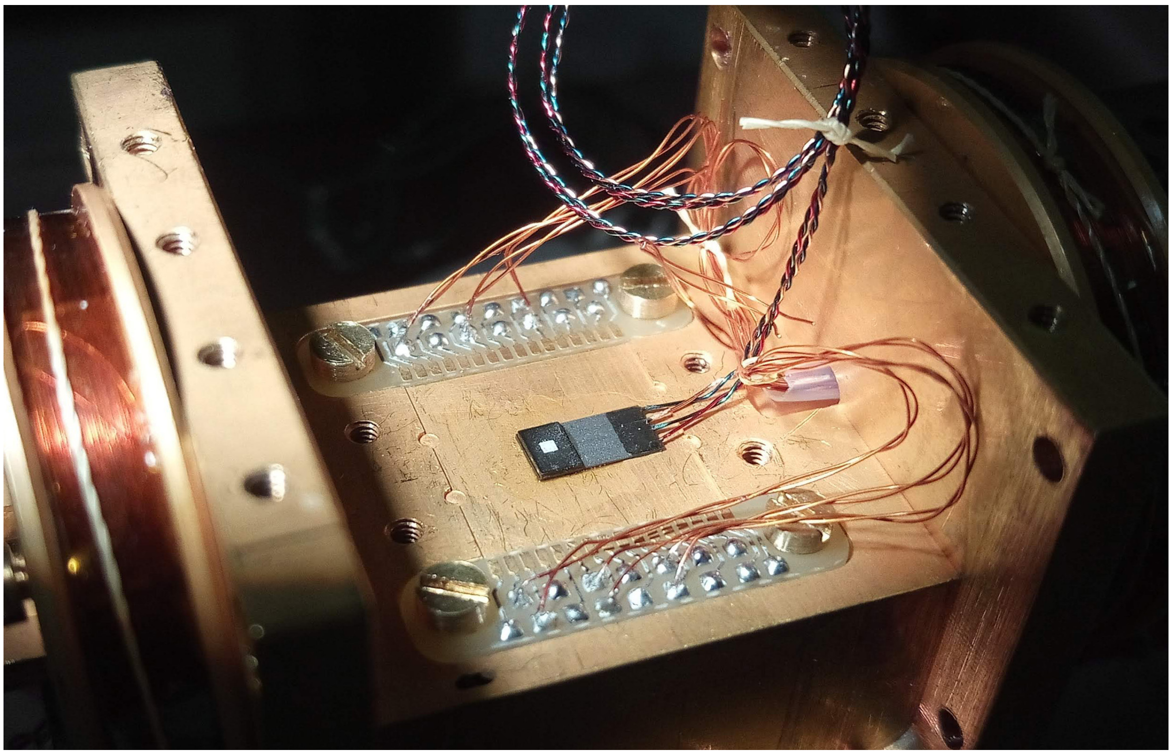
CASE STUDY

2Dex Hall Sensors

Planar Hall Effect Investigation in Cryogenic Environment

University of Cambridge – Quantum Sensors Group



Lake Shore
CRYOTRONICS

Background

Accurate magnetic field measurement is often a challenge in fundamental research scenarios, particularly when dealing with vector fields in cryogenic environments. Cryogenic conditions rule out many of the clever new **monolithic/integrated 3-axis Hall probes** that include signal conditioning circuitry in the sensor itself. As for technology specifically designed for cryogenic environments:

- Some **fluxgates** are designed for cryogenic operation but are limited in their ability to measure higher field values and can be quite large compared to the actual sensing area.
- **SQUID magnetometers** are another option, with some researchers even building 3-axis versions to measure vector fields. These instruments are extremely sensitive and useful for measuring small fields. However, these instruments are also limited in their upper field measurement capabilities and can also be relatively large with the added complexity and cost of the support electronics.

Hall sensors therefore are a compelling option due to several factors:

- Very small active areas allowing measurements to be made with high locational precision.
- A simple, resilient sensor structure that allows a wide range of operating conditions including temperature and radiation.
- This simplified structure also results in a reduced price when compared to other magnetic field measurement solutions.
- Though not capable of measuring fields as low as fluxgates or SQUIDs, Hall sensors can measure a very wide range of fields, from less than Earth field to beyond the power of even research-grade superconducting magnets, all on a single sensor.
- Options for 3-axis measurements that are more compact than fluxgates or SQUIDs.

