Block 17 — Magnetic Flux Density and Forces

Student Group

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Learning objectives

After this 90-minute block, you can

- …

Preparation at Home

Well, again

- read through the present chapter and write down anything you did not understand.
- Also here, there are some clips for more clarification under 'Embedded resources' (check the text above/below, sometimes only part of the clip is interesting).

For checking your understanding please do the following exercises:

- …

90-minute plan

1. Warm-up (x min):
    1. ….
2. Core concepts & derivations (x min):
    1. …
3. Practice (x min): …
4. Wrap-up (x min): Summary box; common pitfalls checklist.

Conceptual overview

1. …

Core content

…

Common pitfalls

- …

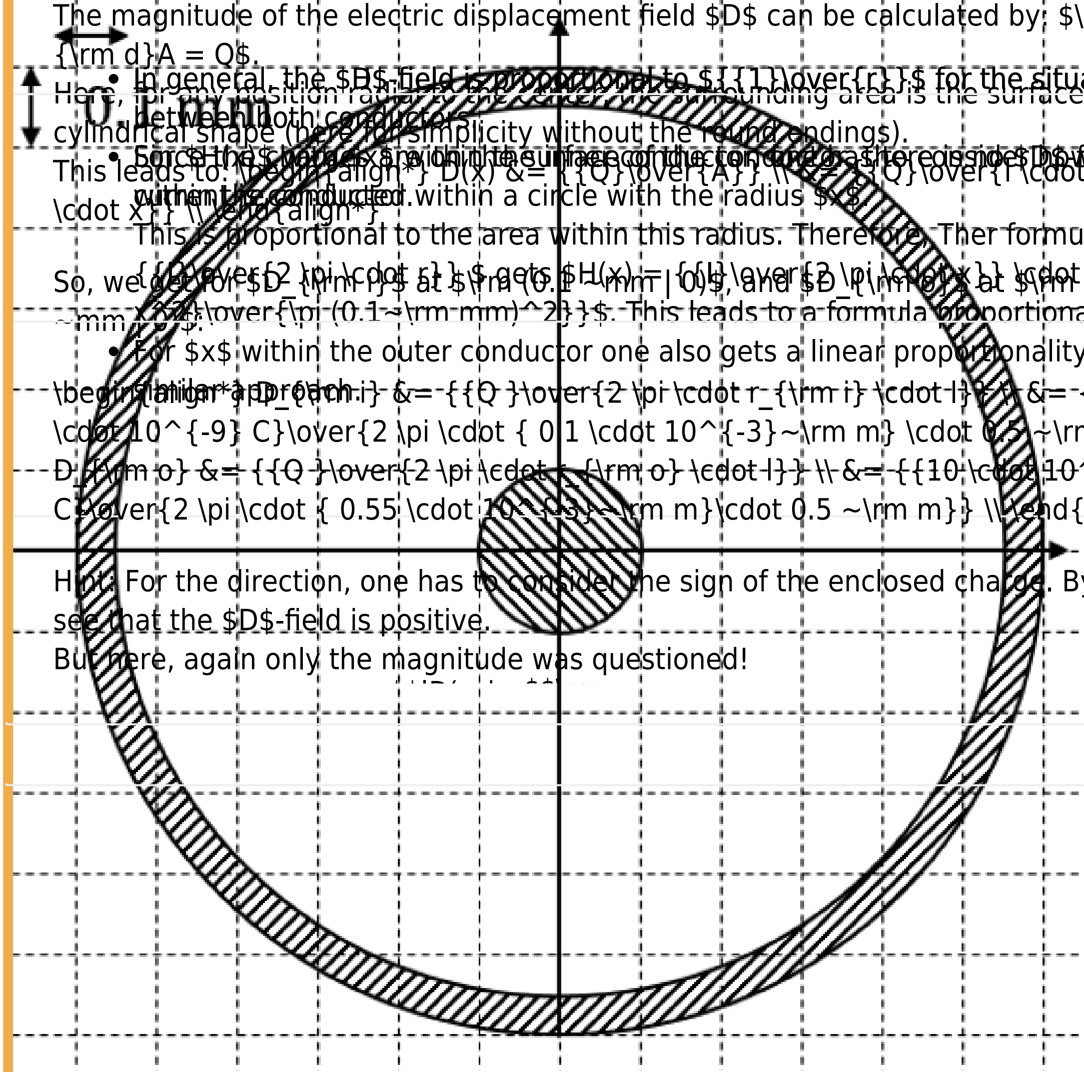
Exercises

Exercise E10 Fields of an coax Cable
(written test, approx. 12 % of a 120-minute written test, SS2024)

