Physics of Intense Electron Current Sources for Helicity Injection

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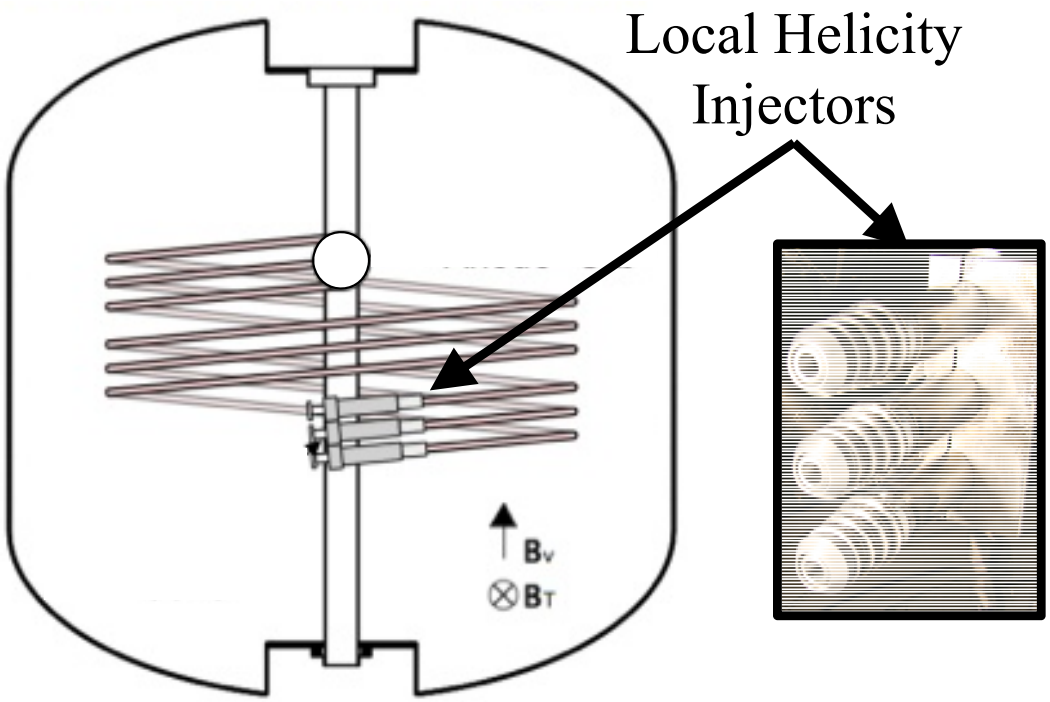


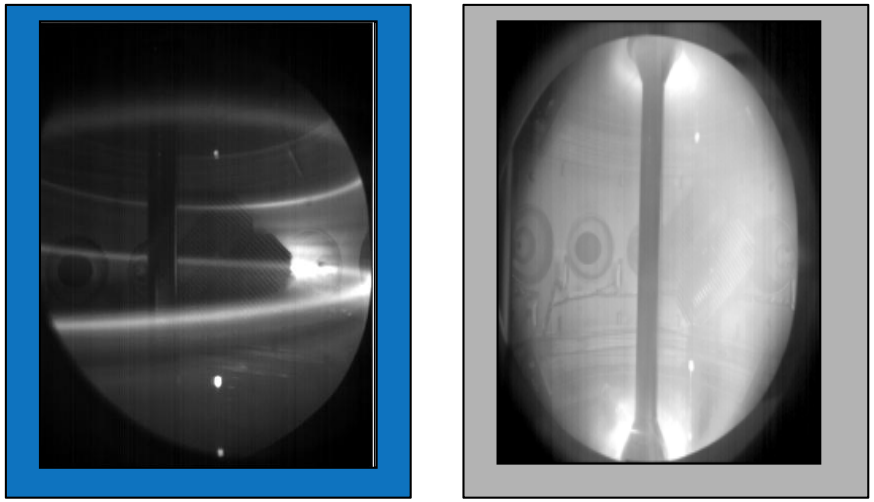
PEGASUS Toroidal Experiment

Summary

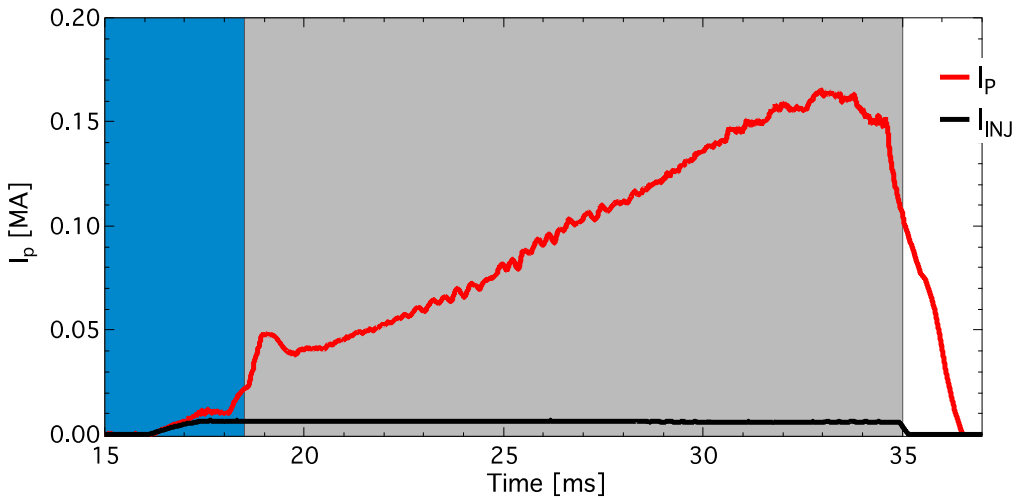
- Current injectors are deployed on Pegasus for helicity injection-based start-up
- A predictive model of the relationship between injection voltage and current is necessary for scaling this technique to larger facilities
- Injector I-V characteristics scaling as $I_{INJ} \sim n_e V_{INJ}^{3/2}$ suggest a double layer governs the injector impedance for low V_{INJ}, I_{INJ}
- During LHI and at higher power, $I \sim n_e V^{1/2}$ scaling is observed
  - Two hypotheses for the origin of this scaling will be tested

Pegasus is an Ultralow-A ST Developing Localized Helicity Injection Start-Up





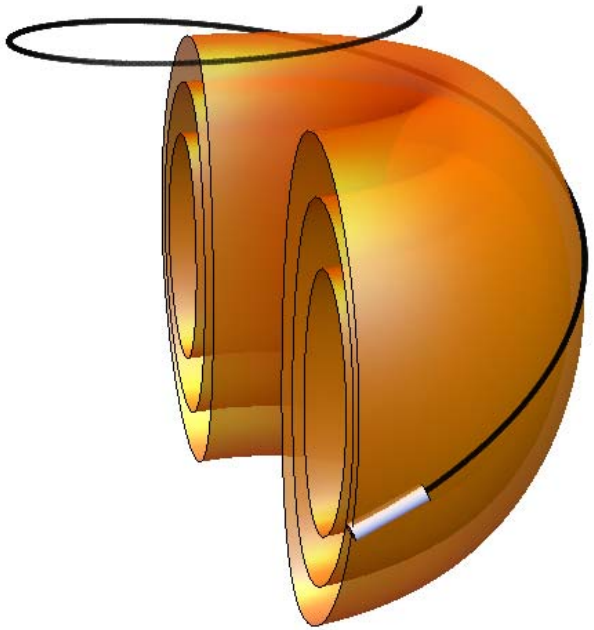
- Current injected along field lines
- Unstable current streams relax towards tokamak-like Taylor state consistent with helicity conservation
- Current growth ensues

