Low-field extension for magnetometers (TinyBee) used for investigations on low-dimensional superconductors with $B_{c1} < 5$ G

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Abstract
In this paper, a simple and easy-to-install low magnetic field extension of the SQUID magnetometer Quantum Design MPMS-7 is described. This has been accomplished by complementing the MPMS-7 magnet control system with a laboratory current supply for the low magnetic field region ($B \leq 200$ G). This hardware and software upgrade provides a significant gain in the magnetic field accuracy up to an order of magnitude compared with the standard instrument’s setup and is improving the resolution to better than 0.01 G below 40 G. The field control has been integrated into the Quantum Design MultiVu software for transparent and user-friendly operation of this extension. The improvements achieved are especially useful when low magnetic field strengths ($B < 1$ G) are required at high precision. The specific advantages of this application are illustrated by sophisticated magnetic characterization of low-dimensional superconductors like Sc$_3$CoC$_4$ and SnSe$_2$[Co(η-C$_5$H$_5$)$_2$]$_x$.

Keywords: magnetometer, current supply, low magnetic field, low-dimensional superconductor

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(Some figures may appear in colour only in the online journal)

1. Introduction
The generation of small magnetic fields in a highly reproducible manner is one of the key prerequisites to study the magnetic properties of superconductors. In particular, the precise determination of $B_{c1}$ is of ultimate importance in the case of the characterization of low-dimensional, granular or organic superconductors [1–3]. Furthermore, small magnetic fields may play a crucial role in the identification and verification of the paramagnetic Meissner effect in high-temperature superconductors (e.g. in Bi-2212) [4, 5]. However, the need for reliable low magnetic fields goes beyond the mere characterization of superconducting substances, as these also play a role in the determination of the remanent magnetization of materials used in the construction of cryogenic instruments [6].

As an application example of our low-field extension, we will show precise magnetic case studies of low-dimensional superconductors, namely the quasi one-dimensional scandium carbide Sc$_3$CoC$_4$, which was recently discovered to be superconducting [7, 8] and the metal dichalcogenide 18R-SnSe$_2$[Co(η-C$_5$H$_5$)$_2$]$_{0.19}$. Precise magnetization measurements $M(B)$ at 1.8 K and zero-field-cooling/field-cooling studies $\chi(T)$ of Sc$_3$CoC$_4$ indicate...
magnetic flux trapping even below 0.15 G. In the case of the layered superconductor \(18R\text{-}\text{SnSe}_2\{\text{Co}(\eta\text{-C}_5\text{H}_5)\}_0.19\), we demonstrate by applying low magnetic fields with minute changes (increments \(\Delta B = 0.25\) G) that the accuracy of our hardware extension is precise enough to identify strong flux pinning above \(B = 0.8\) G.\(^4\)

These precise magnetization measurements were achieved by designing a low magnetic field extension for the commercial available SQUID-based magnetic property measurement system *Quantum Design* MPMS-7. This hardware upgrade will be denoted *TinyBee* in the following.\(^5\) The intention of this extension is not to compete with state-of-the-art commercial systems or completely custom-tailored research instruments, but to offer a low-cost upgrade for the numerous research groups already operating a similar instrument as described herein.

The SQUID-magnetometer (MPMS-7) in its standard configuration is able to provide field increments as low as 0.1 G with a typical relative deviation of the order of 10% for \(B = 1\) G when using the superconducting magnet coil.\(^6\) Since the setup of the magnetic field control of the MPMS-7 is well arranged, and the control software *MultiVu* allows the incorporation of custom-tailored modules via the *external device control* (EDC) interface, it was possible to extend the magnetic field control with a more accurate current source and to achieve a seamless integration into the normal *MultiVu* measurement interface. The extension described herein consists of a hardware modification (section 2) and a software control module (section 3). The discussion of the accuracy and reproducibility of the magnetic field values is completed by a comparison of our test case magnetization measurements with alternative commercial systems (section 4). Finally, we discuss our new results on the flux trapping behaviour in the low-dimensional superconductors \(\text{Sc}_3\text{CoC}_4\) and \(18R\text{-}\text{SnSe}_2\{\text{Co}(\eta\text{-C}_5\text{H}_5)\}_0.19\) using the *TinyBee* option (section 5).

