

Non-solenoidal Startup and Operations in PEGASUS

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Abstract

- Non-solenoidal startup using point-source DC helicity injectors (plasma guns) has been achieved in the PEGASUS Toroidal Experiment for plasmas with I_p in excess of 100 kA using $I_{inj} < 4$ kA.
  - Maximum achieved I_p tentatively scales as $(I_{TF}I_{inj}/w)^{1/2}$
  - I_p limits conform to a simple model involving helicity conservation and Taylor relaxation
- Observed MHD activity reveals additional dynamics during the relaxation process
- Recent upgrades to the gun system provide:
  - Higher helicity injection rates
  - Smaller edge current width, w
- Future goals include:
  - Extending parametric scaling studies
  - Determining conditions where parallel conduction losses dominate helicity dissipation
  - Building the physics understanding of helicity injection to confidently design gun systems for larger, future tokamaks.

Work supported by U.S. DOE Grant DE-FG02-96ER54375

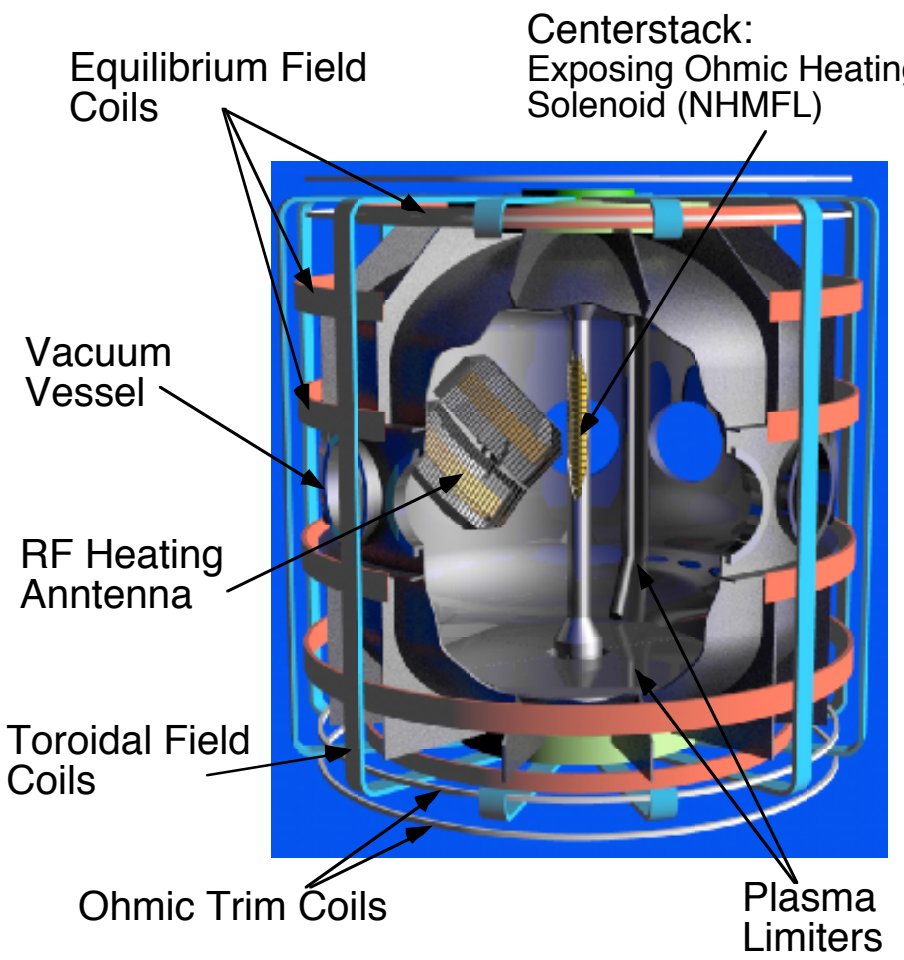
Point-source helicity injection is an attractive non-solenoidal startup technique

- Solenoid-free startup and ramp-up have been identified by FESAC as critical ST issues (FESAC TAP report)

- Solenoid-free startup with point-source helicity injection significantly extends the PEGASUS operating space
  - Saves limited Ohmic transformer flux
  - May enable high-I_N, high-β studies on PEGASUS

- Point-source helicity injection is flexible
  - Gun assemblies can be placed at convenient locations
  - Presently being studied on PEGASUS (to date: I_p up to 0.17 MA)

PEGASUS device and plasma characteristics



Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

- Non-inductive startup and sustainment
- Tokamak physics in small aspect ratio:
  - High-I_N, high-β operating regimes
  - ELM-like edge MHD activity

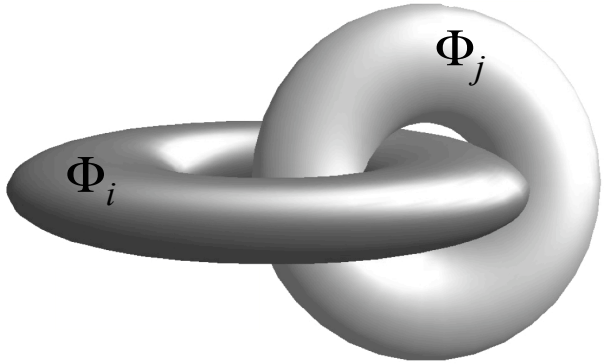
(see poster by E.T. Hinson, this session)

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Current drive in a tokamak can be described using the concept of magnetic helicity

- Helicity describes linking of magnetic flux

$$K = 2\Phi_i\Phi_j$$



- Total helicity within a bounded volume

$$K = \sum_{i=1}^{N}\sum_{j=1}^{N} L_{i,j}\Phi_i\Phi_j = \int_V \mathbf{A}\cdot\mathbf{B}\ \mathrm{d}^3\mathrm{x}$$

Current along B field = helicity
Current drive = helicity injection

Berger, M. Plasma Phys. Controlled Fusion **41**, 1999

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Current drive in a tokamak is equivalent to magnetic helicity injection

