Abstract (1): HICD in PEGASUS

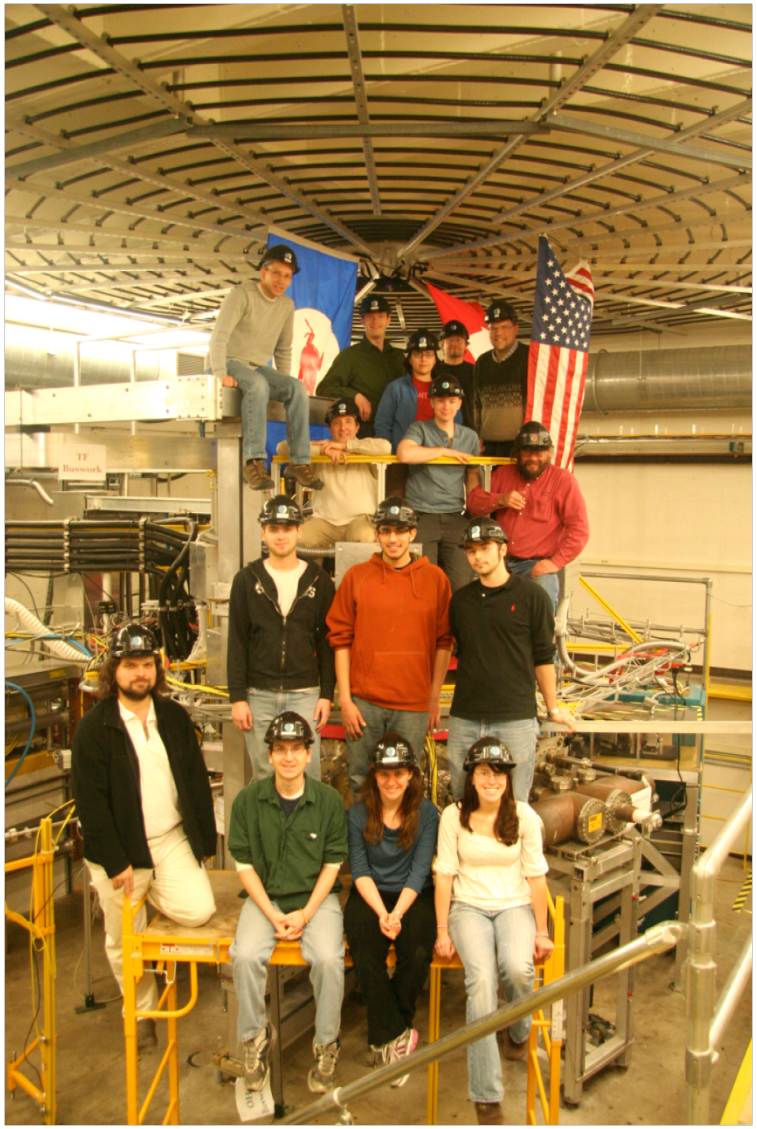
- Plasma startup and steady-state sustainment without using an Ohmic solenoid is a general problem facing tokamaks. This problem is most acute in small aspect ratio tokamaks, in which the relatively small center stack assembly does not allow the luxury of a significant Ohmic solenoid.
- The PEGASUS Toroidal Experiment is an ultra-low aspect ratio tokamak (A~1.15), dedicated to exploring the physics of low-A tokamaks and the boundary between typical tokamak and spheromak operating spaces.
- PEGASUS uses compact plasma sources ("washer guns") as point-source magnetic helicity injectors to form tokamak discharges.
- This non-solenoidal startup technique has produced up to 100 kA of toroidal current in published studies [Battaglia *et al*, Phys. Rev. Lett. v.102, p.225003 (2009)], and after recent hardware modifications has produced up to 174 kA.
- The maximum toroidal current during helicity injection is limited by helicity balance and a relaxation limit, with this limit corresponding to the usual lowest-energy Taylor state. This theoretical current limit scales with the TF coil current, the gun-injected current, and the injection geometry, and these predicted scalings are consistent with the results from experimental scans over those parameters.

Abstract (2): HICD in PEGASUS

- Addition of Ohmic solenoid drive during the gun injection period enhances the helicity injection rate, but the maximum current cannot exceed the relaxation limit, demonstrating that this is a hard limit on the plasma current.
- Conversely, Ohmic solenoid drive can be used to sustain and enhance the gun-generated plasma, if the Ohmic drive is applied after the gun injection ceases.
- The current-profile relaxation associated with this helicity injection technique correlates with bursts of low-n MHD activity on the outboard side of the discharge.
- Planned near-term physics studies include the direct observation of the current-profile relaxation using an internal Hall-effect magnetic probe array and enhancement of the gun drive with shaped electrodes.
- In the longer term, the relaxation limit model is guiding the enhancement of the gun injection and TF coil power supplies, with the goal of reaching 300-400 kA of gun-driven toroidal plasma current.

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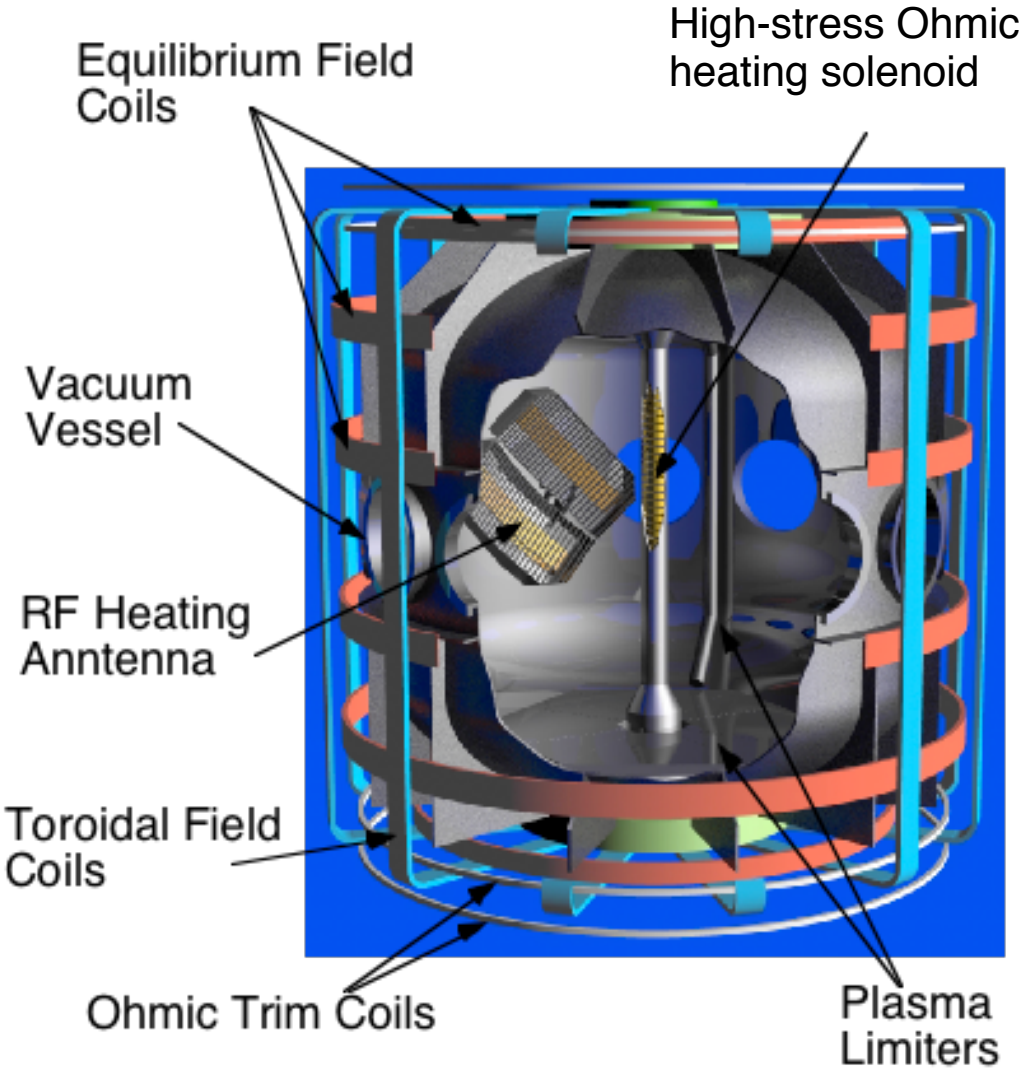
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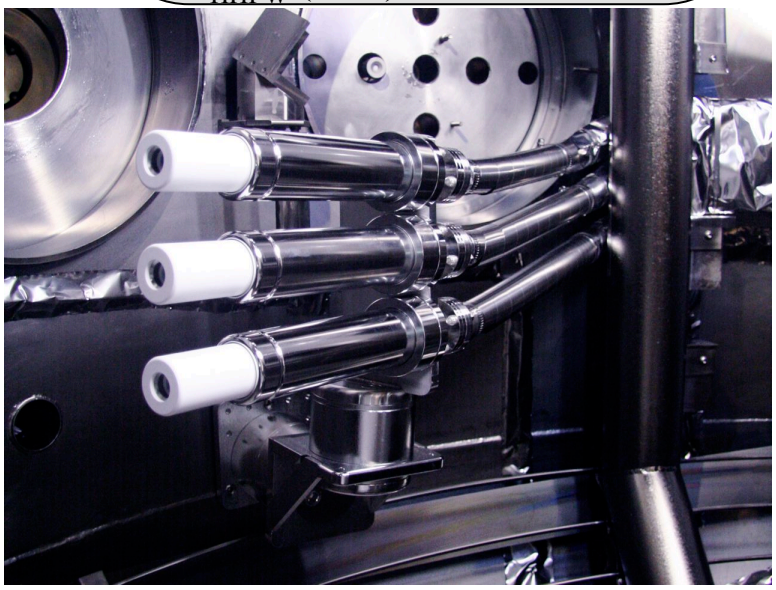
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PEGASUS is a Compact Ultralow-A ST



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



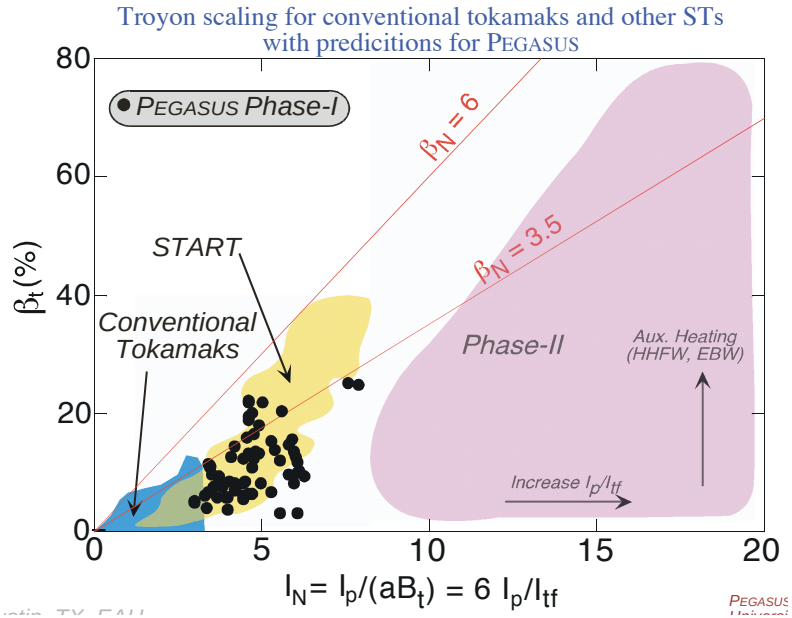
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PEGASUS is Creating High-I_p Non-Solenoidal Discharges Which Enable High-I_N Studies

