Poster NP6.00135

Non-solenoidal Startup in PEGASUS Discharges

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Non-solenoidal Startup in PEGASUS Discharges

- Recent PEGASUS experimental studies are directed at developing non-solenoidal startup techniques for ST and tokamak applications.
- High-field-side magnetic helicity injection with washer-stack current-sources (plasma guns) produces discharges with toroidal current I_p up to 50 kA, using only 3 kA of injected current.
- Discharges driven by low-field-side injection typically require outer-PF ramps for radial force balance, also providing inductive current drive, and have achieved I_p=80 kA using less than 2 kA of injected current.
- In either injection geometry, I_p persists for a significant interval after gun shutoff, while the plasmas relax into typical tokamak equilibria with well-defined edges.
- According to a semi-empirical model, the maximum gun-driven I_p is determined by the helicity injection rate, radial force balance, kink stability, and the Taylor relaxation criterion.
- Higher helicity injection rates will extend the PEGASUS operating space, allowing higher I_p and normalized current I_N, and enabling both flux amplification studies and predictive testing of the I_p model.

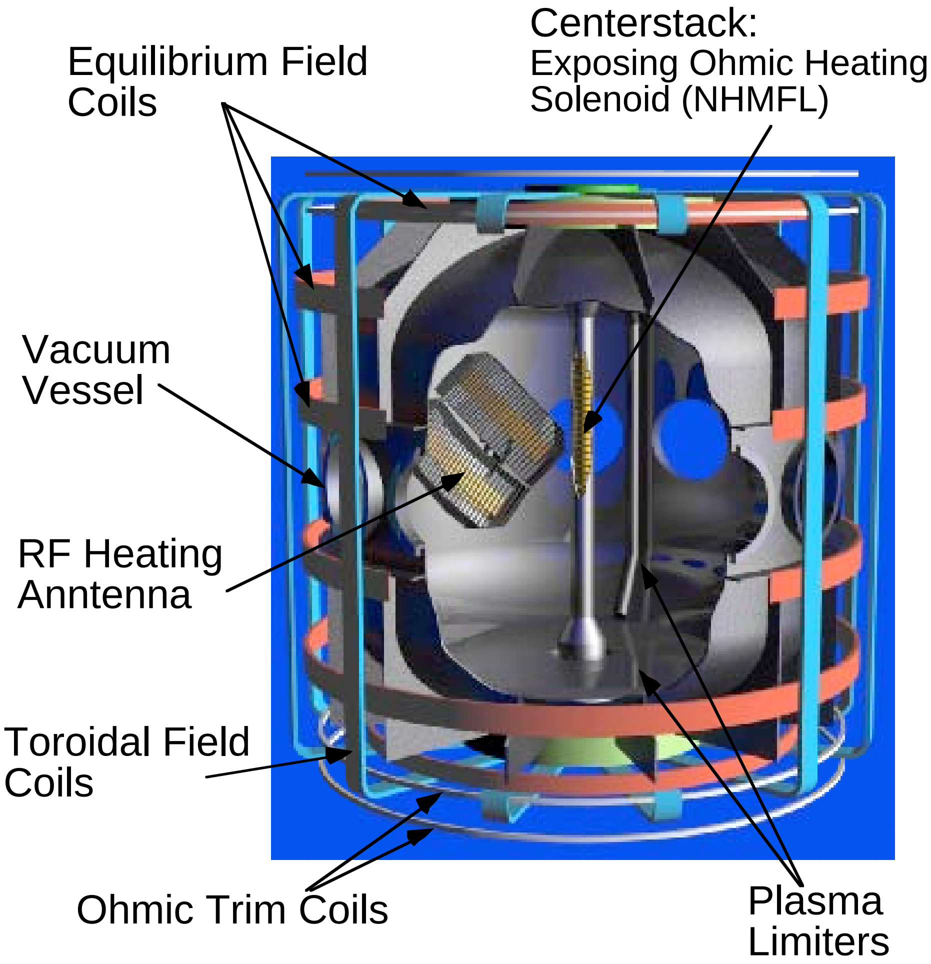
Point-source helicity injection could be critical for PEGASUS and other ST devices

- 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
  - Formation of the startup plasma saves limited Ohmic transformer flux
  - May enable high-I_N, high-β studies on PEGASUS
  - Enables completely solenoid-free operation

- Point-source helicity injection is flexible, and may provide solenoid-free startup in future toroidal devices
  - Biased plasma guns produce low-impurity plasma
  - Gun assemblies can be placed at any experimentally convenient location
  - Power supplies, gun design, operating scenarios, and the underlying theory are presently being studied on PEGASUS

Studying ST science and engineering with PEGASUS



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)	≤ 0.18	≤ 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)	≤ 0.02	≤ 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 Bongard, poster NP6.00136)

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

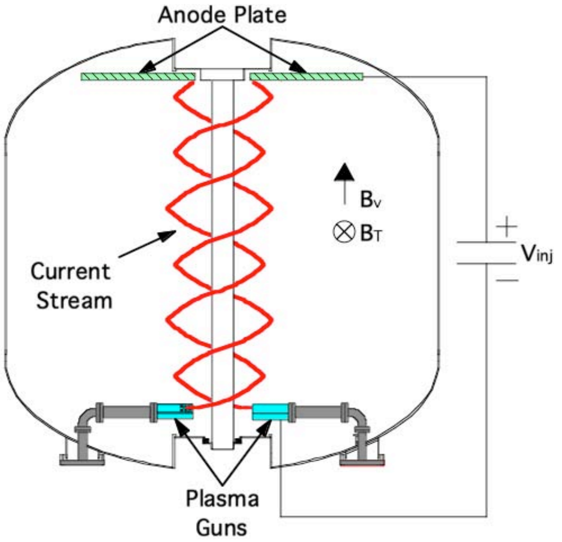
Total helicity in a tokamak geometry: $K = \int_V \left(\mathbf{A} + \mathbf{A}_{vac}\right) \cdot \left(\mathbf{B} - \mathbf{B}_{vac}\right)\, \mathrm{d}^3\mathrm{x}$

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

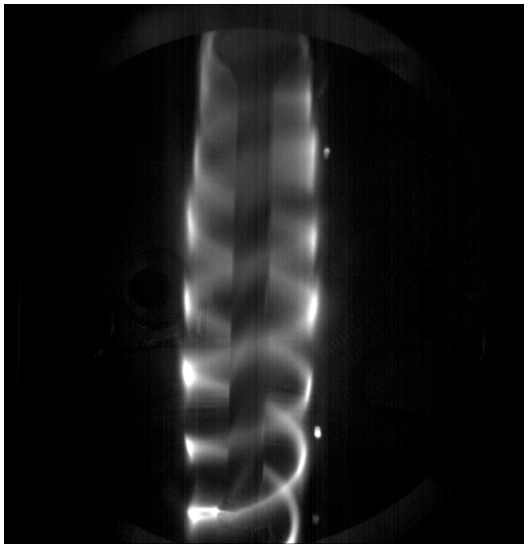
- Resistive Helicity Dissipation
  - $\mathbf{E} = \eta \mathbf{J}$ → much slower than energy dissipation ($\eta \mathbf{J}^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity
- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
- DC Helicity Injection: $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot \mathrm{d}\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$

DC helicity injection with biased plasma guns

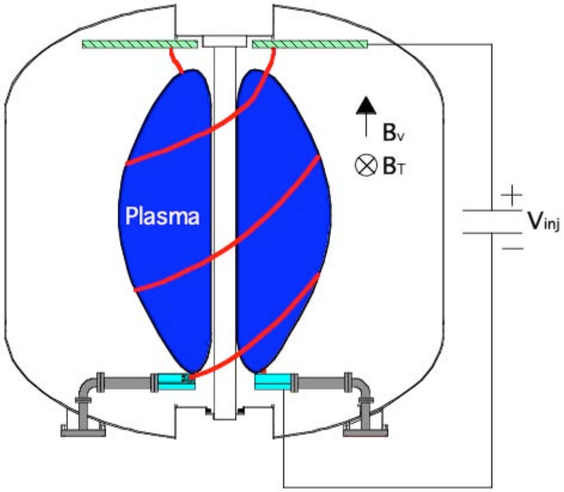
- As an example, two divertor-mounted guns are shown.
- The gun-driven filaments can relax to form a tokamak plasma.
- Non-solenoidal formation and sustainment of a tokamak plasma.



