Durham Magneto Optics Ltd

Technical Report TR160711rev3

Characterisation of the Montana Instruments® Cryostation® C2 for low temperature Magneto-Optical Kerr Effect measurements using the NanoMOKE®3

EXECUTIVE SUMMARY

This technical report summarises the results of the integration of the Montana Instruments® Helium-free Cryostation® C2 with the NanoMOKE®3 magnetometer from Durham Magneto Optics Ltd. Three samples were measured in this study: a continuous film with in-plane magnetisation, a patterned sample with in-plane magnetisation, and a continuous film with out-of-plane magnetisation. The magnetometry study shows strong artefact-free hysteresis loops at low temperature (4 K), with a signal exceeding 20 mdeg in all the samples, making it possible to capture the magnetic reversal with single-shot measurements. The magnetic microscopy study shows clear domain images at 4 K, using both the scanning laser microscope and the CCD camera. The maximum field applied in the longitudinal configuration is over 0.470 T[1] and in the polar geometry is over 0.350 T. The system is extremely stable and the noise at low-temperature is about 0.6 mdeg in the longitudinal configuration — 1.2 times the specified room temperature noise — and about 1 mdeg in the polar configuration — twice the specified room temperature noise.

BACKGROUND

In this study three samples were measured at low temperature using the Helium-free Cryostation® C2 from Montana Instruments®. They are the standard test samples that are provided to every NanoMOKE®3 customer — see TR160215r1 for room temperature measurements. The samples consist of one Permalloy continuous film (20 nm in thickness) with in-plane magnetisation, one set of Permalloy microwires (25-um wide, 24-nm thick) with in-plane magnetisation, and one Ta(4 nm)/Pt(10 nm)/CoFeB(0.6 nm)/Pt(2 nm) thin film with perpendicular magnetic anisotropy. The two Permalloy samples were measured in the

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[1] Field, noise and temperature values presented in this report are those measured under a variety of experimental conditions using the prototype system. They should be interpreted as “typical” values, not guaranteed performance specifications.

longitudinal configuration at 25° incidence using the high-mag lens set; the out-of-plane sample was measured in polar geometry. Both Kerr rotation and Kerr ellipticity were measured; the loops displayed in this report show Kerr rotation as a function of applied field (measurements of the Kerr ellipticity of these samples yield similar or weaker signal strength). For each configuration of the Kerr effect, a thorough noise analysis was performed for three states of the cryopump, i.e. fully on (target temperature of 2 K), idling (target temperature of 20 K) and off. Also, the variations in temperature as a function of different field conditions were recorded.

ULTRA-THIN COFEB

(minimum sample temperature recorded: 4.580 K
minimum platform temperature recorded: 3.296 K)

Figure 1 shows three hysteresis loops measured at three cryopump regimes, i.e. fully on (sample temperature of 4.5 K), idling (sample temperature of 20 K) and off (sample temperature of approximately 30 K while rising). These hysteresis loops were averaged for 60 s, and the applied field was a cosine waveform of amplitude 3000 Oe and frequency 1 Hz. The loops exhibit strong magnetic signal, over 60 mdeg, and it is possible to capture the magnetic reversal with single-shot measurements, as shown in Figure 2. The coercive field of the sample at 4 K is H_{CLT} = 0.231 T, as opposed to H_{CRT} = 0.018 T found at room temperature. This change in coercive field is explained by the fact that domain wall nucleation is a thermally assisted process. The signal-to-noise ratio of the single-shot loops is excellent, the noise being only 5% of the total loop amplitude in the case where the cryopump is running at full strength (black curve).

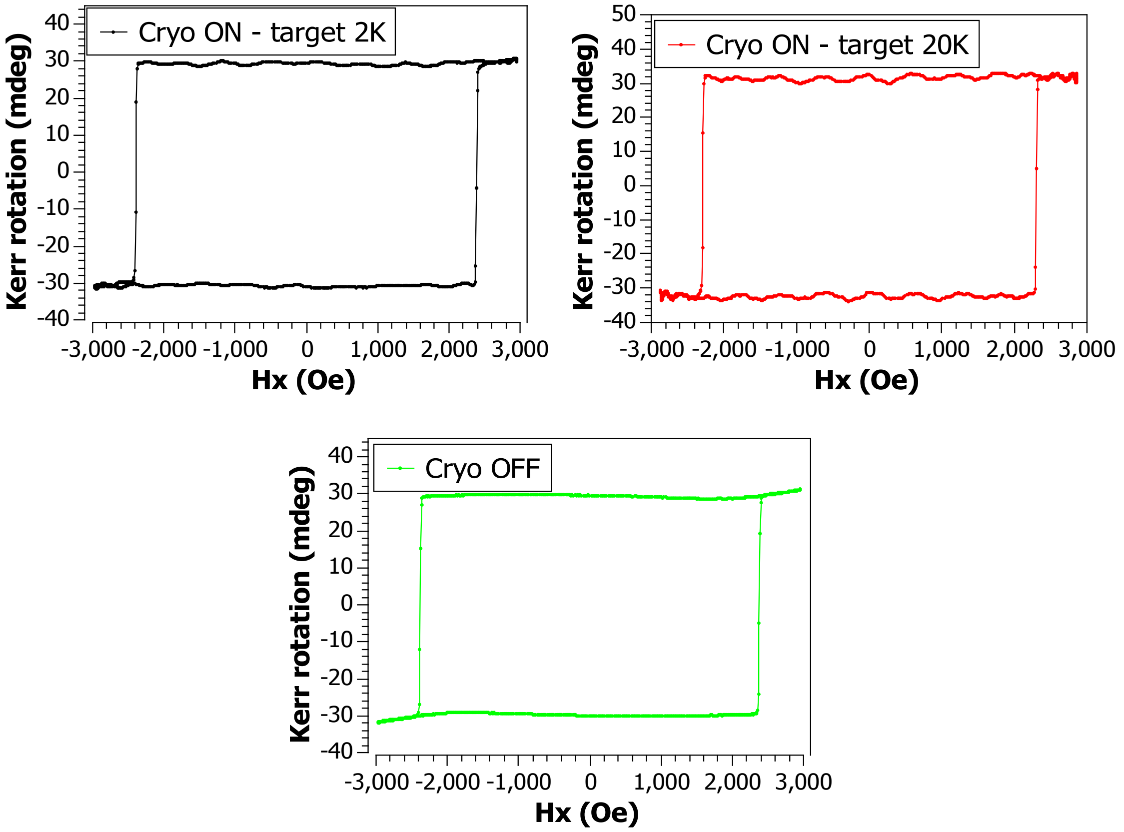

Figure 1: Hysteresis loops averaged for 60 s taken in the polar configuration for three cryopump regimes; black: fully on (sample temperature of 4.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of approximately 30 K).

