Thermal Behavior and Demagnetizing Factor of Nd-Fe-B & other Magnets: Disadvantage and Advantage in Their Applications

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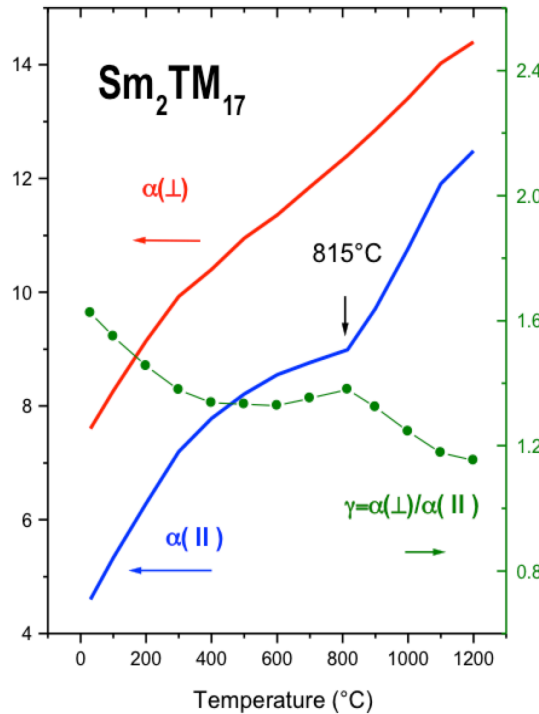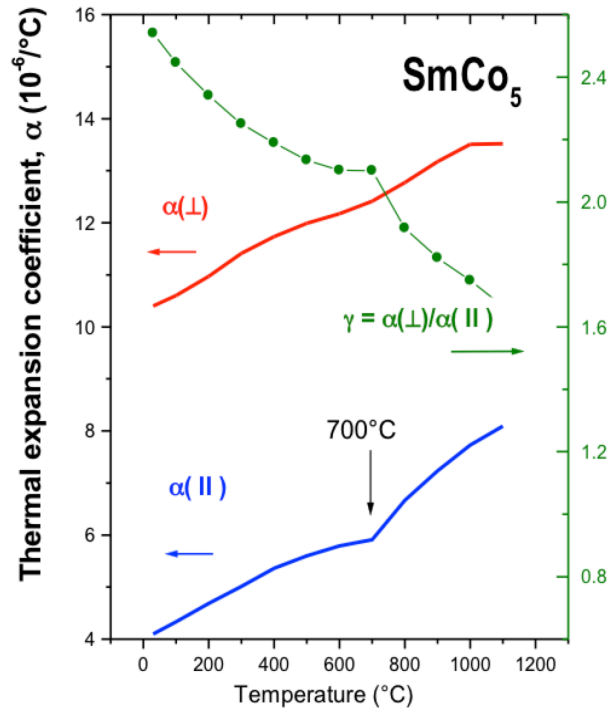Ningbo **Songke** Magnetic Material Co., Ltd., Zhejiang

Outline

❑ Describing the thermal behavior and the demagnetizing factor of Nd-Fe-B and other magnets.

❑ Discussing the disadvantages and advantage for their applications. The disadvantages include high magnetic flux loss at elevated temperatures or exposing to various radiations-induced heat.

❑ The high temperature coefficients of α (B) and β (H_{ci}) are the major reasons for the addition of Dy and other heavy RE elements into Nd-Fe-B for PM motor applications.

❑ The advantages include thermal magnetization using a significant smaller magnetic field to saturate the magnets.

Introduction

❑   Nd-Fe-B and other magnets are in high demand in today's sustainable energy applications. The global market for these magnets is expected to reach USD 31 billion by 2020.

❑   Growth of global automobile industry is expected to be a key-driving factor for permanent magnets market. Various components such as motors, alternators and gearbox require permanent magnets for their mechanism.

❑   Understanding the behavior of the permanent magnets should help many designers to design and make better PM motors.

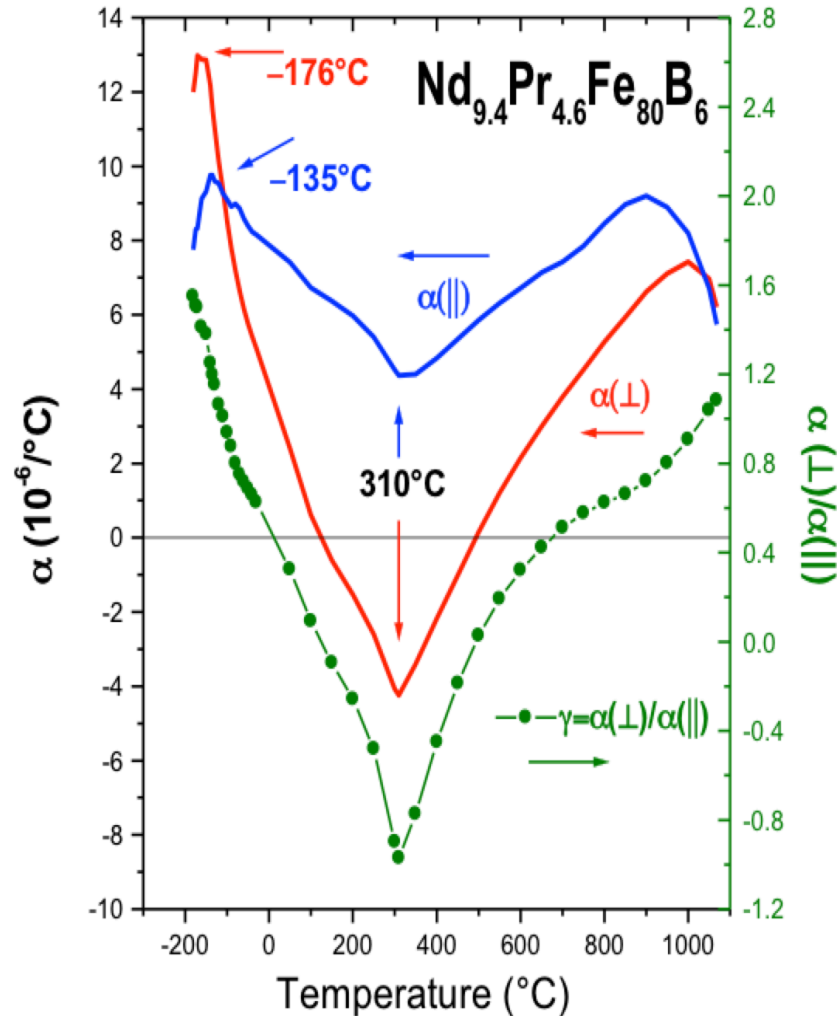| Material	T_c [a] (°C)	Thermal abnormal	γ [b] @30°C	Structure
$Nd_{9.4}Pr_{4.6}-Fe_{80}B_6$	310	310	0.42	Tetragonal
$SmCo_5$	691	700	2.54	Hexagonal
Sm_2TM_{17}	820	815	1.63	Rhombohedral

❑ Thermal expansion coefficients α in both directions: The degree of thermal expansion anisotropy (TEA) is defined as the ratio $\gamma = \alpha(\perp)/\alpha(//)$.