Filaments



Shot #37460



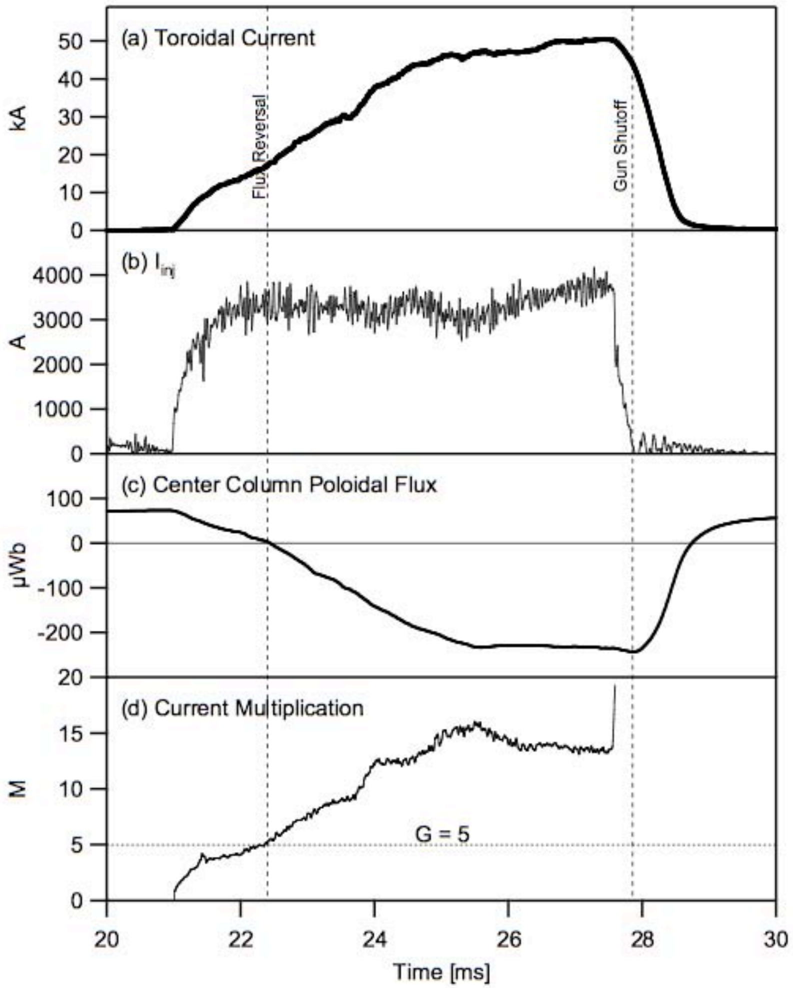
Relaxed State

Shot #37222

Magnetic relaxation enhances the driven I_p beyond the vacuum-field windup

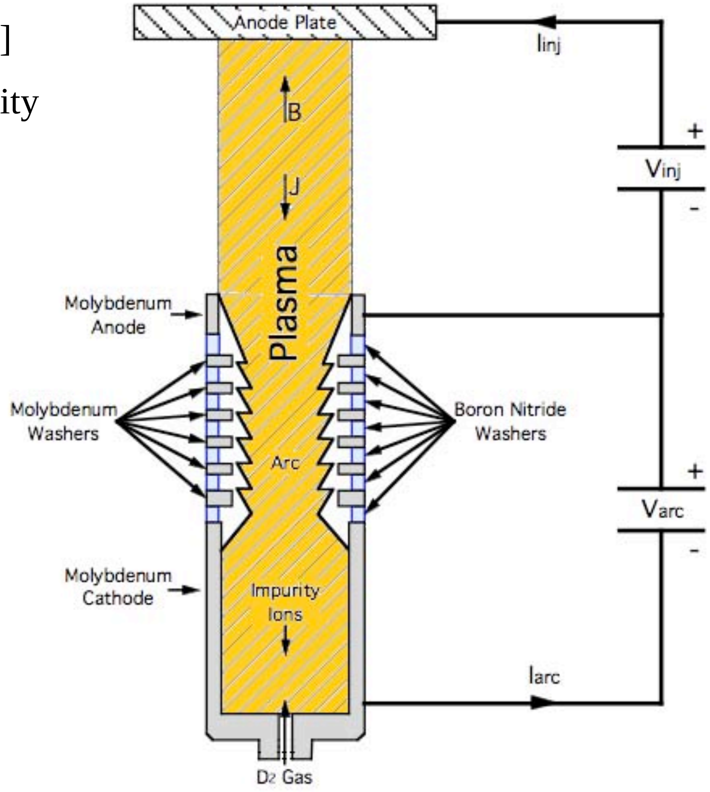
- I_p > 50 kA driven by $I_{bias} \leq 4$ kA:
  - Plasma current persists after $I_{bias}=0$
  - Coil currents static (no PF ramps)
  - B_T=11 mT at plasma magnetic axis
  - Vacuum vertical field is 7 mT
- Poloidal flux reversal on column is hallmark of significant relaxation:
  - Coincident with the current multiplication ratio (defined $M=I_p/I_{bias}$) exceeding the vacuum-field current windup factor G
- Current multiplication up to 15:
  - Consistent with flux amplification
  - Vacuum-field windup in #32606 was 5

Shot #32606



Biased plasma guns are low-impurity helicity injection point sources

- Arc discharge sustained in washer stack cavity
  - Washers stabilize arc while limiting surface contact [1]
  - Sputtered high-Z impurities mostly trapped in gun cavity
- Plasma column supports large J_{inj} without space charge limitations [2]
- Requires separate current arc and bias power supplies.
- In the present PEGASUS system,
  - I_{arc} = 2 kA using a pulse forming network
  - V_{arc} = 100 - 500 V
  - $I_{bias} < I_{arc}$ for impurity sputtering
  - I_{bias} feedback-controlled in real time
  - V_{bias} up to 2000 V



[1] Den Hartog, D.J., Plasma Sources Sci. & Tech. **6** (1997)
[2] Fiksel, G, et. al., Plasma Sources Sci. & Tech. **5** (1996)

Self-consistent model for gun-driven discharges is under development

- Current along gun-driven streams produces poloidal-field null region
  - 2D filament calculations illustrate the formation of a field null.
  - Experimentally, variations in vertical field and/or gun-driven current (equivalently, variations in the total toroidal current in the gun-driven streams) lead to sharp boundaries between relaxation and no-relaxation cases.

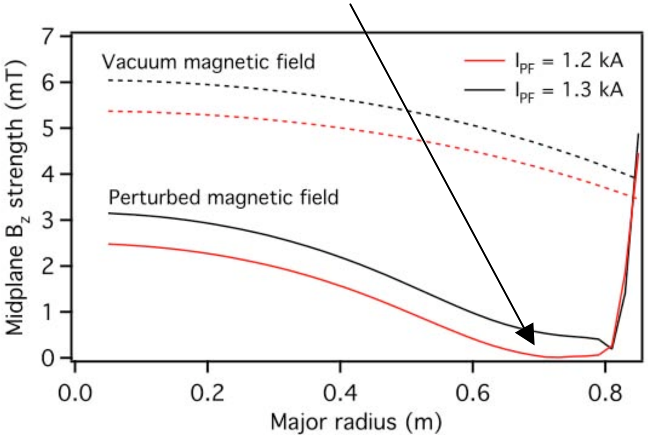
- Once relaxation occurs…
  - The relaxation process is not stopped by changes in the vertical field (*e.g.*, to maintain radial force balance)
  - Plasma position (R_0), size (a), shape (ε)… can be modelled
  - The plasma current simultaneously satisfies four conditions:
    (1) Radial force balance
    (2) Tokamak stability (*vs* kinks, *etc*)
    (3) Helicity balance (injection *vs* dissipation)
    (4) Taylor relaxation requirement

A 2-D current filament code illustrates the formation of a poloidal field null

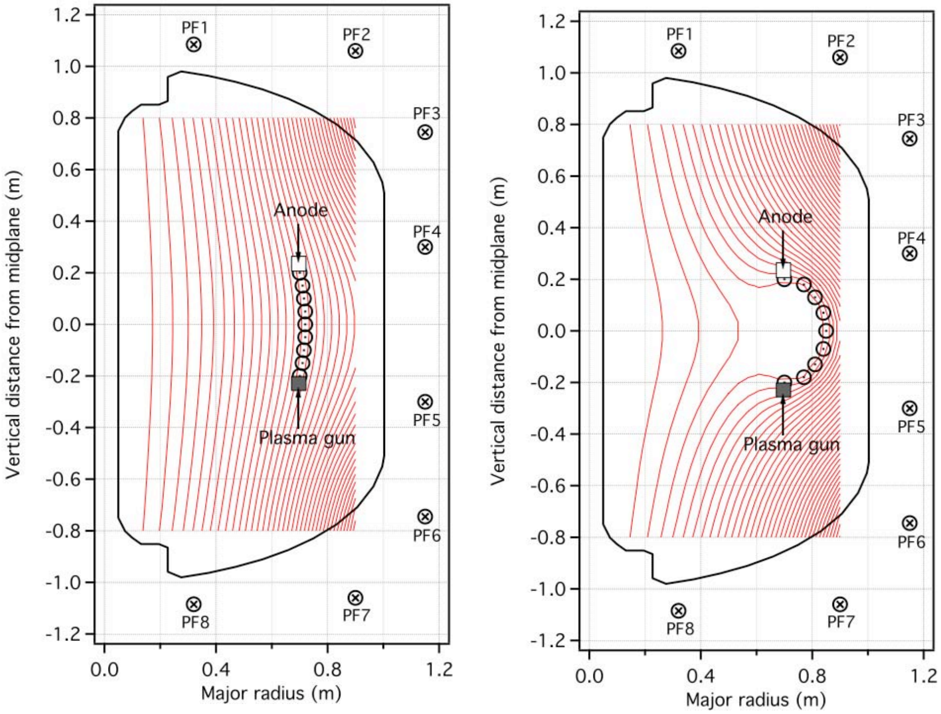
- Experimental observation: M > G correlates with inboard B field reversal

- Calculations assume G = 2
  - Treat the discrete filaments as a toroidally averaged current sheet tied to a flux surface

- Max B_v that allows field reversal when I_{PF} ~ 1.2kA
  - B_v ~ 0 at inner sheet edge



Force-free plasma filaments perturb the vacuum magnetic field



I_{inj} = 0 A

I_{inj} = 2 kA

I_{TF} = 300 kA, I_{PF} = 1.2 kA (PF1-3, 6-8)
Calculations by D.J.Battaglia

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Helicity balance and Taylor relaxation constrain the achievable plasma current I_p

Helicity balance in a tokamak geometry:

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

- 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:

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

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

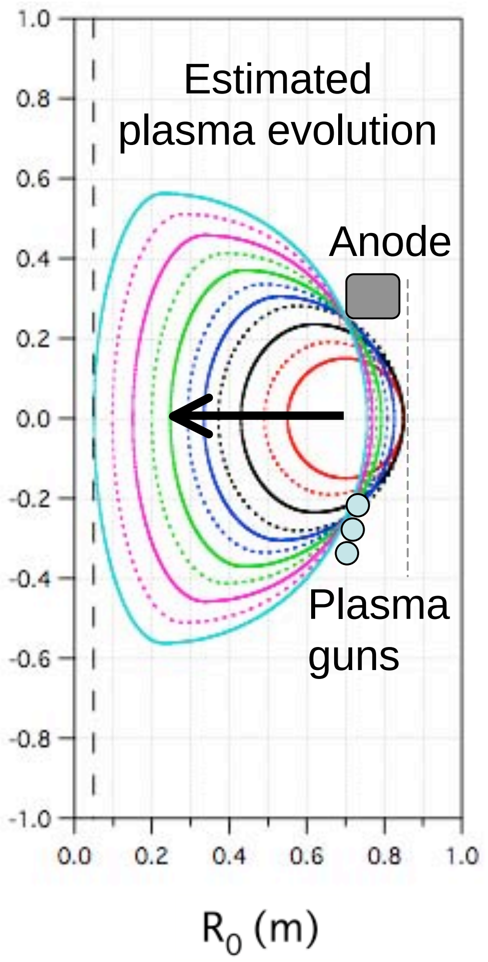
$$\Rightarrow \quad \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2}$$

