Local Current Injector Systems for Nonsolenoidal Startup in a Low Aspect Ratio Tokamak

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PEGASUS Toroidal Experiment

Motivation: Intense Electron Current Sources Needed for Local Helicity Startup

- Significant progress with non-solenoidal startup of ST
  - Exploiting local helicity injection via current sources in plasma edge region
  - Technical attractiveness: can remove sources and anode after startup
  - Understanding of helicity balance and relaxation current limits guide hardware and operational changes
    - Helicity injection discharges couple to other current drive methods
- Tests and development on the Pegasus Toroidal Experiment
  - $A \sim 1$; $I_p = 0.1\text{-}0.3$ MA; $B_{tf} = 0.15$T
  - $I_p \sim 0.17$ MA using helicity injection and outer-PF rampup; ~ 0.08 MA with HI only
  - Goal ≈ 0.3-0.4 MA non-solenoidal Ip to extrapolate to next level/NSTX
    - Issues in physics understanding: j_{edge}, Z_{inj}, confinement, etc.
- Exploitation of point-source helicity startup requires large-area sources of intense electron current
  - Developing understanding and designs of robust electron sources based on plasma arc sources
  - Exploring possibility of simpler large-area sources via gas-fed electrodes
  - Requires 2 kV, 15 kA programmable power systems

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Local Helicity Injection Offers Scalable Nonsolenoidal Startup

- Inject Helicity for I_p startup using electron current source at the tokamak plasma edge
  - I_p limited by available helicity drive, including PF induction. Helicity balance gives:

$$I_p \leq \frac{A_p}{2\pi R_0 \langle \eta \rangle}\left(V_{ind} + V_{eff}\right) \qquad V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi_T} V_{bias}$$

  - Max I_p set by relaxation to Taylor (constant λ) state:

$$I_p \leq \left[\frac{C_p}{2\pi R_{inj} \mu_0} \frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

  - Helicity dissipation thru resistive losses in plasma

A_p Plasma area

C_p Plasma circumference

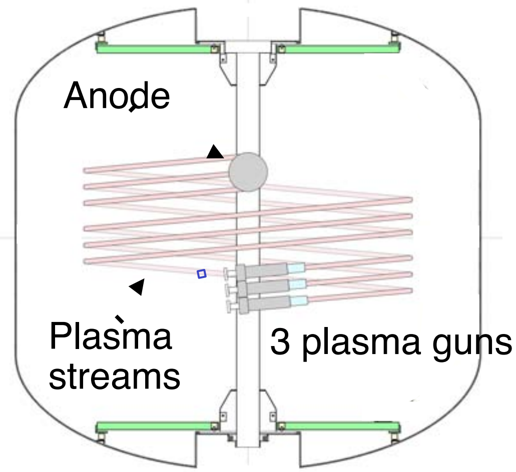
Ψ_T Plasma toroidal flux

w Edge current channel width

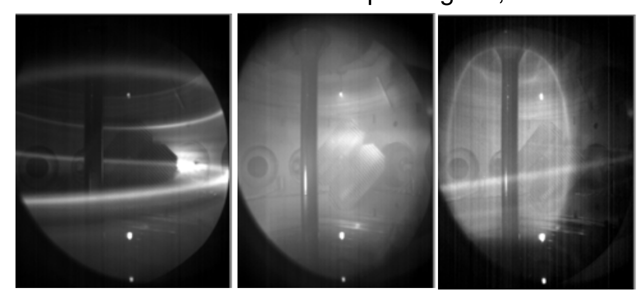
- Maximizing I_p requires
  - Large helicity input rate: High A_{inj}, V_{inj}
  - High relaxation limit: High I_{in}j, low *w*

Outer LFS Injection Adds Poloidal Induction to Helicity Injection

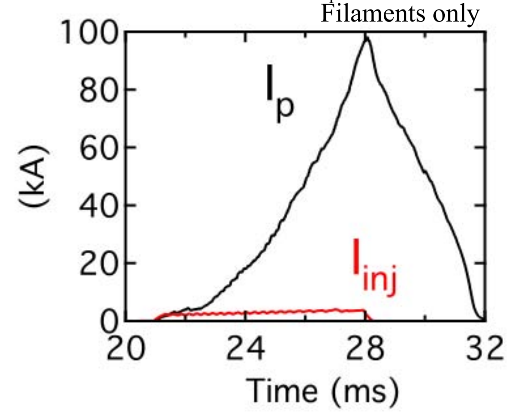
- Flexible geometry for injector locations
  - Outer midplane allows "port-plug" installation
- PF null via injection into helical (TF + PF) field; followed by relaxation to tokamak-like state
  - Rapid inward expansion and growth in I_p at low A
- Poloidal field induction adds to current growth



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



I_p=2-3 kA Filaments only | I_p=42 kA Driven plasma | I_p=37 kA Guns off Decaying



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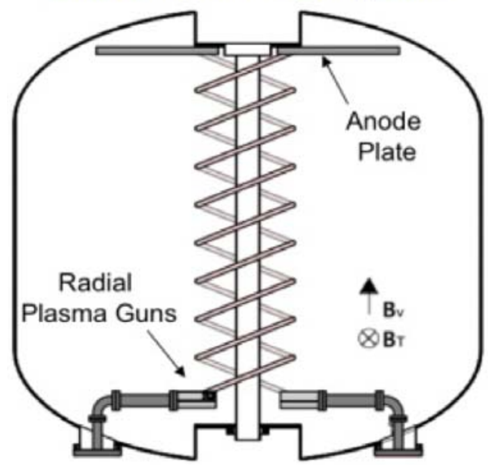
Inboard HFS Injection in Divertor Region Maximizes Helicity Input Rate

