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Response of the plasma to the size of an electron collecting electrode biased near the plasma potential

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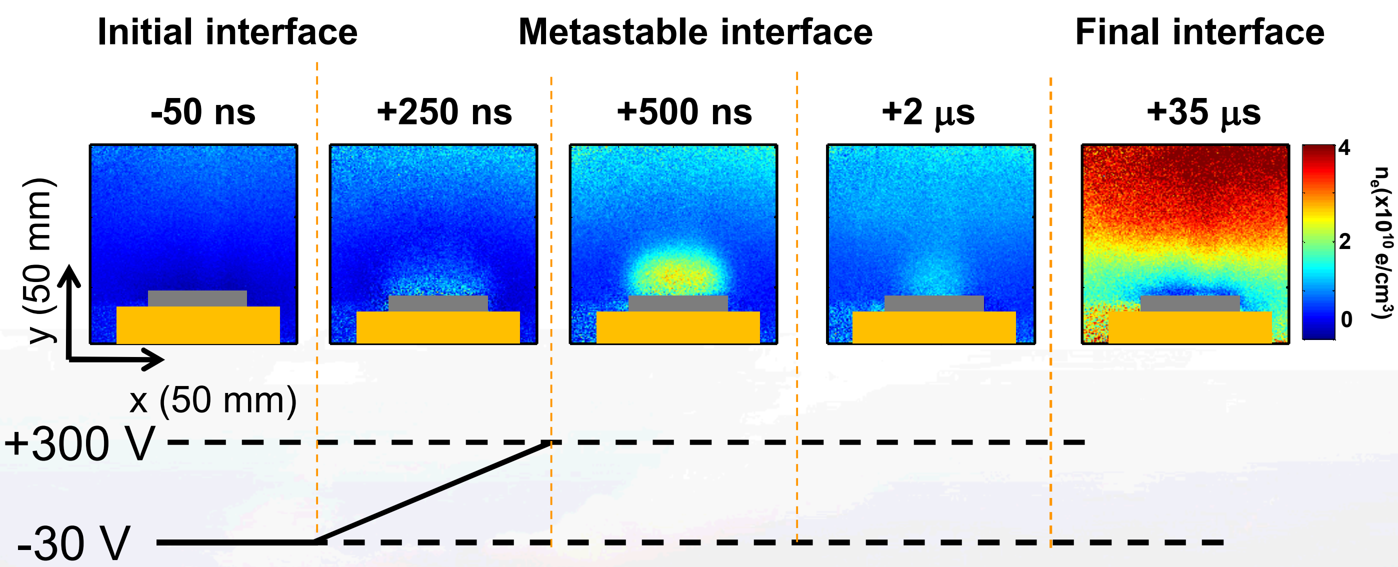
Outline – overview of the talk

- **Understand static and dynamic coupling between plasma and an electron collecting electrode**
  - Physics that governs plasma-surface interactions
- **Experiments to test scaling of electrode in host plasma**
  - Setup – test static theory
  - Key scaling trends
  - Comparison
- **Conclusions and next steps**
  - Simulations
  - Observations during pulsed excitation

Transient structure observed during pulsing of an anode immersed in a host plasma

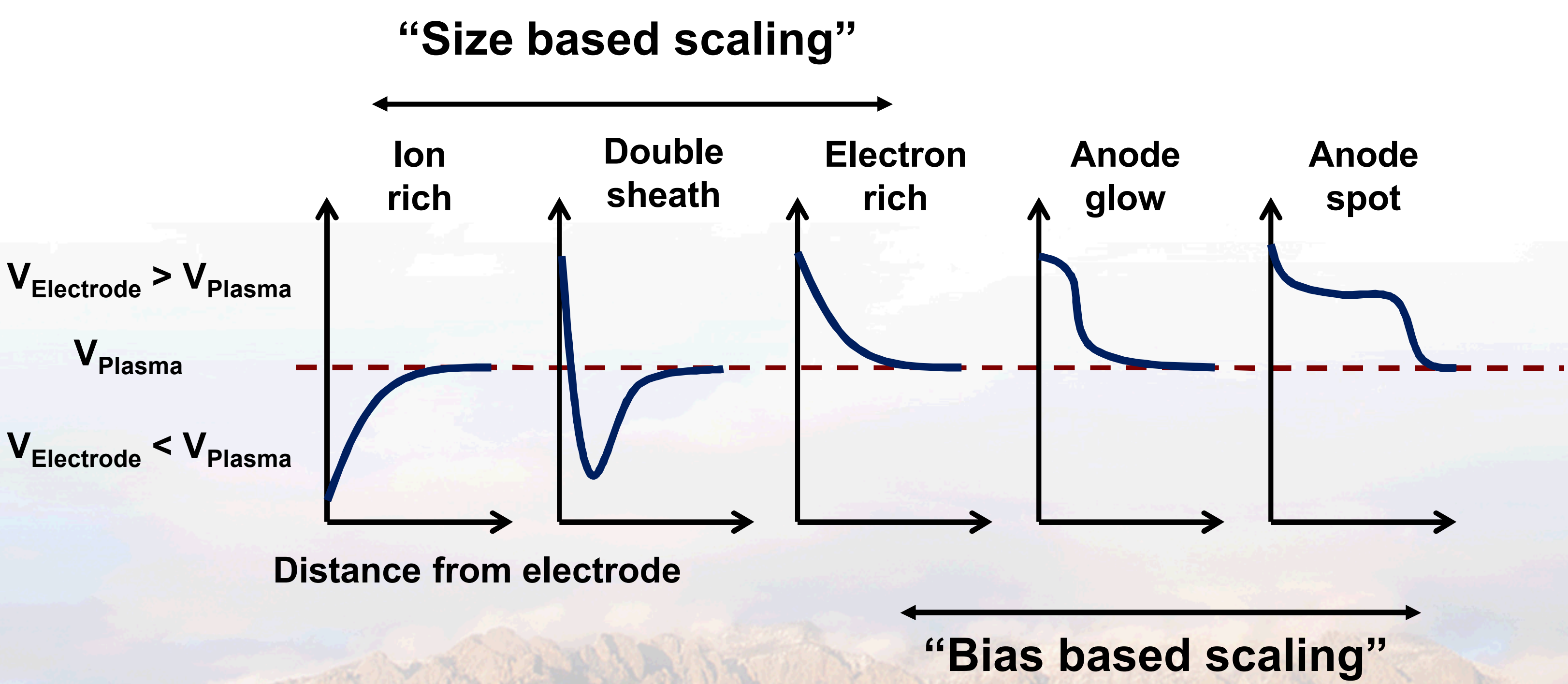
- **Observed during laser-diagnostic development**
  - **Anticipated one effect while observed something quite different**



