Quantum Design

MPMS Application Note 1014-208

Remnant Fields in MPMS Superconducting Magnets

This application note discusses remnant fields in the MPMS 1 and 5.5 tesla magnets and how the use of different magnet charging modes can affect remnant fields. The goal is to achieve the lowest possible remnant field in your system. Further technical information and the results of a variety of measurements performed at Quantum Design are also included in this application note.

General Discussion

Many researchers are interested in measuring the magnetic behavior of samples in very low magnetic fields. Magnets wound from superconducting wire will trap remnant fields in their windings after being charged to high magnetic fields. Warming the magnet windings above their critical temperature may only expel this *trapped flux*. Furthermore, after a superconducting magnet is charged to the specified field, and a persistent current is stored in the magnet, the magnetic field will continue to relax for some period of time as the flux lines slowly move to their final equilibrium states.

Oscillate Mode

Trapped flux is minimized in MPMS systems when the magnetic field is set using the Oscillate mode. In this mode approaching the final field through a series of decreasing amplitude oscillations changes the magnetic field. This effectively forces the magnet to relax during the charging operation by cycling it through a series of smaller and smaller hysteresis loops. By using this technique, the remnant field in the 5.5 tesla MPMS magnet will typically be 2 to 6 gauss when discharging the magnet from a high field. The remnant field will relax very little after the discharge is completed.

By using the Oscillate mode, the MPMS system can normally perform measurements in both low and high fields immediately following a magnetic field change. This is accomplished without having to wait for the field to relax in order to eliminate excessive drift in the SQUID detector. It is important to note, however, that even when using the Oscillate mode, there will still be some drift in the SQUID detection system immediately following a change in the magnetic field. Measurements requiring the highest possible sensitivity should be delayed for five to ten minutes following a change in the magnetic field.

No Overshoot Mode

Since it is clearly undesirable to expose samples with hysteretic behavior to the field oscillations in the Oscillate mode, the MPMS system also allows the magnetic field to change in the No Overshoot mode. The software algorithms for the MPMS magnet control system ensure that when operating in the No Overshoot mode the desired magnet current is approached monotonically from the initial magnet current without overshooting the final value. However, since the process does not involve the forced relaxation process of the Oscillate mode, the drift in the SQUID detector will be much greater following a No Overshoot field change. There will be significantly more relaxation in the final field, especially when discharging the magnet from high to low fields.

Remnant Fields in 5.5 Tesla MPMS Magnets

This section summarizes the most important points regarding the remnant field in the 5.5 tesla MPMS magnets when using the different charging modes as well as other special conditions.

Oscillate Mode

Factory measurements have shown that the remnant fields at the center of the MPMS 5.5 tesla magnet will typically be 2 to 6 gauss when it is discharged from a high field to zero in this mode. The magnet approaches its final setting through decreasing amplitude oscillations. When the magnet is discharged to zero, relaxation of the remnant field after the discharge is minimized.

No Overshoot Mode

When discharging the MPMS magnets in the No Overshoot mode, the final field in the magnet is set using a careful approach to reach the final field from one direction. This ensures no overshoot past the desired field setting. When discharging the magnet from high fields to zero, the remnant field will typically be 20 to 40 gauss. It will often display significant relaxation toward zero over several hours following the discharge.

Remnant Fields, High Fields Discharged to Zero

After a magnet has been charged to high field and subsequently discharged to zero using either charging mode, the remnant fields have a relatively complicated structure over the full length of the magnet. Consequently, using the shortest possible scan length will further minimize the field variation experienced by the sample.

Magnet Reset Option

Once the magnet has been charged to fields greater than a few hundred gauss, only warming the magnet windings above their critical temperature (about 9.5K) can eliminate the trapped fields in the magnet. This requires either removing the magnet from liquid helium (not generally recommended), or using the MPMS Magnet Reset Option to quench the superconducting state in the magnet. The Magnet Reset Option is discussed at greater length later in this application note.

Remnant Field, Low Fields

If you want measurements at very low fields such as those less than 100 guass, treat the remnant field in the magnet as a constant field superimposed on the field produced by the current in the magnet.