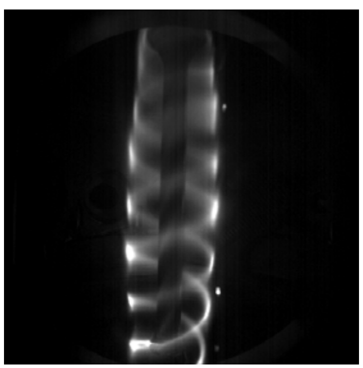
- HFS injection near centerstack maximizes helicity input rate
- Reduced plasma position control requirements
  - Static fields support easy control of position

Inboard Divertor Gun Injection



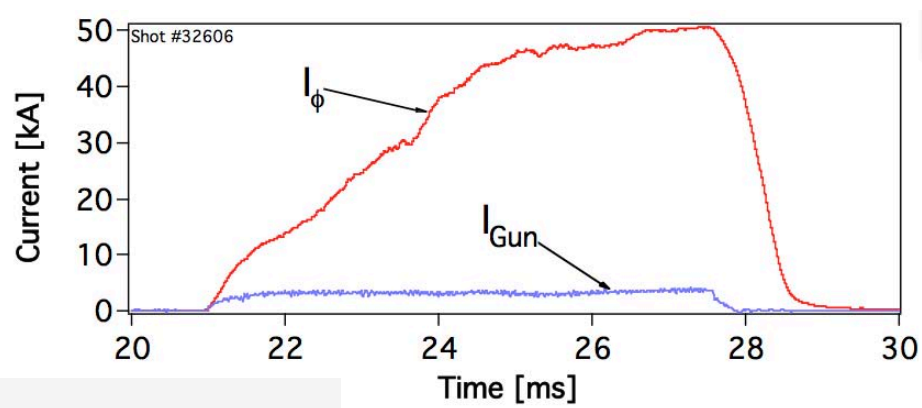
R_{gun} = 16 cm, Z_{gun} = - 75 cm

Increased I_{inj}
Reduced B_z



Current filaments

Relaxed tokamak



Plasma Arc Sources

Compact Plasma Arc Sources Provide Dense Plasma for Electron Current Extraction

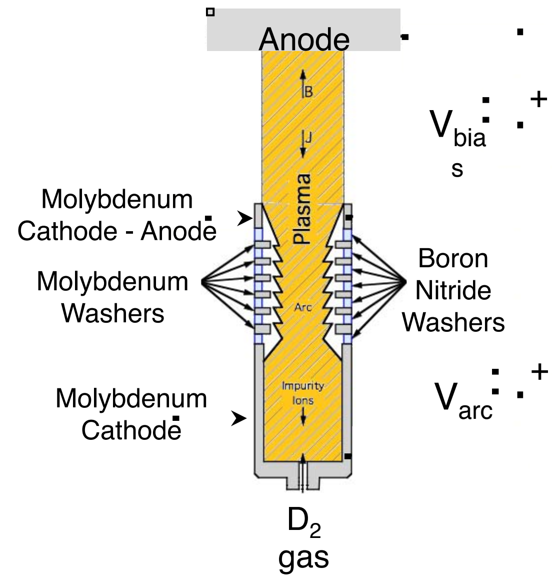
- Plasma arc(s) biased relative to anode:
  - Helicity injection rate:

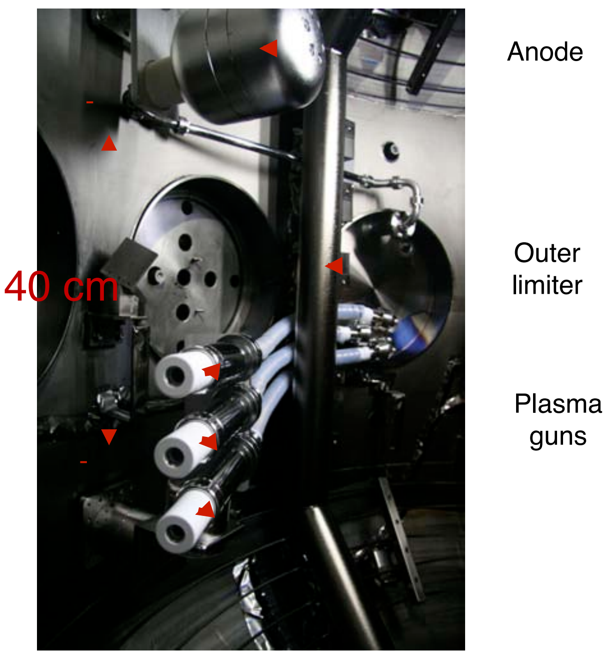
$$\dot{K}_{inj} = 2V_{inj}B_N A_{inj}$$

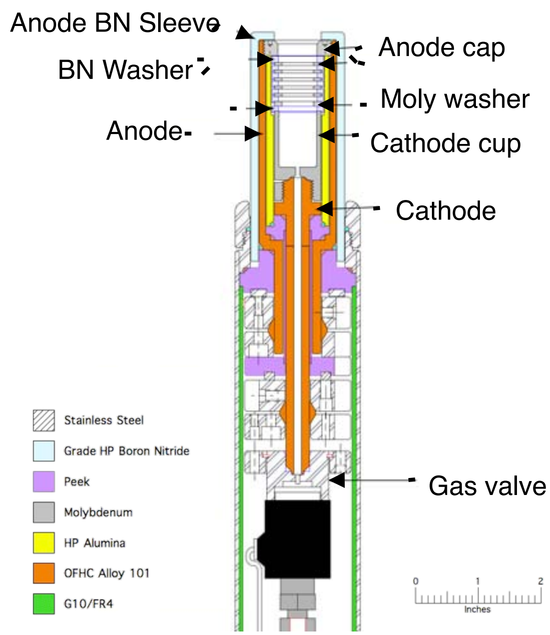
V_{inj} - injector voltage

B_N - normal B field at gun aperture

A_{inj} - injector area







- Arc plasma fully ionized
  - $N_e \sim 10^{20} - 10^{22}\ m^{-3}$
  - $T_e \sim 10$ eV