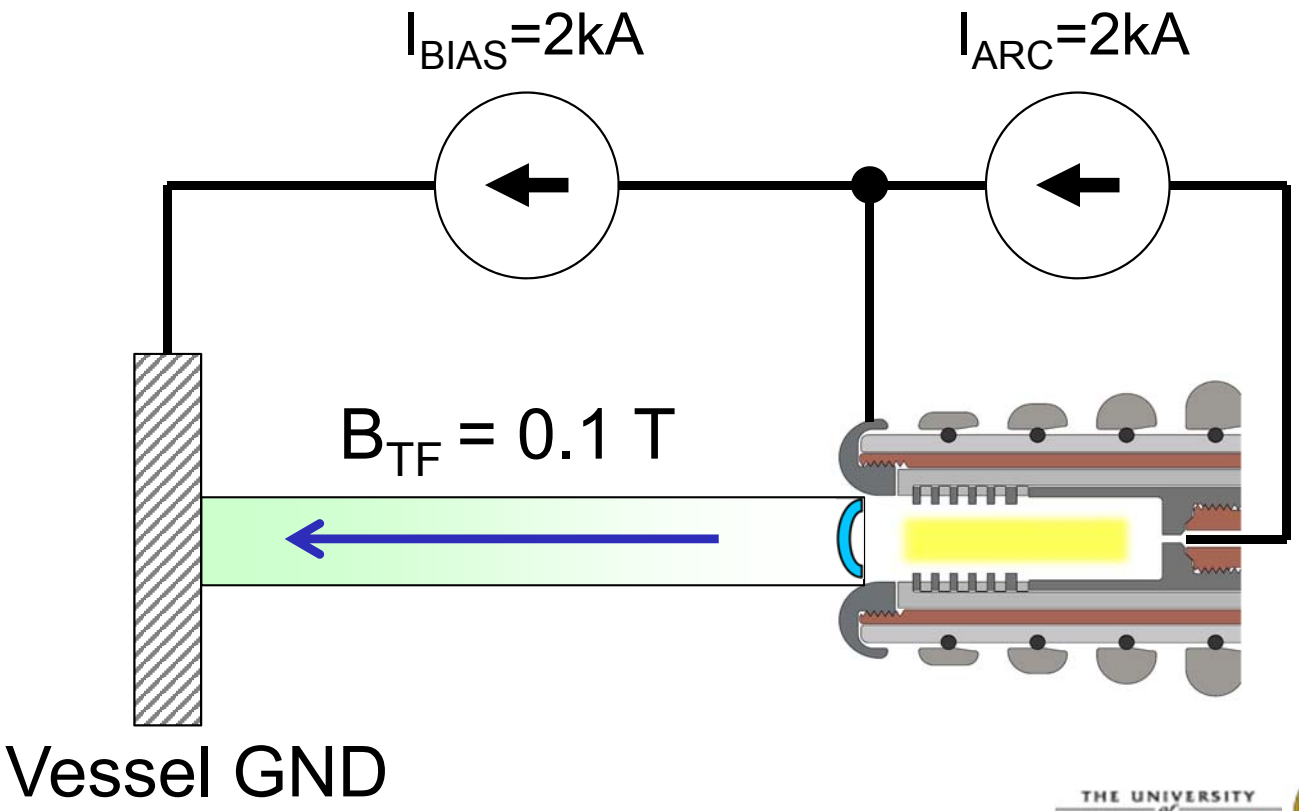


Injector Circuit Diagram

- Injector biased with respect to vessel
  - Current-feedback power supplies – voltage (~1kV) set by plasma physics

- Bias, Arc circuits joined at bias cathode/arc anode





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Gun Impedance Relates Key Figures of Merit

- The simple model for injection in Pegasus posits two Ip limits related to the injector circuit
  - Helicity balance limit depends on injector voltage V_{INJ}:

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

  - Taylor relaxation limit depends on injector current I_{INJ}:

$$I_p \le f(\varepsilon,\delta,\kappa)\sqrt{\frac{\kappa A_p I_{TF} I_{INJ}}{2\pi R_0 w}}$$

- Injector impedance fixes relationship between V_{INJ} and I_{INJ}
  - Determined by plasma conditions
  - Determines feasibility and power requirements for scaling this technique up

Injector Impedance Determined by Intense Beam Physics

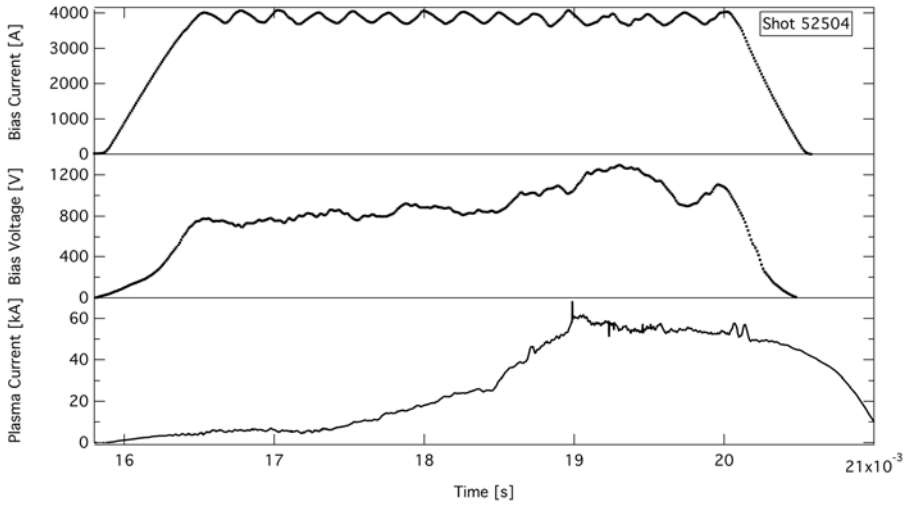
Several sources of impedance are plausible:

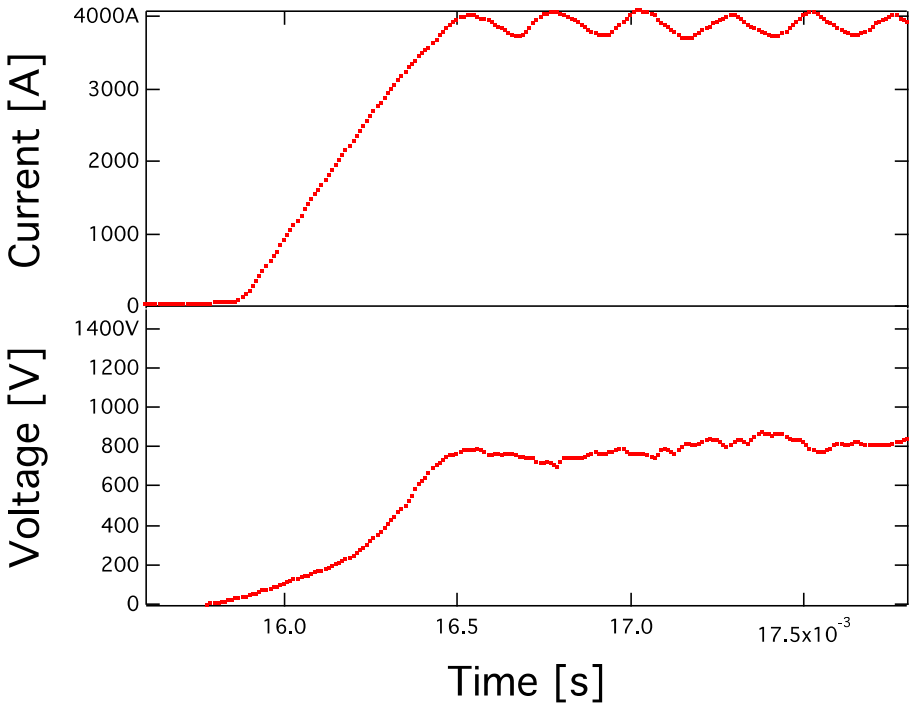
- Sheath expansion
- Lack of beam charge neutralization from edge
- Magnetic Limiting (seen in higher power devices)

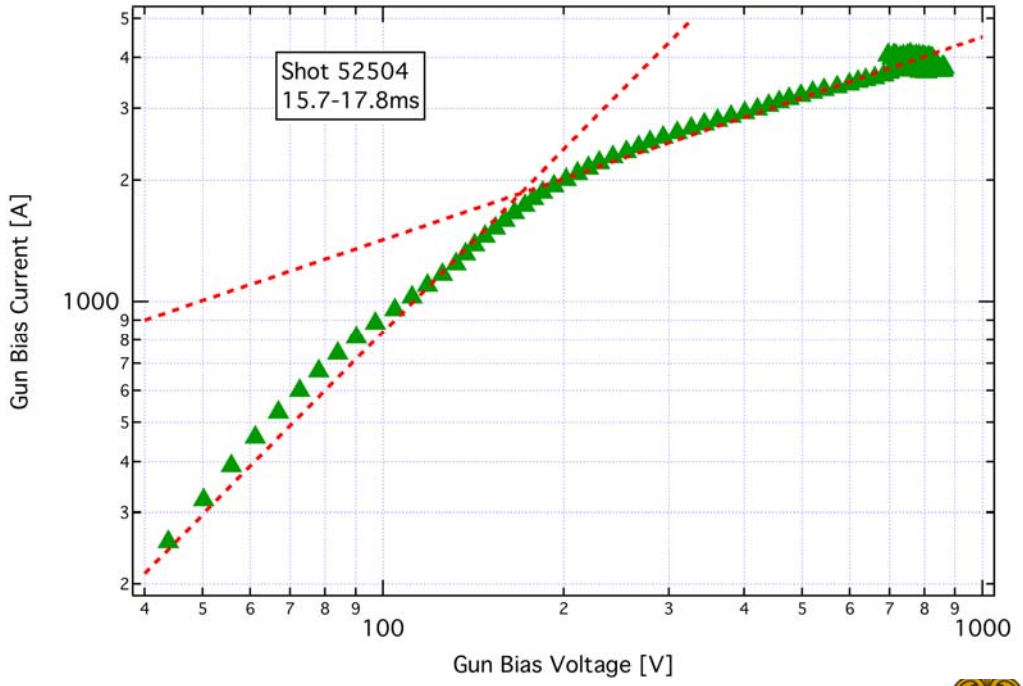
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Pegasus Injectors for Fixed Fueling Show Two Power Law Regimes

