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Effects of pulsed photoemission in plasma breakdown

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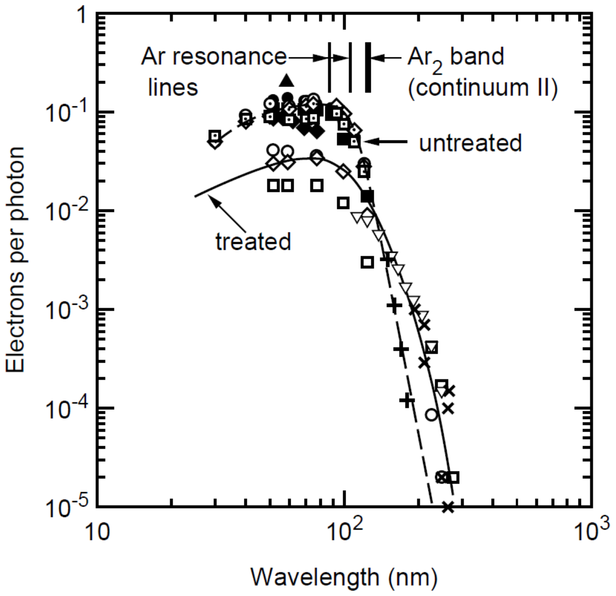
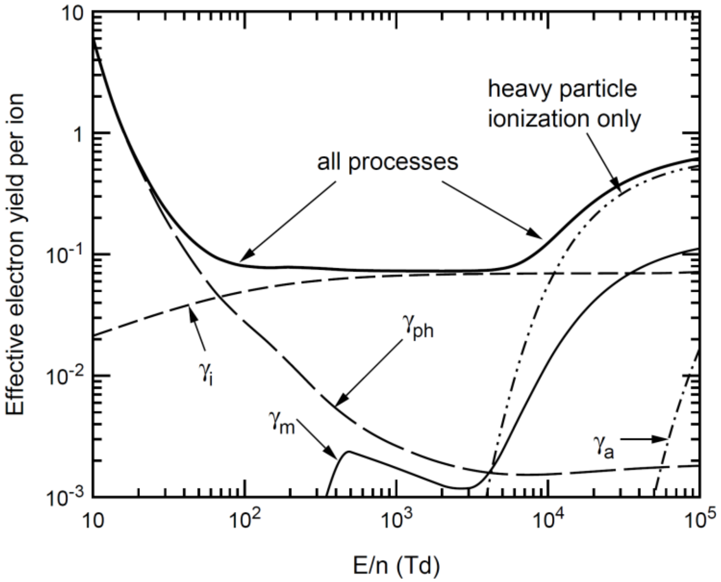
Photoelectron Emission

- Photons supply energy to release electrons from surfaces
  - Photoemission influences or sustains plasma (at low E/N)
- Laser-induced photoemission not as well understood
  - Important for laser-triggered breakdown





A. V. Phelps and Z. Lj. Petrovic , *Plasma Sources Sci. Technol.* **8**, R21, 1999.

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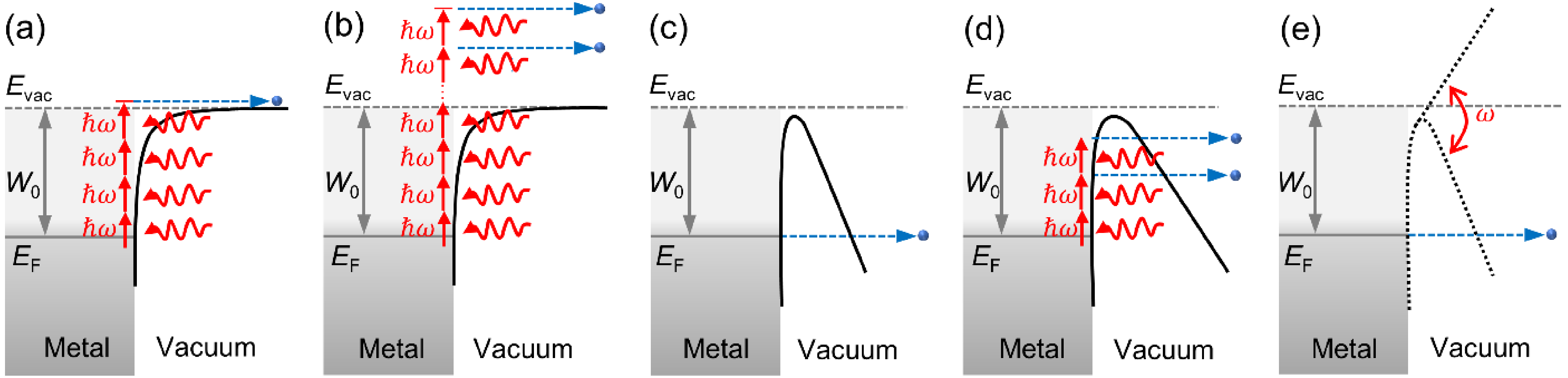
Photon/Laser Induced Electron Emission



Multiphoton Photoemission

Above-threshold Photoemission

Field Emission

Photon-assisted Field Emission

Optical-field Emission

Emission process depends on:

- Laser wavelength, intensity
- DC bias
- Surface properties.

