Progress in Nonsolenoidal Plasma Startup Using Point-Source Helicity Injection in the Pegasus ST

R.J. Fonck, J.L. Barr, M.W. Bongard, M.G. Burke,
E.T. Hinson, A.J. Redd, D.J. Schlossberg, K.E. Thome

2010 APS
DPP
Conference

Chicago, IL
Nov 8-13, 2010



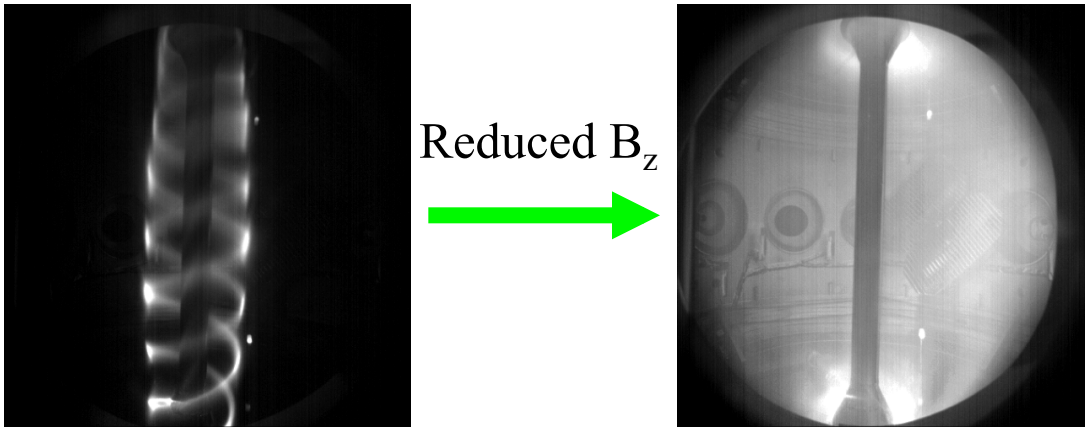
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PEGASUS
Toroidal Experiment

Local Plasma Current Sources + Helical Vacuum Field Give Simple DC Helicity Injection Scheme

- Current is injected into the existing helical magnetic field
- High I_{inj} & modest B $\Rightarrow$ filaments merge into current sheet
- High I_{inj} & low B $\Rightarrow$ current-driven B_θ overwhelms vacuum B_z
  - Relaxation via MHD activity to tokamak-like Taylor state w/ high toroidal current multiplication



Current filaments

Relaxed tokamak

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DC Helicity Injection Startup on PEGASUS Utilizes Localized Washer-Gun Current Sources

- Plasma gun(s) biased relative to anode:
  - Helicity injection rate:

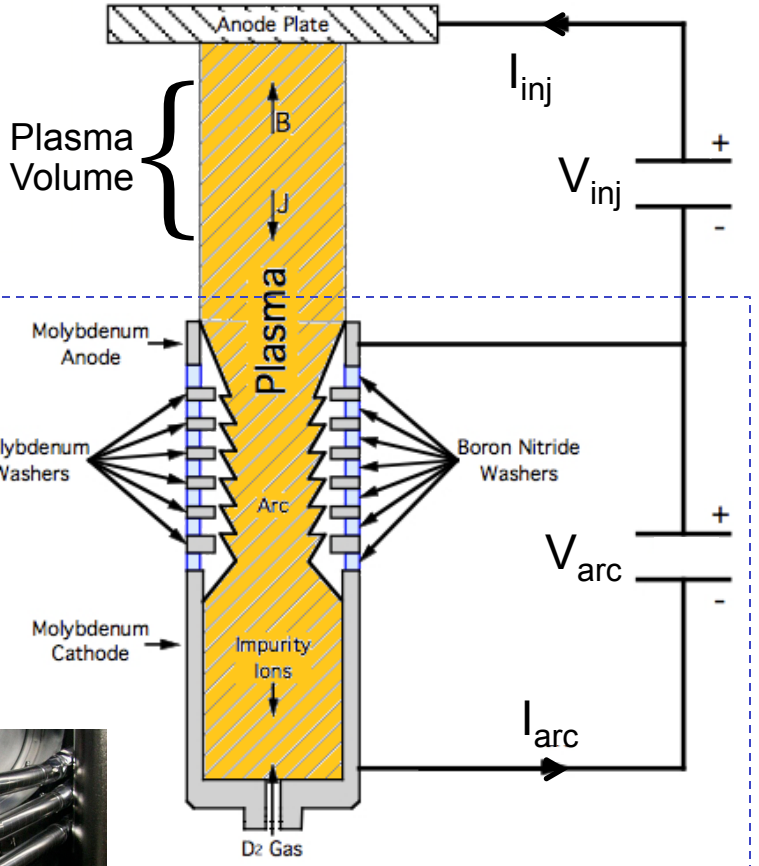
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