Why did this metastable interface form?
How long will this metastable interface persist?
....

Interfaces formed near an electron collecting electrode can take several forms

- **Interface above an ion collecting electrode is (usually) ion rich**
  - Plasma potential is more positive than the cathode.
- **Electron-rich interface above an electron-collecting electrode not guaranteed**
  - Structure and polarity of the interface depends on size and bias of the anode.



Interface is going to dictate coupling of the boundary to the host plasma

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Global current balance is the governing physics that dictates the interface

- **Earlier studies performed by Baalrud[1] predict key scaling trends**
  - Plasma in a box bound by A_E and A_W.

$$I_e = e\Gamma_e \left\{ A_E exp\left[-\frac{e(V_p - V_E)}{T_e}\right] + A_W exp\left[-\frac{eV_p}{T_e}\right] \right\} = e\Gamma_i\{A_E + A_W\} = I_i$$ where $\Gamma_e = \frac{1}{4}n\sqrt{\frac{8T_e}{\pi m_e}}$ and $\Gamma_i = 0.6n\sqrt{\frac{T_e}{M_i}}$

$$\exp(-\frac{eV_p}{T_e}) = \left\{ \frac{A_E + A_W}{A_W}\mu - \frac{A_E}{A_W} exp\left[-\frac{e(V_p - V_E)}{T_e}\right] \right\}$$ where $\frac{\boldsymbol{\Gamma_i}}{\boldsymbol{\Gamma_e}} \equiv \boldsymbol{\mu} = \sqrt{\frac{\mathbf{2.3}\boldsymbol{m_e}}{\boldsymbol{M_i}}}$

$V_P < V_E$ (Electron sheath)

Zero ion current to electrode
$\exp[(V_P-V_E)/T_e]>=1$

$V_P > V_E$ (Ion sheath)

$V_P/T_e >> 0$ and $(V_P-V_E) \sim T_e$

$V_P \sim V_E$ (Transition)

$$\frac{A_E}{A_W}\Big|_{Electron\ Sheath} \leq \mu$$

$$\mu < \frac{A_E}{A_W}\Big|_{Double\ Sheath} < 1.7\mu$$

$$\frac{A_E}{A_W}\Big|_{Ion\ Sheath} \geq \left(\frac{0.6}{\mu} - 1\right)^{-1} \sim 1.7\mu$$

Polarity of interface depends on the size of the anode and mass of the ion species

The University of Iowa

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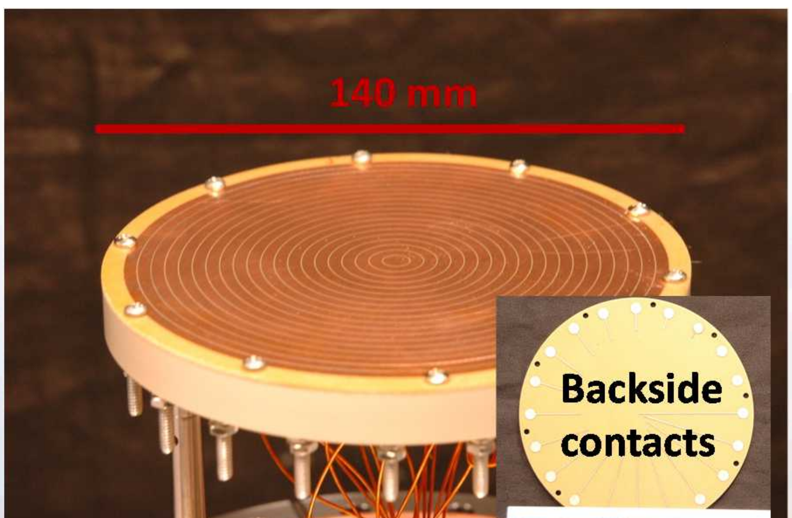
[1] S. D. Baalrud, N. Hershkowitz, and B. Longmier, Phys. Plasmas **14**, 042109 (2007)

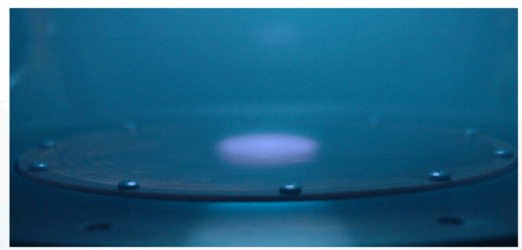
Experiments were performed to test static size-dependent coupling between plasma and electrode

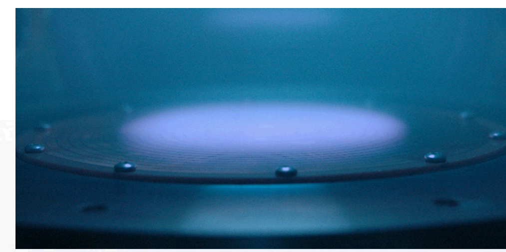
- **Earlier studies demonstrated size-dependence of interface**
  - Did not fully test scaling by identify transitions
- **Segmented electrode utilized to perform this test**
  - 20 individually addressable elements