Remnant Fields in 1.0 Tesla MPMS Magnets

This section summarizes the results of measurements made at Quantum Design to characterize the remnant fields in the 1.0 tesla $MPMS_2$ magnets. During the measurements described in this section, the MPMS 1.0 tesla system was placed inside a permalloy magnetic shield (Option M107) to reduce the effects of the earth's field. Magnet charging and discharging operations were performed in the Oscillate mode. Further technical data and discussions are included later in this application note.

Magnet Quench Heater

The 1.0 tesla $MPMS_2$ magnet incorporates a magnet quench heater capable of warming the superconducting windings in the magnet above their critical temperature. After applying current to the magnet quench heater for five seconds, the remnant field in the magnet (when inside the permalloy shield) is typically between 0.04 and 0.07 gauss. Experiments have shown that regardless of the magnet charging history, the remnant field in the magnet can be consistently reduced to the range of 0.04 to 0.07 gauss when using the magnet quench heater.

Remnant Field, 10 Kilogauss to Zero

After charging the magnet to 10 kilogauss and then discharging it to zero in the Oscillate mode, the remnant field in the $MPMS_2$ magnet will typically be about 0.5 gauss or less. However, the specific magnetic history of the magnet is very important and some conditions may yield remnant fields larger than 0.5 gauss.

Low Fields

An additional copper winding in the 1 T magnet can generate fields as high as about 10 gauss, allowing the system to achieve fields lower than 0.003 gauss. Placing a magnetic field sensor in the sample chamber, applying a compensating field through the copper winding, and then trapping the compensating field in the superconducting windings achieve these low fields. This provides a very low field at the center of the sample chamber.

Effects in MPMS Magnets

None of the MPMS systems employs a field sensor. Instead, the magnetic field is set by accurately setting a current in the magnet by using the measured field-to-current ratio of the magnet to compute the precise current required to achieve the desired field.

Linear Theoretical Fit

When operating the system at low fields (below about l00 gauss), the remnant field in the magnet can be treated as a constant field superimposed on the field produced by the current in the magnet. The data shown in Figure 1 were collected with a palladium reference sample in fields of +10 to -10 gauss, after the magnet had been discharged to zero field in the Oscillate mode. The palladium sample is paramagnetic, so its magnetic moment is linear in the applied field over this range.

The data in Figure 1 describe this accurately by the linear theoretical fit. Note, however, that the linear fit of the data intersects the horizontal axis at a field of about -0.8 gauss. We expect the magnetic moment of the palladium to be zero in precisely zero field and to be linear in field over this region. The data show that the remnant field appears in these measurements as a constant dc field superimposed on the field produced by the current in the magnet. Measurements up to 100 gauss typically yield similar results.

A variety of measurements have been performed on the MPMS magnets to characterize their remnant fields after charging the magnets to high fields. The remnant fields in these magnets can be minimized by using the Oscillate mode for the magnet when discharging the magnet from a high field to either a very low or zero field.

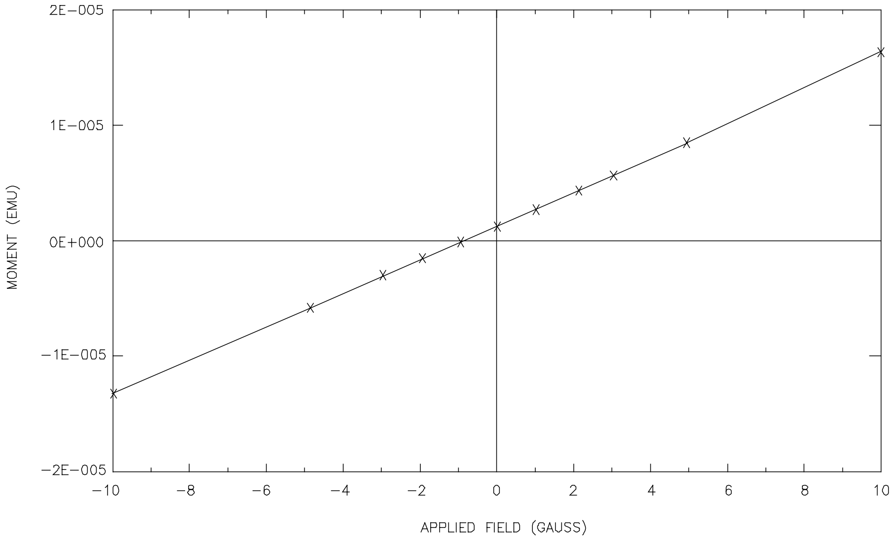

Figure 1. Remnant Field Test: Linear Theoretical Fit

Oscillate Versus No Overshoot Mode

Two examples of remnant fields appear in Figure 2, where we have plotted the longitudinal magnetic field (parallel to the longitudinal axis of the magnet) versus longitudinal position in the magnet with the center of the magnet at zero.

