Plasma Startup via Local Helicity Injection in Pegasus

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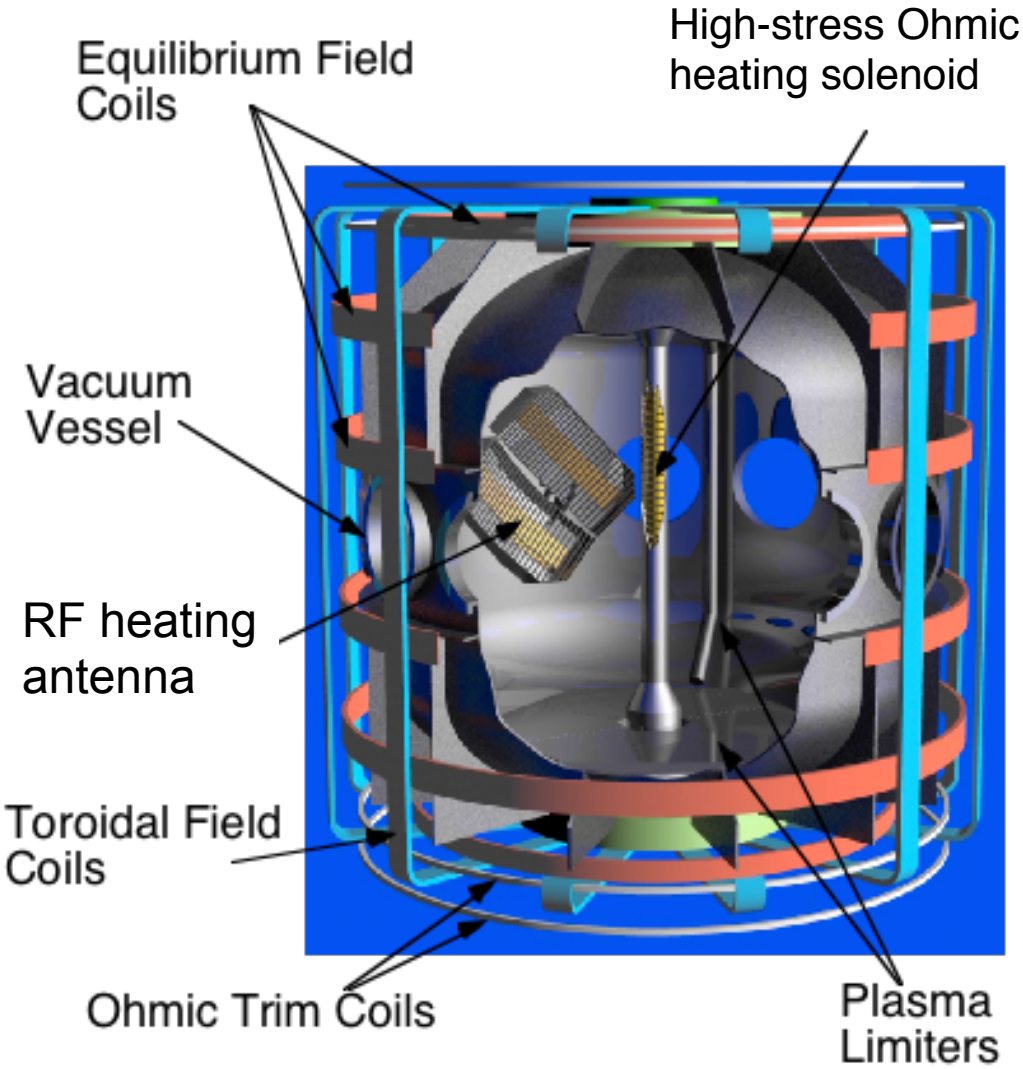
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PEGASUS Toroidal Experiment

ABSTRACT

Magnetic helicity injection from localized current sources at the outboard plasma edge and poloidal field induction produced plasma currents $I_p \leq 0.17$ MA using ~4 kA injected current I_{inj}, consistent with a model invoking helicity balance and Taylor relaxation. Varying the edge current density via source realignment raised the attainable I_p, as expected. A double-layer sheath describes the impedance of the current injectors, setting the helicity injection rate for a given I_{inj}. This suggests the helicity input and discharge evolution can be manipulated by the edge density. MHD activity during plasma growth correlates with rapid equilibrium shifts and current redistribution into the plasma interior. Impurity ion spectroscopy indicates strong heating during helicity drive. Plasmas can also be smoothly driven through the growth stage using passive, gas-fueled electrodes as the helicity sources, after initial tokamak formation with the active current sources. Such electrodes hold promise for optimization of both the Taylor limit that sets the maximum I_p and the achievable helicity input rates needed to attain it. Developing a fully predictive model of this startup technique will allow application to next-step fusion experiments. **Work supported by US DOE Grant DE-FG02-96ER54375**

PEGASUS is a Compact Ultralow-A ST



Experimental Parameters

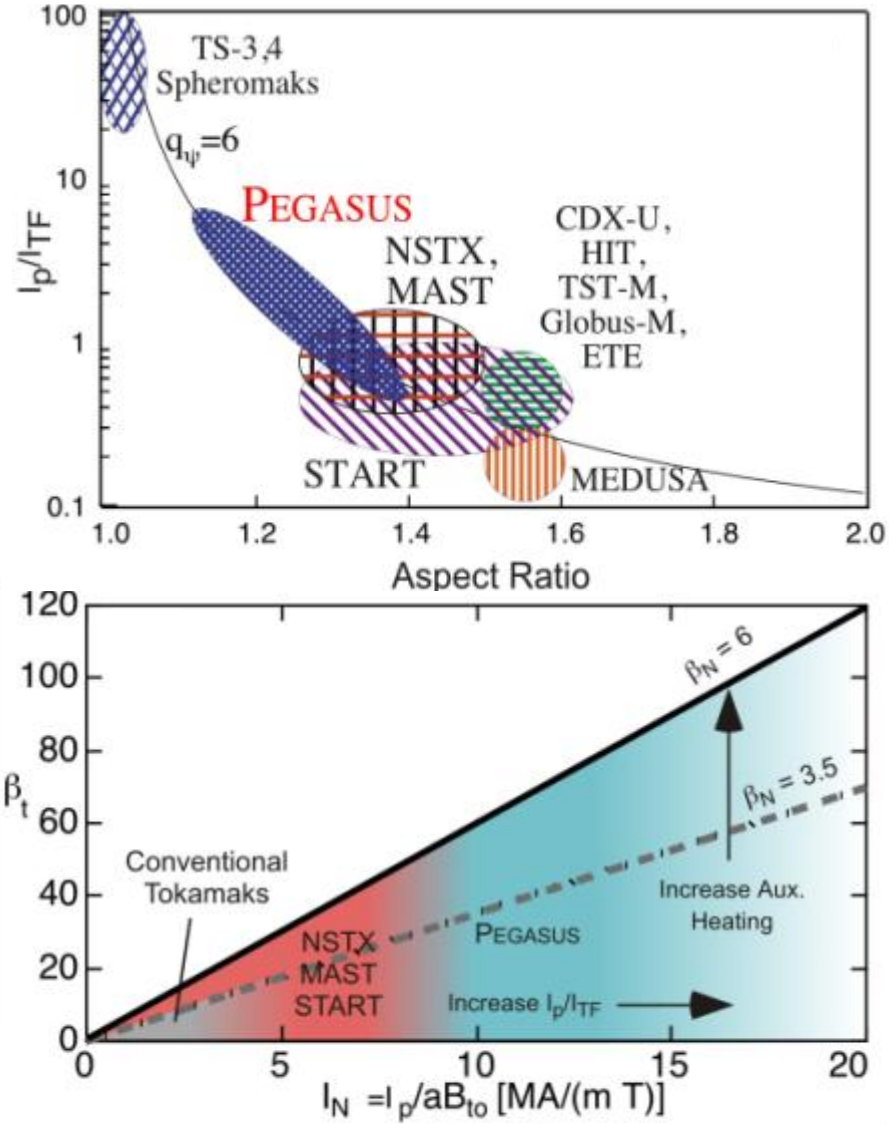
Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.0
τ_{shot} (s)	≤ 0.025
β_T (%)	≤ 25
P_{HHFW} (MW)	0.2



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PEGASUS Mission: Physics of Low A → 1

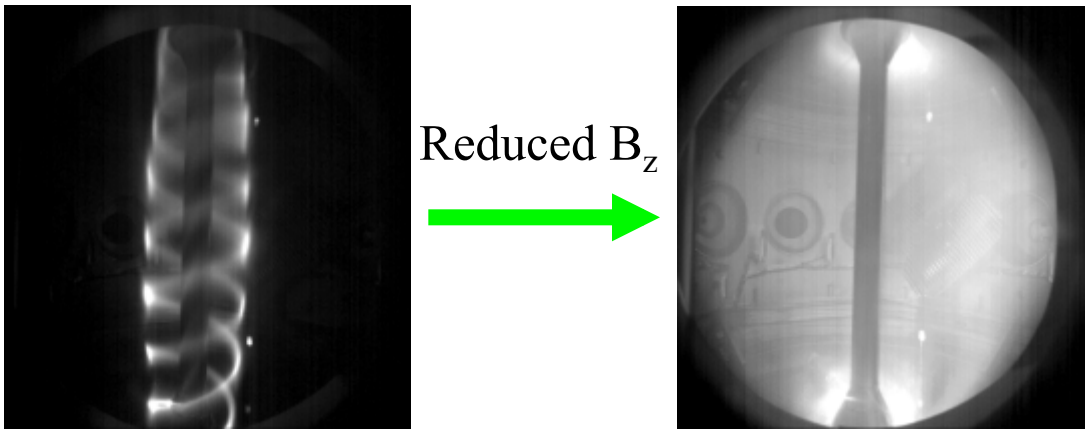
- University-scale, Low-A ST
  - $R_0 \leq 0.45$ m, a ~ 0.40 m
- Physics of High I_p/I_{TF}
  - Expand operating space of the ST
  - Study high β_T plasmas as A→1
- Non-solenoidal startup
  - Point-source helicity injection
  - Helicity injection discharges couple to other current drive methods
- Peeling-mode studies
  - Experimental tests of peeling-ballooning theory (ELM, ITER)



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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

- Technical attractiveness: can remove sources and anode after startup

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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:

