Point-source DC Helicity Injection on the Pegasus Toroidal Experiment

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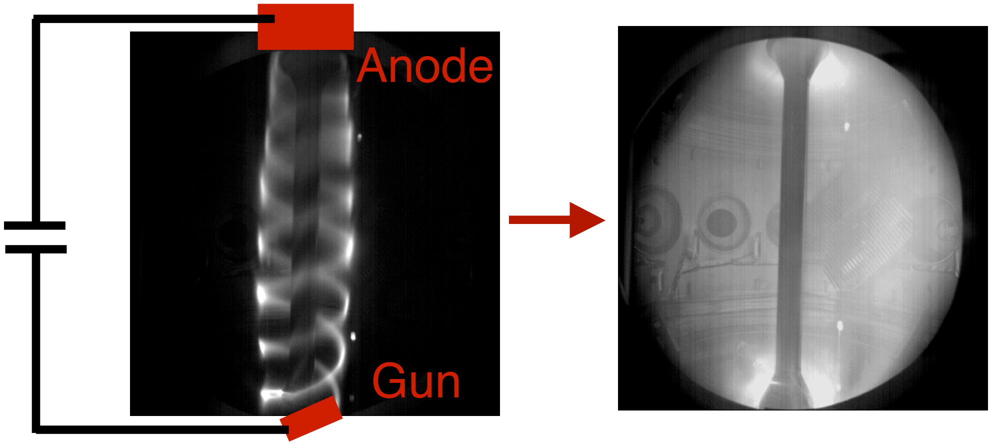
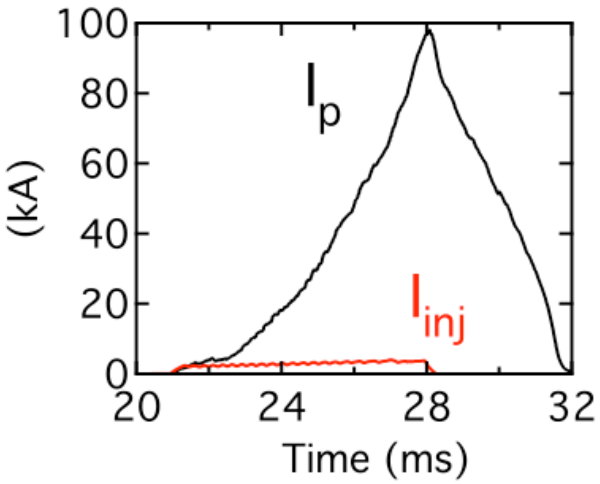
Point-source DC helicity injection is an attractive non-solenoidal startup technique

