Impedance Model for Outboard-Midplane Helicity Injection Sources

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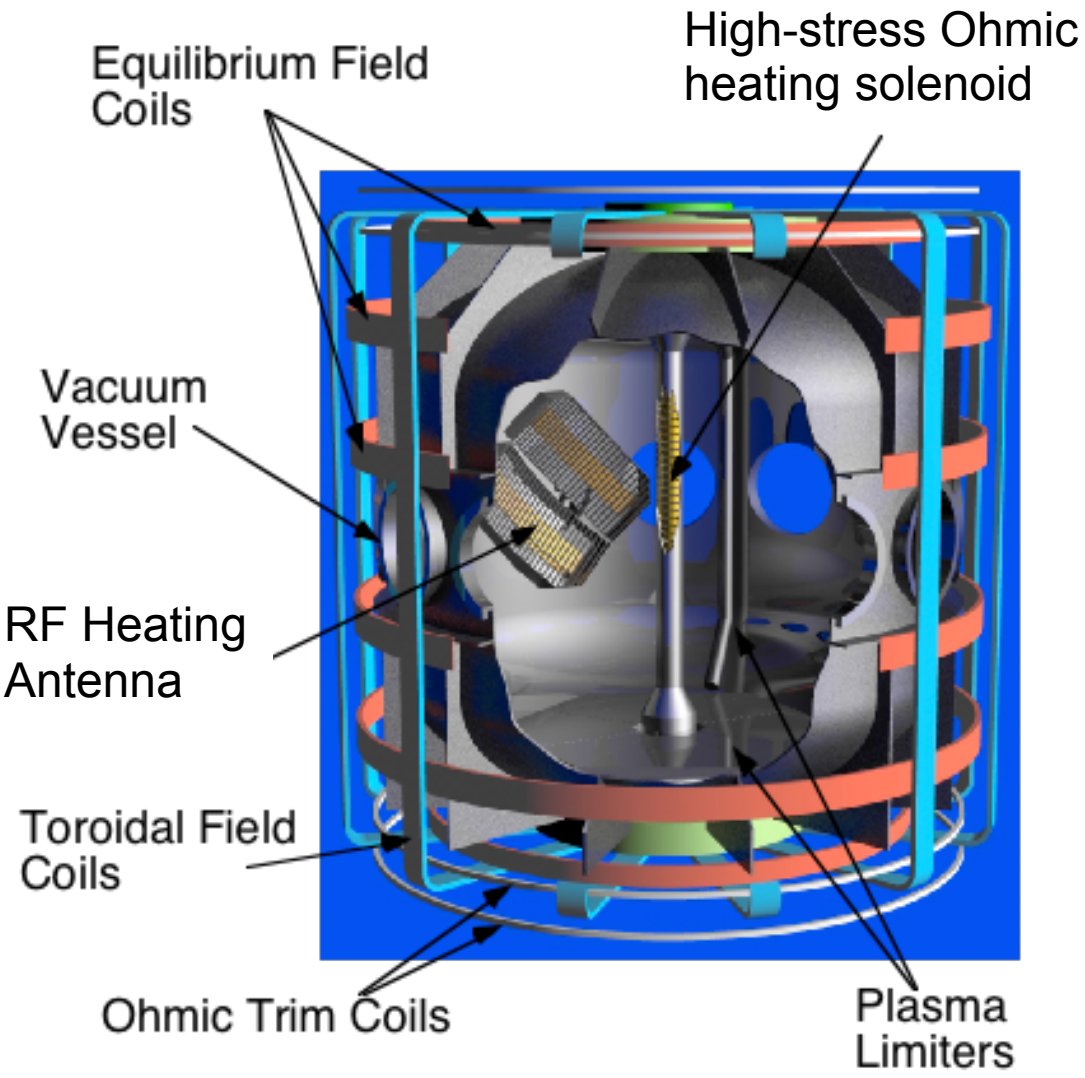
Poster PP9.00004
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November 16, 2011

PEGASUS Toroidal Experiment

Summary

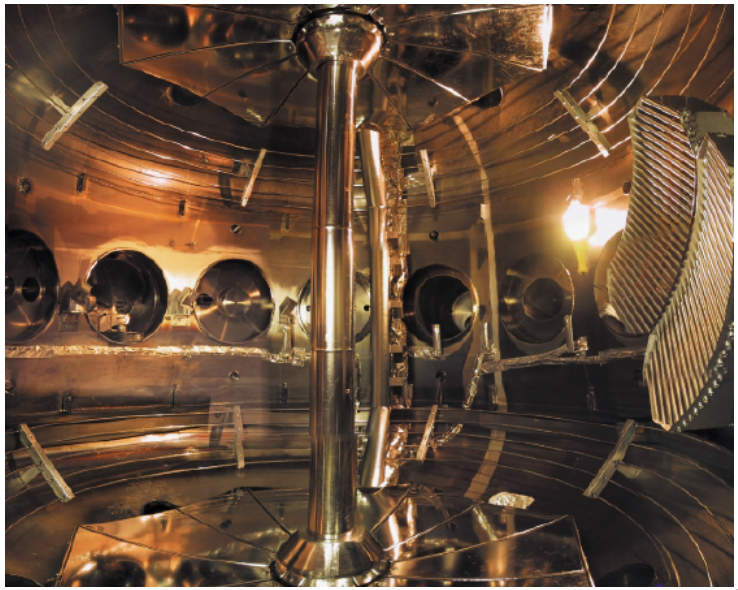
- Current injectors have been deployed on Pegasus for helicity injection start-up
- Impedance observed through the plasma greatly exceeds that expected for Spitzer-like resistivity
- Impedance is observed to decrease with neutral fueling
- Observed I-V characteristics suggest a strong double layer governs the impedance seen in the bias circuit
- At high currents, either current saturation or a $I \sim V^{1/2}$ characteristic is observed
- When injectors are operated as simple, passive electrodes, the impedance remains consistent with that predicted by the Child-Langmuir Law for double sheaths

PEGASUS: A University Scale, Ultralow-A ST



Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
I_N (MA/m-T)	6 – 12
ℓ_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



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Pegasus is Developing Current Drive via Helicity Injection

Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, d^3x - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot d\mathbf{s}$$

- Resistive Helicity Dissipation
  - $\mathbf{E} = \eta \mathbf{J} \rightarrow$ much slower than energy dissipation ($\eta \mathbf{J}^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity

- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
  - Ψ is toroidal flux, ψ is poloidal flux (*e.g.*, current drive through solenoid induction)

- DC Helicity Injection $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$
  - Φ is electrostatic potential

Helicity Injection Rate is Proportional to Injector Voltage

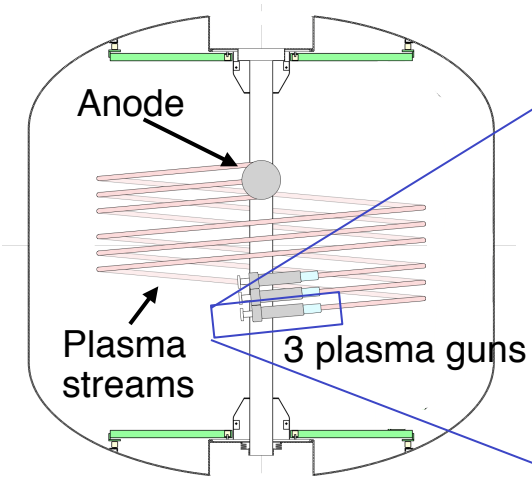
- Plasma gun(s) biased relative to vessel:
  - Helicity injection rate:

