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Trapped field of YBCO single-domain samples using pulse magnetization from 77K to 20K

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Abstract. ReBCO single-domain bulk superconductors have been shown to trap significant magnetic field at 77K and below. They can advantageously replace permanent magnets in cryogenic motors; more power in a smaller volume can be achieved. But practically, their magnetization has to be performed in situ. Usually it implies the use of pulse magnetization which is severe for the samples. This technique generates heat and stress on the superconductors. The magnetic-flux-trapping capabilities of YBCO single-domain samples were explored using the pulse-field facilities at the LNCMP (National Pulsed Magnetic Field Laboratory) at Toulouse, France. The flux dynamic was monitored during magnetic pulses by measuring the surface induction with a Hall probe on top of the samples at different temperatures from 77K to 20K. The samples were 16 mm in diameter and about 10 mm in height. The best one trapped 400 mT at 77K and 2.5T at 20K. The trapped field increases almost linearly down to 40K. The magnetic pulse is seen to generate heat. The temperature rise increases with decreasing temperature dwell because of lower heat capacity. The achieved trapped field is a compromise between the temperature rise and the applied field, and depends greatly of the magnetization history.

1. Introduction

YBCO bulk material as superconducting permanent magnet can provide much larger field than classical NdFeB permanent magnets. High trapped fields can be achieved in YBCO single-domain samples (9T@40K,12.5T@20K)[1]. A few years ago, a record trapped field above 17 T was obtained at 29 K on a 3 cm diameter single-domain sample [2]. The main drawback is the necessity of cooling the superconductors at 77K or even lower. However, for some specific applications such as motors, the increase of performance, i.e., more power in a smaller volume, is worth to study this solution.

An example is the development of a synchronous motor with ReBaCuO bulk superconductors as pole-field magnets in an axial-gap type rotating machine at the Tokyo University of Marine Science and Technology [3]. For practical reasons, an in-situ magnetization by means of pulsed magnetic field has to be preferred to a field cooled magnetization in the static field provided by a laboratory superconducting coil. Due to their very high sweep rates [4], pulse magnetic fields are considered to be a very good tool to investigate non-relaxed critical current density. But the final practical value will be a relaxed quantity after thermally-activated flux motion. High sweep rates and high magnetic field are also reported to generate flux jumps [5], as well as heat and stress [6]. Cracking are also reported during activation, even for low sweep rate, due to high Lorentz forces [7].

The present work was an opportunity to explore the trapped field capabilities of our samples under pulsed field conditions at different temperatures. The use of pulse magnetization is severe for the samples and implies intricate phenomena. The achieved trapped field is the result of dynamic vortex penetration, heating, relaxation, and eventually cracking, depending also on temperature and magnetization history.

2. Experimental setup

2.1. Samples

The studied samples were $YBa_2Cu_3O_{7-\delta}$ (Y123) single domains elaborated by top-seeding melt-growth. Their diameter was 16 mm to fit the sample holder. They were pressed with 0.7 mm diameter steel needles to create a hexagonal network of vertical holes (aligned along c-axis)[8]. After crystal growth, the holes are reduced to a 0.5 mm diameter. A first sample, S1, was oxygenated in a classical way under flowing oxygen 144 hours at 420°C and then 288 hours at 380°C. A second sample, S4, was oxygenated using a 160 bars high pressure process at 800°C [9]. Both have a Tc about 92K. The holes network is intended to reduce diffusion path in the material during oxygenation. It is also intended to increase thermal diffusivity and to allow eventually mechanical reinforcement and thermal stability enhancement by filling the holes with a metallic alloy or a charged epoxy [2,10].

2.2. Measurements

The measurements were performed using the high field facilities of the LNCMP at Toulouse, France[1]. A copper coil cooled by a pumped nitrogen bath and powered by a bank of capacitors was used. Magnetic pulse up to 36T with a capacitor load of 10000V can be produced. The maximum field can be modulated through the capacitor load, the minimum practical value being 1000V (3.6T).

