I.A.5 Electron Optics / Electron Lenses

Key Concepts
(lots of them, of course!)

- **Thermionic emission** creates a source of electrons
- **Charged objects** produce an **electric field**
- Electrons passing through an **electric field** are bent or **refracted**
- Electrons passing through a **magnetic field** are bent or **refracted**
- **Focal length** of electromagnetic lens determined by **field strength**
Electrons don’t escape metal surface at room $T$ due to attractive force of positively charged ions.

As $T \uparrow$ some $e^-$ acquire sufficient energy to overcome the attraction and leave the metal temporarily.
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I.A.5.a Electron Emission

- Electron gun filaments are **thin tungsten wires** which are heated by passing an electric current through them.

Electron gun tungsten filament (cathode)

From Agar, Fig. 2.5, p.45
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I.A.5.a Electron Emission

- Electron gun filaments are **thin tungsten wires** which are heated by passing an electric current through them.

- A certain level of energy (**work function**) must be supplied to allow $e^-$ to escape the filament.

- Each metal has a characteristic work function.

  Tungsten ($W$): **low work function** metal

  $W$ emits more $e^-$ than metals with higher work functions.
- **FACT**: Electrons accelerate in an applied electric field

- Strong electrostatic field applied in a vacuum between a wire [cathode] and an **anode**, causes $e^{-}$ to accelerate away from the wire towards the anode.

From Sjostrand, Fig. II.15, p.26
- **Speed** of the e- depends on **strength** of the electrostatic field (voltage) between the cathode and anode.

- **Number** of e\(^-\) which leave the wire depends on the **temperature** to which the wire is heated (which depends on **filament current**)

From Sjostrand, Fig. II.15, p.26
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Electric Field / Equipotentials

**FACT:** electrically-charged **object** has associated with it an **electric field**

Lines of force at a positively charged spherical body

From Sjostrand, Fig. II.20, p.32
DEFINITION: Direction of an electric field is defined as the direction of force acting on a positive charge.

- An electrically-charged particle, when brought near a charged object, is influenced by an electrical force in the vicinity of the object.

- Force is directed toward the charged object if the charges are of opposite signs and away from the object if they are of similar sign.

From Sjostrand, Fig. II.20, p.32
Lines of force and equipotential surfaces (stippled lines) associated with two equal charges of opposite sign

From Sjostrand, Fig. II.21, p.32
Along lines of force connecting two charges, the electric potential will change gradually between the extreme values represented by the two charges.

**DEFINITION:** Equipotential lines define the points along lines of force with identical electrical potential.

- **Equipotential surfaces:** always oriented perpendicular to lines of force.

From Sjostrand, Fig. II.21, p.32
Equipotential surfaces at two parallel plates of opposite charge with the path of an electron

From Sjostrand, Fig. II.22, p.33
- Electrons which enter a field between two parallel plates in a direction parallel to the plates are affected by the force directed perpendicular to the plates

- Electrons are attracted toward the positive plate

- Path changes in a series of gradual steps at the equipotential surfaces

**RESULT:** fundamentally same as given by Snell's Law of refraction (light optics). **Curved** equipotential surfaces exhibit the properties of a lens.

From Sjostrand, Fig. II.22, p.33
Advantage:

Refractive index does not change abruptly
Hence, no troublesome reflections at equipotentials as occur at air/glass interfaces

Disadvantage (a serious one):

Equipotentials cannot be shaped and combined in arbitrary fashion to correct for chromatic aberration and other errors as is possible with glass surfaces
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Electrostatic Lenses

Read about electrostatic lenses in the lecture notes: pp.21-22.
Magnetic field: An electric current passing through a conductor gives rise to a magnetic field

- **Direction** in which magnetic field lines point = North
- **Magnetic flux** = total number of lines
- **Flux density** = number of lines per unit area of a surface.

From Sjostrand, Fig. II.26, p.35
**I.A.5 Electron Optics / Electron Lenses**

**I.A.5.c Magnetic Fields and Magnetic Lenses**

**Magnetic field**: An electric current passing through a conductor gives rise to a magnetic field

**RIGHT Hand Rule:**

- **Thumb** points toward **current** direction
- **Fingers** curl in direction of **field** (towards N)

**CONVENTION**: Direction of e⁻ flow is **OPPOSITE** that of current flow

**ADDITIONAL NOTE**: I don’t make the rules. I just follow them!!!

From Sjostrand, Fig. II.26, p.35
Flux density depends on the properties of the material surrounding the conductor.

Iron induces a higher flux density than air or a vacuum.

Property of the material which affects the flux density is called the permeability, m:

- m = 1.0 for air and vacuum
- m > 10^5 for ferromagnetic materials

From Sjostrand, Fig. II.26, p.35
Flux density greatest at center of loop.

Magnetic field induced by current passing through a solenoid.

If conductor has the shape of a circular loop, the lines of force form circles around the loop.

