DC Voltage Breakdown Studies

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Townsend Criterion/First Ionization Coefficient

Townsend's First Ionization Coefficient

$$\alpha = Ape^{-\frac{Bp}{E}}$$

A,B = Empirical Constants based on gas properties

α represents the amount of ionization that is possible over a certain length, a common unit is cm^{-1}.

Townsend's Breakdown Criterion

$$e^{\alpha d} = 1 + \frac{1}{\gamma_{se}}$$

γ_{se} is the secondary emission coefficient and represents the number of electrons that are excited off the electrode surface and is directly related to the work function of the metal and the surrounding gas

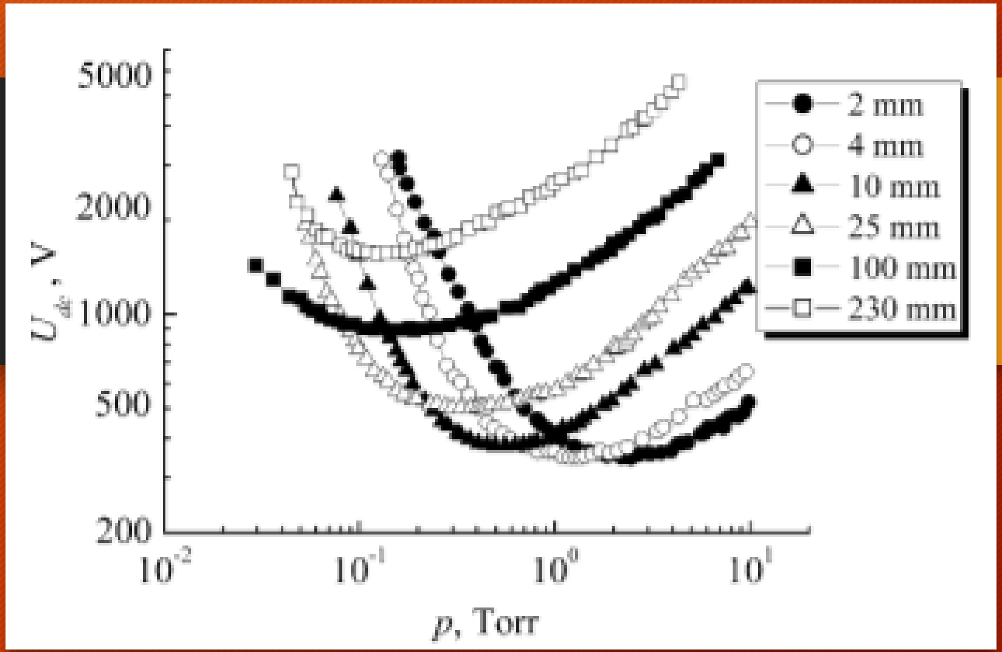
A. M. Howatson,An introduction to gas discharges,eng, [1st ed.]., The Commonwealth and internationallibrary. Applied electricity and electronics division ; v.8 (Pergamon Press, Oxford).

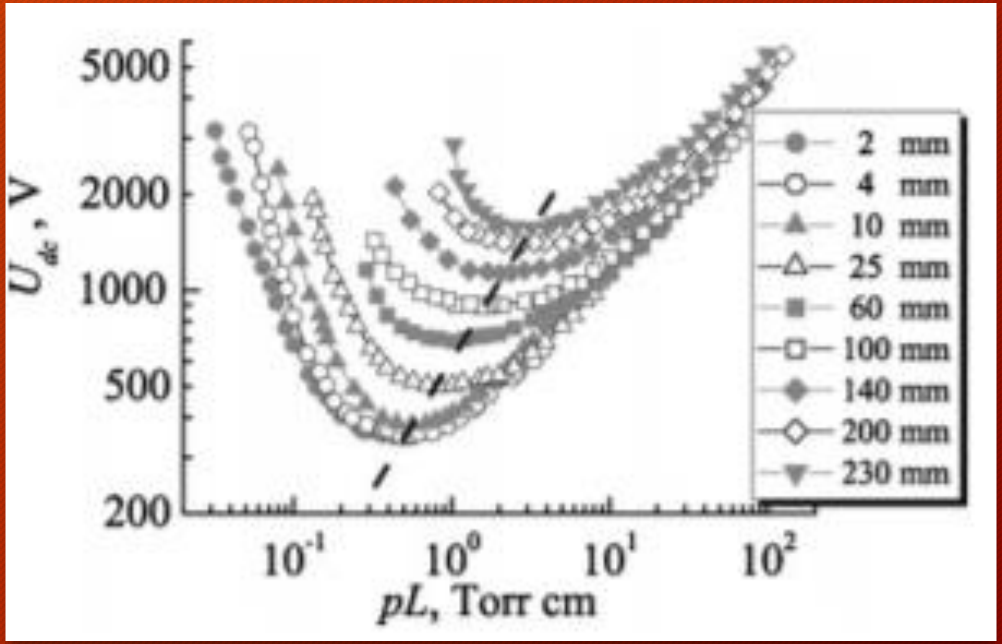
Paschen’s Law

$$V_B = \frac{Bp\,\mathrm{d}}{\ln(Apd) - ln\left(ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)}$$

