Investigating the flux jump behaviour during single waveform control pulsed field magnetization of GdBaCuO superconducting bulk

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Abstract. We aimed to improve the trapped magnetic flux density obtained with a waveform control pulsed field magnetization (WCPM) by using a negative feedback control of the magnetic flux density on the growth sector boundary of a GdBaCuO superconducting bulk sample. The WCPM method with negative feedback control has previously shown that it could help increase the trapped magnetic flux density, compared to conventional passive pulsed flux magnetization, if the magnetic field penetrates the bulk centre substantially using a flux jump. The flux jump sometimes greatly changes the magnetic and thermal state of the bulk, which limits the maximum trapped magnetic field. The active control method of the applied magnetic field helps to overcome this limit if the control conditions are appropriate. While searching for the ideal control conditions of the WCPM, the magnetization characteristics have been investigated. We found that the flux jump, which assists the flux in penetrating the centre of the bulk, can be “slowed down” thanks to the negative-feedback WCPM. This operation helped to decrease the heat generated by the moving flux inside the bulk and reduced the temperature rise, which contributed to the increase of the trapped magnetic flux density.

1. Introduction

Encouraged by the increasing need for high power density superconducting motors in various industries, new pulsed field magnetization (PFM) methods, which can allow high magnetic field to be trapped in a short time, are being developed. Currently, superconducting motors which use high-temperature superconducting (HTS) bulks as field poles usually utilize the field cooling method to magnetize the bulks [1]. This method is not well suited for practical application as it often requires a few hours of magnetization as well as heavy and expensive superconducting coil magnets, which are difficult to integrate inside a superconducting motor. Methods based on PFM, consist of applying one or multiple strong external magnetic fields for a few hundred milliseconds, using relatively small copper coils. This reduction in magnetization time often comes at the expense of the strength of the trapped magnetic field. Consequently, it is important to find ways of improvements of PFM methods in order to improve the trapped magnetic flux density, as well as the distribution of the trapped magnetic field in the bulk.

A phenomenon that plays a major role during PFM is the flux jump, and its importance has been discussed by several researchers [2–7]. The flux jump, which is an avalanche-type phenomenon, allows a large number of flux vortices to move inside the bulk and penetrate to the centre of the bulk. During the flow of flux vortices, viscous losses and pinning losses are appearing [8], generating heat and hence...
raising the temperature of the sample. This heating process has been considered as adiabatic if the thermal diffusion coefficient is lower than the magnetic diffusion coefficient [9]. The generated heat due to the fast-moving flux cannot be carried away fast enough and results in the rise of the temperature of the sample. The rise of temperature is a limiting factor to the maximum trapped magnetic flux density in the sample because an increase in the temperature reduces the critical current density in the superconductor. It has been shown previously that our method of waveform control pulsed field magnetization (WCPM) has appeared to be effective in reducing the rise in temperature during the magnetization process. This reduction of the temperature rise was often accompanied by great improvement over traditional passive pulsed field magnetization at 77 K, 70 K, and 60 K [2,3]. In this paper, we have investigated the magnetization characteristics during WCPM with negative feedback.

2. Waveform controlled pulsed field magnetization

The experimental setup has been made to reproduce the internal arrangement of an axial-gap type superconducting motor which uses high-temperature superconducting (HTS) bulks as field poles [10-12]. The GdBaCuO QMG bulk sample, made by Nippon Steel, was placed between two vortex-type magnetizing copper coils, and was cooled down by a GM cryocooler (Cryomech AL330) to \( T_{\text{init}} = 60 \, \text{K} \). This arrangement and cooling system have been previously described in detail [2]. The positioning of the 5 Hall sensors (Toshiba THS118) used for measuring the magnetic flux density during the magnetization process can be seen on the schematic of the seed-side surface of the bulk in figure 1 (a). These Hall sensors were positioned on the growth sector boundary edge (GSBe), the growth sector boundary (GSB), the growth sector (GS), the growth sector edge (GSe), and on the centre of the bulk sample. Figure 1 (b) shows the location of the Hall sensors situated at the bottom surface of the bulk, which was used to provide the negative feedback of the magnetic flux density used during the WCPM. The sensors were placed on the top and bottom of the HTS bulk to separate the sensors sending magnetic flux density data to the WCPM system from the sensors measuring the magnetic flux density. This separation aimed to prevent digital noise interference from the pulse magnetization system. We prioritized the measurement of the magnetic flux density on the seed plane and therefore used the top of the bulk to place the measurement sensors. A temperature sensor (Cernox) was placed on the GSB and was used to measure the maximum temperature reached during the magnetization.