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

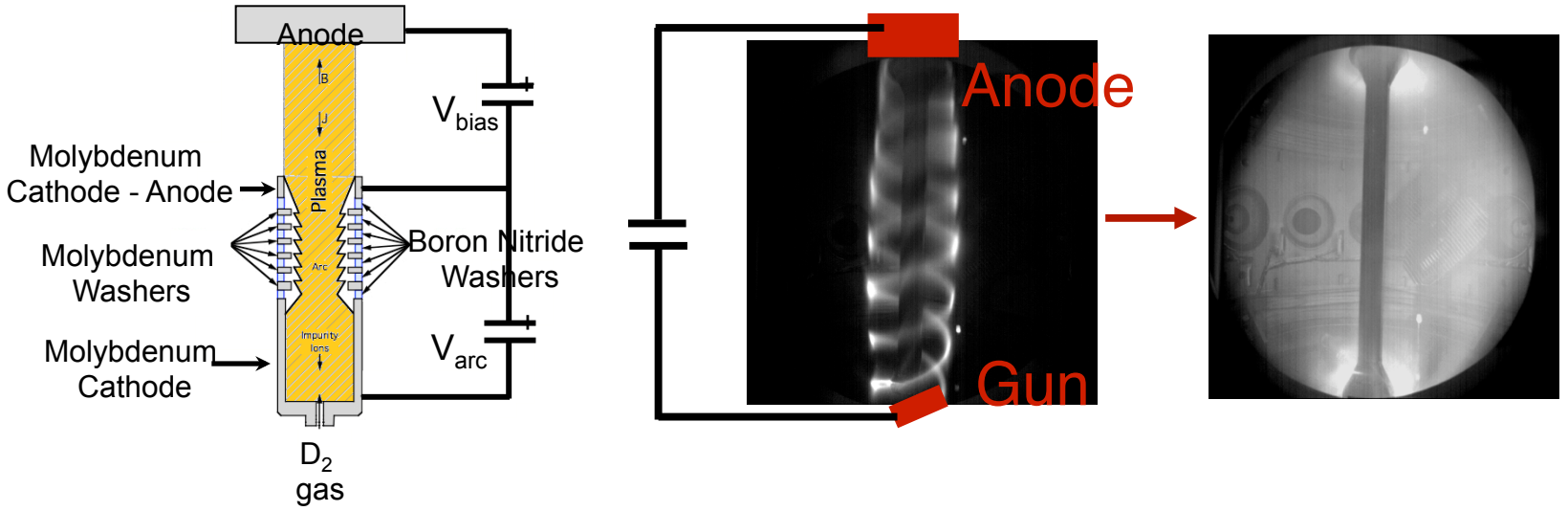
$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, \mathrm{d}^3\mathrm{x} - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot \mathrm{d}\mathbf{s}$$

- 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: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
- DC Helicity Injection: $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot \mathrm{d}\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$

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Point-source DC helicity injection on Pegasus

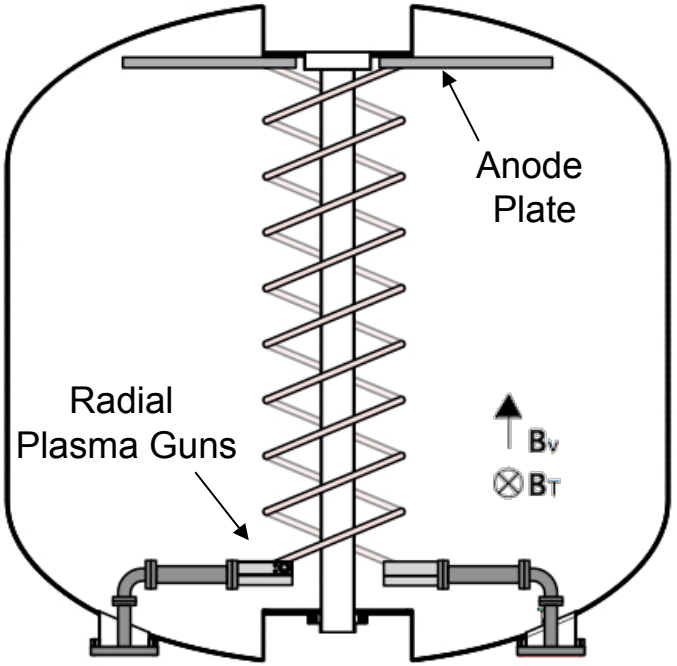
- Non-solenoid startup is a critical issue for future long-pulse STs
  - Would extend efficiency of OH drive and provide j(R) modification on present experiments that already have a central solenoid
- Plasma gun point-source DC helicity injection tested on Pegasus
  - Low impurity, high J_{inj} source
  - Scalable design ⇒ flexible & compact



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Gun design allows flexibility for positioning within the device

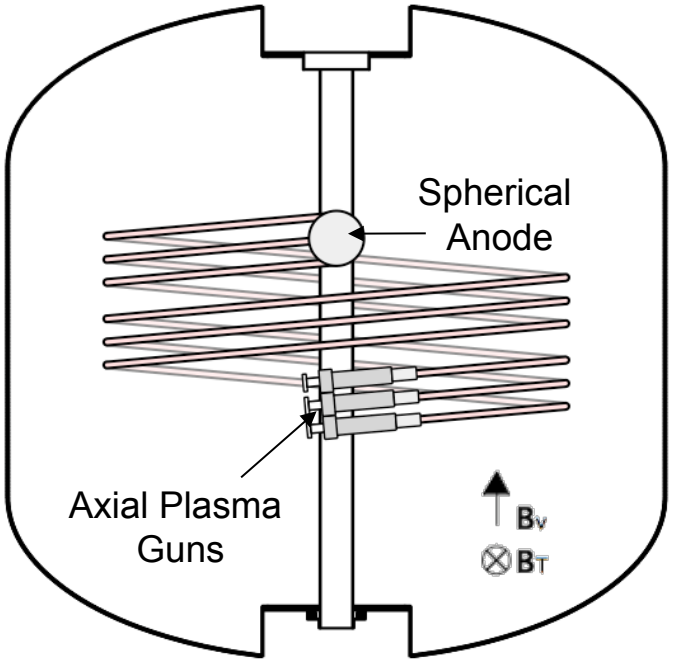
Inboard Divertor Gun Injection



R_{gun} = 16 cm, Z_{gun} = - 75 cm

N.W. Eidietis UW-Madison Ph.D thesis, 2007

Outboard Midplane Gun Injection



R_{gun} = 70 cm, Z_{gun} = - 20 cm

D.J. Battaglia UW-Madison Ph.D thesis, 2009*

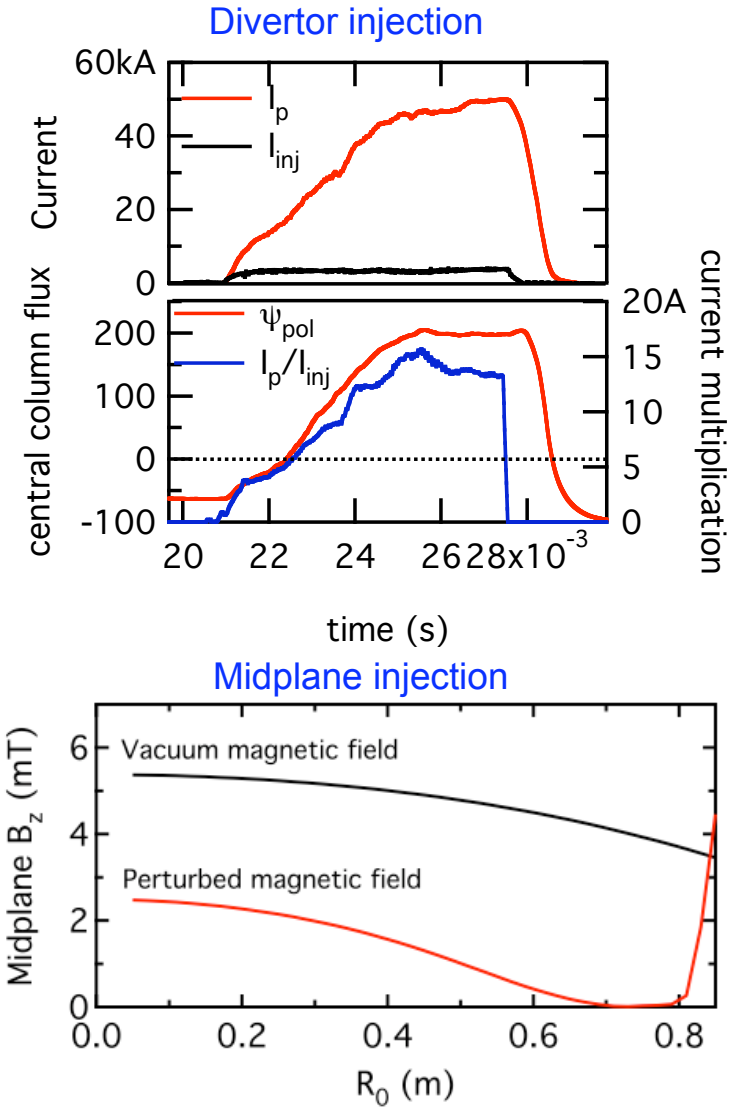
*Much of the data shown here was obtained, analyzed, and published by D.J. Battaglia (see refs)

