Microscale Gas breakdown voltage dependence on electrode surface

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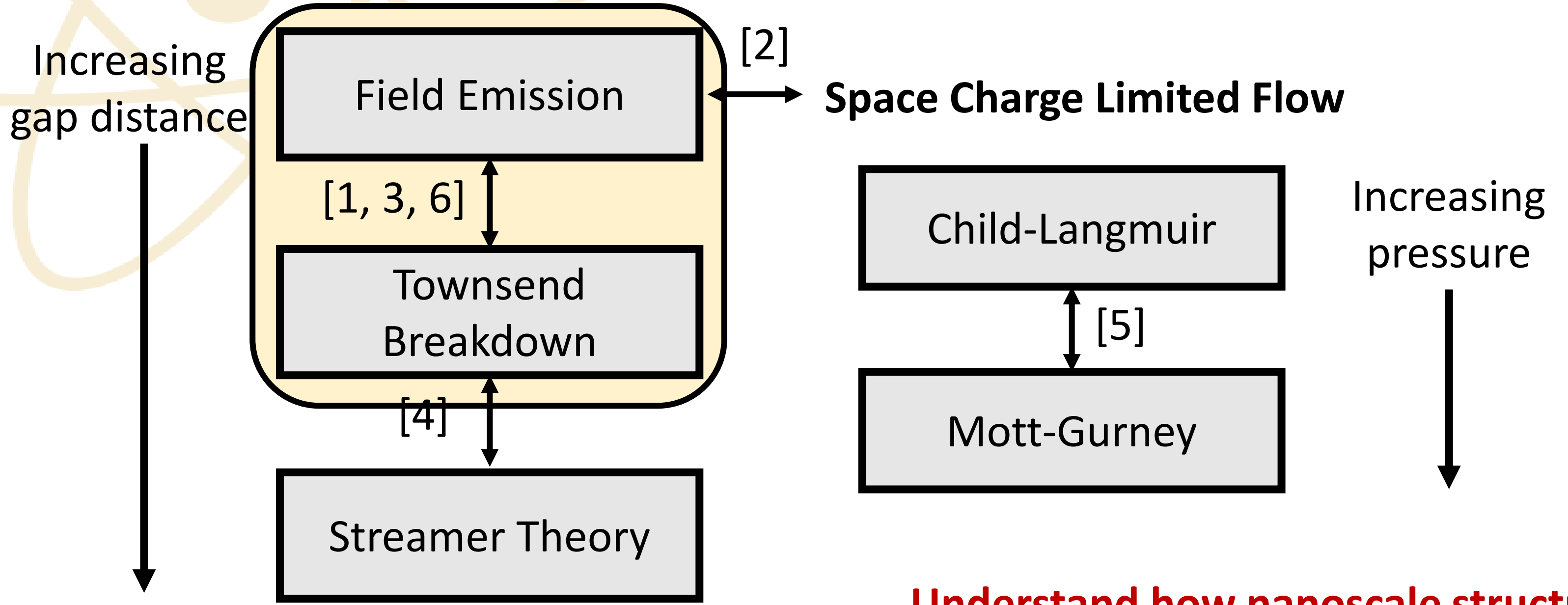
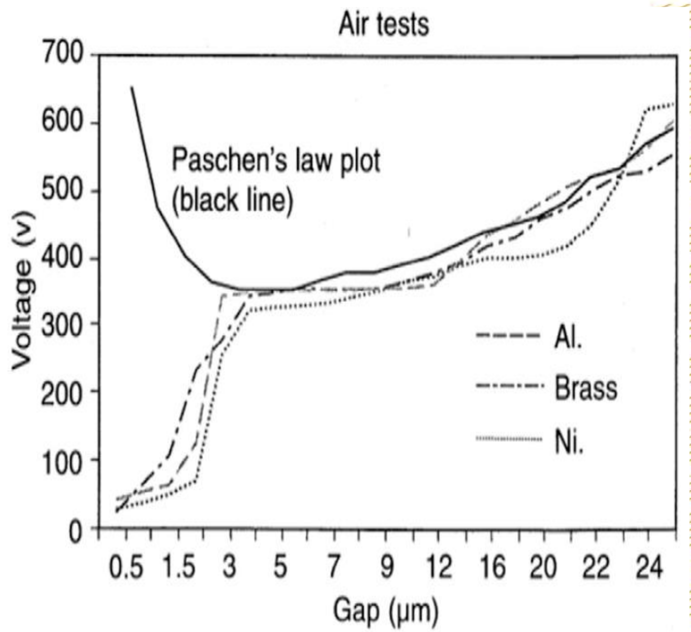
Motivation: Applications

- Induce breakdown
  - Combustion[1]
  - Electric micropropulsion[2]
  - Medicine[3]
- Prevent breakdown
  - For electric pulse applications[4]
  - Microelectromechanical systems (MEMS) are used in biotechnology, medicine, and communications[5]

[1] Y. Ju and W. Sun, "Plasma assisted combustion: Dynamics and chemistry," *Prog. Energy Combust. Sci.*, vol. 48, no. C, pp. 21–83, 2015.
[2] W. P. Wright and P. Ferrer, "Electric micropropulsion systems," *Prog. Aerosp. Sci.*, vol. 74, pp. 48–61, Apr. 2015.
[3] M. Martinez-Sanchez and J. E. Pollard, "Spacecraft Electric Propulsion-An Overview," *J. Propuls. Power*, vol. 14, no. 5, pp. 688–699, Sep. 1998.
[4] A. L. Garner, A. Caiafa, Y. Jiang, S. Klopman, C. Morton, A. S. Torres, A. M. Loveless, and V. B. Neculaes, "Experimental Validation of a Compact, Flexible Pulsed Power Architecture for Ex Vivo Platelet Activation," PLoS ONE, vol. 12(7), 2017, Art. No. e0181214.
[5] R. Bogue, "MEMS sensors: past, present and future," *Sens. Rev.*, vol. 27, no. 1, pp. 7–13, Jan. 2007.
[6] H. G. Craighead, "Nanoelectromechanical Systems," *Science (80-.).*, vol. 290, no. 5496, pp. 1532–1535, Nov. 2000.

Motivation: Paschen's Law





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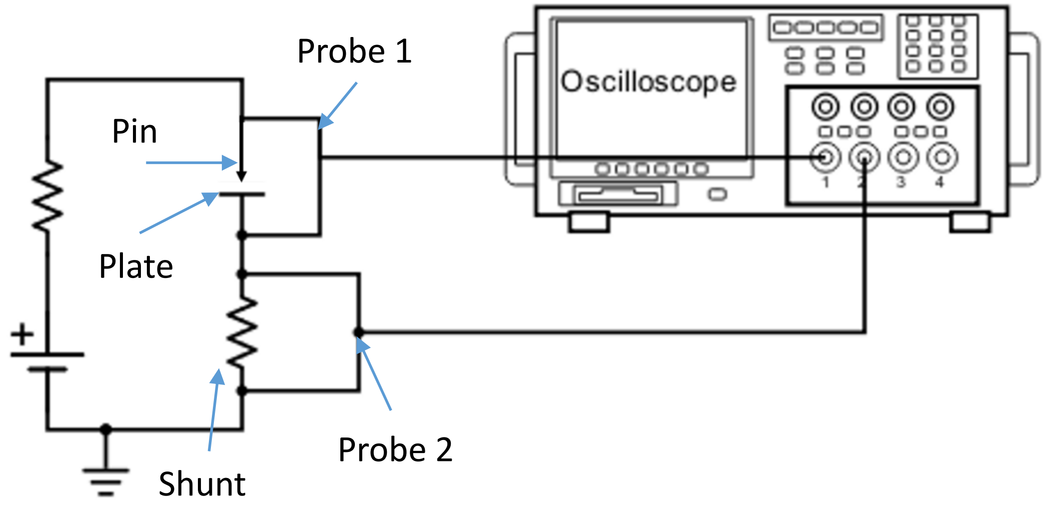
Understand how nanoscale structure impacts electron emission to provide predictive models for both emission and microscale breakdown.

