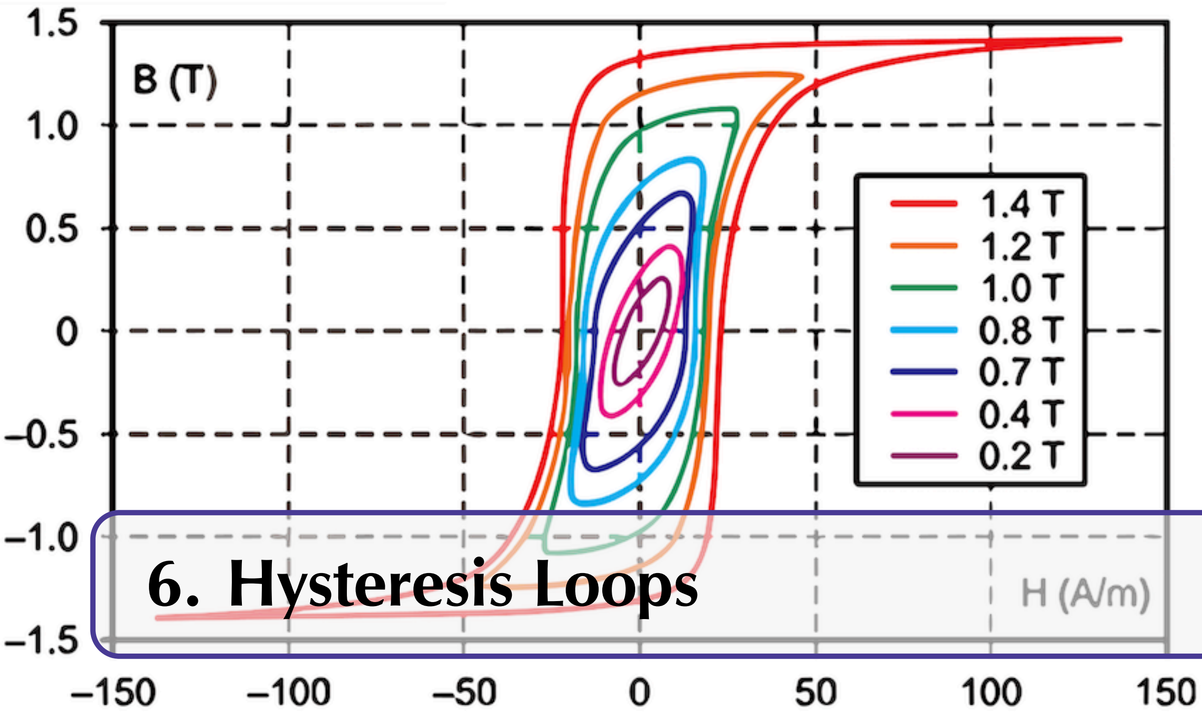

6. Hysteresis Loops

Learning aims

1. To gain confidence with tackling physics problems where you have some background understanding but are trying to investigate and tie down more detailed phenomena.
2. To gain experience with designing and testing circuits to meet the requirements for a given experiment.
3. To increase your skills in recognising and accounting for systematic error.

6.1 Using a solenoid to measure B-H curves

Recall that a current I passing through a long air-cored solenoid (the primary coil, so we will use subscript p) of n_p turns occupying a length L_p will produce inside the solenoid a magnetic field strength H given by

$$H = In_p/L_p. \tag{6.1}$$

We can conveniently measure I by passing it through a resistance R_p and measuring the voltage across it. Later you'll be displaying this voltage on the x-axis of the oscilloscope, so we'll call it V_x. Thus

$$V_x = IR_p = \frac{L_p R_p}{n_p} H. \tag{6.2}$$

If there is a second coil inside the first then, provided I is varying, Faraday's Law says there will be an EMF induced in the secondary coil given by

$$\mathcal{E}_s = n_s \frac{\partial \phi}{\partial t}, \tag{6.3}$$

where ϕ is the magnetic flux through the secondary and n_s is the total number of turns. If the magnetic field density B inside the secondary is uniform across the cross-section A_s of the coil then

$$\phi = BA_s. \tag{6.4}$$

It is not useful to measure the EMF directly, but if it is applied to an integrator (see section 2.2) and the output plotted as a voltage V_y on the y-axis, we have

$$V_y = -\frac{1}{R_i C}\int \mathcal{E}_s dt = \frac{n_s A_s}{R_i C} B, \tag{6.5}$$

where R_i is the input resistance (*not* the shunt resistance) and C is the feedback capacitance of the integrator.

For most materials we expect B to be proportional to H ($B = \mu_0 \mu_r H$ where μ_r the relative permeability of the material) and hence V_y to be proportional to V_x.