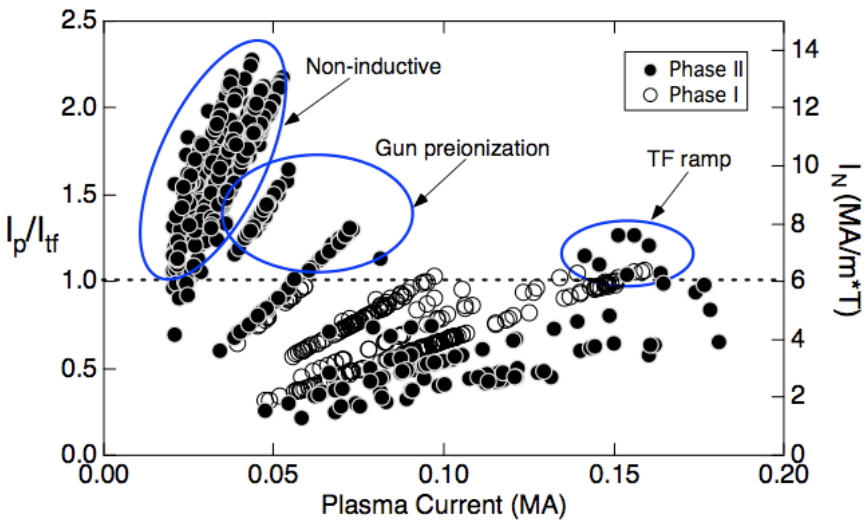
- Using DC helicity injection for solenoid-free startup
  - I_p up to 174 kA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
  - I_p up to 135 kA smoothly "handed off" to Ohmic, then driven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



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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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

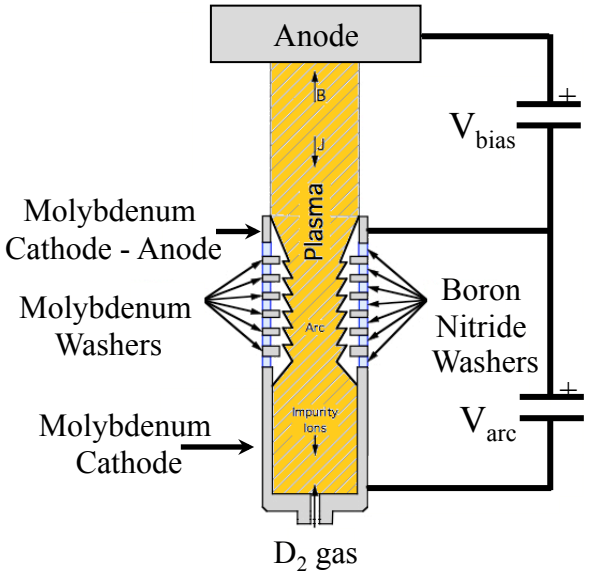
Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

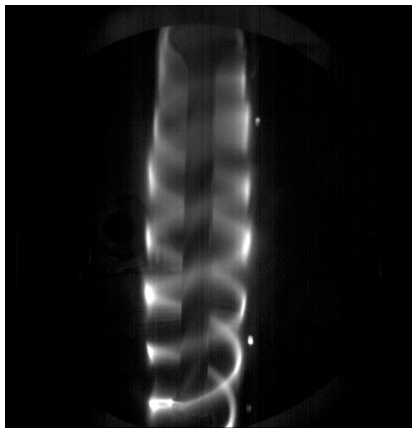
$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, d^3x - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot d\mathbf{s}$$

- 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 $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$
  - Φ is electrostatic potential

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



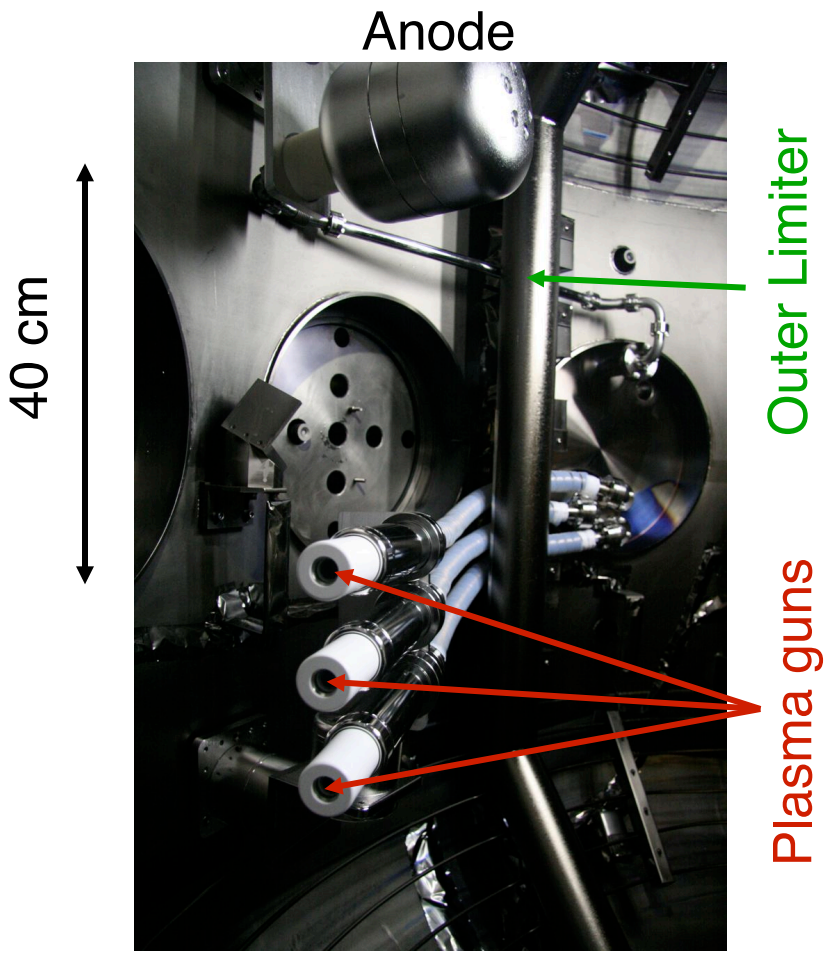


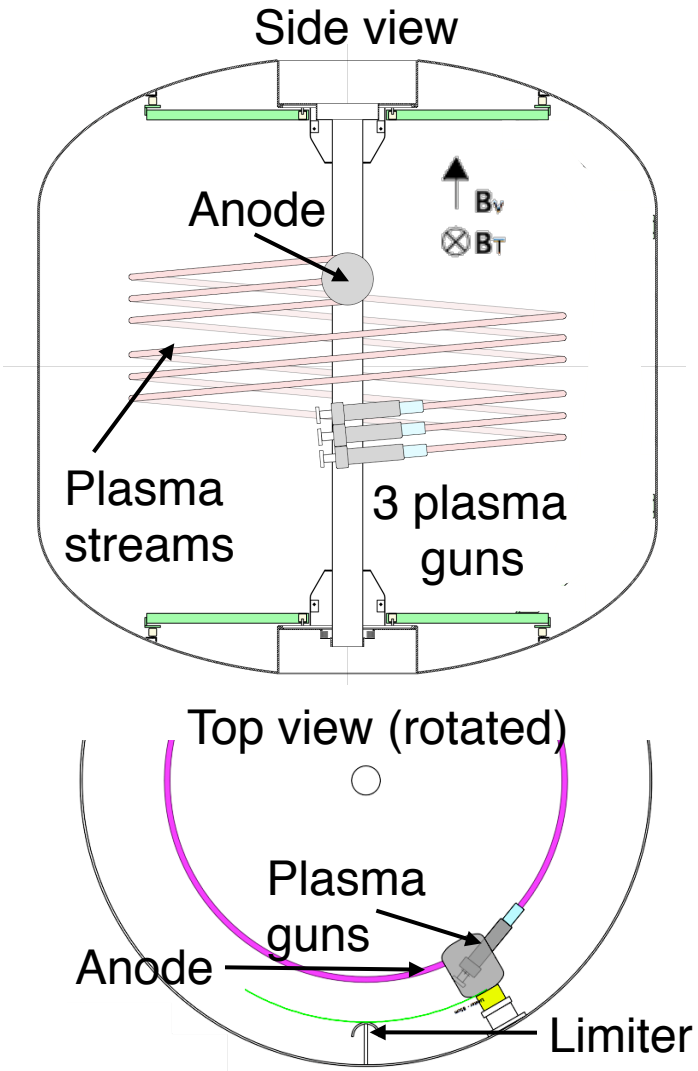
Reduced B_z



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





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

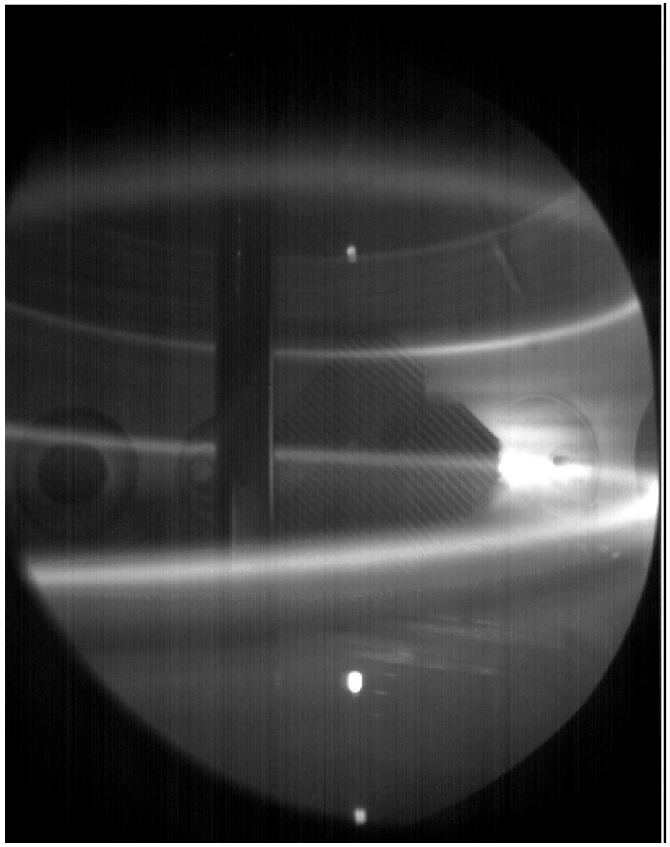
- Driven helical filaments are strongly unstable
- Tokamak-like equilibrium satisfies a set of conditions
  - Radial force balance, helicity/power balance, kink stability (edge q > 3), and a Taylor relaxation current limit
- Max I_p determined by dK/dt and Taylor relaxation limit:

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

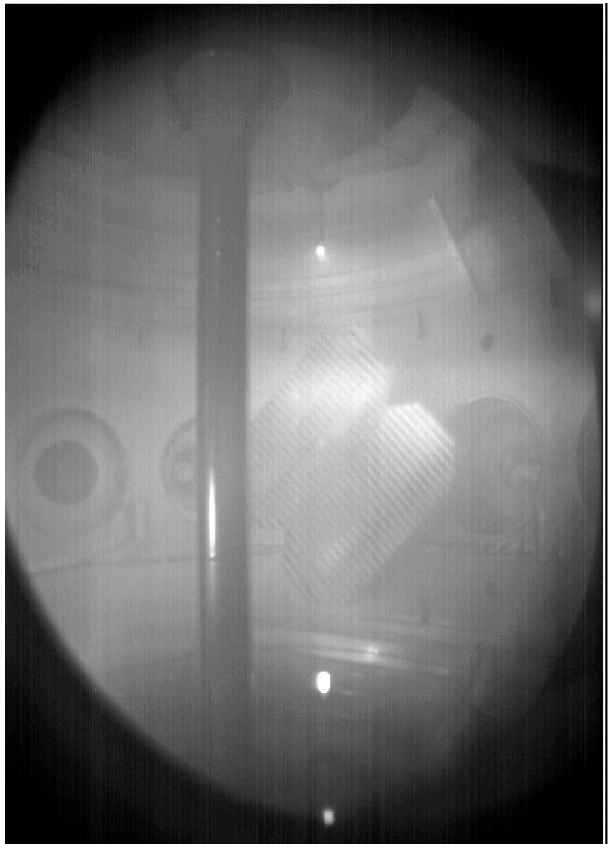
where ε is the inverse aspect ratio, A_p is the plasma cross-sectional area, I_{TF} is the TF coil current, I_{inj} is the gun bias current, R_{edge} is the gun location, w is the width of the driven plasma region, and f_G is a scalar function ranging from 1 to 3, depending upon geometry.
See Battaglia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

Evolution of midplane-gun-driven plasma

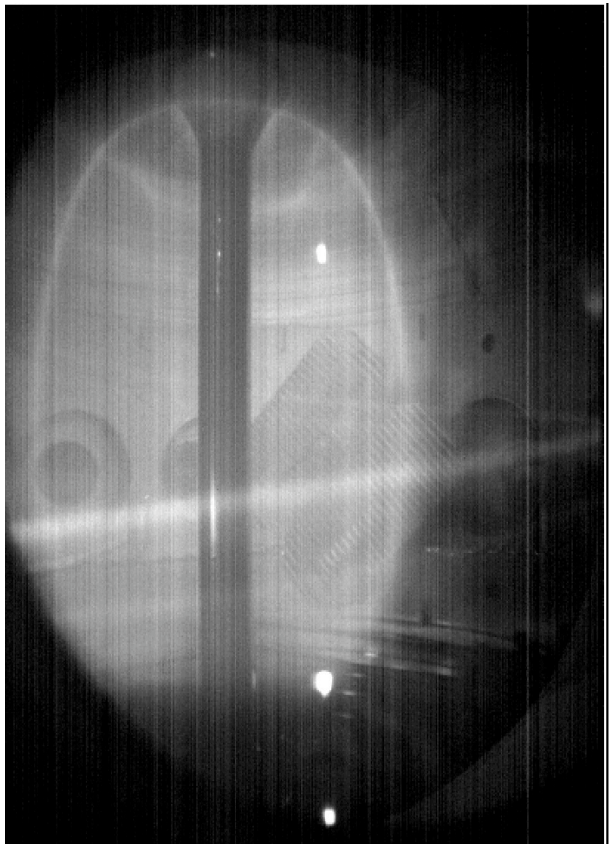
PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



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



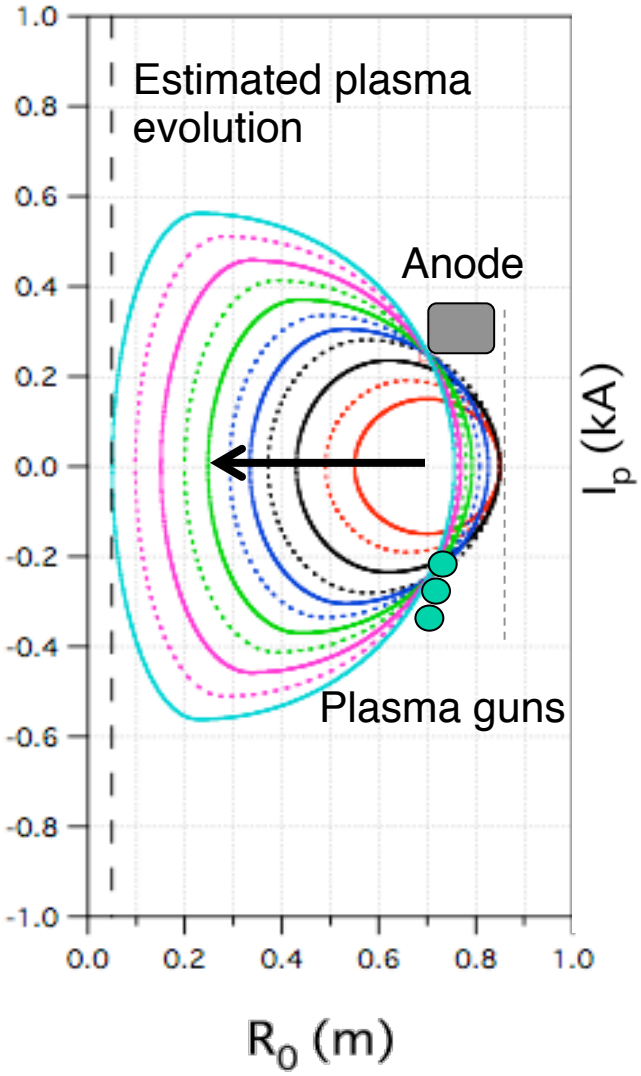
t=28.8 ms, I_p=42 kA
Driven diffuse plasma