[1] A. Venkattraman and A. A. Alexeenko, *Phys. Plasmas*, vol. 19, art. no. 123515, 2012.
[2] Y. Y. Lau, Y. Liu, and R. K. Parker, *Phys. Plasmas*, vol. 1, pp. 2082-2085, 1994.
[3] D. B. Go and D. A. Pohlman, *J. Appl. Phys.*, vol. 107, art. no. 103303, 2010.
[4] L. K. Warne, R. E. Jorgenson, and S. D. Nicolaysen, Sand. Nat. Lab., Albuquerque, NM, and Livermore, CA, Rep. SAND2003-4078 (2003).
[5] M. S. Benilov, *Plasma Sources Sci. Technol.*, vol. 18, art. no. 014005, 2009.
[6] A. M. Loveless and A. L. Garner, *Appl. Phys. Lett.*, vol. 108, art. no. 234103, 2016.

Experimental Setup

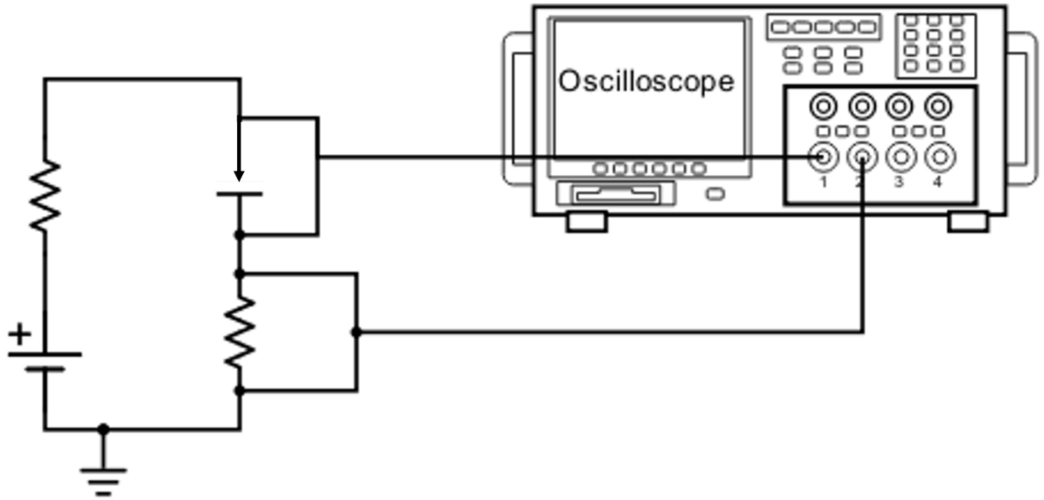
R. S. Brayfield, II, A. J. Fairbanks, A. M. Loveless, S. Gao, A. Dhanabal, W. Li, C. Darr, W. Wu, and A. L. Garner, “The impact of cathode surface roughness and multiple breakdown events on microscale gas breakdown at atmospheric pressure,” J. Appl. Phys., vol. 125, 2019, Art. no. 203302.

- Tungsten dissection needles
  - 1 μm tip (Roboz Surgical Instrument Co., RS-6065)
- Copper plate cut to 12.7 mm^2
- Two 1 MΩ resistors
  - Current limiting
  - Current viewing shunt
- DC high voltage supply (Stanford Research System, PS365, 10 kV)
- Two 100:1 voltage probes were connected across pin-plate connection and shunt resistor
- LeCroy Oscilloscope to record voltage and current at breakdown

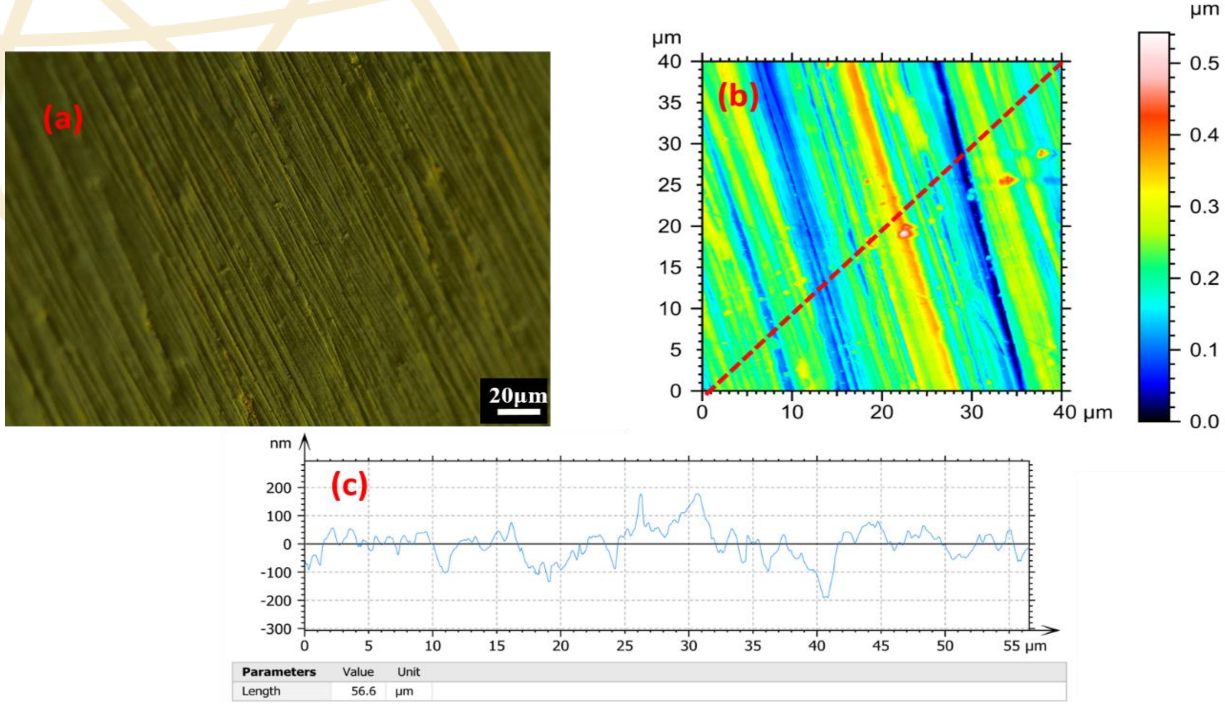


Experimental Design

- Copper plate surface modification
  - Wet polishing station with 400, 800, and 1200 grit polishing pads (Pace Technologies)
  - After polish the samples were soaked in acetone
- Plate surface divided into 2 regions
  - 1 breakdown event
  - 10 breakdown events
- AFM conducted pre-test
  - Initial surface roughness
  - Contamination
- Gaps distance set
  - Applied 35V and shorted gap
  - 1, 5, and 10 μm
- Voltage slowly increased (~3V/s) until breakdown occurred
  - Current across gap observed on oscilloscope
- Measure voltage and current at which gap broke down