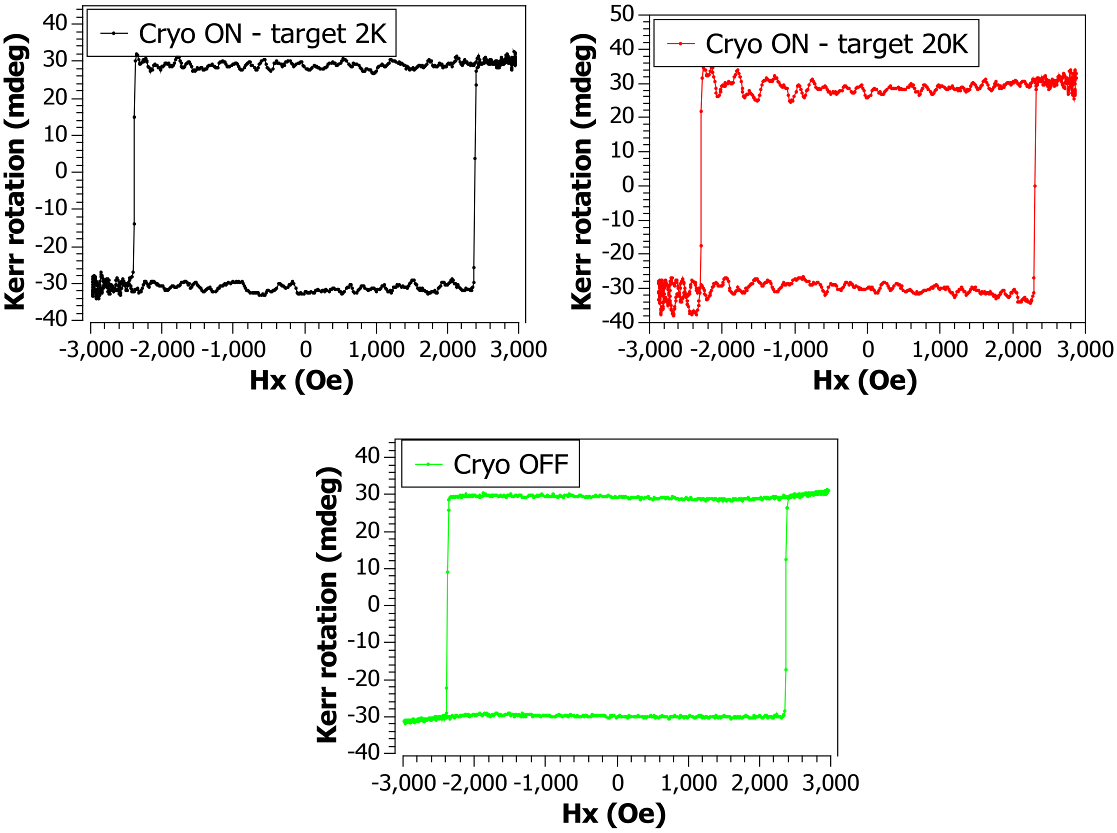

Figure 2: Single-shot hysteresis loops taken in the polar configuration for three cryopump regimes; black: fully on (sample temperature of 4.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of approximately 30 K).

Figure 3 shows magnetic microscopy images at a sample temperature of 4.5 K using the Scanning Laser Microscope (SLM). The top-left image shows the sample fully saturated one way, and clockwise are the images obtained as the field is ramped up, until the sample is fully saturated in the opposite direction (middle-left image). Whereas at room temperature reversal occurs via nucleation and propagation of large domains (see TR TR160215r1), numerous, smaller domains are preferred at low temperature. Microscopy images using a CCD camera are presented in Figure 4, where the same domain structure is observed.

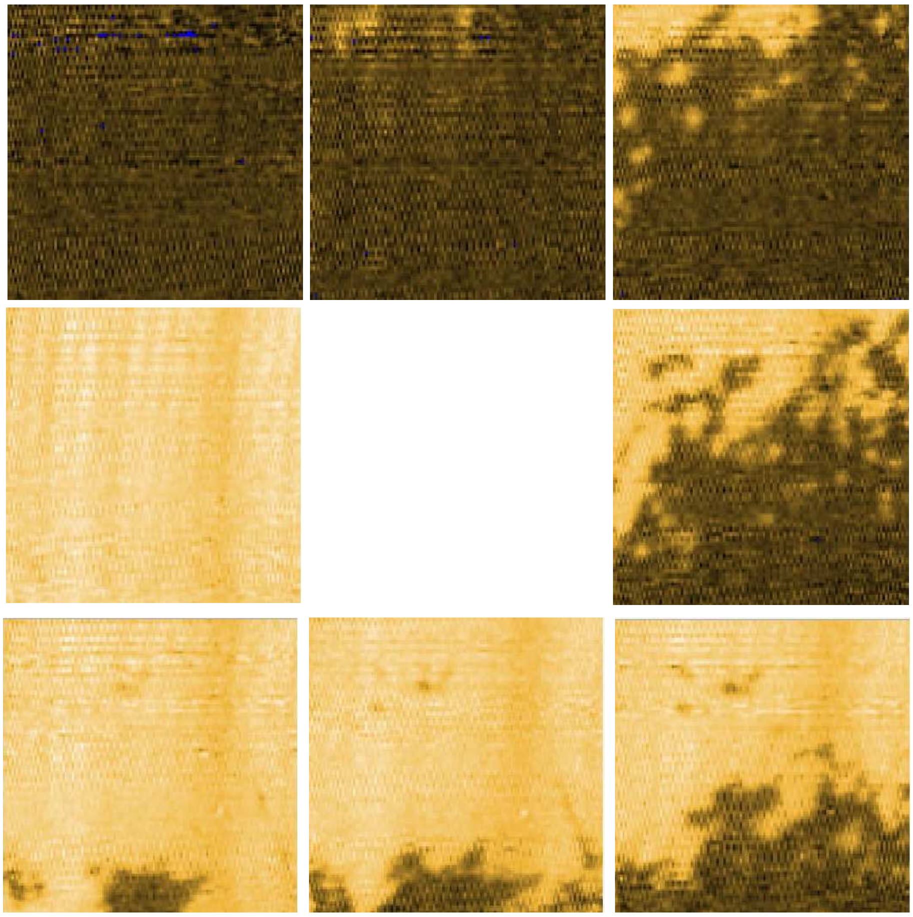

Figure 3: Domain images of the ultra-thin CoFeB sample acquired with the scanning laser microscope at a sample temperature of 4.5 K.

