PULSED-FIELD MAGNETIZATION APPLIED TO HIGH-\(T_c\) SUPERCONDUCTORS

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Abstract—The pulsed-field magnetization (PFM) technique has been elaborated as the most efficient and effective tool in magnetizing the melt-processed high-\(T_c\) bulk superconductor in the temperature range 30–80 K. The dynamic motion of magnetic fluxes penetrating into the YBCO superconductor during the PFM operation has been analyzed and the flux propagation speed has been accurately evaluated. The viscous force is found to play a very crucial role in the PFM process. Detailed analysis of the flux motion in the presence of both viscous and pinning forces enabled us to find a very efficient method for magnetization by the PFM operation. The iteratively magnetizing pulsed field operation with reducing amplitudes abbreviated as ‘IMRA’ has been developed and proved to be very effective in magnetizing high-\(T_c\) superconductors at temperatures as low as 30 K. By making full use of these findings, we constructed a prototype quasi-permanent magnet system capable of producing magnetic field of 0.8 T in the outerspace at 7 mm above the surface of the magnetized YBCO superconductor.

INTRODUCTION

Both critical current densities and trapped magnetic fluxes of the melt-processed high-\(T_c\) bulk superconductors have been dramatically enhanced for the past several years through the remarkable progress in the synthetic techniques such as the successful dispersion of submicron-level non-superconducting particles in the superconducting matrix as pinning centers and the growth of a \(c\)-axis oriented large quasi-single crystal [1]. Furthermore, in order to achieve superconducting characteristics better than those reported for the conventional YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) or YBCO, the synthesis of the REBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) superconductors with \(\text{RE} = \text{Nd, Sm etc.}\) has been extensively carried out in a reduced oxygen atmosphere [2–4]. With striking progress in the synthetic techniques, trapped magnetic fluxes, even at 77 K, have already far exceeded values produced by conventional permanent magnets like Nd–Fe–B [1–5]. Therefore, the flux-trapped high-\(T_c\) superconductors have received intense attention as quasi-permanent magnets superior to conventional ones and have been referred to as a superconducting bulk magnets (SBM) or simply ‘Supermagnet’ [6, 7].

Our eventual goal is to raise the performance of the Supermagnet so much that it is widely used as a commercial product superior to ordinary permanent magnets despite the drawback of cooling below its superconducting transition temperature. Another crucial point in achieving this goal is to develop the most effective and efficient way to magnetize high-\(T_c\) superconductors. The pulsed-field magnetization (hereafter abbreviated as PFM) technique is believed to be the most convenient and promising, since it can magnetize them even \(\text{in situ}\) mounted in a device. Indeed, Itoh \textit{et al.} [8] applied the PFM technique to the superconducting motor they constructed and could successfully magnetize 20 YBCO bulk superconductors cooled to 77 K with liquid nitrogen by feeding a pulsed current through solenoid coils wound around them in series. Because of its compactness, the PFM technique certainly has the advantage over conventional...
static magnetization techniques using a large-scale electromagnet or superconducting magnet. Even in certain cases the geometrical limitation forces us to rely on only the PFM technique for magnetization.

We consider it very urgent that we deepen our understanding of the flux motion during the PFM operation and examine to what extent the elaborated PFM technique can trap magnetic fluxes in comparison with the ordinary static field method known as field cooling (FC) and zero-field cooling (ZFC) modes. We have recently studied the two-dimensional distributions of magnetic fluxes trapped by the PFM technique in the melt-processed YBCO at 77 K and compared the results with that derived in the FC and ZFC modes [6, 9, 10]. The work has been extended to gain further insight into the behavior of the dynamical motion of magnetic fluxes during the PFM operation [7, 11]. The usefulness of the PFM technique has been also tested by lowering the temperature of the sample to 30 K, since both the critical current density and the trapped fluxes are known to increase substantially with decreasing temperature [12–14].

In the present paper, we review a series of our recent studies concerning the flux motion during the PFM operation in the temperature range 30–80 K and prove the usefulness of the PFM technique to magnetize the high-$T_c$ superconductors in the temperature range 30–80 K.