Paschen Curves

- All Paschen curves are graphed against the pressure multiplied by the electrode distance (bottom)
- This is because those two variables are multiplied by each other in the Paschen equation and are what usually varies, i.e. the independent variables
- This creates a correlation in the minimums of the curves and aligns the curves

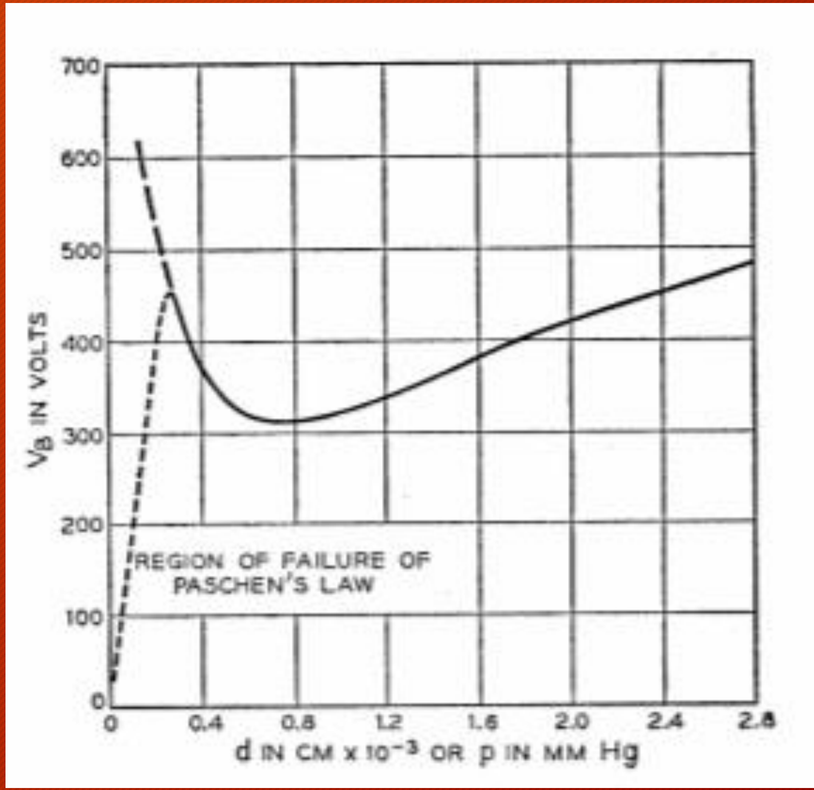




V. Lisovskiy, V. Koval, and V. Yegorenkov, “Dc break-down of low-pressure gas in long tubes”, Physics Let-ters A375, 1986–1989 (2011).

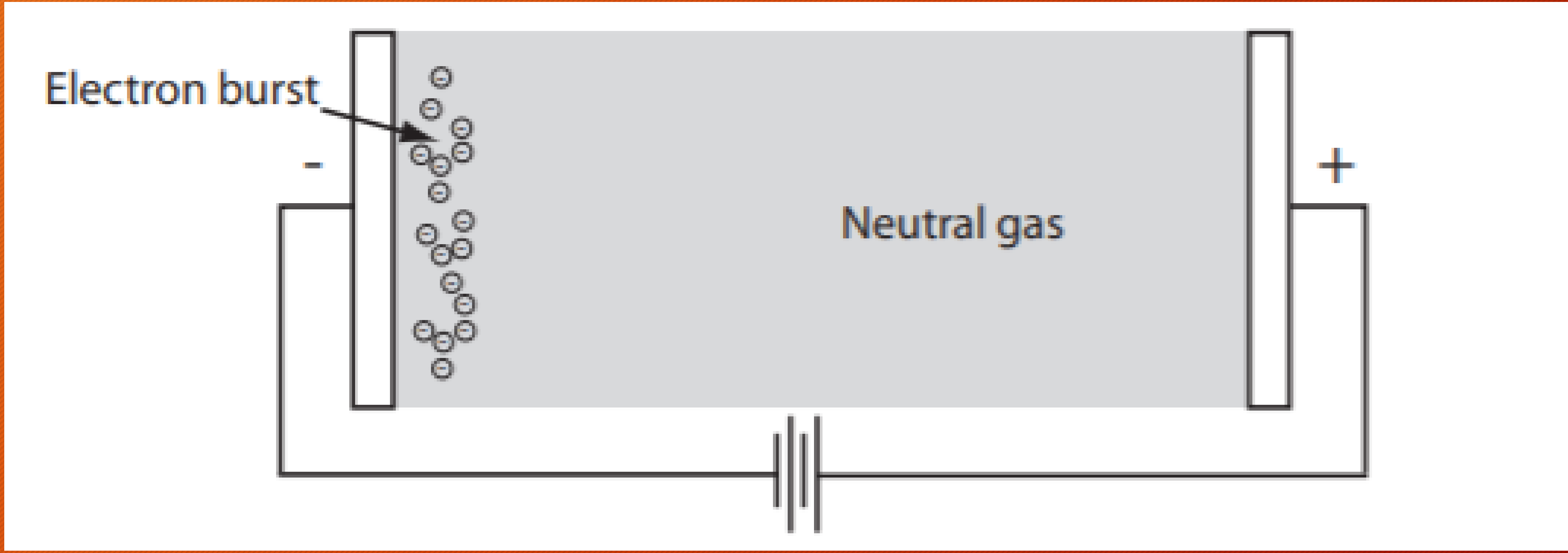
Failure of Paschen's Law

- From its creation Paschen's law was only valid in a certain range
- The law fails at higher pressures of gas as well as at very small electrode distance
- Some have surmised this is due to the ionization of the gas which in turn modifies the electric field