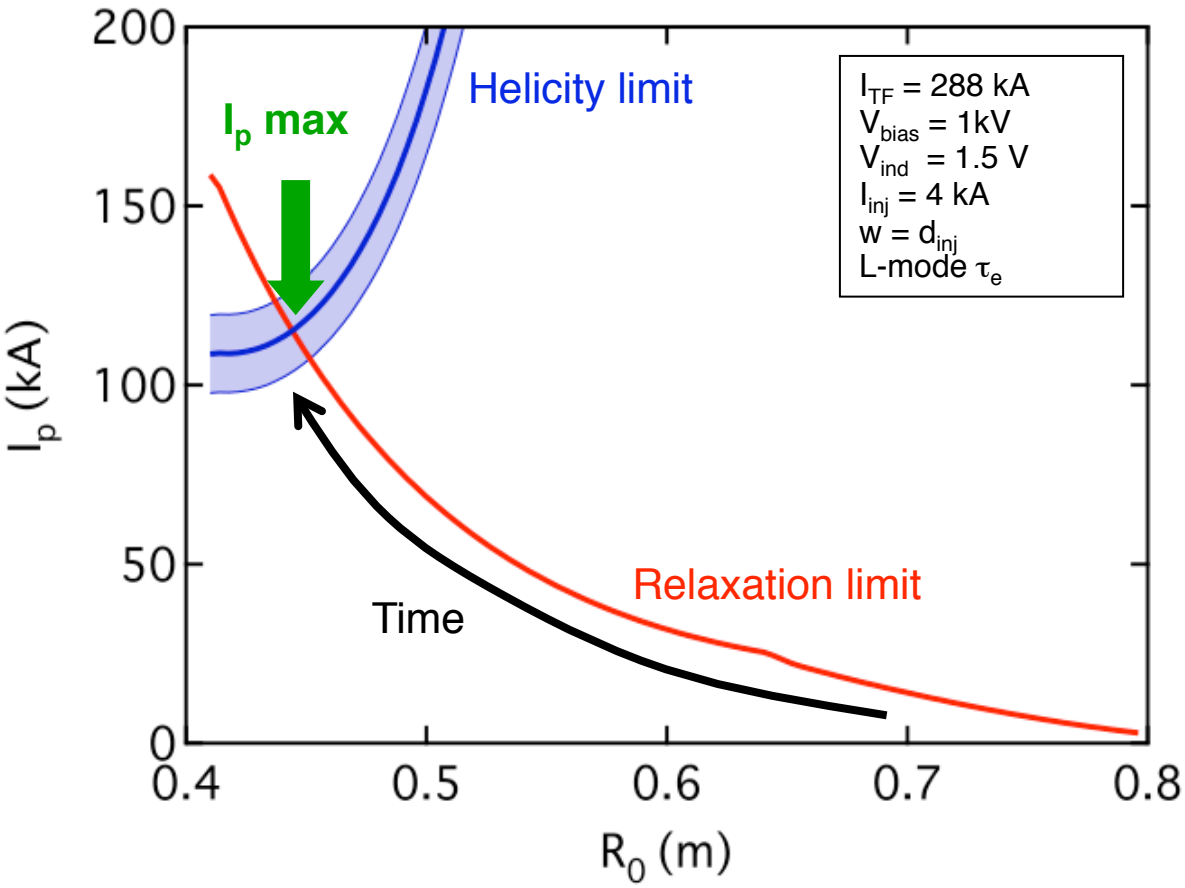


t=30.6 ms, I_p=37 kA
Guns off, Decaying

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

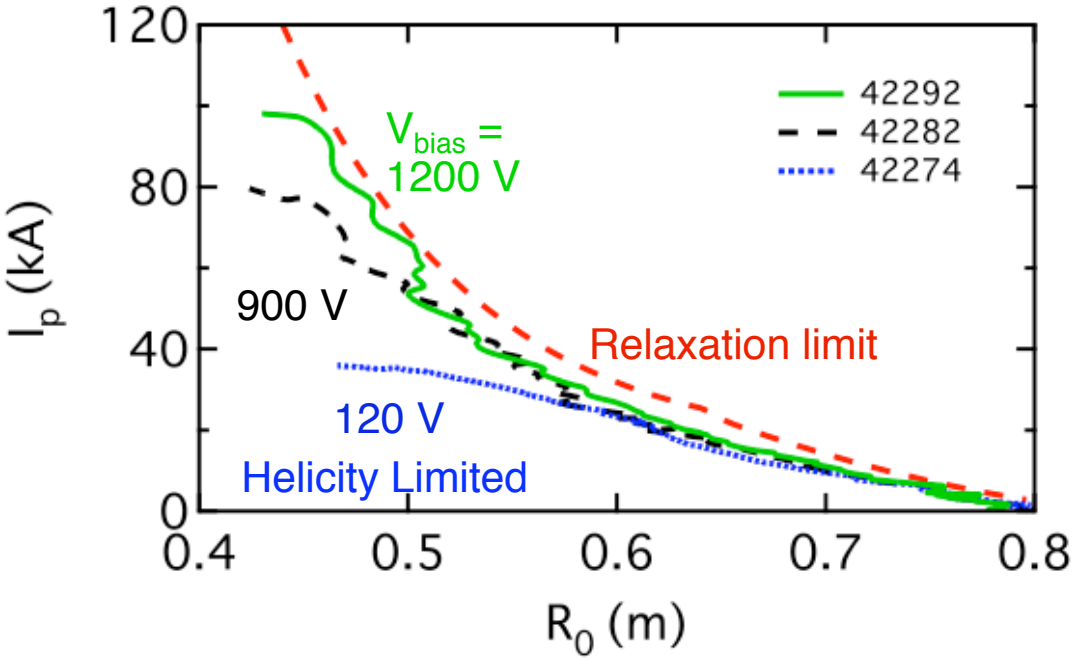




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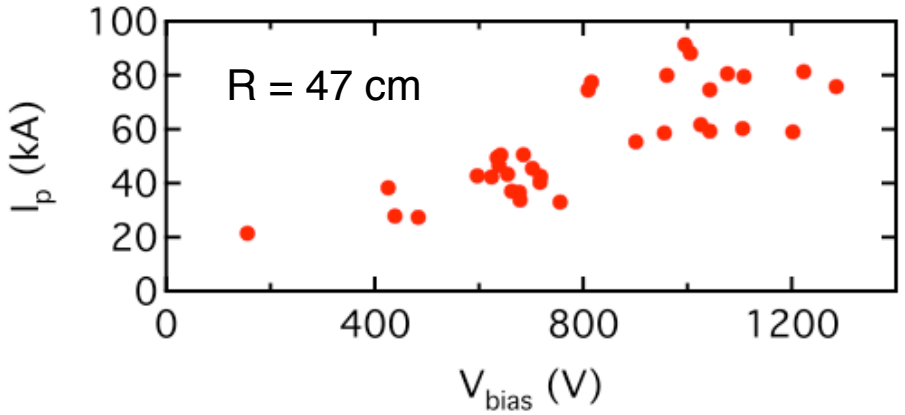
Sufficient helicity injection is required to drive the plasma up to the relaxation limit



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

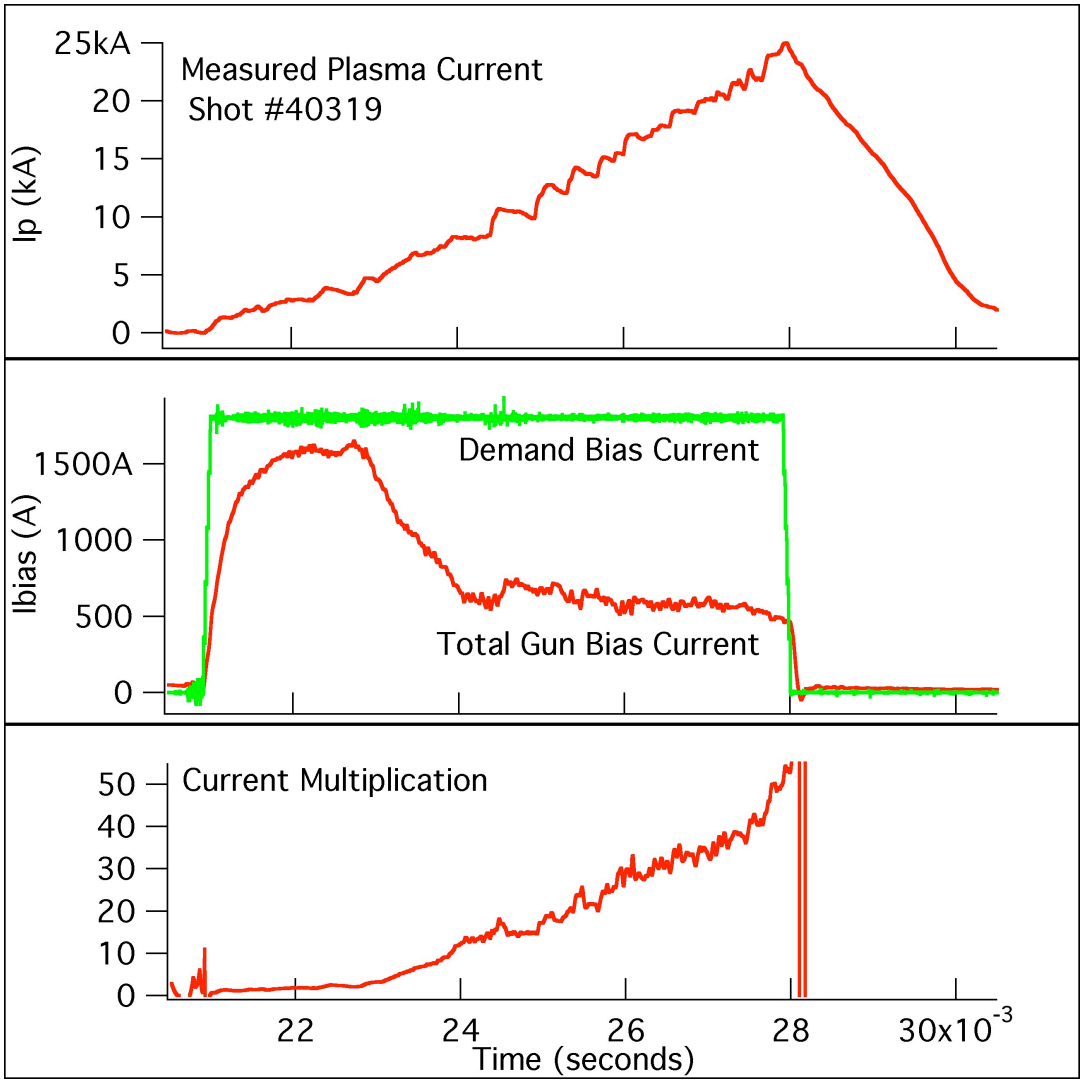
High dK/dt with modest I_{bias} requires high impedance Z_{inj}

Max I_p increases with V_{bias}



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

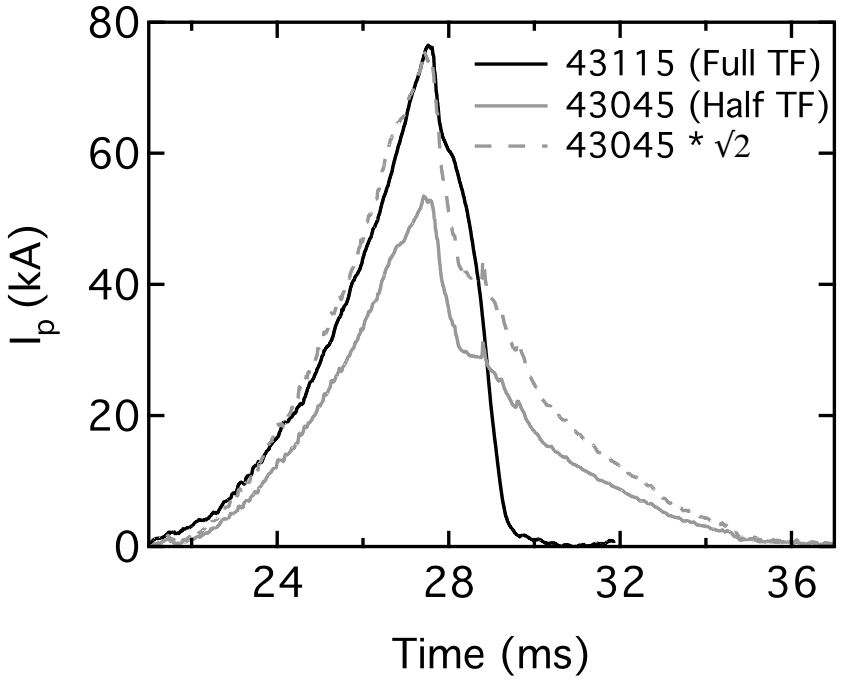
- Single-gun discharge with no PF ramps.
- Current multiplication above 50 at gun shutoff.
- Discrepancy between demanded and actual bias current is due to insufficient bank voltage.

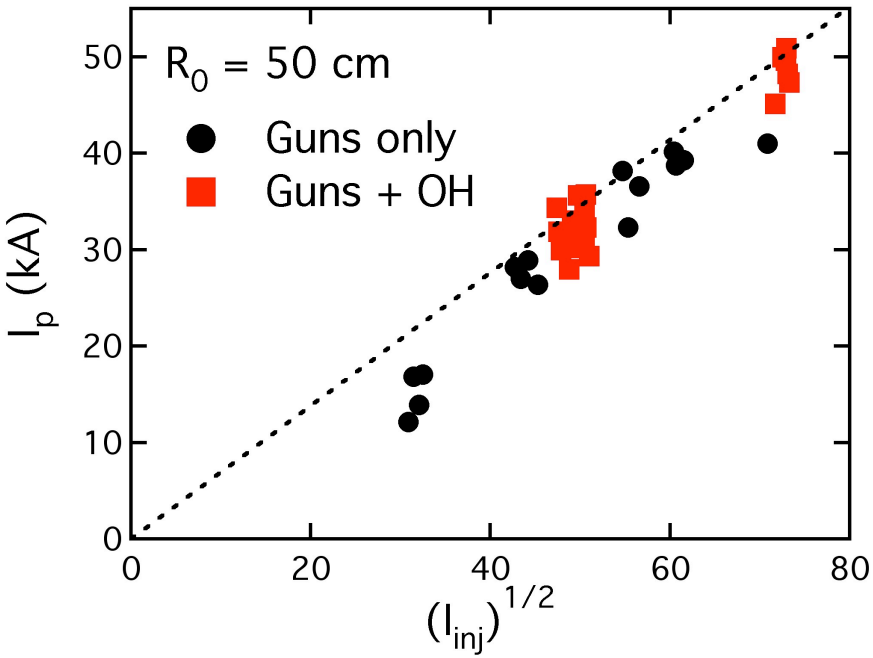


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Empirical scalings with I_{TF} and I_{bias} are consistent with relaxation limit model

