Unveiling of Bragg glass to vortex glass transition by an ac driving force in a single crystal of Yb$_3$Rh$_4$Sn$_{13}$

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Abstract
We present here some striking discrepancies in the results of ac and dc magnetization measurements performed in a single crystal of a low-$T_c$ superconductor, Yb$_3$Rh$_4$Sn$_{13}$. The fingerprint of a transition from an ordered vortex lattice \textit{a la} Bragg glass (BG) phase to a partially disordered vortex glass (VG)-like phase is unearthed under the influence of an ac driving force present inevitably in the isothermal ac susceptibility ($\chi'$) measurements. In contrast to its well-known effect of improving the state of spatial order in the vortex matter, the ac drive is surprisingly found to promote disorder by helping the BG-to-VG transition to occur at a lower field value in this compound. On the other hand, the isothermal dc magnetization ($M$–$H$) scans, devoid of such a driving force, do not reveal this transition; they instead yield the signature of another order–disorder transition at elevated fields, i.e., peak effect (PE), located substantially above the BG-to-VG transition observed in $\chi'$($H$) runs. Further, the evolution of the PE feature with increasing field as observed in iso-field ac susceptibility ($\chi'$($T$)) plots indicates the emergence of an ordered vortex configuration (BG) from a disordered phase above a certain field, $H^*$ (∼4 kOe). Below $H^*$, the vortex matter created via field cooling (FC) is found to be better spatially ordered than that prepared in zero field-cooled (ZFC) mode. This is contrary to the usual behavior anticipated near the high-field order-disorder transition (PE), wherein an FC state is supposed to be a supercooled disordered phase and the ZFC state is comparatively better ordered.

Keywords: peak effect, second magnetization peak, thermomagnetic history effects, generic vortex phase diagram

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

1. Introduction
In the context of the mixed state of a type II superconductor, the seminal discovery [1, 2] of a well-ordered thermodynamic phase, i.e., Bragg glass (BG), exhibiting Bragg’s reflections, and its possible transition(s) [3] to a disordered phase devoid of Bragg’s reflections, led to a generic vortex phase diagram [4] applicable to almost all pinned superconductors. Owing to the possibility of a sudden proliferation of dislocations on progressively increasing the magnetic field at a constant temperature, the quasi long-range-ordered BG phase is anticipated [1, 2] to transform first into a multi-domain (partially disordered) vortex glass (VG) phase. Such a...
transition usually reflects as a second peak in (isothermal) magnetization ($M-H$) loops, termed as the second magnetization peak (SMP) anomaly [5–11]. Thereafter, at elevated fields closer to the upper critical field ($H_{c2}(T)$), there occurs another anomaly known as the quintessential peak effect (PE) phenomenon [3, 9, 10, 12–18] in field/temperature variation in critical current density, $j_c$. The PE is argued [12] to signal the collapse of the elasticity of an ordered vortex lattice at a rate faster than the pinning force density near $H_{c2}(T)$.

Although theoretical treatment related to the BG-to-VG transition exists in the literature (for example, as in reference [2]), the experimental tools, particularly those employed to explore the bulk pinning properties such as the dc magnetization ($M-H$) measurements, do not always capture this transition. Therefore, in the context of vortex phase diagram studies, it is tempting to ask a question: is the BG-to-VG phase transition generic? If it is so, then this anomaly must get exposed in the $H-T$ space of all pinned superconductors, possessing a certain amount of quenched disorder. To address this issue, we have investigated, via detailed magnetization measurements, a low-$T_c$ isotropic superconductor Yb$_3$Rh$_4$Sn$_{13}$. The Ginzburg–Landau parameter value ($\kappa$) for this compound is around 15.2 (penetration depth, $\lambda = 1856\,\text{Å}$, and GL coherence length, $\xi = 122\,\text{Å}$ at $T = 3\,\text{K}$), which is less than the $\kappa$ value ($\kappa \sim 21$) obtained by Sato et al [14] for another crystal of the same compound. The ratio of depinning and deparing current densities ($j_c/j_b$) for the Yb$_3$Rh$_4$Sn$_{13}$ crystal investigated in the present study is of the order $\sim 10^{-4}$, and, hence, this system falls under the category of weakly pinned superconductors. To date, this compound has been known to display [14–16] only the PE phenomenon. A claim of the presence of the SMP anomaly (or its counterpart) in this compound has so far not been made by anyone. We have now found that the BG-to-VG (akin to the SMP anomaly) transition in this compound gets exposed prior to the onset of the PE under the influence of an ac driving force present in the (isothermal) ac susceptibility scans ($\chi'(H)$). Counter-intuitively, shaking of the vortex array by an ac drive in the present study has been seen to promote the spatial disordering in the vortex matter by assisting the BG-to-VG transition process. This observation is in complete contrast to the usual role of an ac driving force, which is to improve the state of the spatial order in multi-domain vortex matter, as reflected [17] by the enhanced brightness of the Bragg spots in the field-temperature phase space prior to crossover to the PE region in the vortex phase diagram. Another interesting aspect of the present study is a revelation of the inequality $j_c^{FC}(H) < j_c^{ZFC}(H)$ at lower fields (below a characteristic field, $H^* \approx 4\,\text{kOe}$). This amounts to stating that the vortex matter created in the field-cooled mode (FC) below $H^*$ exhibits better spatial ordering than that obtained in the zero field-cooled (ZFC) manner. This feature also is in sharp contrast to the behavior [19–22] seen at the higher fields, where one encounters the order–disorder transition (a la the PE phenomenon). The vortex matter created via field-cooling is expected to be spatially more disordered (than the ZFC state) due to supercooling of an amorphous vortex matter below the PE region. We present evidences that $H^*$ signifies a crossover regime from an ordered BG phase into a disordered amorphous phase while reducing the field.

