RADIATION EFFECTS ON RARE-EARTH COBALT

PERMANENT MAGNETS

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1. INTRODUCTION

A permanent magnet material of essentially rare earth-cobalt (REC) composition has its interest in its relatively high remanent induction \( B_r \) and its high coercive force \( H_c \) (Fig. 1). Recently also the high energy physics community has become interested and several permanent magnetic devices for particle beam guidance such as quadrupoles, sextupoles and even dipoles for specific uses have been built and are in operation. Although many properties of REC material have been investigated, little is known about its radiation resistance. As this property might turn out to be crucial for an application of such magnets at CERN, we considered it essential to undertake this study.

2. SAMPLES; IRRADIATION CONDITIONS AND DOSIMETRY

The test samples which have been obtained from various producers are listed in Table 1. We requested small sized parallelepipeds magnetized parallel to the longer side, in order to ease the measurement procedure.

Working in an accelerator laboratory it is natural to use a particle beam for irradiating our samples. We do not, however, need a beam of well defined characteristics but only particles of sufficient number in order to obtain the wanted high irradiation values. We therefore arranged our samples around the beam acceptance without disturbing the proper particle beam (see Fig. 2 and 5). The geometrical acceptance of a high energy particle beam is usually quite small, typically some microsteradians. The particle flux outside this acceptance which generally is absorbed in a collimator has been used. In this way the irradiation could be made purely parasitically.

The actual device used can be seen in Figs 2 and 4. All samples have been mounted identically with their magnetic field parallel to the beam axis and with the S-pole towards the target. The sample holder was installed between the beam production target and the collimator at about 1 m from the centre of the target T6 (see Fig. 5).
The activation of an Al foil placed inside our device allowed together with the measured number of protons on the target to determine the integrated dose for each sample. The energy of the incident proton beam was 400 GeV/c.

The parameters for dosimetry and exposure time were determined in a separate experiment\(^{(3)}\). The high energy particle fluence was measured with an aluminium foil by counting the induced activity in the gamma peak at 1.276 MeV in 22 Na obtained in a hadron-spallation reaction (27 Al \(\text{(h, spall)}\) 22 Na)\(^{(4)}\) which has a threshold energy of 40 MeV. The particle fluence \(\phi\) in \(\text{cm}^{-2}\) was determined by:

\[
\phi = \frac{D \cdot T}{(1 - e^{-\lambda T}) \cdot n \cdot \sigma}
\]

\(D\) = total number of nuclei decaying per second at exposure end = \(\text{cps/}e^{-\lambda t} \\epsilon\)

\(\lambda\) = decay constant in \(s^{-1}\)

\(T\) = irradiation time in \(s\)

\(t\) = time lapse between exposure end and measurement in \(s\)

\(\text{cps}\) = net counts in \(s^{-1}\)

\(\epsilon\) = efficiency of the counter

\(\sigma\) = reaction cross-section in \(\text{cm}^2\)

\(n\) = number of atoms, \((n = N/W/A)\) where:

\(W\) = sample weight in g

\(N\) = Avogadro's number \((6 \cdot 10^{23})\) in \(\text{mol}^{-1}\)

\(A\) = Atomic mass in g \(\text{mol}^{-1}\)

Together with the Al foil, RPL glass dosimeters\(^{(3)}\) were exposed which allowed to assess a fluence to dose conversion factor which was found to be \(5 \cdot 10^8\) rad per particle and \(\text{cm}^2\). This value is in excellent agreement with earlier published data\(^{(4)}\).
The obtained radial dose distribution normalized to the number of protons incident on the target is plotted in Fig. 3. From this result we concluded, that within the available exposure times during SPS operation irradiation intensities corresponding to $10^3-10^4$ rad could be obtained. Different irradiation intensities can be obtained simultaneously by arranging the samples radially as can be seen from Fig. 2 and 3, respectively.

3. TEMPERATURE

In order to distinguish between the demagnetizing effect of temperature on the one hand and the irradiation on the other hand the sample temperature was continuously monitored by means of two Pt resistors inserted in the sample holder. During beam time the temperature fluctuated typically between 30 and 80°C (see Fig. 6 for a typical temperature record). Max. temperatures of 90°C were reached for a duration of about 48 hours. According to the manufacturers the demagnetization effect at these temperatures should be below the 1 % level.

We checked on the temperature dependence by keeping one non-irradiated sample of each kind for 120 hours at constant temperature of 90°C in an oven. The measured demagnetisation was as follows:

- Recoma 20 - 0.24 %
- Vacomax 200 - 0.19 %
- Koermax 160 - 0.05 %
- Krupp Sm$_2$Co$_{17}$ - 0.18 %

No significant temperature effects therefore could be observed; the measured variation barely exceeds the limits given by the reproducibility of our measurements which is ± 0.1 %.
4. MAGNETIC MEASUREMENT

The measuring device can be seen in Fig. 7 and 8. It was designed such that the measurements of the irradiated samples could be carried out by a remote controlled manipulator (MANTIS). It consisted mainly of a base plate for positioning the sample and a search coil with a square bore which fitted closely on the samples having a $10 \cdot 10$ mm$^2$ cross-section.