However, for certain materials, called ferromagnetic materials, we do not get this linear behaviour and instead the B-H curve has a complex shape such as those shown in Figure 6.1. The curve shows *hysteresis*, where the curve for increasing magnetic field is different to the curve for decreasing magnetic field because the material has become magnetised, and there is a magnetic field even when no current is applied.

We will investigate this phenomenon experimentally. You are not expected to know the theory of this ferromagnetic behaviour, though you may have come across it if you do Materials Science options. Discuss the theory with your demonstrator if you want to know more. If you are planning on writing up this experiment for your Scientific Report it is worth reading up on the relevant theory.

6.2 Initial setup and test

6.2.1 Background

Some small coils are available to use as the basis of your circuit. The coil with thicker wire has nominally 400 turns, the thinner nominally has 500. Use the 6 V AC from the power supply for the primary current, with a 2.0Ω resistor connected in series with the primary and the supply. This resistor serves to limit the current to prevent the coil overheating, and acts as R_p — it is supplied already mounted on the coil stand and connected to the primary coil.

You will need to design a suitable integrator, bearing in mind that the capacitor impedance at 50 Hz must be much less than that of the 1 MΩ shunt resistor. Build it and quickly check its performance near 50 Hz.

You will need to use XY-mode: see section 1.5.1 to refresh your memory on this. The choice of whether to use AC mode or DC mode in the oscilloscope here requires some judgement — try both and compare, especially later on when using the ferromagnetic samples, but **always use the same mode on both the A and B inputs**.

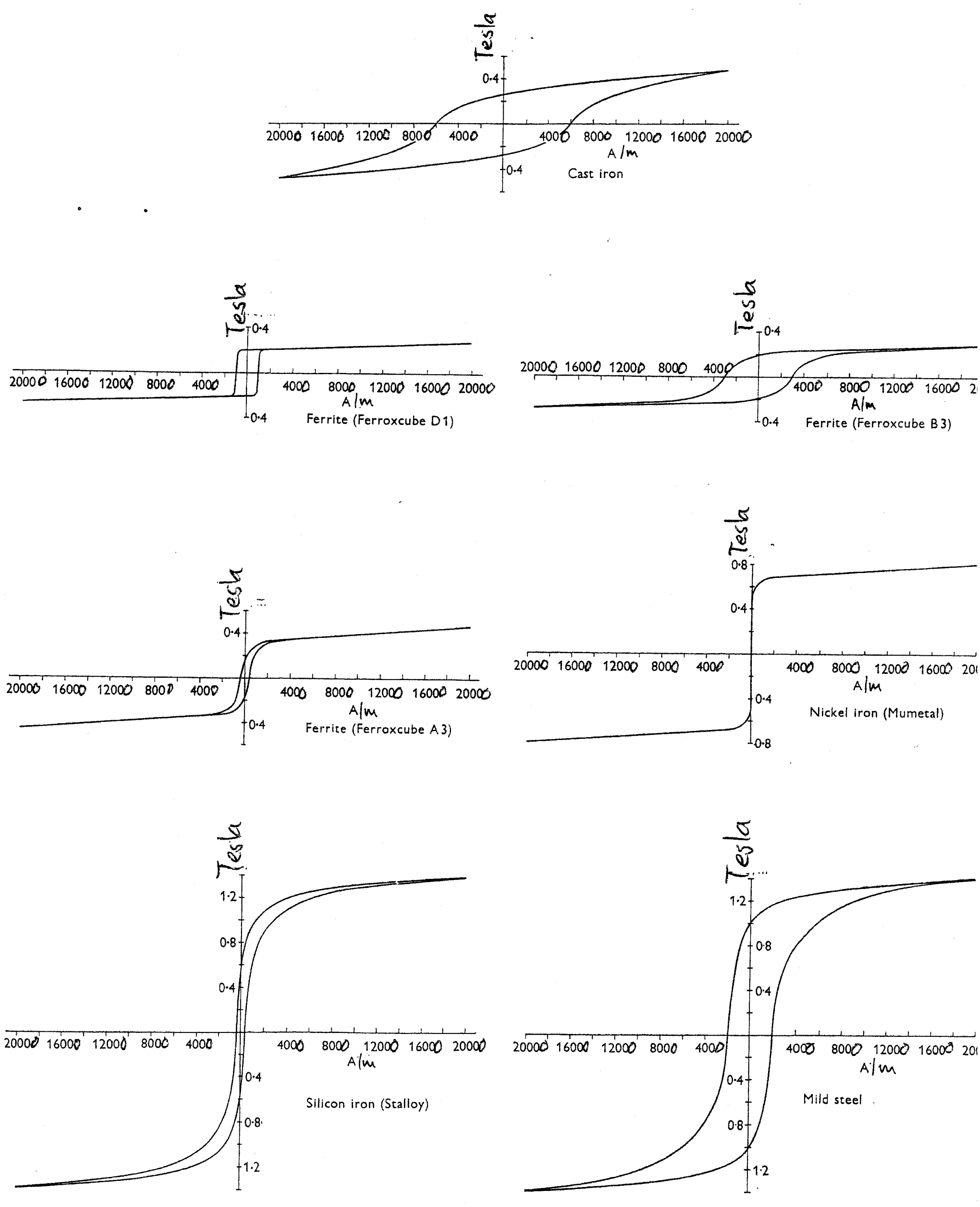

Figure 6.1: B-H curves for some ferromagnetic materials.