2. Experimental details

Single crystals of Yb$_3$Rh$_4$Sn$_{13}$ have been grown by the tin flux method [23]. The specimen chosen for the present study is platelet-shaped, with a planar area of 5.76 mm$^2$ and a thickness of 0.62 mm. The superconducting transition temperature ($T_c$) of this crystal is found to be nearly 7.5 K. Magnetization data, both ac as well as dc, were recorded using the same instrument, i.e., a superconducting quantum interference device–vibrating sample magnetometer (SQUID-VSM, Quantum Design Inc., USA). The magnetic field was directed along the crystalline [110] axis, with a possible error in the alignment to be within 5°. The demagnetization factor in this orientation is expected to be small, as the field is applied in the plane of the thin platelet, i.e., the normal to the smallest dimension (thickness) of the sample. In the dc measurements, we kept the amplitude of vibration of the sample to be small ($\leq 0.5$ mm) so as to minimize the field inhomogeneity along the scan length. During the ac susceptibility measurements ($\chi'(H, T)$), an ac field of amplitude...
1 Oe and frequency 211 Hz was superimposed on the applied dc field.

3. Experimental results

3.1. Isothermal dc M–H loops: Manifestation of the peak effect phenomenon

The inset panel of figure 1(a) displays the first two quadrants of an isothermal dc M–H curve obtained at $T = 2$ K for field applied parallel to the [110] plane of the Yb$_3$Rh$_4$Sn$_{13}$ crystal. The $M(H)$ curve can be seen to be hysteretic between the forward ($M(H^+)$) and the reverse ($M(H^-)$) sweeps of the magnetic field, as expected for a pinned type II superconductor. However, there exists an unusual enhancement in the hysteresis width ($\Delta M = M(H^+) - M(H^-)$) prior to $H_{c2}$, as is apparent from the encircled portion of the $M(H)$ curve. A magnified view of this portion is displayed on an expanded scale in the main panel of figure 1(a). Using a prescription of the Bean’s Critical State Model [24], Fietz and Webb have shown [25] that the hysteresis width ($\Delta M$) can be taken as a measure of the critical current density, $j_c$. Therefore, the enhancement in $\Delta M$ reflects an unusual increase in $j_c(H)$ a little below $H_{c2}$, which can be identified as the PE phenomenon. The onset field ($H_{on,dc}^{pe}$) and the peak field ($H_{pk,dc}^{pe}$) of the PE stand located in the main panel of figure 1(a). The merger of $M(H^+)$ and $M(H^-)$ beyond the bubble feature identifies the irreversibility field ($H_{irr}$).

We show in figure 1(b) the fingerprint of the PE feature at different temperatures, as indicated. On increasing the temperature, a systematic decrease in the onset and the peak field values of the PE is quite apparent. The decrease in $H_{on,dc}^{pe}$ and $H_{pk,dc}^{pe}$ with $T$, nearly following the variation of $H_{c2}$ with $T$, is a characteristic feature of the PE phenomenon. The order–disorder transition pertaining to PE has been argued to have a first-order character, as was well evident in the results of the small-angle neutron scattering study in a low-$T_c$ superconductor Nb [17] and those of scanning Hall probe microscopy in 2 H-NbSe$_2$ [26].

3.2. Isothermal ac susceptibility $\chi'(H)$ responses: Identification of an additional anomaly in conjunction with the PE phenomenon

To investigate further the order–disorder transition(s) in the vortex matter, we recorded the isothermal ac susceptibility ($\chi'(H)$) responses, as shown in figure 2. The sample was initially cooled down to a chosen temperature in the (near) zero field, and thereafter the $\chi'$ data were recorded while ramping the field to higher values. The $|\chi'|$ values at $T = 2$ K can be seen to fall monotonically with increasing field until about a certain field, marked as $H_{p}^{on,ac}$ ($\approx 12.5$ K.Oe; see main panel of figure 2(a)). Above $H_{p}^{on,ac}$, a broad (anomalous) dip-like feature encompassing a large field interval (i.e., $H_{on,ac}^{pk} < H < H_{c2}$) can be noticed. Note that the identification of the onset field ($H_{on,ac}^{pk}$) of this dip feature was made possible by locating the first zero crossing in the derivative plot of $\chi'(H)$, as displayed in the inset panel of figure 2(a).

The second zero-crossing in $\chi'(H)$ identifies the peak position (marked as $H_{pk,ac}^{on}$) of the anomalous variation in $\chi'(H)$ across the dip region. We recall here that the $\chi'$ value reflects $j_c$ through the two relations [27].