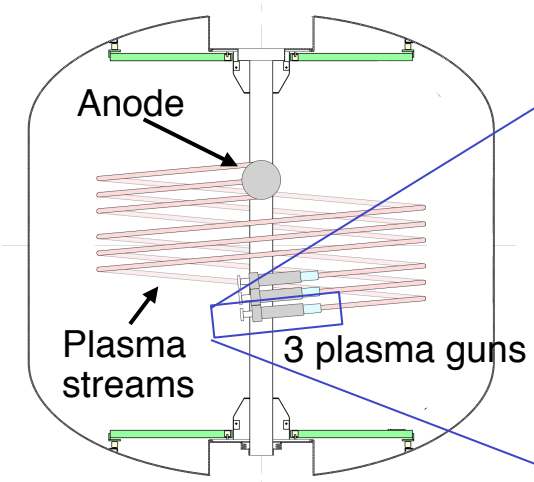
V_{inj} - injector voltage

B_N - normal B field at gun aperture

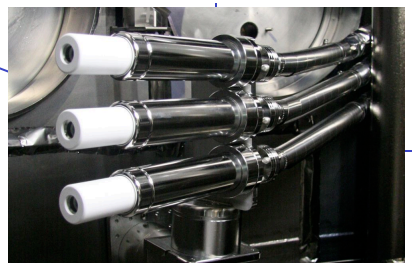
A_{inj} - injector area

Simplified illustration of a plasma gun for helicity injection *(not to scale)*





Midplane Injection



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Taylor Relaxation Criteria Sets the Maximum I_p for a Given Magnetic Geometry

Helicity balance in a tokamak geometry:

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

- *Helicity injection can be expressed as an effective loop voltage*
- I_p limit depends on the scaling of plasma confinement via the η term

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

Taylor relaxation of a force-free equilibrium:

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

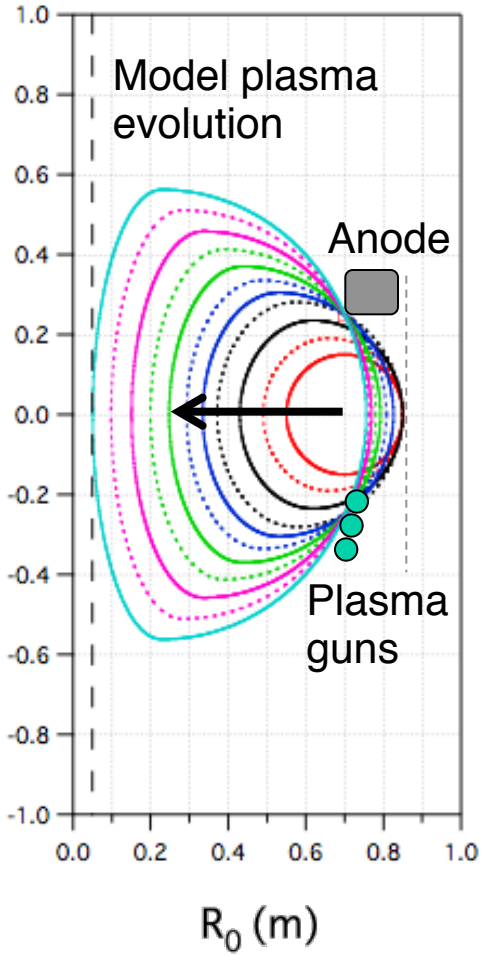
Assumptions:

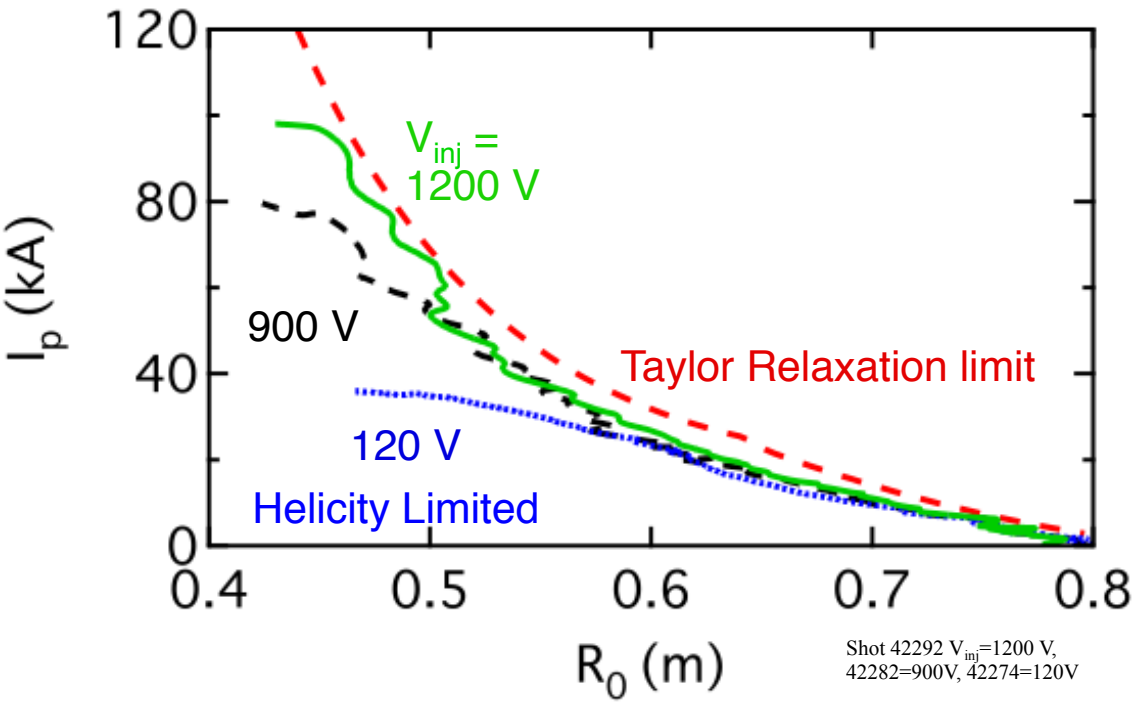
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

A_p Plasma area
C_p Plasma circumference
Ψ_T Plasma toroidal flux
w Edge current channel width

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Achieving the Maximum I_p at the Taylor Limit Requires Sufficient Helicity Injection Input Rate





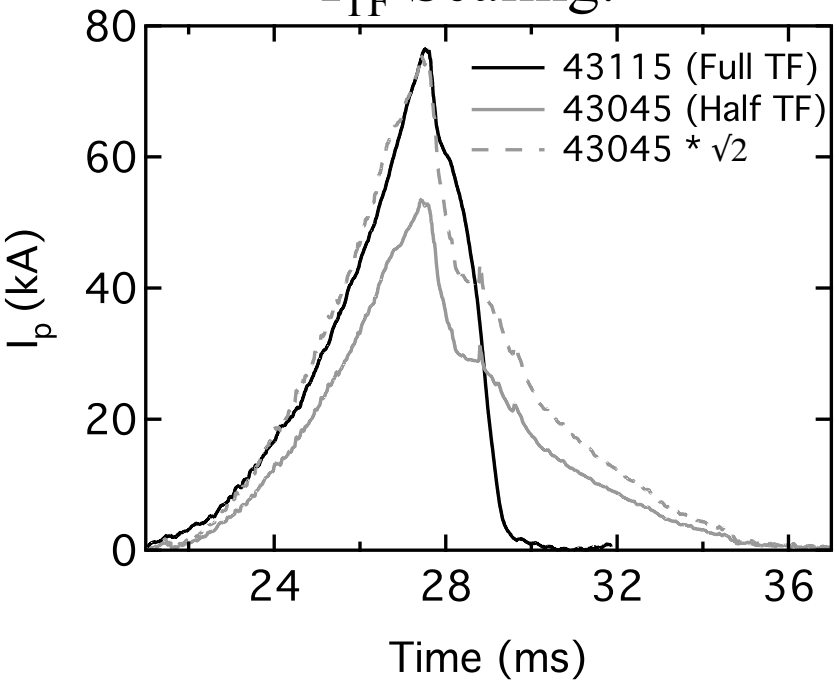
- Helicity input rate, and effective net volt-seconds, increases as V_{inj} increases
- Sufficient net V-sec needed to reach Taylor relaxation limit