The data in Figure 2a were collected after an oscillating discharge from 3.0 tesla to zero. The data in Figure 2b show the remnant field following a No Overshoot discharge from 2.5 tesla to zero. Note that for similar initial fields, the remnant field in the magnet using the Oscillate mode is roughly a factor of ten smaller than the remnant field achieved when using the No Overshoot mode. Typically, the remnant field following a discharge from high fields in the Oscillate mode will be in the range of 2 to 6 gauss, while a similar discharge in the No Overshoot mode will yield a remnant field of 20 to 40 gauss.

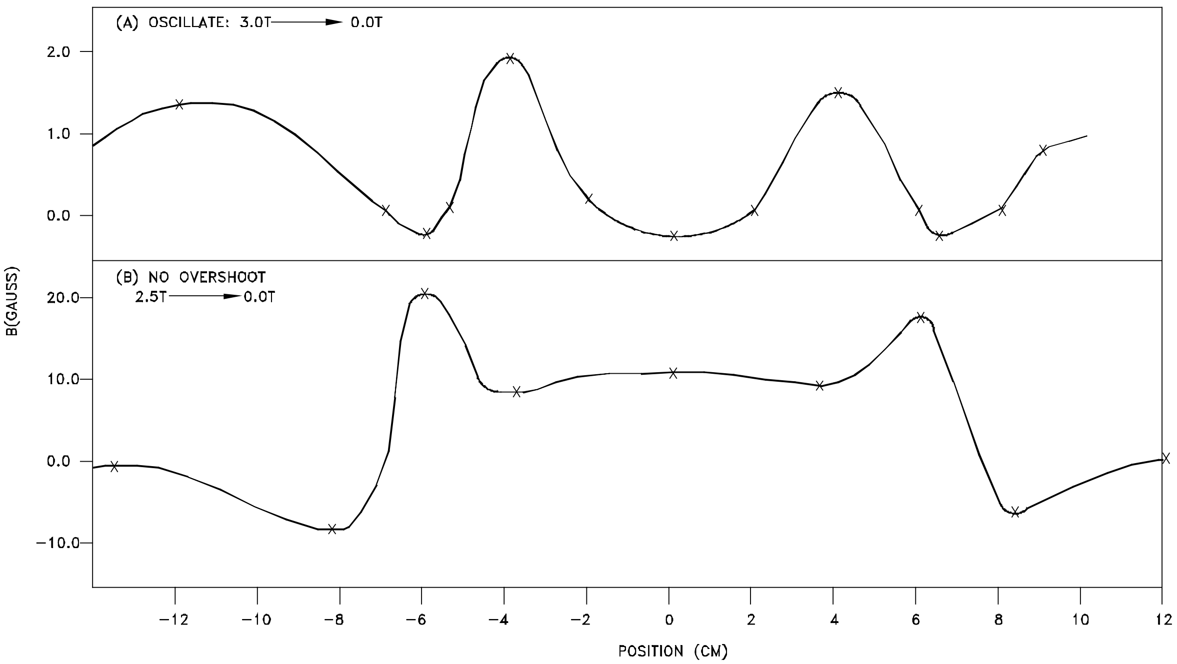

Figure 2. Oscillate versus No Overshoot Charging Mode

Remnant Field Relaxation After 24 Hours

Figure 2 shows that the remnant fields trapped in the magnet have complicated shapes. When a magnet is discharged in the No Overshoot mode, the remnant field can undergo significant relaxation for several hours after the discharging operation has ended. For example, the solid line in Figure 3 shows the remnant field in a magnet immediately following a No Overshoot discharge from 3,000 to zero gauss. The dashed line shows the remnant field in the magnet after sitting undisturbed for 24 hours. In this case (after 24 hours) the remnant field had relaxed to only about 20% of its value immediately following the discharge.