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

V_{inj} - injector voltage

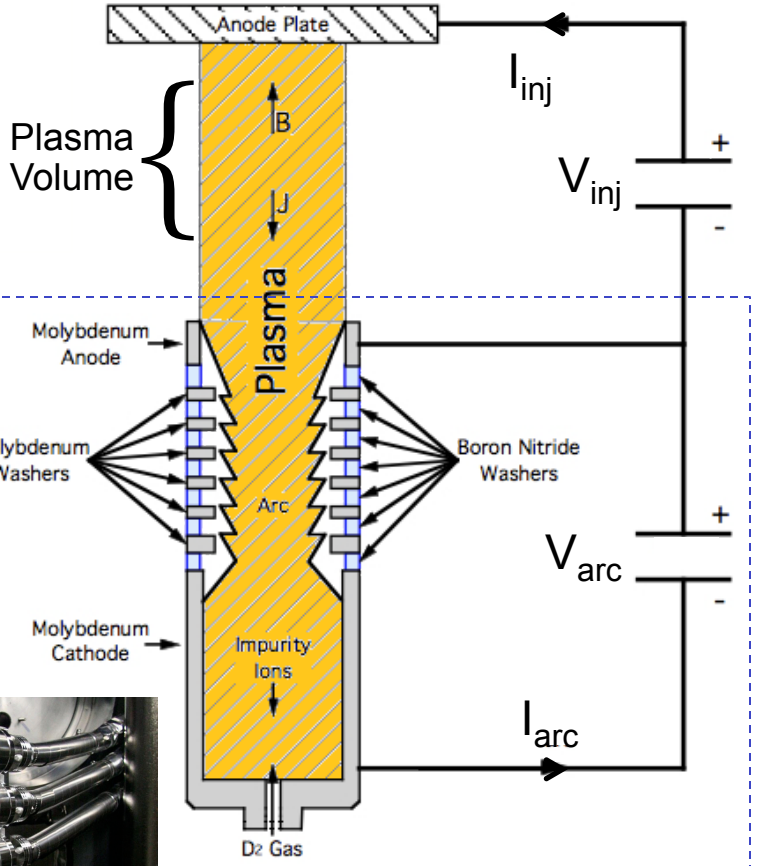
B_N - normal B field at gun aperture

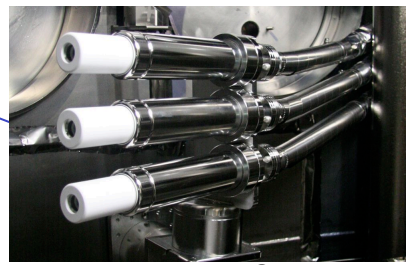
A_{inj} - injector area



Midplane Injection

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

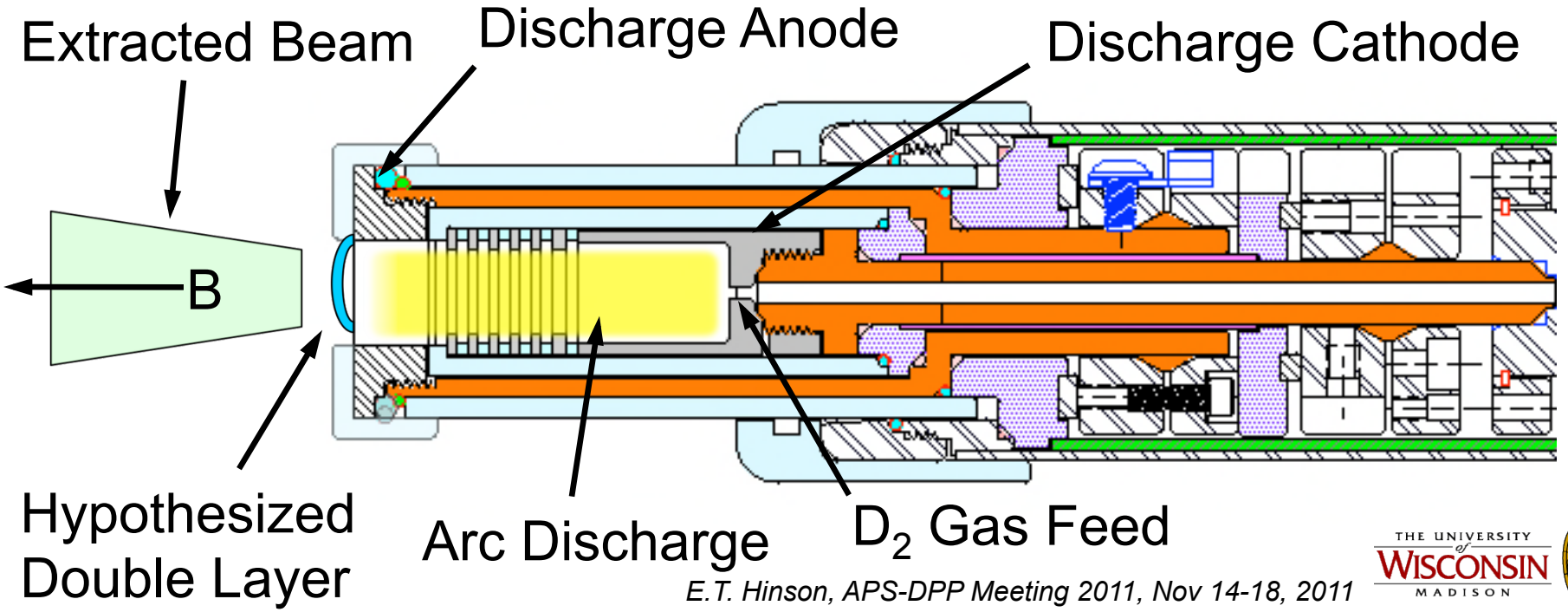




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Predictive Model of Injector Voltage is Necessary

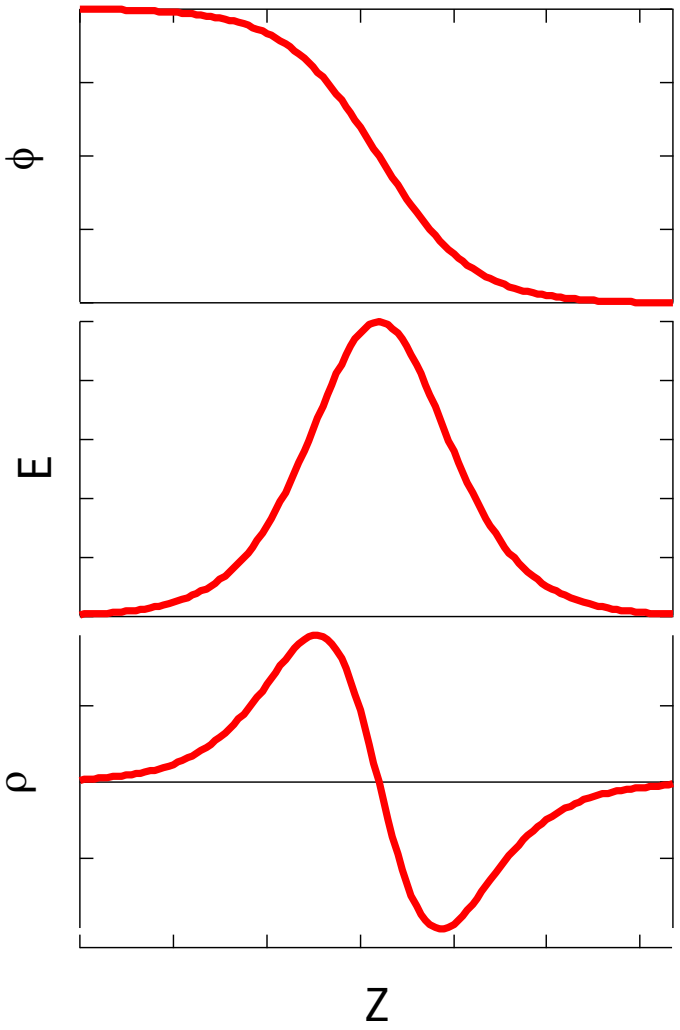
- Helicity injection current drive has been accomplished in Pegasus with washer-stack guns and electrodes
- Current extracted from washer-stack guns is drawn from a plasma cathode formed with an arc discharge
- It is hypothesized that an electrostatic double layer at the discharge anode determines the impedance of the injector



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A Double Layer Sheath Model is Under Consideration