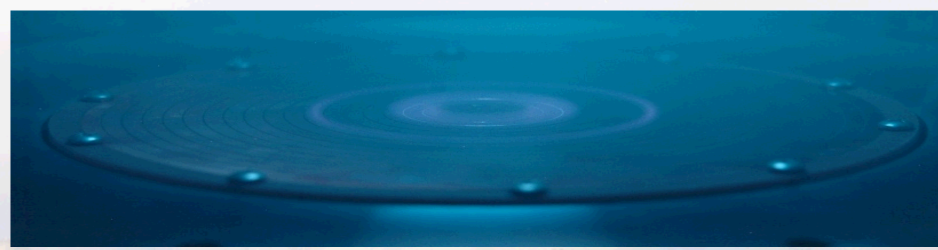
Segmented electrode array



Implementation







Segmented array enables In-situ reconfiguration of anode size

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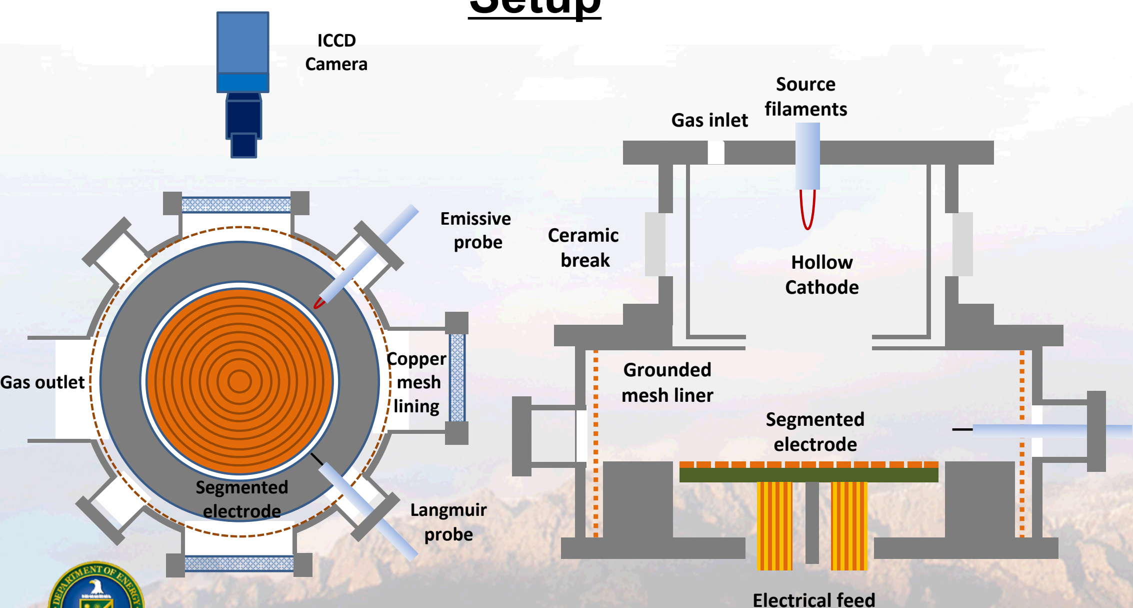
Size dependent scaling is tested in both argon and helium plasmas

- **Modified GEC chamber utilized to house the measurements**
  - Filament generated plasma to generate "quiet" plasma
  - Copper mesh lined chamber to bound size of the "walls"
- **Array of diagnostics are utilized to assess the coupling between the plasma and the electron collecting electrode**
  - Electrode I-V, emissive probe, Langmuir probe and optical emission

Setup



Anticipated scaling

ANODE RING	R_o [mm]	A_{AE} [mm^2]	ANTICIPATED SHEATH TYPE (He)	ANTICIPATED SHEATH TYPE (Ar)
6	19.1	1145.5	ELECTRON	ELECTRON
7	22.2	1547.5	ELECTRON	ELECTRON
8	25.4	2025.8	ELECTRON	DOUBLE
9	28.6	2568.4	ELECTRON	DOUBLE
10	31.8	3175.3	ELECTRON	DOUBLE
11	34.9	3824.6	ELECTRON	ION
12	38.1	4558.1	ELECTRON	ION
13	41.3	5355.9	ELECTRON	ION
14	44.5	6218.0	DOUBLE	ION
15	47.6	7114.5	DOUBLE	ION
16	50.8	8103.2	DOUBLE	ION
17	54.0	9156.2	DOUBLE	ION
18	57.2	10273.6	ION	ION
19	60.3	11417.3	ION	ION

