Comment on "Flux-coherent series SQUID array magnetometers operating above 77K with superior white flux noise than single-SQUIDs at 4.2K" [Appl. Phys. Lett. 107, 162602 (2015) and SNF Highlight STH35, HP101]

D. Drung, J.-H. Storm, and J. Beyer

Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, D-10587 Berlin, Germany

Email: dietmar.drung@ptb.de

In a recent paper [1], Chesca et al. presented very large arrays of superconducting quantum interference devices (SQUIDs) made of $YBa_2Cu_3O_7$. They developed devices with specially designed large area narrow flux focusers for increasing the field sensitivity, thereby obtaining sensitive magnetic field sensors. Very low white flux noise levels $\sqrt{S_\Phi}$ down to 0.25 $\mu\Phi_0/\sqrt{\text{Hz}}$ were obtained (Φ_0 is the flux quantum) at operation temperatures in the range of 77 K to 83 K. The authors claim that, in this respect, their high-temperature superconductor (HTS) series SQUID arrays (SSAs) outperform niobium-based single-SQUID sensors showing a typical flux noise of 1 $\mu\Phi_0/\sqrt{\text{Hz}}$ when operated at 4.2 K. They state in the summary that "HTS SSAs are therefore ideal candidates to replace single-SQUIDs in many applications." In this comment, we show that the presented method of comparing flux noise levels is inadequate, and that low-temperature superconductor (LTS) magnetometers operated at 4.2 K have a much lower field noise than the presented HTS devices, up to about three orders of magnitude as already demonstrated in 1993 [2].

SQUIDs are very sensitive magnetic flux detectors. They are commonly configured either as magnetometers or as current sensors, respectively [3]. In the first case, the magnetic field to be measured is directly applied to the SQUID or coupled to it via a flux transformer. In current sensing applications, an electrical current is fed into an input coil that is inductively coupled to the SQUID. In either case, it is necessary to specify the noise figure of the sensor in units of the quantity to be measured. In the case of a magnetometer, this is the magnetic field H or (more commonly) the flux density B but *not* the magnetic flux $\Phi = B\,A_{\text{eff}}$. Here, A_{eff} is the effective field-sensitive area of the SQUID magnetometer; often, the inverse $1/A_{\text{eff}}$ in units of Tesla per flux quantum is referred to as field sensitivity.

The magnetic field sensitivity of the presented HTS arrays is not explicitly specified in Ref. [1], and the comparison between the HTS arrays and a "typical" LTS single-SQUID is done on the basis of flux noise only. Taking a field sensitivity of about 4 μT/Φ_0 from Fig. 2 in Ref. [1] a flux density noise $\sqrt{S_B} \approx 1$ pT/$\sqrt{\text{Hz}}$ is obtained for the presented 770 SQUID series array at 77 K. Single Nb-based integrated magnetometers optimized for field sensing and operated at 4.2 K have demonstrated minimum noise levels of 4.5 fT/$\sqrt{\text{Hz}}$ in 1990 [4] and even 1.13 fT/$\sqrt{\text{Hz}}$ in 1993 [2]. Today, such low noise levels are routinely achieved with LTS magnetometers being operated with simple and fast readout electronics [3-5]. Therefore, practical SQUID magnetometers operated at 4.2 K have at least two orders of magnitude lower flux density noise $\sqrt{S_B}$ than the presented SQUID array magnetometers at 77 K [1]. In the case of the common washer-type SQUID [6] intended for current sensing, the device is still sensitive to magnetic fields (which is an undesired effect in current sensing applications). For example, the SQUID in Ref. [6] had a noise level of 0.7 $\mu\Phi_0/\sqrt{\text{Hz}}$ at 4.2 K, corresponding to about 50 fT/$\sqrt{\text{Hz}}$ as estimated from the geometry of the SQUID washer. Therefore, even Nb-based SQUIDs intended for current sensing are often more sensitive to magnetic fields than the HTS arrays in Ref. [1] optimized for magnetic field sensing.

The flux density noise $\sqrt{S_B}$ of a linear HTS SSA can be improved by placing flux transformers on both sides of the SSA consisting of large-area pickup loops and narrow-line input coils routed along the length of the array. Such a configuration has been demonstrated in Ref. [7] with a single-layer fabrication process and would be applicable to the devices in Ref. [1] as well. The array is then wired as a current sensor that measures the screening currents in the superconducting flux transformers. Due to the large number of SQUIDs in the arrays of Ref. [1], a relatively high input coil inductance $\gtrsim$ 10 nH can easily be realized with single-turn input coils. This would be adequate for inductance matching between input and pickup coils integrated on 10×10 mm^2 bicrystal substrates.