- Fast ramps (<1ms) to operating point reveal I-V characteristic
- Two regimes appear
  - $I \sim V^{3/2}$ regime at low voltage
  - $I \sim V^{1/2}$ regime at higher current, voltage



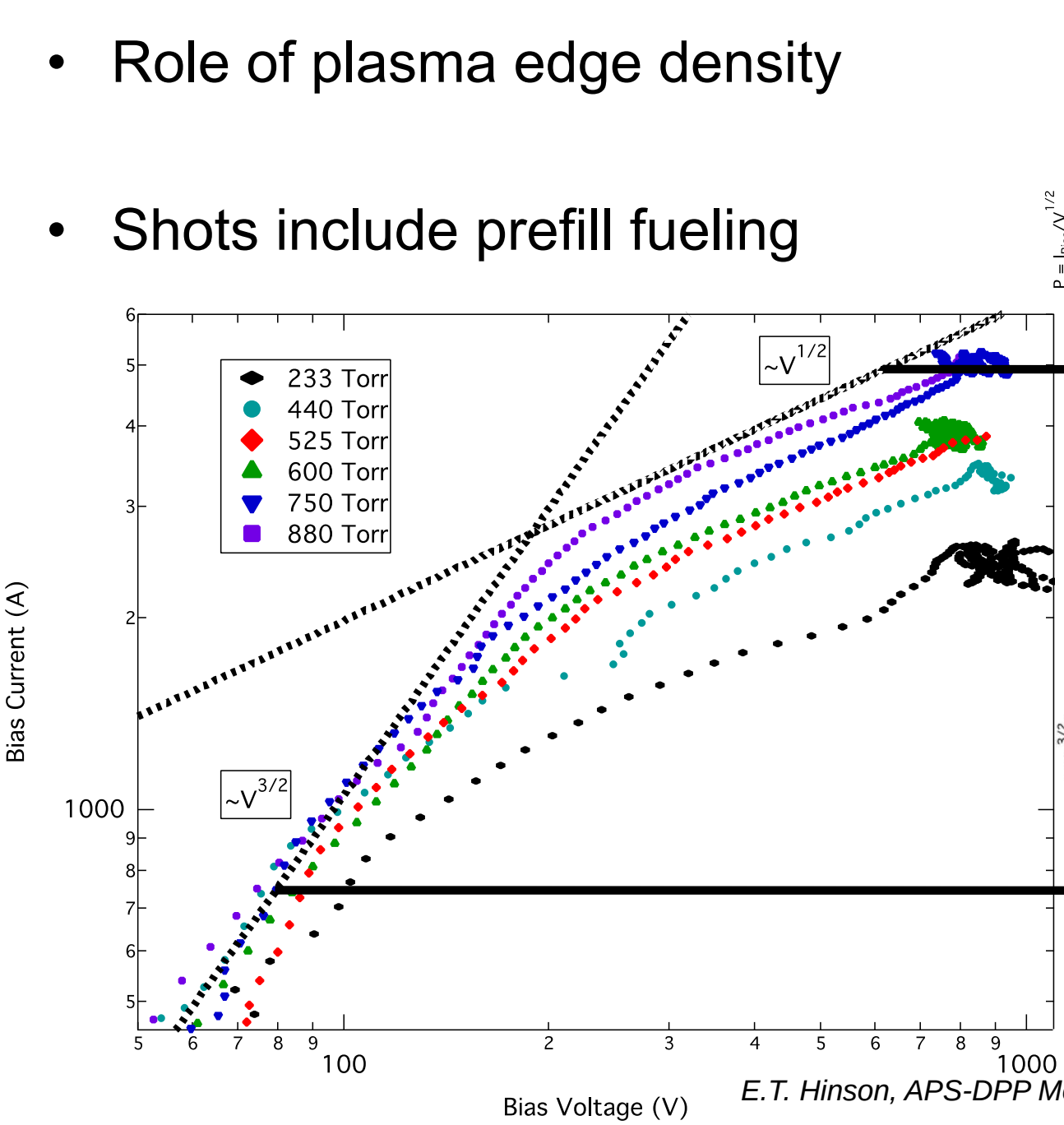


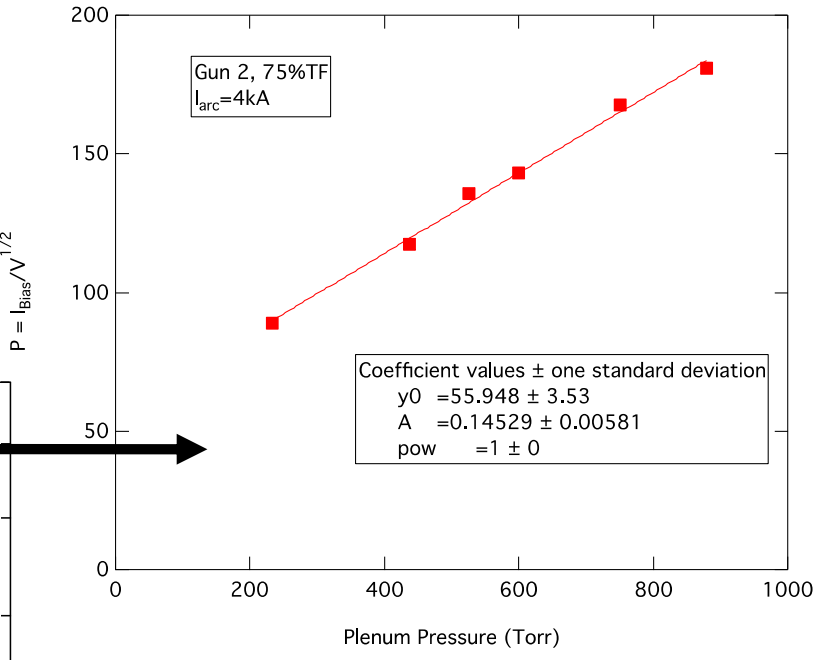


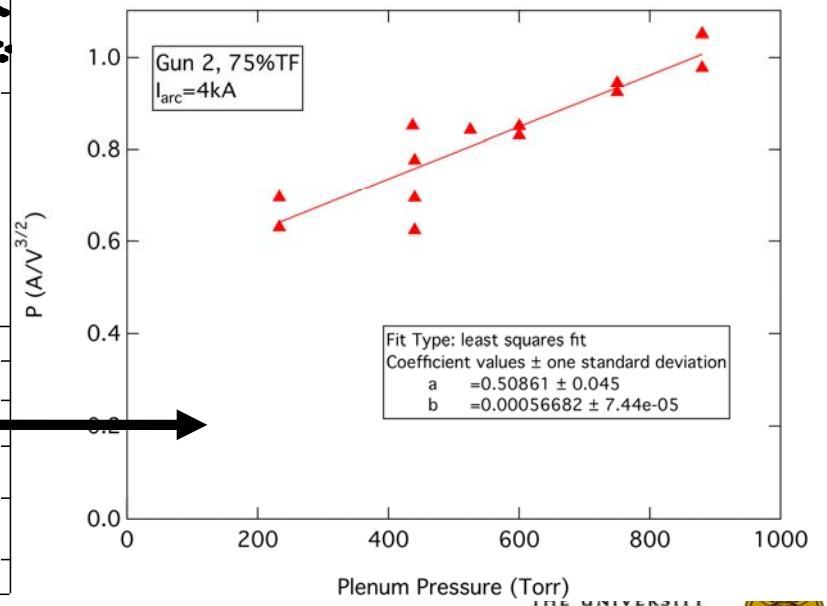
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I_{BIAS} at Fixed V_{BIAS} is Offset-Linear in Fueling