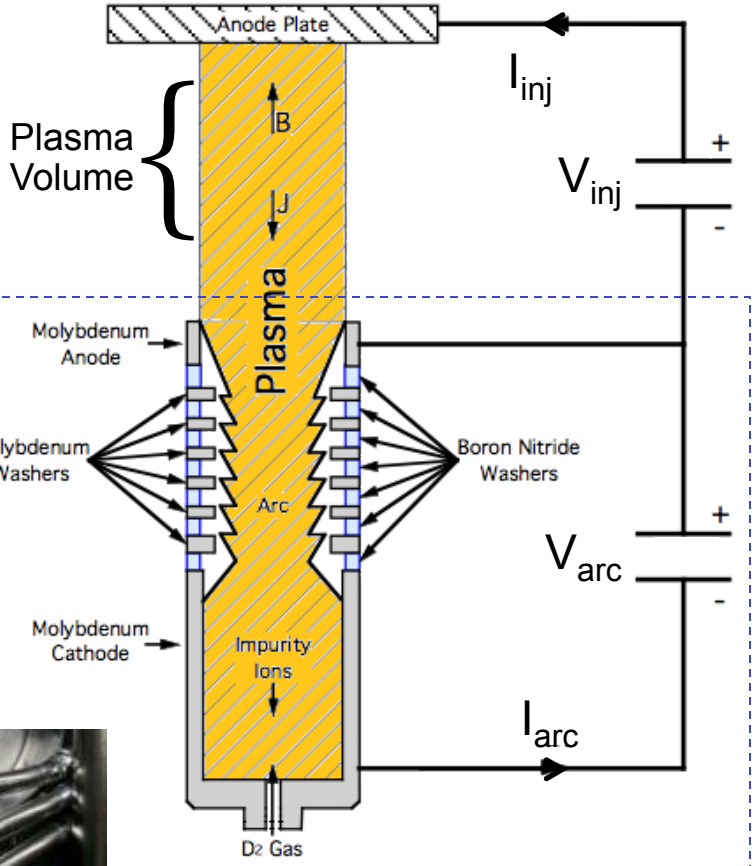
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

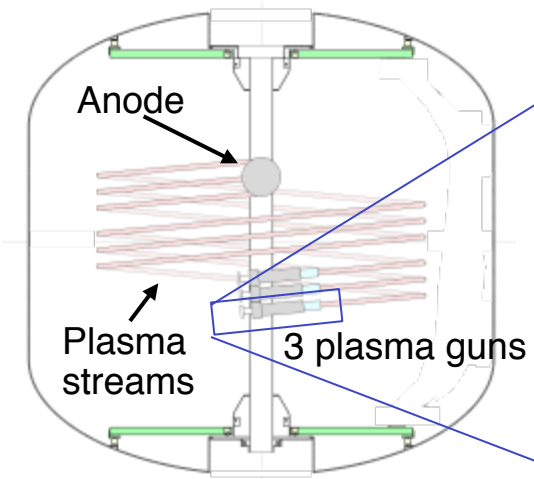
V_{inj} - injector voltage

B_N - normal B field at gun aperture

A_{inj} - injector area

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





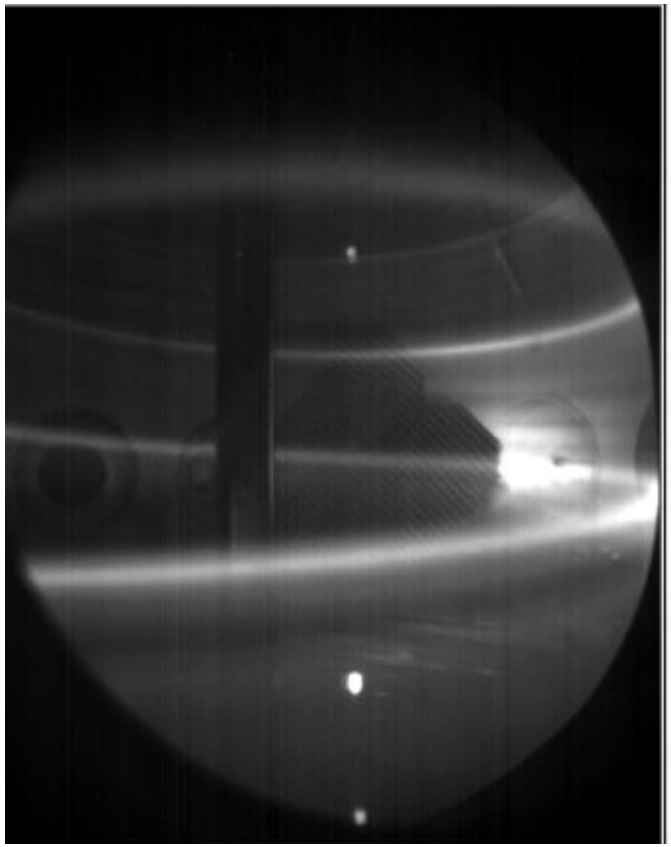
Midplane Injection



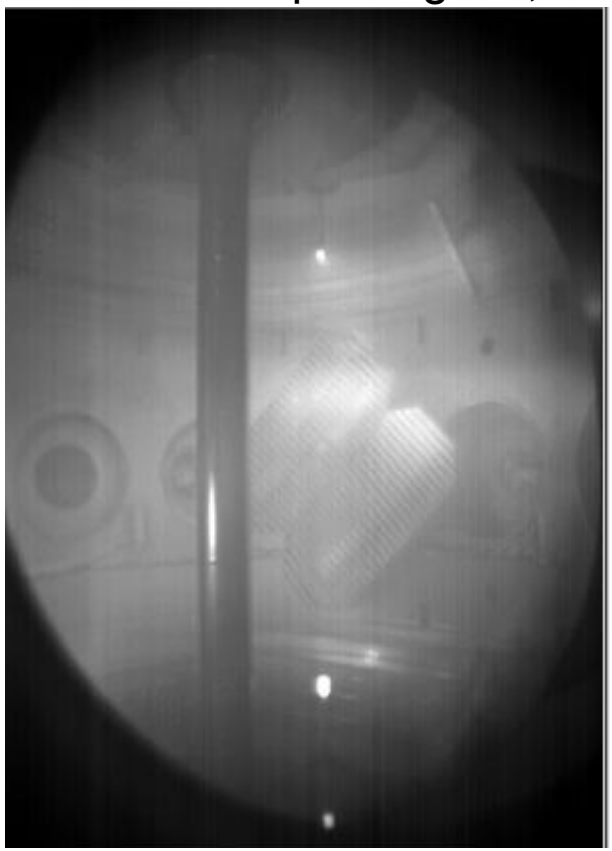
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Evolution of midplane-gun-driven plasma

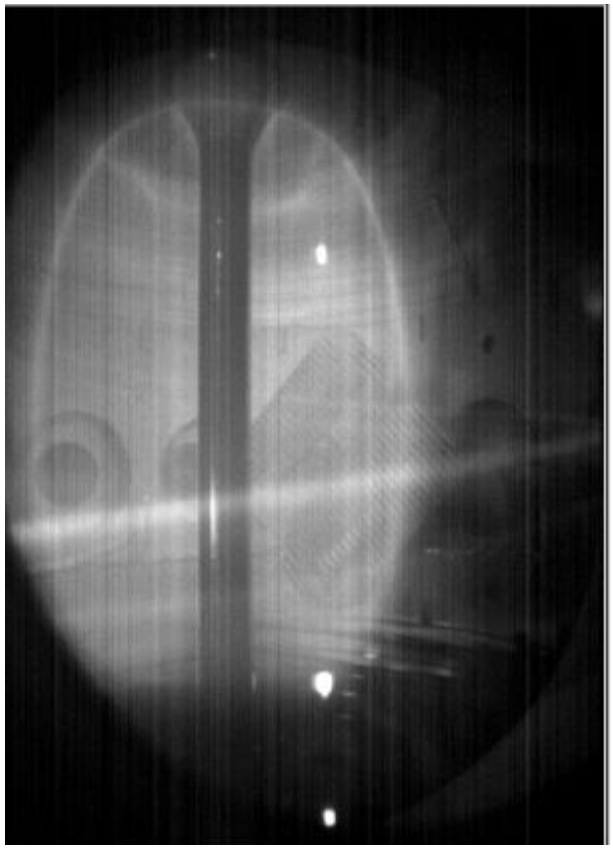
PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



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

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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:

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

Assumptions:

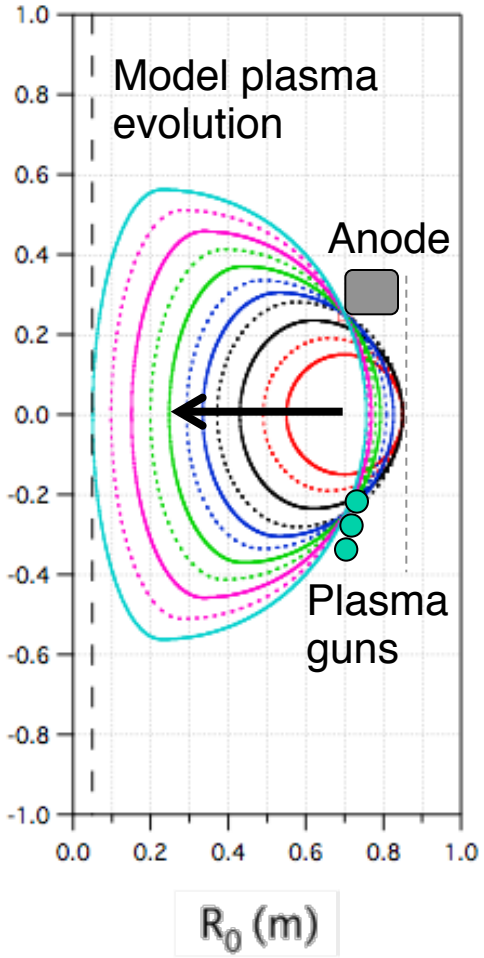
- Driven edge current mixes uniformly in SOL
- Edge fields average to tokamak-like structure

