

Technical and Commercial Challenges in High Tc SQUIDS and Their Industrial Applications

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D. F. Lu
Midwest Superconductivity Inc.
Lawrence, KS 66049

A SQUID is the most sensitive device for measuring changes in magnetic flux. Since its discovery in the sixties, scientists have made consistent efforts to apply SQUIDS to various applications. Instruments that are the most sensitive in their respective categories have been built, such as SQUID DC susceptometer that is now manufactured by Quantum Design, pico-voltmeter which could measure 10^{-14} volts, and gravitational wave detectors. One of the most successful applications of SQUIDS is in magnetoencephalography, a non-invasive technique for investigating neuronal activity in the living human brain. This technique employs a multi-channel SQUID magnetometer that maps the weak magnetic field generated by small current when information is processed in brain, and its performance is marvelous.

All the wonders of SQUIDS have been realized using low temperature superconducting (LTS) SQUIDS that must be cooled using liquid helium. Since the discovery of high temperature superconductors in 1986, people have long expected to replace LTS SQUIDS with their high Tc counterparts in some applications, or to find new applications for high temperature superconducting (HTS) SQUIDS. A HTS SQUID is capable of working at liquid nitrogen temperature, which is far more advantageous to liquid helium in terms of cost and in terms of possibility for field applications. Many efforts have been made to take advantage of HTS SQUIDS. Various types of HTS thin film or bulk SQUID magnetometers and gradiometers have been studied. The best HTS SQUID is very competitive with its LTS counterpart in properties and performance. However, there has not been any real commercial application of HTS SQUIDS yet. Despite the promising features of HTS SQUIDS, there are still many challenges ahead before HTS SQUIDS can be widely used in commercial products. In this short paper, we would like to briefly discuss some of the issues that people need to be concerned with when trying to use a HTS SQUID in a particular application.

First of all, people have to ask themselves in what type of applications that a HTS SQUID has advantages over other techniques. Although a SQUID device is more sensitive, the cost involved is generally higher and the requirement of knowledge to operate a SQUID device is more stringent. Therefore, people need to determine for themselves how competitive a SQUID device is compared with other techniques. How much better is it to use a HTS SQUID in a particular application than those currently used systems? How much improvement can we expect over other techniques if we use a HTS SQUID in that application? Is the improvement substantial that it can be easily accepted and adopted by end users? As Weinstock always points out, one should not use a SQUID-based instrument when a simpler technology will suffice [1].

Suppose that a SQUID is a necessity for an application, should a HTS SQUID be used? For instance, can a HTS SQUID replace a LTS SQUID in susceptometers, gravitational wave detectors without or with only little compromise? Compared with LTS SQUIDS, HTS SQUIDS have only one big advantage. That is, it has a higher transition temperature and it can work at liquid nitrogen temperature instead of liquid helium temperature. This is much preferred economically, and it does open doors to a lot of possible uses of HTS SQUIDS. However, as pointed out by John Clark, a SQUID working at this temperature will never achieve as good a resolution as can their counterparts working in liquid helium [2].

At the same time, since high temperature superconductors are ceramics, they are much more difficult to process than low temperature superconductors. A superconducting transformer made of high T_c wires similar to low T_c transformers, which helps to place SQUIDs in a magnetically shielded environment, has not been realized. A HTS SQUID gradiometer cannot be made as symmetric as a LTS SQUID gradiometer, which achieves one part per million in symmetry. Thus, it will be very hard for HTS SQUIDs to replace LTS SQUIDs for sensitive measurements.

Nevertheless, we need to realize that there are still many other applications in which the sensitivities of HTS SQUIDs will suffice. For these applications, we must take full advantages of high transition temperatures of HTS SQUIDs. If they are combined with small size cryocoolers, portable HTS SQUID devices may become possible for field and industrial applications. This cannot be accomplished with LTS SQUIDs.

Of course, to apply HTS SQUIDs for field or industrial applications, many practical matters need to be taken care of. The immediate concern for field applications is that a SQUID is subject to environmental noises, such as interference from powerline, machinery, electronic equipment, and etc. It is not like those biomagnetic instruments and those scientific instruments where almost everything, such as SQUID sensors, superconducting transformers, and even the sample, is enclosed in a magnetic shielded room. Therefore the field sensed by the SQUID sensors is very small, and is all the information people want. Everything detected is useful. For field or industrial applications, there is no shielded room to use. Otherwise it cannot be portable or the cost involved is too much. Without any shielding, the SQUID is exposed to a large environmental field or interference. The interference in general is alternating fields which render a SQUID magnetometer simply not usable since most of SQUID electronics has a range of only $\pm 500\Phi_0$, while the flux produced by the interference may be hundreds times larger. The SQUID electronics just has to reset itself too frequently to be usable. HTS SQUID gradiometers may be used. However, they are also influenced by the interference due to limited symmetry. This difficulty has to be overcome for HTS SQUIDs to have a big market. Techniques may involve redesign or modification of electronics.

The large environmental noise also affects the properties of a SQUID itself. In almost all the LTS SQUID applications, the SQUID is placed in a shielded chamber and the surrounding field is tiny. The measured signal is transformed by a superconducting transformer with the pick-up coil placed outside the shielded chamber. But for high temperature superconductors, such a flexible superconducting transformer cannot be fabricated yet. A HTS SQUID has to be exposed to external field, even with thin film transformers. When it is exposed, many of its properties may change depending on the magnitude of the field. For instance, the critical current in the junction may vary with the applied field, which will certainly affect the SQUID properties. At the same time, for high temperature superconductors, flux trapping may be quite important in large field, thus causing large noises.

It is usually expected that a device with a HTS SQUID performs better than those without SQUIDs in many applications. It should be able to do what the current systems cannot do. It should be able to detect even smaller signals. While talking about possible benefits they may obtain with a SQUID, people often tend to omit the fact that the signal to noise ratio is reduced for small signals. Although the noise may be smaller than currently detectable signal, will it overwhelm the expected smaller signal detectable only by SQUIDs? If it does, the sensitivity of SQUIDs cannot be fully utilized. People need to find a way to reduce the noise further to improve the signal to noise ratio. I will take nondestructive testing of metal as an example. The conventional eddy current method is not able to detect small cracks at a depth greater than 0.5 inches. We are working on using a HTS SQUID as a sensor to replace the coil sensor in conventional eddy current method for detection of small cracks at large depth. Since our target crack (hereafter the target) is farther from the coil than the crack (hereafter the crack) that can be detected using conventional eddy current method, the current density induced at the target is smaller than that at the crack. Similarly, since the target is also farther from the sensor than the crack, the field change

generated by the target decays faster than by the crack. Because of these factors, the signal from the target is much smaller. However, the noise level remains the same. The effect of change in lift-off, the distance between the coil or sensor and the sample, is still large with the eddy current method. If such a change in lift-off cannot be controlled, it will generate a noise that may be much greater than the signal generated by the target. Useful signal will be buried in the noise. This may be more important practically than the noise of a SQUID system.

There are of course many other things people need to consider and discuss for specific applications. There is a bright future for SQUID applications in industry, there are also a lot of things to be done before it becomes a reality. Overall, researchers have to study the particular applications they are interested in, and make all necessary adjustments to build usable devices.

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References:

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