Effects of Magnetic Fields on the Behavior of Gases

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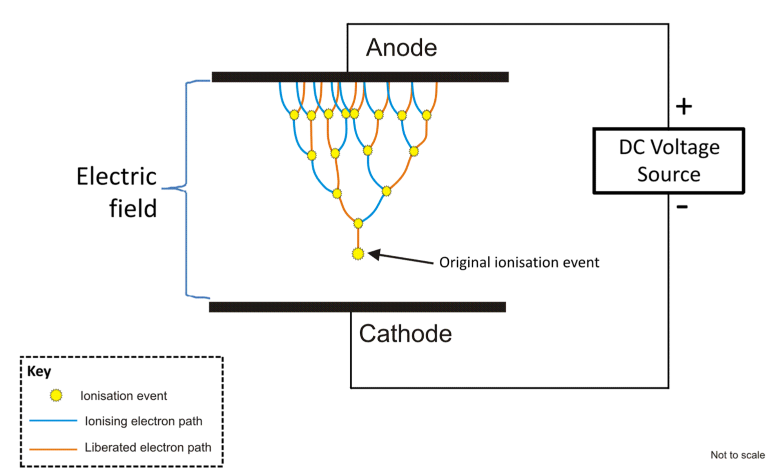
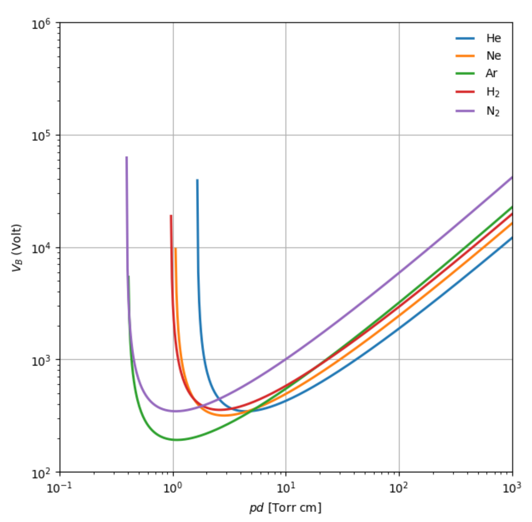
Scientific Background on Glow Discharge

- What is **breakdown voltage (V_b)**? Insulating substances, including gases allow electric current to pass through once its dielectric strength (E_{ds}) is exceeded
- One ionized electron can trigger a **Townsend Avalanche**, a chain reaction that causes many gas molecules to be ionized and glow