Results: Pre-test AFM results



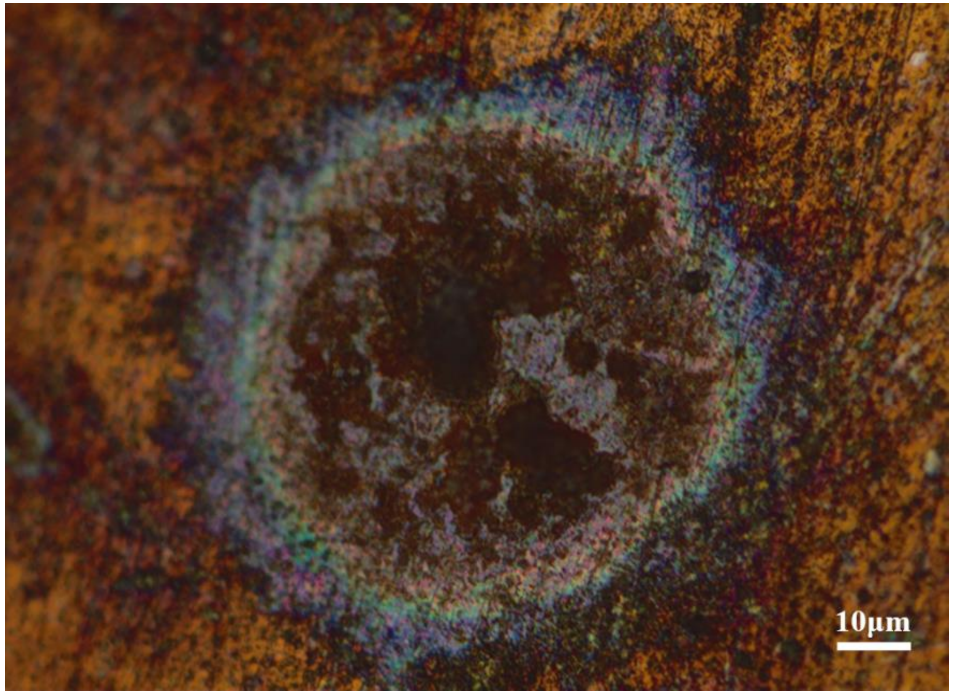
Grit	Number of samples	Peak to Peak Average (µm)	Standard Deviation (µm)	RMS (nm)
400	9	1.47	1.08	535.22
800	9	0.26	0.18	65.99
1200	9	0.24	0.23	39.48

- 3 different surface modifications conducted
- RMS values show each surface has a different overall roughness
- Gives baseline for any change due to the discharge event during testing

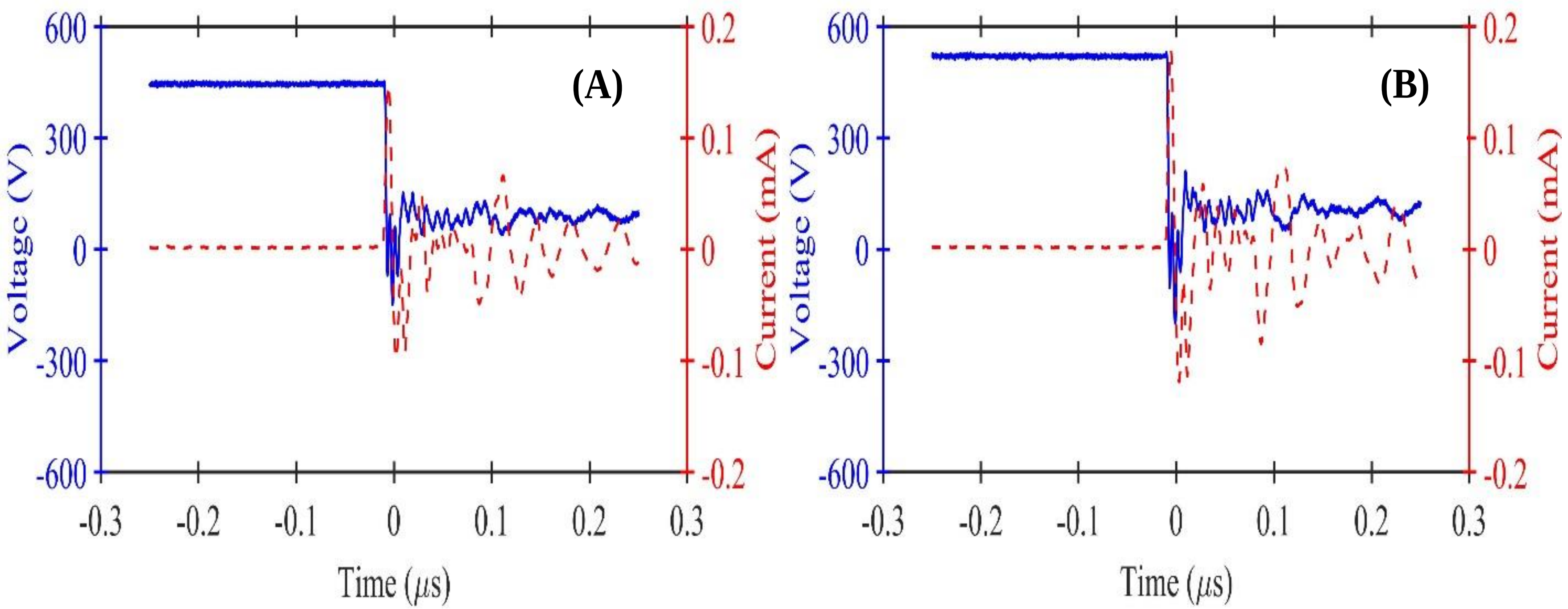
Results: Observed Ablation

- Ablated craters observed after test
  - Too deep to use AFM, so optical estimation was made

Grit (gap distance)	Depth (µm)	Grit (gap distance)	Depth (µm)	Grit (gap distance)	Depth (µm)
400 (10 µm)	9.7	800 (5 µm)	6.2	1200 (1 µm)	12.1
400 (10 µm)	6	800 (5 µm)	7.4	1200 (1 µm)	3.5
400 (10 µm)	13.5	800 (5 µm)	12.4	1200 (10 µm)	4.8
400 (5 µm)	41.2	800 (5 µm)	5.3	1200 (10 µm)	5.4
400 (5 µm)	19.6	800 (5 µm)	5.2		
400 (1 µm)	42.5				