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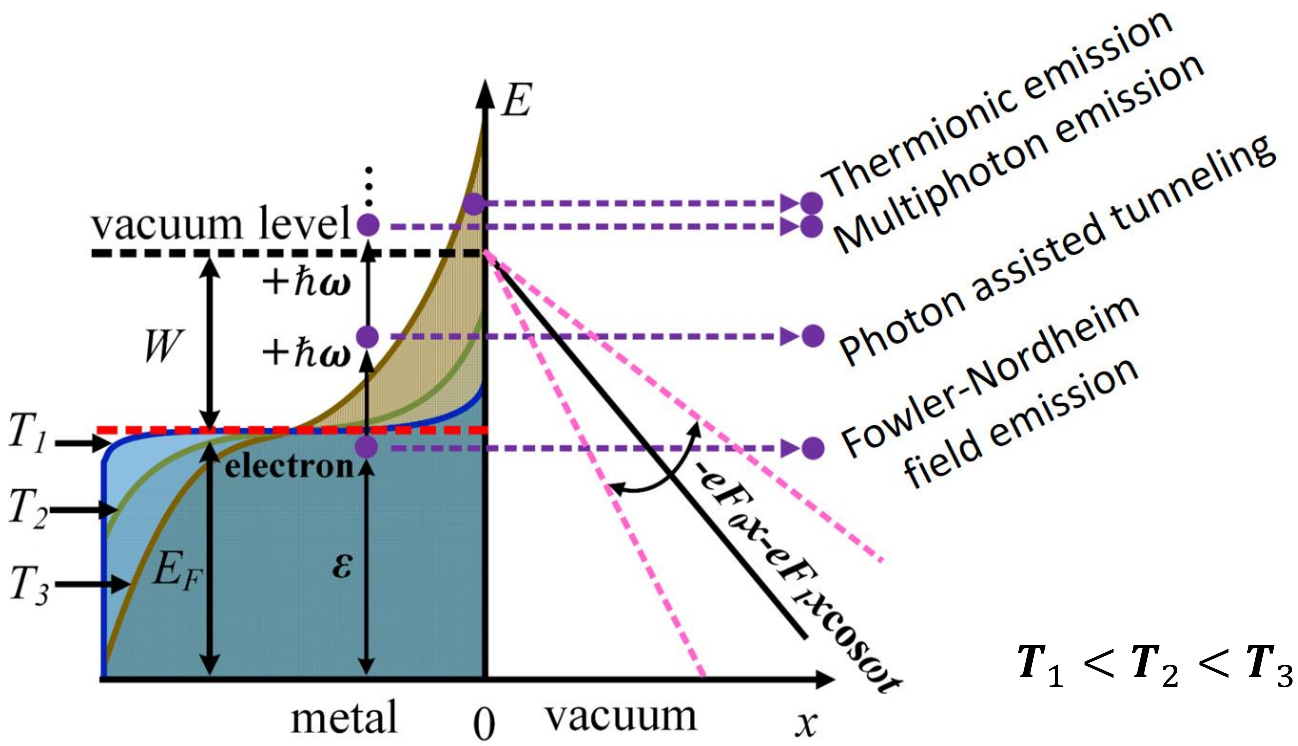
General quantum theory for thermionic-field-photoelectron emission [1-6]

- Exact solution to time-dependent Schrödinger equation (TDSE)



$$i\hbar \frac{\partial \psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi(x,t)}{\partial x^2} + \Phi(x,t)\psi(x,t)$$