The relevant figure of merit for a single-SQUID current sensor is the coupled noise energy $\varepsilon = S_\Phi/(2k^2L)$, where L is the SQUID inductance and k is the coupling constant between the input coil and the SQUID loop. One could expect that the low flux noise $\sqrt{S_\Phi}$ of the HTS arrays in Ref. [1] implies a correspondingly reduced noise energy. However, as discussed in Ref. [8], the coupled noise energy of an SSA current sensor is equal to that of the individual array elements. For the best HTS array in Ref. [1] involving 770 SQUIDs with $L \approx 30$ pH, the flux noise of the individual array element amounts to $\sqrt{770} \times 0.25\ \mu\Phi_0/\sqrt{\text{Hz}} \approx 7\ \mu\Phi_0/\sqrt{\text{Hz}}$. Assuming ideal coupling ($k = 1$) this results in a noise energy $\varepsilon_c \approx 5200\ h$, which is a factor of 270 worse than that of the LTS single-SQUID in Ref. [6] and about two orders of magnitude higher than for state-of-the-art Nb-based devices at 4.2 K (for example the current sensors routinely fabricated at PTB [9]). In practice, it is difficult to efficiently couple an input coil to the presented single-layer HTS arrays of low-inductance SQUIDs. The coupling coefficient k will hardly exceed 30% which means another order of magnitude degradation in coupled noise energy compared to LTS devices with coupling constants close to unity. Thus we conclude that the reported HTS SSAs are by no means a fully adequate replacement for single-SQUIDs at 4.2 K, neither for magnetometry nor for current sensing applications.

In summary, we have discussed that the flux density noise $\sqrt{S_B}$ should be used for comparing different magnetometers rather than the flux noise $\sqrt{S_\Phi}$. For current sensors the adequate figure of merit is the coupled noise energy ε_c. The examples given here demonstrate that the relevant noise performance of LTS single-SQUIDs operated at 4.2 K is two to three orders of magnitude better than that of the presented HTS series SQUID arrays operated at 77 K. The claim of the authors of Ref. [1] that HTS series arrays have now reached a noise level to replace LTS single-SQUIDs without loss in performance is based on an inadequate noise specification and is not substantiated. In our opinion this paints a misleading picture with respect to the state-of-the-art of SQUID sensors.

References

[1] B. Chesca, D. John, and C. J. Mellor, “Flux-coherent series SQUID array magnetometers operating above 77 K with superior white flux noise than single-SQUIDs at 4.2 K,” Appl. Phys. Lett. **107**, 162602 (2015).

[2] D. Drung and H. Koch, “An integrated DC SQUID magnetometer with variable additional positive feedback,” Supercond. Sci. Technol. **7**, 242 (1994).

[3] *The SQUID Handbook*, Vol. I: Fundamentals and Technology of SQUIDs and SQUID Systems, edited by J. Clarke and A. I. Braginski (Wiley-VCH, Weinheim, 2004).

[4] D. Drung, R. Cantor, M. Peters, H. J. Scheer, and H. Koch, “Low-noise high-speed dc superconducting quantum interference device magnetometer with simplified feedback electronics,” Appl. Phys. Lett. **57**, 406 (1990).

[5] D. Drung, C. Hinnrichs, and H.-J. Barthelmess, “Low-noise ultra-high-speed dc SQUID readout electronics,” Supercond. Sci. Technol. **19**, S235 (2006).

[6] M. B. Ketchen and J. M. Jaycox, “Ultra-low-noise tunnel junction dc SQUID with a tightly coupled planar input coil,” Appl. Phys. Lett. **40**, 736 (1982).

[7] S.-G. Lee, Y. Huh, G.-S. Park, I.-S. Kim, Y. K. Park, and J.-C. Park, “Serial array high T_c SQUID magnetometer,” IEEE Trans. Appl. Supercond. **7**, 3347 (1997).

[8] V. Foglietti, K. G. Stawiasz, M. B. Ketchen, and R. H. Koch, “Performance of a flux locked series SQUID array,” IEEE Trans. Appl. Supercond. **3**, 3061 (1993).

[9] D. Drung, C. Aßmann, J. Beyer, A. Kirste, M. Peters, F. Ruede, and T. Schurig, “Highly sensitive and easy-to-use SQUID sensors,” IEEE Trans. Appl. Supercond. **17**, 699 (2007).

January 27, 2016; Editorial Note: This is a revised version of the original Comment, which appeared online on December 15, 2015. We replace that original document per authors’ request.