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A Thermally Actuated Flux Pump for Energizing YBCO Pucks

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ABSTRACT

This paper presents results for the magnetization of a disc of YBCO by sending heat pulses through a disc of dysprosium below it. As the heat pulses move through the dysprosium its magnetic properties change producing a wave of magnetization across the disc of YBCO. This wave of magnetization sweeps vortices into the YBCO and each subsequent wave sweeps in more vortices, gradually increasing the magnetization of the YBCO. The YBCO disc was 30 mm in diameter and 15 mm high and the dysprosium was 30 mm in diameter and 14 mm high. The dysprosium undergoes a change from ferromagnetic to anti-ferromagnetic as it passes through a temperature of 85 K so the temperature range of the heat pulses went from below this temperature to a temperature above it. The dysprosium and YBCO were connected into an iron magnetic circuit to create a low reluctance path with three copper coils on parts of the circuit. Currents through the coils generated flux in the magnetic circuit. The circuit was cooled using a cryocooler and heat pulses were applied to the dysprosium by turning the cold head on and off. These heat pulses varied the temperature of the dysprosium above and below the ferromagnetic anti-ferromagnetic transition, sweeping vortices into the YBCO causing a magnetic field to gradually accumulate. It was found that the field initially grew to a certain level and then stayed constant no matter how long the pulses were applied. The pattern was found to be the same for four different coil currents and therefore two different starting values for the flux in the circuit.

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A Thermally Actuated Flux Pump for Energizing YBCO Pucks

Executive Summary

This paper describes the energizing of a yttrium barium copper oxide (YBCO) puck using a thermally actuated flux pump. These flux pumps consist of layers of superconducting material and thermal magnetic material immersed in a magnetic field from a permanent magnet or a coil. The thermal magnetic material is a material that undergoes a change in permeability with a change in temperature. Heat pulses are transmitted through the thermal magnetic material sweeping magnetic field lines into the superconducting puck.

We used YBCO as the superconductor with dysprosium as the thermal magnetic material. Dysprosium has the property that below about 85 K it is ferromagnetic but above 85 K it is antiferromagnetic, so heat pulses that go above and below 85 K should create a wave of magnetism across the face of the YBCO puck.

The YBCO and dysprosium pucks were 30 mm in diameter and contained in a magnetic circuit to reduce the reluctance and increase the flux. The magnetic field was provided by three coils wrapped around the three legs of the magnetic circuit. Heat pulses were generated by turning the cold head on and off.

The results showed that magnetic field lines initially accumulate in the YBCO but then the magnetization of the puck levelled off. The temperature of the YBCO fluctuated with the pulsing, with the crests of the waves exceeding the critical temperature of the YBCO (about 90 K). The temperature was measured using a sensor attached to the side of the puck which may not indicate temperatures inside the puck. We believe the results will improve if the temperature of the YBCO can be held constant at a value well below its critical temperature.

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1. Introduction

Currently the Royal Australian Navy uses dyads for magnetic influence minesweeping. These are large, heavy, permanent magnets that cannot be transported by air because their magnetic fields would interfere with aircraft navigation. Two types of dyads are in use, the mini dyad which is about 7.7 metres long and weighs 1,600 kilograms, and the maxi dyad which is about 10 metres long and weighs 10,000 kilograms. The purpose of this research is to make a smaller, lighter magnet with a magnetic field that can be turned off to facilitate air transport.

One approach to achieving this is to have a torpedo shaped body filled with superconducting pucks. If the pucks could be magnetized or demagnetized in place the field of the minesweeping magnet could be adjusted up and down and completely turned off during transport.

Magnetic fields can be trapped in high temperature superconducting (HTSC) discs like YBCO by one of two methods, zero field cooling or field cooling. Zero field cooling requires a field of twice the value to be trapped and field cooling requires the field to be approximately the same as the field to be trapped. Both methods require pucks to be placed inside coils generating large fields. When the pucks are magnetized they would have to be removed and placed in the machines or circuits they're designed for. This would involve handling the pucks at cryogenic temperatures. It would be much more convenient to magnetize the puck in place by a flux pumping method involving the application of small fields. Thermally actuated flux pumping might be a way of achieving this. This method consists of placing the superconducting puck on top of a puck with magnetic properties that depend upon temperature (a thermal magnetic material) in a magnetic circuit and apply heat pulses to the thermal magnetic material. Each heat pulse would create a magnetic wave that would move across the surface of the YBCO sweeping vortices into the superconductor. These vortices would gradually accumulate in the superconductor. Successes have been reported for YBCO using NdFeB [1] and Gadolinium [2] as a thermal magnetic materials.

This experiment used dysprosium as the thermal magnetic material because of the large ferromagnetic anti-ferromagnetic transition at 85 K. Figure 1 (below) shows how the specific magnetization of a single crystal of dysprosium changes with temperature.

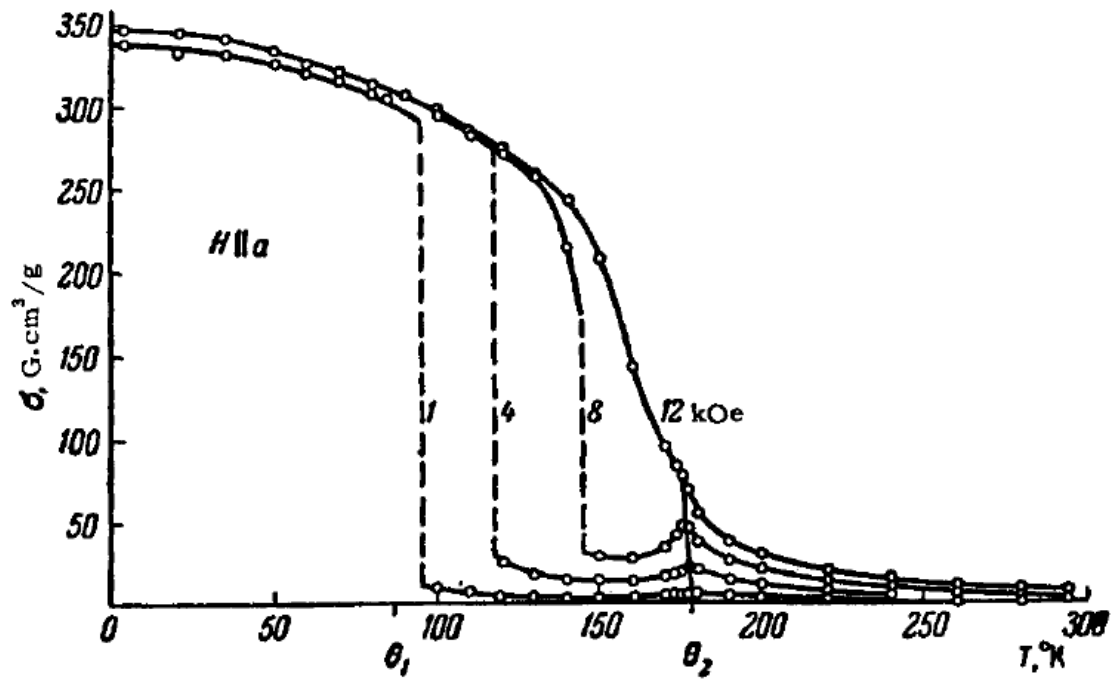


Figure 1: The temperature dependence of the specific magnetization of a dysprosium single crystal in the basal plane (along the a -axis) in various fields [3]

From figure 1 (above) it can be seen that the specific magnetization (the ratio of magnetization to density) of a dysprosium single crystal undergoes a large transition at 85 K and a second transition at approximately 179 K in fields of 1 kOe. Oersted is the unit for H (field strength) in the CGS system and 1 Oe corresponds to $1000/4\pi$ amperes per metre in the SI system of units. The first transition at 85 K is from ferromagnetic to antiferromagnetic, and then there is an increase in magnetization near 179 K and a second transition from antiferromagnetic to paramagnetic. As the field is increased the ferromagnetic/antiferromagnetic transition takes place at increasingly higher temperatures.

2. Experimental Setup

2.1 YBCO Dysprosium Flux Pump

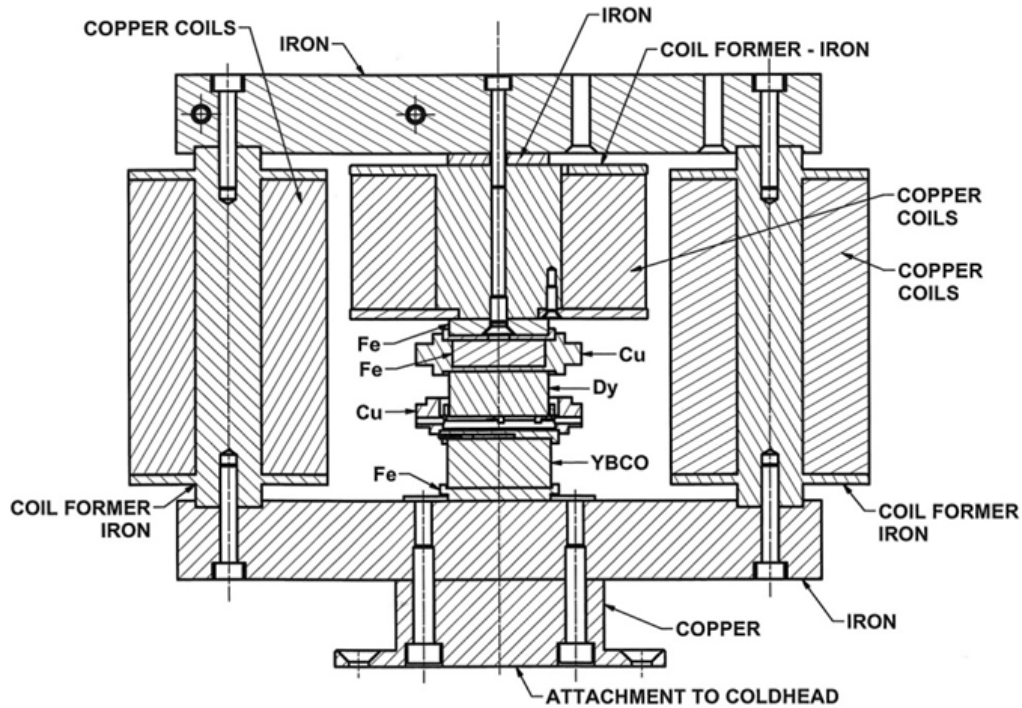


Figure 2: The dysprosium YBCO flux pump

The YBCO was in the form of a disc or puck 30 mm in diameter and 15 mm thick and was arranged below a similar puck of dysprosium 30 mm in diameter and 14 mm thick. These were connected in an iron magnetic circuit with three copper coils as shown in Figure 2 above. This magnetic circuit should create a low reluctance path that would increase the flux through the YBCO. The cold head was attached to the iron circuit and turned on and off to send heat pulses through the dysprosium.

2.2 The Magnetic and Temperature Sensors

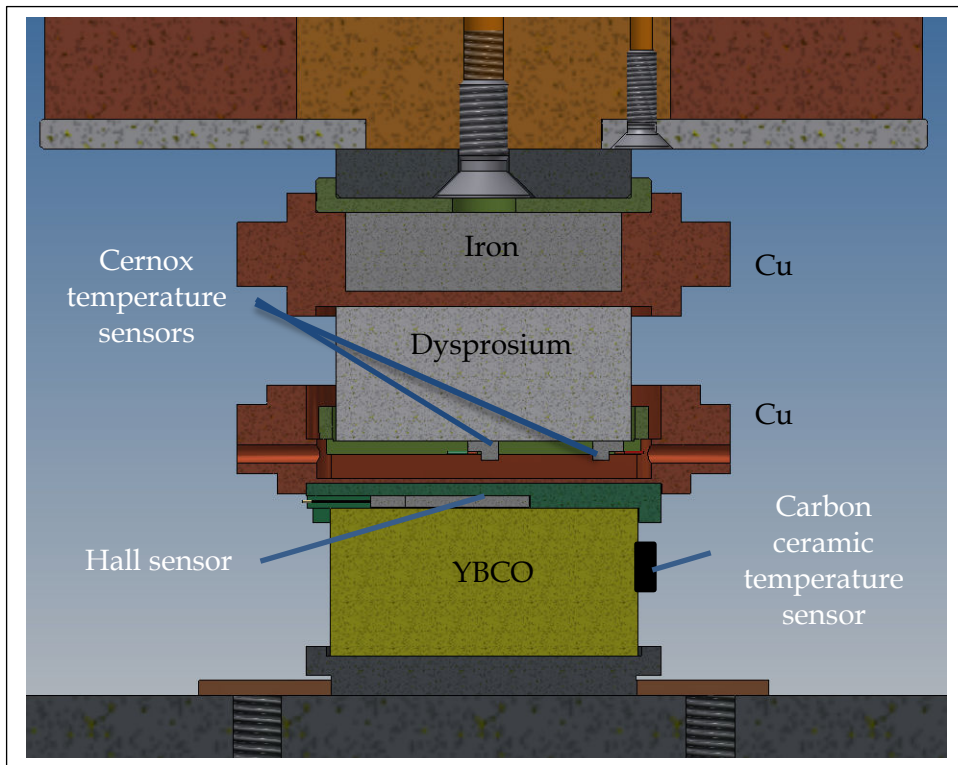


Figure 3 : The locations of the magnetic and temperature sensors

Cernox temperature sensors supplied by Lakeshore were positioned at the centre and the outside circumference of the dysprosium and a carbon ceramic sensor supplied by TMi Cryogenic Instrumentation Division was positioned on the outside circumference of the YBCO. Also a Hall sensor with an advertised active area of approximately 1.016 mm diameter supplied by Lakeshore was positioned in the centre of the YBCO as shown in Figure 3.

3. Experimental Results

3.1 Accumulation of Magnetic Flux in the YBCO

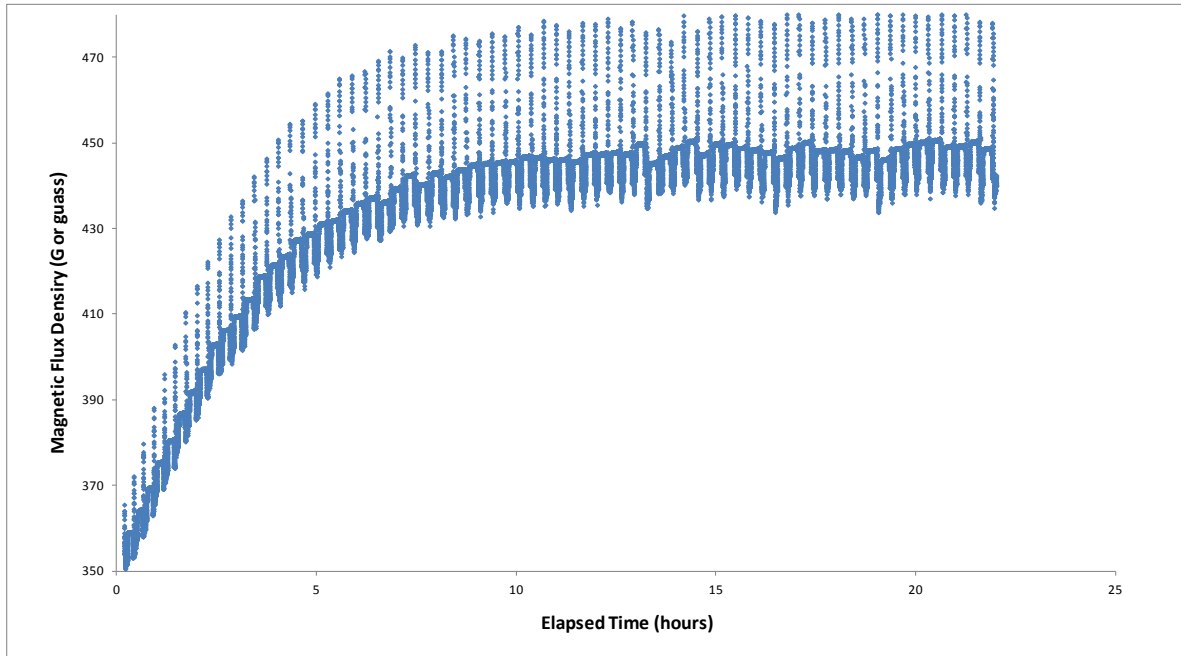


Figure 4: The above graph shows the accumulation of magnetic flux in the YBCO with an initial field through the YBCO of 350 G

Pulses of heat were transmitted through the dysprosium by turning the coldhead off and on and these heat pulses caused the dysprosium, or parts of the dysprosium, to move through the ferromagnetic/antiferromagnetic transition creating a travelling magnetic wave across the surface of the YBCO, sweeping magnetic field lines into the YBCO. Figure 4 above shows the accumulation of magnetic flux during this pulsing of the dysprosium. Starting at 350 G the field at the centre of the YBCO puck has increased to almost 430 G over a period of 22 hours. Most of the increase occurred during first 5 to 10 hours then there seemed to be a levelling off.