$T_1 < T_2 < T_3$

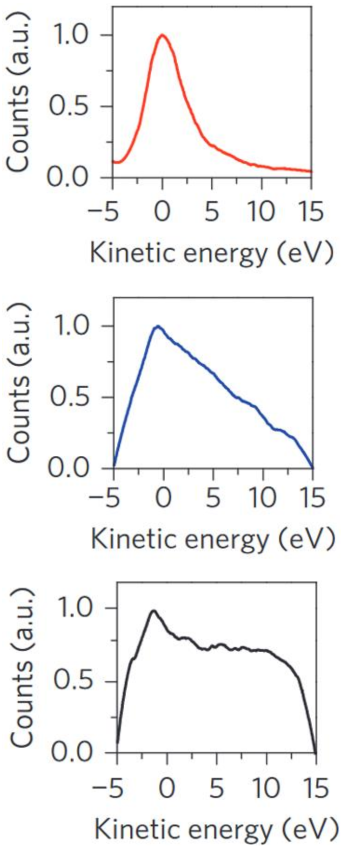
[1] P. Zhang and Y. Y. Lau, Sci. Rep. 6, 19894 (2016).
[2] Y. Luo, and P. Zhang, Phys. Rev. B, 98, 165442 (2018);
[3] Y. Luo, and P. Zhang, Phys. Rev. Applied 12, 044056 (2019).
[4] Y. Zhou, and P. Zhang, J. Appl. Phys. 127, 164903 (2020).
[5] Y. Luo, Y. Zhou and P. Zhang, Phys. Rev. B 103, 085410 (2021).
[6] Y. Zhou and P. Zhang, J. Appl. Phys. 130, 064902 (2021).

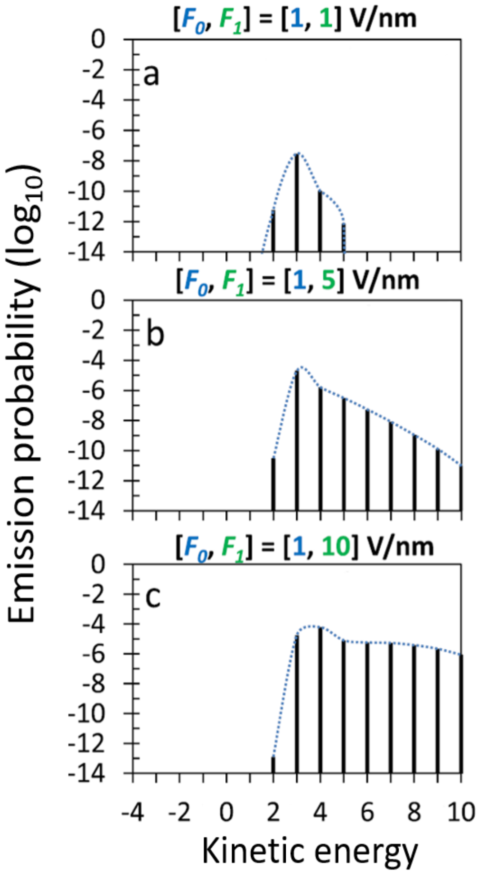
Controlling Photoelectron Energy Distribution & Emission Current

Electron energy spectra

Experiment | Our Theory

Laser intensity increases



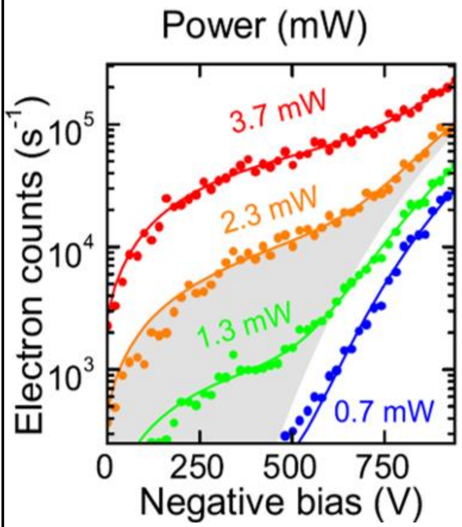


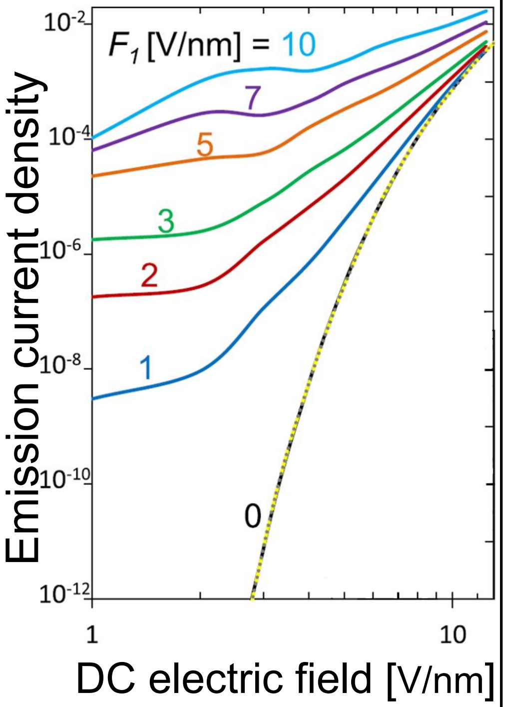
B. Piglosiewicz, et. al. *Nat. Photonics* **8,** 37–42 (2014).