1 Fiksel, G, et. al., Plasma Sources Sci. & Tech. **5** (1996)

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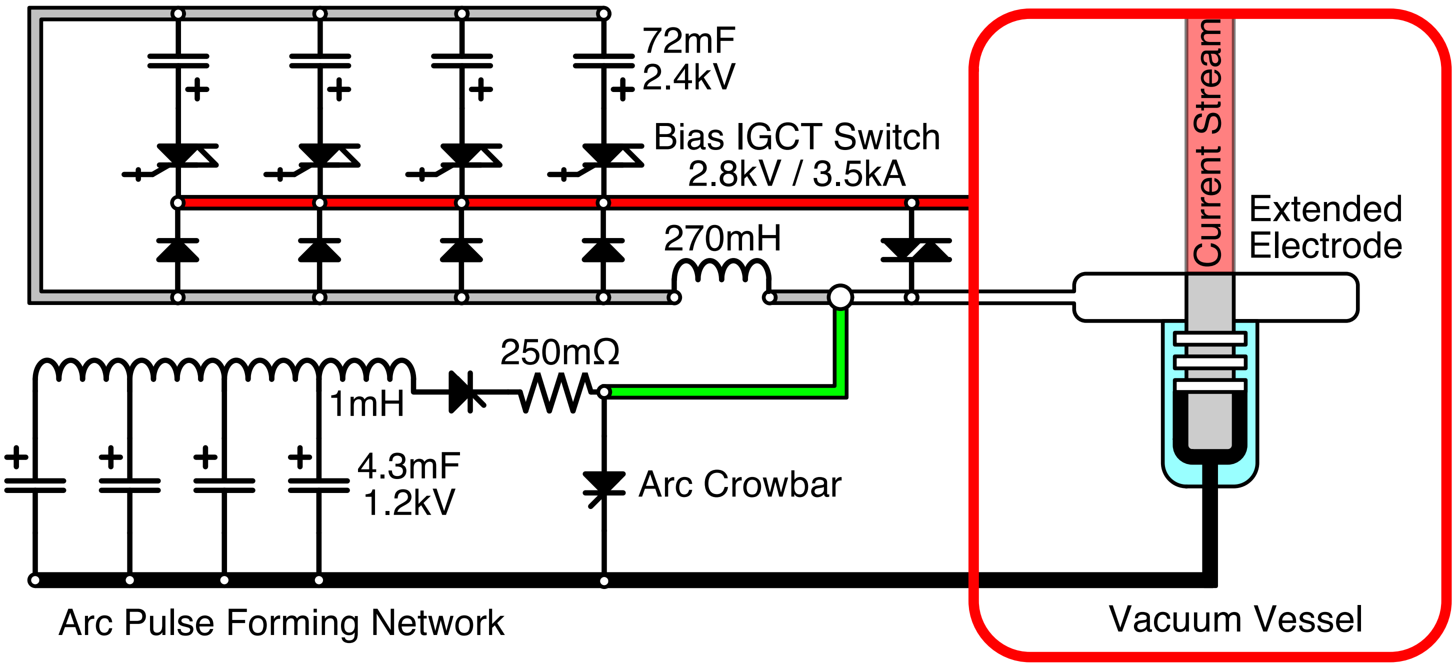
Robust Switching Power Supplies Deployed for Arc & Injection

- Plasma Arc uses simple Pulse Forming Network
  - Once arc is established: I_{arc} = 1-2 kA @ V_{arc} = 100-200 V
  - SCR terminates arc on demand
- Injection (Bias) circuit uses 4 IGCT switches in parallel
  - Total: $I_{inj} \leq 14$ kA @ $V_{inj} \leq 2.2$ kV
  - Preprogrammed current control via stabilized PWM feedback controller
  - Series inductance stabilized, sometimes with parallel stabilizing capacitor and ballast resistor