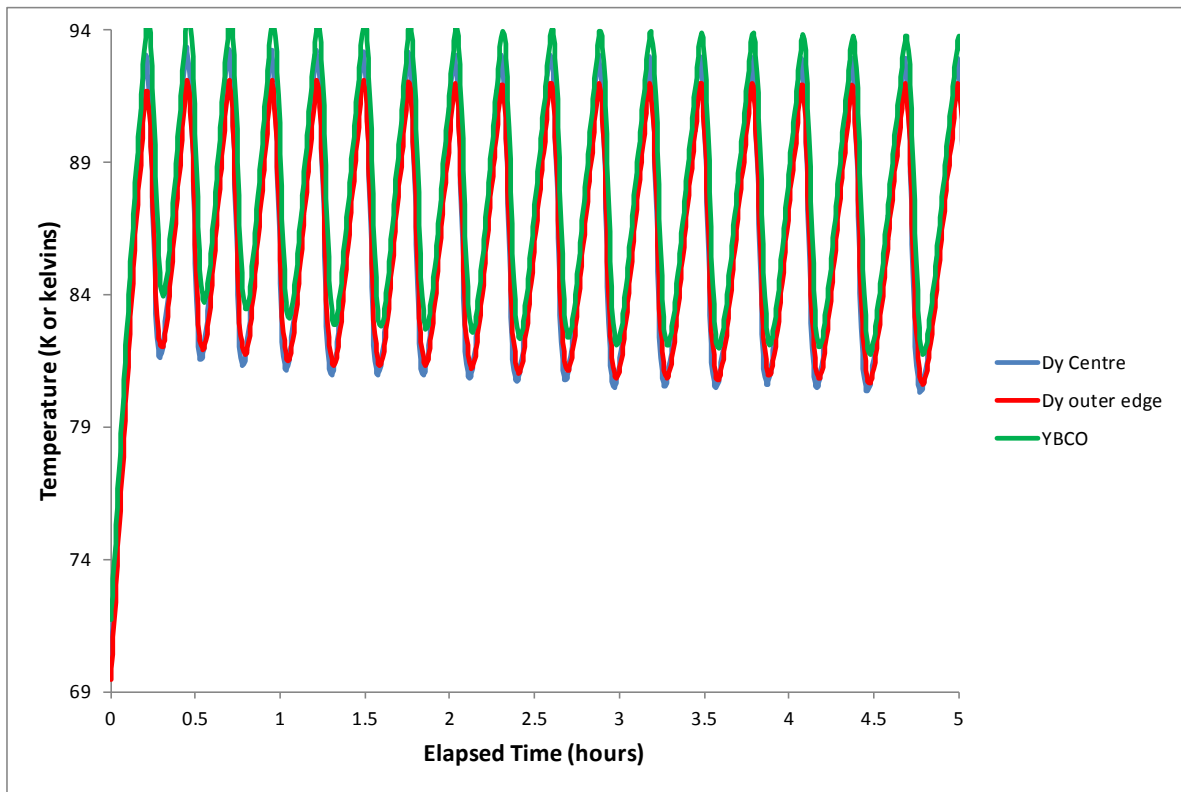


Figure 5: The temperatures of the, centre of the surface of the dysprosium, outer edge of the dysprosium and the YBCO

Figure 5 above shows how the dysprosium and YBCO temperatures varied as the cold head was turned off and on. The temperature sensors were located at the centre and the outer perimeter on the surface of the dysprosium closest to the cold head, and on the side of the YBCO (see Figure 3). The YBCO temperatures oscillated with the cycling of the cold head with the crests of the waves reaching the critical temperature of the YBCO (90 to 94 K) [4].

4. Conclusion

We were able to demonstrate some accumulation of vortices in the YBCO but the temperature of the YBCO varied with the pulses, the peak of the temperature pulses rising to temperatures above the critical temperature of the YBCO. The temperature sensor was located on the side of the YBCO puck so the temperatures inside the puck are unknown. These high (relatively speaking) YBCO temperatures enabled the amplitudes of the magnetic pulses to exceed the lower critical magnetic field of the YBCO which becomes smaller and smaller as the critical temperature is approached.

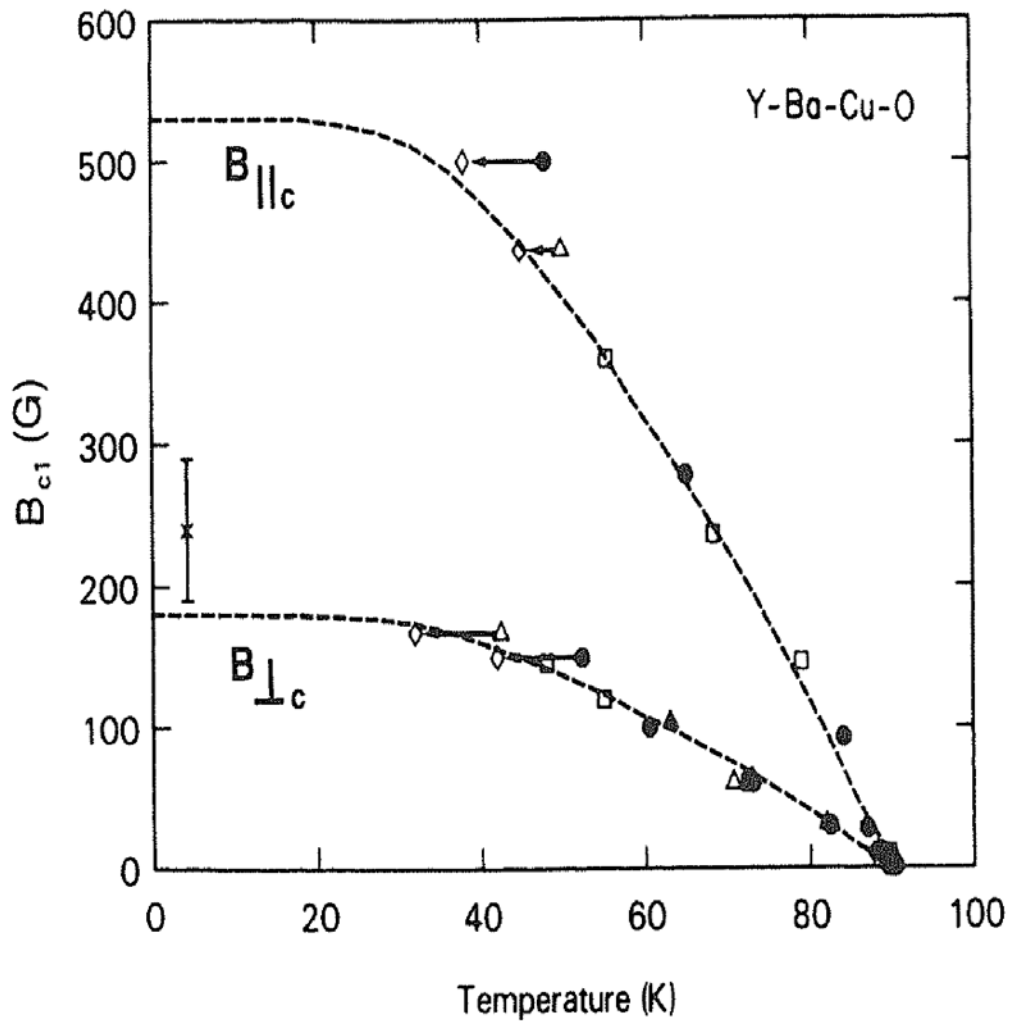


Figure 6: The lower critical field of YBCO as a function of temperature for B fields parallel or perpendicular to the c plane of a YBCO crystal [5]

Figure 6 above shows that the lower critical fields of YBCO get smaller as the temperature approaches the critical temperature. At 0 K the magnetic pulses would need to have amplitudes of almost 200 G but near the critical temperature they can be much smaller.

If we can maintain the YBCO at a constant temperature well below its critical temperature the results might improve.

5. References

- [1] T. Coombs, Z. Hong and X. Zhu, "A thermally actuated superconducting flux pump," *PHYSICA C*, vol. 468, pp. 153-159, 2008.
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- [4] B. R. Lehnendorff, *High-Tc Superconductors for Magnets and Energy Technology*, Berlin Heidelberg New York: Springer, 2001.
- [5] C. P. Poole Jr, R. Prozorov, H. A. Farach and R. J. Creswick, *Superconductivity*, London Amsterdam Oxford Burlington San Diego: Elsevier, 2007.

Appendix A: Initial Field 350 G

A.1 Magnetic Flux Density versus Time

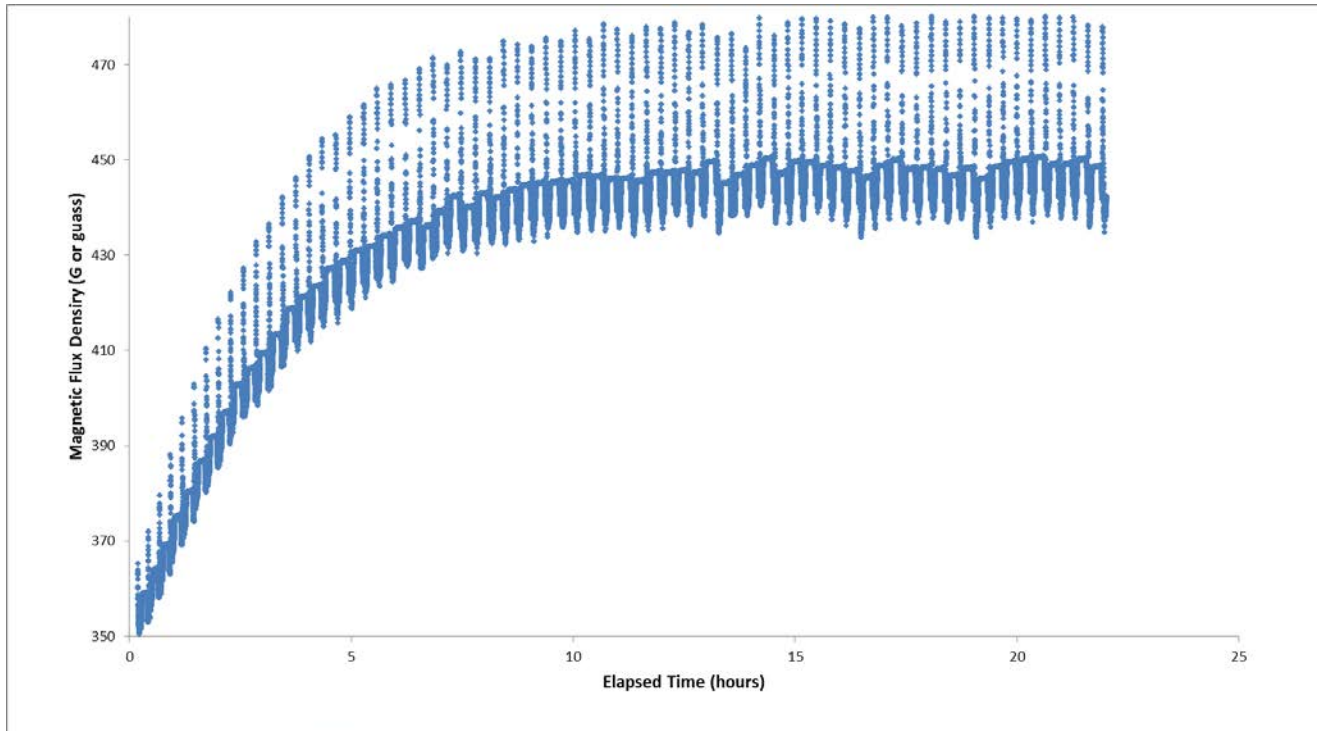


Figure 7: The above graph shows the accumulation of magnetic flux in the YBCO starting at 350G

Figure 7 show that magnetic flux has accumulated in the YBCO with the heating and cooling of the dysprosium by turning the cold head off and on. Starting at approximately 350 G (or gauss) the field at the centre of the YBCO puck has increased to almost 430 G (or gauss) over a period of 22 hours. The vortices are seen to accumulate in the YBCO initially and then there is no further increase.

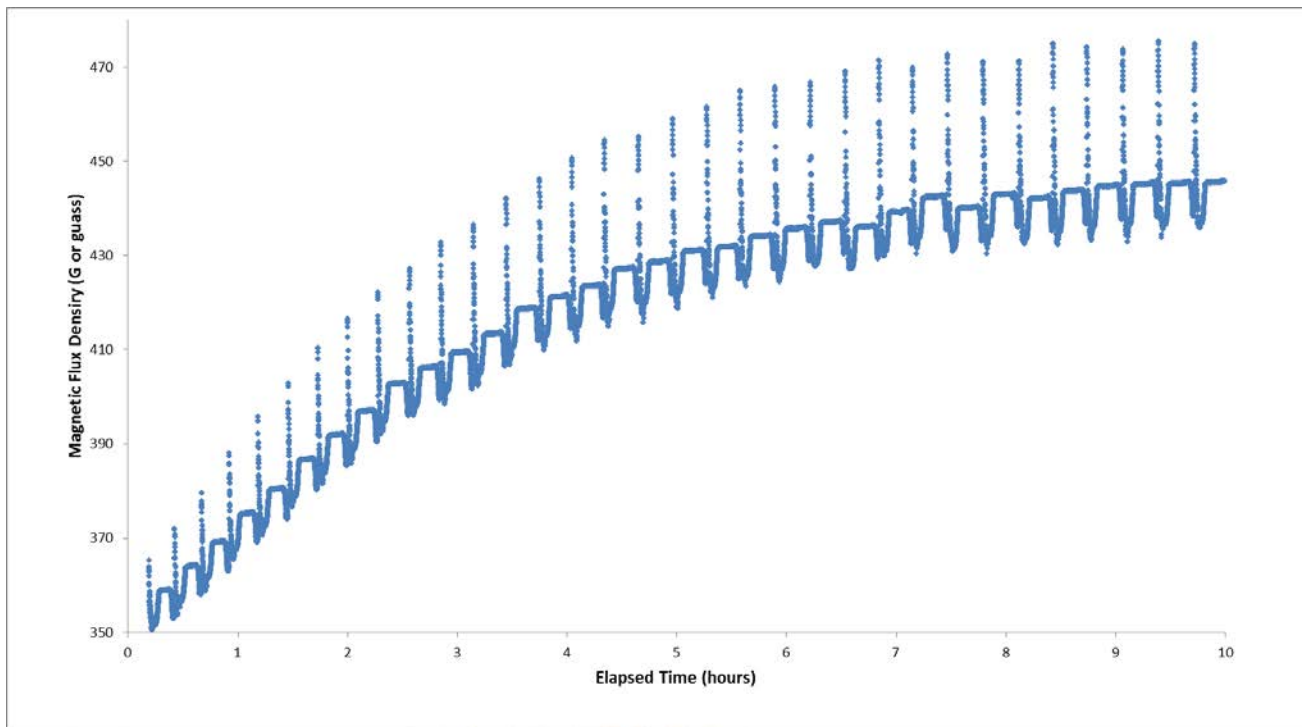


Figure 8: The same data from Figure 7 with the horizontal scale reduced to a smaller time period

If the time scale of Figure 7 is reduced to 10 hours the shape of the magnetic pulses can be clearly seen. These pulses are recorded by the hall sensor attached the lower surface of the YBCO.