![Figure 1. Schematic of the sensor placement on the top surface (a) and the bottom surface (b) of the HTS bulk. The Hall sensors for the data logger have been placed 2 mm away from the top surface of the bulk while the Hall sensors for the negative feedback have been placed 2 mm away from the bottom surface.](image-url)
For the magnetization, three different methods were used. The first method, a passive PFM, was used as a baseline to compare the results. For the second method, our pulse magnetization system, which has previously been described [2,3], was used to perform a WCPM. In this system, a microcontroller unit sent a PWM signal to drive an Insulated Gate Bipolar Transistor (IGBT), which was used to shape the waveform of the pulsed magnetic field. The IGBT can be seen as a switch opening and closing depending on the control signal sent by the microcontroller. When the IGBT is “closed”, the current flows from the capacitor bank to the magnetizing copper coils. On the contrary, when the IGBT is “opened”, the current flow is stopped, thus the applied magnetic field gradually decreases due to the counter electromotive force. The PWM signal was configured with a constant duty ratio, so the IGBT was in the open state and close state for the same amount of time for each period of one millisecond during the magnetization. In contrast, the third method used a PID controller built within the microcontroller unit to determine an optimized duty ratio. Before each magnetization process by the method, the PID controller was set up with a target magnetic flux density. The PID controller compared the magnetic flux density of the negative feedback from one of the Hall sensors placed on the bottom surface of the bulk with the target magnetic flux density. This allowed it to determine the adequate duty ratio, at each millisecond to control the IGBT so that the magnetic flux density target can be achieved.

3. Importance of the flux jump
We wanted to compare the use of a single PFM with and without flux jump, to understand if the trapped magnetic field would be increased by the lower temperature rise when no flux jump has occurred. Figure 2 shows a comparison of the penetration magnetic flux density $B_p$ measured on the centre of the bulk during passive pulsed field magnetizations for different magnetizing energies. The inset shows the pulsed current flowing through the copper coils at the different magnetizing energies.

![Figure 2: Time-dependent penetration magnetic flux density $B_p$ measured on the centre of the bulk during passive pulsed field magnetizations for different magnetizing energies. The inset shows the pulsed current flowing through the copper coils at the different magnetizing energies.](image)

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Figure 3. Time-dependent penetration magnetic flux density \( B_p \) on the centre of the bulk during a WCPM for different constant duty ratio at a magnetizing energy of \( E = 12.3 \) kJ. The inset shows the pulsed current flowing through the copper coils at the different magnetizing energies.

Figure 3 shows the penetration magnetic flux density \( B_p \) measured on the centre of the bulk at a magnetizing energy of 12.3 kJ, for different values of duty ratio \( D \). The pulsed current is displayed in the inset graph for different values of duty ratio. At a duty ratio of \( D = 30 \)%, no flux jump occurred, resulting in a low trapped magnetic flux density. But at \( D = 35 \)%, a flux jump was triggered at about 1.6 T, and allowed to greatly improve the results of the trapped magnetic flux density, by almost 6 times (1.19 T). Figure 3 also shows the improvements using the WCPM compared to a passive PFM, which is noted \( D = 100 \) % on the graph.

From these results, it can be seen that the flux jump plays an important role in the trapping of a strong magnetic field in the centre of the bulk. Our goal is therefore to reduce the temperature rise while keeping the flux jump.

4. **Influence of the measurement position for negative feedback of WCPM**

Previously, Hall sensors on the GS and the centre had been used to provide negative feedback to the microcontroller unit. In this study, we tried to use a Hall sensor positioned on the GSB, visible in figure 1 (b). The best results of the trapped magnetic flux density on the centre (\( B_{\text{Centre}} \)) using various control conditions and for various magnetizing energy can be seen in figure 4. The results obtained with the GSB’s Hall sensor shows improvement compared to passive PFM results but are overall below the results obtained with the sensor on the centre. For past and current experiments, the Hall sensors for negative feedback control have been installed on the opposite side of the seed crystal to not interfere with the measurement of magnetic flux density. Therefore, if a Hall sensor for negative feedback control is provided on the surface of the seed crystal which has good crystallinity, it can improve the ability to control the flux jumps.

