 0.025
β_T (%)	$\leq$ 25
P_{HHFW} (MW)	0.2

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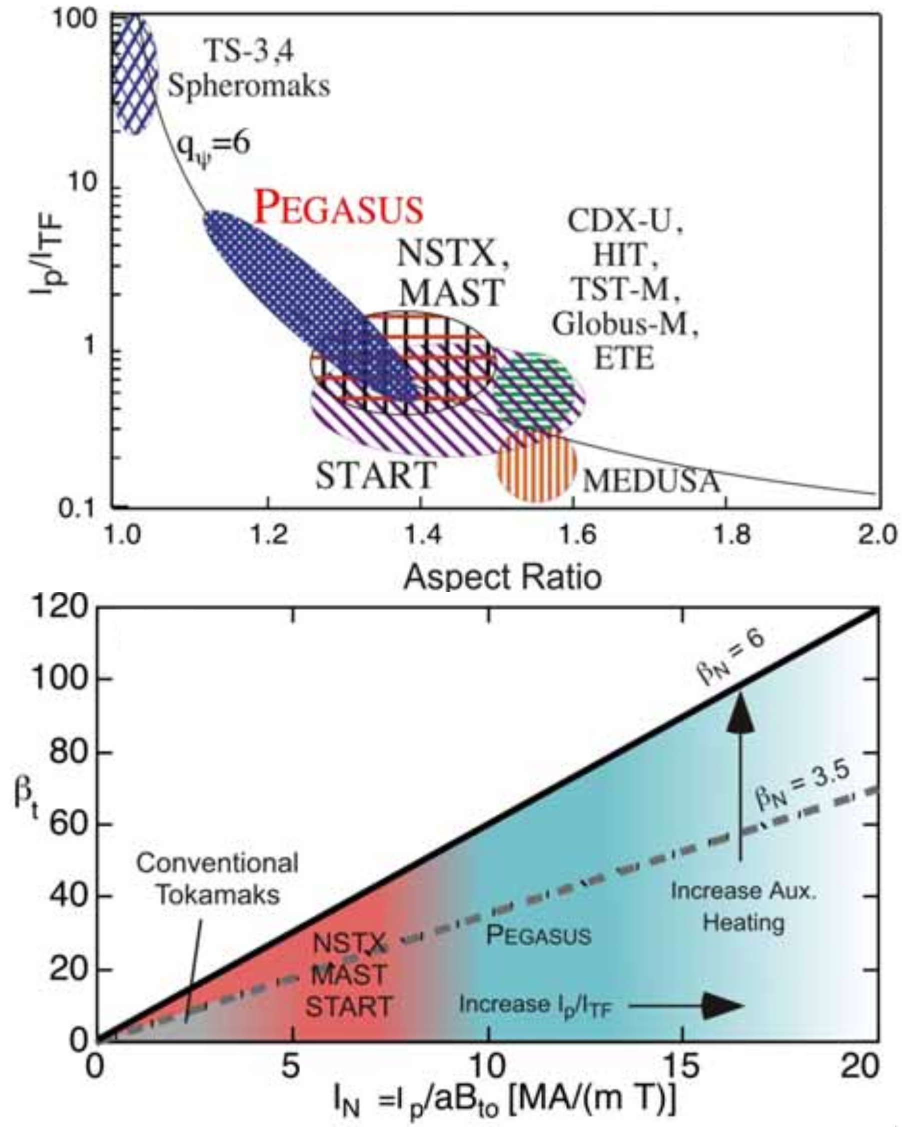
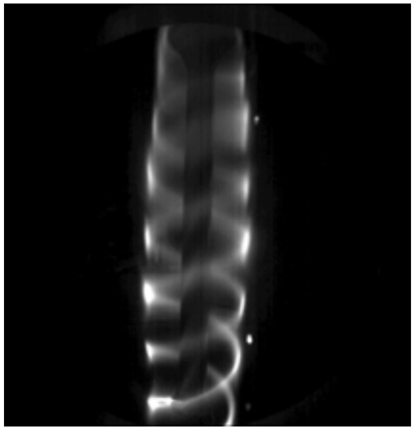
PEGASUS Mission: Physics of Low A → 1

- 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 β_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)

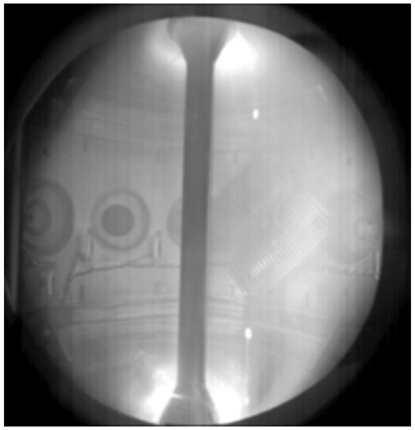


Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- 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_θ overwhelms vacuum B_z
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication



Reduced B_z



Current filaments

Relaxed tokamak

- Technical attractiveness: can remove sources and anode after startup

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

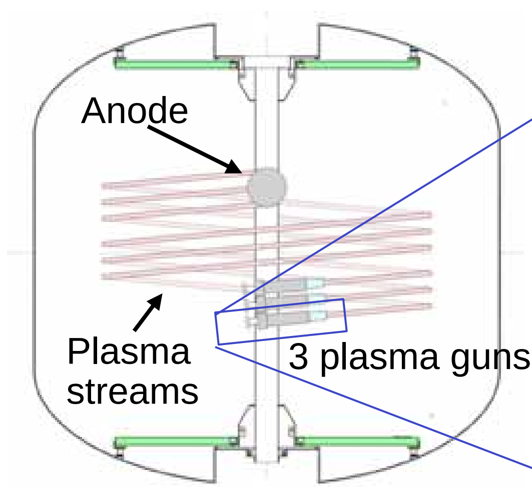
- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

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

V_{inj} - injector voltage

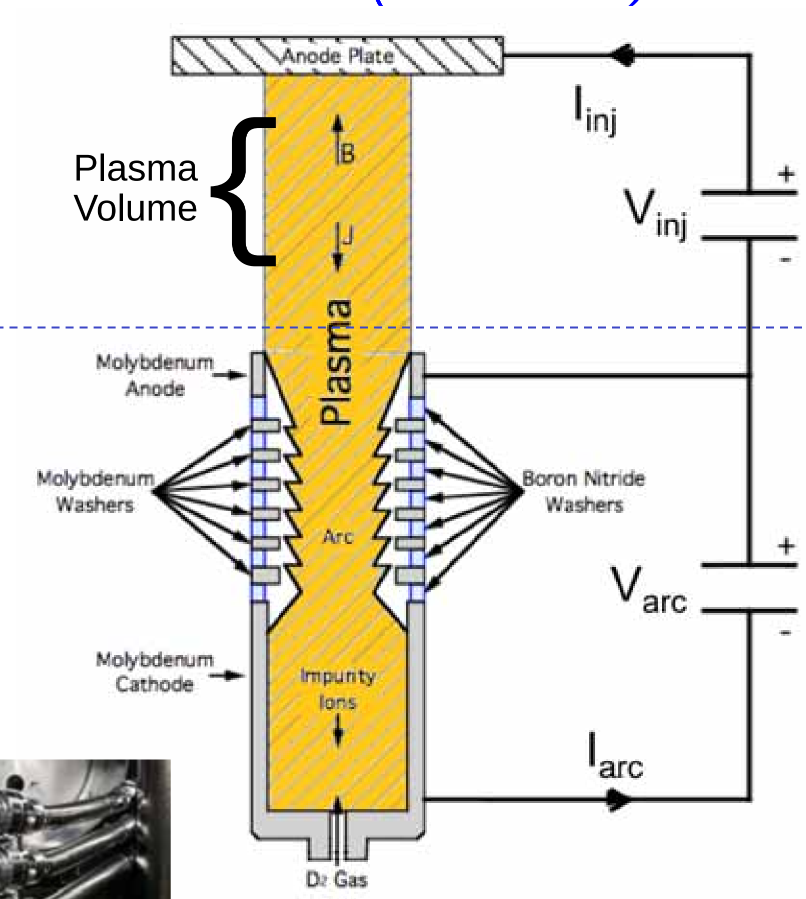
B_N - normal B field at gun aperture

A_{inj} - injector area



Midplane Injection

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



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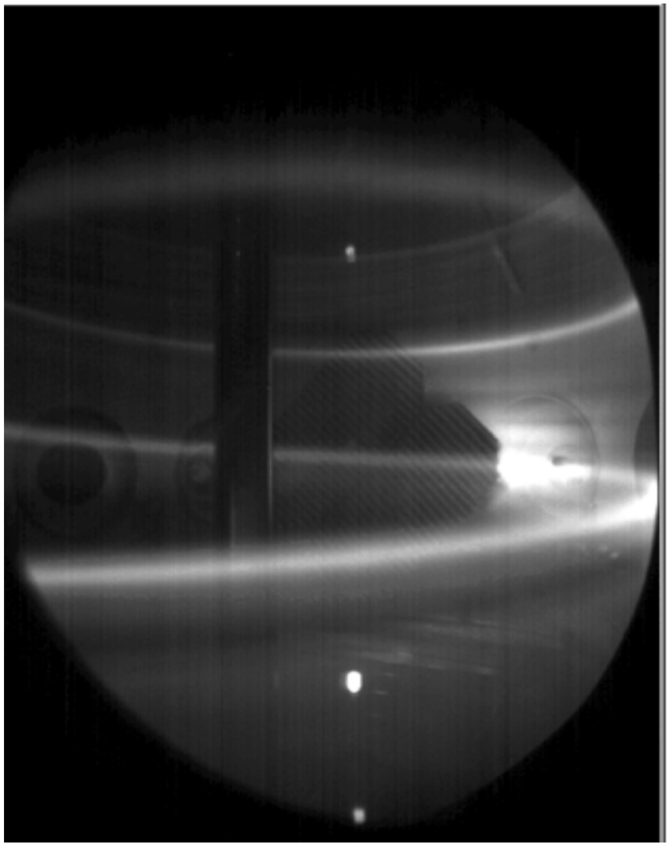
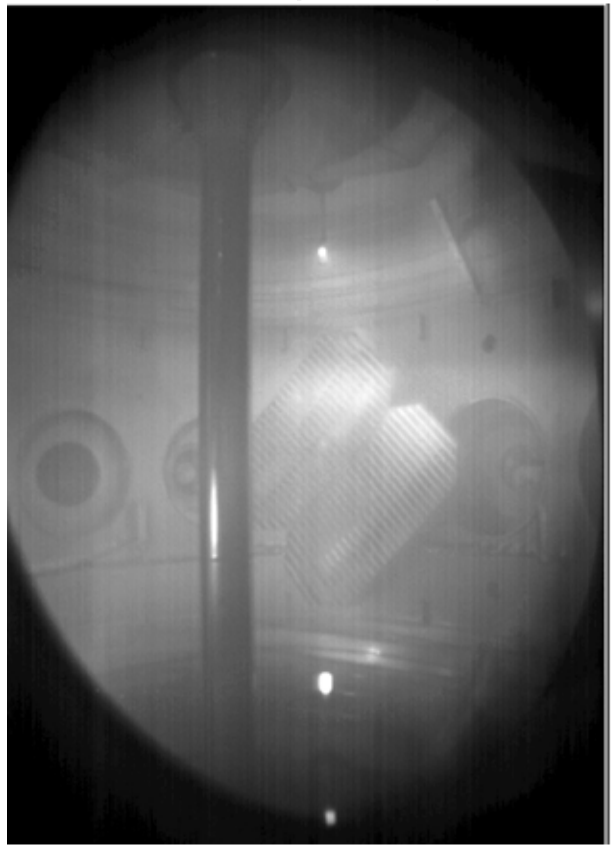
Evolution of midplane-gun-driven plasma

