APPLICATION NOTE

Magnetic field measurement at cryogenic temperatures

Accurately measuring magnetic fields can be challenging at the best of times. Taking measurements while in a cryogenic environment brings a whole other range of considerations. This application note provides the guidance needed to be successful in this space.

Scope

This document focuses on magnetic field measurement using Lake Shore F71 or F41 teslameters and the Hall sensors or probes used with them. Other technologies such as SQUID magnetometers or fluxmeters measuring wire coils can also measure fields at cryogenic temperatures, but are not covered in this document.

Hall sensors in cryogenic environments

Of the various measurement methods available for magnetic fields, simple Hall sensors remain the most versatile, even in cryogenic temperatures. The challenge in cryogenic environments comes in correcting various performance metrics that change with temperature while also limiting unnecessary power dissipation into the very cold environment.

Lake Shore CRYOTRONICS

The 2Dex™ sensors developed by Lake Shore have some beneficial characteristics that make them excellent candidates for magnetic field measurement in cryogenic environments:

- Can take advantage of TruZero™ technology found in Lake Shore teslameters, removing the need to 'zero' the sensors, which normally requires placing the sensor in a zero gauss chamber and zeroing out the field measurement. This is particularly complicated if the sensor is installed in a cryogenic environment.
- Relatively small size compared to a coil-based system that would be required for a fluxmeter.
- Good field sensitivity, even at low sensor excitation levels.
- Simple Hall sensor construction that is compatible with cryogenic environments.
- Fairly simple measurement requirements when compared to fluxmeters and SQUID magnetometers.

Given the 2Dex sensor's improved suitability for cryogenic environments, there are several factors to keep in mind when operating at these temperatures that will allow you to take advantage of the measurement performance possible with these sensors.

Temperature dependence of Hall sensitivity

As the temperature of a Hall sensor changes, the Hall sensitivity (voltage generated for a given field [V_H/B]) will also change. For 2Dex sensors, the average change in Hall sensitivity can be seen in Figure 1, showing that Hall sensitivity will change by 1 to 2% at cryogenic temperatures. These changes impact accuracy directly, and compensating for this offset is handled automatically by the F71 and F41 teslameters as long as temperature values are supplied to the instrument.

Quantum oscillations

At high field and low temperatures, additional quantum mechanical properties of the 2DEG material begin to become apparent. The Shubnikov-de Haas (SdH) effect causes the Hall sensitivity value to oscillate, impacting measurement accuracy. An example of these oscillations for one particular 2Dex sensor is shown in Figure 2.

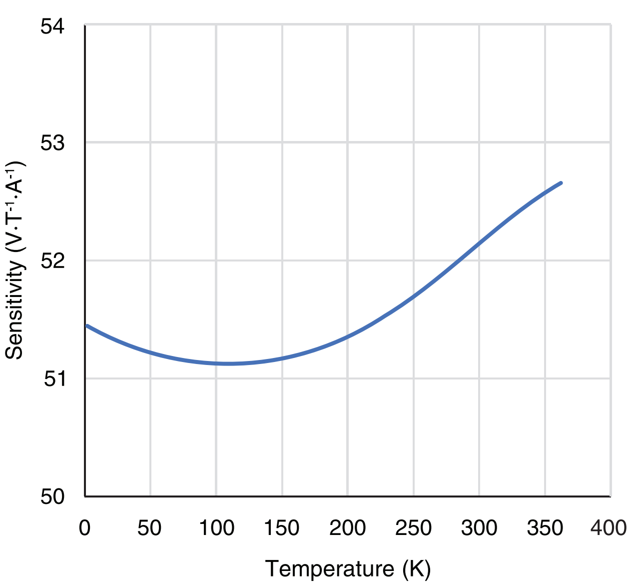

Figure 1: The average sensitivity of 2Dex Hall sensors changes slightly over its full operating temperature range. Luckily, this is relatively easy to compensate for in the measurement instrument if the temperature is known.