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Several constraints must be satisfied for relaxation to a tokamak-like state

- Conditions for relaxation to occur:
  - B_v: low to allow null formation
  - B_{TF}: high to increase helicity injection
  - B_v, B_{TF}: tokamak equilibrium - force balance, q_a
  - B_v/B_{TF}: avoid collision with injector hardware

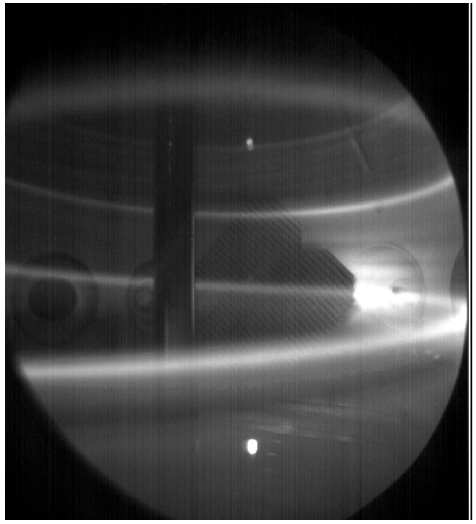
- Consistent with experimental observations
  - divertor injection:
    - *center-post limited discharges*
    - *relaxation coincides with reversal of central poloidal flux*
  - midplane injection:
    - *model of perturbed magnetic field shows null in relaxed cases*



See D.J. Battaglia, et al., J. Fusion Energy, **28** (2009) 140-3

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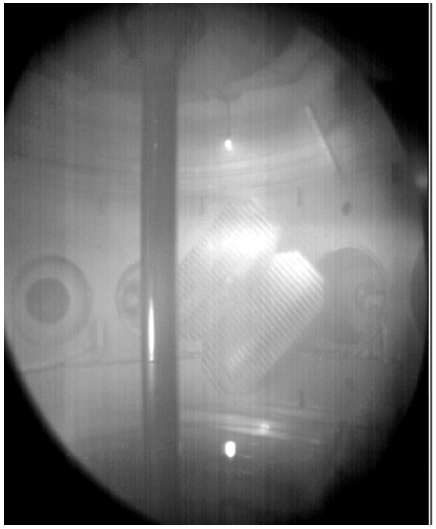
Typical outboard current injected discharge



Open field line current
M = G

Injected current perturbs vacuum magnetic field

Current multiplication:
$M \equiv I_\phi / I_{inj}$



Tokamak-like plasma
M > G

Plasma expands inwards to fill the volume while connected to guns

Limits dictated by helicity and Taylor relaxation

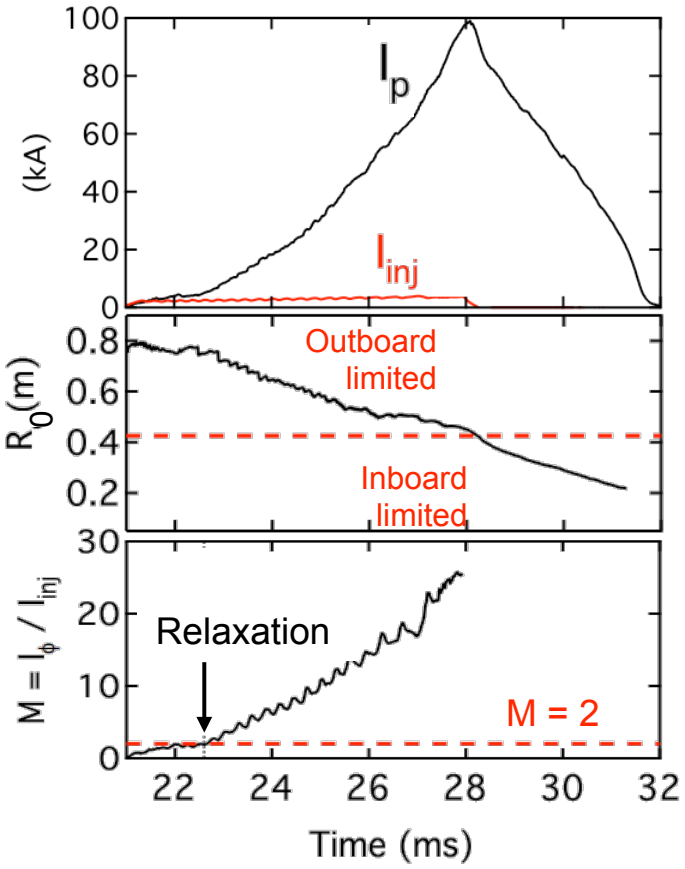


Decaying plasma

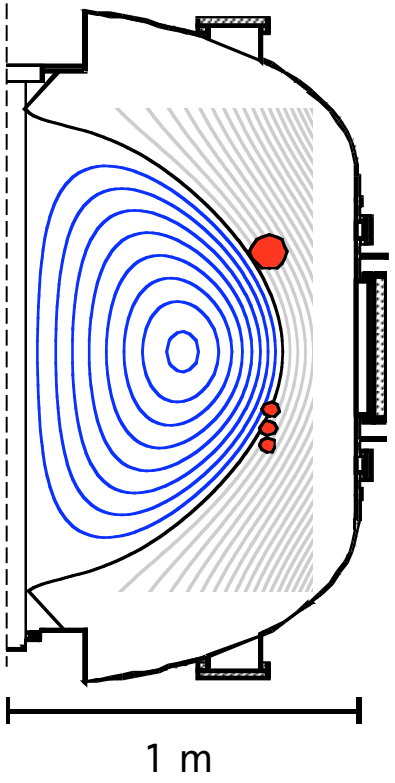
Stochastic magnetic fields "heal" into closed magnetic surfaces

Non-inductively driven plasma expands to fill the available volume

Discharge evolution for typical non-inductive plasma



Equilibrium reconstruction of similar discharge with I_p = 75 kA at 28 ms



$B_{\phi,0}$	0.15 T
R_0	0.40 m
a	0.35 m
A	1.14
κ	1.65
l_i	0.30
β_p	0.29
β_ϕ	0.01
q_0	5.0
q_{95}	37

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Helicity balance and Taylor relaxation constrain the achievable plasma current

