SAND2022-15041C

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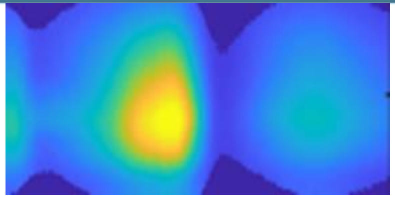
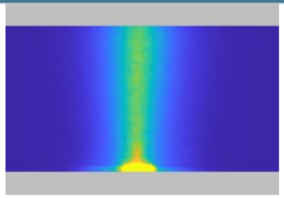
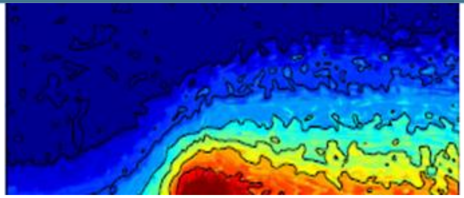
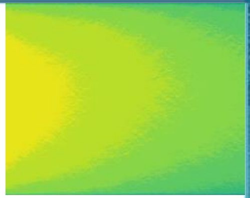
SPRF: Photoemission Induced Plasma Breakdown in Argon

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10/28/2022, DOE LTP Centers and User Facilities, Poster Session I

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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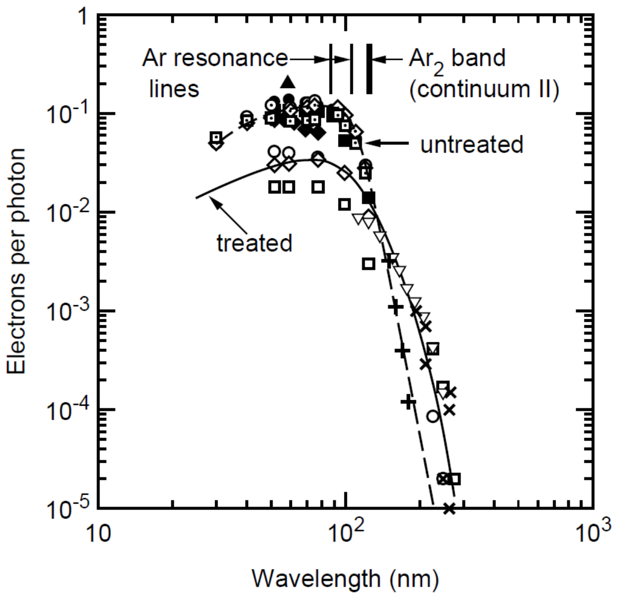
Photoelectron Emission

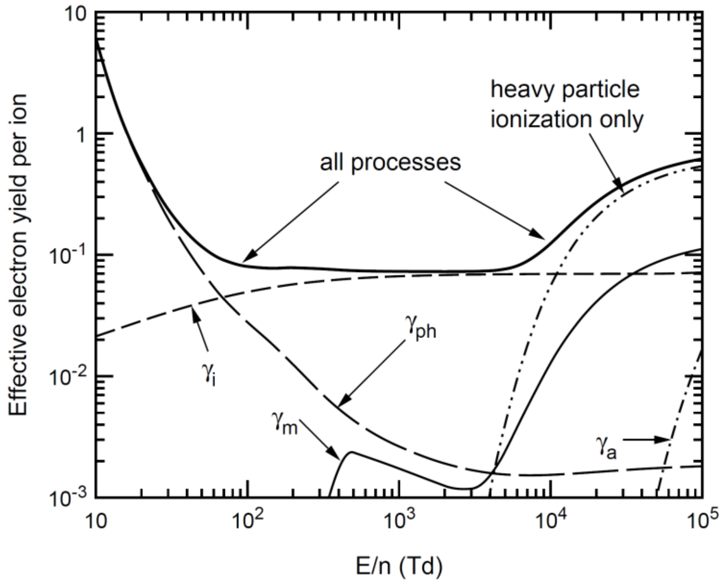
Photons supply energy to release electrons from surfaces

- Photoemission influences or sustains plasma (at low E/N)