The cryogenic environment for the samples was provided by a helium flux cryostat. The temperature was regulated using a Neocera LT-11 controller. The sample is placed into a glass fibres holder at the end of a glass fibres rod inserted into the cryostat. The local induction at the sample surface is measured in two points by Hall probes (Arepoc) and the temperature by a carbon glass temperature probe. These sensors are mounted on the top part of the holder in order to face the top surface of the sample. One Hall probe aims at the centre of the top surface while a second one is 3 mm aside. The Hall probes signals are read by synchronous detections. The applied field during a pulse is obtained by integrating the signal of a calibrated pick up coil far from the sample. A high speed acquisition (every 10µs) is used to monitor the pick up coil and the two Hall probes during the 1 second duration of the pulse, so that a local magnetization curve can be derived. A lower speed acquisition records the Hall probes and the temperature gauge signals every 3 seconds, so that the trapped field and the temperature evolution of the sample can be followed in time.

3. Results-discussions

3.1. General features

Figure 1 shows the shape of the pulse field and of the derived surface induction versus time during a 1000V shot. The pulse duration is about 1 second, but the field reaches its maximum value (3.6T) in 110 ms. Note the relaxation of the surface induction as the applied field is fully removed (last 0,25 s of the plot). Figure 2 is a typical magnetization curve at 77 K derived from the local surface induction and applied field measurements during the magnetic pulse.

Figure 3 illustrates the experimental procedure on sample 4. The sample was cooled from room temperature to different temperatures starting from 77K. Series of magnetization pulses were applied at different temperature dwells (77K, 60K, 50K, 40K and finally 20K). The sample was cooled down from one dwell to another, with no intermediate heating step, i.e., the trapped field is not removed.

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Since cracking has been reported as a major concern during activation, the first intention is to proceed dwell after dwell until the increase of performance with the cooling will lead eventually to the failure of the sample.

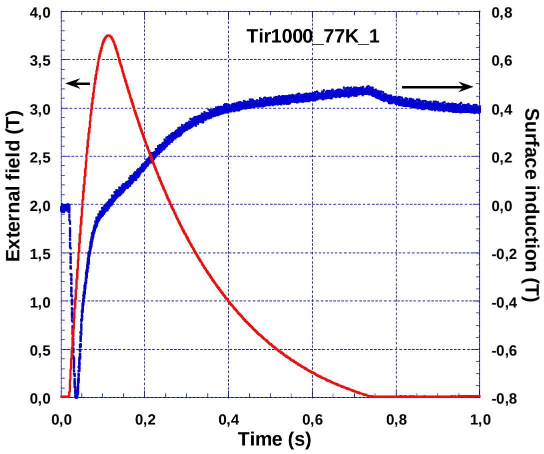

Figure 1. Plot of the applied pulsed field and the surface induction (Hall probe 1 signal – External field) versus time at 77 K. Note the relaxation of the trapped field once the applied field is fully removed.

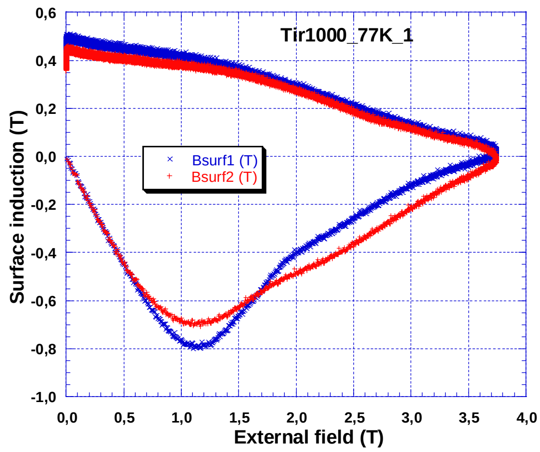

Figure 2. Example of a magnetization curve at 77 K derived from the data acquired during a pulse on virgin sample S4.

Different points are to be observed: the evolution of surface induction with temperature, the heat generation by magnetic pulses, its consequence on a flux trapping strategy, the exponential decrease of the surface induction in the first hundred seconds following the pulse.

