

Measurement System for Investigating the Long-Term Stability of Permanent Magnets for Sensor and Actuator Systems

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The efficient long-term use of permanent magnets requires reliable prediction of temperature-, field-, and time-dependent magnetization losses. This study presents an automated Helmholtz coil measurement setup to quantify time- and temperature-dependent polarization changes in NdFeB samples of various grades and geometries. The measurements distinguish time- and temperature-dependent changes between reversible and irreversible contributions, enabling determination of a temperature-based magnetic viscosity parameter S_v^T for prediction of future losses. In addition, temperature-based magnetic stabilization effectively eliminates irreversible losses and enables constant magnetic stability. A combination of both approaches supports optimizing the design of magnetic systems.

Keywords: Permanent magnets, long-term prediction, viscosity parameter, magnetic stabilization

1. Introduction

Permanent magnets are essential in applications such as electric motors, generators, sensors, and actuators [1]. They all share a common challenge: their magnetization must remain stable under varying field and temperature conditions over time, as instability can lead to reduced precision in sensors or decreased efficiency in, e.g., electric motors. Accounting for such magnetic losses typically relies on the magnetic viscosity parameter S_v , the ratio of time-dependent to direct field- or temperature-induced losses [2]. The value of S_v enables future loss prediction through the use of the fluctuation field [3]. However, the determination of S_v , mainly by vibrating sample magnetometry (VSM) is costly, technically demanding, and sensitive to uncertainties especially when adjusting from external to internal fields [4], [5]. As a simple alternative approach, a novel measurement approach based on temperature rather than field as the influencing quantity has been developed [6]. It enables quantification of temperature-driven polarization changes and their time-dependent decreases, yielding a temperature-based viscosity parameter S_v^T as an alternative to the established field-based S_v approach [4]. Using only temperature as the influencing quantity simplifies interpretation and improves applicability for system designers. Although the viscosity parameter enables future loss prediction, it does not suppress time-dependent losses. Thermal stabilization through pre-aging offers a complementary approach by shifting the magnet into a lower but stable polarization

state prior to application [7], [8]. This work therefore presents the measurement setup, the determination and application of the temperature-based viscosity parameter, and the complete suppression of time-dependent losses through thermal stabilization.

2. Background

In contrast to soft magnetic materials such as steel or electrical sheet, permanent magnets are designed for high remanent polarization J_r , the polarization at zero external field and high coercive field strength H_{cj} , the field-strength at $J = 0$. These properties make them an effective alternative to electromagnets, which require soft magnetic cores, copper windings, and external power supply. In open-circuit conditions (e.g. in air at zero external field), permanent magnets exhibit its self-demagnetizing field [9] quantified as

$$H_{\text{self}} = -\frac{N \cdot J}{\mu_0} \quad (1)$$

where N is the geometry-dependent demagnetization factor [10], J is the magnetic polarization of the sample, and μ_0 is the vacuum permeability. The presented setup targets open-circuit applications, using temperature variations as the influencing factor resulting in $J(T, t)$ curves showing polarization as a function of temperature T and time t . These polarization states correspond to the intersections of the material $J(H_{\text{int}})$ curves at specific temperatures with the sample load line as visualized in Fig. 1.