Mesh liner prevents plasma filling the side ports

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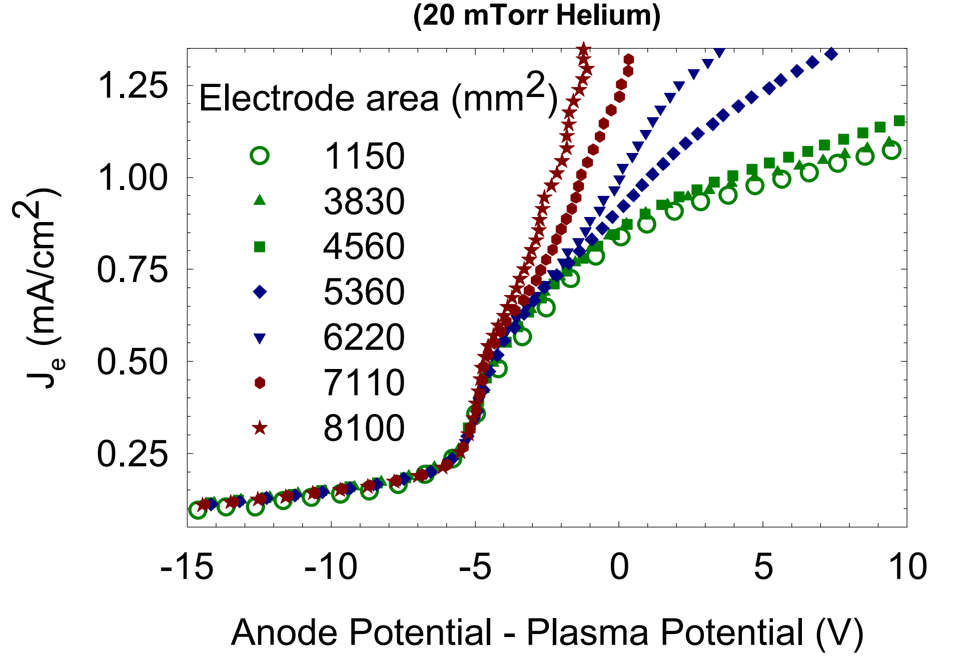
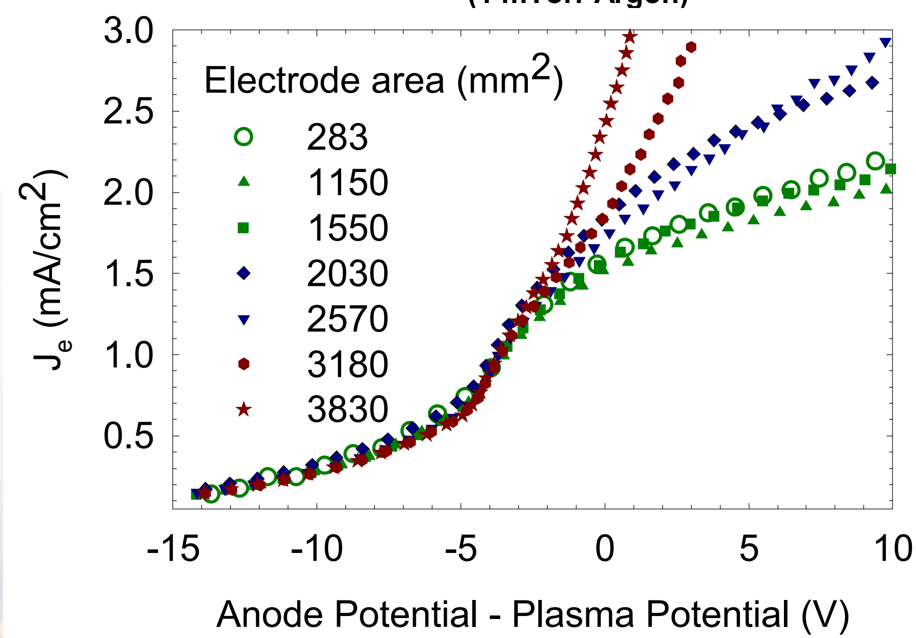
Size dependent scaling is tested in both argon and helium plasmas

- **Characteristic trends size dependence are observed in both plasmas**
  - Current density most indicative of changes in plasma-electrode coupling

Scaling trends in helium



Scaling trends in argon



Transitions are identified by abrupt changes in scaling of current and locking of plasma potential

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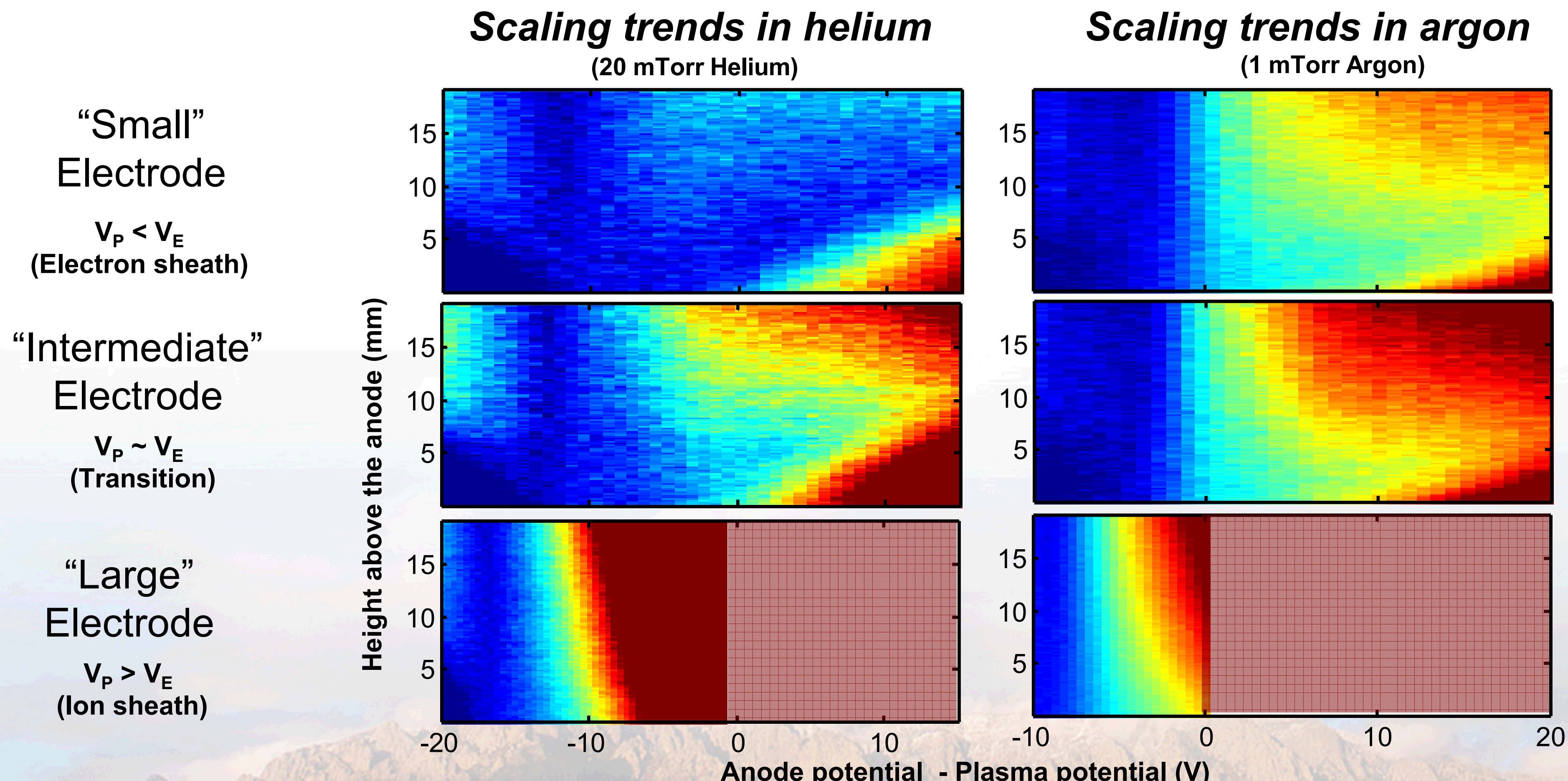
Plasma induced emission further identify changes in interface structure