- Role of plasma edge density
- Shots include prefill fueling



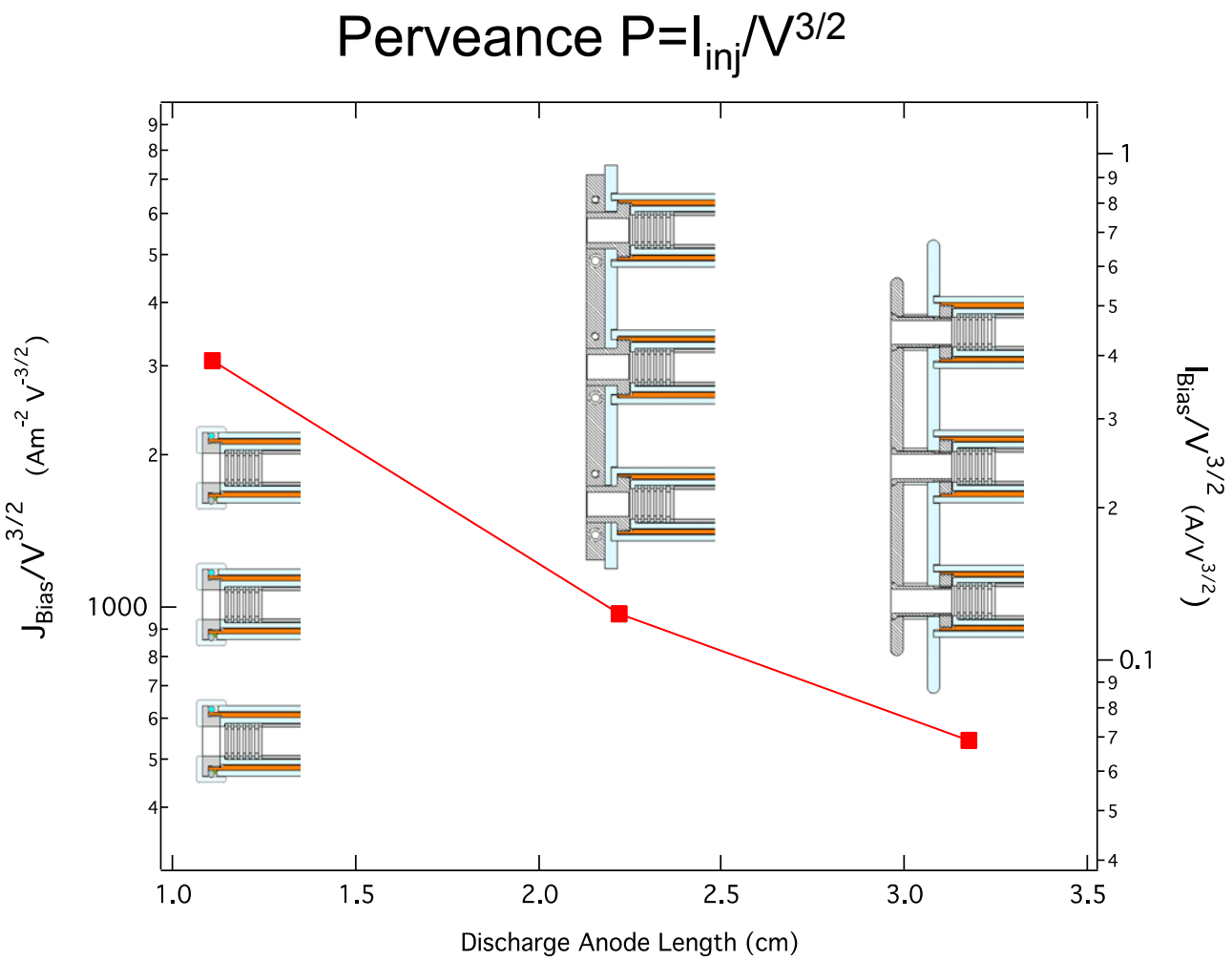




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Perveance Seen to Decrease as Discharge Anode Length Increases

- Increasing perveance with reduced discharge anode suggests DL depends on density from arc discharge



E.T. Hinson, APS-DPP Meeting 2014, Oct 27-31, 2014

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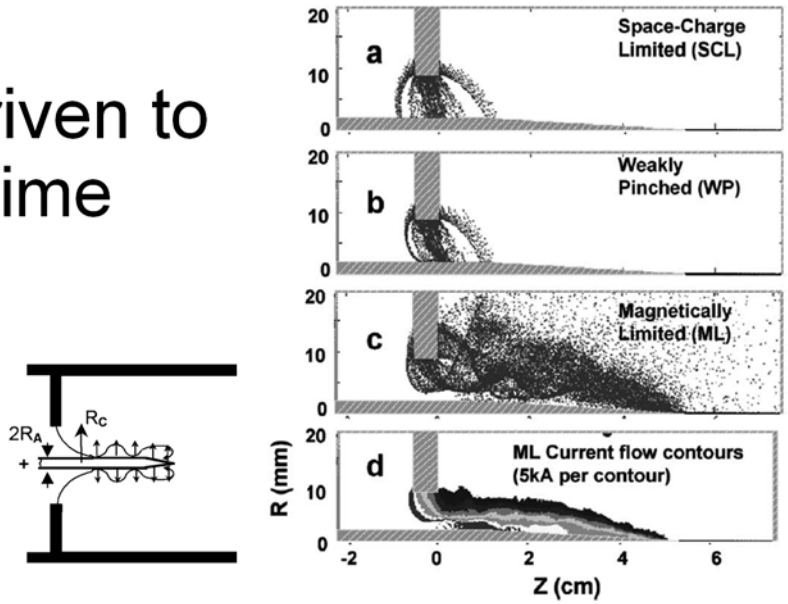
Higher-Power Diodes Show ~$V^{3/2}$ ➔ ~$V^{1/2}$ Scaling due to Magnetic (self-field) Limit

- Example: Rod pinch diode can be driven to from SCL to magnetically-limited regime
  - Self magnetic field produces I~$V^{1/2}$

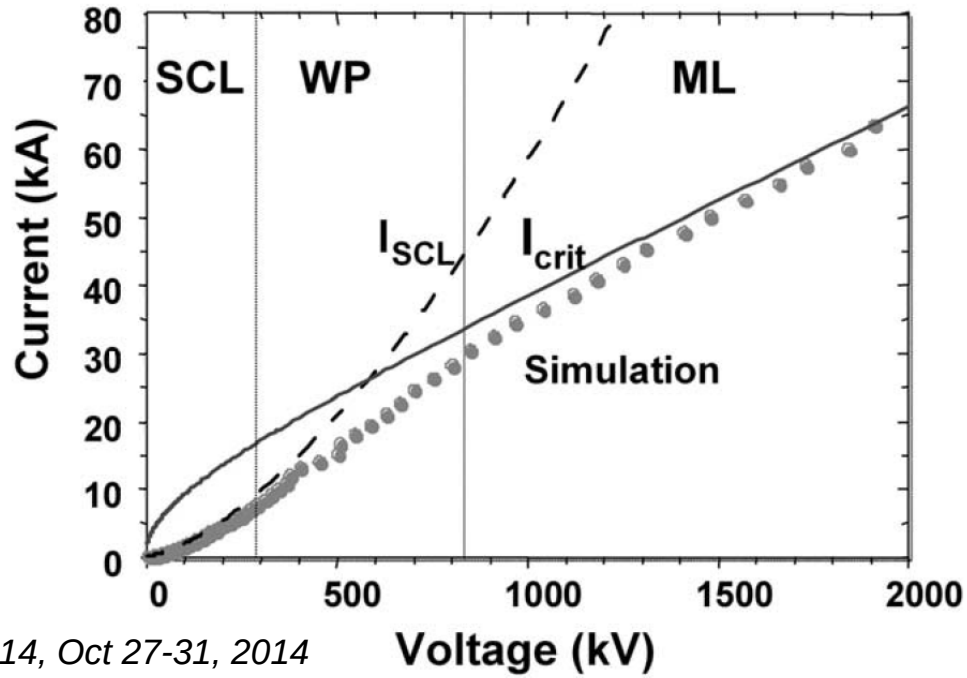
$$I_{Mag}^{RP} \sim I_A \frac{\left(\gamma^2 - 1\right)^{1/2}}{\ln\left(R_C / R_A\right)}$$

$$I_{Mag}^{Lim} \sim I_A \frac{v}{\sqrt{2}c} \frac{1}{\ln\left(R_C / R_A\right)} \sim V^{1/2}$$