Laser-induced photoemission not as well understood

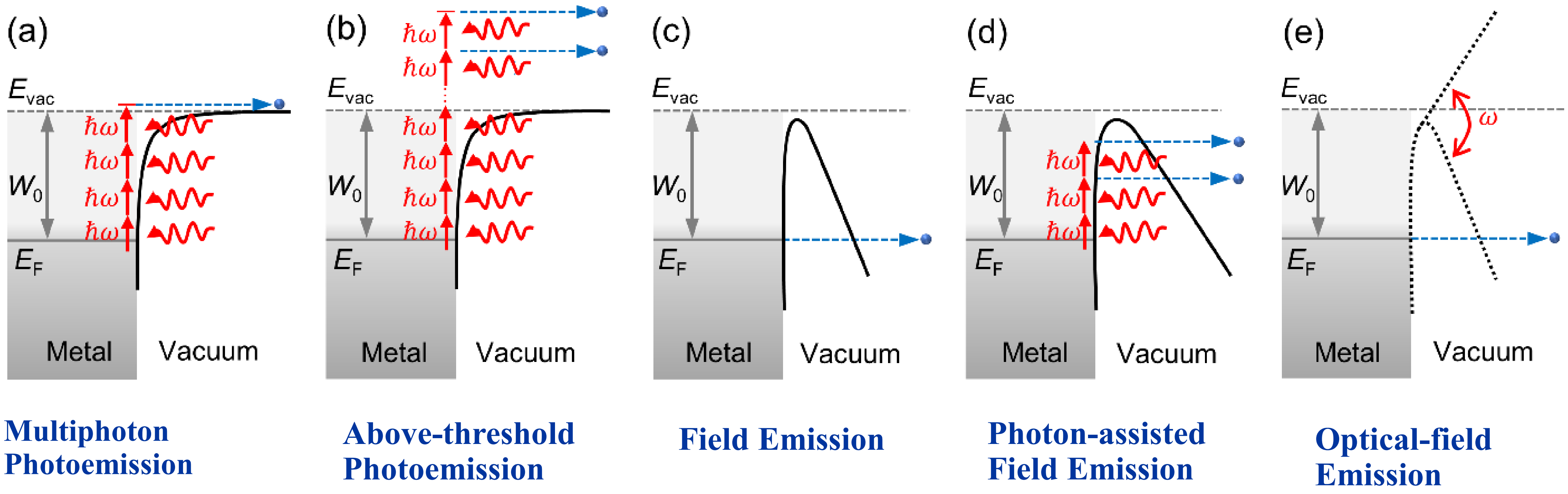
- Important for laser-triggered breakdown





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

Laser-Induced Photoemission



Emission process depends on laser wavelength, intensity, DC bias, surface properties

Pursued experiments to validate photoemission quantum model [1]

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

[1] Y. Zhou and P. Zhang, J. Appl. Phys. **130**, 064902, 2021.

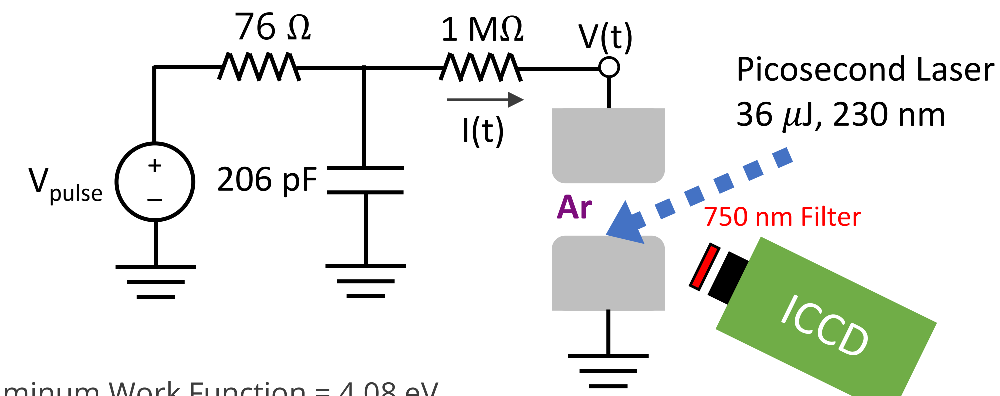
Experiments in Low Space Charge Regime (<100 μA)