The coil mounted on a support and precisely guided with respect to the base plate was placed onto the sample. The voltage induced during this motion was measured with an integrating digital voltmeter (DVM). A second measurement was taken when the coil was removed from the sample. The DVM-reading thus obtained is proportional to the flux component parallel to the longitudinal coil axis penetrating the coil in this particular position. Apart of one M 3·6 steel screw (to keep the sample firmly in place during the measurement) there was no ferromagnetic material acting as flux return yoke. The signal measured therefore corresponds essentially to the "open circuit remanent flux" (OCRF). In order to determine correctly the relative demagnetization effect each sample was measured before and after irradiation using exactly the same measuring procedure.

The measured values do not represent the maximum signal of each sample since the coil centre did not coincide with the sample midplane (see Fig. 7). The coil was 2.3 mm above the midplane in case of the samples with a length of 20 mm and 4.3 mm above the midplane in case of the samples with $L = 16$ mm. In Fig. 9 (measured manually without manipulator) it can be seen that in the first case about 98 % of the maximum signal was captured and 89 % in the second case.

But even if a correction for the relative coil position is made, a direct comparison of the absolute values of the different samples would be meaningless since:

a) a difference in the cross-section ($d \cdot d$) causes a difference in the total flux;

b) the difference in the ratio length/cross-section results in a different loadline $B/\mu_H$ and therefore in a different operating point on the demagnetisation curve;
c) the relative flux seen by the measuring coil changes with the absolute size of the sample.

However, since we were interested only in the relative demagnetization effect due to irradiation those considerations should be rather irrelevant, except eventually the questions related to the difference of the working point. A study of the thermal stability of REC magnets\(^7\) has shown that the working point has an influence on the irreversible losses caused by elevated temperatures. It was shown that if the loadline \(B/\mu_0 H\) (which is approximately proportional to the ratio length/diameter of the sample) decreases, the irreversible losses tend to increase. In our case \(L/d\) varies between 1.6 and 2 thus causing a loadline difference of about \(20\%\). Assuming a similar loadline dependence as found in this thermal stability study, one should expect the sample with \(L/d = 1.6\) to suffer a slightly stronger demagnetization.

However, as can be seen from the results in Table 3 and the plot in Fig. 11, if this dependence exists at all, it is far from being the decisive parameter. As a matter of fact the samples with \(L/d = 1.6\) (1K, 2K, 3K) turned out to be much less demagnetized than the samples (1V, 4V, 3V) which have nominally the same composition and a ratio of \(L/d = 2\).

The operation point of a sample is not only determined by its geometry but as well by external fields superposing its proper field. A measurement was made to evaluate the mutual interference of the adjacent samples on the sample holder (see Fig. 10). It was found that the flux in one sample decreases by \(5\%\) if a second sample (with the same N-S orientation) is installed at \(10\,\text{mm}\) distance. Since all the samples had been installed with the same N-S orientation the total flux decrease caused by neighbouring samples was approximately

<table>
<thead>
<tr>
<th>Decrease</th>
<th>Samples</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-20%)</td>
<td>1K, 1V</td>
<td>(r = 13.5,\text{mm})</td>
</tr>
<tr>
<td>(-15%)</td>
<td>1D, 1B</td>
<td>(r = 13.5,\text{mm})</td>
</tr>
<tr>
<td>(-10%)</td>
<td>2K, 4V, 2B</td>
<td>(r = 25.0,\text{mm})</td>
</tr>
<tr>
<td>0%</td>
<td>3K, 3V, 3B, 2D</td>
<td>(r = 53.0,\text{mm})</td>
</tr>
</tbody>
</table>
The flux decrease for the innermost samples ($r = 13.5$ mm) corresponds to a change of the loadline of roughly 50%. Assuming again a loadline dependence as found in the thermal stability study, one would expect the innermost samples to be more susceptible to demagnetization due to the proximity of the neighbouring samples. Our result shows actually that the demagnetization effect per dose unit is more pronounced for these innermost samples. However, it would require an additional investigation to tell if this really can be attributed to a change of the load line or rather to a non-linear relationship between dose and demagnetization.