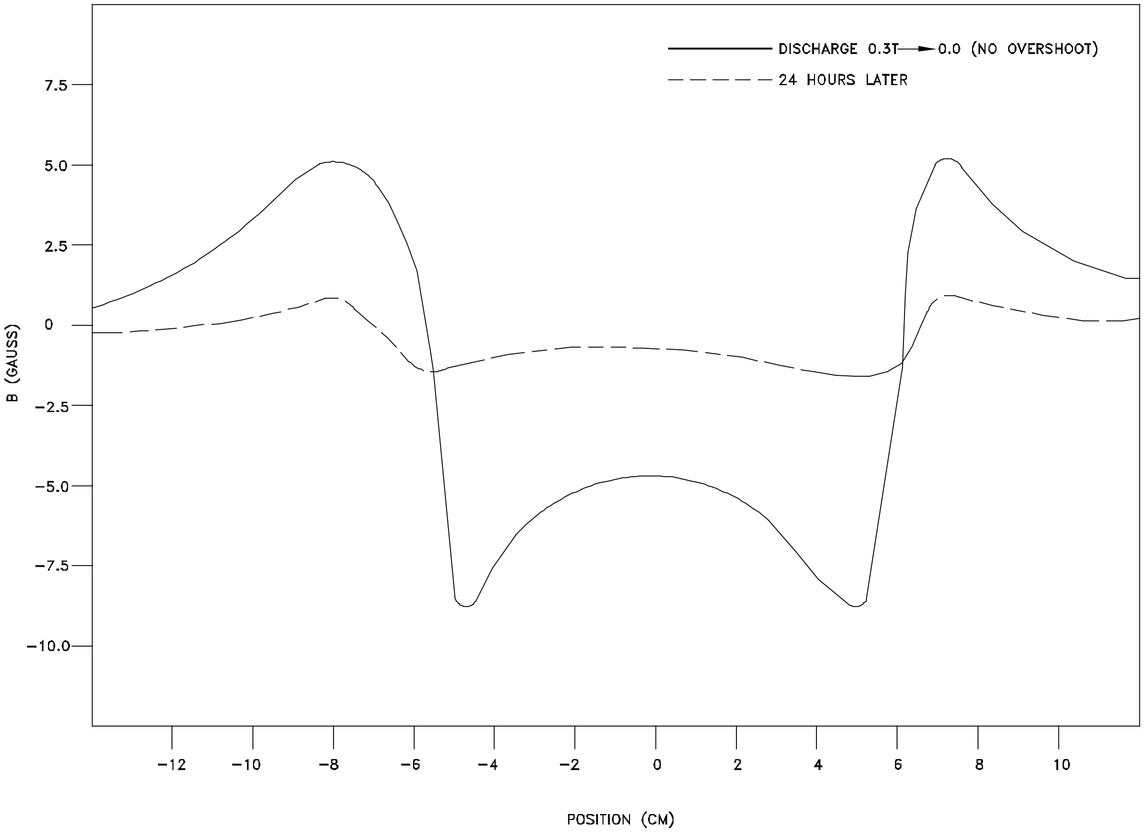

Figure 3. Remnant Field Relaxation after 24 Hours
The solid line represents the discharge from .3 T to zero.
The dashed line represents the remnant field 24 hours later).

Magnet Reset Option

The Magnet Reset Option can be used to purge trapped fields from the magnets by quenching the magnets from a high field. During this operation, the energy stored in the magnet is dumped into the windings as heat. This warms the magnet above its superconducting temperature and releases the trapped fields from the magnet winding.

Figure 4 shows the remnant field in the magnet following a magnet reset initiated from a field of 3.0 tesla. Since these measurements were made with no magnetic shielding, the magnet is not shielded from the earth's field. Notice the structure in the remnant field is near the lower end of the magnet. We have remedied this situation in MPMS magnets. This feature does not appear in the remnant fields measured in our 1.0 tesla MPMS$_2$ magnets.