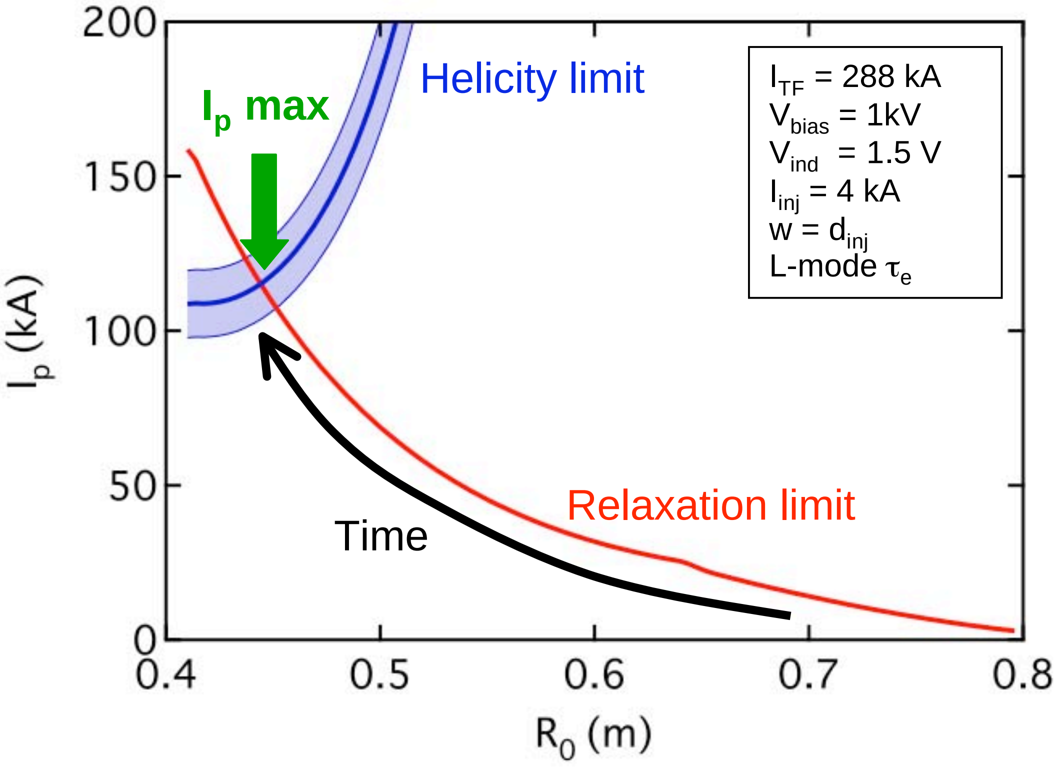
Assumptions:

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

A_p	Plasma area
C_p	Plasma circumference
Ψ	Plasma toroidal flux
w	Edge width

Maximum possible I_p reached when helicity and relaxation criteria are satisfied simultaneously

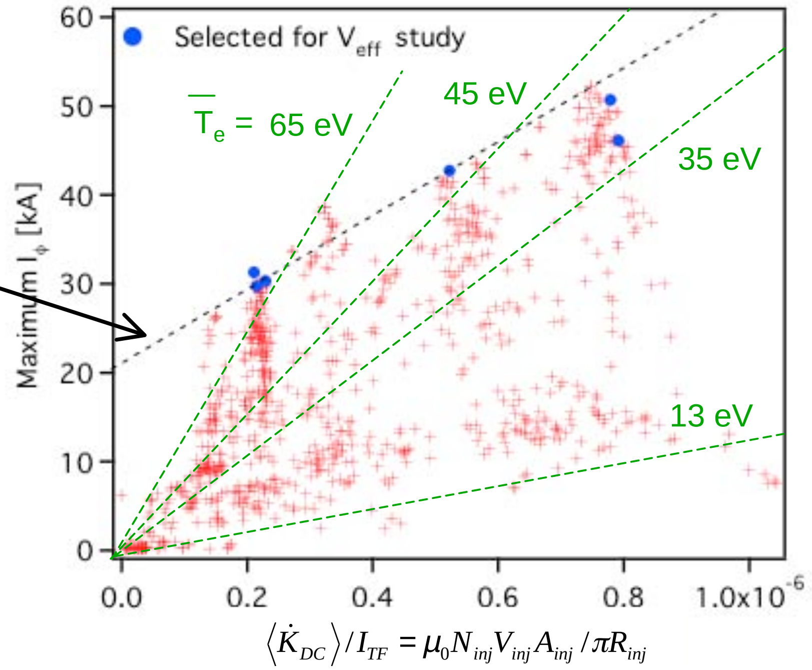


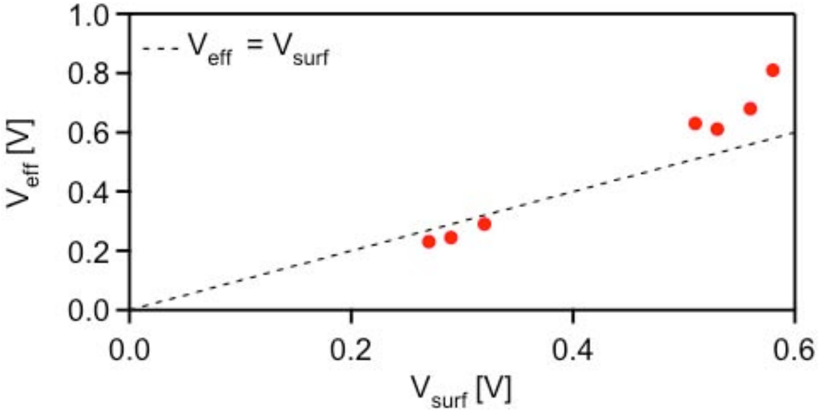


- Radial force balance requires an outer-PF ramp
- Total “loop voltage” from relaxation and PF ramp

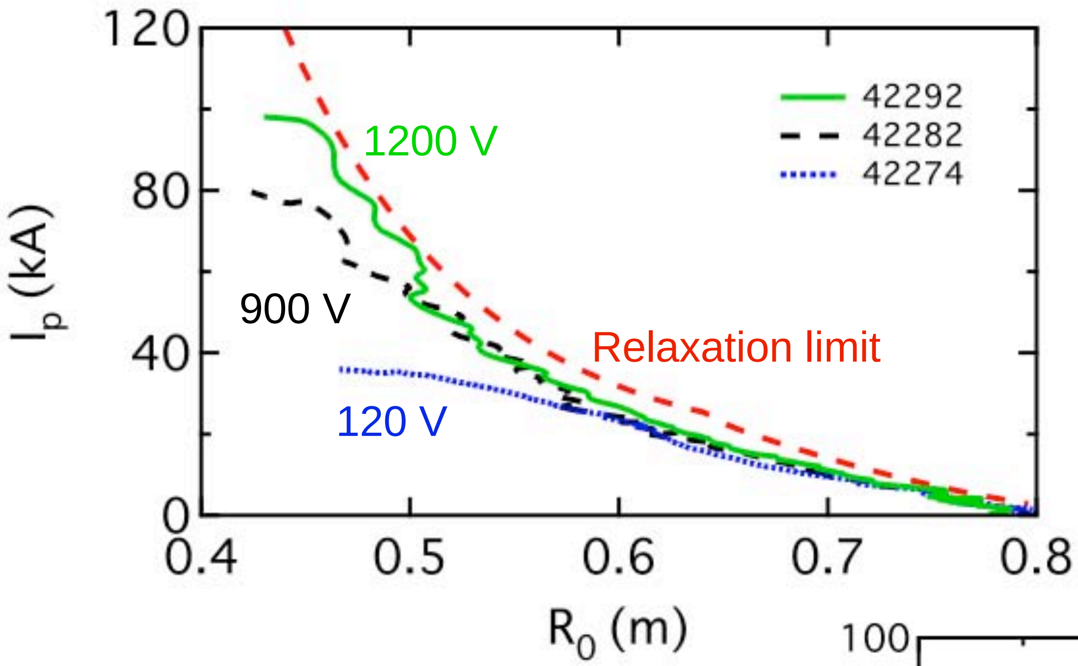
Maximum I_p occurs when helicity injection is countered by resistive helicity dissipation

- Data set for static B fields
  - Each point represents one discharge
  - Includes one and two gun operations
  - Max I_p for given conditions achieved at max B_v that allowed flux reversal
- Steady-state helicity balance roughly approximates average T_e
  - Assume Spitzer η & $Z_{eff} = 2.5$
  - Calculated average T_e = 35 - 65 eV, assuming L-mode confinement
- $V_{surf} \approx V_{eff}$ suggests plasmas achieve helicity equilibrium
  - V_{surf} estimated using a flux measurement at center column
  - G-S solver provides plasma geometry for V_{eff} calculation





Sufficient helicity injection is required to drive the toroidal current up to the relaxation limit