De-couple electrode phenomena from space charge effects

- Effect of photoemission becomes observable

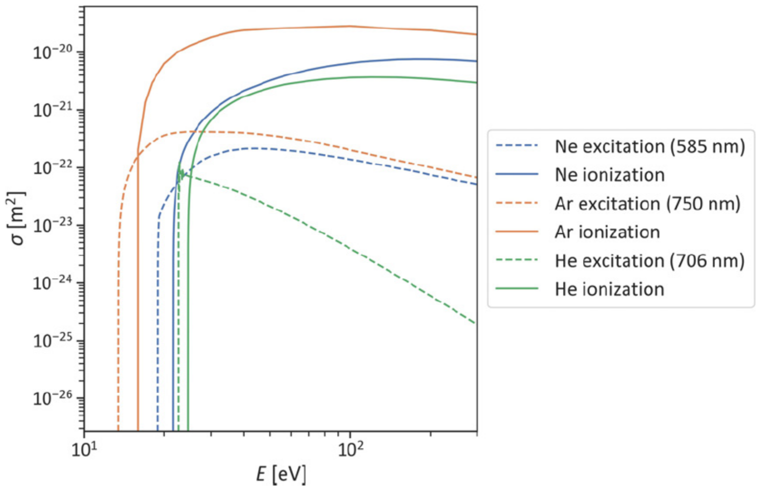
Townsend breakdown is a good approximation

- Provides global model to combine with photoemission quantum model



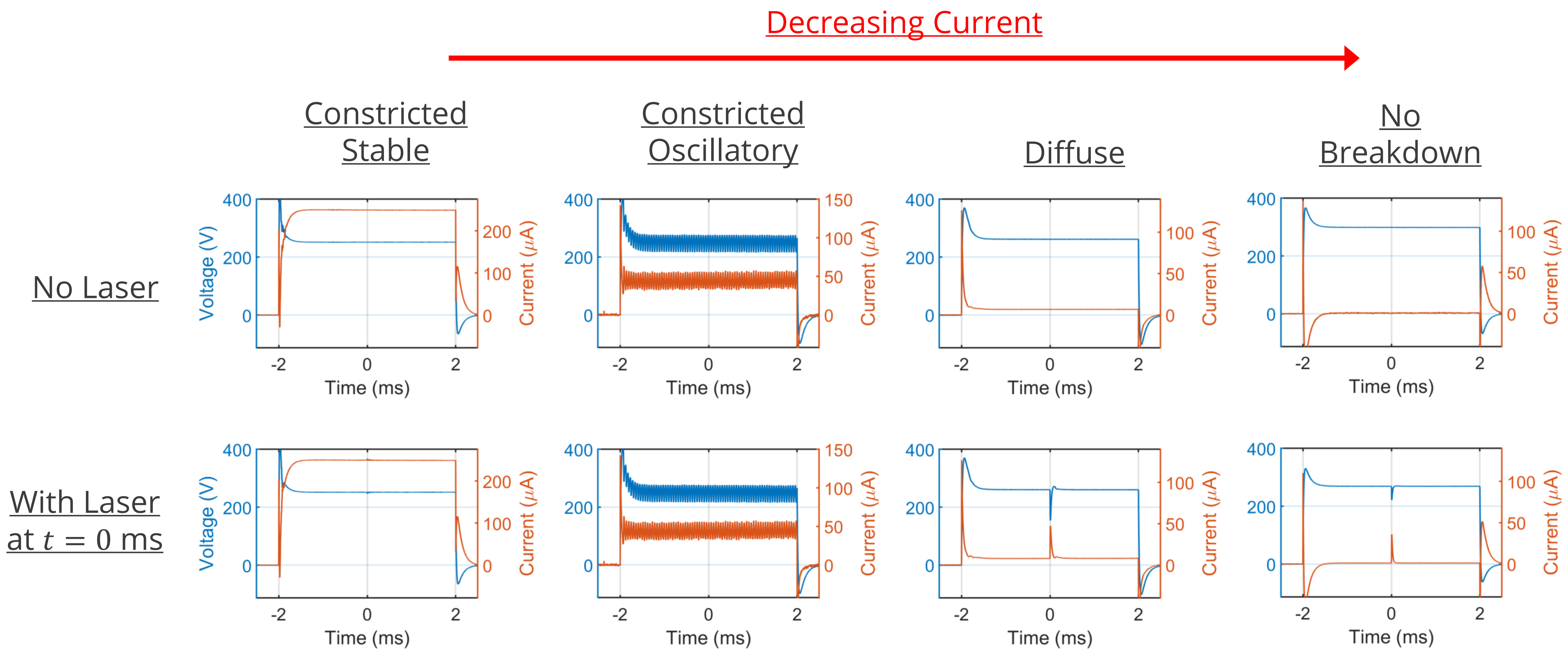
Aluminum Work Function = 4.08 eV
Laser 230 nm = 5.39 eV

