Magnetization decay in neutron irradiated MgB₂ bulk samples

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In this paper the magnetization decay behavior of neutron irradiated MgB₂ bulk samples and an estimate of the strength of the introduced pinning centers are presented. The magnetization decay measurements appear much more complex than usual, in fact, they may be logarithmic or not, depending on the values of temperature and magnetic field and, as the region of low temperatures and fields is approached, they are affected by a “noise” that is out of experimental uncertainties. This “noisy” behavior is attributed to the small flux jumps, related to the dendritic flux penetration, widely observed in MgB₂ samples. We identify a phase diagram that divides the H - T plane in two regions: one, at relatively low temperatures and fields, where the decay observed is noisy, the other, outside it, where the decay is “clean.” This noisy region extends up to $T/T_c \cong 0.5$ and up to a field of some teslas, i.e., in a range of instability much more extended than that found in previous measurements. At high magnetic field the pinning energy turns out to be higher in irradiated samples than in the pristine one, in agreement with the observed increase in the critical current density. However, at high enough fields and temperatures, pinning is no longer effective and, by varying the measurement frequency, differences in the magnetic valuation of critical current density are observed. This fact may be of importance because it occurs at magnetic field and temperature conditions where technological applications of MgB₂ are expected. © 2008 American Institute of Physics. [DOI: 10.1063/1.2948923]

I. INTRODUCTION

Since its discovery in 2001,¹ magnesium diboride has attracted the attention of many researchers for various reasons. From the fundamental point of view, it has renewed the interest in unique effects in two-gap superconductivity. Regarding the applications, the surprisingly high critical temperature, more elevated than that observed in Nb-based superconductors, together with the fact that magnesium diboride does not suffer from weak link coupling across the grain boundaries² has suggested the possibility of using this superconductor with simple and cheap cryocooler. The critical field H_{c2} can reach extraordinarily high values, close to the paramagnetic limit, in the case of thin films.^{3–5} In bulk samples, H_{c2} can be enhanced by C or SiC substitution^{6,7} or by irradiation,^{8–10} and it reaches the value of about 40 T, smaller than in thin films, yet interesting for applications. Actually, as pointed out by Matsumoto *et al.*,⁷ in the case of polycrystalline samples, such value is totally misleading because, for practical applications, the limiting field is the irreversibility field, H_{irr} , which is about half of H_{c2} . Regarding the critical current density value, J_c , which is also crucial for power applications, its improvement in high magnetic fields is obviously related to the increase in H_{c2} . Nevertheless, the addition of pinning centers other than grain boundaries, the principal pinning centers in MgB₂,¹¹ appears necessary, and different methods for the introduction of defects with opportune size have been attempted.^{7,12,13}

To find out what kind of pinning mechanisms comes into play, it is customary to consider the pinning force F_p as a function of H/H_{irr} . A maximum at $H/H_{irr}=0.2$ indicates grain boundary pinning, while other pinning mechanisms, such as pointlike defects or spatial variations of the order parameter, manifest themselves with shift of the pinning force maximum to higher H/H_{irr} .¹⁴ Although in some MgB₂ samples with substitution or addition of impurities the critical current density turned out to be improved, no evidence of important shifts of the pinning force maxima was observed. As a consequence, the J_c improvement was attributed to the H_{c2} enhancement. The only unambiguous evidence of the instauration of a new pinning mechanism with a considerable shift of the maxima of the pinning force curves toward higher fields was observed in neutron irradiated bulk samples.¹⁵ Furthermore, transmission electron microscopy showed that neutron irradiation creates, within the crystal lattice, nanometric amorphous regions whose size matches with the coherence length.¹⁶ To evaluate the pinning energy U_0 , the magnetization decay is a usual technique.¹⁷ Various papers in literature deal with magnetization decay on different types of MgB₂ samples: powder,¹⁸ bulk sample,^{19–22} and film.²³ It is worth noting that nearly all the papers consider pure MgB₂ samples. In general, the magnetization decay is treated as logarithmic in the temporal window used in the measurement and the Kim–Anderson approach is applied to calculate the pinning energies U_0 or, equivalently, the creep rate $S=KT/U_0$. The U_0 values depend on the type and thickness of sample, and present a considerable range of variation

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depending on field and temperature. However, they are higher than those reported for high- T_c superconductors and similar to those of A15 superconductors,²³ which confirm the technological interest in this material. When magnetization decay was measured on MgB_2 samples with addition of impurities²⁴ the pinning energy U_0 turned out to be unchanged with respect to the pure sample, thus indicating that the H_{c2} increase must be the driver of the observed J_c enhancement.