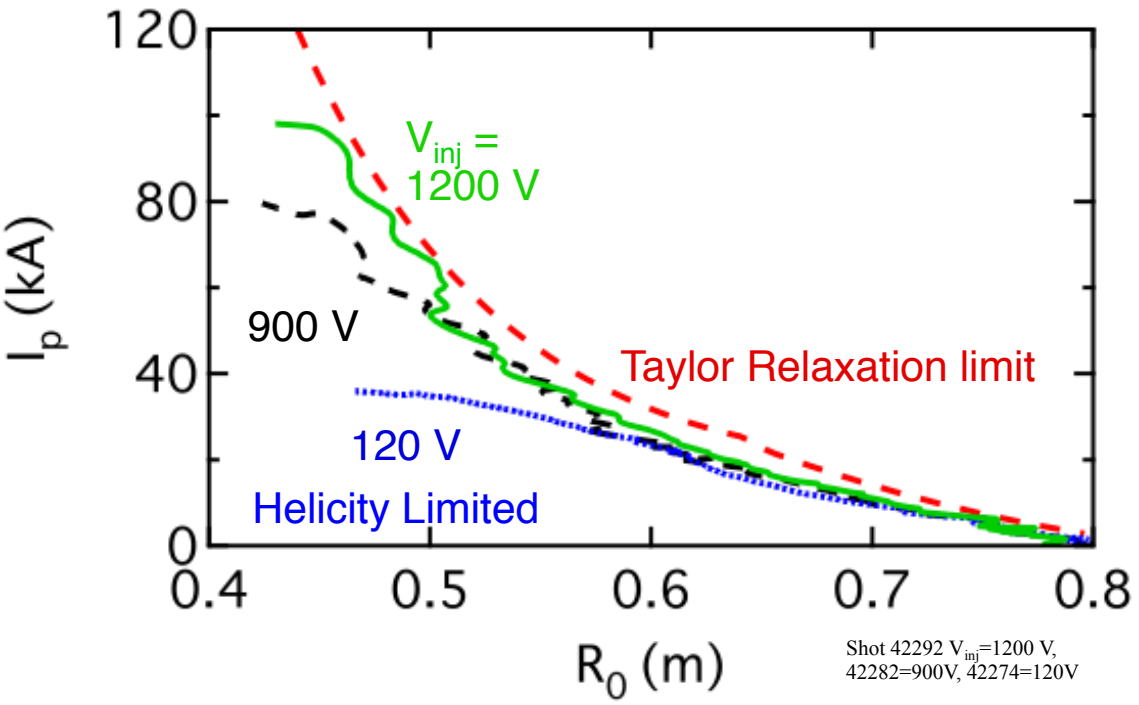
A_p Plasma area
C_p Plasma circumference
Ψ_T Plasma toroidal flux
w Edge current channel width

Ref: Battaglia et al., Nucl. Fus. 51, 073029 (2011)

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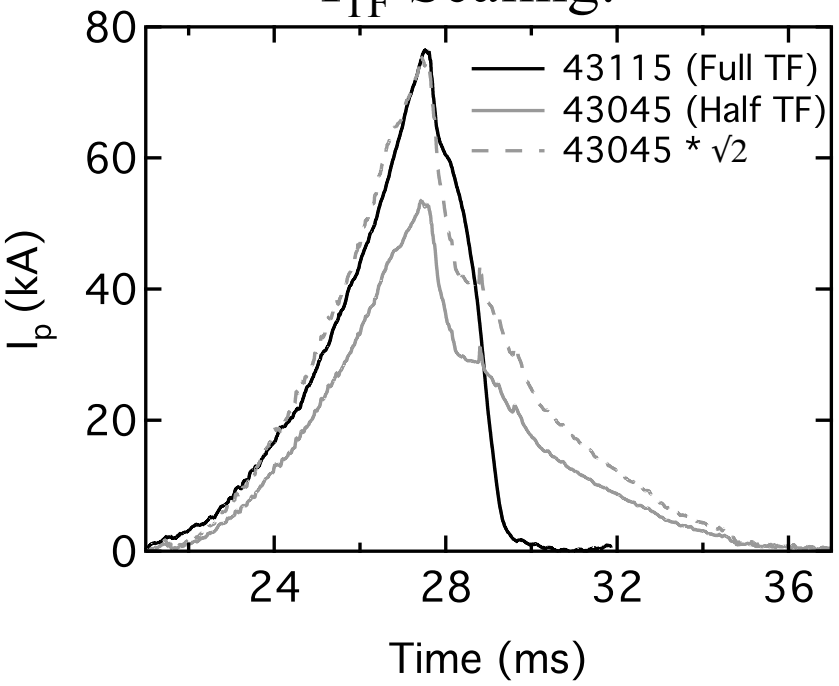
Experiments Confirm Relaxation Limit Scalings with I_{TF} and I_{inj}

- The relaxation limit I_p scales with:

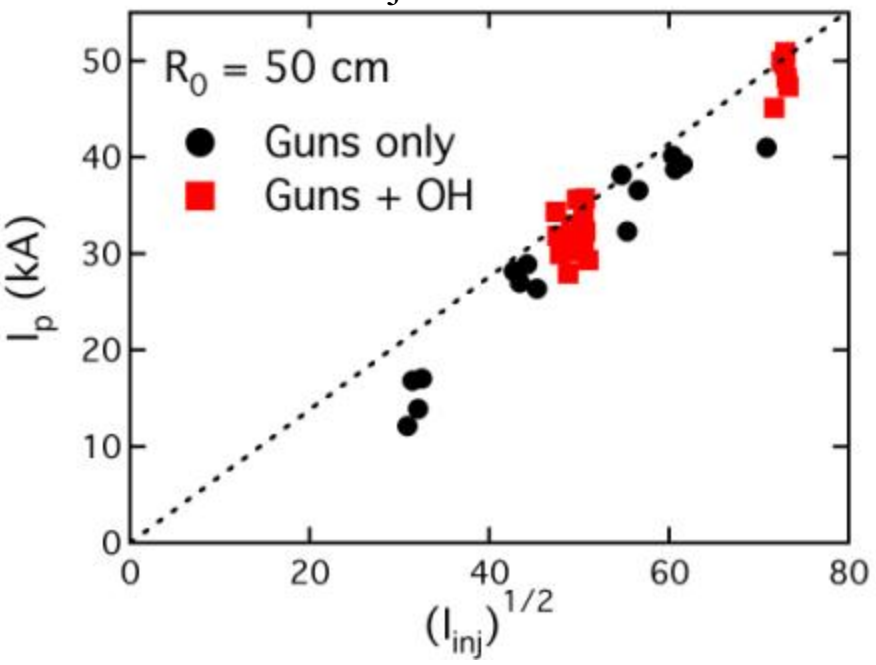
$$I_p \propto \left[\frac{I_{TF} I_{inj}}{w}\right]^{1/2}$$

- Experimental plasma current limits follow these scalings:

I_{TF} Scaling:



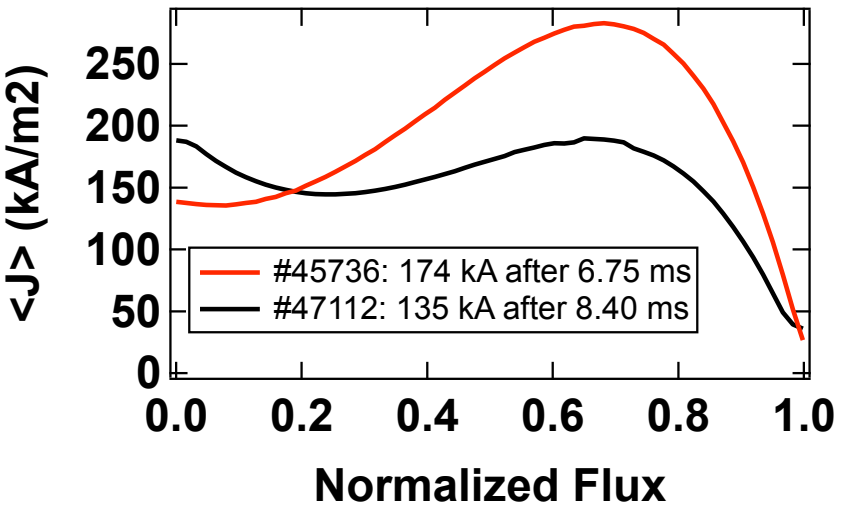
I_{inj} Scaling:

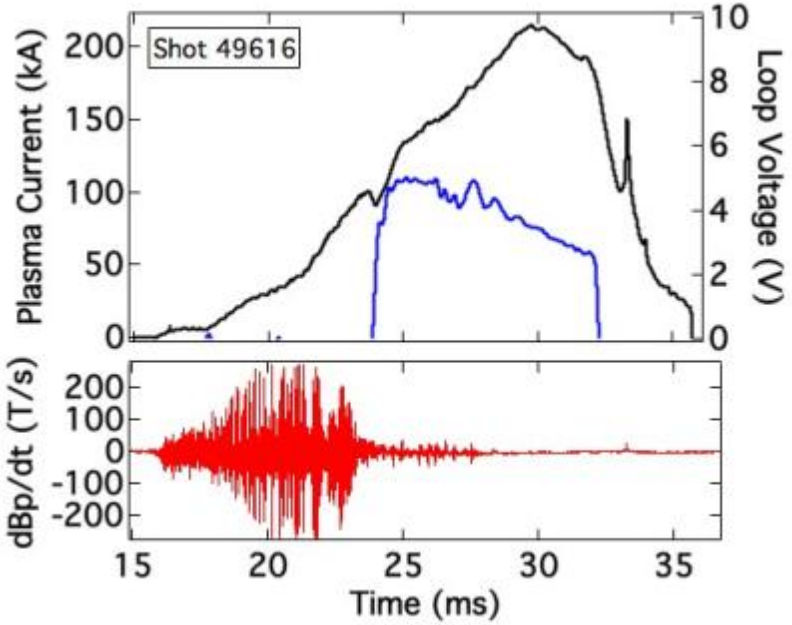


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Slowly-evolving Gun-driven Plasmas Hand Off Most Efficiently to Ohmic Drive