Results: VI data



- Recorded for each test run
- Used current to act as indicator of breakdown

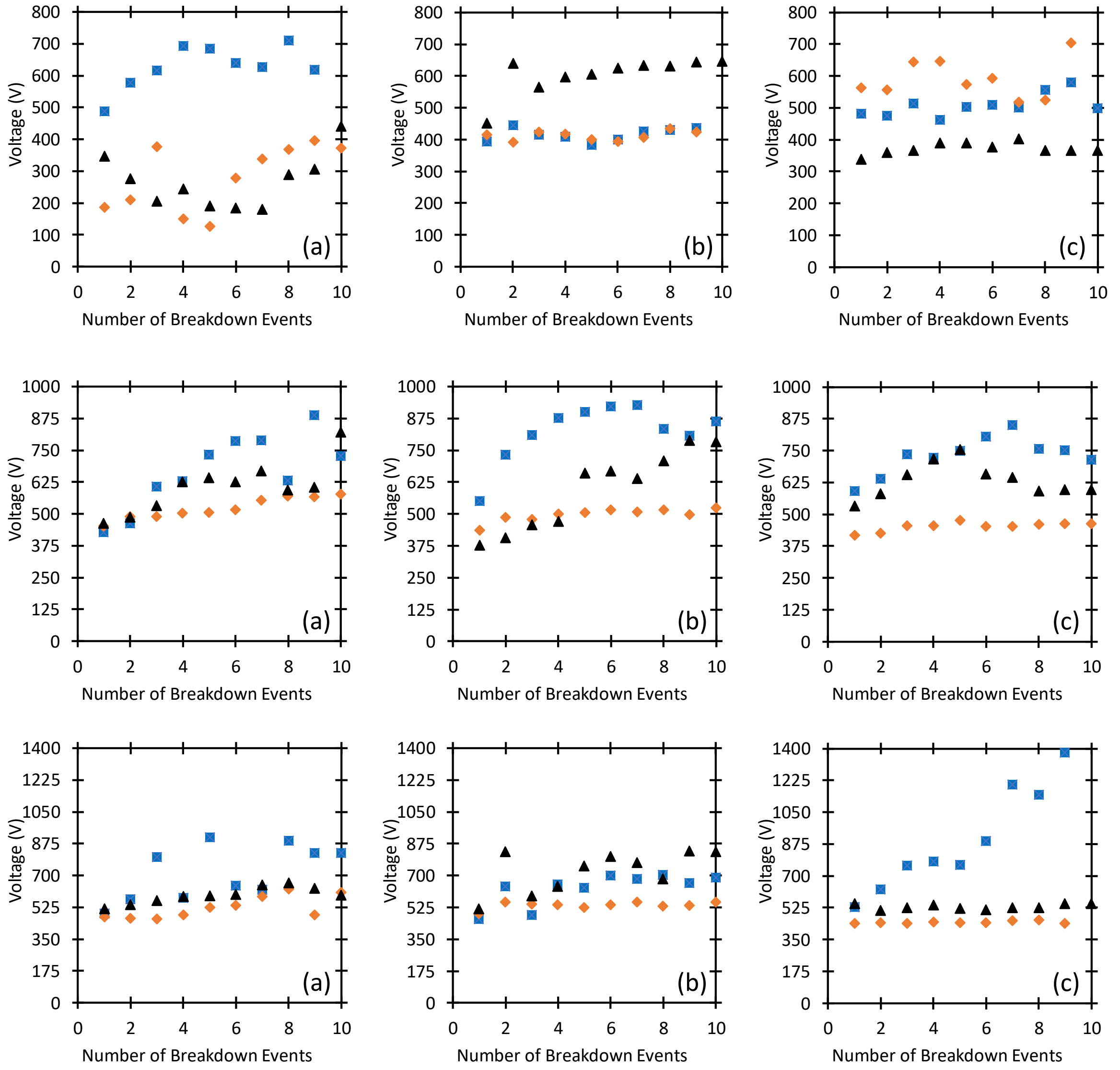
Results: Breakdown Voltage

- (a) 400 grit (b) 800 grit and (c) 1200 grit
- Clear increasing trend with number of breakdown events
- Breakdown events after the fifth event yield a statistically significant breakdown voltage between the 1 μm gap and the other gap distance
- Behavior arises because the breakdown events alter the electrode surface, which contributes to the increased variation after multiple events

1μm

5μm

10μm



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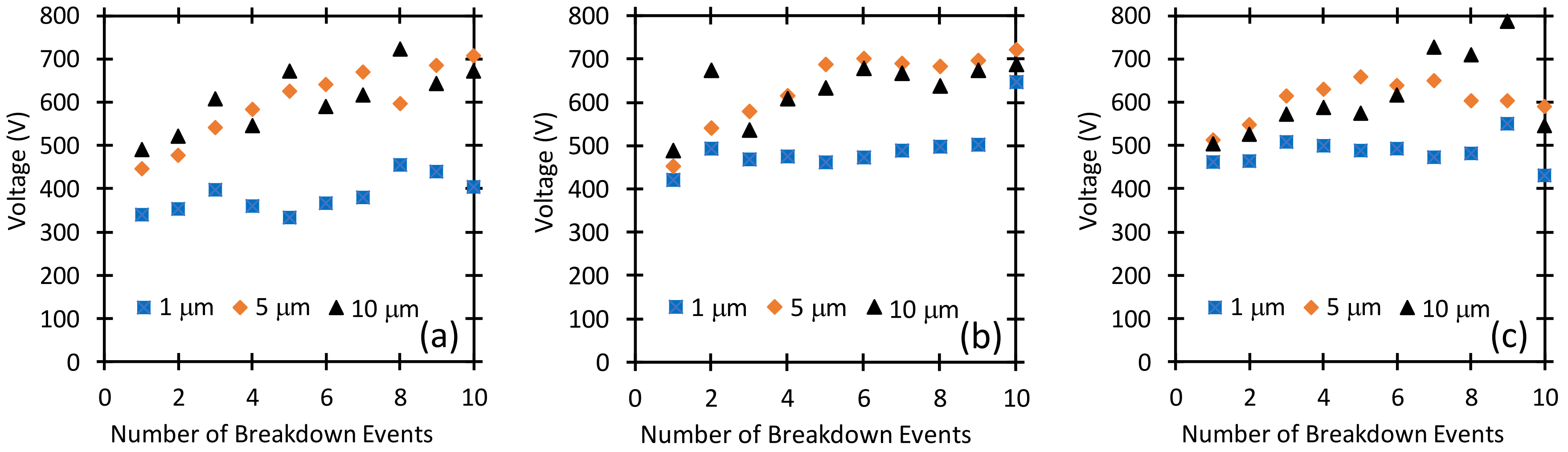
Results: Altered Breakdown Voltage



(a) 400 grit (b) 800 grit and (c) 1200 grit

- Larger gap did not always result in higher breakdown voltage
- Crater significantly impacted required breakdown voltage

Results: Effective Gap Distance

Grit	Starting Gap Distance (μm)	Average Crater Depth (μm)	Average Breakdown Voltage for 1st Event (V)	Average Breakdown Voltage for 10th Event (V)
400	1	42.5	339	405
400	5	30.4	446	707
400	10	9.73	491	672
800	5	7.3	454	723
1200	1	7.8	462	432
1200	10	5.1	504	545

Results: Data vs. Model

- Fit to experimental data using breakdown model given by [1]

$$\frac{\exp[\bar{\phi}^{3/2}/(\beta\bar{E})]}{\beta\bar{\phi}^{1/2}\exp(\bar{\phi}^{-1/2})}\sqrt{\frac{\bar{T}\bar{E}}{\bar{p}\bar{d}_{eff}^{\,2}}}\frac{\{1-\gamma_{SE}[\exp(\bar{\alpha}\bar{d}_{eff})-1]\}}{\exp(\bar{\alpha}\bar{d}_{eff})-1}$$
$$=\exp(1)(1+2\bar{E}),$$

where $\bar{d}_{eff}$ is the nondimensionalized gap distance plus the crater depth

- Also consider analytic limit given by [2]

$$V=\left(E_* L\,\bar{d}_{eff}/\Lambda_2\right)\left[-\Delta_2-\left(\Delta_2^2-2\Lambda_2\bar{\phi}^{3/2}/\beta\right)^{1/2}\right],$$

Where $\Delta_2=-[\bar{\mu}+\bar{\nu}]$ and $\bar{\mu}=\ln(\Lambda_2)/2+\ln\left(\beta\bar{\phi}^{1/2}\right)+\bar{\phi}^{-1/2}+3/2$ and $\bar{\nu}=\ln\{\exp[\bar{p}\bar{d}_{eff}\exp(-1)]-1\}-\ln\{1-\gamma_{SE}[\exp(\bar{p}\bar{d}_{eff}\exp(-1))]\}-\ln\left[\bar{T}\bar{p}^{-1}\bar{d}_{eff}^{\,-2}\right]/2$ represent the field emission and Townsend contributions, respectively, and $\Lambda_2=10^{-5}$ is a fitting parameter