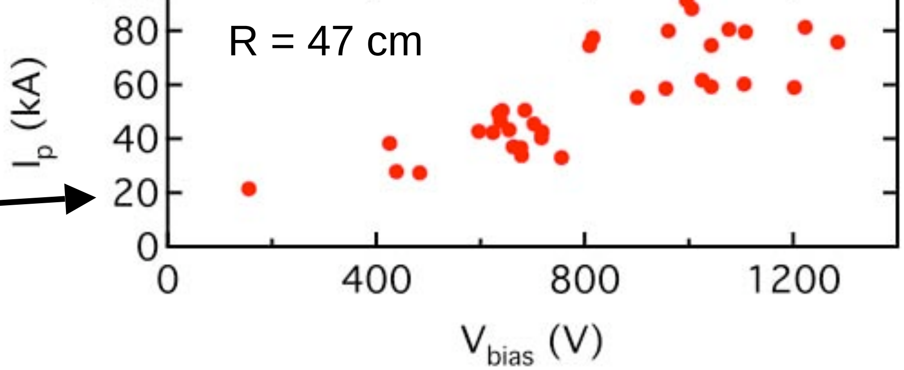
$V_{bias} = Z_{inj}\ I_{inj}$

Set by gun limit

Varied via neutral fueling

Thus, $\dot{K}_{DC} \propto Z_{inj}$

As a general trend, the maximum I_p observed in PEGASUS discharges increases with bias voltage V_{bias}



Relaxation appears to be correlated with the presence of low-n MHD activity

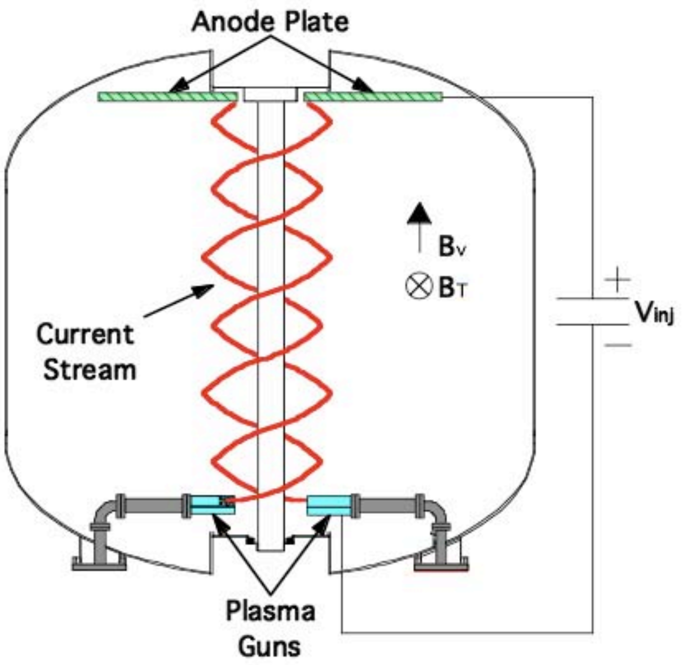
- When the bias current is off, or if relaxation cannot occur (e.g., due to the lack of a field null), there is no significant MHD activity measured in the magnetic probe arrays.

- While relaxation is occurring, there is significant MHD activity:
  - Typically n=1, with frequencies varying from 20 kHz to 60 kHz
  - Observed mode can be either continuous or intermittent
  - Mode frequency and amplitude may vary with magnetic field

- External kink mode (n=1) correlates with current-profile relaxation in CHI-driven spheromaks and STs:
  - Computational work by X.Tang, D.Brennan, and A.Bayliss (see Refs) each provide detailed studies of current-profile relaxation through the action of low-n modes
  - A similar mechanism may be responsible for relaxation in PEGASUS

Initial PEGASUS plasma gun experiments used guns located at the lower divertor

- Anode plate near the upper divertor
- Crossed B_v and B_ϕ vacuum field
- Low current plasma follows helical field line connecting gun & anode
- Resulting discharges were centerstack limited
- The divertor-region guns were easily retrofitted into PEGASUS



Zero current plasma filaments in vacuum magnetic field

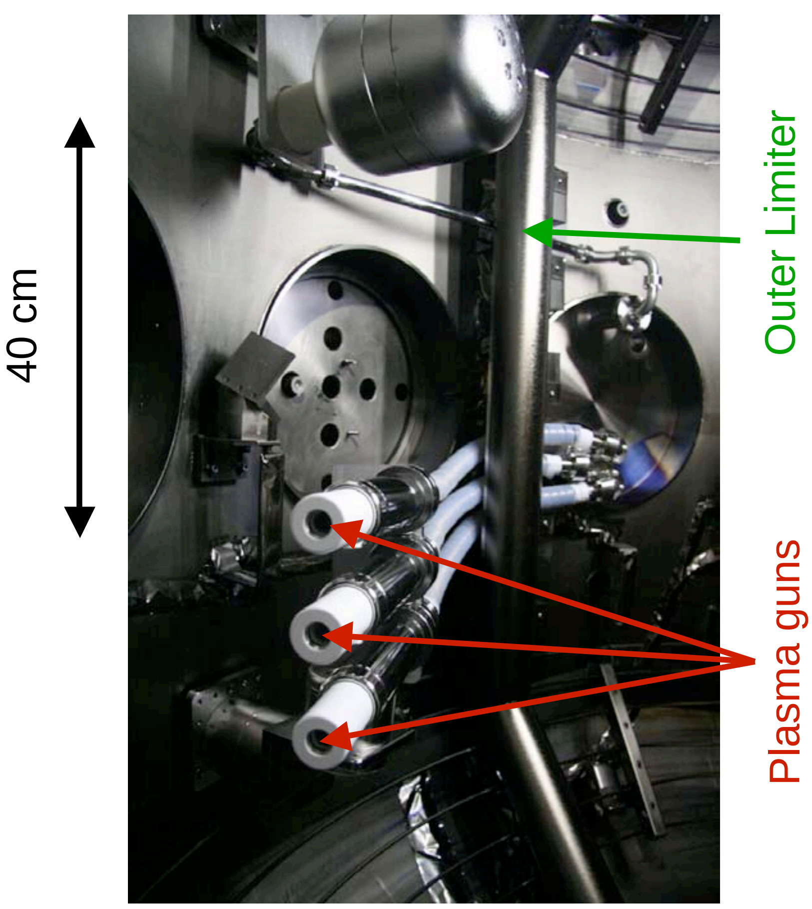
Point-source injectors can be placed anywhere

- Divertor-gun-driven tokamaks couple to Ohmic drive, but require significant coil-current ramps
  - To maintain radial magnetic stability, and
  - To reach typical Ohmic operating parameters (*e.g.*, increased TF to maintain kink stability).

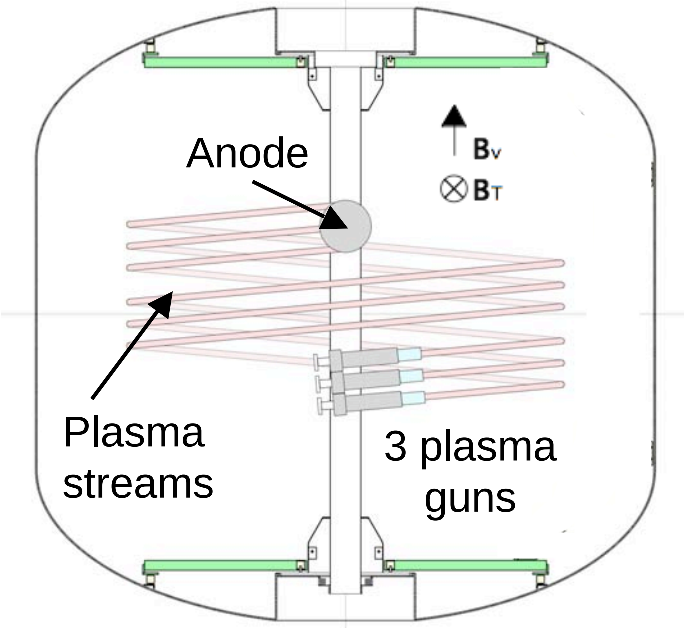
- Tokamaks formed by outboard midplane guns would
  - Form with typical Ohmic parameters (relatively high TF).
  - More easily couple to outer-PF induction.
  - Be more accessible to diagnostics
  - Have longer L/R decay timescales

- Studies using these two extreme geometries can determine a more optimum injector configuration for PEGASUS.
  - Further studies could indicate the optimum injector configuration for another device, such as NSTX.

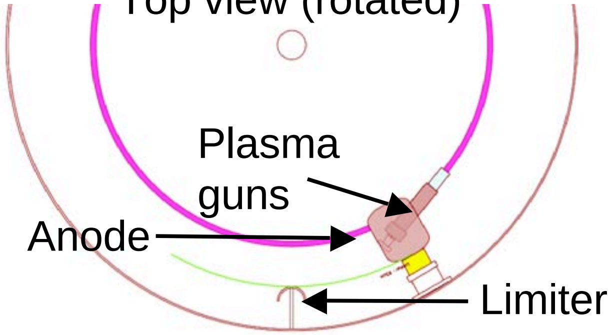
Outboard plasma gun system designed to explore point-source injection at the other geometric extreme