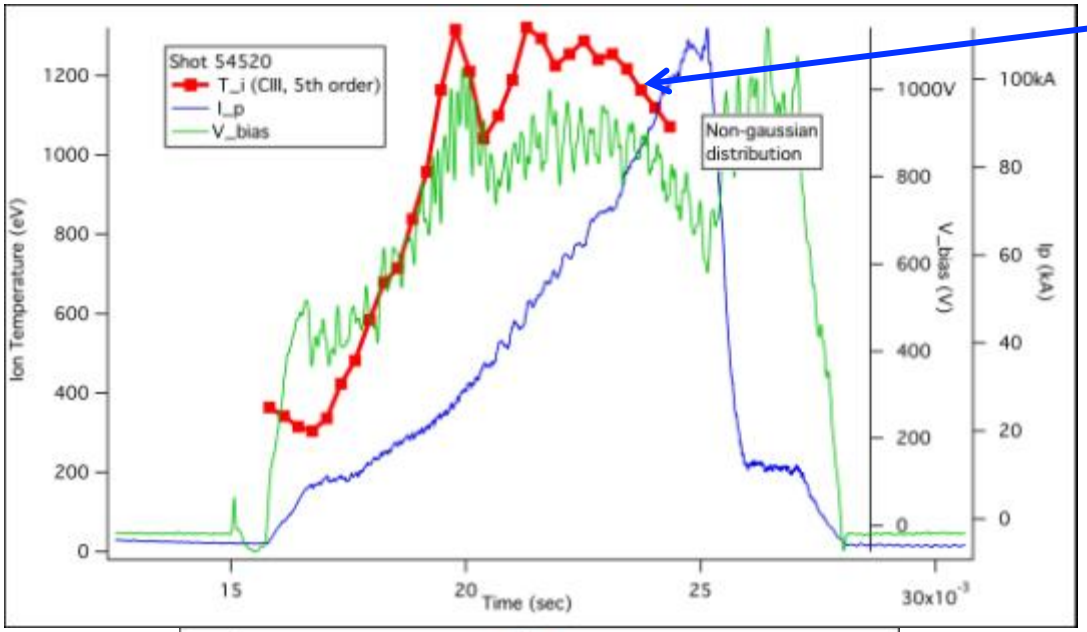
- Poloidal flux generated by helicity injection is equivalent to that generated by Ohmic Drive
  - $I_{total} = I_{HI} + I_{OH}$
- Excessive skin current => poor coupling to OH drive
- Slowly evolving: ~ flat j(r) (black)
  - Smooth handoff to Ohmic inductive drive (j(R) profiles from external-only equilibrium reconstructions; $l_i < 0.3$)
- Rapidly evolving: ~ hollow, strong skin j(r) (red)
  - Does not hand off efficiently to Ohmic drive

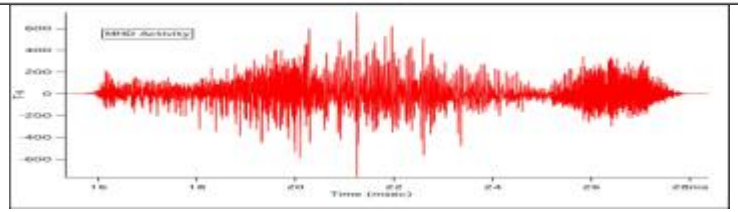




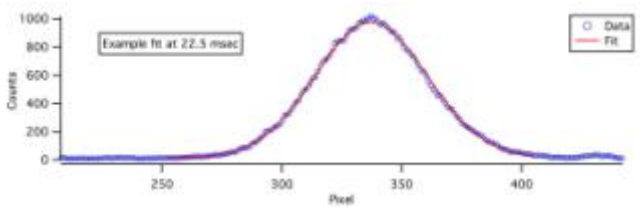
Initial Spectroscopy Measurements Show Energetic Ions

- Spectroscopic T_i suggest high ion energies during reconnection period

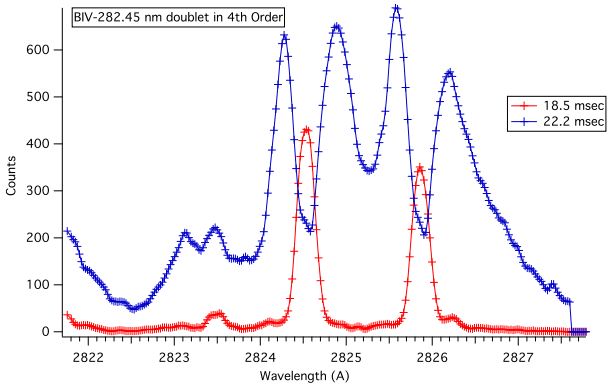




Doppler T_i from radial view:



Complex multi-line structures from tangential view:



- However, situation is much more complex if viewed toroidally
  - Need improved time-resolution and spatial scans

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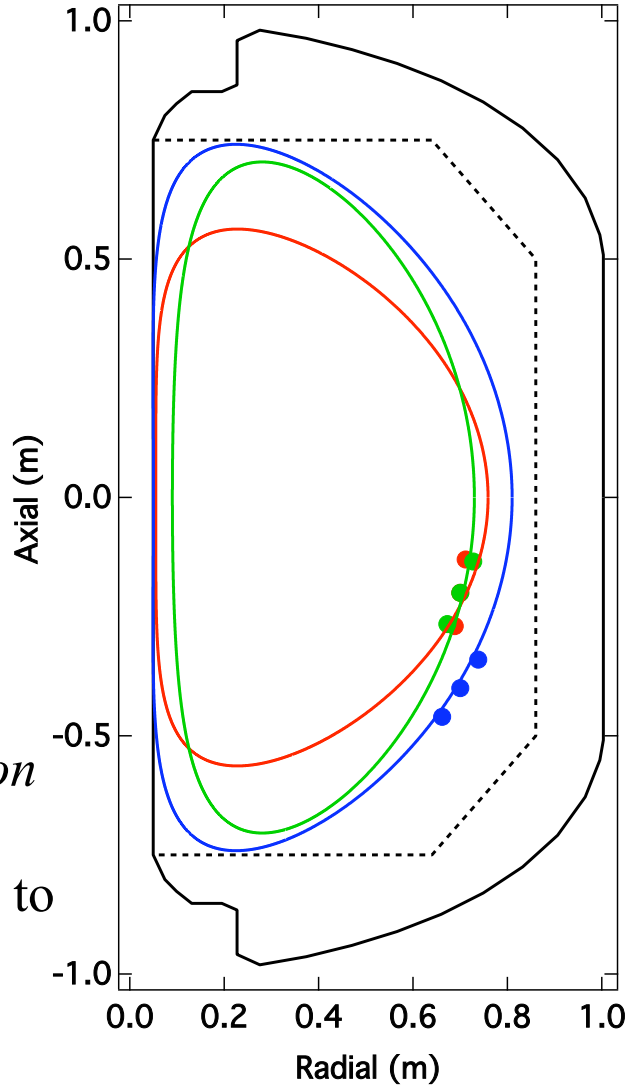
Several Issues Being Addressed for a Predictive Model

- Extension to higher current, longer pulse
  - Verify limit scalings
  - Discharge evolution for long growth phase
  - Test confinement properties, especially $T_e(r,t)$
    - Helicity dissipation scaling model
- Optimal gun-electrode configuration
- Increased helicity injection rate
  - Test regime where helicity drive dominates PF induction for growth
  - Active guns vs. passive electrode approach for long-pulse growth
- Injected current source impedance model
  - What sets helicity injection rate?
- Edge j(r) measurements and $\lambda(\psi,t)$
  - Physics of ultimate relaxation limits
  - Current transport: MHD behavior
- Impurity assessment and control

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Gun-Electrode Geometry: PF Induction, Plasma Size, and Null Formation

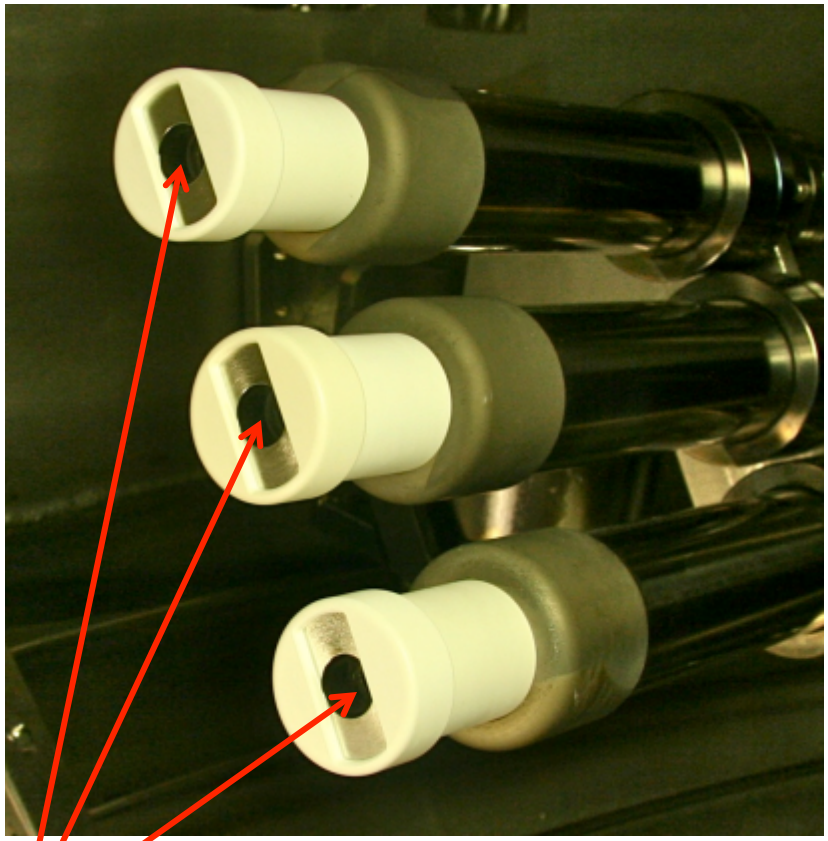
- Original: array was nearly vertical (red):
  - J_{edge} width *w* scaled with # of guns
  - Maximum I_p = 0.11 MA.
- Aligned gun array tilt (green):
  - Maximum I_p = 0.17 MA.
  - 3-fold reduction in *w*., consistent with changing the projected width at midplane.
- Maximize plasma size: array moved further away from midplane (blue):
  - Maximum I_p ~ 0.13 MA
  - Larger startup plasma = *reduced PF induction*
  - *Poorer poloidal field null* formed by current streams = more difficult to induce relaxation to tokamak state
- Tight gun-anode geometry preferred



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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 either more plasma guns or larger guns.
- Helicity injection physics is agnostic to the exact source of the edge charge carriers.
- Passive electrodes allow arbitrary shaping:
  - Can optimize both helicity input (large cross-sectional area) *and* the Taylor limit on I_p (narrow in radial direction)