Helicity balance in a tokamak geometry:

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

- Assumes system is in steady-state (dK/dt = 0)
- I_p limit depends on the scaling of plasma confinement via the η term

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

Taylor relaxation of a force-free equilibrium:

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

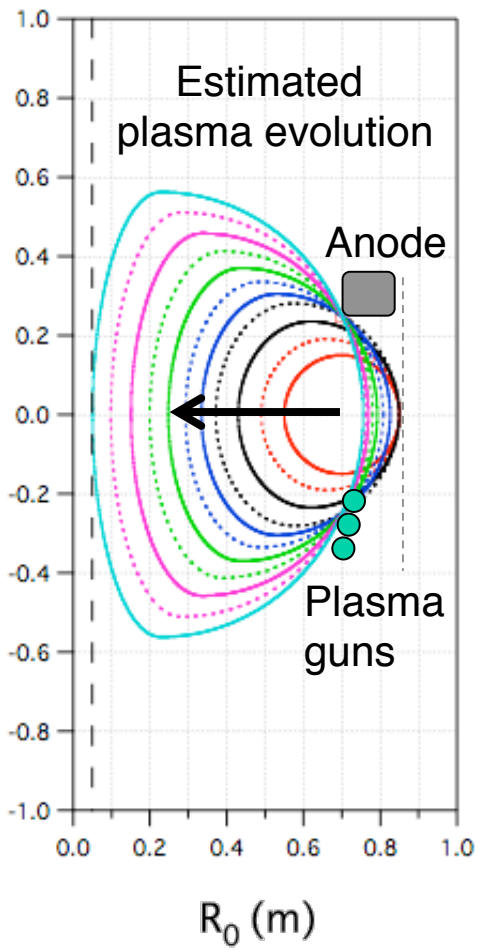
Assumptions:

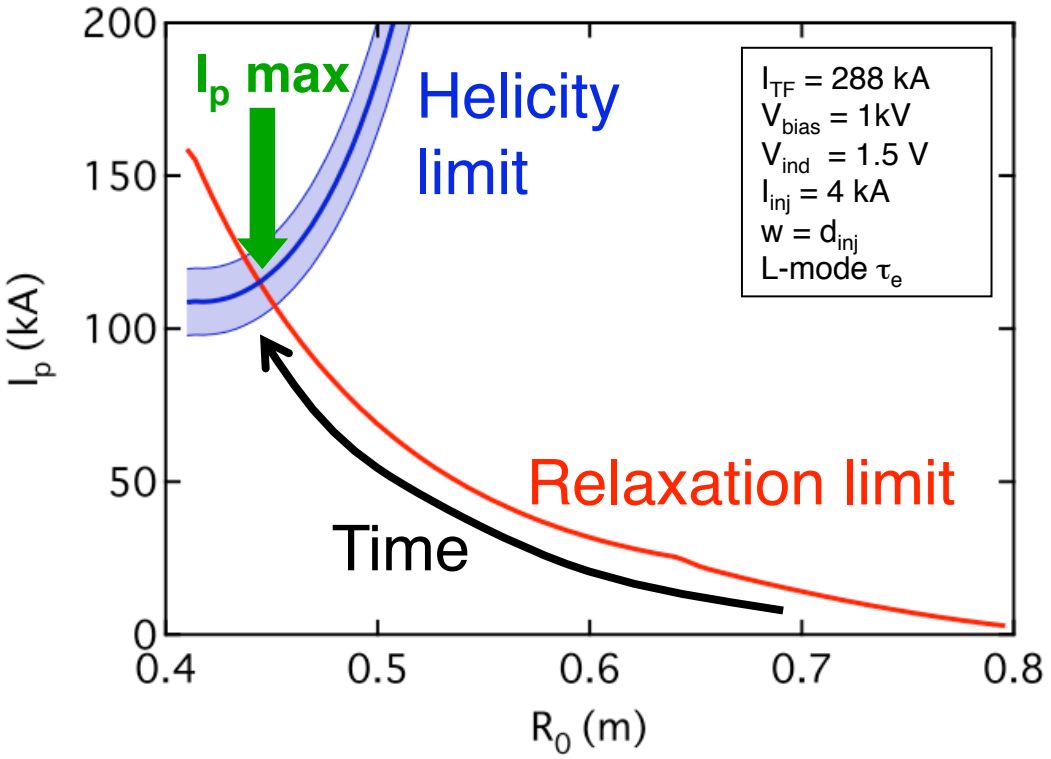
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

A_p Plasma area
f_G Plasma geometric factor
I_{TF} Toroidal field current
w Edge width

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With sufficient helicity input, maximum I_p set by relaxation limit