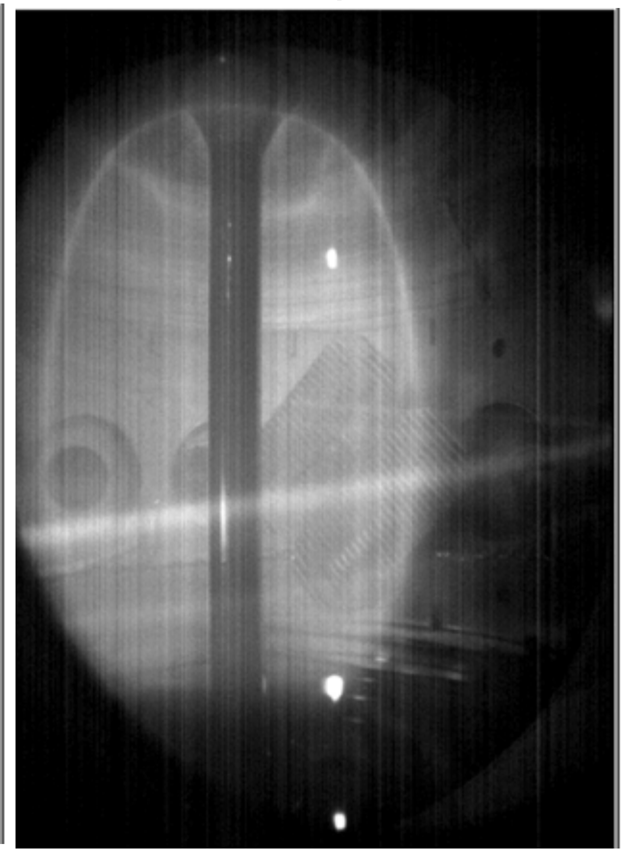
PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



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

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 η term

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

Taylor relaxation of a force-free equilibrium:

$$\nabla\times B = \mu_0 J = \lambda B$$

$$\lambda_p \le \lambda_{edge}$$

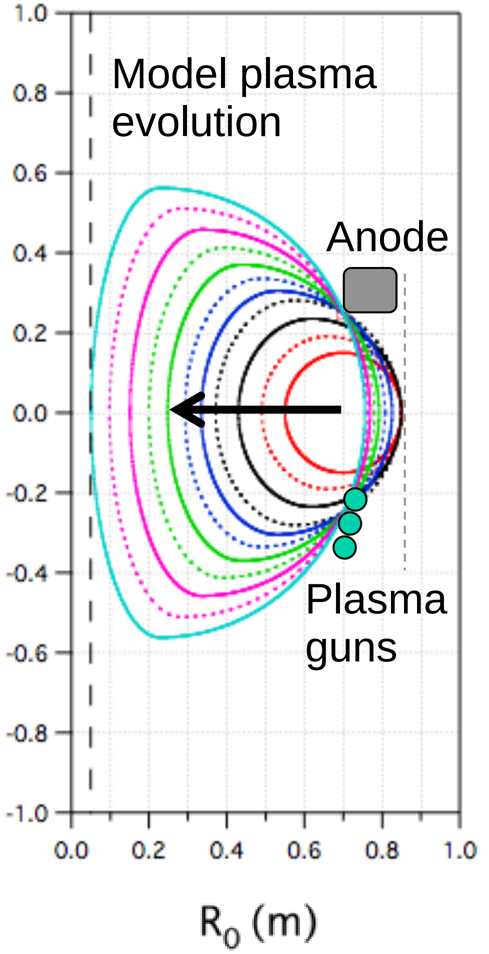
$$\Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

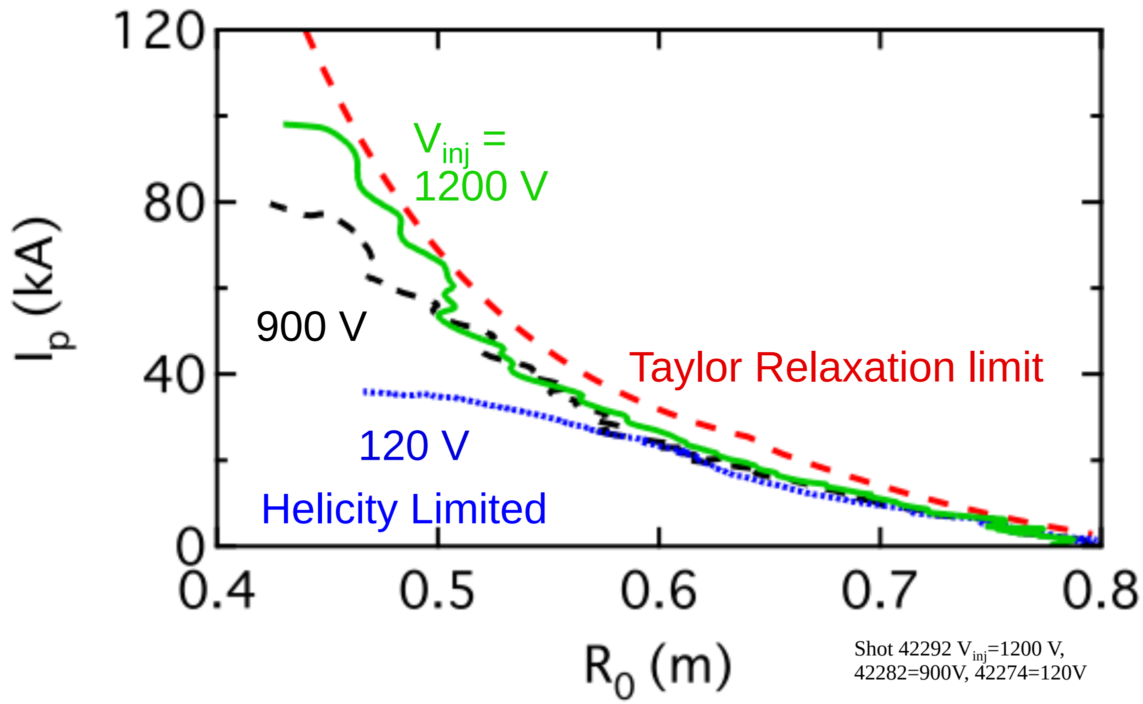
Assumptions:

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

A_p	Plasma area
C_p	Plasma circumference
Ψ_T	Plasma toroidal flux
w	Edge current channel width

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

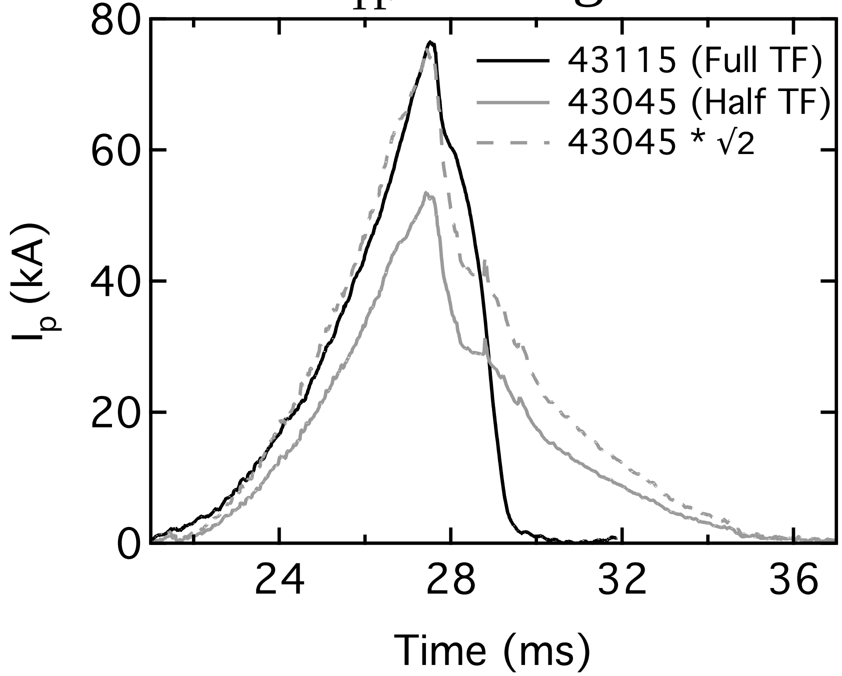
Experiments Confirm Relaxation Limit Scalings with I_{TF} and I_{inj}

- The relaxation limit I_p scales with:

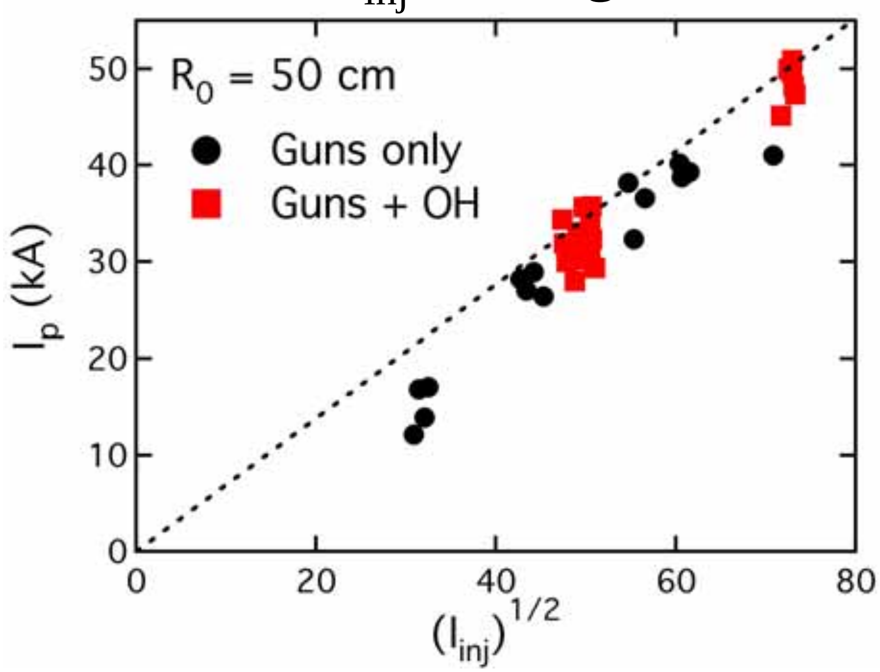
$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$

