Summary: Helicity Injection Startup

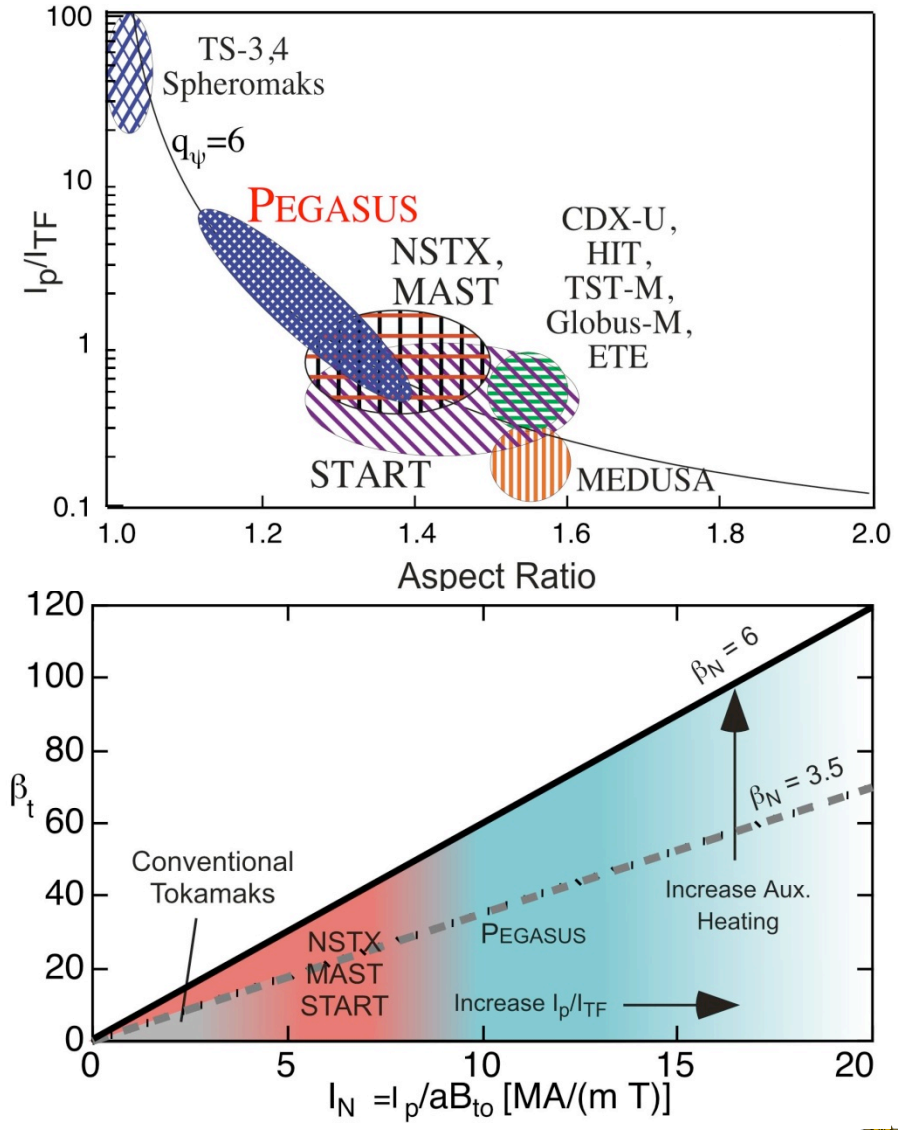
- Point-source helicity injection current drive non-inductively generates high-I_p (up to 174 kA) tokamak discharges
- An empirically-supported model for the maximum gun-driven I_p has guided experiments
- Gun-formed plasmas exhibit bursty MHD activity during the gun drive, with the bursts corresponding to rapid equilibrium changes.
  - Studying onset of the bursts, and detailed mechanisms for the rapid changes
- Gun-formed discharges hand off most efficiently to Ohmic with a very slow I_p rise during helicity injection, consistent with controlling the current-profile evolution toward a broad profile.
  - Have demonstrated handoff with 135 kA, driven with Ohmic up to 218 kA (for I_p/I_{TF}=0.7), which is a significant extension to the PEGASUS operating space
  - More optimization is possible with the present power supplies
- High-current gun-drive formation with handoff to other current drive techniques may lead to high-I_N, high-β_T PEGASUS operations

Summary: High-I_N and Peeling-mode Studies

- The PEGASUS ultra-low A (~1.1-1.2) allows access to high I_p/I_{TF}
  - Normalized current $I_N = 5AI_p/I_{TF}$
  - Presently achieved I_N=14
- Low-A, low-field PEGASUS Ohmic plasmas are peeling-unstable
  - Peeling-ballooning modes are leading candidate for explaining ELMs
  - Filamentary structures observed: electromagnetic, low-n and high-m, with radial acceleration
  - PEGASUS offers a unique opportunity to test peeling-ballooning theory

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

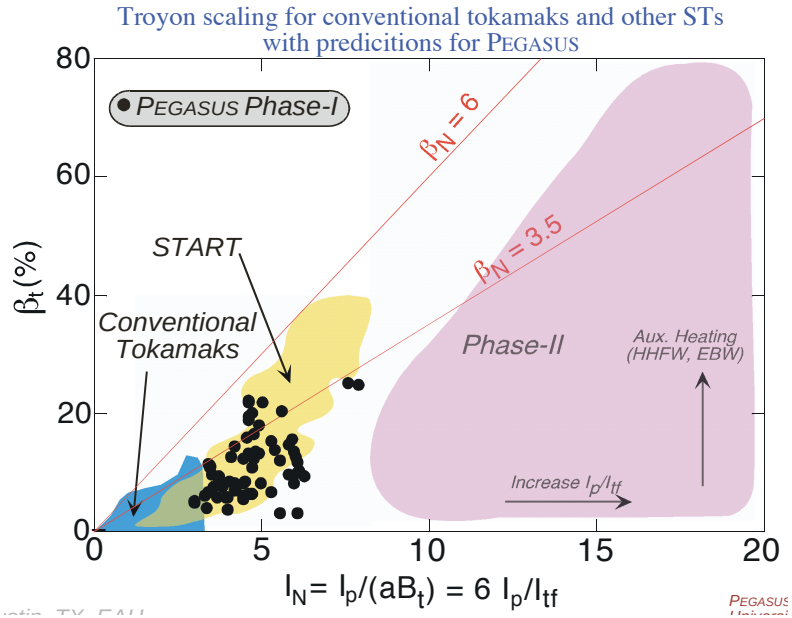


PEGASUS is Creating High-I_p Non-Solenoidal Discharges Which Enable High-I_N Studies

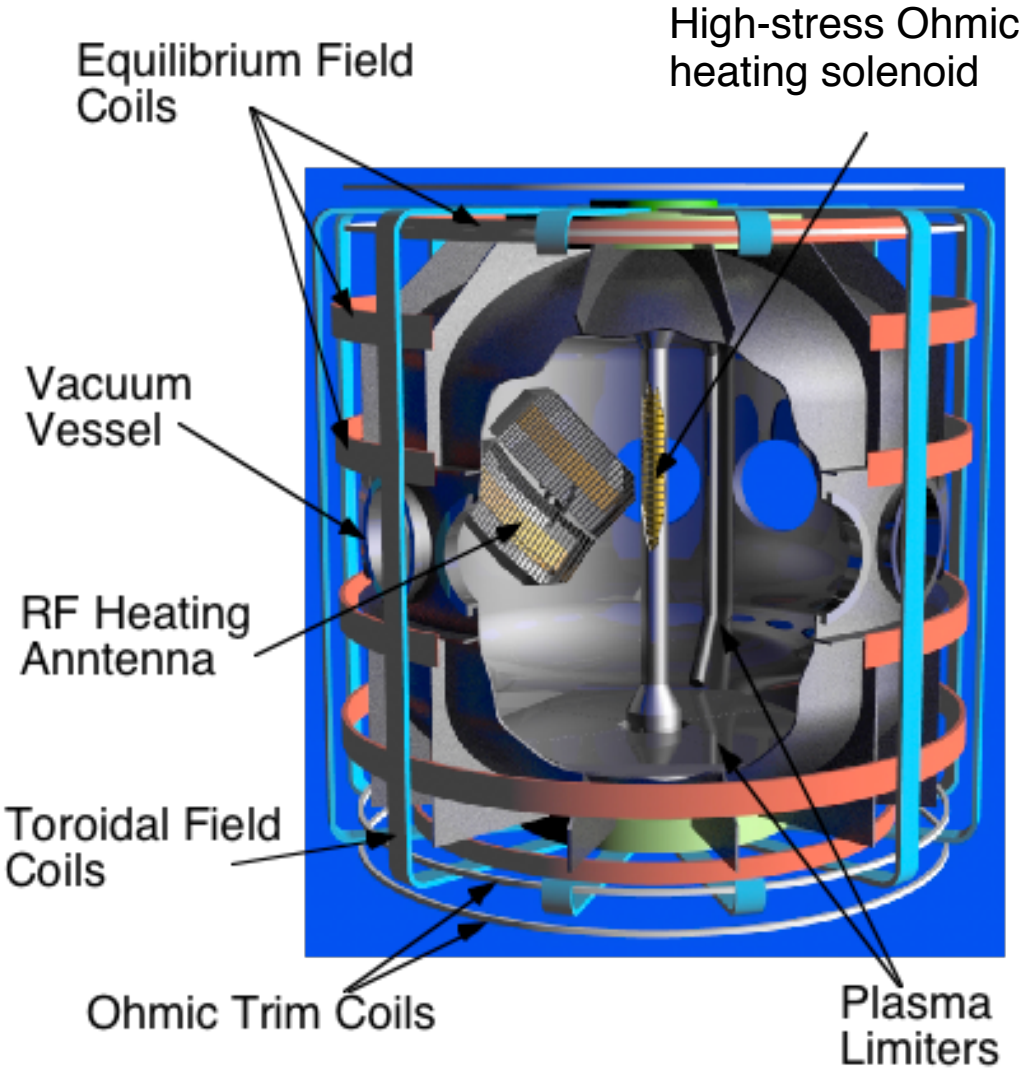
- Using DC helicity injection for solenoid-free startup
  - I_p up to 174 kA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
  - I_p up to 135 kA smoothly "handed off" to Ohmic, then driven to 218 kA

- High-I_p non-solenoidal startup enables exploration of high I_N, β_T operating space
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved
  - Extend to high I_p, n_e for high β_T

- Experimental tests of peeling-mode theory

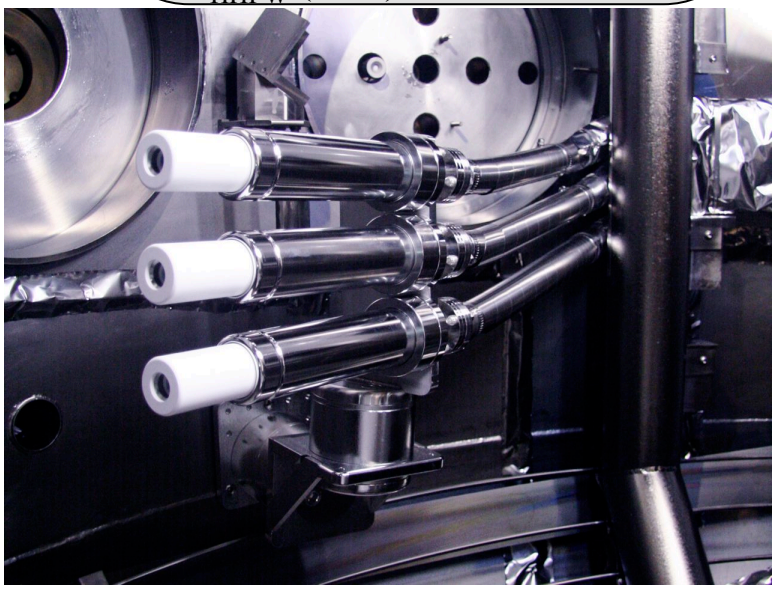


PEGASUS is a Compact Ultralow-A ST



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
κ	1.4 – 3.0
τ_{shot} (s)	≤ 0.025
β_T (%)	≤ 25
P_{HHFW} (MW)	0.2

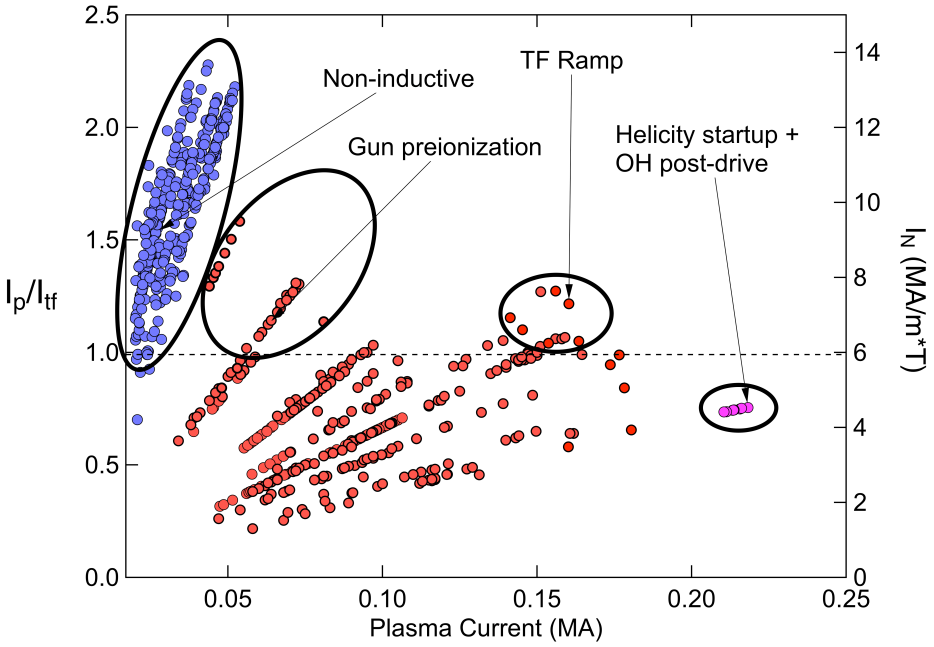


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Helicity Injection Startup Provides a Path to High-I_N, High-β_T Noninductive Ops