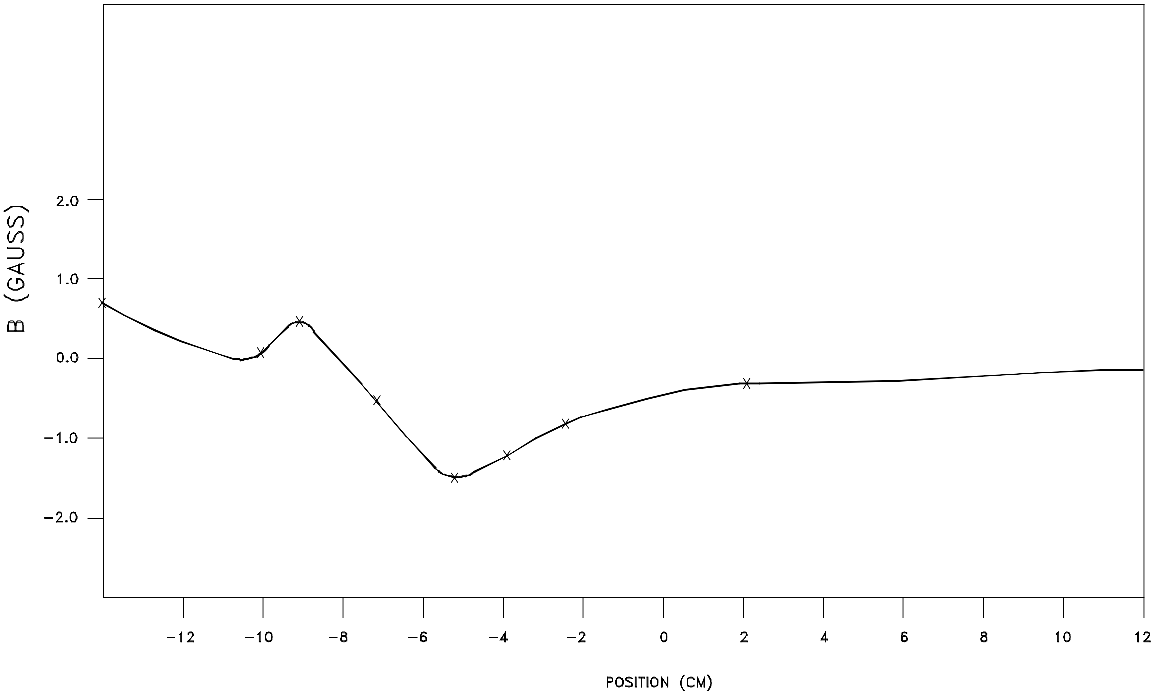

Figure 4. Magnet Reset Option (remnant field from magnet reset operation from 3.0 tesla)

Magnet Reset Option, Quench Method

Figure 5 shows data from the palladium reference sample over the range -10 gauss to +10 gauss following a magnet reset operation. In this particular case, the remnant field was reduced to a few tenths of a gauss by the reset operation. Again, as in Figure 1, the data give an excellent fit to the expected linear behavior of the palladium reference sample.