For the technological applications of MgB_2 not only the J_c values but also the J_c stability is a crucial parameter. Since its discovery, magnetic measurements on MgB_2 have shown extensively the presence of flux jumps.²⁵ Flux jumps are a typical phenomenon of type II superconductor; because of small temperature or field fluctuations the critical state may become unstable and an avalanchelike process begins. Such a process diminishes J_c to a large extent and might possibly even reduce it to zero. While the conventional theory of thermomagnetic instability deals with uniform flux jumps (UFJs), when the instability tends to involve nearly all the sample, under other conditions, thermomagnetic instability may produce dendritic flux patterns, where the flux front forms fingers,^{26,27} the so-called small flux jumps (SFJs). This last type of jump is more easily formed in films.²⁸

Although flux jumps of both types have been often observed in both low and high T_c superconductors, MgB_2 appears to be the most sensitive material to instability.²⁹ In magnesium diboride films, dendritic patterns have been very clearly observed by magneto-optic imaging.^{30–32} In hysteresis loop measurements not only UFJs are commonly observed, but also SFJs, which appear as a “noisy” component (i.e., an erratic sequence of small discontinuities). They are related to the dendritic penetration of the flux front, as clearly evidenced in films by comparison of magnetic and magneto-optic measurements.^{30,31,33} These SFJs have a local effect and do not destroy the flux profile significantly. One effect is to flatten the hysteresis loop at low field and temperature in such a way that the paradoxical J_c increase with increasing temperature may be observed in the proper temperature region.³⁴ Also in MgB_2 bulk samples both UFJ and SFJ may be observed in hysteresis loop measurements, although to a smaller extent, in particular for SFJ.^{35,36}

In this paper we report hysteresis loop and magnetization decay measurements performed on pure and irradiated MgB_2 bulk samples. The magnetization decay shows a very complex behavior: it may appear logarithmic or not and, in addition, going toward the region of low temperatures and fields it presents a noisy behavior, clearly outside experimental uncertainties. We attribute this behavior to the SFJs due to the dendritic flux penetration, and we suggest decay measurements as a possible method to define the instability region in the H - T plane.

When the U_0 values are derived from the standard flux creep model, it emerges that in neutron irradiated samples the pinning energies increase, mainly at high magnetic field (>1 T), in agreement with the improvement of the critical current density, which confirms the addition of new effective pinning mechanisms. However, when temperature increases, the creep rate remarkably increases as well, and a J_c depen-

TABLE I. Characteristics of the samples here considered: sample name, neutron fluence, resistivity in the normal state, critical temperature, transition width, and $\mu_0 H_{c2}$.

Sample	Φ (cm^{-2})	$\rho(40\text{ K})$ ($\mu\Omega\text{ cm}$)	T_c (K)	ΔT_c (K)	$\mu_0 H_{c2}(0)$ (T)
P0	0	1.6	39.1	0.2	17.1
P1	1.0×10^{17}	2.4	38.9	0.3	18.0
P3	7.6×10^{17}	16	35.9	0.3	34.0
P3.5	2.0×10^{18}	26	33.3	0.3	36.7
P3.7	5.5×10^{18}	41	27.3	1.0	24.4

dence on the electric field is expected. At high temperature, in fact, we have observed differences in the width of the hysteresis loops obtained in different experimental setups (i.e., with different measurement frequencies).