❑ The TEA data are actual very useful in guiding material manufacturing and device designing. For example, $SmCo_5$ has a very large TEA with $\gamma = 2.54$, which results in extremely difficulty to make radially oriented, anisotropic magnetic rings for $SmCo_5$.

Thermal Behavior of Nd-Fe-B & Other Magnets: Thermal Expansion Coefficients

- ❑ @ ~ −150C: $Nd_2Fe_{14}B$ phase changes from a uniaxial (easy-axis) to an easy-cone: thermal expansion coefficients changes:
a consideration for some applications at extremely low temperature

- ❑ @ ~310C: Curie point T_c. Thermal expansion coefficients change dramatically near T_c. A consideration for melting the alloys: In order to make the melting crucible last longer, it should not be cooled down below 310C, and continuous melting is desired.

- ❑ The TEA [$\gamma = \alpha(\perp)/\alpha(//)$] of NdFeB also results in a difficulty to make radially oriented, anisotropic magnetic rings.

| Material	Tc [a] (°C)	Thermal abnormal	γ [b] @30°C	Structure
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Temperature dependence of energy product and coercivity
for NdFeB and other magnets
(data were obtained in year 2000, and the values
in parentheses are the $(BH)_{max}$ at 25°C)

Thermal Behavior of Nd-Fe-B & Other Magnets:
Thermal Magnetic Loss vs Magnets' Geometry & Type
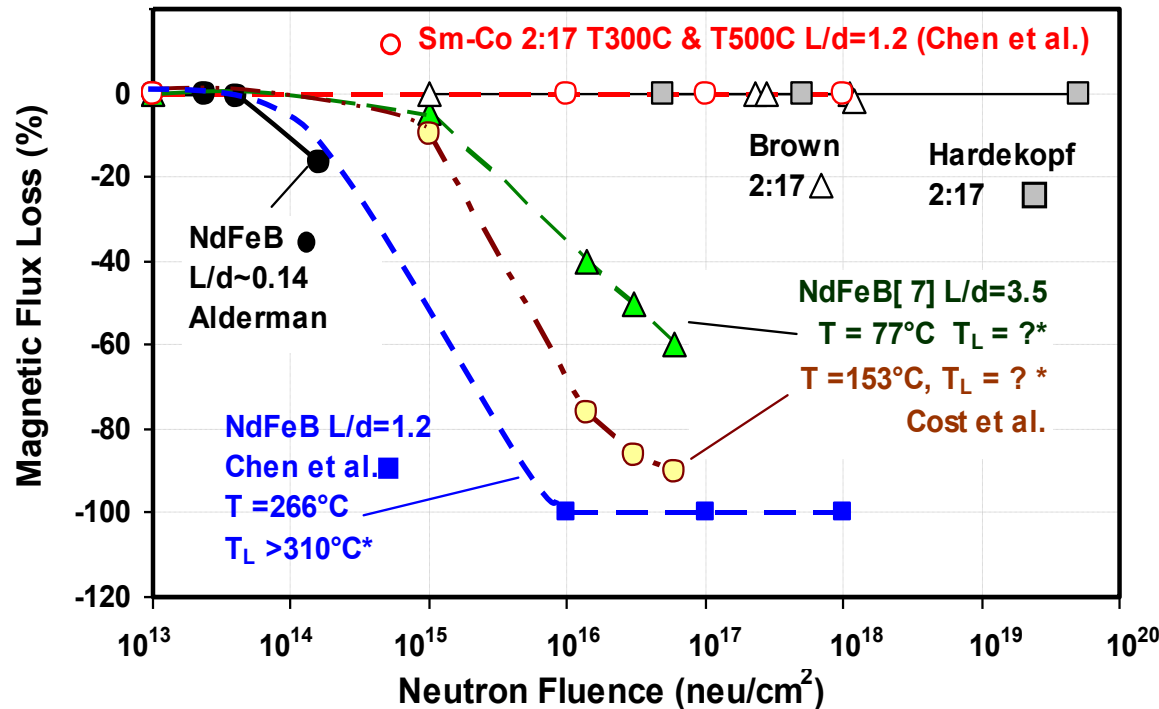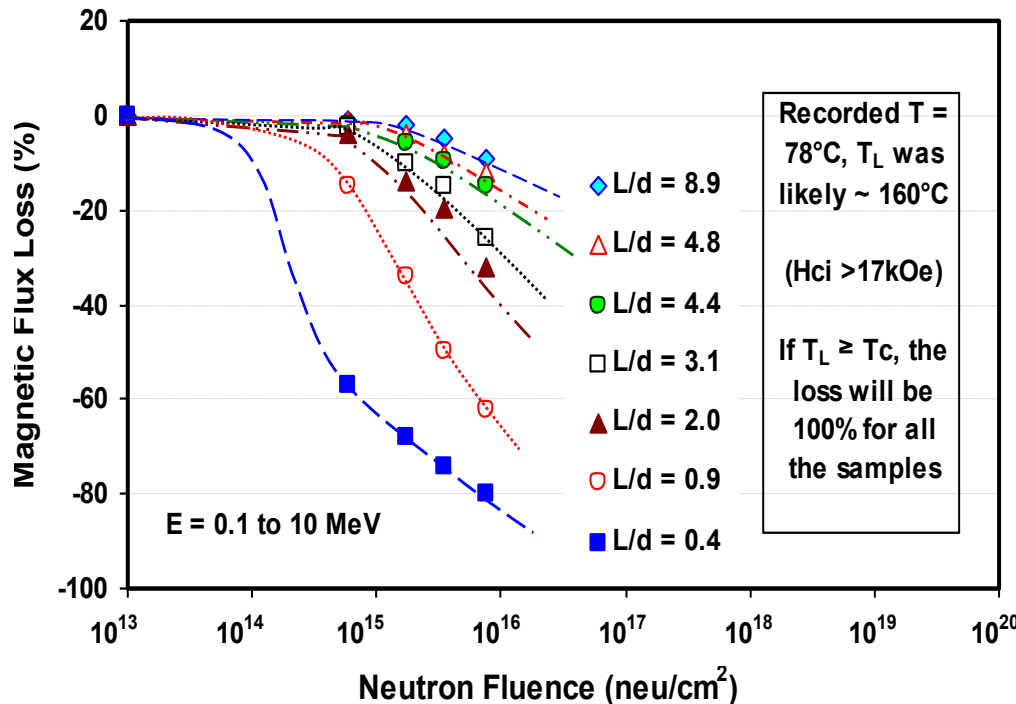

