

Pegasus-III Experiment

Taylor Limit Studies for Local Helicity Injection Plasma Startup on Pegasus-III

Justin Weberski

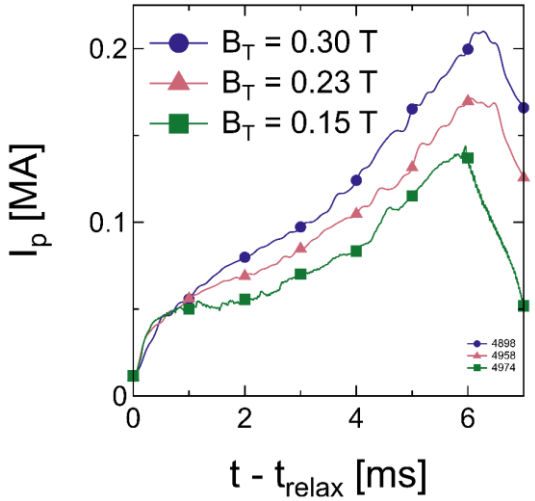
66th Annual Meeting of the APS Division of Plasma Physics
Atlanta, GA, Presentation GI03.00005
8 October 2024
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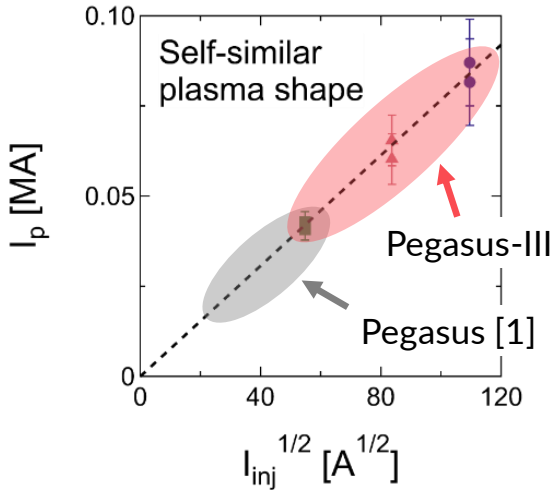


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Increased Taylor Limit Leads to Higher I_p in Pegasus-III

- Pegasus-III uses Local Helicity Injection (LHI) solenoid-free startup
- Robust $I_p \leq I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$ scaling in Pegasus-III operating space
- Excess helicity input increases $\tilde{b}$ when sustained at Taylor limit





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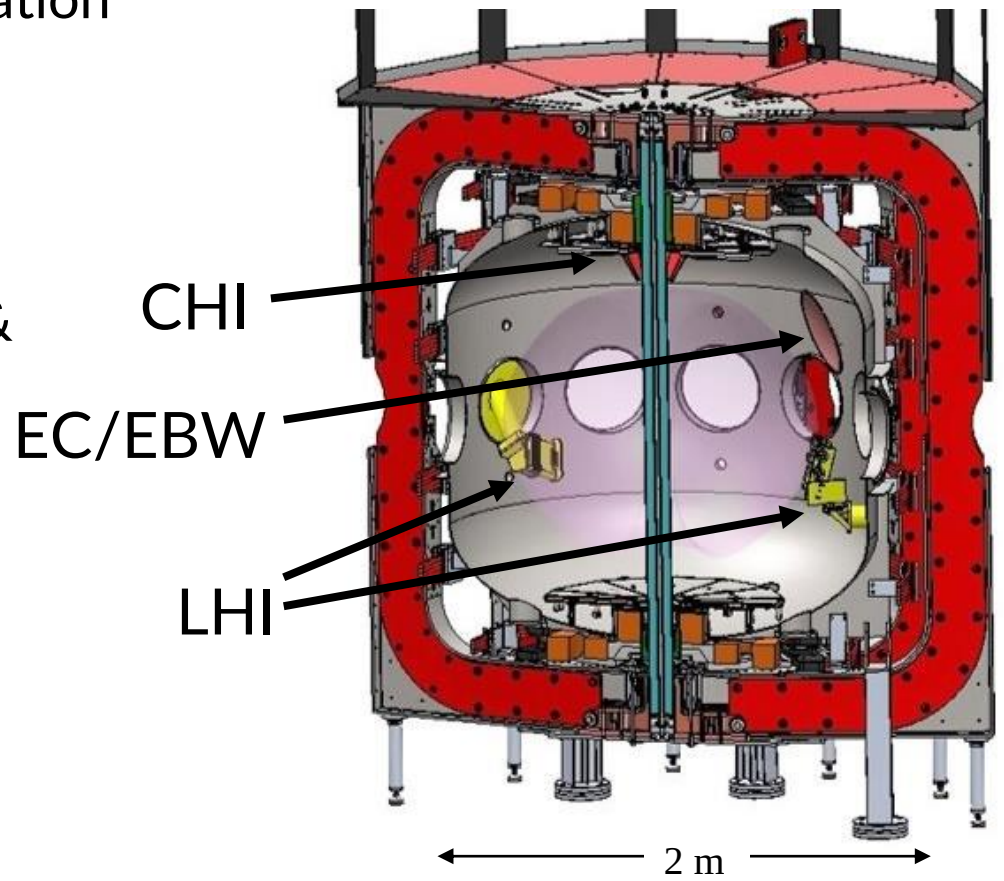
[1] D. J. Battaglia *et al.*, *Nucl. Fusion* **51**, (2011).

Pegasus-III is Addressing Need for Solenoid-Free Startup

- Future tokamak designs call for solenoid-free operation
  - Minimize OH due to shielding/cost

- Pegasus-III mission: Developing validated physics & tech basis for MA startup
  - Local Helicity Injection (LHI)
  - Coaxial Helicity Injection (CHI)
  - Microwave assist, sustainment and startup

Solenoid-free Pegasus-III facility

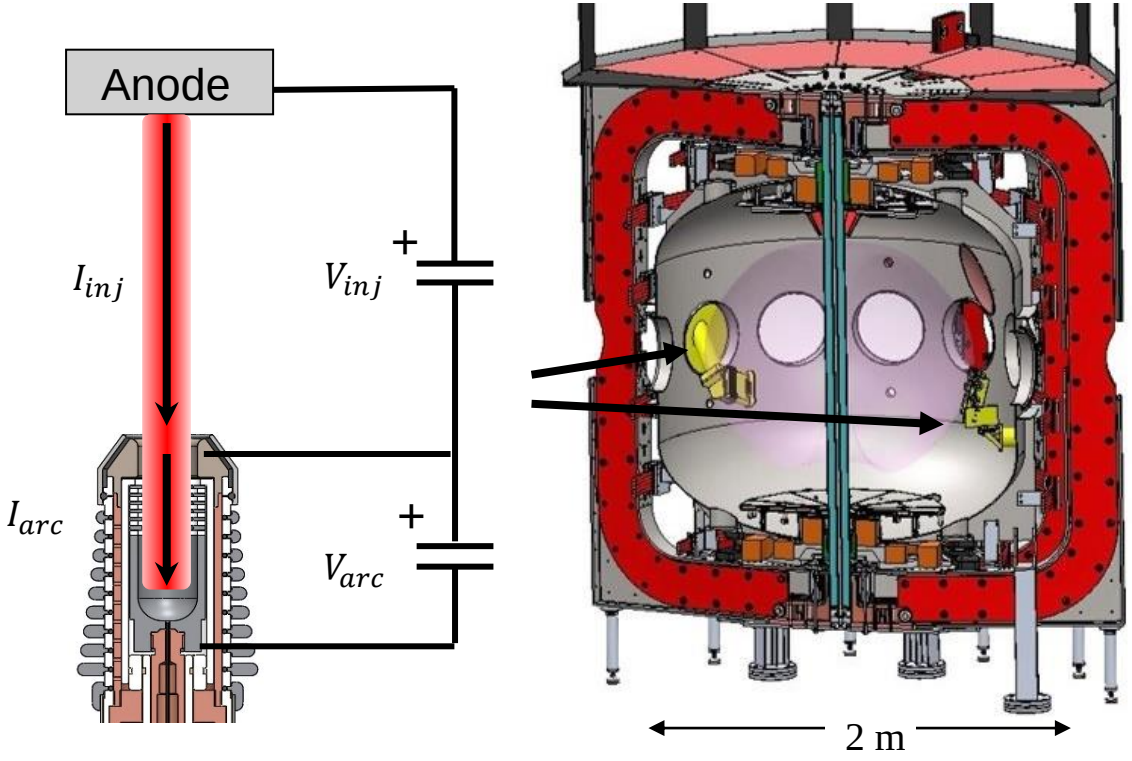


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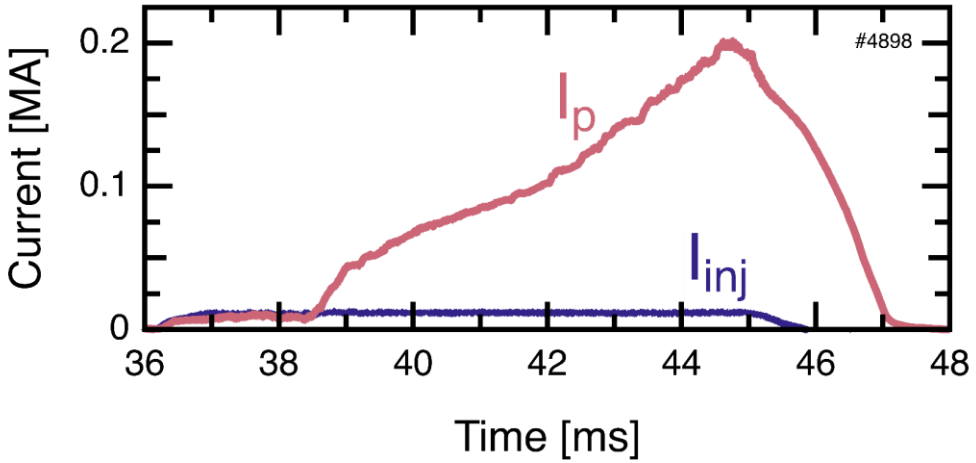
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LHI Exclusively Used for Startup on Pegasus-III

LHI injectors deployed on Pegasus-III



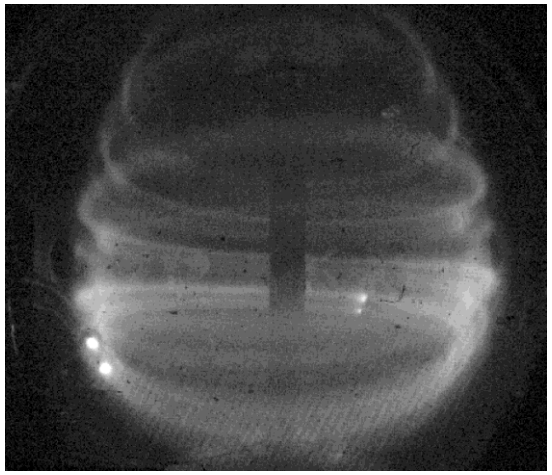
Pegasus-III LHI plasma with $I_p \gg I_{inj}$



- Edge current extracted from small, modular injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities

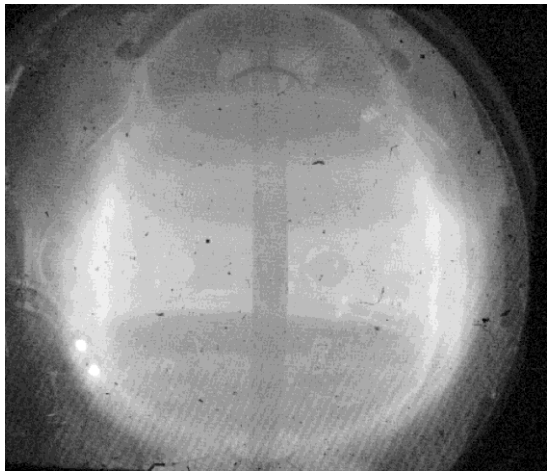
LHI Initiates a Tokamak-Like System

Fast camera images of LHI stages on Pegasus-III



$I_p \approx N_{turns} I_{inj}$

1. Injected current follows helical $\vec{B}$



$I_p \gtrsim N_{turns} I_{inj}$

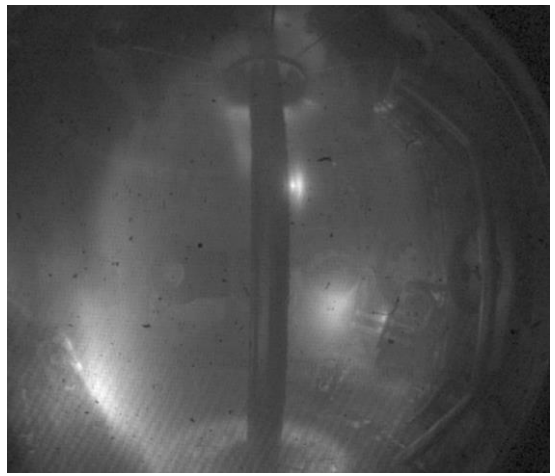
2. Current streams go unstable, reconnect



$I_p \gg N_{turns} I_{inj}$

3. Plasma relaxes to a "tokamak-like" state

Majority of magnetic energy is in axisymmetric mode



$I_p \neq 0, I_{inj} = 0$

4. Tokamak plasma remains after injector shutoff

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Helicity Balance and Magnetic Relaxation Lead to Global I_p Limits

1) Helicity balance

2) Magnetic relaxation

Helicity Balance and Magnetic Relaxation Lead to Global I_p Limits

1) Helicity balance
   - In a tokamak: magnetic helicity $K \propto I_p \Psi_T$

$$\frac{dK}{dt} = \dot{K}_{AC} + \dot{K}_{DC} - \dot{K}_{diss}$$

   - To drive I_p : $\dot{K}_{AC} + \dot{K}_{DC} > \dot{K}_{diss}$

2) Magnetic relaxation

AC Helicity Injection

$$\dot{K}_{AC} = 2\Psi_T V_{IND}$$

DC Helicity Injection

$$\dot{K}_{DC} = 2\Psi_T V_{LHI}$$

$$V_{LHI} = V_{inj}\frac{B_n A_{inj}}{\Psi_T}$$

Helicity Dissipation

$$\dot{K}_{diss} = 2\int_V dV\left(\eta \vec{J} \cdot \vec{B}\right)$$

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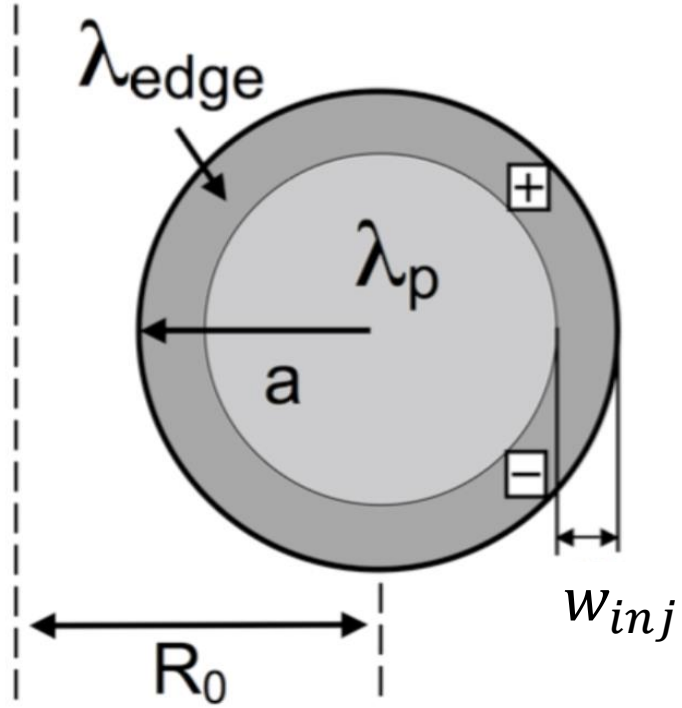
$$\frac{dK}{dt} = \dot{K}_{AC} + \dot{K}_{DC} - \dot{K}_{diss}$$