A $\rm 50 ~\rm m$ long coax cable ... cross-section ... in the origin in the center of the coax cable. ... the following situation appears:

1. What is the magnitude of the electric displacement field $D(x)$ ... $\rm (0.1 ~mm | 0)$ and $\rm (0.55 ~mm | 0)$? ... Use proper dimensions and labels for the diagram.

- Inner conductor: $+3.3 ~\rm mA$, $+10 ~\rm nC$ (current into the plane of the diagram)
- Outer conductor: $-3.3 ~\rm mA$, $0 ~\rm nC$ (current out of the plane of diagram)



Path

Path

The magnitude of the electric displacement field D can be calculated by: $\int D {\rm d}A = Q$.
Here, for any position radial to the center, the surrounding area is the surface of a cylindrical shape (here for simplicity without the round endings).
This leads to: $D(x) = {{Q}\over{A}} = {{Q}\over{l \cdot 2\pi \cdot x}}$

So, we get for $D_{\rm i}$ at $\rm (0.1 ~mm | 0)$, and $D_{\rm o}$ at $\rm (0.55 ~mm | 0)$:

$$\begin{align*} D_{\rm i} &= {{Q }\over{2 \pi \cdot r_{\rm i} \cdot l}} \\ &= {{10 \cdot 10^{-9} C}\over{2 \pi \cdot { 0.1 \cdot 10^{-3}~\rm m} \cdot 0.5 ~\rm m}} \\ D_{\rm o} &= {{Q }\over{2 \pi \cdot r_{\rm o} \cdot l}} \\ &= {{10 \cdot 10^{-9} C}\over{2 \pi \cdot { 0.55 \cdot 10^{-3}~\rm m}\cdot 0.5 ~\rm m}} \end{align*}$$

Hint: For the direction, one has to consider the sign of the enclosed charge. By this, we see that the D-field is positive.
But here, again only the magnitude was questioned!

Result:

- for $(0.1 ~\rm mm | 0)$: $D_{\rm i} = 31.8... ~\rm µC/m^2$ / $H = 5.25... ~\rm A/m$
- for $(0.55 ~\rm mm| 0)$: $D_{\rm o} = 5.78... ~\rm µC/m^2$ / $H = 0.955... ~\rm A/m$

- In general, the H-field is proportional to ${{1}\over{r}}$ for the situation between both conductors.
- For the values x within the inner conductor the current is not the whole current, but only the current within a circle with the radius x. This is proportional to the area within this radius. Therefore, Ther formula $H = {{I}\over{2 \pi \cdot r}}$ gets $H(x) = {{I}\over{2 \pi \cdot x}} \cdot {{\pi x^2}\over{\pi (0.1~\rm mm)^2}}$. This leads to a formula proportional to x.
- For x within the outer conductor one also gets a linear proportionality with a similar approach.

2. What is the magnitude of the magnetic field strength H at $\rm (0.1 ~mm | 0)$ and $\rm (0.55 ~mm | 0)$?

3. Plot the graph of the magnitude of $H(x)$ ... x ... $[-0.6 ~\rm mm, +0.6 ~\rm mm]$ ...

Path

The magnitude of the magnetic field strength H can be calculated by: $H = {{I}\over{2 \pi \cdot r}} $
So, we get for $H_{\rm i}$ at $\rm (0.1 ~mm | 0)$, and $H_{\rm o}$ at $\rm (0.55 ~mm | 0)$:

\begin{align*} H_{\rm i} &= {{I}\over{2 \pi \cdot r_{\rm i}}} \\ &= {{+3.3 A}\over{2 \pi \cdot { 0.1 \cdot 10^{-3}~\rm m}}} \\ H_{\rm o} &= {{I}\over{2 \pi \cdot r_{\rm o}}} \\ &= {{+3.3 A}\over{2 \pi \cdot { 0.55 \cdot 10^{-3}~\rm m}}} \\ \end{align*}

Hint: For the direction, one has to consider the right-hand rule. By this, we see that the H-field on the right side points downwards.
Therefore, the sign of the H-field is negative.
But here, only the magnitude was questioned!

