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**

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I.A.5.a Electron Emission

Thermionic emission:

Process by which thermal energy is supplied to loosely bound e^- in a metal in order to form a source of e^-

Electrons don't escape metal surface at room T due to attractive force of positively charged ions

As T □ some e^- acquire sufficient energy to overcome the attraction and leave the metal temporarily

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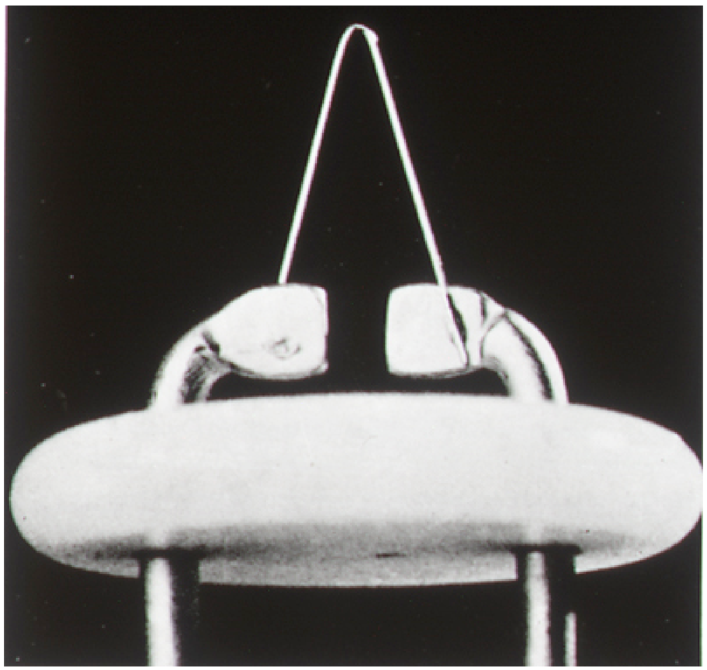
I.A.5.a Electron Emission

- 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

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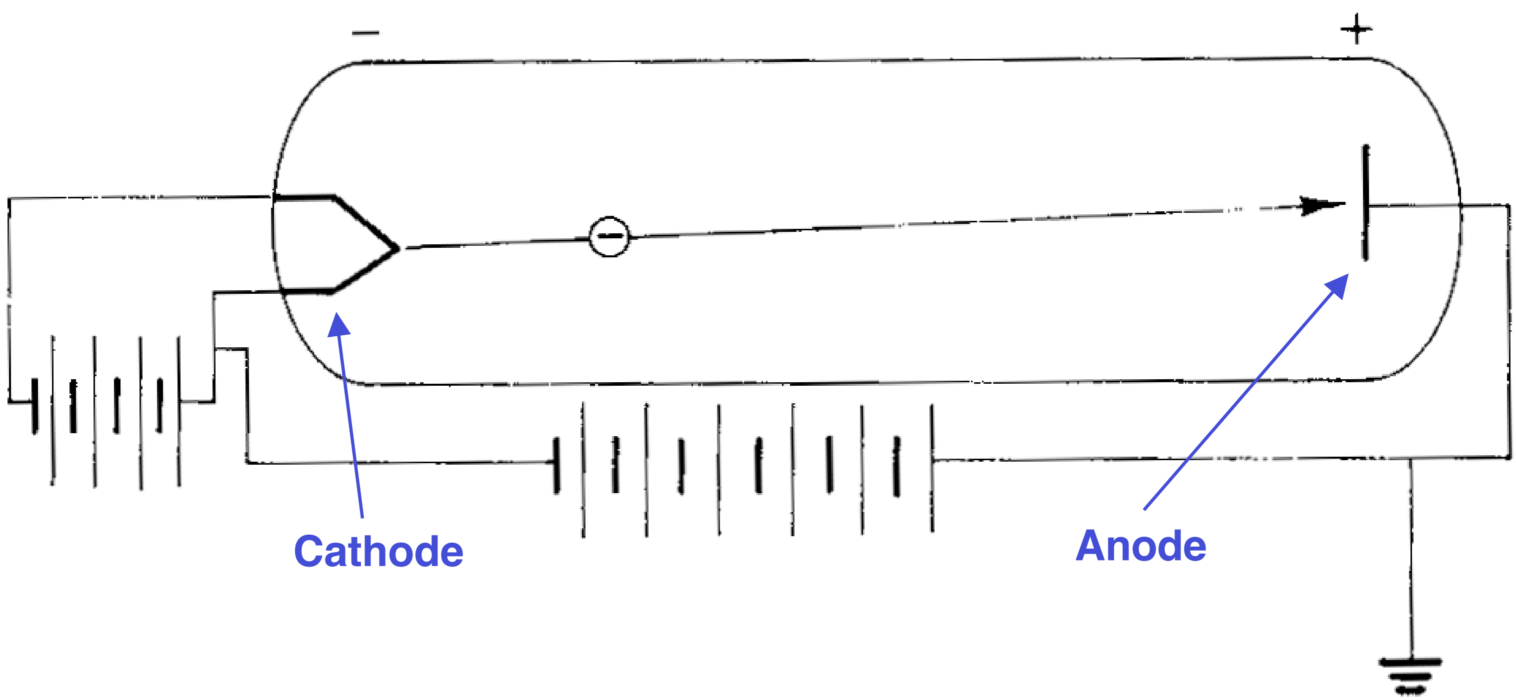
I.A.5.a Electron Emission

- **FACT:** Electrons accelerate in an applied electric field

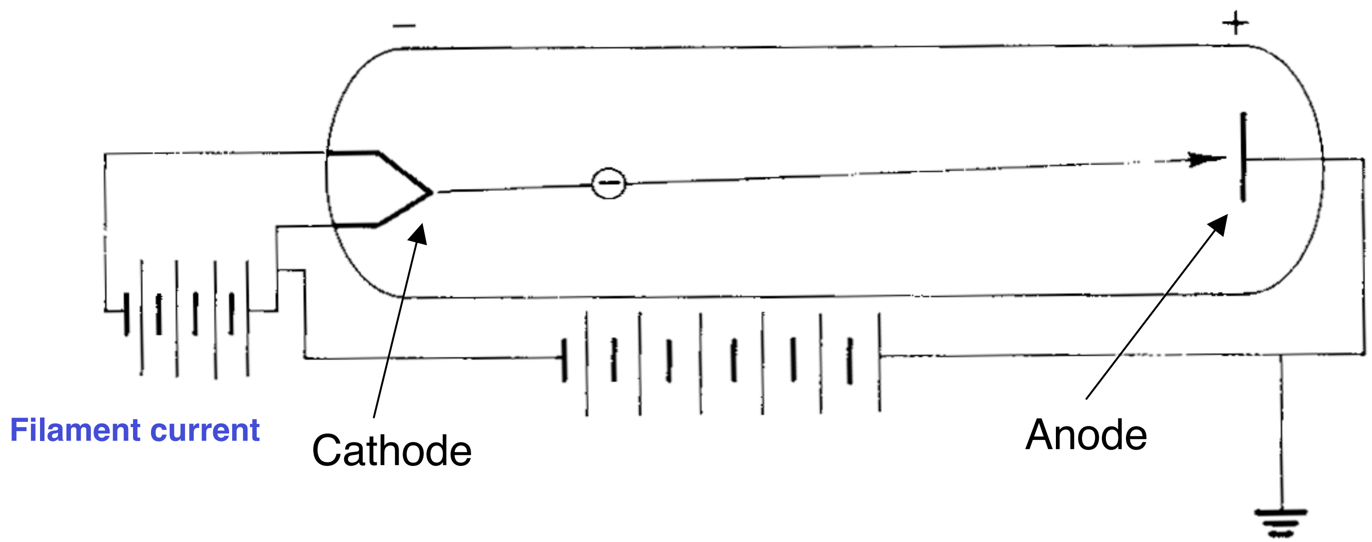
- Strong electrostatic field applied in a vacuum between a wire [**cathode**] and an **anode**, causes e^- to accelerate away from the wire towards the anode



