## Experiment #4: Magnetic properties

### Part 1. Mapping the Magnetic Field of an Nd Magnet using a Hall Sensor

**Overview.** In this part, you will measure the magnetic field of a neodymium (Nd) magnet as a function of distance from the magnet surface. Measurements are taken at both the center position and the edge position, and in two directions: $B_{||}$ and $B_{\perp}$. Since magnetic field is a vector quantity, both magnitude and direction are important.

**Probe orientation and sign convention:**

- Place the flat side of the probe tip against the surface being measured.
- A negative reading indicates the probe is touching the south pole; a positive reading indicates the north pole.
- Record both $B_{||}$ and $B_{\perp}$ at each position.
- Convert gauss to tesla in the final results: 1 G = $10^{-4}$ T

**What you will measure:**

- **Position points:** (2,0), (4,0), (6,0), (0,2), (0,4), (0,6)
- $\boldsymbol{B_{||}}$ **and** $\boldsymbol{B_{\perp}}$ at each point.

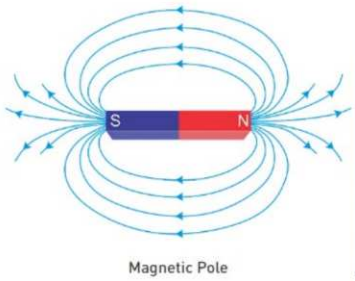
**The data table in Excel will look something like:**

Position | $B_{||}$ | $B_{\perp}$ | $B_{\text{total}}$ | Angle $\theta$ (°)

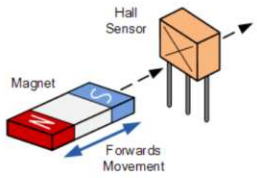
**Calculations:**

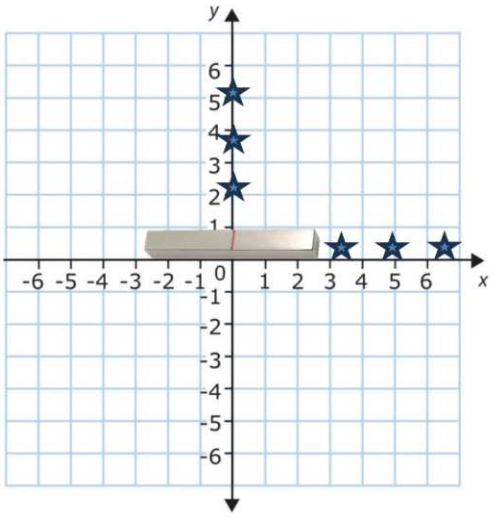
- $B_{tot} = \sqrt{B_{||}^2 + B_{\perp}^2}$
- $\theta = \arctan(B_{\perp}/B_{||})$

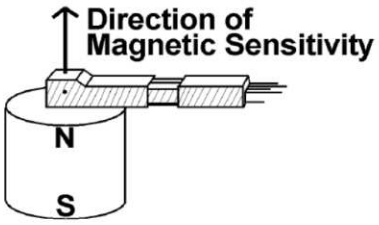
**Be sure to plot your data!** Some figures on the next slide may be helpful, for reference.

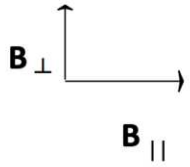



Magnetic Pole



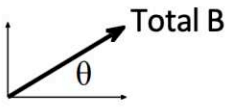




- Place the flat side of the probe's end (not the square bulge side) against the surface to be measured.
- A negative sign indicates that the probe is touching the south pole of a magnetized object; in contrast, a north pole will read positive.

| Position | $B_{\parallel}$ (Gauss) | $B_{\perp}$ (Gauss) | Total B (Gauss) | Angle $\theta$ |
|---|---|---|---|---|
| (2,0) | 61 | 1.0 | | |
| (4,0) | 11 | 1.0 | | |
| (6,0) | 5 | 1.0 | | |
| (0,2) | 43 | 1.0 | | |
| (0,4) | 9 | 1.0 | | |
| (0,6) | 3 | 1.0 | | |

Values shown here are illustrative. Convert gauss to T



## Part 2. *B*–*H* Hysteresis in a Toroidal Core

**Overview.** In this part, you will study the relationship between magnetic field strength (***H***) and magnetic flux density (***B***). By applying an AC current through a toroidal core and recording the resulting voltages with an oscilloscope, you will calculate both ***H*** and ***B*** as functions of time and construct a ***B***–***H*** (magnetization) curve. From this curve, you'll identify key magnetic properties of the core material: its remanence, coercivity, and relative permeability.