Parameter	Name	Value	Unit
ϕ	Work function	4.7	eV
ϕ_*	Work function scale	96.81	eV
d	Gap distance	Variable	m
L	Gap distance scale	3.92×10^{-12}	m
p	Pressure	760	Torr
p_*	Pressure scale	1.70×10^{8}	Torr
E	Breakdown electric field	Variable	V/m
E_*	Breakdown electric field scale	6.20×10^{12}	V/m
V	Breakdown voltage	Variable	V
V_*	Breakdown voltage scale	24.3	V
T	Temperature	300	K
T_*	Temperature scale	7976	K
β	Field enhancement factor	Variable	N/A
γ_{SE}	Secondary emission coefficient	10^{-5}	N/A

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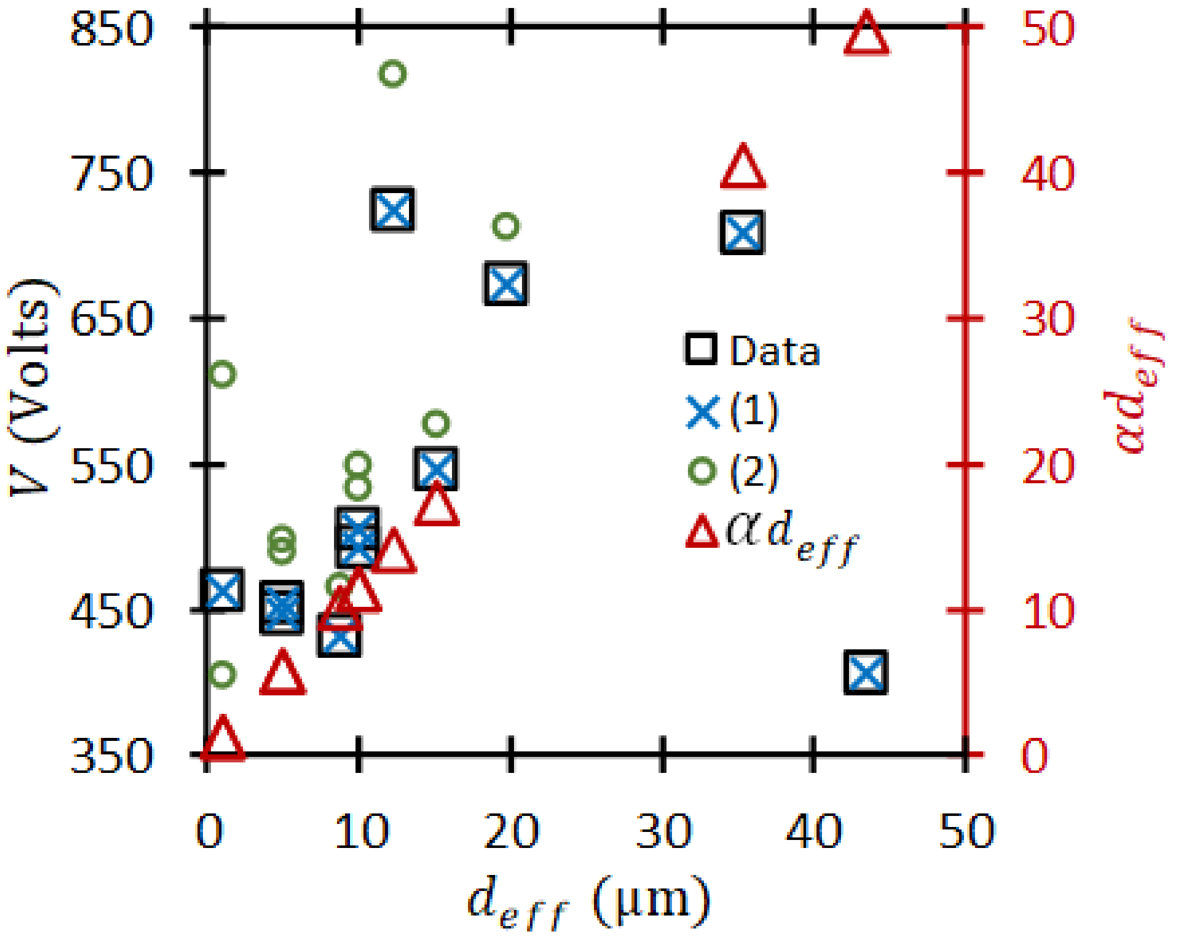
[2] G. Meng, X. Gao, A.M. Loveless, C. Dong, D. Zhang, K. Wang, B. Zhu, Y. Cheng, and A.L. Garner, Phys. Plasmas, vol. 25, 2018, Art. no. 082116.

Results: Data vs. Model

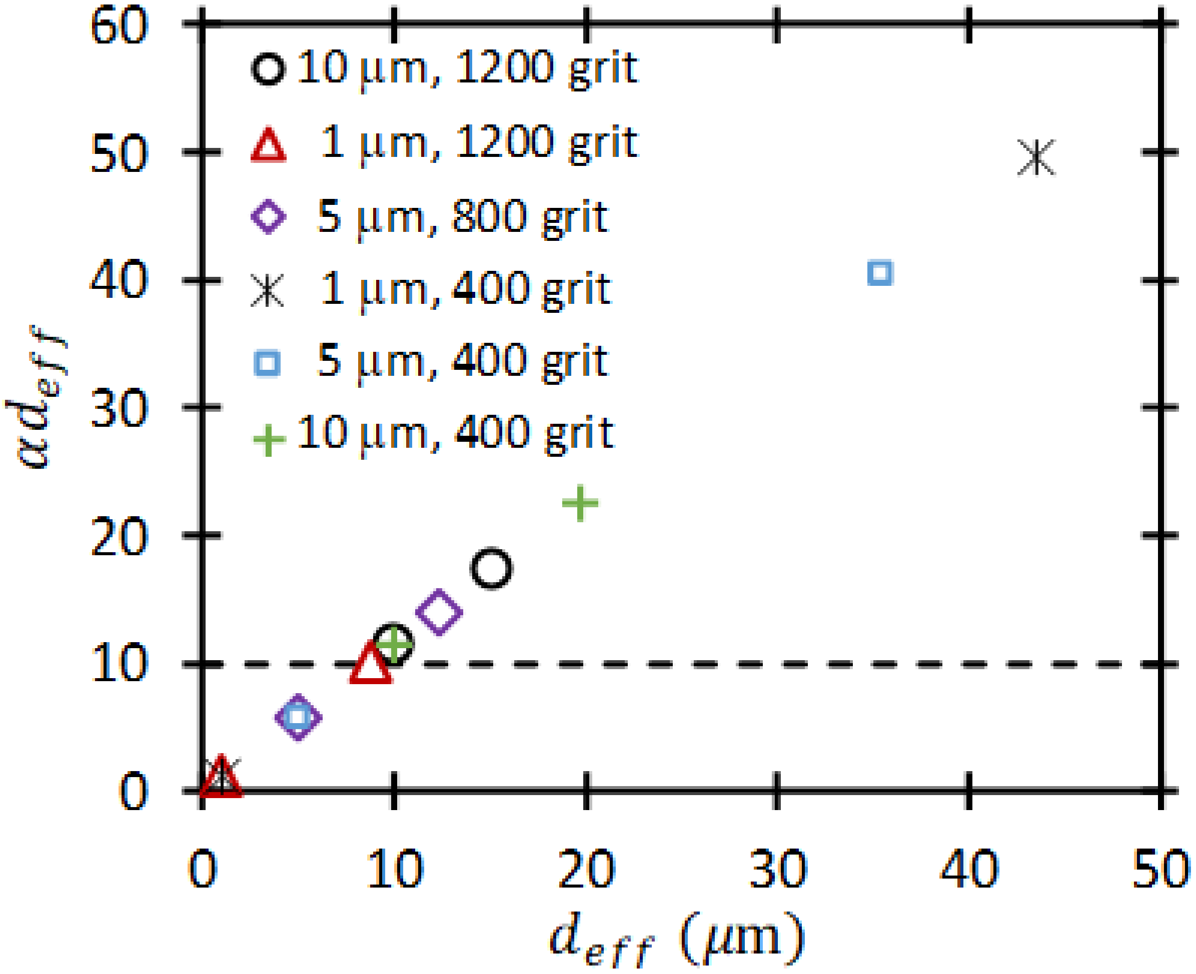
- (1): Numerical solution
- (2): Analytic solution
- (1) and (2) differ by ~10% until the largest gap distances
- At largest gap distances, $\bar{\alpha}\bar{d}_{eff} > 18$ – Meek's criterion for streamer discharge
  - Can we get streamers at microscale?