Side view

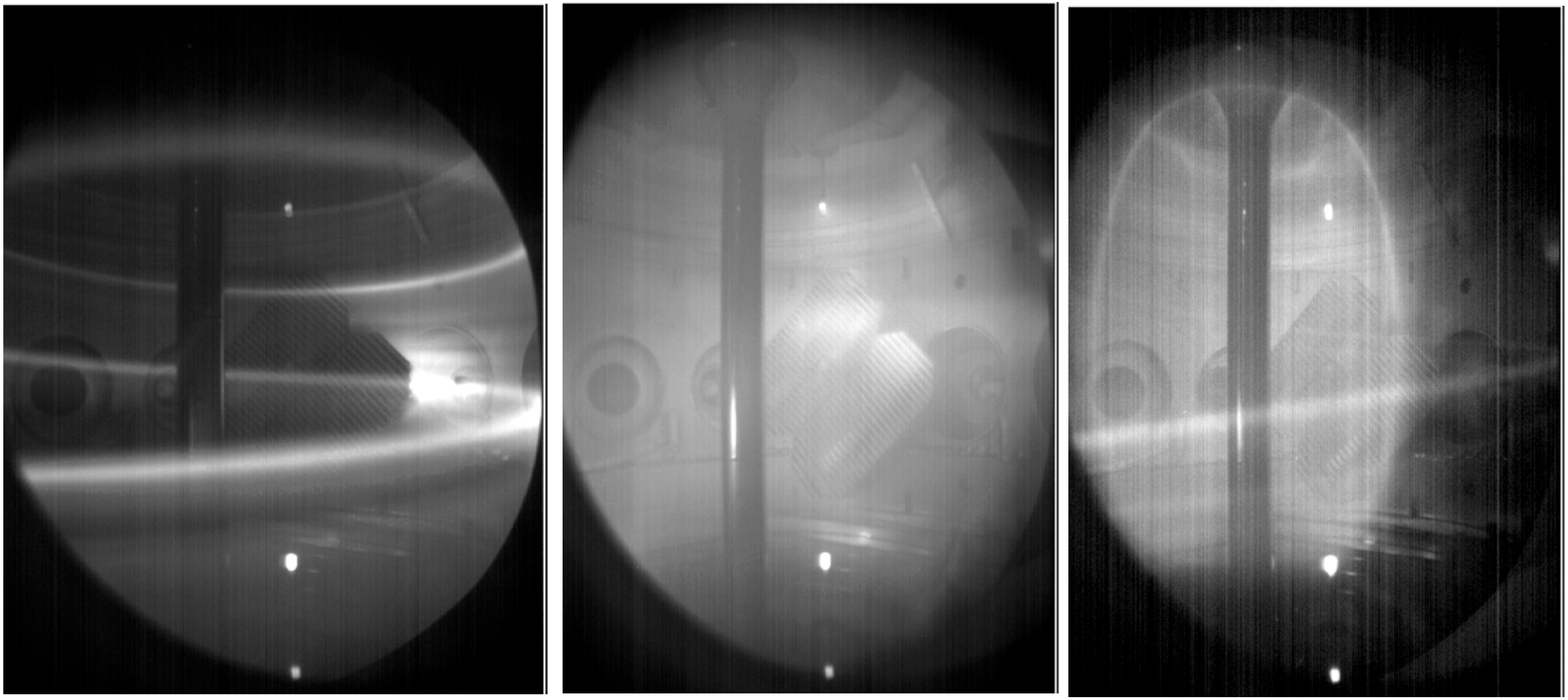


Top view (rotated)



Evolution of midplane-gun-driven plasma

Pegasus shot #40458: two midplane guns, outer-PF ramp, typical discharge



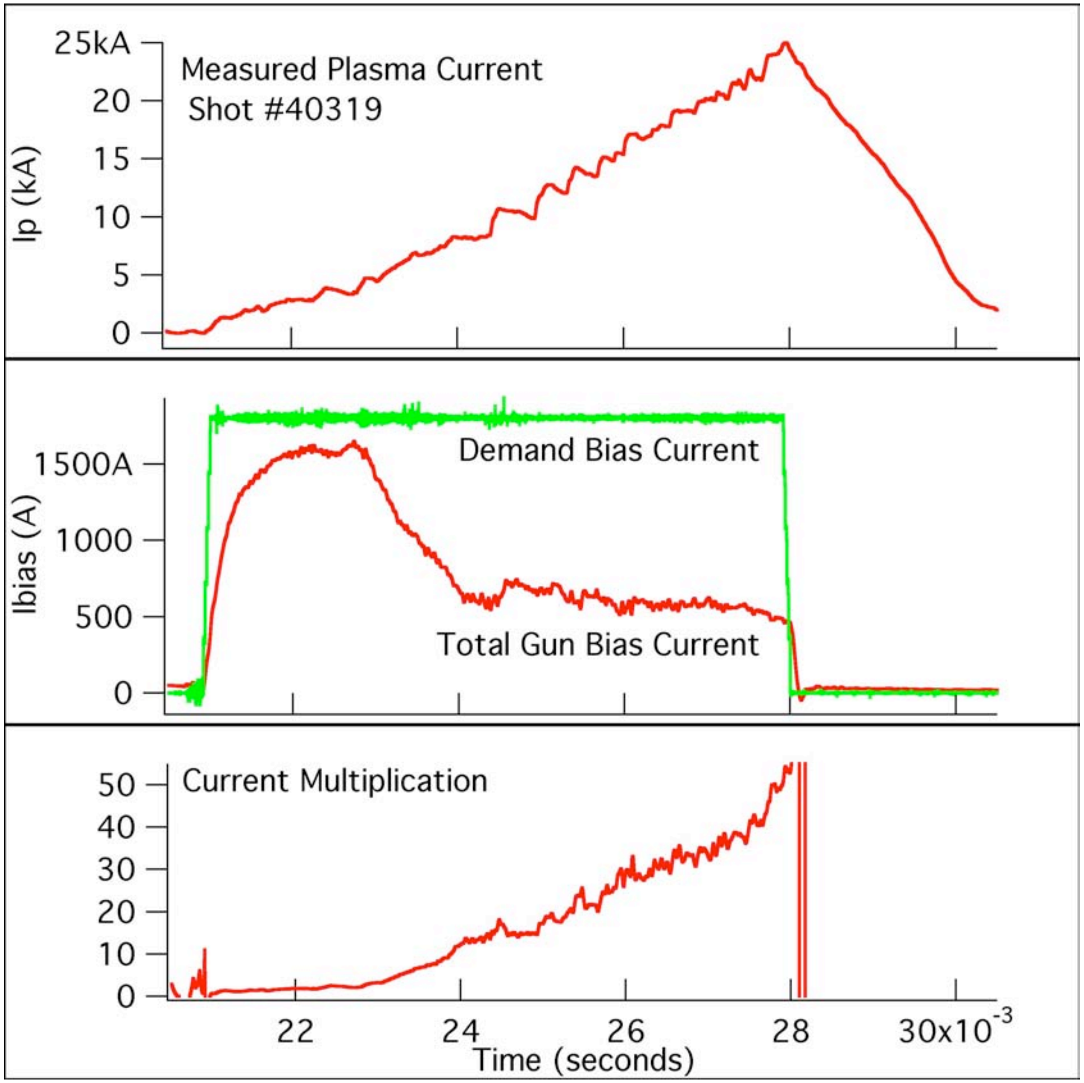
t=21.1 ms, I_p=2-3 kA
Filaments only

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

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

High current multiplication with midplane guns

- Single-gun discharge with no PF ramps.
- Current multiplication above 50 at gun shutoff.
- Sharp rises in I_p during rampup correspond to “bursts” of low-n MHD activity, which may also correspond to low-order rational values for the edge-q.



Plasma particle confinement observed in relaxed gun-driven plasmas

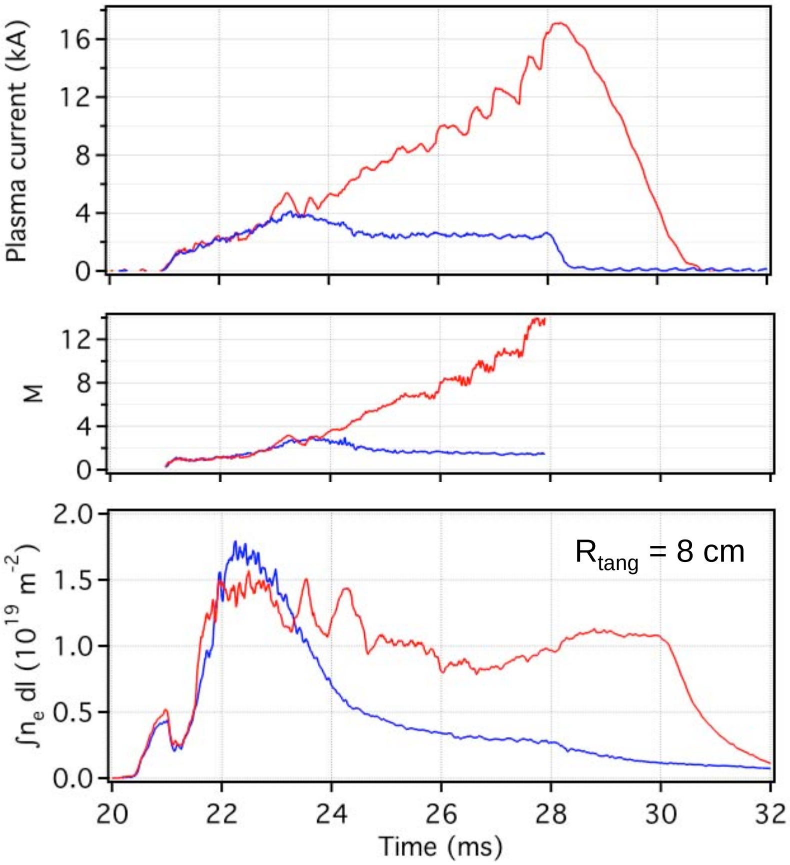
Compare two single-gun discharges:

- One discharge relaxed (#39761), while the other did not (#39762)
- Shot #39762 did not form a null, which prevented relaxation
- In the relaxed discharge (#39761):
  - Vacuum-field windup G ~ 2 (as in #39762), but the relaxed discharge achieved current amplification M > 12
  - Long I_p decay after gun shutoff at 28 ms
  - $\int n_e \, dl$ time trace shows improved particle confinement over unrelaxed case
  - Line averaged density in relaxed plasma is near the Greenwald density limit