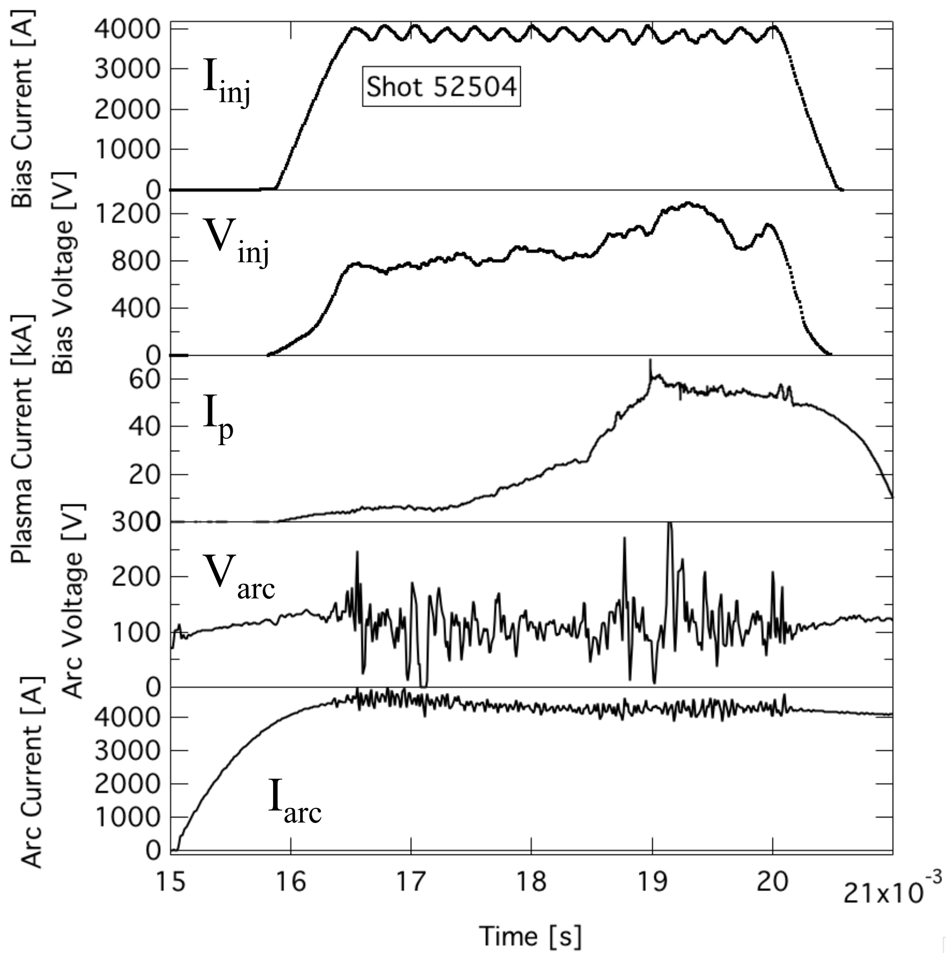


Power Systems Provides Routine Programmable Injected Current and Helicity

- Injection circuit provides current feedback control
  - Impedance varies with resulting tokamak plasma so that V_{inj} varies through shot
  - Future upgrade: go to voltage feedback control
    - Active control of helicity injection rate

- Arc circuit fully ionizes injected gas
  - $I_{arc} \sim$ 2-4 kA @ $V_{arc} \sim$ 150 V
  - With 1.3 cm diameter arc chamber, routine operation at 2 kA, with reduced lifetime at 4 kA

- Shot sequence
  - Inject gas flow into arc chamber
  - Strike Arc current; allow ~ 1ms to establish arc
  - Extract I_{inj}; usually with $I_{inj} < I_{arc}$



Arc Source Impedance

Predictive Impedance Models Required to Project to Future Startup Systems

- Current injector impedance is a critical parameter in local helicity injection startup
  - I_{inj} sets Taylor relaxation maximum Ip
  - V_{inj} sets effective V_{loop} for current drive
  - Impedance couples the two to define power requirements

- Double-sheath space-charge limits I_{inj} at low I_{inj} and V_{inj}

$$J_e = \frac{4}{9}\varepsilon_o \sqrt{\frac{2e}{m_e}} \frac{V^{3/2}}{(\chi \lambda_{De})^2}$$

- At high I_{inj} (> I_A) and V_{inj} > 10 kT_e/e, the Alfven-Lawson magnetic current limit dominates

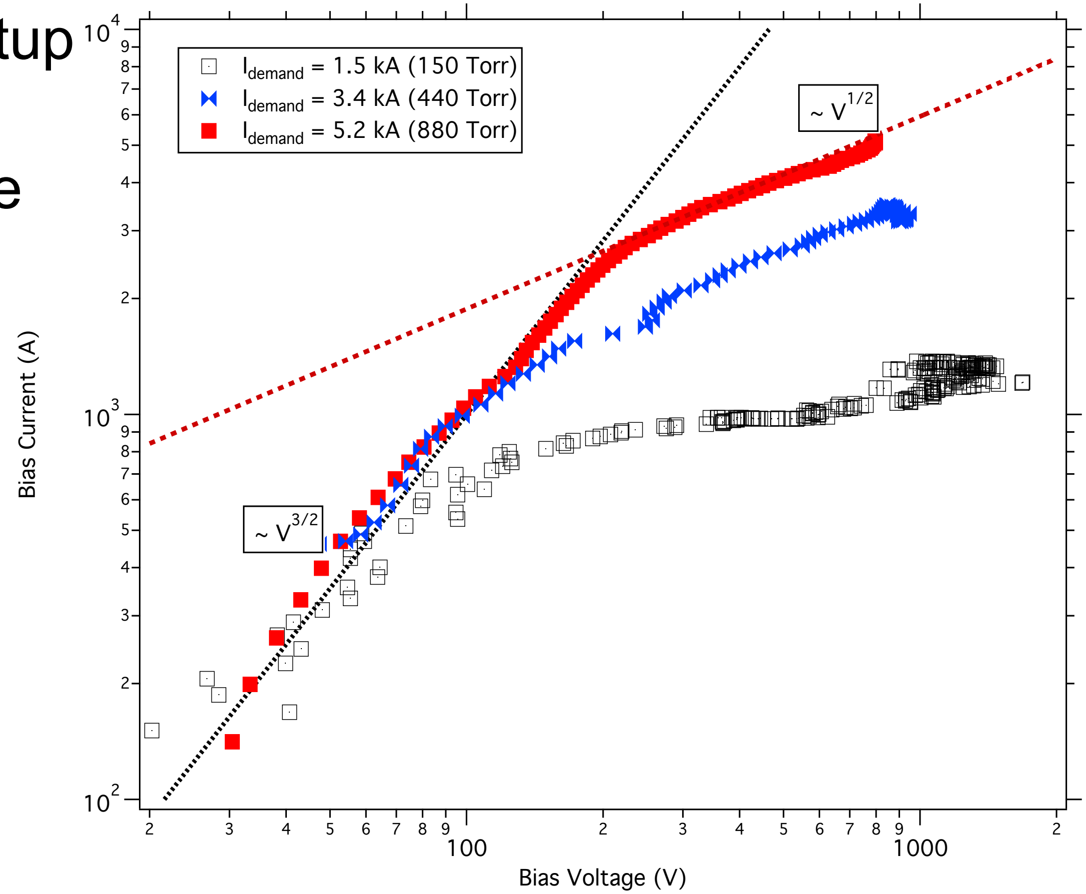
$$I_{AL}^{e} = 1.65 \frac{4\pi m_e v_e}{e\mu_o} \equiv 1.65 I_A = 56\sqrt{V_{inj}}$$