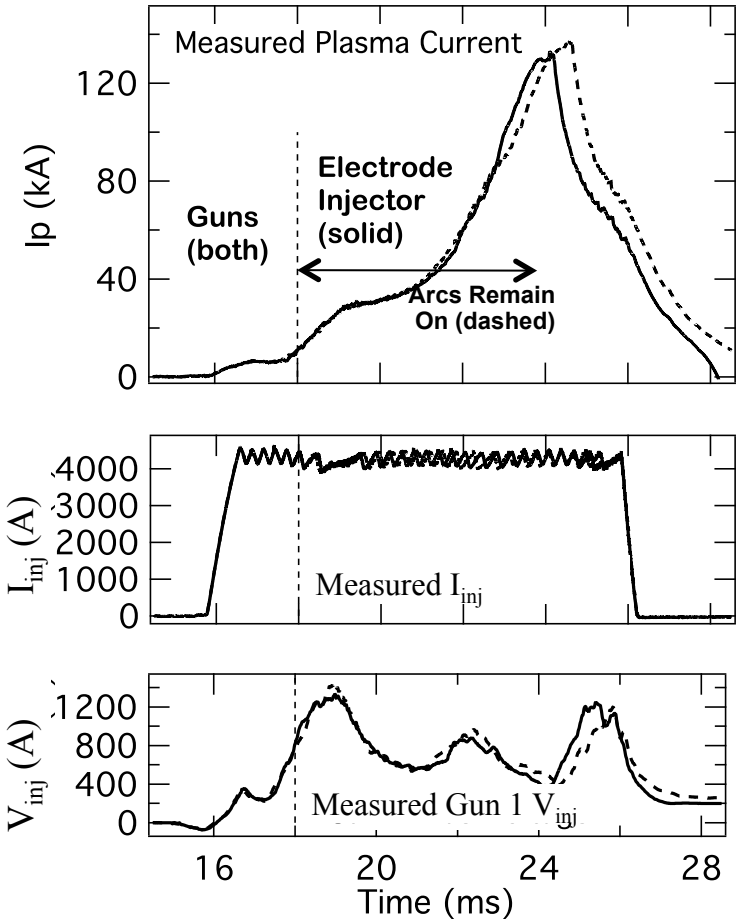


Plasma Guns with Integrated Slotted Electrodes

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Initial Tests of Gun/Electrode Helicity Injection System Are Promising

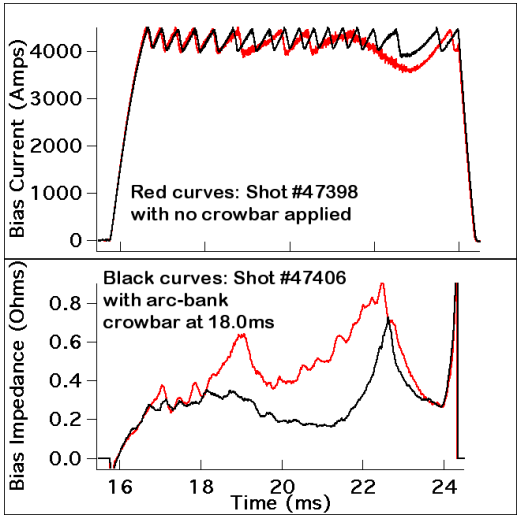
- Operations use two steps:
  - 1. Form initial tokamak-like state with minimal active arc gun
  - 2. Grow to much larger I_p with passive electrodes fed by electrode charge carriers induced and moderated by tokamak edge plasma.
- First tests were promising
  - Arc current off after relaxation and formation of tokamak-like state
  - I_p rise is virtually the *same,* whether arc discharge or passive electrode provide the charge carriers

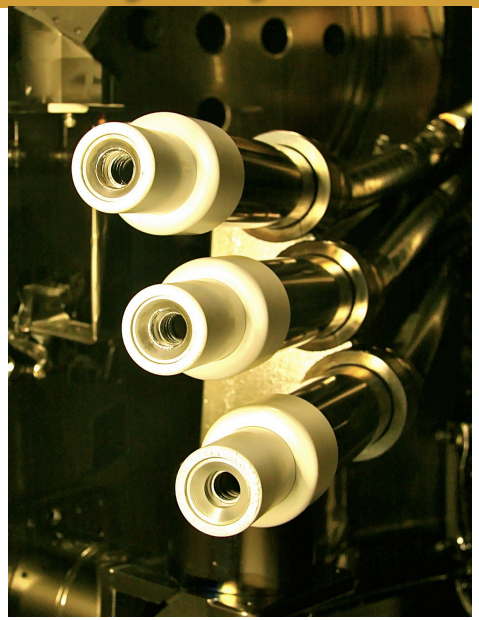


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Gun/electrode geometry evolved to increase helicity injection

- Demonstrated transition from active gun drive to passive electrode drive
- Narrowed electrode widths to increase the Taylor limit
  - Increased area => increased helicity injection
- Performance limited by plasma-material interactions at the Mo/BN interface

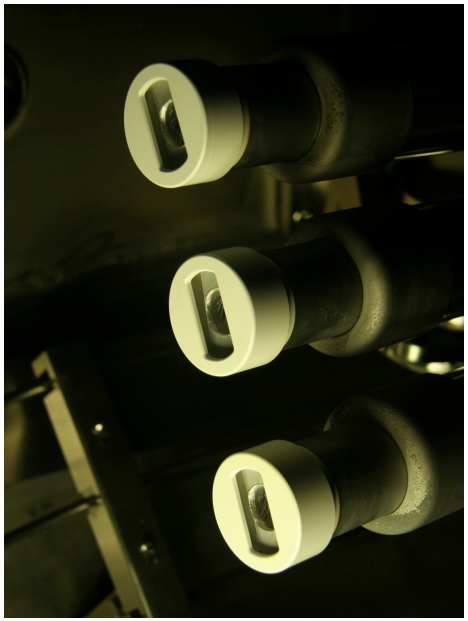




1. Circular beveled Mo faces

2. "Slot" Mo faces with BN caps



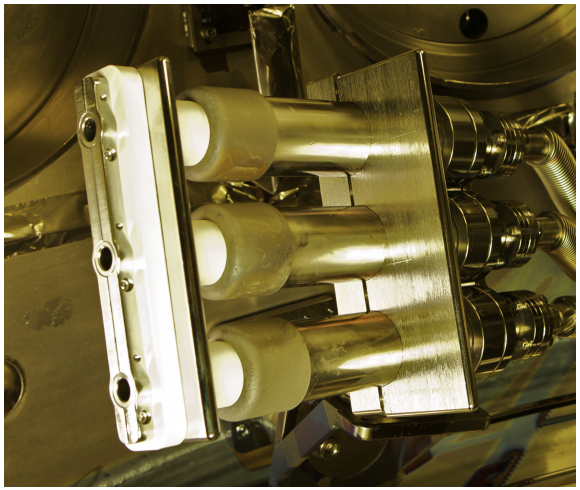


3. "Slot" caps with BN raised ~1 cm Above Mo faces

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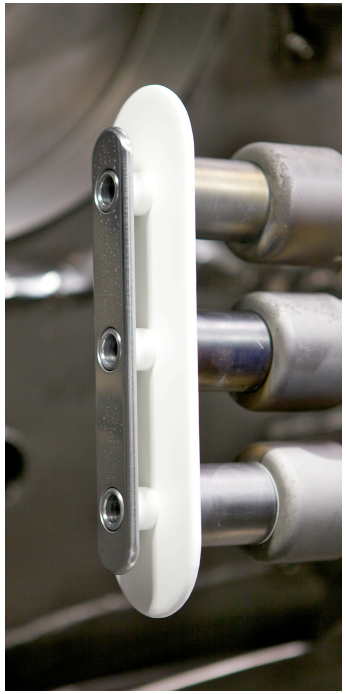
Combining active plasma guns with passive electrodes to increase drive

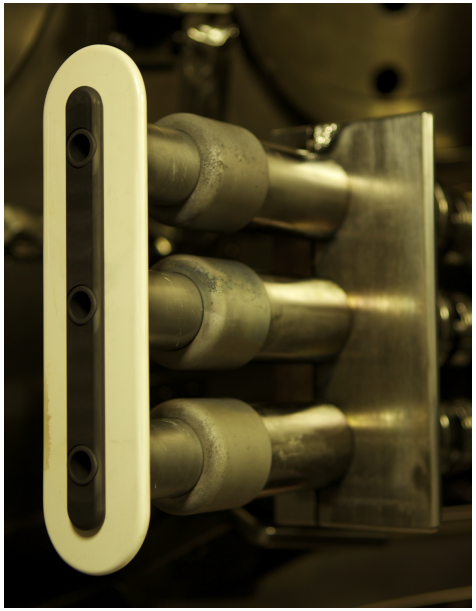
- Increased electrode area to increase helicity injection
  - Narrow radial width for high Taylor limit on I_p
- Overall reduction in impurity content
  - via VB, SPRED, bolometers
  - Analysis for 2010 APS-DPP indicated $Z_{eff} \sim 2\text{-}3$
- Present system appears promising for high-power, high-current operations



4. Two-piece Mo electrode with ***local scraper limiters***

5. One-piece C electrode with local limiters:



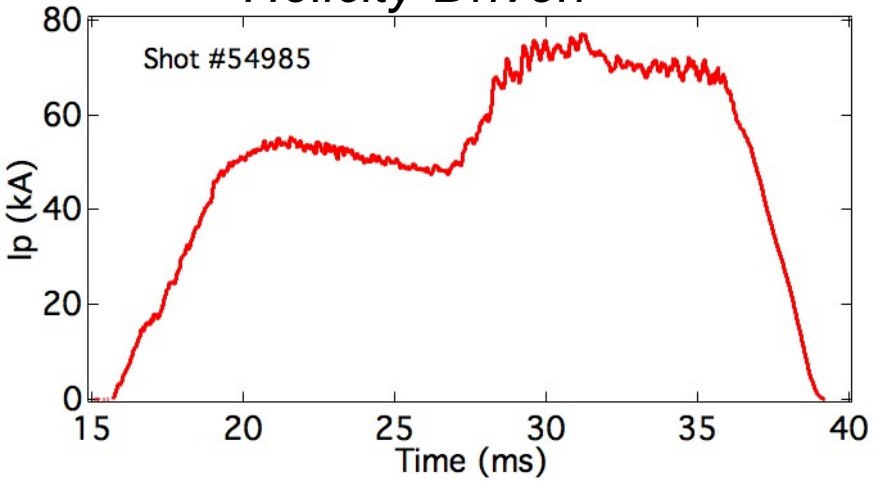


Present system:
Mo electrode raised off the BN limiter

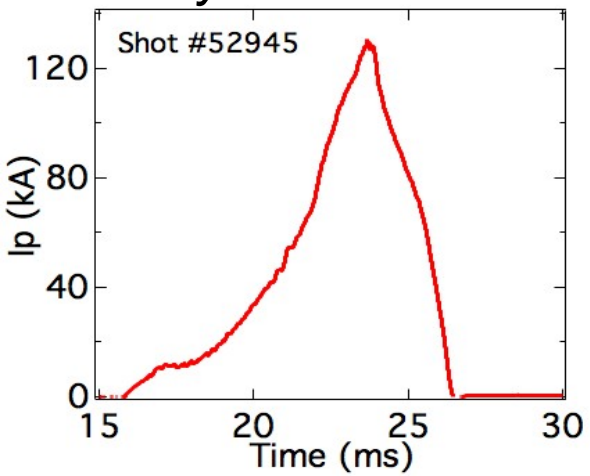
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Pegasus discharges formed and sustained by helicity injection alone