Single gun, static B field discharges

Shot 39762: I_{TF} = 300 kA, I_{PF} = 1.3 kA

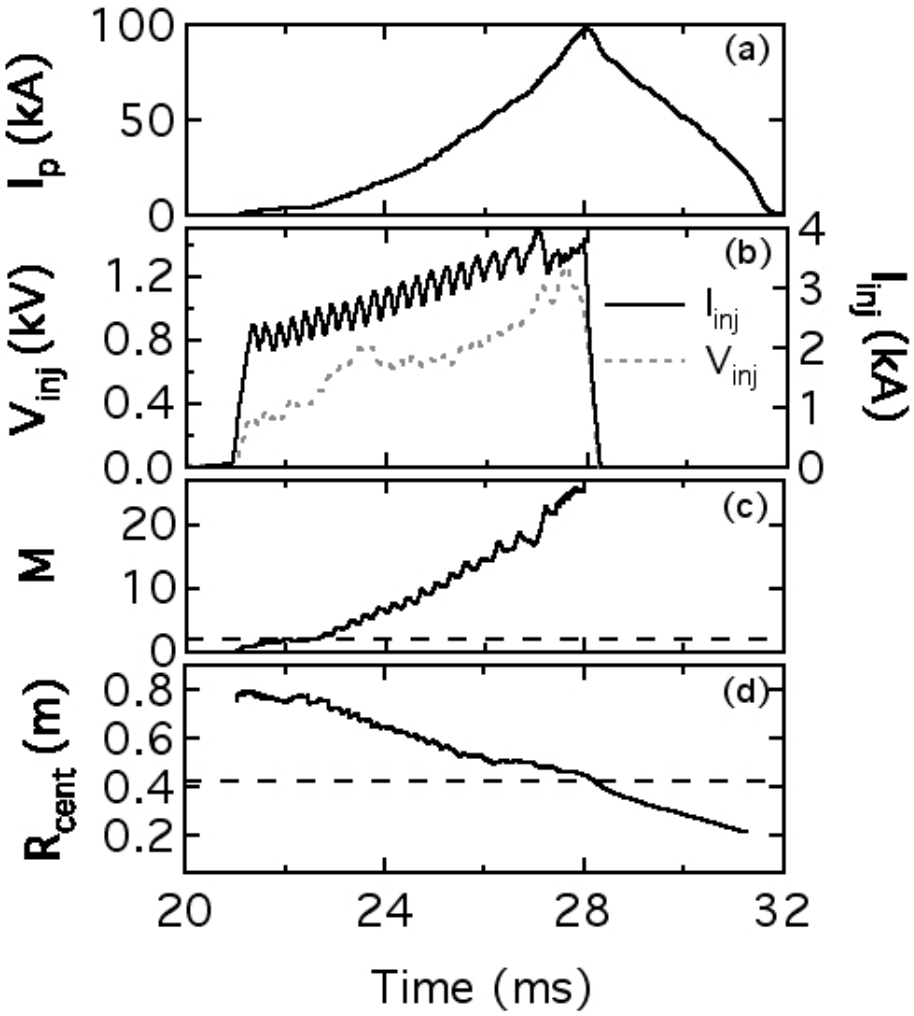
Shot 39761: I_{TF} = 300 kA, I_{PF} = 1.2 kA



Relaxation with outer-PF ramps can produce plasma currents up to 100 kA

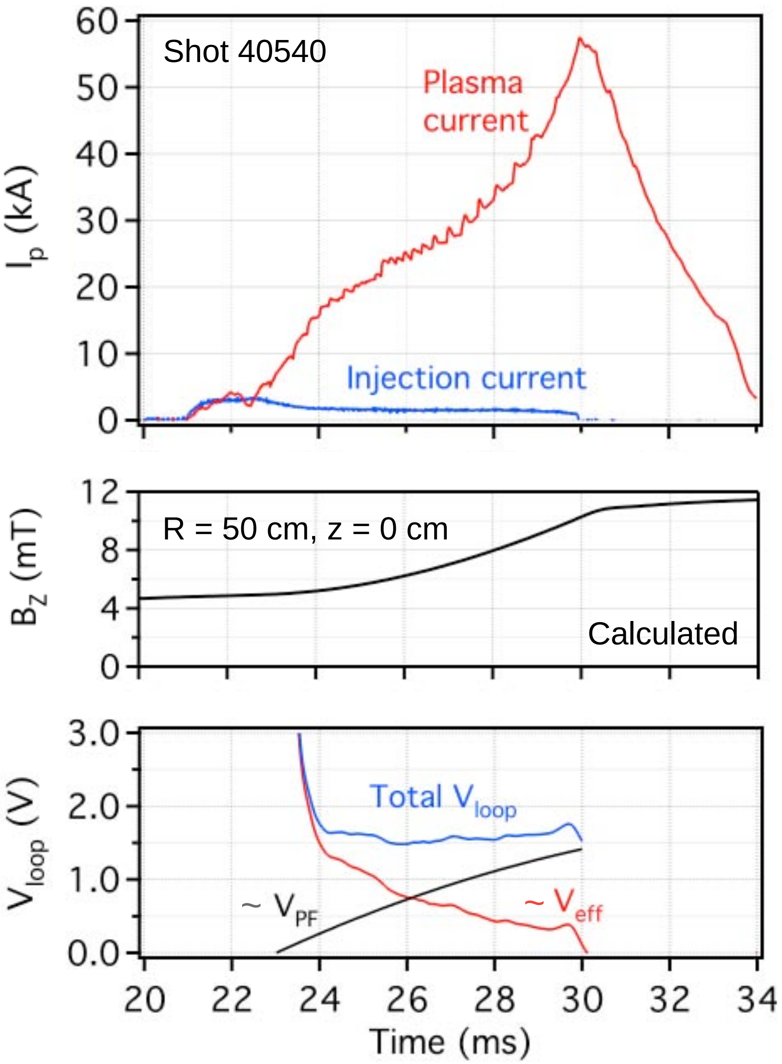
Three-gun discharge #42292:

- Uses 2 kV feedback-controlled bank to drive gun bias current
- Outer-PF ramp starts shortly after relaxation begins
- Peak current I_p is 100 kA
- Current multiplication above 25 at gun shutoff
- Bias voltage rises through shot
- Discharge fills confinement region at gun shutoff; afterwards, plasma is centerstack-limited

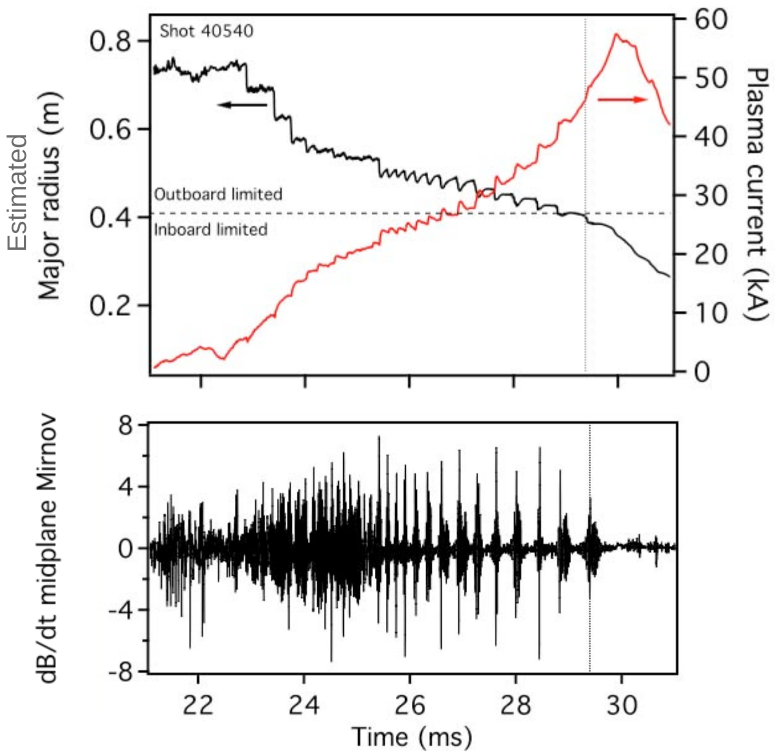


Toroidal loop voltage contributions due to relaxation and PF induction can be calculated

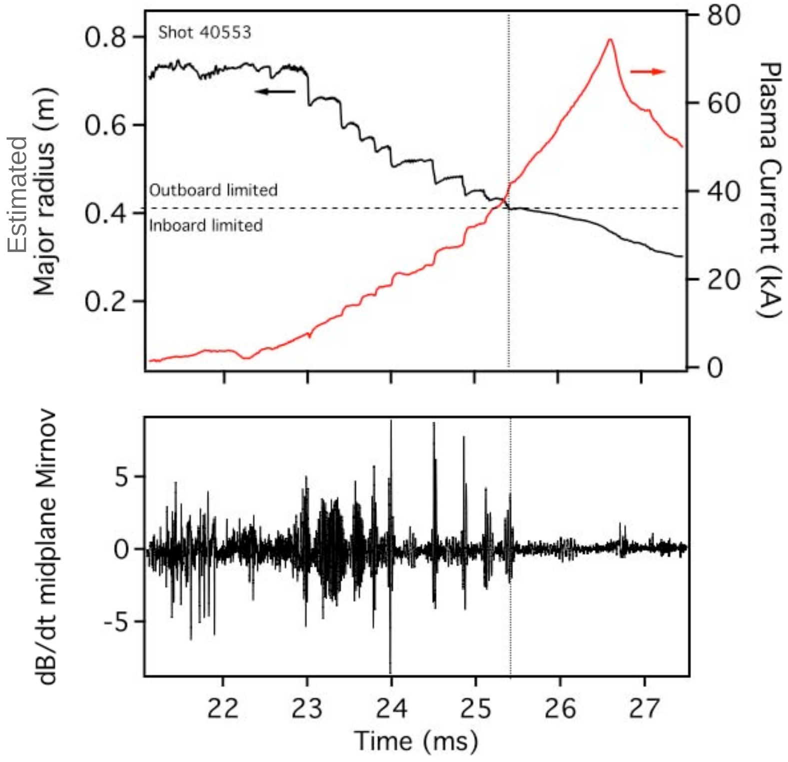
- Multi-gun discharges often require outer-PF ramps for equilibrium
  - Low B_v required for field reversal
  - Larger B_v required after field reversal to maintain radial force balance with larger I_p
- Outer-PF ramps also impose a toroidal loop voltage, comparable to the V_{eff} from relaxation
  - Two plasma guns in operation
  - Ramp begins after field reversal
- Calculated total $V_{loop} \approx 1.5$ V
  - V_{eff} calculated using R_0 and plasma shape estimation from magnetic measurements
  - V_{PF} calculated using 2-D vacuum field model that includes wall effects