From Sjostrand, Fig. II.15, p.26

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission



- **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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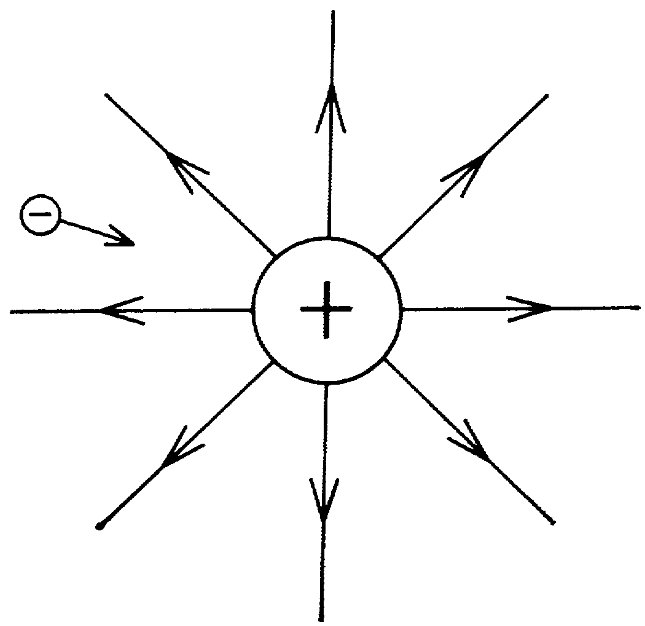
I.A.5.a Electron Emission

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

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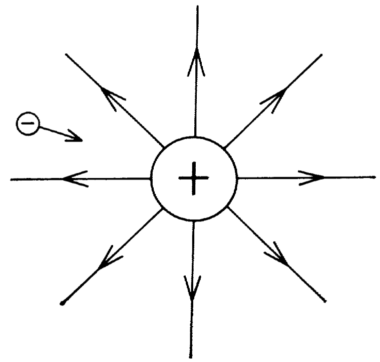
I.A.5.a Electron Emission

Electric Field / Equipotentials



- 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

DEFINITION: Direction of an electric field is defined as the direction of force acting on a **positive** charge

From Sjostrand, Fig. II.20, p.32

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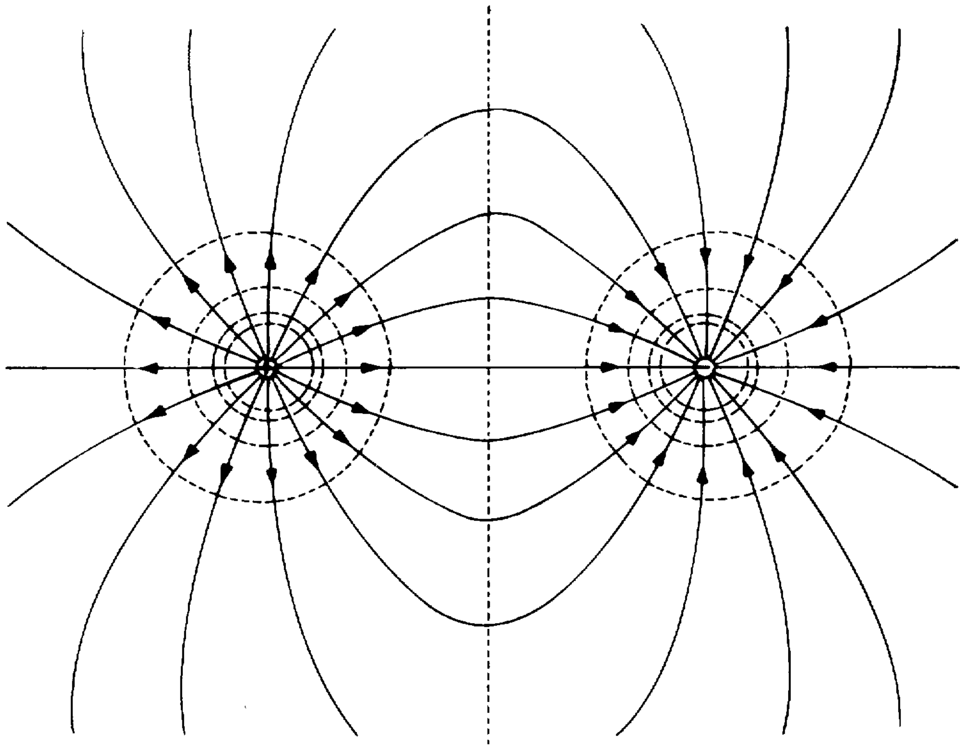
I.A.5.a Electron Emission

Electric Field / Equipotentials



Lines of force and **equipotential surfaces** (stippled lines) associated with two equal charges of **opposite** sign

From Sjostrand, Fig. II.21, p.32

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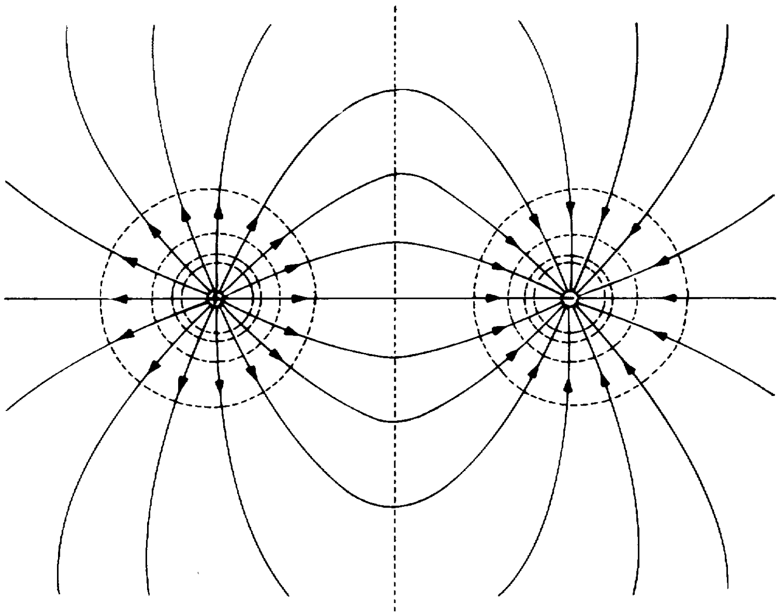
I.A.5.a Electron Emission

Electric Field / Equipotentials



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

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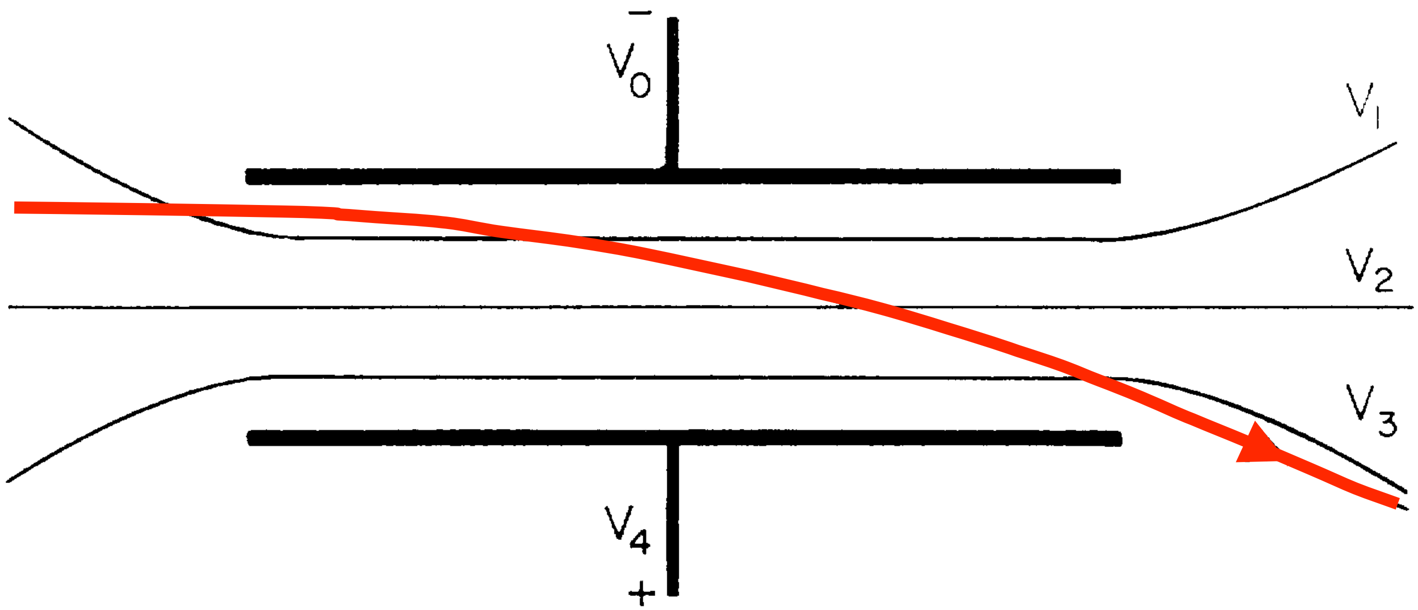
I.A.5.a Electron Emission