   - To drive I_p : $\dot{K}_{AC} + \dot{K}_{DC} > \dot{K}_{diss}$

2) Magnetic relaxation
   - System driven to minimum energy state that conserves K
   - Relaxed/Taylor state: uniform $\lambda(r) \equiv \frac{\mu_0 J_\parallel}{B}$

Taylor Limit: $$I_p \leq \sqrt{\frac{1}{2\pi R_{inj} w_{inj}} \frac{\Psi_T I_{inj}}{B_{p,inj}/I_p}}$$

Simplified plasma geometry for Taylor limit approximation [1]



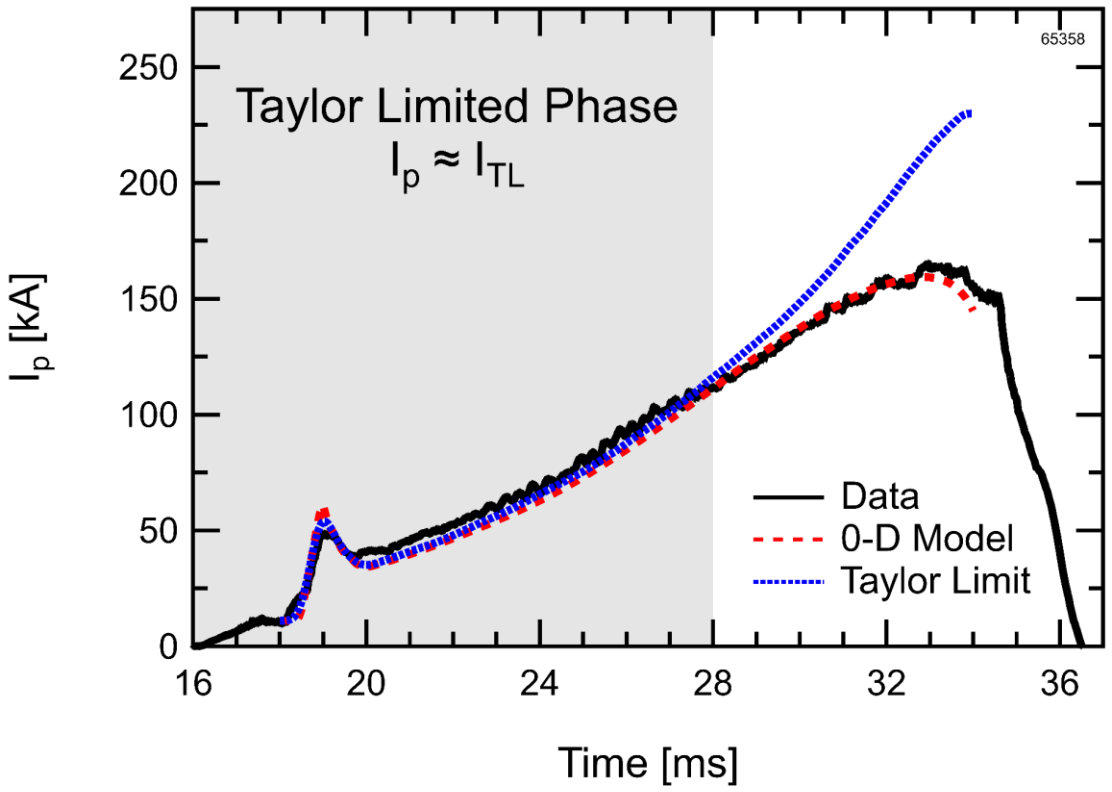
In LHI: $\lambda_{edge} \geq \lambda_p$

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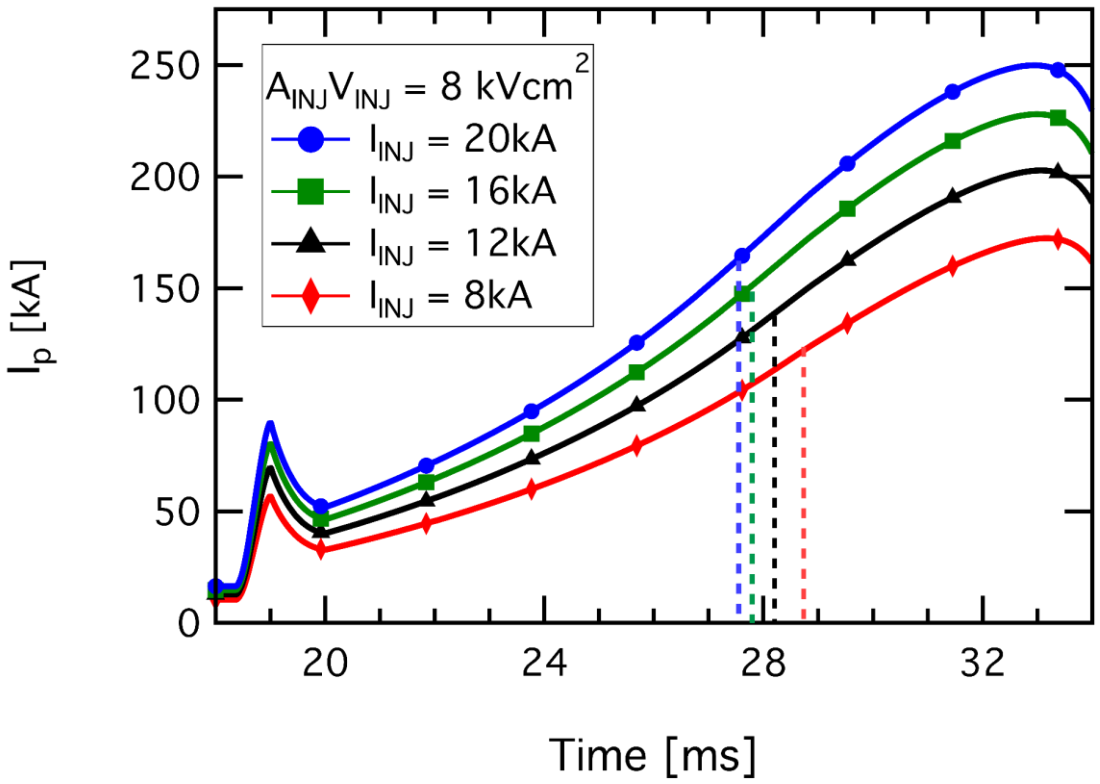
[1] D. J. Battaglia *et al*, *Nucl. Fusion* **51**, (2011).

Increased I_{TL} more Efficiently Uses V_{LHI} to Achieve Higher I_p

0-D power balance model predicts extended period where $I_p = I_{TL}$ [1]



0-D model projections at increasing I_{TL} and fixed V_{LHI} demonstrate path to higher I_p [1]

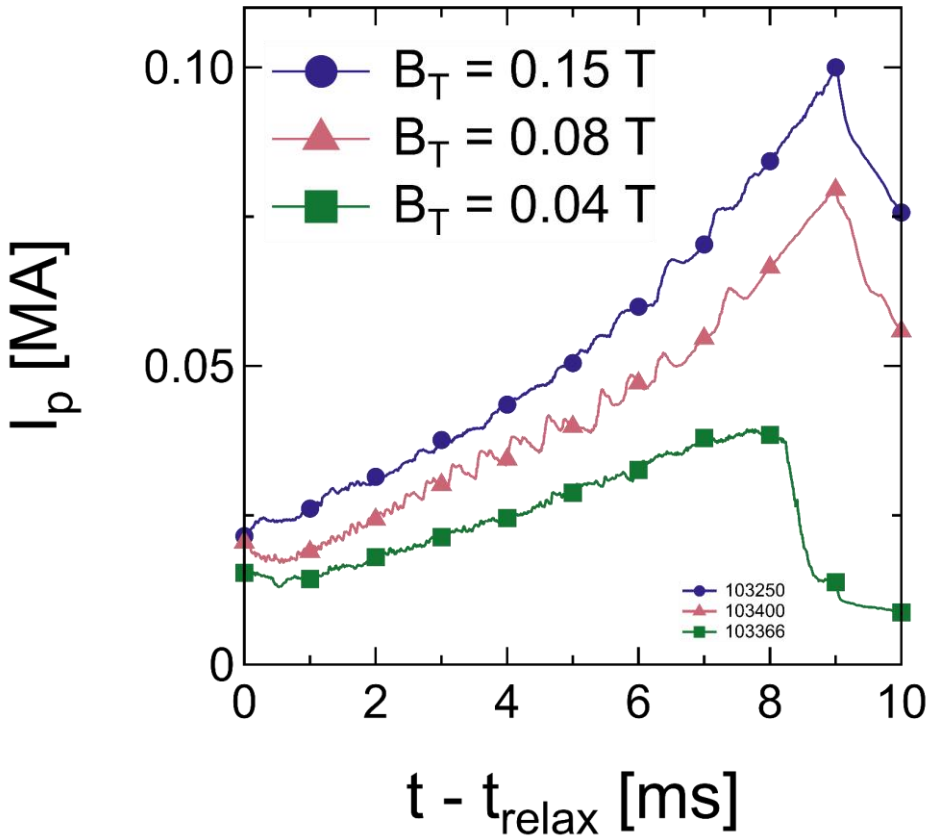


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[1] J. L. Barr *et al.*, *Nucl. Fusion* **58**, (2018).

Pegasus Demonstrated Path to Higher I_p for B_T up to 0.15 T

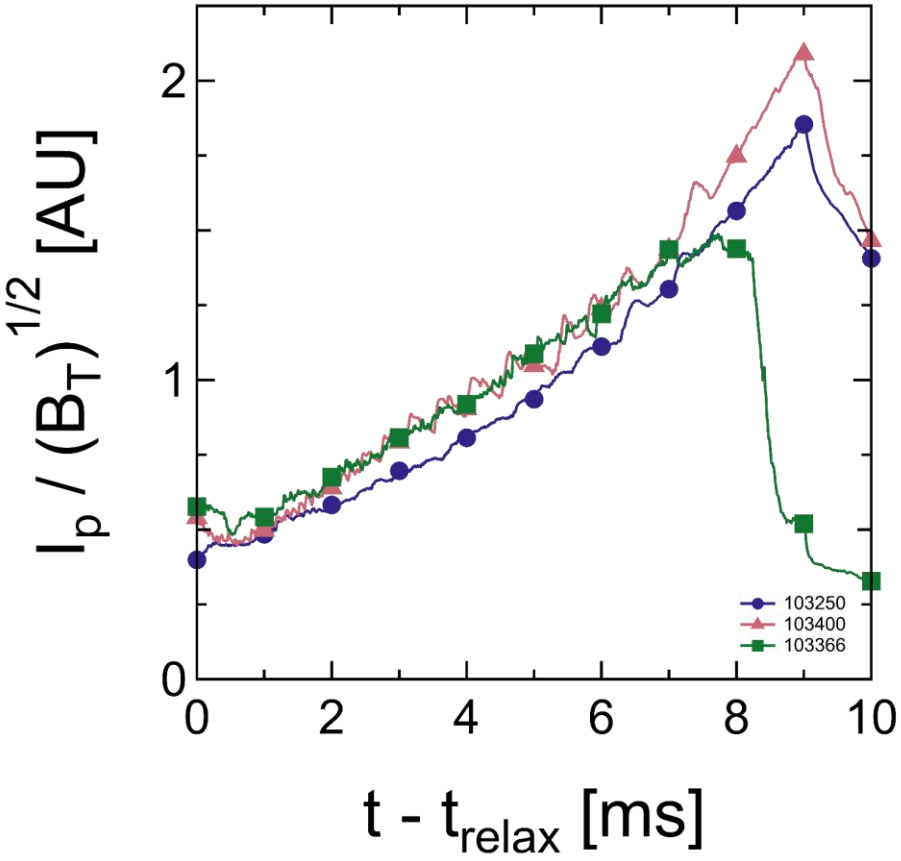
I_p increases with B_T up to $0.15\ T$ in Pegasus discharges with fixed helicity input



I_p normalized by expected $\sqrt{B_T}$ scaling

$$I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$$

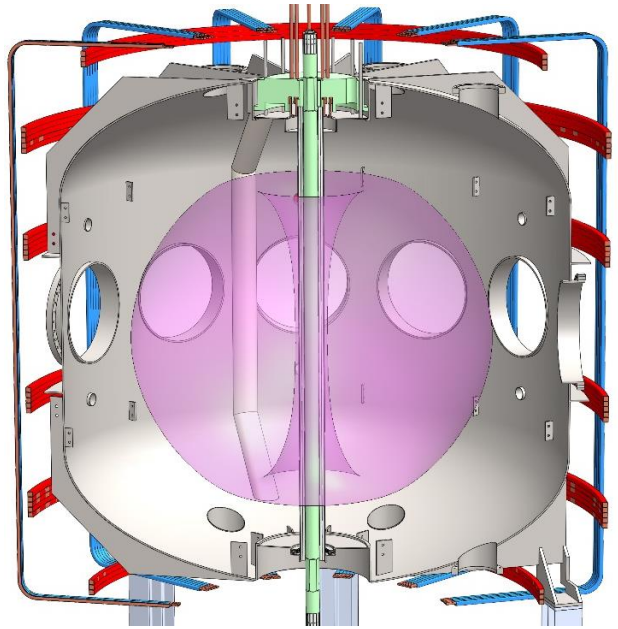
I_p follows expected $I_{TL} \propto \sqrt{B_T}$ scaling



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Optimizing Taylor Limit in Pegasus-III

Pegasus

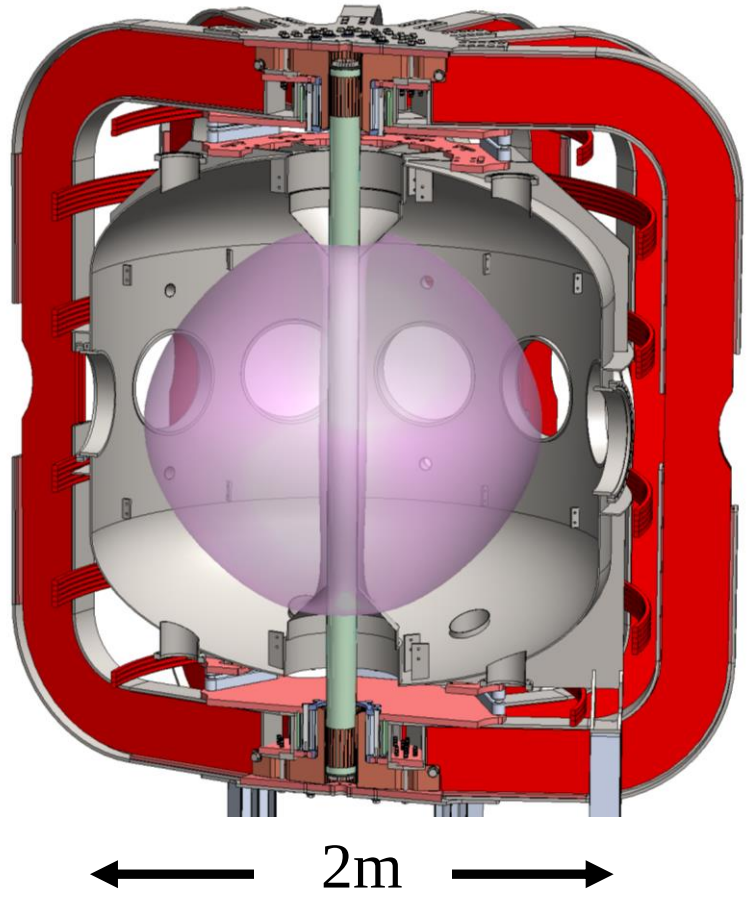


Pegasus-III design significantly increases I_{TL}

Parameter	Pegasus → Pegasus-III
B_T	0.15 T → 0.6 T
I_{inj}	8 kA → 16 kA
w_{inj}	Test non-circular injector design