- Tend to form in current-carrying plasmas and at the interface between very different plasmas
  - Density gradients
  - B-field Gradients
- Are observed to form in field-aligned currents
- Have been observed in discharge anode regions of other plasma-cathode electron sources (Oks 2003*)



*Oks, E. M. Plasma Cathode Electron Sources, (2003)

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Current Through Double Layer is Predicted to be Given by $I \sim V^{3/2}$

- Space-charge limited current through double-layer
  - depends on plasma parameters (n_e, T_e)
  - is proportional to current injection area

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

Where l is the sheath thickness

$$l^2 = \left(\lambda_{De} \cdot \chi\right)^2 = \frac{T_e \varepsilon_0}{n_e e} \chi^2$$

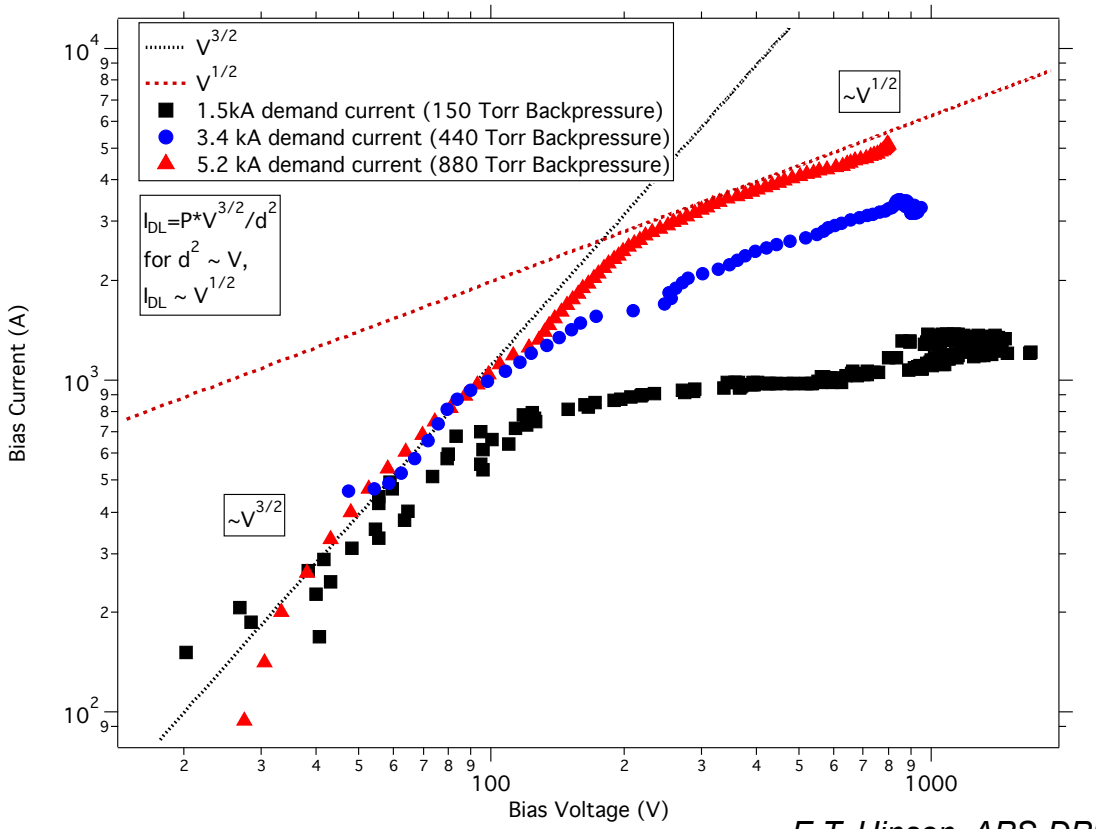
$$J_{inj} \sim \frac{V^{\frac{3}{2}}}{l^2} \sim \frac{V^{\frac{3}{2}}}{T_e} \frac{n_e}{\chi^2}$$

$$I_{inj} \sim \frac{V^{\frac{3}{2}}}{T_e} \frac{n_e}{\chi^2} A_{inj}$$

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Gun I-V Characteristics Exhibit I~$V^{3/2}$ + Saturation Features

- Injector gassing tuned for minimal gassing, such that arc discharge is marginally-stable.
  - Tuned injectors exhibit I~$V^{3/2}$ to current saturation at ~I_{arc}.
- For additional gassing, high currents go as I~$V^{1/2}$



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Double Layer Model Predicts Linear Dependence of I_{inj} on n_e

- Several experimental methods of control over n_e:
  - Control over n_n via fueling through gun
  - Distance between double layer and arc plasma (discharge anode length)
  - External puffing

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

$$l^2 = \left(\lambda_{De} \cdot \chi\right)^2 = \frac{T_e \varepsilon_0}{n_e e} \chi^2$$

$$I_{inj} \sim \frac{V^{\frac{3}{2}}}{\chi^2} \frac{n_e}{T_e} A_{inj}$$

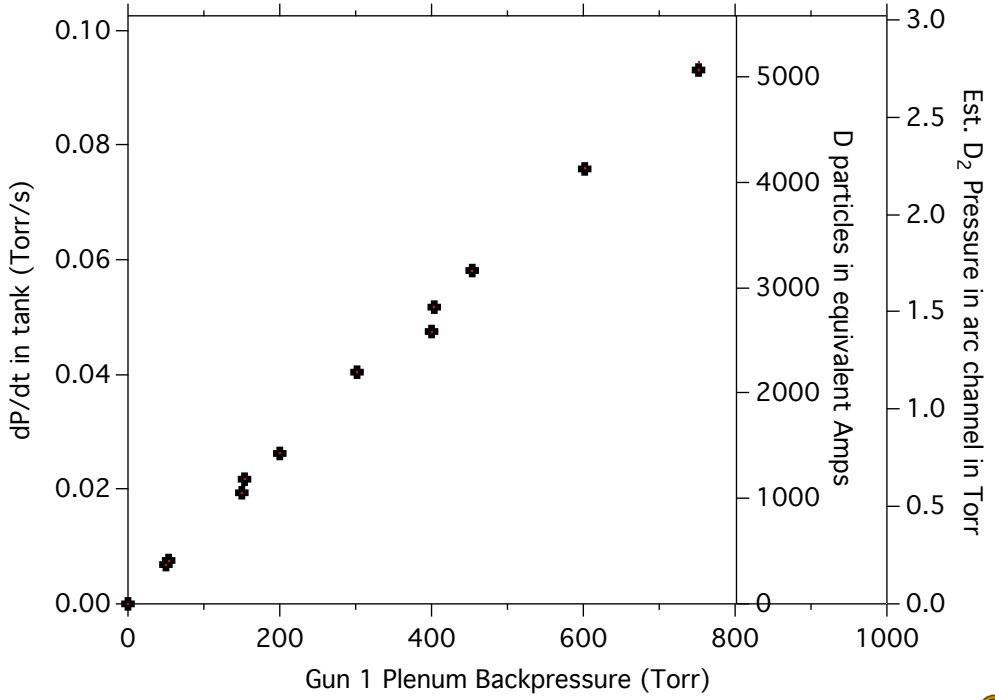
Neutral Throughput, n_n, and Inferred n_e Controlled with Injector Backpressure