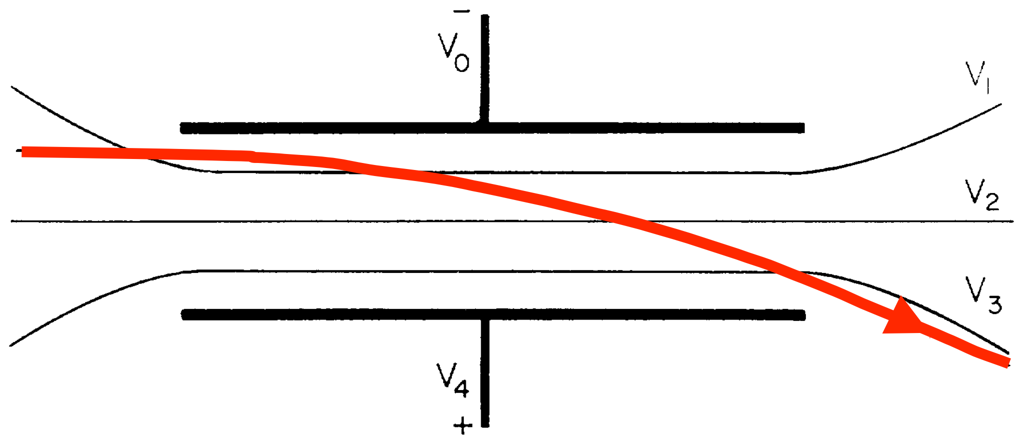
Electric Field / Equipotentials



Equipotential surfaces at two parallel plates of opposite charge with the path of an electron

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

Electric Field / Equipotentials



- 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

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission

Advantage/Disadvantage of Electron Lenses

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

I.A.5 Electron Optics / Electron Lenses

I.A.5.a Electron Emission

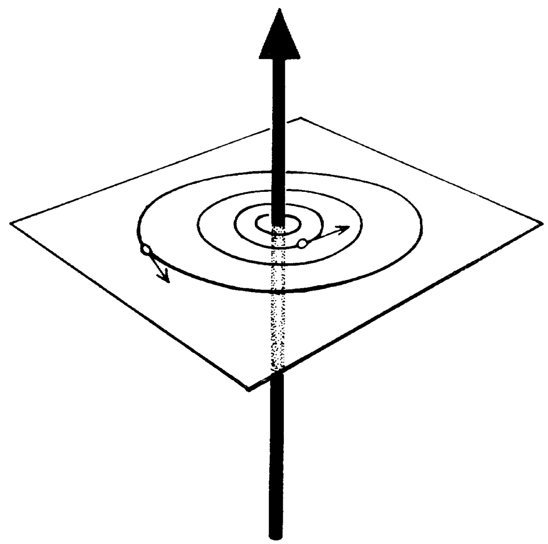
Electrostatic Lenses

Read about electrostatic lenses in the lecture notes: pp.21-22.

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



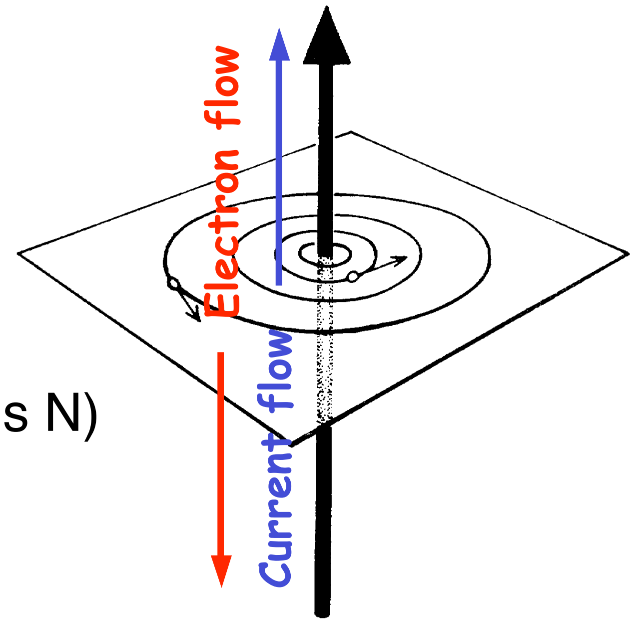
- **Direction** in which magnetic field lines point = North
- **Magnetic flux** = total number of lines
- **Flux density** = number of lines per unit area of a surface.

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

I.A.5 Electron Optics / Electron Lenses

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

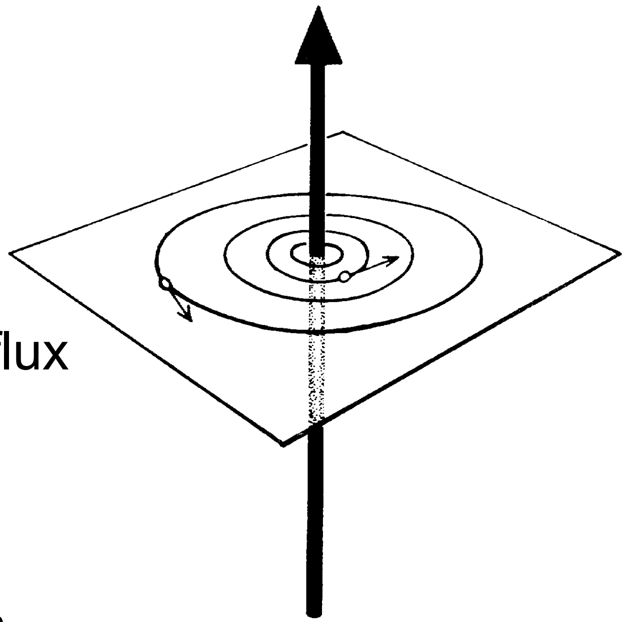
Flux density depends on the properties of the material surrounding the conductor