Zhang, P. & Lau, Y. Y. *Sci. Rep.* **6,** 19894 (2016).

Emission current vs. DC bias

Experiment | Our Theory





C. Ropers, et. al, *Phys. Rev. Lett.* **98**, 043907 (2007).

Zhang, P. & Lau, Y. Y. *Sci. Rep.* **6**, 19894 (2016).

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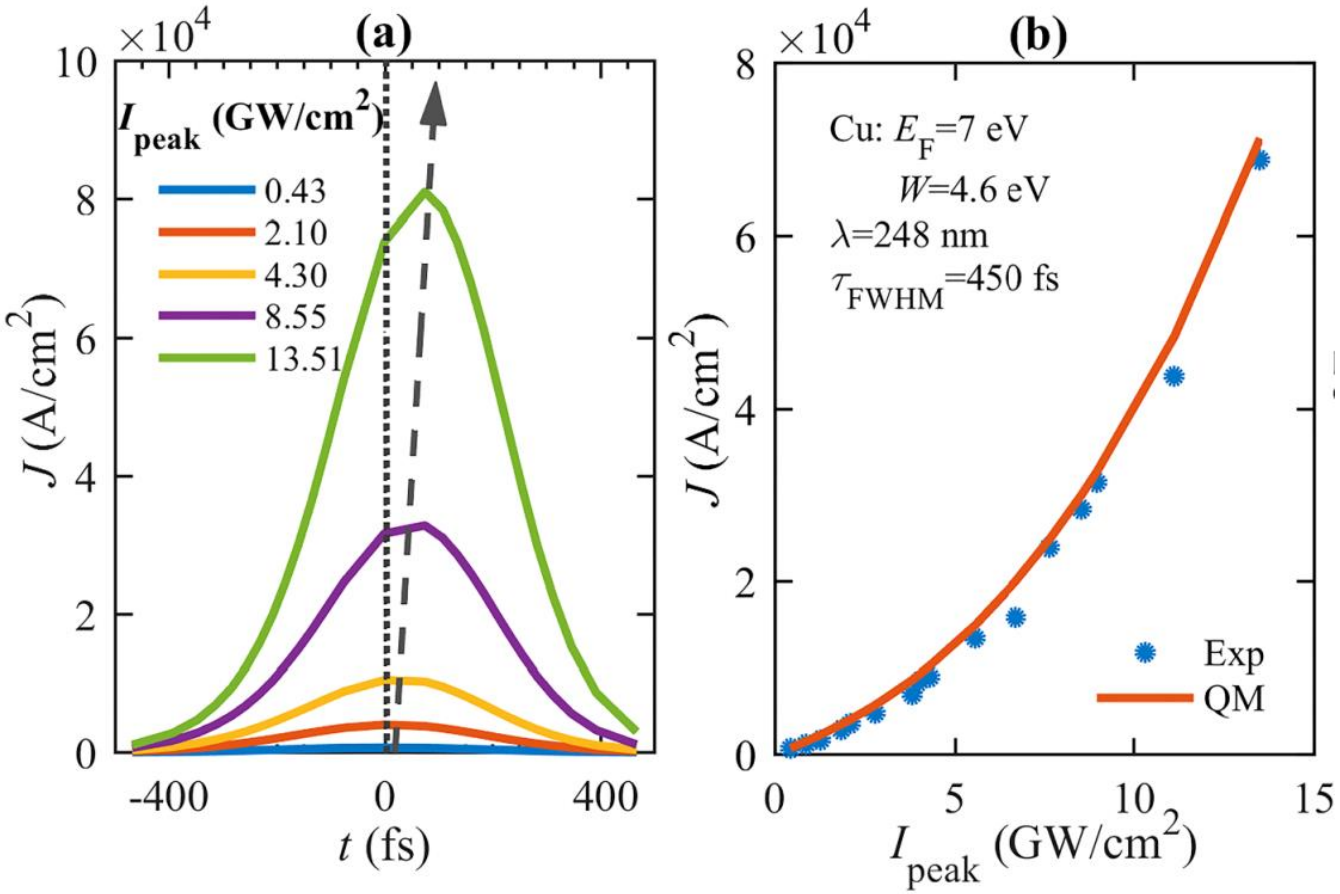
Quantum model for photoemission



- Lag between emission current peak and laser intensity peak
- Good agreement with experimental results [*]

[*] N. A. Papadogiannis et al., J. Phys. D: Appl. Phys. 30, 17 (1997).