(i) $\chi' \sim -1 + \alpha h_{ac}/j_c$, for $h_{ac} < h^*$

(ii) $\chi' \sim -\beta j_c/h_{ac}$, if $h_{ac} > h^*$

where $\alpha$ and $\beta$ are size- and geometry-dependent factors, $h_{ac}$ is the amplitude of the ac fields and $h^*$ is the ac field for full penetration. Following equation (i), the anomalous variation in $\chi'(H)$ above $H_{p}^{on,ac}$ in figure 2(a) amounts to an unusual increase in an otherwise monotonically decreasing $j_c(H)$. Similar anomalous behaviour in $\chi'(H)$ can also be observed at different temperatures, as illustrated in figure 2(b). While the dip feature remains quite broad at lower temperatures, one can note that the width of this anomalous region gets substantially reduced on the higher temperature side. For example, the dip in $\chi'(H)$ at $5$ K is observed to be much sharper with a narrow transition width (of nearly $2$ K.Oe) prior to approaching $H_{c2}$, which, following equation (ii), amounts...
3.3. Isofield ac susceptibility $\chi'(T)$ responses: identification of the PE phenomenon

Figure 3 displays the temperature dependences of the in-phase ac susceptibility ($\chi'(T)$) obtained at various fixed dc fields. The sample was initially cooled down to 1.8 K in (nominal) zero field, a desired field was then applied, and the $\chi'(T)$ data were recorded while warming up to higher temperatures ($T > T_c$). The zero-field superconducting transition temperature, $T_c(0)$, identified via the onset of the diamagnetic response, is found to be about 7.5 K (see inset panel of figure 3). The fingerprint of the PE feature identified by a dip-like characteristic can be observed in all the curves shown in the main panel of figure 3. At $H = 5$ kOe, the dip in $\chi'(T)$ is found to be less prominent; however, it evolves into a sharp (negative) peak at higher field values (see, e.g., the $\chi'(T)$ response in $H = 10$ kOe). On further increasing the field to 15 kOe, the PE region becomes broad, which is apparent from a wider gap between the onset ($H_{\text{on,ac}}^{\text{peak}}$) and the peak ($H_{\text{p}}^{\text{peak}}$) temperatures of the PE marked in the main panel of figure 3. Such a broadening seen in the PE feature at higher fields may be ascribed to effects of an enhancement in ‘effective pinning’ with field, as articulated by Giamarchi and Le Doussal [1, 2] and elucidated in a crystal of a low-$T_c$ superconductor 2H-NbSe$_2$ by Banerjee et al. [21].

A lesser developed (PE) anomaly at lower field value (~5 kOe) suggests the possibility of a lesser ordered vortex matter emerging at that end as well. Such a trend is consistent with the notion that an ordered vortex lattice (Bragg glass) undergoes a transition into a disordered phase on lowering the field [28, 29].

Across the field interval from about 5–14 kOe, the vortex matter seems to evolve into a better spatially ordered (Bragg glass) phase, as is evidenced by a sharp PE feature at 10 kOe in figure 3.

3.4. $H$–$T$ phase diagram

It is instructive to compare the results of the ac and dc magnetization data of figures 1–3. For this purpose, we present in figure 4, an $H$–$T$ phase diagram of Yb$_3$Rh$_4$Sn$_{13}$, which comprises the field/temperature values corresponding to the onset positions of the anomalies seen in figure 1–3. The following features in this phase diagram are noteworthy:

1. The onset field values ($H_{\text{on,ac}}^{\text{peak}}(T)$) of the PE (open triangles) acquired from the $M$–$H$ data (figure 1) fall smoothly with the increase in temperature, a trend similar to the $H_{\text{c2}}(T)$ line.

2. The corresponding onset field values ($H_{\text{on,ac}}^{\text{peak}}(T)$, shown by closed triangles) of the anomaly observed in the $\chi'(H)$ plots (figure 2), however, do not coincide with the onset position ($H_{\text{on,dc}}^{\text{peak}}(T)$) of the PE over a significantly large portion of the $H$–$T$ space (i.e., $T < 4.5$ K). Here, the $H_{\text{on,ac}}^{\text{peak}}(T)$ line stays substantially below the $H_{\text{on,dc}}^{\text{peak}}(T)$ line. Moreover, $H_{\text{on,ac}}^{\text{peak}}(T)$ values exhibit a weaker temperature dependence at temperatures below 4.5 K, unlike the faster temperature dependence seen in the case of $H_{\text{on,dc}}^{\text{peak}}(T)$. The two onset field values, $H_{\text{on,dc}}^{\text{peak}}(T)$ and $H_{\text{on,ac}}^{\text{peak}}(T)$, come closer to each other only in the boxed region (i.e., at $T > 4.5$ K and $5$ kOe $< H < 10$ kOe) and show identical temperature dependence.

3. The discrepancy in the phase diagram (figure 4) pertaining to the location of the onset fields of the anomalies seen in the (isothermal) $M$–$H$ and $\chi'(H)$ data prompts the need to take into consideration the results of the isofield $\chi'(T)$ scans (figure 3) as well. For this purpose, we have plotted in the phase diagram the onset...
temperatures \(T_{\text{on,ac}}(H)\) of the PE (shown by stars) obtained from the \(\chi'(H)\) scans. It is curious to note that the \(T_{\text{on,ac}}(H)\) values fall almost on the onset field \(H_{\text{pe}}(T)\) line of the PE transition. We draw an important inference here that the results of isothermal dc \(M-H\) loops and the isofield ac \(\chi'(T)\) scans predict the onset of the PE anomaly at nearly the same phase boundary, i.e., the \((H_{\text{pe}}^{\text{ac}}, T_{\text{on,ac}})\) line.