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

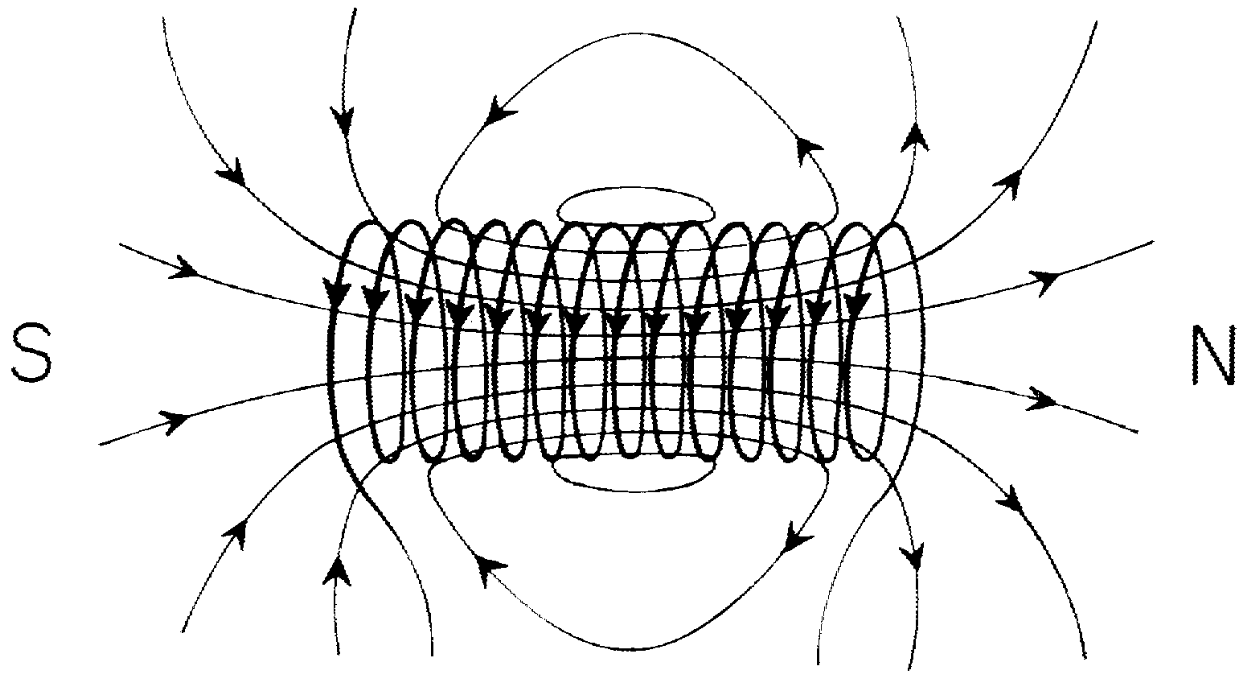


From Sjostrand, Fig. II.26, p.35

I.A.5 Electron Optics / Electron Lenses

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

Magnetic field induced by current passing through a solenoid



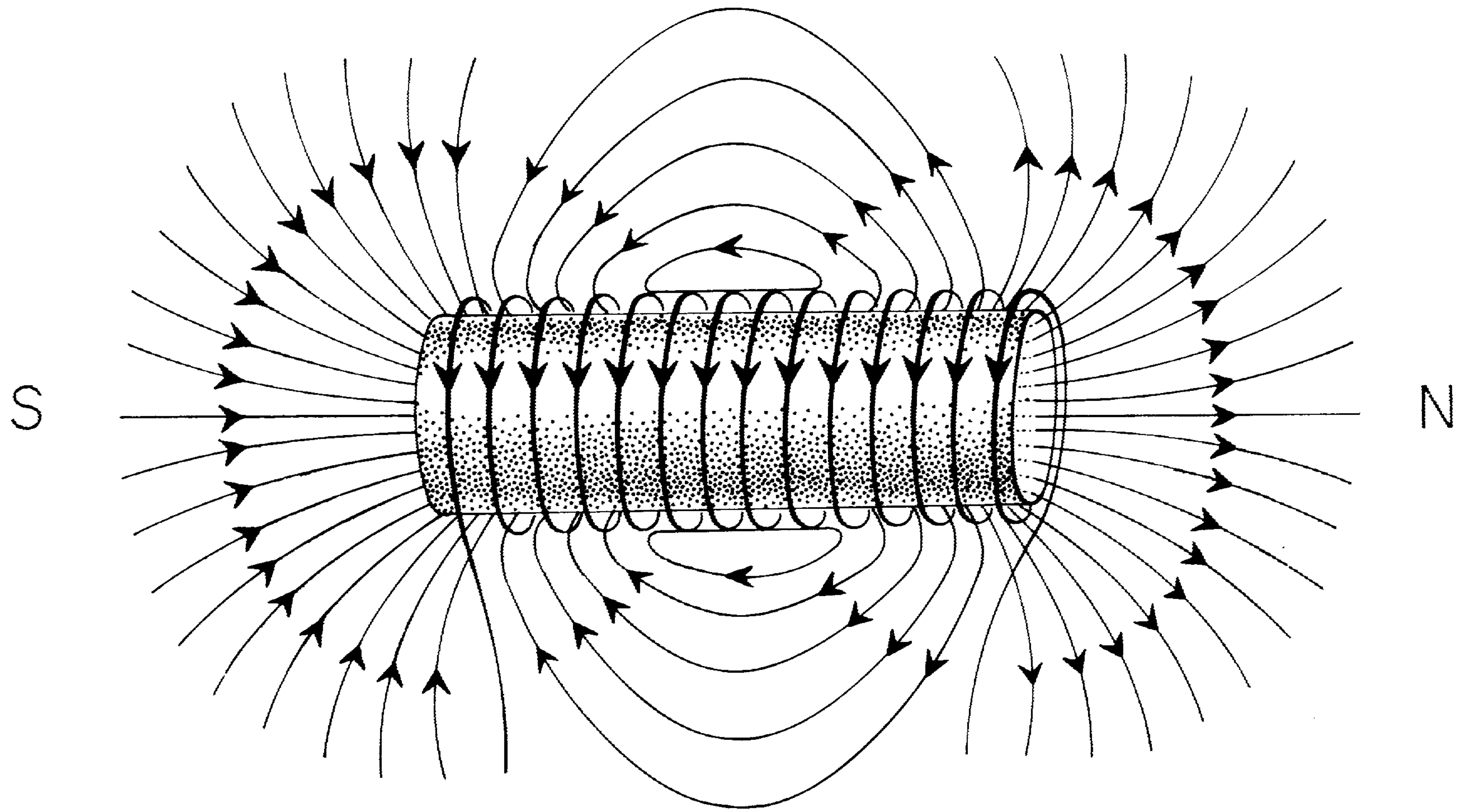
If conductor has the shape of a circular loop, the lines of force form circles around the loop

- Flux density greatest at center of loop

From Sjostrand, Fig. II.28, p.37

I.A.5 Electron Optics / Electron Lenses

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



Solenoid with iron core

From Sjostrand, Fig. II.31, p.40

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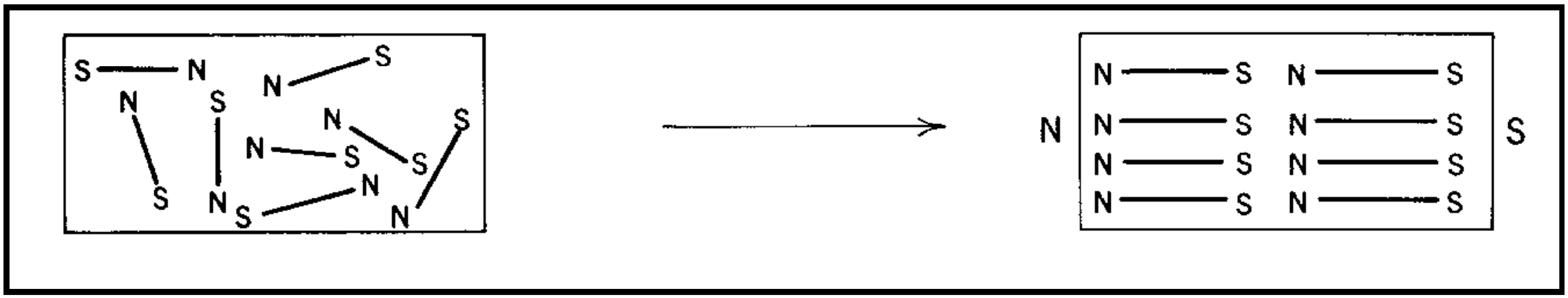
I.A.5.c Magnetic Fields and Magnetic Lenses

High **permeability** of iron is due to the **induced magnetic field** orienting microscopic crystal regions acting as tiny magnets in the iron