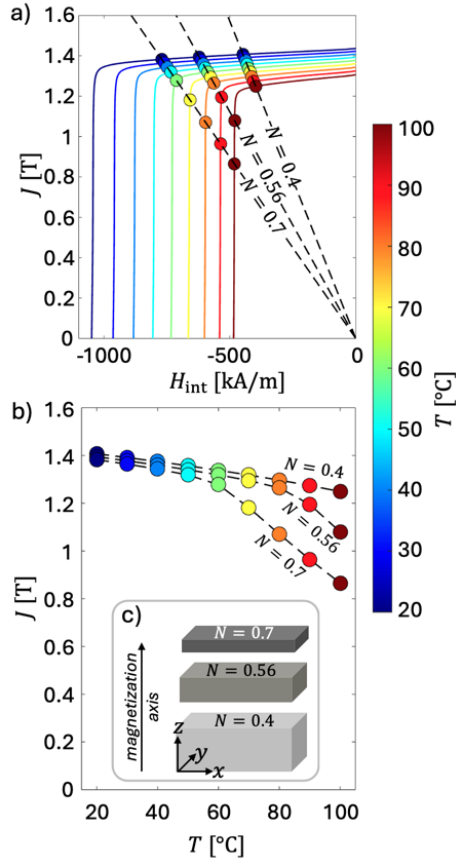


Fig. 1: $J(H)$ curves of an N52 sample illustrating the influence of different sample temperatures and sample geometries in a) (demagnetization factors $N = 0.4$ ($20 \times 10 \times 10 \text{ mm}^3$), 0.56 ($20 \times 10 \times 5 \text{ mm}^3$), 0.7 ($20 \times 10 \times 2 \text{ mm}^3$), overview in c). In b), the resulting $J(T)$ curves are obtained from the intersections of the three load lines with the $J(H)$ curves at increasing temperatures from a).

Fig. 1a shows $J(H_{\text{int}})$ curves at temperatures from 20 to 100 °C together with three sample load lines for different sample geometries with $N = 0.4$, $N = 0.56$ and $N = 0.7$, as shown in Fig. 1c. Their intersections, indicated by colored circles, define the open-circuit $J(T)$ curves in Fig. 1b. Polarization decreases with increasing temperature, with samples of lower demagnetization factors (e.g. $N = 0.4 < 0.56 < 0.7$) or higher coercivity retaining higher polarization at elevated temperatures. For quantifying the maximum temperature stability, the transition temperature T_t , marked in Fig. 2a, is defined as the tangent intersection between the reversible and irreversible regions of the $J(T)$ curve. Starting at room temperature, temperature-induced changes are mostly reversible below T_t . Beyond T_t , losses become predominantly irreversible. In addition to these instantaneous changes, irreversible time-

dependent polarization decreases are critical for long-term magnet performance. Fig. 2b illustrates this effect as the decay from the instantaneous polarization states to the time-dependent polarization decrease $\Delta J^{t.d.}$, representing polarization reduction during prolonged exposure times at the respective temperature due to thermal activation (magnetic viscosity). Consequently, temperatures above T_t should be avoided, as even small variations can induce significant irreversible polarization losses with pronounced time-dependent behavior.

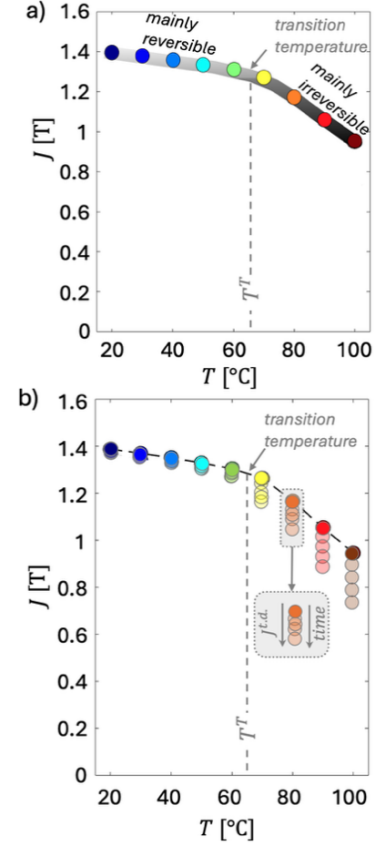


Fig. 2: Schematic $J(T)$ curve illustrating the stability of polarization. a) Section of the $J(T)$ curve highlighting a linear region with mainly reversible changes and an irreversible region beyond the transition temperature with mainly irreversible losses. b) Starting at the transition temperature, additional time-dependent decreases can be expected for longer exposure durations at each temperature step.