Clearly, there exists an additional anomaly (apart from the PE) located deeper (at \(H_{\text{p}}^{\text{ac}}(T)\)) in the mixed state of \(\text{Yb}_{2}\text{Rh}_{4}\text{Sn}_{13}\), which has been unveiled only from the outcomes of the \(\chi'(H)\) data. The other two measurement techniques (i.e., the \(M-H\) and \(\chi'(T)\) scans), on the other hand, reveal the fingerprints of only one kind of anomaly, i.e., the PE. This corroborates our previous assertion that both an ac driving force as well as the dc magnetic field ramping together trigger the said additional anomaly well below the onset of the PE (these two factors not being present together during the individual dc \(M-H\) and ac \(\chi'(T)\) runs).

The lowest field down to which the PE could be discernible in figure 4 is nearly 4.5 kOe. Since there is hardly any fingerprint of the PE feature below this value, we could surmise that the vortex matter there may not be adequately ordered. This proposition is explored further via the thermomagnetic, history-dependent magnetization measurements.

Figure 4. A sketch of the vortex phase diagram in our crystal of \(\text{Yb}_{2}\text{Rh}_{4}\text{Sn}_{13}\). \(H_{\text{on,ac}}^{\text{ac}}(T)\) and \(H_{\text{p}}^{\text{dc}}(T)\) have been extracted from \(\chi'(H)\) and \(M-H\) plots, respectively. Below \(T = 4.5\) K, the former resembles the BG-to-VG transition line (see text in section 4, discussion), while the latter portrays the characteristics of onset of the PE anomaly. In the boxed region, both \(H_{\text{on,ac}}^{\text{ac}}(T)\) and \(H_{\text{pe}}^{\text{dc}}(T)\) lines behave as the onset of the PE transition. The onset temperatures \(T_{\text{on,ac}}^{\text{ac}}(H)\) of the PE obtained from the isofield \(\chi'(T)\) scans almost fall on the onset field values \(H_{\text{on,dc}}^{\text{ac}}(T)\) of the PE extracted from the \(M-H\) loops. \(H_{\text{p}}(T)\), taken from the \(M-H\) loops, depicts the usual linear fall with increase in temperature.

Figure 5 displays the shielding responses \((\chi'(H))\) obtained at 2 K for the system prepared in two different histories, i.e., the ZFC and FC modes. The isothermal \(\chi'(H)\) data in the ZFC mode (open circles) are the same as that presented in figure 2(a). In the FC case, the sample was first cooled from the normal state (\(T > T_c(0)\)) in the presence of a certain applied field \((H < H_{c2})\) down to \(T = 2\) K, and a given \(\chi'(H)\) value was recorded. Therefore, the sample was warmed up again to a higher \(T > T_c(0)\), and the same procedure was followed for recording another \(\chi'_{\text{FC}}(H)\) value in a different cooling field. A collation of such \(\chi'_{\text{FC}}(H)\) data at 2 K is illustrated (closed circles) in figure 5. Three different field intervals can be identified: (I) across the range, 4 kOe \(< H < H_{pk,ac}\), the ZFC and FC curves can be seen to be well separated, with the latter possessing more diamagnetic values than the former. Following equations (Reference [27]),

\[(i)\hat{\chi}' \sim -1 + ah_{ac}/j_c\text{ and}\]

\[(ii)\hat{\chi}' \sim -\beta j_c/h_{ac},\]

a more negative \(\hat{\chi}'\) implies larger \(j_c\). Therefore, in the field interval 4 kOe \(< H < H_{pk,ac}\), the FC state exhibits a higher \(j_c\) than that in the ZFC state (i.e., \(j_c^{\text{FC}} > j_c^{\text{ZFC}}\)). As per the Larkin–Ovchinnikov collective pinning framework [30, 31] for weakly pinned superconductors, \(j_c\) relates inversely to the volume \((V_c)\) of a domain within which the vortices remain well correlated. Therefore, a higher \(j_c\) amounts to a smaller \(V_c\).

The history dependence in \(j_c(H)\) tends to cease above \(H_{pk,ac}\), as we observe the two curves to overlap there. This is in line with the understanding that the vortex matter above the peak field of the PE is generally believed to be ‘disordered in equilibrium’ [17]. (III) The ZFC and FC curves appear to overlap at low fields \((H < 4\) kOe) as well, as is apparent from the two sets of data points in the encircled portion of \(\chi'(H)\) (see main panel of figure 5). However, a closer examination
of the two \( \chi'(H) \) curves in this region on an expanded scale (see inset panel of figure 5) reveals slightly less diamagnetic values (at a given \( H \)) for the FC state than that for the ZFC mode, which implies the reversal of the above inequality between two \( j_c \) values; i.e., \( j_c^{\text{FC}} < j_c^{\text{ZFC}} \) for \( H < 4 \) kOe. We have marked this crossover field value (\( \sim 4 \) kOe) as \( H^\star \) in the inset panel of figure 5. The inequality \( j_c^{\text{FC}} < j_c^{\text{ZFC}} \) at low fields is found to be very robust, as it can be observed at other temperatures as well (all data not shown here, but the \( H^\star \) values at different temperatures have been displayed in the \( H-T \) phase diagram, as shown in figure 8). Although the separation between the \( \chi' \) values for the two states (ZFC and FC) appears narrower for \( H < H^\star \) in figure 5, it was checked (before normalization) that the order of this difference (\( \sim 10^{-4} \) emu/Oe) was much larger than the standard error (\( \sim 10^{-8} \) emu/Oe) involved in the measurements of \( \chi'(H) \).