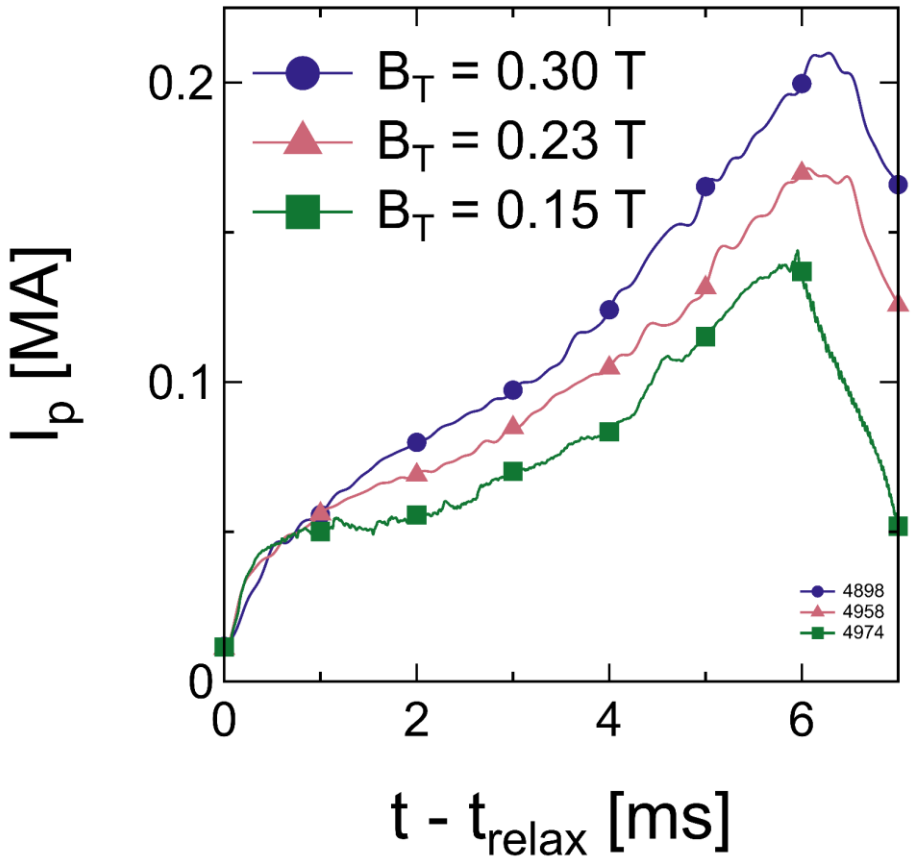
$$I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$$

Pegasus-III



Robust $I_{TL} \propto \sqrt{B_T}$ Scaling Extended for B_T up to 0.3 T

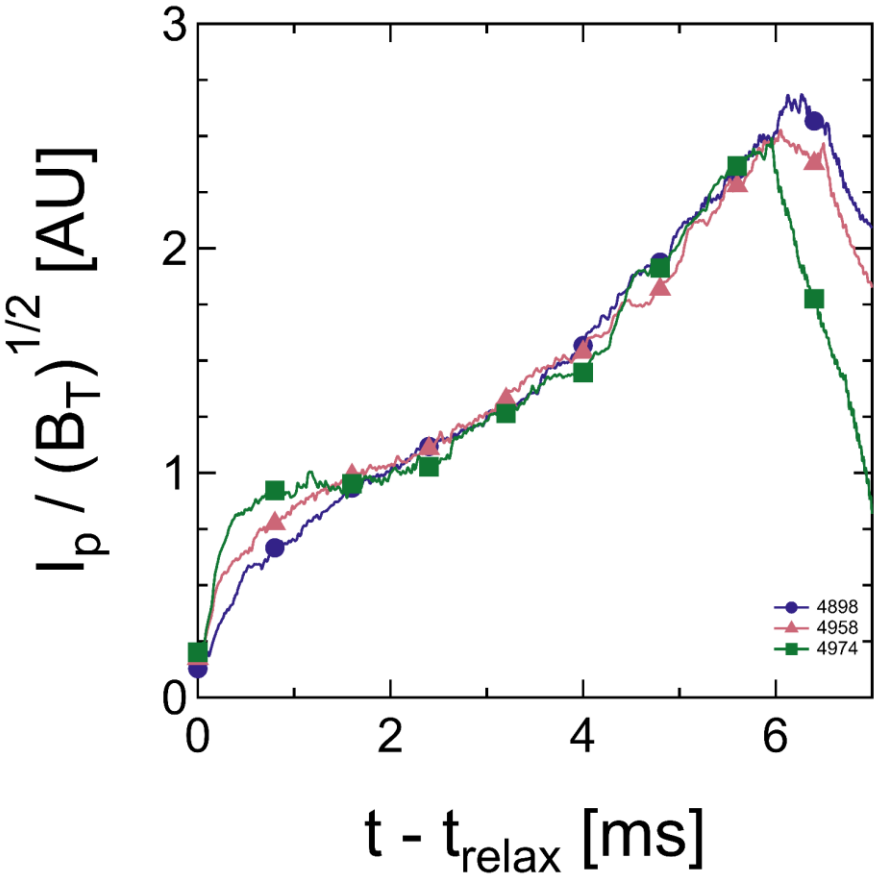
I_p increases with B_T up to $0.3\ T$ in Pegasus-III discharges with fixed helicity input



I_p normalized by expected $\sqrt{B_T}$ scaling

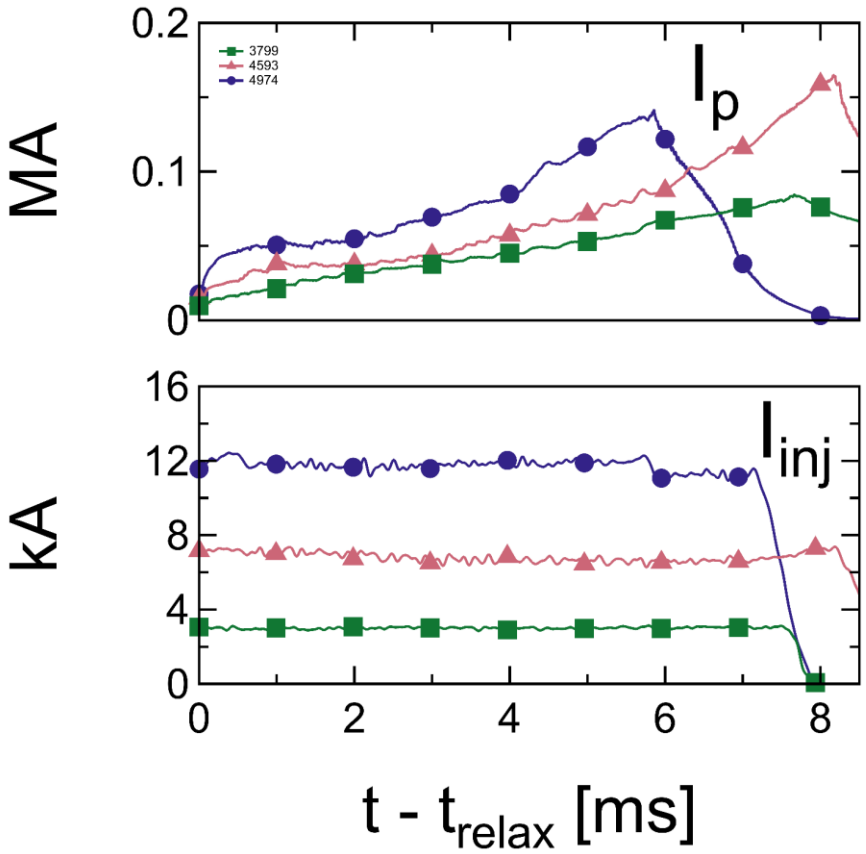
$$I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$$

I_p follows expected $I_{TL} \propto \sqrt{B_T}$ scaling



Robust $I_{TL} \propto \sqrt{I_{inj}}$ Scaling Extended for I_{inj} up to 12 kA

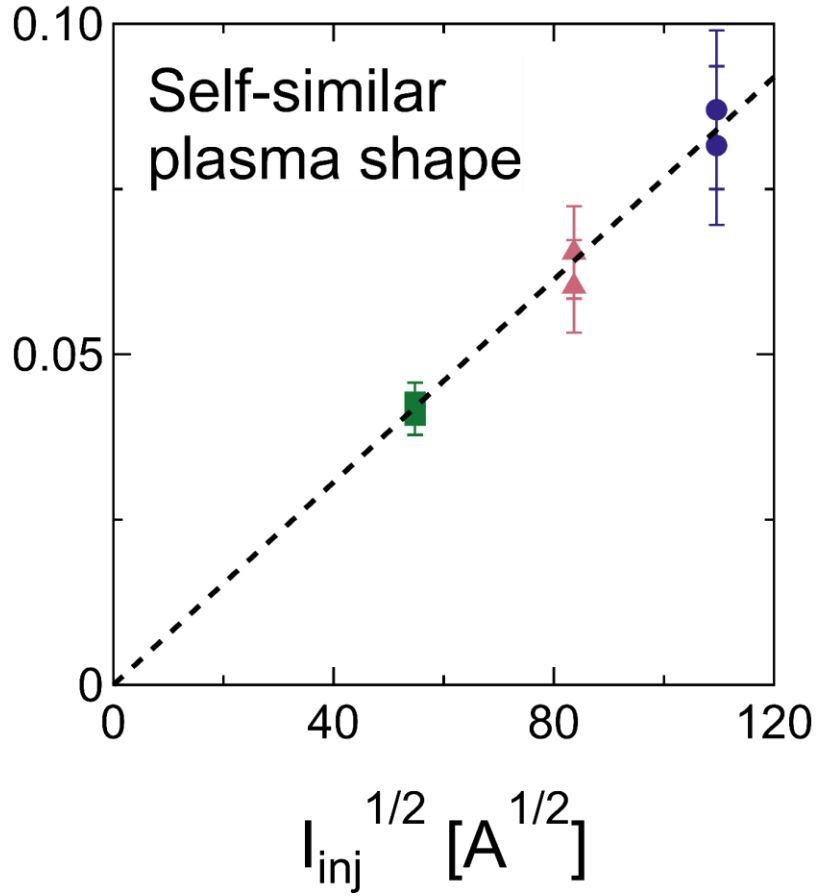
Pegasus-III discharges developed at $B_T = 0.15$ T at varying levels of $I_{inj} \leq 12$ kA



Compare time points with self-similar plasma shapes

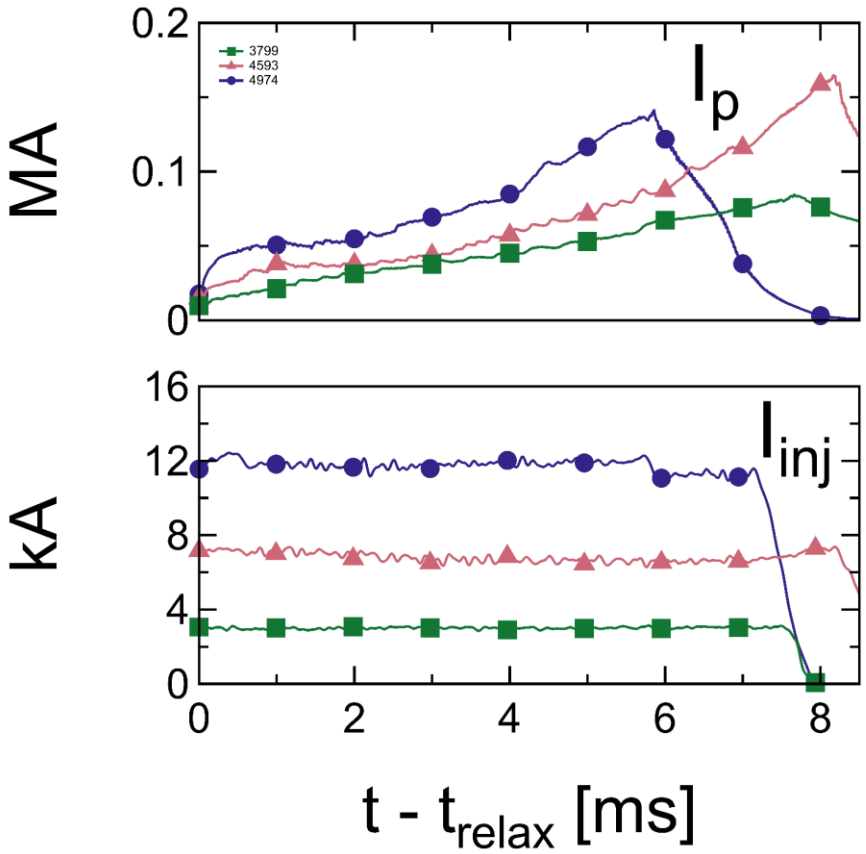
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Robust $I_{TL} \propto \sqrt{I_{inj}}$ Scaling Extended for I_{inj} up to 12 kA

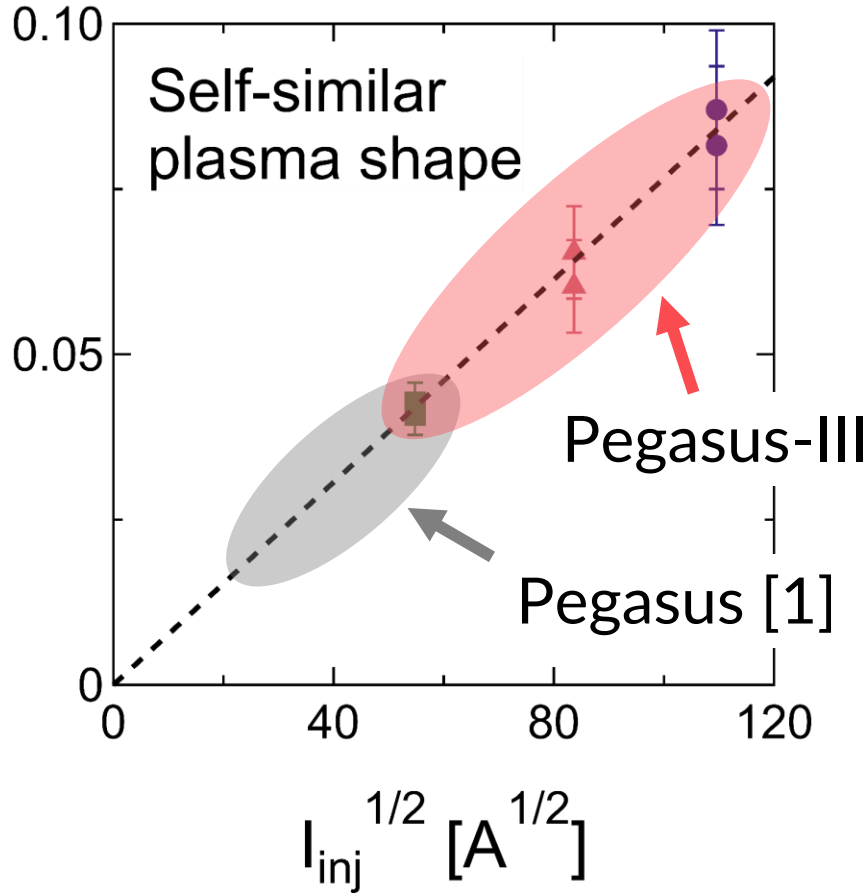
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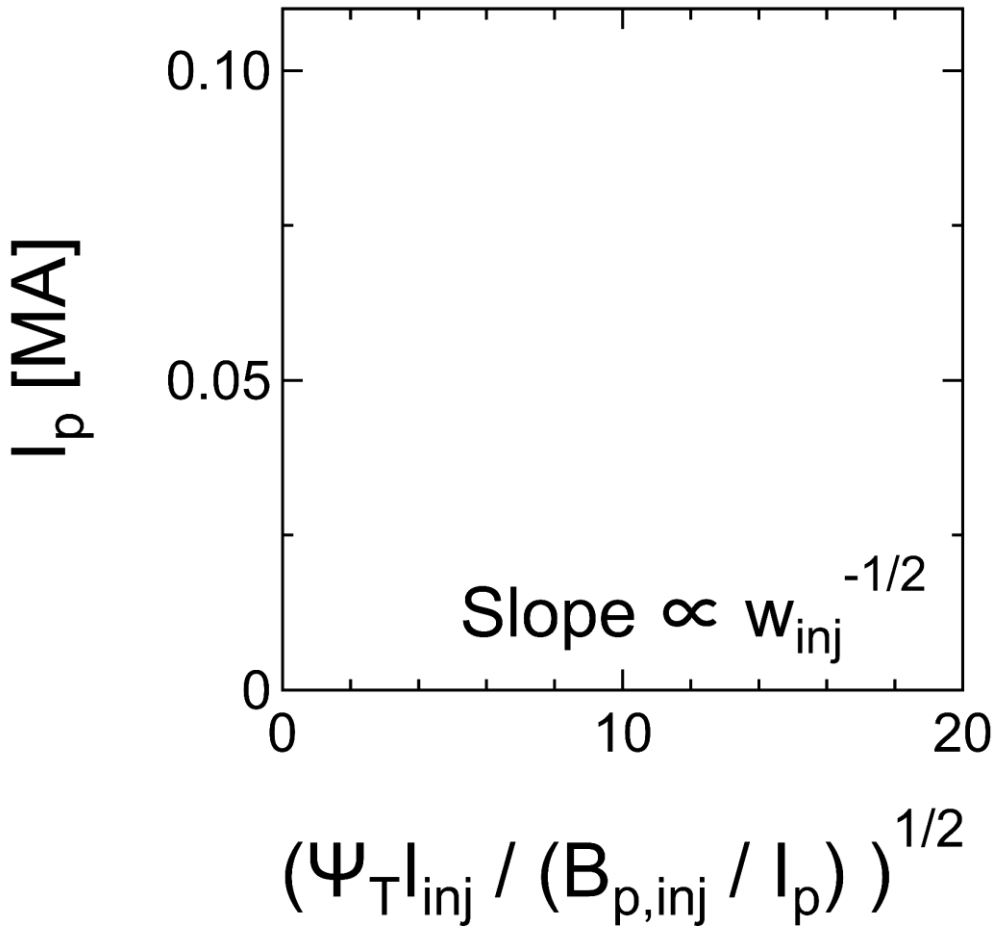
[1] D. J. Battaglia *et al.*, *Nucl. Fusion* **51**, (2011).