- Experimental plasma current limits follow these scalings:

I_{TF} Scaling:

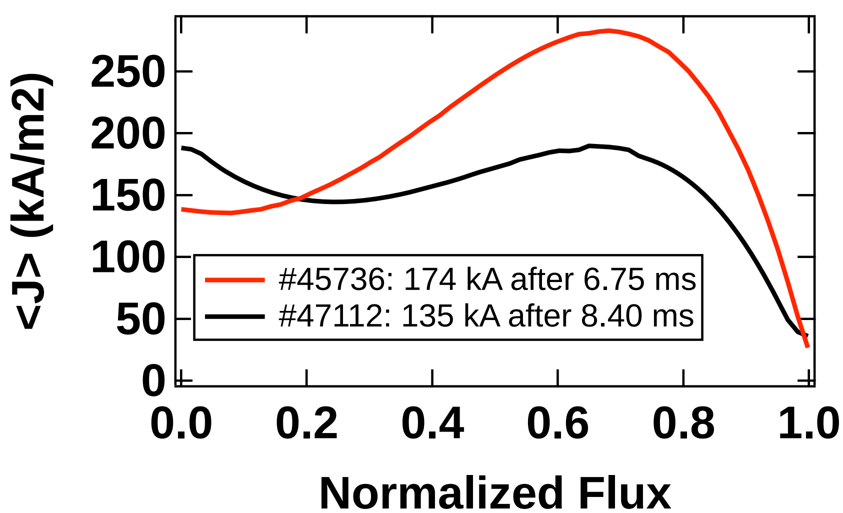


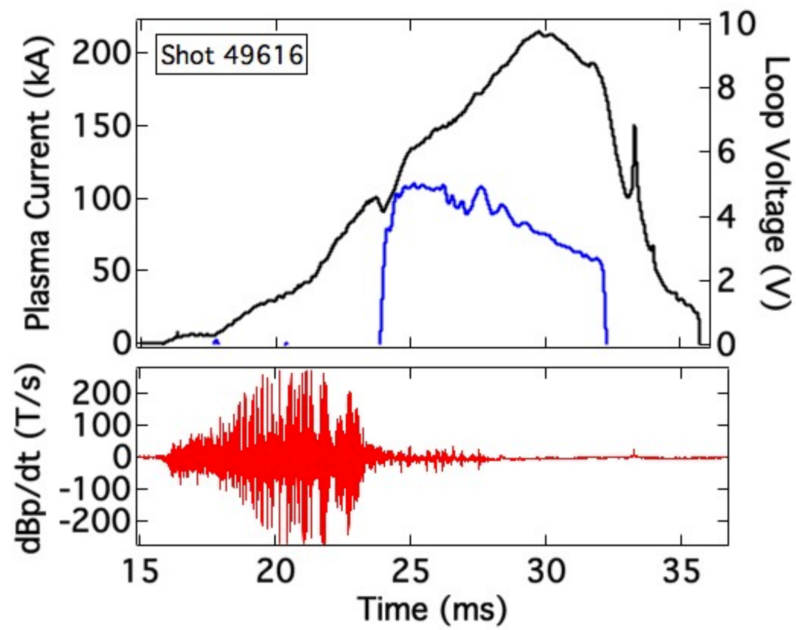
I_{inj} Scaling:



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

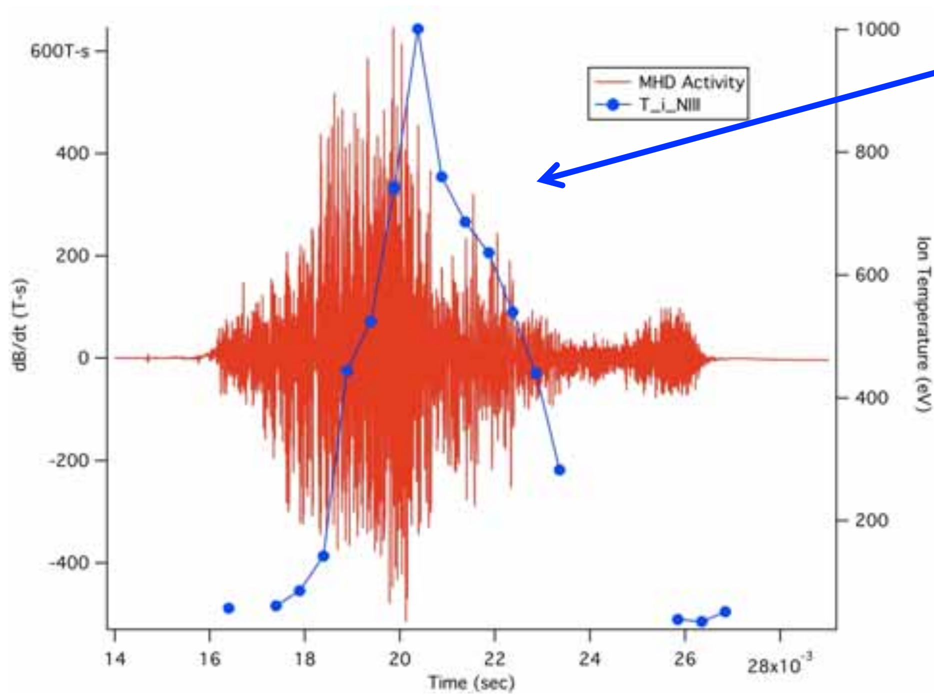
- Poloidal flux generated by helicity injection is equivalent to that generated by Ohmic Drive
  - $I_{total} = I_{HI} + I_{OH}$
- Excessive skin current => poor coupling to OH drive
- Slowly evolving: ~ flat j(r) (black)
  - Smooth handoff to Ohmic inductive drive (j(R) profiles from external-only equilibrium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





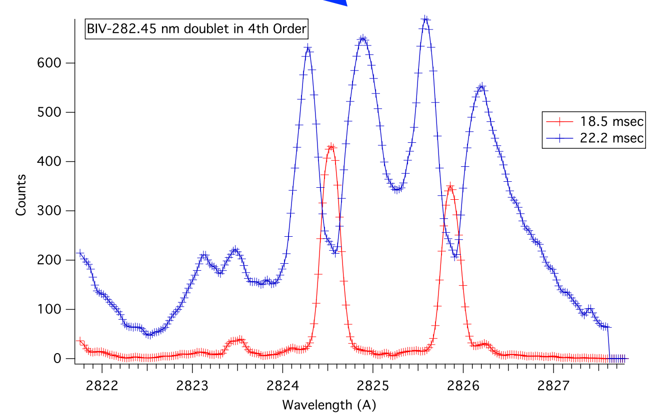
Initial Spectroscopy Measurements Suggest Energetic Ions

- Spectroscopic T_i suggest high ion energies during reconnection period



Doppler T_i from radial view

Complex multi-line structures from tangential view



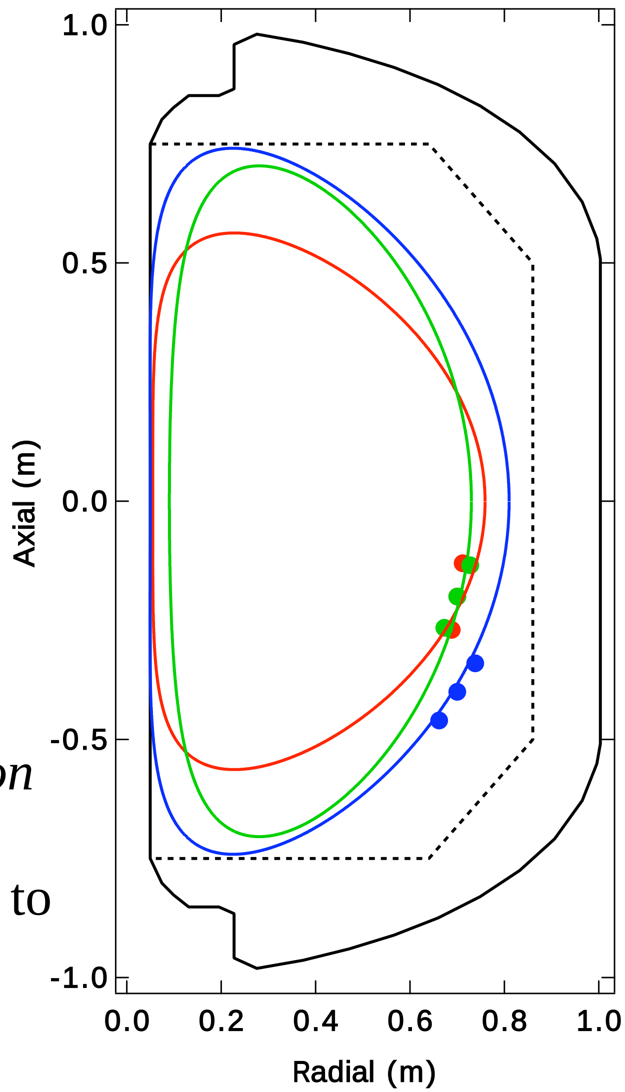
- However, situation is much more complex if viewed toroidally
  - Need improved time-resolution and spatial scans