The \( H-T \) phase space region below \( H^\star \) was further explored via isofield \( \chi'(T) \) scans recorded in different modes, i.e., ZFC, field-cooled cool-down (FCC), and field-cooled warm-up (FCW) runs, as depicted in figure 6. At \( H = 8 \) kOe (figure 6(a)), the shielding response is found to be less diamagnetic for the ZFC case than that observed for the FCC and FCW modes (i.e., \( j_c^{\text{FC}} (8 \text{ kOe}) > j_c^{\text{ZFC}} (8 \text{ kOe}) \) at all temperatures). This implies that the vortex matter created in the ZFC mode is better spatially ordered among the three modes, which is consistent with the observations made at this field value in figure 5. At a lower field (i.e., \( H = 7 \) kOe), the ZFC curve nearly overlaps with the FCW; these two curves stay less diamagnetic than the FCC curve for \( T > 4 \) K (see figure 6(b)). On reducing the field further to 6 kOe (figure 6(c)), the FCW curve can now be seen to be the least diamagnetic among the three curves at all temperatures. Further, there is an unusual intersection of ZFC and FCC curves at a certain temperature marked as \( T^+ \), below which the ZFC is now more diamagnetic than the FCC and FCW curves. The ZFC curve at a lower field of 3.5 kOe (see inset panel of figure 6(d)) can be seen to be more diamagnetic and well separated from the other two (FCC and FCW) curves. This implies the inequality, \( j_c^{\text{FC}} < j_c^{\text{ZFC}} \). Such a situation is the reversal of that depicted in figure 6(a) and is in agreement with the conclusion drawn from the history-dependent \( \chi'(H) \) responses below \( H^\star \approx 4 \) kOe (see figure 5). An expanded portion of \( \chi'(T) \) plots at \( H = 3.5 \) kOe in the main panel of figure 6(d) shows that the fingerprint of the PE ceases to exist in the ZFC mode, whereas a tiny modulation can still be noticed across \( T^+ < T < T_c (H) \) in the case of the FCC and FCW runs. This suggests that the vortex state created in the ZFC manner at \( H = 3.5 \) kOe is disordered to such an extent that any order--disorder vortex phase transition may not be identifiable in the temperature-dependent warm-up measurements. On the other hand, at the same field value (3.5 kOe), a nascent signature \( a \ la \) the PE observed in the FCC and FCW modes suggests that vortex matter is comparatively better ordered when created in the FC mode at 3.5 kOe.

Another demonstration of a more ordered FC state (than the ZFC state) at lower field values is apparent from the results of thermomagnetic history-dependent dc \( M-H \) measurements, as illustrated in figure 7. The \( M-H \) curve shown by open circles pertains to the usual hysteresis loop obtained in the ZFC mode at \( T = 2 \) K. Magnetization data recorded in the FC mode (\( M_{\text{FC}} \), i.e., after cooling the sample from a higher \( T \) (\( \sim T_c (0) \)) down to 2 K in the presence of different chosen field values, have also been displayed by open triangle data points in figure 7(a). If we associate the \( M_{\text{FC}} \) values to the equilibrium (reversible) magnetization (\( M_{\text{eq}} \)) and ignore the contribution due to bulk currents that can get set up due to a gradient in the macroscopic field (\( H \)) (as in the case of ZFC), then, as per equation, \( M_{\text{eq}} = (M (H^+) + M (H^-)) / 2 \) [25]; the \( M_{\text{FC}} \) data are supposed to fall in the middle of the ZFC envelope loop (as is evident, for example, in figure 4 in reference [10]). Figure 7(a) depicts an unexpected scenario, wherein the \( M_{\text{FC}} \) data points stay outside the envelope hysteresis loop for field (\( H \)) values in the interval, 5 kOe < \( H < 15 \) kOe. We can try to rationalize this using a model...
due to Clem and Hao [32], which accounts for the FC magnetization of a type II superconductor when a gradient in the macroscopic field gets established as a consequence of flux expulsion during the FC mode. In such a situation, the $M_{FC}$ values deviate from $M_{eq}$ (the ideal case of no flux pinning). This deviation of FC magnetization from $M_{eq}$ values is indeed anticipated to be governed by the strength of bulk pinning at a given field; the extent of the deviation is more (less) for stronger (weaker) pinning strength ($j_c$). As a further experimentation, on each occasion after a FC state was created at a chosen field $H$ and (iii) a characteristic line $H^*(T)$ (close to $T_c$), the FC state seems to have a lower $j_c$ value than that created in the ZFC for fields below $H'$. This observation fortifies the inferences drawn from data in figures 5 and 6. At $H = 10$ kOe the magnetization data points, while reducing the field, only marginally overshoot the ZFC envelope, and thereafter they retrace the reverse leg ($M(H^{-})$) of the ZFC magnetization curve. It can be argued that the FC state here exhibits a $j_c$ value comparable to that in the corresponding ZFC state. A significant overshooting of the ZFC envelope loop is witnessed at a higher field of 15 kOe, which indicates a larger $j_c$ value for the FC state than that created in the ZFC mode. Note that the field value of 15 kOe lies in the anomalous region, $H_{p}^{on,ac}(T) < H < H_{p}^{on,dc}(T)$ of the $H–T$ space at 2 K (figure 4), which, as discussed in section 4 ahead, is partially disordered in equilibrium, as the multi-domain VG state and the field value of 10 kOe (at $T = 2$ K) lies in the quasi-ordered BG phase (see figure 8). The magnetization data in figure 7 therefore imply that an ac field impulse transforms a supercooled disordered (FC) vortex matter into an ordered one in the domain of the BG phase (for example, at $H = 10$ kOe), and it transforms the same into a more disordered state in the pocket of the (partially disordered) VG phase ($H = 15$ kOe).