**EXPERIMENTAL PROCEDURE**

The YBCO sample, 34 mm in diameter and 14 mm in thickness, was prepared by melt-processing. Appropriate amounts of powders of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (123-phase) and $\text{Y}_2\text{BaCuO}_5$ (211-phase) were thoroughly mixed together with 0.5 wt.% of Pt so as to adjust the resulting atomic ratio to $\text{Y}:\text{Ba}:\text{Cu} = 2.33:2.67:3.67$ or $1.8:2.4:3.4$. The pressed sample was heated to 1100°C for partial melting. A SmBa$_2$Cu$_3$O$_{7-\delta}$ single crystal was dropped as a seed at the center of the melt before solidification started. The quasi-single crystal has grown with its $c$-axis perpendicular to its top surface. The nonsuperconducting 211-phase particles with a mean diameter of 1 μm were homogeneously distributed over the superconducting 123-phase matrix.

The present PFM apparatus is schematically illustrated in Fig. 1(a) [11] and (b) [13]. The sample was immersed in liquid nitrogen bath in (a) whereas it was mounted on the cold stage of the Gifford–McMahon refrigerator (AISIN, GR301) and was cooled to temperatures 30–80 K in (b). A single pulsed current with a rise time of 0.8 or 1.3 ms was fed to the solenoid coil wound around the sample in (a). Likewise, a pulsed current with a rise time of 3 or 5 ms was used in (b). The resulting magnetic field at the center of the coil is calculated from the current and coil constant. Its maximum field is hereafter called the applied field $H_a$ in the PFM. The temperature of the sample was monitored by using a ruthenium oxide thermometer (SI, Model RO-104) mounted on the top surface of the sample.

The trapped fluxes in the sample after the PFM operation were measured by using the Hall sensors (F. W. Bell, BHA-921 or BHT-921) having an active area of 0.5 mm in diameter. Two or three identical Hall sensors were mounted in a line on the top surface of the sample to detect the $z$-component of the trapped magnetic field.

**RESULTS AND DISCUSSION**

*Trapped flux distribution at 77 K in the PFM mode*

The two-dimensional trapped flux distribution obtained at 77 K by the PFM mode is shown in Fig. 2 [6]. It is clear that the peak of the trapped flux reaches its maximum at the applied field of 1.9 T but begins to decrease with further increase in applied field. A total magnetic flux $\Phi_T$ trapped in the sample is obtained by integrating the flux distribution in Fig. 2 and plotted in Fig. 3 as a function of applied field $\mu_e H_a$ [6]. Here the data obtained in the ZFC and FC modes are also included for comparison. The most important point to be noted is that the PFM mode can trap as many fluxes as the static FC and ZFC modes can do. This is true, as far as the measuring temperature is 77 K, and has proved the PFM technique to be very promising from the viewpoint of its practical application. We also note that the total flux in the PFM mode begins to decrease, once the applied field exceeds 1.9 T. This indicates that there is an optimum applied field beyond which the total trapped fluxes decrease. The reason for the reduction in the total trapped fluxes at high applied fields is successfully explained by taking into account the heat generation due to a vis-
Flux motion during the PFM operation

The time dependence of the magnetic flux propagating in the sample was measured at 77 K at three different positions E, M and C corresponding to the exterior, middle and central regions of the sample by varying the amplitude of the pulsed field [7, 11]. As shown in Fig. 4, the decreasing rate $dB/dt$ in the $B$–$t$ curve at positions $M$ and $C$ after passing their respective peaks is more moderate than that at position $E$. When the applied field is increased, however, the corresponding decreasing slope becomes steeper and steeper so as to respond more promptly to the change in the external pulsed field. The $B$–$t$ spectra at positions $M$ and $C$ continue to decrease with increasing time beyond 6–7 ms, at which the external field has completely vanished. This must be attributed to the flux creep after the PFM operation.