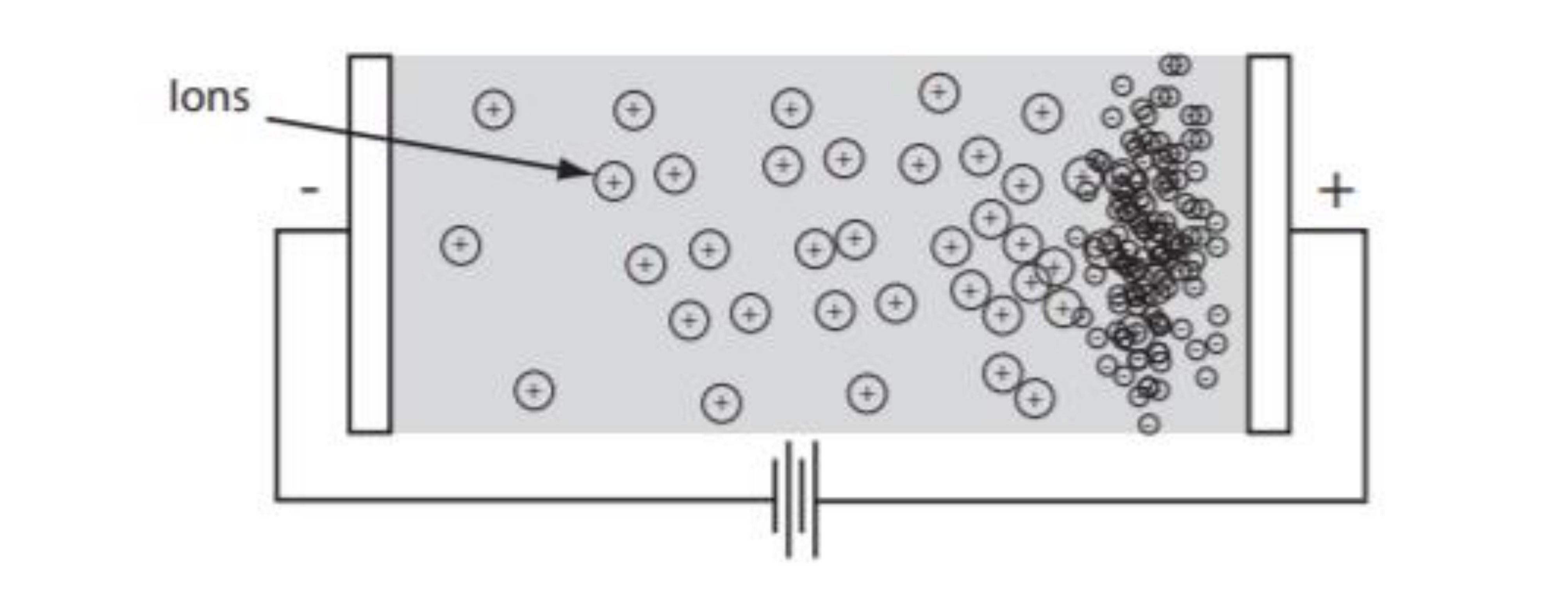
W. S. Boyle and P. Kisliuk, "Departure from paschen's law of breakdown in gases", Phys. Rev.97, 255-259(1955).

Streamer Breakdown



J. E. Cooley,Fundamentals of undervoltage breakdown through the townsend mechanism(Princeton Univer-sity, 2008).

Streamer Breakdown



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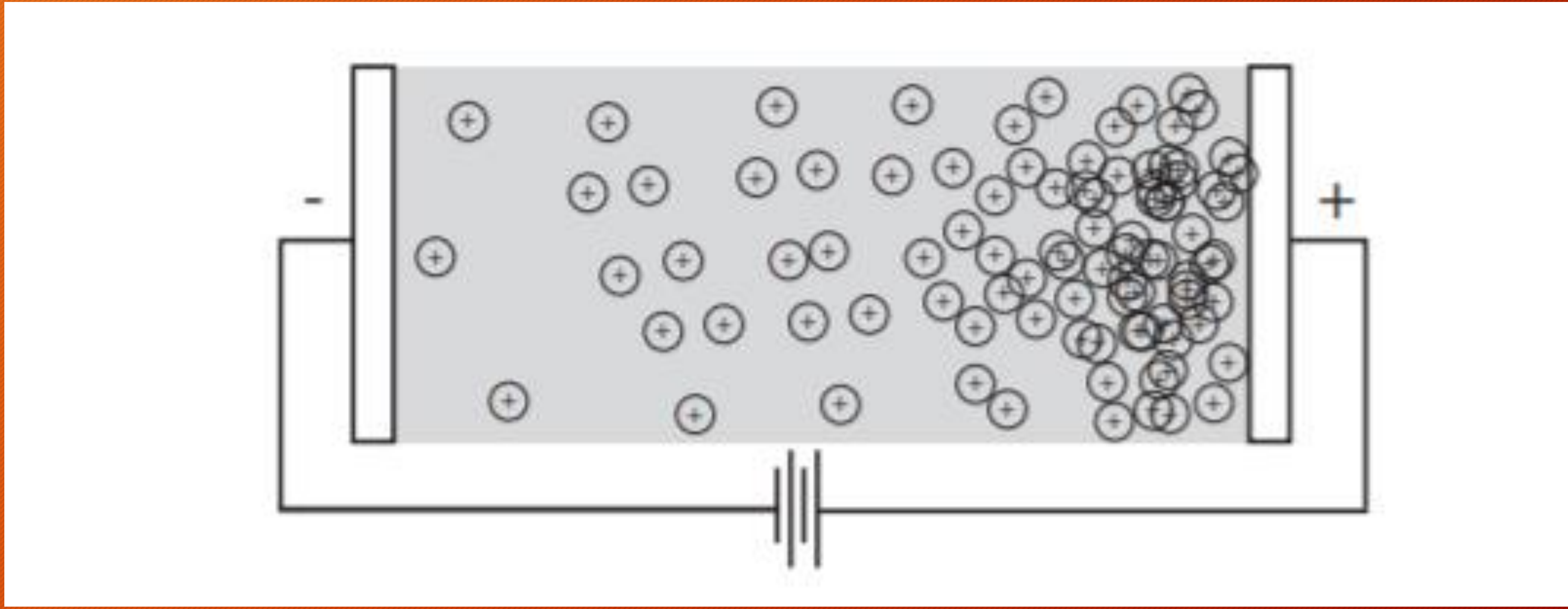
Streamer Breakdown