4. Discussion

The magnetization measurement techniques (both ac and dc) employed in the present work have led to new revelations in $\text{Yb}_3\text{Rh}_4\text{Sn}_{13}$, which have been summarized in the form of a modified $H–T$ phase diagram in figure 8. These include: (i) the occurrence of a broad anomaly located deeper in the mixed state triggering at the $H_{p}^{on,ac}(T)$ line, as seen in the $\chi'(H)$ curves (figure 2), (ii) identification of the onset position of the PE as the $(H_{p}^{on,dc}, T_{p}^{on,ac})$ line, as obtained from both the dc $M–H$ (figure 1) and the ac $\chi'(T)$ (figure 3) plots, and (iii) a characteristic line $H^*(T)$ extracted from figure 5, below which a vortex matter created in the FC mode is somewhat more ordered than that obtained in the ZFC manner. Following a description of L-O theory [30, 31], we argue that the anomaly in $\chi'(H)$ (figure 2) reflects a shrinkage in $V_c$ response of an FC state after perturbation by an impulse conforms to the anticipated respective equilibrium value ($M_{eq}$) (closed-triangle data points) located in the middle of the ZFC envelope loop. The imposition of an ac field impulse results in the reconfiguration of an unperturbed FC state into the state, comparison of whose $j_c$ value with that of the corresponding ZFC state can be very instructive. We thus recorded the ‘FC minor hysteresis loops’, Figure 7(b) shows the magnetization curve obtained while reducing the dc field to zero after the (perturbed) FC states were created (encircled) at $H = 5$ kOe, 10 kOe, and 15 kOe. The initial magnetization value recorded while decreasing the field from $H = 5$ kOe undershoots the ZFC envelope, and the magnetization curve thereafter traverses a path that remains within the envelope loop as the field is ramped down to the zero value. Taking a cue from the linear relation between hysteresis width and $j_c$ [25], the (perturbed) FC state is reckoned to have a lower $j_c$ value than that in the ZFC for fields below $H'$. This observation fortifies the inferences drawn from data in figures 5 and 6.

![Figure 7](image-url)
It has been shown earlier that the annealing effects on the vortex matter, produced either by an ac driving force [17, 33] or by repeated cycling of the dc magnetic field [34, 35], eliminate either partly or completely a metastable disordered vortex phase, yielding an ordered vortex configuration. Also, the residual presence of a disordered (metastable) vortex phase usually governs the onset position of the order-disorder (PE) transition(s) [21, 29, 36]. As a usual behavior, the onset position of the PE shifts to higher field values after the annealing of the (disordered) vortex phase, whereas the same moves to lower fields when the amount of quenched disorder is larger [21, 29]. Surprisingly, the shaking effect of an ac driving force appears to be counterintuitive in the present study, as it promotes the spatial disordering of the vortex matter rather than its usual role of improving the state of the spatial order. This is very apparent by the (early) occurrence of an order-disorder transition at the $H_{\text{on},\text{ac}}^p(T)$ line (see figure 8) in the $\chi'(H)$ runs, which involve the ac drive. In the absence of an ac driving force, as in dc $M-H$ scans, the onset of the order–disorder transition (PE) is seen to happen at higher fields; the $H_{\text{on},\text{ac}}^p(T)$ values in figure 8 are located significantly above the BG-to-VG transition ($H_{\text{on},\text{ac}}^p(T)$) line. If one assumes that the shaking effect on the vortex array by an ac drive results in the lowest equilibrium-like state of the system (as in reference [17]) under given circumstances, then the region bounded by the phase lines $H_{\text{on},\text{ac}}^p(T)$ and $H_{\text{on},\text{dc}}^p(T)$ in figure 8 can be accepted as ‘disordered in equilibrium’ in the form of a multi-domain vortex glass phase. The present findings echo similar assertions made recently by us [18] in another study in a single crystal of a low-$T_c$ superconductor, Ca$_3$Ir$_4$Sn$_{13}$. In that study as well, we had observed that the ac measurement technique ($\chi'(H)$) revealed an order-disorder transition whose onset field was found to be lower than the corresponding onset field of the order–disorder transition observed in the dc $M-H$ loops. However, the dc $M-H$ and ac $\chi'(H)$ runs in Ca$_3$Ir$_4$Sn$_{13}$ [18] had both revealed a broader anomaly, which prima facie appeared to be a juxtaposition of both the SMP as well as the PE anomaly in an unresolved manner. Note that in reference [18] both the onset field lines obtained from the ac and dc magnetization data (i.e., $H_{\text{on},\text{ac}}^p(T)$ and $H_{\text{on},\text{ac}}^{SMP}(T)$) represented the onset of the SMP transition, as they both were located far below the H$_{c2}(T)$ line. As a result, it became very difficult to locate the onset of the PE anomaly distinctly from the onset of the SMP transition in the vortex phase diagram of Ca$_3$Ir$_4$Sn$_{13}$ [18]. We could merely locate the peak position of the order–disorder transitions ($H_{\text{on},\text{ac}}^{SMP}$ and $H_{\text{P},\text{ac}}^{SMP}$) in reference [18], which was surmised as the VG-to-amorphization transition. In the present study in Yb$_2$Rh$_3$Sn$_{13}$, the commencement of the amorphization process of the VG phase (onset of the PE) has been easily identified (i.e., $H_{\text{on},\text{ac}}^p(T)$ and $T_{\text{P},\text{ac}}^{\text{on},\text{ac}}(H)$ lines in figure 8). A difference between the two studies can also be noticed. The onset of the order–disorder transition ($H_{\text{on},\text{ac}}^p(T)$) in reference [18] seen in the ac $\chi'(H)$ data showed a pronounced temperature dependence, whereas that observed in the dc $M-H$ data ($H_{\text{on},\text{ac}}^{SMP}(T)$ in reference [18]) remained nearly temperature-independent (for $T < 4$ K). Contrary to