2. Hardware extension

The original current source (Kepco model JQE 6–45) is used to apply electric currents up to 45 A to achieve magnetic fields as large as 70 kG. Unfortunately, only two current ranges are implemented into the magnetic control system; the current is sensed across common shunt resistors of 0.1 and 0.01 Ω for the low and high magnetic field regions, respectively. The voltage drop is digitized with 16 bit resolution, i.e. the voltage drop at the upper limit of 7500 G of the low current mode. Hence, it is evident that this setup does not meet the requirements of precise magnetic studies at low magnetic fields smaller than 1 G.

We have therefore complemented this standard device by a laboratory current source \((I \leq 100\) mA\), and an automatic switching assembly between high-field \((B > 200\) G\) and low-field \((B < 200\) G\) operations. Our hardware of choice is a discontinued *Keithley* Model 224, but other current sources, e.g. the current *Keithley* Model 6220, are also suitable for this purpose. The used device is programmable via an IEEE-488 interface and provides also four digital output channels, which are used for operational as well as control purposes as described below.

Only minor hardware modifications are necessary as outlined in the block diagram (figure 1). In order to provide automatic switching between the current sources, we patched a high-current relay into each of both current supply lines (approximately AWG 9) from the Kepco power supply to the magnet interface in the MPMS-7 cabinet.\(^7\) In addition, both terminals of the magnet interface are wired (AWG 21) over two DIL relays, located on a perforated board, to the *Keithley* current source. Mandatory fuses \((63\) mA, *flink* characteristic) are looped in to cut off the low-current part from the high current supply as fast and as early as possible in the case of a short circuit. Both relay pairs together act as a changeover switch (as depicted in figure 1). They are excited via two driving stages that are controlled by two of the digital output ports of the *Keithley* current source and hence are accessible over the IEEE bus. At least two independent output ports are necessary as the relays controlling the positive and negative lines can be switched simultaneously, but the high-current path should be interrupted before the low-current part gets attached. The remaining two output ports of this *Keithley* device are used to connect indicator lights, which are mounted on the front panel of the MPMS-7 device.

A detailed schematic diagram can be obtained from the authors.\(^8\)

\(^4\) Although SI units were employed throughout, the unit gauss was used for convenience; \(1\) G \(= 10^{-4}\) T. We also stick to the unit emu for the magnetic moment as given by the MPMS measurement software; \(1\) emu \(= 10^{-3}\) A m².

\(^5\) The name *TinyBee* is intended as a pun for ‘tiny \(B\)’, i.e. low magnetic fields.

\(^6\) The presented extension uses the superconducting magnet coil and not the optional ac primary coils as described in the *Quantum Design* MPMS application note 1014-212. Accordingly, no (potentially risky) modification of the sample tube is necessary, as described in [9].

\(^7\) As an economic alternative for the required high-current switches, the so-called plug-in relays, normally used in automotive engineering, were employed.

\(^8\) Contact the authors directly (M Presnitz). Be aware that the authors take no liability or responsibility whatsoever for any kind of injury, damage or malfunction that may occur during the installation or use of the modification described herein.

![Figure 1. Block diagram of the hardware modification used as extension of the magnetic field control of the MPMS-7. Added components are depicted in red/grey and are emphasized. The changeover switch is realized through four relays.](image-url)
3. Software extension

The control module for our low-field extension was written in the Delphi programming language (Borland Delphi 5) as required by the EDC interface of the MultiVu software of the MPMS-7. All input commands are controlled via a parameter string within the EDC function call, which again is included in the measurement sequence file. Syntax and available commands are specified in detail in the documentation.

In the standard MPMS-7 setup, the No Overshoot mode is used for applying low fields. Hence, we developed a monotonic ramp function that sweeps to the field current for the desired magnetic field in roughly 100 s. This time period is only weakly dependent on the magnitude of the change. Furthermore, it is guaranteed that the set point of the magnetic field is never exceeded. Implementation of additional delays for the relay switching time, the current settling or the change of the persistent switch heater state was also necessary. To determine the correct timings, we analysed the IEEE bus activity during a magnetic field change using the original MPMS-7 magnet control and also monitored directly the state of the controller’s output lines. We further note that the TinyBee software module has been optimized for low activity on the IEEE bus. This is achieved by emulation of the smallest current steps of which the Keithley current supply is capable and by sending a new value to the device only in those cases where this procedure would yield a current change.

It is worthwhile to note the additional implementation of two types of control loops: the repeat and the do loop. Together with the automatic range selection, i.e. all magnetic dependent measurements rather comfortably over a wide range controller, this offers the possibility of performing field-request from the authors; see footnote 8.