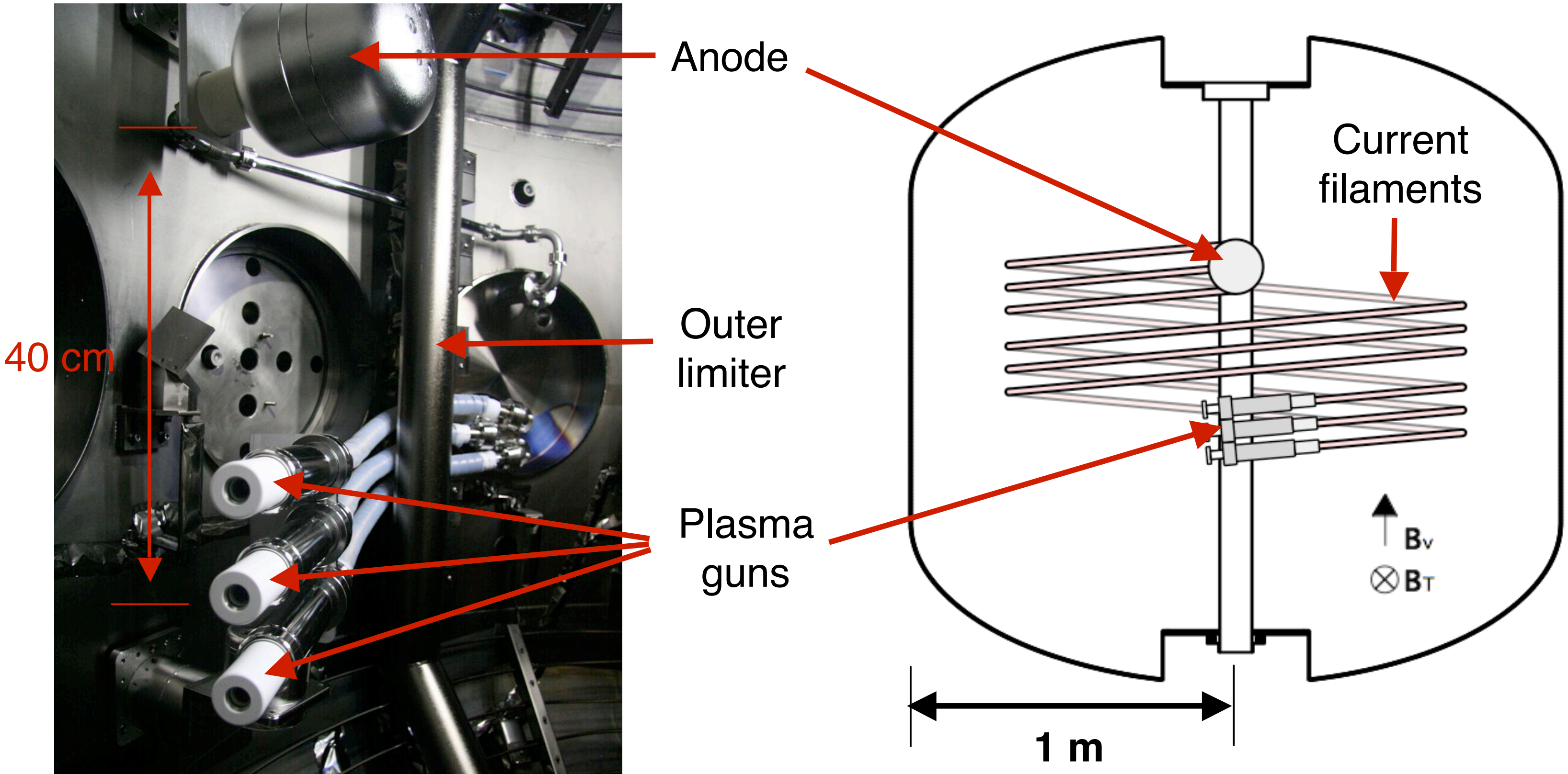
- Non-solenoid startup is a critical issue for future long-pulse STs
  - Would extend efficiency of OH drive and provide j(R) modification on present experiments that already have a central solenoid

- Plasma gun point-source DC helicity injection tested on Pegasus
  - Low impurity, high J_{inj} source
  - Scalable design ⇒ flexible, compact & no toroidal vacuum break