However, they traditionally come with their own set of drawbacks:

- True vector measurements require 3 separate orthogonally positioned sensors when monolithic/integrated 3-axis Hall probes are not feasible.
- Planar Hall effects (Figure 1) in the sensors mean that fields in-plane with a sensor do not result in zero Hall voltage, making it seem like the field is slightly out-of-plane.

Technology advancement

New sensor technology (**2Dex™ Hall sensors**) developed by Lake Shore Cryotronics makes use of 2-dimensional electron gas (2DEG) structures to reduce the planar Hall effect to the point where it can no longer be detected.

Case study

The Quantum Sensors Group at Cambridge University develops ultra-sensitive superconducting detectors to detect radiation across the electromagnetic spectrum. The group built a 3-axis field generator to test these detectors, composed of 3 pairs of superconducting coils arranged orthogonally to create a field in any direction.

The coil pairs in this setup needed to have a larger separation distance than would be the case in a traditional Helmholtz coil configuration. Verification of this system would therefore benefit from true in-situ cryogenic field measurements rather than relying on simulated or calculated field values. These measurements were carried out with the field generator attached to the 2 K stage of a pulse tube cooler.

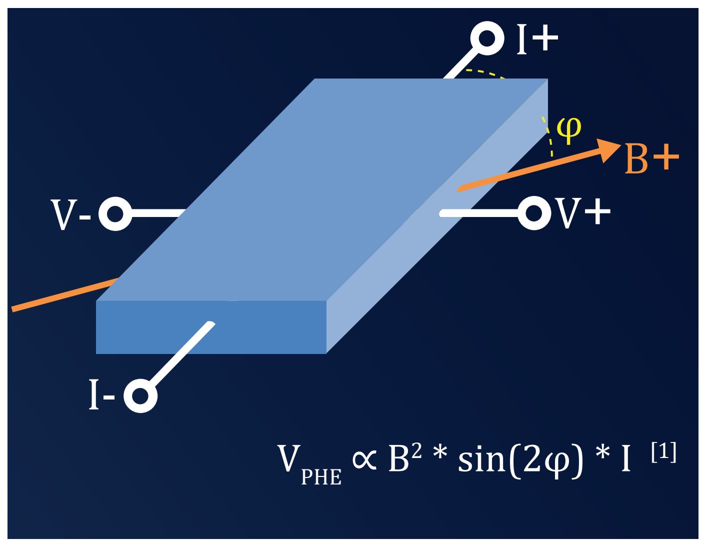


Figure 1: *Planar Hall effect produces an unwanted Hall voltage when the field is in plane with the sensor.*