J. E. Cooley,Fundamentals of undervoltage breakdown through the townsend mechanism(Princeton Univer-sity, 2008).

Meek-Raether Criterion

The meek-rather criterion states that a streamer is most likely to form when the “avalanche gain” reaches around 10^8

$$e^{\alpha d} = 10^8$$

Meek-Raether
Breakdown Criterion

$$e^{\alpha d} = 1 + \frac{1}{\gamma_{se}}$$

Townsend
Breakdown Criterion

J. M. Meek and J. D. Craggs,Electrical breakdown ofgases(1978).

Higher Pressure Experimentation

- Papers and the theory do show that the breakdown generally follows the Paschen law at lower pd values
- At intermediate pd values experimental curves generally follow the meek criterion
- There is not many papers that cite the validity of the laws up and into the high-pressure region
- We have characterized the high-pressure region and shown that Paschen's Law is indeed inaccurate in this region

The Electrodes

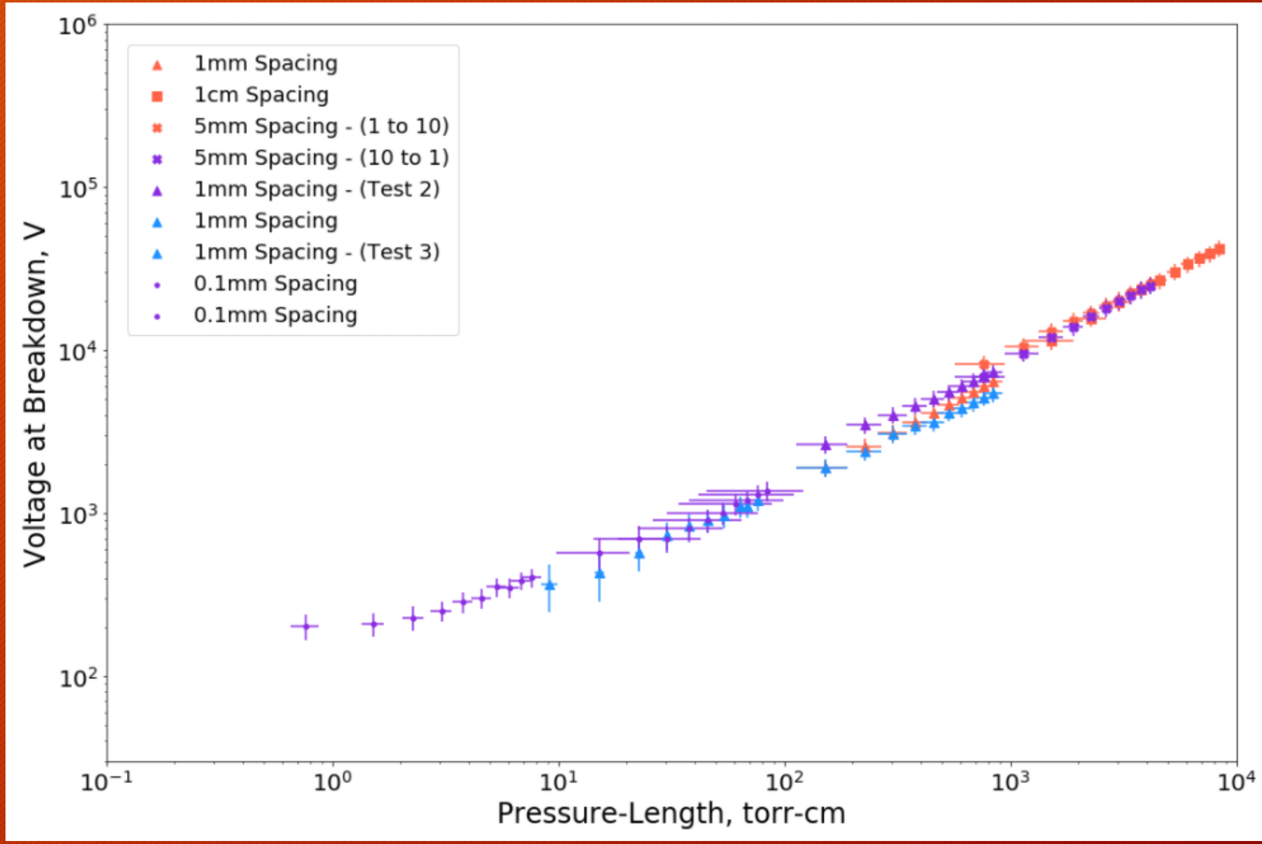
Current Results in Argon

To the right is breakdown data that was all performed with Argon gas

The data ranges from mbar pressures to 10 bar

The electrode separation distances are .1 mm, 1 mm, 5 mm, 1 cm

The values obtained cover a large range of pd values utilizing the same setup, as intended

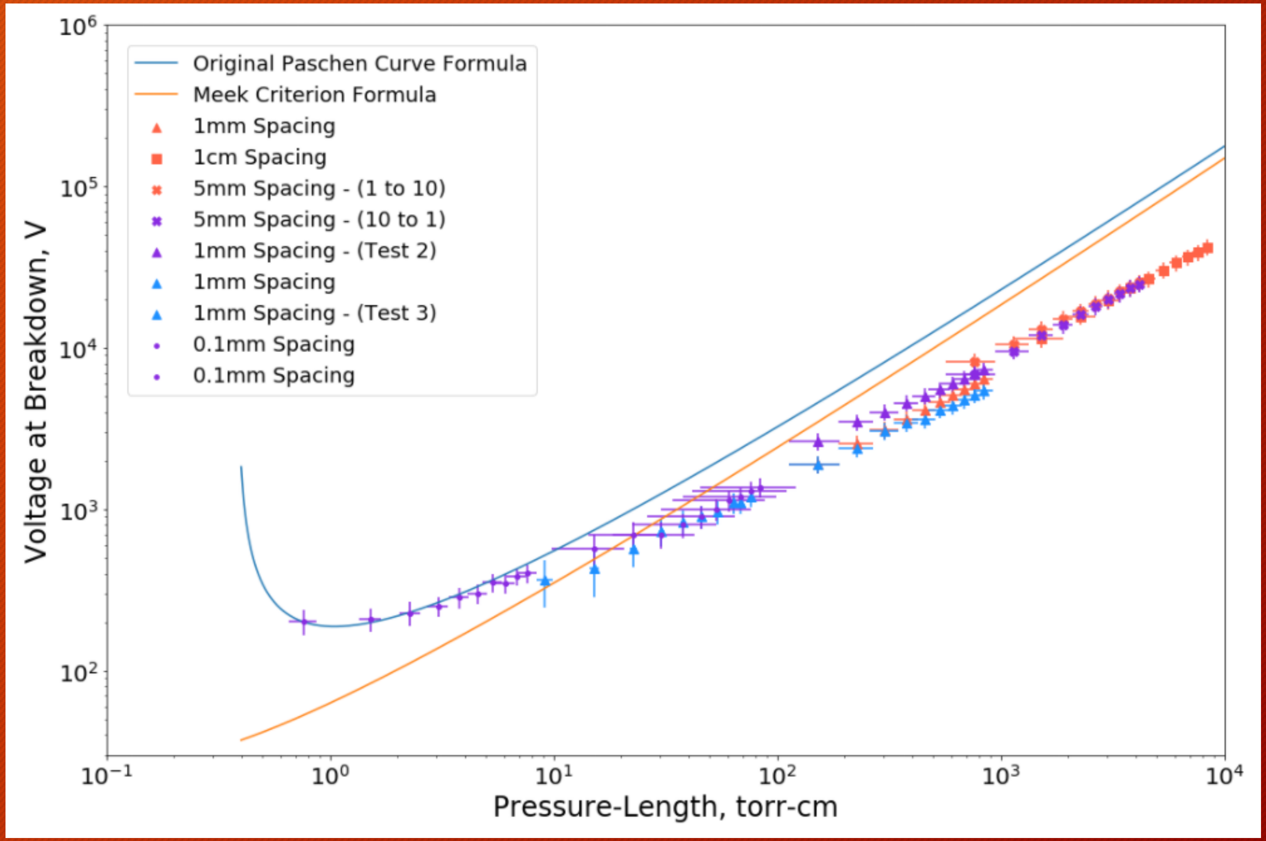


Theoretical Comparisons

The Paschen law is shown in blue on the graph to the right using accepted values for the A,B, and γ_{se}

The meek criterion is also shown in orange as well, with the separation between the two being constant at higher pressures

The data clearly follows a separate slope at higher pressures indicating an extension to the existing criterions/laws is necessary

