A Characterisation of the Figaro Electromagnetic Electron Spectrometer

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Abstract

The aim of this project is to characterize the magnetic field of the CLF Figaro electromagnet electron spectrometer. A Hall probe is used to map the magnetic field and how it varies spatially and temporally. The relationship between the power supply current and magnetic field was deduced, and resistive heating effects were also investigated. The magnetic field produced varies with current by the following equation: $B = 281.3I + 3.5$, where B is the magnetic field strength in mT and I is the current in A. The optimum current range to avoid decline in current due to resistive heating is between 0A and up to 2A, as some decline still occurs up to 2A.

Introduction

The three electron spectrometers in the Vulcan target areas, Figaro, Dick and Harry, have been used as diagnostics at the facility for a number of years. Unfortunately they have never been completely characterised, meaning that users have often had to make preliminary measurements of magnetic field strengths in order to decide which spectrometer suits the needs of their experiment.

The aim of this investigation is to characterize the "Figaro" electron spectrometer, primarily the magnetic field shape and behaviour with the current from the power supply. The ongoing project will characterise all three spectrometers.

Figaro is the smallest of the three electromagnet electron spectrometers. It comprises of two 165mm diameter electromagnet coils, each with 980 turns, from GMW Associates (model 3470) [1]. The coils are held together by an iron yoke and are fixed in place with a separation distance of 17.6mm.

An incoming electron beam is enters the spectrometer through a pinhole at the front and passes between the iron cores within an aluminium tube. The beam travels through to the detector (image plate [2]) which is located behind the electromagnets. The electrons are deflected by the magnetic field through an angle depending on their individual energies. The result is a spectrum of electrons which can be analysed to find the energies of the electrons from the laser-target interaction.

The field was mapped through the centre of the electromagnets at varying current values in order to deduce the relationship between current and field strength. It quickly became clear that the power supply for the spectrometer is not stable due to resistive heating effects in the coils. Thus, an investigation was done into how the current and field strength vary with time. Finally, a water cooling system was connected to the spectrometer with the aim of reducing these heating effects.

Theory

An electron in an electromagnetic field will be affected by the Lorentz force [3]:

$$F = q(E + v \times B), \tag{1}$$

where q is the electron charge (1.6×10^{-19}C), E is the electric field strength, v is the speed of the electron and B is the magnetic field strength. The electron spectrometers only detect electrons, thus only a magnetic field is used, so we can say that the electrons feel a force F:

$$F = qvB. \tag{2}$$

This force is perpendicular to both the magnetic field and the velocity of the electron. The charge is constant, so the deflecting force varies depending on the speed the electrons are travelling at and the strength of the field they are travelling through.

The force induced will cause the electron to travel in a circular path, so we can use the equation for circular motion:

$$F = \frac{mv^2}{R}, \tag{3}$$

where m is the mass of the body (the electron rest mass in our case), v is the speed and R is the radius of the circular path travelled. We have two equations for the centripetal force which we can now equate:

$$\frac{mv^2}{R} = qvB. \tag{4}$$

We rearrange for the radius R:

$$R = \frac{mv}{qB}. \tag{5}$$

Now, we must take into consideration the speed at which our electrons are travelling. The electrons produced in the laser-target interaction will be travelling much faster than the ions and protons due to their smaller mass, at a speed comparable to the speed of light, c, hence we must make a relativistic adjustment to their rest mass.

