Permanent Magnet Diploes and Quadrupoles for FFAGs

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Overview

(BH)$_{\text{max}}$ versus Maximum Operating Temperature
Permanent Magnet Selection

Some factors to consider:

(1) Magnetic performance
(2) Corrosion resistance
(3) Thermal stability
(4) Radiation resistance
(5) Magnetization direction
(6) Manufacturability
(7) Cost
Typical magnetic properties, in terms of energy product, of selected commercial magnets:

- Sintered Nd-Fe-B magnets: up to 50 MGOe
- Sintered Sm-Co magnets: up to 32 MGOe
- Isotropic bonded Nd-Fe-B magnets: up to 10 MGOe
- Sintered ceramic magnets: up to 4 MGOe
- Cast Alnico magnets: up to 9 MGOe
### Rare Earth Magnets

**Maximum operating temperature of sintered magnets**

<table>
<thead>
<tr>
<th>Magnets</th>
<th>Maximum Operating Temp.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB with $iH_c = 12$ kOe</td>
<td>80°C</td>
</tr>
<tr>
<td>NdFeB with $iH_c = 17$ kOe</td>
<td>120°C</td>
</tr>
<tr>
<td>NdFeB with $iH_c = 20$ kOe</td>
<td>150°C</td>
</tr>
<tr>
<td>NdFeB with $iH_c = 25$ kOe</td>
<td>180°C</td>
</tr>
<tr>
<td>Conventional SmCo magnets</td>
<td>300°C</td>
</tr>
<tr>
<td>EEC24-T400 magnets (patented &amp; available)</td>
<td>400°C</td>
</tr>
<tr>
<td>EEC20-T500 magnets (patented &amp; available)</td>
<td>500°C</td>
</tr>
<tr>
<td>EEC16-T550 magnets (patented &amp; available)</td>
<td>550°C</td>
</tr>
</tbody>
</table>
Rare Earth Magnets -- Properties vs. Temperature

(BH)_{max} Versus Maximum Operating Temperature

NdFeB
SmCo

Maximum Operating Temp. (°C)

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Long-term Thermal Stability of SmCo Magnets at 300°C in Air

Magnet Dimensions: 1 cm OD x 1 cm THK

- T550C-16MGOe w/coating
- T550C-16MGOe
- T500C-20MGOe
- T400C-24MGOe
- T330C-27MGOe
- T250C-31MGOe

Magnetic Irreversible Losses (%)

Time at 300°C (Hours)
High temperature magnets

- DoD initiated the More Electric Aircraft program, which requires magnets with maximum operating temperature more than 400°C
- Funded by the Department of Defense, a series of sintered SmCo 2:17 magnets were developed at EEC with maximum operating temperature as high as 550°C
- These patented SmCo UHT magnets were introduced to the industry in 1999.
## SmCo Rare Earth Magnets

<table>
<thead>
<tr>
<th>PM Grades</th>
<th>$B_r$ (kG)</th>
<th>$(BH)_{max}$ (MGOe)</th>
<th>Max. operating temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEC2:17-31</td>
<td>11.6</td>
<td>31</td>
<td>250</td>
</tr>
<tr>
<td>EEC2:17-27</td>
<td>10.8</td>
<td>27</td>
<td>300</td>
</tr>
<tr>
<td>EEC24-T400</td>
<td>10.2</td>
<td>24.5</td>
<td>400</td>
</tr>
<tr>
<td>EEC20-T500</td>
<td>9.3</td>
<td>21</td>
<td>500</td>
</tr>
<tr>
<td>EEC16-T550</td>
<td>8.6</td>
<td>17</td>
<td>550</td>
</tr>
</tbody>
</table>
Nd-Fe-B sintered magnets

**Key features:**
- Highest \((BH)_{\text{max}}\) available (up to 50 MGOe)
- Less expensive than Sm-Co magnets
- Corrosion resistance is not good
- Special coating is required
- Maximum operating temperature is very low compared to SmCo magnets
Nd-Fe-B Type Rare Earth Magnets