Visualisation of a Townsend Avalanche

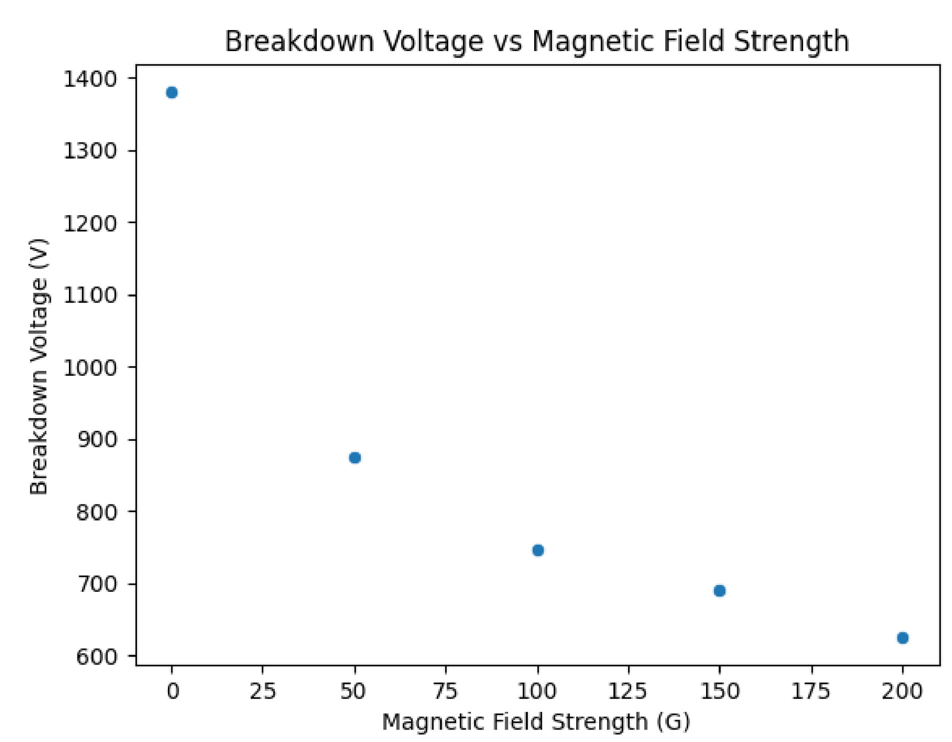




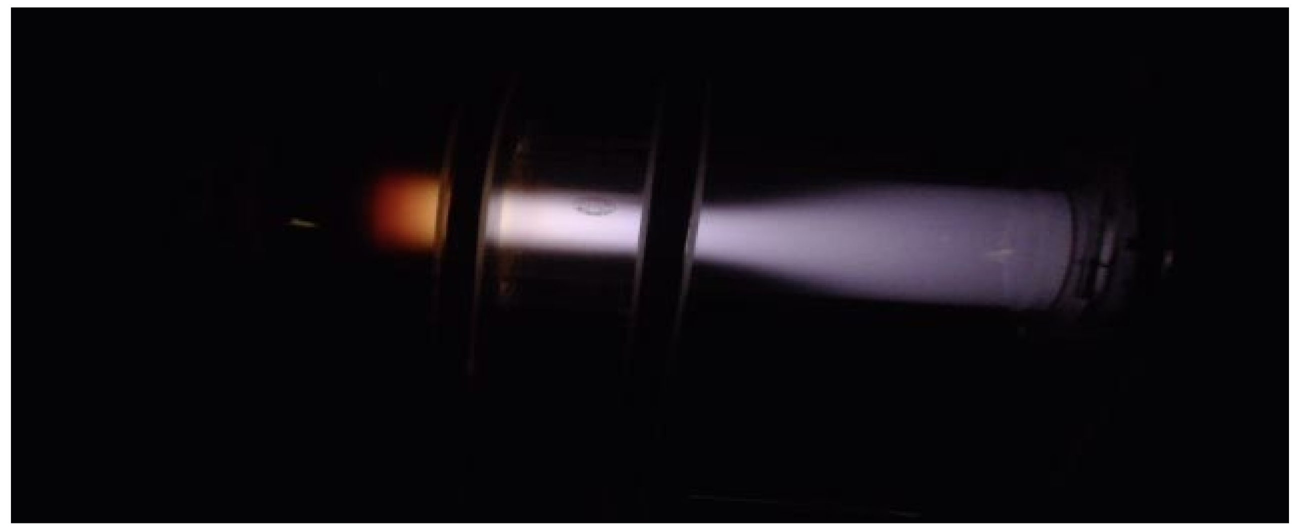
- **Paschen's law** predicts a V shaped curve for the breakdown voltage of a gas when plotted against p·d (the product of pressure and distance)
- If p·d is high, the breakdown voltage is high as electrons lose energy to collisions (larger E-field needed to reionize more gas)
- If p·d is low, the breakdown voltage is also high as electrons may have too few collisions to produce avalanche effect (larger E-field needed to continuously ionize gas)

Effects of Magnetic Field on Breakdown Voltage of Gas

- We used a Princeton Plasma Physics Laboratory (PPPL) Remote Experiment to analyze the effects of a magnetic field on glow discharge
- Strong magnetic fields concentrated the glow discharge into a **smaller cross sectional area**, making it appear brighter
- Quantitatively, **at higher magnetic field strengths, breakdown voltages were lower**; at higher pressures, a similar trend was observed



Weak Magnetic Field Applied (≈ 50 Gauss)



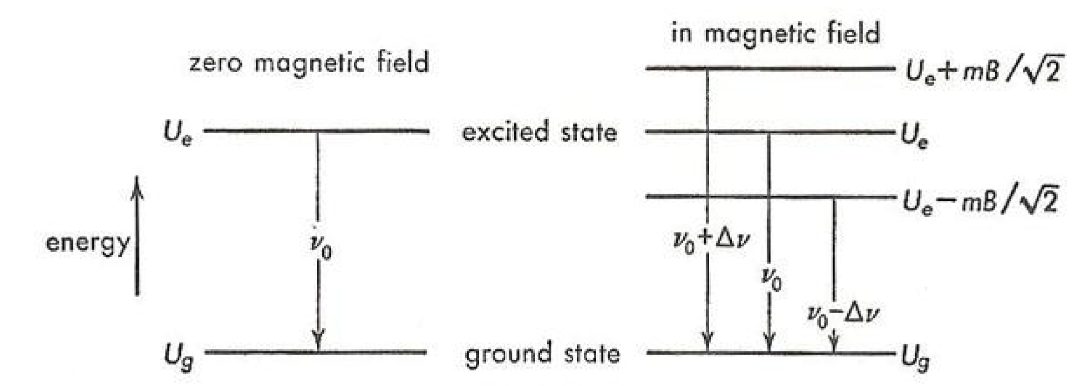
Strong Magnetic Field Applied (≈ 200 Gauss)

Classical and Quantum Effects of Magnetic Fields

- Classically, applying a magnetic field to a plasma will cause an **increase in electron drift velocity**
- Because drift velocity changes, mean free path will also increase, which can be quantified as a **fictitious pressure increase** (the constant C accounts for the effect of the Lorentz force on the electron and is determined experimentally)