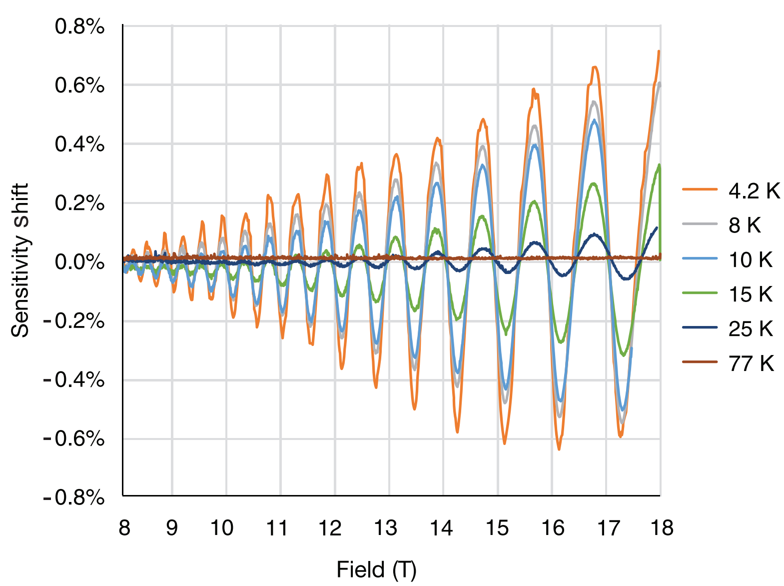

Figure 2: The SdH effect causes quantum oscillations for high fields at cryogenic temperatures. The exact shape of these oscillations is difficult to predict, so they are not easily compensated for and should instead just be accounted for.

Unfortunately, this effect is difficult to compensate for automatically as we do with other effects. The periodicity of these oscillations will change slightly from sensor to sensor, which would require individual characterization of each sensor. Instead, we must be aware of the additional measurement uncertainty that will be present in these conditions. The uncertainty graph (Figure 3) is published on the teslameter specifications page. In general, this condition only needs to be considered when operating below 25 K and above 6 T.

Self-heating

Traditional Hall sensors operate by running a drive current through the sensor and measuring the resulting Hall voltage. Maximizing this drive current creates a proportionally maximized Hall voltage that is easier to measure. However, this drive current dissipates power into the resistive sensor. This results in a balancing act with the goal being maximizing drive current without causing the sensor to heat to the point where temperature errors are introduced.

This issue is particularly relevant in cryogenic systems. Allowing heat to leak into a system unnecessarily can limit the base temperature of a cryogenic system, so measurement solutions that minimize heat dissipation are quite useful.

The plot in Figure 4 shows how several sensor technologies produce Hall voltages compared to the power that must be dissipated into the sensor, with higher sensitivities making it easier to take accurate measurements.

As a practical measurement example sensor/ instrument pairing, Figure 5 shows several configurations with real-world instrumentation. At room temperature (300 K), differences in dissipation of several milliwatts have little importance. However, milliwatts of power can be a significant hindrance at a cryostat's base temperature.

Helpful teslameter features

Although previous generations of gaussmeters and sensors from Lake Shore were recommended for measurement at cryogenic temperatures, the latest generation of sensors and instruments (F71 and F41 teslameters) were designed with cryogenic operation in mind. Several features of this combination make them far more capable for cryogenic operation.

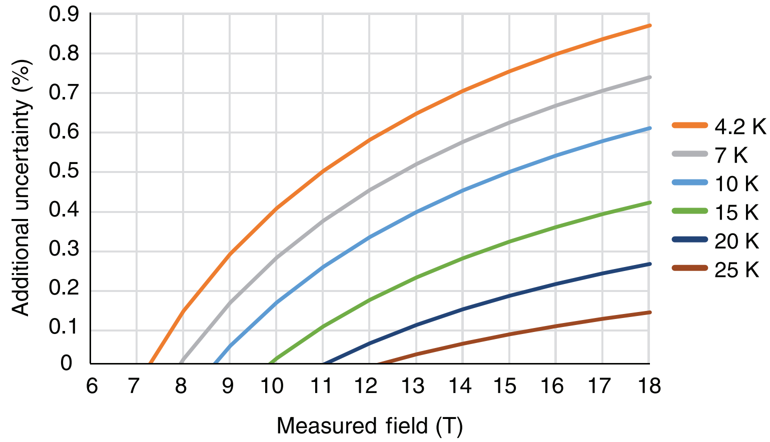

Figure 3: *Quantum Hall oscillations result in additional measurement uncertainty at very high fields in combination with cryogenic temperatures.*