- **Changes in optical emission indicates where energy is deposited.**



Distinct modes of coupling to the plasma

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Observed transitions agree well with anticipated transitions predicted by theory

- **Discretization of electrode limits determination of where transitions occurred**
  - Sufficient fidelity to provide reasonable indication

Comparison

	Argon Discharge		Helium Discharge	
	Small (e) to Intermediate (d)	Intermediate (d) to Large (i)	Small to Intermediate	Intermediate to Large
Anticipated area (mm^2)	1960	3300	6200	10500
Observed area (mm^2)	~ 1770	~ 2900	~ 5000	~ 6200
Percent difference	- 13	- 12	- 20	- 40
Fidelity	< 1 ring	~ 1 ring	~ 2 rings	~ 3 rings

In both cases, the anticipated transition is larger than the observed transition

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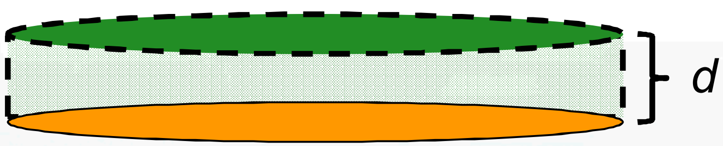
Finite thickness of the interface contributes to global current balance

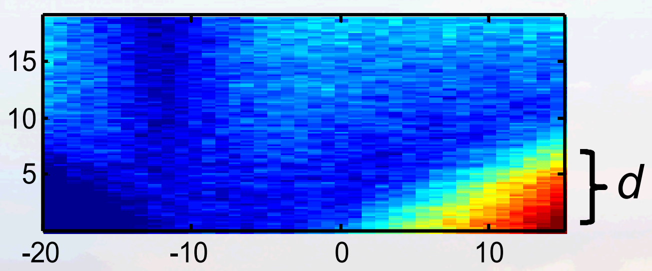
- **Electron current is lost over the entire area of the interface formed between the plasma and the electrode.**

Effective interface

Geometrical area = πr^2

Effective area ~ $\pi r^2 + 2\pi rd$





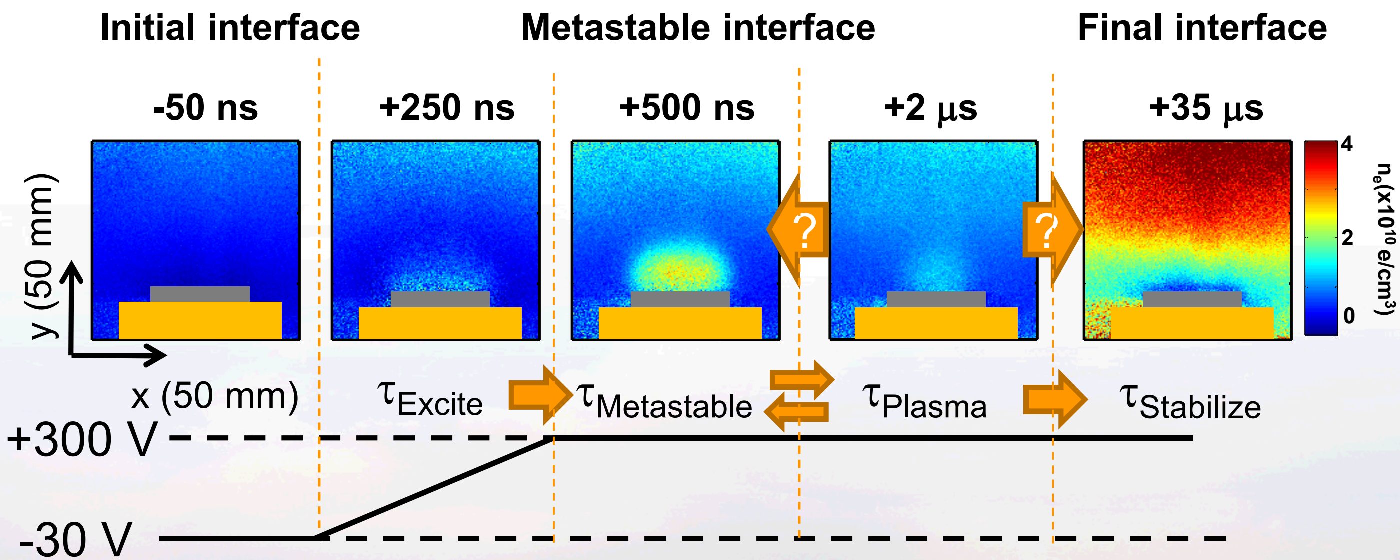
Re-evaluation

	Helium	Argon
	Small to Intermediate	Small to Intermediate
Anticipated area (mm^2)	6200	1960
Observed area (mm^2)	~ 5000	~ 1770
Interface thickness (mm)	~ 5	~ 2
Effective area (mm^2)	6300	1830