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

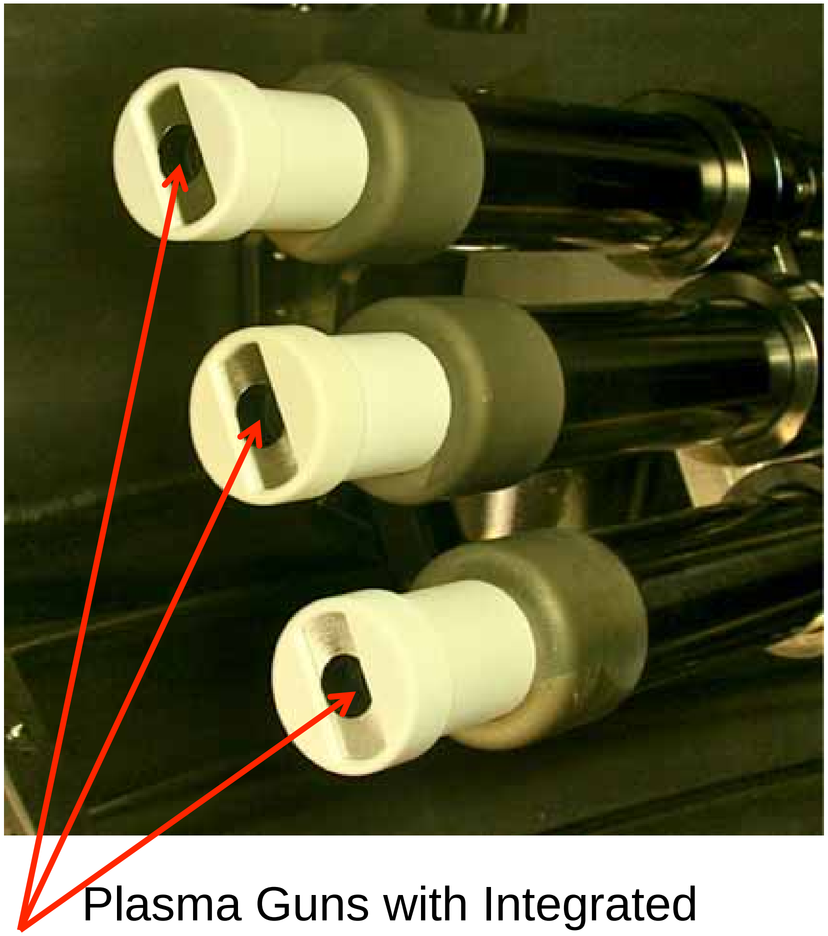
Gun-Electrode Geometry: PF Induction, Plasma Size, and Null Formation

- 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



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

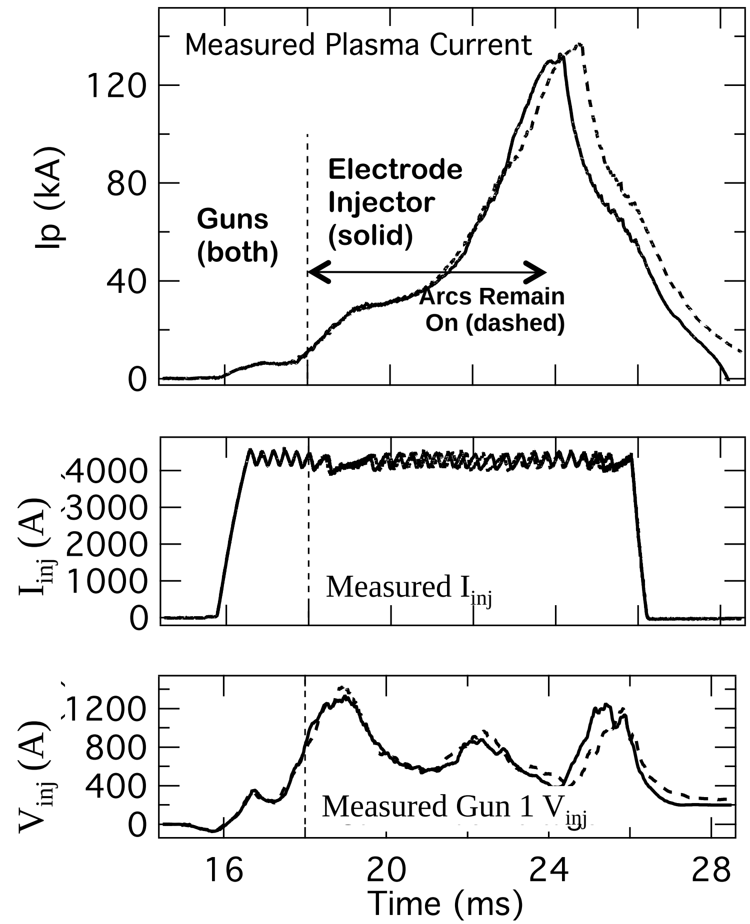
- Potential for much higher I_{inj} without need for either more plasma guns or larger guns.
- Helicity injection physics is agnostic to the exact source of the edge charge carriers.
- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) *and*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



Plasma Guns with Integrated Slotted Electrodes

Initial Tests of Gun/Electrode Helicity Injection System Are Promising

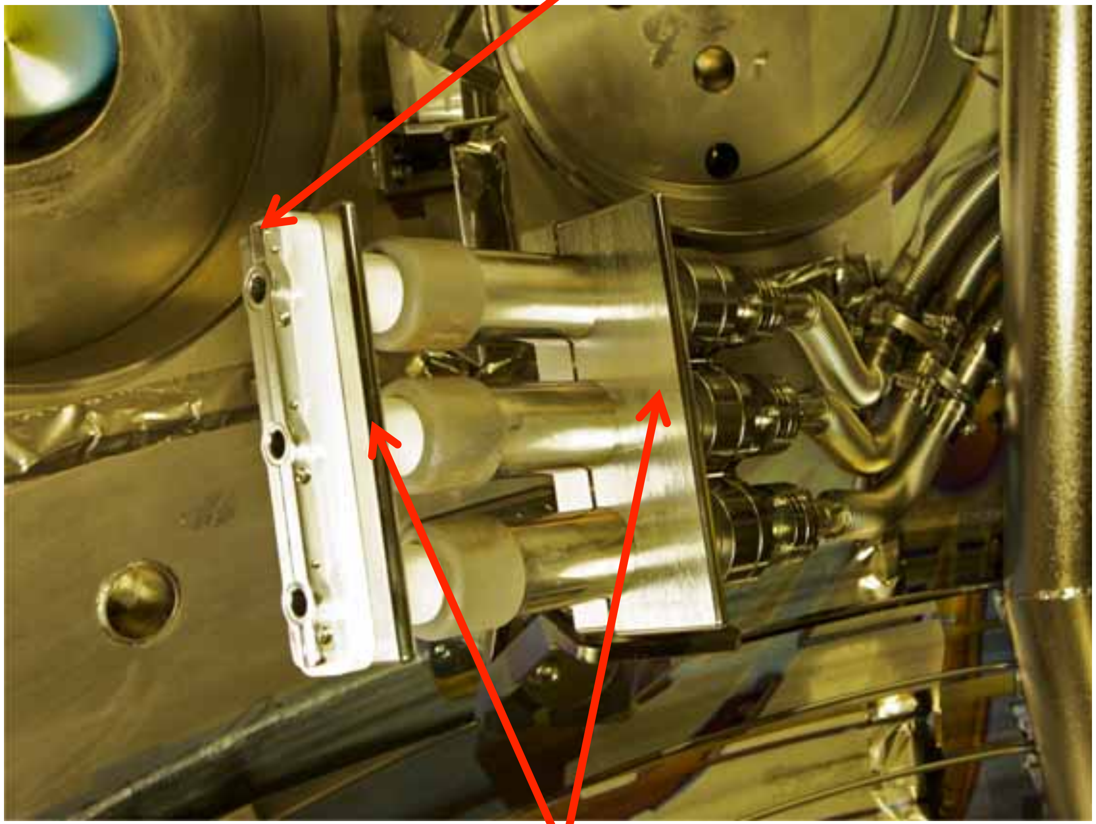
- Operations use two steps:
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes fed by electrode charge carriers induced and moderated by tokamak edge plasma.
- First tests are promising
  - Arc current off after relaxation and formation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



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

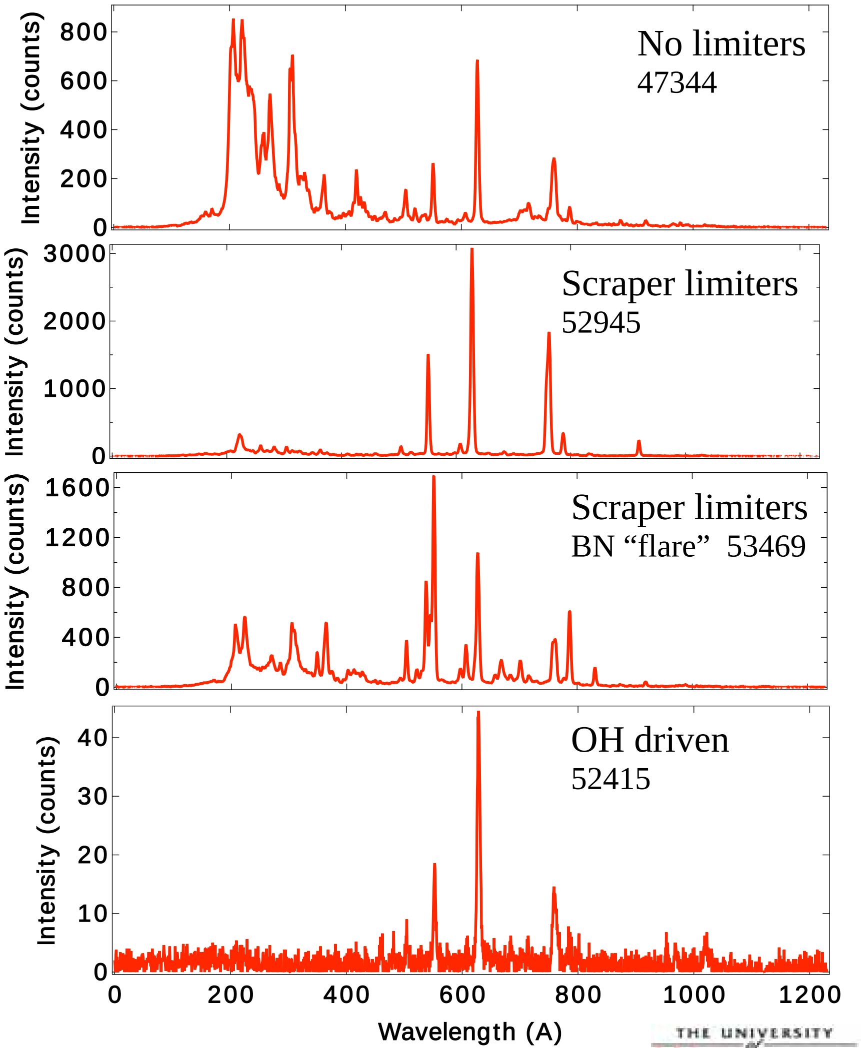
- Integrated scraper limiters to protect assembly and control local edge density
  - Gas-puff control of $V_{bias} \sim V_{loop, effective}$