To extract more detailed information about the motion of the penetrating fluxes, we define the local magnetization $M_{\text{local}}$ as

$$M_{\text{local}} = B - \mu_0 H_{\text{ext}},$$

(1)
where $B$ is the magnetic flux density measured at position where the Hall sensor is mounted and the field $\mu_0 H_{\text{ext}}$ represents the reduced external magnetic field defined in Ref. [7]. Figure 5 shows the $M_{\text{local}} = -\mu_0 H_{\text{ext}}$ curves measured at position $M$ when the pulsed fields with different intensities are applied to the sample. The data obtained in the ZFC mode with a maximum field of 1 T are incorporated in Fig. 5. The line $M_{\text{local}} = -\mu_0 H_{\text{ext}}$ or $B = 0$ indicates that the magnetic flux penetrating into the sample has not reached the measuring point $M$. The maximum value of $\mu_0 H_{\text{ext}}$ in every curve corresponds to the applied field $\mu_0 H_a$. The local magnetization curve expected from the Bean model is marked by a dashed line in Fig. 5.

When the applied field is low, the hysteresis loop is heavily compressed toward the line $B = 0$. This unique behavior is sharply contrasted with the data in the ZFC mode. The data falling on the line $B = 0$ clearly means that the magnetic flux in the PFM mode experiences greater difficulty in penetrating into the sample than that in the ZFC mode. However, the situation changes when the applied field exceeds some critical value. The value of $M_{\text{local}}$ deviates from the line $B = 0$ and results in a broad minimum in the $M_{\text{local}} - \mu_0 H_{\text{ext}}$ curve. The position of the minimum displaces toward higher $\mu_0 H_{\text{ext}}$ with increasing applied field. It is important to realize that all these features appear in the ascending stage of the pulsed field. The $M_{\text{local}} - \mu_0 H_{\text{ext}}$ curve sharply rises after the formation of the minimum and subsequently protrudes along the abscissa, when the applied field exceeds 1.8 T. The sharp rise in $M_{\text{local}}$ observed in the range $\mu_0 H_{\text{ext}} = 1.5 - 2.5$ T signifies a rapid penetration of the flux into the sample as if the initial sluggish motion should be compensated. It is clear that, owing to the sudden penetration of the

![PF0.7T](image1.png) ![PF1.9T](image2.png)

![PF1.1T](image3.png) ![PF3.3T](image4.png)

![PF1.4T](image5.png) ![PF4.5T](image6.png)

Fig. 2. Trapped field distributions at 77 K with different applied fields in the PFM mode. The rise time of the pulse is 0.8 ms.
magnetic fluxes when applied field exceeds 1.8 T, the PFM technique can magnetize the high-$T_c$ superconductor to the level comparable to that in the ZFC or FC mode. It is, therefore, of critical importance to clarify the mechanism of the formation of the initial ‘barrier’, which hampers the penetration of the magnetic fluxes into the sample only under the PFM operation. The barrier apparently appears when the time derivative of the applied pulsed field is very high, but it becomes ineffective when the derivative is lowered below some critical value toward the final stage of the ascending pulsed field. Further work is in progress along this line.

Once applied field exceeds 1.8 T and the penetrating flux reaches a certain level, it begins to respond more readily to the change in the external field and behaves in the way similar to that expected from the Bean model. When the pulsed field enters the descending stage and $\mu_0 H_{\text{ext}}$...
begins to decrease, the value of $M_{\text{local}}$ crosses the abscissa and eventually intercepts the ordinate with a positive value at the end of the PFM operation. The intercept obviously corresponds to the trapped flux at the position $M$. It is seen that the trapped flux decreases, when the applied field exceeds about 1.8 T. This is well consistent with the data in Figs 2 and 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.png}
\caption{Local magnetization curves with various applied fields measured at position $M$. The curves are calculated from the $B$–$t$ spectra shown in Fig. 4 using Equation (1) in the text. The data obtained in the ZFC mode with the magnetic field of 1 T are shown by open circles. The curve based on the Bean model is indicated by a broken line.}
\end{figure}