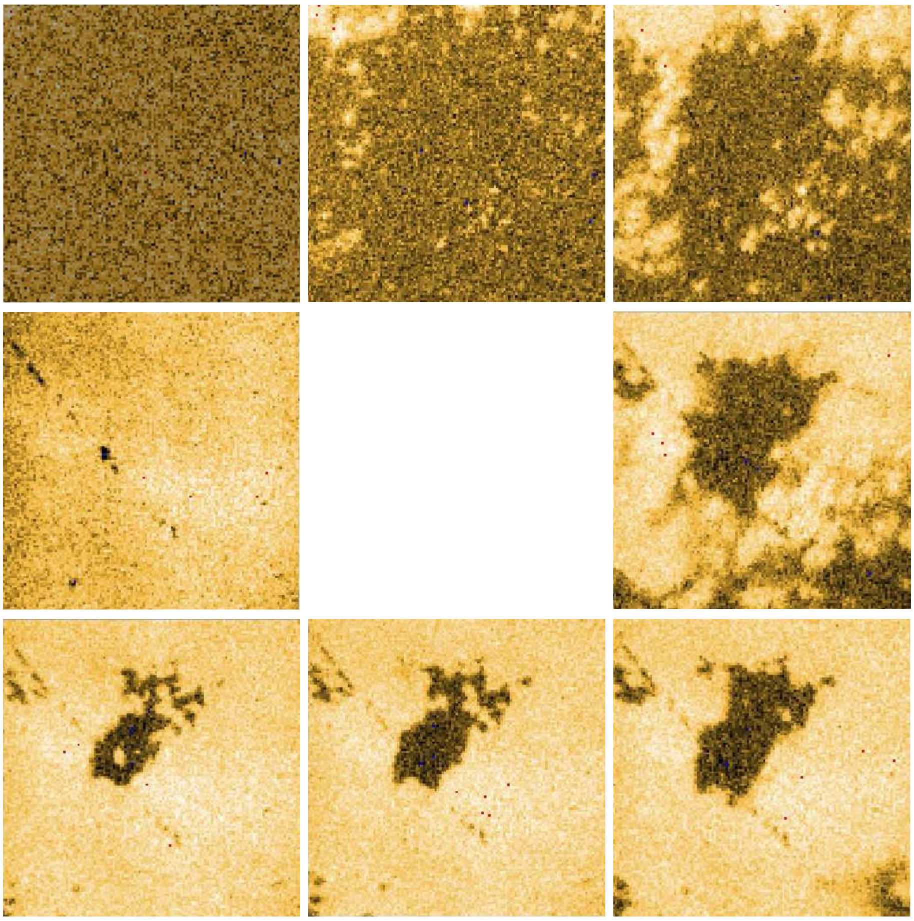

Figure 4: Domain images of the ultra-thin CoFeB sample acquired with the CCD camera at a sample temperature of 4.5 K.

Continuous Permalloy

(minimum sample temperature recorded: 3.499 K
minimum platform temperature recorded: 3.285 K)

Figure 5 shows three hysteresis loops measured at three cryopump regimes, i.e. fully on (sample temperature of 5.5 K), idling (sample temperature of 20 K) and off (sample temperature of 55 K while rising). These hysteresis loops were averaged for 60 s, and the applied field was a cosine waveform of amplitude 500 Oe and frequency 1 Hz. The loops exhibit strong magnetic signal, over 20 mdeg, and it is possible to capture the magnetic reversal with single-shot measurements, as shown in Figure 6. The coercive field of the sample at 5.5 K is H'_{CLT} = 0.013 T, as opposed to H'_{CRT} = 3.10^{-4} T found at room temperature. This change in coercive field is explained by the fact that domain wall nucleation is a thermally assisted process. The signal-to-noise ratio of all three loops is excellent and identical, the noise being only 4% of the total loop amplitude, which is evidence of the high stability of the system.

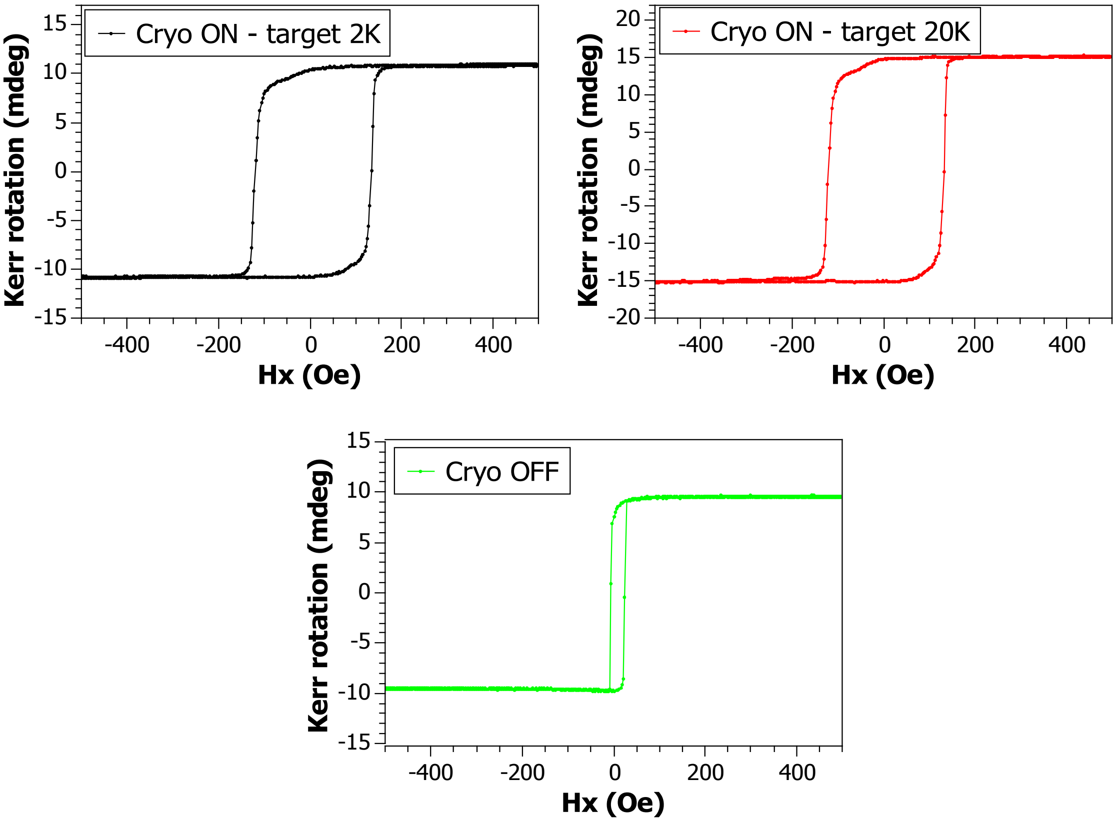

Figure 5: Hysteresis loops averaged for 60 s taken in the longitudinal configuration for three cryopump regimes; black: fully on (sample temperature of 5.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of 55 K).