3. Experimental set up

3.1 Measurement Setup

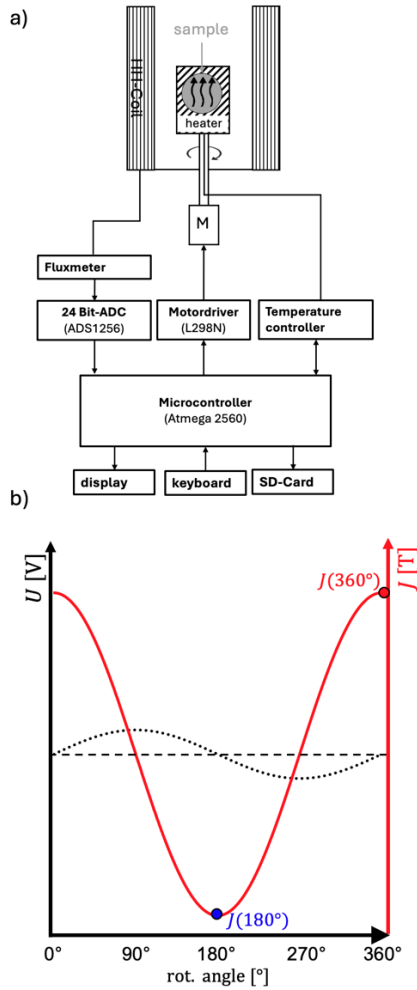


Fig. 3: Measurement setup with a) temperature-controlled sample rotating inside a Helmholtz measurement coil with digital measurement and control circuitry. b) shows the induced voltage and time-integrated polarization signal over one rotation. The induced voltage is integrated by a fluxmeter, digitized, and stored with process parameters on a SD card. Stepwise motor rotation enables discrete data acquisition and angle-dependent polarization extraction by averaging the minimum and maximum extrema, e.g. $(J(180°) + J(360°))/2$ (red curve in b)).

The measurement setup for determining $J(T, t)$ values, shown in Fig. 3a, uses a permanent magnet sample rotated along its magnetization direction inside a Helmholtz measurement coil (MS210, Magnet-Physik GmbH, Germany) [6]. The rotating sample induces a voltage in the measurement coil, which is integrated over time by a fluxmeter (EF-14, Magnet-Physik) to obtain

the magnetic moment. The fluxmeter signals are digitized by a 24-bit ADC and processed by an Atmega 2560 microcontroller, which also controls the stepper motor and communicates with the temperature controller. The stepper motor, with a 1:10 gear, provides 1800 steps per rotation and, together with the ADC, achieves a noise level of approximately 0.00015 T at room temperature and 0.0002 T at 100 °C. The sample rotation, as shown in Fig. 3b, further improves angular accuracy and reduces fluxmeter drift by averaging signal peaks compared to standard manual Helmholtz coil measurements. Heating is achieved via a PTC heating foil (12 V, 40 W) on an aluminum plate, reaching 260 °C with ± 0.1 °C stability.

3.2 Magnetic long-term stability

All permanent magnets exhibit time-dependent effects. The closer the operating temperature is to the transition temperature, the higher the time-dependent losses as shown in Fig. 2b. The measured temperature- and time-dependent polarization decrease enables prediction of future magnetization states, based on the value of the temperature-based viscosity parameter S_v^T presented in section 3.2.2 and the fluctuation temperature T_f , presented in section 3.2.3. Another approach is to eliminate time-dependent losses through magnetic stabilization, presented in the following section 3.2.1. Here, the time-dependent decrease represents the instability region, which is reduced by driving the magnet into a lower, but stable magnetization state. Since this pre-aging step lowers the magnetization level, it is not suitable for all applications, particularly those requiring maximum polarization values or where small time-dependent losses are acceptable.

3.2.1 Magnetic stabilization

Magnetic stabilization, or pre aging, refers to the controlled partial demagnetization of a permanent magnet to a lower but stable polarization state prior to use [7], [8]. This prevents further irreversible losses, including direct and time-dependent effects. Fig. 4 shows a schematic polarization-to-time $J(t)$ course in a) and the set temperature profile $T(t)$ in b). Without stabilization, the sample polarization decreases from point A to B at the maximum application temperature T^{app} . Applying a stabilization temperature $T^{stab} > T^{app}$ reduces the polarization to a lower but stable state, e.g. J^c at point C. Further temperature variations up to this stabilized temperature result in only reversible changes during operation without additional irreversible losses.