Gun-driven plasma can “detach” from the guns during rapid PF ramps



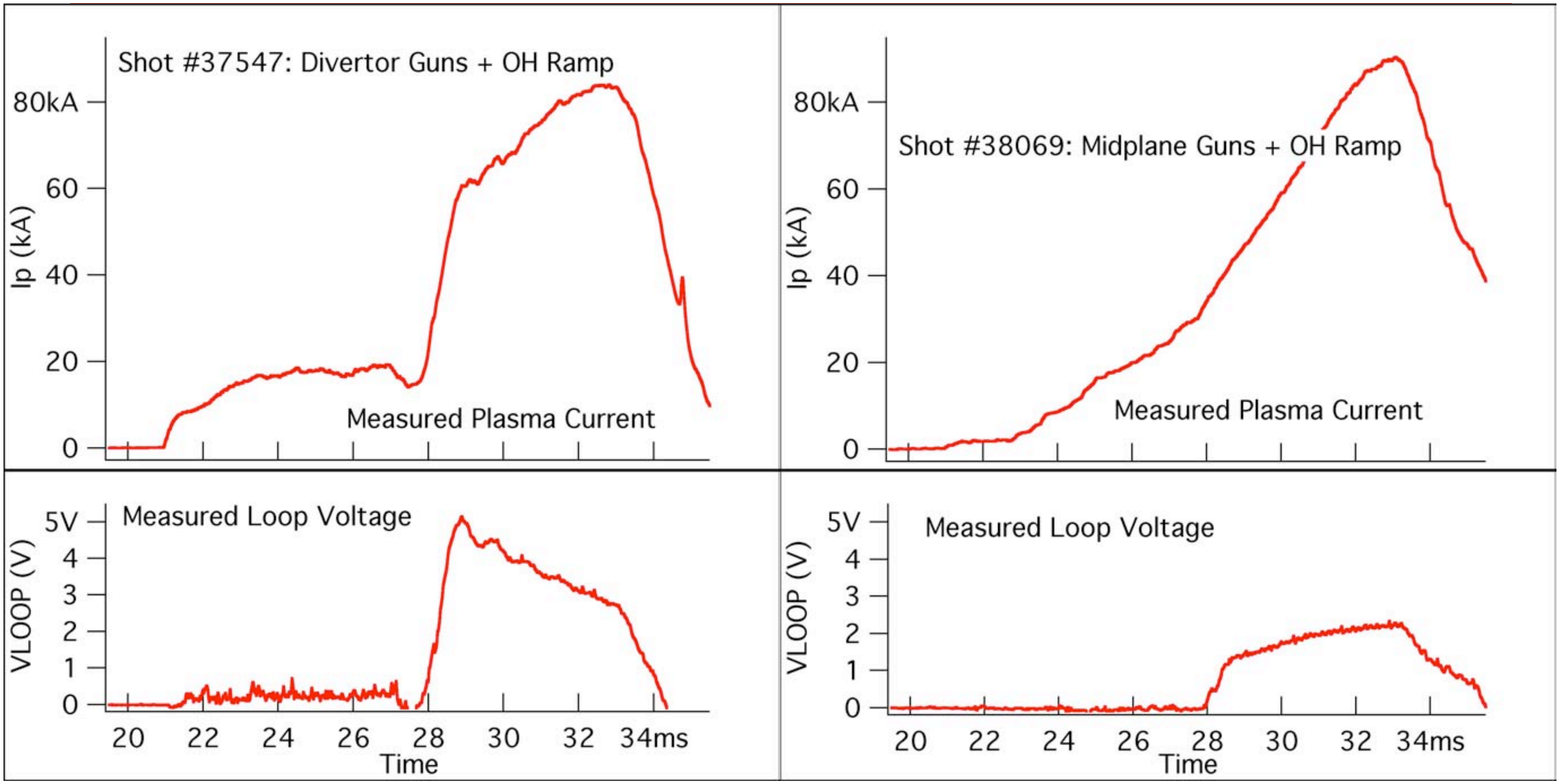
Slower PF ramp
Plasma detaches at 29.4 ms



Faster PF ramp
Plasma detaches at 25.3 ms

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

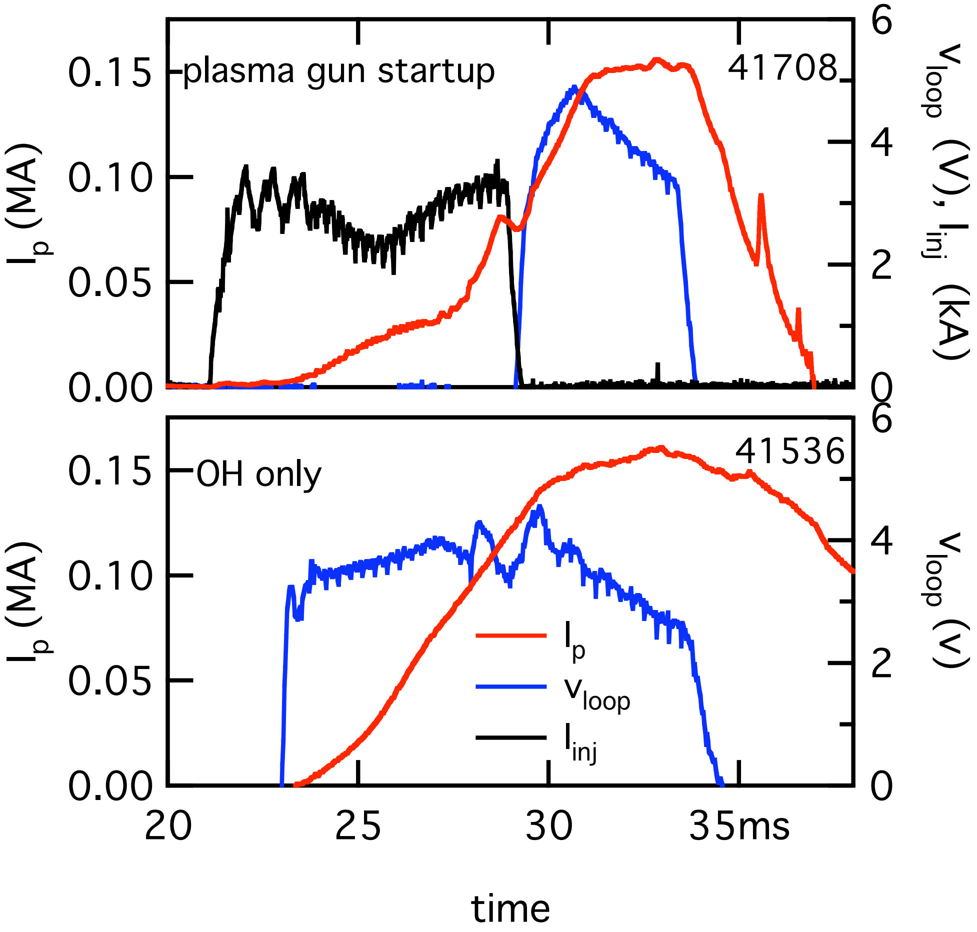
Handoff from plasma gun startup to Ohmic drive has been demonstrated



Both discharges had gun-driven startup, outer-PF ramps, and applied Ohmic drive. The peak current I_p in each discharge was approximately 90 kA.

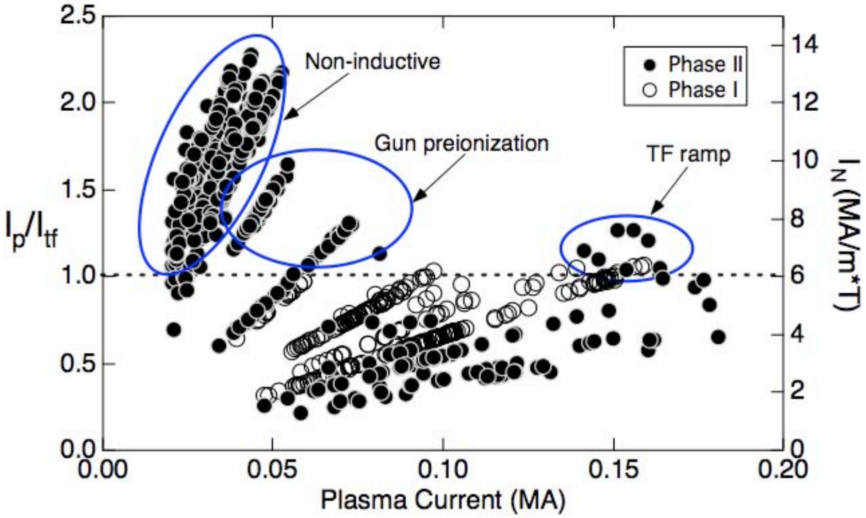
Gun-driven startup + some Ohmic drive matches the best Ohmic-only I_p in Pegasus

- 80 kA gun-driven target handoff to OH drive
- Gun startup + an Ohmic single-swing reaches the same peak I_p as Ohmic double-swing with twice the flux
  - Implies ~ 50% flux savings
- Will assess suitability of gun-driven discharges for other CD techniques
  - 0.8-1.0 MW PEGASUS HHFW



Non-inductive startup provides a path to high β_t operations in the $I_N > 12$ regime on Pegasus

- Point-source edge current drive provides tool for modifying the current profile
- Access to $I_N > 12$ achieved using non-inductive startup
- No evidence of β stability limits at high I_N
  - Discharges have been limited by available current drive
- Non-inductive startup with hand-off to OH drive will extend the operational space
- Hand-off to HHFW in future