\begin{figure}[h]
\centering
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6a.png}
\caption{ZFC 1T}
\end{subfigure}
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6e.png}
\caption{$\mu_0H_{\text{ex}}=2.6T$}
\end{subfigure}
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6b.png}
\caption{$\mu_0H_{\text{ex}}=1.0T$}
\end{subfigure}
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6f.png}
\caption{$\mu_0H_{\text{ex}}=4.1T$}
\end{subfigure}
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6c.png}
\caption{$\mu_0H_{\text{ex}}=1.4T$}
\end{subfigure}
\begin{subfigure}[h]{0.4\textwidth}
\includegraphics[width=\textwidth]{figure6d.png}
\caption{$\mu_0H_{\text{ex}}=1.8T$}
\end{subfigure}
\caption{Change in the flux density distribution in the sample during the PFM process. The distribution in the ascending ($\uparrow$) and descending ($\downarrow$) stages are shown on the left and right-hand sides of each figure, respectively. (a) quasistatic ZFC mode with the applied field of 1 T. (b)–(f) PFM mode with various applied fields.}
\end{figure}
The spatial distribution of the magnetic flux density is deduced from the $B-t$ curves shown in Fig. 4 in both ZFC and PFM modes. The results are shown in Fig. 6. The data on the left- and right-hand sides represent the flux density distributions in the ascending and descending stages of the pulsed field, respectively. Since the value of $B$ is corrected for the finite length of the coil as described in [7], the data in Fig. 6 represent well the flux distribution trapped in the YBCO sample during the PFM operation with an infinitely long solenoid coil. As is clear from Fig. 6, the magnetic flux in the ZFC mode penetrates almost linearly along the radial direction in accordance with the Bean model. In contrast, the flux distribution in the PFM mode with the applied field of 1 T is steeply concave both in the ascending and descending stages of the pulsed field. This means the difficulty in the penetration of the magnetic flux at low fields, as mentioned above. As the applied field increases above 1.4 T, the flux distribution becomes less concave, signaling a gradual ease in the penetration of magnetic flux. Particularly, when the external field exceeds about 2 T, the magnetic flux is able to penetrate very easily into the sample, and the value of $B$ increases almost linearly as if it were in the static ZFC mode. The value of $B$ decreases smoothly in the descending stage in sharp contrast to the unique behavior in the ascending stage.

Viscous motion of the flux during the PFM operation

We can discuss more detailed behavior of the penetrating fluxes by assuming that the flux motion in the superconducting matrix during the PFM operation is entirely decided by the force balance:

\[ F_L + F_p + F_v = 0, \]  \hspace{1cm} (2)

where $F_L$ is the Lorentz force density, $F_p$ is the pinning force density and $F_v$ is the viscous force density. The Lorentz force density $F_L$ is obviously expressed as

\[ F_L = J \times B, \]  \hspace{1cm} (3)

where $J$ is the current density and $B$ is the magnetic flux density. The pinning force $F_p$ is written as

\[ F_p = -\frac{v}{|v|} F_p(|B|, T). \]  \hspace{1cm} (4)

where $v$ is the flux velocity and $T$ is temperature. The viscous force density $F_v$ is expressed as

\[ F_v = -\eta |B| \phi, \]  \hspace{1cm} (5)

where $\eta$ is the viscosity coefficient and $\phi$ is a fluxoid quantum. As is clear from Equations (2)–(5), the sum of $F_p$ and $F_v$ is always balanced to $F_L$.

In the ZFC and FC modes, the magnetic field is quasi-statically varied with time so that the viscous force may well be neglected relative to the pinning force. Indeed, the Bean model assumes only the balance between $F_L$ and $F_p$. For example, the linearly decreasing trapped flux toward the center of the sample in the ZFC mode shown in Fig. 6 can be well explained in the framework of the Bean model without taking into account the contribution due to the viscous force.

In contrast, the viscous force in Equation (5) plays a very crucial role during the PFM operation, since the pulsed field changes with time at the rate of $> 10^2$ T/s. The viscous force should be the largest near the periphery of the sample and decrease to zero toward its center, since the flux velocity decreases rapidly as fluxes move toward the center of the sample. The presence of a large viscous force must be responsible for the formation of an apparent barrier discussed in connection with Fig. 5 and why a high field of 1.9 T is needed for full magnetization in the PFM operation.

The proper evaluation of the flux propagation speed during the PFM operation is essential in order to determine the magnitude of the viscous force during the PFM operation. Its magnitude has been evaluated by Itoh et al. [7] from the peak and kink marked by arrows in the inset to
Fig. 4. They deduced that the propagation speed ranges over 5-30 m/s and increases with increasing applied field. Very recently, Terasaki et al. [15] measured the time dependence of magnetic flux penetrating through totally six concentric pick-up coils mounted on the surface of the YBCO sample kept at 77 K. An integration of the difference in the voltages generated across the two successive pick-up coils over the time interval 0 and \( t \) led them to determine accurately the flux propagation speed averaged over the region between these two coils.