Magnetization

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

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

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

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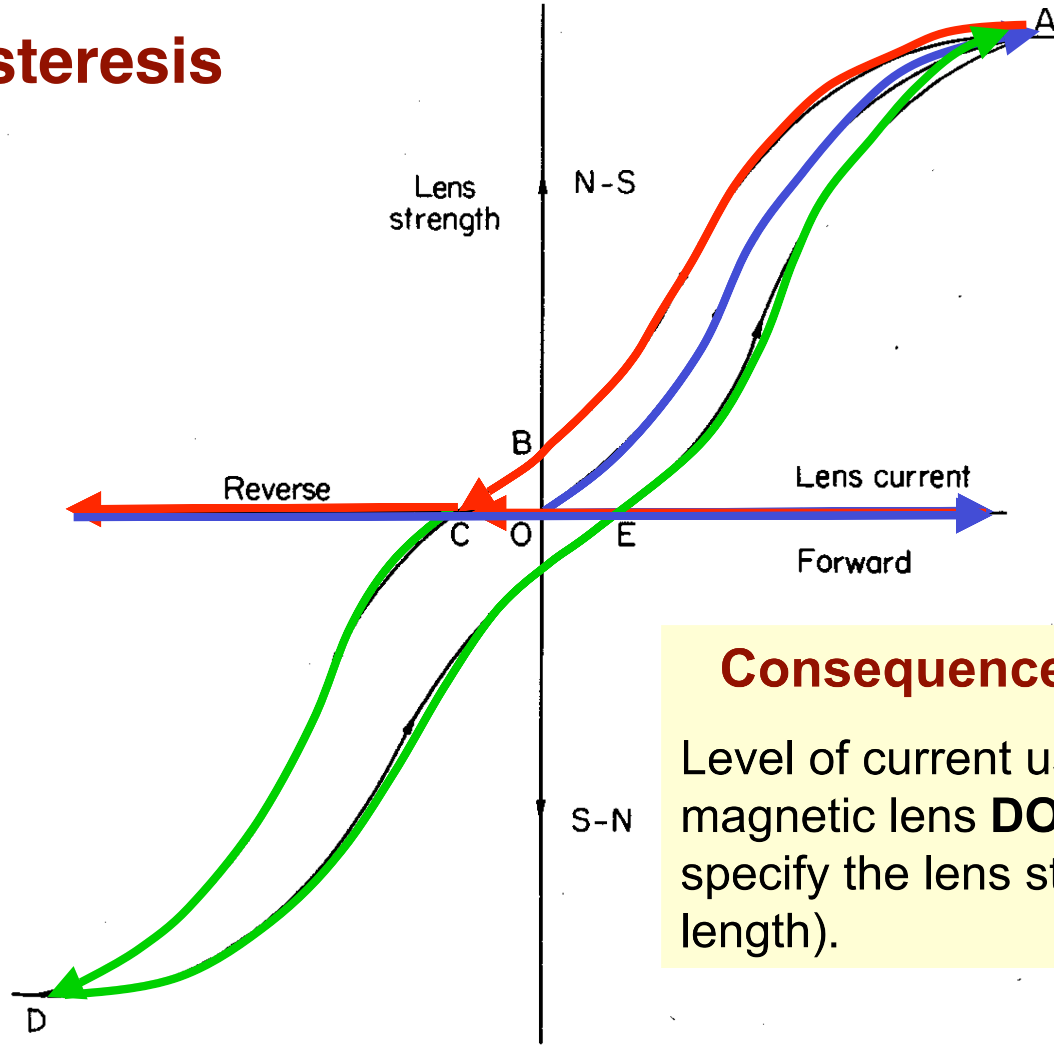
I.A.5.c Magnetic Fields and Magnetic Lenses

Lens Hysteresis



Consequence of 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

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

Lens Hysteresis

TEM lens normalization:

Reduce lens current to zero a predetermined number of times

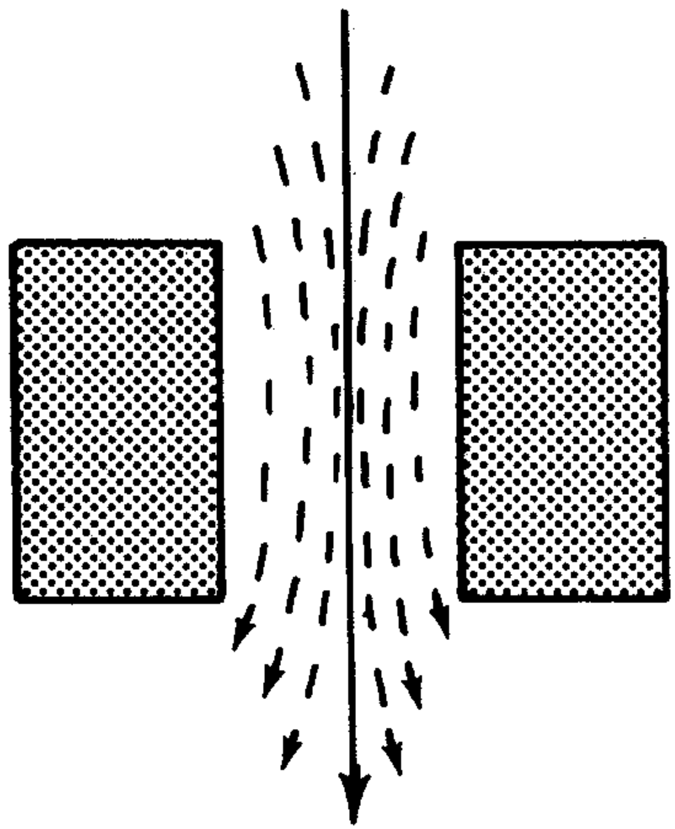
Also minimize hysteresis by:

Taking lens to saturation (highest current)

Then return to working current without overshooting

I.A.5 Electron Optics / Electron Lenses

I.A.5.d The Electromagnetic Lens



Short solenoid

From Wischnitzer, 2nd ed., Fig. 35, p.33

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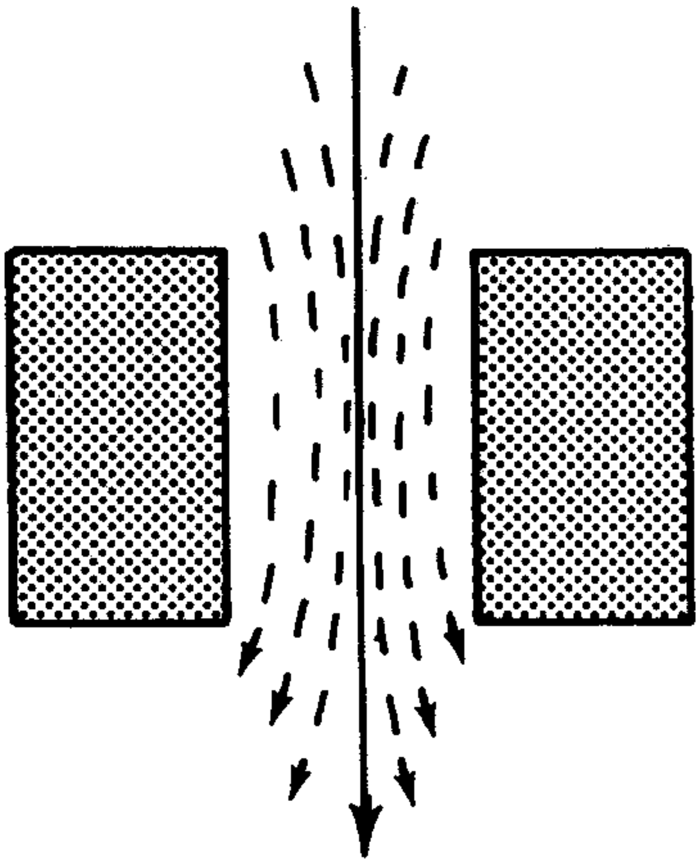
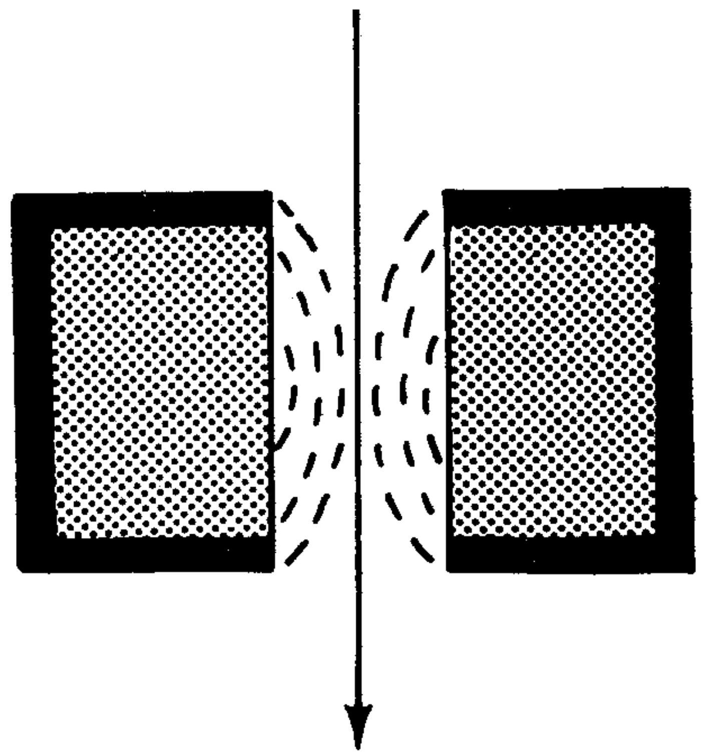
I.A.5.d The Electromagnetic Lens