II. EXPERIMENTAL

The samples were prepared by direct synthesis of magnesium (99.999% purity) and amorphous boron. Mg and B were put in Ta crucible welded in argon and heated up to 950 °C for a few hours as described in Ref. 9 and references therein. In order to study the effects of neutron irradiation on magnesium diboride and to avoid the strong neutron capture reaction of ^{10}B , we used boron isotopically enriched in ^{11}B (99.95% purity) in the sample preparation. The residual ^{10}B concentration is lower than 0.5% so as to guarantee a homogeneous defect distribution. The samples were irradiated in a spallation neutron source at the Paul Scherrer Institut, Villigen, CH, with thermal neutron fluence up to $1.4 \times 10^{20}\text{ cm}^{-2}$. More details of damage effects induced by neutron irradiation on magnesium diboride are widely described in Ref. 8. The neutron irradiation modifies the superconducting properties significantly. The critical temperature decreases monotonously from 39.1 K (pristine sample) to 9.2 K ($1.4 \times 10^{20}\text{ cm}^{-2}$); at the same time, the normal state resistivity increases by more than two orders of magnitude. Upper critical field improves in samples whose critical temperature is only slightly reduced, reaching 37 T at 0 K when $T_c \sim 33$ K, and then it rapidly decreases.⁸ In this work we consider a subsystem of the whole series reported in Ref. 8; for the sake of clarity we use here the same acronyms for the samples. In Table I, the main properties of the samples (from P0 to P3.7) are summarized, i.e., the sample name, the used neutron fluence, the critical temperature T_c , ΔT_c , the resistivity value at 40 K, and $H_{c2}(0)$. H_{c2} was measured at GHMFL, Grenoble, France in a 28 T resistive magnet; the zero temperature values reported in Table I are linearly extrapolated from these measurements.

The critical currents have been valued from hysteresis loops measured by a superconducting quantum interference device (SQUID) magnetometer [Magnetic Properties Measuring System (MPMS) by Quantum Design] through proper application of the critical state model. Hysteresis loops on the sample P3 were measured by a vibrating sample magnetometer (VSM by Oxford Instruments) as well. The magne-

FIG. 1. Critical current densities as a function of magnetic fields at 5, 10, and 20 K for all samples we considered.

tization decay measurements have been carried out after a zero field cooling procedure with the SQUID magnetometer for about 3 h, at constant magnetic field.

III. CRITICAL CURRENTS

In Fig. 1 the critical current densities at 5, 10, and 20 K, are reported for all the samples we have considered. In the pristine sample, P0, the critical current density decreases sharply with increasing magnetic field (by about two orders of magnitude as the field ranges from 0 up to 4 T at 5 K). Moreover, it is interesting to observe that the zero field value is weakly dependent on temperature, in fact, it is not strongly reduced even at 20 K. The in-field behavior of P1 is similar to that of the pristine one, but J_c is slightly higher at all the temperatures. Samples P3 and P3.5 have a smaller critical current density at 0 T with respect to P0 and P1, but their in-field behavior improves significantly, in fact, J_c curves take up a quite peculiar trend, with a nearly flat zone where a very weak dependence on magnetic field is observed. At $T=10$ K such a zone extends up to our maximum measuring field (i.e., 5 T), while at $T=20$ K reaches 3 T. P3.7 maintains

a similar shape but it has a lower J_c everywhere, in particular at 20 K. In Ref. 37 it was proved that the decrease in $J_c(0)$ in the slightly irradiated samples ($\Phi \sim 10^{18} \text{ cm}^{-2}$) is related to the reduced T_c , while for higher fluences also a connectivity loss cannot be excluded. On the other hand, the strong in-field J_c improvement is determined by a modification of the pinning mechanisms induced by neutron irradiation. In the considered range of magnetic field the in-field behavior does not change significantly between 5 and 10 K but it suffers from a great diminution at 20 K. This highlights the fact that at 20 K the introduced pinning centers are no longer particularly effective at high field.

IV. MAGNETIZATION DECAY

Magnetization decay measurements have been performed between $T=5$ K and $T=24$ K at magnetic field between 1 and 4.5 T on all the samples listed in Table I.

In Fig. 2 the magnetization decay curves of the sample P1 at three different temperatures (5, 10, and 20 K) for various applied magnetic fields are shown. Some peculiarities can be pointed out: (1) the decay generally presents a non-

FIG. 2. Magnetization decay of the sample P1 at three different temperatures: for $T=5$ K, the decay at 1.5, 3, and 4.5 T are shown; for $T=10$ K, those at 1.5, 2.5, and 3.5 T; and for $T=20$ K, those at 1, 2, and 3 T.

FIG. 3. Magnetization decay of three different samples (P0, P3, and P3.7) displayed at the same reduced temperature ($T/T_c=0.6$) and at various applied magnetic fields.

logarithmic behavior, particularly at higher fields and (2) the decay may be “clean” or extremely noisy, depending on temperature and applied field. When we say noisy decay we intend that it is affected by an important scattering of points around a monotonic trend, a completely unusual behavior in magnetization decay measurements. It is evident from Fig. 2 that the “noisiest” decay is at the bottom left-hand side (i.e., at the lowest temperature and field); toward the right-hand side or the high side of the figure (i.e., as temperature or magnetic field increases) the decay becomes “cleaner” and cleaner (at $T=20$ K the decay is noisy only at $\mu_0H=1$ T). This behavior is typical for all the samples, as may be seen in Fig. 3, in which the magnetization decay of three different samples at the same reduced temperature ($T/T_c=0.6$) is displayed. Here, when the magnetic field increases, the decay becomes clean, but the threshold magnetic field of the clean decay is different for the different samples.