  - For a uniform current density
  - Possible that sheath expansion also contributes in this region

- So far, these models and supporting evidence imply impedance determined by processes local to the injector and not the background plasma

Helicity Injection Process Governed by Space Charge and Magnetic Current Limits

- Arc source I-V characteristics obtained during plasma startup
- Double-sheath space-charge limits I_{inj} at low I_{inj} and V_{inj} : Initiation phase
  - $I_{inj} \sim n_e V^{3/2}$
- At high $I_{inj} > I_A$ and $V_{inj} > 10\ kT_e/e$, the Alfven-Lawson magnetic current limit dominates
  - $I_{inj} \sim V^{1/2}$
  - Possible that sheath expansion also contributes here



I-V characteristics of arc plasma current injector for varied fueling rates.

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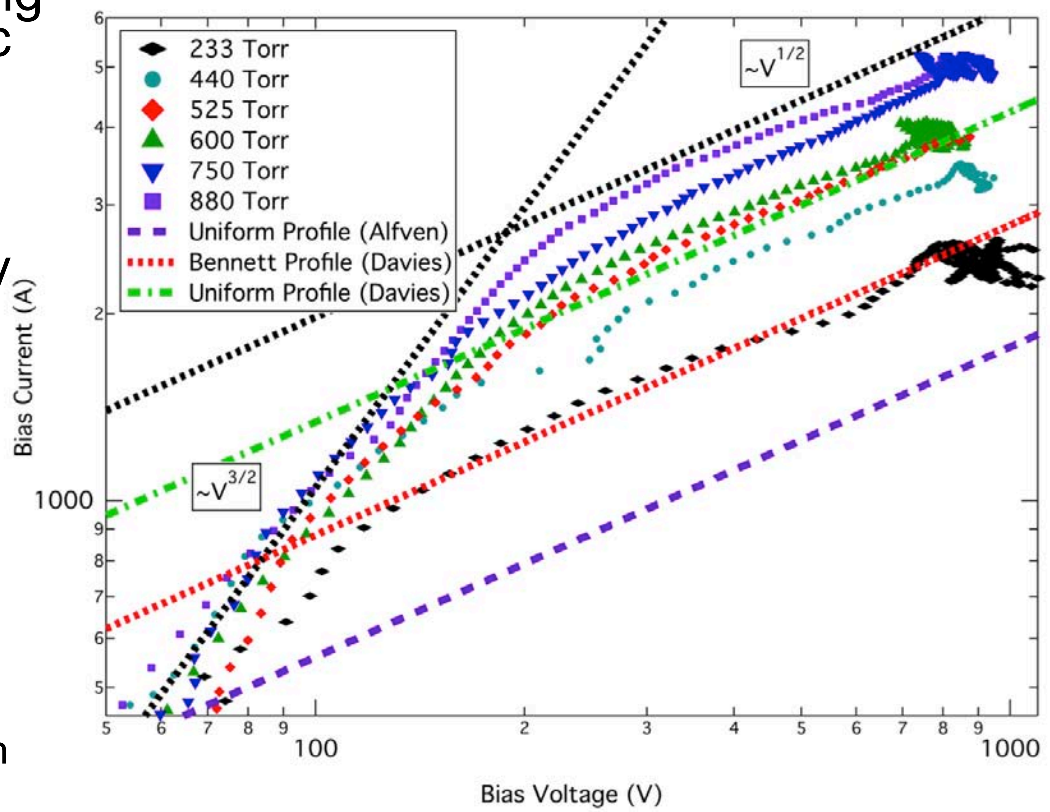
Density Scaling in Injector Impedance May Reflect e^- Beam Profiles?

- I-V characteristics at varied furling rates suggests a scaling with arc density

- Density variation may reflect changes in beam current density profile
  - Alfven: uniform j with backward particle flow

$$I^e_{AL} = 1.65\frac{4\pi m_e v_e}{e\mu_o} \equiv 1.65 I_A = 56\sqrt{V_{inj}}$$

  - Davies: Uniform profile and Bennett profile for j(r)
    - Derived from energy conservation



$$I^e_{uniform} = 4.0\frac{4\pi m_e v_e}{e\mu_o} = 134\sqrt{V_{inj}} \qquad I^e_{Bennett} = 2.59\frac{4\pi m_e v_e}{e\mu_o} = 88\sqrt{V_{inj}}$$

- Data shows inferred trends but detailed measurements needed

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Large Area via Gas-Fed Electrodes