5. MEASURING PRECISION AND LONG TERM STABILITY

Before irradiation all samples were measured repeatedly over a period of two weeks. The reproducibility of the measurements was within ± 0.1%. Part of the samples were used for the particle beam irradiation, the other part was kept for an eventual later exposure in a nuclear reactor. Once the irradiated samples had been measured (after approximately three months), the non-irradiated samples were remeasured as well. The measured variation of the non-irradiated samples was within ± 0.3%; this includes the reproducibility of the measuring procedure as well as the long term stability of the samples.

The samples with a $9.9$ mm$^2$ cross-section were measured with the same coil having a $10.10$ mm$^2$ square bore, which left a clearance of $1$ mm between coil and sample. The precise positioning of the coil, however, was not critical, i.e. the reproducibility was ± 0.1% independent of the sample position.

6. RESULTS

Results of the fluence and dose measurements are given for each sample in Table 2. The total exposure time was 1135 hours and the total number of protons on T6 was $1.5 \times 10^{18}$.

Magnetic measurement results before and after irradiation are given in Table 3. The demagnetization of the various samples is plotted in Fig. 11. It is remarkable that sample 1V was not only practically completely demagnetized, but even a change in flux polarity was observed, leaving a residual flux of 6.13% opposite in polarity to the original magnetization.
7. CONCLUSION

We found an unexpectedly high demagnetization of all samples, with the exception of one (Sm,Co,) and large differences between the samples of different origin. The latter might be due to either differences in the composition and/or production process or to the different amounts of impurities present. The demagnetization on the other hand most likely is due to a change of the crystallographic structure induced by the high energy radiation.

As yearly dose values of several $10^9$ rad are commonly expected around the CERN accelerators SmCo$_5$ material should not be used near high radiation points such as targets, dumps etc.

The LAMPF experiment$^{(1)}$ performed with medium energy neutrons (spectrum from approximately 0.1 - 30 MeV, with less than about 10% of the fluence above 4 MeV) and with higher fluence values (about 5 times our maximum value), showed hardly an effect. The samples they used were supplied by HITACHI Magnet Co.; Hicorex 90B (SmCo$_5$) and Hicorex 96B (5 : 1 compound with Pr substituted for 1/3 of the Sm). This result seems to be in contradiction with our findings. It can, however, be understood, if one considers that energy deposition of medium energy neutrons (in the range keV to several MeV) strongly depends on the atomic number of the target nucleus$^{(2)}$. In this energy range one is still below the nuclear reaction threshold, the neutrons therefore loose their energy mainly by quasi-elastic collisions in the target medium. The actual energy deposition or dose in the LAMPF experiment (not given) is most likely much lower than $10^9$ rad, perhaps in the $10^7$-$10^8$ rad range, in spite of their high fluence values. This would then explain why they did not find an effect.

8. ACKNOWLEDGEMENTS

We would like to thank R. Horne and his crew for their help with the magnetic measurements with the remote controlled manipulator MANTIS. We furthermore would like to thank the manufacturers for putting the samples at our disposal.
9. REFERENCES

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<table>
<thead>
<tr>
<th>Producer</th>
<th>Tradename</th>
<th>Composition (approx.)</th>
<th>Size (d<em>d</em>L) (mm³)</th>
<th>L/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGIMAG RECOMA</td>
<td>RECOMA 20 (sintered RECo₅)</td>
<td>65.6 % Co, 24.1 % Sm, 10.3 % various rare earths</td>
<td>10<em>10</em>20</td>
<td>2</td>
</tr>
<tr>
<td>VAKUUM-SCHMELZE</td>
<td>VACOMAX 200</td>
<td>SmCo₅</td>
<td>10<em>10</em>20</td>
<td>2</td>
</tr>
<tr>
<td>KRUPP WIDIA</td>
<td>KOERMAX 160</td>
<td>SmCo₅</td>
<td>10<em>10</em>16</td>
<td>1.6</td>
</tr>
<tr>
<td>KRUPP WIDIA</td>
<td>Sm₂Co₁₇</td>
<td>Sm₂Co₁₇</td>
<td>9<em>9</em>15.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**TABLE 1**

Different REC material samples irradiated with a particle beam at CERN
<table>
<thead>
<tr>
<th>Sample</th>
<th>Counts per s</th>
<th>Fluence $\times 10^{16}$ cm$^{-2}$</th>
<th>Dose in rad $\times 10^3$</th>
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<tbody>
<tr>
<td>3K</td>
<td>2.192</td>
<td>5.5</td>
<td>2.7</td>
</tr>
<tr>
<td>3V</td>
<td>7.157</td>
<td>5.1</td>
<td>2.5</td>
</tr>
<tr>
<td>2D</td>
<td>6.958</td>
<td>5.6</td>
<td>2.8</td>
</tr>
<tr>
<td>3B</td>
<td>7.842</td>
<td>5.3</td>
<td>2.6</td>
</tr>
<tr>
<td>2K</td>
<td>14.375</td>
<td>10.2</td>
<td>5.1</td>
</tr>
<tr>
<td>4V</td>
<td>16.306</td>
<td>12.4</td>
<td>6.2</td>
</tr>
<tr>
<td>2B</td>
<td>13.298</td>
<td>9.3</td>
<td>4.6</td>
</tr>
<tr>
<td>1K</td>
<td>33.365</td>
<td>22.9</td>
<td>11.4</td>
</tr>
<tr>
<td>1V</td>
<td>31.587</td>
<td>20.8</td>
<td>10.4</td>
</tr>
<tr>
<td>1D</td>
<td>29.728</td>
<td>21.1</td>
<td>10.5</td>
</tr>
<tr>
<td>1B</td>
<td>28.752</td>
<td>19.4</td>
<td>9.7</td>
</tr>
</tbody>
</table>