- n_e is expected to be proportional to n_n, since arc is highly ionized (~10kW/cm^3)
- Neutral throughput into gun is governed by choked flow, giving linear dependence on backpressure
- n_n is also expected to be proportional to gun backpressure

$$\frac{dN}{dt} = ApK$$

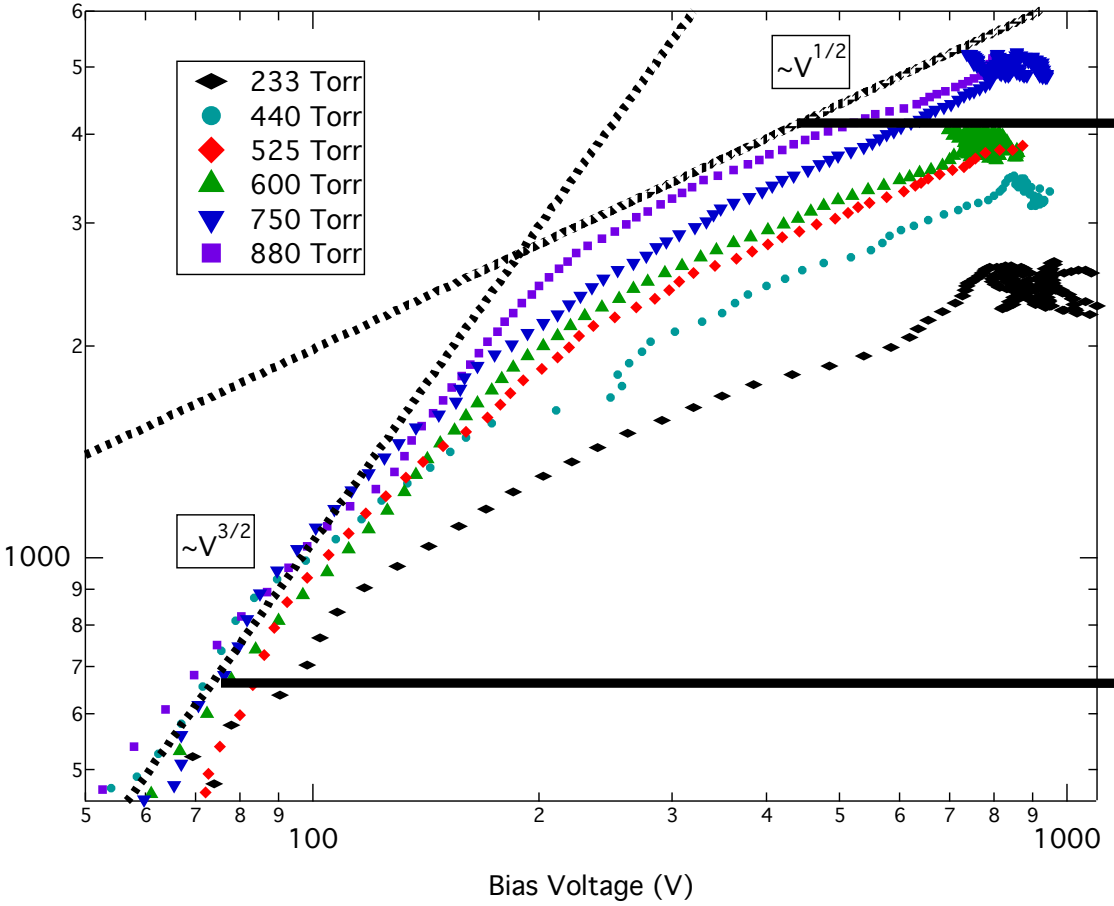
$$K = \frac{\sqrt{\frac{\gamma M_{mol}}{ZRT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}{m_{D_2}}$$

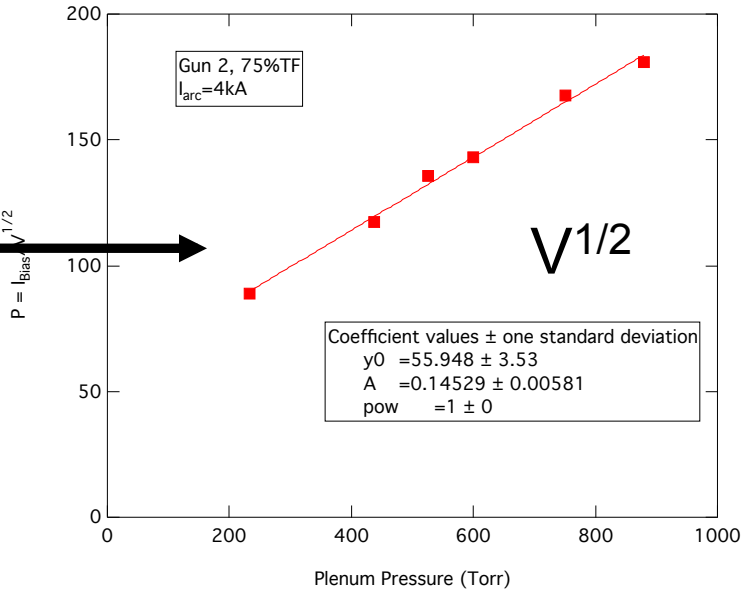
$$K = 1.3 \times 10^{23}\, s^{-1} Pa^{-1} m^{-2}$$

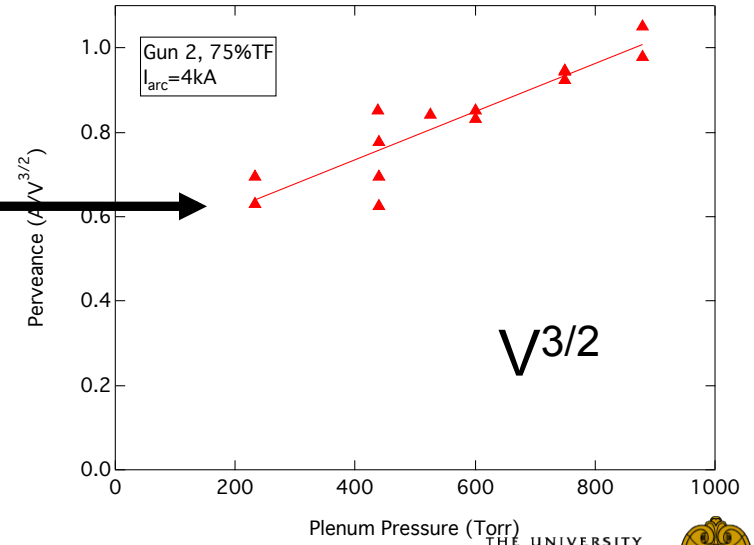


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Bias Current is Linear in Inferred n_e