Local limiters

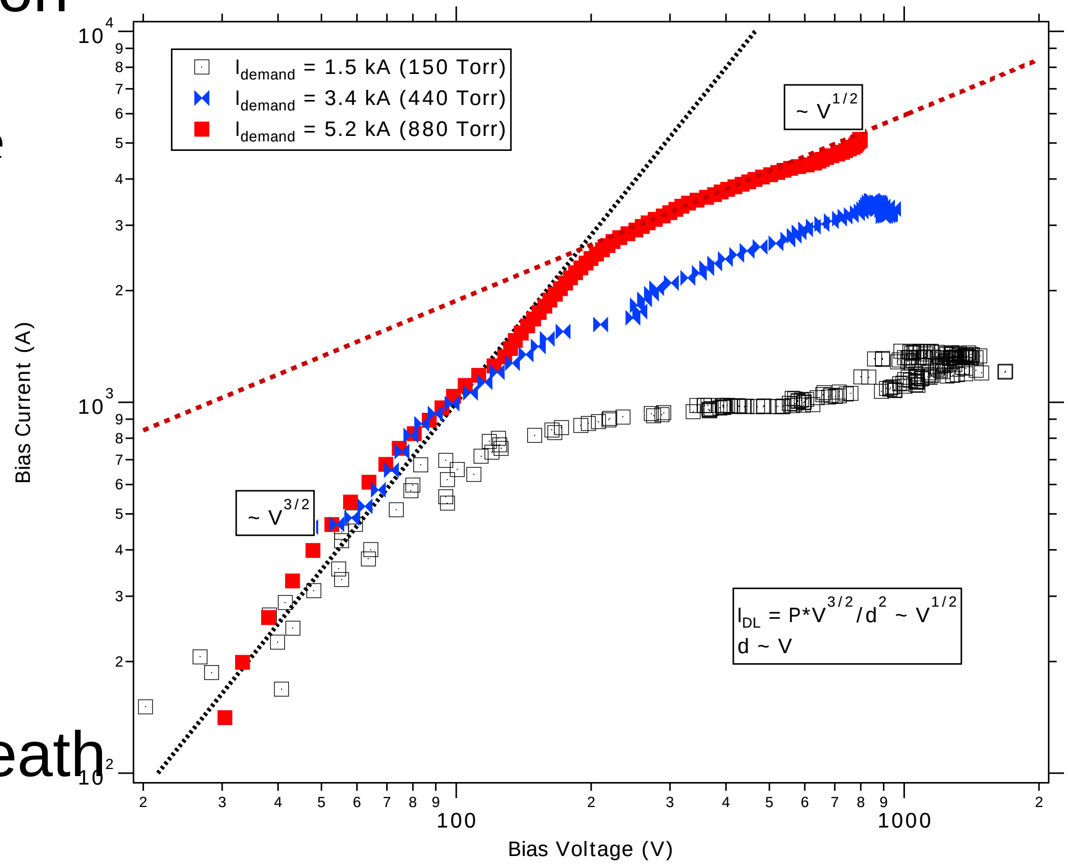
Local Limiters Reduce N to Negligible Levels in Well-behaved Injection Cases

- N dominant impurity with unprotected gun assembly
  - 1st *estimates* of impurity content via bolometer measures
    - Z_{eff} ~ 2.2. +/- 0.8 during injection; ≤ 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



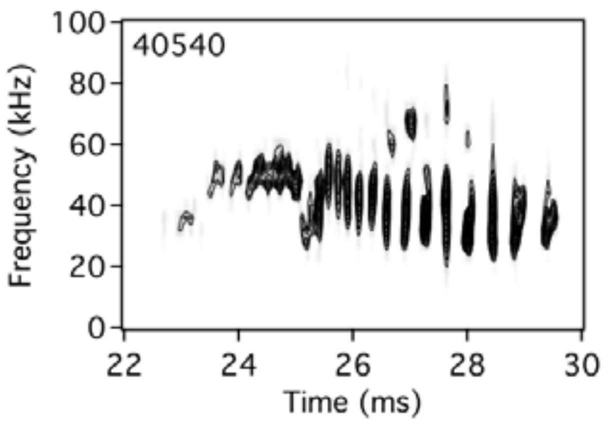
Source Impedance Appears to be Governed by Sheath Physics

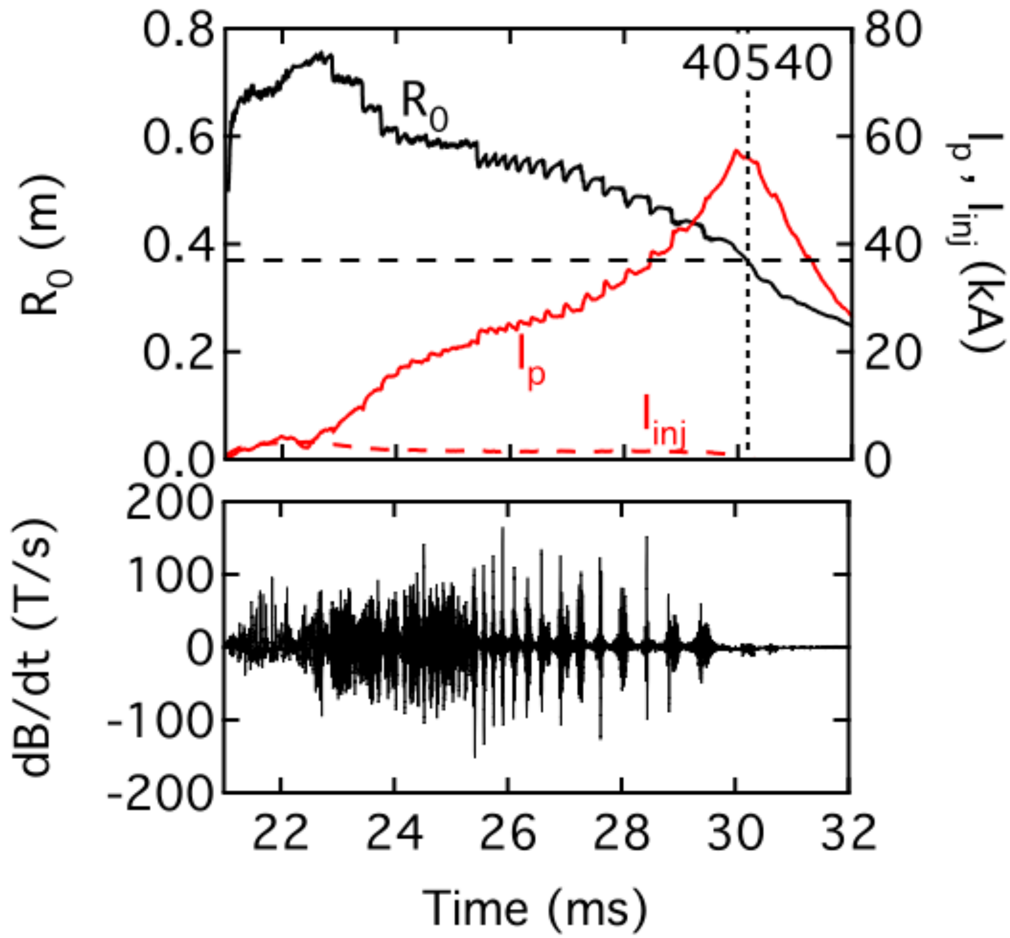
- Model evolving for source impedance ~ helicity injection rate
  - Predicative model requires edge density measurements
- Initiation phase: vacuum space charge limitation
  - $I_{bias} \sim V^{3/2} / d^2$
- High I_{bias} drive phase: expanding double layer sheath
  - $d^2 \sim V \Rightarrow I_{bias}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



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

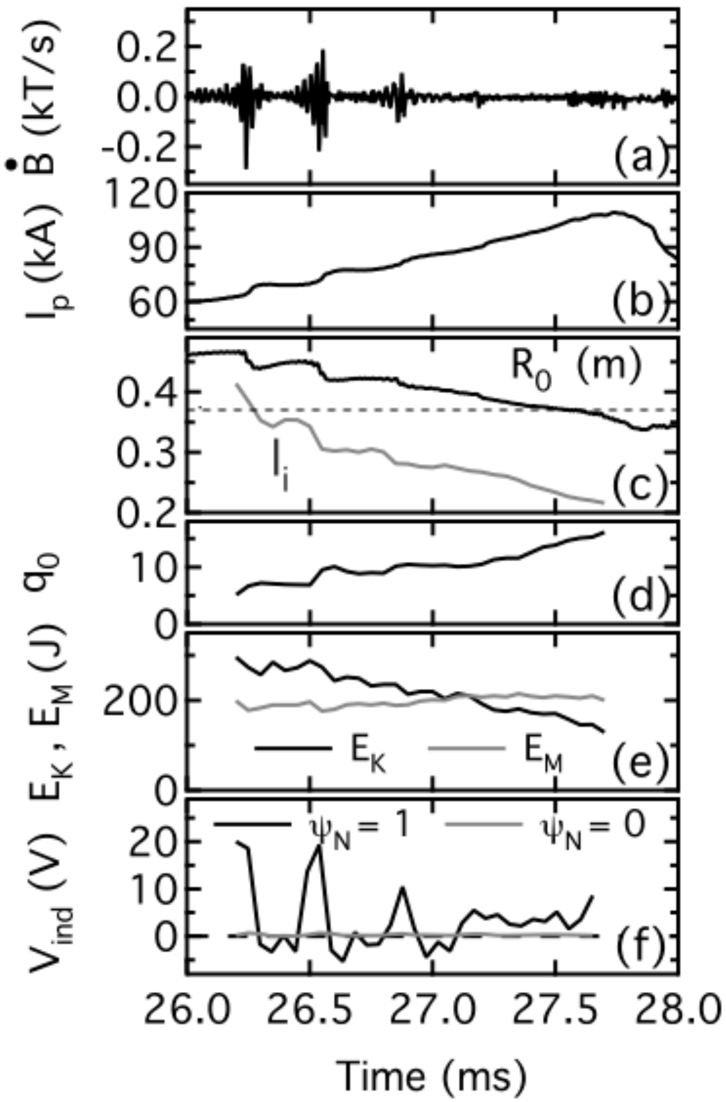
- Bursts of $n = 1$ magnetic oscillations
  - Observed when plasma is coupled to edge current drive
  - Different in nature from inboard current injection experiments





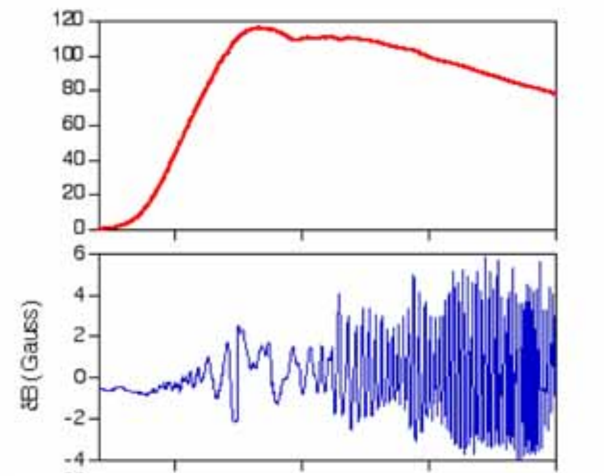
The magnetic topology quickly changes with each burst of MHD activity