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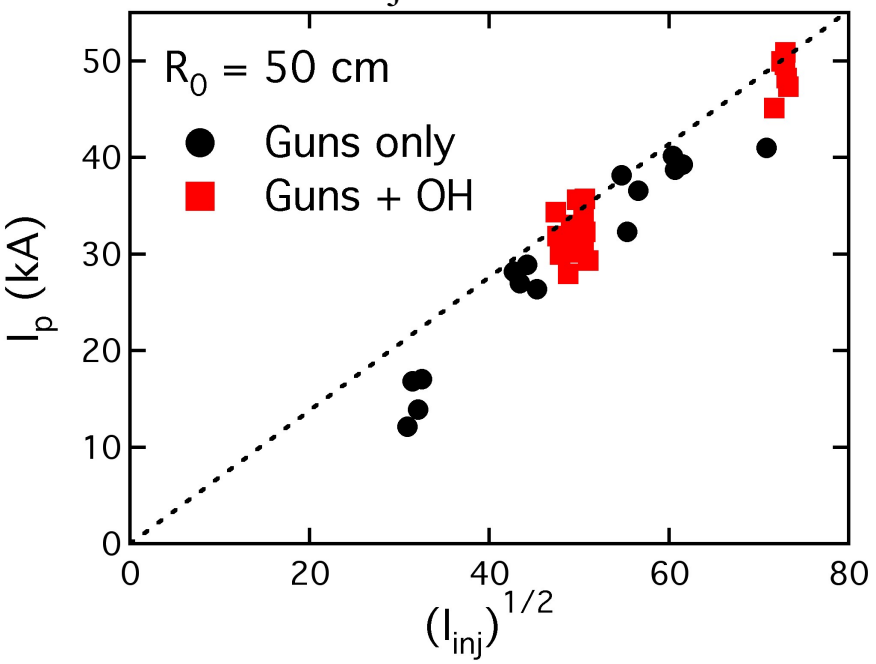
Experiments Confirm Relaxation Limit Scalings with I_{TF} and I_{inj}

- The relaxation limit I_p scales with: $$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$
- Experimental plasma currents appear to follow these scalings:

I_{TF} Scaling:



I_{inj} Scaling:

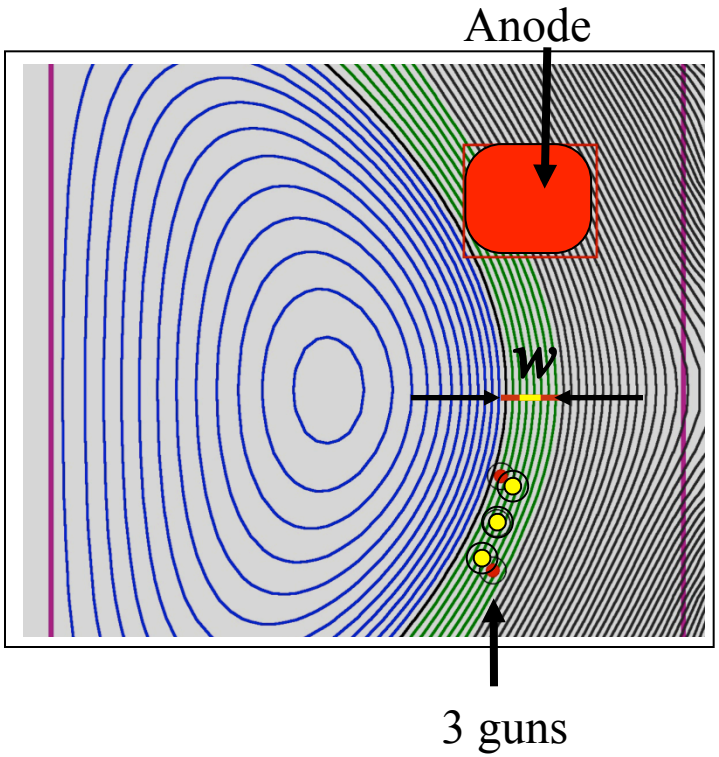


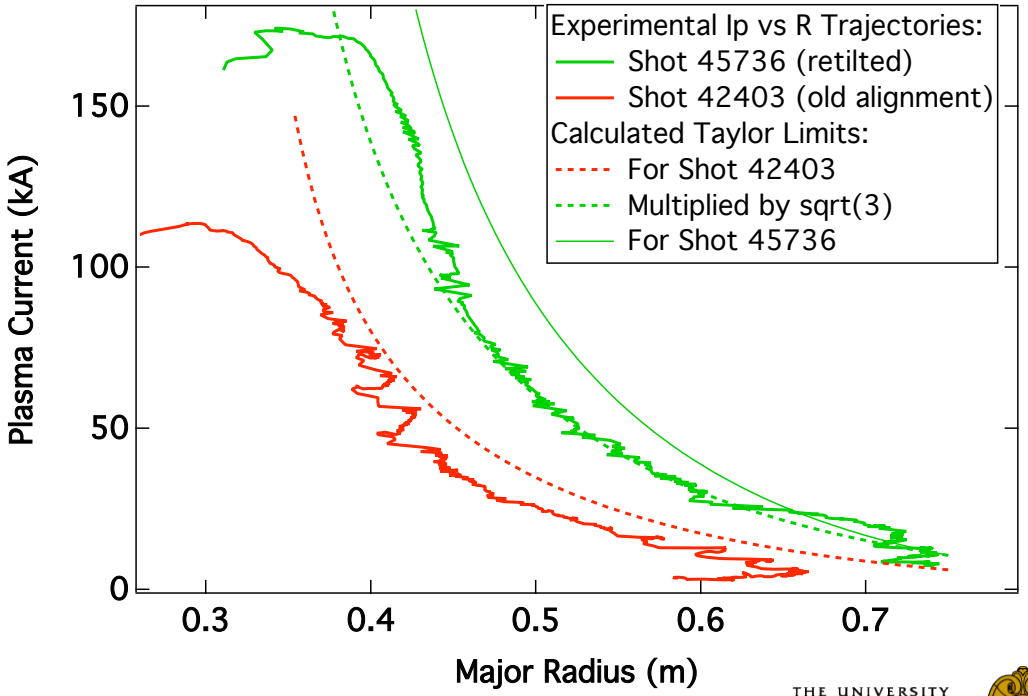
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Gun Array Realigned to Reduce Current Channel Width, Raising $I_{p,max}$

- Changing the tilt of the gun array increased the max I_p by a factor of 1.5-1.7, consistent with a factor-of-3 reduction in *w*

$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$



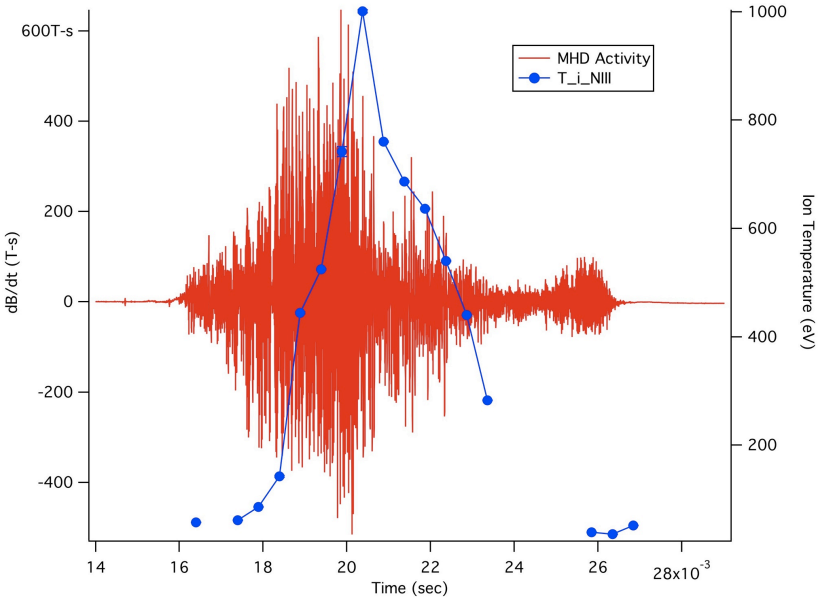


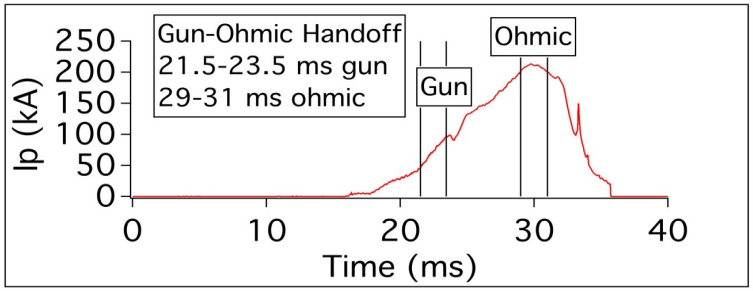
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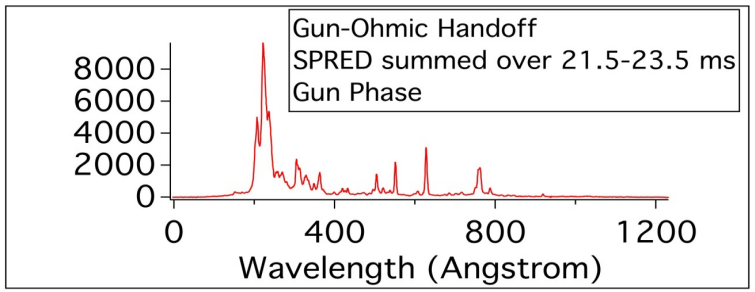
Initial Spectroscopy Measurements Sugest Energetic Ions and Low Impurity Levels