- Scaling doesn't have density dependence



J. Maenchen. Proc. IEEE. 92 1021 2004



Hypothesis: LHI Impedance Governed by n_{edge} Via Regulation of a Double Layer

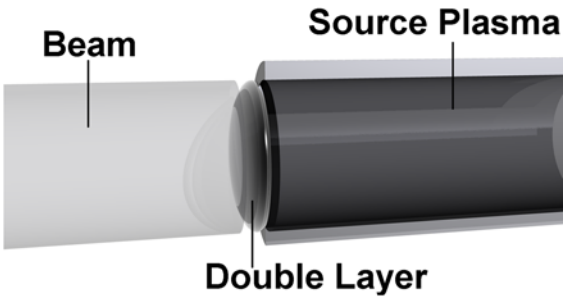
- When edge plasma is sufficiently dense, $I \sim nV^{3/2}$
- At higher I and V, scaling becomes $I \sim nV^{1/2}$, due to either
  - Edge ion density insufficient for space-charge neutralization of beam
  - Sheath expansion seen in simulations at high eV/kT
- Both above mechanisms could explain magnitude/scaling observed in data
- Discriminating between hypotheses requires edge density and arc density measurements

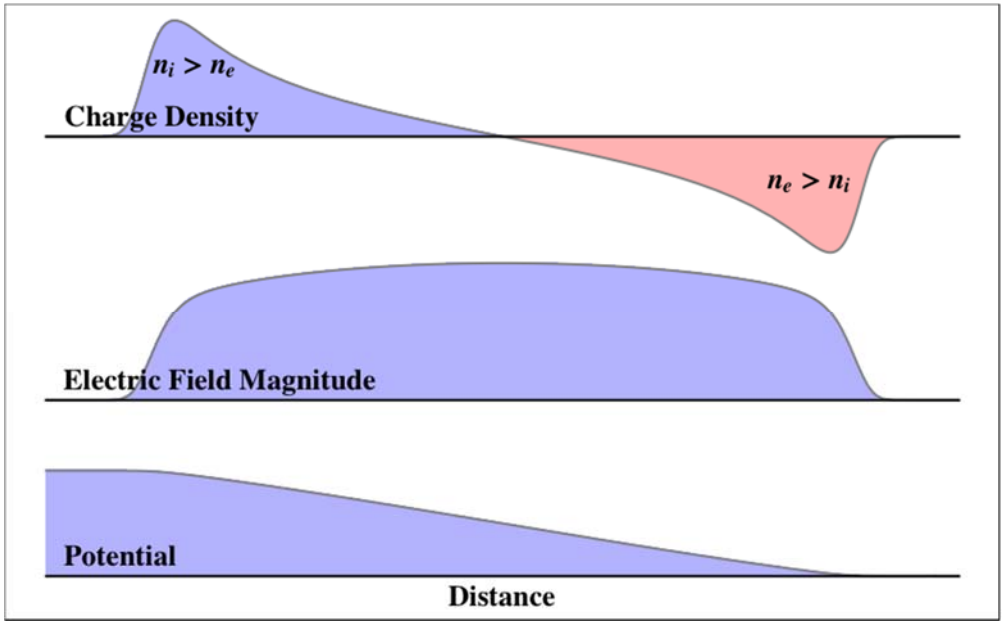
Double Layers are Self-Organized Space-Charged Gaps in Plasmas

- Tend to form in current carrying plasmas/density gradients
- Space charge gap width a plasma-determined quantity
  - Width is order λ_{De} - $\lambda_{De}\left(10\ \text{eV}, 10^{20}\ \text{m}^{-3}\right) = 2\mu\text{m}$
  - Smaller gap can transmit very large currents compared to typical 'vacuum diode' with ~cm dimensions at same voltage
- Efficient particle accelerator of ions and electrons

$$J = \frac{4}{9} 1.865 \varepsilon_0 \left(1 + \sqrt{\frac{m_e}{m_i}}\right)\left(\frac{2e}{m_e}\right)^{\frac{1}{2}} \frac{V^{\frac{3}{2}}}{l^2}$$

$$l^2 = \left(\lambda_{De} \cdot \chi\right)^2 \Rightarrow \boxed{J \sim nV^{\frac{3}{2}}}$$





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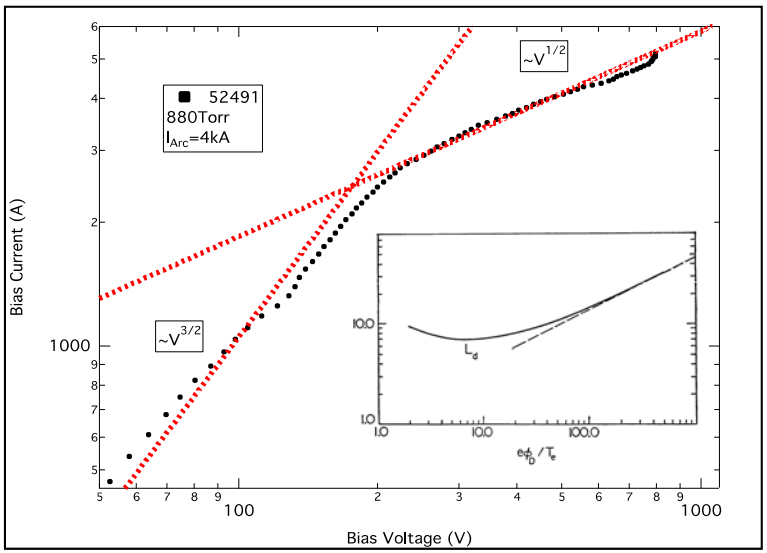
Interpretation 1: Expanding Double Layer Leads to $I \sim n_{arc} V^{1/2}$

- Double layer simulation work finds increasing thickness for large potential steps, $eV_{Bias}/kT_e \geq 10$
- Thickness increases as $V^{1/2}$, (Hershkowitz 1985, Goertz 1975,1978), changing I-V relationship to $I \sim V^{1/2}$
- Observed $I \sim V^{1/2}$ regime occurs at 100-200 V, consistent with expectation ($eV_{Bias}/kT_e \geq 10$)
- (Arc) Density dependence inherited from double layer

$$J \sim \frac{V^{\frac{3}{2}}}{d^2} \sim \frac{V^{\frac{3}{2}}}{(\lambda_{De} \cdot \chi)^2}$$

$$\rightarrow \chi \sim V^{1/2}$$

$$J \sim \frac{V^{\frac{3}{2}}}{\chi^2} \sim \frac{V^{\frac{3}{2}}}{V} \sim V^{\frac{1}{2}}$$



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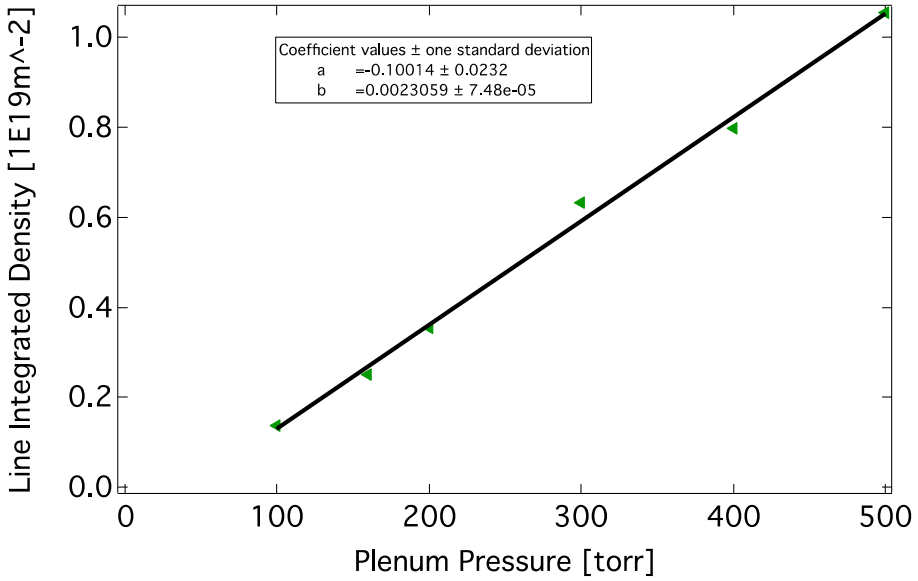
Interpretation 2: Beam Space Charge Neutralization Leads to $I \sim n_{edge} V^{1/2}$