[1]Weiss, H. (1969). *Structure and Application of Galvanomagnetic Devices*

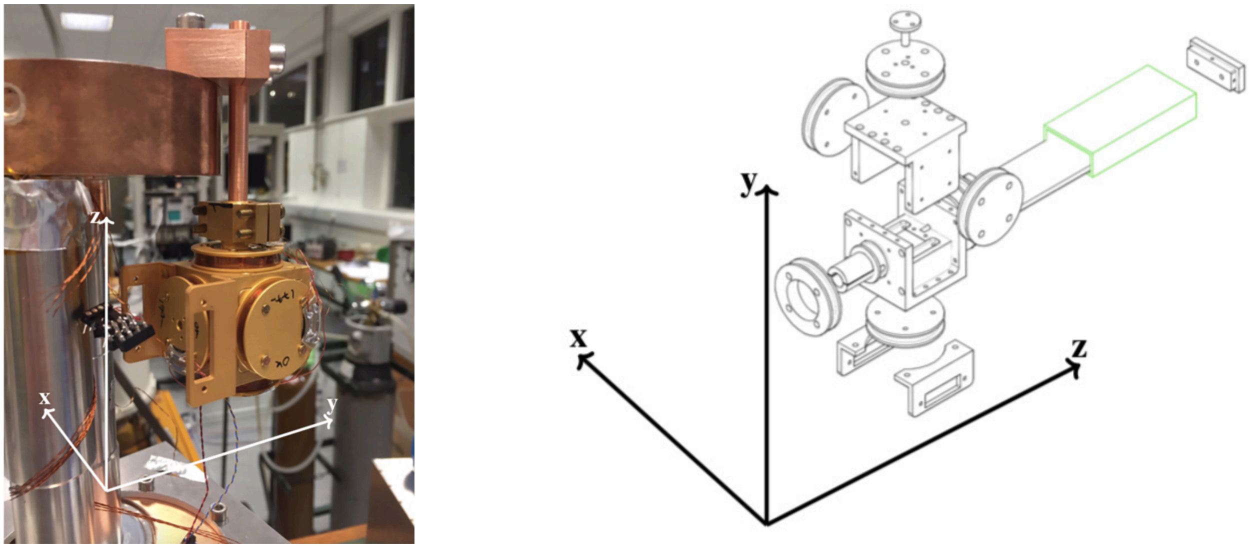


Figure 2: *The experimental setup used to test the Hall sensor. The box containing the sensor is attached to the 2 K stage of a pulse tube cooler (PTC), as shown in the photograph on the left. The exploded image of the box is shown on the right with the axis directions indicated. The Hall probe is mounted in the square region in the center, where the detector chip will sit during testing.*

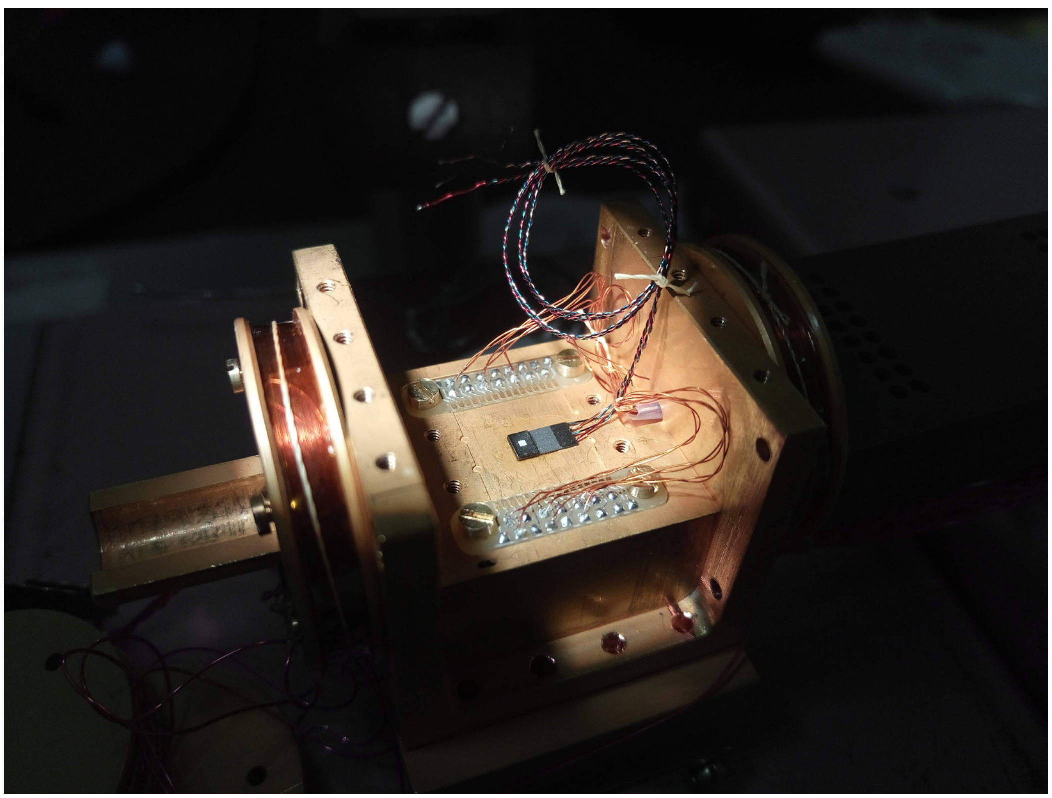


Figure 3: *The 2Dex Hall sensor mounted in the box for testing. One of the superconducting coils can be seen on the left side of the picture. The Hall sensor is mounted to detect magnetic fields in the y direction.*