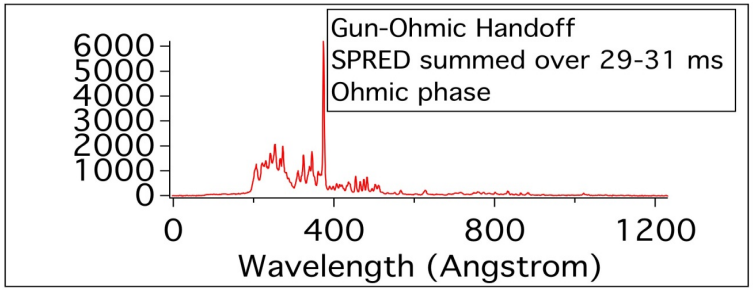
- 1st *estimates* of impurity content via bolometer measures
  - $Z_{eff} \sim 2.2. +/- 0.8$ during injection; ≤ 1.4 after injection
    - Mainly N; $n_e \sim 5 \times 10^{18}$ m^{-3} to 2×10^{19} m^{-3}

- Spectroscopic T_i indicates high ion energies during reconnection





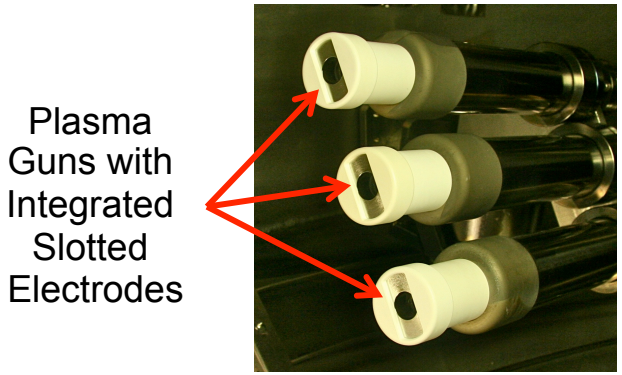


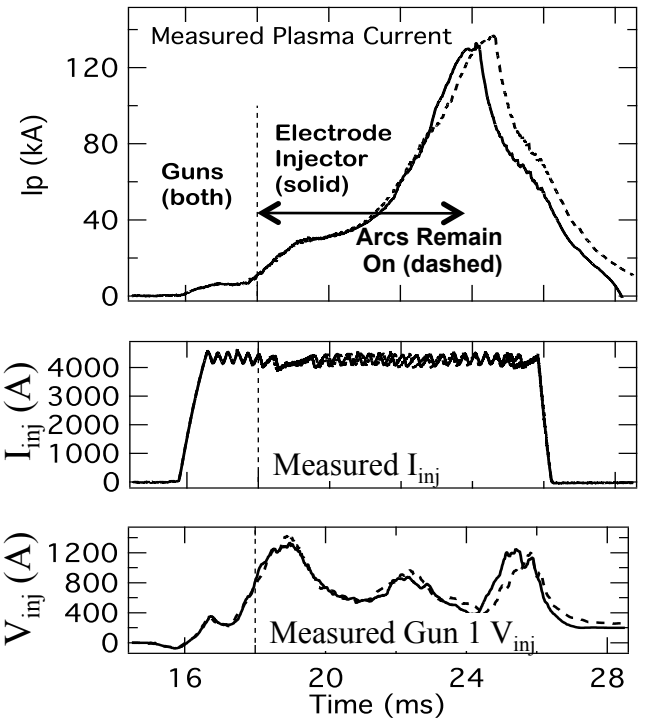


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Active Gun / Passive Electrode Assembly Points to Simpler, Higher I_p Operation