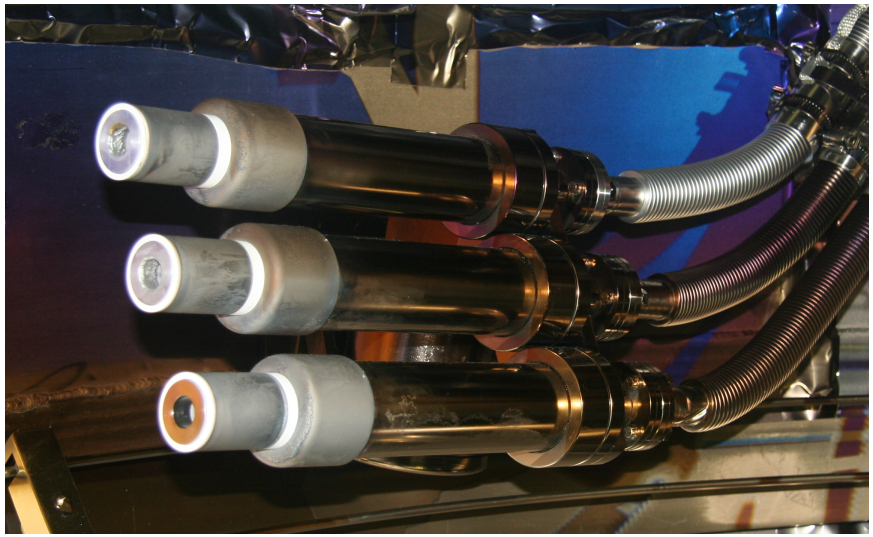


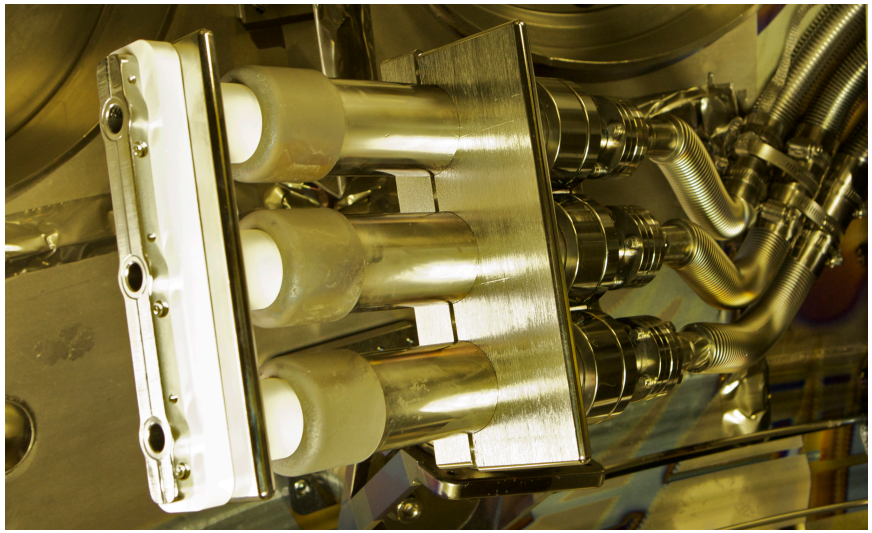


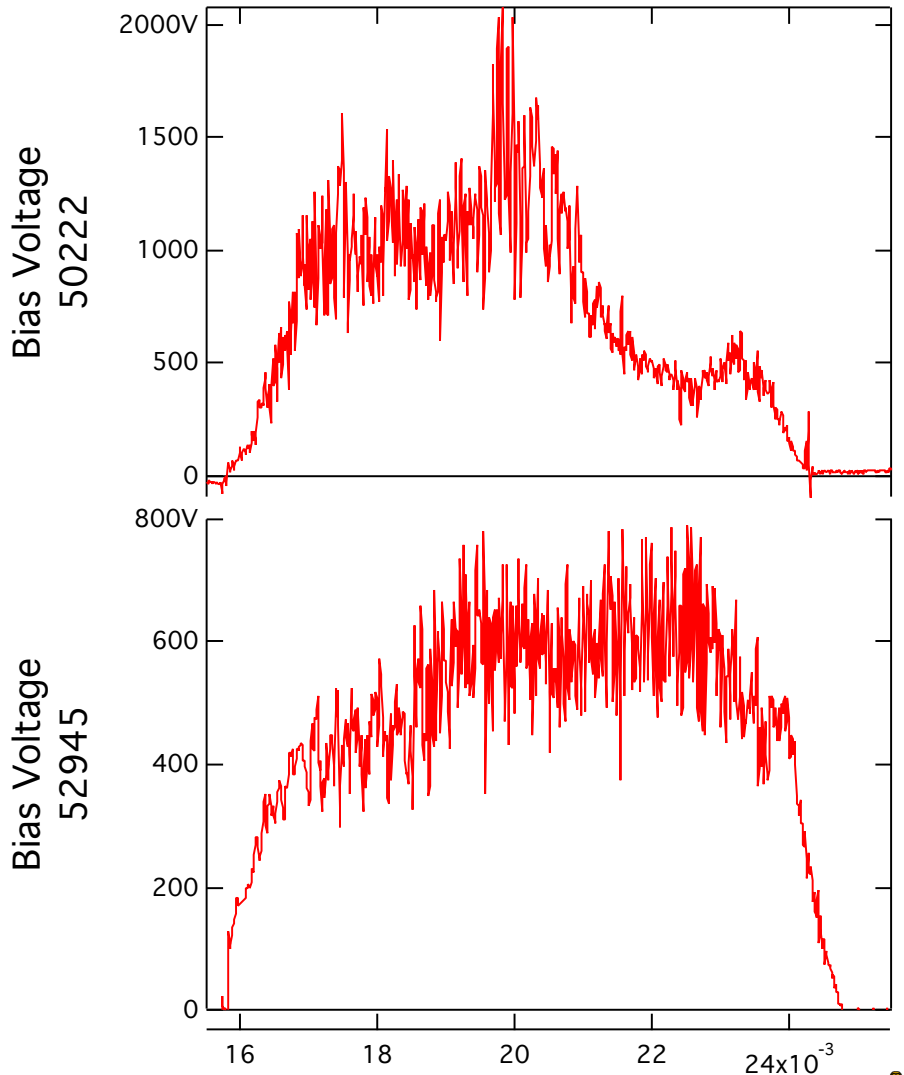


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Local limiters Added to Reduce Plasma Scrape-off n_e Feedback on Injector Voltage







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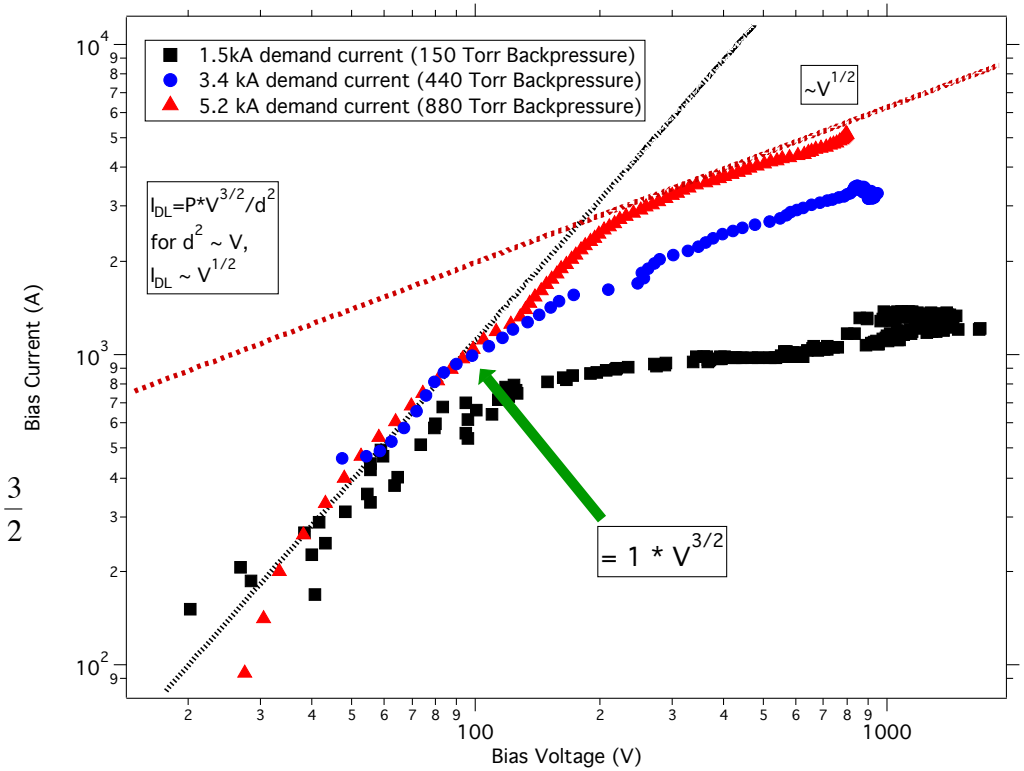
I_{inj} Magnitude Correct for Estimated Plasma Parameters