<table>
<thead>
<tr>
<th>PM Grades</th>
<th>$B_r$ (kG)</th>
<th>$(BH)_{\text{max}}$ (MGOe)</th>
<th>Max. operating temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N50</td>
<td>14-14.5</td>
<td>48-51</td>
<td>70</td>
</tr>
<tr>
<td>N45</td>
<td>13.2-13.8</td>
<td>43-46</td>
<td>70</td>
</tr>
<tr>
<td>N45M</td>
<td>13.2-13.6</td>
<td>43-46</td>
<td>100</td>
</tr>
<tr>
<td>N42SH</td>
<td>12.8-13.2</td>
<td>40-43</td>
<td>120</td>
</tr>
<tr>
<td>N33UH</td>
<td>11.3-11.7</td>
<td>31-34</td>
<td>180</td>
</tr>
</tbody>
</table>
Some Design Considerations

Permeance Coefficient $P_c$

In the magnetic circuit, a magnet will operate at a specific point on its extrinsic demagnetization curve:

$$P_c = \frac{B_d}{H_d}$$

- Also known as load line or operating point
- It is related to the dimensions of the magnets and the associated magnetic circuit
Why straight-line demagnetization curves?

Application with load line #1: Both magnets are okay to use
Application with load line #2: Only magnet #1 is suitable
The effects of radiation on permanent magnets was studied at EEC under a NASA STTR Contract

- All Samples have a L/D ratio of 1.25
- Permanent Magnets Studied:
  - EEC T500 and T300 SmCo 2:17 magnets
  - Nd-Fe-B Magnets
- Radiation Source: Ohio State University Research Reactor

OSU Reactor

Samples in quartz tubes
Permanent Magnets and Radiation Effect


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Working Point and Radiation Effect

Radiation Effect

The major radiation damage is caused by radiation-induced thermal spikes

The dominant factor for radiation tolerance is thermal stability, which is related to the following factors:

1. Curie temperature of permanent magnets
2. Working point of permanent magnet in the system
3. Intrinsic coercivity
Permanent Magnet Dipoles

\[
B_g = \frac{B_m A_m}{k_1 A_g}
\]

- \(A_m\) = Magnet area perpendicular to the direction of magnetization;
- \(B_m\) = Flux density of the magnet corresponding to the operating point of the demagnetization curve;
- \(B_g\) = Flux density desired in the air gap;
- \(A_g\) = Cross section area of the air gap perpendicular to the flux lines.

The Air Gap Flux Density Is A Lot Lower Than The \(B_r\) Of The Permanent Magnets
Permanent Magnet Dipoles

Halbach PM Dipole Structures:

\[ B_g = B_r \ln(\text{OD/ID}) \]

There is no upper limit for air gap flux density in Halbach dipole structures according to above equation. But in reality it would be limited by:

1. The realistic size
2. The demagnetization effect
Halbach Dipole Example

Flux Density Map

Vector Map
Magnetic Mangles

0° Position

Vector Plot

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Magnetic Mangles

45° Position

Vector Plot

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Magnetic Mangles

90° Position

Vector Plot

5.0000e-01
4.5000e-01
4.0000e-01
3.5000e-01
3.0000e-01
2.5000e-01
2.0000e-01
1.5000e-01
1.0000e-01
5.0000e-02
0.0000e+00
Magnetic Mangles

135° Position

Vector Plot
- 5.0000e-01
- 4.5000e-01
- 4.0000e-01
- 3.5000e-01
- 3.0000e-01
- 2.5000e-01
- 2.0000e-01
- 1.5000e-01
- 1.0000e-01
- 5.0000e-02
- 0.0000e+00

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Combination of magnetic mangles and Habach structures can make the air gap flux density adjustable to some degree
4 Tesla PM prototype Halbach cylinder was made in Japan.*

EEC has produced many Halbach structures for a variety of applications.

Sintered SmCo or high $H_{ci}$ NdFeB magnets are good choices

A Example of Halbach PM Quadrupole

B[T]

- 1.0000e+00
- 9.0000e-01
- 8.0000e-01
- 7.0000e-01
- 6.0000e-01
- 5.0000e-01
- 4.0000e-01
- 3.0000e-01
- 2.0000e-01
- 1.0000e-01
- 0.0000e+00

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Adjustable Magnetic Quadrupoles

Adjustable magnetic quadrupoles as reported by Fermi lab and SLAC*:

- Diametrically magnetized SmCo 2:17 tuning rods
- Tuning rods rotation changes the strength of field gradient

* J. T. Volk et al, PAC2001, p217
Summary

- Permanent magnet dipoles and quadrupoles can have high air gap flux density if designed with Halbach principles.
- Innovative designs can make the air gap flux density adjustable.
- Permanent magnet selection might include trade-offs between cost and performance.
- SmCo magnets are far superior to NdFeB magnets with respect to radiation resistance.
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