- Previously achieved $I_N > 12$ using helicity injection alone
- No evidence of β stability limits at high I_N
  - PEGASUS discharges have been limited by available current drive
- Gun startup and Ohmic handoff are extending PEGASUS operational space to higher I_p
- Future: Use RF heating (HHFW, EBW) to reduce dissipation. Also, explore handoff to RF current drive



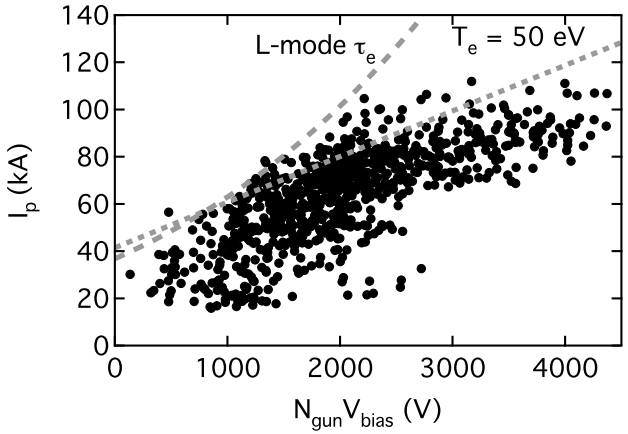
$$\beta_t = \beta_N I_N \qquad I_N = I_P / aB_\phi$$

$$\beta_t = \frac{2\mu_0 \langle p \rangle}{B_{\phi 0}^2}$$

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Further development of gun startup needed for predictive understanding

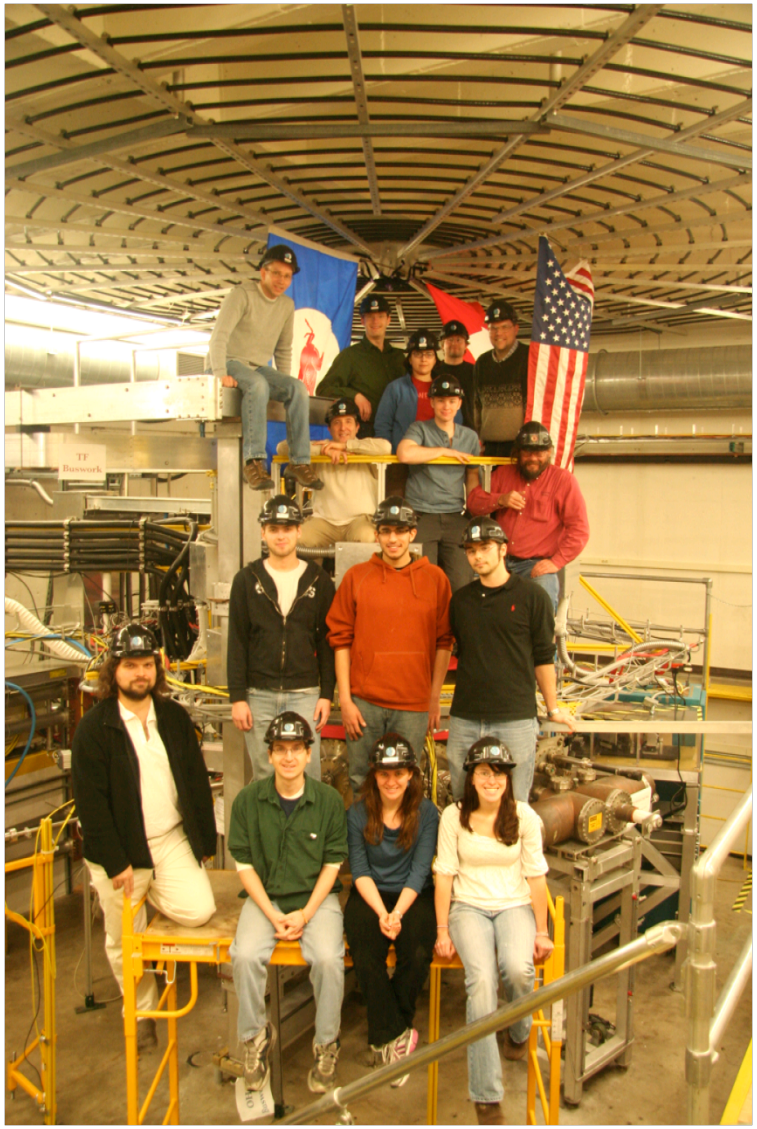
- Test of working model requires access to 0.3-0.4 MA
  - Characterize confinement/dissipation in driven plasma
  - Develop efficient handoff scenarios, to Ohmic and/or RF current drive
  - Access high I_p/I_{TF}, high β parameter regimes
- Outstanding physics issues include:
  - Is the confinement/dissipation stochastic?
  - What sets the bias impedance?
  - What sets the width *w* of the driven region?
  - How well does the simple helicity injection model hold as I_p increases?
- Addressing these issues requires facility modifications:
  - Increase capability of TF supplies: higher transient TF or long-pulse
  - Increase bias gun current and voltage and/or deploy larger guns
  - Augment the guns with shaped electrodes



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The PEGASUS Research Team



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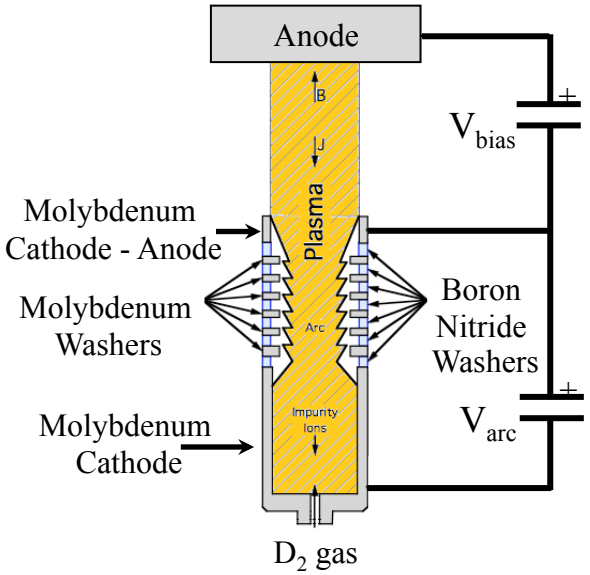
Undergraduates:

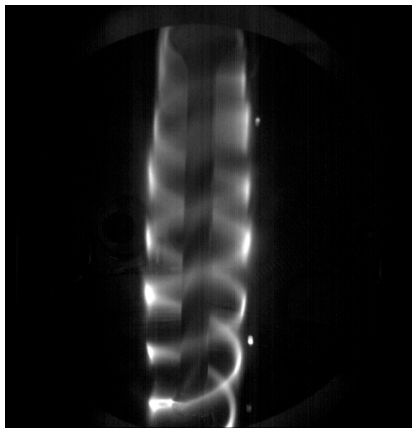
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Jonathon I. Moritz
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Point-Source Helicity Injection Technique

- Current is injected into the existing helical magnetic field
  - Superposition of vacuum toroidal and vertical fields
- High I_{inj} & modest B ⇒ filaments merge into current sheet
- High I_{inj} & low B ⇒ 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

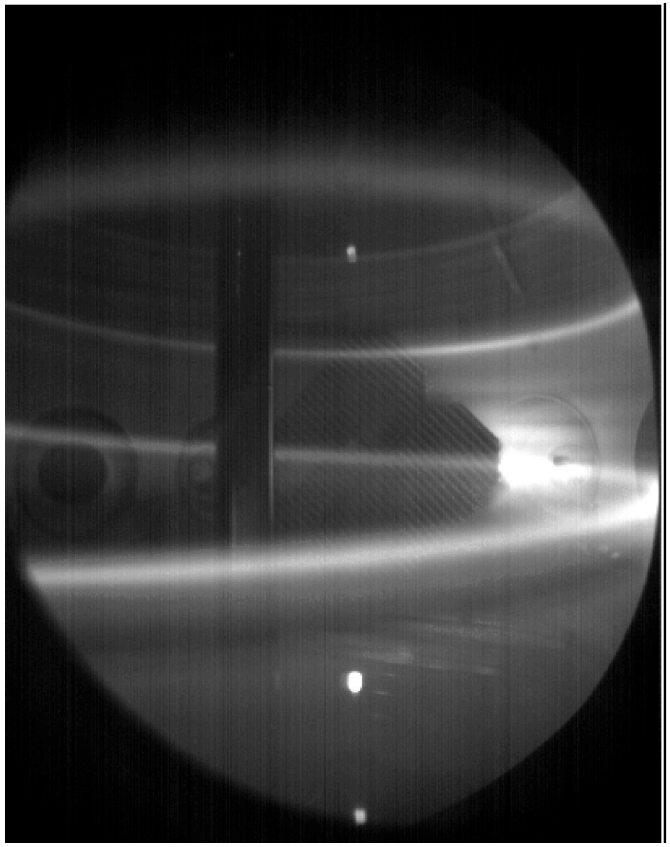


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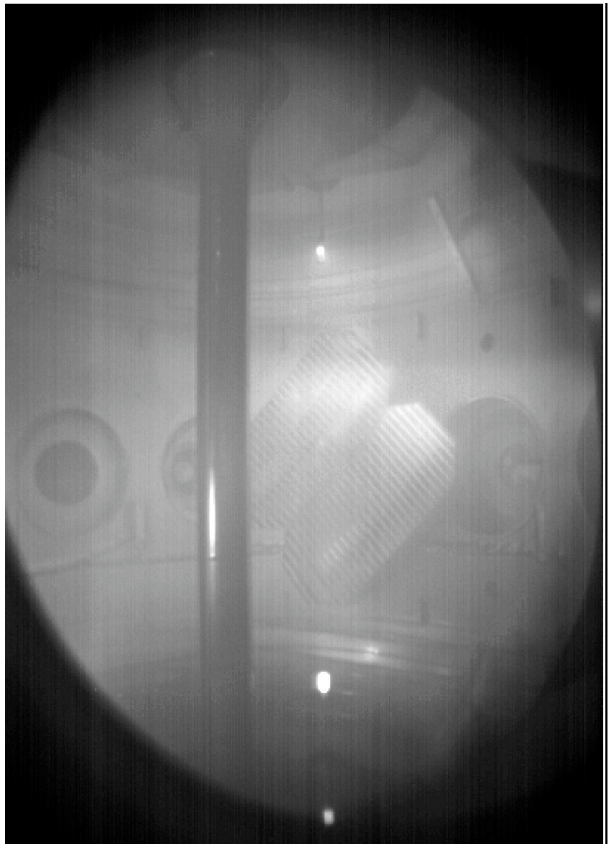
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Evolution of midplane-gun-driven plasma

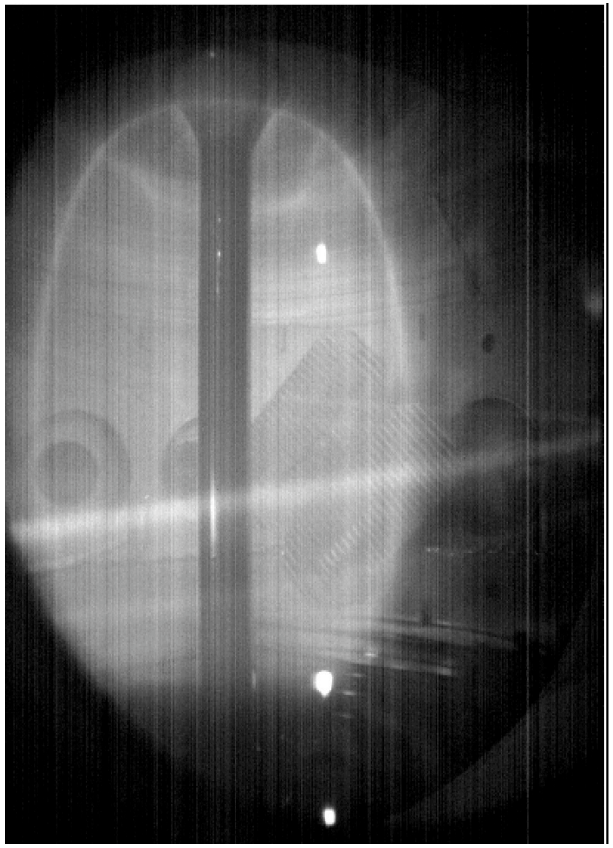
PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



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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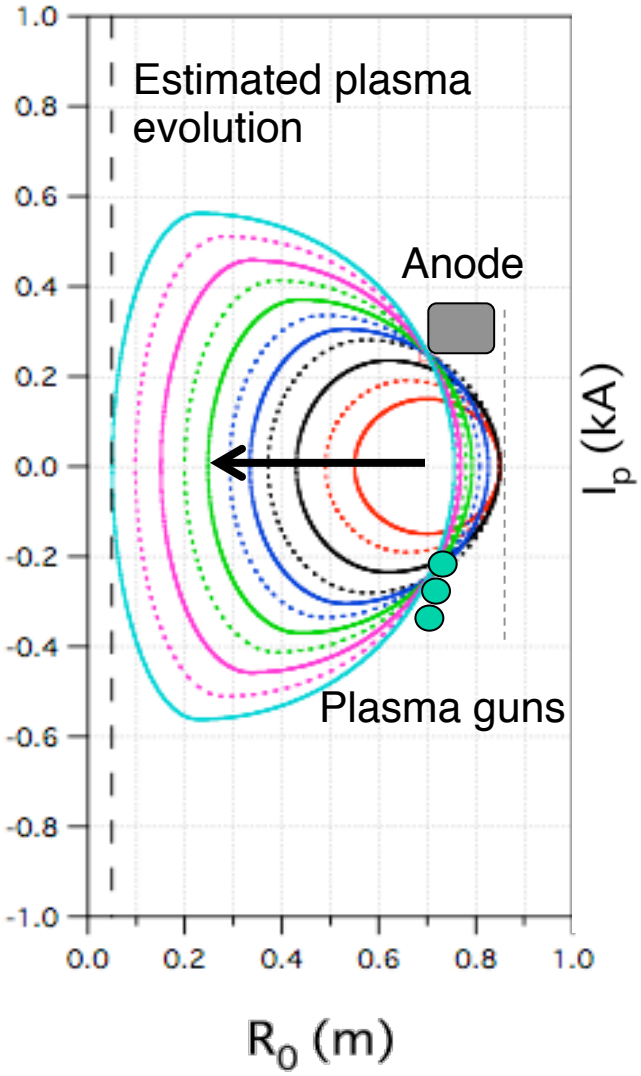
Driven helical filaments can relax to an axisymmetric tokamak-like state