All reports had Neutron E = 0.1-10 MeV.
Neutron flux: 4×10^{12} (Cost) and 2.1×10^{13} n/(cm^2.s) (Chen et al)

❑ T_L is localized temperature at momentary time

❑ **Radiation damage studies have been performed under a variety of radiation fields, such as neutron, electron, proton, and gamma.**

❑ **Sm-Co magnets have been found to be more radiation resistant than Nd-Fe-B magnets, which are actually attributed to their higher Curie temperature and superior thermal properties**

❑ **All the losses associated with radiation are caused by radiation-induced heat.**

❑ **The losses are related to the samples' geometry too**

Thermal Behavior of Nd-Fe-B & Other Magnets:
Thermal Magnetic Loss vs Magnets' Geometry & Type

Recorded T = 78°C, T_L was likely ~ 160°C

(Hci >17kOe)

If $T_L \geq T_C$, the loss will be 100% for all the samples

◆ L/d = 8.9
△ L/d = 4.8
● L/d = 4.4
☐ L/d = 3.1
▲ L/d = 2.0
○ L/d = 0.9
■ L/d = 0.4

E = 0.1 to 10 MeV

Cost et al.(1989) Re-plotted using a scale comparable in this presentation

- T_L is localized temperature at momentary time caused by radiation

- It is very clearly that the magnetic losses caused by radiation-induced heat also depend on the L/D, which is directly related to demagnetizing factor.
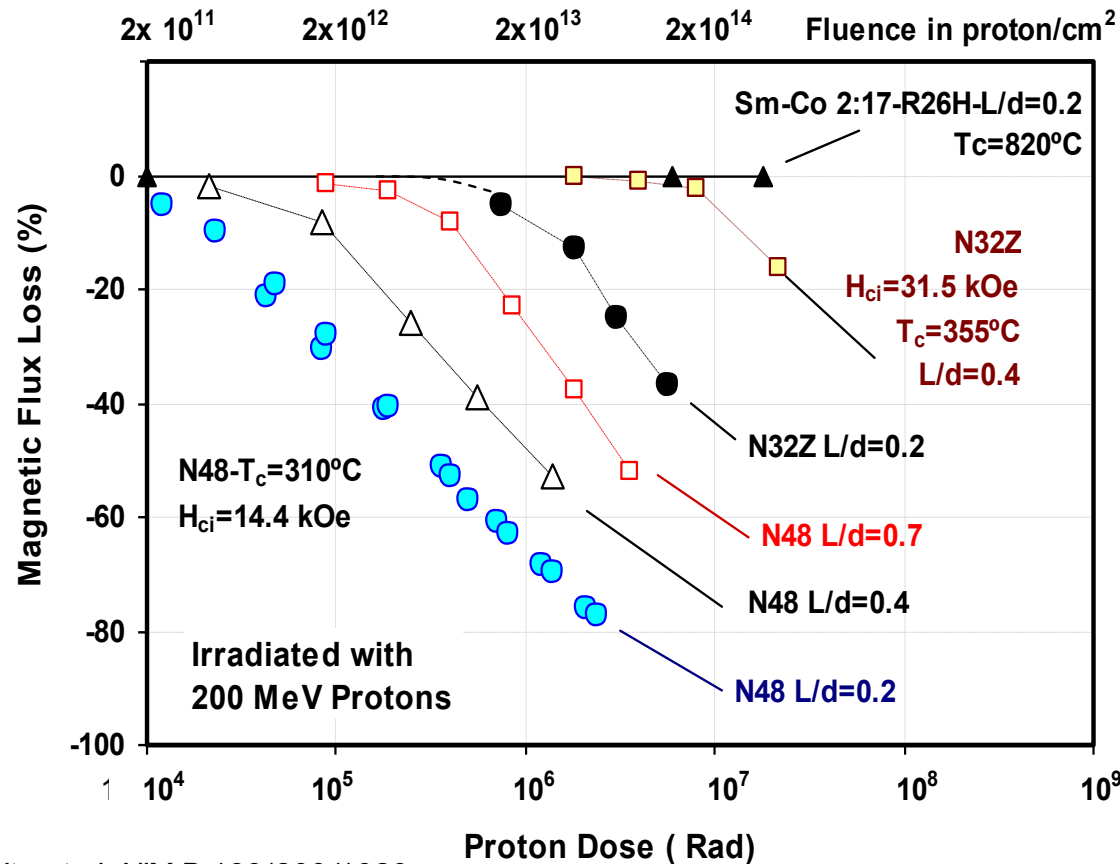
The dominant factor for heat tolerance is the thermal stability of magnets, determined by 3 factors:

- the T_C

- Intrinsic coercivity H_{ci} of magnets and the temperature coefficient of H_{ci}, which determine the linearity of the B-H normal curve;

- The load line of the magnet, related to the L/D ratio or the demagnetizing factor of the magnets;