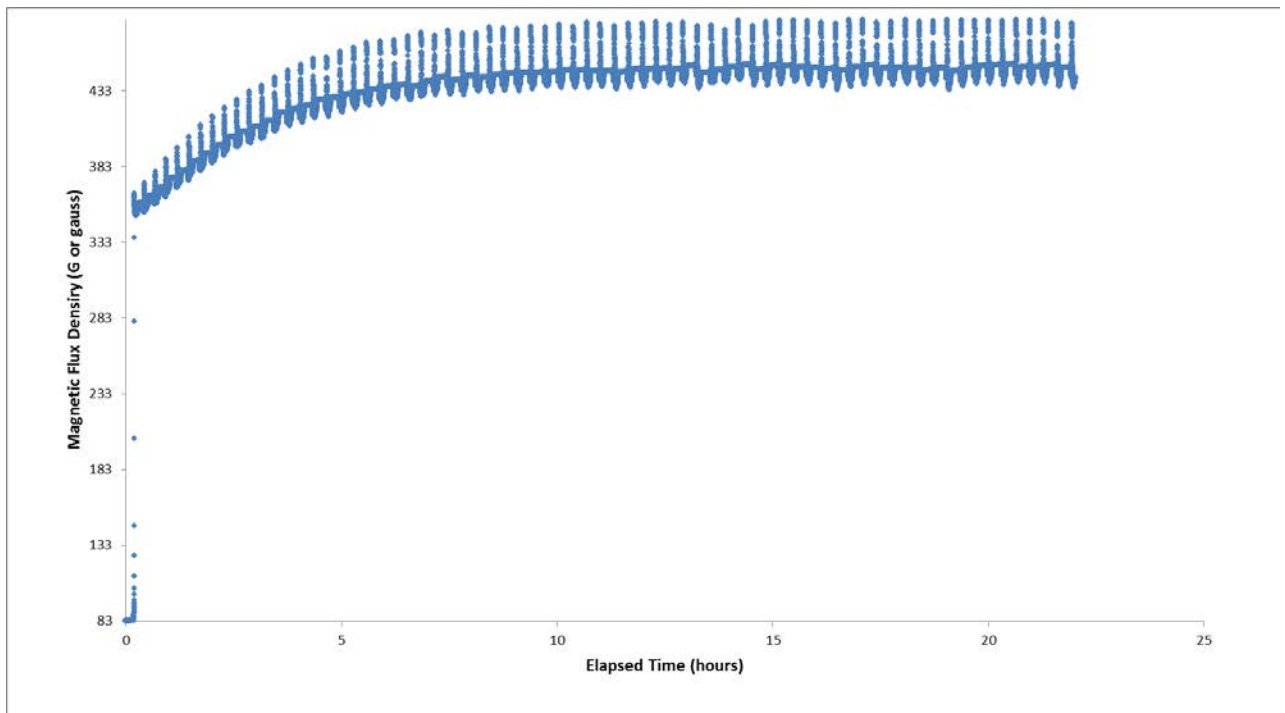


Figure 9: The magnetic flux density jumps from 80 gauss to approximately 350G before the pulses are recorded

Figure 9 shows a jump in the field before the pulses begin. This might be part of the ferromagnetic/antiferromagnetic edge in the dysprosium. This means that the pulses are a result of only a part of the edge. A large fraction of the dysprosium is not moving through the ferromagnetic/antiferromagnetic transition.

If the current through the coils is increased then the initial field through the YBCO is greater but the same trend is seen.

A.2 Dysprosium, YBCO and Coldhead Temperatures

Cernox temperatures sensors (supplied by Lake Shore Cryotronics Inc.) were used to record the temperatures of the centre and outer edge of the dysprosium, the edge of the YBCO puck and the coldhead. The location of the sensors is shown in Figure 3 (above).

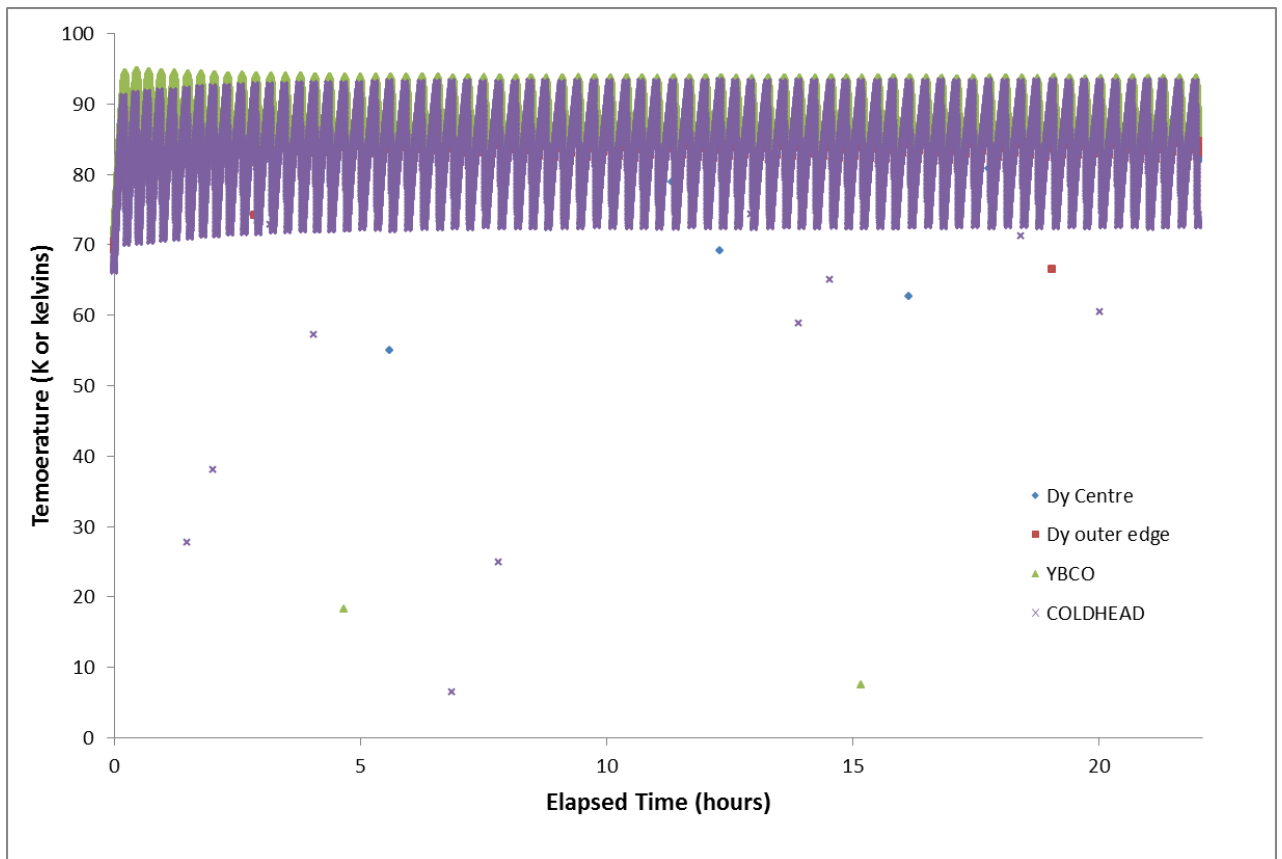


Figure 10: The temperatures of the outside and centre of the dysprosium, the outside edge of the YBCO puck and the cold head

As can be seen in Figure 10 all the temperatures oscillated with the coldhead temperature. In Figure 10 only two curves can be clearly discerned. Figure 11 (below) shows the same graph with the outliers reduced, the points changed to lines and only one in every ten data points are used.

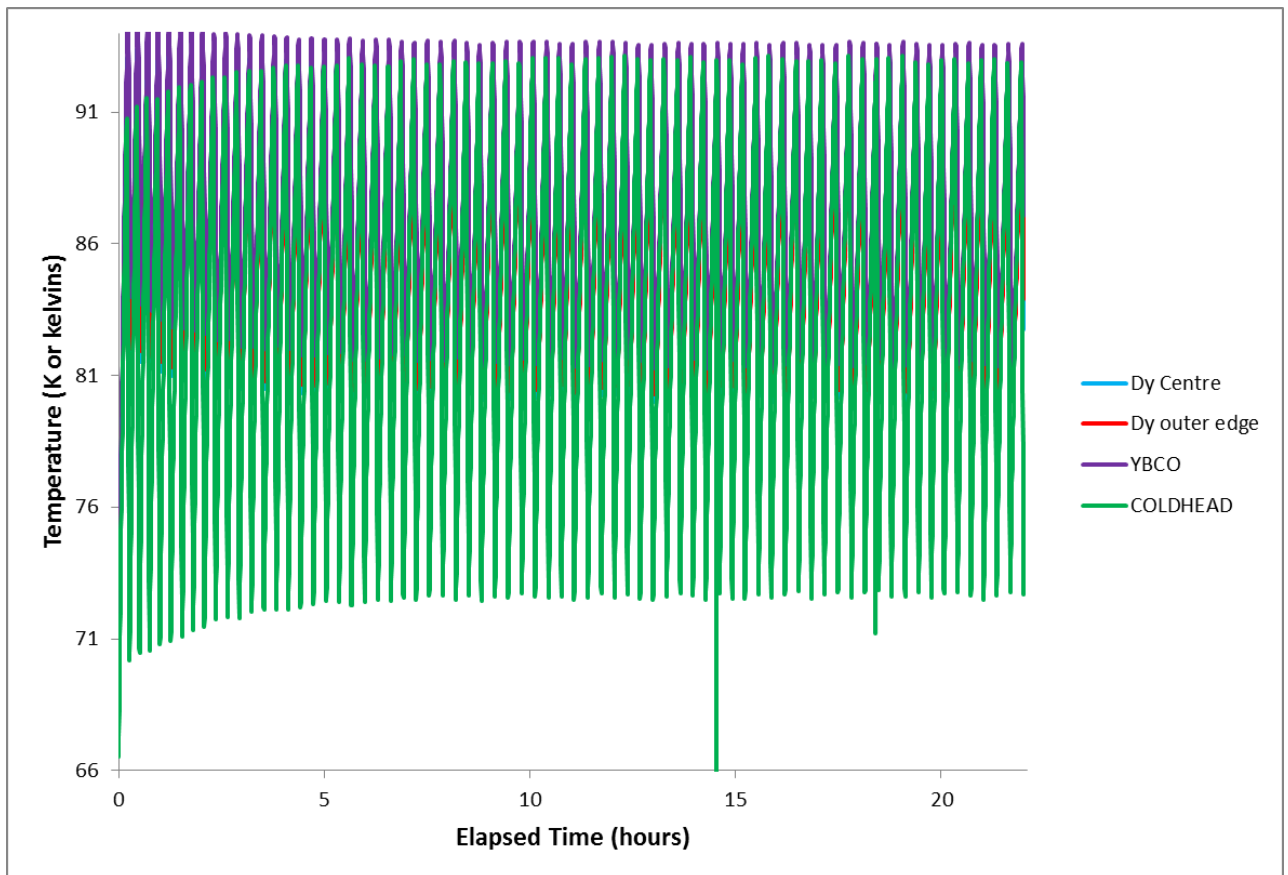


Figure 11: The temperatures of the dysprosium, YBCO and the cold head.

Figure 11 uses every tenth data point used in Figure 10 but it is still difficult to discern the curves for the centre and outside of the dysprosium because the coldhead data completely covers them. The crests of the YBCO curve rise above the coldhead curve but the extent of the variation in YBCO temperatures cannot be seen, Figure 12 (below) shows the curves after the coldhead data is removed.

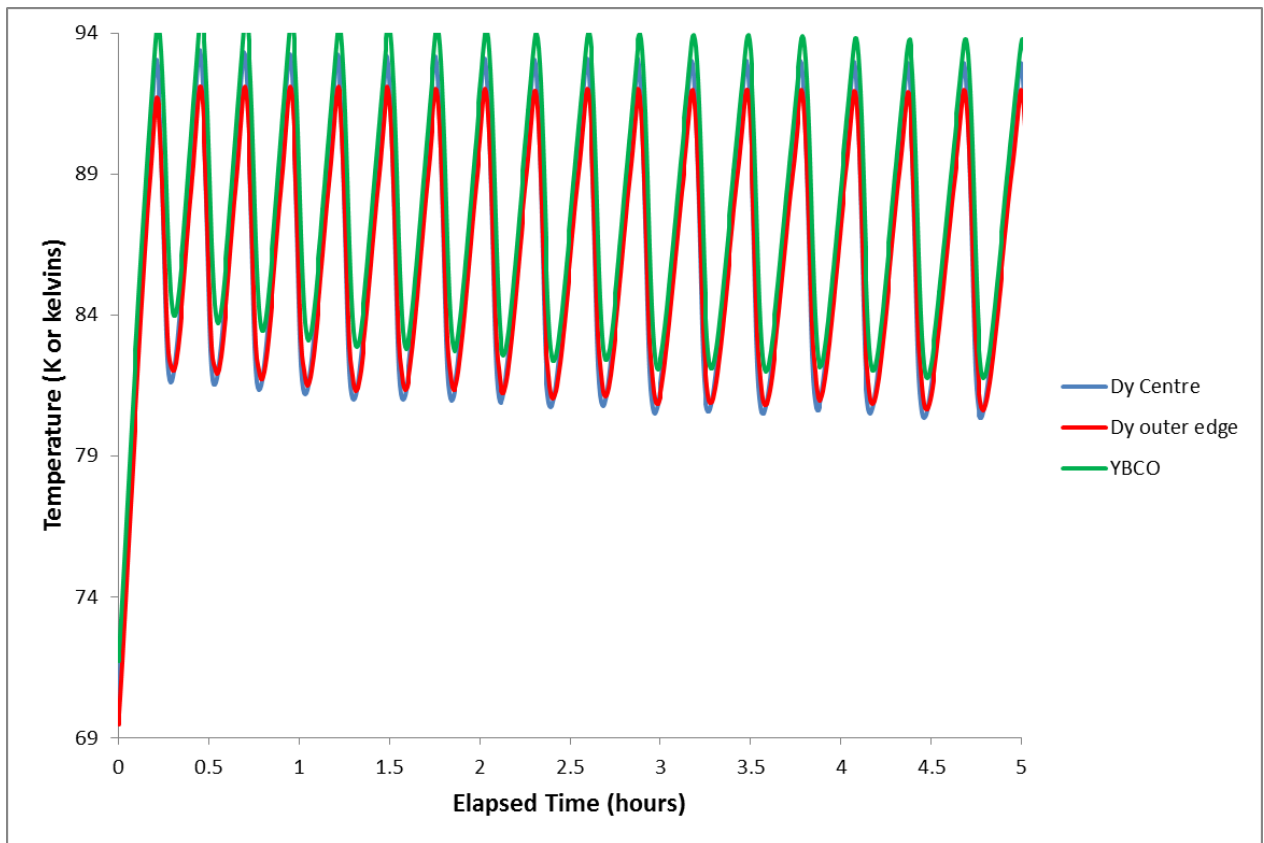


Figure 12: Temperatures of the centre and outer edge of the dysprosium and the YBCO. The time scale has been reduced to 5 hours so that curves can be clearly seen.

As can be seen in Figure 12 the temperature of the YBCO varied with the dysprosium temperatures right up to the critical temperature of the YBCO which is approximately 90 K.

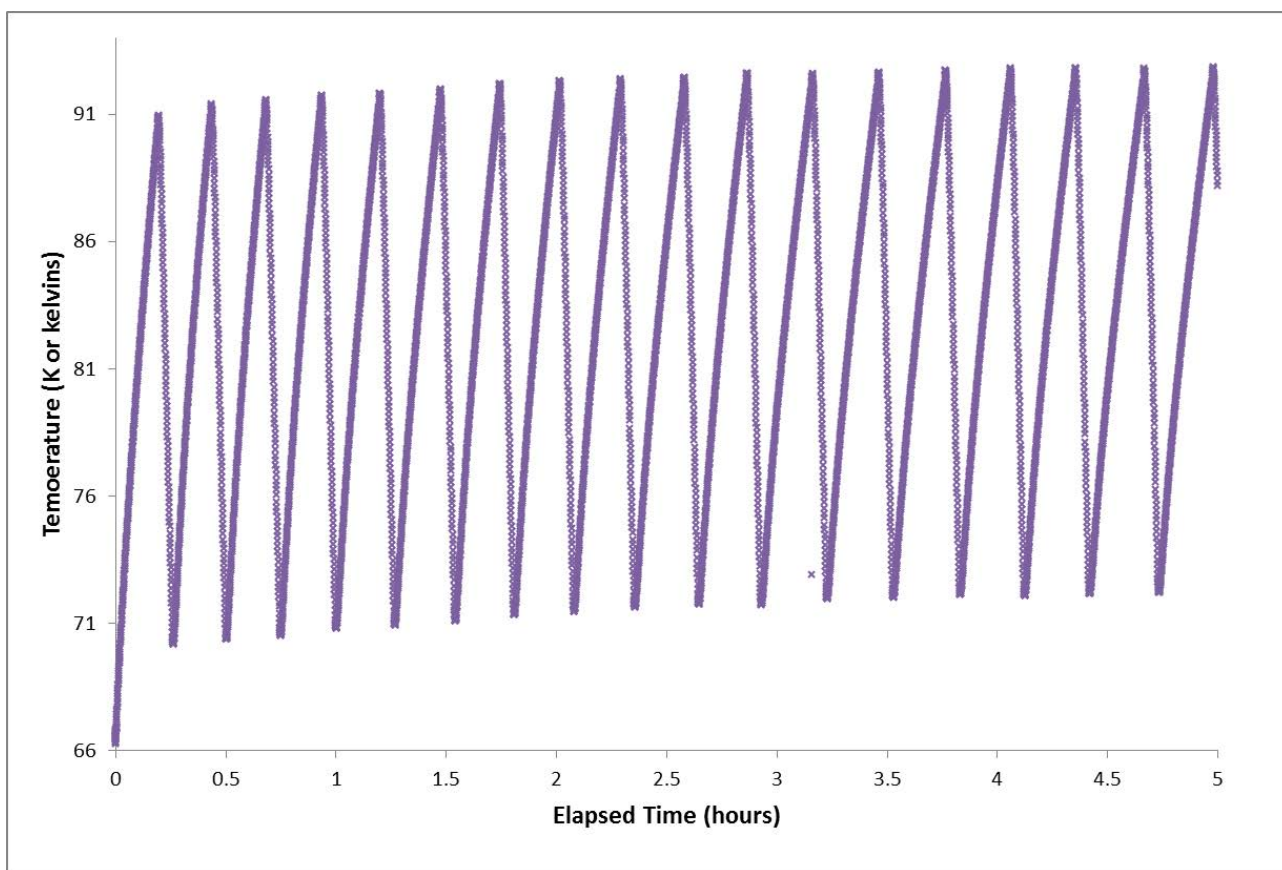


Figure 13: The temperatures of the coldhead

The pulses were created by turning the coldhead on and off. Figure 13 above shows the temperature of the coldhead over a 5 hour time period.