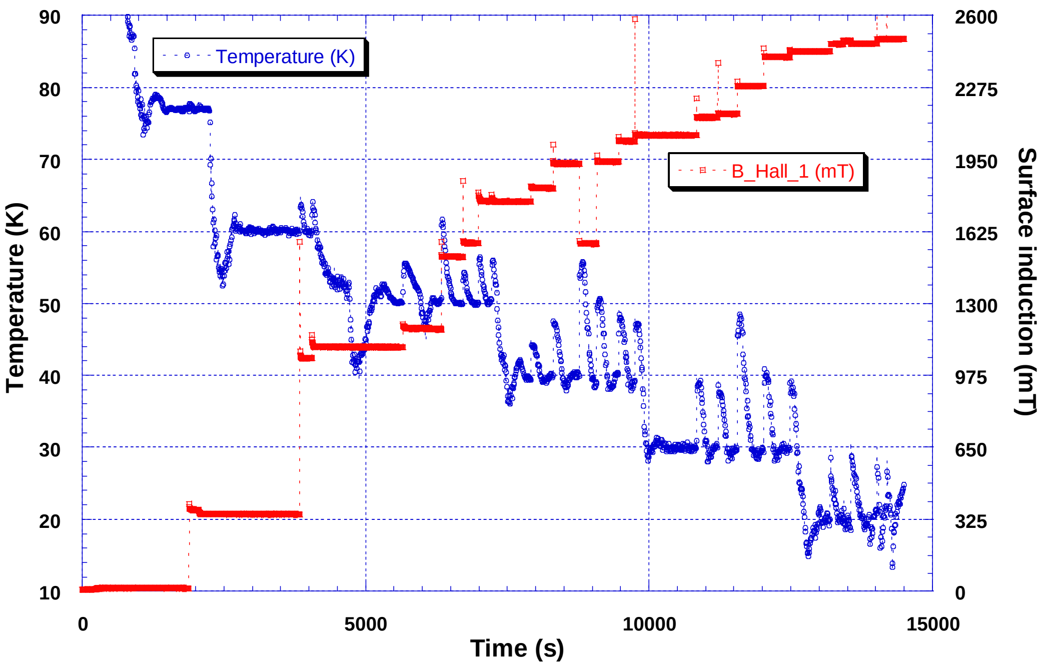

Figure 3. Plot summarizing the pulse field experiment on sample S4. Temperature and surface induction signals are recorded every 3 sec.

From the preliminary observations of the temperature rise during pulse and its supposed effect on the trapped field during the first experimental runs, we have adopted intentionally a compromise strategy to “optimize” the trapped field between the temperature rise and the amount of vortices we force to penetrate the sample at once. This consists in applying series of low power pulse until the trapped field seems to saturate, then to slightly increase the power (from 1000V to 1500V to 2000V) or to lower the temperature. We retrieve similar approach in Japanese papers where the heat generation and propagation appears as a major concern [6,11].

Measurements in static condition at 77K yield some average trapped field values between 160 and 500 mT for 16 mm diameter samples, depending on processing conditions. On first approximation, the maximum surface induction trapped at the center of the top surface of a cylinder with R>h (R being the sample radius and h its height) is given by $B_0=1/2*B_p=1/2*\mu_0RJ_c(0)$ where B_p is the Bean-model full penetration field [12] The maximum achievable trapped field in YBCO at 77K is found to be around 2.5T, a limit obtained for reasonable geometry (R=10mm) and high but realistic Jc, i.e., Jc measured on thin films extrapolated to a bulk material [13]. To reach higher field, it seems more convenient in a short term to lower the temperature than to increase size and Jc of the material at 77K. Lowering the temperature is expected to improve the Jc(B) behavior and the irreversibility field, and the additional cooling cost may be worth for specific applications if the performance are greatly improved.