Thermal Behavior of Nd-Fe-B & Other Magnets:
Thermal Magnetic Loss vs Magnets' Geometry & Type
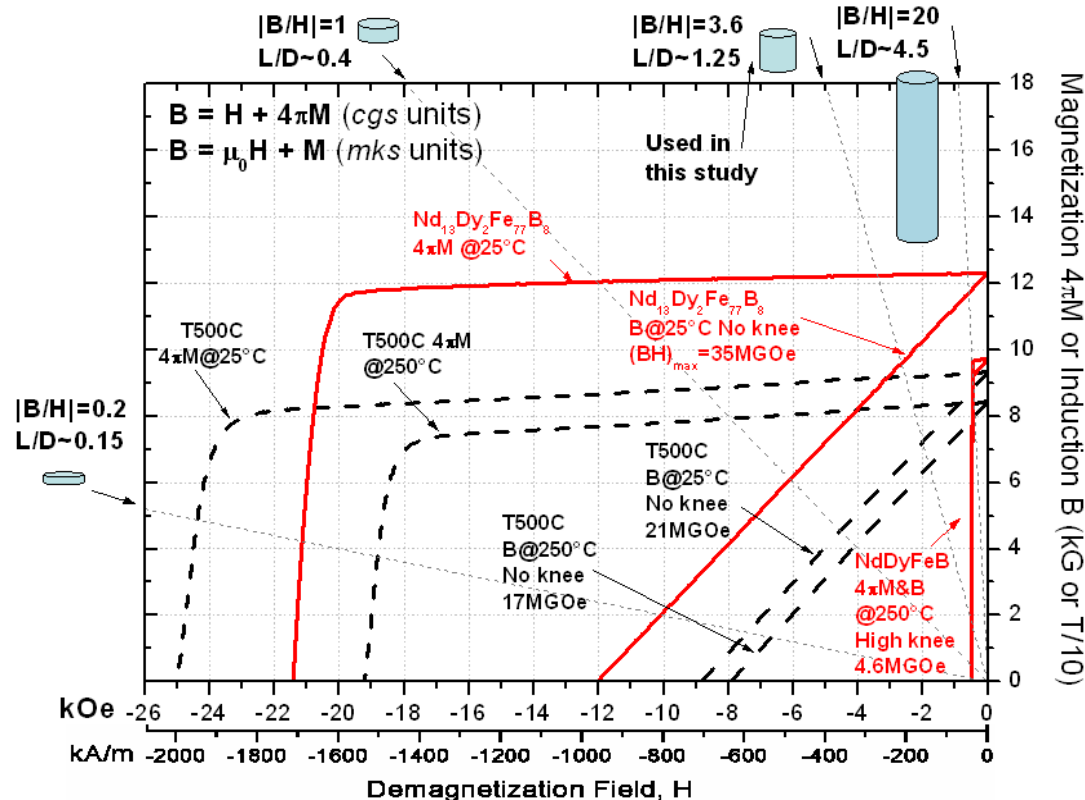
Effects of Intrinsic coercivity and L/D on the thermal loses induced by Proton radiation on the Nd-Fe-B magnets with different Dy contents and different L/D values :

Fluence in proton/cm^2

Magnetic Flux Loss (%)

Sm-Co 2:17-R26H-L/d=0.2 Tc=820ºC

N32Z H_{ci}=31.5 kOe T_c=355ºC L/d=0.4

N32Z L/d=0.2

N48 L/d=0.7

N48 L/d=0.4

N48 L/d=0.2

N48-T_c=310ºC H_{ci}=14.4 kOe

Irradiated with 200 MeV Protons

Proton Dose (Rad)

Ito et al. NIM B 183(2001)323

	N48	N32Z
Hci (kOe)	14.4	31.5
Loss@ 2x10^6 L/D =0.2	− 80%	− 15%
Loss@ 2x10^6 L/D =0.7	− 38%	− 0%

Consideration of Demagnetizing Factor
Permeance coefficient (or a load line)

Demagnetization curves of samples of a Nd-Fe-B and a Sm-Co T500C. Sm-Co is plotted with dotted lines, and the $Nd_{13}Dy_2Fe_{77}B_8$ is plotted with solid lines

❑ Theoretically, as long as the $T < T_C$, a magnet should fully recover its magnet strength after cooling down to room T, if it had a perfect linear extrinsic demag curve (B-H) at the T exposed.

❑ To maintain a linear B-H curve, a high H_{ci} and a low-temperature coefficient of H_{ci} are required.

❑ If a magnet does not have a linear B-H curve, a large permeance coefficient (or a higher load line) is required.

❑ The permeance coefficient B/H, or Load Line, is a critical factor in magnetic design, which is a function of the L/D ratio for a stand-alone magnet.

Consideration of Demagnetizing Factor
An extreme example @ 250°C
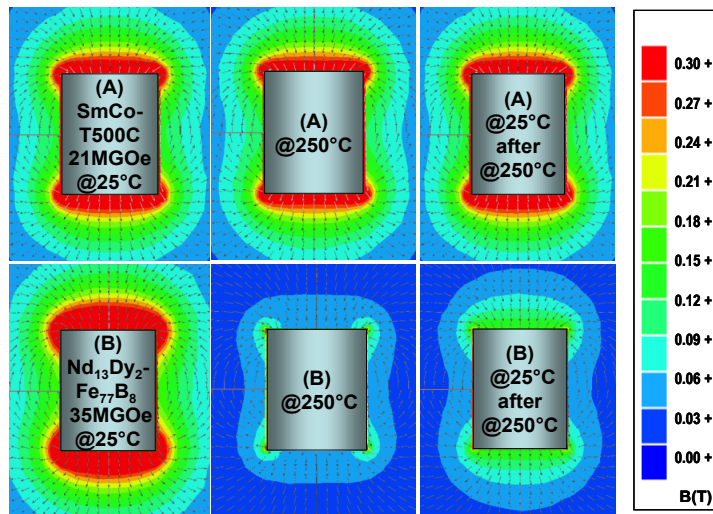
This is an extreme example @ 250°C

Thermal behaviors of $Nd_{13}Dy_2Fe_{77}B_8$ and Sm-Co-T500C with L/D = 1.25 (B/H = 3.6)

Top:

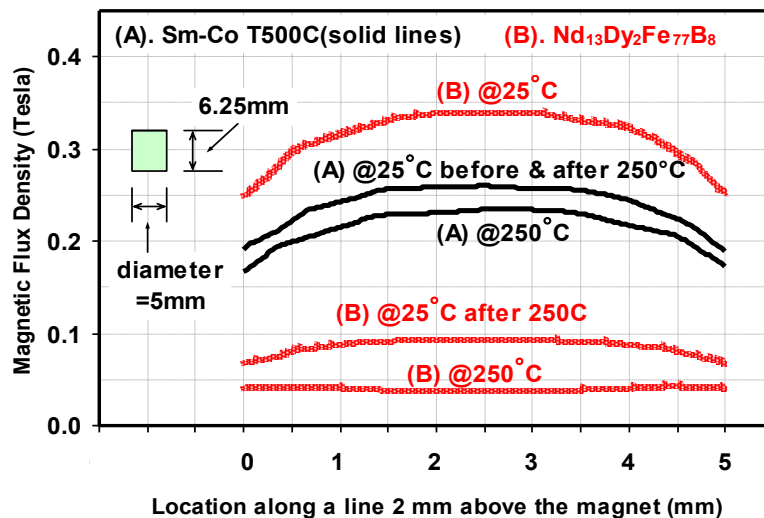Magnetic flux density on the section across the diameter.