The first Hall sensor used to test the system (Lake Shore HGCT-3020 cryogenic Hall sensor) demonstrated a noticeable error component due to the planar Hall effect. Fields applied in-plane with the sensor showed Hall voltages proportional to the coil's applied drive current. The 2Dex plug-and-play Hall sensor (Lake Shore 2X-250-FT-1CBL-2 connected to F71 teslameter) by comparison exhibited a greatly reduced Hall voltage.

The sensor was aligned inside the coils to maximize readings for the axis under test, with measurements taken at a temperature of 2 K. At peak, 100 mA was driven through the field-generating coils, with the results shown in Table 1. As a quick check for the presence of planar Hall effect, one set of measurements were made where the sensor was aligned with the y-axis and the y-axis coils were set to zero current. The other axis coils were powered and the field generated in the sensor was measured. Ideally, this would be zero. Any measured field will either be a result of the planar Hall effect, the coils not being exactly in the Helmholtz configuration, or misalignment between the sensor and the applied magnetic field, as seen in Figure 4.

Driven coil	Measured field
x-axis	478 μT
y-axis	501 μT
z-axis	437 μT

Table 1: *Field measurements for each set of coils with the sensor aligned for maximum field.*

		InAs Hall sensor (HGCT-3020)		2Dex Hall sensor (2X-250-FT)	
Axis	Applied field	Field value	% of applied	Field value	% of applied
x-axis	478 μT	12 μT	2.5%	4.5 μT	0.9%
z-axis	437 μT	18 μT	4.1%	1 μT	0.2%

Table 2: *Field values measured when y-axis-oriented sensor is exposed to in-plane fields.*

It should also be noted that the sensor needed to be a few millimeters off-axis for the x-direction measurement, meaning the field lines would have been slightly off-axis. Simulations of this scenario predict a field reading of 5 μT, meaning this error value of 0.9% is largely due to misalignment, rather than the planar Hall effect.

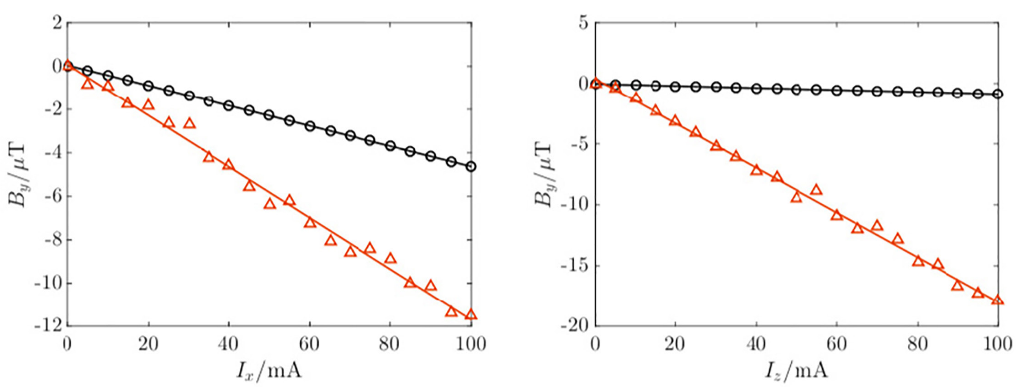


Figure 4: *The magnetic field in the y direction, measured as a function of current through each coil pair not orientated in the same (y) direction as the Hall probe. The black points show data using the 2Dex Hall sensor; the red triangles show data from the InAs Hall sensor. Left: the response of the sensors when the current in the x coil pair is swept. Right: the response of the sensors when the current in the z coil pair is swept.*

To more completely assess the performance of the 2Dex sensor, a spherical scanning technique was then applied. When the Quantum Sensors Group tests detectors, they want to be able to investigate the device response to magnetic fields in all directions so appropriate instrument shielding can be added. They fix the magnitude of the magnetic field and electrically sweep its direction using the 3-axis coil system in order to investigate the directional response.