3.2. Trapped field versus temperature

Figure 4 summarizes the behavior of the surface induction versus temperature for both samples S1 and S4 (dashed lines). The high pressure oxygenation (sample S4) clearly yields better performances. More pinning sites are assumed to be the consequence of an increase of the twin density [14]. S4 traps about 400 mT at 77K, and about 2500 mT at 20K. The enhancement of trapped field is almost linear down to 30K. Working in the 30-40K temperature range may be a good compromise between cooling cost and performance. This can be easily done nowadays using a cryocooler. Below 30K, the trapped field seems to saturate. Two kinds of limitations are reported: thermomagnetic instabilities below 20K and mechanical properties between 20K and 40 K [15].

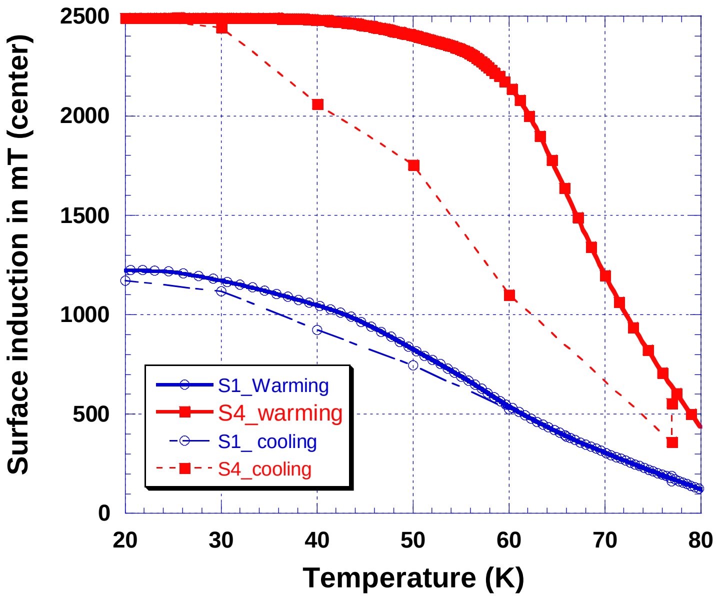

Figure 4: Trapped field capabilities versus temperature of samples S1 and S4. The symbols are showing the maximum trapped field value reached at each dwell while cooling down the samples. The lines are reproducing the trapped field measured continuously while the samples were warming back to room temperature. The temperature sensor is calibrated only for values below 77K.

3.3. Heat generation and temperature jump

A characteristic feature of each magnetic pulse experiment (shot) is a temperature jump as can be seen on figure 3. The temperature rise is proportional to the shot power. Higher applied field means a higher density of vortices to penetrate the sample. For series of shot at constant power, the temperature rise decreases while the trapped field continues to increase, then saturates. The temperature jumps are associated with hysteretic magnetization curves. It seems to be proportional to the amount of new vortices that penetrate the samples. For the same maximum applied field, the temperature rise is more important when the sample presents less trapped field, i.e., less vortices are already pinned. Hence, the sample magnetization and temperature increase during pulse depend on its magnetization history.

The temperature jumps also increases with lower temperature, even at constant shot power, as the heat capacity of the material also diminishes. As a consequence, trapped field seems to saturate, the temperature rise canceling any improvement of the Jc.

At the end of each experiment, the signals of the Hall probes and temperature gauge were recorded while the sample was warming back to room temperature (full lines in figure 4). During warming, the induction values are larger at each temperature than the one obtained previously by pulse magnetization. The trapped field value obtained after a shot does not correspond to the temperature of the dwell, but to a higher temperature resulting from the heat produced by the magnetic pulse in the superconductor. The difference is more striking for the sample S4 than for S1. It may be linked to the better pinning ability of S4.

The temperature jumps can be reduced by increasing the pulse rising time. In the case of field cooled sample in a static field, the values of trapped field are twice larger than those achieved by pulse magnetization [15].

The time for returning to the nominal temperature after a shot is about 300 seconds, as compared to the 30 seconds needed for the trapped field to settle at its dwell value (see figure 3). We believe that this stability is reached as soon as the temperature goes back below the equilibrium temperature at which the field has been trapped taking into account the heat generation. The vortex dynamic and relaxation are masked by thermal effect.