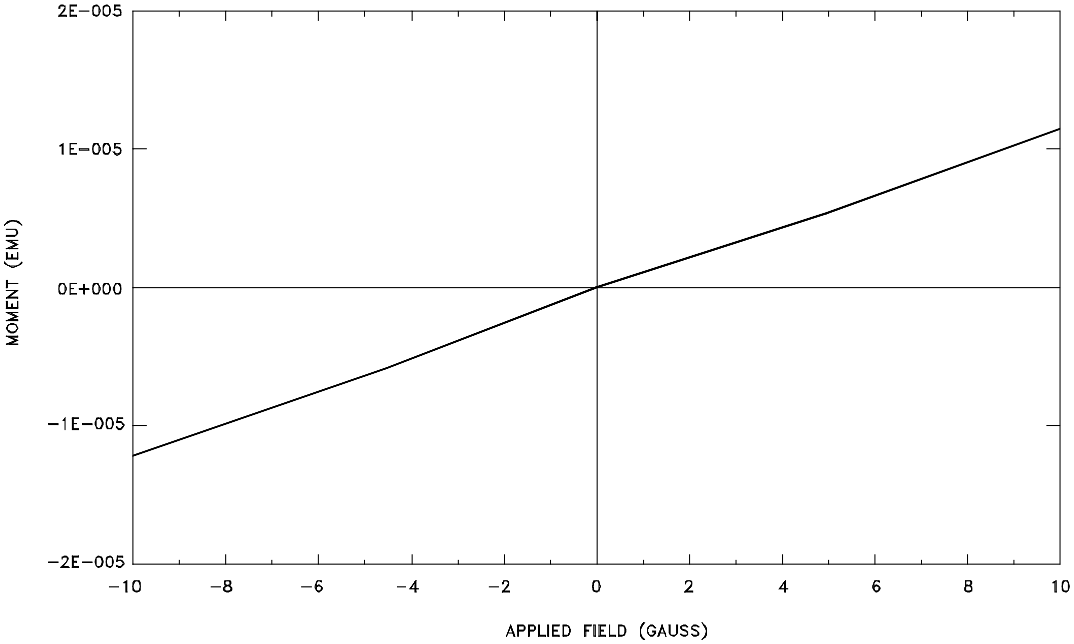

Figure 5. Magnet Reset Option, Quench Method

Remnant Fields in 1.0 Tesla MPMS$_2$ Magnets

Remnant fields are much smaller in the MPMS$_2$ 1.0 tesla magnets because there is much less superconducting material in these magnets, and the innermost windings are on a somewhat larger diameter than the 5 and 7 tesla magnets. A heating element in the magnet and operating the system inside a permalloy magnetic shield (Option M107) further reduces the remnant fields in MPMS$_2$ systems. This also significantly reduces the ambient earth's field that is normally trapped in the magnet when first cooling the system from room temperature.

Magnet Charged to Different Fields, then Discharged to Zero

Figure 6 shows the remnant fields remaining in the magnet after charging the magnet to several different fields, then discharging it to zero. The data show the field profile to the end of the windings at both ends of the magnet.

Remnant fields trapped in superconducting magnets can also have transverse components. All of the measurements described above measured the longitudinal magnetic field at the center of the magnet in a direction parallel to the magnet's solenoid axis. While using a Hall-effect sensor sensitive to fields perpendicular to the longitudinal axis of the magnet, we found that when the longitudinal field has been reduced to about 0.002 gauss. The transverse component of the remnant field is also about 0.002 gauss.

Remnant Field After Reset

The trace 1 shows the remnant field after resetting the magnet with the heating element.

Remnant Field: Fields Less than 200 Gauss

The trace 2, taken after the magnet was charged to 200 gauss and then discharged to zero in the Oscillate mode, indicates that there is essentially no change in the remnant field in the magnet when setting fields less than 200 gauss.

Remnant Field: Different Fields

Traces 3 through 5 show how the remnant field increases and character changes as the magnet is sequentially charged to 1, 5, and 10 kilogauss, while discharging to zero in the Oscillate mode after setting each field.

Effect of the Heating Element on the Remnant Field

Finally, trace 6 shows the remnant field after once again resetting the magnet via the heating element.

Remnant Field, Function of the Last Several Fields Set

It is important to note that the remnant field in the magnet depends strongly on the last few fields that have been set in the magnet and not just the most recent field that was set. For example, in Figure 7, trace 1 shows the remnant field at zero following sequential charges to +0.30, +0.40, +0.50, +0.75, and +1.00 kilogauss. Trace 2 shows the remnant field at zero following a sequence of charges to -5.0, -7.5, -10.0, and +1.00 kilogauss. Note that the remnant field in trace 2 is nearly twice as large as in trace 1.