Plasma responds to "effective" size of the interface

Can transitions in the size of "effective interface" lead to instabilities

- **As the size of the interface grows, a transition in the coupling between the electrode and host plasma can occur**
  - Oscillations between various configurations is likely to occur (Pulsating anode spots/fireballs)



Interface is going to dictate coupling of the boundary to the host plasma

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Size-dependent oscillations are observed electrode current

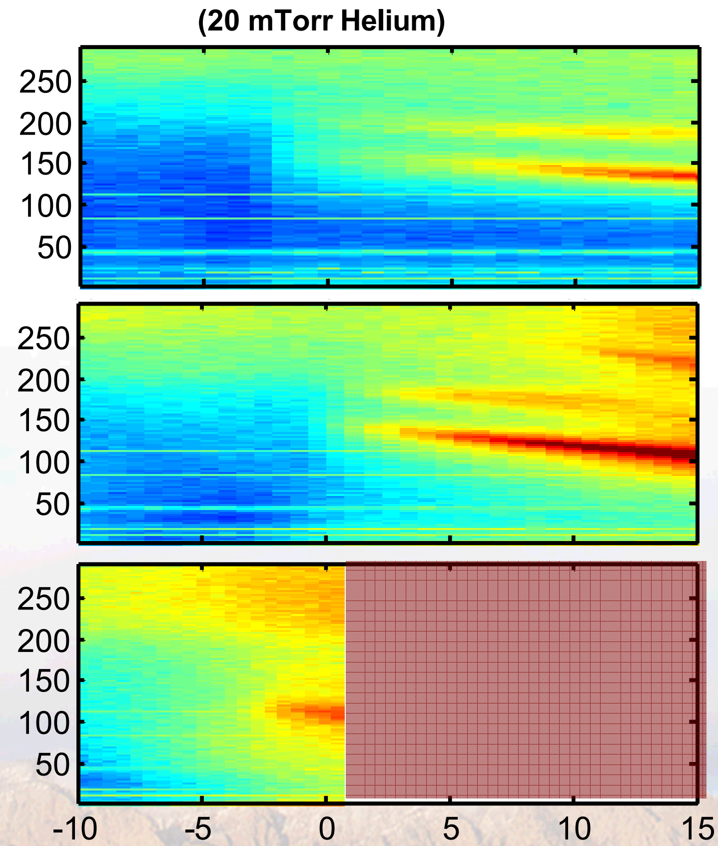
- **Frequency of these oscillations change with size and bias of the anode**

Scaling trends in helium

"Small" Electrode

"Intermediate" Electrode

"Large" Electrode



Similar, but less pronounced trends observed in argon

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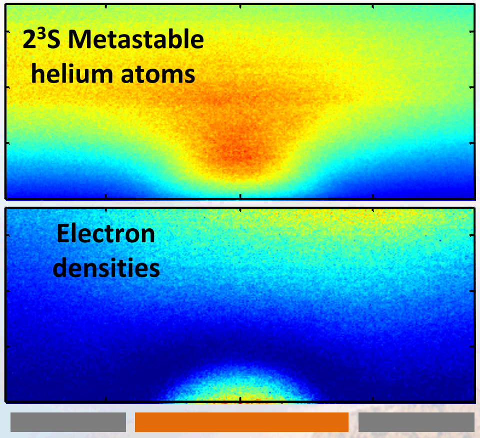
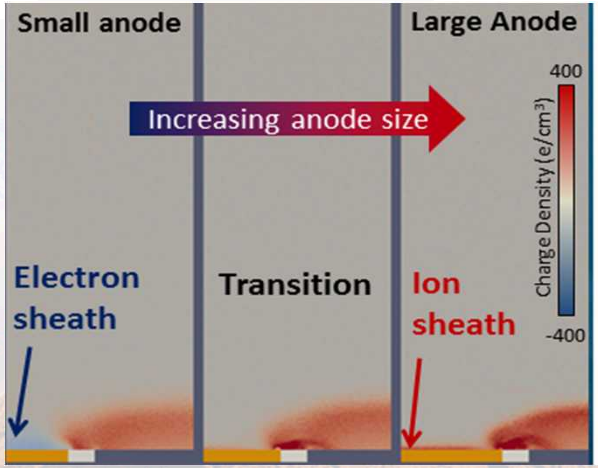
Ongoing and future efforts

- **Quantitative measurements of interface structure**
  - Laser diagnostics of densities (LCIF) and fields (LIF-Dip)
- **Predictive simulations (M. M. Hopkins, B. T. Yee) - Poster:GT1.00050**
  - 3D PIC of plasma-electrode coupling
- **Theoretical modeling (S. Baalrud, B. Scheiner) - Poster:GT1.00005**
  - Identify key physics that governs interface behavior

