Electricity and Magnetism

• Reminder
  – RC circuits
  – Electric Breakdown Experiment

• Today
  – Magnetism
RC Circuits

Variable time constant $\tau = RC$
In-Class Demo

$V_{in}$

$V_C$

$I$

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In-Class Demo

- Changes in $R$ or $C$ change $\tau$
- Large $\tau$ smoothes out signals
- Sharp edges/rapid changes get removed – high frequencies are suppressed
- RC circuits are low-pass filters
Experiment EB

• Electrical Breakdown
  - You have seen many examples
    • Lightning!
    • Sparks (e.g. Faraday Cage Demo!)
    • Fluorescent tubes
  - Study in more detail
  - Reminder: Ionization
Ionization

- Electrons and nucleus bound together
- Electrons stuck in potential well of nucleus
- Need energy $\Delta U$ to jump out of well
- How to provide this energy?
Impact Ionization

$e^- \quad U_{\text{kin}} > \Delta U$

- Define $V_{\text{ion}} = \Delta U/q$
- Ionization potential
- One $e^-$ in, two $e^-$ out
- Avalanche?
Impact Ionization

(2) \( \lambda_{\text{mfp}} \) e\(^-\) (1) \( \lambda_{\text{mfp}} \) : Mean Free Path

\[ E \rightarrow \]

- To get avalanche we need:
\[ \Delta U_{\text{kin}} \text{ between collisions (1) and (2)} > V_{\text{ion}} * e \]

- Acceleration in uniform Field
\[ \Delta U_{\text{kin}} = V_2 - V_1 = e E d_{12} \]

- Avalanche condition then
\[ E > V_{\text{ion}} / \lambda_{\text{mfp}} \]

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Impact Ionization

How big is Mean Free Path?

(i) If Density \( n \) is big \( \rightarrow \lambda_{\text{mfp}} \) small

(ii) If size \( \sigma \) of molecules is big \( \rightarrow \lambda_{\text{mfp}} \) small

\[ \lambda_{\text{mfp}} = \frac{1}{n \sigma} \]
Impact Ionization

Avalanche condition $E > \frac{V_{\text{ion}}}{\lambda_{\text{mfp}}} = V_{\text{ion}} n \sigma$

Experiment EB: Relate $E, V_{\text{ion}}, \sigma$

Example: Air

$n \sim 6 \times 10^{23}/22.4 \ 10^{-3} \ m^3 = 3 \times 10^{25} \ m^{-3}$

$\sigma \sim \pi r^2 \sim 3 \times (10^{-10} \ m)^2 = 3 \times 10^{-20} \ m^2$

$V_{\text{ion}} \sim 10 \ V$

Need $E > 3 \times 10^{25} \ m^{-3} \times 3 \times 10^{-20} \ m^2 \times 10 \ V \sim 10^7 \ V/m$

For $V \sim 800 \ V$: $V = E d \rightarrow d = \frac{800}{10^7} \ m \sim 0.1 \ mm$
Experiment EB

HVPS

\( + \)  \( - \)

\( V \)

1M\( \Omega \)

1M\( \Omega \)

d

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Magnetism

• **Magnets**: Materials with ‘strange’ properties

• Magnets have been known for thousands of years

• It took until end of 19th century to understand the theory of Magnetism
Magnetic Force

• New Force between Magnets
• Unlike Poles attract

\[ \text{SN} \quad \text{F} \quad \text{SN} \]

• Like Poles repel

\[ \text{SN} \quad \text{F} \quad \text{SN} \]

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Magnets

• Permanent Magnets

• Two poles (called ‘north’ and ‘south’)

• Let’s look at some properties
Magnetic Force

- Magnets also attract non-magnets!
Magnetic Force

• New phenomenon

• Magnets carry no net charge!

• Although not understood, magnetic phenomena have been used for a long time -> In-Class Demo!
Electric Dipole in Electric Field

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Compass

• Freely rotating magnets point towards earth’s (magnetic) north pole
Magnetic Field

• Magnets align themselves with Magnetic Field
  like Electric Dipoles in Electric Field

• What is the Source of the Magnetic Field?
Current and Magnet

Wire, I = 0

N
S

Wire, I > 0

N
S
Source of the Magnetic Field

- No effect due to Static Charges
- But: An Electric Current affects Magnet
- Does Magnet affect Current?
Magnet and Current

- Force on wire if $I \neq 0$
- Direction of Force depends on Sign of $I$
- Force perpendicular to $I$
Current and Current

Attraction

Repulsion
Summary

• Observed Force between
  - two Magnets
  - Magnet and Iron
  - Magnet and wire carrying current
  - Wire carrying current and Magnet
  - Two wires carrying currents

• Currents (moving charges) can be subject to and source of Magnetic Force
Free Charges and Magnetic Field

\[ \overrightarrow{F_L} = q (\overrightarrow{E} + \overrightarrow{v} \times \overrightarrow{B}) \]

Lorentz Force

\[ F_{\text{acc}} = \frac{m v^2}{R} = F_L \]

\[ R = \frac{m v}{q B} \]

Cyclotron Radius

\([B] = \frac{N}{(A \, m)} = T \text{ (Tesla)}\]
Magnetic Field and Work

\[ \vec{F}_L = q \vec{v} \times \vec{B} \quad \text{(for } E = 0) \]