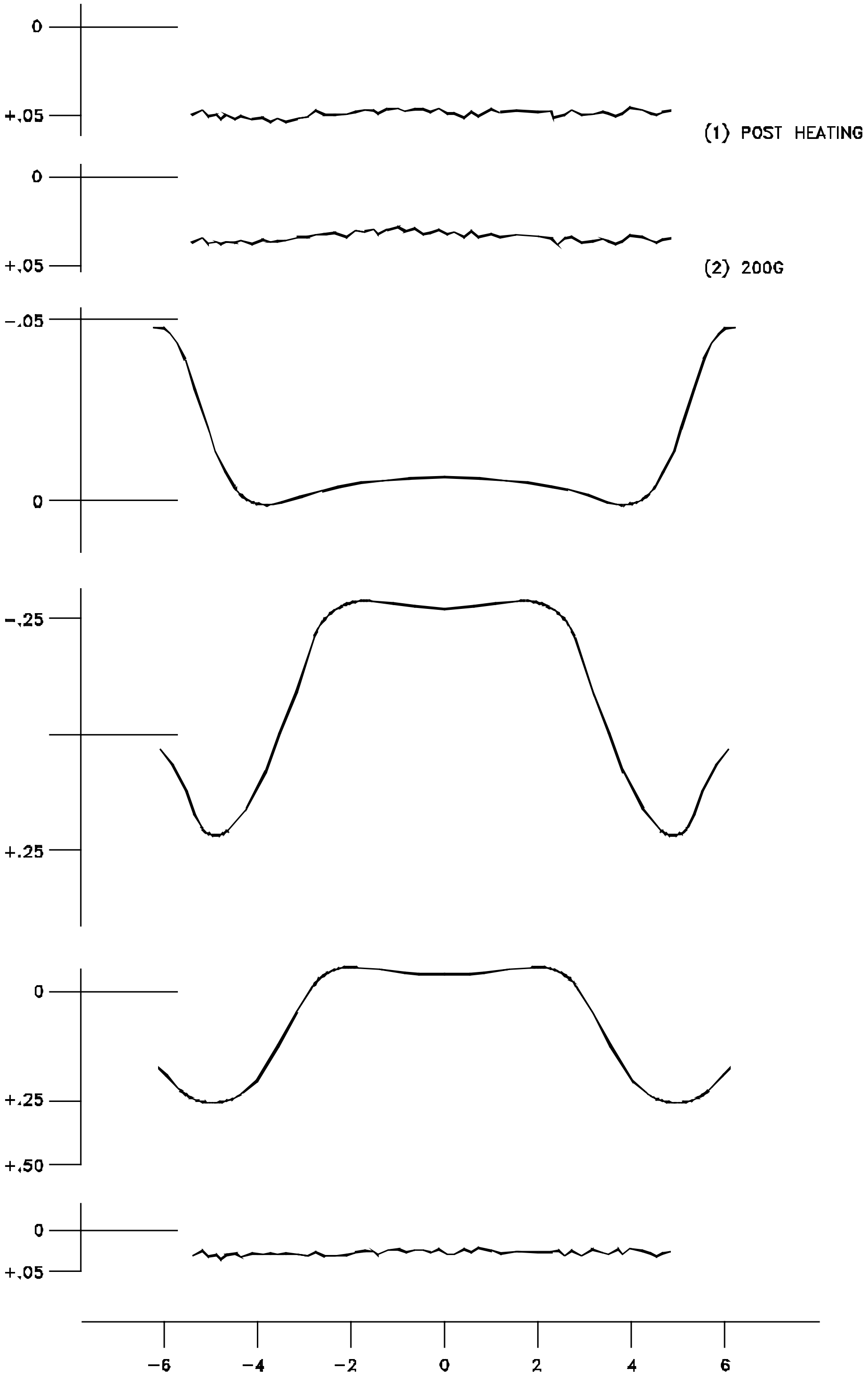

Figure 6. Magnet Profile after Charging to Different Fields then Discharging to Zero