The method used to sweep the magnetic field required some consideration. They wished to use the magnetic field to define a sphere, which can be parameterized in terms of two angles, the azimuthal (φ) and polar (θ) angles. However, moving in fixed increments of φ and θ would oversample the poles of the sphere relative to the rest of the surface. They therefore fixed the increment of φ and the area element and used these to calculate the required increments of polar angle θ. The sampling produced by this method is shown in Figure 5. The path the scan is shown in the right hand figure.

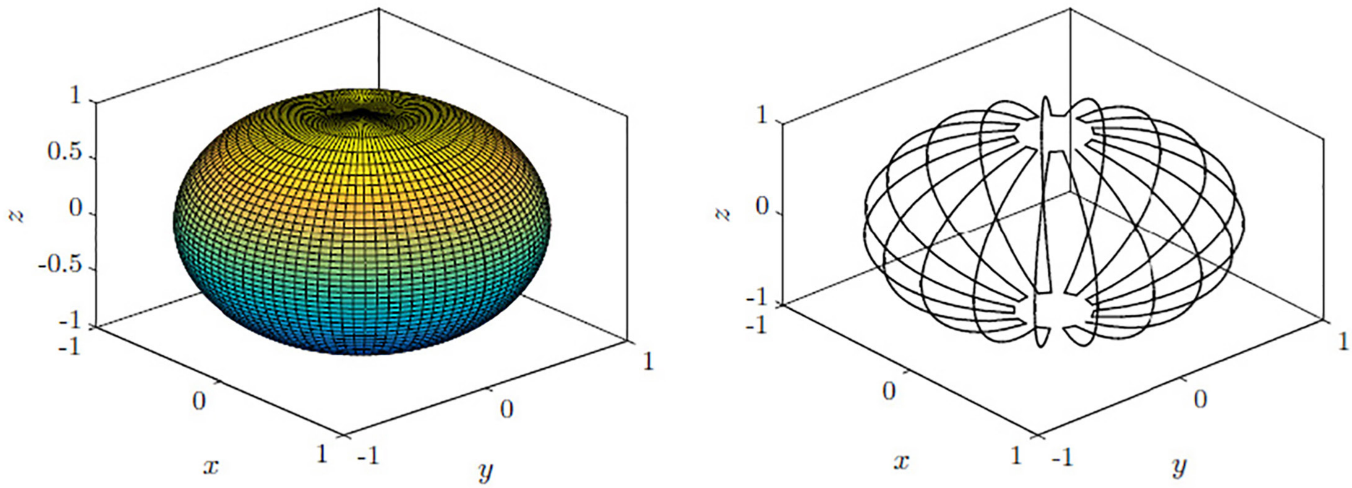


Figure 5: *Left — surface of the sphere is split into sections of equal area. Right — The path of the scan where the azimuthal angle is fixed as the polar angle is scanned over an arc on the sphere, repeating until the entire sphere is covered.*

The voltage across a device of interest can be expressed as a Taylor series expansion shown in Equation 1, where the response to the magnetic field should be linear but may have higher order terms.

$$V = f(|B|_0, \theta, \varphi) + \frac{\partial f(|B|_0, \theta, \varphi)}{\partial |B|}|B| + \frac{\partial^2 f(|B|_0, \theta, \varphi)}{\partial |B|^2}\frac{|B|^2}{2} + \cdots$$

The experimental procedure gives four values: three expressing the vector direction of the field and one expressing its magnitude. Using these, it was possible to plot the points on the surface of the response, but without any information about the functional form of the surface and so the full response surface cannot be plotted directly from the experimental data. By using a spherical harmonic basis, information was gathered about the functional form of the response surface and allowed the full response surface to be plotted.