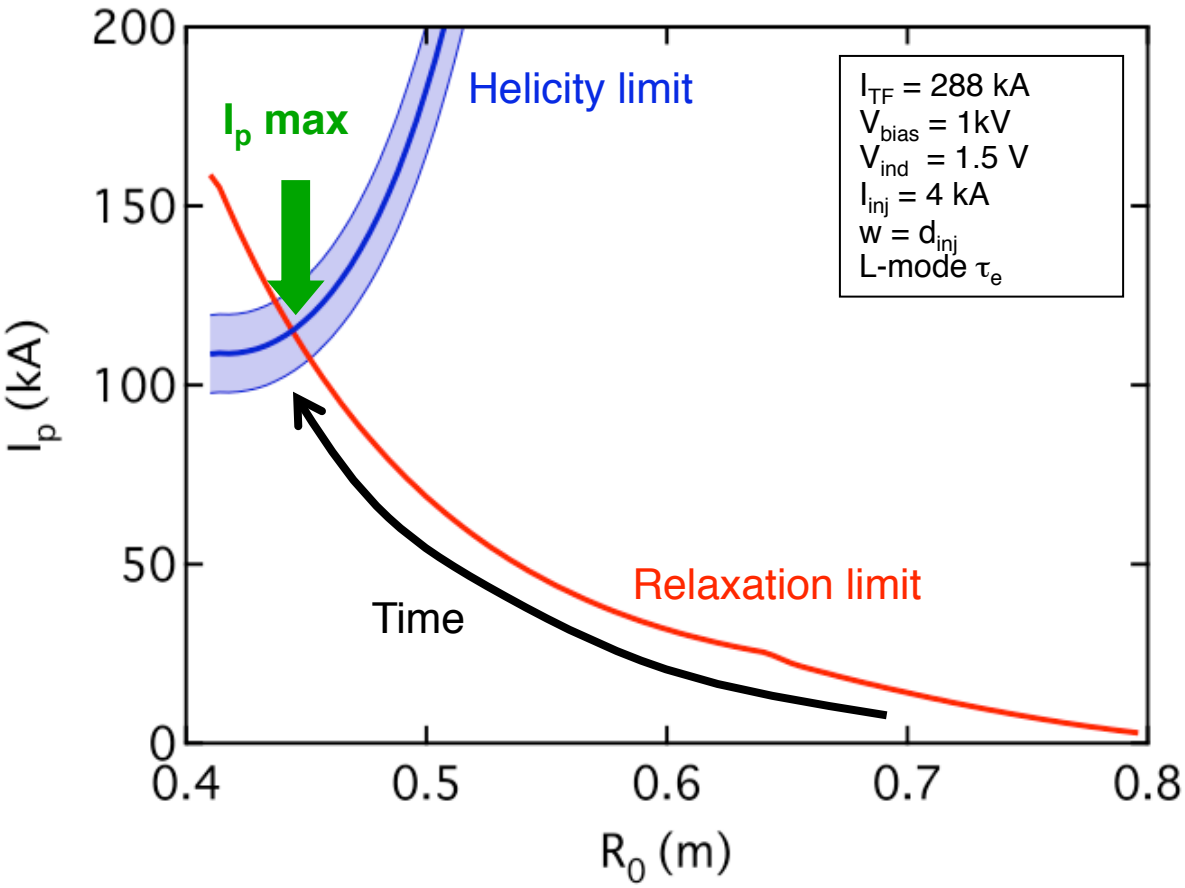
- Driven helical filaments are strongly unstable
- Tokamak-like equilibrium satisfies a set of conditions
  - Radial force balance, helicity/power balance, kink stability (edge q > 3), and a Taylor relaxation current limit
- Max I_p determined by dK/dt and Taylor relaxation limit:

$$I_p \leq f_G \left[\frac{\varepsilon A_p I_{TF} I_{inj}}{2\pi R_{edge} w} \right]^{1/2}$$

where ε is the inverse aspect ratio, A_p is the plasma cross-sectional area, I_{TF} is the TF coil current, I_{inj} is the gun bias current, R_{edge} is the gun location, w is the width of the driven plasma region, and f_G is a scalar function ranging from 1 to 3, depending upon geometry.
See Battaglia *et al*, Phys. Rev. Lett. **102**, 225003 (2009).

Maximum I_p achieved when helicity input is sufficient to reach the relaxation limit

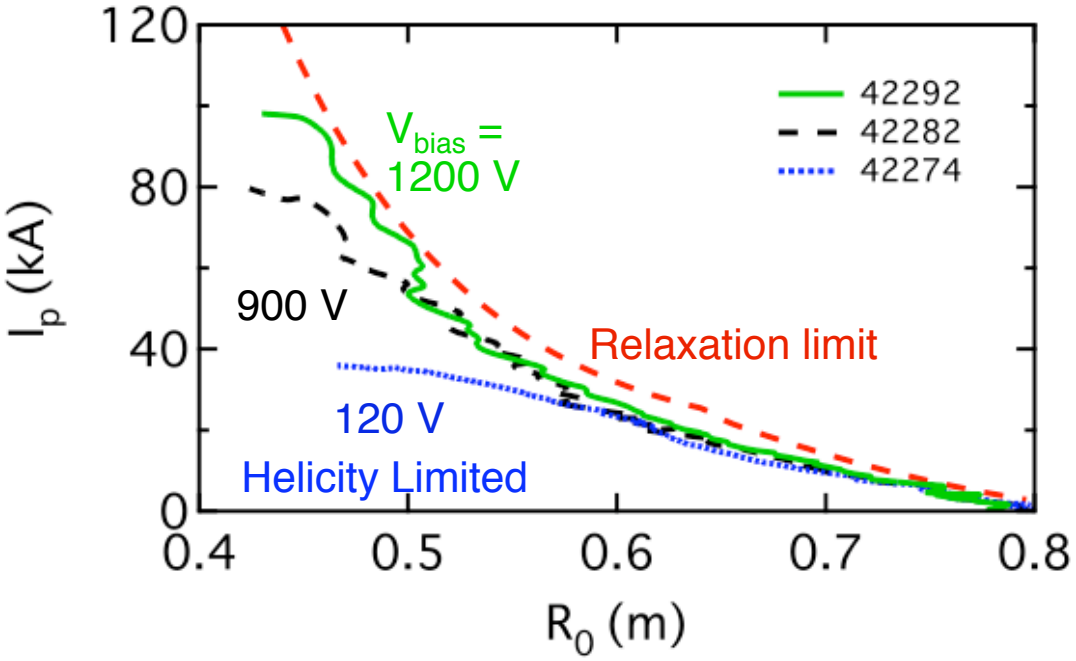




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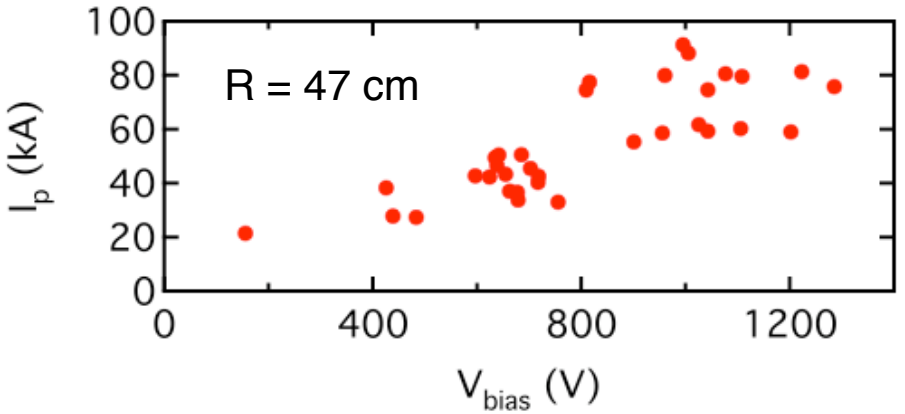
Sufficient helicity injection is required to drive the plasma up to the relaxation limit



$$\dot{K}_{DC} \propto V_{bias} \propto Z_{inj}$$

High dK/dt with modest I_{bias} requires high impedance Z_{inj}

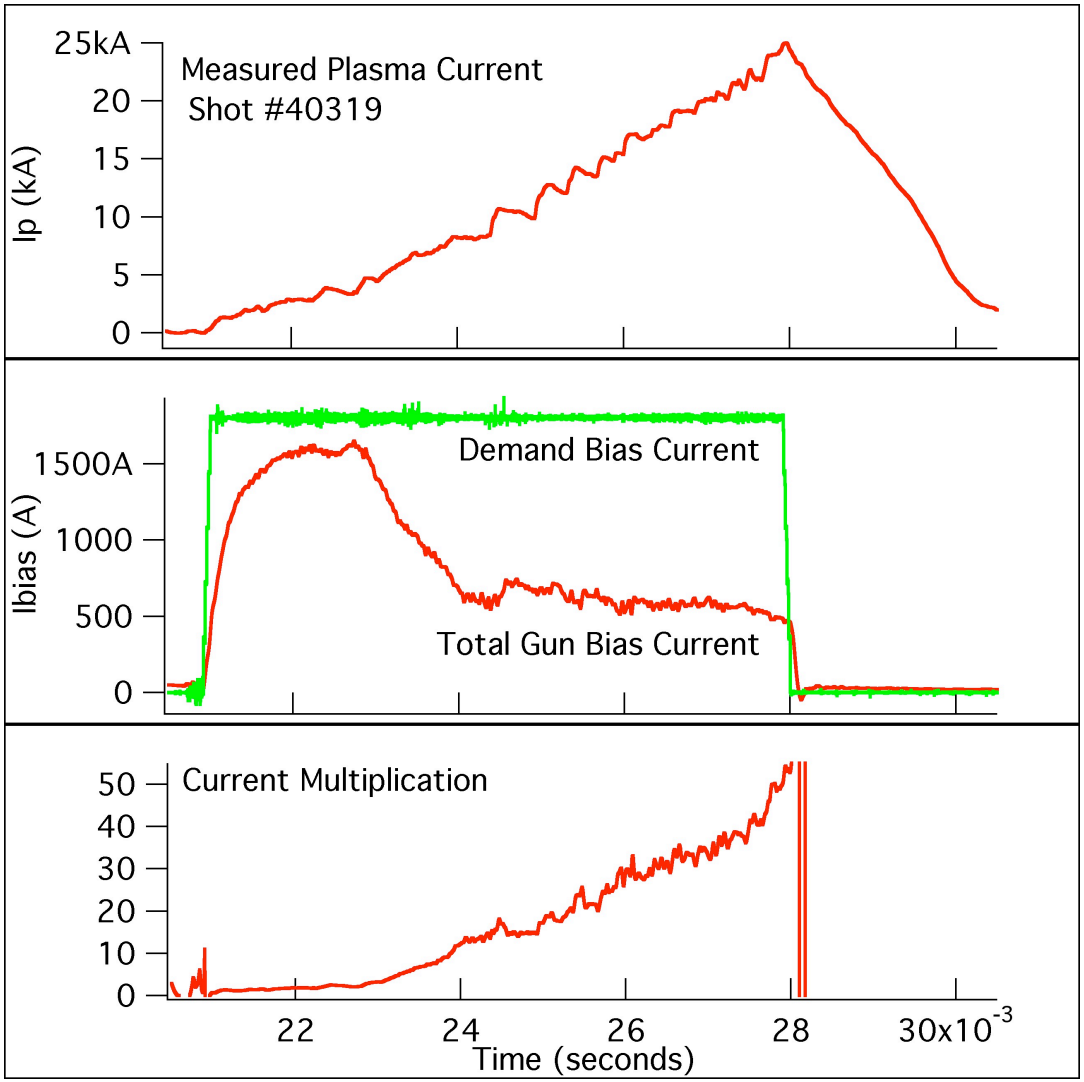
Max I_p increases with V_{bias}



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Current-profile relaxation and high current multiplication can occur without PF ramps

- Single-gun discharge with no PF ramps.
- Current multiplication above 50 at gun shutoff.
- Discrepancy between demanded and actual bias current is due to insufficient bank voltage.



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Magnetic helicity in tokamak plasmas

Magnetic helicity is a measure of the linkage between magnetic fluxes (or, equivalently, the currents that generate those fluxes).
The general definition of magnetic helicity is an integral over a volume that encompasses the linked fluxes:

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



Magnetic helicity is the best-conserved constant of motion in magnetized plasma, decaying on resistive timescales.

In the case of two linked but distinct fluxes ϕ and ψ, similar to the rings shown, the total magnetic helicity of the volume is $K=2\phi\psi$.

In a tokamak, the magnetic helicity K is proportional to the product $I_{TF}I_p$, with I_{TF} determined by the TF coil power supply. Increases in the helicity K correspond to increases in the toroidal plasma current I_p.