Exercise E4 Magnetic Flux Density
(written test, approx. 6 % of a 120-minute written test, SS2021)

An electric motor is operated for experiments in the laboratory. An alternating current with an amplitude of $\hat{I} = 100~\rm A$ is operated.
You stand next to it and think about whether you have any health problems to worry about.
The figure below shows the top view of the laboratory with the supply line between $\rm A$ and $\rm B$.

1) The limit value for the magnetic flux density at the frequency used is $B_0 = 100~\rm \mu T$.
At what distance around the conductor is this value exceeded? (3 points, independent of a))

Result

Path

$B = 0.2 ~\rm m$

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$, $\mu_{r}=1$

The formula for the magnetic field strength can be rearranged: \begin{align*} H &= {{I}\over{2\pi \cdot r}} \\ r &= {{I}\over{2\pi \cdot H}} \\ \end{align*}

Again, the magnetic flux density B is given as: $B = \mu_0 \mu_r H$
Therefore: \begin{align*} r &= \mu_0 \mu_r {{ I }\over{2\pi \cdot B}} \\ &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} {{100 ~\rm A}\over{2\pi \cdot 100\cdot 10^{-6} {~\rm T}}} \\ \end{align*}

a) What is the highest magnetic flux density through the line in your body? (3 points)

Path

The magnetic field strength for a conducting wire is given as:

\begin{align*} H &= {{I}\over{2\pi \cdot r}} \end{align*}

The magnetic flux density B is given as: $B = \mu_0 \mu_r H$

Here, the maximum current is $\hat{I} = 100~\rm A$ and the distance to the cable is $r = \sqrt{(0.1 {~\rm m})^2 + (0.4 {~\rm m})^2}= 0.412... ~\rm m$.

Therefore: \begin{align*} B &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1 \cdot {{100 ~\rm A}\over{2\pi \cdot 0.412... ~\rm m}} \end{align*}

Exercise E5 Toroidal Coil
(written test, approx. 5 % of a 120-minute written test, SS2021)

A magnetic field with a flux density of at least $50 ~\rm mT$ is to be achieved in a ring-shaped coil (toroidal coil).
The coil has 60 turns, wound around soft iron with $\mu_{\rm r} = 1200$.
The average field line length in the coil should be $l = 12 ~\rm cm$.

Result

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$

$I = 66 ~\rm mA$

What is the minimum current that must flow through a single winding?

Path

The magnetic field strength of a toroidal coil is given as:

$$\begin{align*} H &= {{N \cdot I}\over{l}} \end{align*}$$

Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\rm r} \cdot H$.
By this, the formula can be rearranged:

$$\begin{align*} H &= {{N \cdot I}\over{l}} \\ {{B}\over{ \mu_0 \mu_{\rm r}}} &= {{N \cdot I}\over{l}} \\ I &= {{B \cdot l}\over{ \mu_0 \mu_{\rm r} \cdot N}} \end{align*}$$

Putting in the numbers: $$\begin{align*} I &= {{ 0.05 {~\rm T} \cdot 0.12{~\rm m} }\over{ 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1'200 \cdot 60}} \\ &= 0.6631... {{\rm T\cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... {{\rm {{\rm Vs}\over{\rm m^2}} \cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... ~\rm A \end{align*}$$

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Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\rm r} \cdot H$.
By this, the formula can be rearranged:

\begin{align*} H &= {{N \cdot I}\over{l}} \\ {{B}\over{ \mu_0 \mu_{\rm r}}} &= {{N \cdot I}\over{l}} \\ I &= {{B \cdot l}\over{ \mu_0 \mu_{\rm r} \cdot N}} \end{align*}

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Embedded resources

Explanation (video): ...