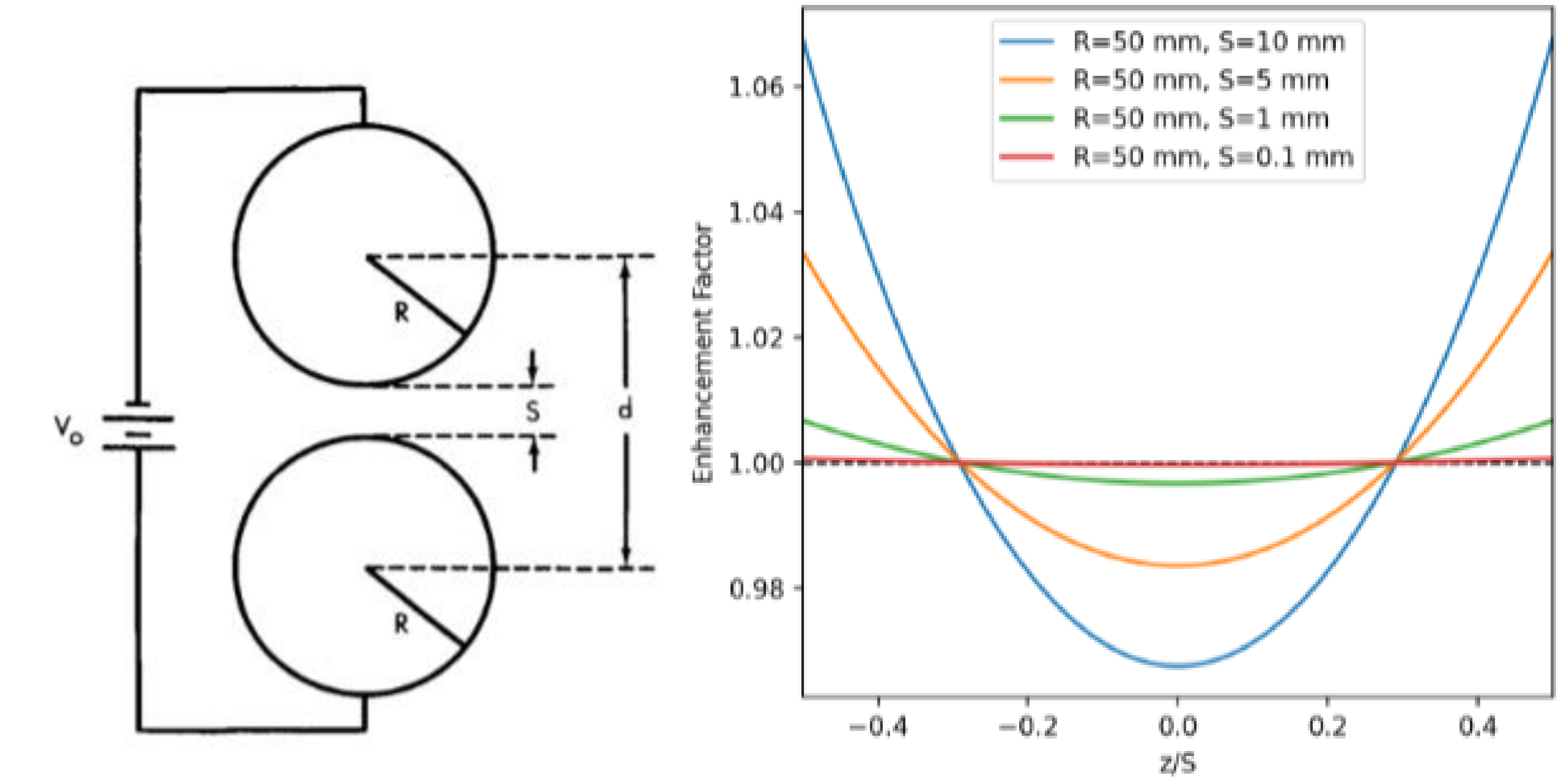


Enhancement factor

Calculated the field enhancement factor due to the spherical electrode geometry

This enhancement of the field is due to the spherical geometries we have used

Since we only used 1 cm maximum separation distance it only accounts for a maximum of 6% uncertainty in the electric field