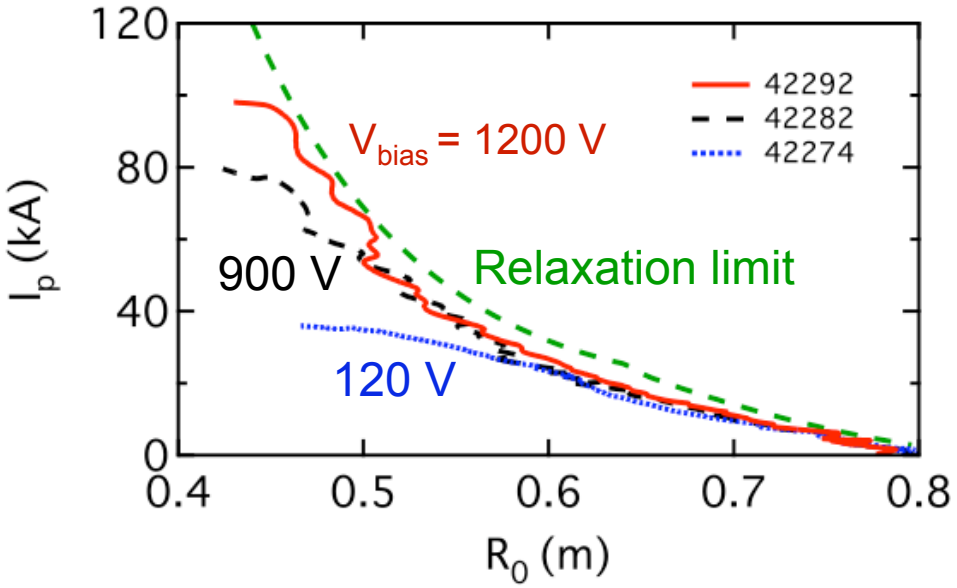


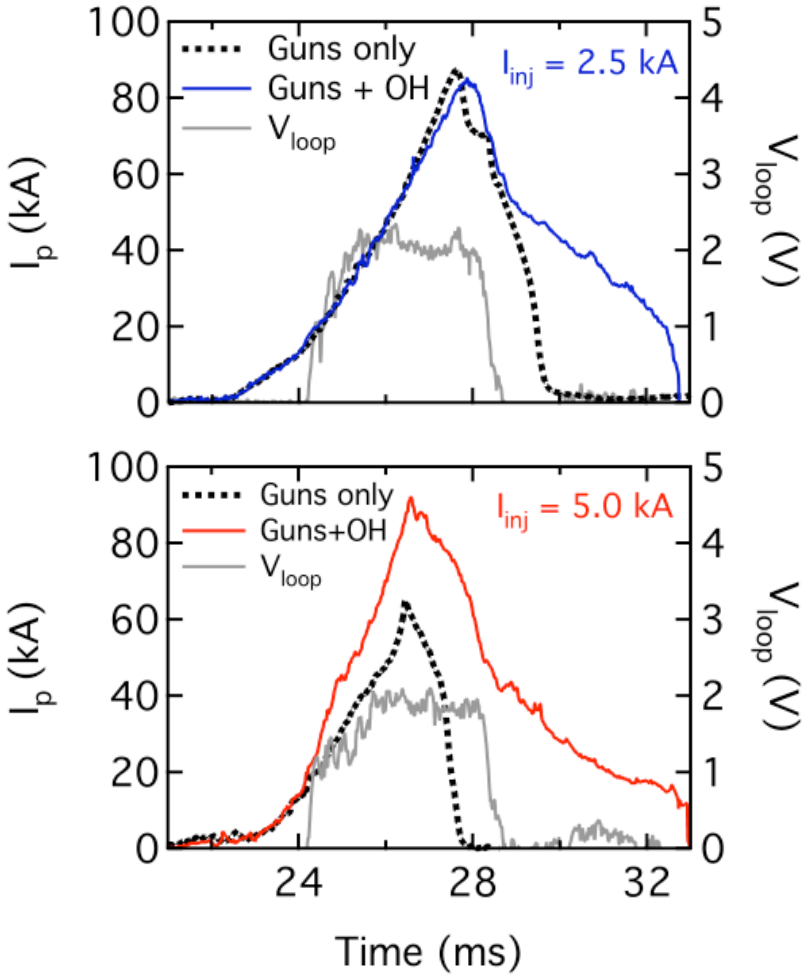
- Total "loop voltage" from relaxation and PF ramp

Recent experimental campaign:
Testing utility and validity of this simple helicity/relaxation model

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





- With guns, need sufficient helicity (i.e. V_{bias}) to reach the relaxation limit[1]
- Can confirm relaxation limit by adding OH drive as helicity source

All three discharges have the same I_{inj} and B_v evolution

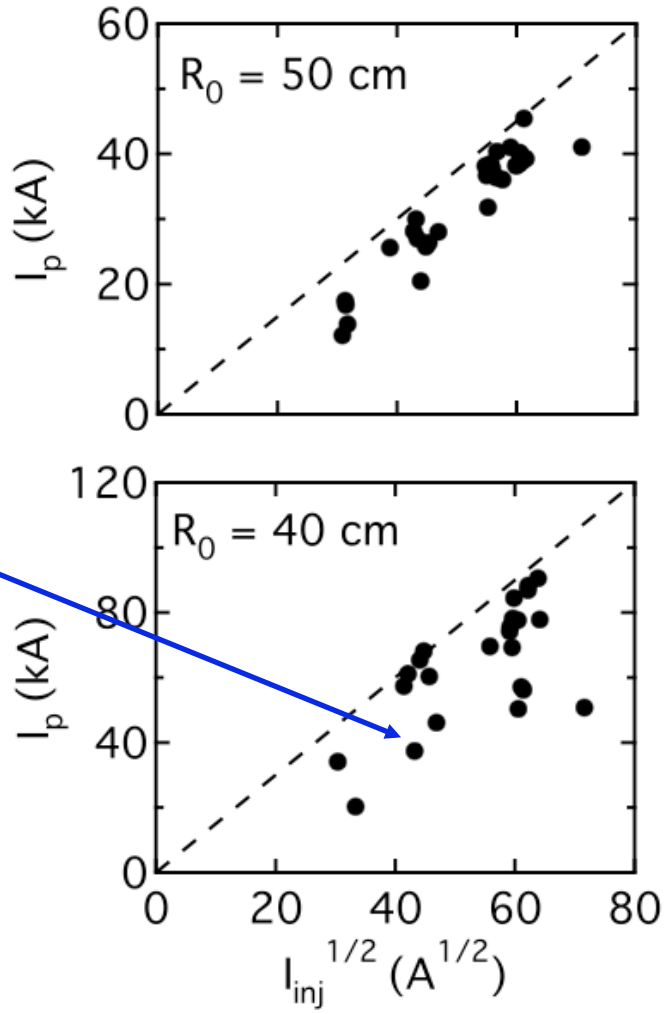
[1] D.J. Battaglia, et al., Phys. Rev. Lett. **102** (2009) 225003

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$I_p \propto (I_{inj})^{1/2}$ from relaxation theory consistent with experiment

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

- At each R_0, max. I_p achieved scales as $I_{inj}^{1/2}$
- K_{inj} insufficient to drive some discharges to limit as plasma expands
- Scan I_{inj}: 1 - 5 kA
  - I_{TF} = 288 kA
  - 3 plasma guns: defines w
  - Assume plasma geometry (thus, $\varepsilon A_p / R_{edge}$) fixed at given R_o



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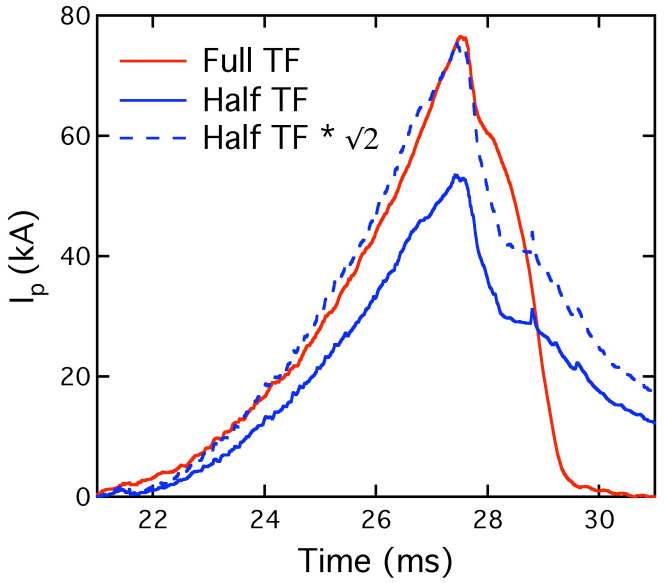
$I_p \propto (I_{TF})^{1/2}$ from relaxation theory consistent with experiment

- Relaxation I_p limit $\propto I_{TF}^{1/2}$
  - Supported by shot-to-shot comparisons
  - Factor of two range in I_{TF}

- Difficult to conclusively demonstrate scaling
  - Limited range of I_{TF} that produce quality discharges
  - Plasma parameters depend on I_{TF}
    - Particle confinement decreases
    - Energy confinement may decrease
    - q is lower → different equilibrium shape