- Each burst typically ~ 0.1 ms
- With each burst…
  - l_i decreases → I_p increases
  - R_0 decreases → plasma expands
  - $B_{\phi 0}$ increases → q_0 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

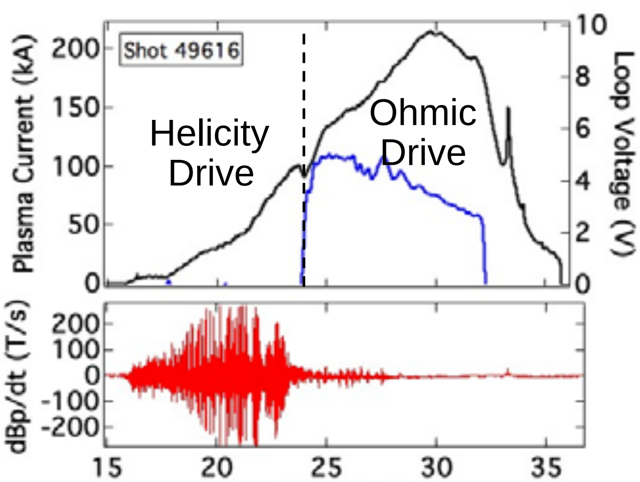


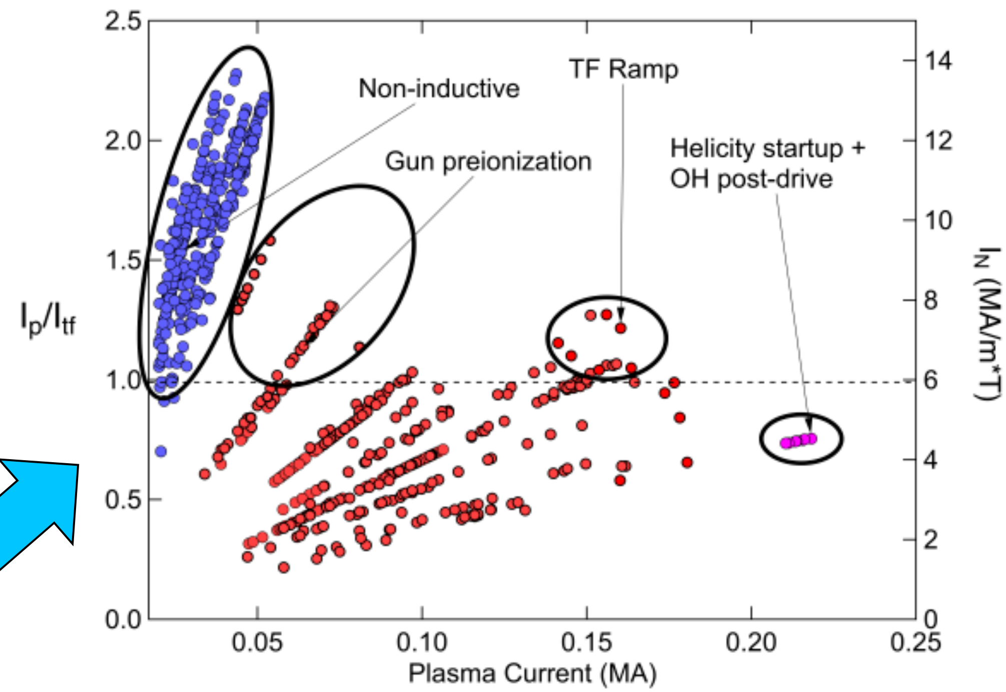
Current Drive Tools Providing Access to High Field Utilization Regime

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 β_T as A≈1

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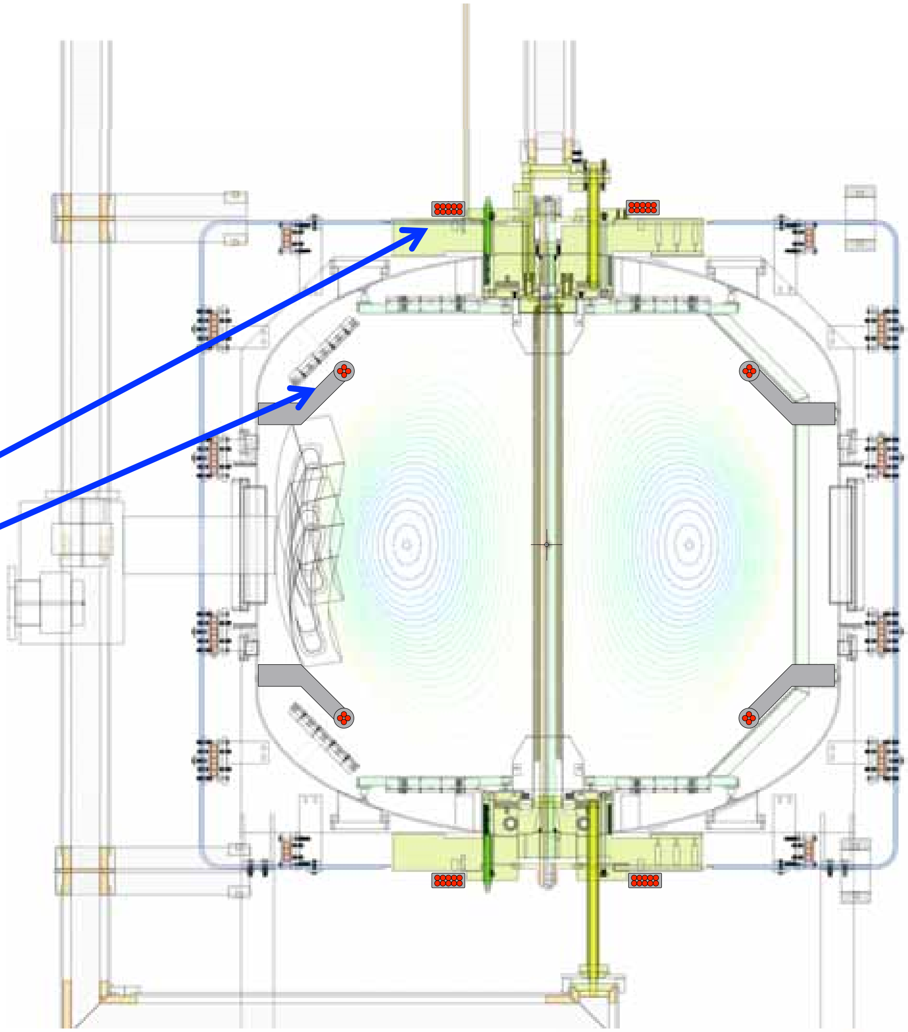
Medium-Term Upgrades Will Allow Further Tests of Point-Source Helicity Injection

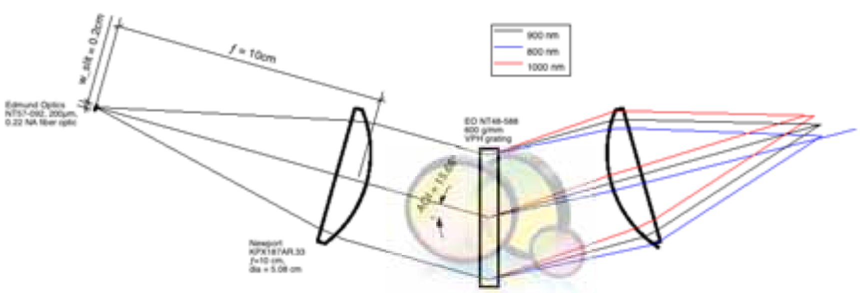
- Gun-electrode Evolution
  - Passive electrode material variations
    - C electrode being installed
  - Separate plasma gun and electrode
- Power Supplies, Heating
  - New helicity injection power: *2 kV, 15 kA*
  - Double TF current: *Taylor limit increase*
  - Commission HHFW system: *electron heating*
- 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*



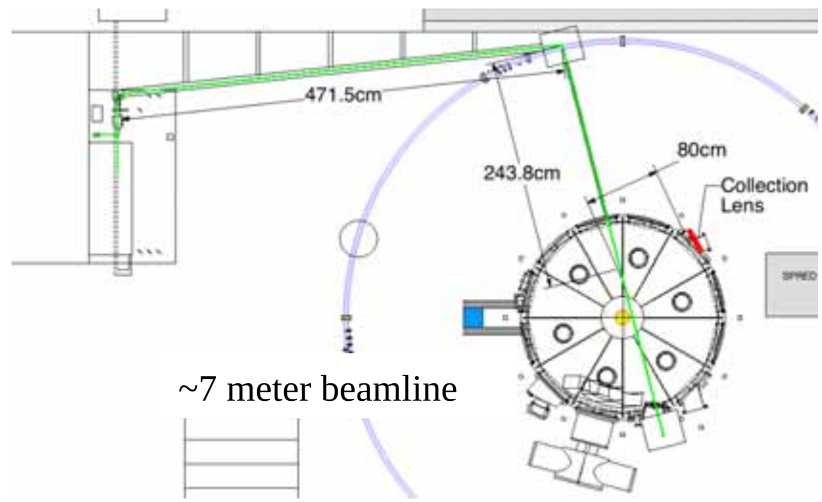
Thomson Scattering system uses new technologies for visible wavelength system

- Frequency doubled Nd:YAG laser provides ~10^{18} photons
- For typical PEGASUS plasma, $n_{scattered}$ ~ 10^4 photons
- VPH grating efficiency >85% for λ_{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



~7 meter beamline

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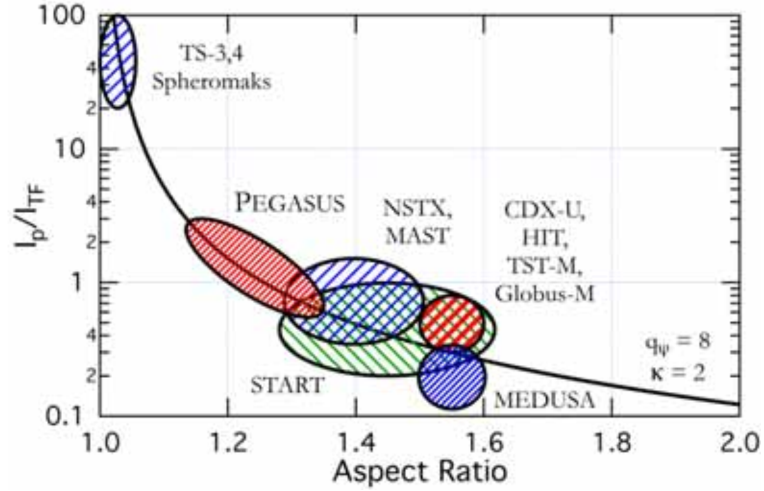
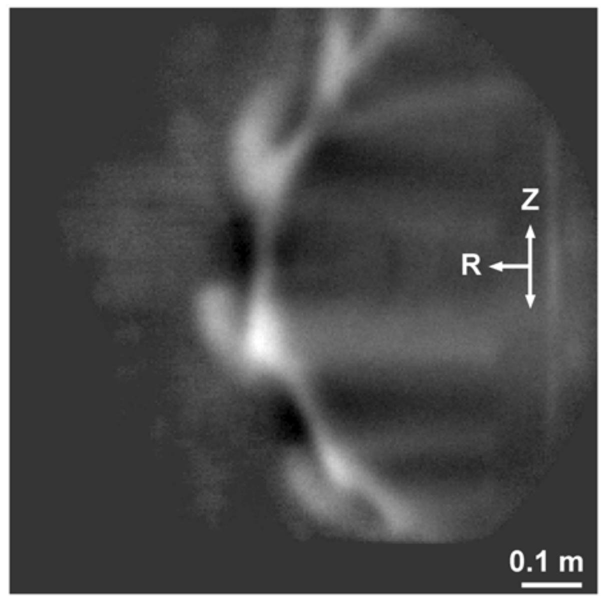
Some Low-A ST ITER-relevance: Access to Peeling Instability and Conditions to Measure J