Current drive in a tokamak is equivalent to magnetic helicity injection

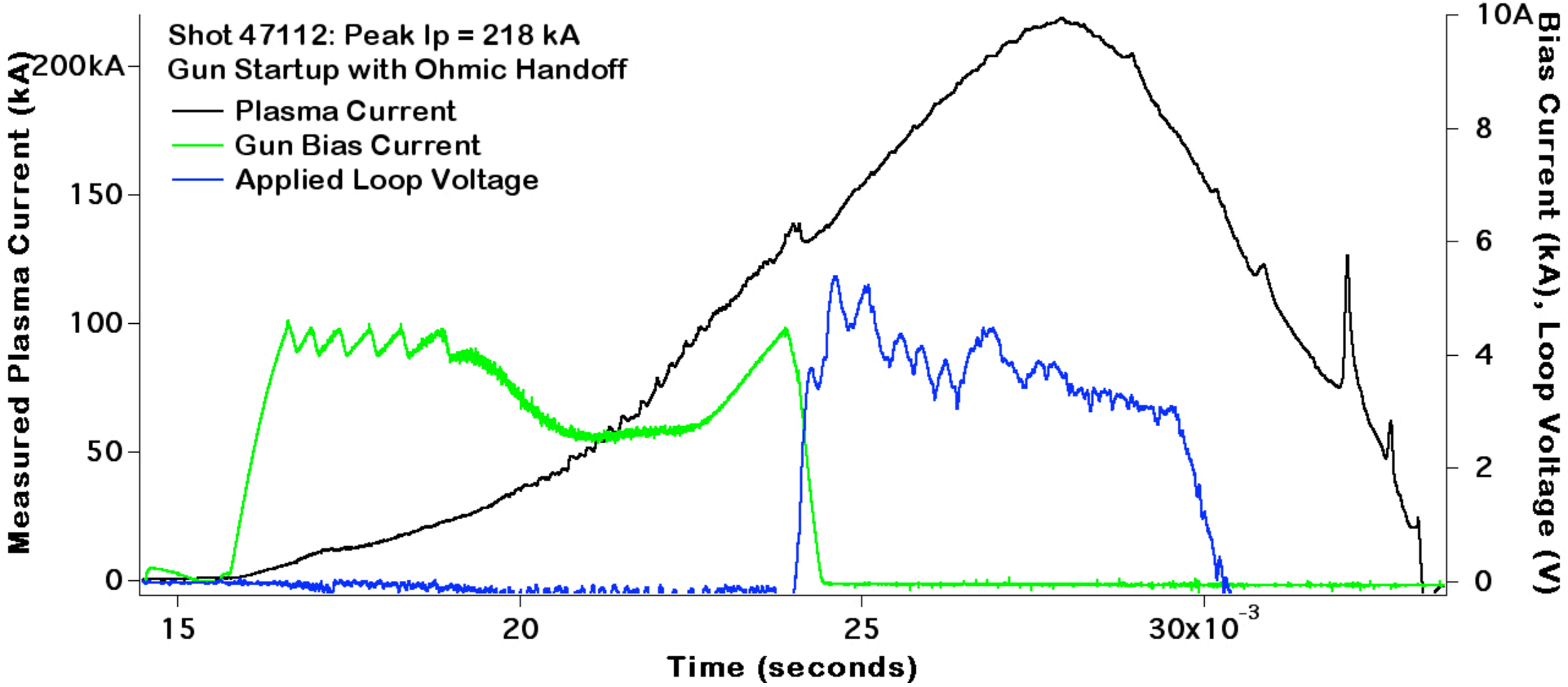
Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, \mathrm{d}^3\mathrm{x}$

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, \mathrm{d}^3\mathrm{x} - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot \mathrm{ds}$$

- Resistive Helicity Dissipation
  - $\mathbf{E} = \eta\mathbf{J} \rightarrow$ much slower than energy dissipation ($\eta\mathbf{J}^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity
- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
  - Ψ is toroidal flux, ψ is poloidal flux
- DC Helicity Injection $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot \mathrm{ds} = 2V_{inj}B_{\perp}A_{inj}$
  - Φ is electrostatic potential

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Handoff to single-swing Ohmic can drive up to I_p/I_{TF}=0.7 at I_p=218 kA

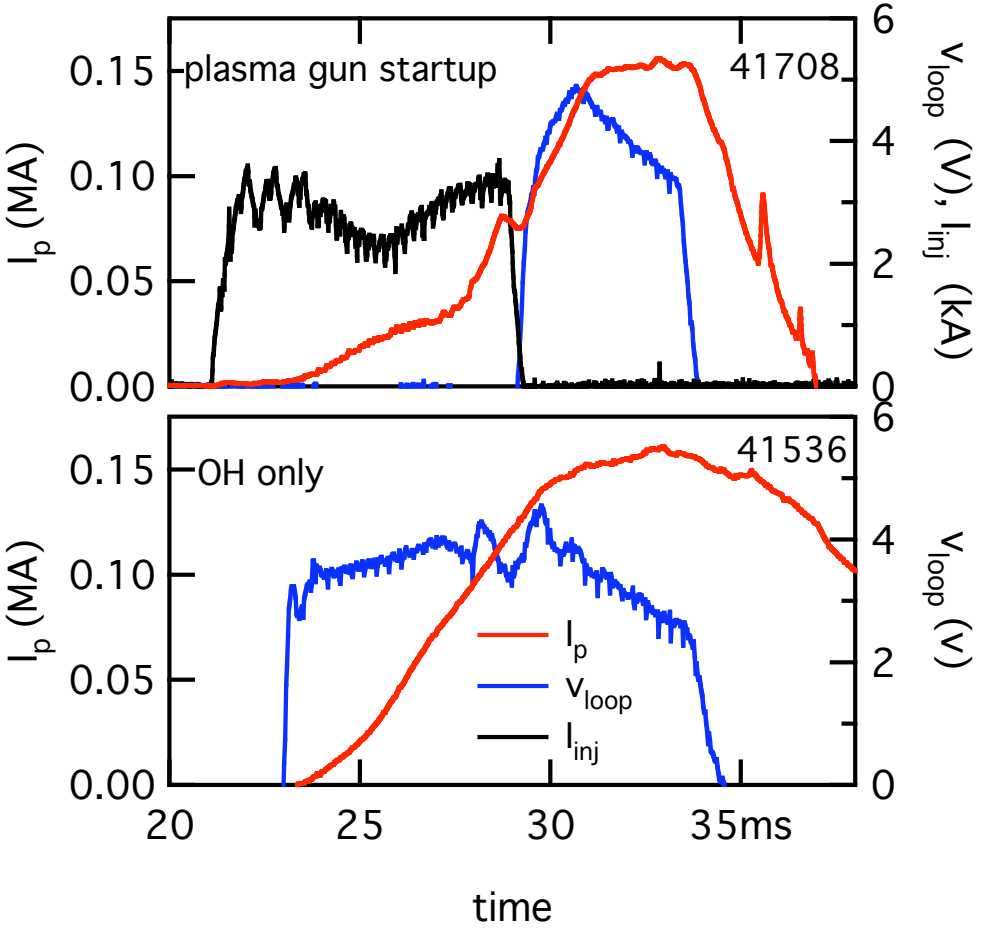


Ohmic evolution is not optimized: plasma is being crushed into the centerstack, which probably causes the I_p rollover.

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Helicity Injection Startup Can Provide 50% Ohmic Flux Savings

- Compare two scenarios:
  1. Handoff of 80 kA gun-driven target to single-swing Ohmic
  2. vs pure-Ohmic double-swing
- Handoff discharge reaches same peak I_p using half the Ohmic flux
  - Implies ~ 50% flux savings
- Can assess suitability of gun-driven discharges for other CD techniques
  - 0.8-1.0 MW PEGASUS HHFW

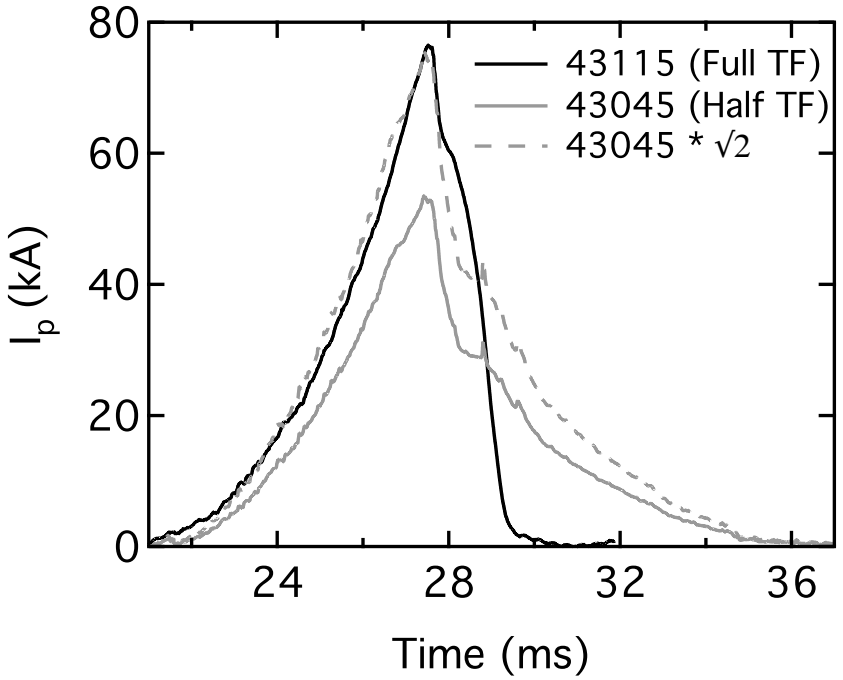


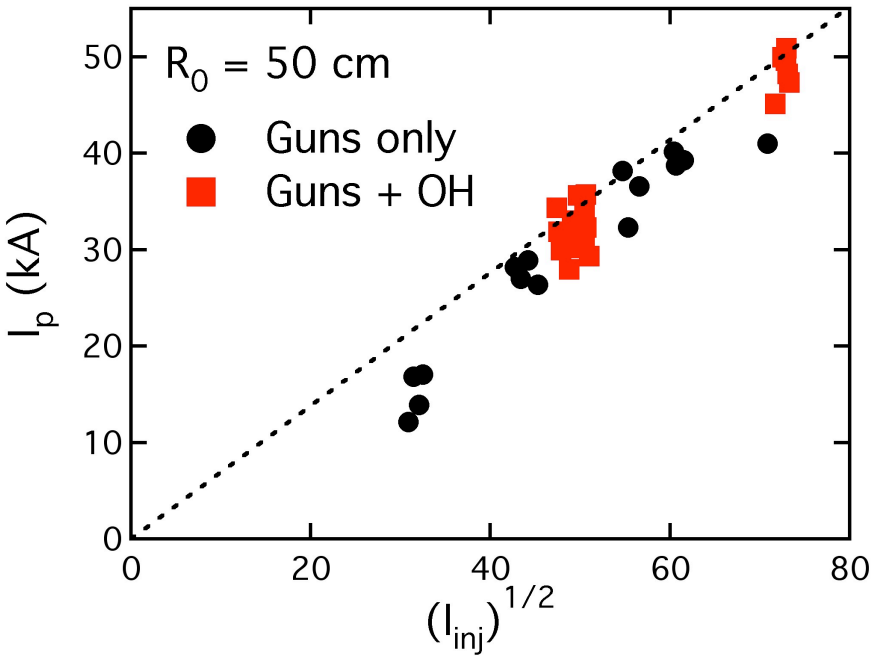
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Empirical scalings with I_{TF} and I_{bias} are consistent with relaxation limit model

- Predicted relaxation limit I_p scales with $(I_{TF}I_{bias})^{1/2}$
- Experimental I_p observed to follow these scalings:



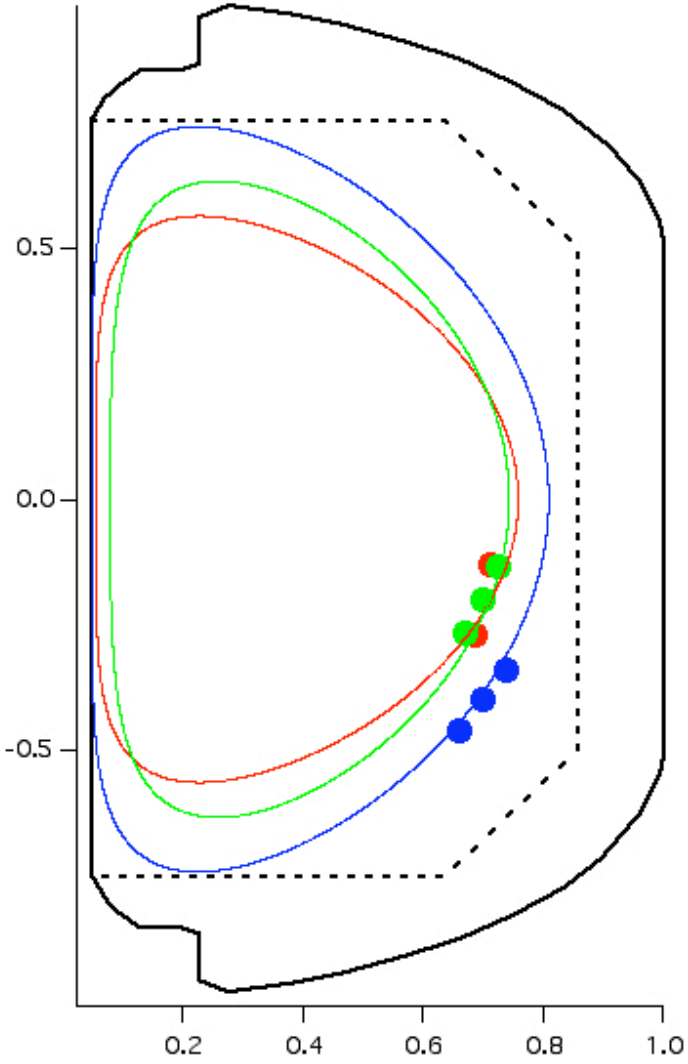


Note: adding solenoid induction during gun drive does not allow driven I_p to exceed the Taylor relaxation limit