The flux propagation speed is found to be distributed over 5–30 m/s in good agreement with those derived by Itoh et al. [7]. The pinning loss and viscous loss are separately evaluated by multiplying the propagation speed by Equations (4) and (5), respectively. The results clearly show that the maximum viscous loss amounts to \( 1 \times 10^8 \) W/m\(^3\) and is of the same order of magnitude as the pinning loss, when the applied field is relative low at around 1 T. However, they revealed that the viscous loss is increased to \( 2 \times 10^10 \) W/m\(^3\) and becomes more than 10 times as large as the pinning loss, when the applied field is raised to 4.4 T. This work has clearly demonstrated that the most characteristic feature of the PFM process is manifested by effects associated with the viscous force and its role increases drastically with increasing applied field, particularly when it exceeds 2 T.

**Flux creep after the PFM operation**

The flux creep is a serious phenomenon particularly in practical applications of high-\( T_c \) superconductors. The flux density \( B \) at positions \( M \) and \( C \) is measured as a function of the elapsed time after the PFM operation at 77 K [7]. The value of \( B \) at position \( M \) is normalized with respect to that at \( t = 10 \) s (\( t_o \)). The results are plotted in Fig. 7 as a function of normalized time \( t/t_o \) on the logarithmic scale. The data obtained in the ZFC and FC modes with 1 T are also included. The creep rate at a given time is defined as the slope of the \( B(t)/B(t_o) \) vs \( \log(t/t_o) \) curve. It can be seen that the value of \( B(t)/B(t_o) \) decreases almost linearly with increasing \( \log(t/t_o) \) in both ZFC and FC modes, indicating that the logarithmic time dependence holds well and that the creep rate is essentially independent of time.

In contrast, the value of \( B(t)/B(t_o) \) in the PFM mode initially decreases very slowly but then accelerates its decrease and eventually tends to be parallel to the line of the ZFC mode. More important is that the creep rate becomes smaller and smaller, as the applied field is increased, and that the creep rate is definitely smaller at position \( C \) than at position \( M \) in the PFM mode [7]. The results can be well accounted for by the generation of heat associated with the sudden

![Fig. 7](image-url)
penetration of the pulsed field during the ascending stage. The higher the applied field, the more heat is evolved and the higher the temperature rise of the sample. This contributes to a reduction in the trapped magnetic flux during the PFM operation but the flux creep is substantially suppressed because the sample immersed in the liquid nitrogen bath restores the original temperature of 77 K immediately after the PFM operation. Therefore, we found that unfavorable flux creep in the ordinary FC or ZFC mode can be greatly circumvented when the PFM technique is employed.

**PFM operations at lower temperatures**

It is well known that the critical current density and the trapped magnetic flux of high-$T_c$ superconductors can be substantially enhanced by lowering the temperature below its superconducting transition temperature. Thus, we consider it to be important to elaborate the PFM technique at temperatures lower than 77 K corresponding to the boiling point of liquid nitrogen. In our studies, the sample can be cooled down to 30 K by using the GM refrigerator shown in Fig. 1(b).

Figure 8 shows the applied field dependence of the trapped flux density measured at the center of the sample cooled to various temperatures. It can be seen that the magnetic flux does not penetrate into the center of the sample until the applied field exceeds some threshold value. It may be worthwhile noting that its value at 77 K is much higher than the value shown in Fig. 3. This is certainly because the data in Fig. 3 represent the total trapped fluxes while Fig. 8 the flux density at the center of the sample. It is clear from Fig. 8 that the threshold field increases with decreasing temperature of the sample and reaches 2.6 T when the temperature is lowered to 35 K. This implies that the barrier against the penetration of the flux increases with decreasing temperature. This unfavorable situation must be somehow circumvented when the PFM technique is employed at low temperatures.