We can rule out the possibility that the observed noise is due to experimental error, in fact, there is no correlation between the amplitude of the measured signal and the scattering of the data, which disappears at higher fields or temperatures where the signal is smaller. We emphasize that the decay measured on samples P3 and P3.7 at the same field and reduced temperature, where both magnetization and magnetization decay assume very similar values, presents a totally different look: noisy for P3 and clean for P3.7 (see Fig. 3). Moreover, in order to verify whether field inhomogeneity could be the cause of this “noise,” following Ref. 18 and references therein, we employed the so-called half-scan method to monitor the decay, but the noise persisted. Therefore, we conclude that the observed phenomenology has a physical origin. To define quantitatively clean or noisy decay we followed this procedure: after fitting a decay curve with a polynomial behavior we evaluated the χ^2 and defined a threshold of 2×10^{-4} for the passage noisy $\rightarrow$ clean. This criterion, in some sense arbitrary, is consistent with what is seen at a glance: for example, in left-hand side of Fig. 3 (sample P0) the decay is noisy at 1 T and clean at 2 T, while for P3 is noisy at 1 and 2 T, but clean at 3 T. Thus, it is possible to

define a noisy-clean transition and to draw a phase diagram in the H - T plane for any sample. This type of phase diagram is shown in Fig. 4 for all the measured samples. Since we carried out decay measurements at few fields only, we may indicate the passage from noisy to clean regime with a bar whose width mainly corresponds to the field distance between the two measurements that marked the passage. As a result, in Fig. 4 the phase diagrams are not indicated by lines but by bands. There is a common trend for all the samples, but different bands are found for different samples. To the best of our knowledge, noisy magnetization decay has been observed only once in pure MgB_2 powder by Mumtaz *et al.*,¹⁸ and at low fields only (fractions of tesla). They correctly correlated this behavior with the magnetization instabilities observed at low temperature and fields on MgB_2 films, but attributed all these phenomenologies to the onset of a reentrant vortex melting state, a highly unstable state where fluctuations may produce the observed noise. This ex-

FIG. 4. Noisy-clean transition from magnetization decay in the H - T plane for the different samples. Due to the limited number of magnetization decay measurements done the passage from noisy to clean regime is indicated with a bar (whose amplitude corresponds to the field distance between the two measurements that marked the passage) and not with a line.

FIG. 5. Hysteresis loop measured at $T=5$ K on sample P3.7. The inset shows an enlarged view of the region between $\mu_0 H=2.8$ T and $\mu_0 H=3.2$ T in which the instabilities are clearly observed.

planation requires very low fields where vortex-vortex interaction is weak, while the magnetization instabilities and our noisy decay are observed up to fields of many teslas. It is now well established that the noise observed in hysteresis loop measurements in superconducting films, and less frequently also in bulk samples, is due to the vortex avalanches with dendritic structures,³³ and it is quite natural to attribute the noise of magnetization decay measurements to the same phenomenon. We point out that the noise, evident in our decay measurements, may appear less visible in the corresponding hysteresis loop measurements. The reason for this lies in the fact that its amplitude, usually of the order of $(2-5) \times 10^{-3}$ emu, is negligible in the major part of a hysteresis loop in comparison with the variation of the magnetization due to the commonly applied change in magnetic field. To observe the noisy behavior in the hysteresis loop we have chosen a region around $\mu_0 H=3$ T for sample P3.7; here magnetization versus field is nearly flat and we carried out measurements every 5 mT. The results are presented in Fig. 5. As one can see, large UFJs are present at low fields. In the inset an enlarged view of the magnetization between $\mu_0 H=2.8$ T and $\mu_0 H=3.2$ T is shown, in which a small continuous ripple is clearly visible.