The response (D) of a device to a magnetic field can be expressed using spherical harmonics as basis functions

$$D = \sum_{l=0}^{3} \sum_{m=-l}^{l} N(l,m) Y_l^m(\theta, \varphi)$$

where Y_l^m are the real spherical harmonic basis functions and N(l,m) is the magnitude of each component. The spherical harmonics are already an orthogonal basis so components can be extracted by integrating the product of the device response with each spherical harmonic.

$$N(l,m) = \sum_{\theta,\varphi} D^* \times Y_l^m dA(\theta, \varphi)$$

The response of an ideal Hall sensor would be expected to vary as cos θ, where θ is the angle between the normal to the plane and the direction of the applied field, so only the (m=1, l = 1) spherical harmonic should be present. This was found to be the case (Figure 6), with the next highest spherical harmonic present only at the 1.4% level. The low-level contributions could indicate errors due to misalignment of the sensor, or stray magnetic fields. The purity of the angular response verified the absence of planar Hall effects at any significant level.

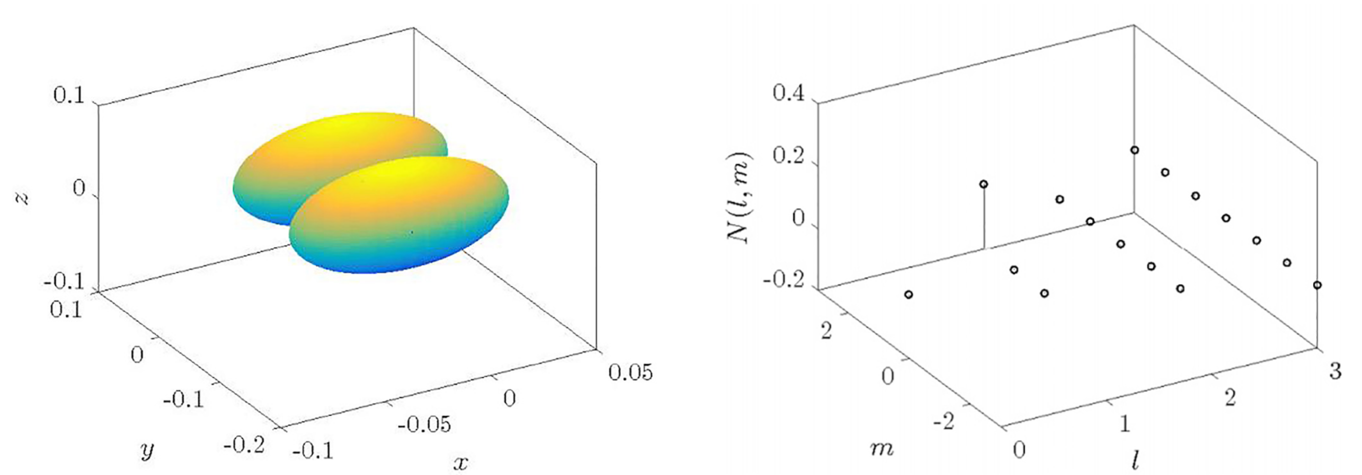


Figure 6: *(Left) The directional response of the 2Dex Hall sensor to a field of 0.1 mT, expressed using a spherical harmonic basis. (Right) The magnitude of each spherical harmonic component in the directional response.*

In addition to improved accuracy when it comes to planar Hall effect, measurement resolution has also been improved with the combination of a 2Dex sensor and a new Lake Shore F71 teslameter.

	HGCT-3020	2X-250-FT
Fluctuation in B with no current	0.2 μT	0.01 μT (20 times less)
Fluctuation with longer average time	0.5 μT	0.01 μT (50 times less)
Fluctuation at 5 mA coil current	0.3 μT	0.02 μT (15 times less)

Table 3: *Fluctuations measured with and without current in the field-generating coils*

Summary

2Dex Hall sensors paired with a Lake Shore teslameter have been demonstrated to provide superior measurements when compared to previous generation gaussmeters and InAs Hall sensors. Measurement errors as a result of offset voltages and the planar Hall effect are eliminated, as well as seeing an improvement in measurement resolution.

Acknowledgements

The results presented were provided by researchers in the Quantum Sensors Group at the University of Cambridge and have not been verified independently by Lake Shore Cryotronics. The measurements were made as part of a PhD project under a studentship awarded by the Engineering and Physical Sciences Research Council.

Disclosure

The 2Dex plug-and-play sensor (2X-250-FT-1CBL-2) was provided and the F71 teslameter was loaned at no cost by Lake Shore Cryotronics for the purpose of comparison to the previous generation product.