- Edge Quasineutrality at Fixed n_{edge} and V_{INJ} Places a Natural Limit on J_{INJ}, which scales as $n_{edge} V_{INJ}^{1/2}$
- Q-N requires: $$J_{INJ}^{e} \leq n_{edge}^{i} e v_e = n_{edge} e \sqrt{\frac{2eV_{INJ}}{m_e}} \sim n_{edge} \sqrt{V_{INJ}}$$
- Limit scales as $\sim n_{edge} V^{1/2}$ with magnitude in reasonable agreement with data (relevant at $n_{edge} \sim 10^{18} m^{-3}$)
- Half-power regime may represent space-charge limit on injected electrons due to edge ion density

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Interferometer Shows $\bar{n}_e$ Prior to Ramp-up is Linear in Arc Fueling

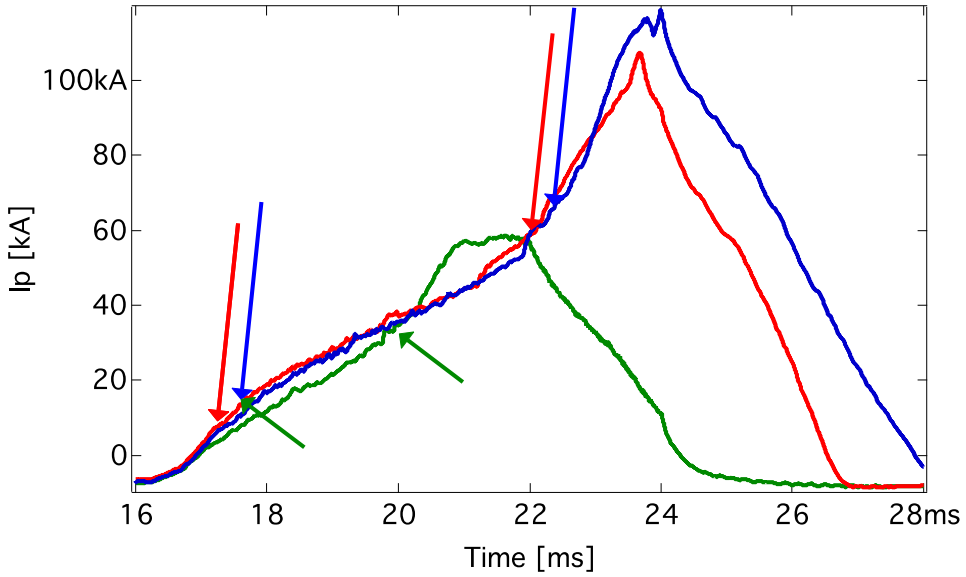
- Sweeping beam across MIF sight line produces no jumps in observed line-averaged density -> well-defined ‘external density’
- Suggests densities of several $10^{18} m^{-3}$ during injector ramp-up
- Conclusion: At ramp-up, fueling is a reasonable linear proxy for ‘edge density’, which is near the space charge limit for beam propagation

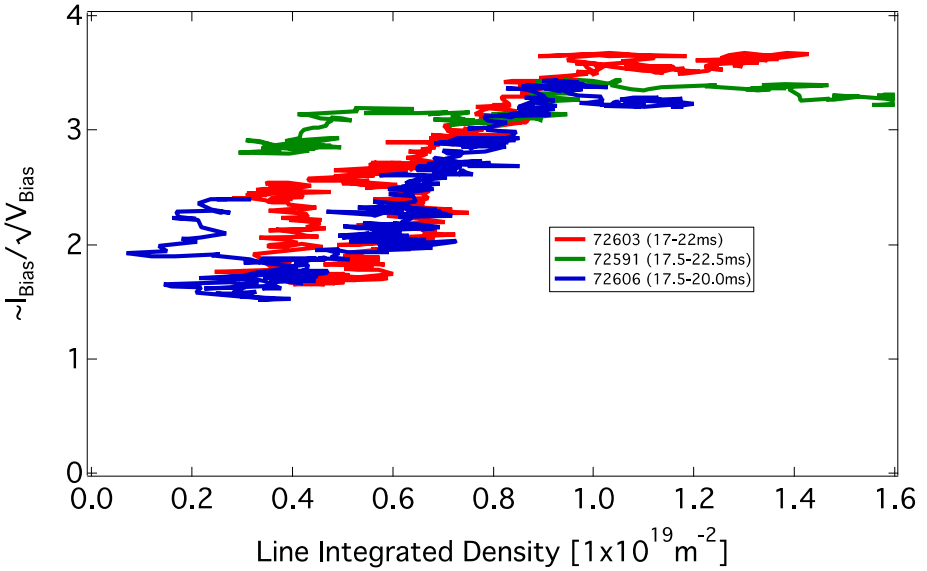


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Interferometer Radial Chord Shows $I_{BIAS}/\sqrt{V_{BIAS}}$ is Linear $\bar{n}$ n_e During Discharge

- Approximately linear dependence of $I_{BIAS}/\sqrt{V_{BIAS}}$ on $\bar{n}_e$ during LHI phase
- Caveat: plasma is growing/ moving – $\bar{n}_e$ subject to corrections
- Available measurements consistent with impedance governed by edge density



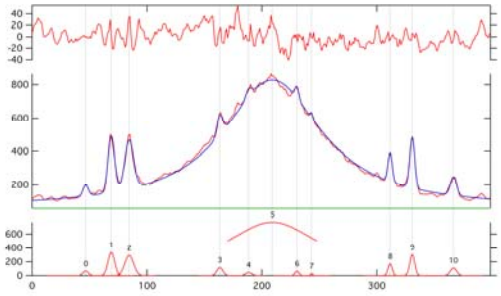


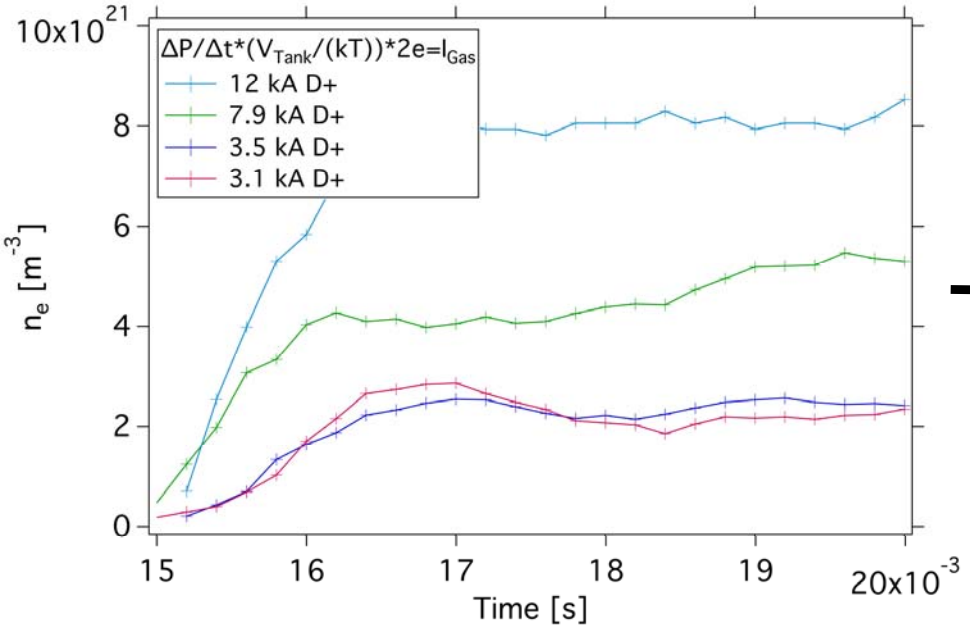
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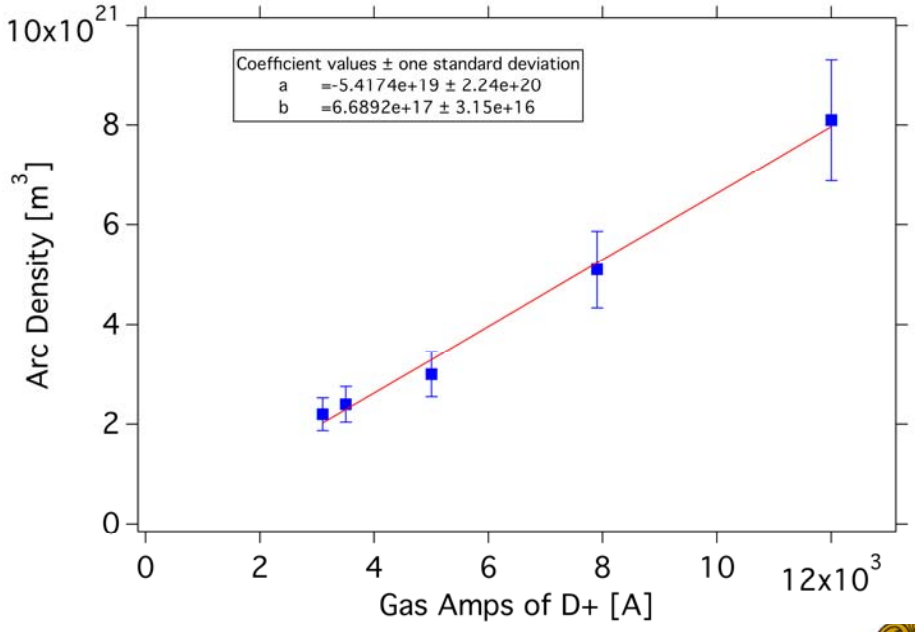
Stark Broadening of H_δ Shows Arc Source Plasma Density is Linear in Fueling