Short solenoid

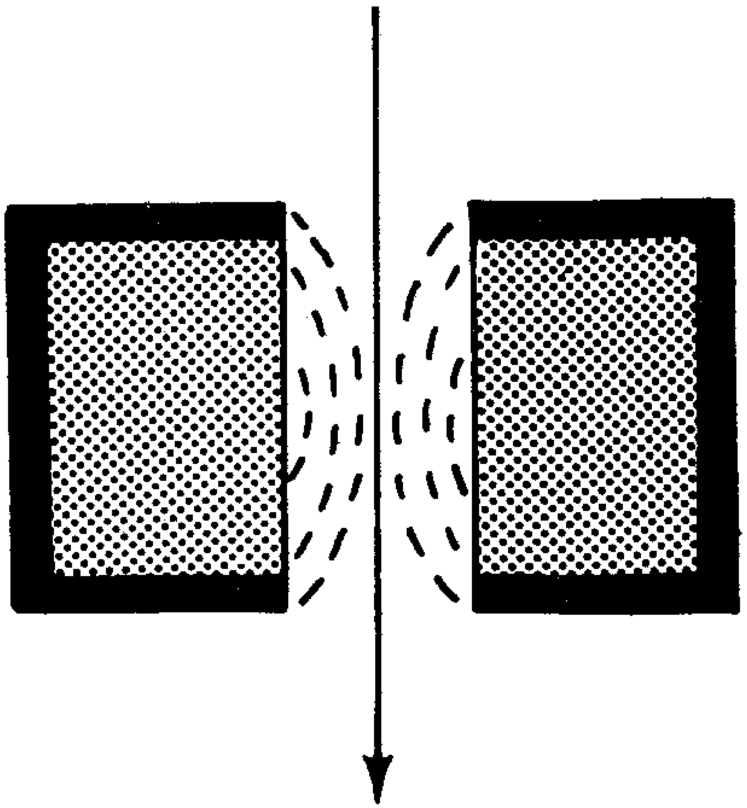


Soft-iron casing enclosing outer solenoid surface - concentrates the field.

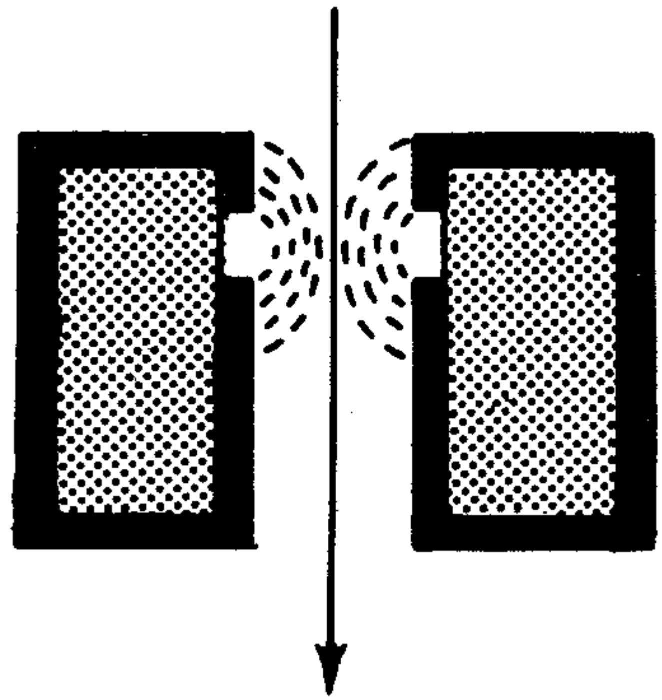
From Wischnitzer, 2nd ed., Fig. 35, p.33

I.A.5 Electron Optics / Electron Lenses

I.A.5.d The Electromagnetic Lens



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

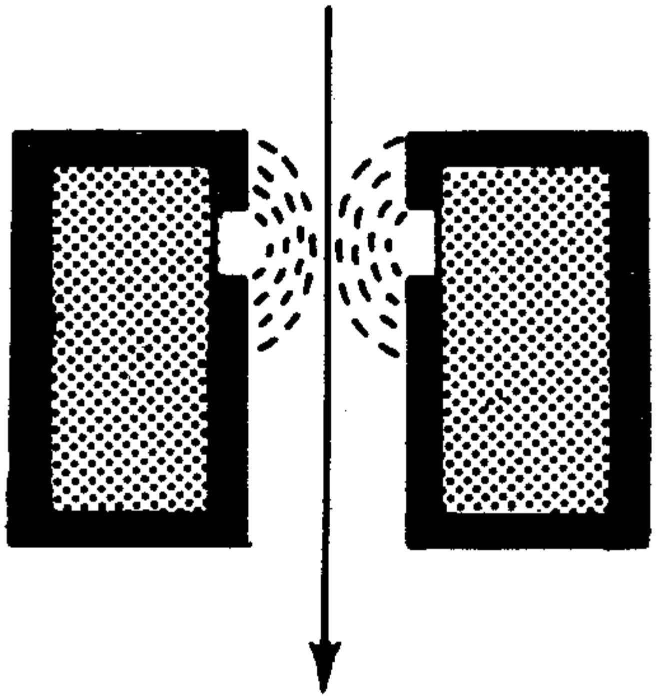


Soft-iron encasing the solenoid with a narrow annular gap to reduce the magnetic field to short region along the lens axis.