Cross sections from ground state into excited states [1]



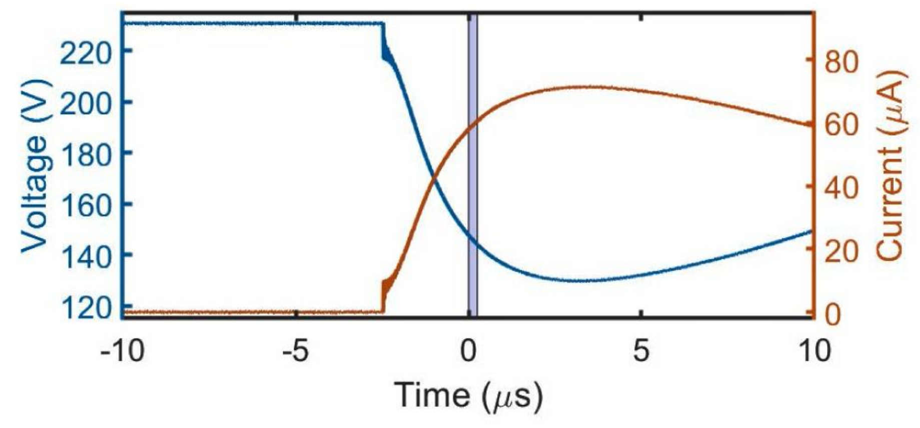
[1] B. Horváth, A. Derzsi, J. Schulze, I. Korolov, P. Hartmann, and Z. Donkó, *Plasma Sources Sci. Technol* **29**(5), 055002, 2020.

pd = 1 (Torr-cm)

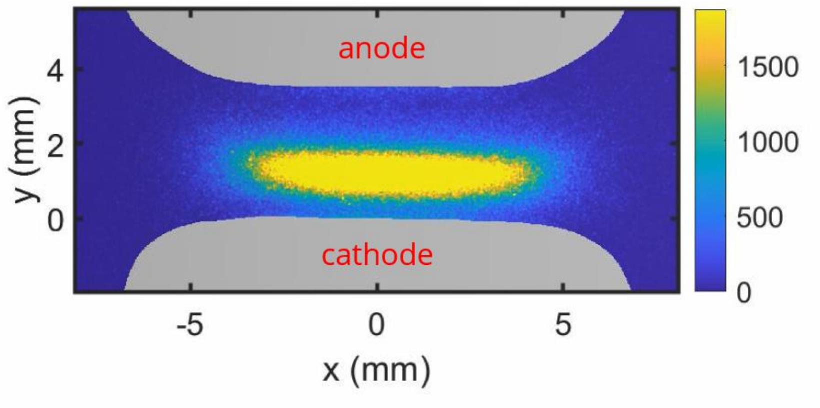

Decreasing Current
Constricted Stable
Constricted Oscillatory
Diffuse
No Breakdown
No Laser
With Laser at $t = 0$ ms
Voltage (V)
Current (μA)
Time (ms)
400
200
0
-2
0
2
150
100
50
0