- H_δ profile obtained with view down center of gun
- Peak arc source plasma density is order $10^{21}m^{-3}$ for Pegasus' operating space
- Suggestive of sheath expansion

$$\Delta\lambda_{H-\delta}^{FWHM} = 0.92\left(n_e^{20}\right)^{2/3}\,[\mathrm{A}]$$







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A Comparison of Relative Impact of Local vs Remote Fueling is Needed

- Simultaneous measurements of density at different locations (arc channel, plasma edge) are necessary
  - Sheath growth hypothesis invokes influence of arc density on impedance
    - Measured with H-δ arc density measurements
  - Edge density hypothesis depends on a remote plasma density
    - Deployment of Langmuir probe in edge imminent

- Hypotheses can be discriminated on the basis of differential impact of fueling and resulting density

PMI Suppression/High Voltage Campaign Results

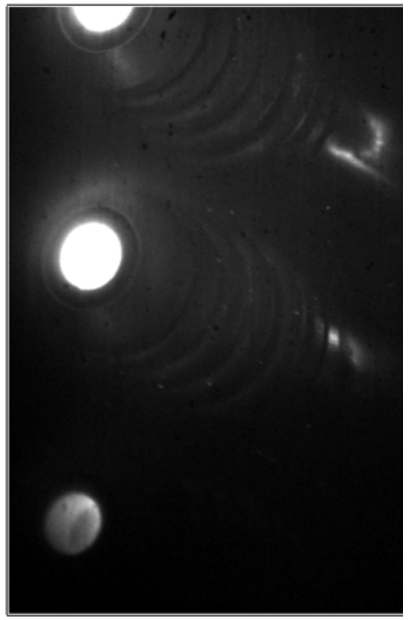
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Applying High Current/Voltage in Edge Region is Formidable Challenge

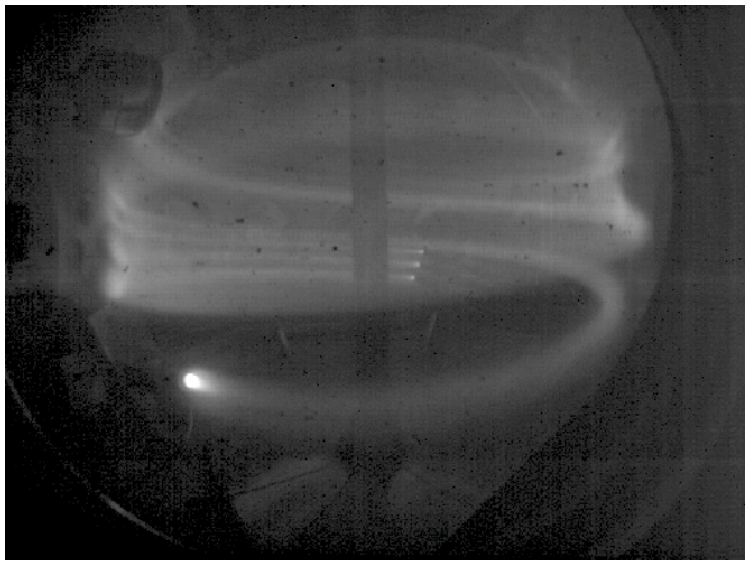
- Injector requirements include
  - Large A_{inj}, J_{inj}
  - $V_{inj} > 1$ kV
  - Multi-MW power input
  - $\Delta t_{pulse} \sim$ 10-100 ms
  - Minimize PMI

  …all adjacent to tokamak LCFS





- Significant evolution of design to meet physics challenges
  - ~3x improvement in V_{inj}, Δt_{pulse}

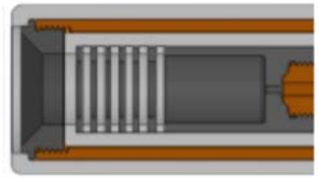


- Present focus on increasing V_{inj}

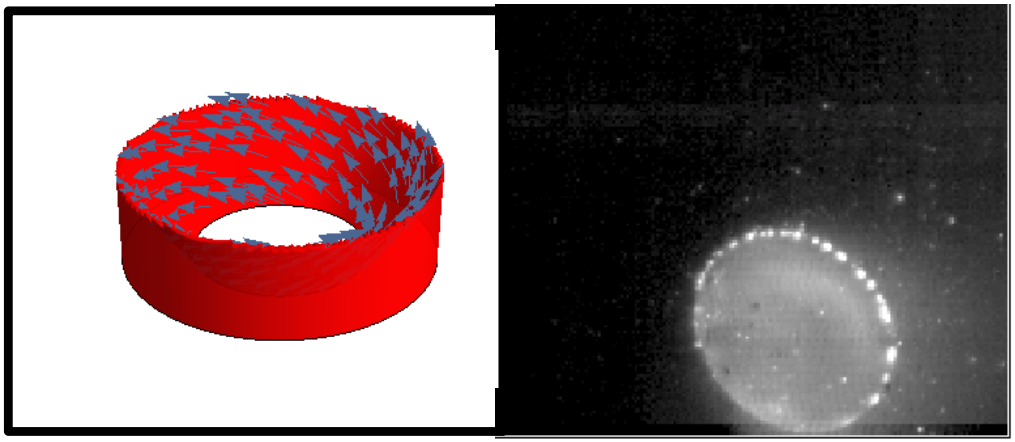
Improved Cathode Design Reduces Impurity Fueling Due to Cathode Spots

- Previous injectors prone to cathode spot damage
  - Spots drift to BN insulator, cause erosion, outgassing
  - Causes severe impurity fueling, loss of bias voltage
- Cathode spot effects mitigated by geometry of cathode
  - Convex cathode face results in cathode spot drift up the cone toward cathode lip, where spots die out
  - Significant reduction in impurity fueling ($Z_{eff} < 1.5$) during LHI

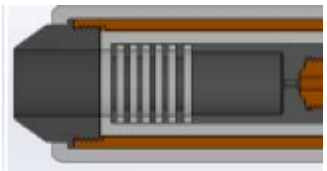
Concave Cathode



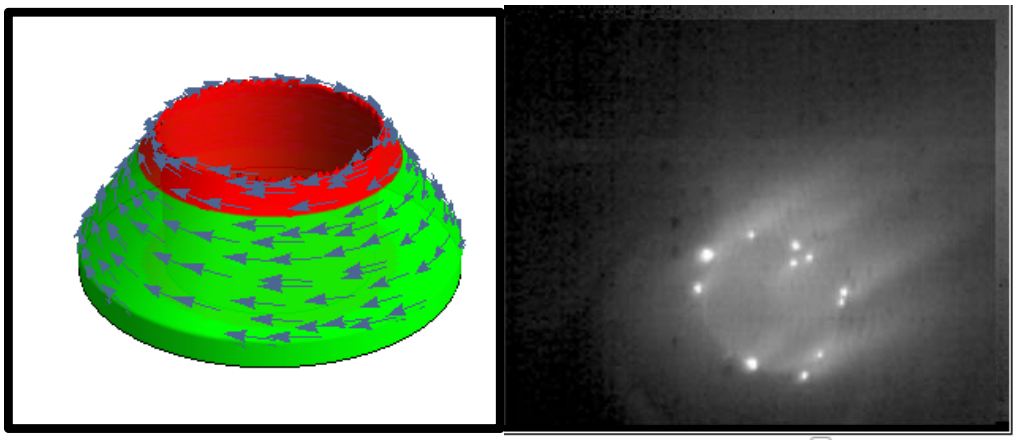
Cathode spots migrate to BN



Convex Cathode

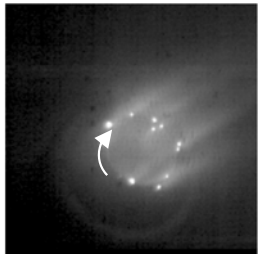
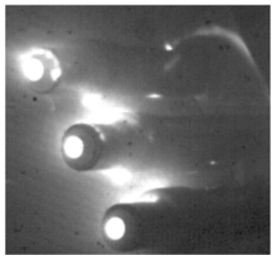