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

$$l^2 = \left(\lambda_{De}\cdot\chi\right)^2 = \frac{T_e\varepsilon_0}{n_e e}\chi^2, \qquad I_{DL} = J_{DL}A$$

$$I_{DL} = \underbrace{\frac{4}{9}1.865\varepsilon_0\left(1+\frac{m_e}{m_i}\right)\left(\frac{2e}{m_e}\right)^{\frac{1}{2}}\frac{en_eA}{\varepsilon_0 T_e\chi^2}}_{=P}V^{\frac{3}{2}}$$

$$I_{DL} \sim PV^{\frac{3}{2}}$$



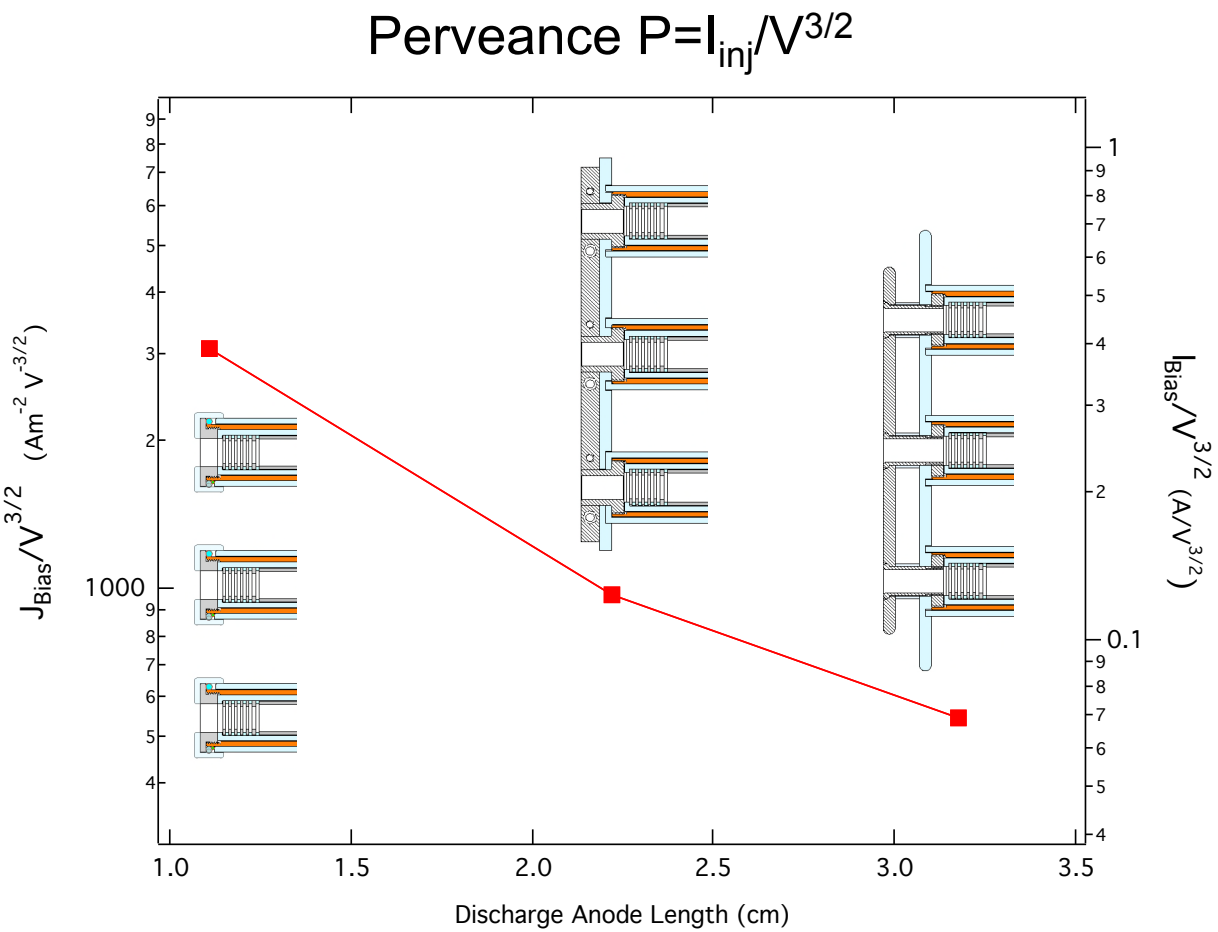
For expected injector - specific parameters :

$$A = 2\times10^{-4}\,m^2,\ \chi\sim10,\ n_e\sim10^{20}m^{-3},\ T_e\sim10eV$$

$P\sim1$, consistent with observed values of perveance

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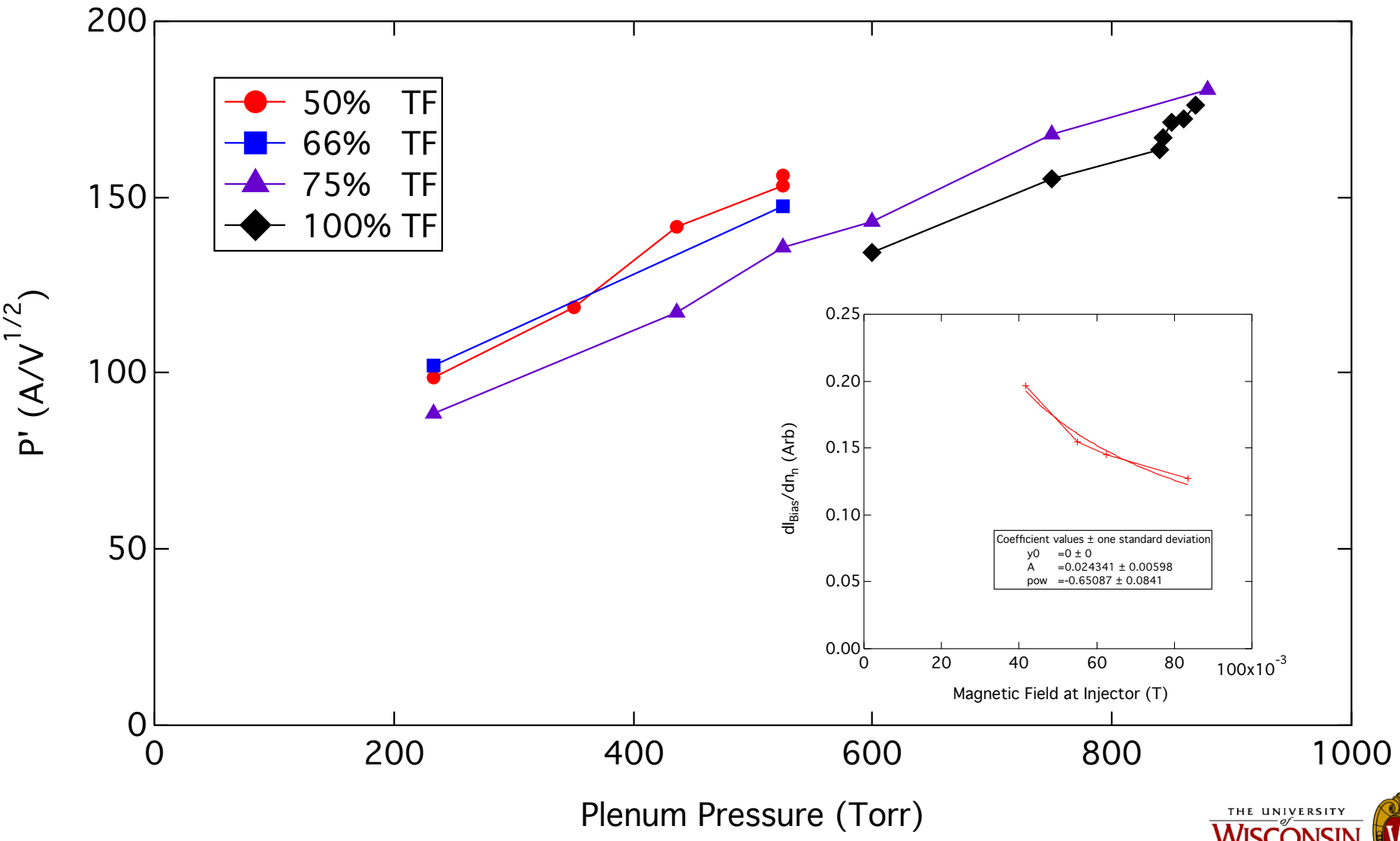
Perveance seen to decrease as discharge anode length increased



- Observed effect could be a combination of reduced impurity fueling and increased distance between DL and arc plasma
- Both effects relate density to impedance in the expected way