Y. Zhou and P. Zhang,
J. Appl. Phys. 130, 064902 (2021).

Better understanding of photoemission may provide more control of plasma breakdown and plasma properties

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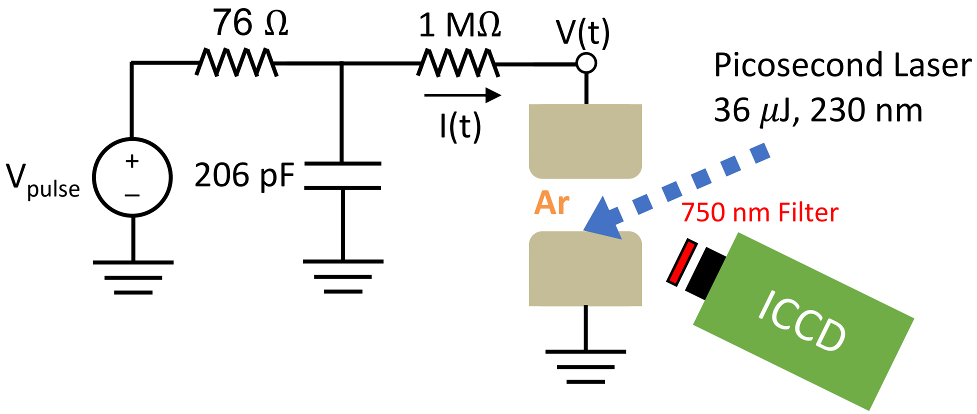
Experiments in Low Space Charge Regime (<100 μA)

- De-couple electrode phenomena from space charge effects
  - Effect of photoemission becomes observable
- Townsend breakdown is a good approximation
  - Provides global model to combine with photoemission quantum model



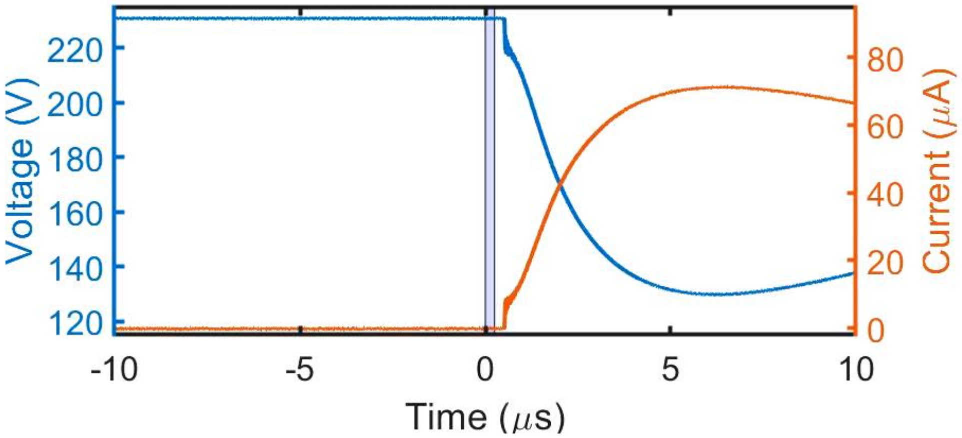
Aluminum: Work function = 4.08 eV

Laser: 230 nm = 5.39 eV

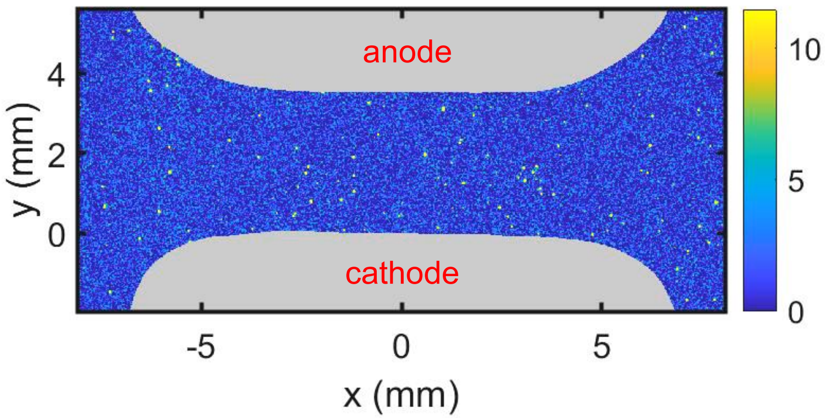
B. Horváth, A. Derzsi, J. Schulze, I. Korolov, P. Hartmann, and Z. Donkó, *Plasma Sources Sci. Technol* **29**(5), 055002, 2020.