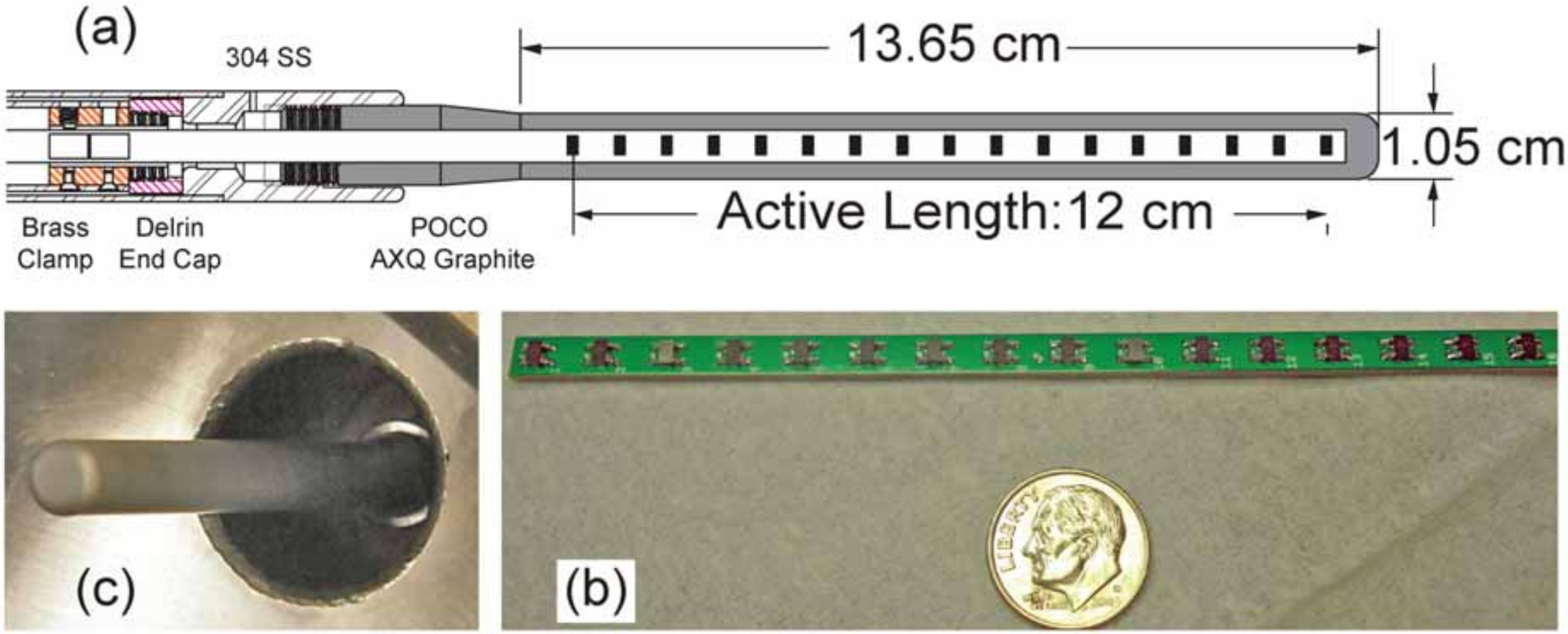
- Spherical tokamaks naturally provide strong peeling drive
  - Toroidal field utilization $I_p/I_{tf} \sim j_{||}/B$
- PEGASUS accesses peeling modes
  - Strong $j_{||}/B$ MA/m^2-T at
  - Comparable to DIII-D in H-mode
- Machine parameters permit internal edge measurements
  - Short pulse lengths (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





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

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)

J_ϕ(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:

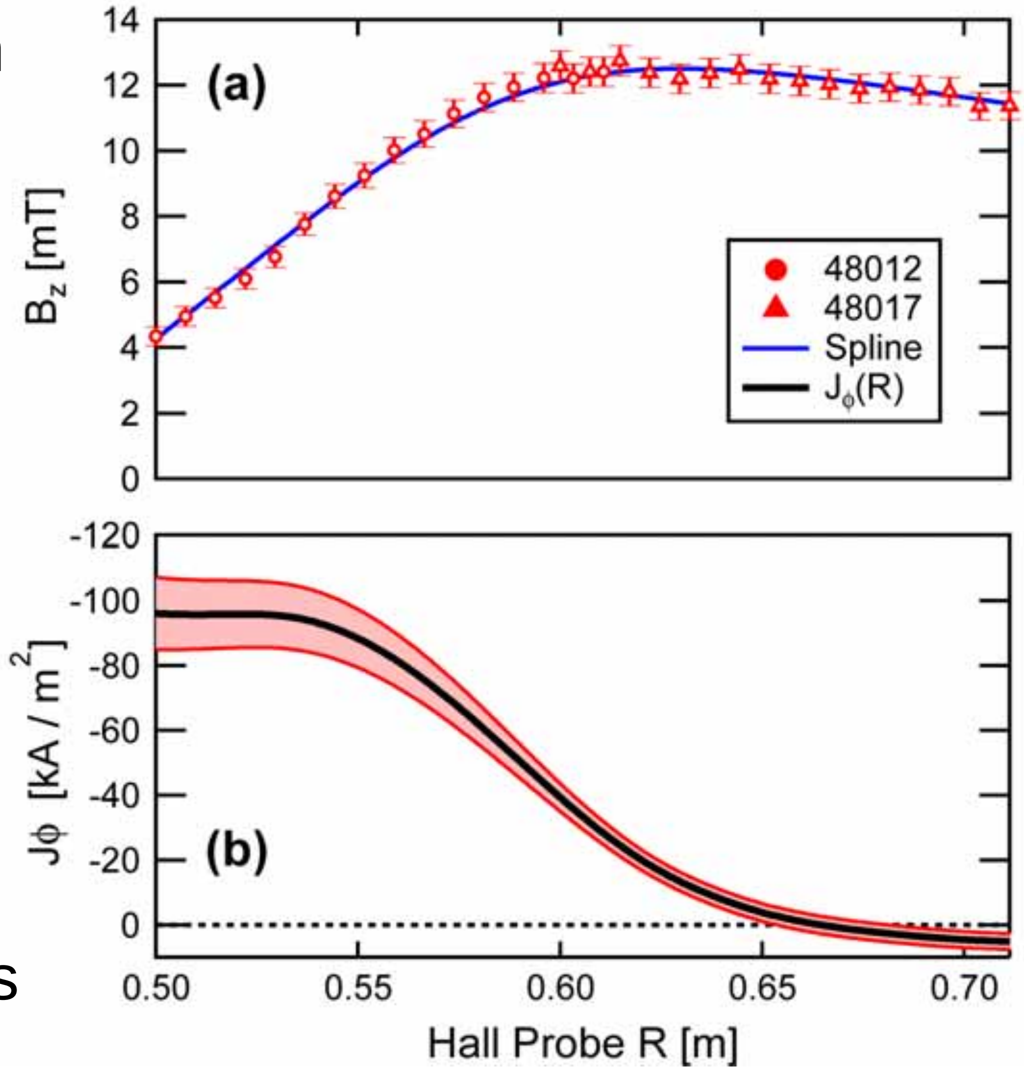
$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2}\right) - \frac{dB_Z}{dR} \left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2}\right)$$

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

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

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

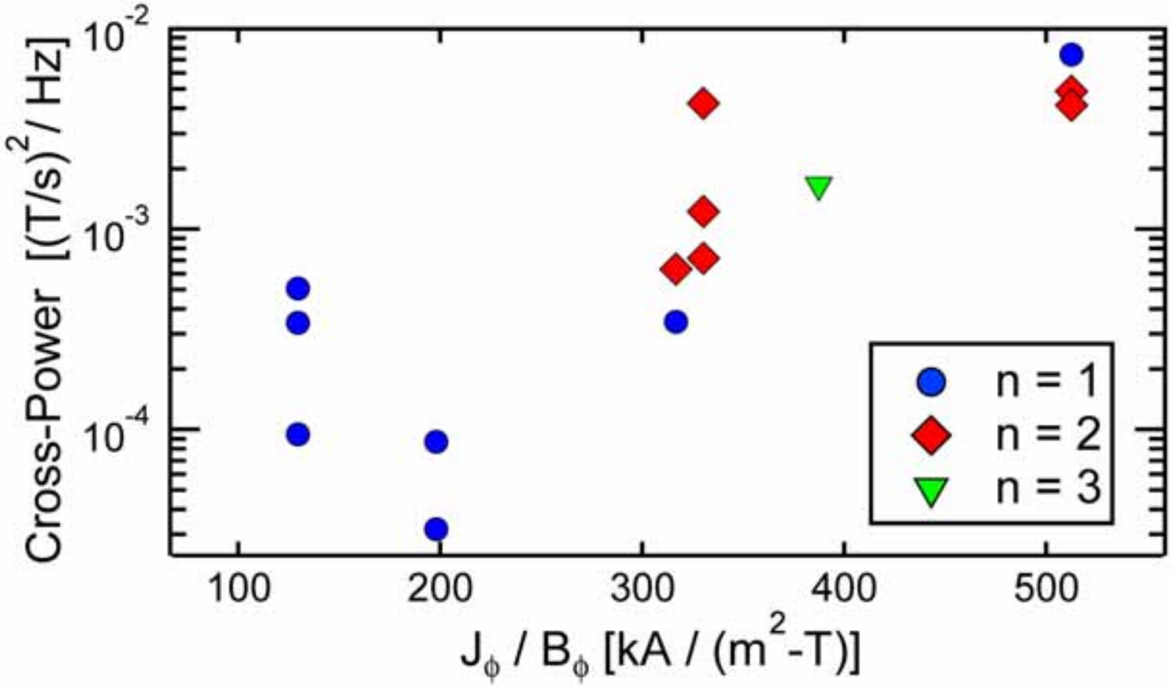
- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute dB_Z/dR using interpolated smoothing spline*
  - Compute $J_\phi(R,t)$ given geometry
- Resultant $J_\phi(R,t)$ consistent with I_p, MHD evolution
- Radial span extendible with multi-shot averaging
- Higher-order shaping effects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