- Flux density greatest at center of loop.

From Sjostrand, Fig. II.28, p.37
Solenoid with iron core

From Sjostrand, Fig. II.31, p.40
High permeability of iron is due to the induced magnetic field orienting microscopic crystal regions acting as tiny magnets in the iron.

These tiny magnets all add their magnetic fields to the induced field.

From Slater, Fig. 17-10, p.361
However...

Use of iron leads to a problem: **lens hysteresis**

- **Lens strength** depends to some extent on the **magnetic history** of the lens

- When lens current is reduced, magnetization decrease does **not retrace the same path** obtained when the current was increased

- **Induction** of magnetization involves a **physical movement** within the magnetized material, requiring the overcome of some inertia

- Hence, **magnetization lags behind** the magnetizing force applied

- Induced magnetic flux can only be returned to zero by **application of a current in the opposite direction**
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Lens Hysteresis

Level of current used to energize a magnetic lens **DOES NOT** precisely specify the lens strength (*i.e.* focal length).

From Meek, 1st ed., Fig. 3.2, p.68
TEM lens normalization:
Reduce lens current to zero a predetermined number of times

Also minimize hysteresis by:
Taking lens to saturation (highest current)
Then return to working current without overshooting
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I.A.5.d The Electromagnetic Lens

Short solenoid

From Wischnitzer, 2nd ed., Fig. 35, p.33
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I.A.5.d The Electromagnetic Lens

Short solenoid

Soft-iron casing enclosing outer solenoid surface - concentrates the field.

From Wischnitzer, 2nd ed., Fig. 35, p.33
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I.A.5.d The Electromagnetic Lens

Soft-iron casing enclosing outer solenoid surface - concentrates the field.

Soft-iron encasing the solenoid with a narrow annular gap to reduce the magnetic field to short region along the lens axis.

From Wischnitzer, 2nd ed., Fig. 35, p.33
Soft-iron encasing the solenoid with a narrow annular gap to reduce the magnetic field to short region along the lens axis.

Soft-iron encased solenoid and soft-iron pole pieces to enormously concentrate the field at the level of the annular gap.

From Wischnitzer, 2nd ed., Fig. 35, p.33
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I.A.5.d The Electromagnetic Lens

Forces Acting on a Current in a Magnetic field

Force on an e- in a magnetic field is at right angles to its direction as well as the direction of the field.

Field acts only on the velocity component directed perpendicular to the lines of force (Use the left hand rule)

Remember - I didn’t make these rules!

From Sjostrand, Fig. II.35-36, p.43
Path of Electron Through Electromagnetic Lens

- Electron starting at point A on axis and at an angle to it follows a spiral path, returning to the axis at point B

- Action is similar to a converging light lens
Geometric optics for a magnetic lens is the same as that for a glass lens, except e⁻ travel in spiral paths through magnetic lenses.
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I.A.5.d The Electromagnetic Lens

Properties of a Magnetic Lens

- Any axially-symmetric magnetic field has the properties of an ideal lens

- All formulas for the ideal lens may be applied

- Magnetic lenses are always convergent

**Consequence:** Spherical and chromatic aberrations can not be corrected by use of positive and negative lenses
Focal length \( f \) determined by the field strength in the lens gap and by the speed of the e\(^-\) (depends on accelerating voltage)

\[
f = \frac{KV_r}{(N \cdot I)^2}
\]

- \( f \) = focal length of the lens
- \( K \) = a constant
- \( V_r \) = accelerating voltage (relativistically corrected)
- \( N \) = # of turns in the excitation coils
- \( I \) = current (in amps)
- \( NI \) = # ampere turns
Focusing an image: achieved by varying current in OBJECTIVE lens

- This changes magnetic field strength and alters lens focal length
  (Equivalent to a combined change in both the "refractive index" and "curvature of surface")

- If voltage is increased (e- velocity increases), lens current must be increased to keep the focal length constant

- Focal length and current are NOT linearly related:

  Strength increases in a sigmoid fashion as current increases until the lens is saturated and no further increase in lens strength can be achieved
I.A.5.d The Electromagnetic Lens

Double Condenser Lens Design

Usually have a relatively large bore and spacing which results in a long field and long focal length

From Agar, Fig. 2.8, p.47
- Typical construction gives **strong field of short axial extent** \((f = 1.5-3 \text{ mm})\) needed to form images at high magnification.

- **Specimen** sits **inside** the magnetic field of the lens.

- Any field introduced by specimen contaminants can distort the lens field.

From Agar, Fig. 2.11, p.51
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Magnetic Lens Design

A few life or death factoids:

- Most of a typical magnetic lens lies outside the vacuum of the microscope

- Only those regions through which the e⁻ beam passes are at high vacuum

- Magnetic lenses must be water-cooled to dissipate large amounts of heat produced by the currents in the electromagnet coils