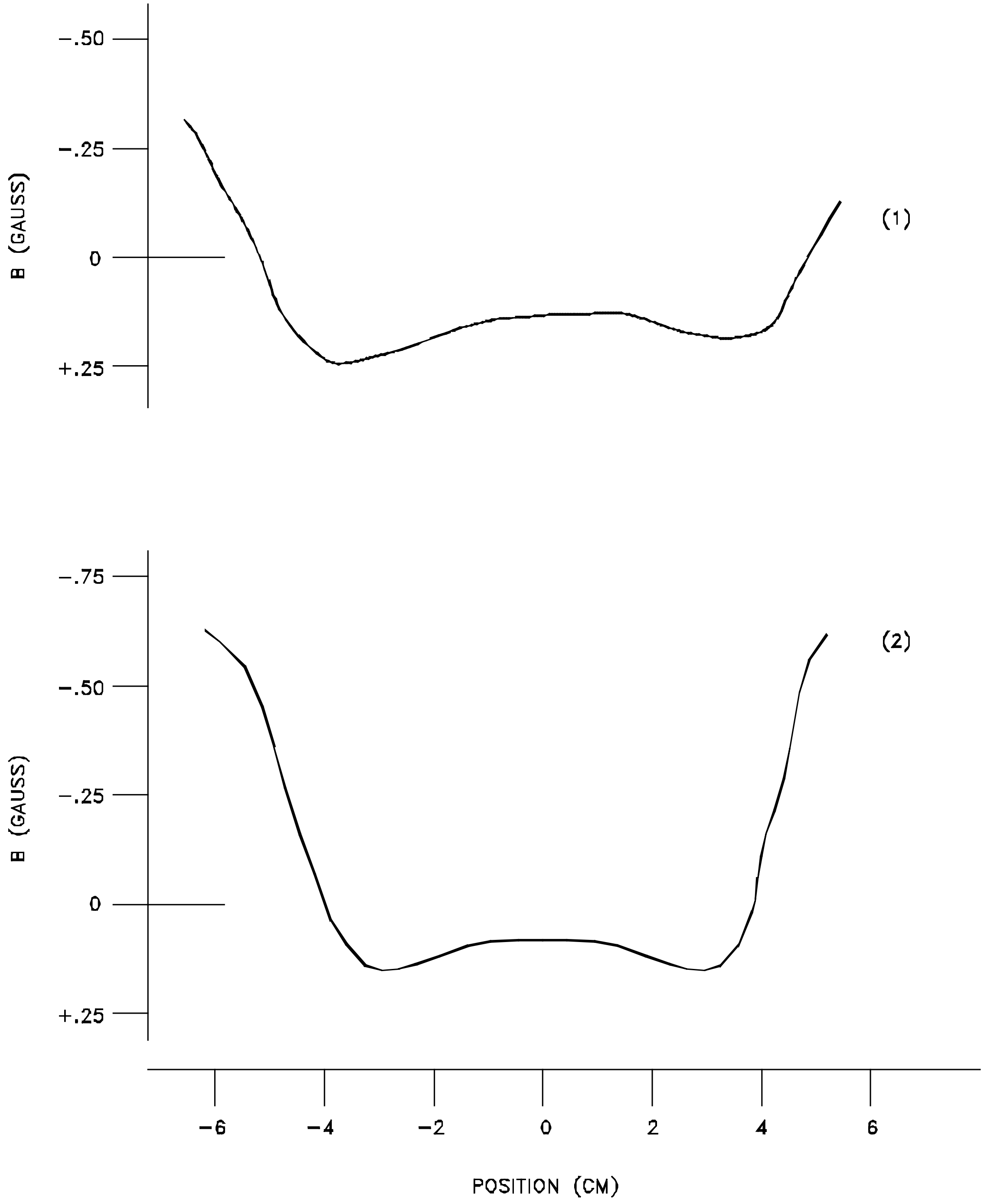

Figure 7. Remnant Field, Function of the Last Several Fields Set

Conclusions

When measuring samples that are particularly sensitive to small variations in the applied magnetic field, non-uniformities in MPMS magnets can affect measurement results. Such effects have been observed in measurements on high-temperature superconducting samples, particularly when making measurements in very low fields. The data shows that the complicated nature of the magnetic fields in the magnets limit the precision with which low field measurements in that system can be made. There are, however, several steps that can be taken to improve the reliability of such measurements.

Shortened Scan Length

The easiest and most important step is to use a short scan length when measuring the sample. Scan lengths as short as 2 cm will give reliable results when using the Linear Regression and Iterative Regression modes. You can see in Figure 2 that using a 2 cm scan length can dramatically reduce the field variations seen by the sample during a measurement when working at both low and high magnetic fields.

Oscillate to Zero and Wait Several Hours

Remnant fields in the magnet can be minimized in preparation for a series of measurements by discharging the magnet to zero in the Oscillate mode. Waiting several hours after the magnet has been discharged will probably yield a small additional reduction in the remnant field, and will help eliminate any residual drift in the SQUID detection system.

Reset the Magnet

When making measurements at very low fields, where the absolute value of the remnant magnetic field, the field uniformity, and the field stability are critical, the most reliable way to prepare the magnet is to purge the remnant field from the magnet. This is accomplished either by using the Magnet Reset Option or warming the entire MPMS probe assembly.

External Magnetic Shield

An external magnetic shield for the system is available, which can be installed around the outside of the MPMS helium dewar (inside the MPMS dewar cabinet) to reduce the ambient field at the center of the magnet to about 100 milligauss (10^{-5} tesla). Combining the shield with the Magnet Reset Option can also reduce the remnant field at the center of the magnet. **Note**: The shield will **not** reduce the amplitude of the structure in the remnant field near the lower end of the magnet (see Figure 4).

Very Low Fields

The 1.0 tesla $MPMS_2$ magnets have been specifically designed to improve the system performance at low fields. Figures 6 and Figure 7 provide data on the $MPMS_2$ field uniformity at very low fields and in several fields up to 1.0 tesla. Measurements requiring high uniformity and reproducibility at very low fields can best be performed on this system.