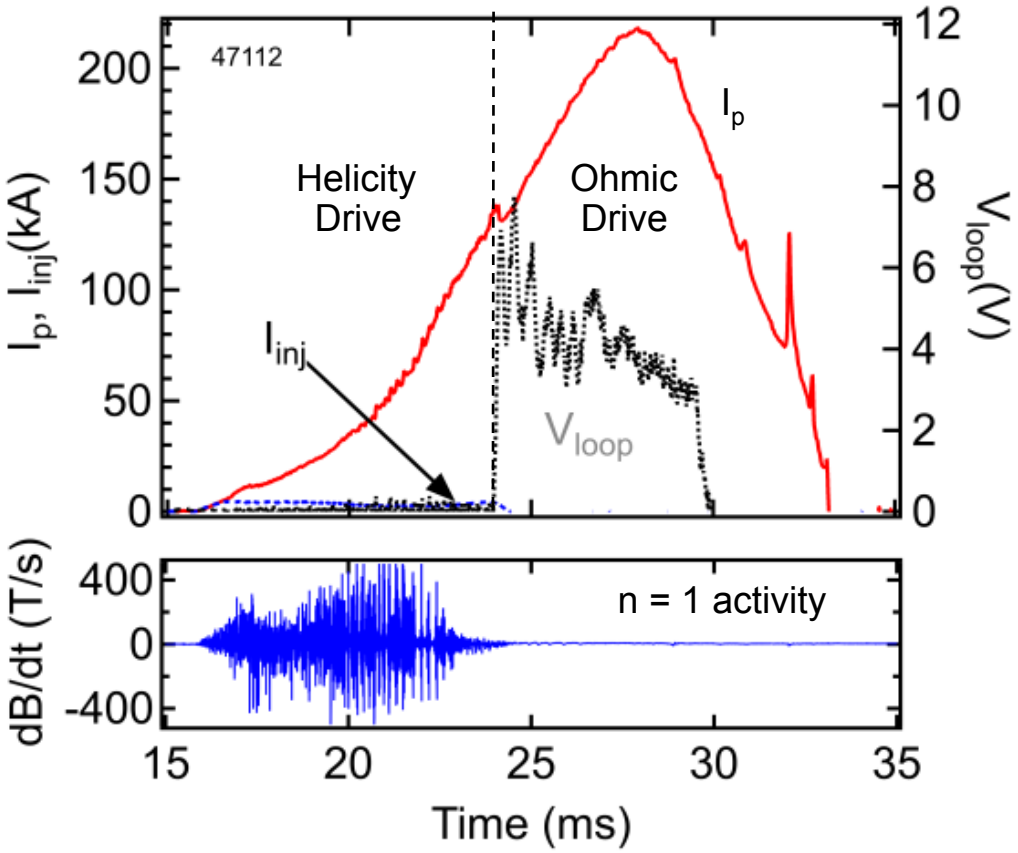
- Potential for much higher I_{inj} without need for larger guns
  - Helicity injection physics = agnostic to source of edge charge carriers
  - Passive electrodes = allow shaping to optimize helicity input *and* Taylor limit
- 2-step process
  - 1. Create initial tokamak-like plasmas with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes fed by charge carriers in tokamak edge region.
- First tests are promising
  - Arc current off after relaxation
  - I_p rise = *same* whether arc current or edge losses provide charge carriers
  - Presently under study…



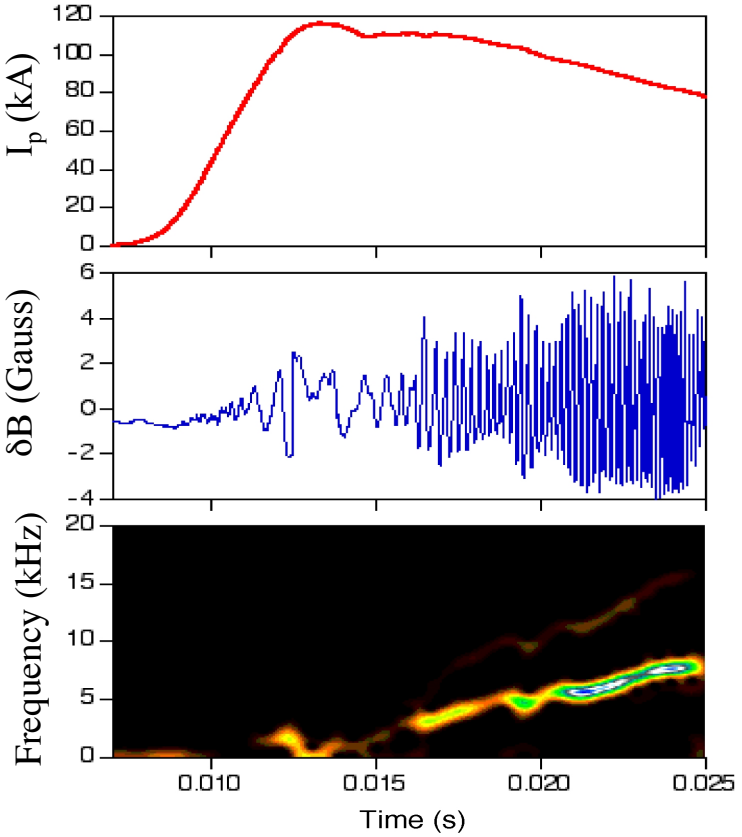


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Ready Handoff to OH; MHD activity strongly reduced after gun bias shutoff