Injector Design can be Leveraged to Optimize I_{TL} via w_{inj}

- w_{inj} variation inferred from scatterplot

$$I_{TL} = \underbrace{\sqrt{\frac{1}{2\pi R_{inj} w_{inj}}}}_{Slope} \sqrt{\frac{\Psi_T I_{inj}}{B_{p,inj}/I_p}}$$

I_p vs $\sqrt{\frac{\Psi_T I_{inj}}{B_{p,inj}/I_p}}$ for different injector geometries



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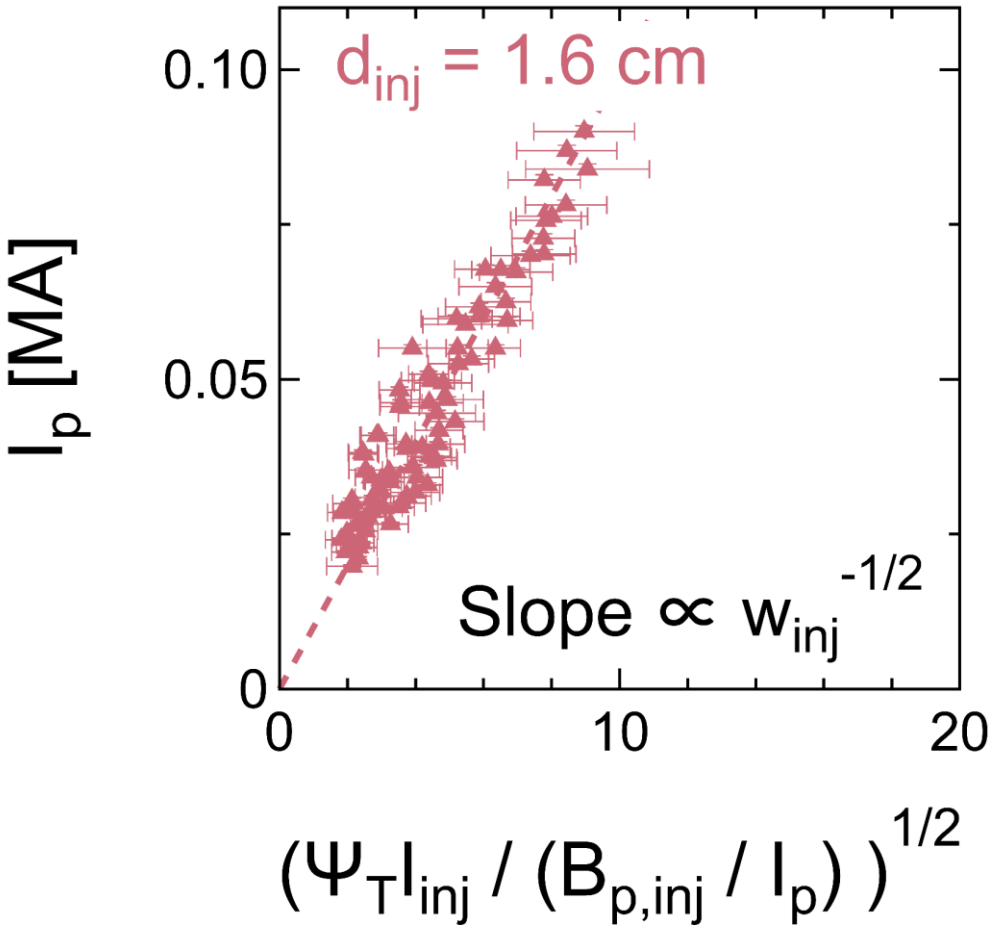
- Compare data from discharges with varied d_{inj}

$d_{inj} = 1.6$ cm

Head-on view of injector:



I_p vs $\sqrt{\frac{\Psi_T I_{inj}}{B_{p,inj}/I_p}}$ for different injector geometries



Injector Design can be Leveraged to Optimize I_{TL} via w_{inj}

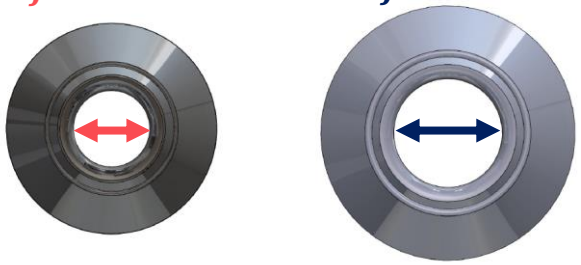
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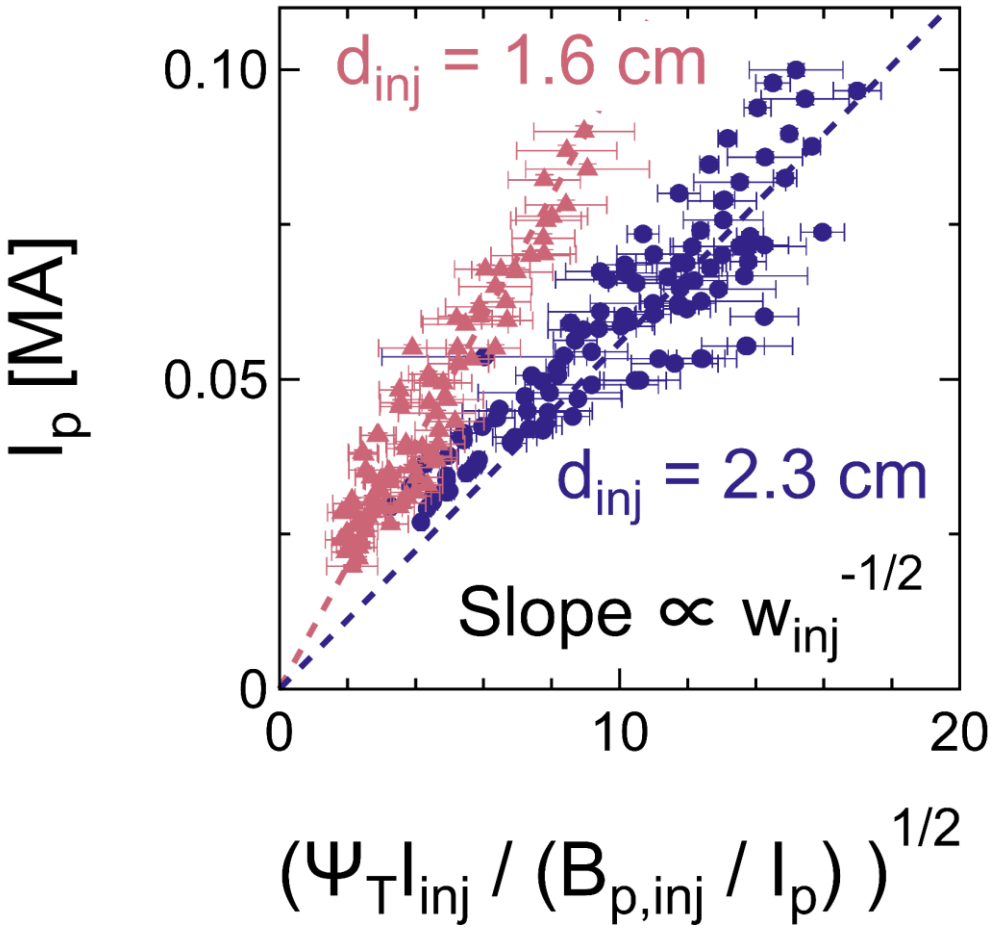
$d_{inj} = 1.6$ cm $d_{inj} = 2.3$ cm

Head-on view of injector:



- Smaller d_{inj} → steeper slope → smaller w_{inj}
  - Injector design can be used to optimize I_{TL}

I_p vs $\sqrt{\frac{\Psi_T I_{inj}}{B_{p,inj}/I_p}}$ for different injector geometries

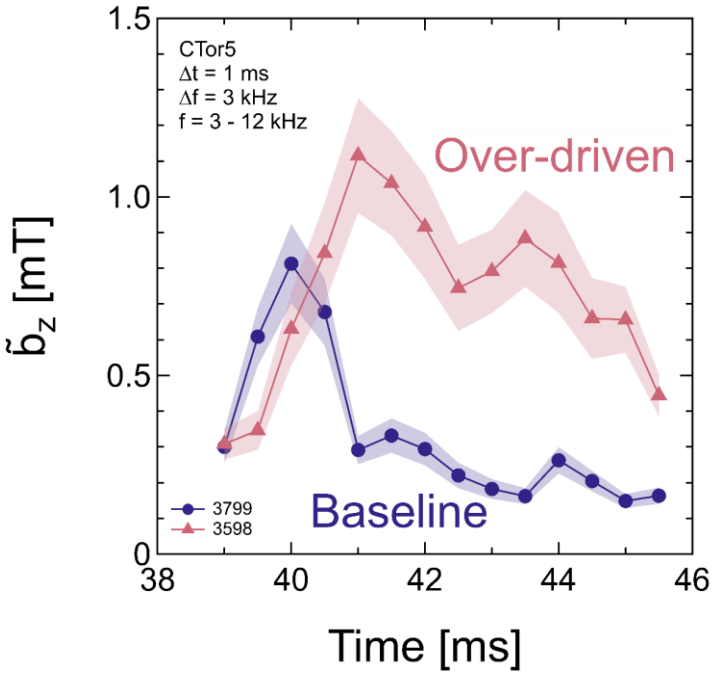


Increased Magnetic Activity in Discharges Over-driven at Taylor Limit

- Pegasus-III uses Local Helicity Injection (LHI) solenoid-free startup
  - Injected current streams relax to tokamak-like plasma
  - Taylor limit largely dictates achievable I_p during LHI discharges

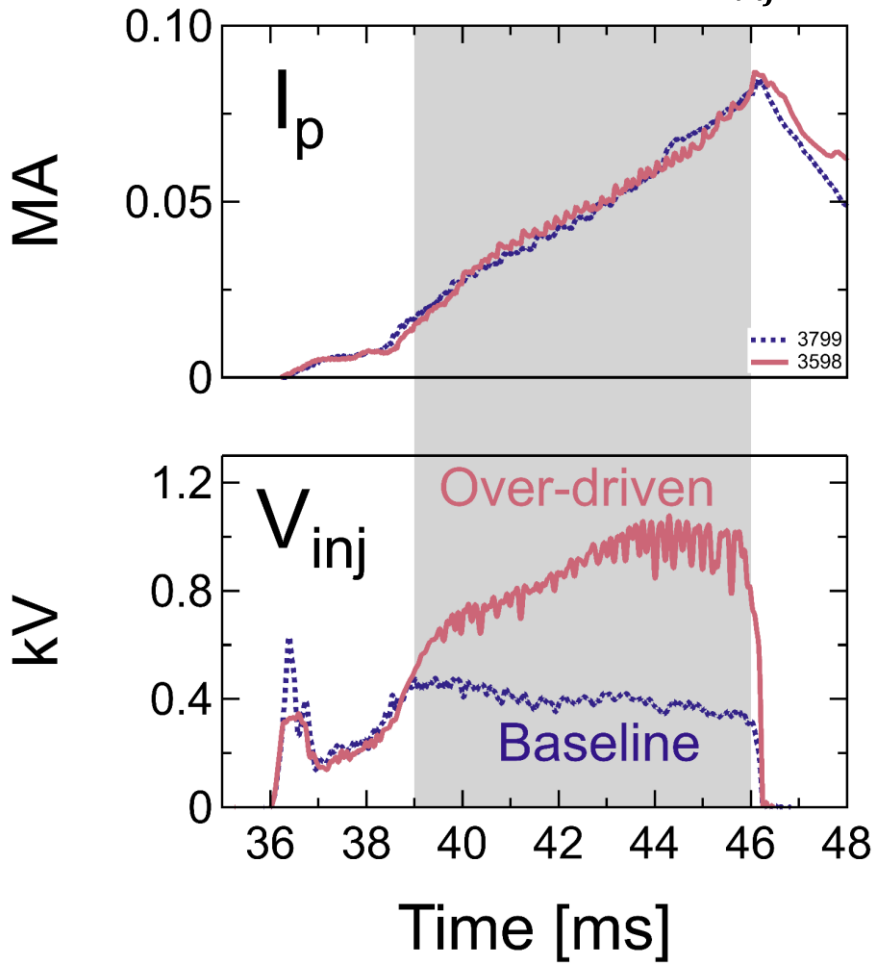
- Robust $I_p \leq I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$ scaling in Pegasus-III operating space
  - $I_{TL} \propto \sqrt{B_T I_{inj}}$ scaling observed for $B_T \leq 0.3$ T and $I_{inj} \leq 12$ kA
  - Demonstrated ability to vary w_{inj} via injector width