Helicity-Driven



Helicity & PF-Induction

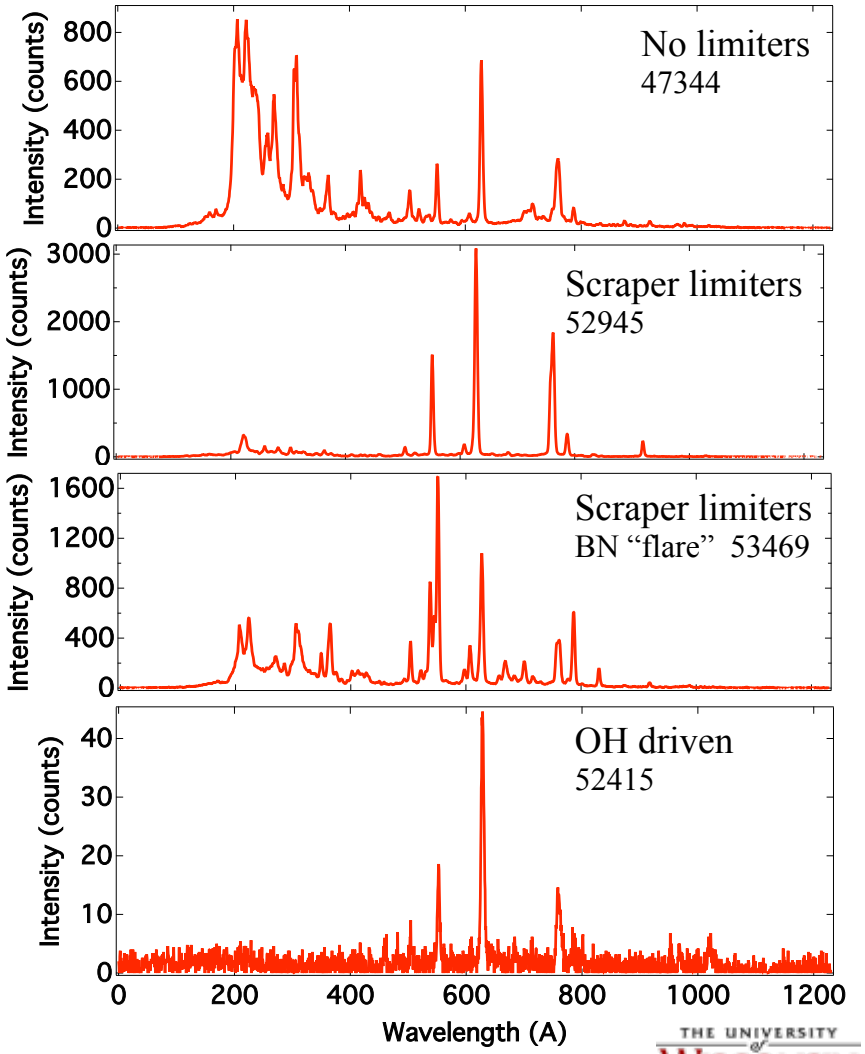


- Demonstrates (using pre-programmed control) there is no physical limit on driving plasmas with helicity injection:
  - Studies at low I_p can quantify the helicity injection needed for high I_p
- Higher current operation will require:
  - Active radial position control, to keep plasma connected to injector
  - Power supply upgrades and injector modification
- Position control and injector upgrades are imminent

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Local Limiters Reduce N to Negligible Levels in Well-behaved Injection Cases

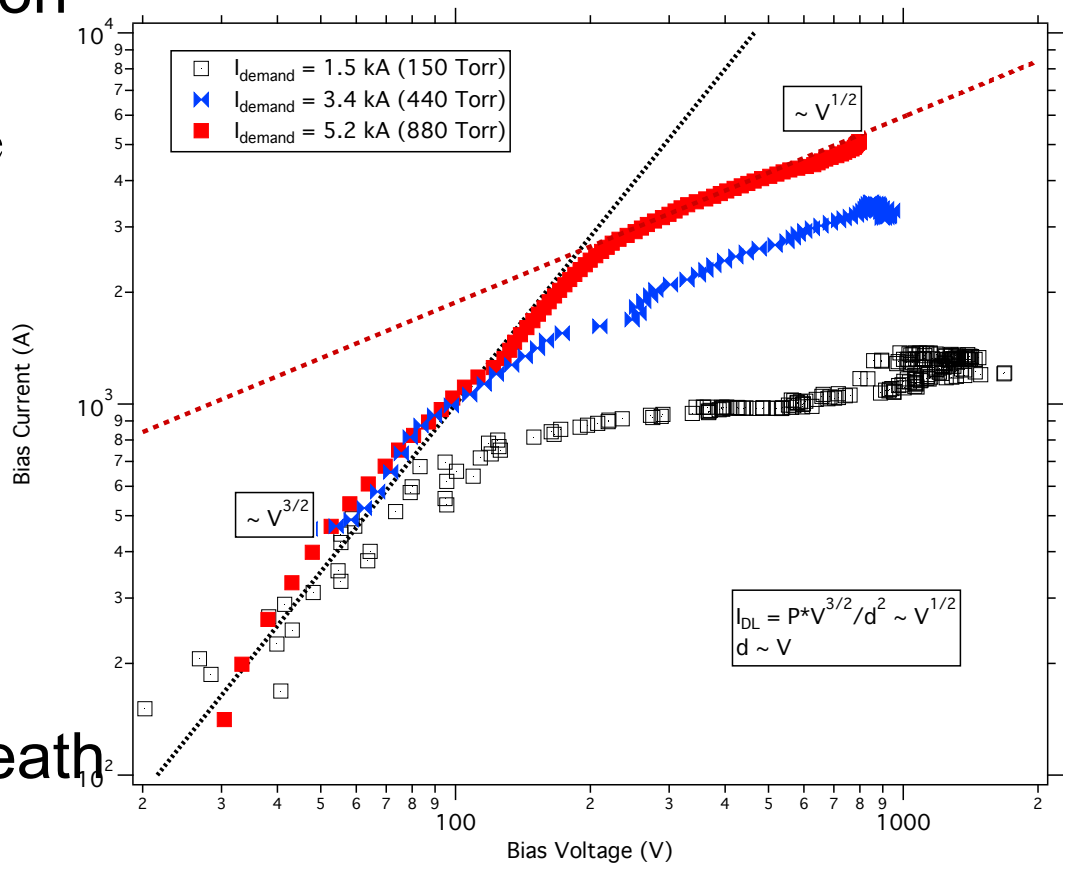
- N dominant impurity with unprotected gun assembly
  - 1st *estimates* of impurity content via bolometer measures
    - $Z_{eff} \sim 2.2. +/- 0.8$ during injection; ≤ 1.4 after injection
    - Mainly N; $n_e \sim 5 \times 10^{18}$ m^{-3} to 2×10^{19} m^{-3}
- Local scraper limiters reduce N, O from unprotected gun case above
  - Depending on geometry bursts of N still evident with flare at BN surface
- Ohmic-only reference plasma very clean: Zeff ≤ 1.2



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Source Impedance Appears to be Governed by Sheath Physics

- Model evolving for source impedance ~ helicity injection rate
  - Predicative model requires edge density measurements
- Initiation phase: vacuum space charge limitation
  - $I_{bias} \sim V^{3/2} / d^2$
- High I_{bias} drive phase: expanding double layer sheath
  - $d^2 \sim V \Rightarrow I_{bias} \sim V^{1/2}$