A.3 Coil Temperatures at 350 G

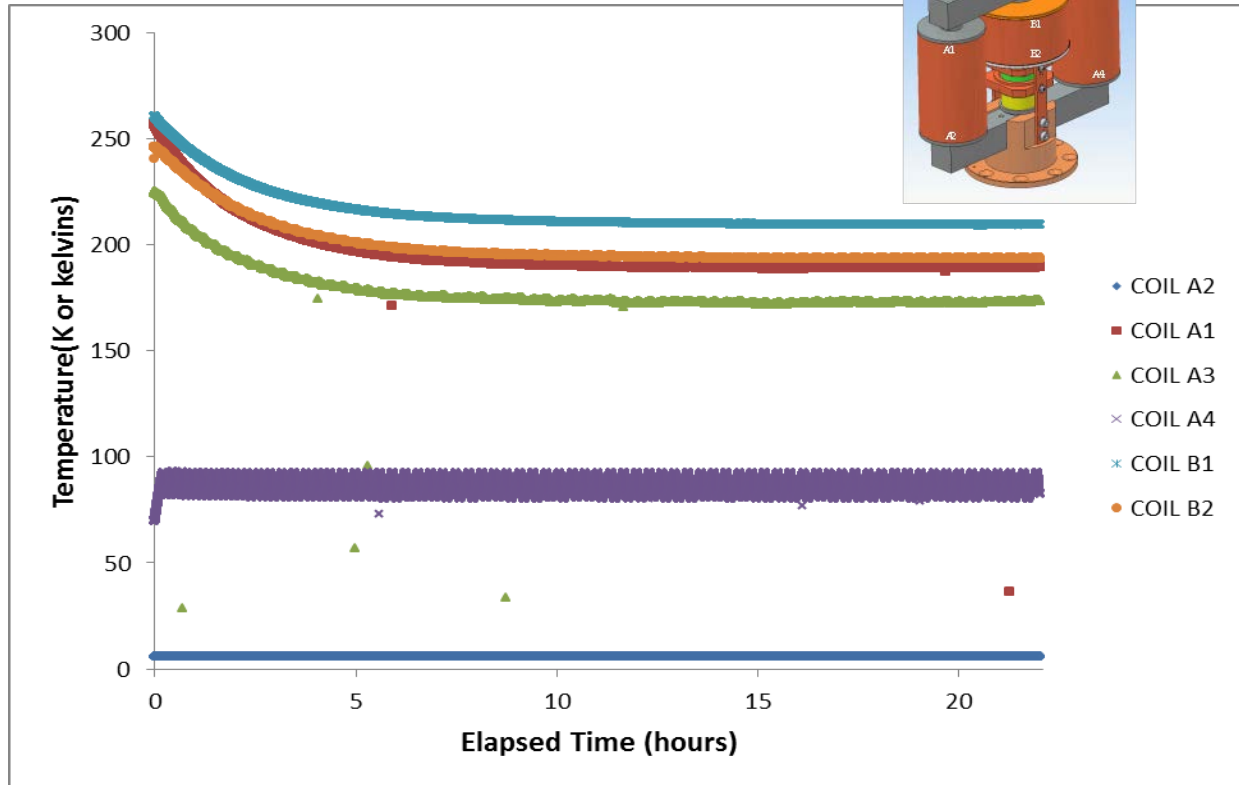


Figure 14 : Temperatures recorded at the top and bottom of the coils

Sensors COIL A2, COIL A4, COIL B2 are on the end of the coils closest to the cold head (see Appendix E Figure 36) so these should all be at lower temperatures. COIL A2 (see Figure 14 above) shows a constant temperature of 5.658 K (or kelvins) and is therefore not working. COIL A4 shows pulsing that is probably caused by the pulsing of the dysprosium but is approximately constant at about 81 K to 92 K. The other sensors show the ends of the coils gradually cooling over a period of 5 hours.

Appendix B: Initial Field 545 G

B.1 Magnetic Flux Density starting at 545 G

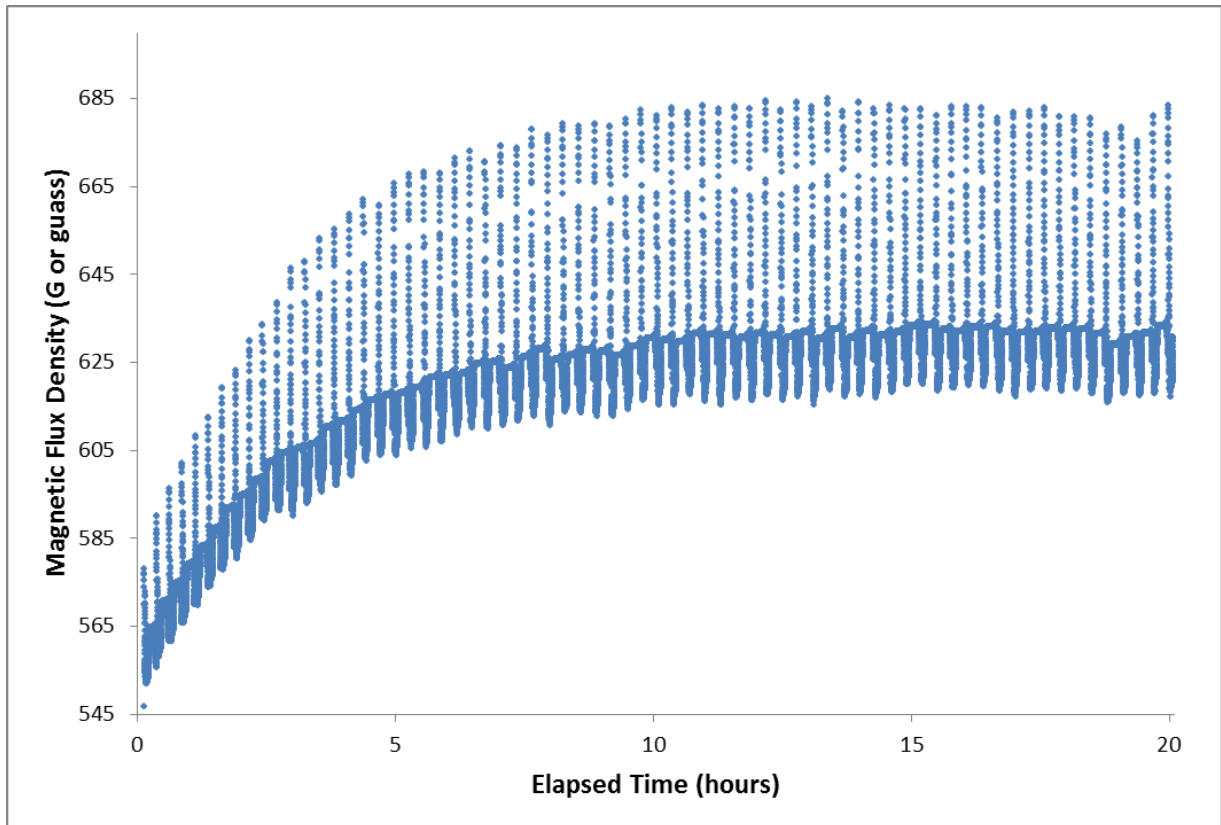


Figure 15: The above graph shows the accumulation of magnetic flux in the YBCO starting at 545 G

Figure 15 shows that if the coils are adjusted to give an initial field through the YBCO so that the starting field is approximately 546 G the same shaped curve results but the increase in magnetization of the puck is smaller.

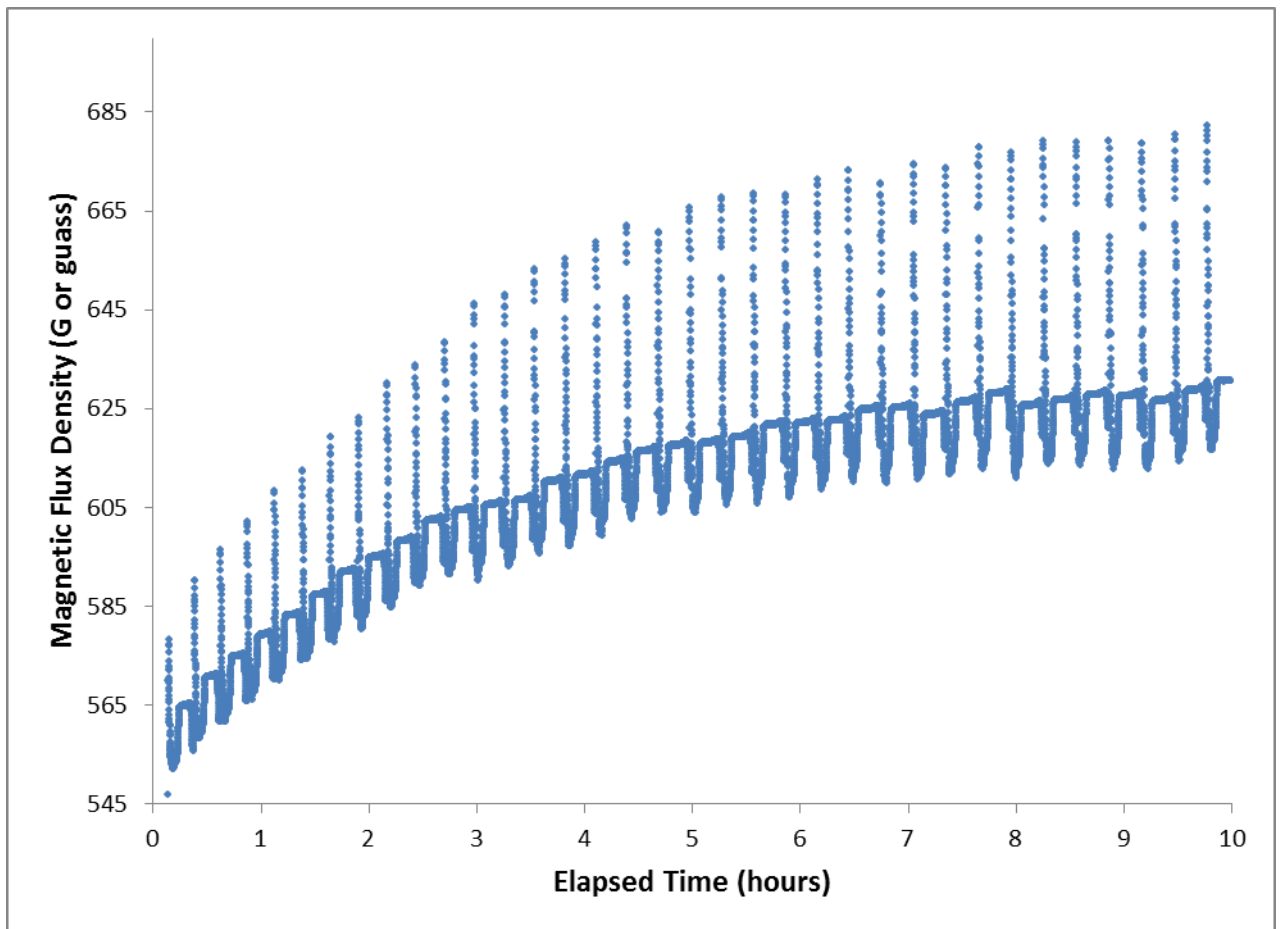


Figure 16 : Magnetic Flux Density versus Elapsed Time over a shorter time interval to show the shape of the pulses

Figure 16 shows a subset of the data over the first 10 hours so the shape of the pulses can be clearly seen.

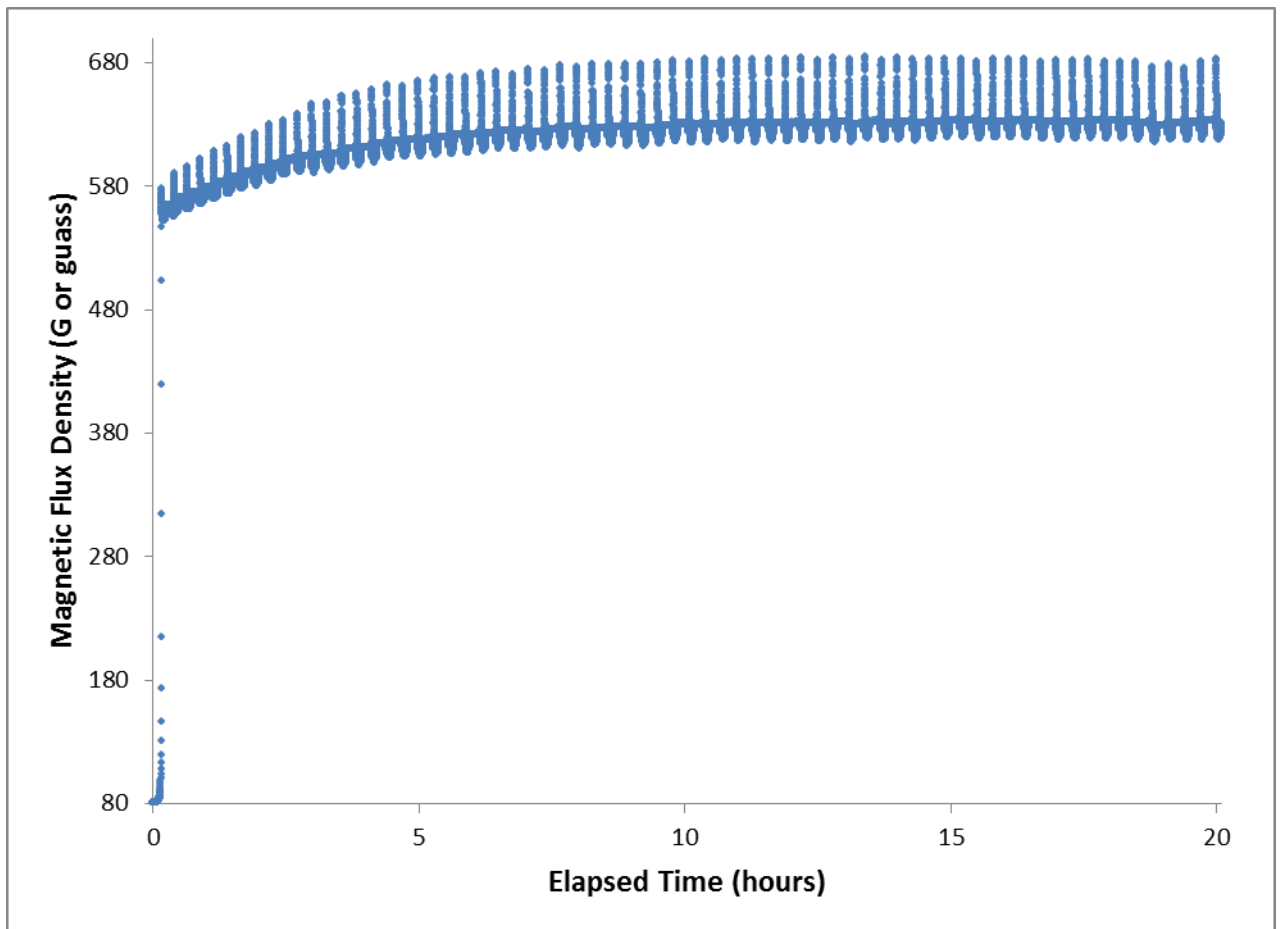


Figure 17: The magnetic curve showing an initial jump in magnetization before the pulsing began

Figure 17 shows that there was an initial jump in magnetization before the pulsing began which might have been due to the ferromagnetic- antiferromagnetic transition. This edge would occur as the dysprosium moved from being ferromagnetic to being anti-ferromagnetic. The pulses are much smaller than this edge, which suggests that only part of the transition was contributing to the pulsing. The temperature pulses were not sending all the dysprosium through the transition.