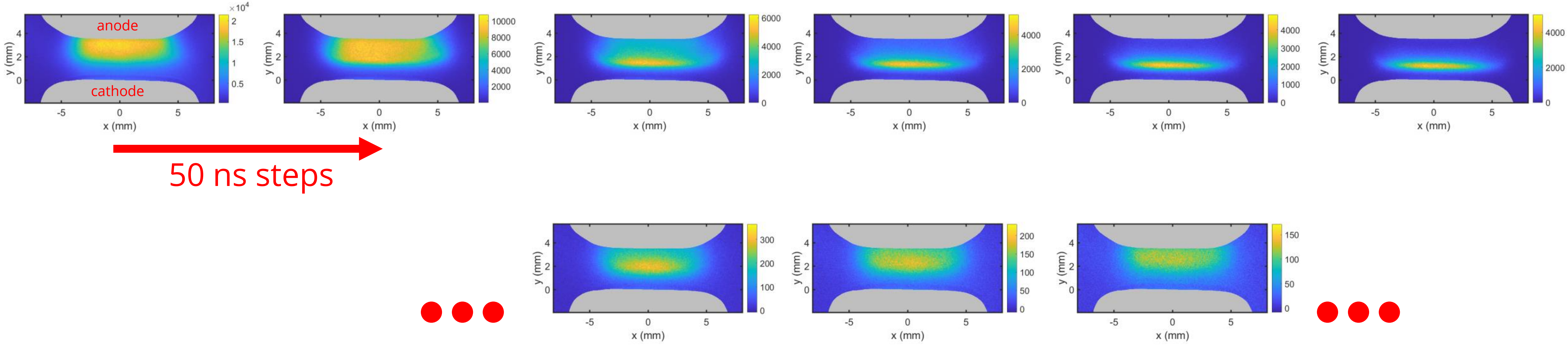
Laser-Induced Breakdown at pd = 1 (Torr-cm)

Waveforms (with Laser)



750 nm Emission (with Laser)