Results: Data vs. Model

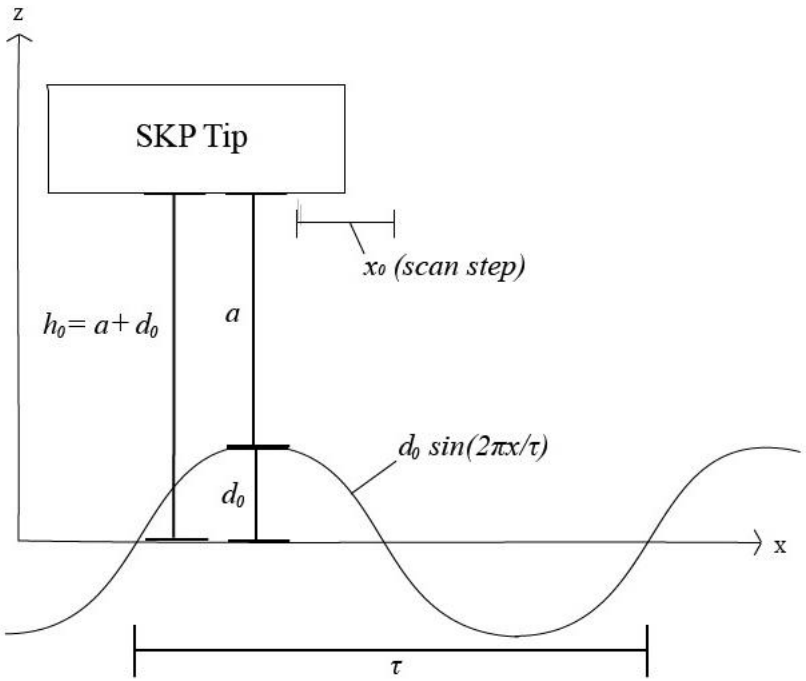
- Each pair of symbols shows the product of ionization coefficient and gap distance after the 1st breakdown event and the 10th breakdown event.

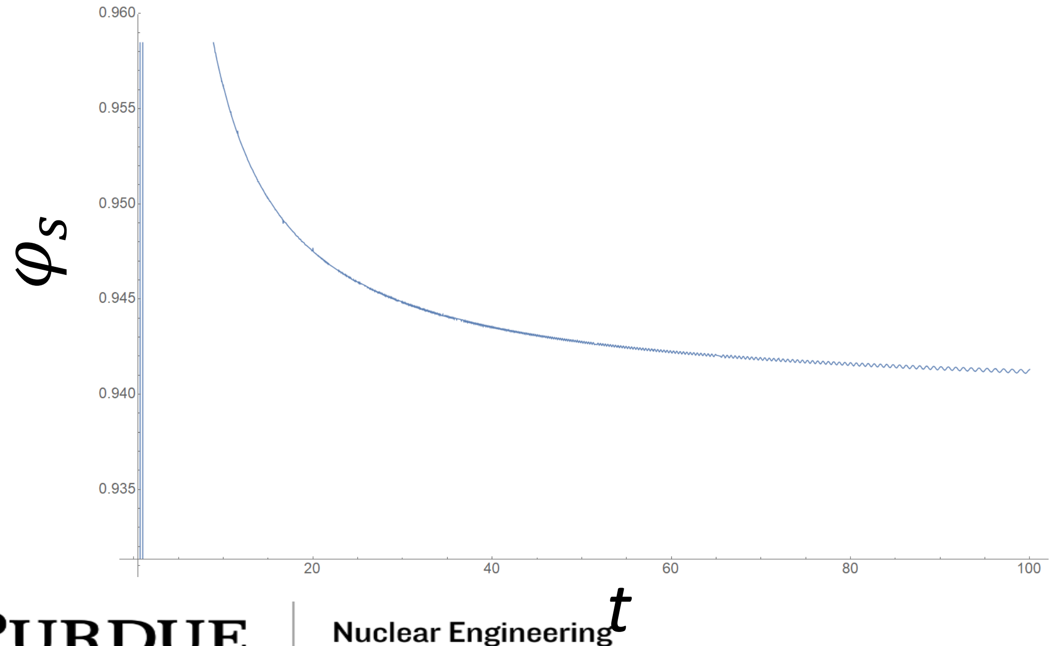
- Crater formation alone can push breakdown behavior into the Paschen law regime even at the 1 and 5 μm initial gap distances.

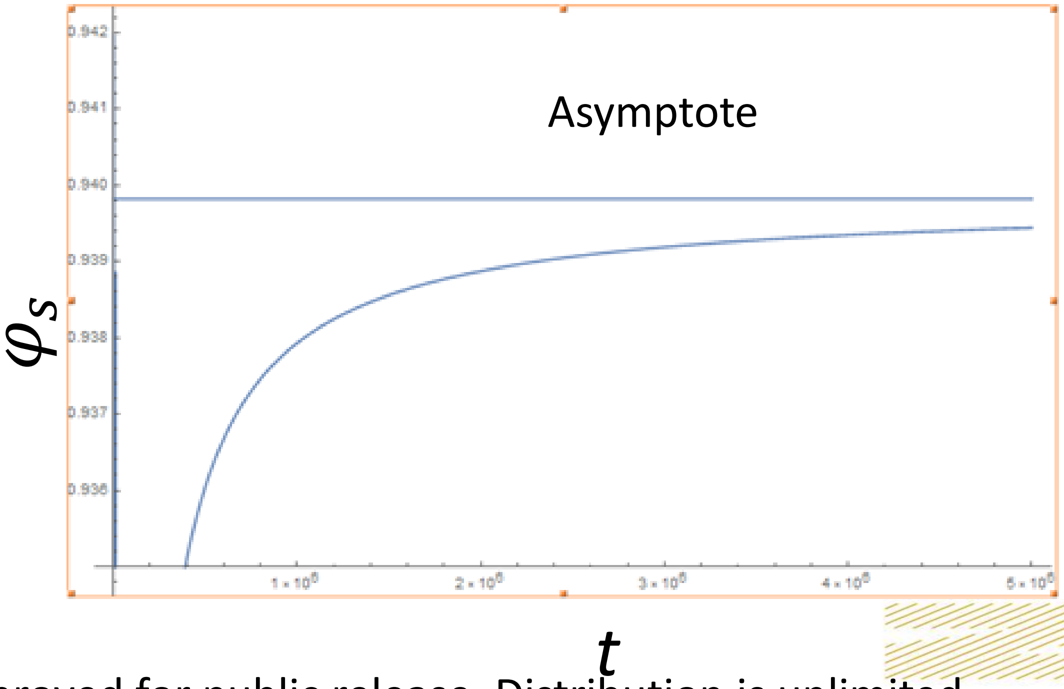


Surface Roughness on φ

- For large bumps (big flat region, or $t = \tau/x << 1$), the φ_s approaches a constant.
- For other periodicity, we can determine the effective φ_s