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



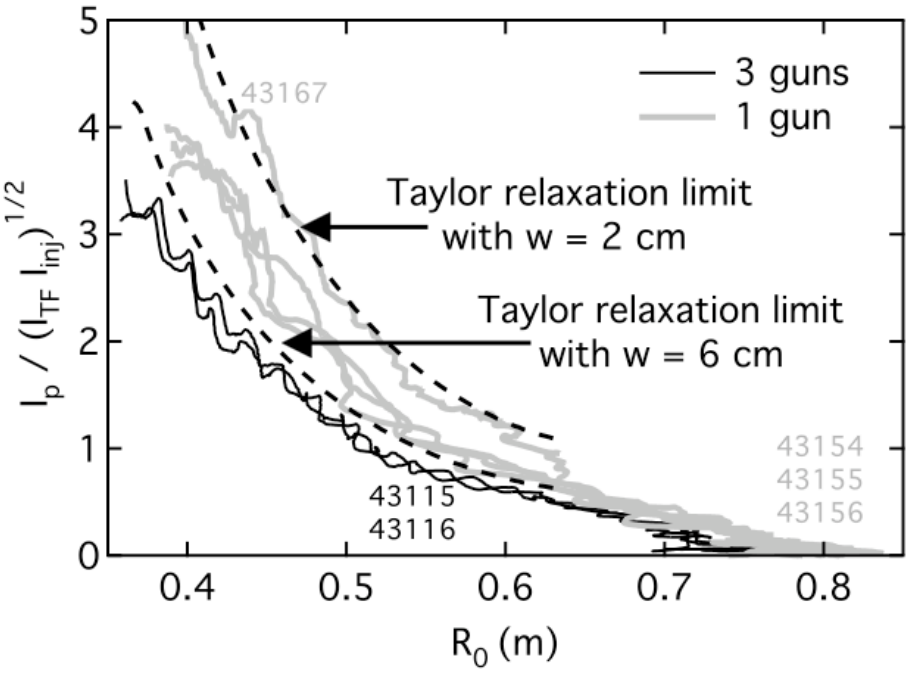


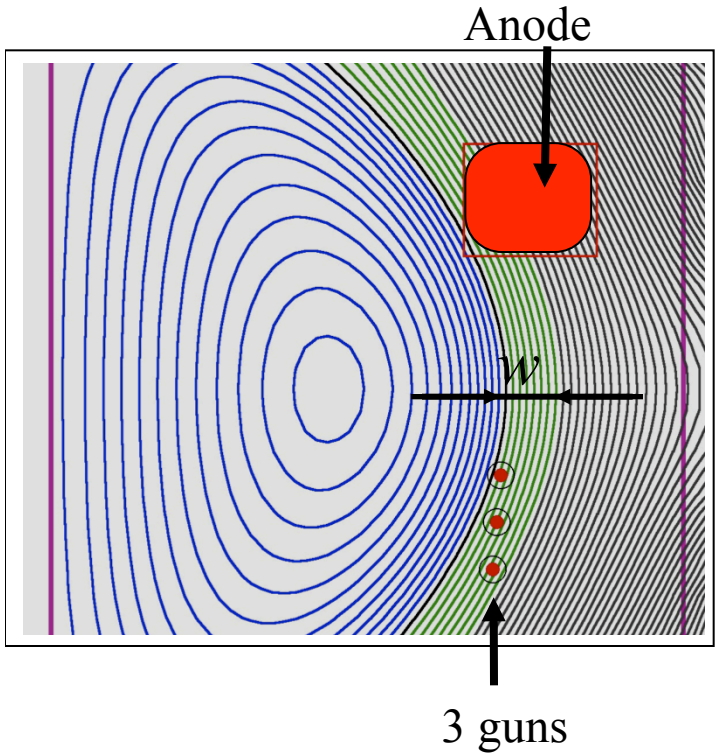
Note: adding solenoid induction during gun drive does not allow driven I_p to exceed the Taylor relaxation limit

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Experiments suggest strong dependence on the width of the driven current layer

- Relaxation current limit scales as $w^{-1/2}$ in the model
- One-gun discharges have higher limits than corresponding three-gun cases, indicating gun array was misaligned:

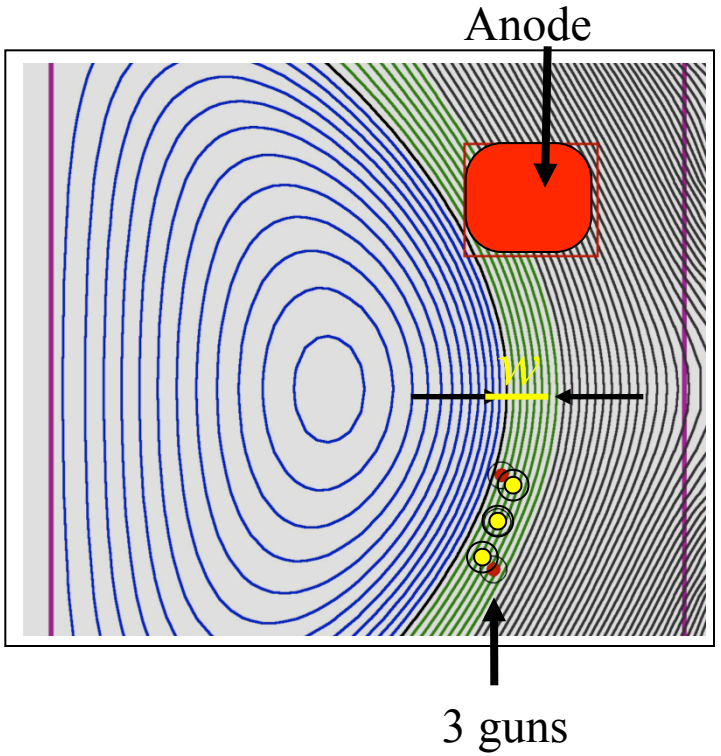


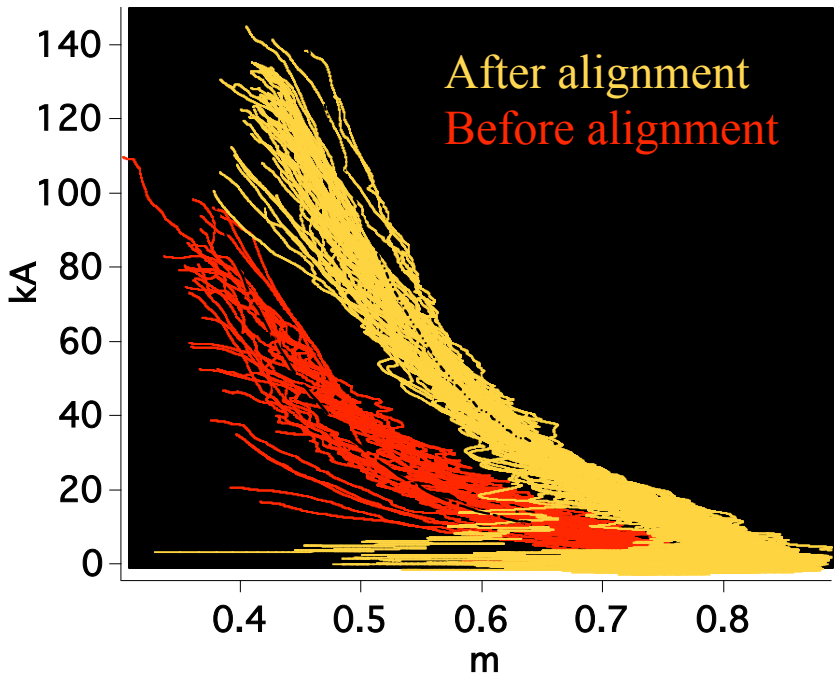


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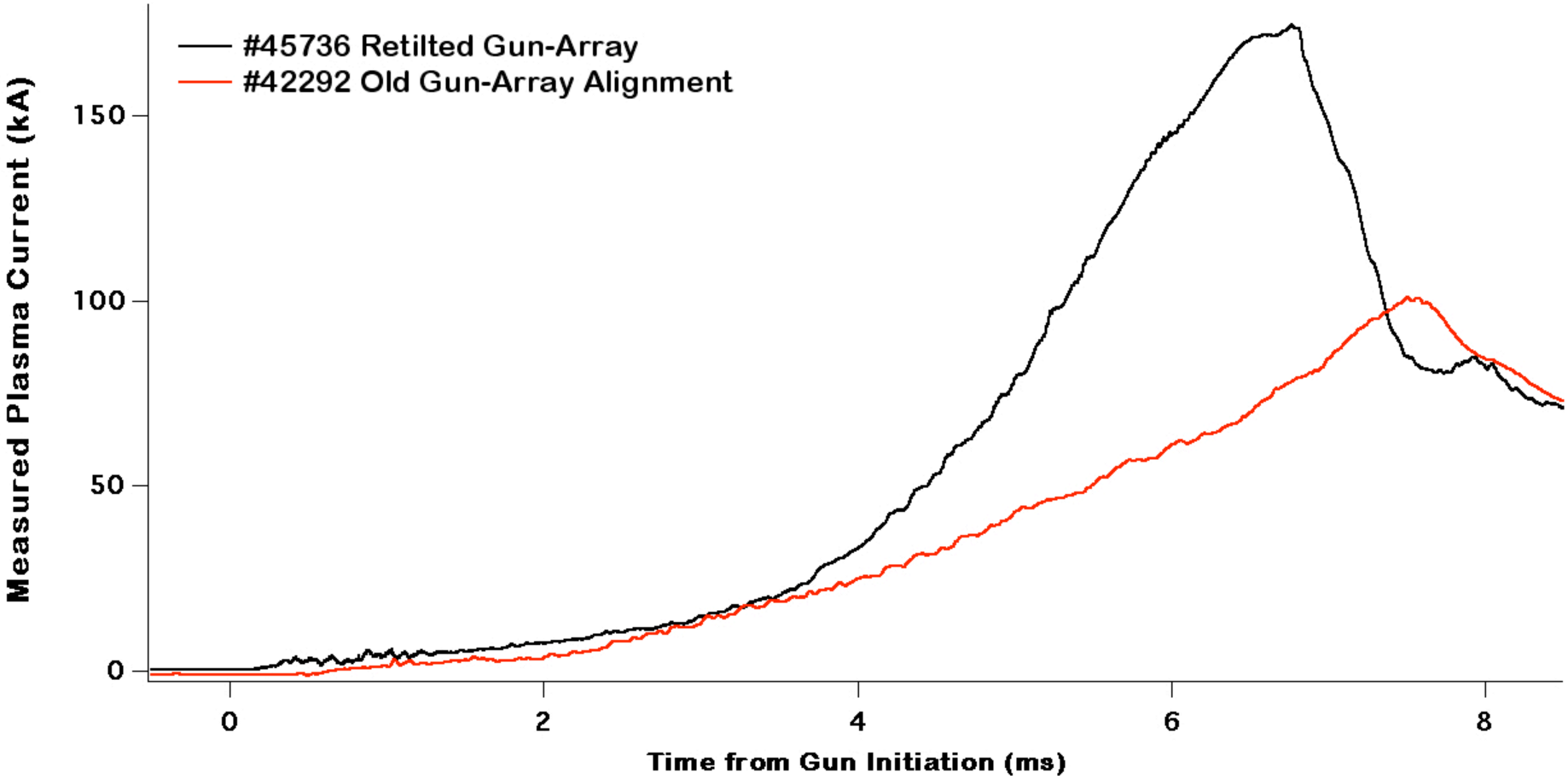
Gun array was realigned to reduce *w*, significantly increasing relaxation limit