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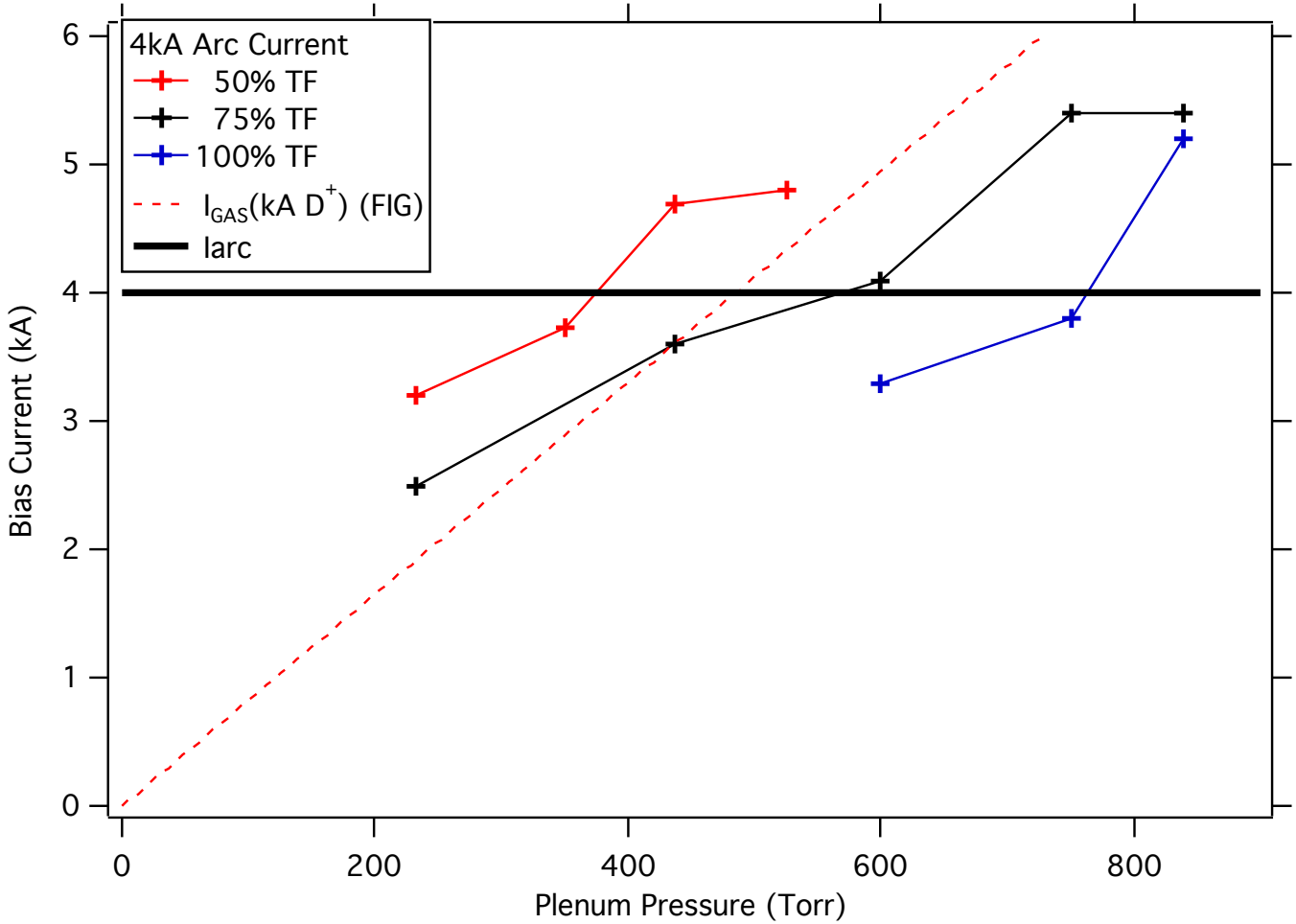
Current at Fixed Voltage and Pressure is Dependent on Magnetic Field



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Achievable I_{bias} from Gun Arc Appears to be a Function of Arc Plasma Density

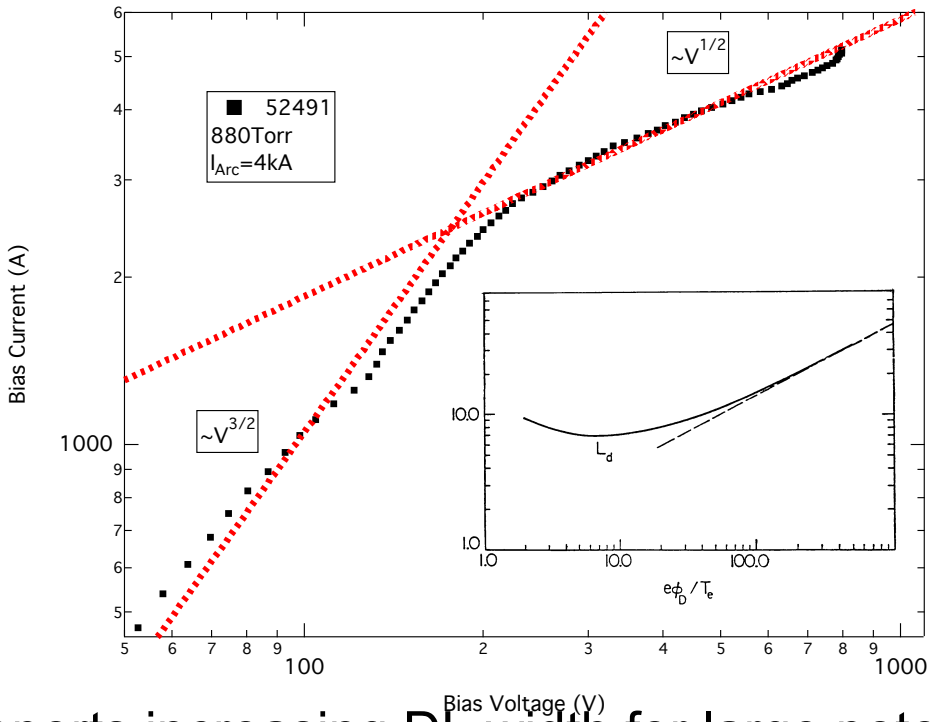
- With sufficient gas fueling, bias currents in excess of the arc discharge current can be drawn without breakdown of the discharge anode and onset of cathode spots.



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Increased Demand Currents with Significant Gassing Drawn with $I \sim V^{1/2}$

- Currents in excess of arc current can be obtained with increased fueling
- At current densities in the range of electron thermal current, the characteristic changes to $V^{1/2}$.
- This transition increases linearly with fueling.



- Literature reports increasing DL width for large potential steps, $\frac{eV_{Bias}}{kT_e} \geq 10$ increasing as $V^{1/2}$, (Hershkowitz 1985, Goertz 1975,1978) consistent with observed I-V curves.

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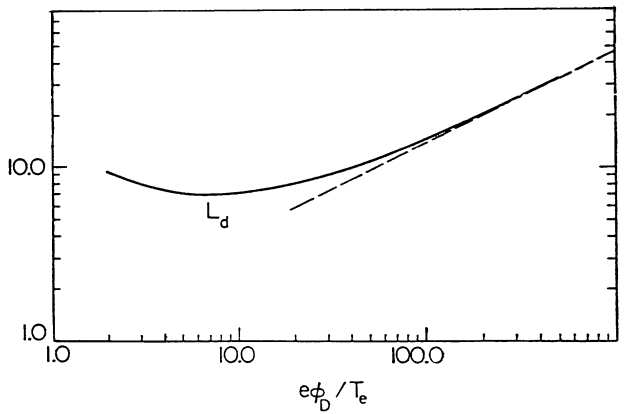
I~V$^{1/2}$ Region Potentially Due to Sheath Expansion