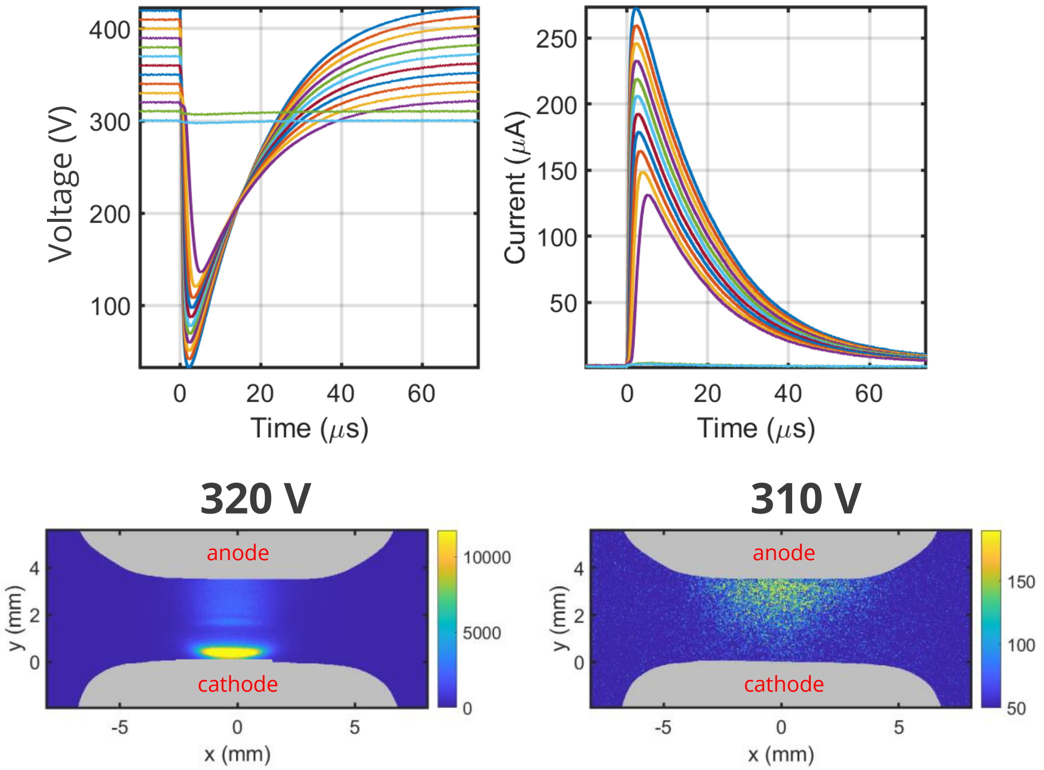


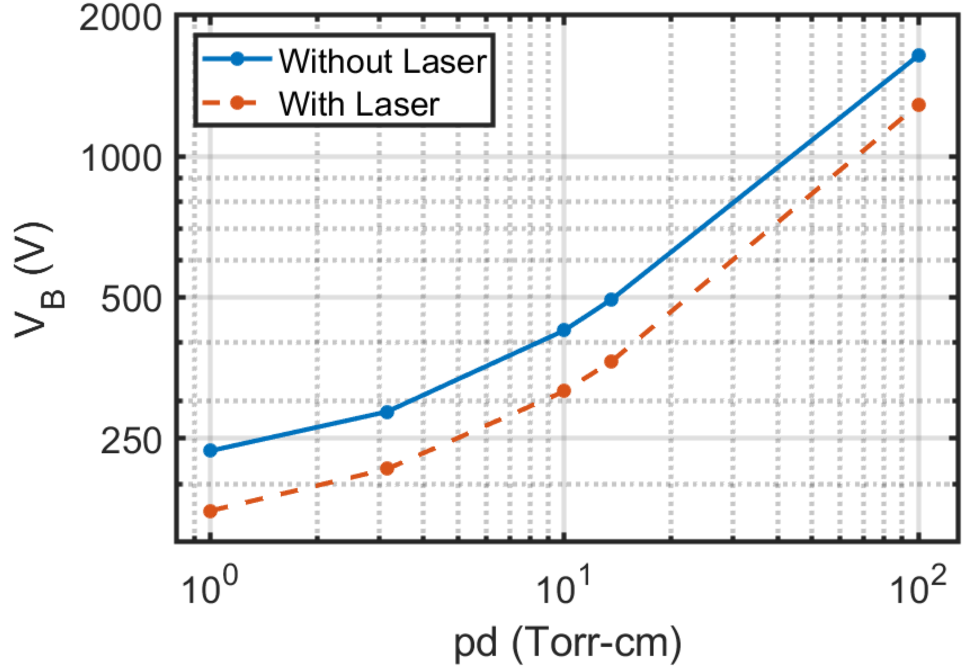


Laser-Induced Breakdown Voltage

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

pd = 10 (Torr-cm)





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

Modeling Photoemission Induced Plasma Breakdown

A. V. Phelps, Z. Lj. Petrović, and B. M. Jelenković [1] → Transient current (I) and voltage (V) model

- A pulse of photoelectrons released from the cathode (corresponding to a photoelectric current pulse, I_p)
- A pulse of voltage (V_0) applied to the discharge circuit

Assumptions [1]

- Small space-charge distortion of the electric field in the observed range of currents
- The times for significant changes in the electric field and current are long compared to the electron and ion transient times
- Electrons are produced at the cathode only by ions → contributions from photons and metastables are small

Effective yield of electrons per ions arriving at the cathode, $\gamma = \gamma_p + k_V\, V + k_I\, I$

γ_p→ "potential ejection" of electrons

k_V→ "kinetic ejection" of electrons

k_I→ first-order effects of space charge on the electric field

[1] A. V. Phelps, Z. Lj. Petrović, and B. M. Jelenković, *Phys. Rev. E* **47**, 2825, 1993.

Modeling Photoemission Induced Plasma Breakdown

Assumptions [1] (continued)

- Ionization by electrons only → ionization by heavy particles neglected
- The electron multiplication is an exponential function of position with a spatial ionization coefficient (α) [2]

$$\alpha = Cpe^{-D\sqrt{\frac{p}{E}}}$$

$p \rightarrow$ pressure ($Torr$)

$E \rightarrow$ electric field ($V\ cm^{-1}$)

$C, D \rightarrow$ fitting coefficients for the specific gas

- Round-trip electron number gain (g) resulting from an electron released from the cathode → a unique function of the gas density (n), electrodes separation (d), and discharge voltage (V)

$$g = \gamma[(1+\delta)e^{\alpha d}]$$

- δ → yield of ions produced by backscattered electrons per electron arriving at the anode
- Electron and ion currents → uniformly distributed over the surface of the electrodes

[1] A. V. Phelps, Z. Lj. Petrović, and B. M. Jelenković, *Phys. Rev. E* **47**, 2825, 1993.
[2] Fu et al., *Plasma Sources Sci. Technol*. **27,** 095014, 2018.