4. Performance of the system

4.1. Calibration of the fluxgate probe

At room temperature, a 10 G fluxgate probe (available from Quantum Design) was used to determine the actual magnetic field strength \( B_{\text{act}} \) at the sample position inside the sample tube. First, we verified the performance of the probe with a self-wound copper coil (solenoid geometry: diameter approximately 15 mm and 1300 windings per 154.3 mm of enamel-coated copper wire, \( \varnothing = 0.10 \) mm), with an estimated error of 1% for the generated magnetic field. Within this error margin, the reading of the fluxgate probe is correct. We then checked the performance of the TinyBee setup: the dependence of the actual values from the set values turned out to be highly linear, i.e. the deviation of each data point from linearity lies within the verified accuracy of the fluxgate probe over the whole measuring range (from –10 to +10 G).

However, we observe a systematic deviation of approximately 4% of the actual field \( B_{\text{act}} \) from the applied magnetic field \( B_{\text{app}} \) within this range. This error can be reproduced using the TinyBee setup as well as the built-in MPMS-7 magnet control. We therefore suppose a slightly field-dependent variation at low fields of the proportionality factor between current and magnetic field of the superconducting field-generating coil. This assumption is based on the fact that the proportionality factor has to be calibrated at fields \( B_{\text{app}} > 10 \) kG, in order that ferromagnetic impurities in the employed palladium reference sample (provided by Quantum Design) can be neglected [10].

4.2. Comparison of the standard MPMS-7 setup with the TinyBee option using a type-I superconductor (Pb)

We also checked the performance of our TinyBee setup with a spherical lead sphere (Str nel Chemicals, purity 6N, \( m = 198.32 \) mg, \( d = 3.2 \) mm). The critical temperature of this type-I superconductor is \( T_c = 7.2 \) K. Below \( T_c \) a high voltage is induced in the pick up coils, indicating a strong (negative) magnetization. In this case, the fit routine, which assumes an ideal dipole sample, can determine the magnetic moment at high precision. For an ideal type-I superconductor, the presence of vortex dynamics or flux trapping can be safely neglected. Therefore, in the superconducting state, the volume susceptibility \( \chi_V \) equals –1. Hence, the relation of the actual magnetic field \( B_{\text{act}} \) and the measured magnetic moment \( M_p \) per sample reduces to

\[
\frac{B_{\text{act}}}{\mu_0} = \left( N + \frac{1}{\chi_V} \right) \frac{\rho}{m} M_p = (N - 1) \frac{\rho}{m} M_p.
\]

Here, \( N \) is the demagnetization factor \( (N = \frac{4}{3} \) for spherical samples), \( \rho \) is the density \( (\rho = \rho_{\text{Pb}} = 11.34 \ \text{g cm}^{-3}) \) and \( m \) is the mass of the sample.

The following procedure was used to estimate the reproducibility of the applied magnetic field \( B_{\text{app}} \): at the beginning, the superconducting magnet was quenched to eliminate the magnetic flux trapped in the coil. Then, after applying a counter field to compensate \( B_0 \), i.e. the Earth’s magnetic field together with possible remaining flux in the \( z \) direction, \( B_0 = 0.66 \) G (measured at 300 K with the fluxgate probe), the sample was cooled down to 2 K in the zero magnetic field.

Subsequently, (i) a field value of \( B_{\text{eff}} = B_{\text{app}} + B_0 = 1 \) G was achieved; (ii) after stabilization for 2 min, the magnetic moment of the sample was recorded; (iii) the magnetic field was reduced to \( B_{\text{eff}} = 0 \) G and after another delay of 2 min \( B_{\text{eff}} = 1 \) G was established again. By repeating these three steps, ten data points were recorded, once with our new TinyBee setup and once again with the built-in MPMS-7 field control system [10]. For the latter setup, the resulting values are noted below in square brackets. The mean value of the measured magnetic moment \( M_p \) is \( M_p = -2.138 \times [-2.209] \) \( \mu \text{emu} \), with a standard deviation of 1.67 [1.47] \( \mu \text{emu} \) (for a remark about the unit emu see footnote 4). According to