Bottom:

From 25°C to 250°C:

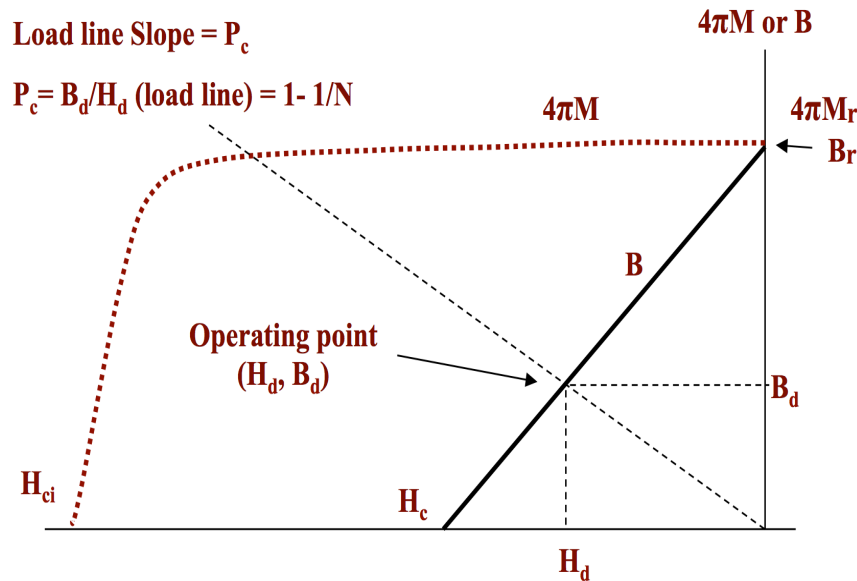Flux density along a line 2 mm above the magnet :Sm-Co-T500C has 9.3% loss, and $Nd_{13}Dy_2Fe_{77}B_8$ has ~89% loss.

After cooling down to 25°C:

Sm-CoT500C was fully recovered with unnoticeable loss, and $Nd_{13}Dy_2Fe_{77}B_8$ still has ~72% loss.

The Relationship of Permeance Coefficient B/H, Load line, Demagnetizing Factor, and L/D

Load line Slope = P_c

$P_c = B_d/H_d$ (load line) = $1 - 1/N$

This magnet has a high H_{ci} and a straight B-H curve, which is ideal for motor applications, and a small L/D can be used.

* Rollin. J. Parker, *Advances in Permanent Magnetism*. ISBN 0-471-82293-0, by John Wiley & Sons, (1990).

The permeance coefficient B/H is a critical factor in magnetic design, which is a function of the L/D ratio for a stand-alone magnet.

The plot on the left illustrates these terminologies:

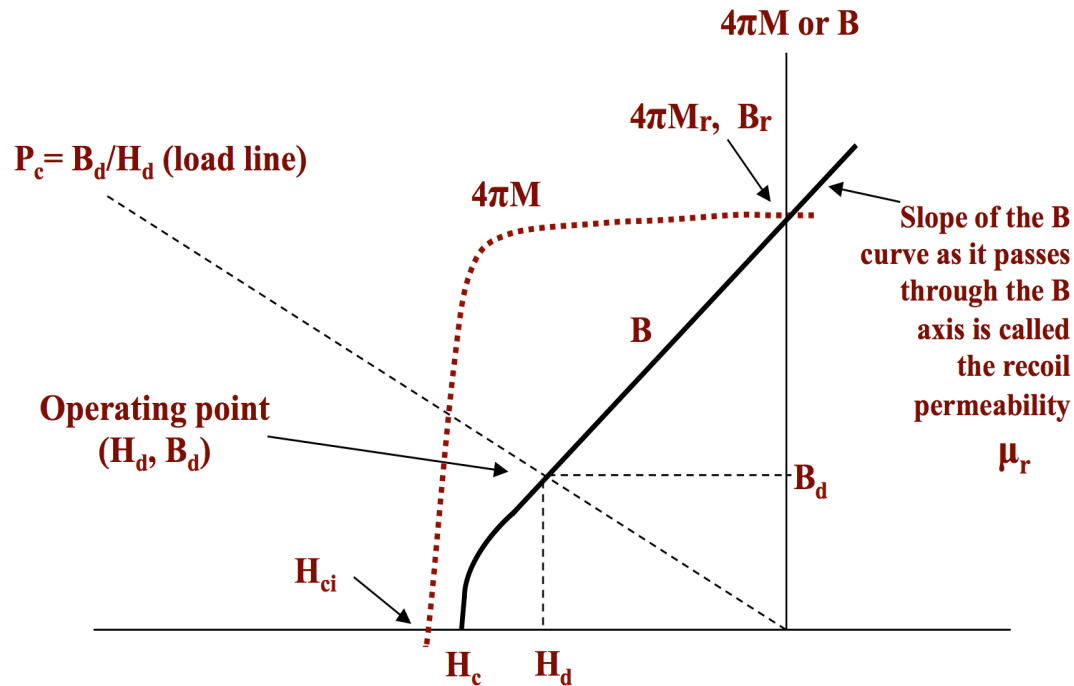the intersection of a Load Line and the B-H normal curve is defined as the Operating Point.

The slope of the line is referred to as the Permeance Coefficient ($P_c = B_d / H_d$).