- Excess helicity input increases $\tilde{b}$ when sustained at Taylor limit

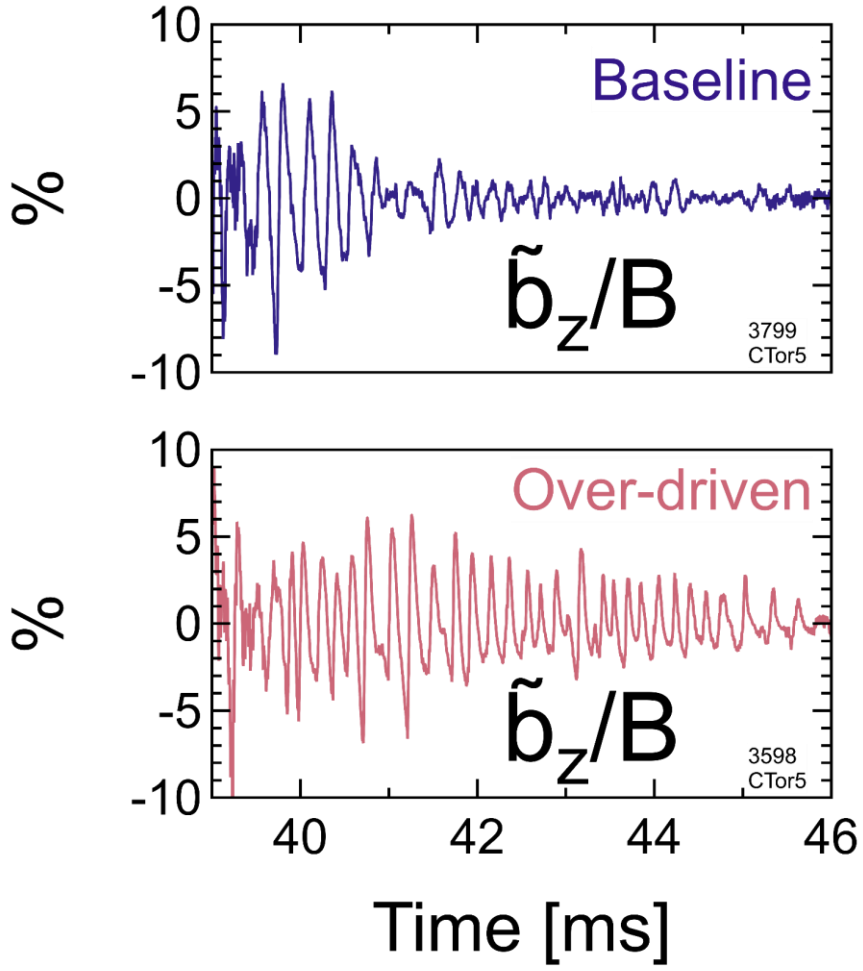


Increased Magnetic Activity when System Over-driven

Same I_p realized with significantly higher helicity input $V_{LHI} \propto V_{inj}$



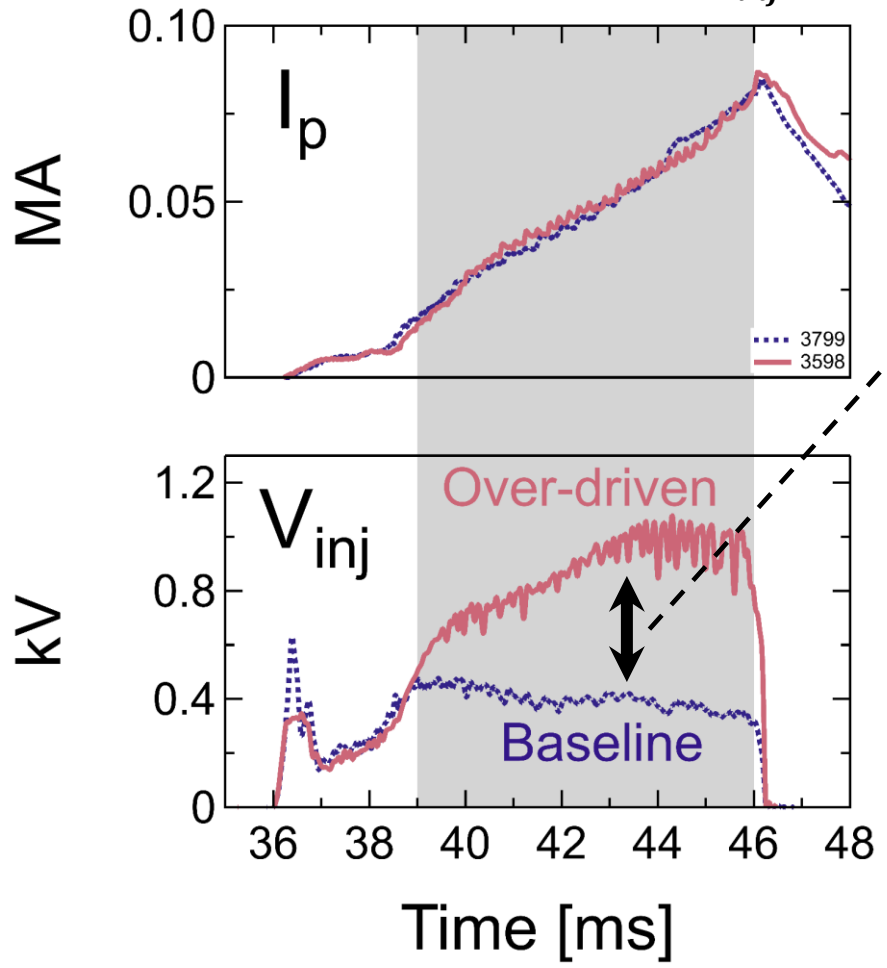
Increased $\tilde{b}$ in over-driven discharge



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Increased Magnetic Activity when System Over-driven

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Higher V_{LHI} at fixed I_{TL}

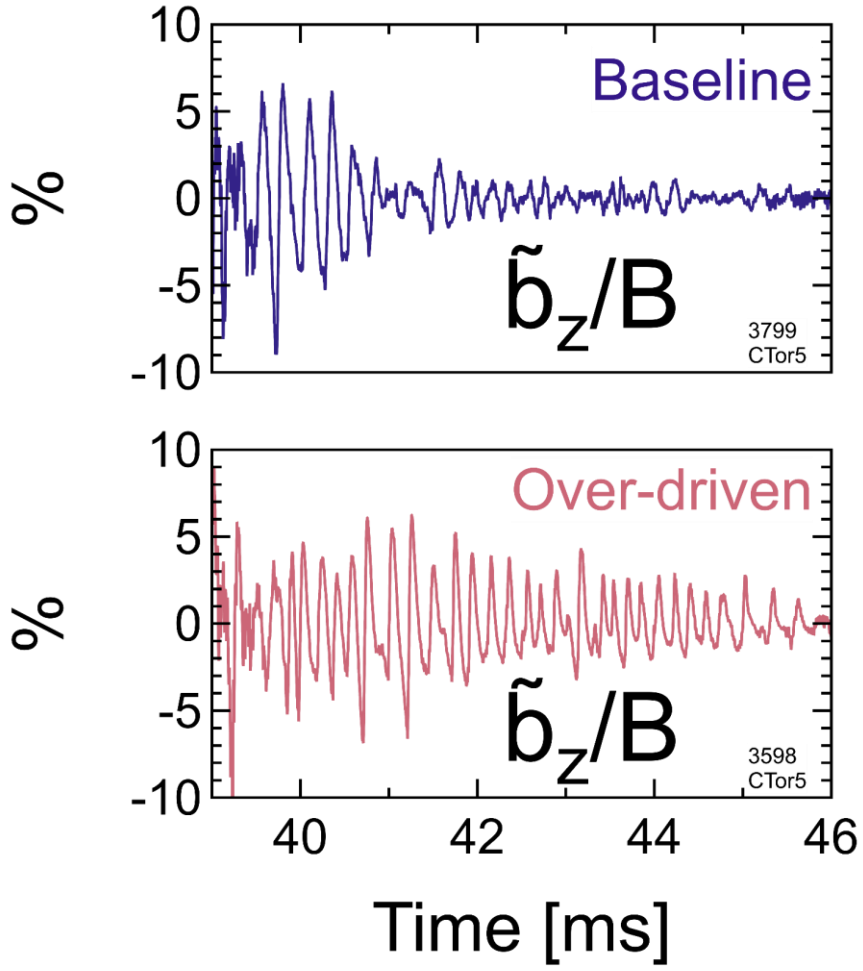
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More excess helicity input

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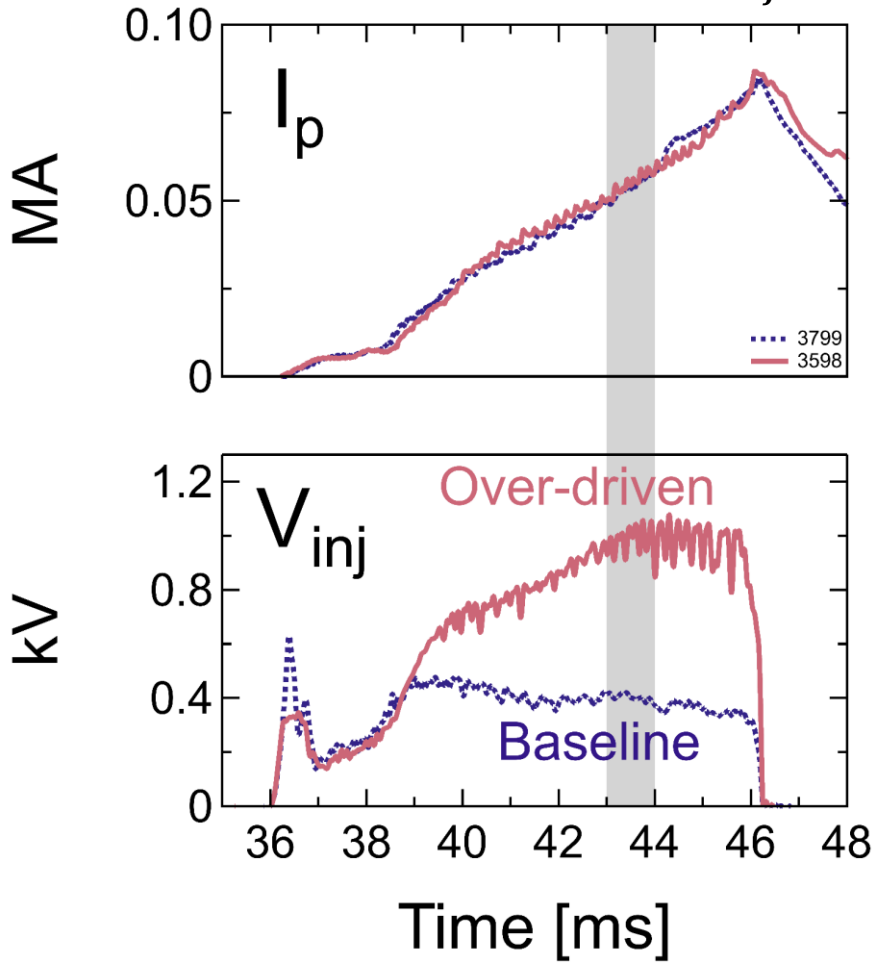
"Over-driven"

Increased $\tilde{b}$ in over-driven discharge

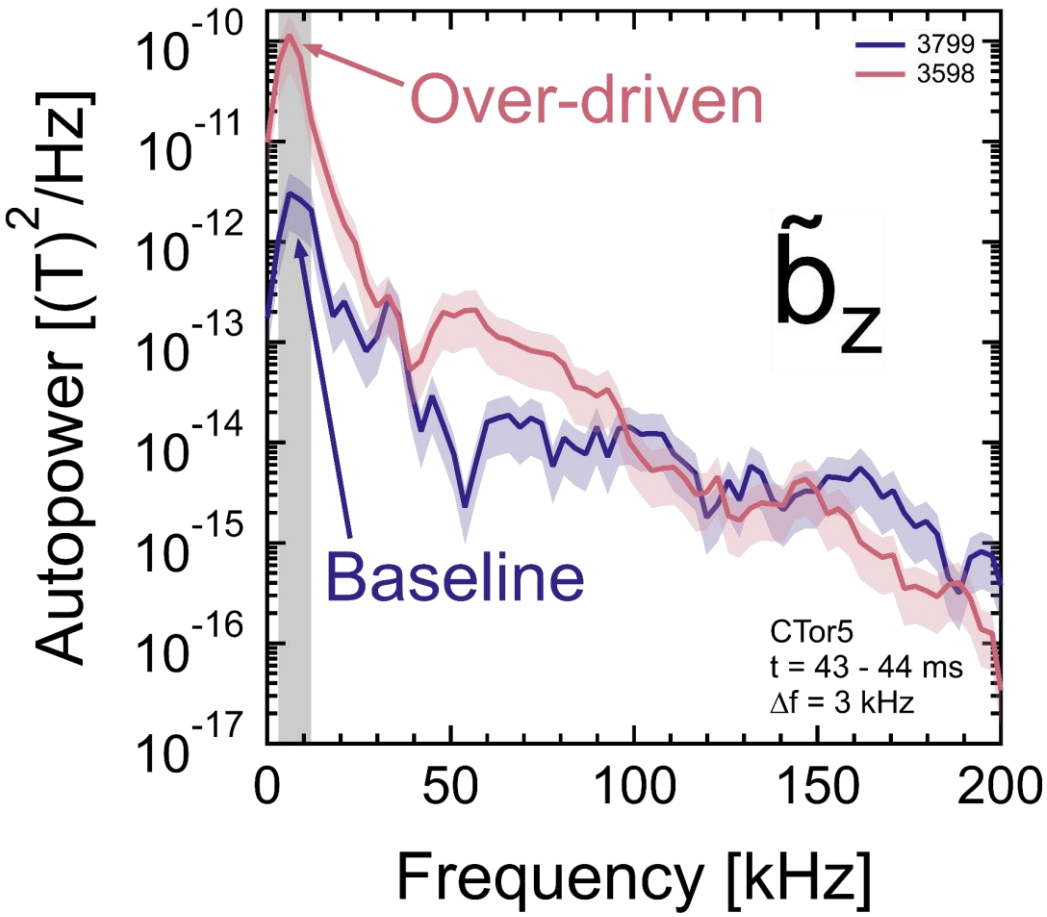


Excess Helicity Input Predominantly Increases Low Frequency Magnetic Activity

Same I_p realized with significantly higher helicity input $V_{LHI} \propto V_{inj}$



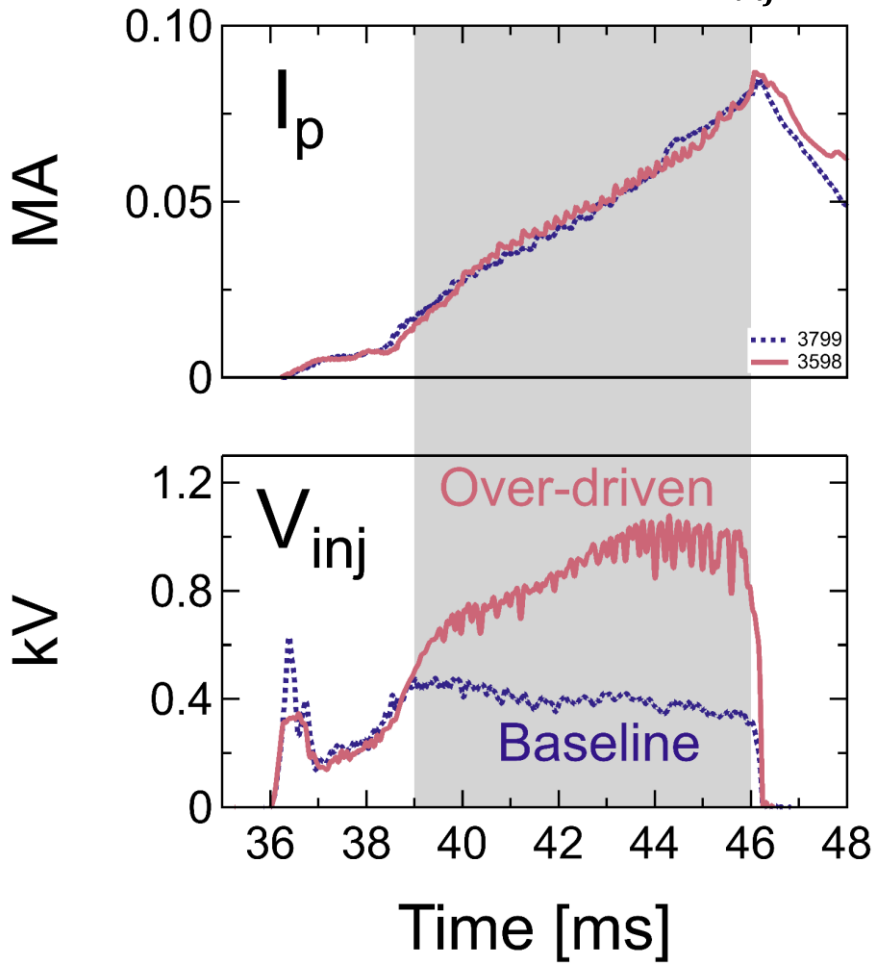
Increased $\tilde{b}$ at low ($\lesssim 10\ kHz$) frequency in over-driven discharge