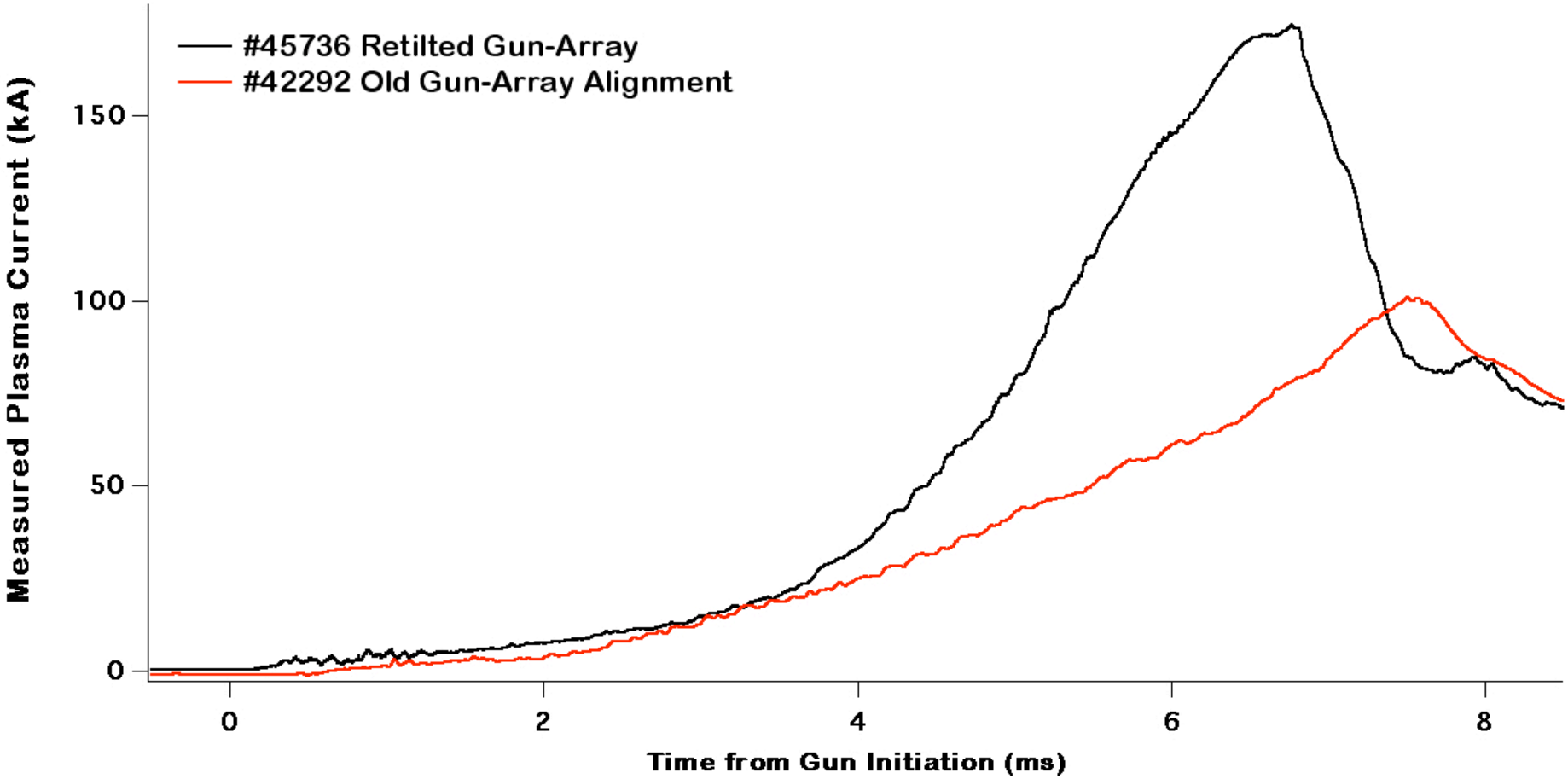
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Gun array was realigned to reduce *w*, significantly increasing relaxation limit

- Current limit scales as $w^{-1/2}$
- Gun array was nearly vertical, leading to poor alignment with the plasma edge
- Best peak I_p was 115 kA with old gun array alignment
- Changing the tilt of the gun array increased the max I_p by a factor of 1.5-1.7, implying a factor-of-3 change in *w*., consistent with changing the projected width at midplane.
- With new alignment, have achieved I_p = 174 kA.



Retilted gun array allows much higher maximum gun-driven I_p



Highest peak currents with old gun-array alignment were around 100 kA
Retilted gun array allows plasma currents of over 170 kA

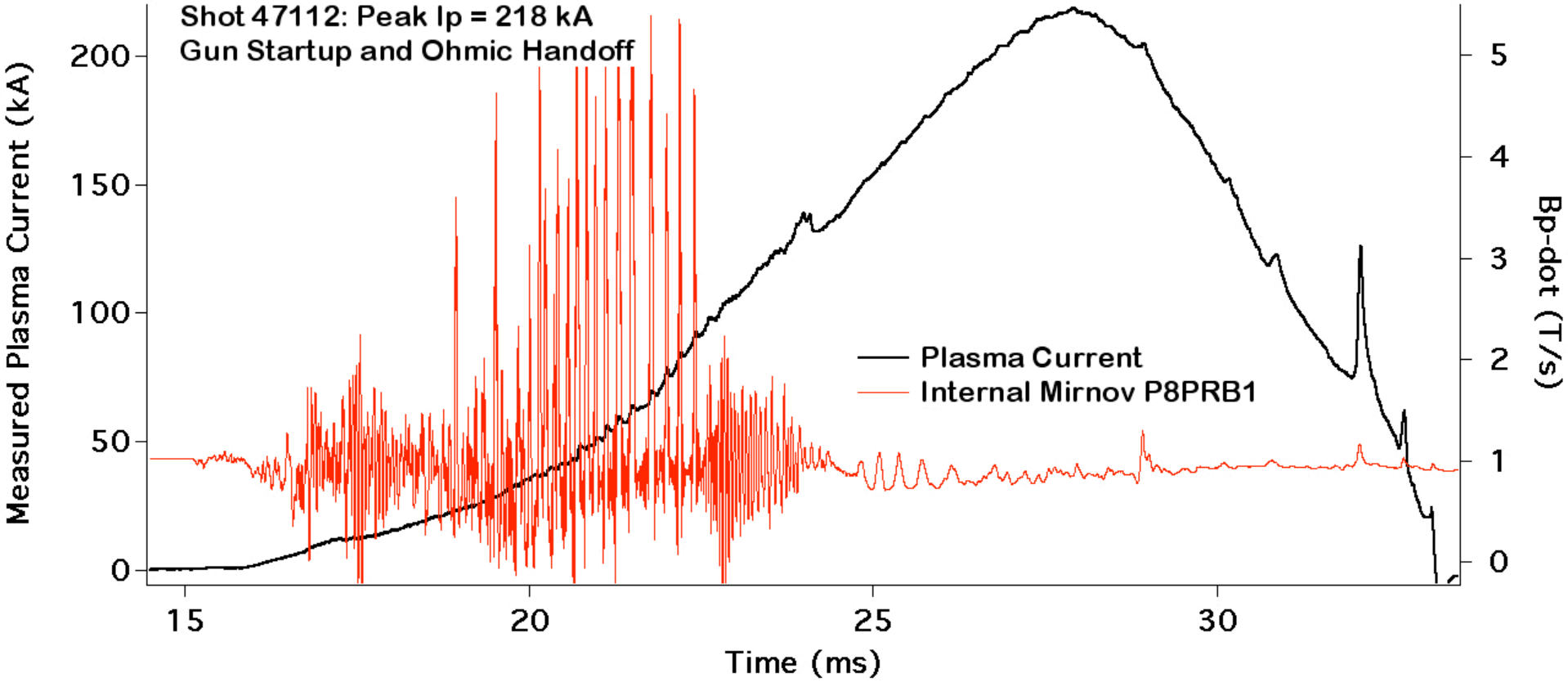
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Slow current evolution during helicity injection allows current-profile relaxation

- dI_p/dt during gun phase is strongly affected by the applied bias current and voltage, outer-PF induction, and fuelling.
- Gun plasmas hand off most efficiently to Ohmic when the gun drive shuts off at the current peak.
  - Higher bias voltage, or more outer-PF induction, raises dI_p/dt
  - More fuelling lowers dI_p/dt
  - Gun-driven current can peak, and the plasma decouple from the guns, before the pre-programmed gun drive ends.
- Efficient handoff relies upon careful tailoring of fuelling, bias current, and outer-PF ramping, which is consistent with controlling the current profile evolution.
  - Good handoff requires a slowly evolving I_p, which would be consistent with a broader, less hollow current profile.

MHD activity tends to be strongly reduced after gun bias shutoff



Shortly after gun shutoff, plasma currents are similar to those in PEGASUS Ohmic discharges, while equilibrium reconstructions indicate that the q-profiles are similar to Ohmic. But the handoff discharges remain quiescent, while the Ohmic discharges are unstable to low-n tearing modes.

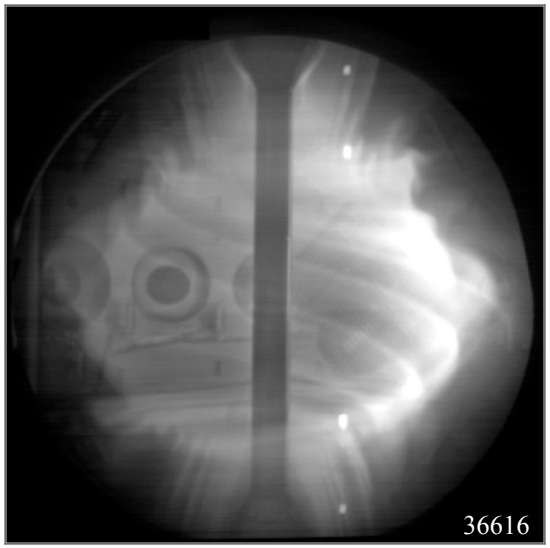
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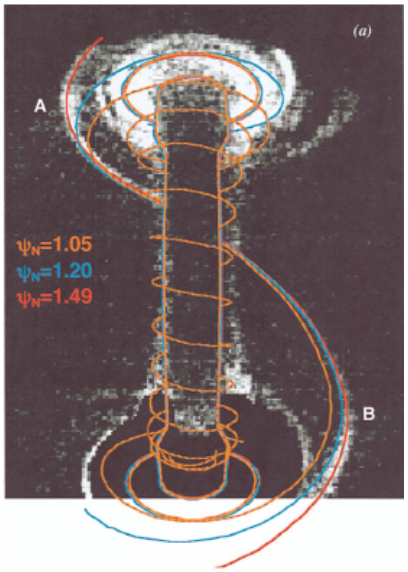
Rapid equilibrium shifts during gun drive correlate with bursty low-n MHD activity

- During helicity injection phase, bursty MHD activity appears:
  - Typically n=1, with frequencies varying from 20 kHz to 60 kHz
  - Can be either intermittent or continuous with "bursts" of large amplitude
  - Mode frequency and amplitude may vary with magnetic field
- "Bursts" correlate with rapid rises in I_p, density dumps, and inward radial shifts of the plasma.
- External kink mode (n=1) correlates with current-profile relaxation and poloidal flux amplification in CHI-driven spheromaks and STs:
  - Computational work by A.Bayliss, D.Brennan, and X.Tang each provide detailed studies of current-profile relaxation through low-n modes
  - A similar mechanism may be responsible for relaxation in PEGASUS
- Presently under study: to understand the onset of the bursts and the detailed mechanism for the equilibrium shifts.

Filamentary ELM-like Structures Observed

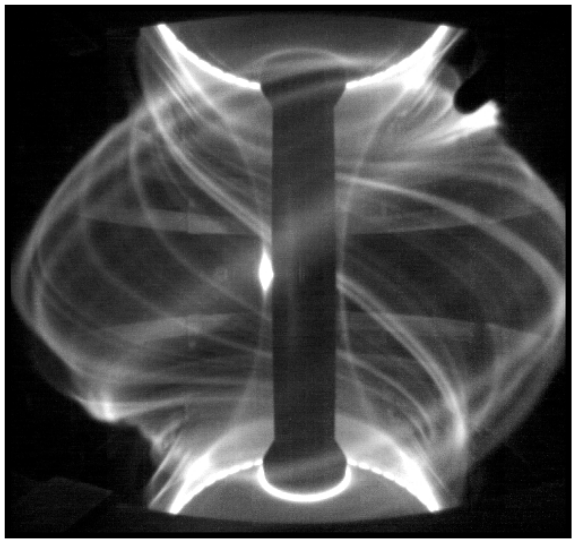


PEGASUS



Maingi, Phys. Plasmas **13**, 092510 ,2006

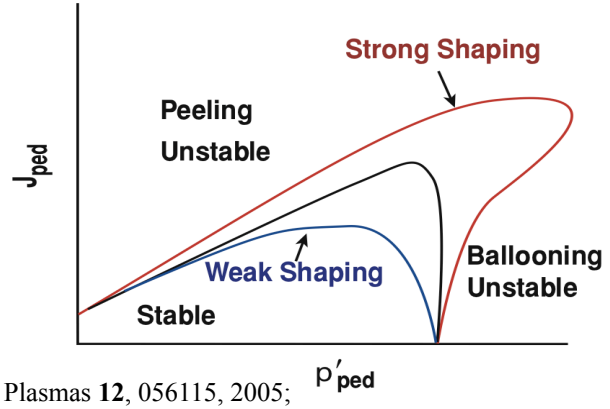
NSTX



Kirk, Plas. Phys. Controlled Fus. **49**, 2007

MAST

- ELMs take form of filamentary, field-aligned structures
  - Peeling-ballooning theory: trigger mechanism
- PEGASUS: L-mode edge assumed
  - Peeling instability candidate mechanism



Snyder, Phys. Plasmas **12**, 056115, 2005;
see also Hegna, Phys. Plasmas **3**, 584, 1996