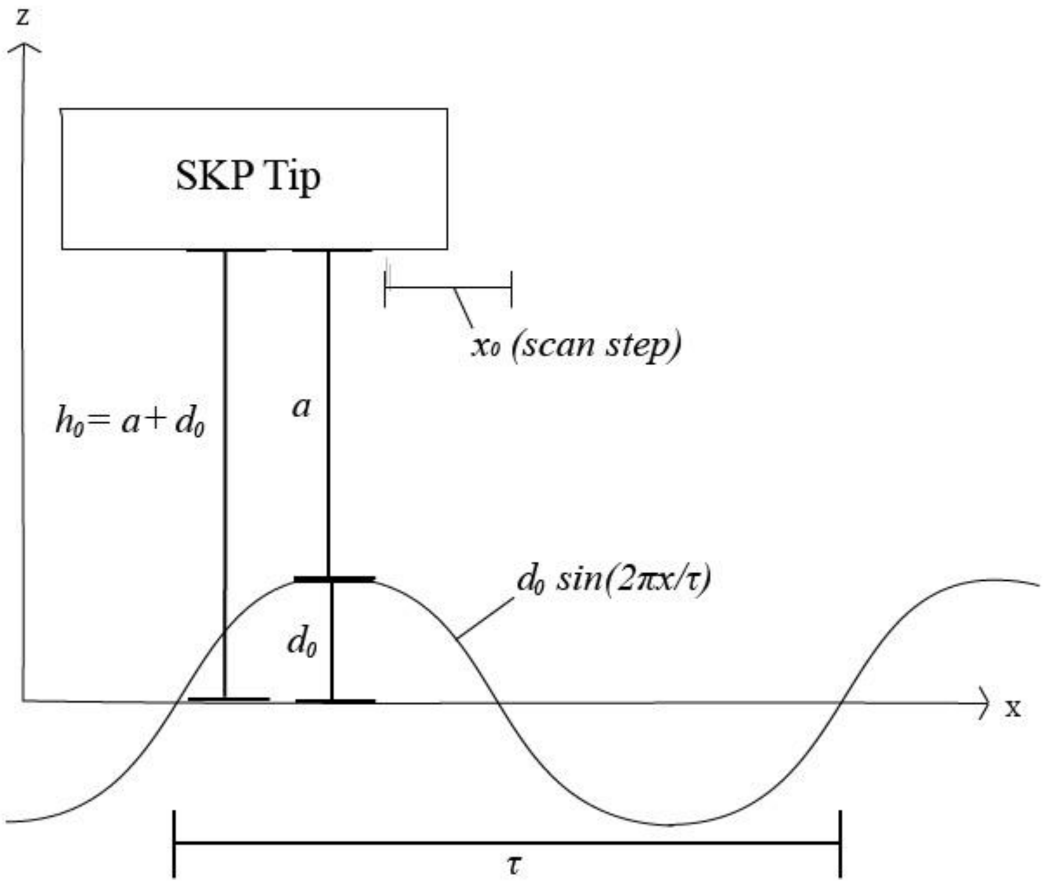
Future Work

- Assess the impact of aspect ratio on field enhancement β using designed nanoscale electrodes at atmospheric pressure, pressure, and sub-microscale gap distances.
- Continue exploring the impact of surface roughness on breakdown, particularly post-breakdown work function ϕ.
- Incorporate β and ϕ into the theory and compare to experiment.

BACKUP

Future Work: Surface Roughness Also Effects Work Function

- Geometry for measuring work function of a rough surface.
- Derive change in work function as a function of the capacitance of each increment of motion of the Kelvin Probe tip.
- Provides insight into the effect of surface roughness on measured work function that may be relevant since the geometry is similar to pin-to-plate.



Model adapted from Y. Wan, Y. Li, Q. Wang, K. Zhang, and Y. Wu, “The relationship of surface roughness and work function of pure silver by numerical modeling,” Int. J. Electrochem. Sci., vol. 7, pp. 5204-5216, 2012.

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Definitions From This Setup

Work function of a surface (where V_c is contact potential difference) :

$$\varphi_s = \varphi_{tip} - eV_c$$

Equation for capacitance:

$$C_k = \int dC_k = \int_{n_0 x}^{(n_0+1)x} \frac{\varepsilon_0 y_0 dx}{h_0 - d_0 \sin x} = \varepsilon_0 y_0 \int_{n_0 x}^{(n_0+1)x} \frac{dx}{h_0 - d_0 \sin x}$$

R_q (surface roughness)

$$R_q = d_0/\sqrt{2}$$

SKP Tip Charge:

$$Q' = \frac{C_{k0}(\varphi_t^0 - \varphi_s^0)}{e} = \frac{\varepsilon_0 A(\varphi_t^0 - \varphi_s^0)}{\mathrm{ea}}$$ (where A is the scan tip area)

Charge per scan area:

$$Q = \frac{Q'S}{A} = \frac{\varepsilon_0 x_0 y_0(\varphi_t^0 - \varphi_s^0)}{ea}$$ (where x_0 and y_0 are the step sizes)

Change in WF per scan:

$$\varphi_s = \varphi_t - \frac{eQ}{C_k} = \varphi_t - e\,\frac{\varepsilon_0 x_0 y_0(\varphi_t^0 - \varphi_s^0)}{ea} 1/\left[\varepsilon_0 y_0 \int_{n_0 x}^{(n_0+1)x} \frac{dx}{h_0 - d_0 \sin\left(\frac{2\pi x}{\tau}\right)}\right]$$

Derived Relationships and Asymptotic Behavior of Work Function

Change in WF over the entire scan area (average of all of the steps of the SKP):

$$= \frac{1}{m}\left(\sum_{n=0}^{n=m-1} \varphi_t - e\,\frac{\varepsilon_0 x_0 y_0(\varphi_t^0 - \varphi_s^0)}{ea} 1/\left[\varepsilon_0 y_0 \int_{n_0 x}^{(n_0+1)x} \frac{dx}{h_0 - d_0 \sin\left(\frac{2\pi x}{\tau}\right)}\right]\right.,$$