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

Discharges with same I_{inj}, V_{bias}

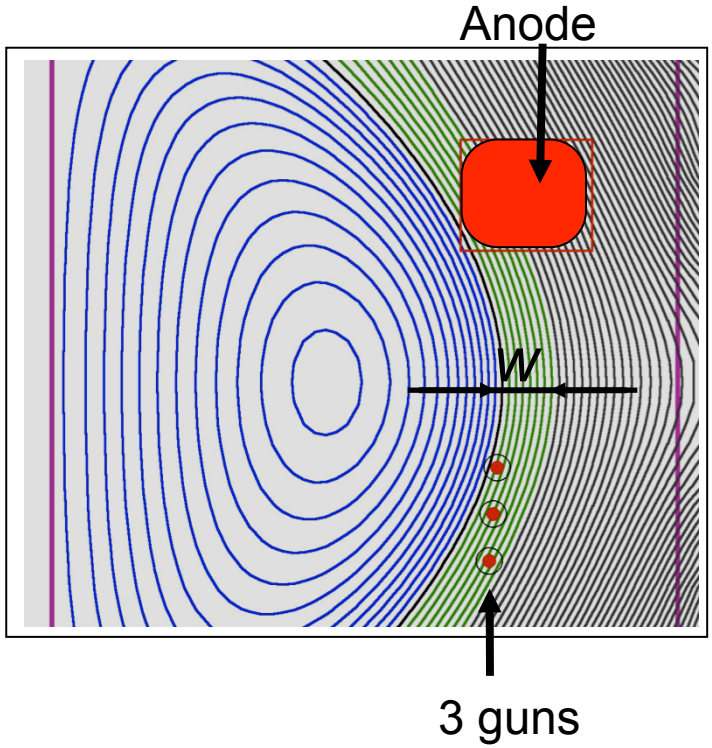


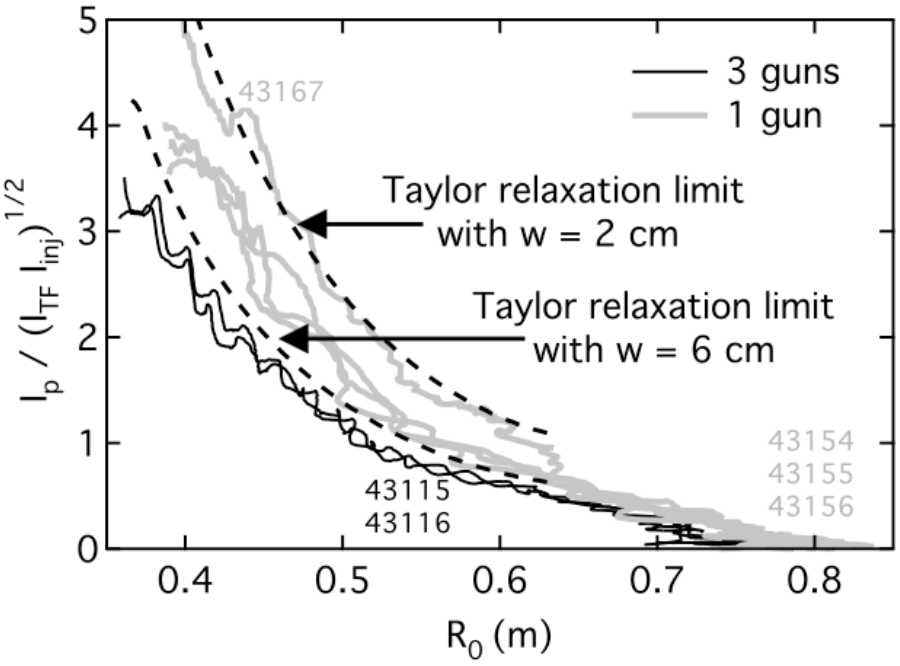
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$I_p \propto (w)^{-1/2}$ from relaxation theory appears consistent with experiment

- Relaxation limit predicted to scale as $w^{-1/2}$
- Data suggests $w \propto N_{gun} D_{gun}$
  - Likely due to alignment of plasma guns with flux surfaces
  - w may also be related to edge instabilities, turbulence, drifts, etc.

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

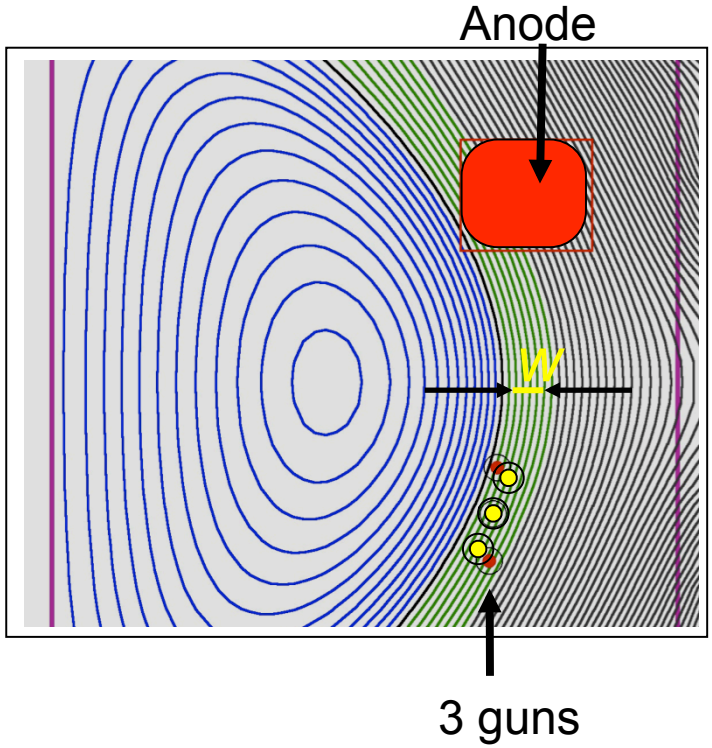


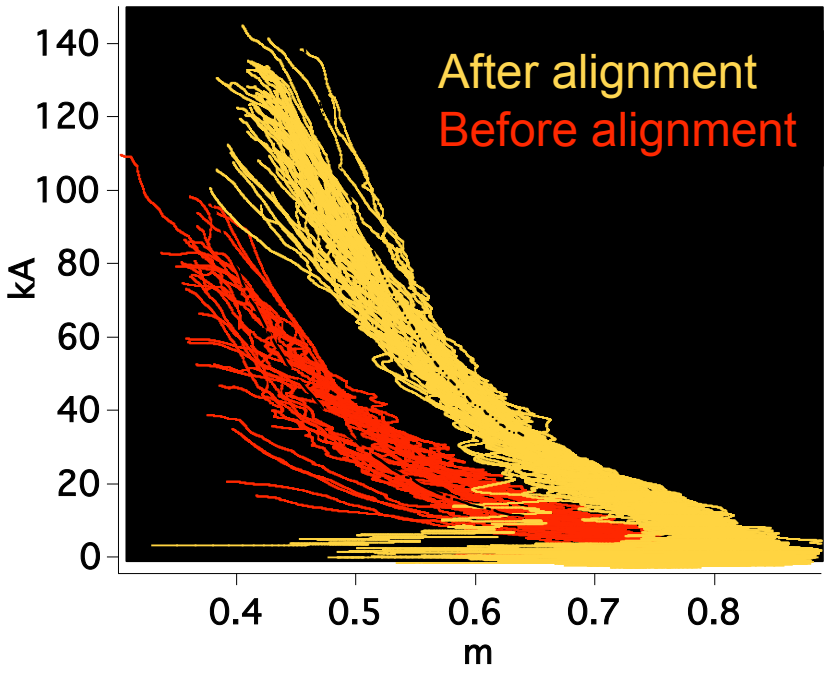


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Reduced edge current channel width yields higher relaxation limit