The demagnetizing factor is defined in equations (1) and (2) in Parker's book *.

$$P_C = \frac{B_d}{H_d} = 1 - \frac{1}{N} \qquad (1)$$

$$N = \frac{1}{1 - \dfrac{B_d}{H_d}} = \frac{1}{1 + \left|\dfrac{B_d}{H_d}\right|} \qquad (2)$$

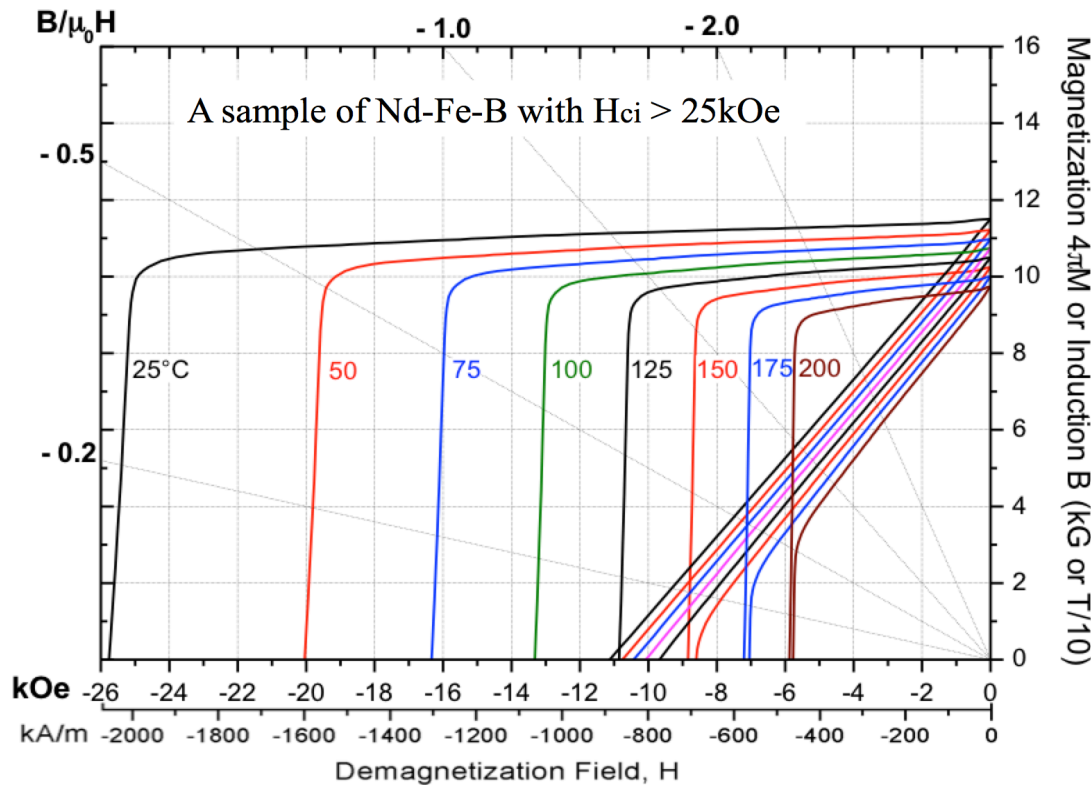# The Relationship of Permeance Coefficient B/H, Load line, Demagnetizing Factor, and L/D

To maintain stable performance, a minimum L/D ratio is required, which must correspond to the B/H Load Line above the "knee" of the B-curve.

Next page gives further illustration on the requirement of linear B-H curve for motor application.

This magnet has a low H_{ci} and non-linear B-H curve, which is not suitable for motor application.

Note: The Recoil Permeability μ_r : Typical values are ~1.05 for Ferrite, Sm-Co and NdFeB. Bonded Neo magnets range from ~ 1.12 to 1.70, depending upon grade. This topic is not in the scope of this presentation.

The Relationship of Permeance Coefficient B/H, Load line, Demagnetizing Factor, and L/D


- ❑ Demagnetization curves for a Nd-Fe-B sample with intrinsic coercivity > 25 kOe at 25°C to 200°C:
- ❑ The 5 B-H curves are linear from 25 to 125°C, and the 3 B-H curves at 150, 175, and 200°C are non-linear with obvious keens.
- ❑ In dynamic applications with elevated temperature, (such as in PM motors) this magnet should be used at T ≤ 125°C.
- ❑ A knee will result in large irreversible loss after exposing to a higher temperature.

To maintain stable performance, a minimum L/D ratio is required, which must correspond to the B/H Load Line above the "knee" of the B-curve. This plot gives further illustration on the requirement of linear B-H curve for motor application.
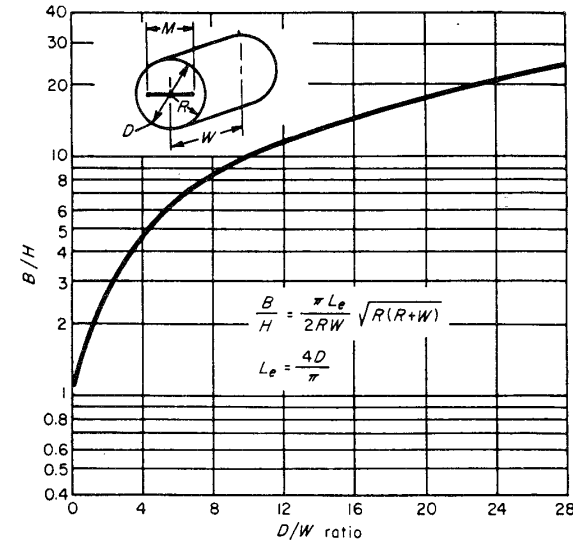
The Relationship of Permeance Coefficient B/H, Load line, Demagnetizing Factor, and L/D

❑ In actual magnetic devices, the demagnetizing field depends on the demagnetizing factor N, which in turn depends on the geometry of the magnets and their permeability.

❑ Theoretically the demagnetizing factor can be calculated precisely only for the case of an ellipsoidal sample; for other regular geometries, it must be determined experimentally or calculated numerically subject to certain assumptions. Errors are inevitable for such calculations. There are various methods to determine the demagnetizing factors, which can be found in many references.