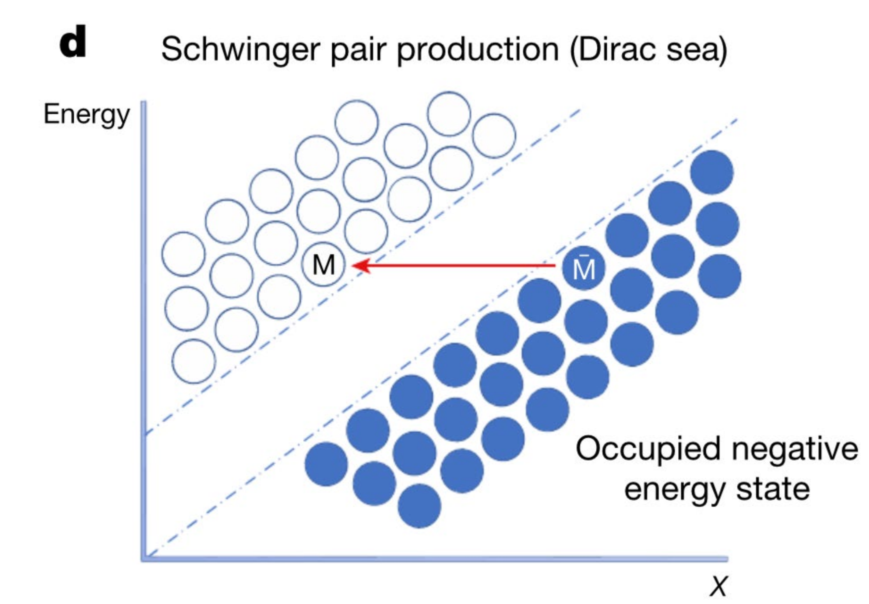
$$W_{H,E} = (E/H)\omega T/(1+\omega^2 T^2)$$

$$p' = p\sqrt{1 + C(\frac{H}{p})^2}$$



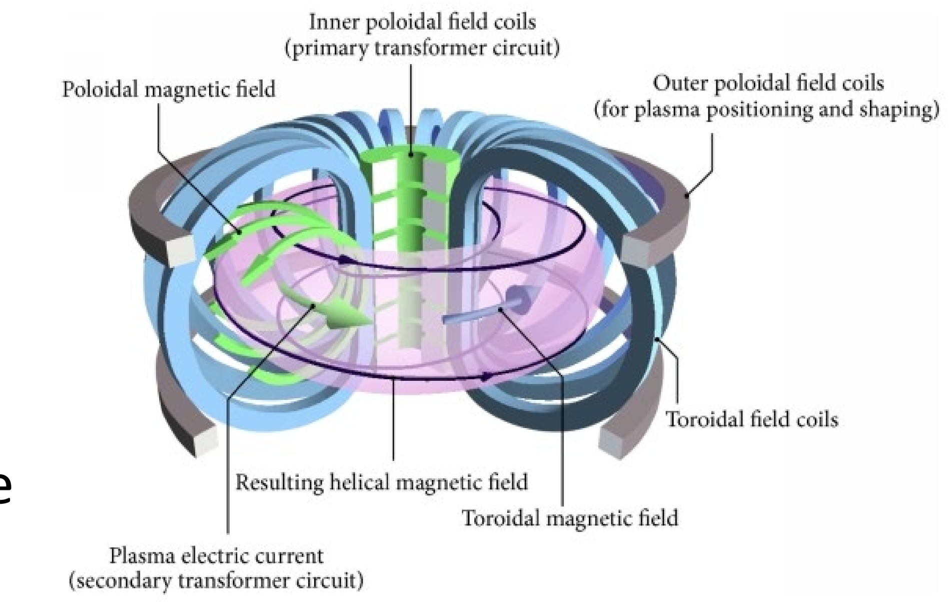
Cite

- The **Zeeman Effect** explains how a magnetic field can interact with the angular momentum quantum number of an electron and **split energy levels of atoms**
- The **Schwinger Effect**, predicted by quantum electrodynamics, suggests the creation of electrons and positrons (anti-electrons) in the presence of a strong electric field
- As with all expressions in electromagnetism, a magnetic analog predicts the **creation of magnetic monopoles** (and its subsequent decay) in the presence of a strong magnetic field



Future Directions

- Measuring effects on breakdown voltage from simultaneous changes in both pressure and magnetic field
- Analyzing Zeeman Effect more quantitatively and determining if it has a significant impact on breakdown voltage due to increasing number of ionization energies (especially in heavy gases requiring larger scales of energy to ionize)
- Applications of behavior of plasma to **tokamaks**, researching the **applicability of superconductors to generate extremely strong magnetic fields** overcoming Coulomb barrier for nuclear fusion



Citations

1. Blevin HA Haydon SC (1958) The Townsend Ionization Coefficients in Crossed Electric and Magnetic Fields. *Australian Journal of Physics* **11**, 18-34. https://doi.org/10.1071/PH580018
2. Acharya, B., Alexandre, J., Benes, P. *et al.* Search for magnetic monopoles produced via the Schwinger mechanism. *Nature* **602**, 63–67 (2022). https://doi.org/10.1038/s41586-021-04298-1
3. Remote Glow Discharge Experiment. https://scied-web.pppl.gov/

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