B.2 Dysprosium, YBCO and Coldhead Temperatures

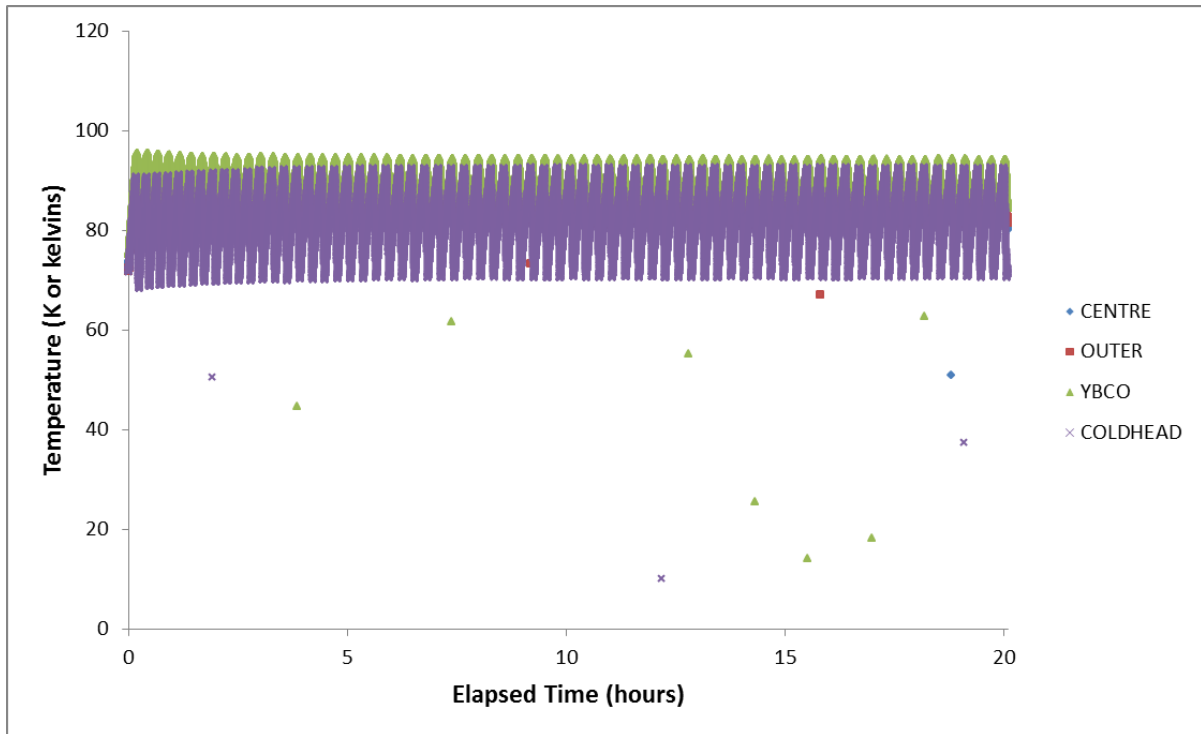


Figure 18: The temperatures of the outside and centre of the dysprosium, the outside edge of the YBCO puck and the cold head for a run starting at 545 G

The curves are all superimposed on each other making it impossible to see the inner and outer dysprosium temperatures. The coldhead and YBCO temperatures are oscillating in unison.

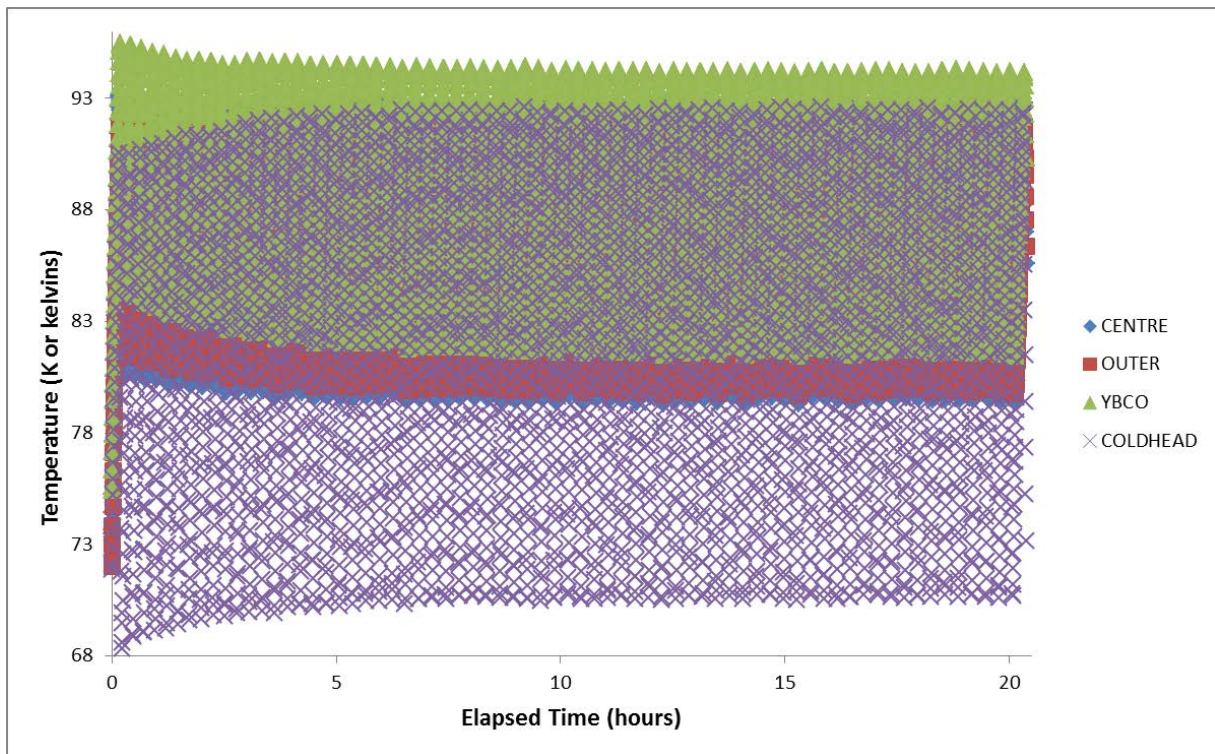


Figure 19: The temperatures of the outside and centre of the dysprosium, the outside edge of the YBCO puck and the coldhead. Only one in ten data points is shown and the temperature scale in the region of interest has been expanded.

The above graph (Figure 19) gives a clearer (but still inadequate) picture of the temperatures of the centre point on the surface and outer perimeter of the dysprosium, the edge of the YBCO and the coldhead. In the following figures various curves are removed to give a clear picture of the temperatures.

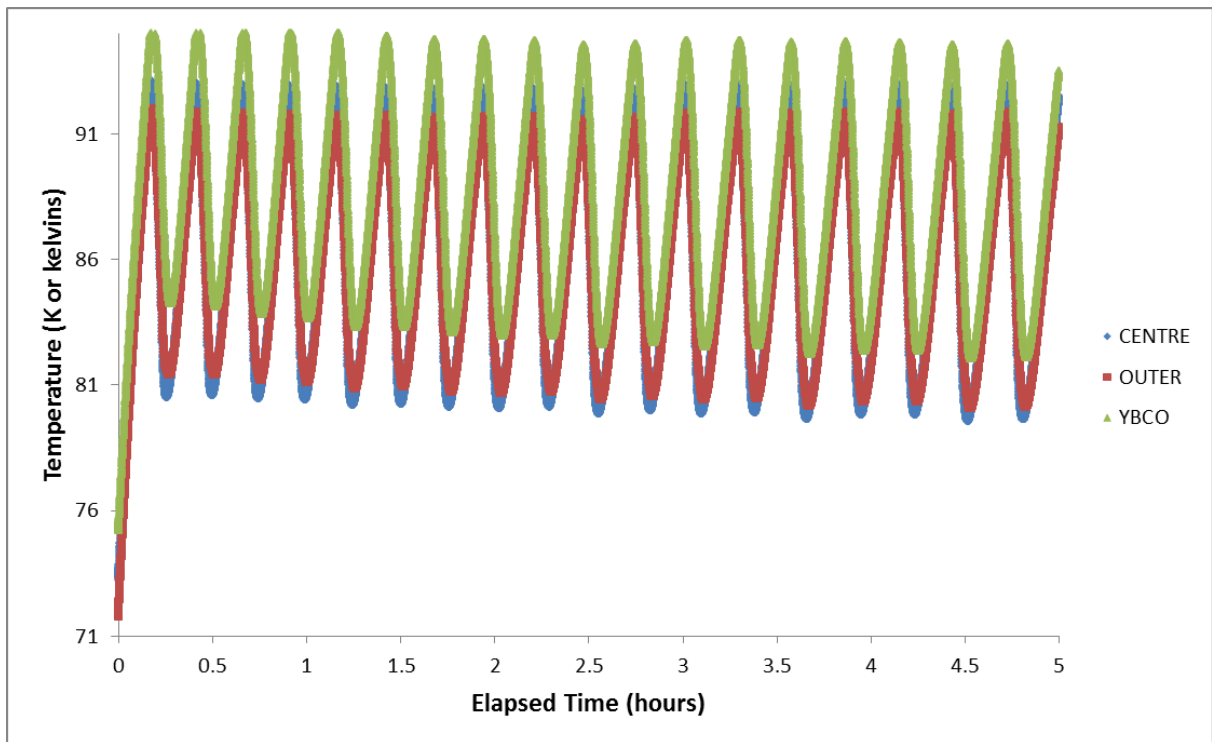


Figure 20 : Temperatures of the centre and outer edge of the dysprosium and the YBCO

Figure 20 (above) shows the temperatures for the dysprosium and YBCO with the coldhead data removed. Each crest of the YBCO curve (green in Figure 18) exceeds the YBCO critical temperature of about 94 K. The temperature sensor was located on the side of the puck. The temperatures of the dysprosium show the temperature at the centre of the surface of the disk rising to lower and higher temperatures than those recorded on the outer perimeter of the same surface. The change from ferromagnetic to antiferromagnetic occurs at approximately 85 K.

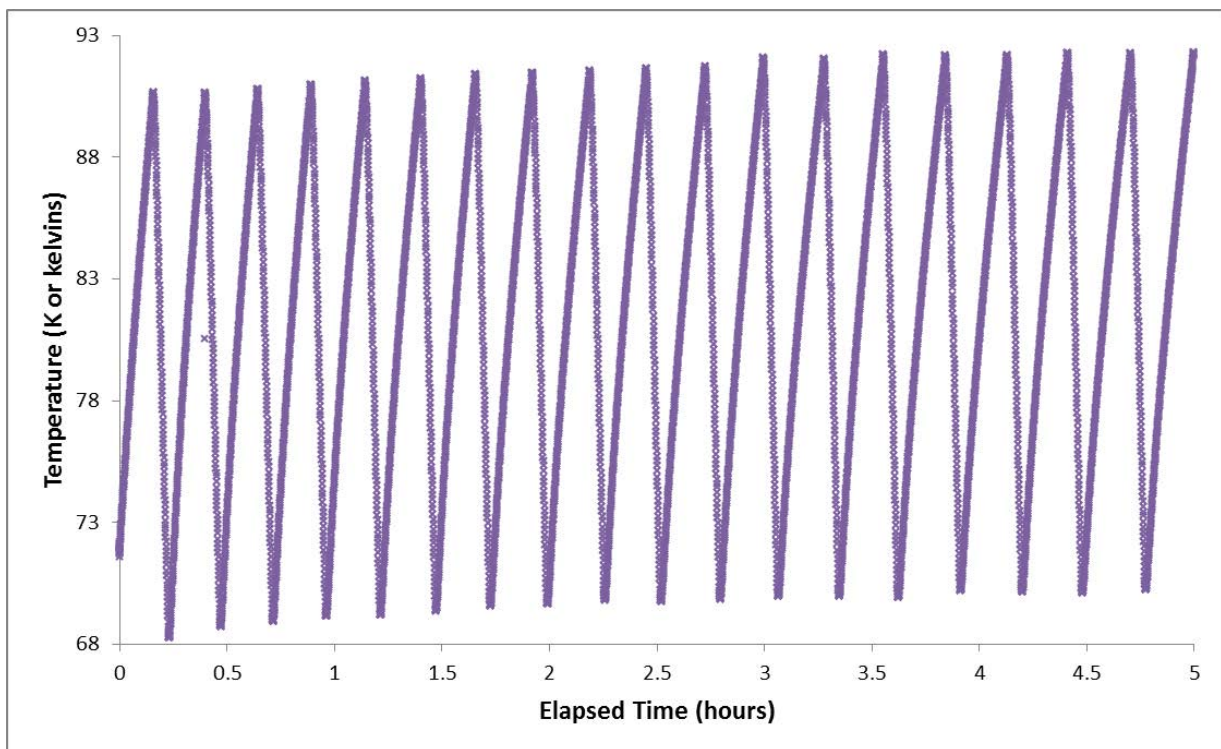


Figure 21: The temperatures of the coldhead

Figure 21 (above) shows the temperature variation of the coldhead head which was achieved by turning the coldhead on and off. A solenoid was used to physically press the on/off button on the compressor (the electric finger).

B.3 Coil Temperatures at 546 G

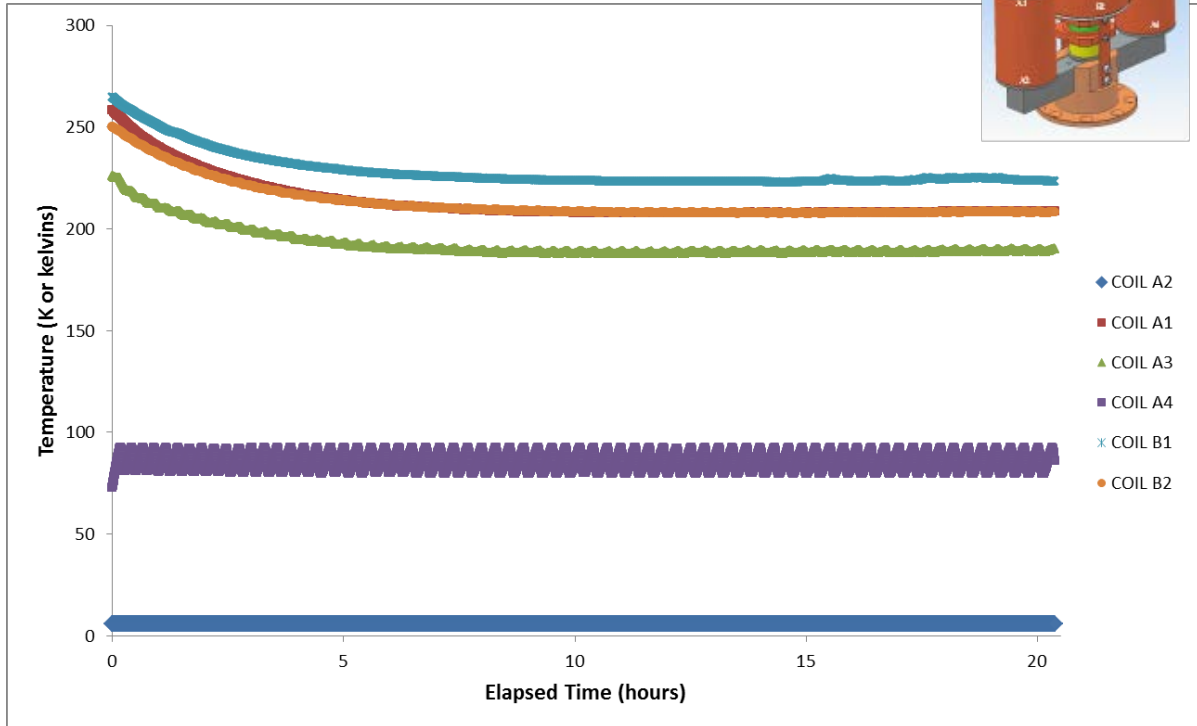


Figure 22: Coil Temperatures at 546 G

As seen in Figures 22 and 14 these coil temperatures seem pretty well identical to those at 350 G so the increased currents through the coils are not having much effect on the coil temperatures.