With reference to the phase diagram in Fig. 4 we point out that the region where decay is noisy corresponds to the low temperatures and fields, but it is very extended, reaching a magnetic field up to about 5 T and a temperature that exceeds 20 K for nearly all the samples, and is even higher for P3. In literature the instability region observed by magnetic or magneto-optic measurements is generally narrower; in films it does not usually extend beyond a temperature of 10 K and a magnetic field of 2 T. Also, in bulk samples, the UFJ and/or SFJ are usually observed at temperatures lower than 10 K, and only in one case up to about 20 K, even though at weaker fields.³⁶ Actually, in our samples the existence of a high critical current density also at high magnetic field may justify the great extension of the instability region.

We recall that the criterion for the formation of nonuniform jumps imposes a threshold electric field that depends

FIG. 6. U_0 values as a function of the applied field at 10 K for all the samples. In the inset: U_0 as a function of the fluence (i.e., for the various samples) at $T=10$ K and $\mu_0 H=3.5$ T.

linearly on the values of J_c , as well as on thermal diffusivity, and a threshold magnetic field that depends on $\sqrt{J_c}$, as well as on specific heat and dJ_c/dT . It is therefore clear that high critical currents favor the phenomenon, thus explaining why it is observed at relatively low fields and temperatures. Indeed the thermal properties are also important, and these explain the differences observed in the phase diagram of Fig. 4 for samples with very similar critical current density values.

V. PINNING ENERGIES

The evaluation of the pinning energy from magnetization decay measurements is based on the classical flux creep theory.¹⁷ In general, when a logarithmic decay is observed, it is customary to use the relationship

$$M = M_0 [1 - k_B T / U_0 \ln(t/t_0)], \quad (1)$$

where M_0 and t_0 are the initial magnetization and time, respectively, to evaluate the relaxation rate $S = \partial \ln M / \partial \ln t \cong 1 / M_0 \partial M / \partial \ln t = -k_B T / U_0$ or the pinning energy U_0 . As already pointed out, in our case the magnetization decay is not strictly logarithmic. This is a phenomenology frequently observed in high T_c superconductors, and, more rarely, also in magnesium diboride.^{18,38}

A logarithmic magnetization decay must not be considered as an obvious behavior; various reasons may hinder its observation: (i) the presence of a distribution function for the pinning energies³⁹ or (ii) the lack of the linear relationship between the pinning energy and the critical current density due to collective pinning phenomena⁴⁰ or to a particular shape of the pinning potential.⁴¹ However, even if the behavior is not strictly logarithmic, relationship (1) can be used to obtain a rough estimate of U_0 . Thus, with the purpose of comparing our results with the literature data, we have applied this formula and in Fig. 6 we report the U_0 values as a function of the applied field at 10 K.

U_0 is about 300 meV for the pristine sample, P0, at 1.5 T, but the magnetic field strongly depresses it down to 70 meV at 3.5 T. For the less irradiated sample, P1, an ex-

FIG. 7. Relaxation rate S (left scale) and n index (right scale) vs $\mu_0 H$ at $T=20$ K for bulk and film samples.

trremely similar behavior is observed. The U_0 values of P3 and P3.5 are very similar to each other and slightly lower than that of P0 at low field, but as the field increases, they remain high, of the order of 150 meV at 3.5 T. Finally, sample P3.7 shows a very low U_0 value at low field (about half the value of the pristine sample) but retains a greater value at high field in relation to the pristine sample. It is worth noticing that at 1.5 T the U_0 values are very similar for all the samples except for P3.7, highlighting the fact that the pinning mechanisms promoted by irradiation are not particularly effective at low field, but became important at higher fields. The U_0 field dependence may be compared to the J_c field dependence at the same temperature. A very good correspondence exists: the behaviors are very similar, showing the same in-field crossovers.

The inset of Fig. 6 reports U_0 as a function of fluence at 10 K and 3.5 T, where the pinning centers introduced by irradiation are more effective; U_0 slightly increases between P0 and P1 ($\Phi \leq 10^{17}$ cm $^{-2}$), but it improves much more significantly in P3 and P3.5, and then strongly decreases in the most irradiated sample ($\Phi > 510^{18}$ cm $^{-2}$). These data indicate that the pinning mechanisms introduced by neutron irradiation improve U_0 values until, for a fluence greater than 10^{19} cm $^{-2}$, the superconducting properties are strongly diminished [P3.7 sample presents $T_c=27.3$ K and $\mu_0 H_{c2}(0)=24.4$ T].