![Figure 8. Complete vortex phase diagram in our crystal of Yb$_2$Rh$_3$Sn$_{13}$. Various regions have been identified (see text for details). A delineation between the BG-to-VG transition (occurring at $H_{\text{on},\text{ac}}^p(T)$) and the PE anomaly (at $H_{\text{on},\text{dc}}^{SMP}/T_{\text{P},\text{ac}}^{\text{on},\text{ac}}$) is quite apparent. The peak field values $H_{\text{P},\text{ac}}^{\text{on},\text{ac}}(T)$ and $H_{\text{on},\text{ac}}^p(T)$ obtained respectively, from the $M-H$ and $\chi'(H)$ data almost fall on the same phase boundary. The region between ($H_{\text{P},\text{ac}}^{\text{on},\text{ac}}(T)$/$H_{\text{on},\text{ac}}^p(T)$) and the $H_{\text{P},\text{ac}}^q(T)$ line presumably comprises pinned amorphous matter, while the narrow space between $H_{\text{on},\text{dc}}^p(T)$ and $H_{\text{c2}}(T)$ may involve unpinned amorphous vortex matter. Below $H_{\text{c2}}(T)$ (obtained from figure 5), the $H-T$ phase space region comprises (reentrant) disordered vortex matter a vortex configuration created here in the FC manner is found to be slightly more ordered than that in the ZFC mode.](image-url)
this, in the present study, the temperature dependences of the corresponding onset fields of the anomaly in the ac and dc measurements (see $H_{p}^{ac}(T)$ and $H_{p}^{dc}(T)$ lines in figures 4 and 8) have been the other way around.

It is pertinent to note that in an earlier study [16] in Ca$_3$Rh$_4$Sn$_{13}$ and Yb$_3$Rh$_4$Sn$_{13}$ by some of the present authors, the signature of the SMP transition in the dc $M$–$H$ loops (devoid of an ac drive) was observed only in the case of the former, whereas the same could not be unveiled in the latter. Such a difference may be attributed to the possibility of the occurrence of symmetry transition from triangular to square flux line lattice (PLL) with increasing magnetic field in the crystals of Ca$_3$Rh$_4$Sn$_{13}$ [37]. The symmetry transition could influence the underlying pinning and may lead to the triggering of the SMP transition in Ca$_3$Rh$_4$Sn$_{13}$. Therefore, the SMP anomaly in the single crystals of Ca$_3$Rh$_4$Sn$_{13}$ can be easily surfaced (without involving an ac drive) in the field-sweeping (dc $M$–$H$) magnetization runs. In the present study, we have found that an additional ac driving force is needed to trigger the SMP transition in Yb$_3$Rh$_4$Sn$_{13}$, which was not the case in Ca$_3$Rh$_4$Sn$_{13}$ [16].

The nature of the BG-to-VG transition had been argued to be of the first order [38] in a high-$T_c$ superconductor. To fortify this proposition, we may emphasize that the region bounded between $H_p^{on,ac}(T)$ and $H_{pe}^{on,dc}(T)$ in figure 8, which is shown from the $\chi'/(\chi'')$ data to be disordered in equilibrium, is indeed an ordered vortex phase when viewed from the outcomes of the dc $M$–$H$ measurements. Therefore, the vortex phase in this region can be treated as a superheated, ordered BG phase. This attests the first-order nature of the BG-to-VG transition in a low-$T_c$ superconductor.