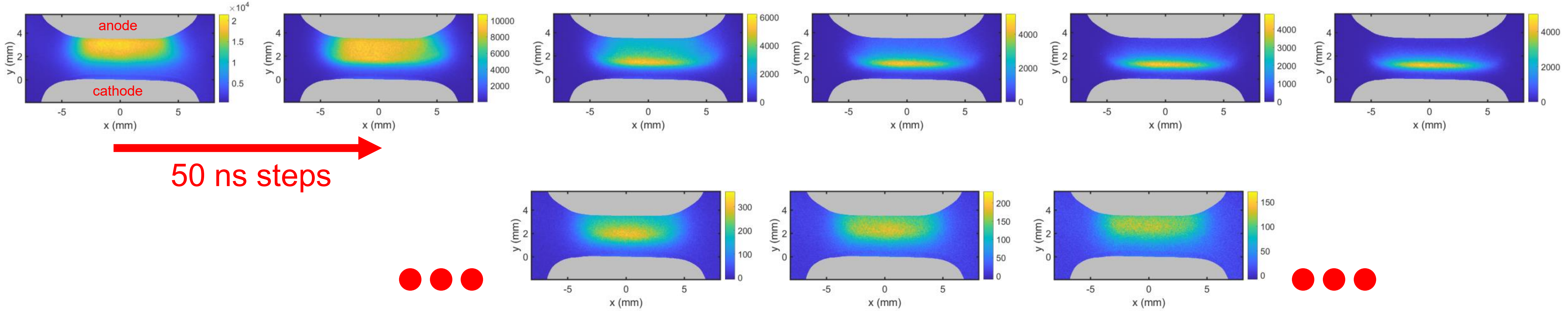
Laser-Induced Breakdown

Waveforms (with Laser)



750 nm Emission (with Laser)



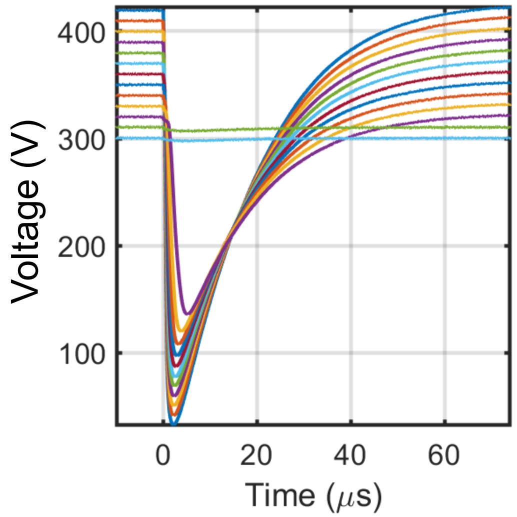


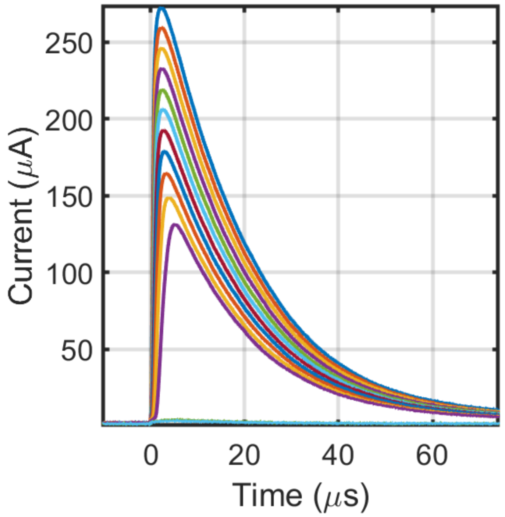
pd = 1 (Torr-cm)

Laser-Induced Breakdown Voltage

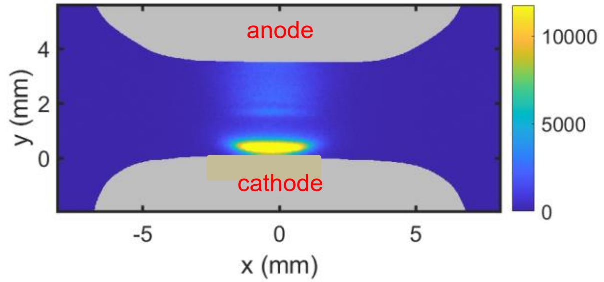
- Transition shown in waveform and image data
- Implies applied voltage threshold for laser-induced breakdown

pd = 10 (Torr-cm)