Discharge Characteristics and Circuit Equations

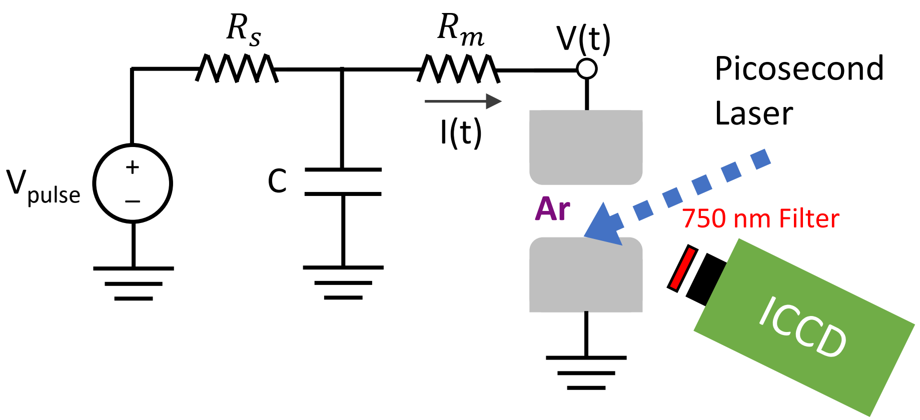
Discharge characteristics equation [1]:

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

Ion transit time, $T = d/v_d$; $d \rightarrow$ Electrodes separation, $v_d \rightarrow$ Ion drift velocity

Equation for the discharge voltage (V) in terms of the discharge current (I) and the circuit components [1]:

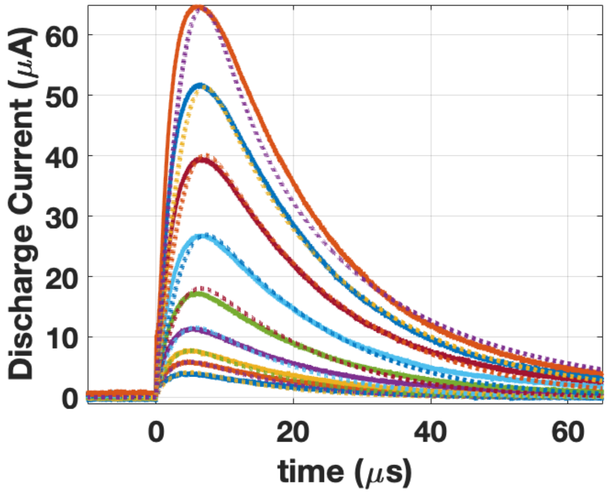
$$\frac{dV}{dt} = \frac{1}{R_s C}[V_0 - V - I(R_s + R_m)] - R_m\frac{dI}{dt}$$



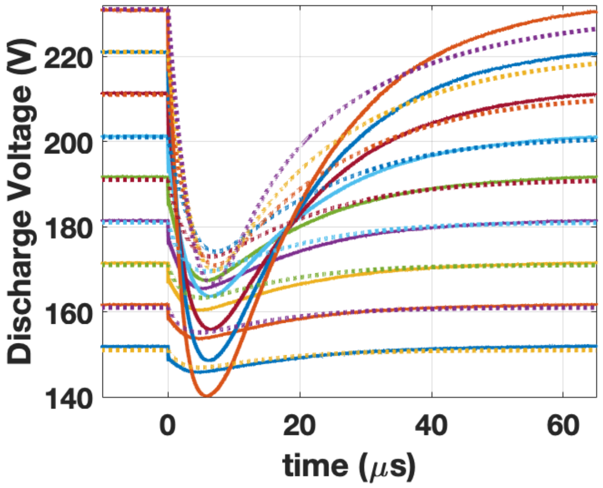
[1] A. V. Phelps, Z. Lj. Petrović, and B. M. Jelenković, *Phys. Rev. E* **47**, 2825, 1993.

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

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

Conclusions

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 hard to capture, modifications to the discharge characteristics equation are needed

Work was supported by the Sandia Laboratory Plasma Research Facility (DOE FES) and the Office of Naval Research (ONR) YIP Grant No. N00014-20-1-2681.

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