❑ A convenient method has been used by many in the industry, which is described in Rollin J Parker's book of Advances in Permanent Magnetism. Parker summarized the relationship of permeance coefficients and various magnet shapes, such as rings, rectangles, which are plotted in the next 4 figures. The formulas for calculating the plots are listed in the figures respectively.
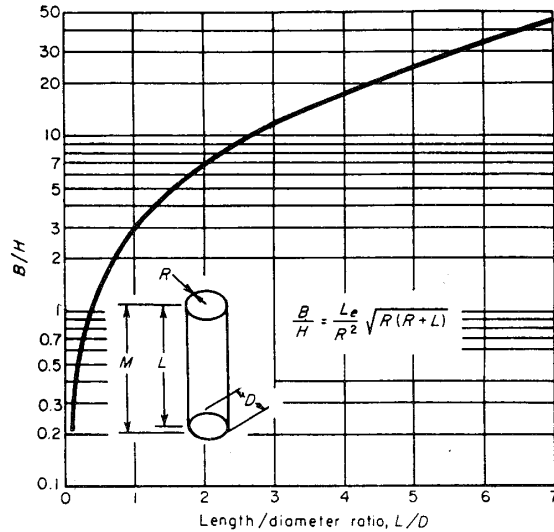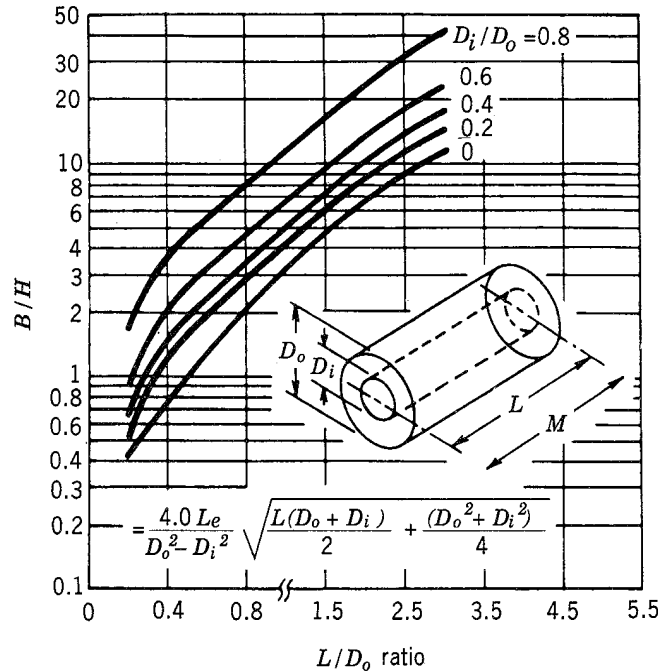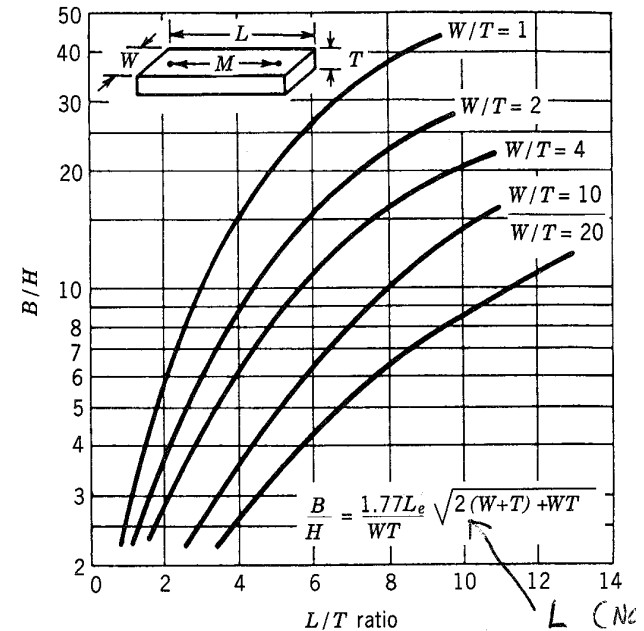
The permeance coefficient B/H vs. L/D for cylinders with axial magnetization

The permeance coefficient B/H vs. D/W for cylinders with diametric magnetization

The permeance coefficient B/H vs. L/D for tubular magnets with axial magnetization

$$\frac{B}{H} = \frac{4.0\,L_e}{D_o^2 - D_i^2}\sqrt{\frac{L(D_o + D_i)}{2} + \frac{(D_o^2 + D_i^2)}{4}}$$

The permeance coefficient B/H vs. L/T for rectangular bars with magnetization along L direction

$$\frac{B}{H} = \frac{1.77\,L_e}{WT}\sqrt{2(W+T) + WT}$$

❑ **A rule of the thumb is that a magnet with a smaller L/D ratio will have a larger irreversible magnetic loss at elevated temperature, compared to a magnet with a larger L/D ratio.**

❑ **In order to estimate the relative irreversible magnetic loss, some engineers usually use a simplified calculation as shown below for some frequently used shapes in PM motors, such as arc shaped magnets.**

$$\frac{L}{D} \cong \frac{c}{2\sqrt{\dfrac{ab}{\pi}}}$$

$$\frac{L}{D} \cong \frac{R - r}{2\sqrt{\dfrac{L*W}{\pi}}}$$
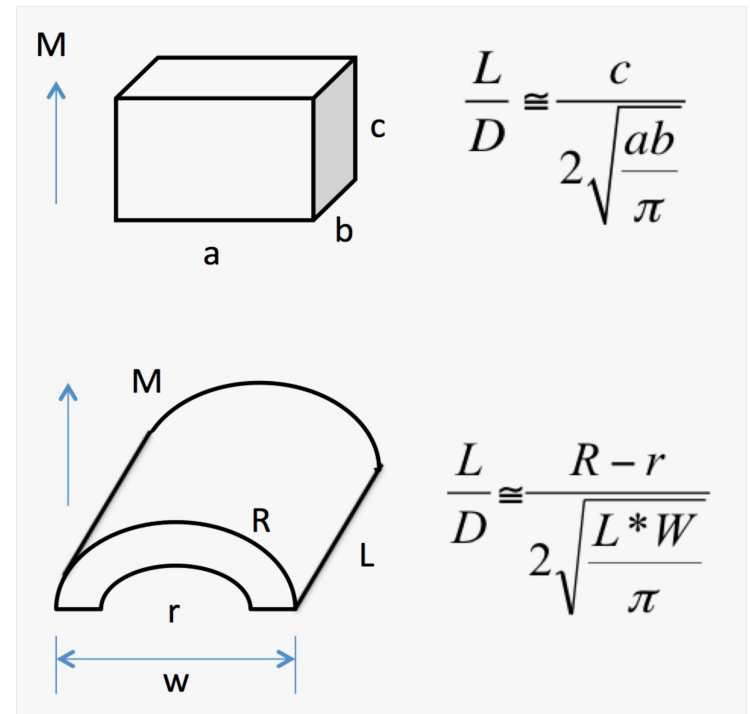
The large Temperature-Coefficient can be Used in Thermal Magnetizing
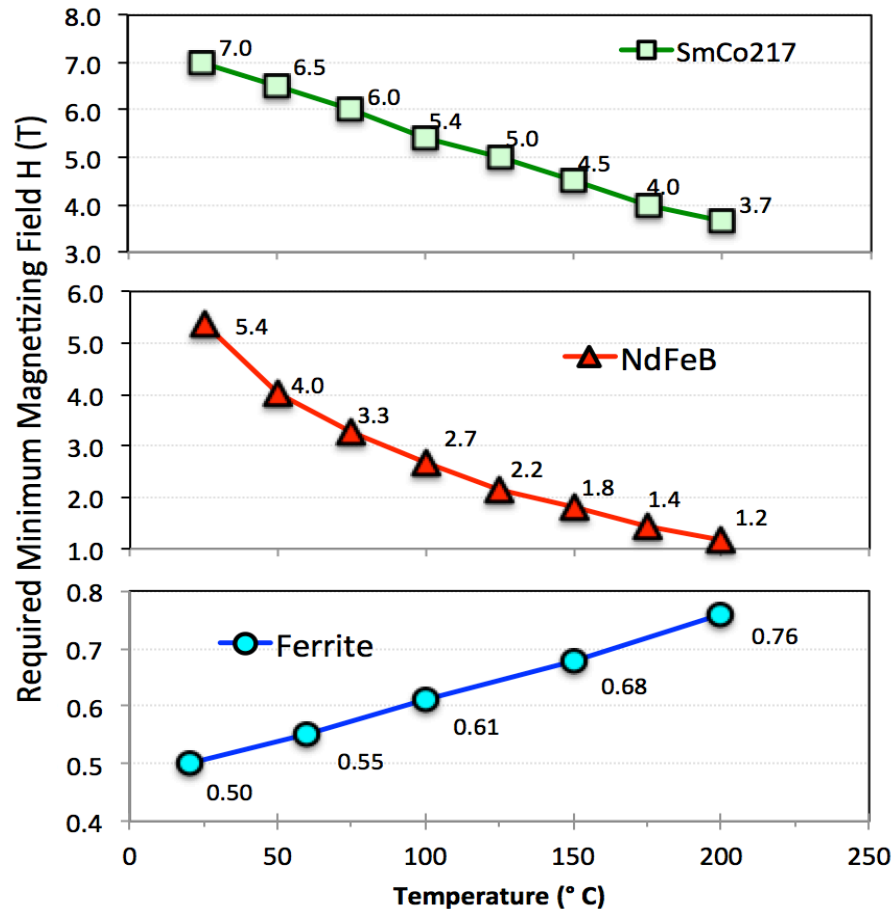