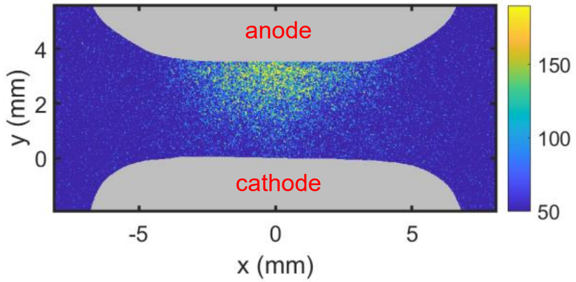


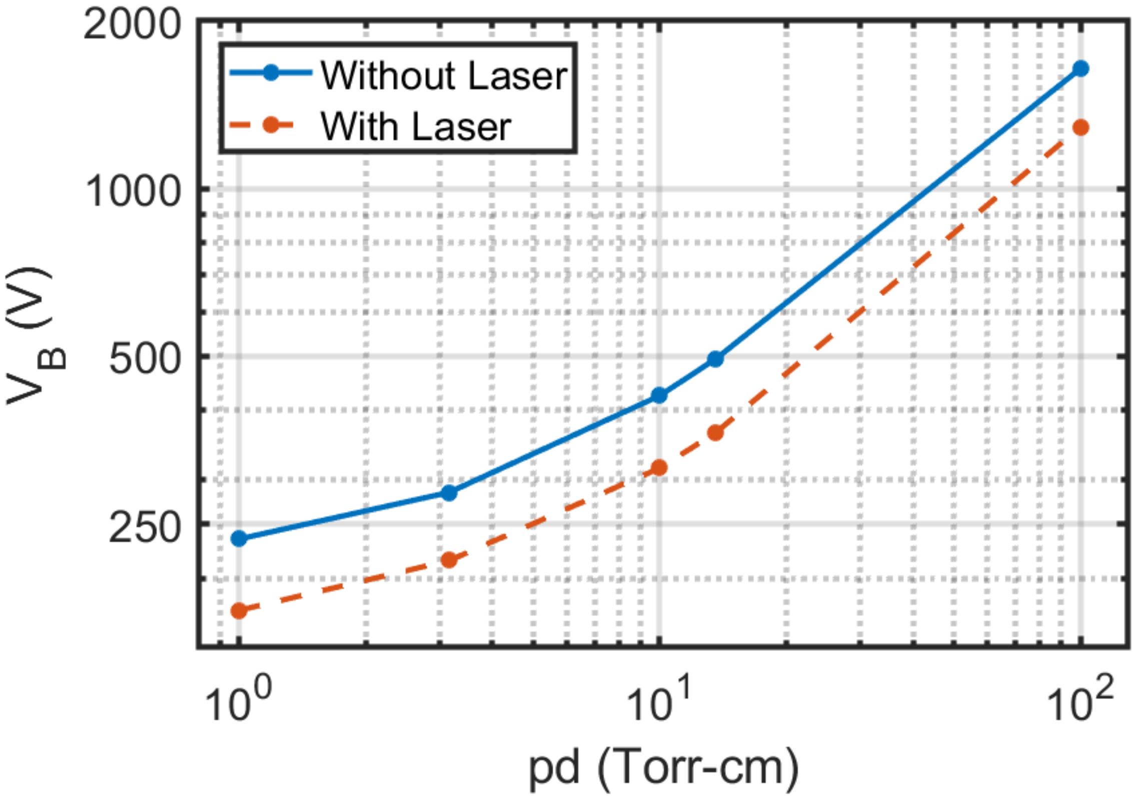


320 V



310 V





- Laser-induced photoemission provides sufficient electrons to reduces breakdown voltage
- Plasma could be sustained at a lower breakdown voltage or E/N

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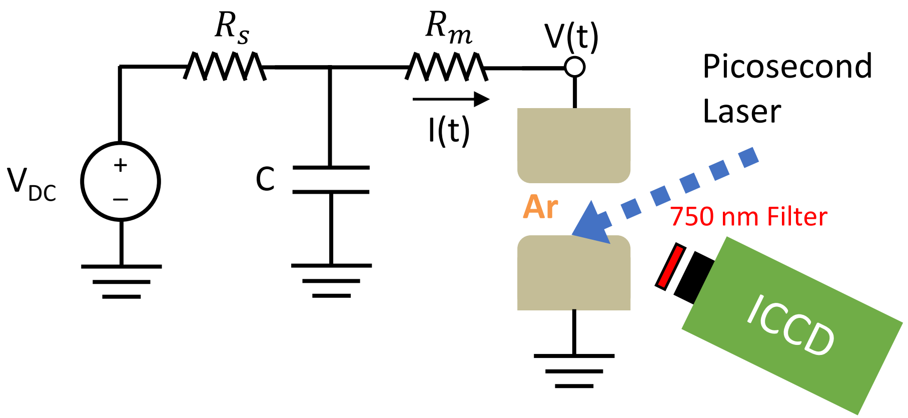
Model of Laser-Induced Plasma Breakdown