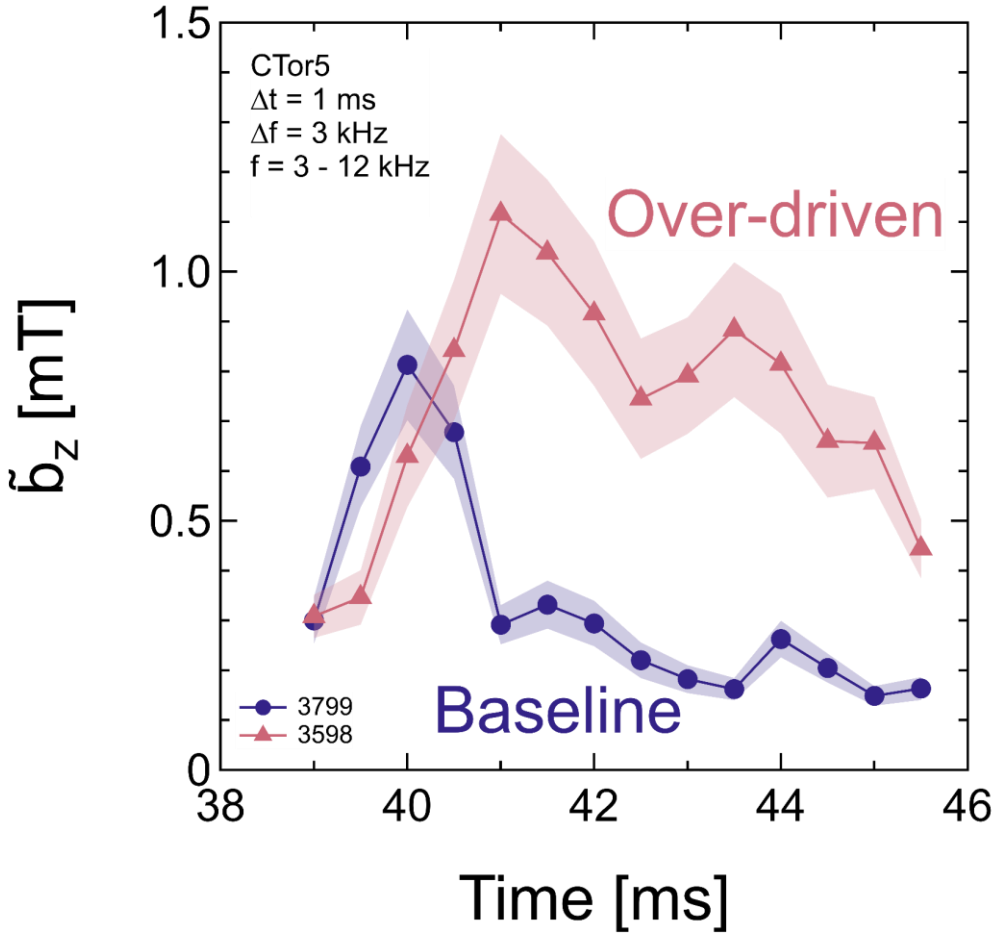
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Low Frequency $\tilde{b}$ Increases as System Over-driven

Same I_p realized with significantly higher helicity input $V_{LHI} \propto V_{inj}$



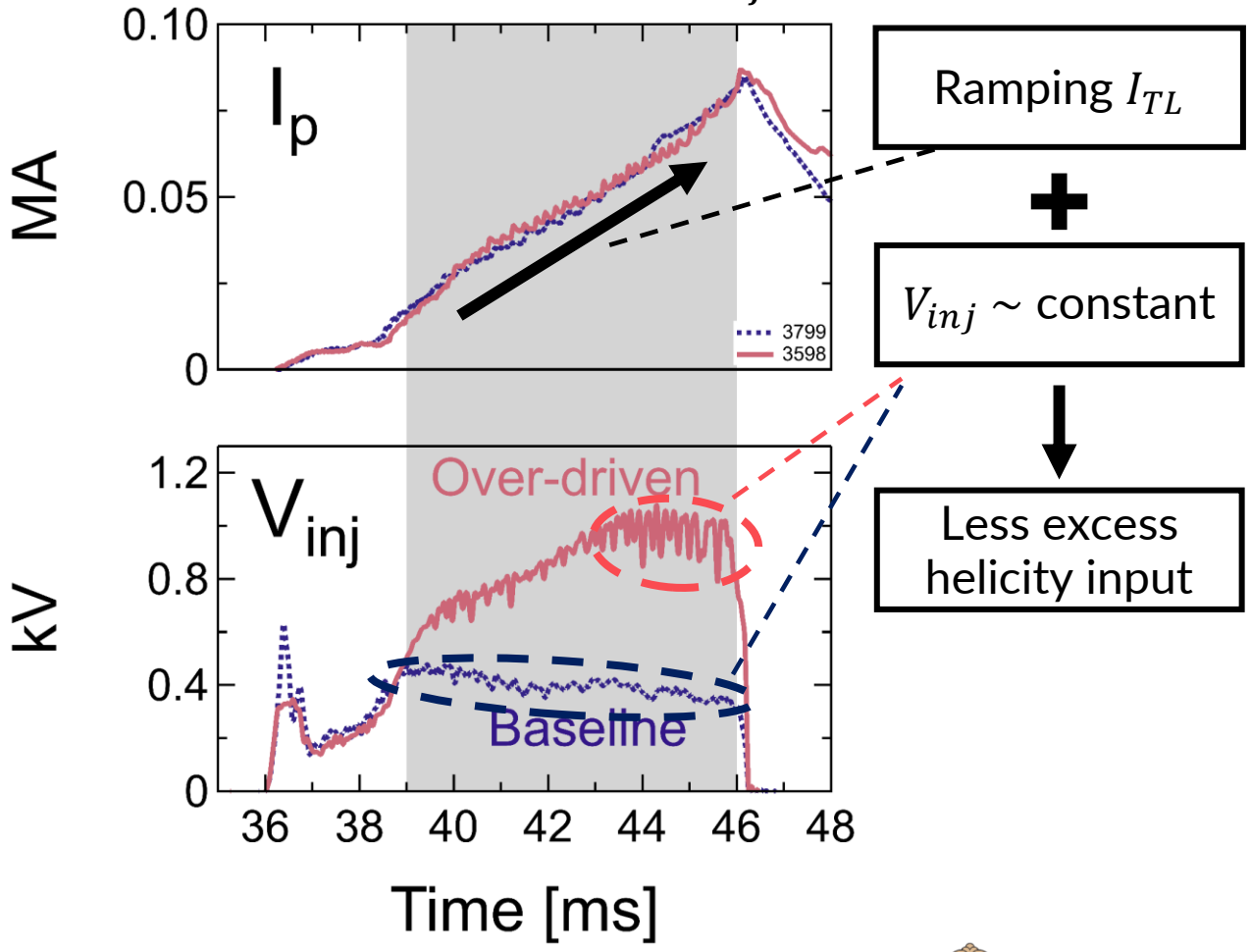
Larger amplitude low frequency $\tilde{b}$ when system over-driven



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Low Frequency $\tilde{b}$ Increases as System Over-driven

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Ramping I_{TL}

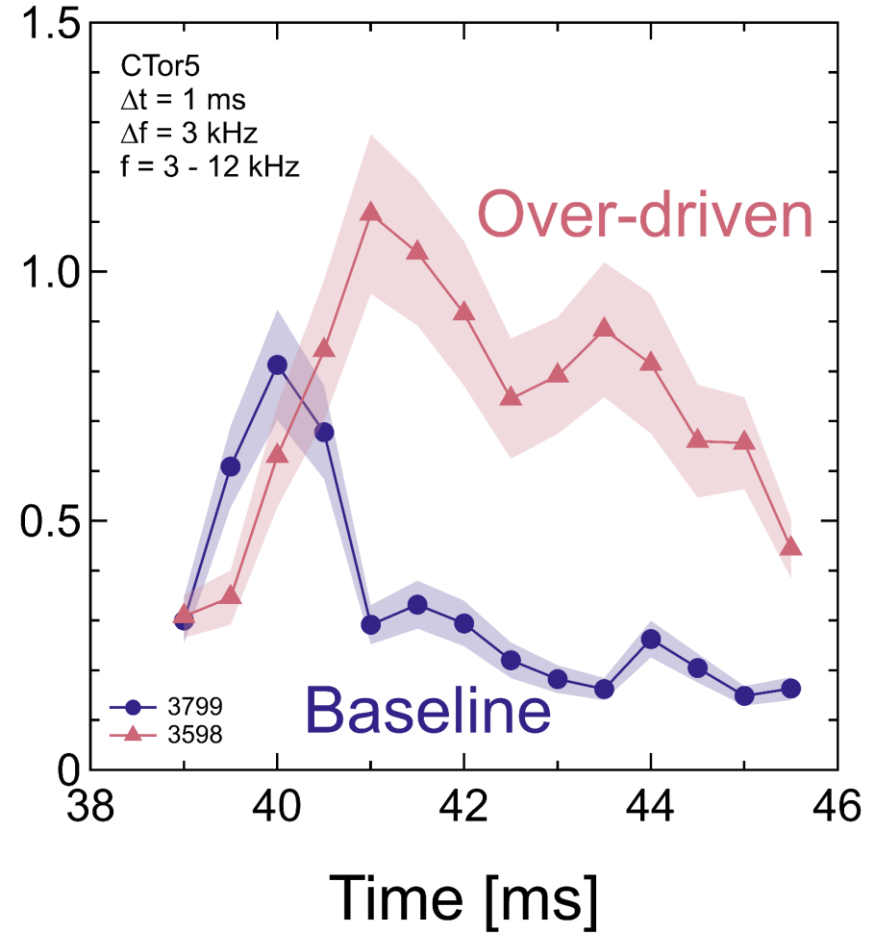
+

$V_{inj} \sim$ constant

↓

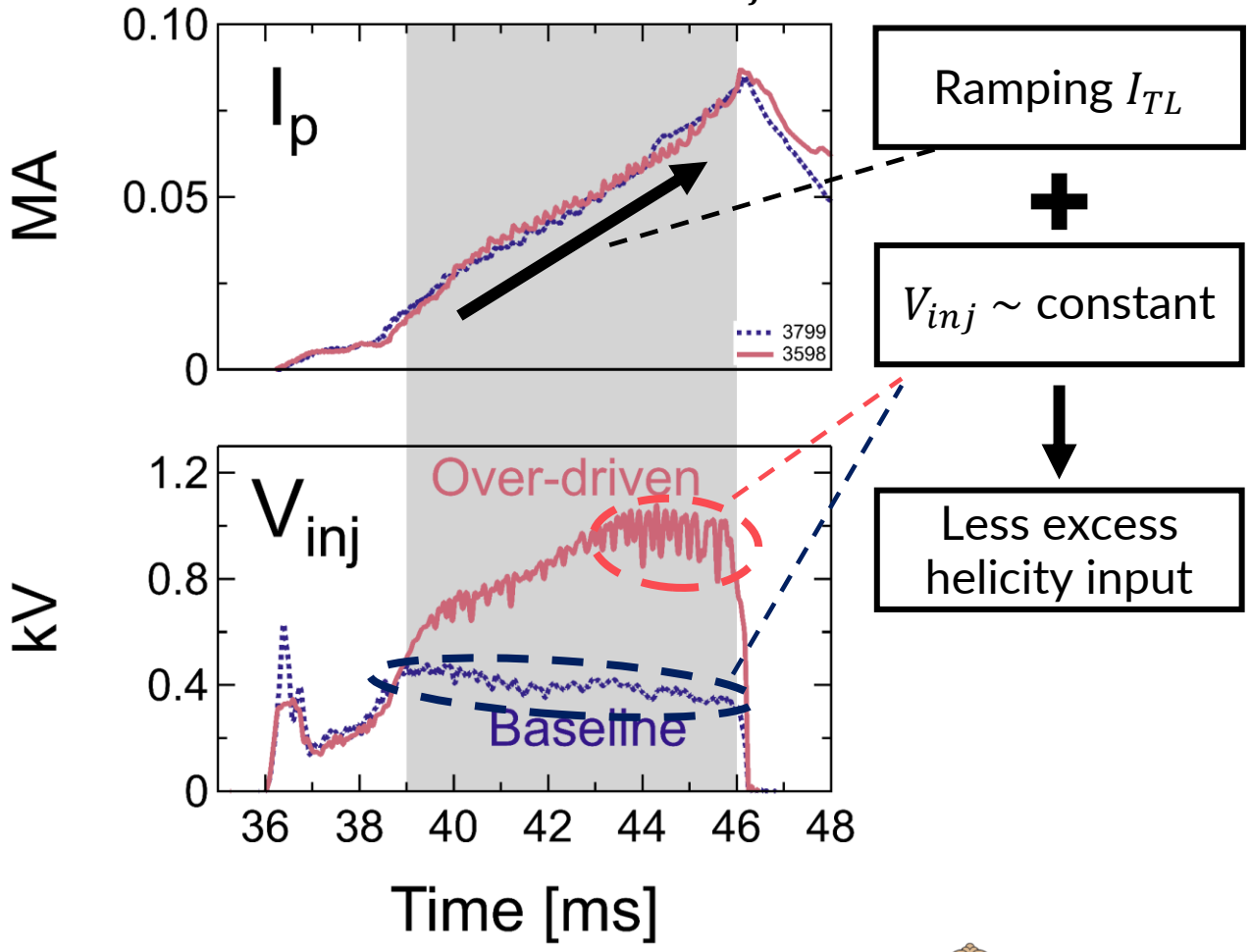
Less excess helicity input

Larger amplitude low frequency $\tilde{b}$ when system over-driven



Low Frequency $\tilde{b}$ Increases as System Over-driven

Same I_p realized with significantly higher helicity input $V_{LHI} \propto V_{inj}$