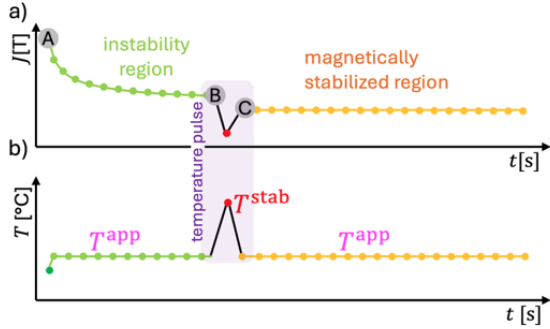


Fig. 4: Schematic visualization of the magnetic stabilization procedure. a) Polarization time course $J(t)$. b) set temperature profile $T(t)$, illustrating the time-dependent decrease of polarization at the application temperature T^{app} within the instability region. This polarization decrease can be suppressed by a temperature pulse T^{stab} , e.g. from point B to C, resulting in a reduced but stable polarization state (stabilized region).

3.2.2 Magnetic viscosity parameter

The magnetic viscosity parameter quantifies the permanent magnet's resistance to external influences over time. Originally defined for magnetic fields as S_v [2], we adapted it for temperature, introducing the temperature-based viscosity parameter S_v^T . S_v^T is measured using a temperature ramp with stepwise heating and constant-temperature phases to determine irreversible polarization decreases. The general measurement procedure for determining S_v^T is shown in Fig. 5.

First, the temperature is increased from T^A to T^B , denoted as $\Delta T^{A,B}$. This causes an immediate polarization change ΔJ^{tot} , which defines the total temperature-dependent response:

$$\frac{\Delta J^{\text{tot}}}{\Delta T^{A,B}} = \frac{J^A - J^B}{T^A - T^B} \quad (2)$$

During the subsequent constant-temperature phase at T^B , the decrease of the irreversible time-dependent polarization $\Delta J^{\text{t.d.}}$ from J^B to J^C is used to determine the magnetic viscosity S as

$$S = \frac{\Delta J^{\text{t.d.}}}{\ln\left(\frac{t}{t_0}\right)}, \quad (3)$$

where t is the exposure time and t_0 the reference time marking the onset of time-dependent demagnetization. The reversible temperature response is measured by a small temperature change between T^C to T^D and is given by

$$\frac{\Delta J^{\text{rev}}}{\Delta T^{C,D}} = \left| \frac{J^D - J^C}{T^D - T^C} \right| \quad (4)$$

The irreversible temperature response is then calculated as:

$$\frac{\Delta J^{\text{irr}}}{\Delta T} = \frac{\Delta J^{\text{tot}}}{\Delta T^{A,B}} - \frac{\Delta J^{\text{rev}}}{\Delta T^{C,D}} \quad (5)$$

Finally, the temperature-based magnetic viscosity parameter S_v^T is calculated as:

$$S_v^T = \frac{S}{\left(\frac{\Delta J^{\text{irr}}}{\Delta T}\right)} [^\circ\text{C}] \quad (6)$$

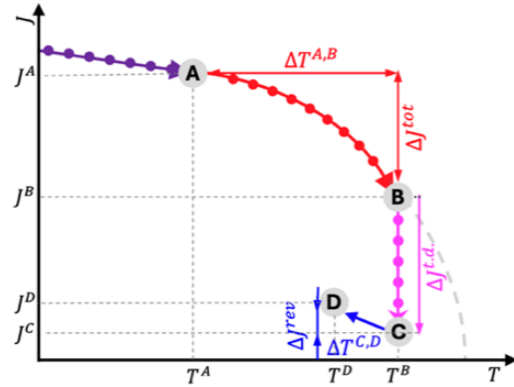


Fig. 5: Schematic measurement procedure for determining the temperature-dependent viscosity parameter S_v^T . The temperature increase $\Delta T^{A,B}$ from point A to point B is used to determine the corresponding total polarization decrease ΔJ^{tot} from J^A to J^B . At constant temperature T^B , the time-dependent decrease $\Delta J^{\text{t.d.}}$ leads from J^B (point B) to J^C (point C) over time t . Finally, a small temperature increase $\Delta T^{C,D}$ from point C to point D is applied to determine the reversible polarization change ΔJ^{rev} .