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Table 1. Deviation of the determined $\overline{B}_{\text{act}}$ values from the applied effective field values $B_{\text{eff}} = B_{\text{app}} + B_0$ for different magnetic fields employing both current supply units. Values given for $B_{\text{app}}$ are calculated according to equation (1) and represent mean values of ten data points. The relative errors follow from $\overline{B}_{\text{act}} / B_{\text{eff}} - 1$ and the RSD is the standard deviation with respect to the actual field $|\overline{B}_{\text{act}}|$.

| $B_{\text{app}}$ (G) | $B_{\text{eff}}$ (G) | $\overline{B}_{\text{act}}$ (G) | Relative error (%) | RSD (%) | $\overline{B}_{\text{act}}$ (G) | Relative error (%) | RSD (%) |
|---------------------|---------------------|---------------------|-------------------|--------|---------------------|-------------------|--------|
| -0.4                | 0.17                | 0.161 -0.53         | 0.52              | -0.067 | -139                | 119               |
| -0.2                | 0.57                | 0.363 -1.9          | 0.10              | 0.115  | -69                 | 4.4               |
| 0                   | 0.57                | 0.566 -0.7          | 0.10              | 0.326  | -43                 | 1.6               |
| 0.2                 | 0.77                | 0.768 -0.3          | 0.01              | 0.872  | 13                  | 11                |
| 0.4                 | 0.97                | 0.971 0.1           | 0.03              | 1.02   | 5.2                 | 5.4               |
| 0.9                 | 1.47                | 1.48 0.7            | 0.03              | 1.57   | 6.8                 | 0.21              |
| 1.4                 | 1.97                | 1.98 0.5            | 0.02              | 1.99   | 1.0                 | 3.4               |
| 4.4                 | 4.97                | 5.02 1.0            | 0.04              | 5.05   | 1.6                 | 0.13              |

In addition, we repeated this procedure for different magnetic fields. For better comparison, we have chosen magnetic field values $B_{\text{app}}$ that can be selected identically with both current supply setups, as the MPMS-7 setup is fixed to values that are multiples of 0.1 G. Together with $B_0$, in this case, $B_0 = 0.57$ G, the effective magnetic field values $B_{\text{eff}} = B_{\text{app}} + B_0$ are obtained and are listed in table 1. $B_{\text{act}}$ values follow again from equation (1), i.e. $\chi_V = -1$ is assumed; the mean value for the ten data points is denoted as $\overline{B}_{\text{act}}$. The table is completed by the relative error $\overline{B}_{\text{act}} / B_{\text{eff}} - 1$ and the relative standard deviation (RSD). The latter is the standard deviation with respect to $|\overline{B}_{\text{act}}|$ and is therefore a measure of the dispersion of the actual field values reached in different cycles for the same $B_{\text{eff}}$ value.

In contrast, figure 2 illustrates the error arising in a practical application. Here, the volume susceptibility $\chi_V$ is plotted versus $B_{\text{eff}}$, where $\chi_V$ is calculated under the commonly used assumption that the actual magnetic field $B_{\text{act}}$ is identical with the applied effective field $B_{\text{eff}}$:

$$\chi_V = \left( \frac{m}{p \mu_0 M_P} - N \right)^{-1}.$$  

Equation (2)

For fields smaller than 1 G, the absolute deviation from the ideal value $\chi_V = -1$ increases dramatically for the built-in MPMS-7 field control device. Eventually, for the smallest field ($B_{\text{eff}} = 0.17$ G), we even observed a change of sign for some of the data points; this is caused by the overcompensation of $B_0$. Therefore, the built-in MPMS-7 field control device is virtually unsuitable for precise measurements below 1 G. By contrast, the alternative TinyBee setup exhibits an excellent accuracy as witnessed by small absolute deviations (see table 1) in combination with good field reproducibility. Even though the RSD values increase with decreasing field values, they stay well below 1% (see the inset in figure 2).

In figure 3, the measured magnetic moment per sample $M_P$ (using the lead sphere described above) versus the applied magnetic field $B_{\text{app}}$ is shown. This demonstrates that the values of $M_P$ display a smooth and continuous transition when the magnetic field exceeds the maximum value feasible by the TinyBee setup. In such a case, the software automatically switches to the built-in MPMS-7 current supply for fields greater than 200 G. Hence, a measurement sequence can be carried out easily over wide magnetic field ranges employing our TinyBee control software without any manual range selection.