Ramping I_{TL}

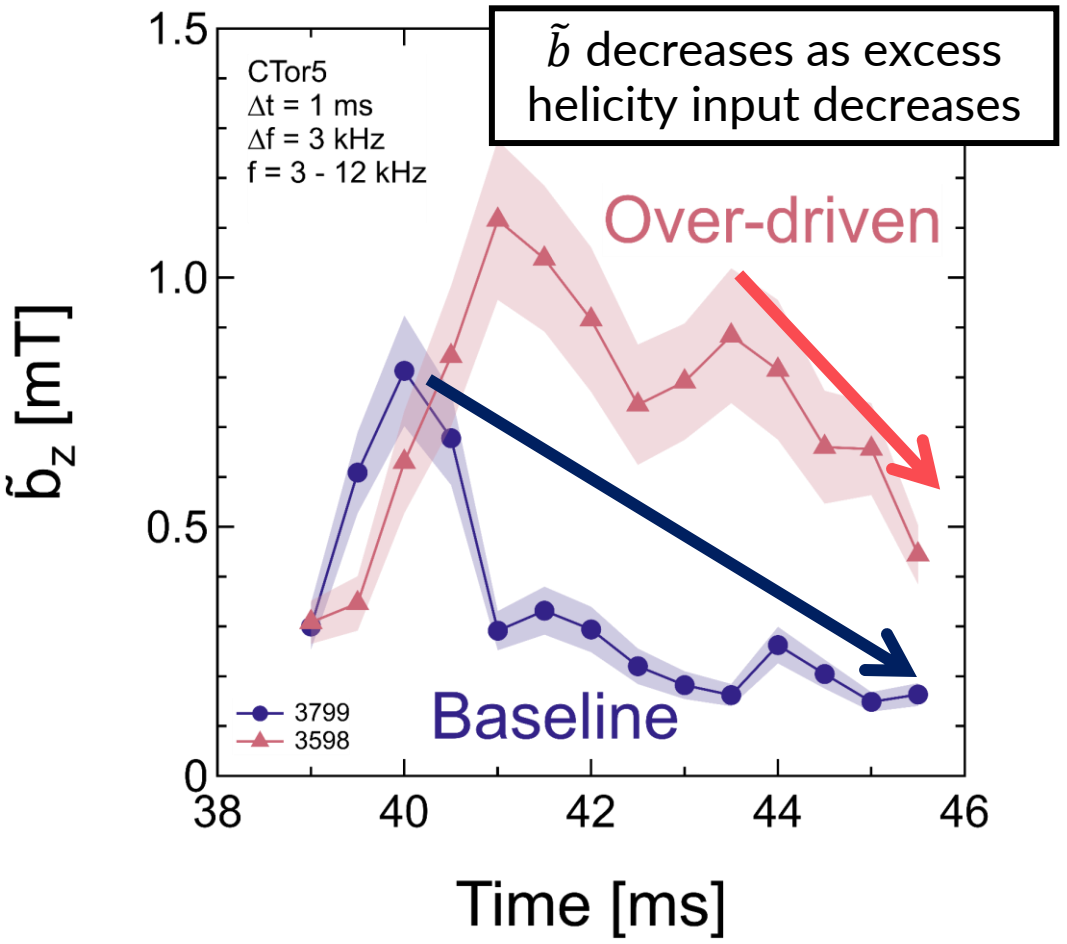
+

$V_{inj} \sim$ constant

↓

Less excess helicity input

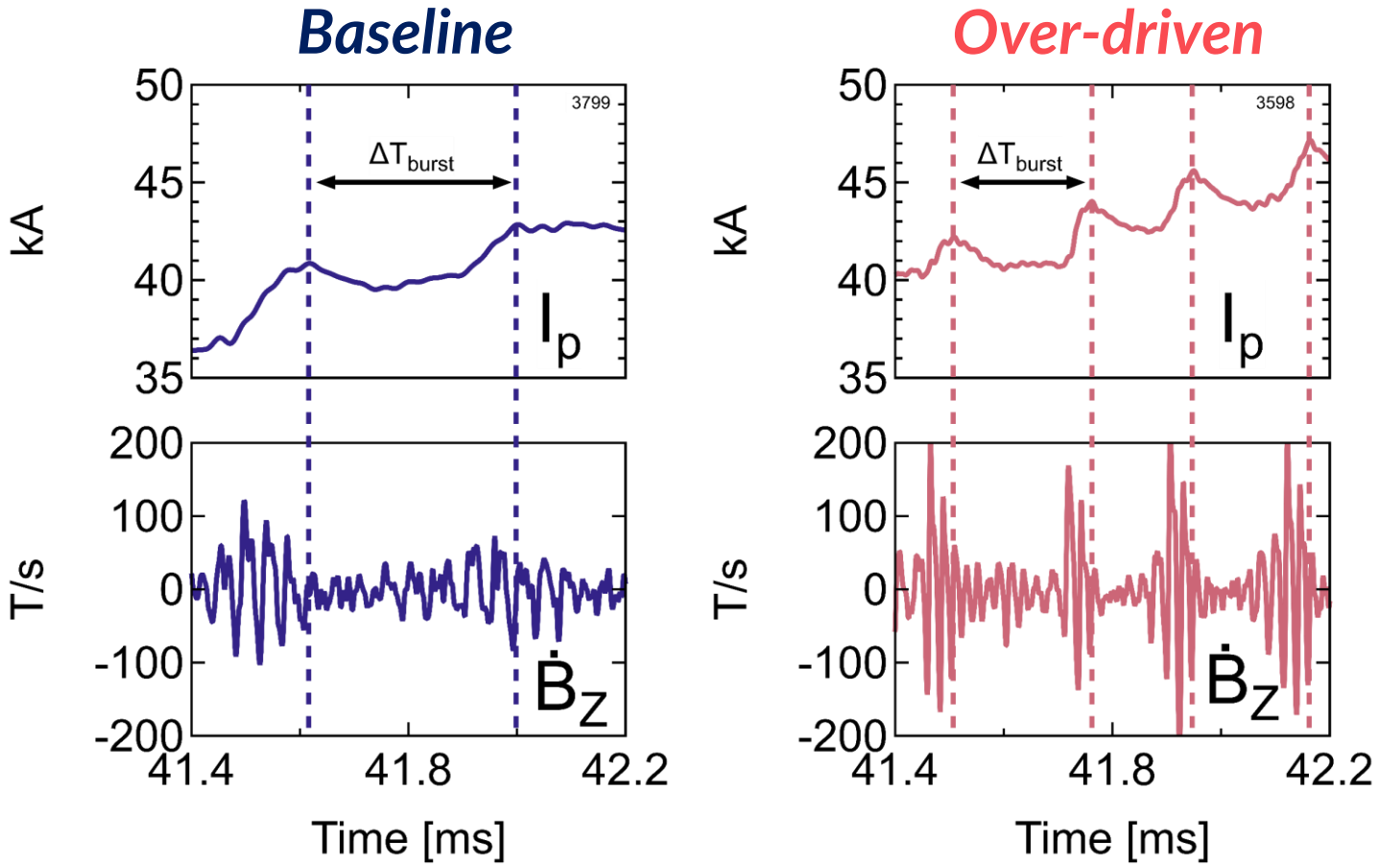
Larger amplitude low frequency $\tilde{b}$ when system over-driven



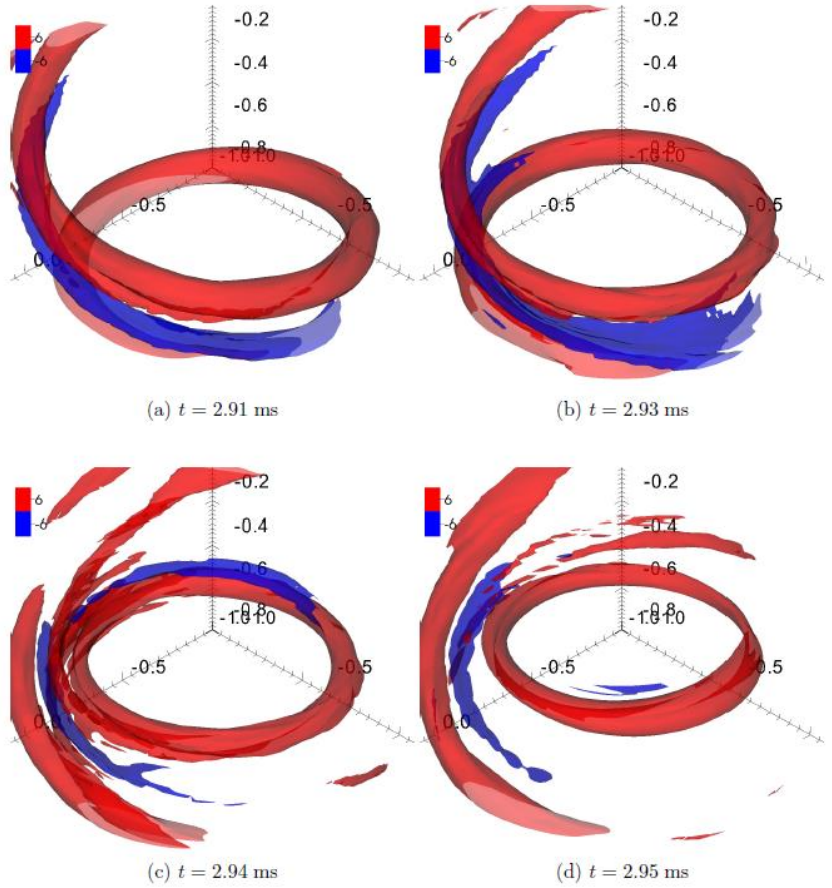
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Discharges Observe Bursts of $n = 1$ Magnetic Activity

Bursts of $n = 1$ activity correlated with I_p increases [1,2]



Bursts consistent with large scale reconnection events predicted by NIMROD [3-5]



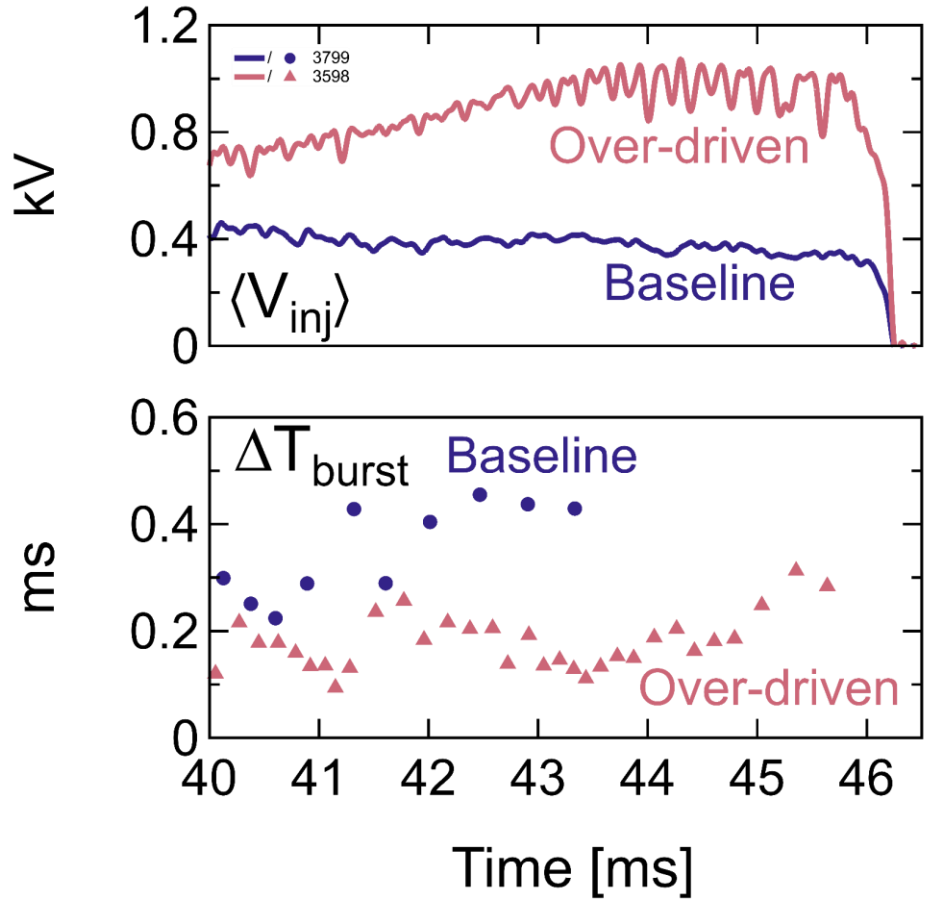
[1] D. J. Battaglia *et al*, *Nucl. Fusion* **51**, (2011)
[2] J. A. Reusch *et al*, *Phys. Plasmas* **25**, (2018)
[3] J. B. O'Bryan, C. R. Sovinec, and T. M. Bird, *Phys. Plasmas* **19**, (2012)
[4] J. B. O'Bryan and C. R. Sovinec, *Plasma Phys. Control. Fusion* **56**, (2014)
[5] J. B. O'Bryan, PhD Thesis, University of Wisconsin-Madison (2014)

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Excess Helicity Input Correlated to $n = 1$ Burst Activity

- Longer ΔT_{burst} in baseline discharge
  - Lower V_{inj} at fixed I_{TL} → Less excess helicity input

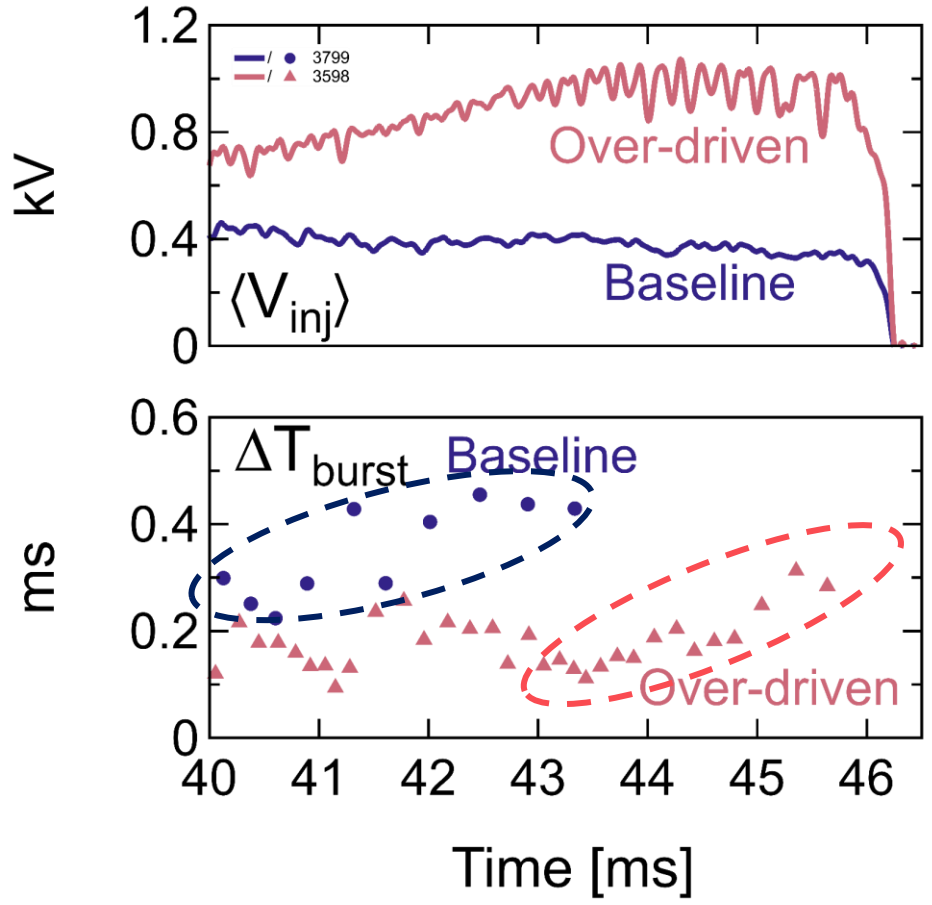
Comparison of burst behavior in baseline and over-driven discharge



Excess Helicity Input Correlated to $n = 1$ Burst Activity

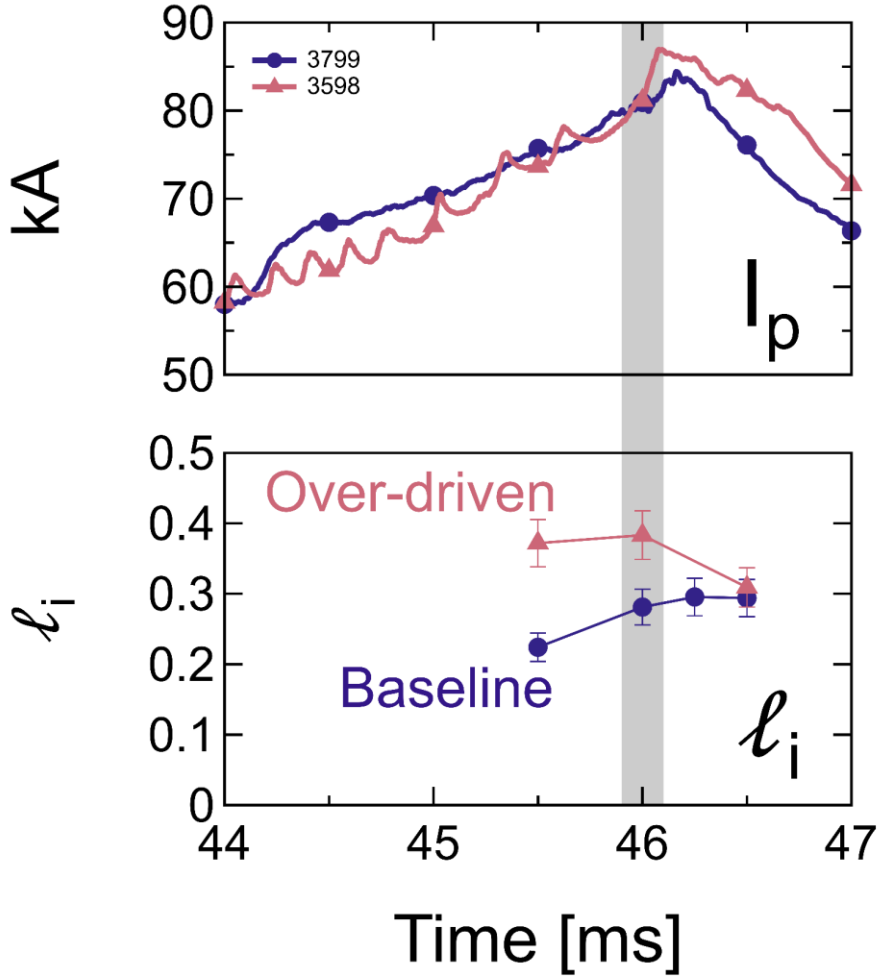
- Longer ΔT_{burst} in baseline discharge
  - Lower V_{inj} at fixed I_{TL} → Less excess helicity input
- Longer ΔT_{burst} as I_p ramps at constant V_{inj}
  - Higher I_{TL} at fixed V_{inj} → Less excess helicity input
- Longer ΔT_{burst} as excess helicity input decreases