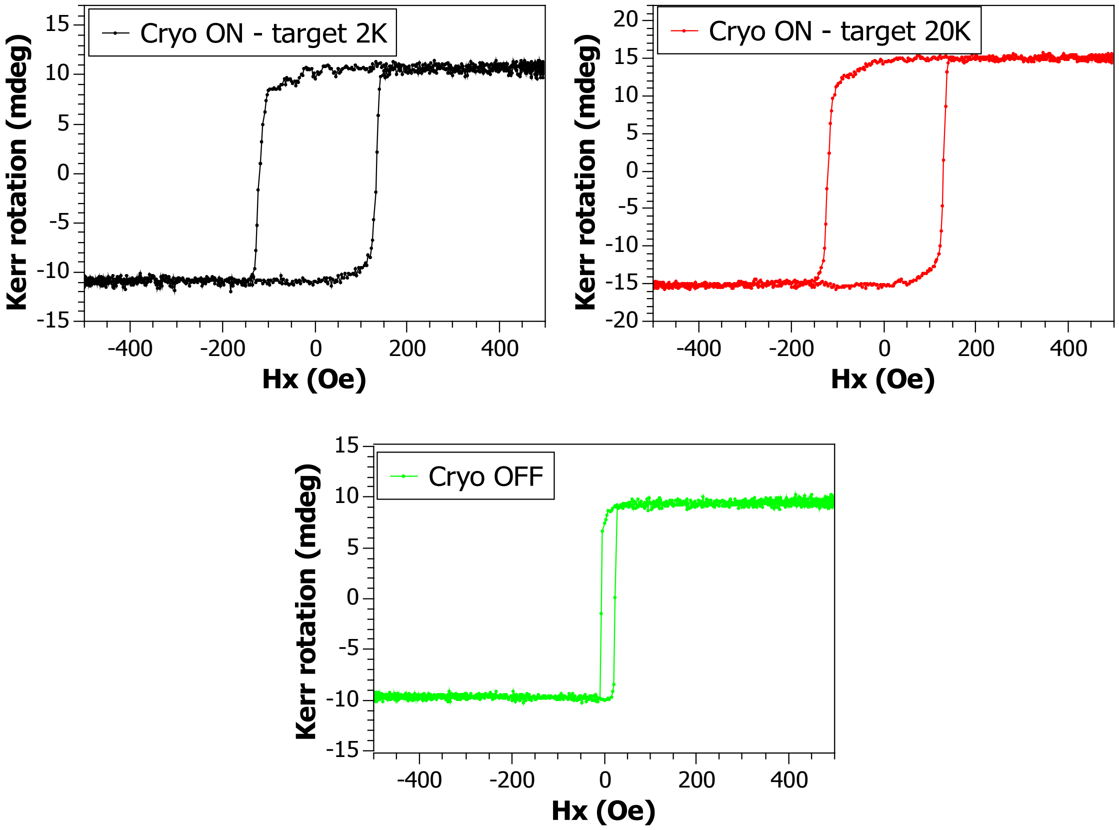

Figure 6: Single-shot hysteresis loops taken in the longitudinal configuration for three cryopump regimes; black: fully on (sample temperature of 5.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of 55 K).

Figure 7 shows magnetic microscopy images at a sample temperature of 5.5 K using the SLM. The image on the left shows the sample fully saturated one way, and as the field is increased/decreased, the sample switches, as shown on the 3D hysteresis loop. The switching seems to occur via coherent rotation of the magnetic moments, which explains the absence of clear domains. In fact, the Permalloy sample shows in-plane easy and hard axes; in order to see clear domains, the sample should always be loaded so the magnetic field is applied along the sample's easy axis.

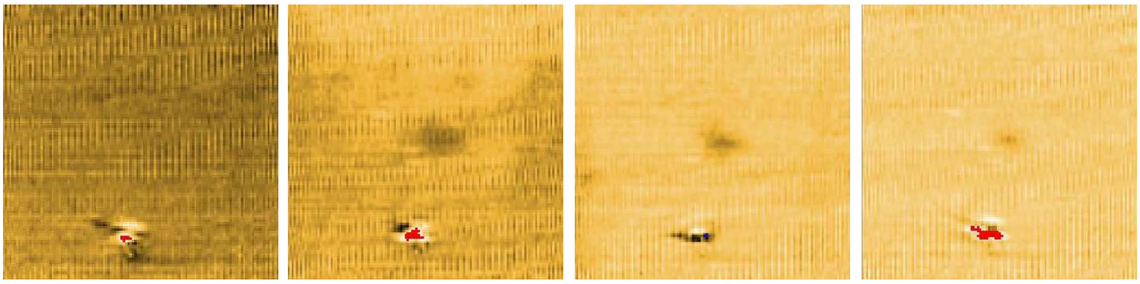

Figure 7: Domain images of the Permalloy film acquired with the scanning laser microscope at a sample temperature of 5.5 K.

PERMALLOY MICROWIRES

Figure 8 shows hysteresis loops measured at 5.5 K sample temperature with the laser spot on a microwire (top row) and between two structures (bottom row). The applied field was a cosine waveform of amplitude 0.03 T and frequency 1 Hz. The middle loops were averaged for 60 s and the loop taken on a microwire exhibits strong magnetic signal, over 50 mdeg in amplitude. It is possible to capture the magnetic reversal with single-shot measurements. The loops taken between two microwires still show sign of magnetic switching, but the amplitude is reduced to 4 mdeg only. The small magnetic signal measured here is a combination of the sample's background and the tails of the Gaussian-like beam profile overlapping with the Permalloy structures. The coercive field of the sample at 5.5 K is H''_{CLT} = 0.012 T, as opposed to H''_{CRT} = 3.10^{-4} T found at room temperature. This change in coercive field is explained by the fact that domain wall nucleation is a thermally assisted process. The signal-to-noise ratio of the on-wire single-shot loop is excellent, the noise being only 3% of the total loop amplitude.

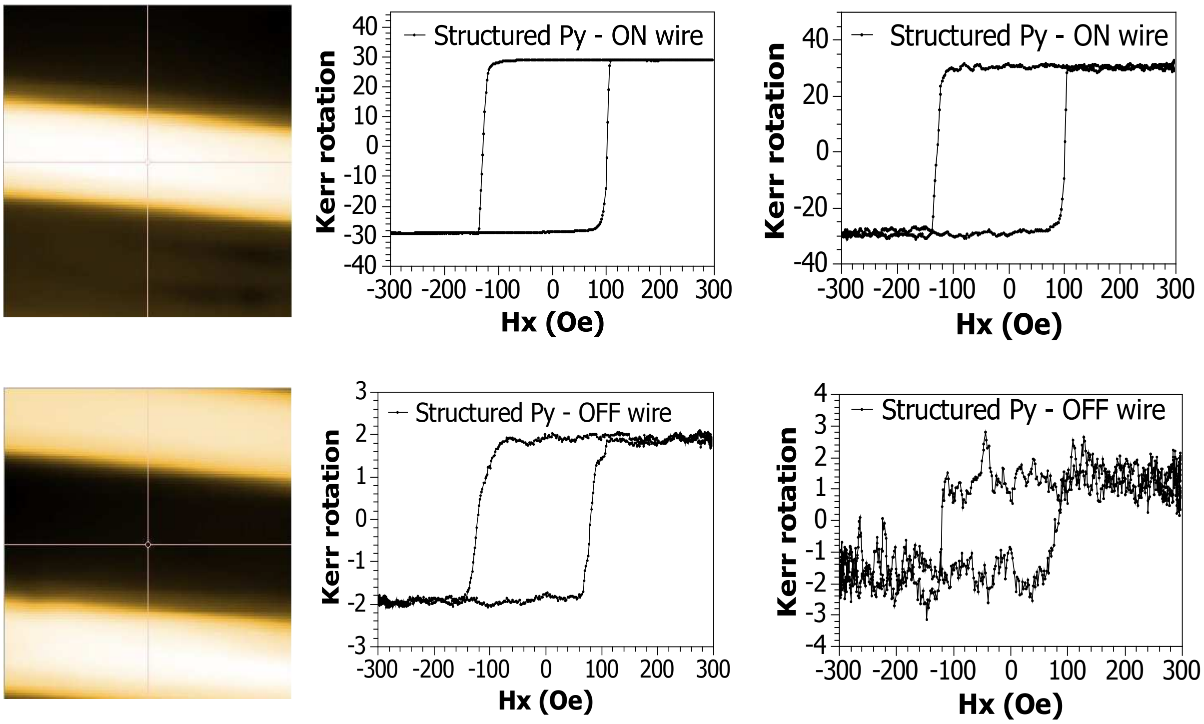

Figure 8: Hysteresis loops taken in the longitudinal geometry at a sample temperature of 5.5 K, on a Permalloy microwire (top row) and between two structures (bottom row). The figure shows averaged loops (middle) and single-shot loops (right).