- 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.
- In this configuration, 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

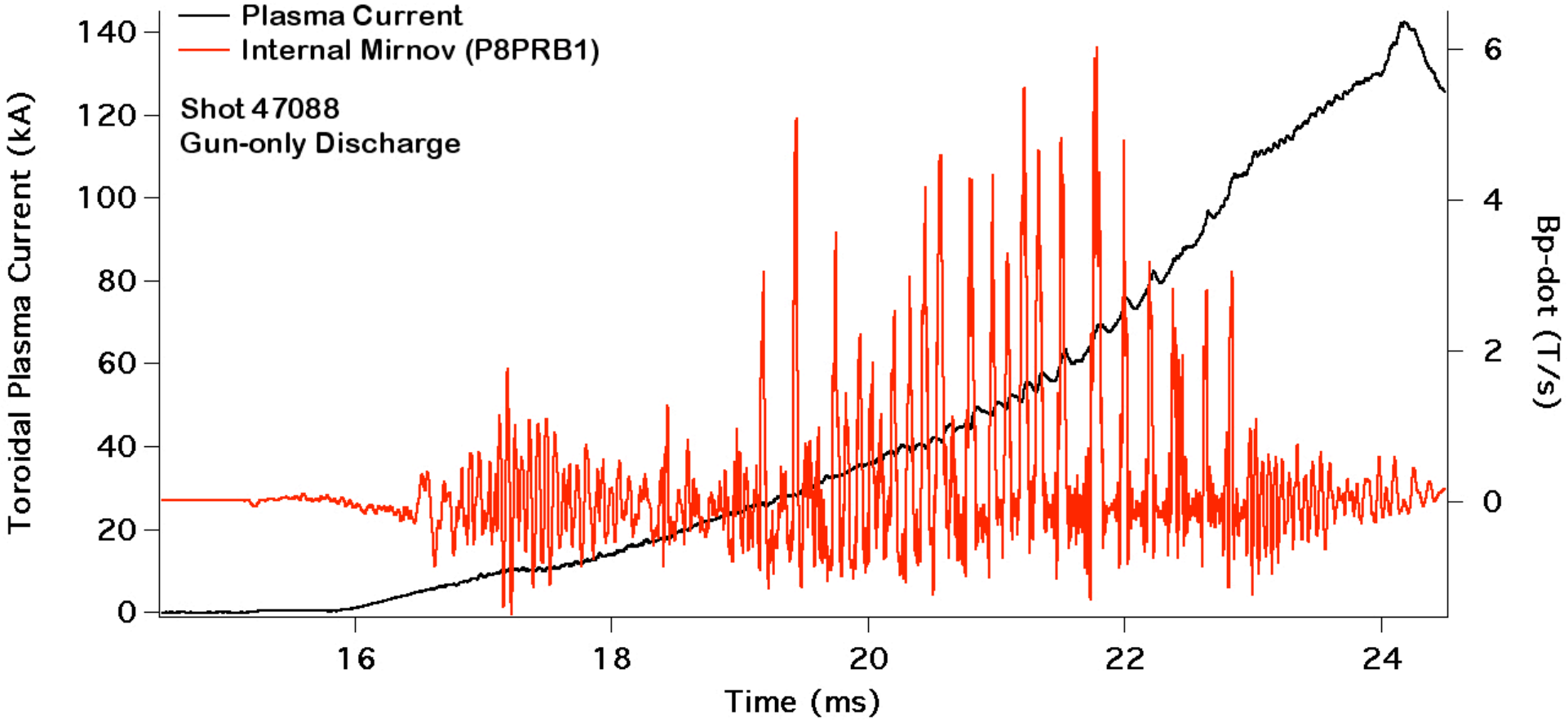
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Rapid equilibrium shifts during gun drive correlate with bursty low-n MHD activity

- 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.

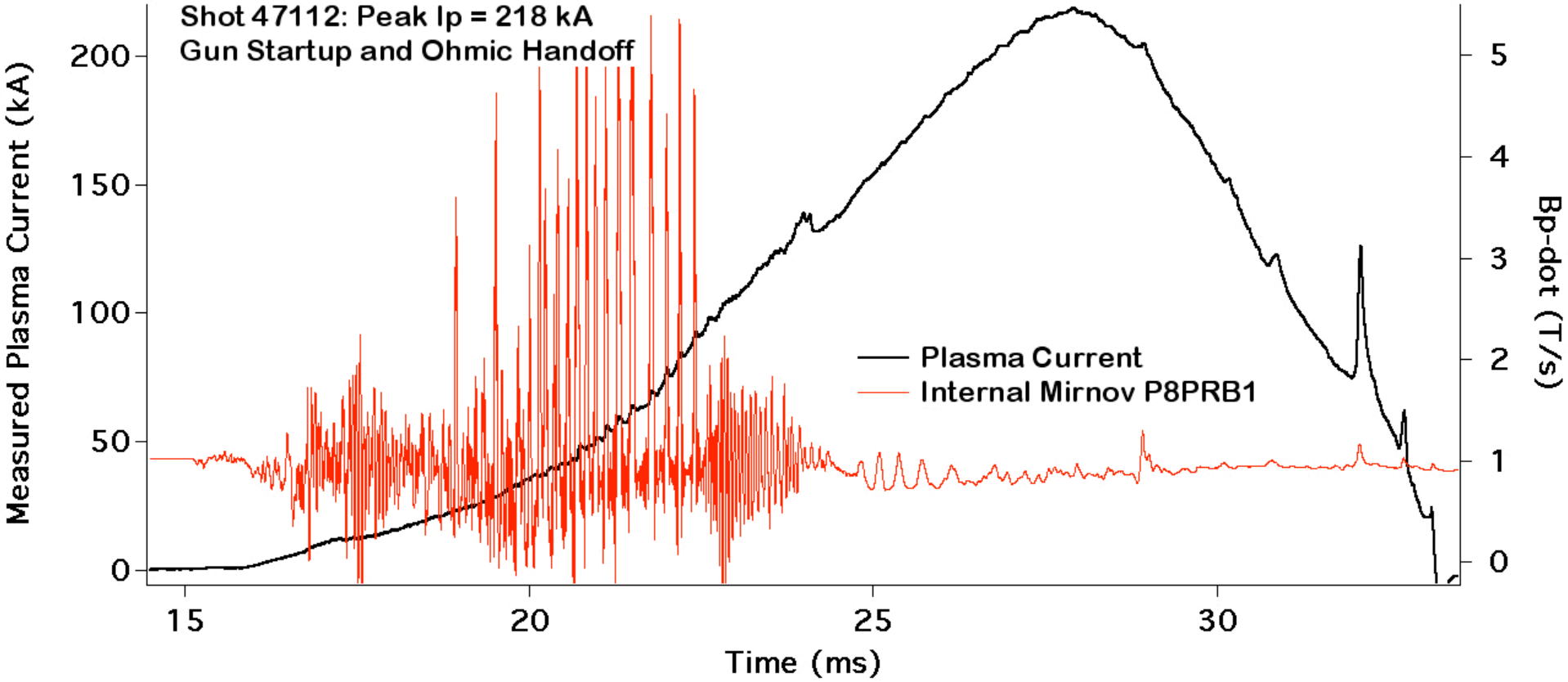
MHD activity bursts during gun drive correspond to rapid rises in I_p



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

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MHD activity tends to be strongly reduced after gun bias shutoff

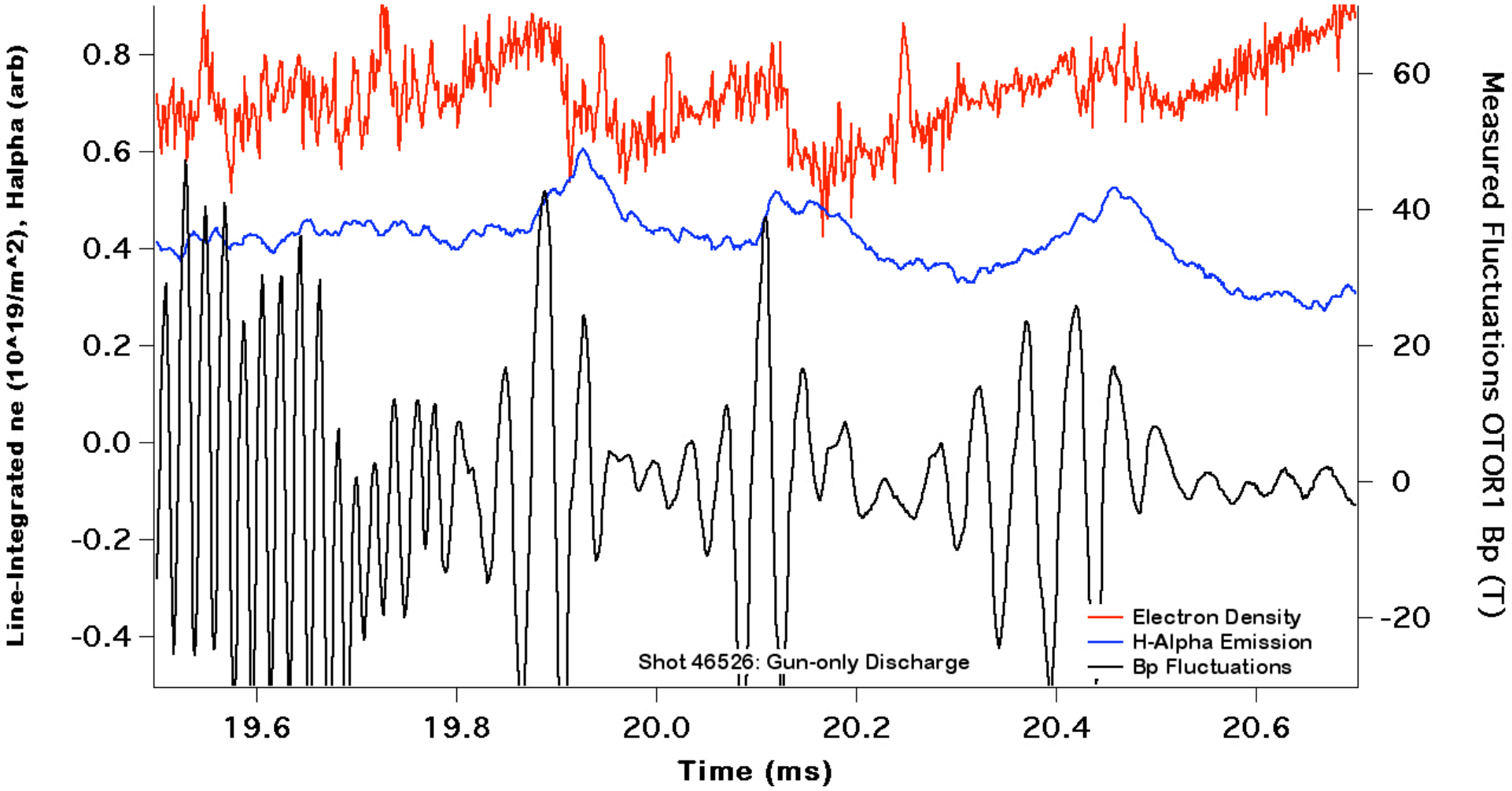


Shortly after gun shutoff, plasma currents are similar to those in PEGASUS Ohmic discharges, while equilibrium reconstructions indicate that the q-profiles are similar to Ohmic. But the handoff discharges remain quiescent, while the Ohmic discharges are unstable to low-n tearing modes.