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11 $B_0$ includes not only the Earth’s magnetic field, but also remaining flux in the $z$ direction and hence can vary about 0.1 G.
4.3. Comparison of the TinyBee setup with different commercial magnetometers

The superconducting compound Sc$_3$CoC$_4$, described in more detail in the next section, had been selected as a benchmark system for a comparison of different commercially available magnetometers. A spherical sample ($m = 152.67$ mg, $d \approx 4.5$ mm) was cooled in the zero magnetic field down to $T = 1.8$ K to record an initial magnetization curve. The field increment was chosen to be very small ($\Delta B \leq 0.15$ G) to demonstrate the high accuracy of the TinyBee setup.

In addition to the MPMS-7 SQUID-magnetometer (with the low-field extension TinyBee setup and with the built-in power supply), two alternative commercial systems were used for comparison, a MPMS-5 and the state-of-the-art SQUID-VSM dc-magnetometer, both from Quantum Design. The resulting field-dependent magnetization measurements are shown in figure 4 for $B < 5$ G. All data points were collected stepwise in the No Overshoot mode at constant magnetic fields, with the exception of the data points extracted from the SQUID-VSM system. Here, the measurements were performed in the Continuous Field Sweep mode, because of the very fast VSM technique (one magnetization point takes 1 s). For high accuracies, we selected 0.1 G s$^{-1}$ as the field sweep rate. As a result, the different data sets are in very good qualitative agreement. Regarding the smoothness and the uniformity of the $M(B)$ data points, the TinyBee curve clearly outperforms all other measurements.

5. Experimental section

5.1. Missing ideal diamagnetism in the quasi-one-dimensional Sc$_3$CoC$_4$

In the following, we present selected case studies to demonstrate the performance of the TinyBee low-field extension. We first focus on the rare-earth transition metal carbide Sc$_3$CoC$_4$ that represent a recent example of a low-dimensional superconductor ($T_{\text{onset}}^{\text{c}} = 4.5$ K) [7]. Sc$_3$CoC$_4$ displays quasi-one-dimensional [CoC$_4$]$_\infty$ ribbons at room temperature [11]. Below 72 K, a structural phase transition occurs causing a zigzag-type chain deformation, due to the alternating displacement of the Co atoms along the [CoC$_4$]$_\infty$ chains. Such a zigzag-type pattern appears to be a typical structural motif displayed by quasi-one-dimensional superconductors and also Sc$_3$CoC$_4$ was identified as one of the few model systems showing the rare phenomenon of quasi-one-dimensional superconductivity [8, 12, 13]. Accordingly, Sc$_3$CoC$_4$ reveals all salient properties connected with low-dimensional superconducting behaviour: (i) the existence of an irreversible field in the magnetic hysteresis loop ($B_{\text{irr}}(2 \text{K}) = 2800$ G), (ii) a broad shape of the specific heat anomaly, and (iii) the upturn of the $B_{\text{c2}}$-curve at temperatures near $T_c$ [8, 14]. Furthermore, the small lower magnetic field of $B_{\text{c1}}(2 \text{K}) = (4.4 \pm 0.2)$ G, due to the large London penetration depth of about $\lambda_L = 9750$ Å, is also another indicator of low dimensionality [8].

Figure 5(a) shows the temperature dependence of the magnetic moment $M$ of the Sc$_3$CoC$_4$ sphere in the presence of an external magnetic field of $B_{\text{eff}} = 0.5$ G using the TinyBee setup. In this case study, the Earth’s magnetic field and the remaining flux was compensated using the TinyBee setup as described in section 4.2 with an accuracy of $\Delta B = \pm 0.005$ G. In the next step, the sample was cooled down to 2 K in zero field ($B_{\text{eff}} = 0$ G). After applying an effective magnetic field of 0.5 G, the magnetization was measured during the warm up sequence from 2 to 2.5 K. To check the reversibility of the temperature-dependent magnetization, the sample was cooled again and the magnetization was recorded down to 2 K. This heating and cooling sequence was repeated four times employing turnaround points at 3, 3.5, 4 and 4.5 K, respectively. After each cycle, a significant increase of the flux...
trapping was observed, until in the last field-cooled sequence starting from 4.5 K the diamagnetic response vanished. In particular, this experiment clearly demonstrates that magnetic flux penetrates the sample, which occurs in quantized flux lines, at magnetic fields just below the lower magnetic field of \( B_{c1}(2\,\text{K}) = (4.4 \pm 0.2)\,\text{G} \) as reported in [8].