Our relativistic correction, γ, is equal to:

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{6}$$

and is the appropriate adjustment we need to make to our electron mass. In the case of Equation (5), the correction is simply $m = \gamma m_0$, where m is the relativistic mass and m_0 is the electron rest mass. Thus, our equation for the radius R becomes:

$$R = \frac{v m_0 \gamma}{qB}. \tag{7}$$

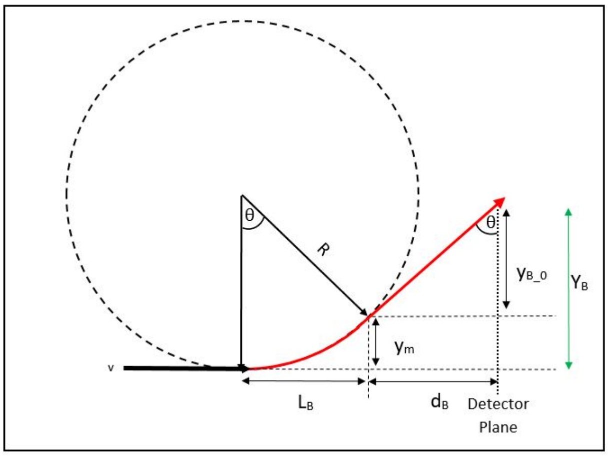

Figure 1: Path travelled by electrons before reaching detector. Inspiration taken from Carroll [4].

Figure 1 shows the incoming path of an electron (black arrow) into the magnetic field B and the deflection into an arc of radius R through angle θ, depending on its speed. The length L_B is the length of the magnetic field, hence the distance for which the electron is affected by the magnetic field. y_B is the vertical distance travelled over this length.

After leaving the magnetic field the electrons travel to the detector, which is located behind the magnets. The length from the end of the magnets to the detector is d_B, and the vertical distance travelled through this length is y_{B_0}. The *total* vertical distance travelled is Y_B, and this is the data that we extract from the image plate. If we can extract this total vertical distance the electrons are deflected through, we can calculate their energies and find out more about the laser-target interaction.

Table 1 displays the values of L_B, d_B and the maximum allowed Y_B for the Figaro spectrometer. The assigned error of ±0.5cm is due to the awkwardness of measuring the values on the spectrometer.

Parameter	Value (cm)
L_B	13.5
d_B	32.1
Y_B	24.5

Table 1: Values of L_B, d_B and the maximum allowed Y_B for the Figaro spectrometer.

Experimental Method

A Hirst Magnetics GM08 Hall Probe was mounted on a motorized xyz stage with 50mm range in each axis. A Sony magnascale box was connected to the stage was used to record the positions of the stage. An image of the setup can be seen in Figure 2.

The whole range of magnetic field measurements could not be done from the front of the spectrometer as the diameter of the entrance tube was less than that of the probe, meaning the probe could only reach just past the centre of the coils. Unfortunately, measurements were only taken from the front side due to lockdown measures. As the electromagnet is symmetrical along the central diagnostic axis, the field can be assumed to have a very similar profile at the back, however the measurements to confirm this assumption were prevented from being taken by Covid-19.

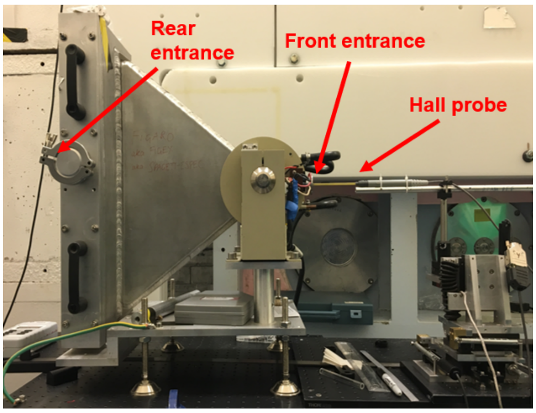

Figure 2: Experimental setup.

Absolute reference points were chosen on both the front and rear entrance of the spectrometer and were assigned as the starting points for the measurements. Figure 4 shows the absolute reference point on the front of the spectrometer.

The magnetic field strength was measured every millimeter for 50mm and then every half millimeter subsequently. This is because the field strength would increase very slowly initially and then rapidly as the probe reached the edge of the electromagnet cores. This was also done in order to keep the number of measurements at a minimum while also recording enough data points to show the true behaviour of the magnetic field.