- Orientation of gun array matched to edge field alignment
  - Re-orientation is equivalent to a reduction in current channel width
  - Experiments show increased relaxation limit

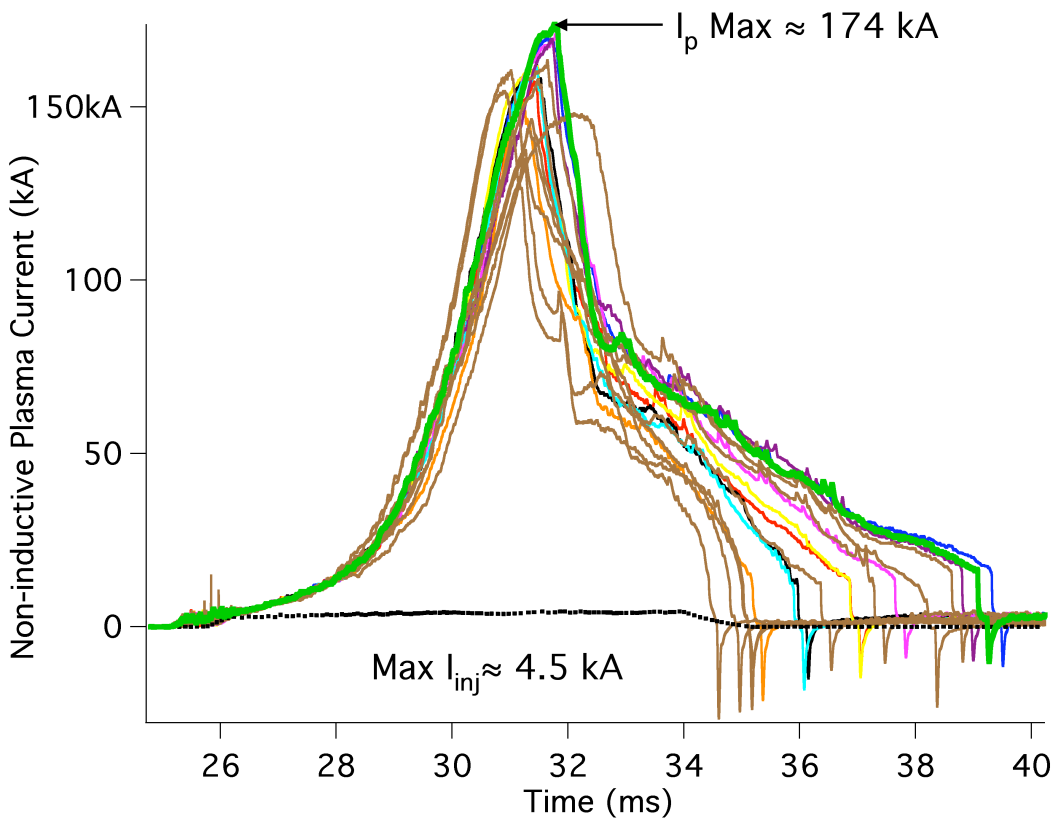




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$I_p \approx 174$ kA non-solenoidal startup achieved using < 4.5 kA injected current

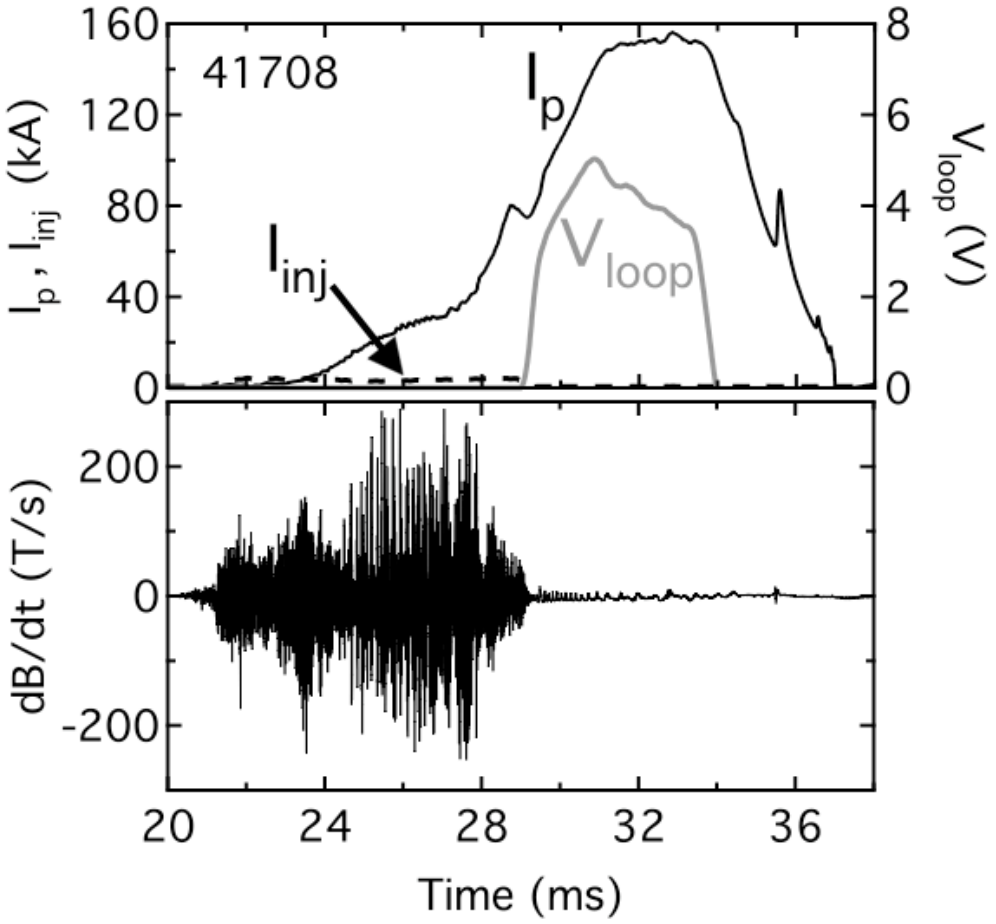
- Current amplification factor M > 35
  - Typical discharges drive $I_p \approx 150$-170 kA using $I_{inj} < 4.5$ kA
- Discharges initially tailored for maximum I_p
  - Rapidly increasing ramp of I_{Bv} during gun drive
  - Maximize flux and helicity injection
- Further tuning in progress to optimize handoff to other current drives