To trace the origin of this conflicting observation, we also performed a magnetization measurement \( M(B) \) at very low magnetic fields, where the TinyBee setup can make use of its inherent advantages due to its high field resolution of 0.005 G to compensate the Earth’s magnetic field very precisely. Indeed, after zero-field cooling, we received the first magnetic response in a field below \( |B_{\text{eff}}| < 0.005\,\text{G} \). In figure 5(b), the magnetization versus the magnetic field is plotted in the range between 0 and 5.5 G using minute increments of \( \Delta B = 0.15\,\text{G} \). The \( M(B) \) dependence reveals no linear region even at lowest magnetic fields. The low noise level of this measurement is a direct result of the accurate magnetic field adjustment with TinyBee (cf. figure 4). The dashed line including the data points for the two lowest measured fields is employed as a guide for the eyes. Even below 0.15 G, the magnetization data deviate from the linearity, indicating flux penetration below 0.15 G. This behaviour strongly suggests the absence of ideal diamagnetism in \( \text{Sc}_3\text{CoC}_4 \). Furthermore, the temperature-dependent magnetization measurement in figure 5(a) proves that the magnetic flux penetrates the sample in quantized flux lines [15]. In the following, superconductors with such behaviour are called very low-field pinning superconductors.

At this stage, we should note that for the high-temperature superconducting cuprate \( \text{RuSr}_2\text{GdCu}_2\text{O}_8 \), the presence of a granular structure has been proposed as the origin of its missing ideal diamagnetic behaviour. The reason for this is that the pinning of the quantized vortices at low magnetic fields is mainly due to the intergrain area (i.e. the area between the grains) [2]. Therefore, the missing ideal diamagnetism does not necessarily hint at a lack of Meissner state. In the case of \( \text{Sc}_3\text{CoC}_4 \), however, we cannot exclude granularity as the reason for missing ideal diamagnetism. However, a more likely explanation might be the pinning associated with the wide spatial separation in-between the superconducting chains due to the embedding of the \([\text{CoC}_5]\infty\) ribbons in the scandum matrix.

### 5.2. Flux pinning at very low magnetic fields in the two-dimensional superconductor \( 18\text{R-SnSe}_2\{\text{Co}(\eta-\text{C}_5\text{H}_5)\}_2\) \(_{0.19}\)

Another promising candidate for pinning behaviour at very low fields is the hybrid dichalcogenide \( \text{SnSe}_2 \) intercalated with 33% cobaltocene (Co(\( \eta-\text{C}_5\text{H}_5)\)) abbreviated as \( \text{CoCp}_2 \) in the following) [16]. This layered superconductor exhibits \( T_C \approx 6.1\,\text{K} \) and a lower critical magnetic field of \( B_{c1} \approx 10\,\text{G} \) at 4.2 K. In the following, we present magnetic measurements of the layered superconductor \( 18\text{R-SnSe}_2\{\text{CoCp}_2\}_{0.19} \) in the superconducting state.

In figure 6(a), the magnetization versus the magnetic field is plotted in the range between 0 and 20 G with increments of \( \Delta B = 0.25\,\text{G} \). Again, we used the TinyBee setup to reach the highest possible accuracy. The linear fit below 1 G deviates from the magnetization data above 2.7 G indicating the onset of flux penetration in connection with a small lower critical magnetic field value of \( B_{c1} \approx 2.7\,\text{G} \). The extraordinary field resolution of the TinyBee approach allows detailed analysis of the data below 2 G (see figure 6(b)). Here, the dashed blue line is a linear fit that only includes data points at lower fields \( (B_{\text{eff}} < 0.5\,\text{G}) \). This fit already deviates from the magnetization curve below 0.8 G—a value that is significantly smaller than the estimated \( B_{c1} = 2.7\,\text{G} \). This again hints at a pinning behaviour at very low fields, which is also supported by the temperature-dependent magnetization measurement (see the inset in figure 6(b)). The zero-field-cooled/field-cooled cycles, as described in section 5.1, clearly demonstrate that the magnetic flux penetrates in quantized flux lines. The origin of such flux pinning at very low fields may be intrinsic, due to the non-superconducting structural voids between the dichalcogenide layers, or extrinsic due to geometric or granular effects [2].