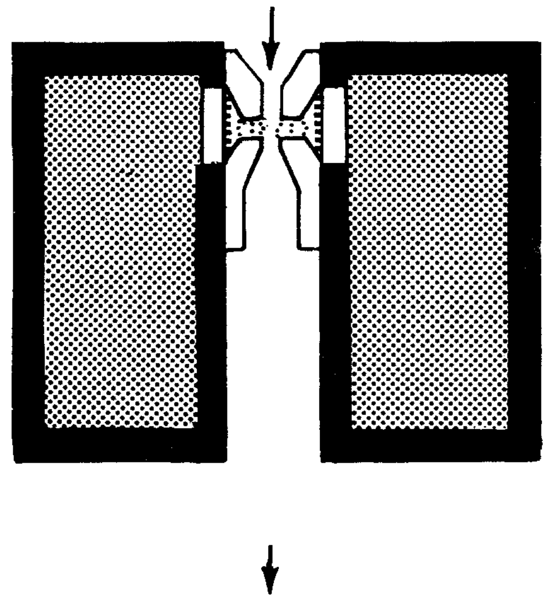
From Wischnitzer, 2nd ed., Fig. 35, p.33

I.A.5 Electron Optics / Electron Lenses

I.A.5.d The Electromagnetic Lens



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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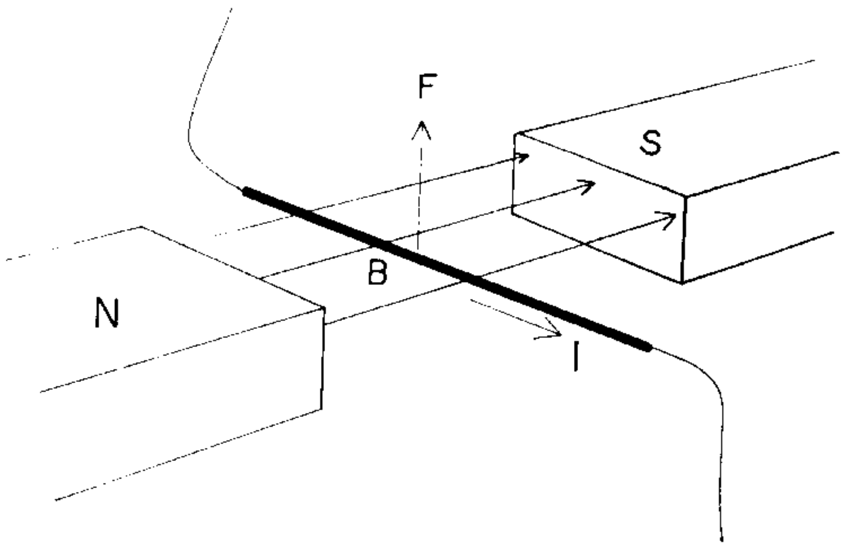
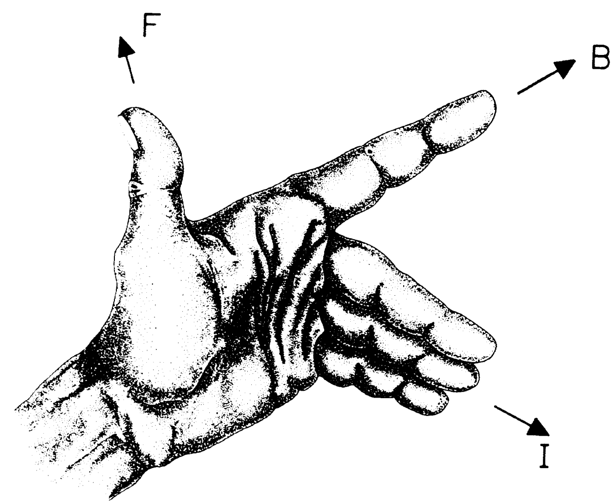
I.A.5.d The Electromagnetic Lens

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

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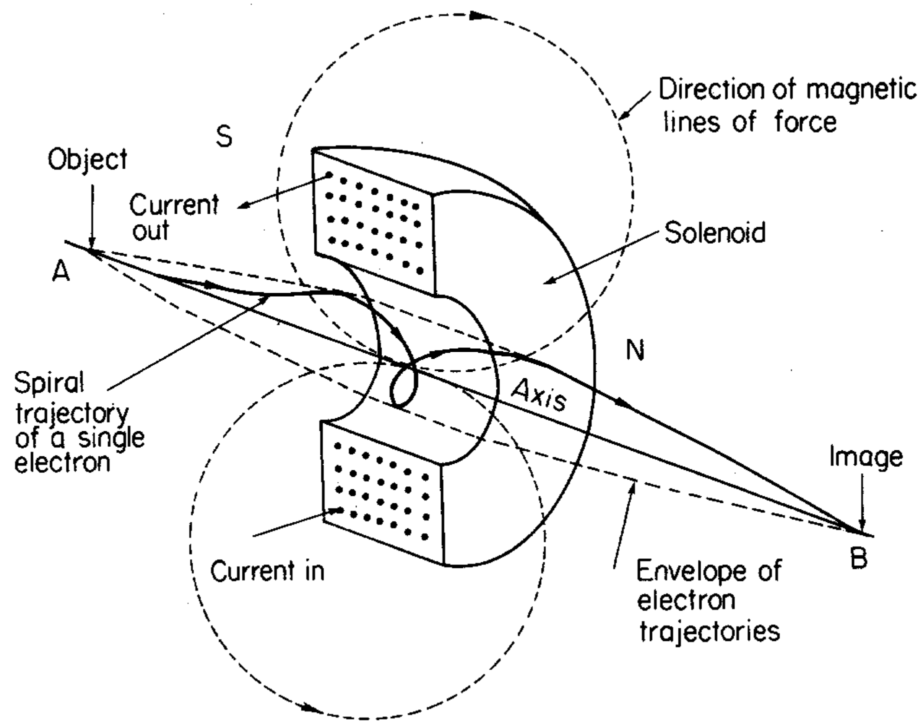
I.A.5.d The Electromagnetic Lens

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

From Meek, 1st ed., Fig. 1.3, p.8

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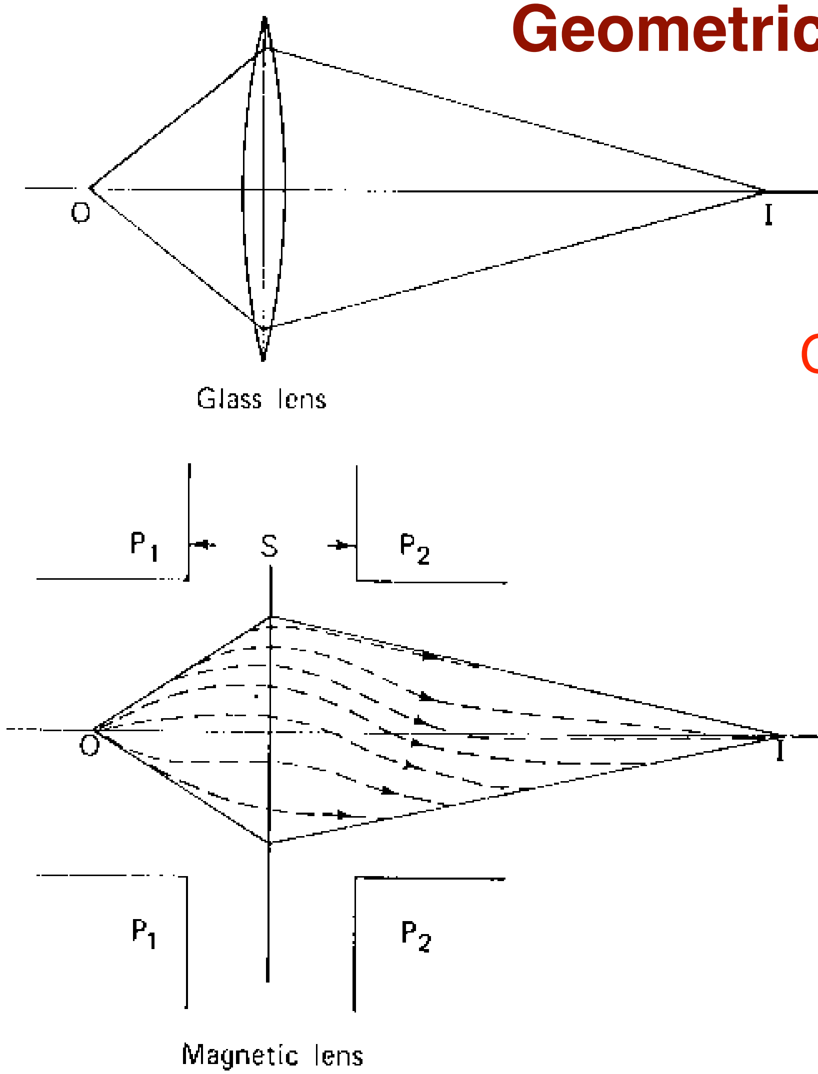
I.A.5.d The Electromagnetic Lens