**TABLE 2**

High energy particle fluence $E > 40$ MeV/c and dose values for irradiated REC magnet samples.

Total irradiation time: 1135 hours, total number of protons on target 6: $1.5 \times 10^{14}$
### TABLE 3
Magnetic Flux before and after irradiation

<table>
<thead>
<tr>
<th>TRADENAME</th>
<th>SAMPLE NUMBER</th>
<th>SAMPLE - BEAM DISTANCE [mm]</th>
<th>DOSE [rad*10^8]</th>
<th>MAGNETIC FLUX before irrad.</th>
<th>MAGNETIC FLUX after irrad.</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RECOMA 20</td>
<td>1B</td>
<td>13.5</td>
<td>9.7</td>
<td>0.2889</td>
<td>0.1655</td>
<td>- 42.7</td>
<td></td>
</tr>
<tr>
<td>ECO5 (10<em>10</em>20)</td>
<td>2B</td>
<td>25</td>
<td>4.6</td>
<td>0.2885</td>
<td>0.2573</td>
<td>- 10.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>53</td>
<td>2.6</td>
<td>0.2744</td>
<td>0.2565</td>
<td>- 6.6</td>
<td></td>
</tr>
<tr>
<td>ACOMAX 200</td>
<td>1V</td>
<td>13.5</td>
<td>10.4</td>
<td>0.3008</td>
<td>- 0.0185</td>
<td>- 106.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4V</td>
<td>25</td>
<td>6.2</td>
<td>0.3002</td>
<td>0.0930</td>
<td>- 69.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3V</td>
<td>53</td>
<td>2.5</td>
<td>0.2996</td>
<td>0.2522</td>
<td>- 15.8</td>
<td></td>
</tr>
<tr>
<td>OERMAX 160</td>
<td>1K</td>
<td>13.5</td>
<td>11.4</td>
<td>0.2177</td>
<td>0.1651</td>
<td>- 24.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2K</td>
<td>25</td>
<td>5.1</td>
<td>0.2139</td>
<td>0.1994</td>
<td>- 6.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3K</td>
<td>53</td>
<td>2.7</td>
<td>0.2201</td>
<td>0.2117</td>
<td>- 3.9</td>
<td></td>
</tr>
<tr>
<td>RUPP Sm2Co17</td>
<td>1D</td>
<td>13.5</td>
<td>10.5</td>
<td>0.1975</td>
<td>0.1923</td>
<td>- 2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>53</td>
<td>2.8</td>
<td>0.1971</td>
<td>0.1967</td>
<td>- 0.2</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1 Demagnetization curves of rare earth cobalt permanent magnets (SmCo$_5$) and conventional magnetic materials.
**FIG. 2 : SAMPLE SUPPORT PLATE**

- **SAMPLES:**
  - RECO$_5$
  - VACOMAX 200
  - KOERMAX 160
  - KRUPP Sm$_2$Co$_{17}$

- **Dimensions:**
  - $\phi 10 \times 10 \text{mm}^2$
  - $\phi 27$
  - $\phi 50$
  - $\phi 106$
The value at each radial distance is an average of 4 distinct measurements made horizontally and vertically around the beam centre. The error bars given by the variation of these 4 values are a measure of the centering of the beam on T6.
Fig. 4, SAMPLE HOLDER (SAMPLES NOT SHOWN)
Fig. 5: Positioning of Sample Holder.
Fig. 6 - SAMPLE TEMPERATURE (measured on sample holder with Pt resistances)
Fig. 7: Magnetic Measuring Device

Scale 2:1
Fig. 9, LONGITUDINAL DISTRIBUTION OF OPEN CIRCUIT REMANENT FLUX
Fig: 10—TOTAL FLUX MEASURED IN SAMPLE (A) AS A FUNCTION OF THE DISTANCE D BETWEEN SAMPLE (A) AND (B)
Fig. 11. DEMAGNETIZATION OF REC PERMANENT MAGNETS DUE TO IRRADIATION