According to Fig. 8, the amount of the trapped flux density obviously increases with increasing applied field but begins to decrease after taking its maximum with further increase in applied field. This is true, regardless of temperatures chosen, and is well consistent with the data shown in Fig. 3. In other words, a decrease in the trapped flux at very high applied fields must be attributed to the heat generation due to the viscous motion of fluxes. During the course of this experiment, we have realized that a single operation of the pulsed field is not satisfactory but repeated operations are quite effective in enhancing trapped fluxes. One of the most effective ways to enhance trapped fluxes is to apply magnetic field large enough to magnetize the central area of the sample in the first operation and then to apply smaller fields repeatedly to supplement the flux escaped from the periphery due to excessive heating in the first operation. In contrast to a single PFM or ‘S-PFM’ method, this unique iteratively magnetizing operation with
gradually reducing amplitudes may be called as ‘IMRA’ method by taking initials of iteratively magnetizing pulsed-field operation with reducing amplitudes.

It is of great interest at this stage to compare the maximum flux density trapped by the PFM technique with that by the static FC method. The sample was magnetized in the FC mode by using a helium-free superconducting magnet with its maximum static field of 5.5 T. The results are plotted in Fig. 9 as a function of temperature of the sample. We see that the present YBCO sample can trap up to 4.5 T under the static FC mode when its temperature is lowered to 30 K. In contrast, the magnetic flux density at the center of the sample trapped by the ‘IMRA’ technique increases with decreasing temperature and reaches 2.1 T when the temperature is lowered to 30 K. This is about twice as low as that attained by the FC mode but the value has already far exceeded 0.5 T generated by the Nd–Fe–B permanent magnet. It may be worthwhile mentioning that the ‘S-PFM’ mode traps only one third of 4.5 T obtained in the static FC mode whereas the ‘IMRA’ mode can trap its half at 30 K.

As is naturally expected from the discussion above, the heat generation due to the viscous motion of fluxes becomes more serious at lower temperatures because of the decrease in the specific heat of the sample. The temperature rise after the PFM operation is measured at various temperatures [12]. As shown in Fig. 10, the temperature rise reaches the value as high as 17 K at 42 K when the applied field exceeds 5 T. This is the reason why we have to devise the efficient way to magnetize the sample in the PFM mode. We believe that the present ‘IMRA’ method is quite advantageous in trapping efficiently magnetic fluxes under increasing difficulties with decreasing temperature.

Finally, we show in Fig. 11 the photograph of the top portion of our prototype quasi-permanent magnet system operated in the PFM mode in the temperature range 30–80 K. After the YBCO sample is cooled to 30 K by the GM-refrigerator, it is magnetized by a pulsed field generated with the solenoid coil, which has been already removed in the photograph. A large num-

![Fig. 9. Temperature dependence of the maximum trapped flux density with the ‘IMRA’, ‘S-PFM’ and FC methods.](image)

![Fig. 10. Applied field dependence of the temperature rise $\Delta T$ after the PFM operation at various temperatures. See Ref. [12] for the detailed PFM operation in this particular experiment.](image)
ber of iron balls with the diameter of 3 mm are attracted by strong magnetic field produced by our Supermagnet. Figure 12 shows the corresponding two-dimensional distribution of the trapped flux density measured at 7 mm above the surface of the YBCO sample magnetized at 30 K. The maximum trapped flux density is 2.1 T immediately above the surface of the Supermagnet and is 0.8 T in the outerspace corresponding to 7 mm above it.

Fig. 12. Distribution of the trapped flux density in the outerspace of the QPM system shown in Fig. 11. A maximum magnetic field of 0.8 T is produced at 7 mm above the top surface of the YBCO sample (note that 2.1 T is trapped immediately above the sample).
CONCLUSION

The PFM technique has been elaborated to magnetize the melt-processed high-$T_c$ superconductor at temperatures 30–80 K. It is demonstrated that our newly developed ‘IMRA’ method is capable of trapping a magnetic field of 2.1 T at 30 K, reaching a half that obtained in the static FC mode. We have also clearly showed that the viscous force plays a dominant role in the PFM operation, particularly when the temperature is lowered. The dynamic flux motion during the PFM operation has been also well elucidated. We presented the prototype quasi-permanent magnet system generating the trapped flux density of 0.8 T in the outerspace when the melt-processed superconductor is magnetized by the PFM at 30 K. There is no doubt that its performance will be enhanced further with efforts directed to the synthesis of more elaborated high-$T_c$ superconductors having higher superconducting characteristics.

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