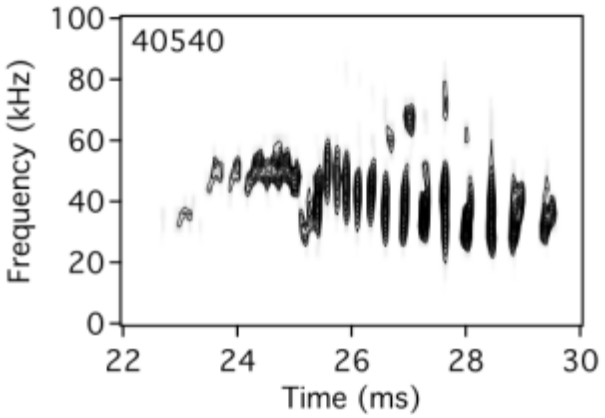


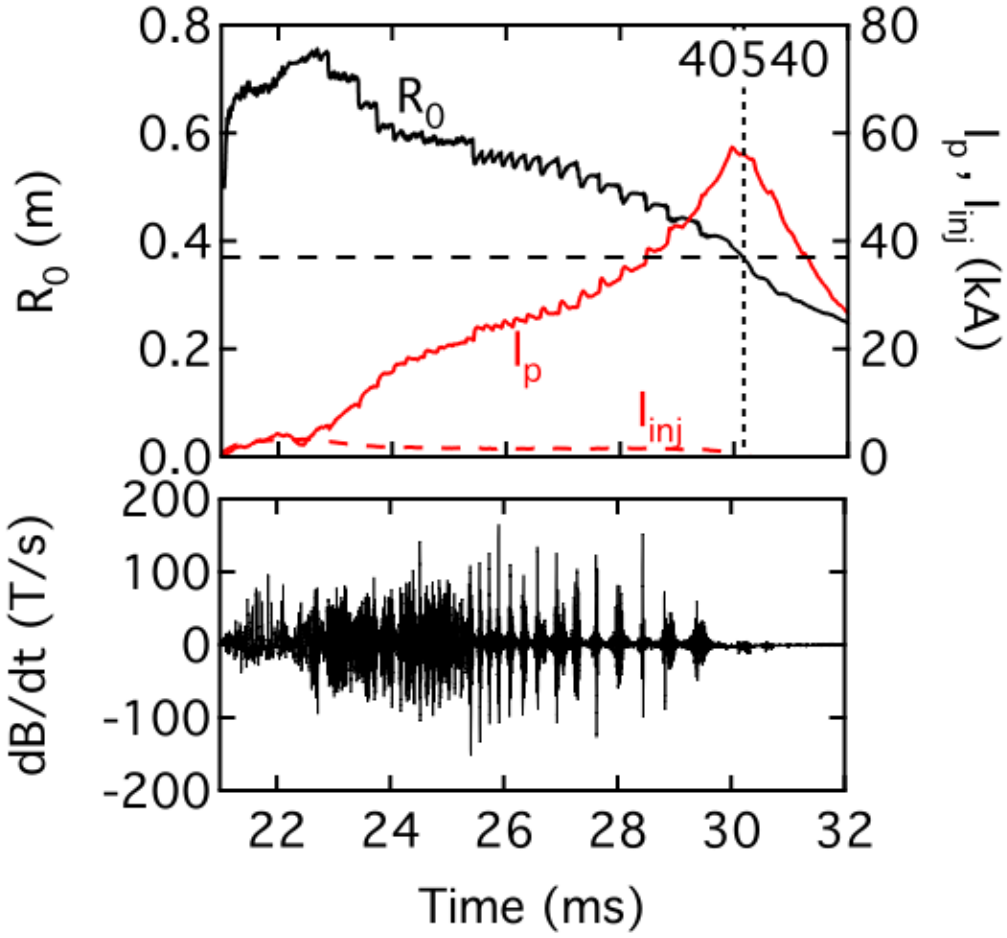
See: PP9.00004 Hinson et al.

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Intermittent 20 - 60 kHz n = 1 mode observed with strong edge current drive

- Bursts of *n* = 1 magnetic oscillations
  - Observed when plasma is coupled to edge current drive
  - Different in nature from inboard current injection experiments

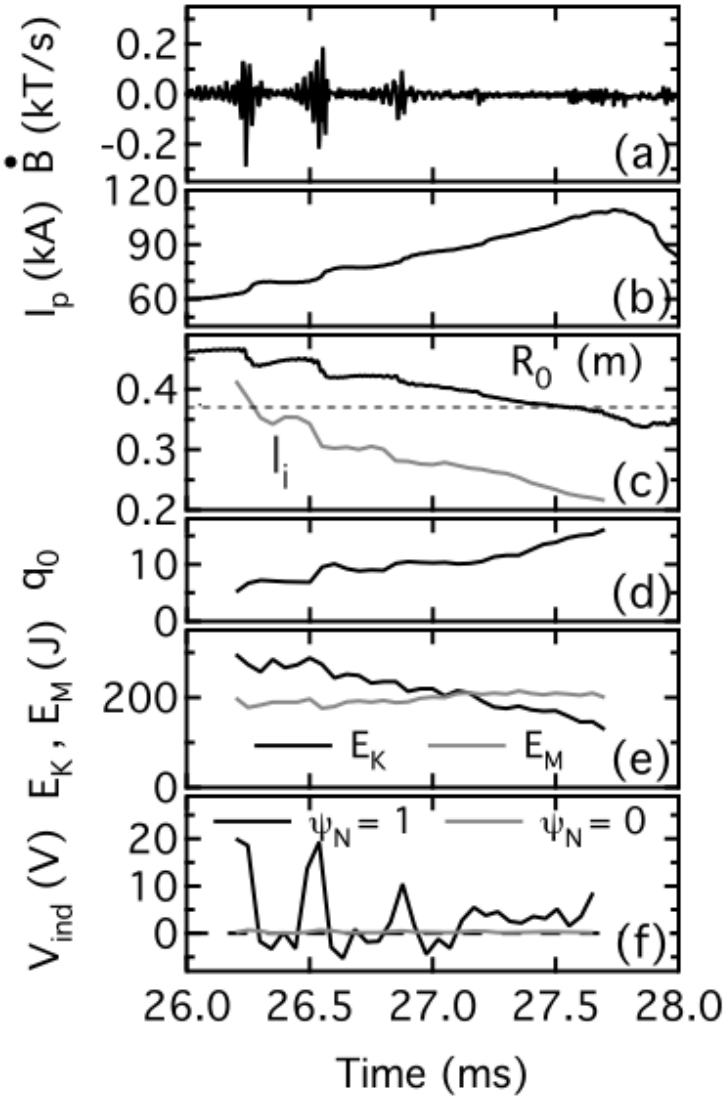




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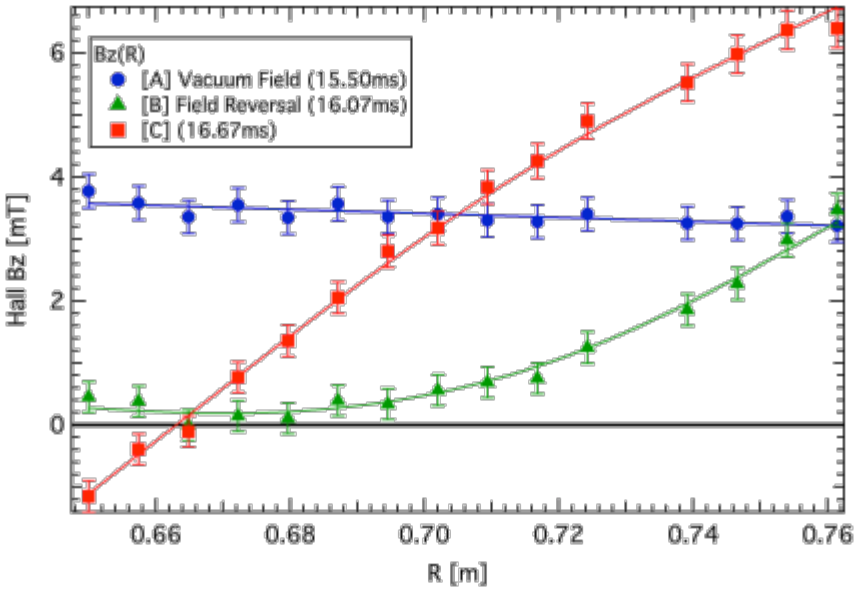
The magnetic topology quickly changes with each burst of MHD activity

- Each burst typically ~ 0.1 ms
- With each burst…
  - l_i decreases → I_p increases
  - R_o decreases → plasma expands
  - $B_{\phi o}$ increases → q_o increases
  - Slight drop in E_k and E_m
  - Very little change in poloidal flux at plasma edge
  - Rapid decrease in the total trapped poloidal flux
- Temporally and spatially averaged V_{ind} ~ 1.5 V

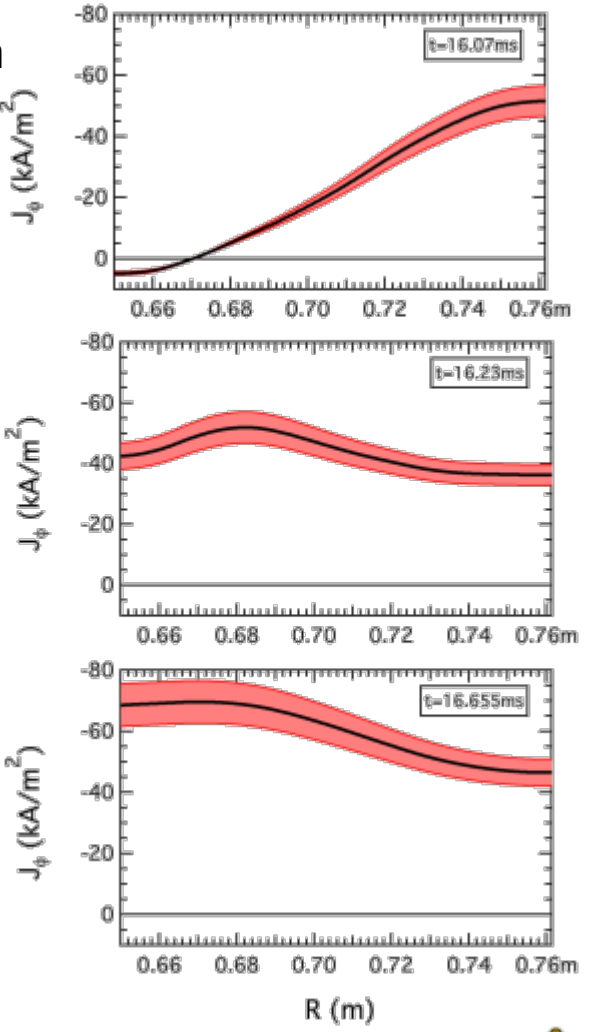


Internal $J_\varphi(R)$ Measurements Providing Details on Tokamak Formation

- Direct measurements of B_z via a Hall probe array confirms the creation of a field null at relaxation:



- HI creates an initial current profile that is very hollow
- The current profile relaxes, carrying current towards the core
- A tokamak-like current profile is formed

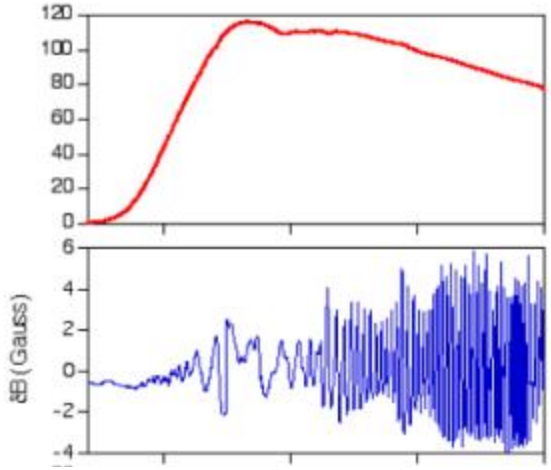


See: PP9.00005 | Barr et al.