Figure 9 shows magnetic microscopy images at a sample temperature of 5.5 K using the SLM. The top-left image shows the sample fully saturated one way, and clockwise are the images obtained as the field is ramped up, until the sample is fully saturated in the opposite direction (middle-left image). Images show that magnetic domains are nucleating at each wire end, but also at random locations in the microstructures. Microscopy images using a CCD camera are presented in Figure 10, and switching of individual microwires is probed. Another sign of the high stability of the system is the absence of jitter in domain images, the edges of the microwires are straight and the imaging quality is identical to that of room temperature measurements.

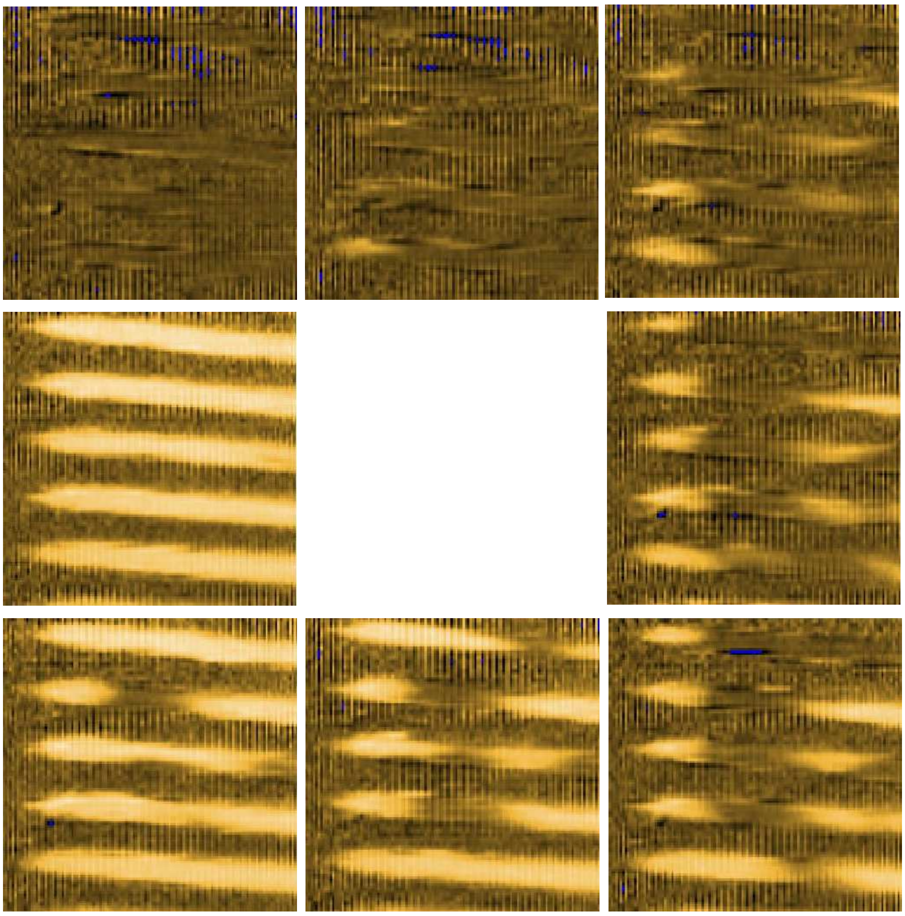

Figure 9: Domain images of the Permalloy microwires acquired with the scanning laser microscope at a sample temperature of 5.5 K.

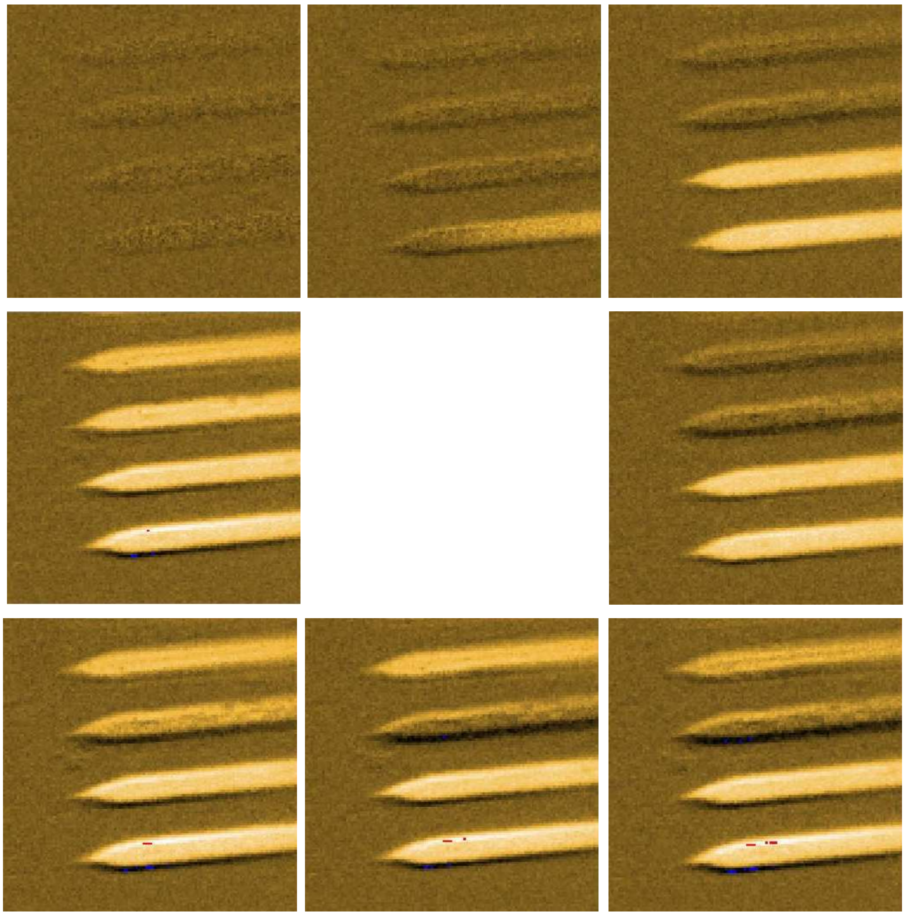

Figure 10: Domain images of the Permalloy microwires acquired with the CCD camera at a sample temperature of 5.5 K.

DIPOLE PERFORMANCE IN POLAR CONFIGURATION

The maximum field applicable using the Montana Instruments® dipole magnet in the polar configuration and at a sample temperature of 4 K was measured to be just over 0.350 T, as shown in Figure 11. The field waveform was a cosine function of frequency of 0.05 Hz, so that despite the slow response time of the electromagnet, the correct field was applied.