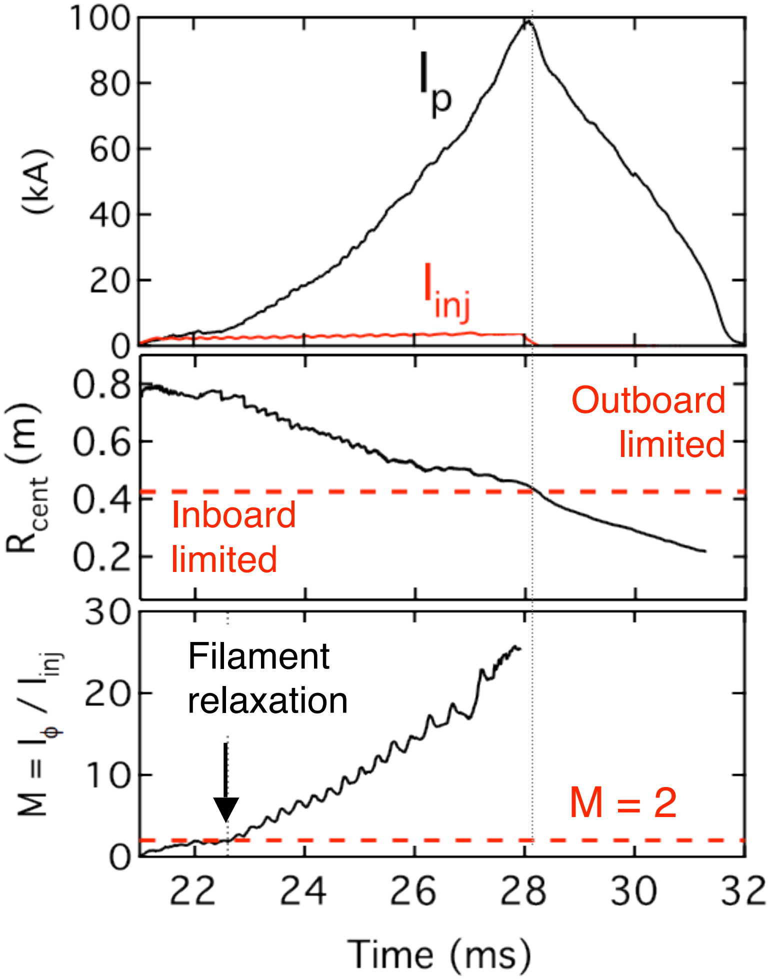




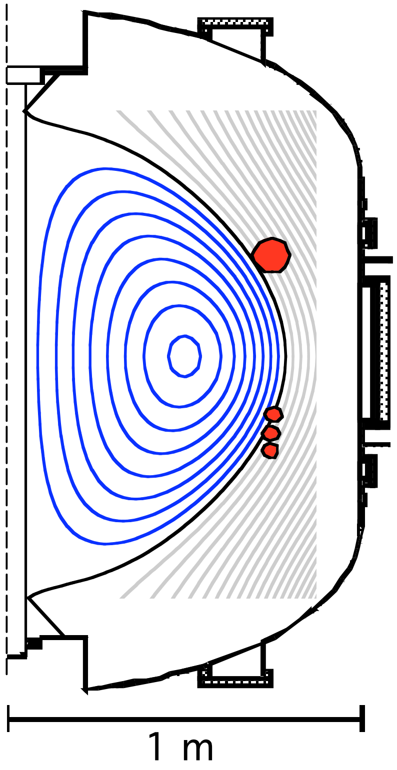
Outboard point-source injection on Pegasus features a scalable “port-plug” design



$I_p \sim 0.1$ MA non-solenoidal startup achieved using < 4 kA injected current



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

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Achieved I_p depends on helicity and relaxation constraints

Helicity balance in a tokamak geometry:

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

- 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:

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

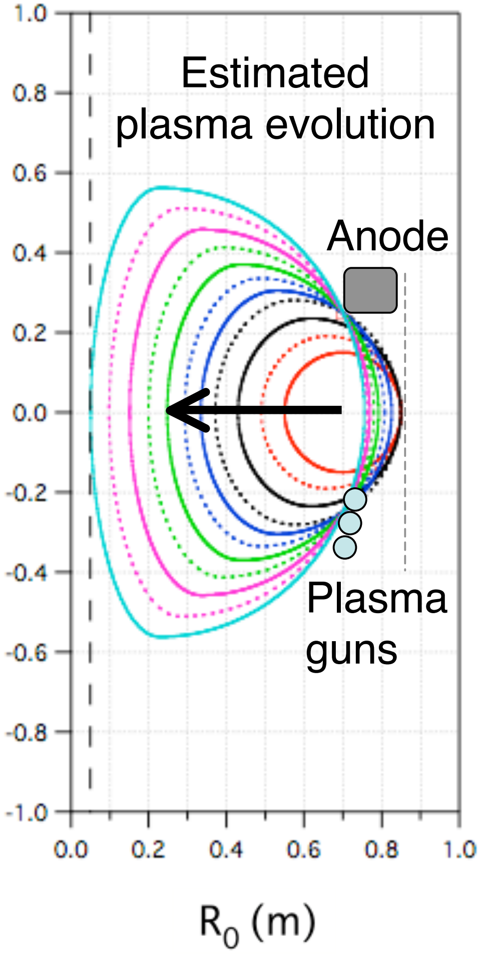
$$\lambda_p \le \lambda_{edge} \;\Rightarrow\; \frac{\mu_0 I_p}{\Psi} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \;\Rightarrow\; I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi I_{inj}}{w}\right]^{1/2}$$