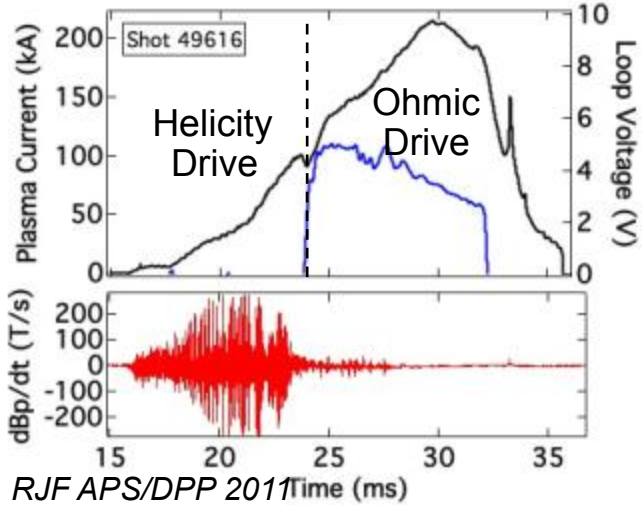
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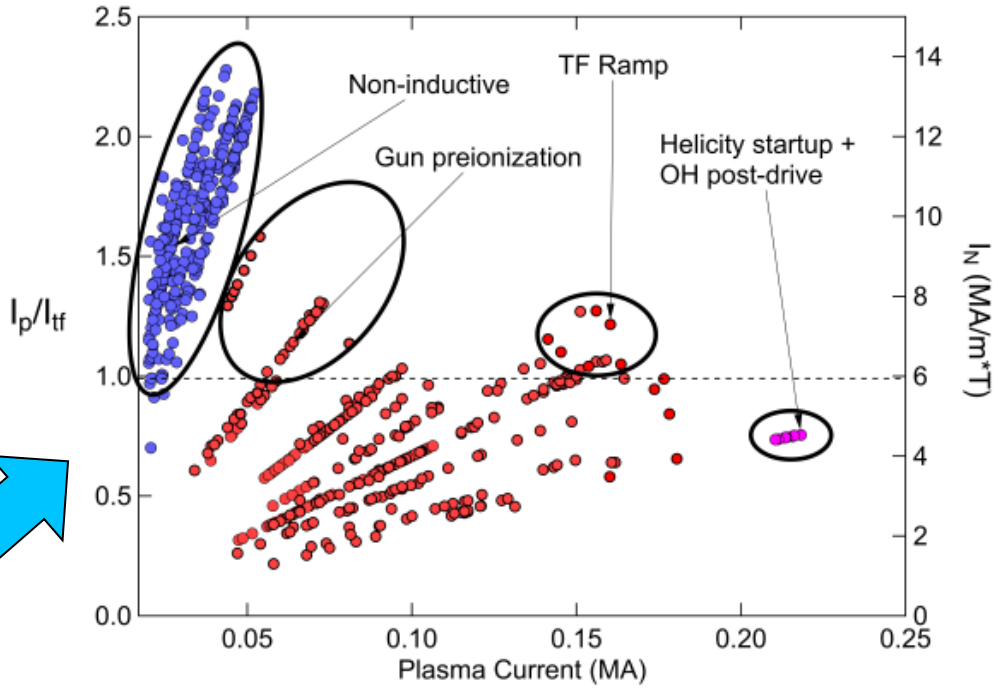
Current Drive Tools Providing Access to High Field Utilization Regime

OH only = large 2/1 modes limit I_p



HI startup = MHD quiescent



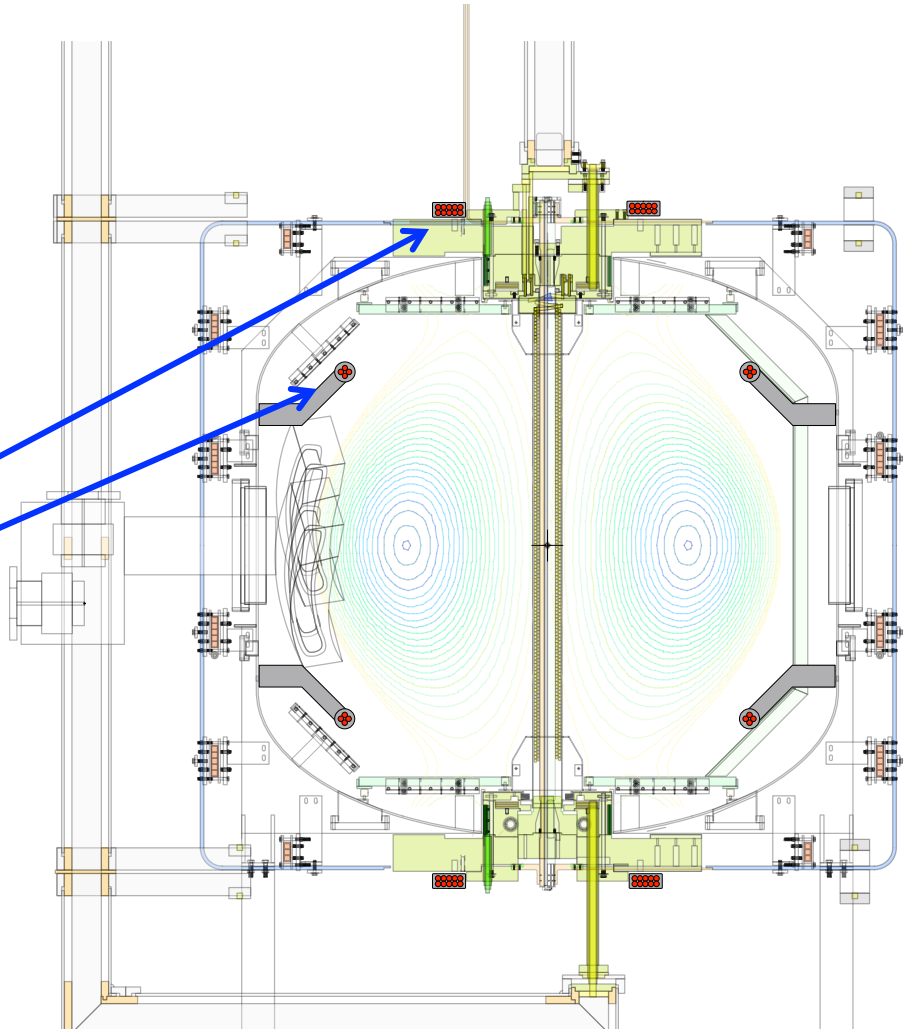


- Helicity injection startup and Ohmic sustainment provides MHD-stable profiles at $I_p/I_{TF} < 1$
- Need to extend to higher I_p, then to low I_{TF} for high I_N and high β_T as A≈1

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

- Gun-electrode Evolution
  - Passive electrode material variations
    - Stand-off Mo electrode looks promising
  - Separate plasma gun and electrode
- Power Supplies, Heating
  - New helicity injection power: *2 kV, 15 kA*
  - Double TF current: *Taylor limit increase*
  - ~ 1 MW HHFW system available: *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
  - High-speed $T_i(r,t)$
    - *Anomalous reconnection heating*

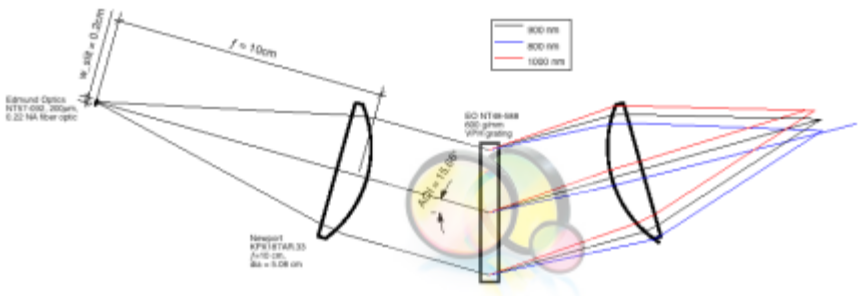


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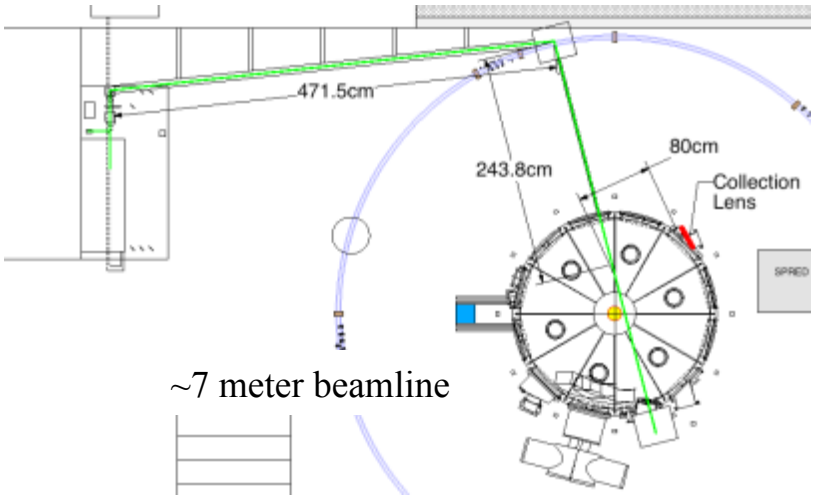
Thomson Scattering system uses new technologies for visible wavelength system

- Frequency doubled Nd:YAG laser provides ~10^{18} photons
- For typical PEGASUS plasma, $n_{scattered} \sim 10^4$ photons
- VPH grating efficiency >85% for λ_{inc} = 532 - 632 nm
- Gen III image intensifiers ~50% efficient in visible region
- ~ 6 ns ICCD gating provides easy detector technology

Laser Specifications	Value
Output Energy at 532 nm	≥ 2000 mJ
Beam diameter at head	12 mm
Beam diameter at waist	3 mm
Pointing stability	≤ 50 μrad
Divergence	≤ 0.5 mrad
Repetition Rate	≤ 10 Hz
Pulse length	≥ 10 ns



Volume Phase Holographic (VPH) Grating



See: PP9.00007 Schoenbeck et al.
and: PP9.00008 Schlossberg et al.

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HI Conclusion: 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; ~ 0.08 MA with HI only
  - Understanding of helicity balance and relaxation current limit guide hardware and operational changes
    - So far, predicted scalings supported
    - HI-only driven plasma points to long-pulse, high I_p startup
  - Goal ≈ 0.3-0.4 MA non-solenoidal I_p to extrapolate to next level/NSTX
    - Developing physics understanding: λ_{edge}, Z_{inj}, confinement, *etc.*
  - Deploying plasma control tools and new diagnostics to better understand processes
- 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 may be feasible

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