Comparison of burst behavior in baseline and over-driven discharge

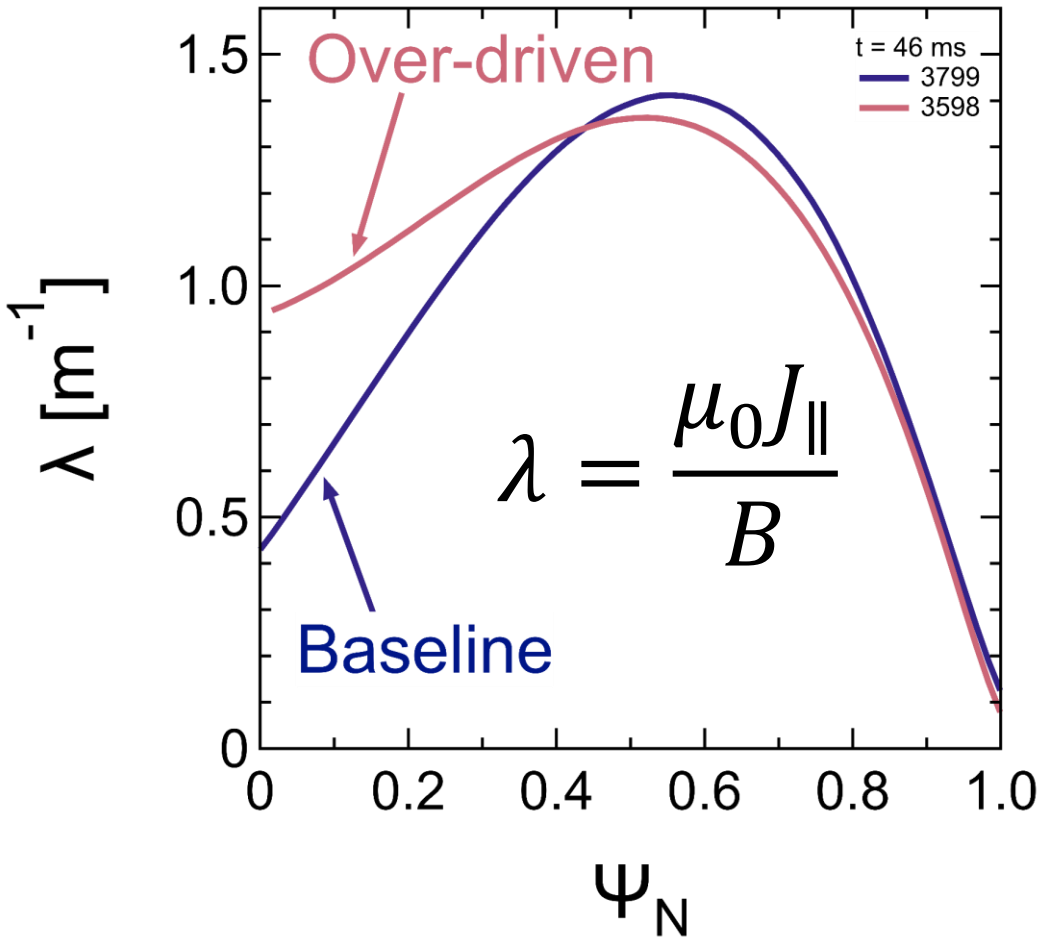


Increased Magnetic Activity Drives System Toward more Uniform λ Profile

Reconstructed ℓ_i indicates more peaked J profile in over-driven discharge



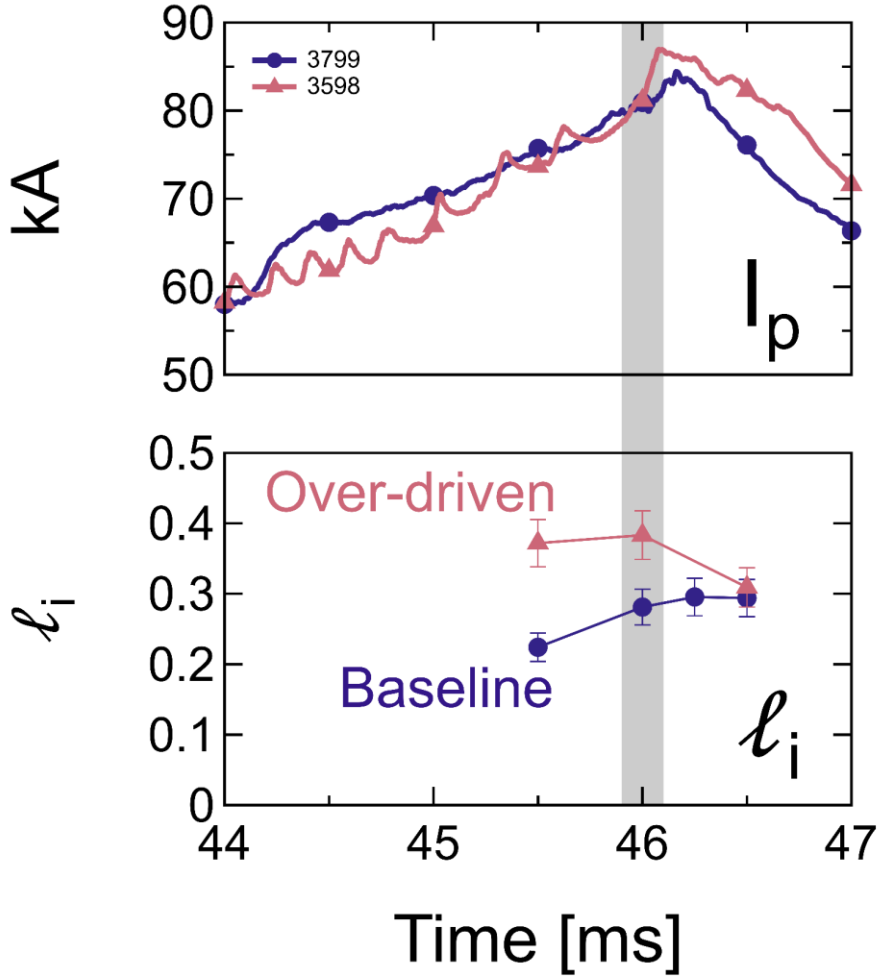
Increased current driven in core flattens $\lambda(\psi_N)$ with similar λ_{edge}



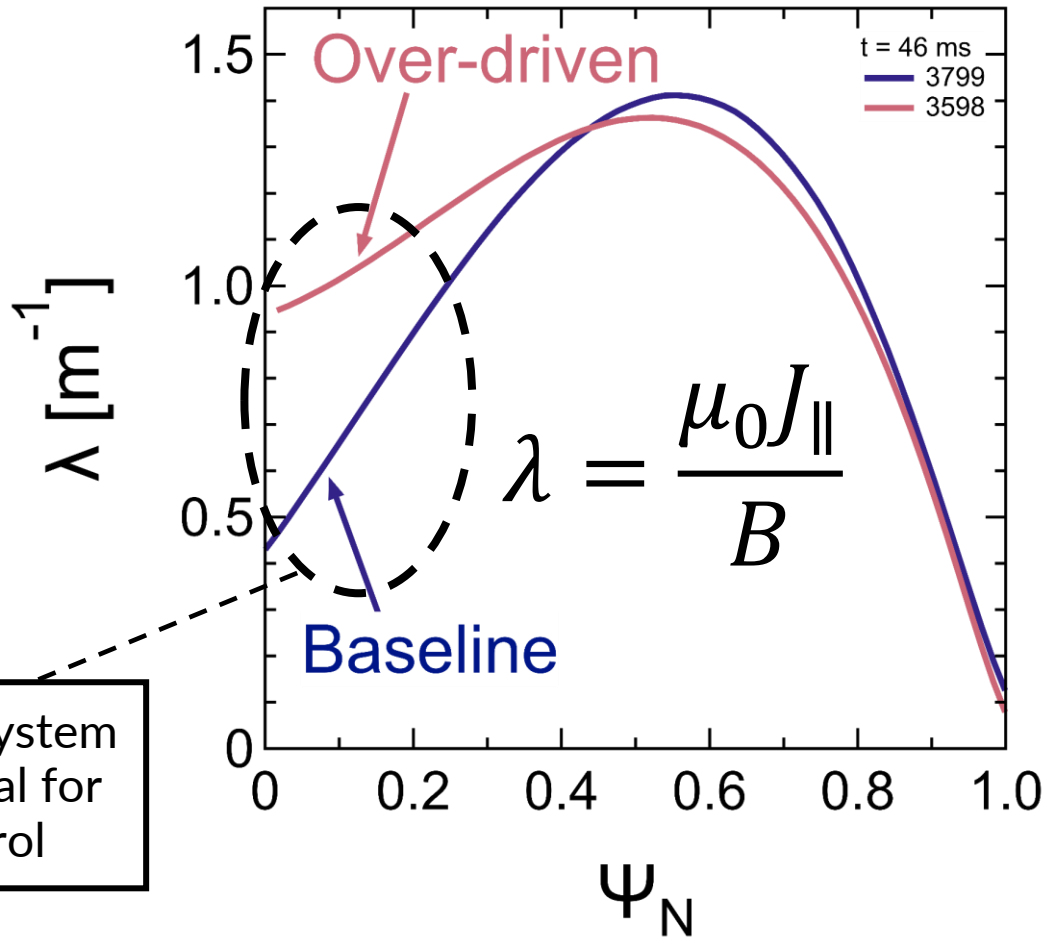
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Increased Magnetic Activity Drives System Toward more Uniform λ Profile

Reconstructed ℓ_i indicates more peaked J profile in over-driven discharge



Increased current driven in core flattens $\lambda(\psi_N)$ with similar λ_{edge}



Over-driving system offers potential for $J(\psi_N)$ control

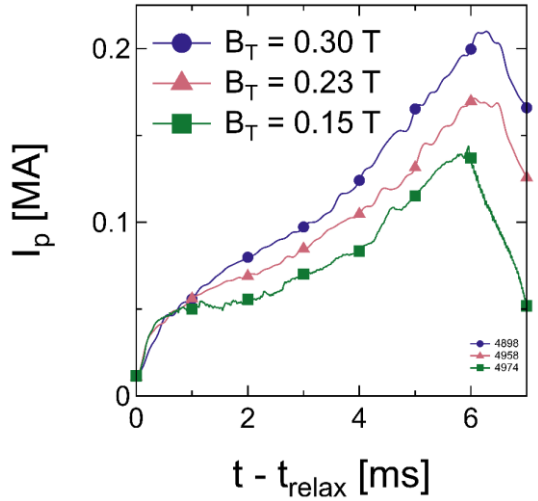
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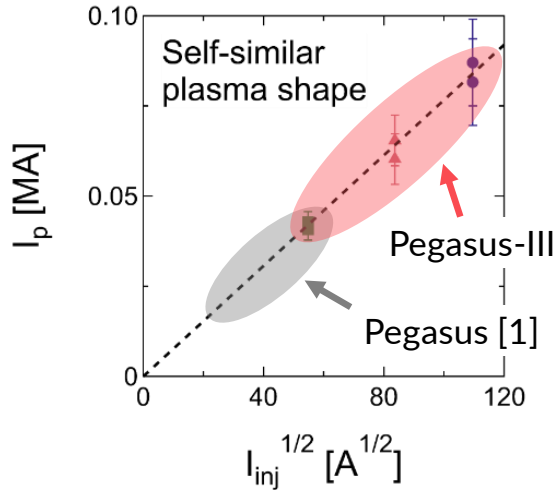
Increased Taylor Limit Leads to Higher I_p in Pegasus-III

- Pegasus-III uses Local Helicity Injection (LHI) solenoid-free startup
  - Injected current streams relax to tokamak-like plasma
  - Taylor limit largely dictates achievable I_p during LHI discharges

- Robust $I_p \leq I_{TL} \propto \sqrt{\frac{B_T I_{inj}}{w_{inj}}}$ scaling in Pegasus-III operating space
  - $I_{TL} \propto \sqrt{B_T I_{inj}}$ scaling observed for $B_T \leq 0.3$ T and $I_{inj} \leq 12$ kA
  - Demonstrated ability to vary w_{inj} via injector width

- Excess helicity input increases $\tilde{b}$ when sustained at Taylor limit
  - Low frequency ($\lesssim 10$ kHz) $\tilde{b}$ increases as system increasingly over-driven
  - Increased magnetic activity drives system toward more uniform λ profile





[1] D. J. Battaglia *et al.*, *Nucl. Fusion* **51**, (2011).

Pegasus-III Continues to Advance LHI and Other Solenoid-Free Startup Techniques

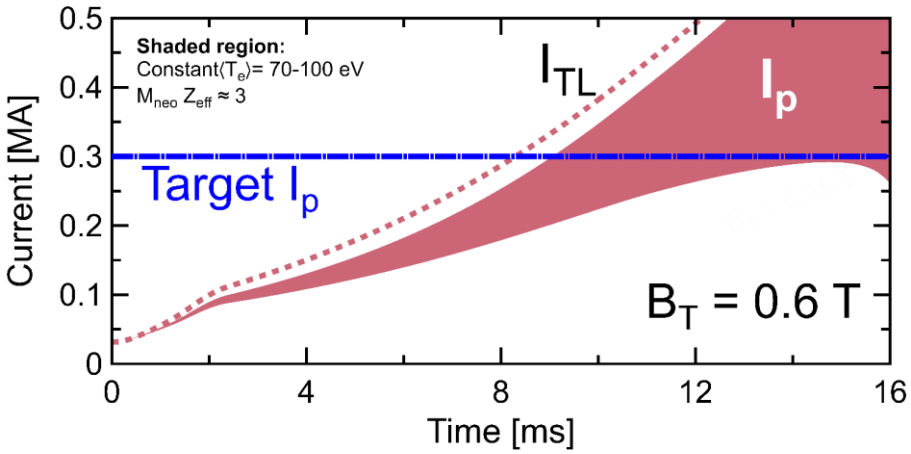
- Inform extrapolation to MA-class LHI startup
  - Increase $B_T \leq 0.6$ T
  - Test advanced non-circular injector design
- Compare/combine with other promising techniques
  - Coaxial helicity injection (CHI)
  - Microwave assist, sustainment and startup

See also:

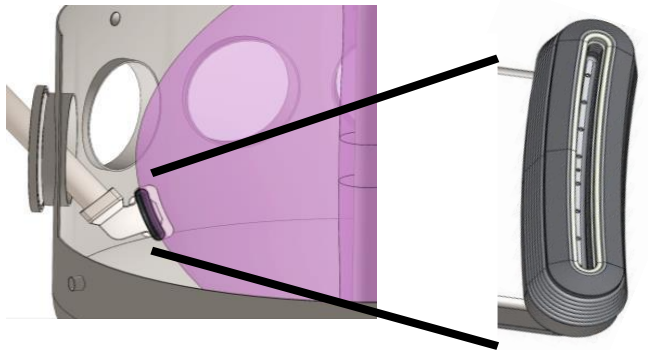
- S.J. Diem contributed talk - BO05.00001 (Mon. AM)
- Posters in JP12 session (Tues. PM)

For more information, visit:
https://pegasus.ep.wisc.edu

Pegasus-III $I_p(t)$ projections at $B_T = 0.6\ T$



Advanced non-circular injector to be tested in upcoming Pegasus-III campaigns



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