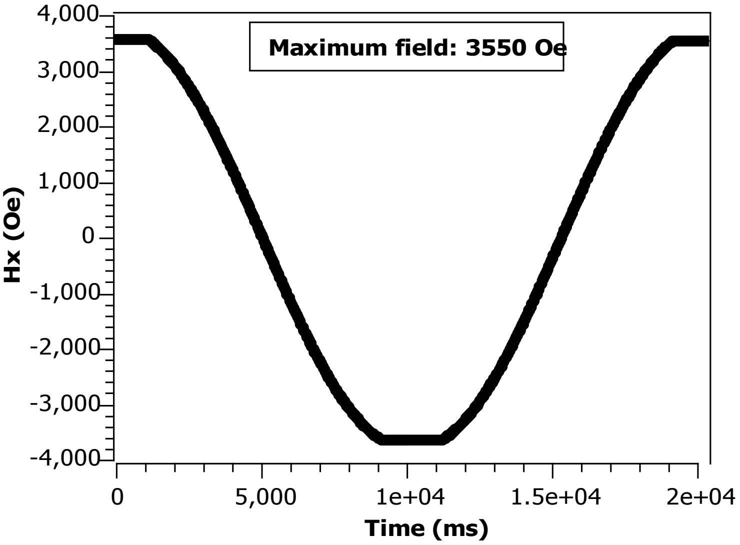

Figure 11: Field vs time of a cosine waveform of frequency 0.05 Hz, generated with the polar pole pieces. The maximum field produced in the polar configuration is 3550 Oe.

The next two figures quantify the temperature rise observed when applying a magnetic field, through the generation of eddy currents, for different field conditions. First, Figure 12 shows the change in platform and sample temperatures as a function of the duration of the applied field. The field, a cosine waveform of amplitude 0.3 T and frequency 1 Hz was run for 1, 2 and 3 minutes. The cryostation was cooled back to the base temperature between each measurement. The rise in temperature from the base sample (platform) temperature of 4.5K (3.3 K) was recorded at the end of each sequences. Figure 12 shows the temperature rise is independent of the field duration and is below 300 mK for the sample and 200 mK for the platform under these field conditions.

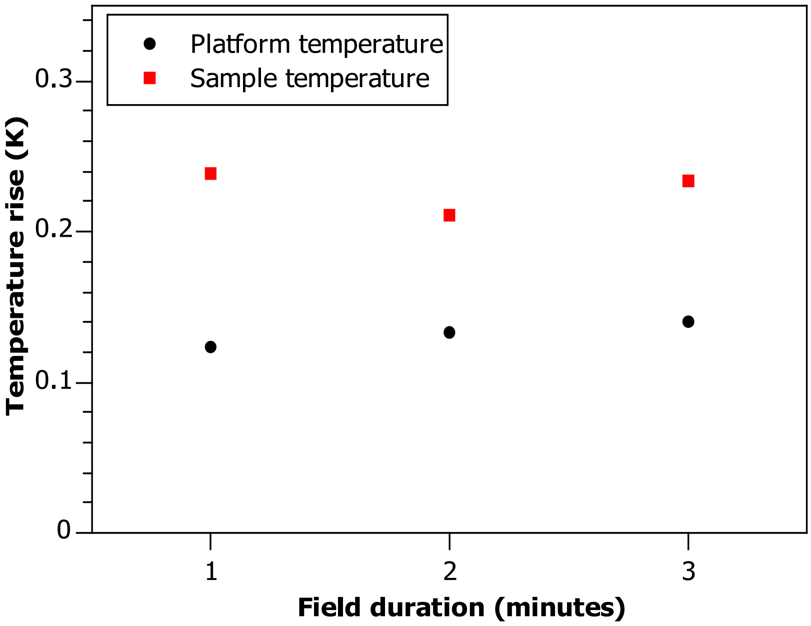

Figure 12: Sample and platform temperature rise relative to the base temperature as a function of the field duration, in the polar configuration.

Figure 13 shows the temperature rise relative to the base temperature, as a function of the frequency of the applied field. A 0.3 T cosine field set in software was applied for a minute, and the base and final temperatures were recorded. Because of the response time of the electromagnet, the cosine waveform turns into a saw-tooth function with reduced amplitude at high frequency. The floating labels next to each data point show the true amplitude as measured by the Hall sensor. Figure 13 shows that the temperature rises linearly with frequency, up to 2.5 K at 5 Hz and then plateaus at higher frequencies. The reason why the temperature rises less at 10 Hz than it does at 5 Hz is the much reduced field amplitude (0.23 T at 5 Hz, 0.13 T at 10 Hz). Even while driving the maximum applied field for extended periods or at high frequencies, a platform temperature of <5 K could be maintained.

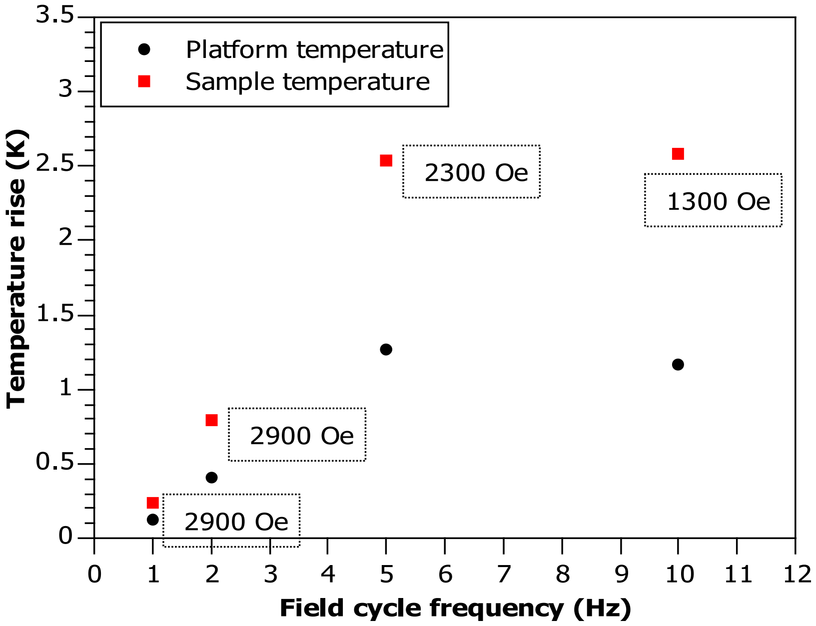

Figure 13: Sample and platform temperature rise relative to the base temperature as a function of the frequency of the applied field, in the polar configuration. The field was set in software to be a cosine waveform of amplitude 0.3 T. The floating labels indicate the amplitude of the field as measured by the Hall sensor.

The next figure quantifies the noise in the Kerr signal. Figure 14 shows the measured root mean square (AC) of the Kerr signal over an extended period of time (up to 1700 s), for three different cryopump regimes. The black data points denotes the noise when the cryopump is working at its full strength, i.e. the target temperature is set to 2 K. The red data points show the noise when the temperature set point is 20 K, and the green data points show the noise level when the cryopump is turned off. There is little difference between the black and red curves, with a noise level around 1 mdeg, which is twice the specified room temperature noise. The higher level of noise recorded on the red curve around t=0 s is attributed to a sudden change in the cryopump regime as the target temperature was changed from 2 K to 20 K. When the cryopump is off, the noise level drops to below 1 mdeg. Although vibration is the main source of noise, Figure 14 highlights the high stability of the system, compared to other cooling systems.