where m is the total number of scan steps

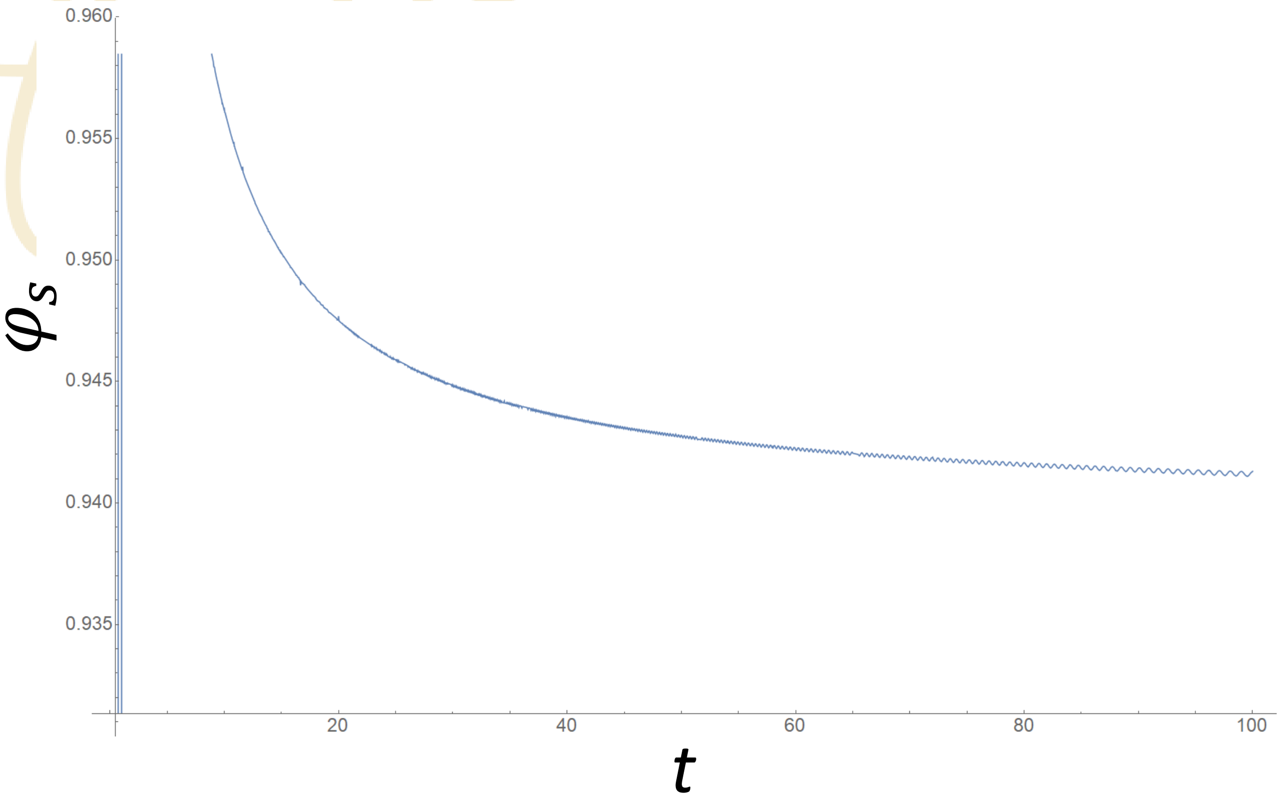
$$= \varphi_t - \frac{x_0(\varphi_t^0-\varphi_s^0)}{\text{a}}\frac{\pi}{\tau}\left(\frac{1}{m}\right)\sqrt{h_0^2 - d_0^2}\left[\frac{1}{\left(\arctan\left(\frac{d_0+h_0\tan\left(\frac{\pi}{\tau}x_0\right)}{\sqrt{h_0^2-d_0^2}}\right)-\arctan\left(\frac{d_0}{\sqrt{h_0^2-d_0^2}}\right)\right)} + \frac{1}{\left(\arctan\left(\frac{d_0+h_0\tan\left(\frac{\pi}{\tau}2x_0\right)}{\sqrt{h_0^2-d_0^2}}\right)-\arctan\left(\frac{d_0+h_0\tan\left(\frac{\pi}{\tau}x_0\right)}{\sqrt{h_0^2-d_0^2}}\right)\right)} \ldots + \frac{1}{\left(\arctan\left(\frac{d_0+h_0\tan\left(\frac{\pi}{\tau}(m)x_0\right)}{\sqrt{h_0^2-d_0^2}}\right)-\arctan\left(\frac{d_0+h_0\tan\left(\frac{\pi}{\tau}(m-1)x_0\right)}{\sqrt{h_0^2-d_0^2}}\right)\right)}\right]$$

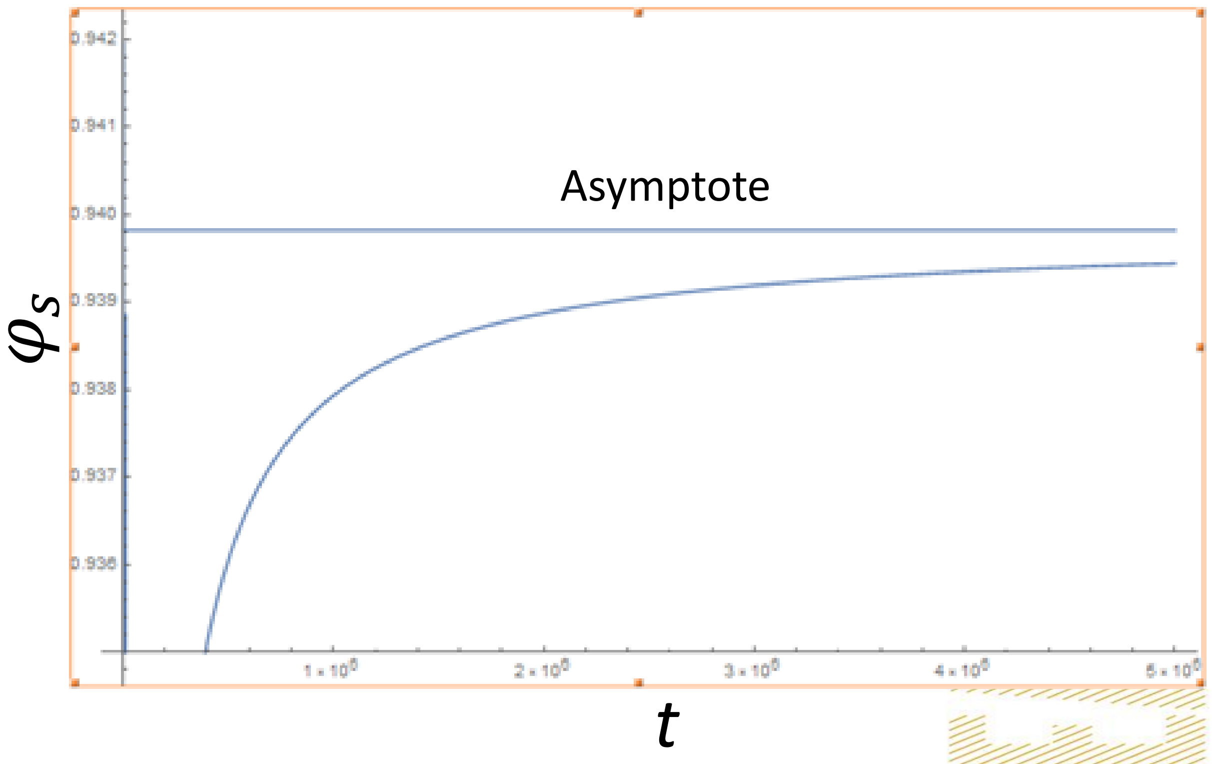
For large τ (step size much smaller than surface roughness), we apply the small angle theory ($\tan x \approx x$) and use L'Hopital's rule to obtain

$$\varphi_s \approx \frac{h_0}{\pi\sqrt{h_0^2 - d_0^2}}$$

$$\overline{\varphi_{s,Ave}} = \overline{\varphi_t^0} - \frac{\left(\overline{\varphi_t^0}-1\right)}{\text{a}} h_0$$

Surface Roughness Periodicity on Surface Work Function





- For large bumps (big flat region, or $t = \tau/x << 1$), the φ_s approaches a constant.
- For other periodicity, we can determine the effective φ_s
- May allow fine-control of surface and full incorporation of surface effects into breakdown theory.

Results: Tukey Test

Breakdown Event	Difference between 5 μm and 1 μm	Difference between 10 μm and 1 μm	Difference between 10 μm and 5 μm
5	0.015*	0.038*	0.914
6	0.017*	0.044*	0.900
7	0.036*	0.035*	1.000
8	0.141	0.026*	0.693
10	0.002*	0.005*	0.988

- Breakdown events after the fifth event yield a statistically significant breakdown voltage between the 1 μm gap and the other gap distance
- Behavior arises because the breakdown events alter the electrode surface, which contributes to the increased variation after multiple events