3.2.3 Prediction of long-term losses

Based on the value of the temperature-dependent magnetic viscosity parameter S_v^T , future polarization states can be estimated using a fictitious fluctuation temperature, analogous to the fluctuation field concept as described in [11] according to Néel [3]. The time-dependent polarization decrease $\Delta J^{\text{t.d.}}$, for example shown in Fig. 6 from J^B (point B) to J^C (point C), can also be described by adding an additional fictitious fluctuation temperature $T_f(t)$ to the maximum temperature T^B .

The fluctuation temperature can be quantified as the product of S_v^T and the logarithm of the exposure time t , defined as the duration of maximum temperature exposure, with t_0 denoting the reference time:

$$T_f(t) = S_v^T * \ln(t/t_0) \quad (7)$$

Adding $T_f(t)$ to the maximum temperature T_{max} , here T^B results in the effective temperature $T_{\text{eff}} = T^E$:

$$T_{\text{eff}}(t) = T_{\text{max}} + T_f(t) \quad (8)$$

The polarization value at T^E is J^E and therefore identical to the time-dependent decrease, i.e. $J^C = J^E$. Consequently, instead of measuring the time-dependent polarization decrease over

a long time, the fluctuation temperature approach allows determining the polarization state at present to predict its behavior under long-term future temperature exposures.

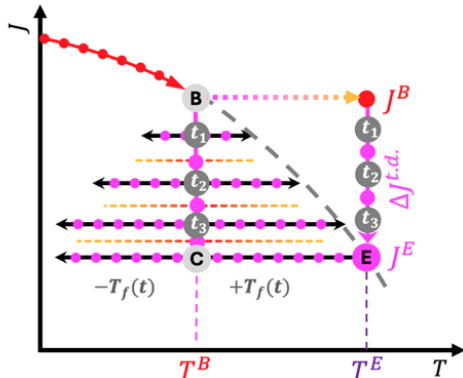


Fig. 6: Schematic visualization of the fictitious fluctuation temperature. The time-dependent decrease $\Delta J^{t.d.}$ reduces the polarization from J^B to J^C . The same polarization state can alternatively be reached by applying an effective temperature, defined as the maximum temperature T^B plus the fictitious fluctuation temperature $T_f(t)$ as a function of exposure time t , resulting in T^E with $J(T^E) = J^E$, which is equal to J^C .

4 Results and Discussions

4.1 Application of Permanent magnets for sensor systems

For the application of permanent magnets, two material grades were selected: (A1) N52 ($H_{cJ} = 955$ kA/m) and (B) N52-SH ($H_{cJ} = 1590$ kA/m), both with $J_r = 1.4$ T in disc geometry with a diameter of 40 mm and a height of 4 mm corresponding to a demagnetization factor of $N = 0.8$, while for comparing different geometries sample A2, is realized in block geometry with dimensions of $40 \times 10 \times 4$ mm³ and $N = 0.65$, as schematically shown in Fig. 7.

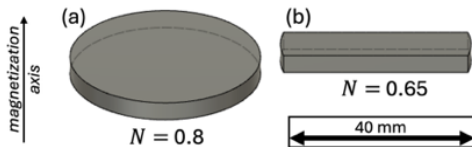


Fig. 7: Overview of the sample geometries. a) Disc sample with a diameter of 40 mm and a height of 4 mm, $N = 0.8$. b) Block sample with dimensions of $40 \times 10 \times 4$ mm³ and $N = 0.65$. In both cases, the magnetization direction corresponds to the 4 mm dimension.

The resulting $J(T)$ curves of these samples are shown in Fig. 8, together with the corresponding

transition temperatures T_t and the time-dependent decrease $J^{t.d.}$, measured over 18 min (1080 s) at selected temperatures.