- Validated 0D model would support component and circuit design
- Discharge characteristics equation [1]:

$$\frac{dI}{dt} = \left[\frac{(1+\gamma)I_p}{\gamma T} + \frac{(g-1)I}{T} - \frac{I k_V}{\gamma(1+\gamma)}\frac{dV}{dt}\right] \times \left[1 + \frac{I k_I}{\gamma(1+\gamma)}\right]^{-1}$$

- Photoemission current I_p, ion transit time T, $\gamma = \gamma_p + k_V\, V + k_I\, I$
- Photoemission quantum model gives I_p [2]
- Coupled to circuit equation [1]:

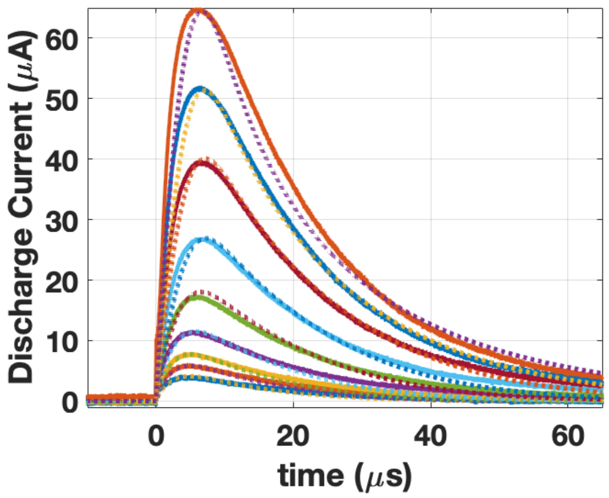
$$\frac{dV}{dt} = \frac{1}{R_s C}\left[V_0 - V - I(R_s + R_m)\right] - R_m \frac{dI}{dt}$$



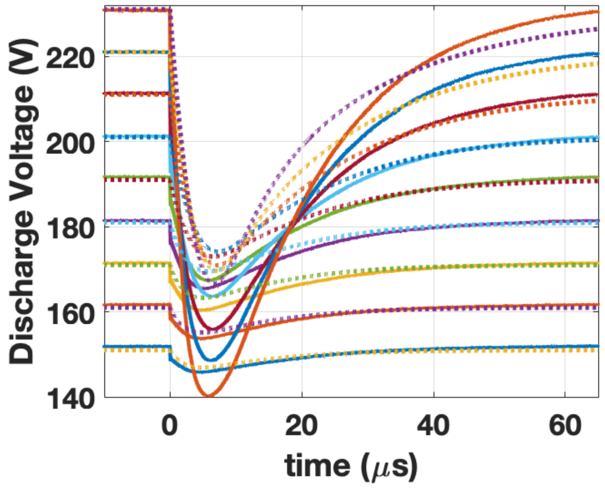
[1] A. V. Phelps, Z. Lj. Petrović, and B. M. Jelenković, *Phys. Rev. E* **47**, 2825, 1993.
[2] Y. Zhou and P. Zhang, *J. Appl. Phys.* **130**, 064902, 2021.

Results

Discharge Current for
$pd = 1 Torr\ cm$



Discharge Voltage for
$pd = 1 Torr\ cm$



Dotted lines: Model
Solid lines: Experiment

- Good match to experiment for currents <10 μA.
- Empirical fitting: Similar observations were made by Petrović and Phelps [1].
  - Gaussian-shaped simulated photoemission pulse, $I_p(t)$, must have 25 μs pulse width
  - A small charge transfer ($10^{-12}C$ to $10^{-13}C$) due to photocurrent pulse is necessary to fit the observed current amplitude → much smaller than the calculated emitted charge due to photoemission from the cathode ($2.1033 \times 10^{-10}C$).
  - An improved discharge characteristics equation is needed to capture effects of photoemission

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[1] Z. Lj. Petrović and A. V. Phelps, *Phys. Rev. E* **47**, 2806, 1993.

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Conclusion

- Effects of laser-induced photoemission become observable at low currents/space charge
- 0D models provide an avenue to study surface effects like photoemission on breakdown
  - Requires small space-charge distortion of the electric field in the observed range of currents
- Higher order effects of photoemission are yet to be captured, modifications to the discharge characteristics equation are needed

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http://www.egr.msu.edu/~pz

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