Appendix C: Initial Field 606 G

C.1 Magnetic Flux Density starting at 606 G

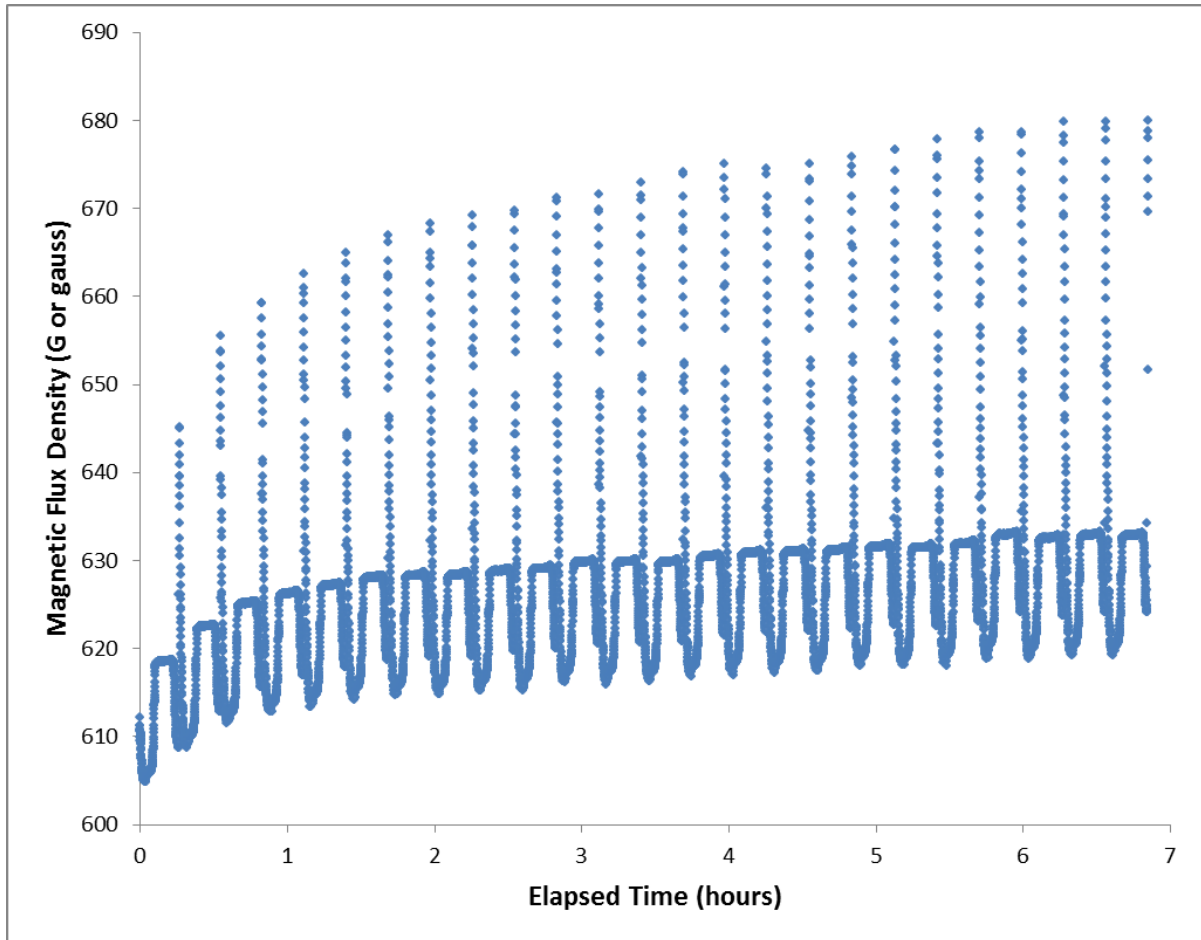


Figure 23: Results obtained with a larger current flowing through the coils providing a starting field of 606 G.

The results shown in Figure 23 were collected over 7 hours and show the same pulse shape as the other runs.

C.2 Dysprosium, YBCO and Coldhead Temperatures

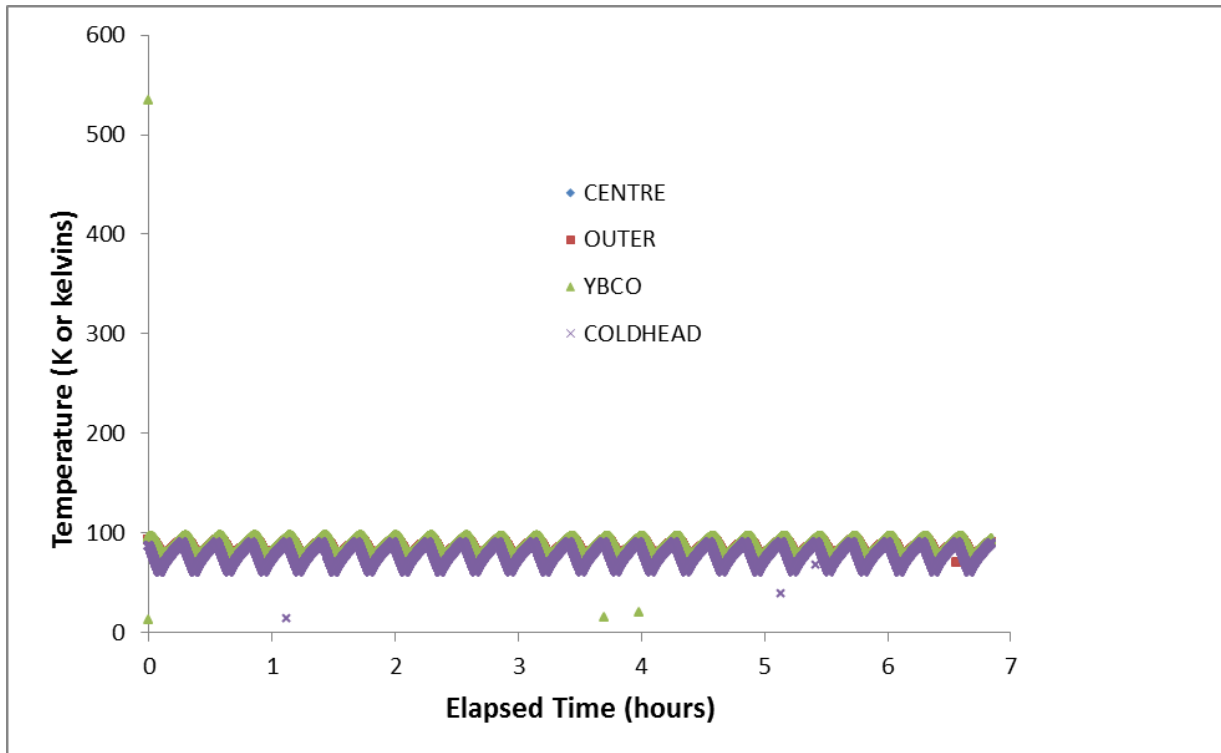


Figure 24: The temperatures of the outside and centre of the dysprosium, the outside edge of the YBCO puck and the cold head for a run starting at 606 G

In Figure 24 (above) a spurious temperature reading of 534.63 K was recorded initially for the YBCO. The curves are all superimposed and only the YBCO and coldhead curves can be seen. In the next figure the coldhead data is removed and the temperature scale expanded so that the temperatures of interest are clearly seen.

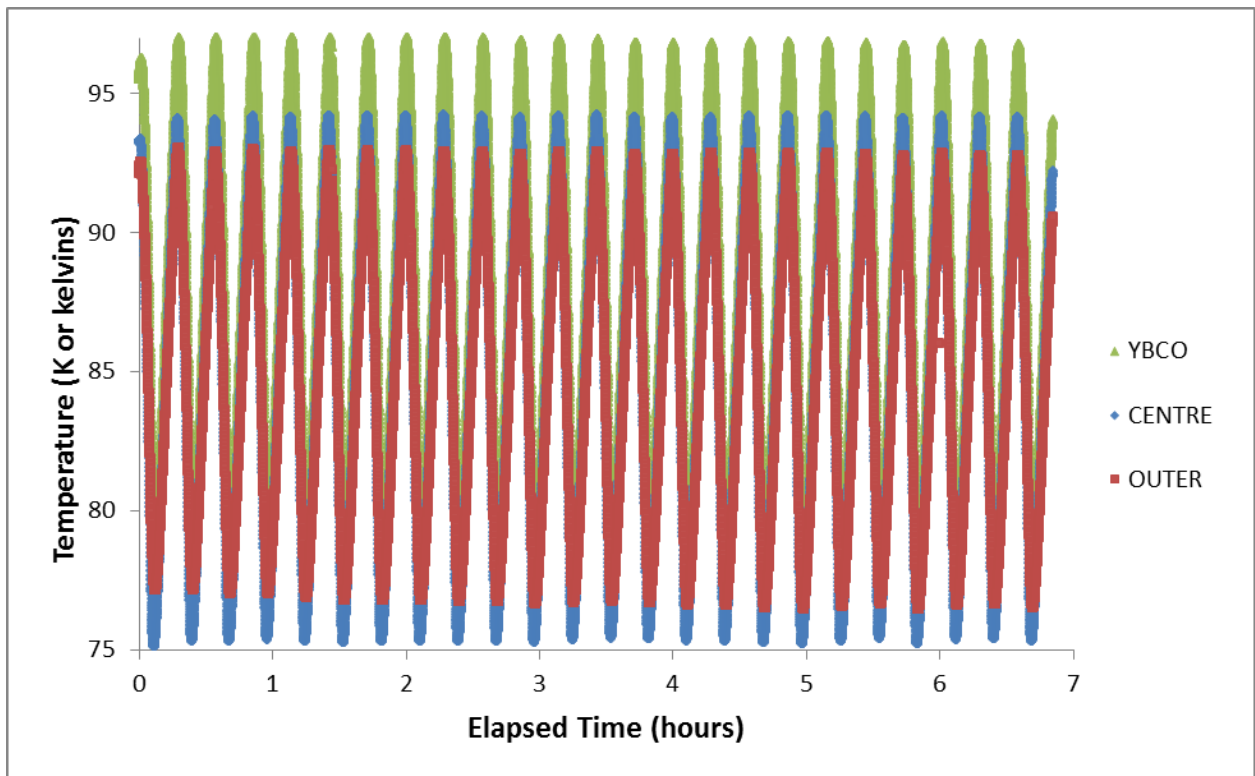


Figure 25: Temperatures of the centre and outer edge of the dysprosium and the YBCO

In Figure 25 all the temperature waves are shown superimposed without the coldhead data. Once again the sensor located on the central point of the surface of the dysprosium recorded higher and lower crests and troughs than the sensor located on the outside of the flat surface and the YBCO sensor recorded crests that exceeded the critical temperature of the YBCO of 94 K.

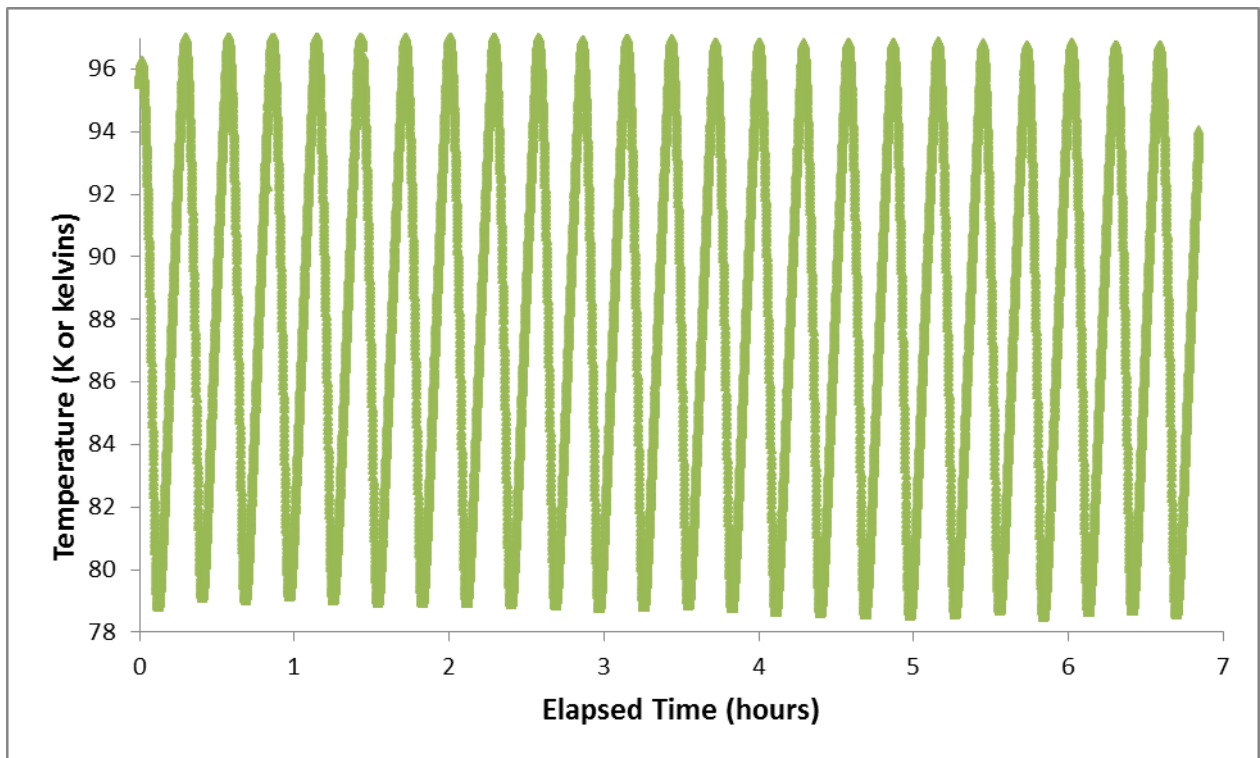


Figure 26: The temperatures of the YBCO

Figure 26 (above) shows the temperatures of the YBCO as recorded by a carbon ceramic sensor in contact with a side of the puck. The temperature crests rise well above the critical temperature of 94 K.

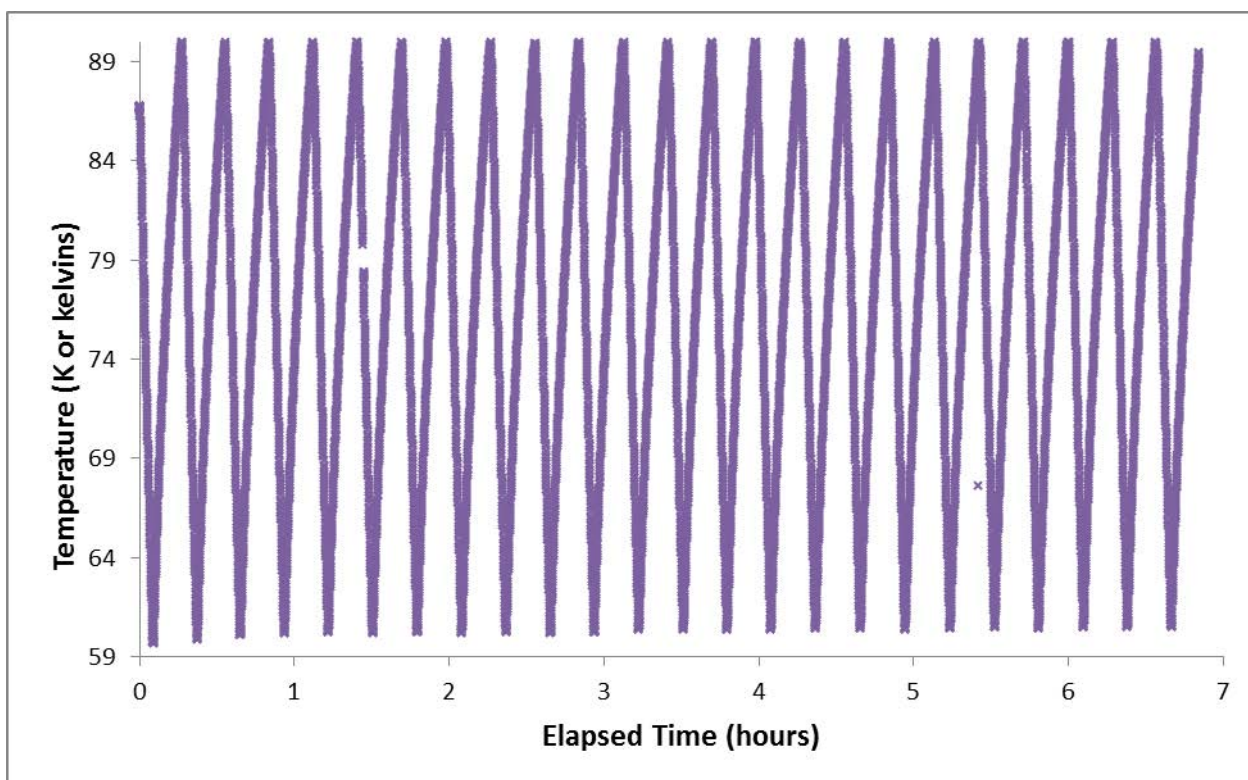


Figure 27: The temperatures of the coldhead

Figure 27 shows the variation of the temperatures of the coldhead as the “electric finger” turns the compressor on and off.