![Figure 5](image-url)

*Figure 5.* (a) Temperature dependence of the magnetic moment of a \( \text{Sc}_3\text{CoC}_4 \) sphere in an external magnetic field \( B_{\text{eff}} = 0.5\,\text{G} \). The open circles mark the reversal points in the temperature of the applied heating and cooling sequences (illustrated by arrows). (b) The initial magnetization curve \( M(B) \) up to 5.5 G of \( \text{Sc}_3\text{CoC}_4 \). The blue dashed line is a guide for the eyes through the two lowest data points.

\[
\begin{align*}
M_a \text{ (a.u.)} & \quad \text{Figure 5.} \\
T (K) & \quad \text{Sc}_3\text{CoC}_4 \\
2 \ 3 \ 4 \ 5 \ 0 & \quad 2 \ 3 \ 4 \ 5 \\
-1.5 & \quad -1.0 & \quad 0.0 & \quad 4.0K \ 4.5K \\
& \quad 3.5K \ 3.0K \ 2.5K \ 0.0 & \quad (a) \ B_{\text{eff}} = 0.5G \\
& \quad (b) \ T = 1.8K \\
& \quad B_{\text{eff}} (G) \\
0 & \quad 5 \ 10 \ 15 \ 20 \ 25 & \quad -40 & \quad -10 & \quad -0 \\
0 & \quad 0 \ \Delta T & \quad 0.0 & \quad 0 \ \Delta M & \quad 0 \ \Delta M & \quad 0 \\
\end{align*}
\]
In the following, we investigated whether flux pinning at very low fields in 18R-SnSe$_2$(CoCp$_2$)$_{0.19}$ might be misinterpreted in terms of the presence of a paramagnetic Meissner effect [5] (see the supplementary data available at stacks.iop.org/MST/23/085002/mmedia). Accordingly, magnetization measurements were carried out in a MPMS-7 magnetometer in its standard configuration, where the sample was moved in a small field gradient of 0.05 G cm$^{-1}$ at 1 G. In this case, the magnetic moment of a zero-field-cooled hard type-II superconductor may produce an artefact, if the suppression of the Earth’s magnetic field to $B_{\text{eff}} = 0$ G is not precisely zero [17]. In particular, for a very low-field pinning superconductor, flux will be trapped during the ‘zero’-field-cooling process, and after moving the sample through the magnetic field gradient, a paramagnetic signal may be observed. Indeed, 18R-SnSe$_2$(CoCp$_2$)$_{0.19}$ displays paramagnetic behaviour after zero-field cooling and field cooling when the commercial MPMS-7 setup is employed (see the supplementary data). We therefore repeated our zero-field-field-cooled measurements after suppressing the Earth’s magnetic field with the TinyBee setup as discussed above and this time no paramagnetic response was found. Subsequent magnetic studies in a static magnetic field with a homemade SQUID magnetometer and a normal conducting solenoid [18, 19] also ruled out any presence of a paramagnetic Meissner effect in this dichalcogenide.

This clearly affirms that samples characterized by flux pinning at very low fields demand an accurately determined efficient magnetic field, in order to avoid effects from trapped flux. We therefore recommend the usage of our TinyBee approach especially in cases where a paramagnetic Meissner effect is observed using the standard setup of MPMS SQUID-magnetometers [20–23].

6. Concluding remarks

Due to the complementation of the standard MPMS-7 magnetic field control with an external current supply for low field values ($B \leq 200$ G), it is possible to increase the accuracy of applied magnetic fields by one order of magnitude and to achieve good reproducibility. The necessary effort is comparatively small and includes no critical tasks, as the hardware extension preserves the probe assembly of the standard MPMS-7 setup (in contrast to a previous reported construction [9]). Only modifications of the supply lines for the magnetic field coil are needed.

At the time of publication, the TinyBee extension has already been used and tested successfully in routine tasks for more than 24 months. With this setup, it is now possible to compensate the Earth’s magnetic field and other residual fields very precisely via application of an opposing field. Thus, zero-field cooling measurements, which are important for investigations on superconductors or spin glass systems, become significantly more precise and facilitated.

Moreover, for the correct determination of the magnetic field where the flux penetrates the sample and of the lower critical field $B_{c1}$, the possibility of applying small magnetic field with small increments together with high accuracy and reproducibility is vital. It has been demonstrated for two examples that for samples with flux pinning at very low fields, it is highly necessary to control low external magnetic fields very accurately in order to avoid misleading flux-trapping effects. Therefore, the TinyBee setup may be proved in future as a very useful tool for such studies.

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