In literature magnetization decay measurements have been reported mainly for undoped samples: powders,¹⁸ films,^{23,42} or bulk samples.^{19–22} Since the creep rate S is more frequently reported than U_0 , in Fig. 7 we show S versus $\mu_0 H$ data both for bulk samples and films at $T=20$ K, a possible working temperature for MgB $_2$ devices. The only data shown are for P0 and P3, which represent the limit conditions in our samples (the pristine and the best). It is immediately clear that, while at low field all the samples exhibit small and very similar values, the increase in the magnetic field introduces huge differences. We point out that the samples presented in this work show S values much lower than those usually observed in bulk samples and comparable with those observed in films. As to the bulk samples, the values more similar to

FIG. 8. Critical current density measured on P3 sample at $T=5$ K (upper panel) and $T=20$ K (lower panel) both with the SQUID magnetometer and with the VSM.

ours are those found by Senatore *et al.*²⁴ in wires doped with C and SiC. The same behavior seen at $T=20$ K may be observed also at $T=5$ K.

The creep rate, S , is directly related to the current-voltage characteristic of a material: $S \cong 1/n$, where n is the exponent in the relationship $E=j^n$,⁴³ therefore n values, reported in the right scale of Fig. 7, indicate how steeply J_c increases with E . This is an important piece of information for applications; n of the order of 100 ensures the possibility of realizing coils operating in stable persistent mode, like those employed, for example, for magnetic resonance imaging.

Moreover, n defines the region where the J_c values obtained from different magnetic or transport measurements may coincide despite the different electric fields involved. In Fig. 8 we show the critical current density measured on sample P3 at $T=5$ K (upper panel) and $T=20$ K (lower panel), both with the SQUID magnetometer and with the VSM. As one can see, at $T=5$ K the two curves are superimposed. At 20 K the two curves nearly overlap up to $\mu_0 H \sim 3$ T, and then diverge more and more as the magnetic field increases ($n < 100$), the lower being the curve obtained with the SQUID magnetometer. It is evident that VSM measurement gives larger J_c than SQUID, in particular at high fields. This behavior depends on the fact that the measured magnetization value in an isothermal hysteresis loop depends on the dynamic equilibrium between two effects: the magnetization relaxation and the magnetization variation related to the field sweep rate value.⁴⁴ Different measurement frequencies and

field sweep rates imply different electric fields on the sample that may produce different amplitudes of the hysteresis loop. In our case, being the field sweep rates in the used magnetometers very similar, the great difference is due to the different measuring times.

They are of the order of 10 s for SQUID and 0.02 s for VSM. From the relationship $\vec{\nabla} \times \vec{E} = -\partial \vec{B} / \partial t \cong -\mu_0 \partial \vec{M} / \partial t$, we have evaluated $\partial M / \partial t$ from the decay measurement at 3 T and estimated the electric fields corresponding to the two different measurements. They vary by about three orders of magnitude: from about 10^{-8} V/m (SQUID) to about 10^{-5} V/m (VSM). This is the reason why volt-amperometric measurements, which define J_c with 10^{-4} V/m criterion, are in better agreement with VSM measurements. In the light of what is shown in Fig. 8, it is important to take into account the instrument employed for the J_c estimate in the conditions that are commonly used for MgB_2 (i.e., at $T \cong T_c/2 \cong 20$ K and at applied field of tesla). Moreover, we point out that, in case of coils operating in persistent mode, the current that the coil can sustain is the J_c measured at the lowest electric field.

VI. CONCLUSIONS

The main conclusions of this paper can be summarized as follows.

- (i) The magnetization decay behavior is complex and a transition between noisy and clean magnetization decay at higher temperatures and field is detected. Therefore, it is possible to determine, in the H - T plane, a phase diagram, for each sample, between a region of magnetic instabilities and a stable one. These instabilities manifest themselves in wide magnetic field and temperature ranges. We have speculated that this “noiselike” behavior is related to the SFJs, due to the well-known dendritic flux penetration, widely observed in MgB_2 samples.
- (ii) In irradiated bulk, the pinning energy, derived from the classical creep model, proves to be higher than that of the pristine sample, mainly at high magnetic field, in agreement with the increase in the critical current density, which confirms the introduction of new effective pinning centers. This manifests itself in very low values of the creep rates S at high fields, much lower than the data reported in literature.
- (iii) Where the creep rate increases, i.e., at high field and temperature, we have shown how remarkable differences in the critical current density can be detected by varying the frequency used in the measurements, as a consequence of the different electric fields involved.

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