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Near-unity A: Naturally Strong Peeling Drive

Device	J_{edge} (MA/m^2)	$B_{\varphi,0}$ (T)	J_{edge}/B
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**
DIII-D*	1 – 2	2	**0.5 – 1**

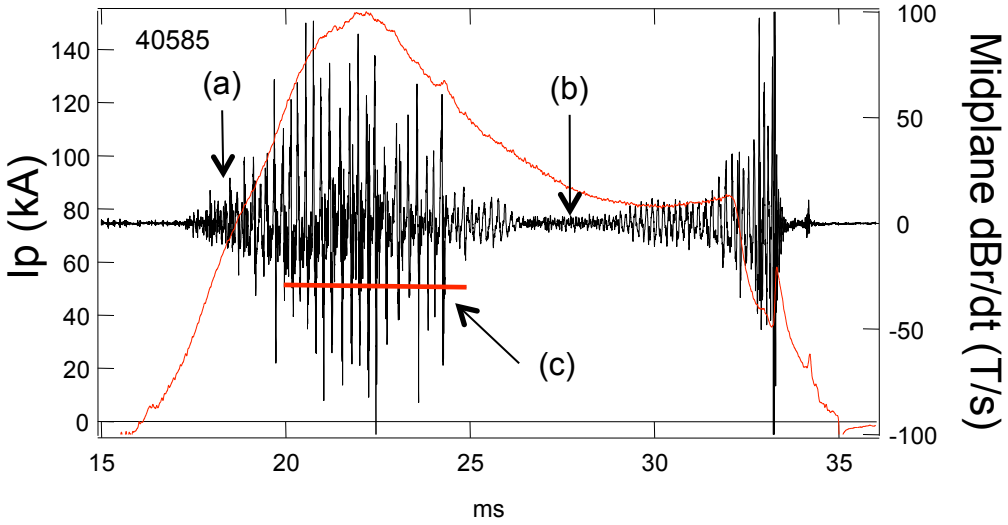
*: Thomas, Phys. Plasmas **12**, 056123 2005

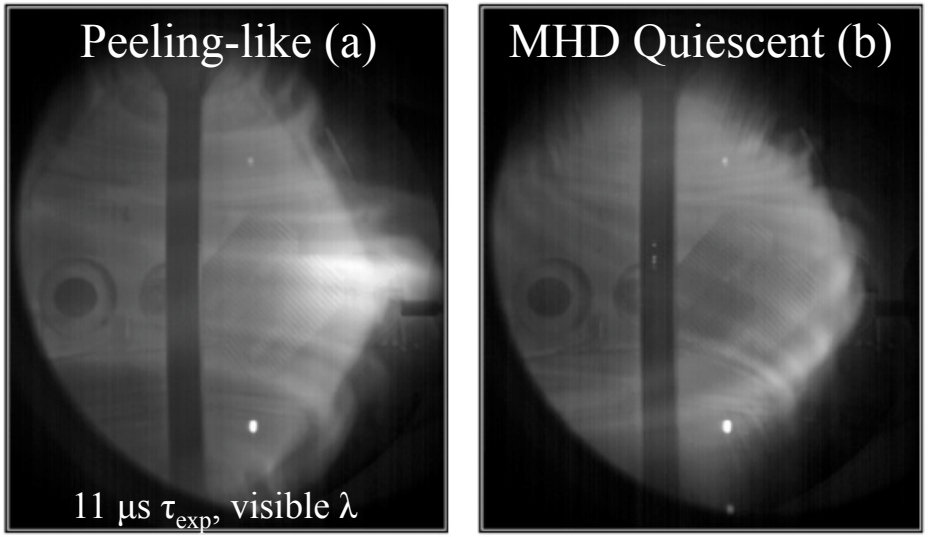
- j_{edge}/B is a figure of merit for quantifying peeling drive
- PEGASUS operations at A → 1 lead to naturally high j_{edge}/B
  - Comparable to larger machines in H-mode
- However, *source* of peeling drive different
  - Large machines: H-mode p' → j_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current

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Two Distinct Filament Classes Observed

- Peeling-like (a)
  - EM signature: high m, low n
  - Coherent spatial structure
  - Filament rotation
  - Detachment, radial propagation
- MHD Quiescent/L-mode (b)
  - No EM signature
  - Electrostatic turbulence: short-lived filaments observable when $\tau_{exp} \leq 20$ μs
- Separated by n=1 internal tearing phase (c)





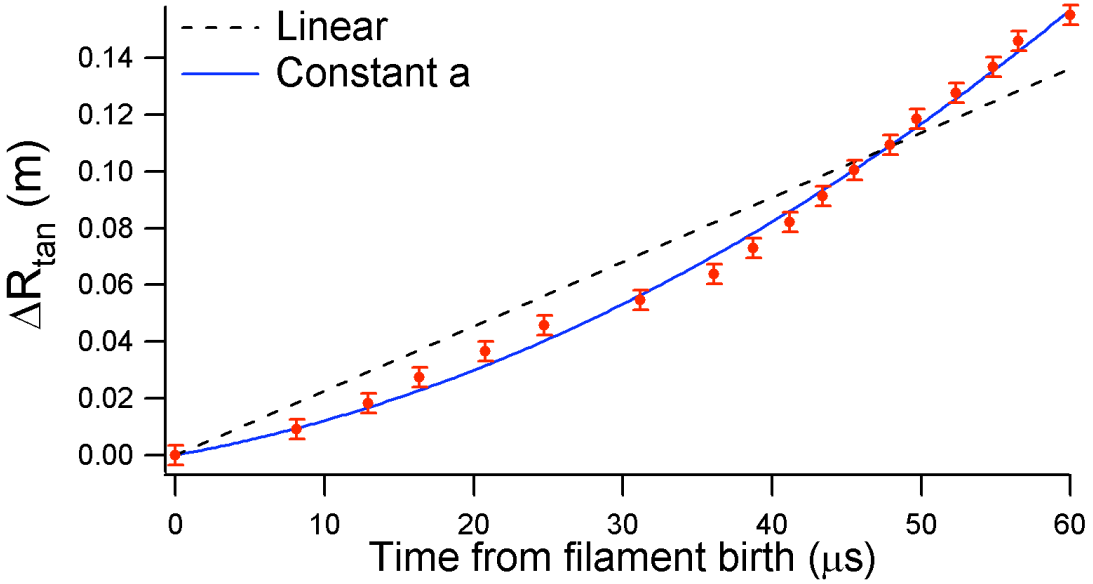
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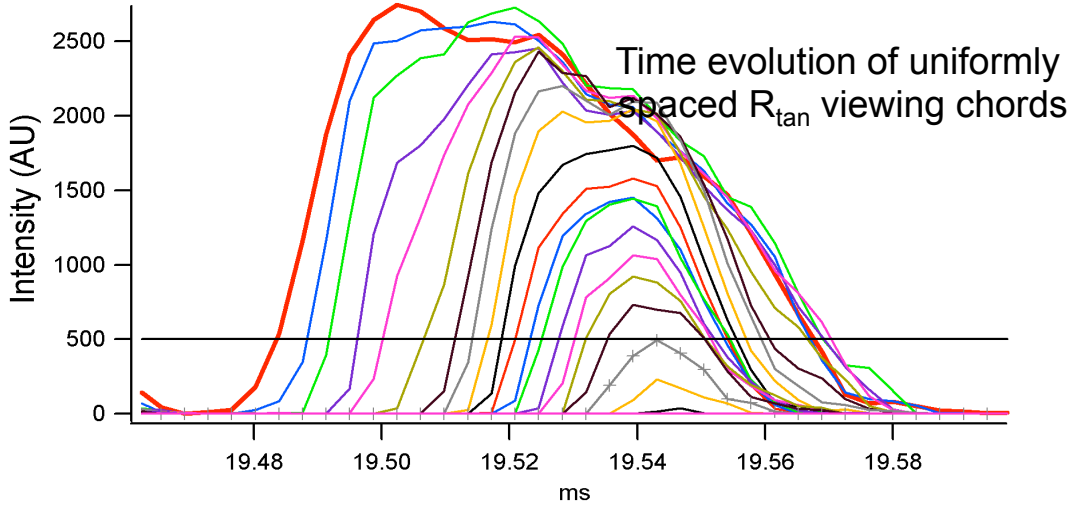
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Peeling-like Filaments Accelerate Radially

- Filaments detach from edge, propagate radially outboard
- Significant a_r measured
  - $a_r = 2.8 \times 10^7$ m/s^2
  - v_r: 1 → 4 km/s over 60 μs
- MAST*: Type-I ELM filaments accelerate radially

  *Kirk, Plas. Phys. Controlled Fus. **49**, 2007
- Filaments are by nature electromagnetic, and exhibit low-n and high-m

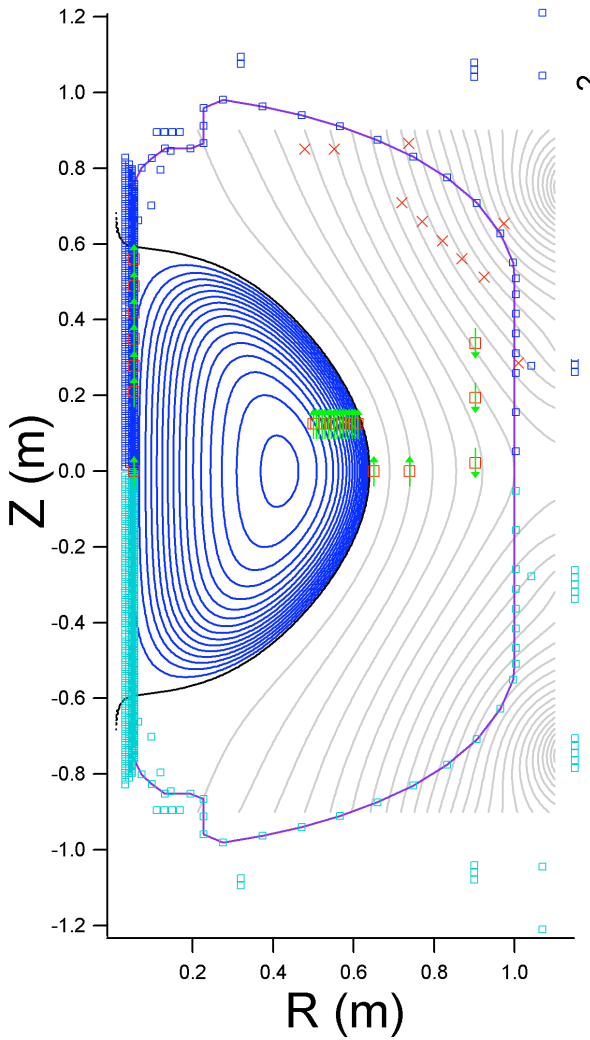


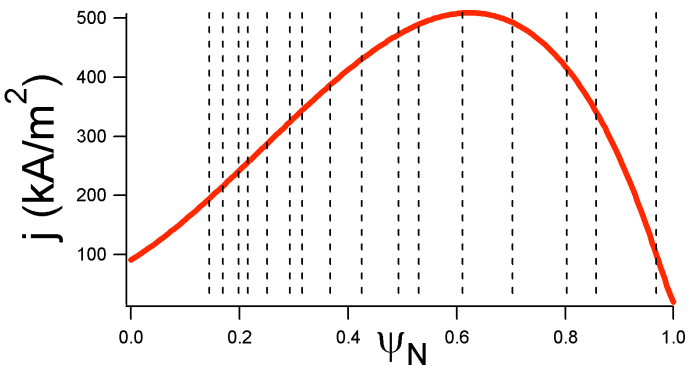


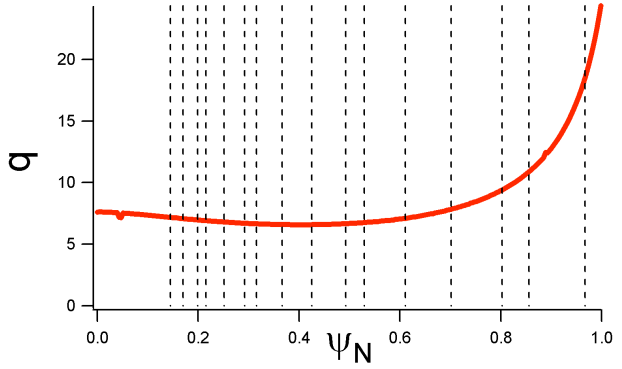
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Hall Probes Can Constrain J(ψ)





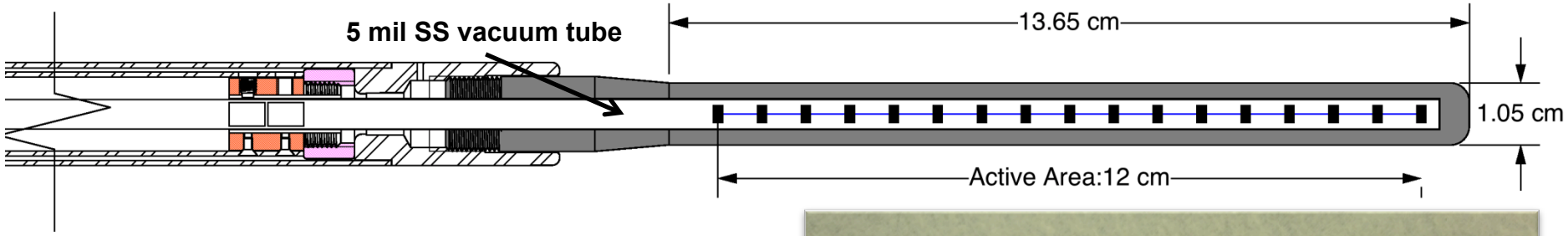


Representative profiles using 3-term polynomial fit

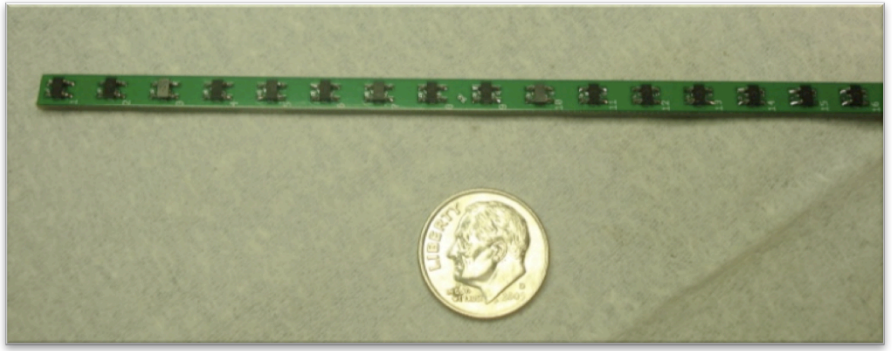
- Strong constraint over full ψ_N possible
  - Constraint locations ( ) vary in time due to evolution of plasma over fixed location of probes
- Polynomial parameterization inadequate to accurately fit internal data
  - Additional parameterizations in development