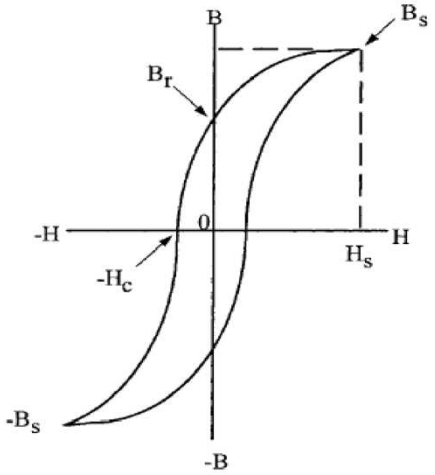
**Some background.** The magnetic field strength ***H*** (units: A/m) describes the magnetizing force applied to a material by an external current source. The magnetic flux density ***B*** (units: Tesla) describes the total magnetic field inside the material, accounting for both the applied field and the response of the material itself:

$$\boldsymbol{B = \mu_0 \mu_r H}$$

Where $\mu_0 = 4\pi \times 10^{-7}$ N/A$^2$ is the vacuum permeability, and $\mu_r$ is the relative permeability of the material. Ferromagnetic materials (like the iron-based core used in this lab) can have $\mu_r \gg 1$, meaning they greatly amplify the applied magnetic field through alignment of internal magnetic domains.

Keep in mind that ***B*** does not increase linearly with ***H***. Instead, as we increase applied ***H***, magnetic domains progressively align until the material reaches saturation. When ***H*** is reversed, the material does *not* retrace the same path – a phenomenon called hysteresis. The resulting ***B***–***H*** loop (shown to the right) encodes several properties:

- Saturation flux density ($\boldsymbol{B_S}$): the maximum flux ***B*** achievable at high field strength ***H***
- Remanence ($\boldsymbol{B_R}$): the residual ***B*** when the field is turned off (***H*** = 0) after reaching saturation
- Coercivity ($\boldsymbol{H_C}$): the reverse field required to bring ***B*** back to zero after saturation
- Relative permeability ($\boldsymbol{\mu_r}$): determined from the slope of the ***B***–***H*** curve (usually near the origin)



Our experiment today will use a toroidal core wound with two coils ($N_1 = N_2 = 25$ turns each). An AC transformer drives current through the primary coil at 60 Hz, while the secondary coil voltage is recorded along with the voltage across a 1 Ω sense resistor in series with the primary coil.