It can be observed that sample A1 shows a transition temperature of around 25 °C, sample A2 around 50 °C, and sample B around 90 °C. The transition temperature marks the shift from mainly reversible to irreversible losses. Consequently, the time-dependent decrease also increases above the transition temperature, as shown by the $\Delta J^{t.d.}$ measurements: in the linear region, where mainly reversible losses occur, time dependency is nearly zero within the observed time frame, while a strong decrease appears beyond the transition temperature. The magnitude of $\Delta J^{t.d.}$ therefore reflects the time stability at each temperature: smaller time-dependent decreases correspond to higher stability of the sample polarization.

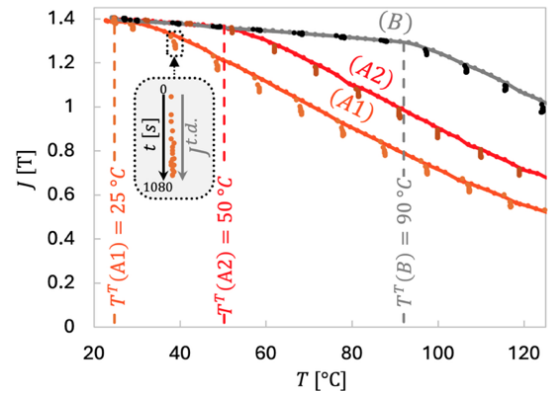


Fig. 8: $J(T)$ curves of selected materials A1 ($N = 0.8$, N52), A2 ($N = 0.65$, N52) and B2 ($N = 0.8$, N52-SH) with indicated transition temperatures. Time-dependent losses are indicated by $J^{t.d.}$ during 18 min of constant temperature exposure. An increasing time dependence is observed at temperatures above the transition temperature.

4.1.1 Magnetic stabilization

Since sample A1 exhibits a transition temperature of only 25 °C and sample A2 of 50 °C, both samples were temperature-stabilized using a temperature pulse of 65 °C (as an example), as shown in Fig. 9.

After stabilization, both samples show increased temperature resistance, with a new transition temperature of approximately 65 °C, effectively minimizing irreversible and time-dependent decreases up to this temperature. The polarization level of sample A1 was reduced to approximately 1.10–1.07 T, while that of sample A2 was reduced to approximately

1.30–1.27 T. The nearly zero time-dependent decrease within the extended reversible region confirms the effectiveness of the stabilization process.

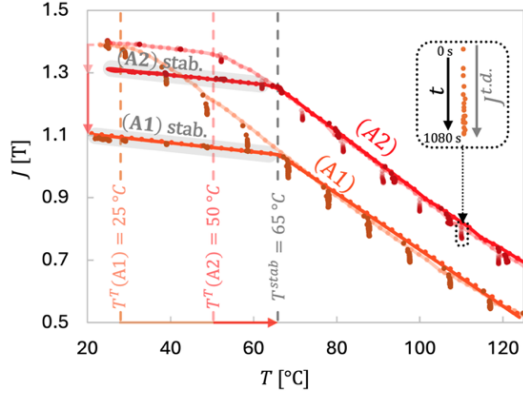


Fig. 9: $J(T)$ material curves of N52 samples A1 ($N = 0.8$), A2 ($N = 0.65$) illustrating the effect of temperature stabilization with 65 °C, extending the initial transition temperatures T_t from 25 °C for A1 and 50 °C for A2 to 65 °C, thereby eliminating irreversible time-dependent losses ($J^{t.d.}$) below this temperature.

4.1.2 Long-term prediction

The procedure for determining the temperature-based magnetic viscosity parameter described in Section 3.2.2 was repeated several times over a temperature range of 45 to 160 °C with increasing temperature of ΔT^{tot} and $t = 18$ min per cycle for samples A and B. The measurement results of S_v^T [°C] are shown in Fig. 10.