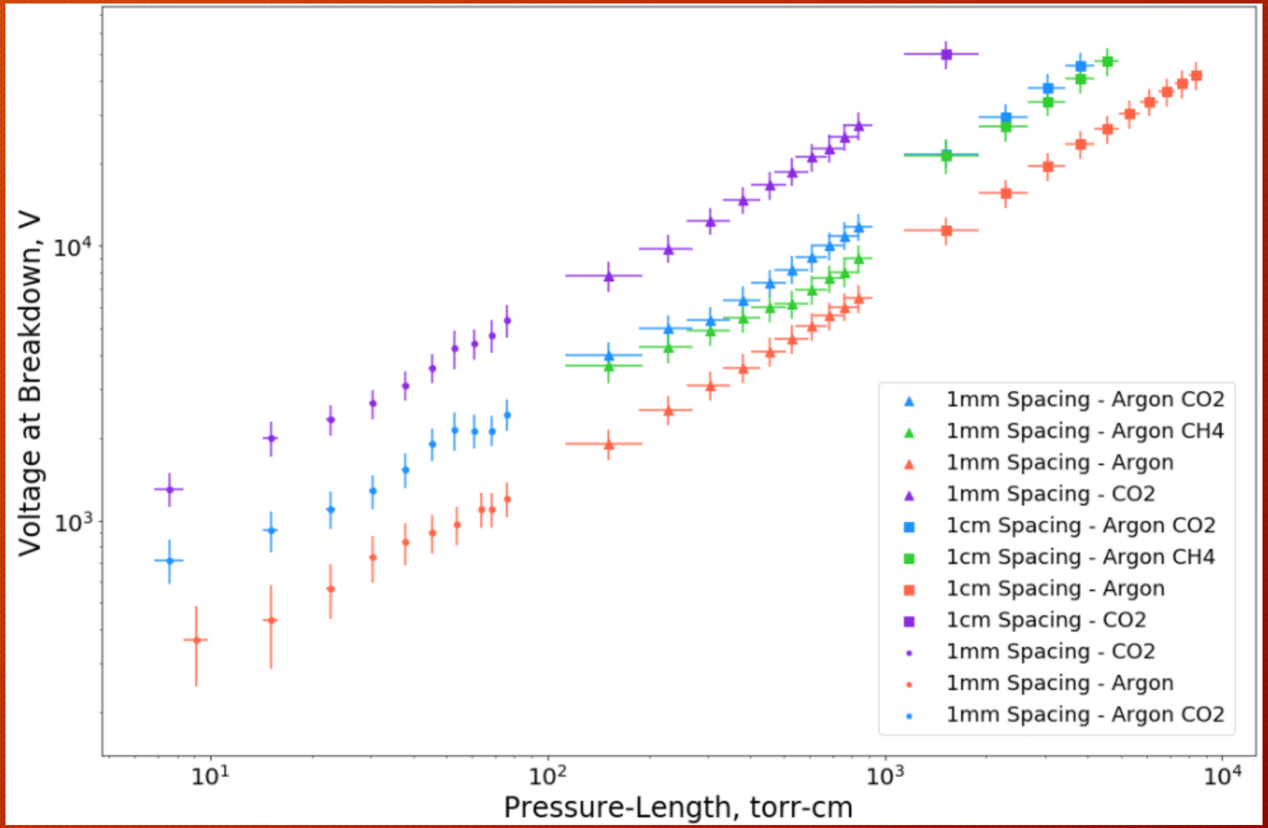
Results in CO_2 and Argon

To the right is breakdown data that was all performed with Argon gas, pure CO_2, and a mixture of 10% CO_2 /90% Argon

The data ranges from mbar pressures to 10 bar

The electrode separation distances are 1 mm and 1 cm

This log scale is useful to see the trends the lines follow and is used as a standard in breakdown measurements

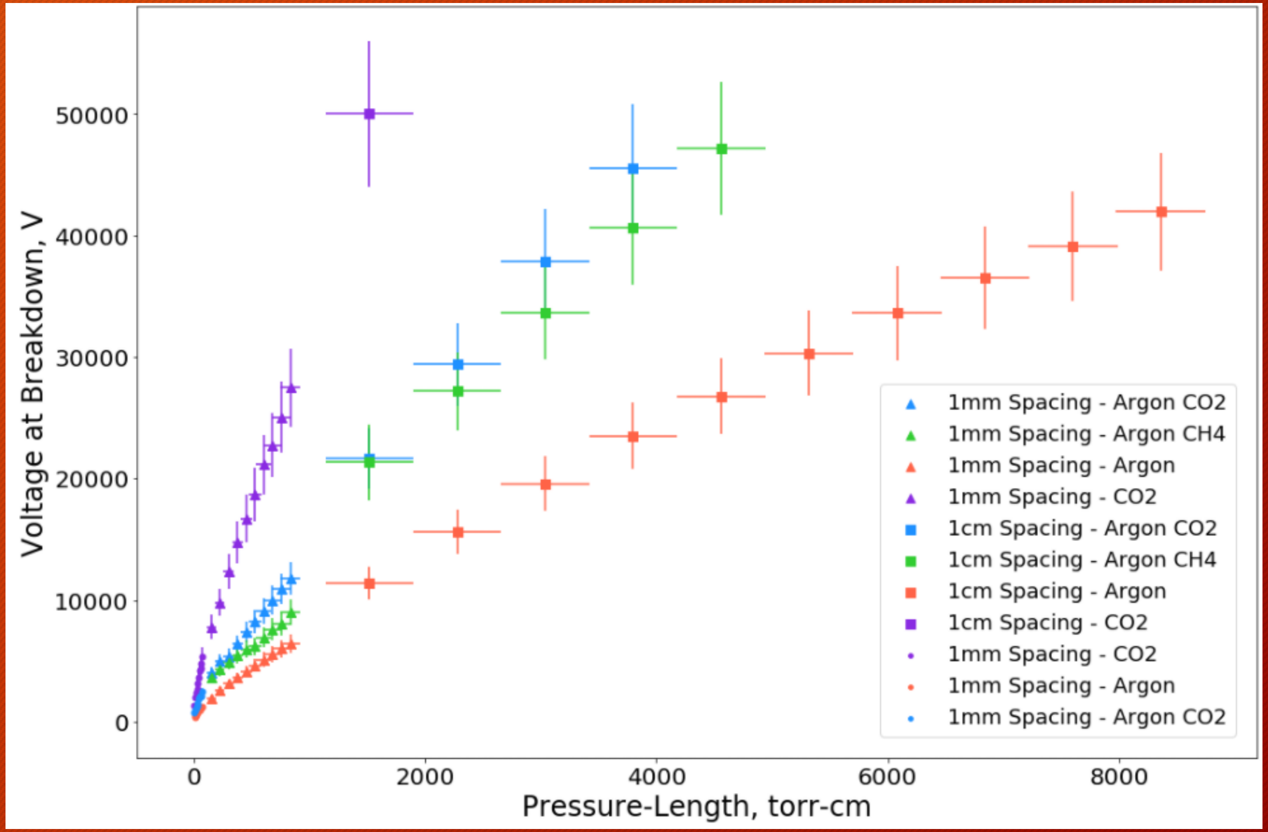


Linear Graph

To the right is the same graph as the previous slide but on a linear scale instead