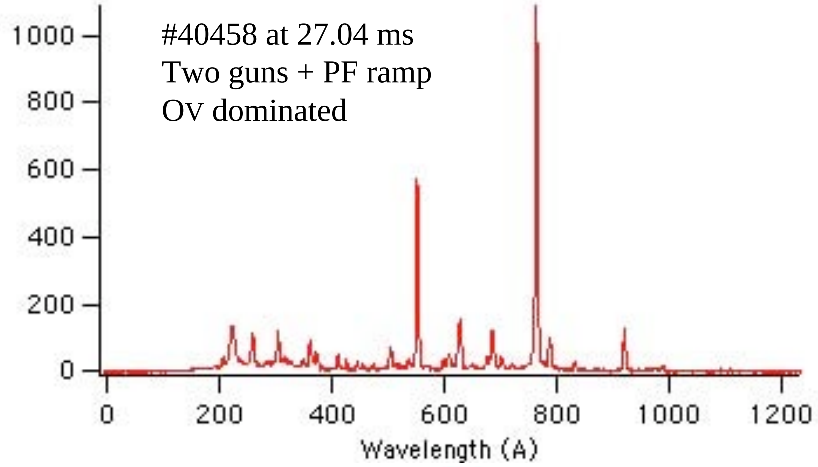


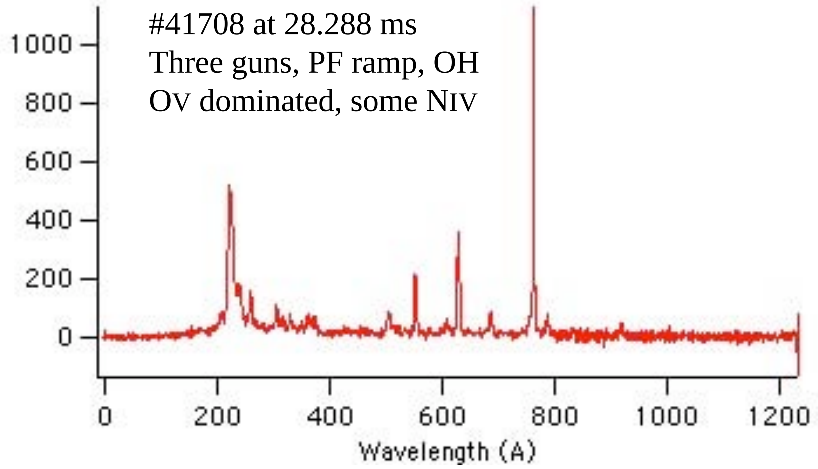
$$\beta_t = \beta_N I_N \qquad I_N = I_P / aB_\phi$$

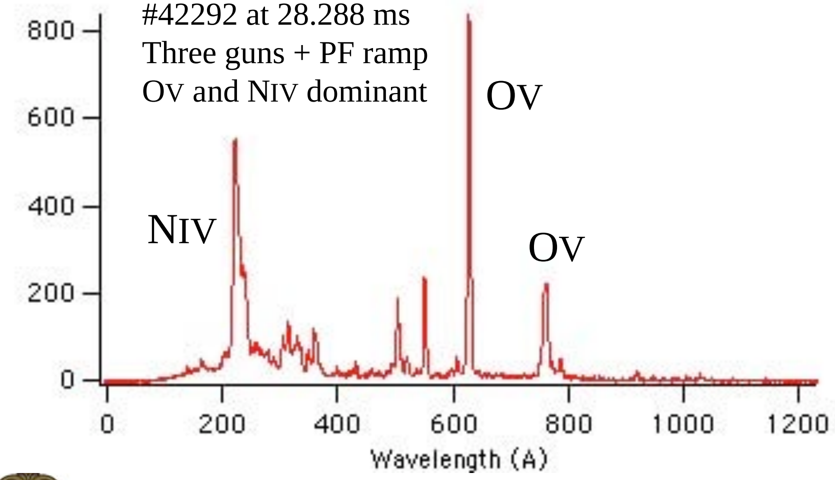
$$\beta_t = \frac{2\mu_0 \langle p \rangle}{B_{\phi 0}^2}$$

Gun-driven discharges appear to be high-temperature, low-impurity plasmas

SPRED spectra from various times in gun-driven Pegasus discharges


#40458 at 27.04 ms
Two guns + PF ramp
OV dominated


#41708 at 28.288 ms
Three guns, PF ramp, OH
OV dominated, some NIV


#42292 at 28.288 ms
Three guns + PF ramp
OV and NIV dominant

The SPRED spectra for gun-driven discharges do not show significant metal contamination, and are dominated by OV (113.9 eV), implying electron temperatures of 50-70 eV.

The NIV emission may result from the plasma limiting on the boron nitride gun casing.
It is possible that operational improvements will reduce or eliminate this nitrogen impurity.

Pegasus non-solenoidal startup summary

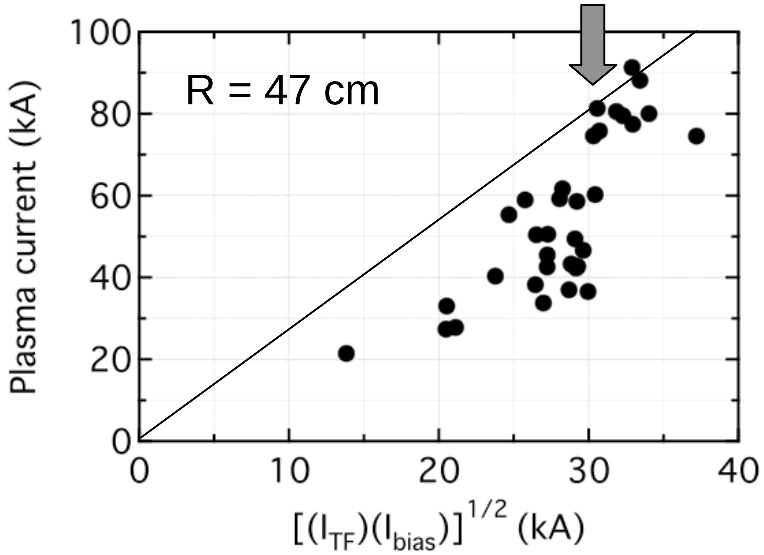
- ST startup and current drive via point-source DC helicity injection has been demonstrated on the Pegasus Toroidal Experiment
  - Formation of tokamak-like plasma correlates with inboard field reversal
  - Maximum I_p described by force and helicity balance
  - Observed in relaxed gun-driven discharges:
    - Improvement in particle confinement
    - Increase in L/R decay time, and
    - Modest plasma heating

- Magnetic induction compatible with DC helicity injection
  - Outer-PF induction provides current drive and maintains radial force balance with larger I_p plasma
  - Fast PF ramps can cause the tokamak-like plasma to detach from the gun
  - Handoff to OH induction is robust
  - Plasma-gun startup is equivalent to a Pegasus Ohmic half-swing

Projecting to future designs requires additional knowledge of parameter scalings

- What determines λ_{edge}?
  - J_{edge} broadening due to magnetic turbulence (edge and global), magnetic shear, gun characteristics, physical geometry, *etc.*
  - Plan to measure directly using probes and study dependence on I_{TF}, I_{inj} & plasma properties
- How does τ_e (or τ_K) scale with I_p?
  - $\chi_\perp$ versus $\chi_{||}$ in the presence of magnetic turbulence
  - Confinement will depend on degree of stochasticity in core plasma
  - Requires T_e and T_i measurement
- What influences Z_{inj}?
  - Voltage drop across sheath and filament length
  - Measure with floating probe in SOL

Terms may have I_p dependence
ex: paramagnetism and shaping



Near-term non-solenoidal startup work

- More completely characterize PEGASUS discharge parameters
  - P_{RAD}, n_{el} and n_e, T_e, impurities, flows
  - Possibly implement Thomson scattering (for n_e and T_e) and IDS (T_i and flows)
- Test the proposed scalings of I_p limits
  - Langmuir and magnetic probes → measure λ_{edge} directly, study relaxation mechanism
  - Increase gun area → determine effect on *w* & increase K_{inj}
  - Decrease R_{inj} & maintain outboard injection → should increase both limits
  - Increase $L_{filament}$ → determine effect on Z_{inj}
  - Possibly implement Thomson scattering and ion Doppler shift → T_e and T_i
  - Increase TF by 20-30% → extend database to higher toroidal field
- Improve and extend modeling and analysis efforts
  - Routine equilibrium fitting with KFIT Grad-Shafranov solver
  - Stability calculations using DCON
  - PF induction/compression modeling using TSC
- Handoff of 100+ kA target plasmas to Ohmic (single- and double-swing)

References

- Bayliss, Sovinec, and Redd, “MHD simulations of CHI with weak relaxation in the HIT-II spherical tokamak,” in preparation.
- Redd *et al.*, Journal of Fusion Energy DOI 10.1007/s10894-008-9183-9 (Nov 2008).
- Battaglia *et al.*, Journal of Fusion Energy, in press (2008).
- Garstka *et al.*, Journal of Fusion Energy **27**, 20-24 (2008).
- Redd *et al.*, Physics of Plasmas **14**, 112511 (2007).
- Unterberg *et al.*, Journal of Fusion Energy **26**, 221-225 (2007).
- Eidietis *et al.*, Journal of Fusion Energy **26**, 43-46 (2007).
- Garstka *et al.*, Nuclear Fusion **46**, S603 (2006).
- Holcomb *et al.*, Physics of Plasmas **13**, 022504 (2006).
- Tang and Boozer, Physics of Plasmas **12**, 102102 (2005).
- Garstka *et al.*, Physics of Plasmas **10**, 1705 (2003).
- Brennan, Browning, and Van der Linden, Physics of Plasmas **9**, 3526 (2002).
- McCollam and Jarboe, Plasma Physics and Controlled Fusion **44**, 493 (2002).