Geometric Optics



Geometric optics for a magnetic lens is the **same** as that for a glass lens, except e^- travel in spiral paths through magnetic lenses

From Agar, Fig. 1.4, p.5

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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

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I.A.5.d The Electromagnetic Lens

Magnetic Lens Focal Length

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

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I.A.5.d The Electromagnetic Lens

Magnetic Lens Focal Length

- **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

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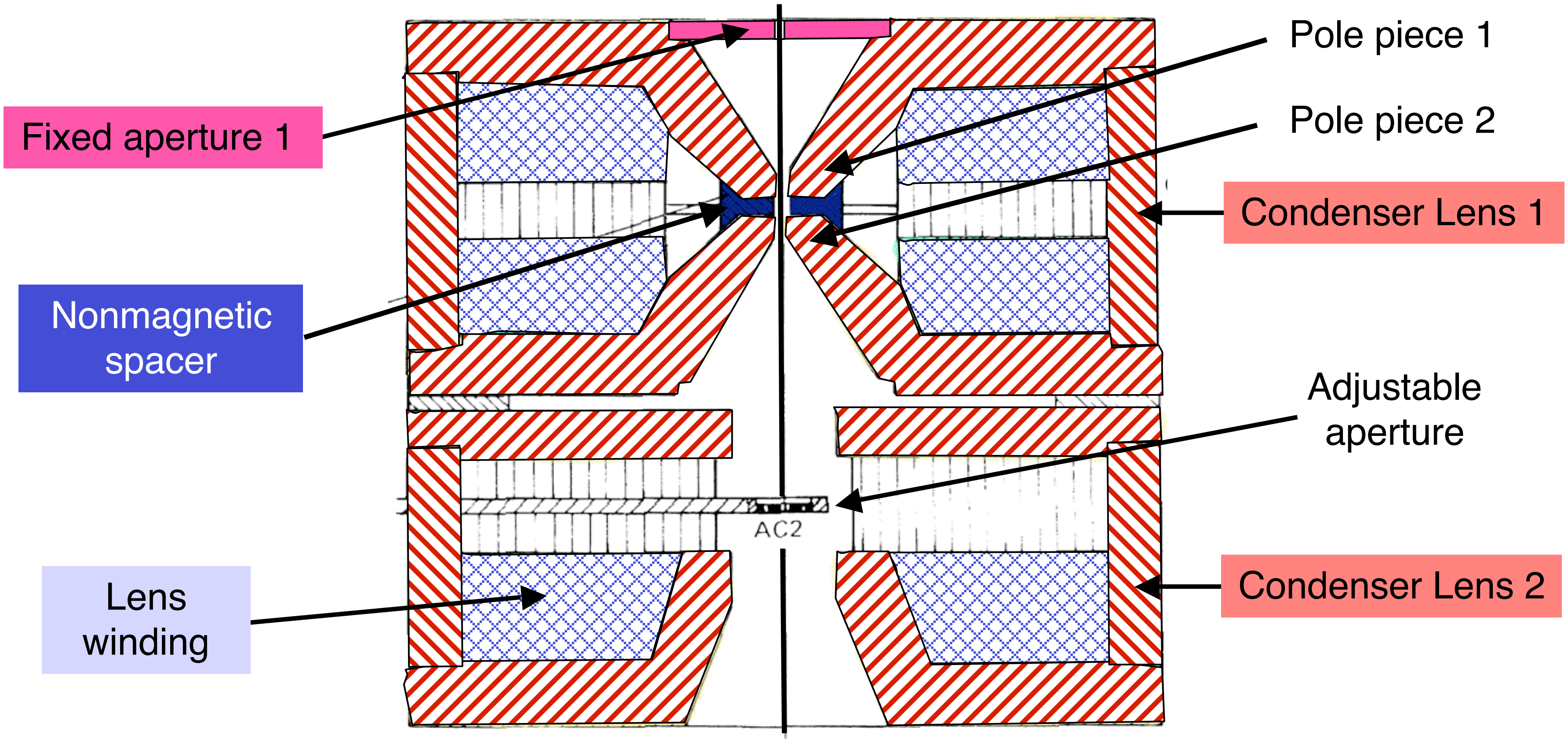
I.A.5.d The Electromagnetic Lens

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

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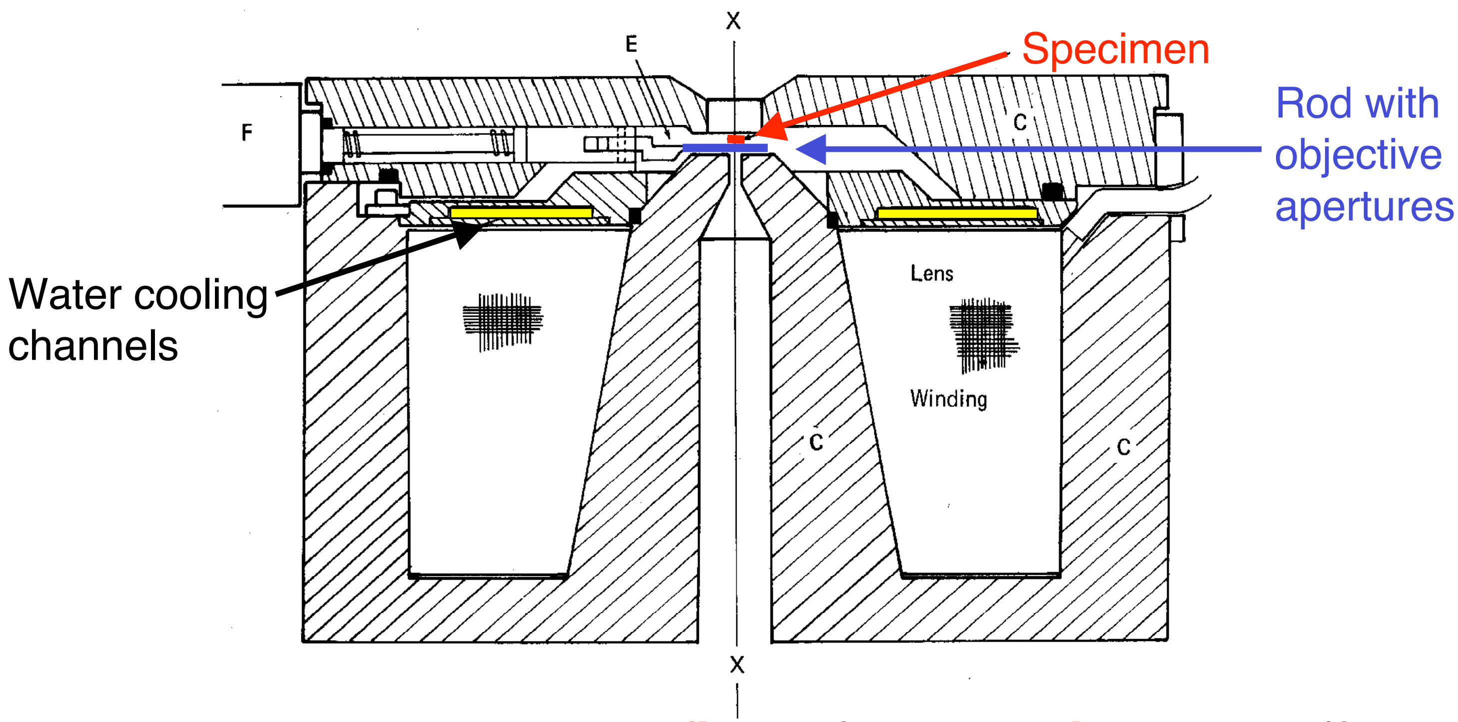
Objective Lens Design



- Typical construction gives **strong field** of **short axial extent** (f = 1.5-3 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

I.A.5 Electron Optics / Electron Lenses

I.A.5.d The Electromagnetic Lens

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 electro-magnet coils