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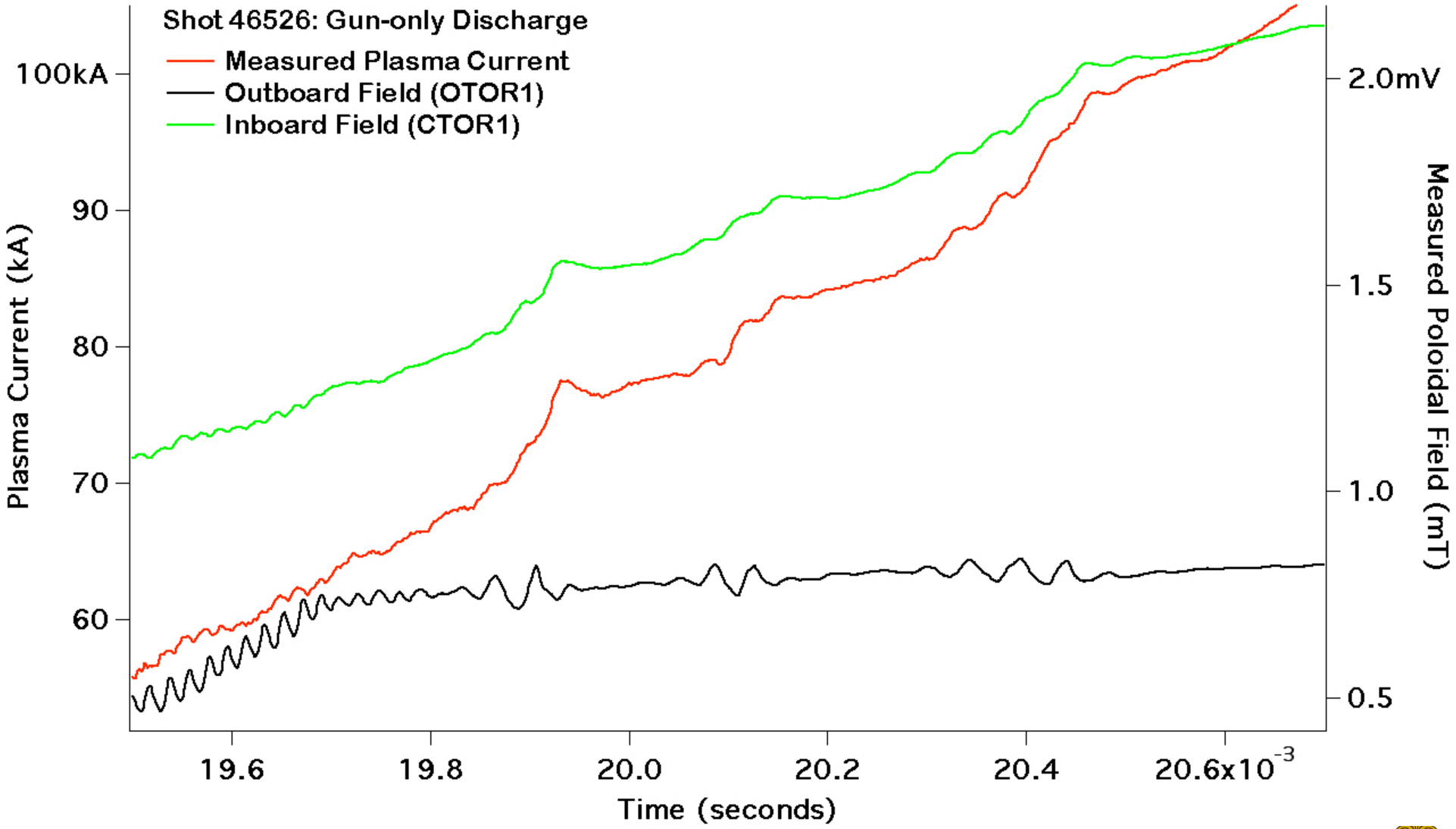
MHD activity “bursts” also can correlate with density dumps



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MHD activity “bursts” correlate with rapid inward radial shifts



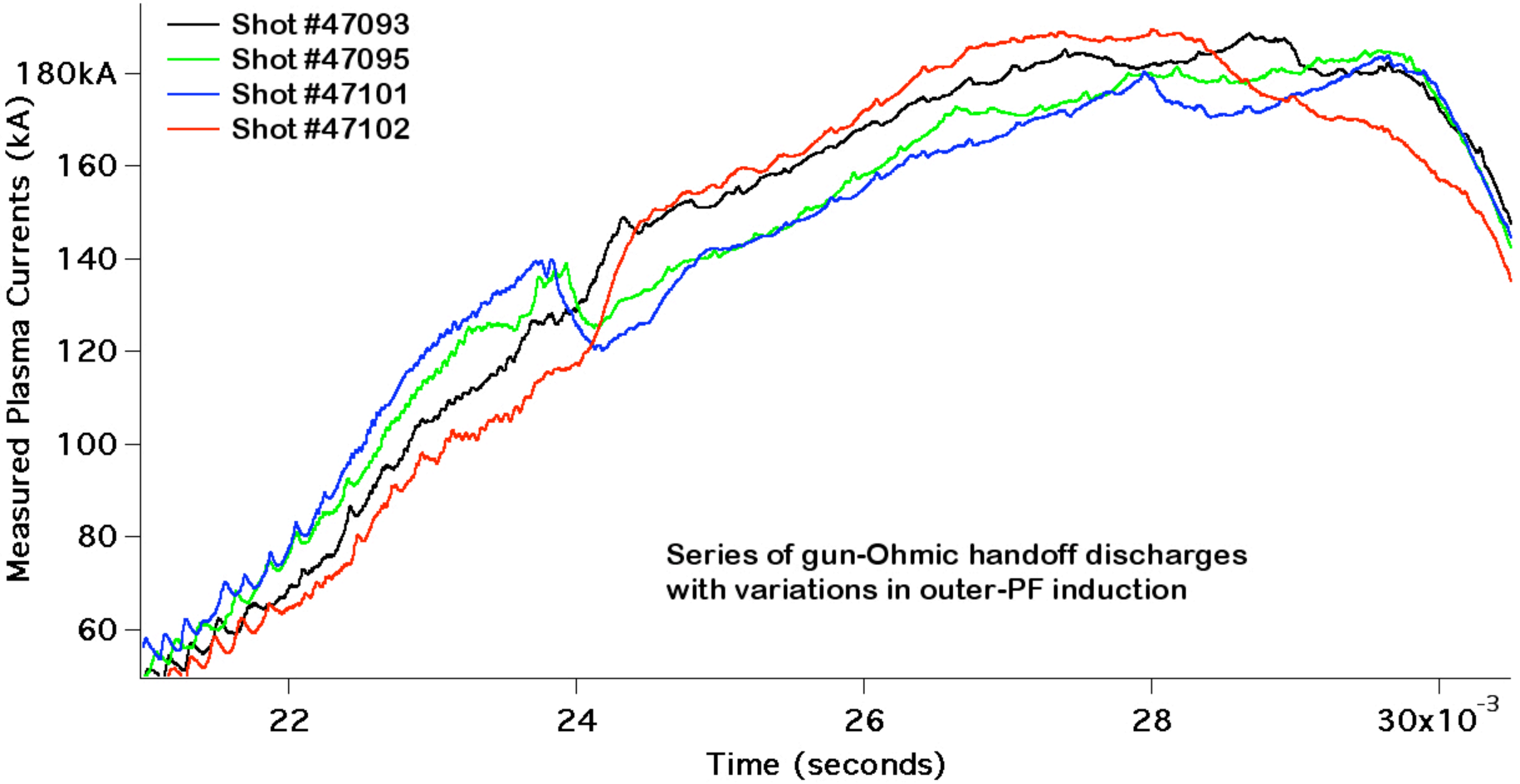
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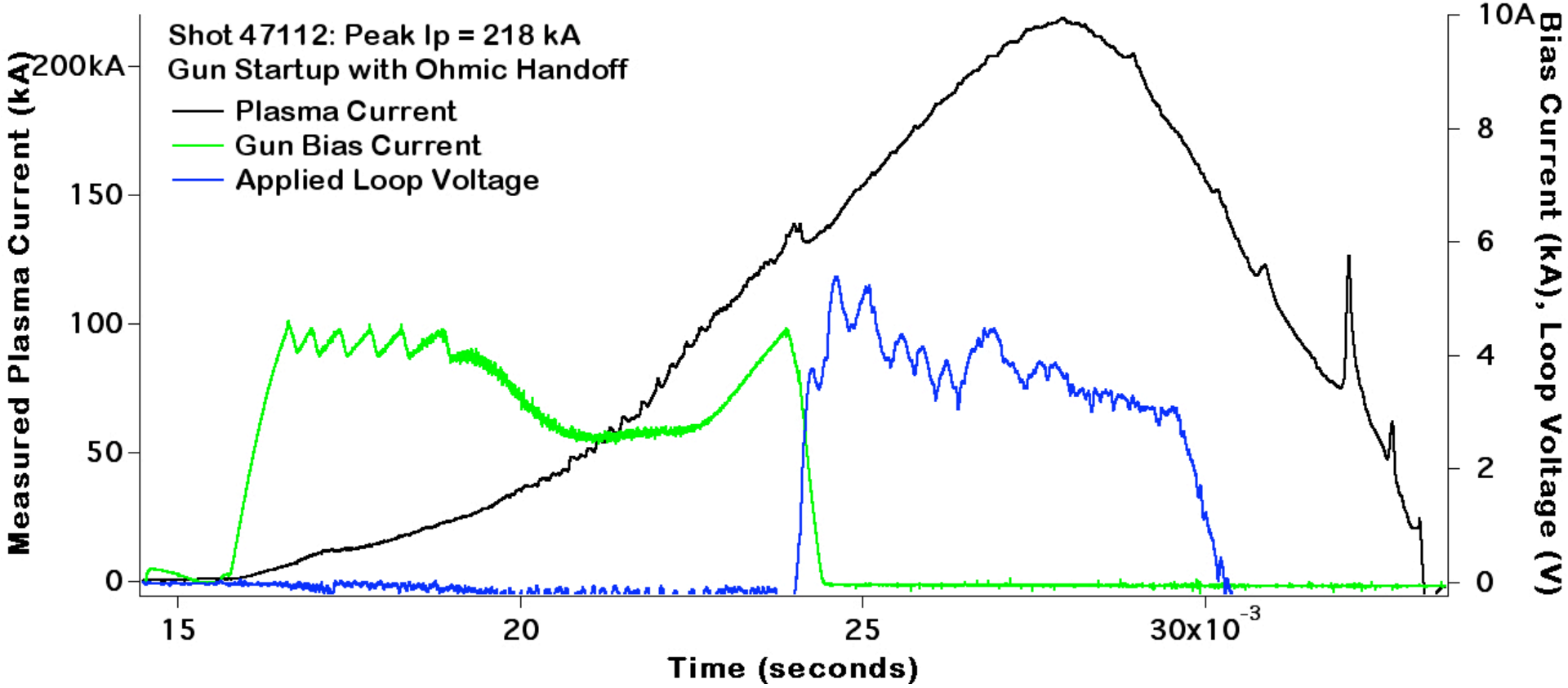
Slow current evolution during helicity injection allows current-profile relaxation

- 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.