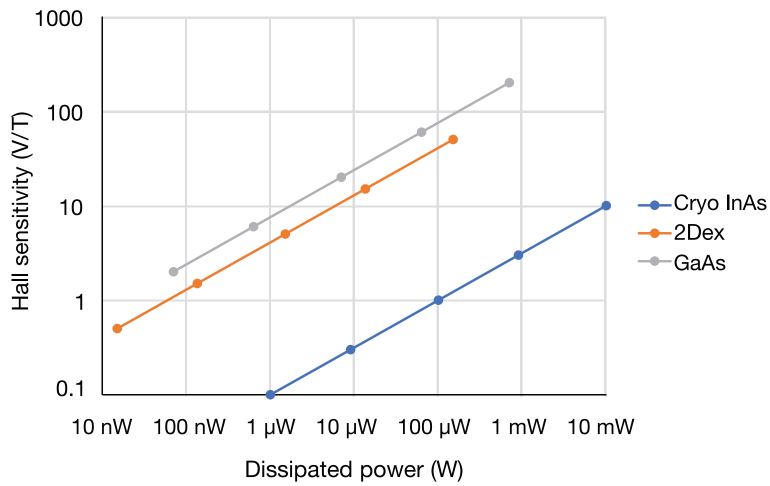

Figure 4: *Comparison of three different Hall sensor technologies. 2Dex and GaAs sensors produce much higher Hall sensitivity for a given amount of sensor heating. Unfortunately, GaAs sensors have several characteristics that make them unsuitable for cryogenic temperatures and very large fields, so 2Dex tends to be the better choice for these scenarios.*

			4 K		300 K	
Sensor technology	Associated measurement instrument	Excitation	Typical sensor resistance	Power dissipated*	Typical sensor resistance	Power dissipated*
Cryo InAs	475 gaussmeter	100 mA	0.5 Ω	5 mW	1 Ω	10 mW
2Dex	F71 teslameter	2 mA	150 Ω	0.6 mW	600 Ω	2.4 mW
2Dex	F71 teslameter (cryo mode)	0.2 mA	150 Ω	0.006 mW	600 Ω	0.024 mW

**Calculated using $P = I^2R$*

Figure 5: *When a sensor is measured by an instrument, power is dissipated into the sensor. These examples show the difference in power dissipation between several sensor/instrument combinations. Cryogenic systems may be negatively impacted if power dissipation is too high.*

External temperature compensation

The teslameter can accept temperature values from external sources and compensate appropriately based on known sensitivity changes of the 2Dex Hall sensors used with these instruments.

Keep in mind, though, that this compensates for the average Hall sensitivity change only. Due to the unpredictable nature of the quantum Hall effect, there will still be some additional uncertainty at very high fields when at cryogenic temperatures. This uncertainty is particularly problematic if making precise delta measurements, as the errors will swing from positive to negative over relatively small field value changes.

Cryogenic excitation mode

At very low temperatures, particularly below 4 K, where the cooling power of systems drops significantly, it is recommended to use the teslameter's cryogenic mode Figure 7b, which reduces power dissipation into the sensor by 2 orders of magnitude.

Cryogenic sensors and probes

If measuring field values in a location with direct accessibility from outside, such as a Dewar, a cryogenic Hall probe could be a convenient option. These have been designed to handle submersion in cryogen and are extremely long (up to 150 cm) to allow full submersion while still holding the probe.

For situations where access is not possible, or more precise positioning is desired, 2Dex plug-and-play sensors are also available that can be mounted to a convenient surface. A little more thought and effort is required to mount the sensor and then route the wiring out of the environment to the teslameter. These sensors provide all the benefits of a calibrated Hall probe mentioned above, but add the flexibility of internal mounting in a cryogenic environment.