C.3 Coil Temperatures at 606 G

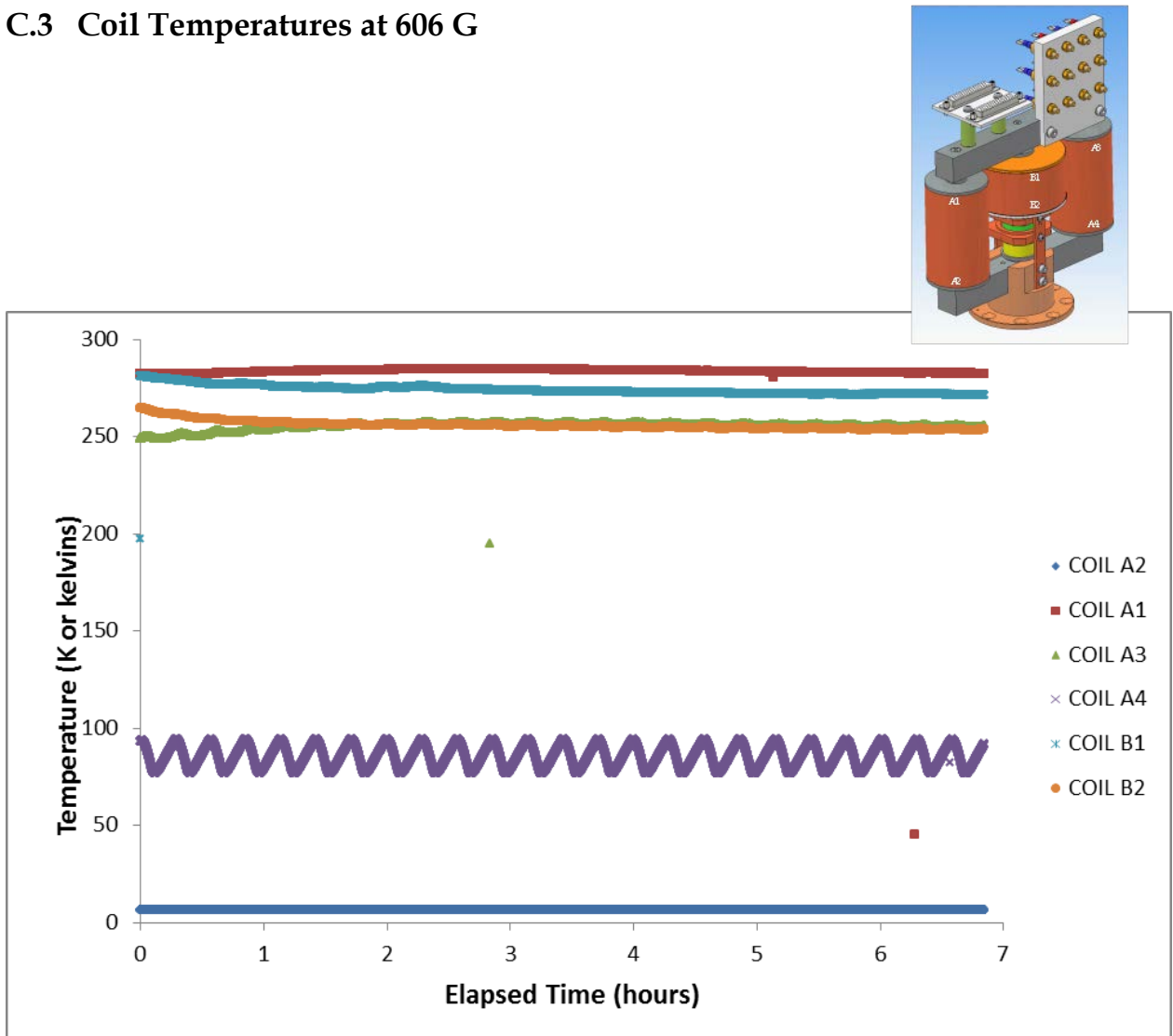


Figure 28: The coil temperatures for 606 G

The temperatures shown in Figure 28 are different because they don't show an initial drop but seem to show the top and bottoms of the coils at constant temperatures.

Appendix D: Initial Field 616 G

D.1 Magnetic Flux Density starting at 616 G

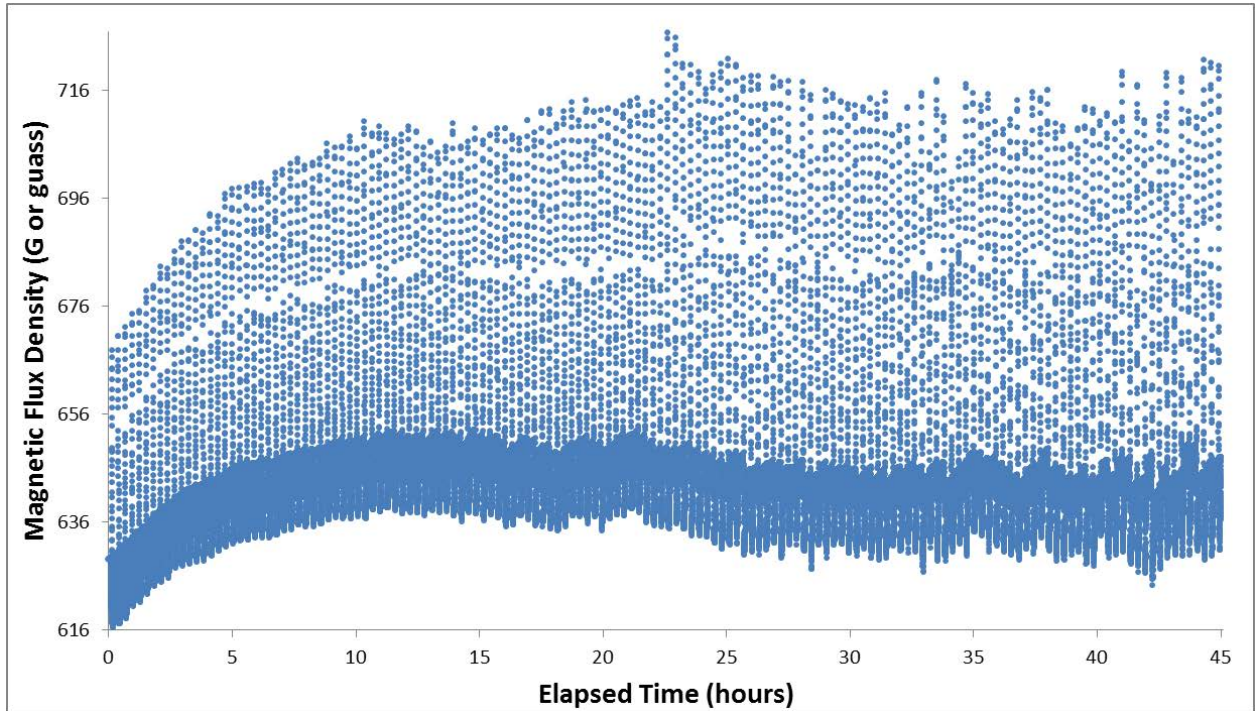


Figure 29: Results obtained with a larger current flowing through the coils providing a starting field of 616 G

With larger currents through the coils the field accumulated in the YBCO seems to be less. This might be due to a change in the reluctance of the magnetic circuit.

The shape of the individual pulses displayed above can be seen in in Figure 30 below where the horizontal scale, "Elapsed Time (hours)" has been reduced from 45 hours down to 10 hours.

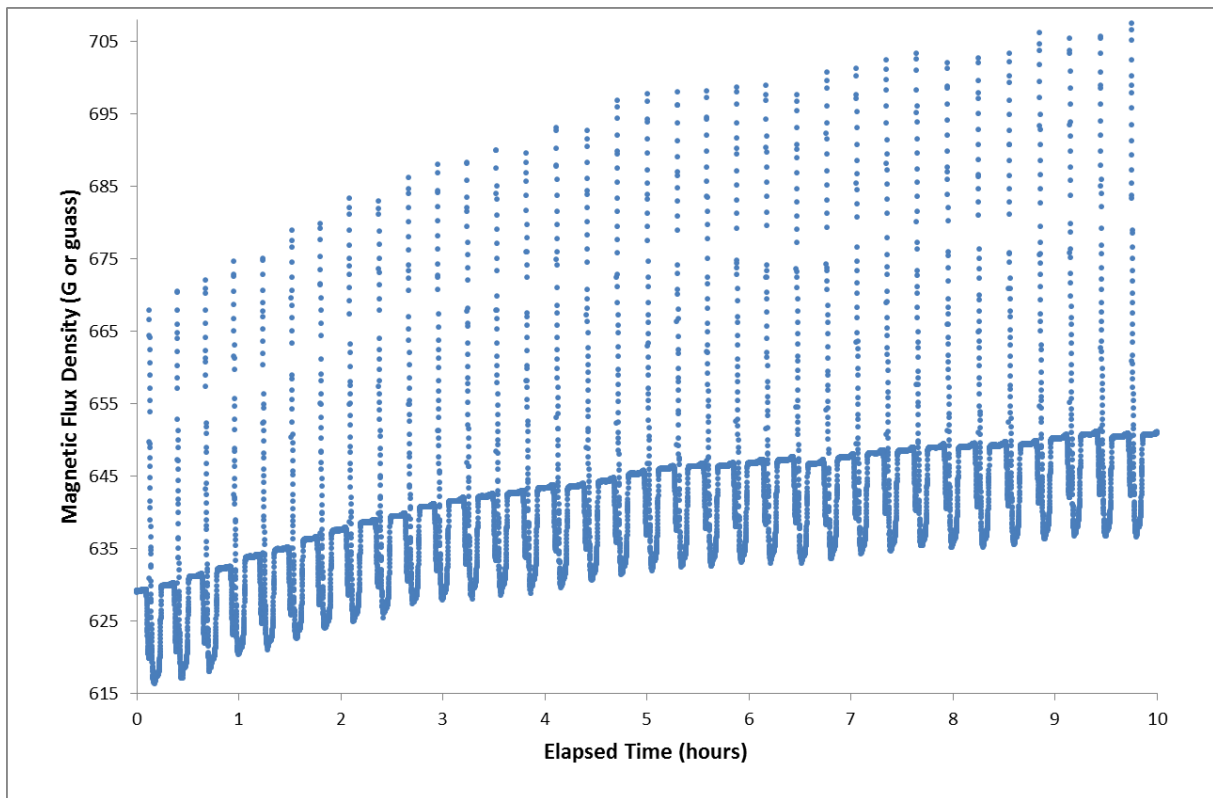


Figure 30: The shape of the pulses recorded by the hall sensor beneath the YBCO

Over a period of 10 hours the field increased from 616.5 gauss to 636.6 gauss measuring from the lowest point on the pulses.

D.2 Dysprosium, YBCO and Coldhead Temperatures

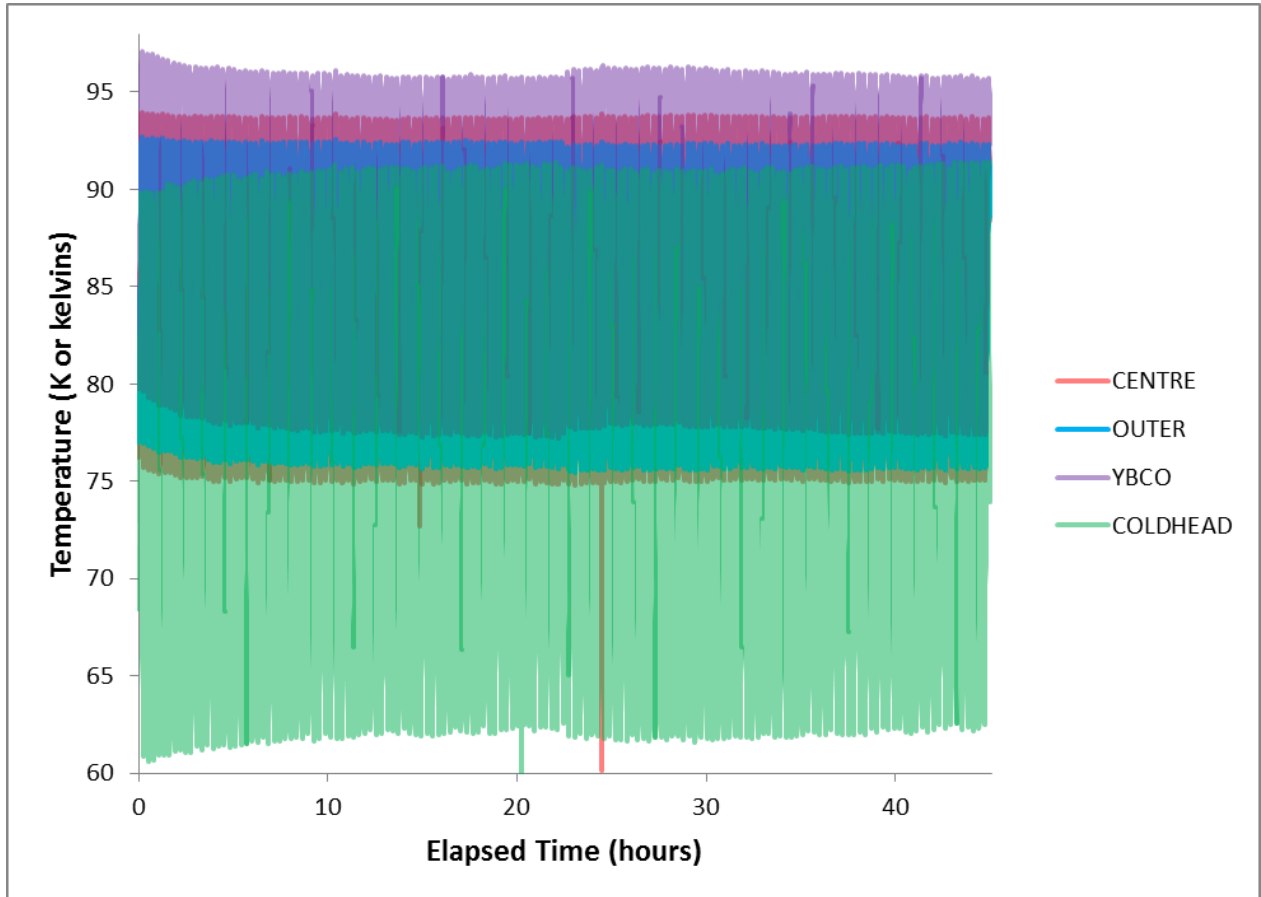


Figure 31: The temperatures of the outside and centre of the dysprosium, the outside edge of the YBCO puck and the coldhead

In Figure 31 (above) all the temperatures overlap and are difficult to see. The YBCO (purple) shows along the top and the coldhead (green) along the bottom. The brown colour is the light green of the coldhead and the orange of the dysprosium centre overlapping. The outer edge of the dysprosium is blue but shows up as two darker shades of green and blue on the graph. All these difficulties are resolved by reducing the density of points and the time scale to 5 hours.