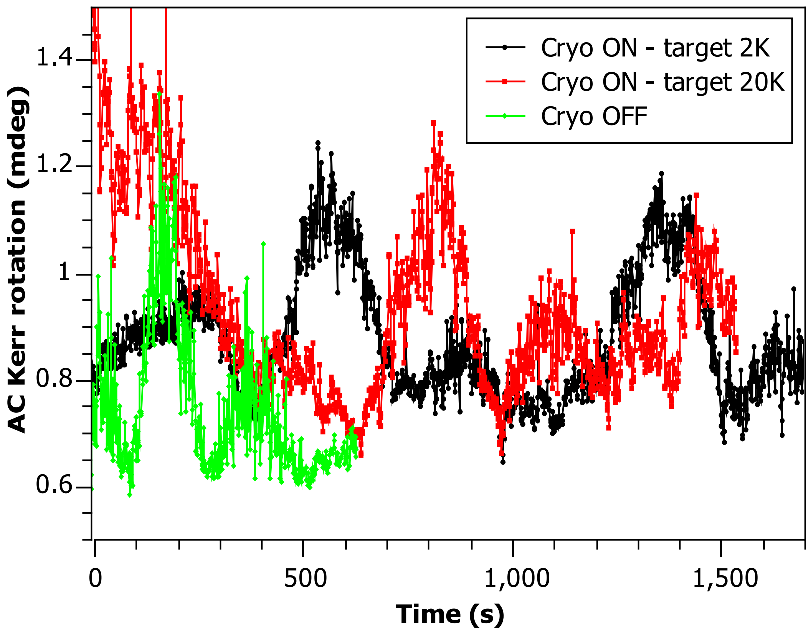

Figure 14: Root mean square of the Kerr signal over an extended period of time, in the polar configuration for three cryopump regimes; black: fully on (sample temperature of 4.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of approximately 30 K).

DIPOLE PERFORMANCE IN LONGITUDINAL CONFIGURATION

The maximum field applicable using the Montana Instruments® dipole magnet in the longitudinal configuration and at a sample temperature of 5.5 K was measured to be just over 0.470 T, as shown in Figure 15. The field waveform was a cosine function of frequency of 0.05 Hz.

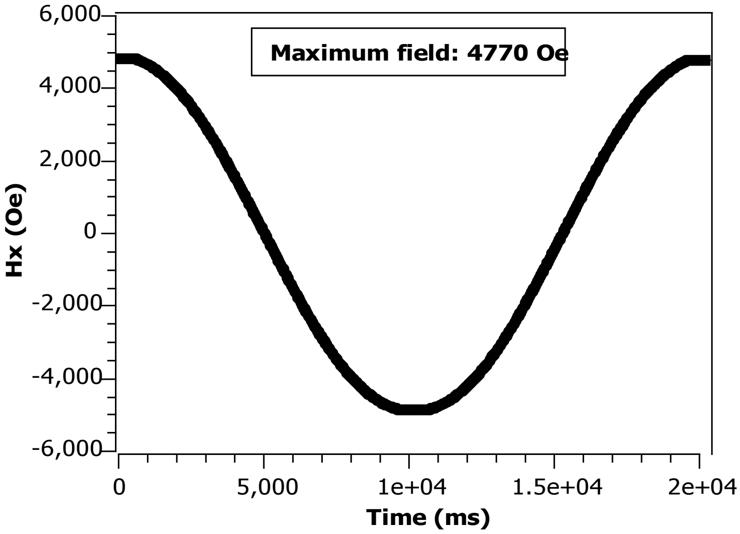

Figure 15: Field vs time of a cosine waveform of frequency 0.05 Hz, generated with the longitudinal pole pieces. The maximum field produced in the longitudinal configuration is 4770 Oe.

The next two figures quantify the temperature rise observed when applying a magnetic field, through the generation of eddy currents, for different field conditions. First, Figure 16 shows the change in platform and sample temperatures as a function of applied field duration. The field, a cosine waveform of amplitude 0.3 T and frequency 1 Hz was run for 1, 2 and 3 minutes. The cryostation was cooled back to the base temperature between each measurement. The rise in temperature from the base sample (platform) temperature of 5.5K (3.5 K) was recorded at the end of each sequences. Figure 16 shows that the field duration has little impact on the sample temperature, with a recorded rise of 210 mK after 3 minutes, at these field conditions.

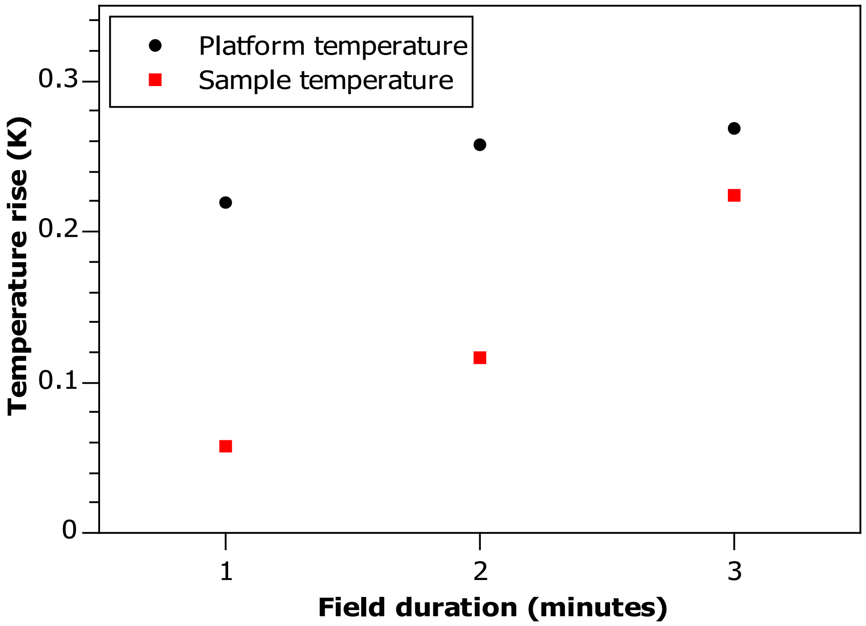

Figure 16: Sample and platform temperature rise relative to the base temperature as a function of the field duration, in the longitudinal configuration.

Figure 17 shows the temperature rise relative to the base temperature, as a function of the frequency of the applied field. A 0.3 T cosine field set in software was applied for a minute, and the base and final temperatures were recorded. Because of the response time of the electromagnet, the cosine waveform turns into a saw-tooth function with reduced amplitude at high frequency. The floating labels next to each data point show the true amplitude as measured by the Hall sensor. Figure 17 shows that the temperature rises linearly with frequency, up to 1.1 K at 5 Hz and then goes down at higher frequencies. The reason why the temperature rises less at 10 Hz than it does at 5 Hz is the much reduced field amplitude (0.3 T at 5 Hz, 0.19 T at 10 Hz). Even while driving the maximum applied field for extended periods or at high frequencies, a platform temperature of <5 K could be maintained.