The inline connector provides a transition from sensor wiring to cable that runs outside the cryogenic environment to the teslameter. This inline connector can be removed for direct soldering to a feedthrough if necessary for a particular cryogenic environment. If different wiring would be preferred for a given scenario, sensor customizations can be offered to suit.

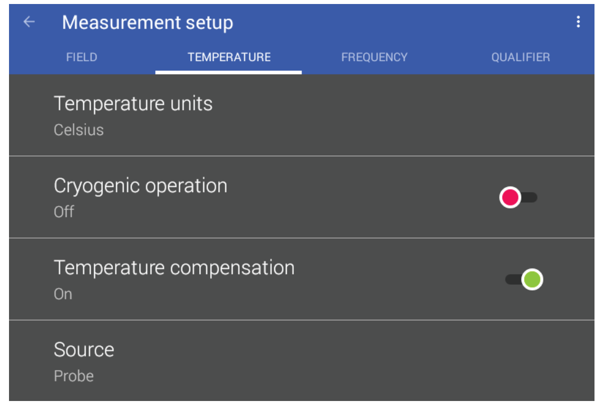

Figure 7a: *Probe configuration for room temperature.*

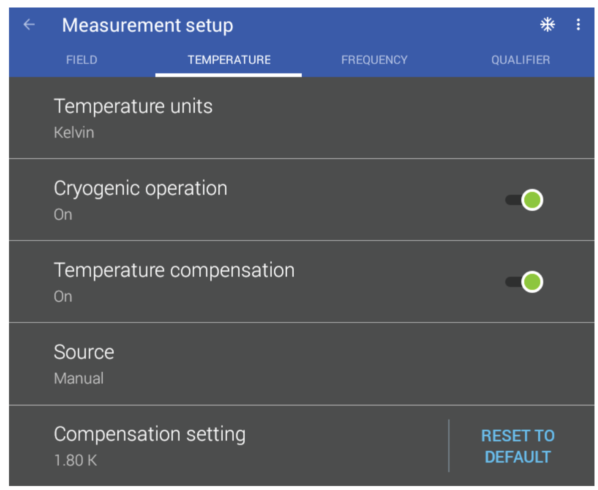

Figure 7b: *Probe configuration for cryogenic temperatures.*

Figures 7a and 7b: *Differences in teslameter configuration when operating at cryogenic temperatures. Turning on "Cryogenic operation" and setting the compensation temperature will maximize accuracy while minimizing the heat load on the system.*

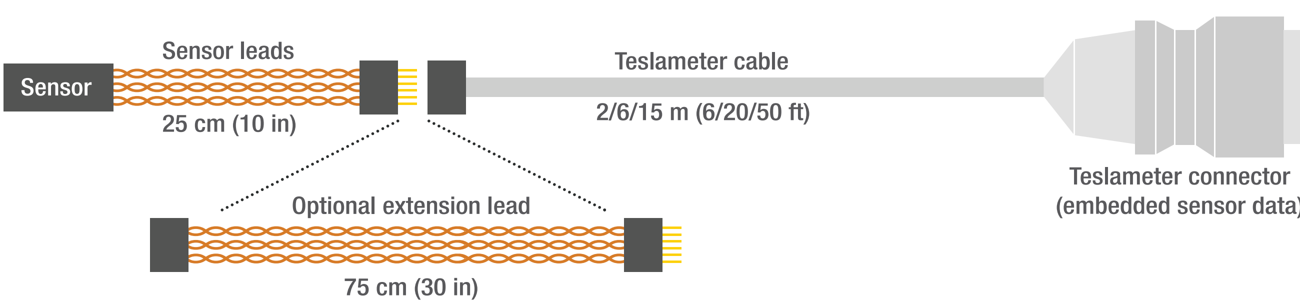

Figure 9: *Plug-and-play Hall sensors for installation in cryogenic environments where direct access from the outside is not possible or additional locational accuracy is needed.*