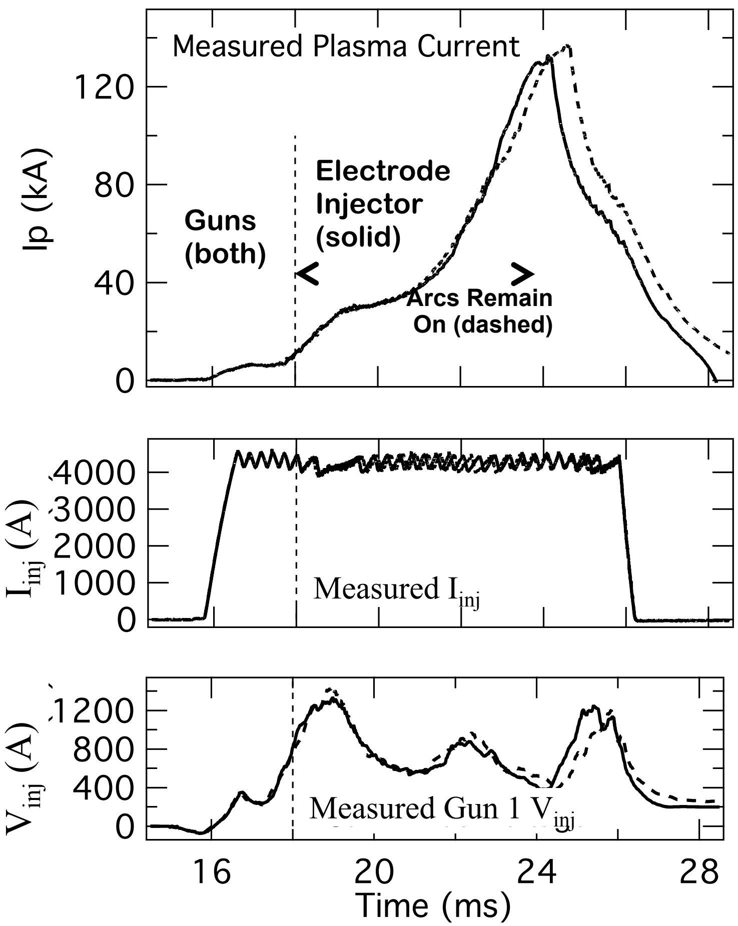
Exploring Passive Injectors to Increase Helicity Injection Rates

- Maximizing Helicity (i.e., current drive) requires large area electron emitters

- Two possible paths
  - Large area active high-density plasma sources
  - Passive electron emission through driven electrodes

- To mitigate the effort in producing electron current, it is worthwhile to explore simple passive (i.e., no plasma arc) current sources
  - Form initial tokamak-like state with minimal active arc gun
  - Increase I_p with passive electrodes.
  - Critical feature is how to diffuse the current extracted from metallic electrode

- First tests were promising
  - Arc current cut off after relaxation and formation of tokamak-like state
  - Gas fueling through chamber continued
  - I_p rise is virtually the *same,* whether arc discharge or passive electrode provide the charge carriers
  - Suggests continuing development of electrode emitters

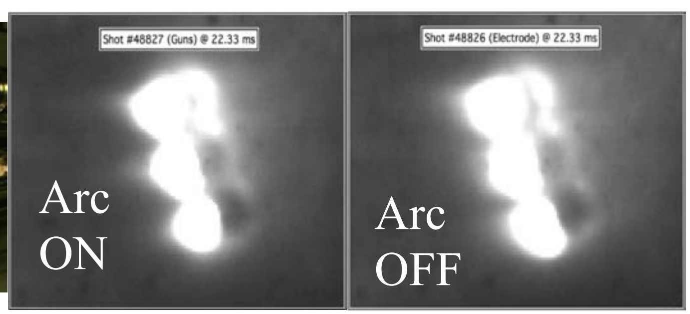


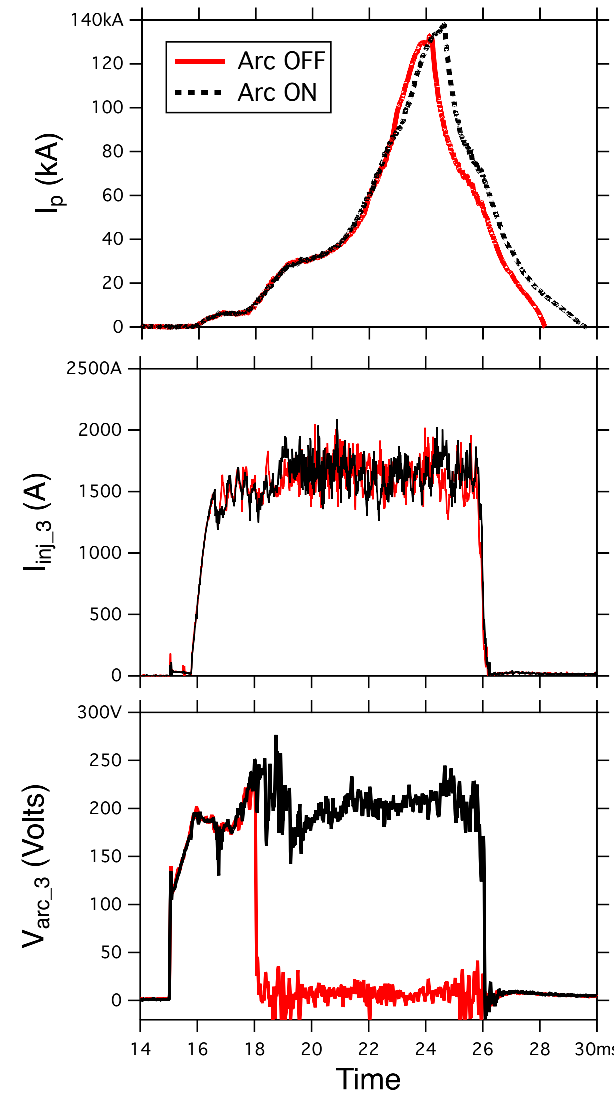
Identical Discharge Evolution Seen with Plasma Arc Turned Off