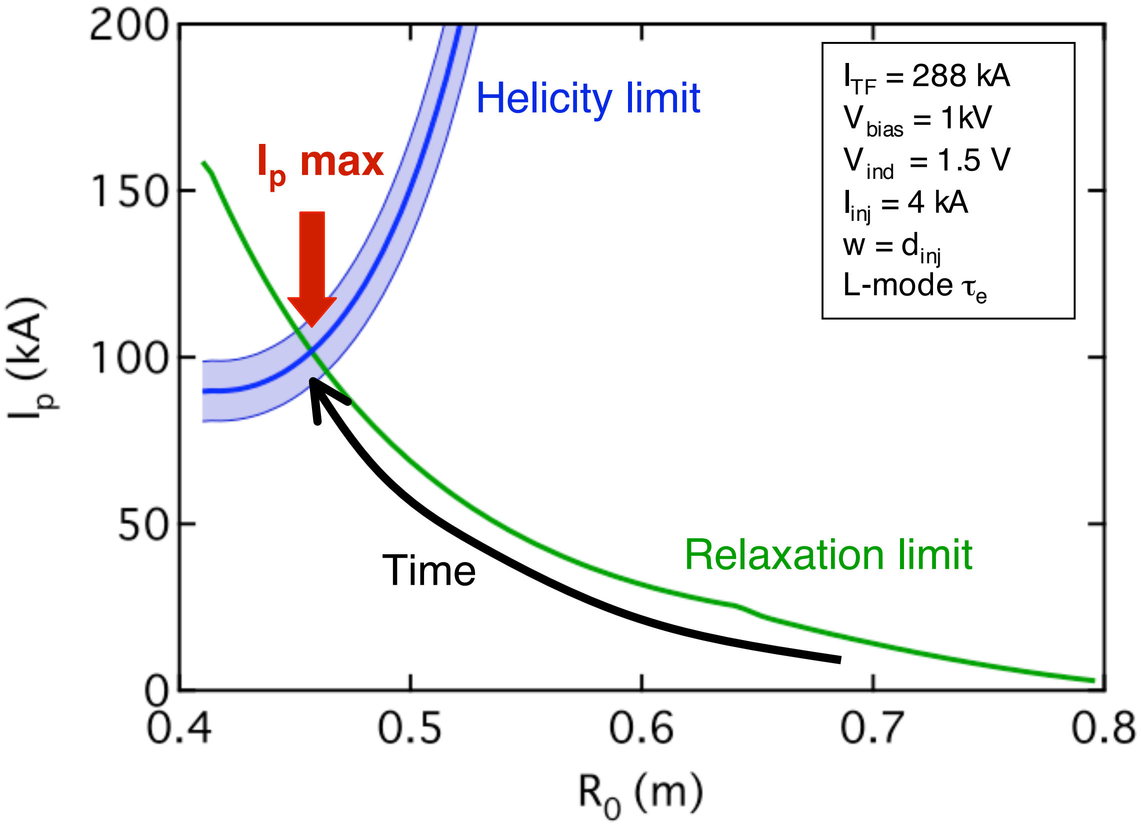
Assumptions:

- 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

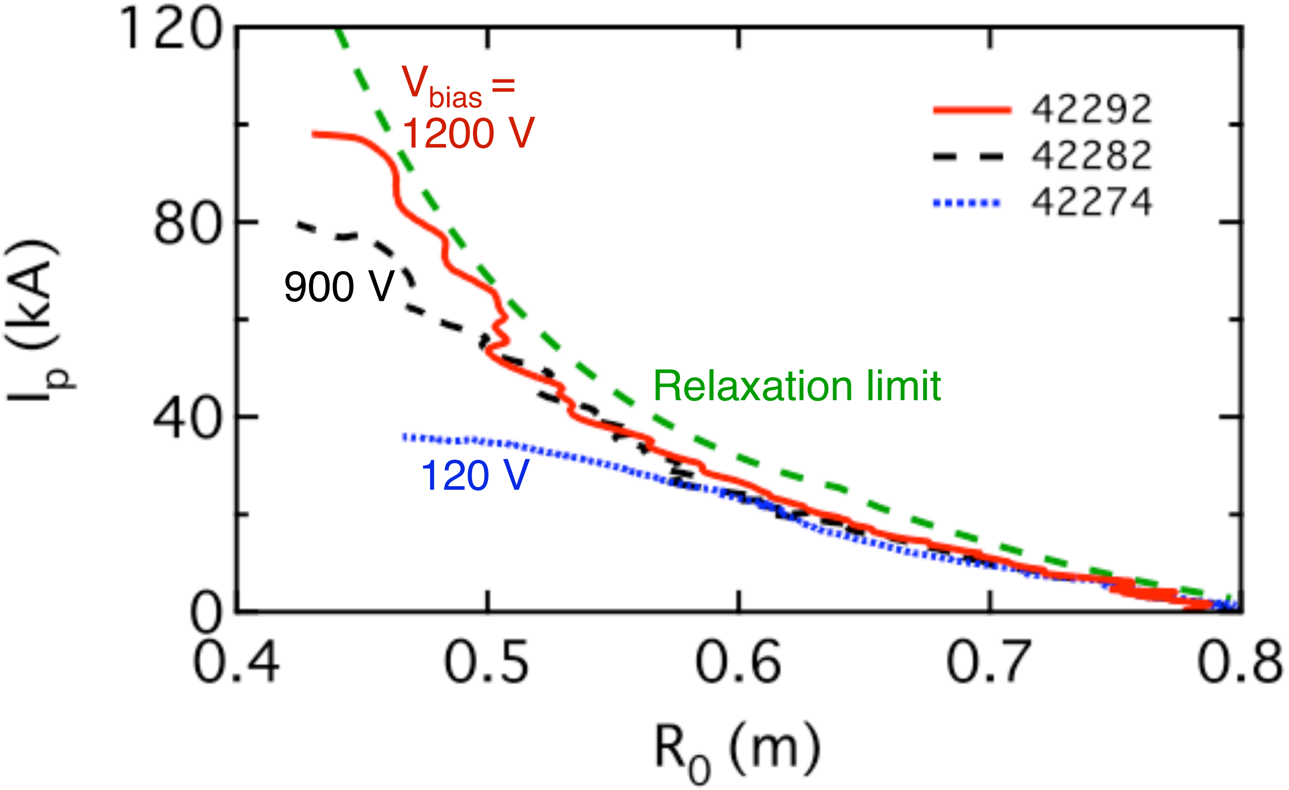
Max I_p achieved when helicity and relaxation criteria are simultaneously satisfied





- Requires B_v ramp for radial force balance & V_{ind}

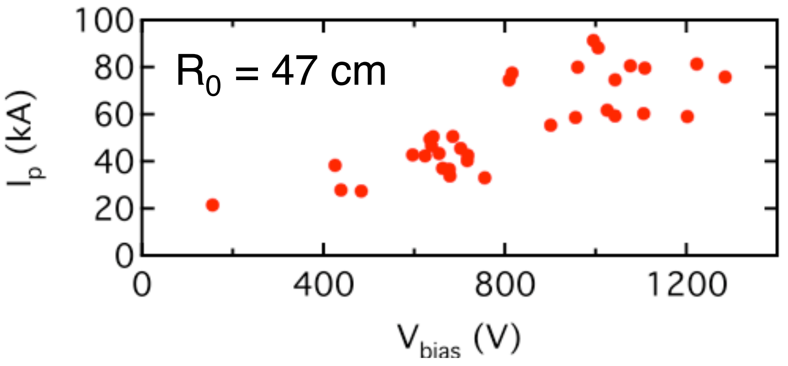
Sufficient helicity injection is required to drive plasma to the relaxation limit

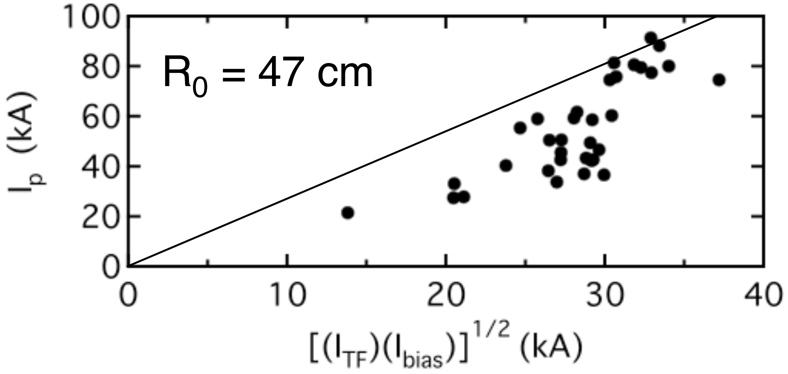


- All three discharges have the same I_{inj} and B_v evolution

Several issues need to be addressed in the near term to test the simple model

- What determines λ_{edge}?
  - J_{edge} broadening due to magnetic turbulence (edge and global), magnetic shear, gun characteristics, physical geometry, *etc*.
- 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
- What influences Z_{inj}?
  - $V_{bias} = Z_{inj} I_{inj}$
  - Neutral fueling
  - Filament path length