The change in the magnetic field tunes the inter-vortex spacing, which, in turn, can influence the balance between the strength of vortex pinning and the (elastic) interactions between the vortices. As a result, the extent of spatial ordering/disordering in the vortex matter may vary in different regions of the $H$–$T$ phase space. Further, an enhancement in effective pinning at a given field value can give rise to a qualitative change in the evolution of the size of the Larkin domain [30, 31], as had been experimentally demonstrated [39] via the evolution of the PE feature in the iso-field $\chi'(T)$ measurements in crystal(s) of 2 H-NbSe$_2$. Motivated by this, we shall now examine how the PE feature evolves with the magnetic field in the case of our crystal of Yb$_3$Rh$_4$Sn$_{13}$. We show in figure 9 the normalized $|\chi'/\chi''_p|$ plots ($\chi''_p$ corresponds to the $\chi'$ value at the peak position of the PE, where vortex matter is most disordered for a given inter-vortex spacing and the underlying quenched random disorder) against the reduced temperature $T/T_p$ ($T_p$ is the peak temperature of the PE obtained in the ZFC mode for various fixed fields). The PE feature remains absent at fields below $H = 4.5$ kOe (data not shown here), which may be because of disordered vortex matter prevailing there. Note that the larger inter-vortex spacings at low flux density result in weaker interaction between the vortices to counter the disordering influence of the pinning centre. The vortex configuration created at low fields ought to be highly disordered, akin to the reentrant amorphous vortex matter anticipated in earlier studies [40–43]. With the increase in field, the interaction effects strengthen, and, consequently, a sparse disordered vortex configuration can progressively change into an ordered one, as has been demonstrated earlier in reference [44, 45]. This is apparent from figure 9 by the appearance of a tiny PE feature firstly at $H = 4.5$ kOe. A more pronounced signature of the PE occurring at $H = 5.5$ kOe suggests further improvement in the spatial ordering of vortex matter with the increase in field prior to the onset of the PE. At a higher field of 7 kOe, there emerges a very well-developed PE feature, which is indicative of a well-ordered vortex (BG) phase prevailing prior to the onset of the PE transition at this field value. At $H = 11$ kOe, the anomaly in the $|\chi'/\chi''_p|$ curve begins to broaden, which may be due to the fact that at this field value, one has to cross two first-order transition lines, i.e., the BG-to-VG transition line and the VG-to-amorphization line, on approaching the $T_c(H)$ line. The order–disorder transition can be seen to be much broader at a higher field of $H = 15$ kOe. We surmise that the vortex phase prior to the order–disorder transition at this field value is partially disordered ($\alpha$ la the multi-domain VG phase), so that any order–disorder transition would reflect a lesser shrinkage in $V_c$ (as compared to that at lower fields) or, equivalently, a lesser increment in $j_c$ [30, 31] associated with this state. In all, the $|\chi'/\chi''_p|$ plots of figure 9 have led us to infer that a disordered vortex phase at the low-field end ($H < 4.5$ kOe) transforms into an ordered one (BG phase) with an increase in field. A further enhancement in field may transform an ordered vortex phase (BG) into a partially disordered (VG) state prior to the onset of the PE.

A very recent study in a crystal of Yb$_3$Rh$_4$Sn$_{13}$ by Mazzone et al [46] has revealed that the order–disorder
transitions in the vortex matter of this compound occur at both low and high fields. Since the magnetic-field variation of the pinning force density in our crystal (with $f_H \sim 10^{-4}$) can be different from that investigated in reference [46] due to the differences in the purity of the two samples, the onset position of the order–disorder transitions in our study may not tie up exactly with that in reference [46]. For example, it has been asserted in [46] that the low-field order–disorder transition occurred at 700 Oe, whereas we have observed the same at 4.5 kOe.

In the end, we draw attention towards the thermo-magnetic history effects investigated at lower fields (figure 5–7). It is customary to witness a more disordered FC state than the ZFC in the vicinity of the PE phenomenon [19–22]. However, the history-dependent magnetization behavior at lower fields ($H < H^\ast$) studied here in Yb$_3$Rh$_4$Sn$_{13}$ has revealed that the vortex matter in the ZFC mode is more disordered than that in the FC case. The following scenario seems plausible to explain this feature. In the ZFC mode, the injection of vortices at high velocities into a superconducting specimen is influenced by surface barriers and edge effects [47, 48] such that the vortices eventually penetrate the sample through the weakest point of the barrier. Inside the superconducting specimen, the vortices moving in bundles get randomly pinned at respective pinning sites such that the inter-vortex spacing is non-unique, which leads to a non-uniform distribution of the flux density. As mentioned earlier, the vortices are well separated at lower fields, and, therefore, the (elastic) interactions between them remain weak, resulting in a stronger pinned (disordered) vortex configuration in the ZFC mode. Although the vortex matter created in the FC mode also remains disordered at lower fields, the vortices in this mode nucleate more uniformly, as they remain oblivious to the disordering effects of the surface barriers and the non-uniform injection through the edges, etc. Therefore, at lower fields, the vortex configuration in the FC mode is less disordered than in the case of ZFC. At higher fields, the vortices get closer to each other, and, hence, the interaction effects become dominant, yielding a better spatial ordering even during the moving state of creation of vortex matter in the ZFC mode. On the other hand, during the FC mode, the vortex matter has to cross the PE boundary in the $H$–$T$ phase space, which results in supercooling the disordered vortex matter prevailing at the peak position of the PE anomaly. Thus, at higher fields, the vortex matter created in the ZFC mode is more spatially ordered than that in the FC mode.

5. Conclusion

We have investigated via magnetization measurements a weakly pinned single crystal of a low-$T_c$ superconductor, Yb$_3$Rh$_4$Sn$_{13}$. The present results have led to the identification of the BG-to-VG transition line and the sketch of a characteristic field ($H^\ast(T)$) line in the $H$–$T$ phase space of this compound. Surprisingly, the SMP transition-like phase boundary has been unearthed under the combined influence of an ac driving force and magnetic field-sweeping involved in the (isothermal) ac susceptibility ($\chi'(H)$) measurements. This transition was, however, not observed in the (isothermal) dc $M$–$H$ loops and the temperature-dependent ac susceptibility scans ($\chi'(T)$). The latter two modes of measurements yield the signature of only the quintessential PE anomaly, signaling the collapse of elasticity of the vortex solid at higher fields. An apparent demarcation between the domain of the SMP-like transition and the onset of the PE anomaly has been made in the vortex phase diagram of Yb$_3$Rh$_4$Sn$_{13}$. The results presented in our specimen answer in affirmative the question of the generic nature of the BG-to-VG transition in a pinned superconductor. In the low-field region ($H < H^\ast$), the vortex matter is construed to be highly disordered. Here, a vortex state created in the FC mode is found to be more ordered than that obtained in the ZFC mode.

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