- Current at the transition to V$^{1/2}$ region increases linearly with increasing neutral gassing
- If electron saturation current is reached, just as with a Langmuir probe in ion saturation, sheath will begin to expand with additional bias (V increasing, J fixed, or weakly-dependent on sheath thickness l)
- Additionally, literature (simulations) report increasing sheath thickness at eV/kT>10, which is approximately where it is observed in Pegasus (V~100 V, T~10eV)

$$J \sim \frac{V^{\frac{3}{2}}}{l^2}$$

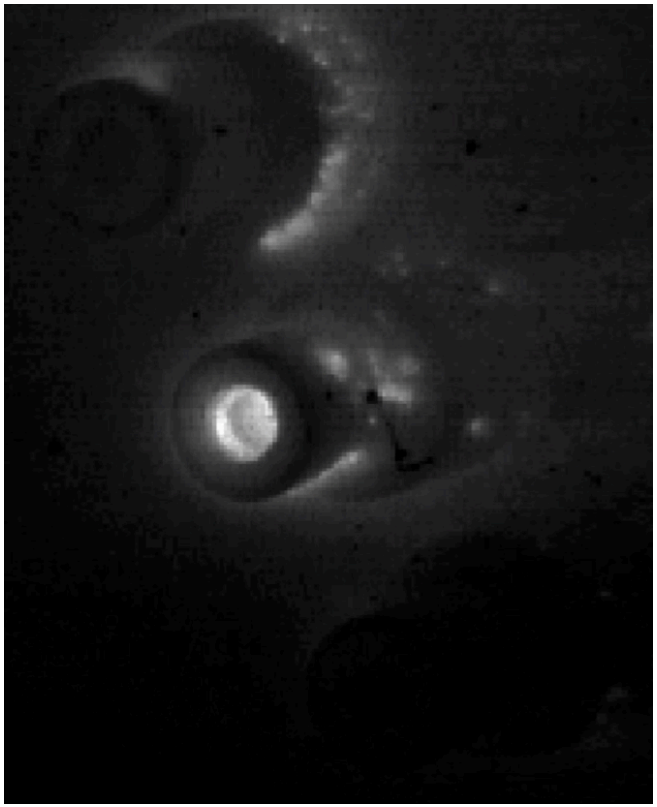
$$l^2 = \left(\lambda_{De} \cdot \chi\right)^2 = \frac{T_e \varepsilon_0}{n_e e} \chi^2$$

$$J \sim \frac{V^{\frac{3}{2}}}{T_e}$$

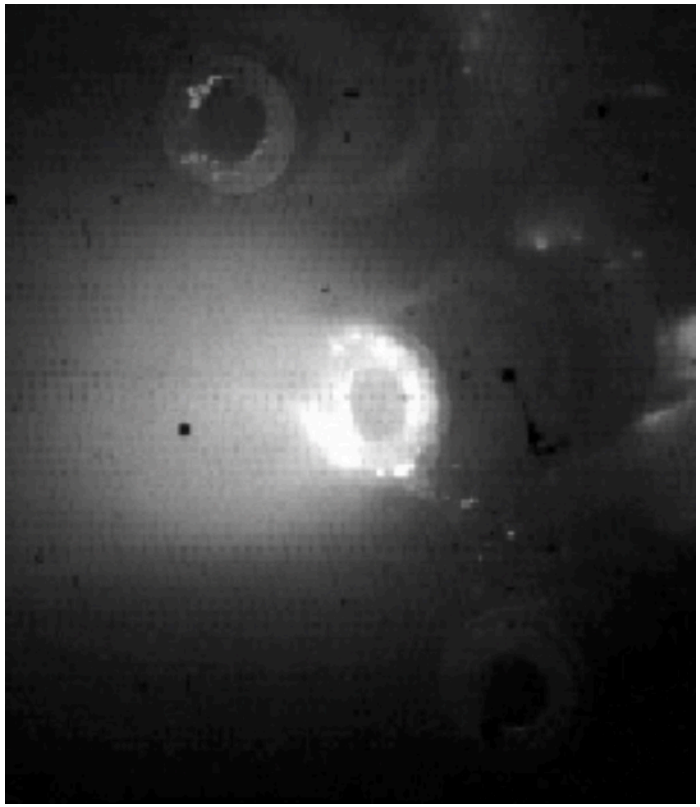


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Current Injection Mechanism During Electrode Drive Switches to Cathode Spots



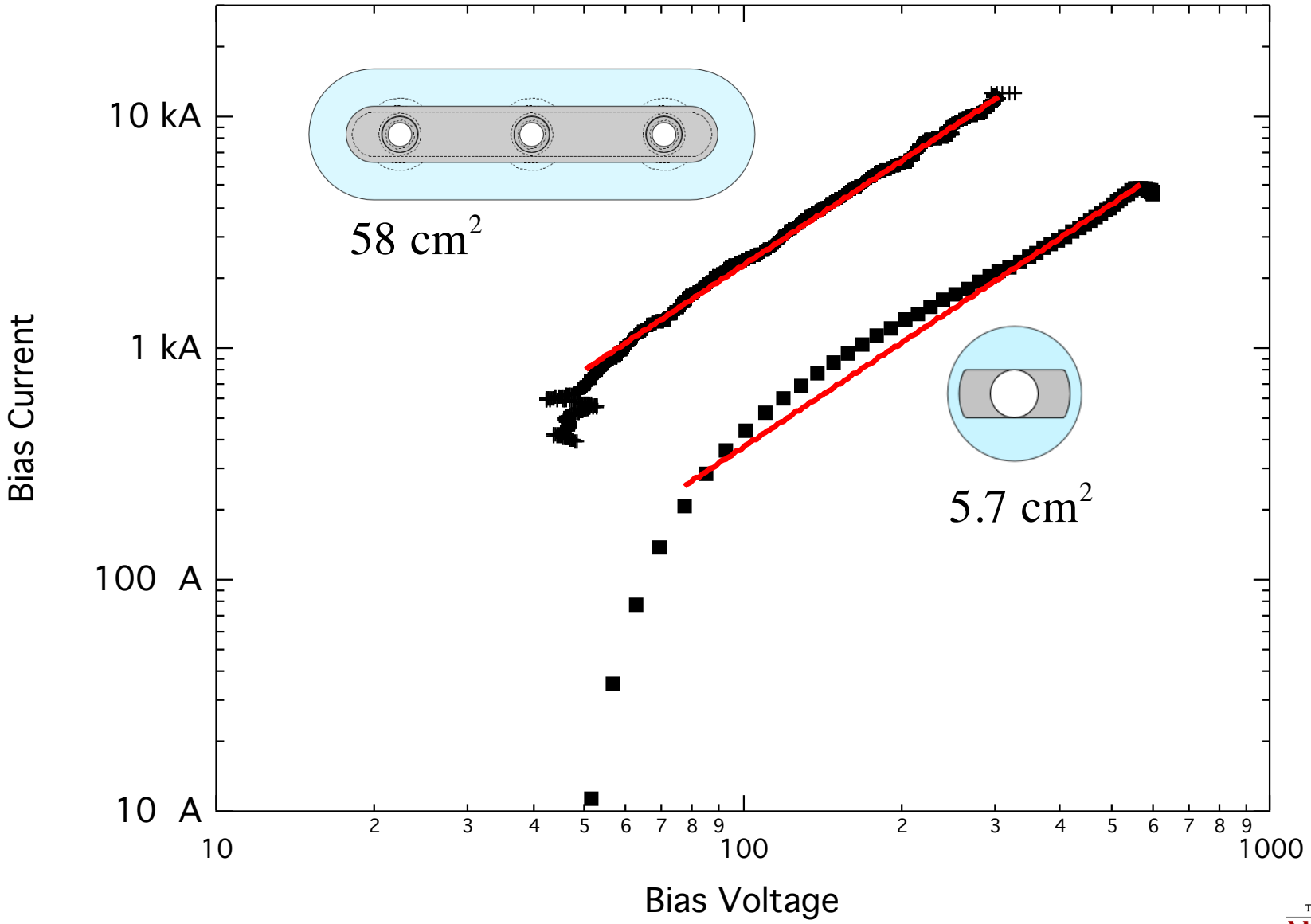
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- Impedance characteristics during electrode drive also under investigation
- Expected to reflect high current through cathode spots, but also manifest high impedance - current appears space-charge limited

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Electrode Impedance at I_{BIAS} Ramp-down also Consistent with $I \sim V^{3/2}$



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