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

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

Peeling MHD Strongly Scales with Theoretical Drive

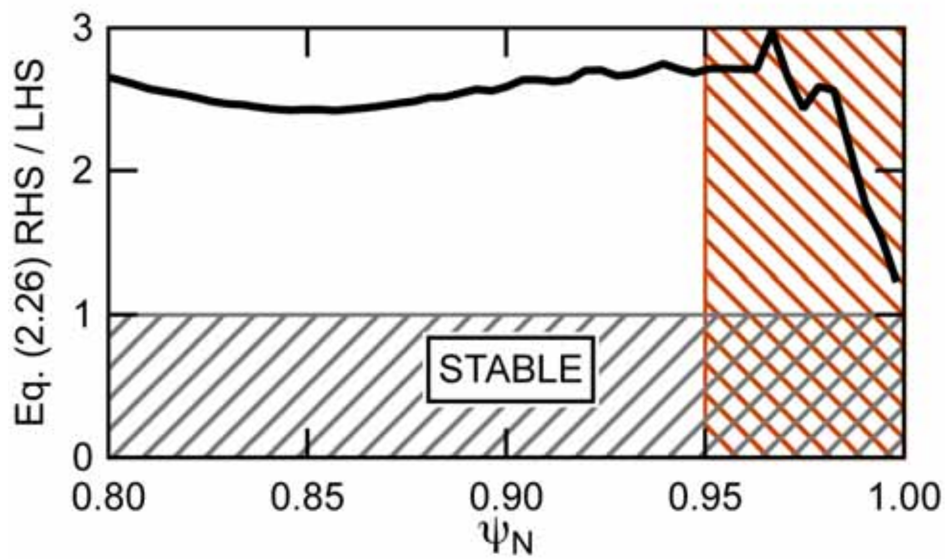


- Mode helicities estimated from port 8 Mirnov array
  - $n < 3$ via cross-phase analysis
  - $m_{lab} \geq 10$ via radial decay rate
  - $10 \leq m_{lab} / n \leq 30$ ($\psi_N > 0.9$)
- MHD power spans two orders of magnitude with factor-of-five variation in J/B

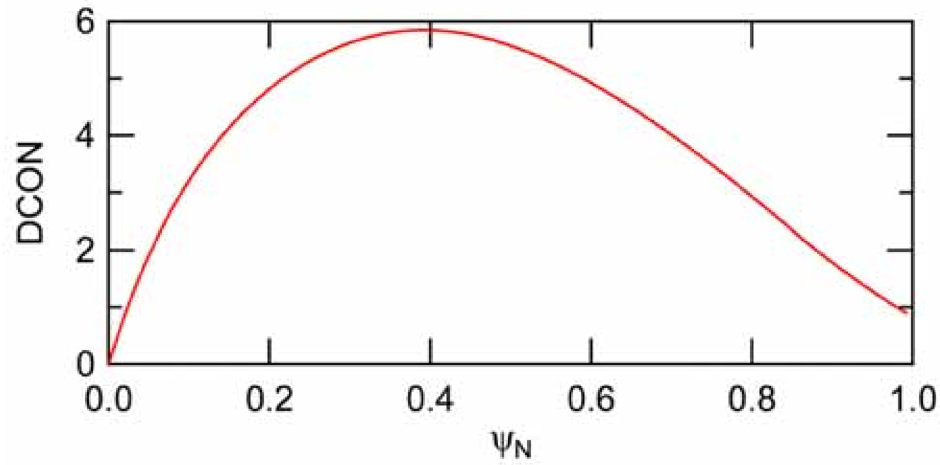
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

Stability Analysis Confirms Peeling Instability

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

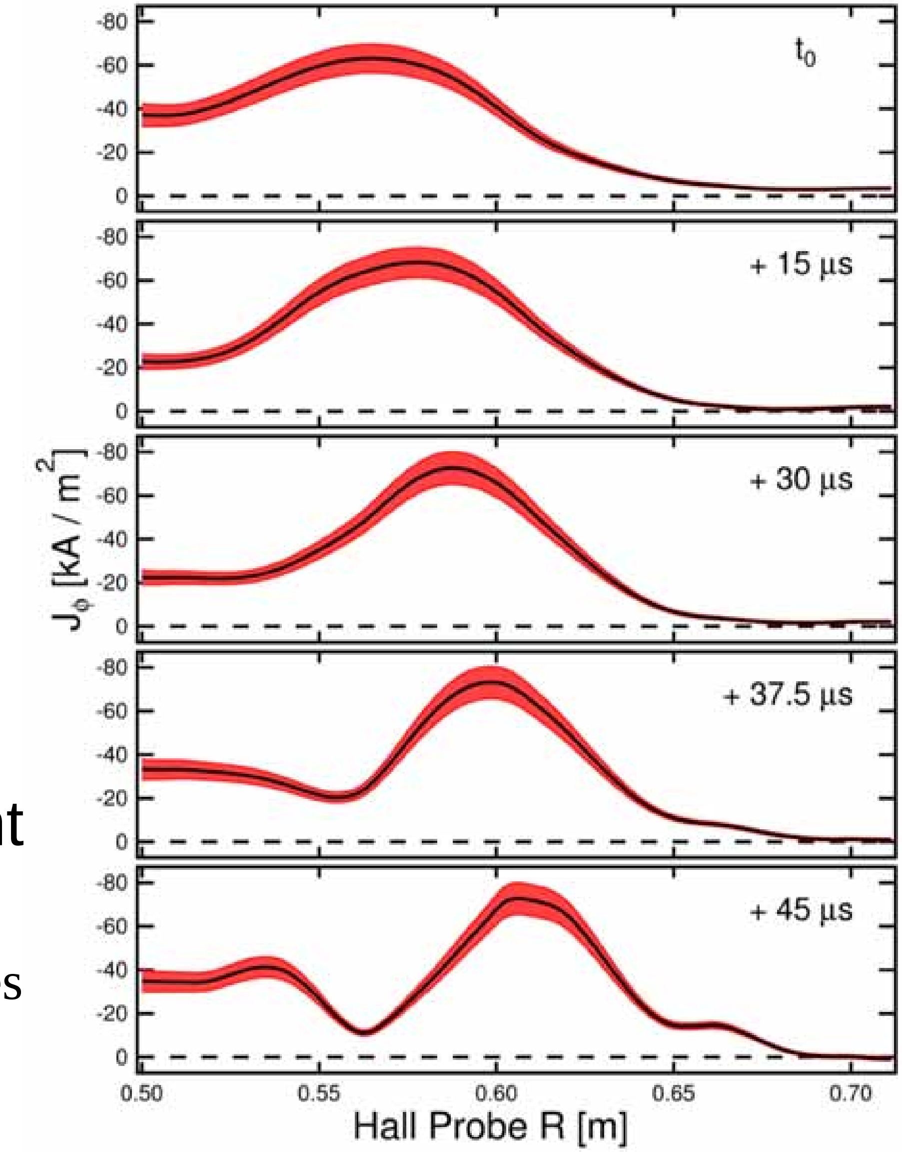


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



J_{edge} Dynamics Measured on ELM Timescales

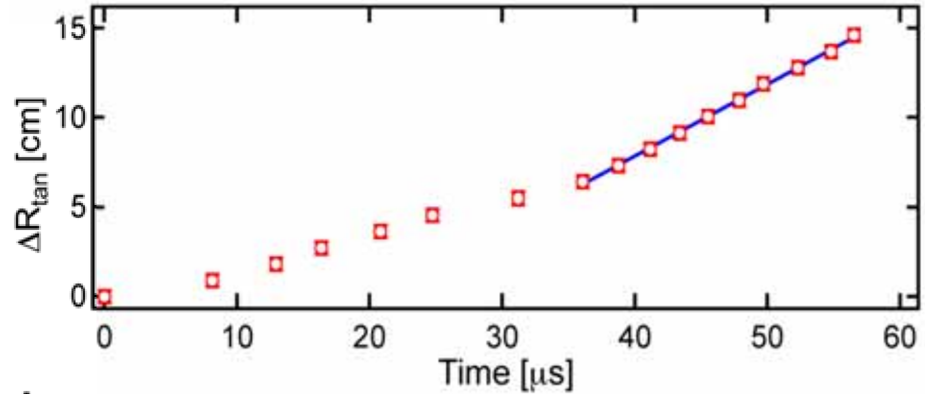
- J_{edge} resolved during peeling filament generation
- Propagating filament forms from initial "current-hole" J_{edge} perturbation
  - Validates formation mechanism hypothesized by EM blob transport theory
- Filament carries toroidal current $I_f \sim 100–220$ A
  - Comparable to MAST ELM estimates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



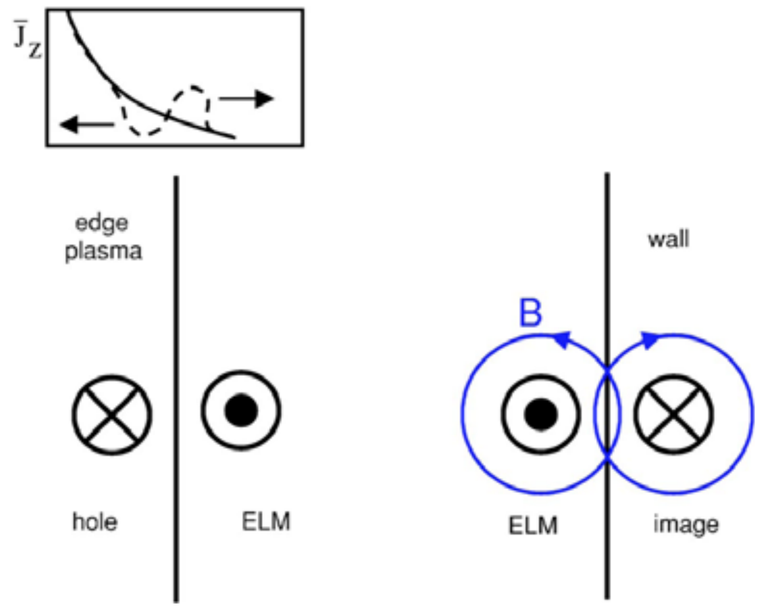
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

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
- 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 ~ 4 km/s; VR,IB ~ 8 km/s
  - Agrees to O(1) accuracy of theory



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



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

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

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

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

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  - I_p ~ 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
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