3.4. Flux jumps

As the temperature is lowered and the screening ability of the superconductors is improved, the same shot power yields a magnetization curve with lower hysteresis. The associated temperature jump is reduced, but also the increase in trapped field. To continue to improve the trapped field, the applied field has to be increased. But then, we encounter flux jumps. In sample S4, flux jumps already occur at 50K as can be seen on figure 5. At this temperature, no flux jumps are detected on sample S1, but the trapped field is also twice smaller. Note that the Hall probes separated by 3 mm do not experience the same jump sequence. This indicates that the observed flux jumps are not concerning the entire volume of the sample as can be seen at very low temperature. They are signature of local redistribution of the magnetic field and are associated with the pulse magnetization process.

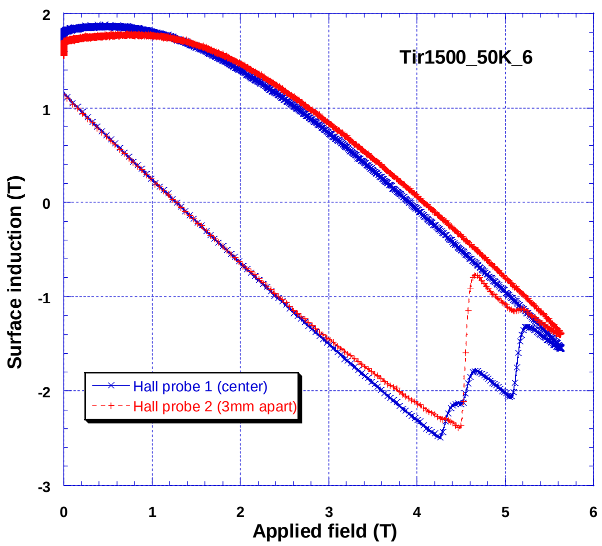

Figure 5. Flux jump occurrence on a magnetization curve at 50K during a 1500V shot (5.4T) on sample S4. The induction measured at the center and the one measured 3 mm apart are both represented showing a difference in the local response. This indicates local field redistribution process.

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3.5. Mechanical considerations

Apart heat generation, another limiting factor is the mechanical strength of the YBCO bulk single domain. The pinning-induced tensile stress in a fully magnetized cylindrical superconductor is given by $\sigma \approx (2B_0)^2/2\mu_0 = (\mu_0 R J_c(0))^2/2\mu_0$ where B_0 is the trapped surface induction. A trapped field of 3T will produce a remnant state tension of 20-30 MPa, which is of the same order than the average tensile strength of YBCO bulk single domain. Value of 60-100 Mpa have been reported for high quality samples [16], leading to 6-8 T capabilities. Without mechanical reinforcement, 10T seems to be a limit. Note that local stresses can be higher during the activation process as, for instance, an activation field 1.5 time the full penetration field yields a stress twice the one reached when the activation field is equal to the full penetration field [17].

No significant mechanical degradation of the samples has been noticed during these experiments, but the probability of damage will increase if we obtained more than 3T in the future. We have also to consider that a succession of pulses will act as a cycling effort.

As a matter of fact, sample S4 broke while we were attempting to trap field in static field cooled condition at 4.2K and 13 T.

4. Conclusions

The trapped field capabilities of YBCO single-domain samples under pulse magnetic field condition were explored at different temperatures from 77 K to 20 K. The flux dynamic was monitored during pulse by measuring the surface induction with a Hall probe on top of the samples. Our best sample, 16 mm in diameter, 10 mm in height and oxygenated under high oxygen pressure (160 bars), trapped 400 mT at 77K and 2.5T at 20K. Lowering the temperature is shown to be an efficient way to improve the trapped field capabilities with an almost linear increase down to 30 K. But the magnetic pulse inherently generates heat. The temperature rise increases with decreasing temperature dwell because of lower heat capacity. The achieved trapped field is a compromise between the temperature rise and the applied field, and depends greatly of the magnetization history. Best results are obtained in the 30-40 K range. Below flux jump and heat generation limits drastically the trapped field. However, the trapped field remains below the value at which mechanical properties also become a limiting factor. Local flux jumps occurring already at 50 K reveals field redistribution process during pulse.

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