Early peaking of gun-driven I_p reduces handoff current and impacts subsequent I_p



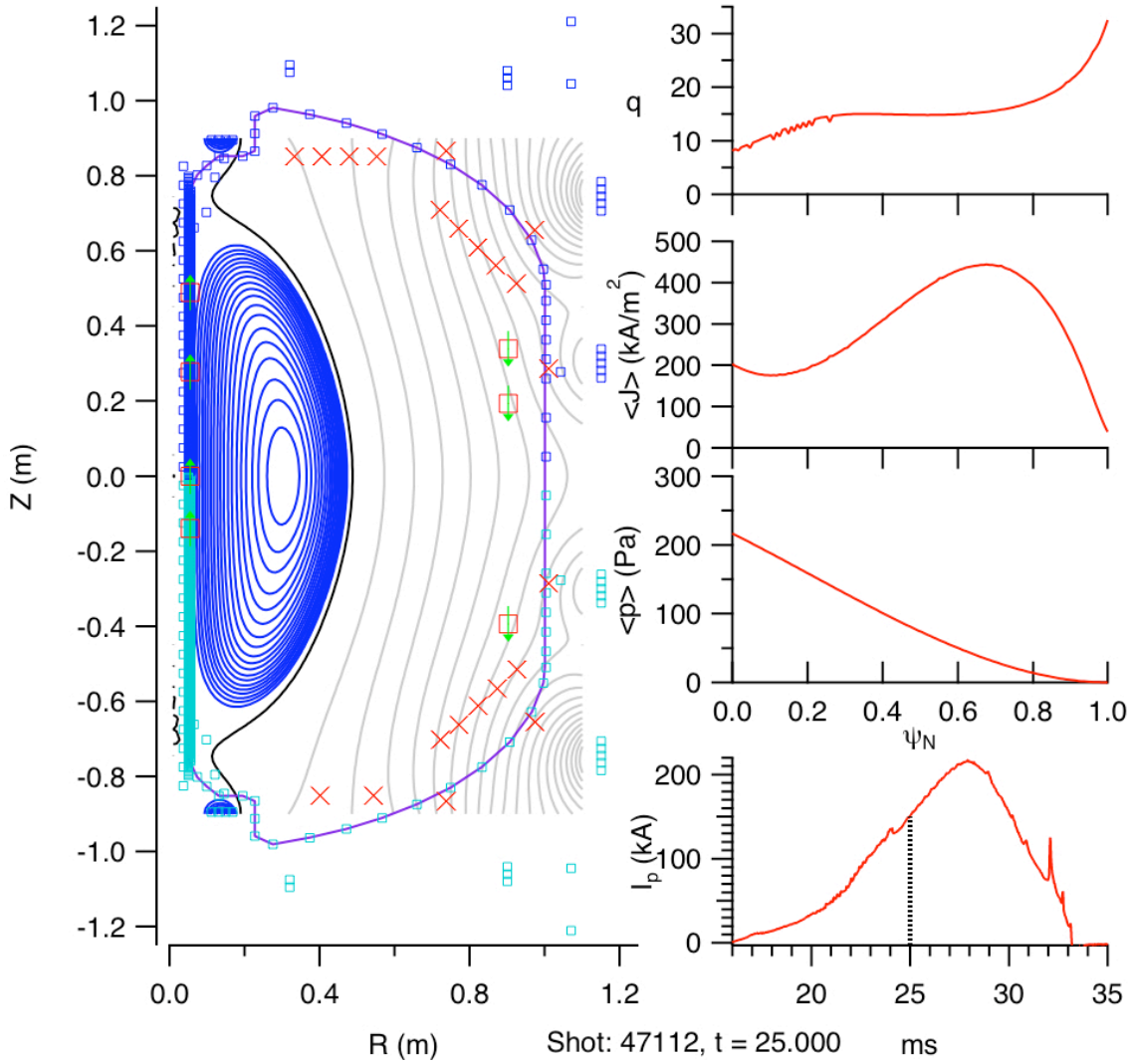
Handoff to single-swing Ohmic can drive up to I_p/I_{TF}=0.7 at I_p=218 kA



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

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Equilibrium reconstructions indicate that further optimization is possible



KFIT equilibrium fit @ 25.0 ms in PEGASUS discharge #47112

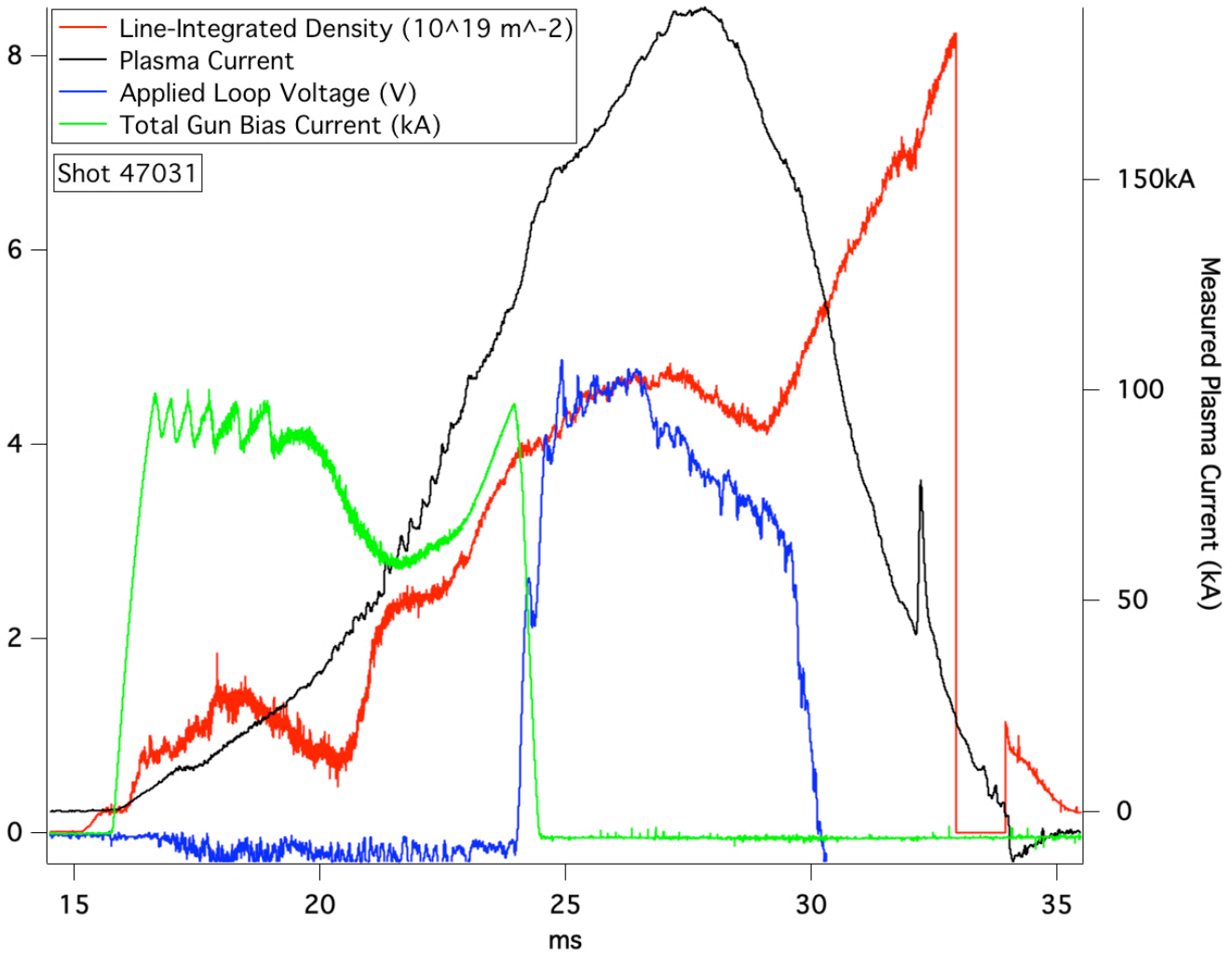
Equilibrium Parameters:

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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Gun-formed discharges have reasonable electron densities



Chord length: exact determination is difficult, but is approximately 1-2 meters

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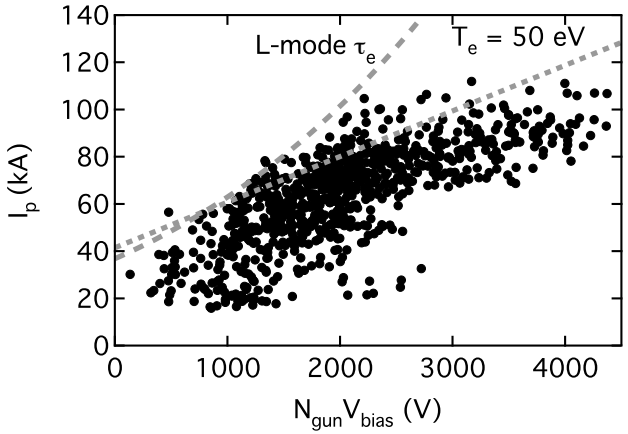
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Summary: HICD in PEGASUS

- 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

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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Point-source helicity injection could be critical for PEGASUS and other ST devices

- Solenoid-free startup and ramp-up have been identified as critical ST issues (ReNeW report, FESAC TAP report)
- Solenoid-free startup with point-source helicity injection significantly extends the PEGASUS operating space
  - Formation of the startup plasma saves limited Ohmic transformer flux, and increases the current I_p that can be achieved with the same Ohmic flux
  - May enable high-I_N, high-β studies on PEGASUS
  - May enable completely solenoid-free operation with RF current drive
- Point-source helicity injection is flexible, and may provide solenoid-free startup in future toroidal devices
  - Gun assemblies can be placed at any experimentally convenient location
  - Point-source helicity injection science and technology is being developed
- The PEGASUS program is strongly focused on developing a deep physical understanding of this approach

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