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PEGASUS Hall Probe To Constrain J(ψ)

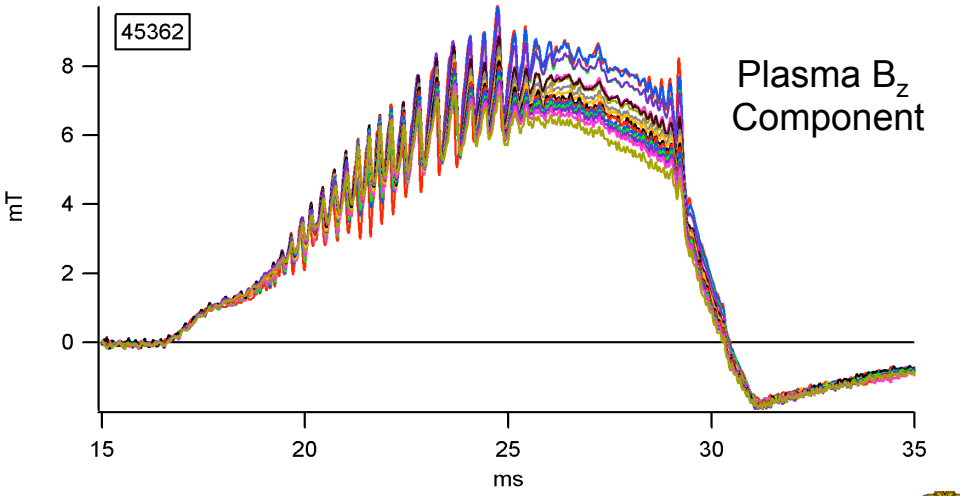


- Diagnostic Capability: $B_z(R,t)$
  - 16 Sypris SH-410 Hall detectors
  - 7.5 mm channel spacing
  - C armor: Low-Z PFC



- Good Temporal Resolution
  - Frequency response: ≤ 25 kHz

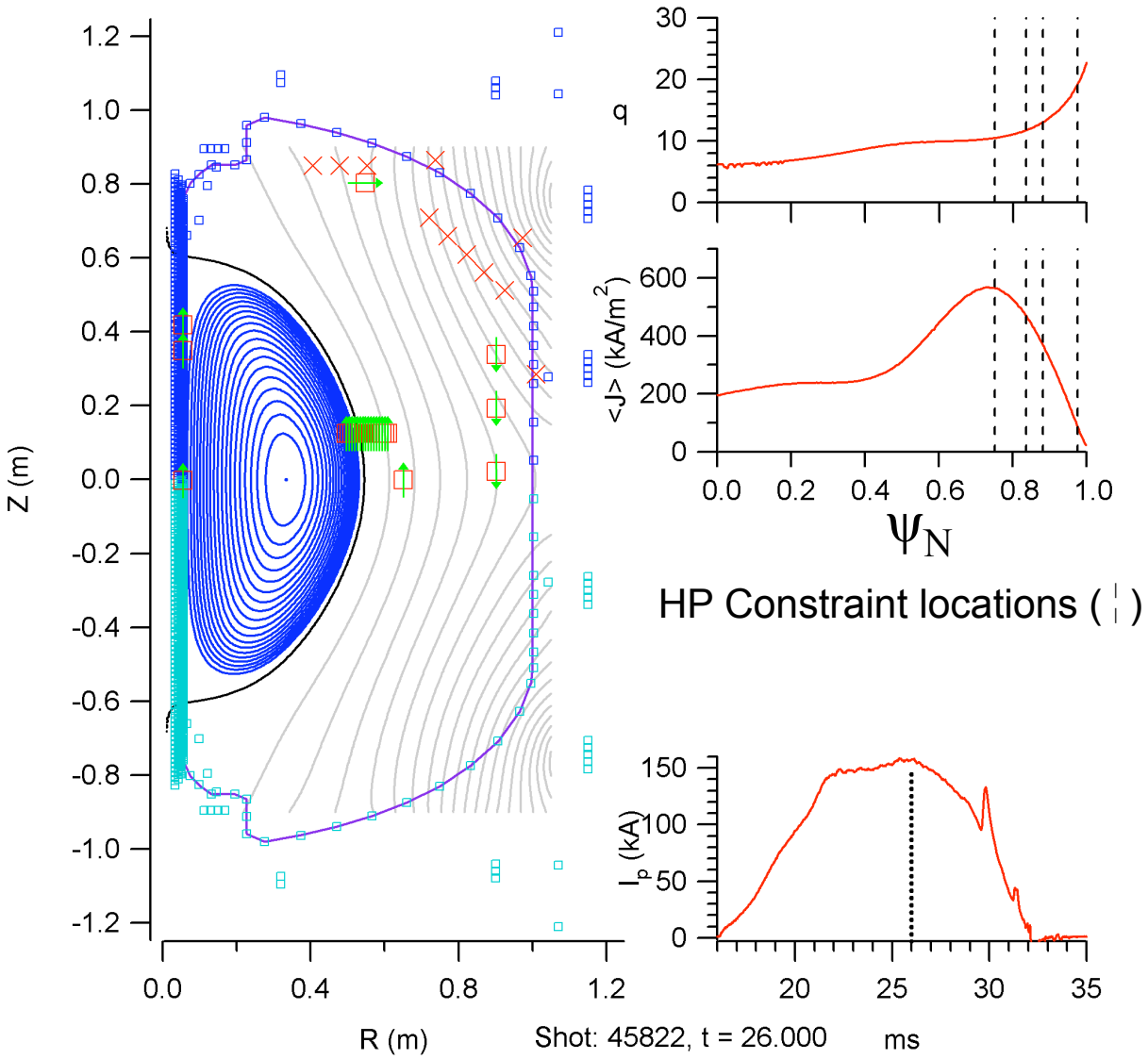
- Negligible plasma perturbation



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Improving Models to Determine $J_{edge}(\psi)$



- 5-knot cubic spline parameterization using KFIT* Grad-Shafranov solver

*Sontag, A, Nuclear Fusion, **48,** 095006 , 2008

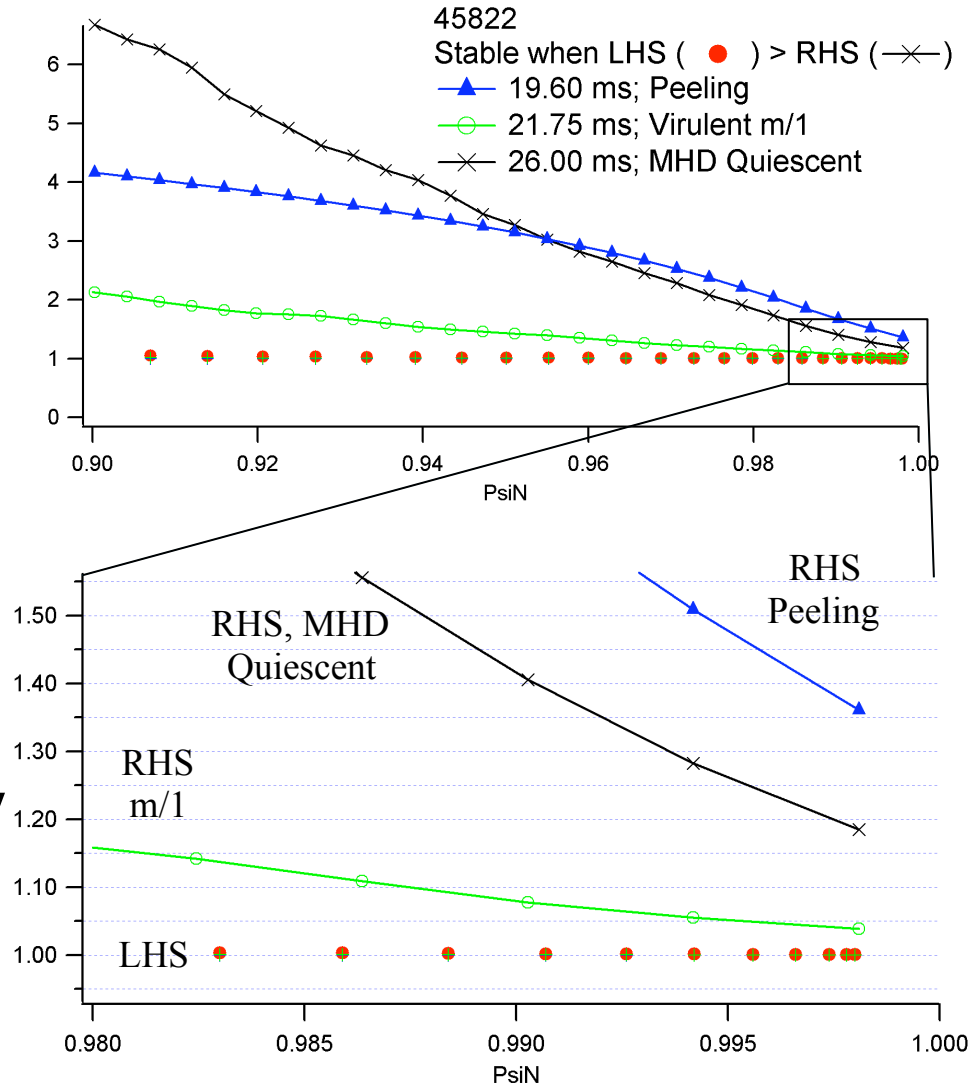
I_p	157 kA
R_0	.30 m
a	.24 m
A	1.2
κ	2.2
ℓ_i	.25
β_p	.10
β_t	.02
q_0	6.1
q_{95}	17

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Filament Appearance Consistent with Peeling Stability Criterion

- Connor's peeling stability criterion computed
  - KFIT spline fits coupled to DCON
- Peeling calculated unstable at all times (not observed)
  - However, peeling phase *is* least stable of all phases
- Future: Detailed comparison with peeling-ballooning theory
  - Stability analysis via DCON, ELITE

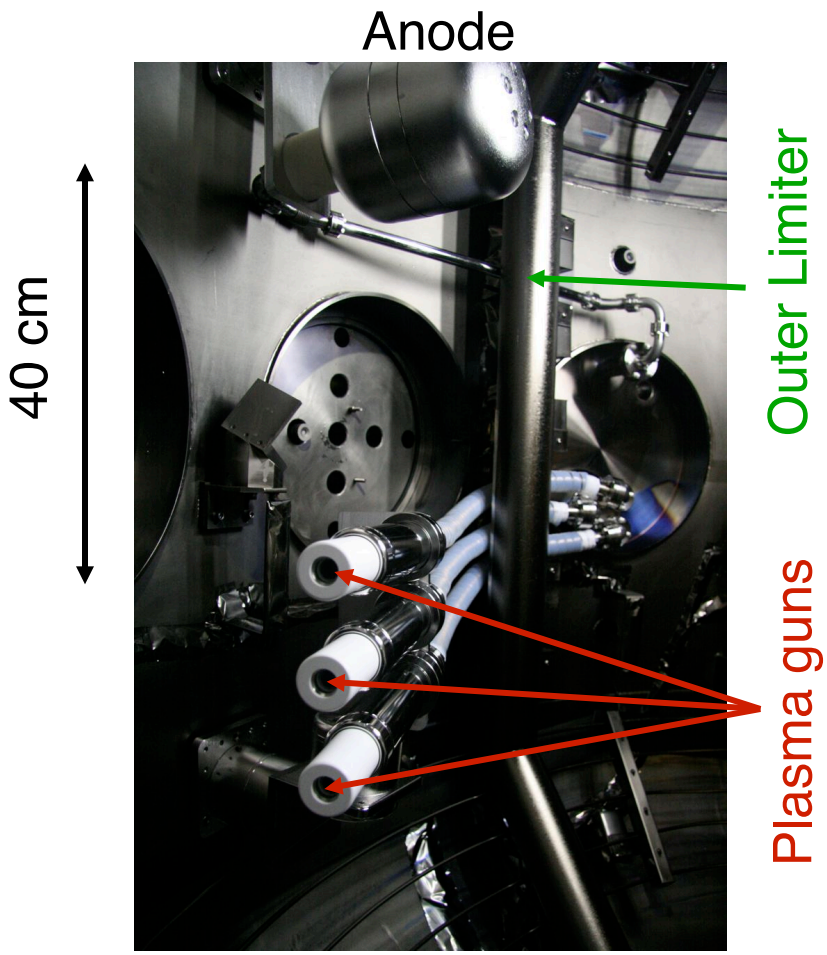


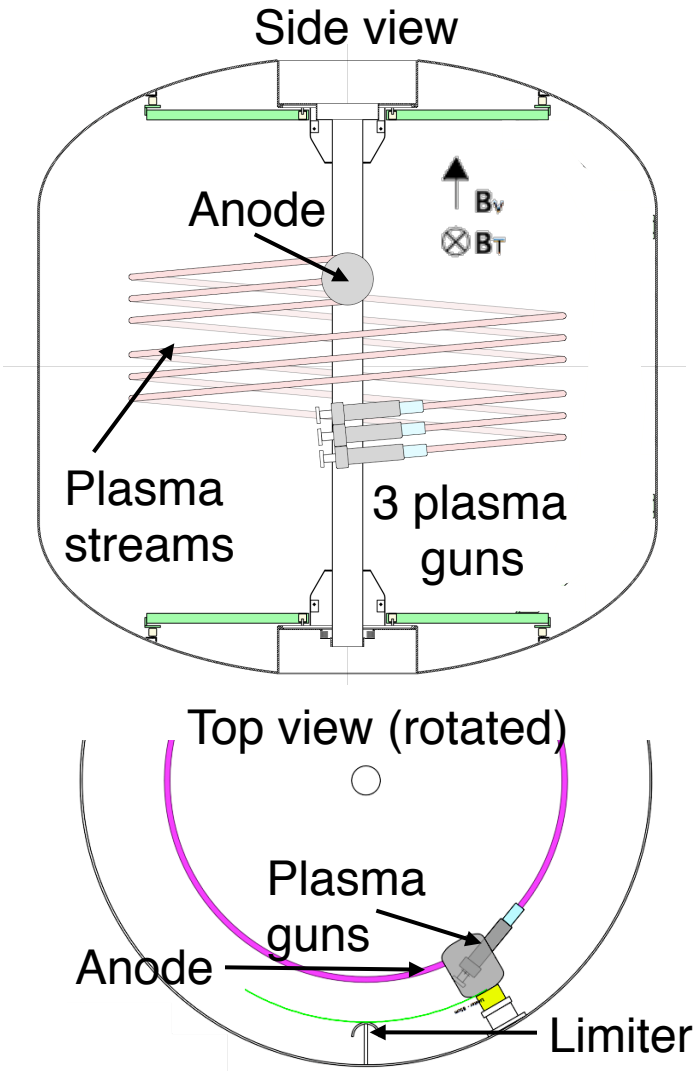
Unstable if RHS > LHS

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PEGASUS Point-Source Helicity Injection Uses an Array of Three Plasma Guns