If you use DC mode, the signals you will get in the main experiment will likely be limited by the available *voltage resolution*, an effect of the limited number of bits of precision of the analogue-to-digital converter used in the PicoScope. If you see signals which appear to be "staircased", explore the effect of increasing the effective number of bits of voltage resolution (changing the voltage resolution can be accessed under the "Channel Options" for the A and B channels, under "Resolution enhancement"). Note that increasing the voltage resolution comes at the expense of smoothing out some true variation in the signal (it is effectively a time average), so use the minimum number of bits which gives an acceptable signal.

6.2.2 Setting up the experiment (1hr 30 minutes)

Set up a system to measure and display V_y as a function of V_x, taking note of the previous points. But before you actually carry out this, read this section, look at the kit, decide what to do, and draw a diagram of the whole system.

6.2.3 Checking the experiment (1 hr 30 mins)

Using equation (6.2) and equation (6.5) and from measurements of R_p, C and so on (if you don't know how to use calipers, etc, ASK or look for the posters on the wall of the lab), work out the relationship between V_y and V_x you expect your set-up to have with a core material of known $B - H$ relationship — air.

Now measure this relationship directly with your set-up and compare it quantitatively with your predictions.

6.3 Measuring the metal samples

6.3.1 Background

We now insert a number of different metal samples into the secondary coil. Note that the sample does not fill the secondary coil — the area of the sample is not the area of the hole, and so B is not uniform across the cross-section of the coil. This means that equation 6.4 does not hold. If however we can assume that the magnetic flux inside the sample is much greater than the flux in the rest of the coil then we can write the flux through the secondary coil as

$$\phi \approx B_{\text{sample}} A_{\text{sample}} \tag{6.6}$$

where B_{sample} is the field inside the sample and A_{sample} is the cross-sectional area of the sample.

Most of the samples will show a directionally-dependent behaviour known as "hysteresis". Associated with hysteresis is an energy loss as regards the electrical system: energy is dissipated as heat inside the material. The energy loss per unit volume of material per cycle round the loop is $\int H dB$, i.e. the area enclosed by the loop on a B vs H plot.

6.3.2 Qualitative and quantitative measurements (3 hours)

Considering the signals in V_y versus V_x, determine the B vs H behaviour of the mild steel sample. Draw graphs of your hysteresis loops: it will help to scale your axes so that they can be compared with some sample hysteresis plots such as those shown in Figure 6.1.

Evaluate the power dissipated per unit volume (with an error estimate) and the maximum and minumum relative permeabilities $\mu_{\mathrm{r,max}}$ and $\mu_{\mathrm{r,min}}$ for the mild steel case.

Estimate the total power dissipated in the sample due to this hysteresis loss and comment on your result.

Similarly, make a hysteresis plot for the transformer iron sample and measure the power dissipated per unit volume and the range of μ_r.

In the case of the last sample, a Cu/Ni alloy, a change in hysteresis properties occurs around 40 °C. Make plots first above and then below this temperature and estimate the power dissipated per unit volume below 40°C.

The coils may be immersed in water for the second part. (DO NOT heat water in a beaker carrying the coils — melting, shorting and fire could result.)

Note that you can capture data from the PicoScope directly in Python — see Appendix A — and this can potentially make the process of plotting and analysis of the multiple hysteresis curves simpler.

Comment on how good this apparatus would be at measuring the changes in hysteresis properties over a few degrees (hint — how well does it measure the sample temperature?). How would you improve it?

Some things to consider if you write up this experiment as a Scientific Report

- Consider how much detail to report about different parts of the experiment — some elements of your work may not be of significant concern to a reader who is interested in the final result even though they may have taken you a significant amount of time to perform.
- Your experimental results will need to be compared to theoretical expectations and/or other experimental results from the literature in order to interpret them. A critical evaluation of what the uncertainties (systematic and random) are in your results is clearly essential to this comparison.
- Theory predicts that when a ferromagnetic material becomes saturated then μ_r approaches unity — is this borne out by your experimental results?

- As usual, saving your data in order to be able to re-plot it for the report will likely come in handy.