- Arc crowbarred out after tokamak discharge established to transition from arc plasma source to driven electrode system
  - Keep electrode widths narrow to maintain Taylor limit
  - Some limitations from PMI interactions at Mo/BN interface

- Demonstrated transition from active gun drive to passive electrode drive
  - Same extracted current whether arc is on or off, with same gas flow
  - Driven I_p virtually identical
  - Camera (low-res) images suggest similar current source regions

"Slot" Mo faces with BN caps





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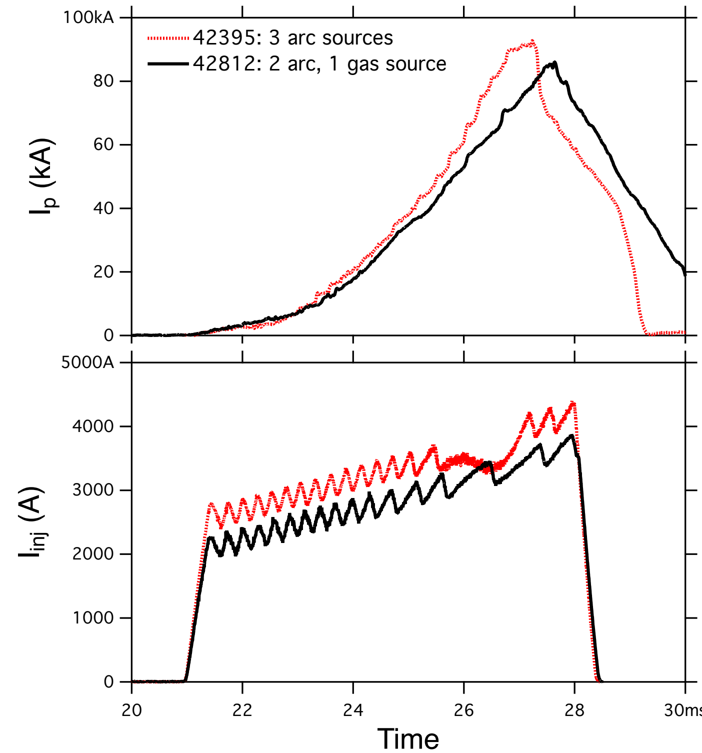
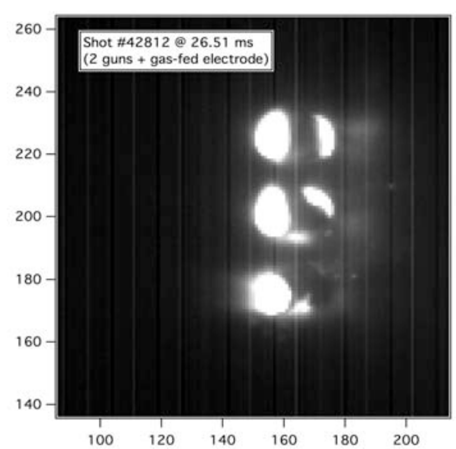
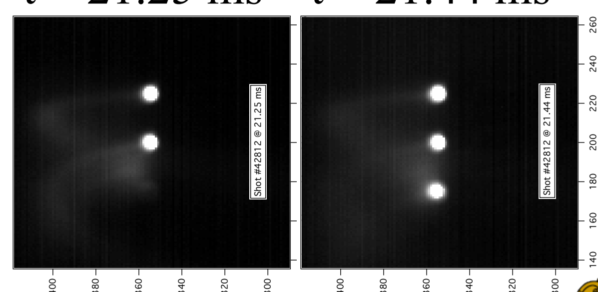
Electrode with Integrated Gas Feed Behaves Similarly to Arc Source

- Simple gas-fed electrode replaced a single arc source to test electrode concept
  - Passive electrode turns on spontaneously after 2 arc sources establish discharge
  - Discharge evolution to similar 3-arc source plasma
    - Suggests effective area of ~ size of gas source region
- Current ~ equally shared amongst 3 injectors