Spots remain on ridge of frustum



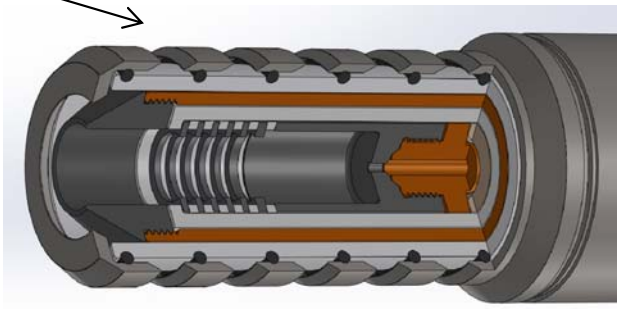
Injector Shielding Has Allowed Higher Achievable Bias Voltage

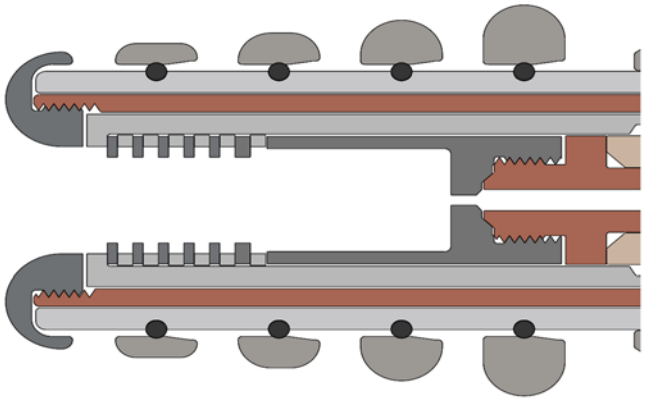
- Frustum geometry provides cathode spot control
  - Still suffered arc-back of injector

- Molybdenum rings added outside of BN gun sleeve
  - Breaks arc-path, requiring multi-point failure
  - Allowed tripling of bias voltage
  - Thermal loading lead to fractures

Guard Rings

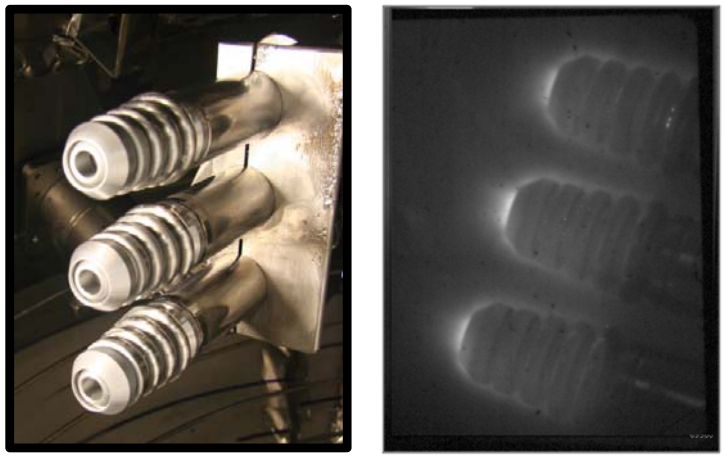



- Rounded cathode currently installed, being tested

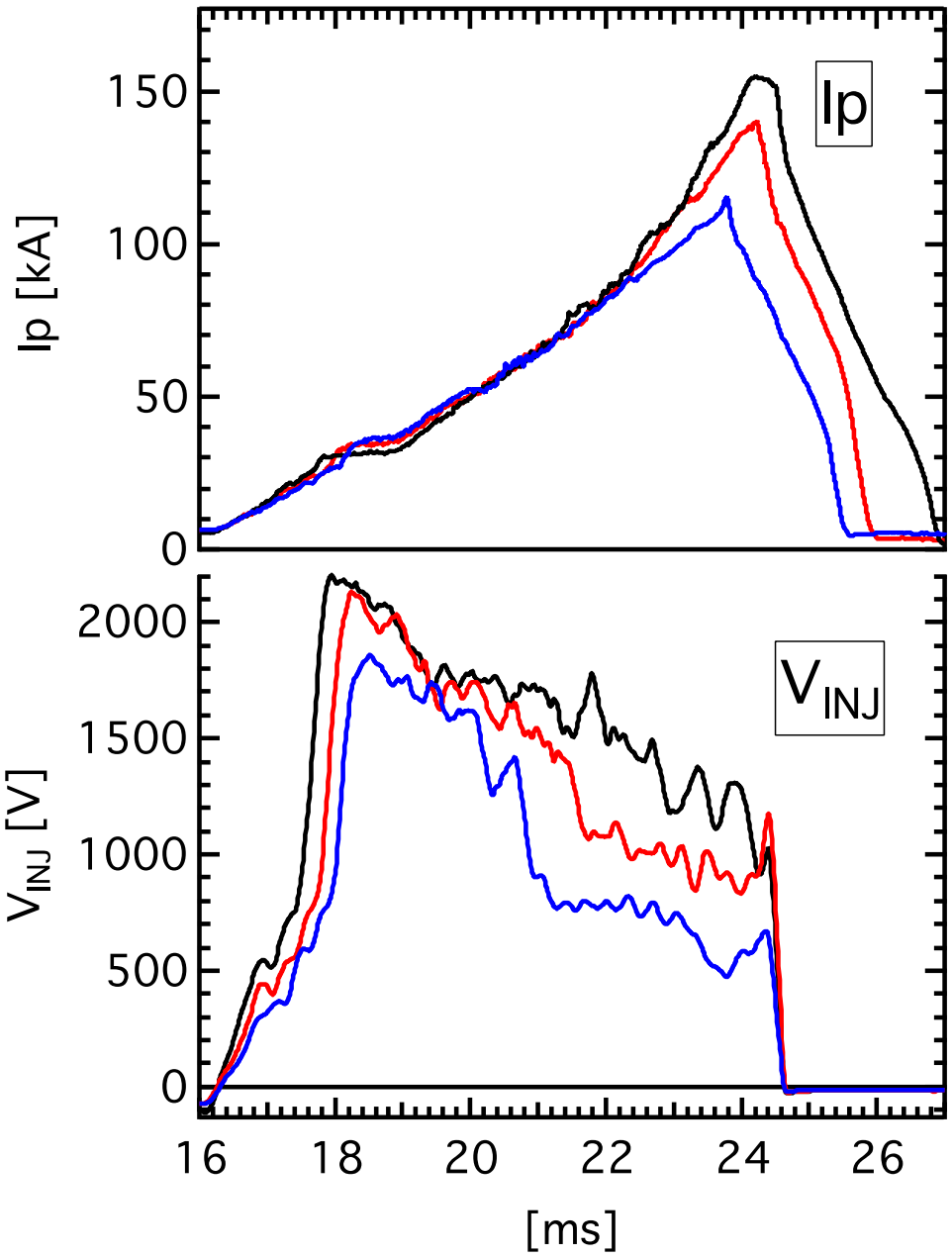
Higher I_p Evident as HI Rate Increases

- Higher injector voltage operation shows increased I_p at as V_{eff} increases
  - Enabled by new high V_{INJ} injector

"Pagoda"-style injectors with quiescent operation



Injector voltages and associated I_p



Summary

- Plasma current limits of DC helicity injection depend on injector voltage and current
  - Relationship between voltage and current is a plasma-determined quantity
  - Power supply requirements will be determined by impedance
  - Scaling of voltage/current requirements determine feasibility of technique on larger devices

- Relationship between voltage and current is determined by space-charge effects/sheath physics

- Injector design improvements have allowed increased achievable bias voltage

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