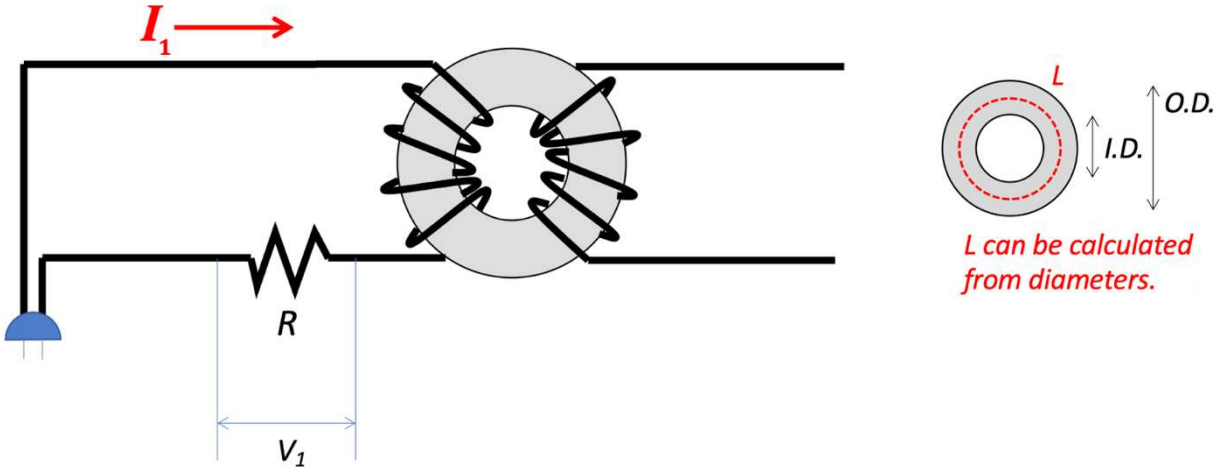



**Figure 1:** A schematic of the experiment. Wires are coiled around the toroidal core 25 times.

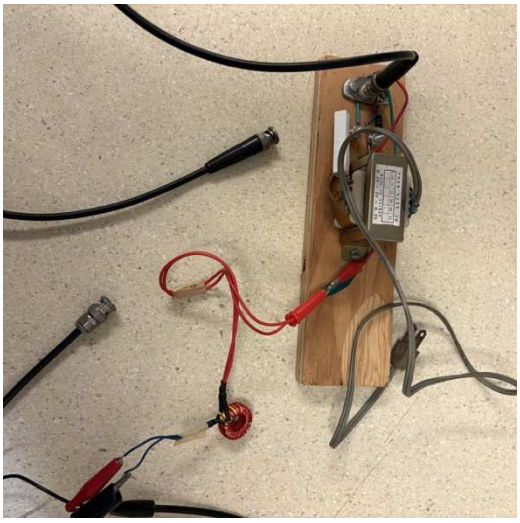


**Photo of the experimental setup**




**AC transformer**

**Measuring *H* from the first circuit:**

The voltage $V_1$ across the resistor (in **Figure 1**) gives the current directly (since $R = 1\ \Omega$):

$$I_1 = V_1/R$$

This is just Ohm's law rearranged. The magnetic field strength inside the toroid is then:

$$\boldsymbol{H = I_1(N_1/L)}$$

where $L$ is the mean circumference of the toroid, calculated from its inner and outer diameters, as shown in the right panel of **Figure 1**.

**Measuring *B* from the second circuit:**

By Faraday's law, the voltage induced in the secondary coil is:

$$V_2 = N_2 A\ dB/dt$$

Where $A$ is the cross-sectional area of the core. $B$ is recovered by rearranging this equation and numerically integrating $V_2$ over time. Keep in mind that $V_2$ is a function of time!

**What you will measure:**

- Oscilloscope traces of $V_1$ and $V_2$ over AC cycles
- Inner and outer diameter of the toroidal core (to calculate $L$ and $A$)
- The resulting $B$–$H$ hysteresis loop and several derived quantities ($\mu_r, B_r, H_c$)




**Figure 2:** The oscilloscope displays a graph with voltage on the $y$-axis and time on the $x$-axis. The yellow line on the monitor represents CH1, while the blue line is CH2.

**Procedure:**

1. **Set up the circuit.**

- Connect the 1 Ω sense resistor in series with the first coil ($N_1$) of the toroidal core.
- Connect the transformer to the first coil and set the input voltage to 20 V.
- Connect the oscilloscope *via* BNC cables: CH1 measures $V_1$ (voltage across the resistor), CH2 measures $V_2$ (voltage from the second coil).

2. **Record the oscilloscope data.**

- Confirm that the oscilloscope is displaying both CH1 and CH2 waveforms. CH1 (yellow) will appear sinusoidal; CH2 (blue) will appear shifted in phase since it relates to $dB/dt$.
- Save the data to a USB drive in CSV format (press "Save" on the oscilloscope). The file will have three columns: time ($t$), $V_1$ (CH1), and $V_2$ (CH2).
- Repeat steps 1 and 2 while increasing the input power in 20V increments up to 100V.