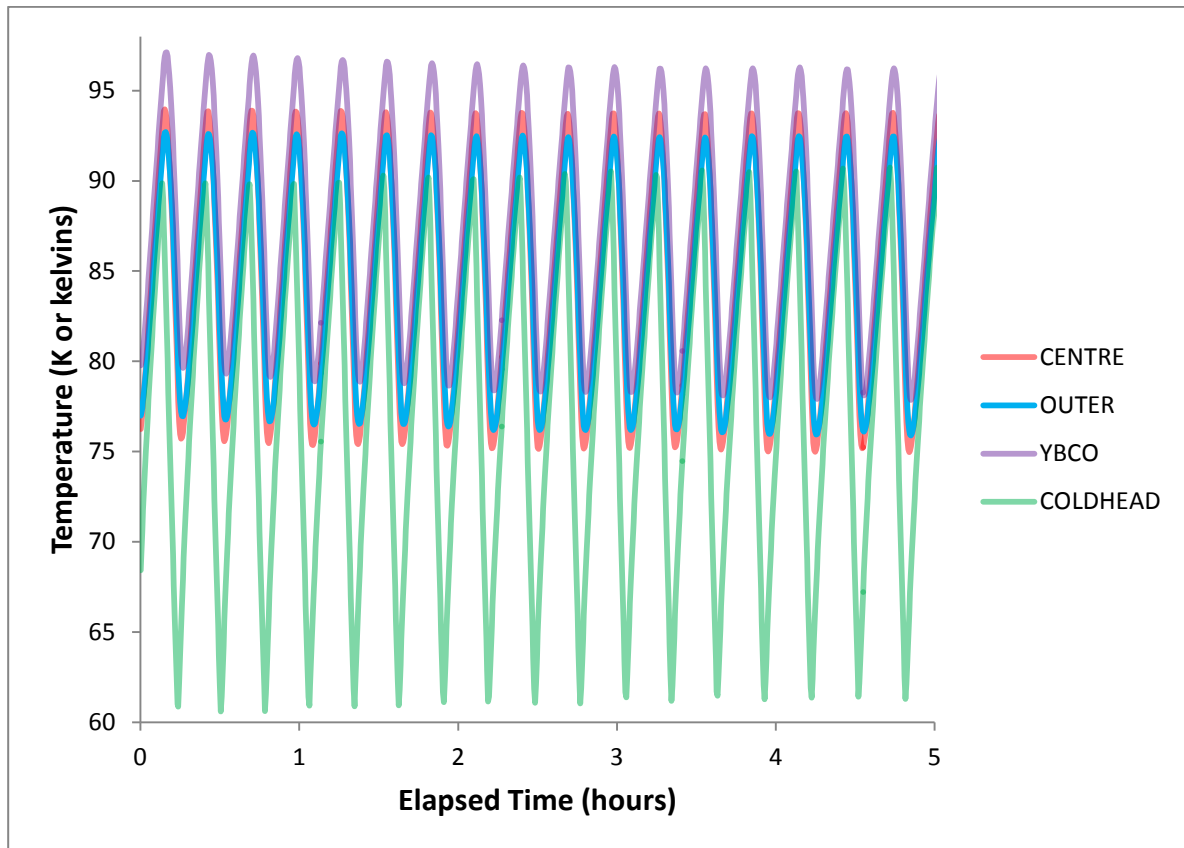


Figure 32 : The temperatures of the dysprosium, YBCO and coldhead plotting every tenth point and reducing the time scale to 5 hours

Figure 32 clearly shows the temperatures of the coldhead, dysprosium and the YBCO. The YBCO crests exceed its critical temperature of 94 K and the centre of the face of the dysprosium oscillates at a higher temperature than the outside edge.

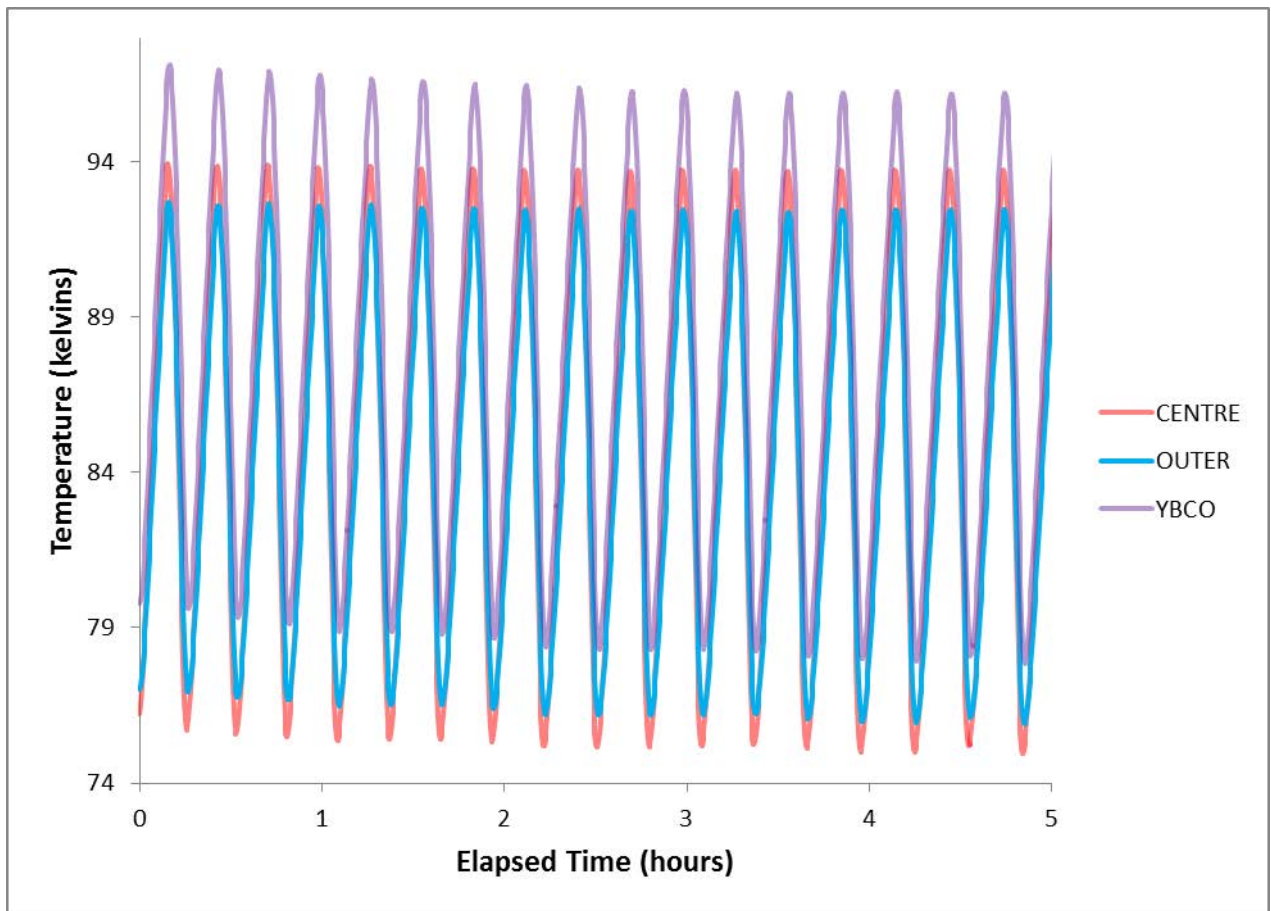


Figure 33: The temperature of the YBCO during the pulsing of the dysprosium

From Figure 33 (above) it can be seen that the YBCO temperature changed with the pulsing of the dysprosium. The critical temperature of YBCO can be from 90 K to 94 K but the temperature rises to approximately 96 K with each pulse. The carbon ceramic temperature sensor was located on the outside edge of the YBCO and the internal temperature might not have varied to the same extent.

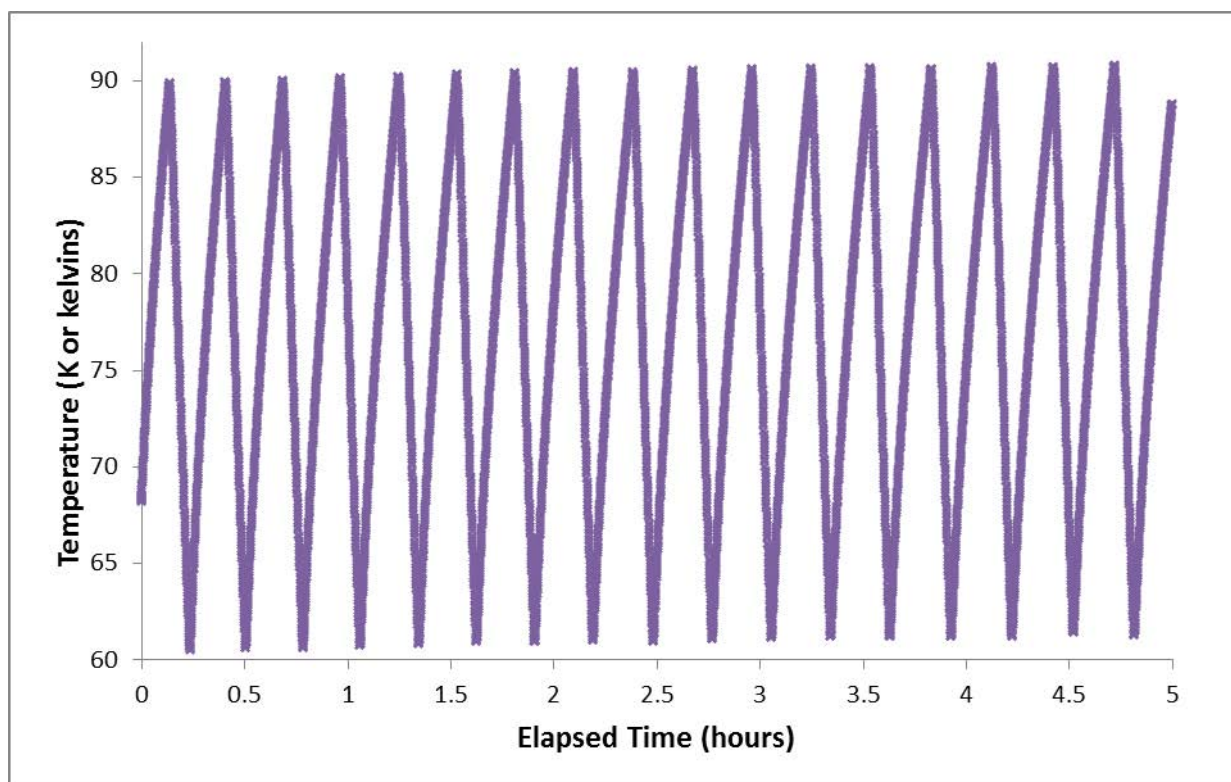


Figure 34: The temperatures of the coldhead

D.3 Coil Temperatures at 616 G

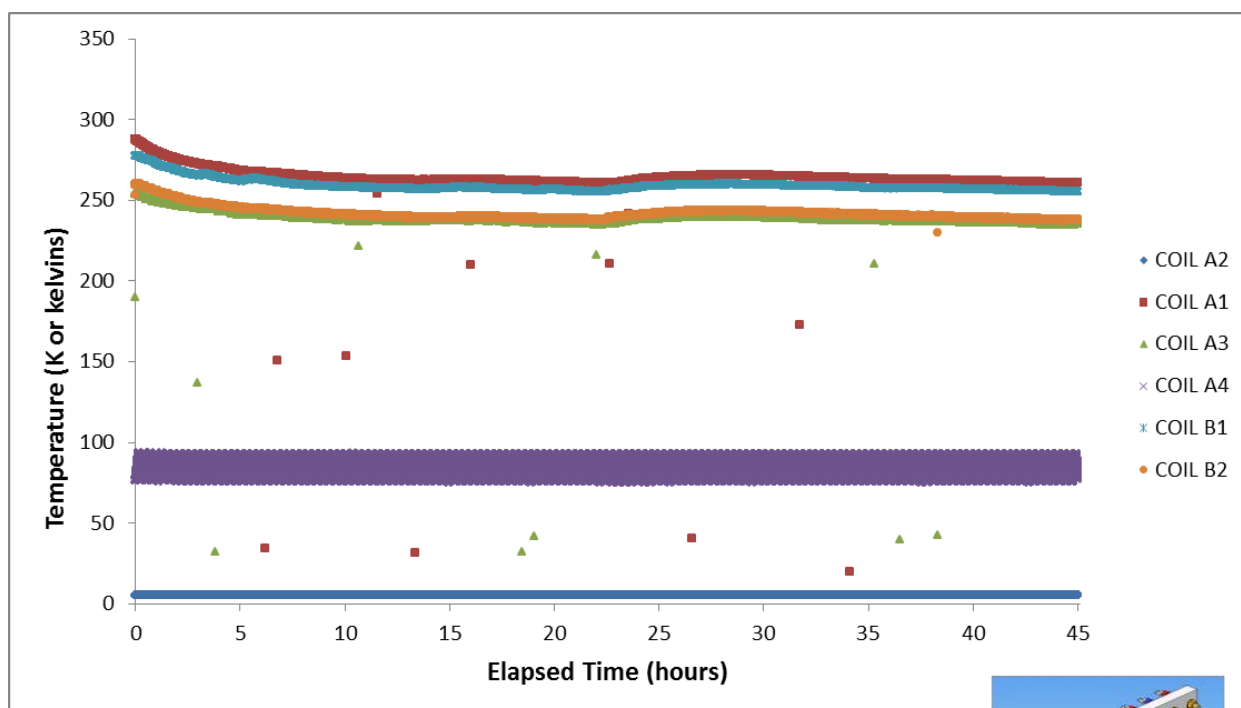
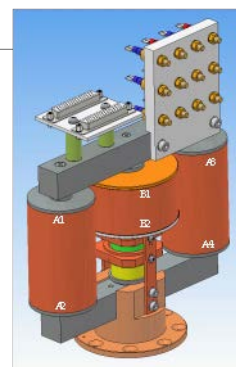


Figure 35: Temperatures recorded at the top and bottom of the coils



Appendix E: Coil Temperature Sensors

Carbon ceramic temperature sensors were attached at the top and bottom of the coils at the positions shown in Figure 11 (below).

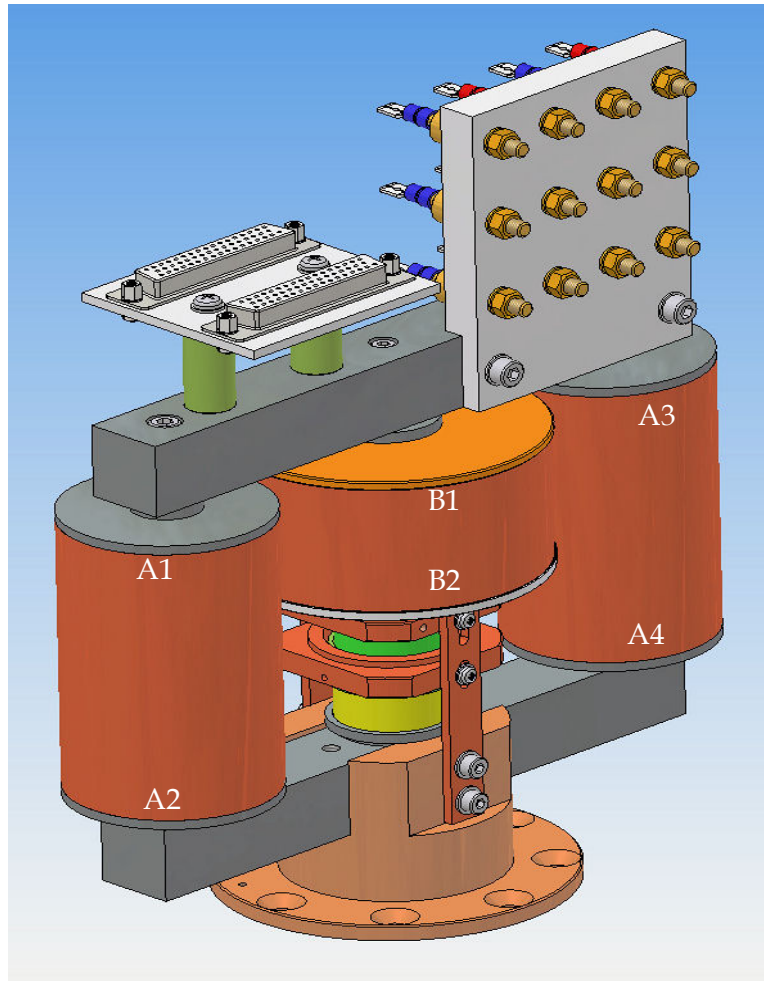


Figure 36: The positions of coil the temperature sensors

The coldhead was attached to the copper fitting (coldhead connecting spigot) at the bottom of the figure so that A2, A4, and B2 will be closest to the coldhead and should record the lowest temperatures. The coldhead connecting spigot is attached to the iron magnetic circuit.

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19. ABSTRACT This paper presents results for the magnetization of a disc of YBCO by sending heat pulses through a disc of dysprosium below it. As the heat pulses move through the dysprosium its magnetic properties change producing a wave of magnetization across the disc of YBCO. This wave of magnetization sweeps vortices into the YBCO and each subsequent wave sweeps in more vortices, gradually increasing the magnetization of the YBCO. The YBCO disc was 30 mm in diameter and 15 mm high and the dysprosium was 30 mm in diameter and 13 mm high. The dysprosium undergoes a change from ferromagnetic to anti-ferromagnetic as it passes through a temperature of 85 K so the temperature range of the heat pulses went from below this temperature to a temperature above it. The dysprosium and YBCO were connected into an iron magnetic circuit to create a low reluctance path with three copper coils on parts of the circuit. Currents through the coils generated flux in the magnetic circuit. The circuit was cooled using a cryocooler and heat pulses were applied to the dysprosium by turning the cold head on and off. These heat pulses varied the temperature of the dysprosium above and below the ferromagnetic anti-ferromagnetic transition, sweeping vortices into the YBCO causing a magnetic field to gradually accumulate. It was found that the field initially grew to a certain level and then stayed constant no matter how long the pulses were applied. The pattern was found to be the same for four different coil currents and therefore two different starting values for the flux in the circuit.				

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