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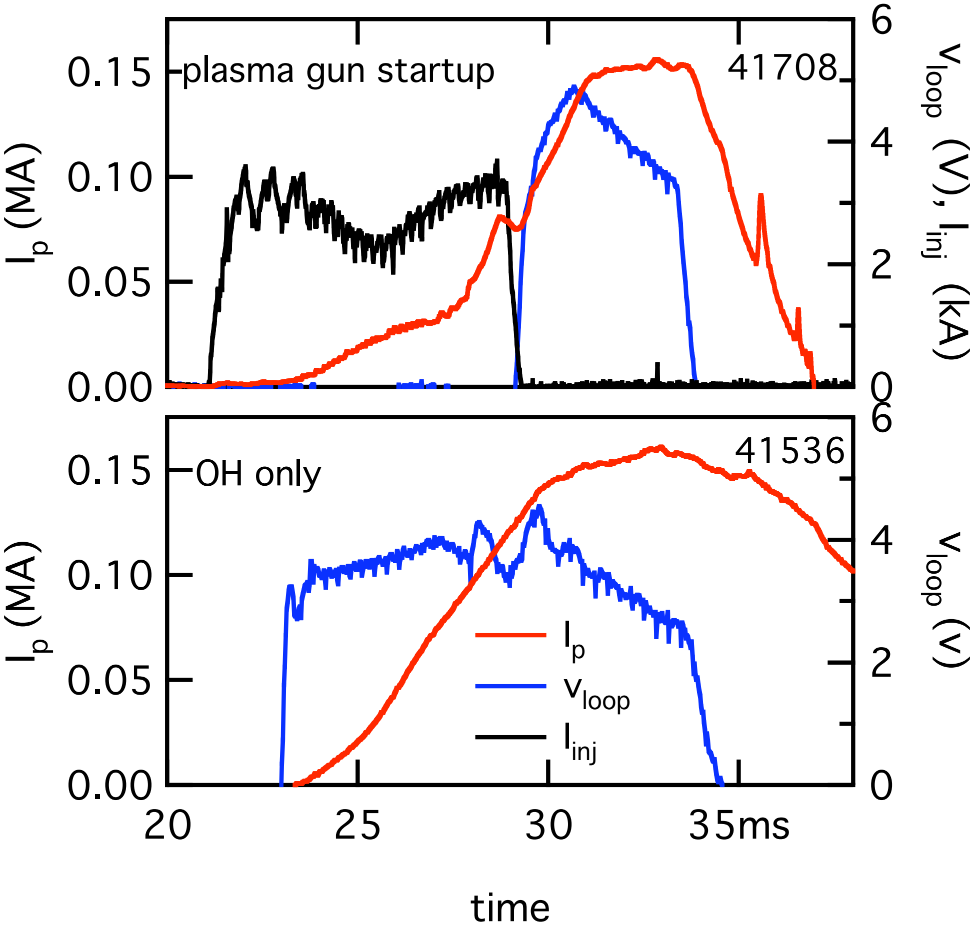
Target plasma from point-source DC helicity injection readily coupled to OH induction

- 80 kA target handoff to OH drive
- Equivalent I_p with 1/2 OH flux swing
  - ~ 50% flux savings
- Need to assess target suitability for other CD means



Summary

- High current (~ 0.1 MA) ST startup and current drive via point-source DC helicity injection has been demonstrated on Pegasus
  - Maximum I_p described by helicity balance and relaxation criteria

- Magnetic induction compatible with gun produced target plasmas
  - PF induction provides current drive and maintains radial force balance with larger I_p plasma
  - Handoff to OH induction robust

- Near-term work will test proposed scaling of I_p limits
  - Langmuir and magnetic probes → measure λ_{edge} directly
  - 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}
  - Characterize plasma
    - n_{el}, P_{RAD}, T_e, impurities
    - Possibly implement Thomson scattering and ion Doppler shift → T_e and T_i