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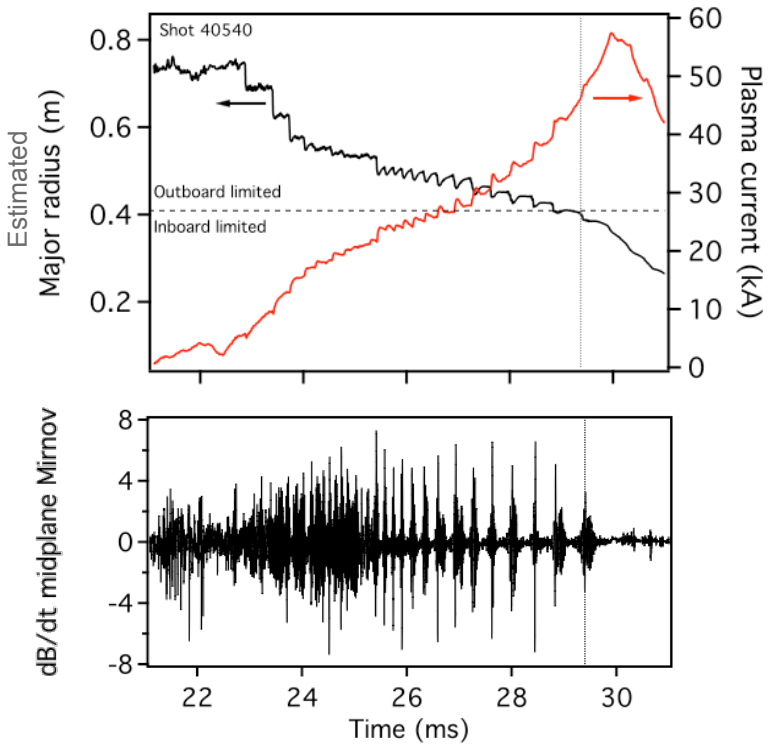
Smooth handoff from plasma gun startup to Ohmic drive achieved

- 80 kA target handoff to OH drive
  - Best coupling achieved when OH drive applied shortly after gun turnoff
- 150 kA with 18 mV-s
  - ~ 50% flux savings
- Extending operation space
  - No significant MHD during Ohmic phase
  - Unlike OH only, where large scale n=1 activity limits plasma evolution
  - Equilibrium reconstruction of gun created plasmas show very low l_i ~ 0.2-0.3, and hollow J(r)

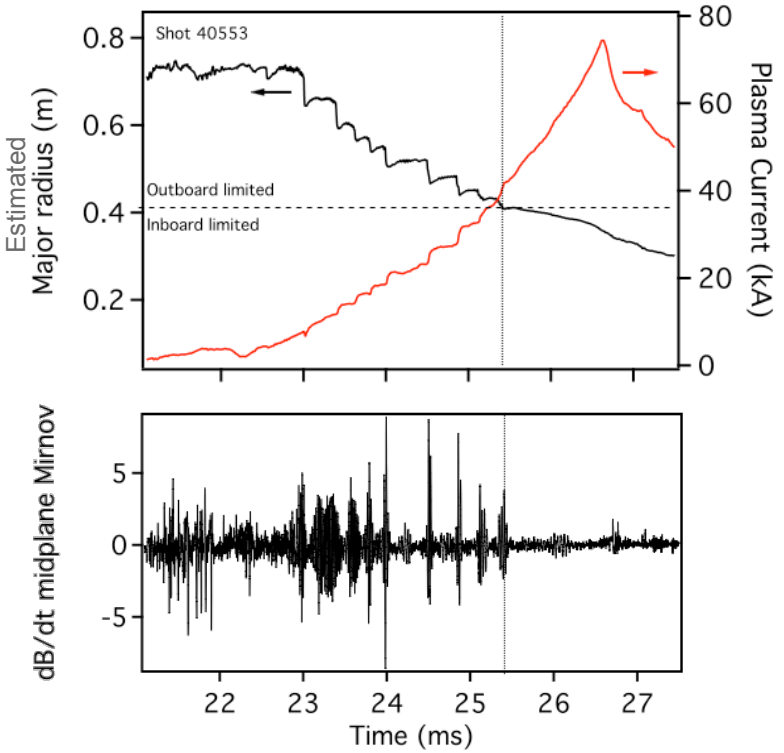


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Full resistive MHD model needed to understand relaxation dynamics



Slower PF ramp
Plasma detaches at 29.4 ms



Faster PF ramp
Plasma detaches at 25.3 ms

After detachment, current drive is purely inductive and MHD activity is reduced.

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Future Directions

- What determines λ_{edge} and λ_p?
  - Edge current measurements with probes
  - Larger range of I_{TF} to test scaling
  - Re-tilted guns
- How does τ_e scale with I_p?
  - Thomson scattering
  - Increase V_{bias} to achieve larger I_p
- What determines Z_{inj}?
  - Filament path length and modeling
- Tokamak-like plasma properties: T_i, T_e
  - Spectrometer, Thomson scattering

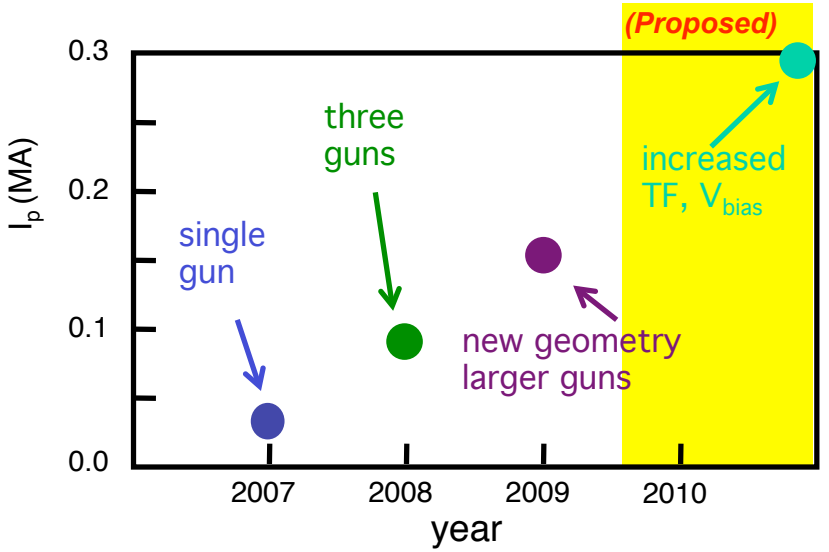
Near-term hardware improvements to drive non-inductive I_p to 300 kA

- Proposed improvements to power systems will:
  - Increase I_{TF} by factor of 2
  - Increase I_{inj} by at least a factor of 2

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

- Repositioning gun hardware will increase available A_p
  - Increasing R_{inj} will enlarge A_p by factor of ~1.7

- Additional upgrades:
  - Increase I_{TF} further by upgrading our center stack
  - Optimize λ_{edge} by introduction of passive electrode structures
  - Push limits of gun performance by increasing I_{inj}



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Pegasus is creating high-power non-solenoidal discharges

- Outboard midplane gun startup results show great promise
  - $I_p \sim 0.17$ MA achieved with simple 3-gun array and PF induction
  - Helicity & Relaxation limits being identified to guide design to higher current
    - *Simple dc relaxation-helicity conservation model describes macroscopic scaling of current limit*
    - *Many outstanding questions: λ_{edge}, Z_{inj}, confinement, etc*
    - *Full understanding at microscopic level (e.g.. Intermittent MHD) will require deeper analysis (i.e. NIMROD)*
  - Pegasus goal: ~0.3 MA non-solenoidal target & hand-off to RF heating & growth
    - Allows validation of understanding for projection to larger facilities (e.g.. NSTX up to MA)

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For additional information, see:

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