Three repeat measurements were made for every field

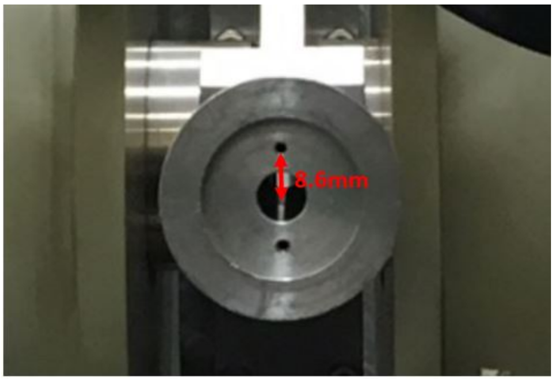

Figure 3: Absolute reference from spectrometer front.

strength value recorded, as the field measured by the probe showed a constant fluctuation. The average of these measurements was used to ensure a reliable data set. An absolute error of ±5mT was assigned to the probe, as changing between the four ranges (chosen depending on strength of the field) in the exact same position showed a change in field strength of around this size. This error also includes the constant fluctuation shown by the probe.

The magnetic field was measured this way for a current range of $0 - 2.5$A in increments of 0.5A. The maximum current allowed for the coils is stated as 3.5A, 2.5A was the highest measured in this project due to the resistive heating effects. After spatial measurements were completed the probe was placed at the position of maximum field strength along the z-axis and the current was varied in the same manner. The corresponding field strengths were recorded in order to record maximum field strength variation with current.

The variation of field strength with time was recorded using two different methods. The first method saw the power supply turned on to each current value for one hour with measurements of magnetic field strength, current and voltage taken every minute. These measurements aimed to investigate how resistive heating effects affects the magnetic field produced by the coils.

The second method mimics the use of the spectrometer on an experiment in order to see how the heating effects could impact the electron spectra produced shot-to-shot. The power supply was turned on and the same data were was recorded for 20 minutes. The power supply was then turned off for a rest period of 30 minutes, and this was repeated a total of four times, mimicking the typical four shot pump-down on TAP experiments.

A water cooling system was then fitted to the spectrometer and the time-varied measurements were repeated. This data was recorded during the first run of the TAP Carroll 2020 experiment, so due to time constraints only measurements for 2A and 2.5A were taken.

Results and Discussion

I. Spatial Variation of Magnetic Field Strength

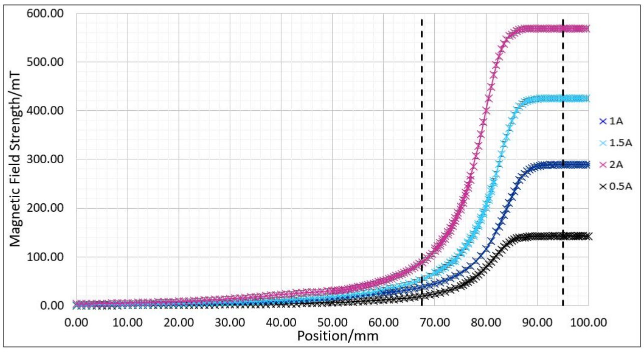

Figure 4: Spatial measurements of the magnetic field of the spectrometer. The dashed lines represent the edge (left) and the centre (right) of the electromagnets.

The results for this section are summarised in Figure 4. The x-axis shows the position of the field in mm, where the starting position is the absolute reference point. Increasing values of position correspond to the probe entering the spectrometer housing and travelling through the centre of the magnets.

The results show half of the characteristic top-hat shape of the magnetic field, which was to be expected. It is important to note that these were the first results taken, and because of this the heating effects were still unknown. At 2.5A the current was unstable and decreased quite quickly, so measurements were only made up to 2A.

II. Maximum Field Strength Variation with Current

The results of the maximum field strength variation with current can be seen in Table 2.

Current/A	Max. Field/mT ± 5mT
0.5	144
1.0	293
1.5	422
2.0	567
2.5	703

Table 2: Table of results of maximum field strength with current.

