Search for possible radiation damage on a NdFeB permanent magnet structure after two years of operation

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Recently there has been some concern about possible radiation damage due to ionizing particles present in high energy storage rings such as multi-GeV electrons, fast neutrons, or hard photons. Partial demagnetization has been observed on undulators after mis-steering of the injected electron beam. Our interest was focused to possible radiation damage of a permanent magnet insertion device during routine operation of a storage ring. Therefore, we repeated the magnetic measurements on one of the three 4.0 m long x-ray wiggler magnets at place #2 in DORIS III. This device is in operation since 1991. The results were compared to the data taken before installation. The total dose was determined from measurements with thermoluminescence dosimeters and the known number of stored ampere hours. The results which show no significant degradation of the magnetic properties are presented and discussed. © 1995 American Institute of Physics.

I. INTRODUCTION

Today, insertion devices (IDs) based on permanent magnet materials are widely used in storage rings to produce highly brilliant radiation. Until about seven years ago, the best commercially available permanent magnet material was based on samarium and cobalt. Since then, even better permanent magnet material based on neodymium, iron, and boron sometimes with additions of dysprosium was developed. The main drawback of NdFeB material as compared to SmCo compounds is its lower Curie temperature leading to increased sensitivity to thermal demagnetization. Besides that, the NdFeB material offers higher energy product and lower production price. It is now most commonly used for permanent magnet IDs. There was quite some interest in using and operating devices containing permanent magnet material in high radiation areas, such as in particle accelerators. The resistance to irradiation of SmCo (Refs. 1, 2, 5-7) as well as NdFeB (Refs. 3-7) magnets to high energy protons, electrons, as well as hard photons, has therefore been subject to several studies.

In these studies, it was seen that it is very difficult to correlate, for example, results that were made with neutrons and that was valid for electrons or hard photons. However, it was observed that Sm$_2$Co$_{17}$ compounds offer by far the highest stability to any kind of radiation. SmCo$_2$ is less stable, but still better than any of the NdFeB compounds. Among the NdFeB compounds, it was seen that those with high coercivity seem to be more stable to irradiation than those with lower coercivity.\textsuperscript{3,7}

Severe degradation of the magnetic properties has been observed recently on two IDs at the ESRF\textsuperscript{9} as a result of mis-steering the injected electron beam from the booster synchrotron onto the vacuum chamber wall of the ID. A subsequent irradiation test with an 180 MeV electron beam showed severe degradation of magnetic properties at an estimated dose of 7 X 10$^{6}$ Gy.\textsuperscript{7} It is well known that, in electron/positron storage rings near the beam, the radiation level is mainly due to y bremsstrahlung and the hard component of synchrotron radiation. Per ampere-hour of stored beam, it is found to be in the range 0.1 - 1 X 10$^{6}$ Gy.\textsuperscript{9} These values also agree with the results of this work (see below). Assuming that the doses given in Ref. 7 for electron irradiation are also valid for storage rings, the NdFeB permanent magnet material in such a radiation environment would allow for a lifetime on the order of a few hundred to at most a few thousand ampere hours.

In DORIS III, currently 10 IDs with a total length exceeding 32 m are now routinely in use. In seven of these devices, NdFeB is used; the remaining three use SmCo magnets. In third generation x-ray sources, like the APS, up to 34 straight sections each 5 m long will be available to accommodate IDs. For reliable long-time operation, the stability against radiation damage is therefore of paramount importance. We consequently decided to repeat magnetic measurements on the x-ray wiggler used on place #2 in DORIS III (BW2) and compare it with data taken during the acceptance tests right before installation in 1991. This NdFeB structure was the first installed in DORIS III and has been in operation since September 1991. It is the one with the longest operational time and thus has experienced the highest radiation exposure. This investigation was made under routine operational conditions of DORIS III. The results should allow to see if there are any radiation induced effects which could degrade the light emission properties of an ID or the compatibility with storage ring operation. The measurements were performed in February 1994.

II. EVALUATION OF THE RADIATION DOSE

In order to estimate the radiation exposure of the magnetic structure, three radiophotoluminescence glass dosimeters were mounted at place #2 on the upstream front end of the ID very near the gap surface. These devices are routinely used for radiation monitoring and are well proven. The vertical distance to the beam was about 17 mm. One RPL was...
TABLE I. Doses measured on the surface of the upstream front end of the magnetic structure at different horizontal positions. Zero horizontal position corresponds to the reference orbit. Column 3 gives the dose measured during the three week run period. The corresponding integrated current was 17.9 A h. Column 4 is the dose normalized to this value. Column 5 is the total dose estimated from Sept. 1991 to Nov. 1993 corresponding to a total stored current of 214 A h.

<table>
<thead>
<tr>
<th>RPL#</th>
<th>Hor. pos. (mm)</th>
<th>Dose (Gy)</th>
<th>Nom. dose (Gy/A h)</th>
<th>Total dose (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-40</td>
<td>2800</td>
<td>156</td>
<td>3.3x10^3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>6000</td>
<td>335</td>
<td>7.2x10^3</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>10000</td>
<td>559</td>
<td>1.2x10^4</td>
</tr>
</tbody>
</table>

fixed about 40 mm horizontally outside the orbit axis, one right above the beam, and one 40 mm inside. The dose was measured over a period of three weeks in a run period in Oct/Nov 1993. For normalization, the ampere hours of the stored beam were calculated from the storage ring log file. To estimate the total dose absorbed by the magnetic structure, the normalized values were multiplied by the ampere-hours since 1991. The sensitivity of the RPLs in use to γ and hard x rays is practically energy independent in the range 10 keV to about 3 MeV. Furthermore, they have a quite large dynamic range. In principle, it is also possible that fast charged particles and to a lesser extent also fast neutrons contribute to the radiation level if the stored beam hits the vacuum chamber wall. These effects cannot be excluded completely. However, they are very unlikely since no sudden beam losses have been observed and DORIS III has a good working high efficiency injection system (>95%, Ref. 11). We therefore assume that the doses measured with the RPLs are predominantly caused by γ and hard x rays. Table I shows these data.