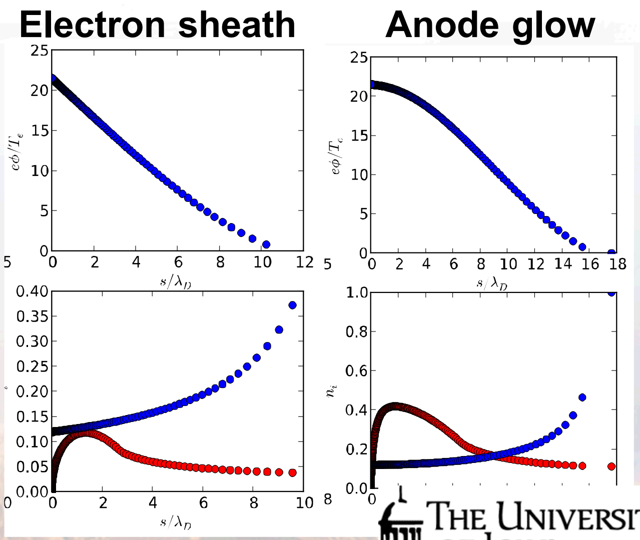
Quantitative measurements



Predictive simulations



Theoretical modeling



Thank you!

References

Auxiliary slides

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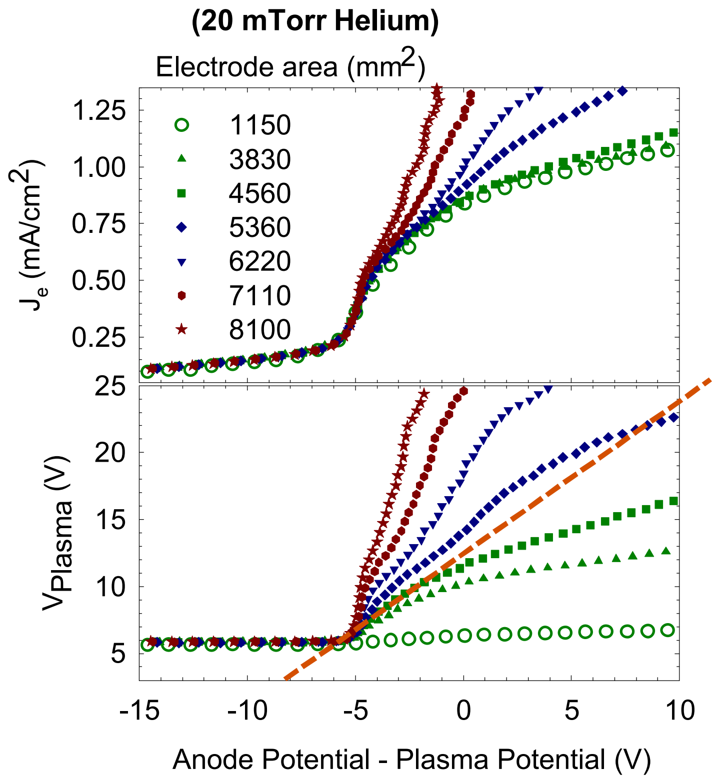
Size dependent scaling is tested in both argon and helium plasmas

- **Characteristic trends size dependence are observed in both plasmas**
  - Current density most indicative

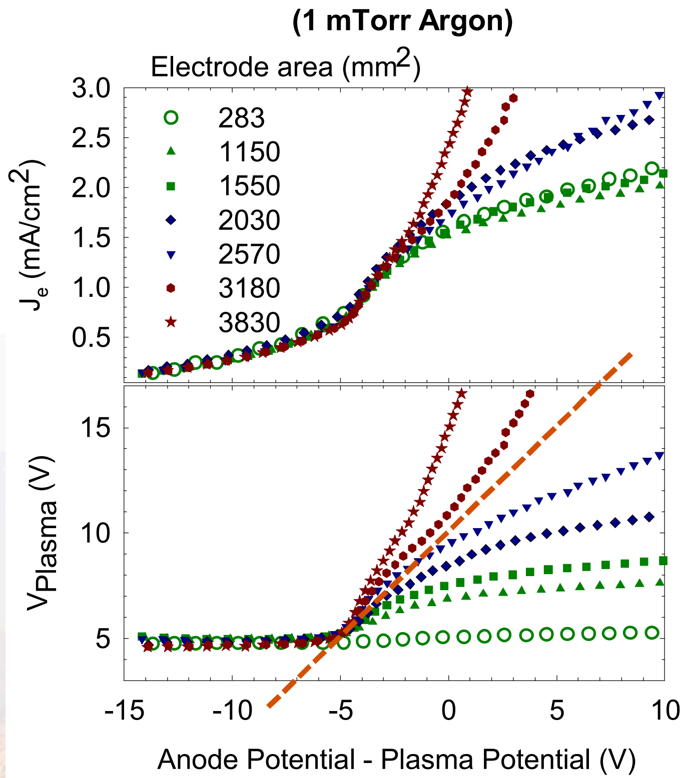
Extracted current

Plasma potential

Scaling trends in helium



Scaling trends in argon



Transitions are identified by abrupt changes in scaling of current and locking of plasma potential

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Size-dependent oscillations are observed electrode current

- **Will the interface oscillate between two configurations as the size of the interface changes?**
  - Words