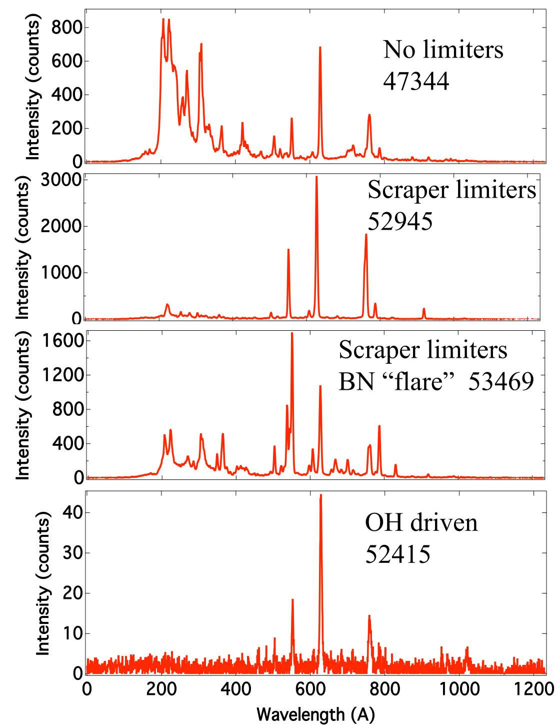


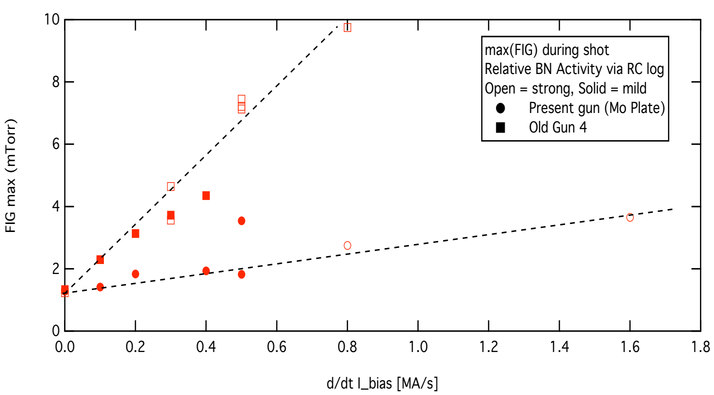
t = 21.25 ms   t = 21.44 ms



Electrode Systems Evolved to Mitigate Deleterious Plasma-Material Interactions

- N dominant impurity with unprotected gun assembly
  - $Z_{eff} \sim 2.2.$ +/- 0.8 during; ≤ 1.4 after injection
- Local scraper limiters reduce N from unprotected gun case
  - Also controls local edge N_e and injector impedance
  - O dominant impurity in OH and "well-behaved" helicity-driven plasmas
- Mo backing plate reduces BN interactions and undesired gas emission
  - Arc-backs to limiter still occur at times





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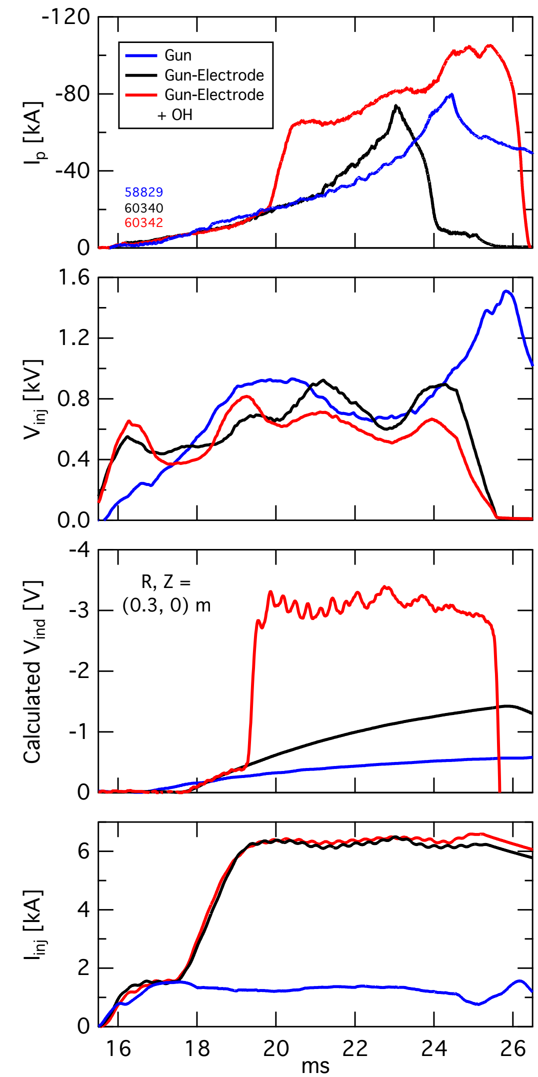
Extended Passive Electrode Tested as 1st Possibility for Large-Area Source

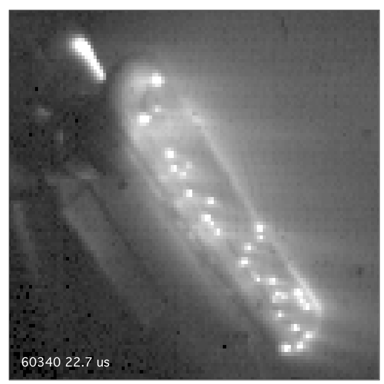
- Tests of current distribution on metallic electron emitter
  - No gas feed through electrode
  - Current in presence of plasma emitted from localized cathode spots
    - Similar to emission in vacuum
    - ~200-400 A per spot
    - For I_{inj} ~ 6kA, max effective area < 0.3 cm^2 ~ $A_{arc}/4$
  - Both single arc source and large passive electrode give similar I_p, well below the relaxation limit
    - Limit demonstrated with additional OH V_{loop}



- Need integrated gas fueling to spread I_{arc} across large area
  - Tests with single arc source cap underway to confirm and optimize

Single arc source with integrated large-area passive electrode

Small cathode spots emit current from simple metallic electrode



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Summary: Significant Progress in Developing Edge Current Sources for Local Helicity Injection

- Miniature plasma arc sources provide local current sources for non-solenoidal startup of ST and other confinement devices
  - Very flexible geometry options
    - Can be combined with poloidal field induction when located in HFS region
  - Technical attractiveness: can remove sources and anode after startup
  - 1-2 kA/cm^2 available; low impurity content
- Arc source impedance, and helicity injection rate, appears to be governed by sheath effect sand magnetic current limits
  - Further tests needed to understand apparent density scaling
- High helicity input requires large area current source and narrow current channel in edge region
  - Preliminary tests suggest gas-fed electrodes may be combined with arc sources to drive high I_p
  - Electrode design requires PMI mitigation techniques

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