The hard components of the synchrotron radiation coming from the adjacent dipole magnet and the hard γ-radiation are collimated around the tangential directions of the electron orbit. Therefore, the doses on equivalent points inside and outside the reference orbit differ considerably as seen in Table I. Equivalent observations were also made on other locations of DORIS III, which were monitored for comparison.

III. MAGNETIC MEASUREMENTS

At HASYLAB, a 5 m long bench for magnetic measurements has been used for the magnetic characterization of the 4.0 m long IDs for DORIS III.12 All structures have undergone an extensive program of magnetic measurements including field mapping using Hall probes, field integral measurement using Hall probes and short coils, determination of normal and skew integrated multipole components, gap dependence of field integrals, etc. To do so, a magnetic structure is mounted onto a drive system and optically aligned so that the device axis coincides with the bench axis.

Typical accuracy for field measurement is 0.1 to 1 mT in the 1 T range resulting in ΔB/B of typically several times 10^-4. Field integral measurements using Hall probes typically have an accuracy of 0.02 to 0.05 T mm. Accuracy can be further increased using search coils but this technique is more consuming. There are three potential sources of errors when comparing the 1994 to the 1991 measurements:

First, two different Hall probes were used in the 1991 and 1994 measurements. Although both were carefully calibrated against NMR probes, this might still result in slight changes in the field data.

Second, different gap separation mechanisms were used. All support structures and gap separation mechanisms for DORIS III are made of magnetic steel. The one used for the 1994 measurements was an enforced version of the mechanisms used on the other DORIS III locations. Magnetically, the flux return path is different. Its main effect is a slight change of the dipole field on axis, but also higher multipoles can be slightly affected.

Third, there was a temperature difference between the 1991 and 1994 measurements of about 3 °C. This certainly has lead to length changes in the 4.0 m long x-ray wiggler structure on the order of 0.3 mm. as can be calculated using

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FIG. 2. Transversal roll off of the first field integral in the orbital plane. The good field region is ± 25 mm corresponding to ten standard deviations of the horizontal beam size.

the expansion coefficient of steel. These effects have to be considered when data are compared, especially when two spectra are subtracted.

IV. RESULTS

Before explaining the magnetic measurements in detail Table II gives an overview of the key parameters of the x-ray wigglers under investigation. The upper part of Fig. 1 shows the field distribution along the symmetry axis of the wigglers as measured in February 1994, after more than two years in operation. The gap was closed to 30 mm resulting in a peak field of 1.13 T. Instead of reproducing the corresponding curve taken in August 1991, during the acceptance tests, we show the difference between both measurements in the bottom part of Fig. 1. The peak value of the difference is about 20 mT; the rms value is 6 mT corresponding to 0.5% of the peak field.

Figure 2 shows the comparison of the transversal roll off of the first field integral. Both measurements are almost identical. The 1994 curve is much smoother, which is due to improvements in the resolution of the measurement technique. Normal multipole coefficients up to order 3 were obtained by a third order polynomial fit with subsequent error analysis to the good field region of the data shown in Fig. 2. The good field region corresponds to ± 25 mm, which is equal to ten standard deviations of the horizontal beam size. Table III reproduces these data.

There are slight differences in the measurements, but they are quite symmetric. Since the exposure to radiation was asymmetric by more than a factor of 3 (see Table I), radiation-induced changes also should show some asymmetry. In any case, Fig. 2 shows rather an improvement than deterioration in device performance.

These changes are also reflected in the slightly decreased normal quadrupole moment observed in the 1994 measurement as compared to 1991. The other coefficients agree within their error limits. Very similar results to those shown in Fig. 2 were also obtained for the gap dependence of the first field integral.

In total the results of this work are quiescent. After more than two years of routine operation of DORIS III the radiation exposure given in Table 1 was determined.

We were not able to detect any radiation induced effects within the accuracy of our measurements. However in future we plan to repeat these investigations when a significant larger dose will be accumulated.

ACKNOWLEDGMENTS

One of us (J. V.) wants to thank DESY for their hospitality during the measurements. This work was supported by the U.S. Department of Energy under Contract No. W-31-109-Eng-38.

TABLE III. Comparison of normal multipole coefficients as determined from the 1991 and 1994 measurements. The errors are determined by the accuracy of the filling procedure. For details, see the text.

<table>
<thead>
<tr>
<th>Int. multipole coefficients</th>
<th>1991</th>
<th>1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad. (G)</td>
<td>417±22</td>
<td>345±13</td>
</tr>
<tr>
<td>Sext. (G/cm)</td>
<td>89±24</td>
<td>63±13</td>
</tr>
<tr>
<td>Oct. (G/cm^2)</td>
<td>0.2±3</td>
<td>0.8±2</td>
</tr>
</tbody>
</table>

P. Elleaeume (private communication).
O. Kaul (private communication).