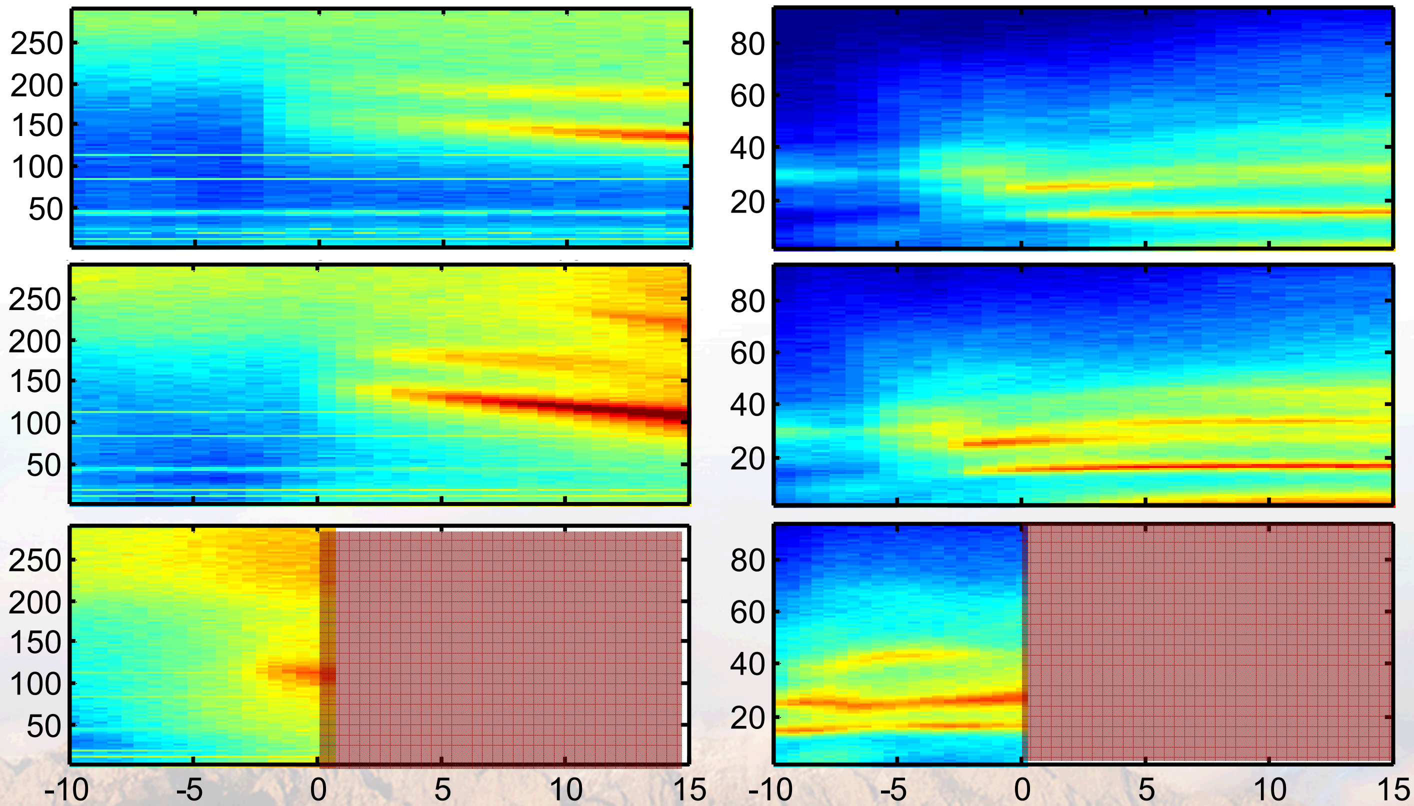
Scaling trends in helium | ***Scaling trends in argon***

(20 mTorr Helium) | **(1 mTorr Argon)**

"Small" Electrode

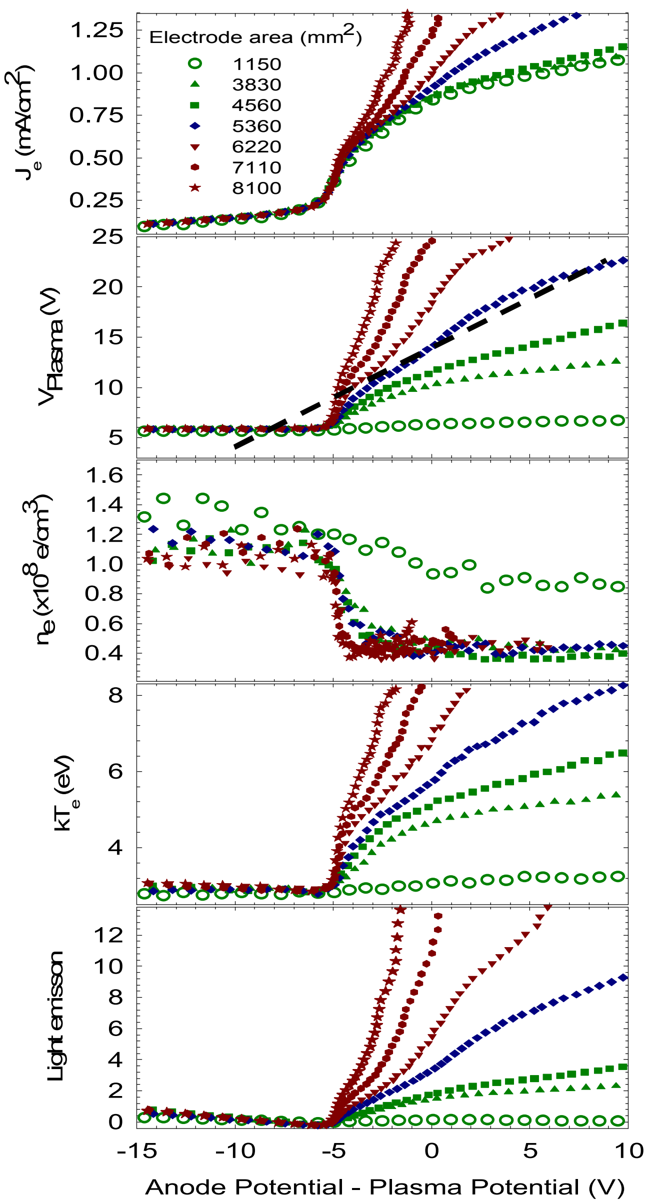
"Intermediate" Electrode

"Large" Electrode



Conclusions

20 mTorr Helium



1 mTorr Argon