In this experiment, the maximum magnetic flux density during the magnetization was often higher in the GSB than in the GS, which suggests that a larger amount of flux vortices was passing through the GSB than through the GS to go in the centre during the flux jump. The flux jump and temperature change in the bulk may have reduced the pinning effect of the GSB and therefore decreased the critical current of the GSB. In figure 5, it can be noticed that the changes in magnetic flux density on the GSB were strongly linked to the changes in magnetic flux density on the bulk edge represented by GSe and GSBe. Whereas these changes had little impact on the magnetic flux density in the centre or the GS. As a typical example, one local maximum and one local minimum are highlighted by black triangles in figure 5. These two peaks are noticeable on the edges and on the GSB, but almost disappeared in the centre and
the GS. Many other similarities are visible on the waveforms of the magnetic flux density in the GSB, GSBe, and GSe. This can explain why the control is slightly less performant when using the GSB’s Hall sensor, since the changes in magnetic flux density on the bulk edge were greatly affected by the applied magnetic field.

Figure 4. Maximum trapped magnetic flux density $B_{\text{centre}}$ on the centre of the bulk for various magnetizing energies and using the 3 different magnetization methods and the 3 different placements of the Hall sensor for the negative feedback during the WCPM with negative feedback control.

Figure 5. Time-dependent magnetic flux density in the different sectors of the bulk during a PFM at a magnetizing energy of $E=12.3$ kJ. The four black triangles are indicating two of the many noticeable peaks and similarities in the waveform of the magnetic flux density in the GSB, GSBe, and GSe, but almost invisible in the GS and the centre of the bulk.

As shown in figure 6, the temperatures measured during the use of the Hall sensor on the GSB are similar to the temperatures obtained when using the negative control feedback with the sensors in the centre and on the GS. Despite this, the trapped magnetic flux density remained lower than the results obtained with the Hall sensors on the centre and on the GS, especially between 8 kJ and 16 kJ. Therefore, the temperature is not the only limiting factor to the maximum trapped magnetic flux density in the centre.

5. Rate of increase of the magnetic flux density during the flux jumps
To have a better understanding of the impact of our control methods on the flux jumps and the trapped magnetic flux density, we have investigated the rate of increase \( \frac{dB_{centre}}{dt} \) during the flux jumps in the centre of the bulk. We measured the time and magnetic flux density at the beginning and the end of the flux jump in the centre of the bulk. In this paper, we have defined the change from 10 % and 90 % of the flux jump increment as the rise time of the flux jumps.

Figures 7 (a), (b), and (c) show the trapped magnetic flux density as a function of the rate of increase of \( B_{centre} \) during the flux jump for \( E = 10.5 \) kJ, \( E = 12.3 \) kJ, and \( E = 15 \) kJ respectively. All of the plots for various magnetization energies give similar trends. Although there are some dispersions in the data, partially due to the measurement of the starting and ending values of the flux jump, a linear curve fitting seems to be adequate. This case is similar for different magnetizing energies. A high rate of increase of the magnetic flux density during the flux jump led to a low trapped magnetic flux density in the centre. When the rate of increase was reduced, it resulted in better outcome for the trapped magnetic flux density due to the “slow down” of the flux jump. The reduction of the rate of the increase was possible using our WCPM with negative feedback control by optimizing the control condition. For example, the rate of increase during the flux jump was reduced from 917 T/s using a passive PFM to 170 T/s using WCPM with control feedback, for a magnetizing energy of 15 kJ as shown in figure 7 (c). The reduction of the rate of increase resulted in higher trapped magnetic flux density in the centre overall. This result is encouraging as it shows that the flux jumps can be influenced by the control of the discharge current. Precise control of the flux jumps can result in even higher trapped magnetic flux density, using a single pulsed field magnetization.
Figure 7. Magnetic flux density trapped in the bulk centre as a function of the rate of increase of the magnetic flux density during the flux jumps for different magnetizing energies (a) $E = 10.5$ kJ, (b) $E = 12.3$ kJ, (c) $E = 15$ kJ.
6. Conclusion
We tried to improve the trapped magnetic flux density in a superconducting bulk, by properly changing the placement of the Hall sensor used for providing the negative feedback of the magnetic flux density to our magnetizing system. We managed to improve the results compared to a passive PFM and compared to constant duty ratio WCPM, especially between 10 kJ and 15 kJ. In particular, the results obtained using the Hall sensor on the centre are better overall and more consistent at the different magnetizing energies.

We investigated the rate of increase of the magnetic flux density during the flux jumps obtained in the centre of the bulk, during the PFM using various control methods for the magnetization and various magnetizing energies. It was confirmed that our magnetization method can reduce the temperature rise by “slowing down” the flux jump and presumably reducing the heat generation. More importantly, it has been found that the trapped magnetic flux density in the centre is increased when the rate of increase of the magnetic flux density during the flux jump $dB_{\text{centre}}/dt$ is reduced. This result is encouraging as better control of the flux jump will most likely result in the improvement of the trapped magnetic field.

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