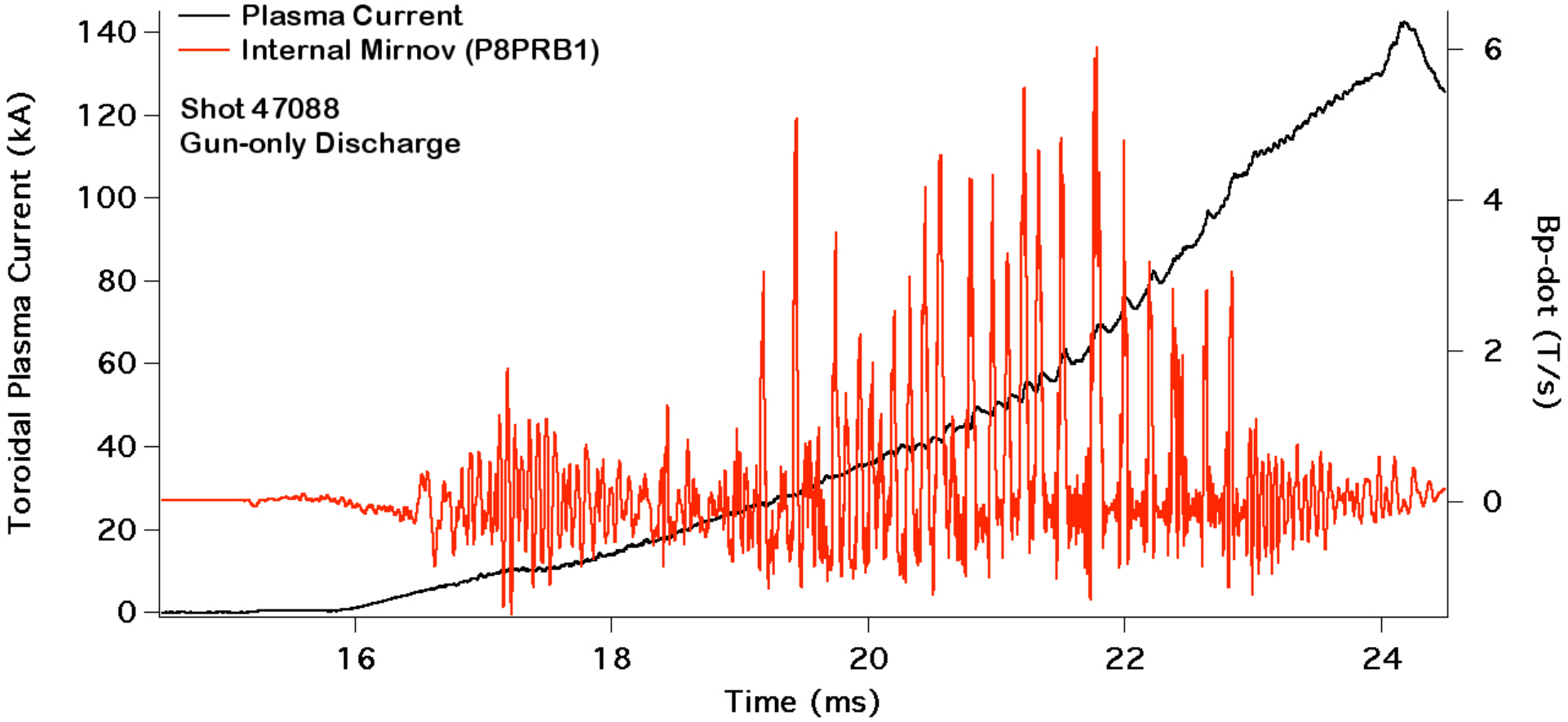




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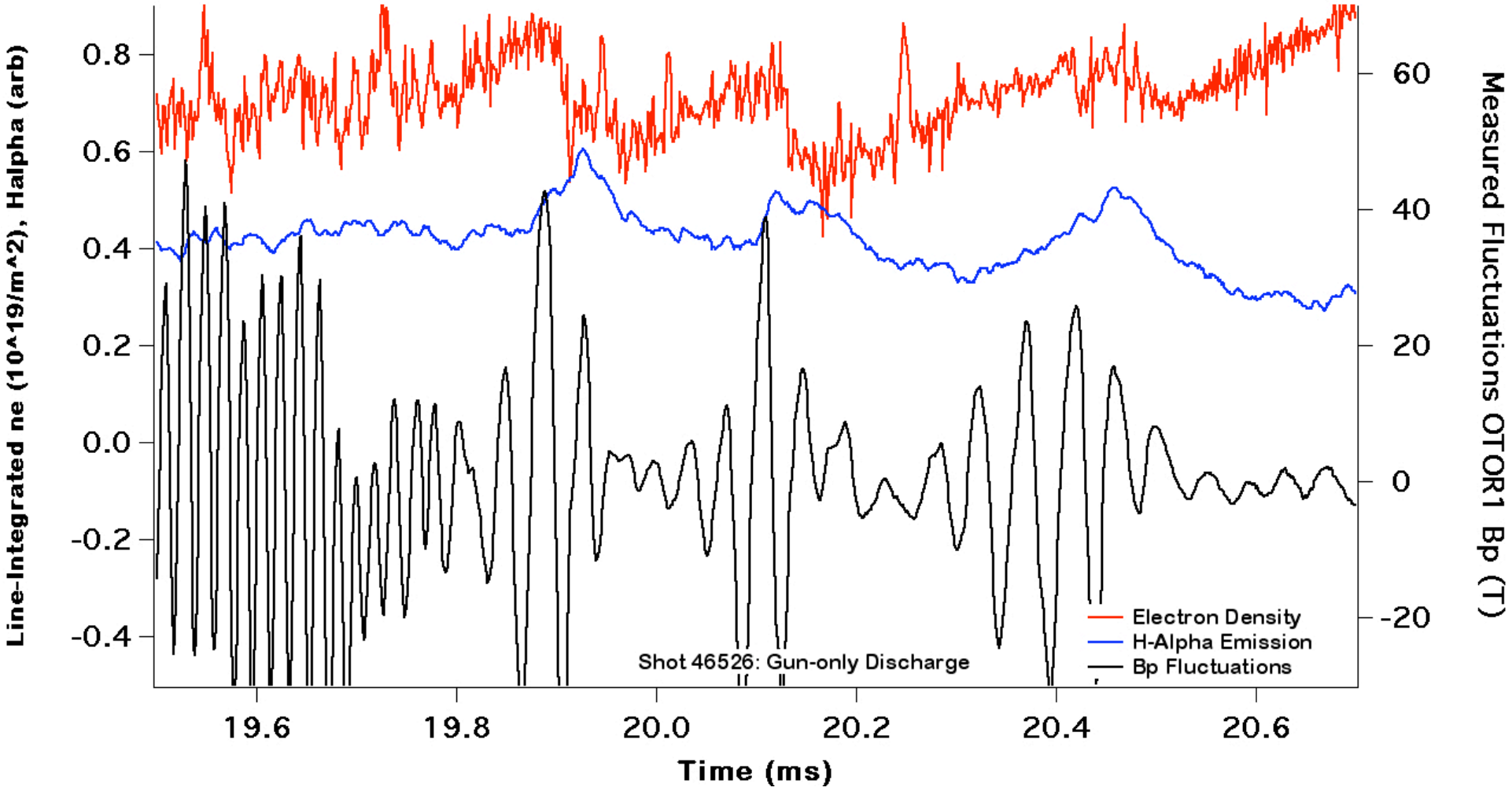
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MHD activity bursts during gun drive correspond to rapid rises in I_p



Rapid I_p rises correspond to inward shifts of the current channel, as noted in D.J.Battaglia's PhD dissertation (2009).

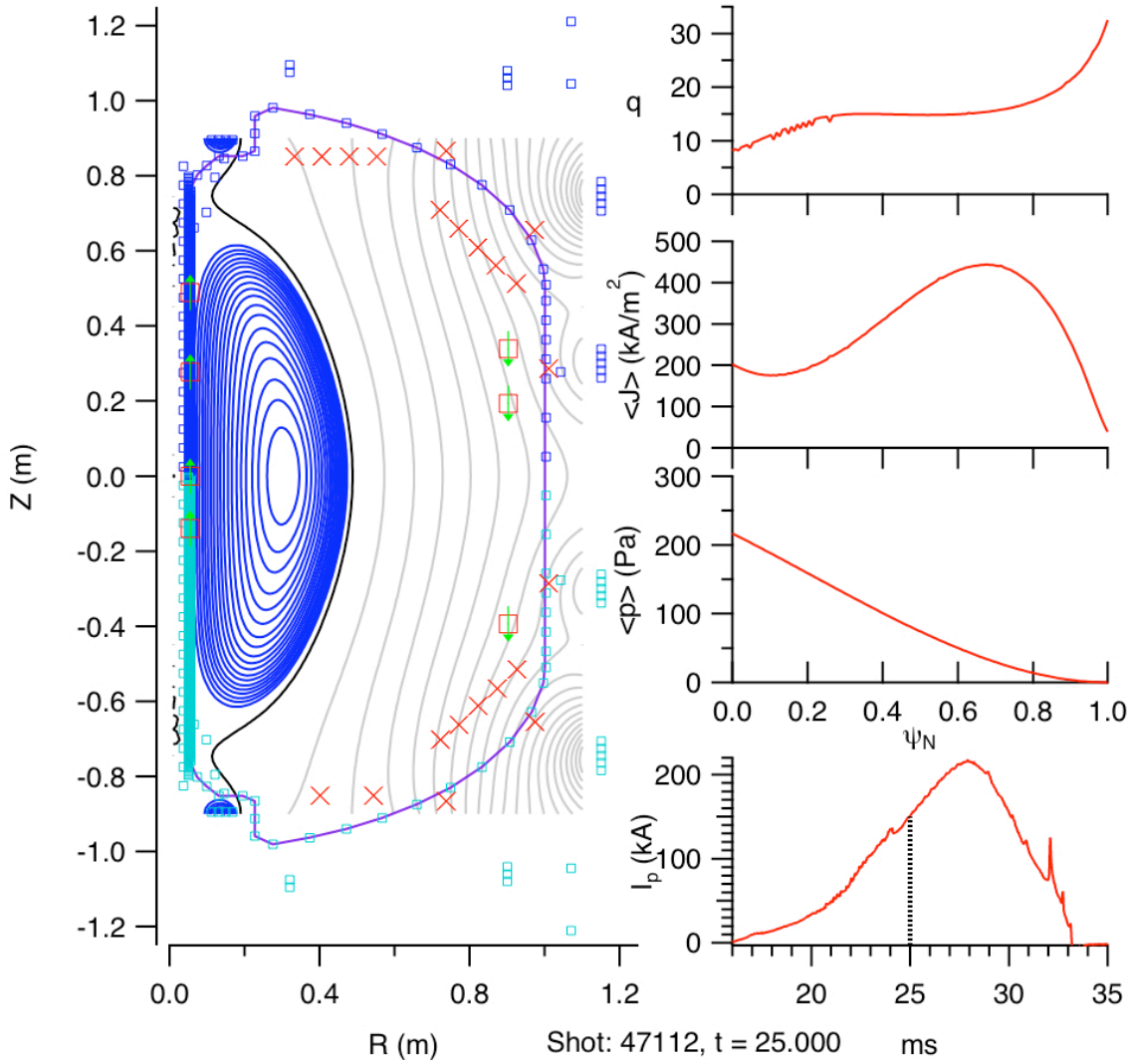
MHD activity "bursts" also can correlate with density dumps



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Equilibrium reconstructions indicate that further optimization is possible



KFIT equilibrium fit @ 25.0 ms in PEGASUS discharge #47112

Equilibrium Parameters:

I_p = 151 kA	I_{TF} = 288 kA
R_0 = 0.24 m	β_T = 5.4%
a = 0.195 m	β_p = 0.061
A = 1.2	l_i = 0.27

Approximately 1 ms after the shutoff of helicity injection, and the plasma has rapidly moved inward away from the guns (at approximately R=0.75m)

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