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For more information

- JP6.00012 Numerical Simulation of MHD Relaxation during Non-Inductive Startup of Spherical Tokamaks T.M. Bird, *et. al.*
- NP6.00134 Overview of the Pegasus Toroidal Experiment A.C. Sontag, *et. al.*
- NP6.00135 Non-solenoidal startup in Pegasus discharges A.J. Redd, *et. al.*
- NP6.00136 Characterization of edge instabilities in the Pegasus Toroidal Experiment M.W. Bongard, *et. al.*
- NP6.00138 Pegasus power system facility upgrades B.T. Lewicki, *et. al.*
- NP6.00139 Computational study of a non-ohmic flux compression startup method for spherical tokamaks J.B. O'Bryan, *et. al.*
- VI2.00001 Non-solenoidal Plasma Startup in the Pegasus Toroidal Experiment A.C. Sontag

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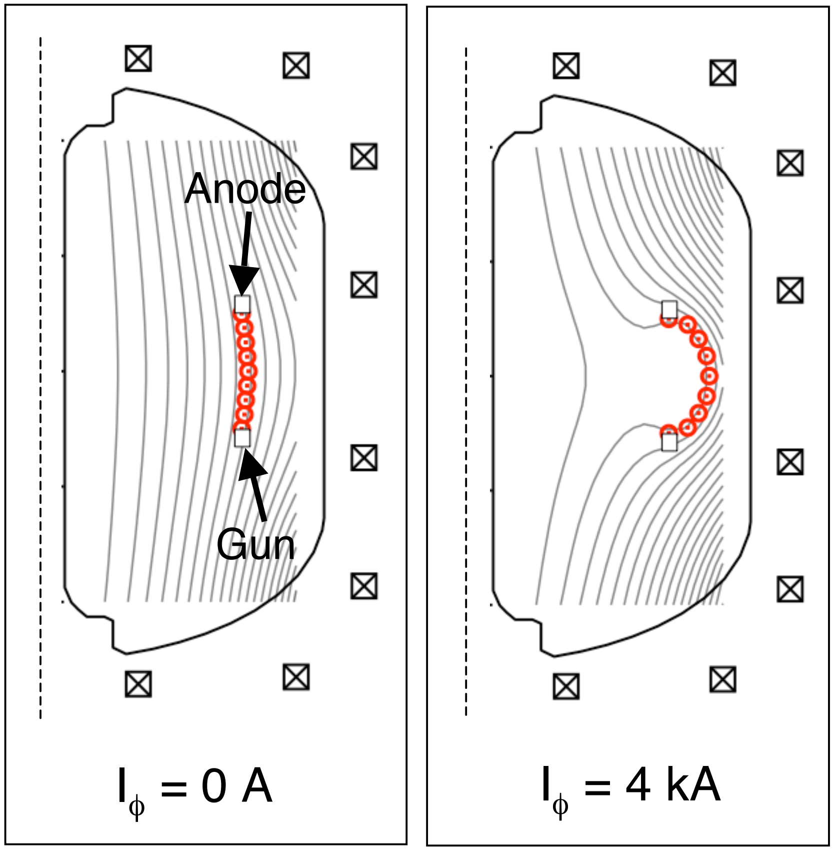
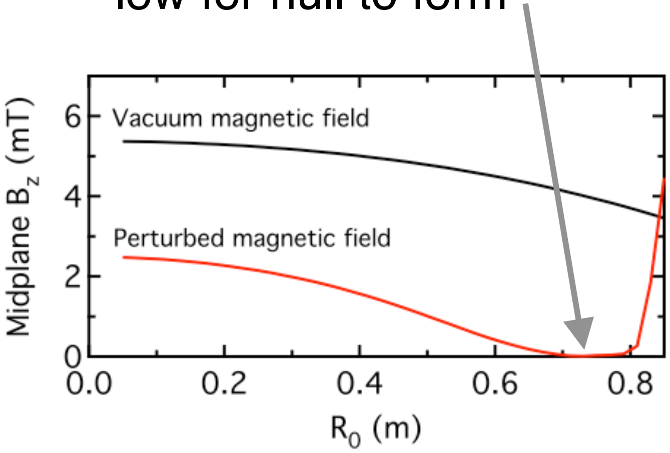
The relaxation of filaments to a tokamak-like topology requires an inboard null region



2-D force free current model

- Current along injected filaments perturbs the vacuum magnetic field
- B_v must be sufficiently low for null to form



- Null formation is required, but not sufficient for relaxation

D.J. Battaglia, APS-DPP Dallas 2008