- ❑ **If it requires two times of intrinsic coercivity ($2 \times H_{ci}$) to saturate a magnet (actually ~99% of saturation), a minimum magnetizing field is required to saturate a magnet.**

- ❑ **At 25°C, for typical Sm-Co 2:17 magnet, a high coercivity Nd-Fe-B, and a Ferrite magnet, the required minimum magnetizing field is 7.0 T, 5.4T, and 0.5 T respectively.**

- ❑ **By using the thermal behavior, we can reduce the minimum magnetizing field significantly for Nd-Fe-B magnets since they have large temperature coefficient.**

# Large Power Surface-Mounted PM Motors Using Post-Assembly Magnetization at 150°C
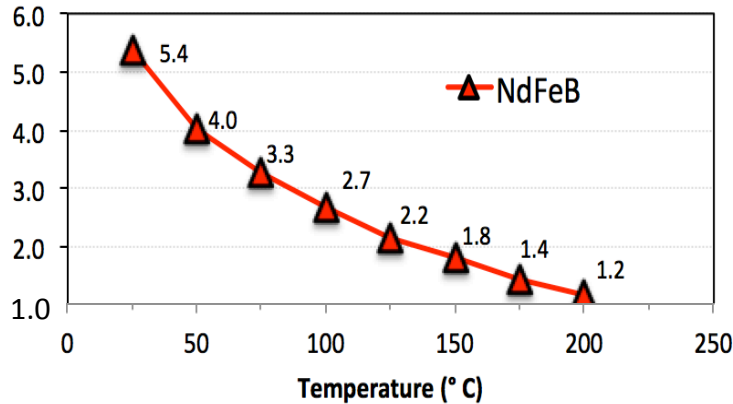
@25C: M_{min} =5.4T, and @200C: M_{min} =1.2T

❑ **Rare-earth PM brushless motors are usually assembled with the magnets pre-magnetized. However, as the motor size & output power ⬆⬆, the handling of the pre-magnetized components can be difficult & it increases the processing cost.**

❑ **Hence, the "post-assembly magnetization" represents a potential solution.**

❑ **By using the thermal behavior, we can reduce the min. magnetizing field greatly for Nd-Fe-B PM motor since the large temperature coefficient.**
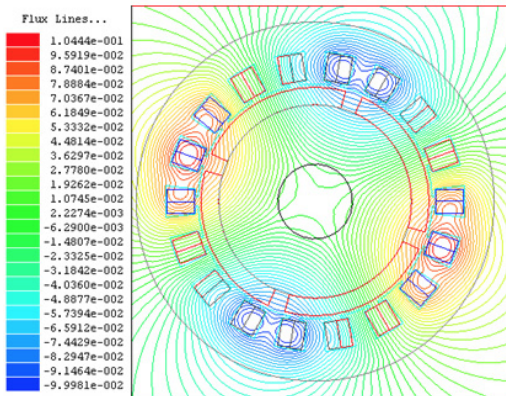
(a)
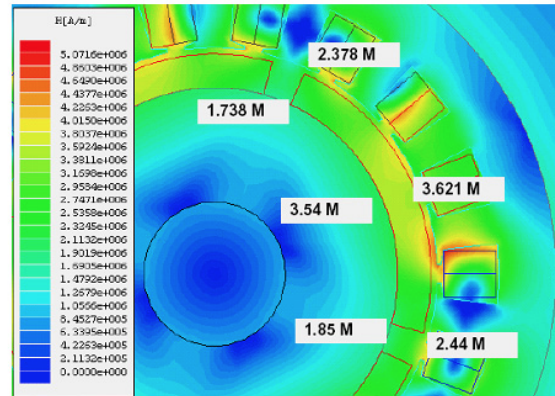
(b)

(a) distribution of a motor's magnetic flux lines (output 2000 amperes): it can be seen that the wiring of the windings can indeed produce the correct charge and magnetic poles;

(b) the magnetic field strength distribution, wherein the unit M is 10^6 A / m.

Summary

❑ **The thermal behaviors of Nd-Fe-B and other magnets their disadvantages and also advantages for their applications.**

❑ **The disadvantages include high magnetic flux loss at elevated temperatures or exposing to various radiations-induced heat.**

❑ **The high temperature coefficients of α (for induction B) and β (for coercivity Hci) are the major reasons for the addition of dysprosium and/or other heavy rare earth elements into Nd-Fe-B for PM motor applications.**

❑ **The advantages include thermal magnetization using a significant smaller magnetic field to saturate the magnets.**