The spectrometer can reach magnetic field strengths of higher than 700mT as it can be operated up to 3.5A, however field strengths that can be achieved within the optimum range of the power supply are upwards from 0 to 566mT.

III. Variation of Magnetic Field Strength with Time

This section is split into two subsections, with the first section describing the hour-long measurements and the second describing the on-off repeat measurements.

III.a Hour-long measurements

The hour long measurements were taken every minute, recording the magnetic field strength, current and voltage. The results can be seen in Figure 5.

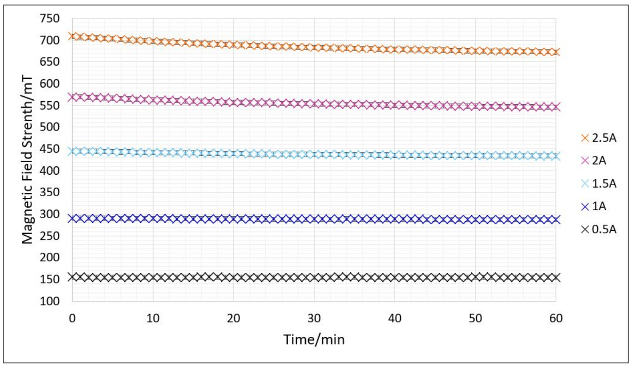

Figure 5: Hour-long measurements of magnetic field.

The current and corresponding magnetic field strength began to decrease almost immediately when above 2A, with the drop due to the coils heating up as a result of resistance effects, as the power supply works by supplying a constant voltage, so an increase in resistance causes a decrease in current. This was apparent as the coils were warm to touch after a few minutes of running. In this case, a drop in current as small as 0.01A causes a decrease in magnetic field of 10mT ± 5mT.

The resistive heating effects are less obvious below 2A, although still prevalent. The overall decrease after an hour of the power on was about 15mT which is a small value, however still significant. The current was essentially steady at currents 0.5A and 1A, with a small decrease of $\sim$ 2mT and $\sim$ 4mT respectively. 1.5A also saw a small change in field strength over the hour. Thus it is concluded that the ideal operating range for the power supply is from between $0\text{A} < I < 2\text{A}$, and for more stable results currents higher than 2A should be avoided.

This is perhaps one of the most important findings in this project. The potential change in field strength during the time from setting the current to locking up the target area and taking the shot, as well as changes between shots if left running, could potentially affect calculations made using the data. The cause is simple, the coils are heating up and to keep the voltage constant, the current is decreasing. This is, however, an issue with the power supply not the electromagnet.

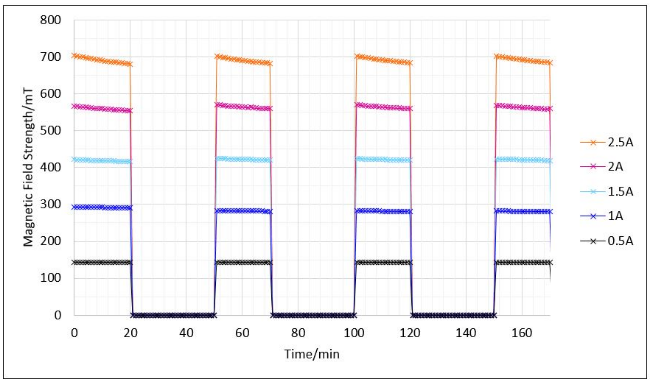

Figure 6: Repeat on-off measurements of magnetic field strength with time.

III.b On-off repeat measurements

The results for this section are summarised in Figure 6. This part of the project was to investigate whether there were any effects of repeatedly using the spectrometer for 20-minute periods as it would be used on experiments. However, it became clear that the 30-minute rest period was enough time for the coils to cool down enough to not affect the next result taking period, as the decrease in current and magnetic field remained constant in the lower current cases over the four repeat periods.