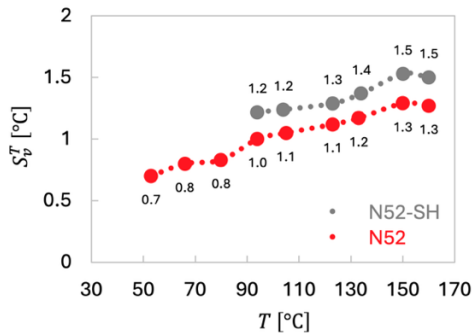


Fig. 10: Measurement results of S_v^T for the N52 sample (red) and the N52-SH sample (grey) over a temperature range from 45 °C to 160 °C. For the N52 sample, S_v^T varies from 0.7 °C at 50 °C to 1.3 °C at 160 °C. For the N52-SH sample, S_v^T varies from 1.2 °C at 100 °C to 1.5 °C at 160 °C.

The low-coercivity N52 sample exhibits S_v^T values of 0.7 °C at approximately 45 °C, increasing to 1.3 °C at approximately 160 °C, while the high-coercivity N52-SH sample shows

$S_v^T = 1.2$ °C at approximately 90 °C, rising to 1.5 °C at approximately 160 °C.

Missing values for N52-SH are mainly attributed to the difficulty of detecting the comparatively small time dependence at lower temperatures. The values of S_v^T can then be used, together with the previously described fluctuation temperature (section 3.2.3), to predict future polarization states, as shown in Fig. 11, based on the $J(T)$ curves from Fig. 8. The colored dashed lines with marked peak times ranging from 10 s up to 10 years are linked to the $J(T)$ material curves by corresponding colors. Their intersections with each effective temperature (as a function of exposure time) indicate the predicted polarization states based on $T_{\text{max}} = 40$ °C. At this maximum temperature, sample A1 is already above its transition temperature T_t and therefore does not provide time stability. Sample A2 can be used with only minor expected time-dependent irreversible losses for durations of up to approximately one week at T_{max} , as the resulting temperature remains just below the transition temperature. For longer durations, such as one year, the temperature exposure becomes critical, as the temperature exceeds the transition temperature, resulting in significant time-dependent irreversible losses. In contrast, sample B demonstrates good performance even after 10 years at T_{max} , with a projected effective temperature of maximum 65 °C, which is far below the transition temperature and therefore suitable for long-term use.

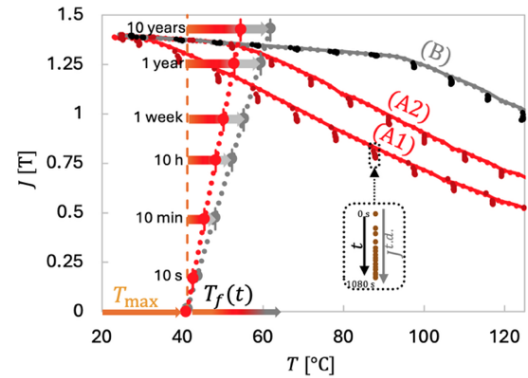


Fig. 11: Application of the fluctuation temperature $T_f(t)$ to predict long-term polarization states at a maximum temperature of $T_{\text{max}} = 40$ °C for exposure times t ranging from 10 s to 10 years. The colored dashed lines correspond to the respective $J(T)$ material curves. The value of $T_f(t)$ at a given exposure time t on the $J(T)$ curve indicates the predicted polarization state after that time.

5 Summary and Conclusions

A novel measurement setup has been developed to characterize the long-term stability of permanent magnets under open-circuit conditions and thermal influence, enabling evaluation of both direct and time-dependent polarization changes. Two complementary strategies are presented: thermal stabilization and long-term state prediction. For assessing long-term stability in magnetic systems, the following steps can be considered:

1. **Evaluation:** Determine whether the sample magnetization state can be reduced while still meeting the requirements of the intended application.
2. **Stabilization:** If reduction is possible, magnetic stabilization effectively eliminates time-dependent losses by operating the sample at a reduced polarization state.
3. **Viscosity-based prediction:** If a high magnetization state is required, the temperature-dependent viscosity parameter and the resulting fluctuation temperature allow straightforward prediction of future magnetization states of the magnetic material.

The use of both strategies provides a practical framework to mitigate time-dependent demagnetization, enabling informed material selection and efficient use of permanent magnets across a wide range of applications.

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