OH-only: I_p rolls over and decays with onset of large n =1 modes

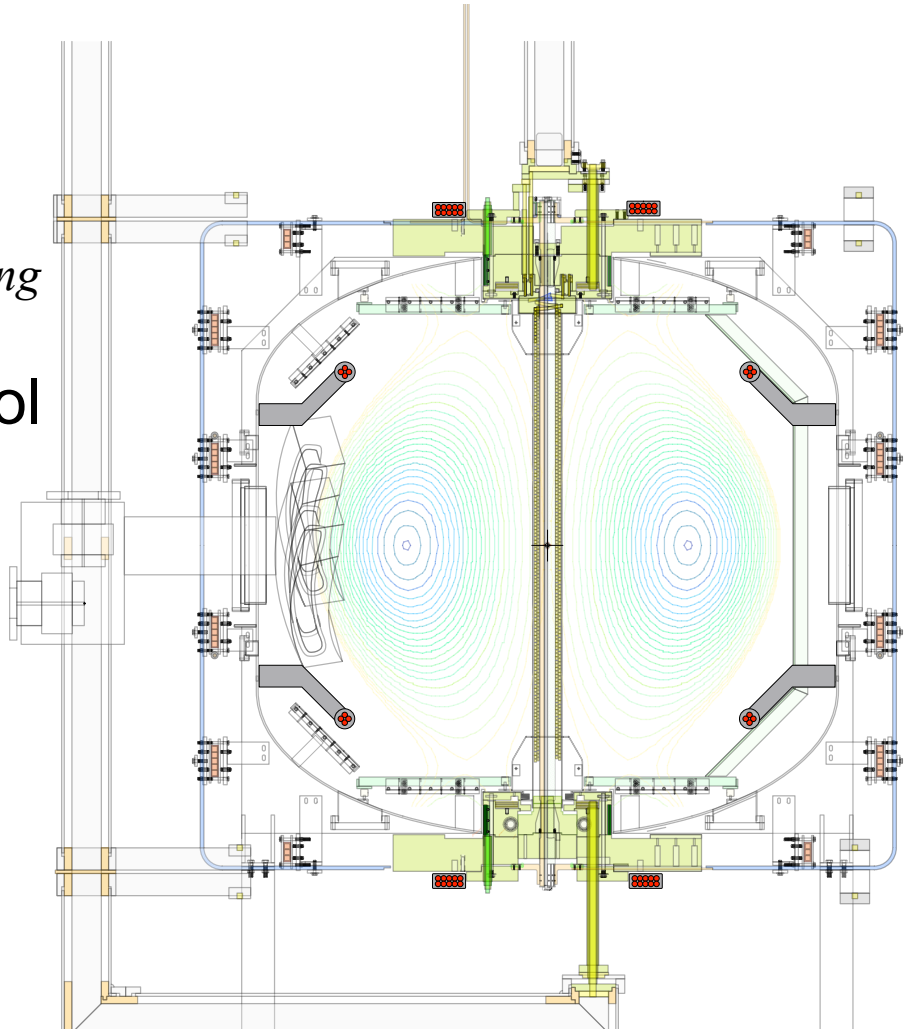


- After helicity injection, OH phase of discharges are *stable* to low-n tearing modes
  - Provides additional source of current and J(r) control

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Medium-Term Upgrades Will Allow Further Tests of Point-Source Helicity Injection

- Power Supplies, Heating
  - New helicity injection power: *3 kV, 15 kA*
  - Double TF current: *Taylor limit increase*
  - Commission HHFW system: *electron heating*
- Expanded PF Coil Set and control
  - Internal coils for radial position control
  - New external divertor coils
  - Implement GA Plasma Control System
- Diagnostic Additions
  - Multipoint Thomson Scattering
  - SXR MHD diagnostics



High-I_p Non-Solenoidal Startup via Point-Source Helicity Injection Looks Promising

- Significant progress with non-solenoidal startup of ST
  - $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup
  - Using understanding of helicity balance and relaxation current limit to guide hardware and operational changes
    - So far, predicted scalings supported
  - Goal $\approx$ 0.3-0.4 MA non-solenoidal I_p to extrapolate to next level/NSTX
    - Outstanding physics questions: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Deploying plasma diagnostics to better understand properties
- Exploration of high I_N, β_t space facilitated by j(r) tools
  - $I_p/I_{TF} > 2$, $I_N > 14$ achieved; extend operation to high I_p, n_e for high β_t
- Holds Promise as a Scalable Non-Inductive Startup Technique
  - Simpler injection system using plasma gun – passive electrode combination looks feasible