The breakdown of pure CO_2 is about 5 times higher than Argon in most of the measurements and about 2-2.5 times the breakdown of the Argon- CO_2

It seems that the trend in breakdown of pure CO_2 will continue to diverge however, from the breakdown of Argon and the Argon-CO_2 mixture



Extrapolated Values

We were able to take Argon data all the way up to 1 cm at 10 bar, so we used this data to extrapolate the values of the other gases

We used the differences from the last slide while assuming they stay as linear as they had in the lower measurements

This puts the breakdown of pure CO2 at 1 cm gap distance and 10 bar around 210,000 Volts with some uncertainty of course

Pressure (Bar)	Breakdown Field at1 cm gap (kV/cm)			
	Argon	Ar-CH4	Ar-CO2	CO2
10	41.9	80.58	83.8	209.5

Summary

- Paschen's Law evaluated from Townsend Breakdown Criterion
- Valid for a certain range only, lower pressures
- It is suggested that Meek-Raether criterion for breakdown is the dominant mechanism at higher pressures
- Further study has gone into the high-pressure region and more is still needed to understand the transition region and possibly other mechanisms taking place at high pressures
- The CO2 studies show that pure CO2 is five times larger than Argon and 2.5 times larger than the Argon-CO2 mixture

The End

Thank you for listening,

Any Questions?

References

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- 10 P. Osmokrovic, M. Vujisic, K. Stankovic, A. Vasic,and B. Loncar, “Mechanism of electrical breakdownof gases for pressures from 10- 9 to 1 bar and inter-electrode gaps from 0.1 to 0.5 mm”, Plasma SourcesScience and Technology16, 643 (2007).
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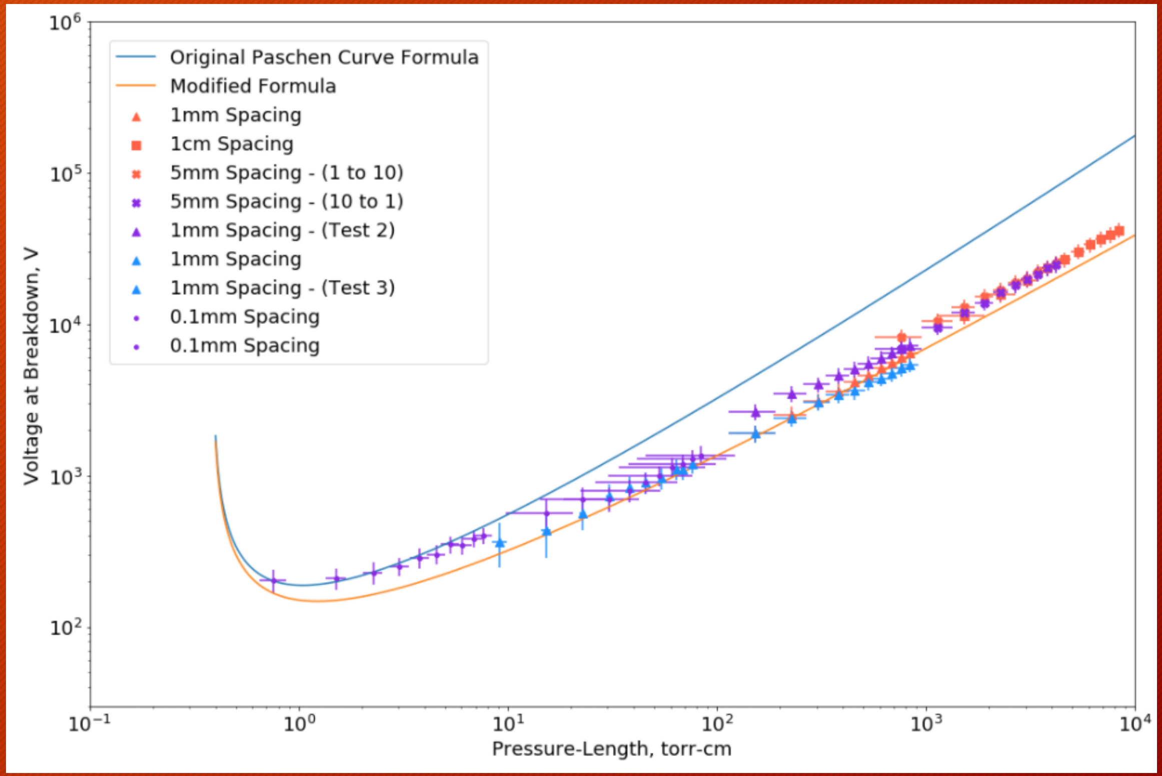
One Interesting Find

$$V_B = \frac{Bp^k \, \mathrm{d}}{\ln(Apd) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)}$$

One of the papers we came across included this "quenching factor" k, to denote a secondary gas introduced to quench the breakdown, and it produces curves that line up with the data



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