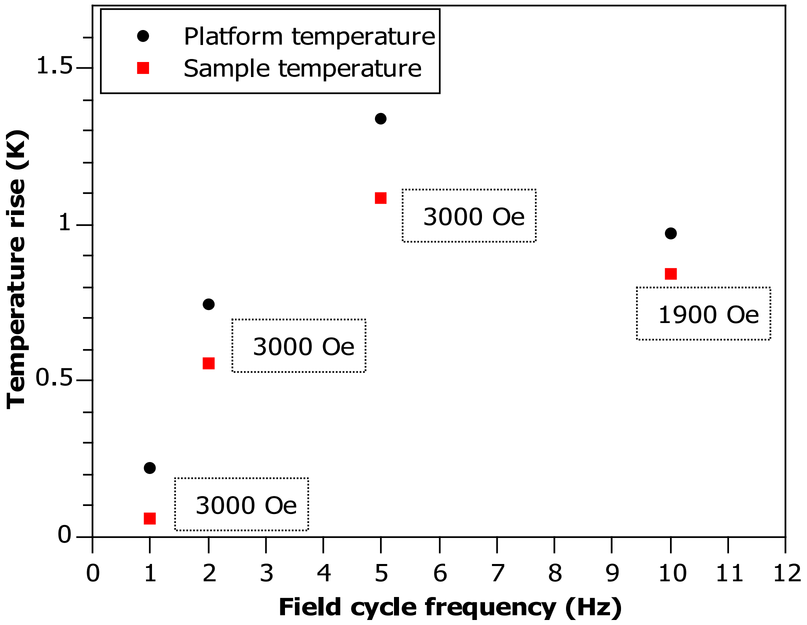

Figure 17: Sample and platform temperature rise relative to the base temperature as a function of the frequency of the applied field, in the longitudinal configuration. The field was set in software to be a cosine waveform of amplitude 0.3 T. The floating labels indicate the amplitude of the field as measured by the Hall sensor.

The next figure quantifies the noise in the Kerr signal. Figure 18 shows the measured root mean square (AC) of the Kerr signal over an extended period of time (up to 1500 s), for three different cryopump regimes. The black data points denotes the noise when the cryopump is working at its full strength, i.e. the target temperature is set to 2 K. The red data points show the noise when the temperature set point is 20 K, and the green data points show the noise level when the cryopump is turned off. There is little difference between the three traces, indicating that the system is extremely stable. This is in agreement with the single-shot loops displayed in Figure 6, where for all three loops the amplitude of the noise is only 4% of the total loop amplitude. The level of noise is in average equal to 0.5 mdeg, which is as good as the performance at room temperature. This last result shows how stable the system can be and how well vibrations within the cooling unit are dampened.

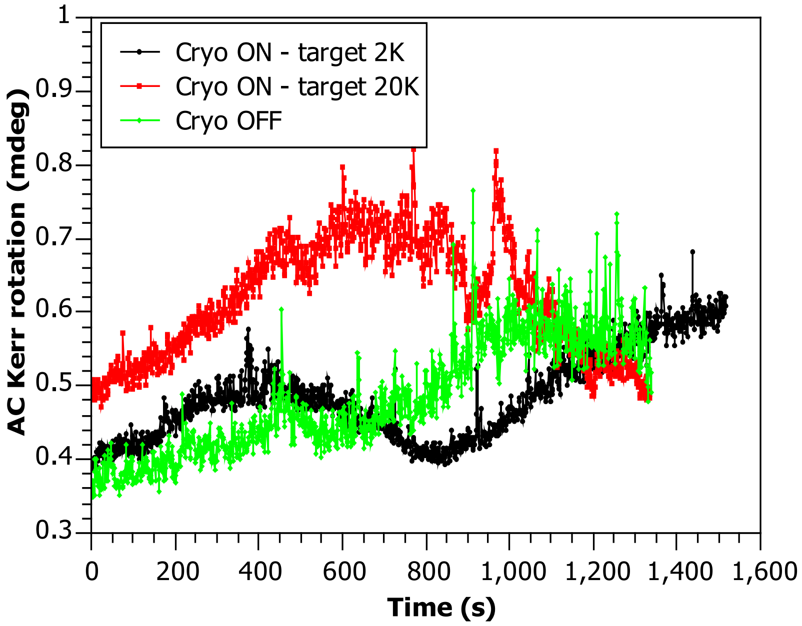

Figure 18: Root mean square of the Kerr signal over an extended period of time, in the longitudinal configuration for three cryopump regimes; black: fully on (sample temperature of 5.5 K), red: idling (sample temperature of 20 K) and green: off (sample temperature of 55 K).

The next figure quantifies the noise in the Kerr signal with the laser spot sitting on top of a Permalloy microwire. Figure 19 shows the measured root mean square (AC) of the Kerr signal over an extended period of time (just under 500 s), with the cryopump running full strength, i.e. the target temperature set to 2 K. The noise level is excellent, 0.54 mdeg in average, which is in agreement with the findings in the continuous Permalloy film. This value of 0.54 mdeg is just over the specified noise at room temperature for longitudinal measurement. Throughout this 8-min long measurement, the laser spot remained in the same position and no drift was observed.

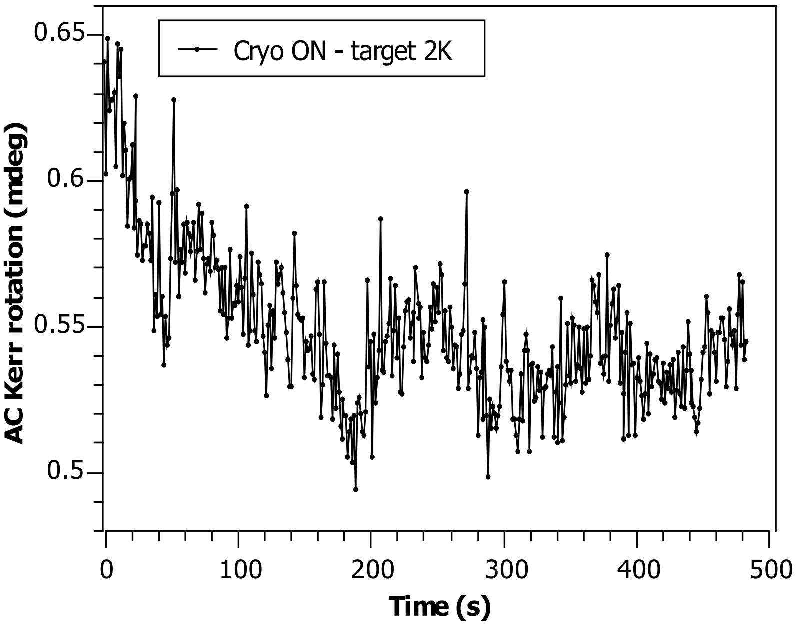

Figure 19: Root mean square of the Kerr signal over an extended period of time in longitudinal configuration, with the cryopump running at full strength (sample temperature of 5.5 K) and the laser spot sitting on top of a Permalloy microwire.