In some cases a slightly higher voltage of $\sim$ 0.1V was required to match the original current strength after one or two measurement periods, indicating that the resistance had not yet fallen to its normal value. This is only specific to the higher currents of above 1.5A. This did not seem to have any effect on the measured field, however, or the rate at which the current decreased.

The results from this section reiterate the heating effects for different currents and rebut any significant cumulative effects of heating during use of the spectrometer on experiment, given it is left enough time to cool down. Again the results show an optimum range of 0A to 2A.

IV. Water Cooled Variation of Magnetic Field Strength with Time

The water cooling system was fitted to the spectrometer in the hopes that its use would combat the heating of the coils and stabilize the power supply. The water cooling did negate some of the heating effects as they are less prevalent in the results, however at 2.5A the current still decreases immediately, albeit the decrease is smaller by about 10mT than without the cooling.

For 2A the decrease in current is less, and the difference between the cooled and non-cooled results is only a few mT, so the water cooling does make a slight difference. The results can be seen in Figure 7, displaying both cooled and non-cooled measurements for 2.5A and 2A. The y-axis has been adjusted so that the difference between the results is clear.

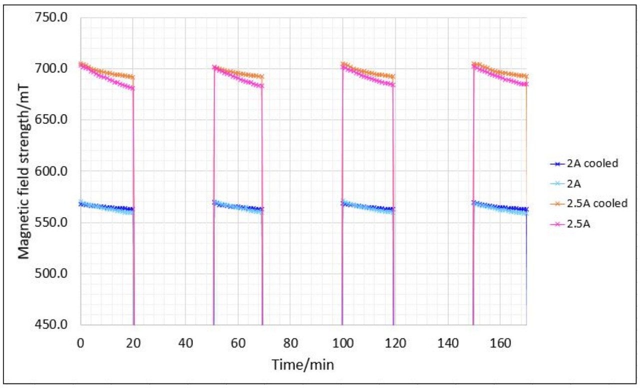

Figure 7: Results for water cooled measurements for currents 2.5A and 2A.

While the cooling system did make some difference for 2A, the difference is not significant enough to justify use of the cooling system. This is unfortunate as this means it is difficult to use the spectrometer to its full capacity, however there are two larger spectrometers which could be used instead if necessary. It is also useful to know the optimal range for the power supply.

Conclusion

The results from this project show how the magnetic field strength of the electromagnets behaves with current and position. The field has been mapped and also compared over time. This information will be useful to user groups which use the Figaro spectrometer.

The ideal operating range for the current has been deduced at between 0.1A to 2A as the decline in current due to heating is less apparent. The spectrometer can be operated up to 3.5A of course, however users should be aware of changes in current over time which could affect their results.

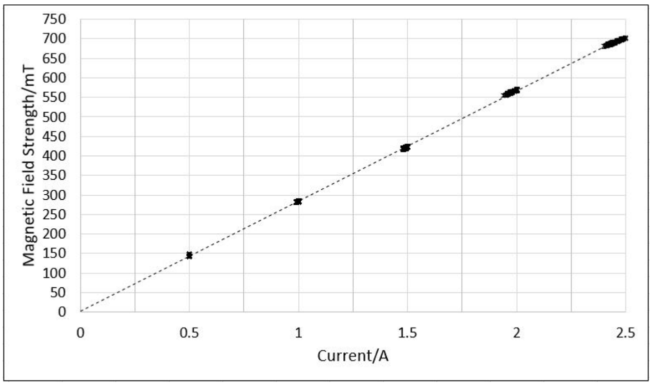

Figure 8: Graph of magnetic field vs. current.

The results from this project were compiled to find the relationship between current and field strength. This will allow Vulcan users to calculate which settings they will use for the power supply during their planning, as opposed to taking measurements on site once they have arrived. The data is displayed in Figure 8.

The linear fit to the measured magnetic field, B, in mT with current, $I(A)$, in amps is $B(\mathrm{mT}) = 281.3I\mathrm{A} + 3.5$. The data shows a clear trend and there are no outliers, meaning the current and magnetic field are linearly proportional.

References

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