3. **Measure the toroid dimensions.**

- Use calipers to measure the outer diameter and inner diameter of the toroidal core.
- Calculate the mean circumference (the path length through the core material) as:

$$L = \pi(\text{outer } + \text{ inner diamter})/2$$

- Calculate the cross-sectional area $A$ of the toroid:

$$A = \pi(\text{outer } - \text{inner diameter})^2/4$$

4. **Calculate H from CH1 data.**

- In Excel, compute the current at each time step:

$$I_1 = V_1/R$$

- Calculate the magnetic field strength:

$$H = I_1(N_1/L)$$

5. **Calculate B from CH2 data.**

- Follow these sub-steps in Excel. The column layout is shown in **Figure 3** below.

    1. **Adjust the raw data offset.** Subtract the mean of the $V_2$ column to center the data around zero.
    2. **Compute $\Delta t$ and $\Delta V$.** For each row $n$, calculate:

$$\Delta t = t[n] - t[n-1] \text{ (column E)}$$

$$\Delta V = V_2[n] + V_2[n-1]/2 \text{ (column F)}$$

3. **Compute $\Delta(t \times V)$.** Multiply $\Delta t \times \Delta V$ at each row (column G).
4. **Integrate numerically.** Build a running cumulative sum of column G to obtain an approximation of $\int V_2 dt$ (column H).
5. **Remove the DC offset.** Compute the mean $M = (\max + \min)/2$ of column H, then subtract $M$ from each value in column H (column I). This removes any DC drift accumulated during integration.
6. **Convert to Tesla.** Multiply column I by $2\pi f/(N_2 A)$ where f = 60 Hz, $N_2$ = 25, and $A$ is the core cross-sectional area from Step 3 (column K). This will give you $B$ in Tesla:

$$B = 2\pi f(\text{col } H - M)/(N_2 A)$$

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time | Voltage (CH1) | Voltage (CH2) | | Δt | ΔV | Δ(t x V) | integral | offset | x 2πf | ÷ NA |
| 1 | -7.00E-01 | -2.40E-02 | 6.40E-03 | | =(A2-A1) | =(C2+C1)/2 | =E1xF1 | =G1 | =H1-M | =I1 x 2πf | =J1 ÷ NA |
| 2 | -7.00E-01 | -3.20E-02 | 6.20E-03 | | =(A3-A2) | =(C3+C2)/2 | =E2xF2 | =G2+H1 | =H2-M | =I2 x 2πf | =J2 ÷ NA |
| 3 | -7.00E-01 | -2.80E-02 | 6.00E-03 | | =(A4-A3) | =(C4+C3)/2 | =E3xF3 | =G3+H2 | =H3-M | =I3 x 2πf | =J3 ÷ NA |
| 4 | -7.00E-01 | -2.80E-02 | 5.80E-03 | | =(A5-A4) | =(C5+C4)/2 | =E4xF4 | =G4+H3 | =H4-M | =I4 x 2πf | =J4 ÷ NA |

**Figure 3.** The calculation for **B**, using excel.

**Data analysis notes:**

- Use data spanning only **1–2 complete AC cycles** for cleaner results.
- For the DC offset correction, compute M from **column H** (the integrated signal) as:

$$\boldsymbol{M = (\text{max value of col } H + \text{min value of col } H)/2}$$

- When plotting $B$ vs $H$, use **scatter format** (not line format) in Excel.

6. **Plot the B–H curve.**
   - Create a scatter plot in Excel with $H$ on the x-axis and $B$ on the y-axis.
   - The result should be a closed hysteresis loop. If the loop does not close cleanly, check your offset correction M in Step 5.

7. **Extract magnetic properties.**
   - Identify $B_r$ (remanence) and $H_c$ (coercivity) directly from your $B$–$H$ plot. Note that because the AC drive voltage is fixed, the loop does not reach saturation, so $B_s$ cannot be determined from this measurement.
   - Estimate the relative permeability $\mu_r$ from the slope of the linear portion of the curve: $\mu_r = \text{slope}/\mu_0$
   - Based on the shape of your hysteresis loop, classify the core material as a *soft* or *hard* ferromagnet and briefly justify your answer.