RARE EARTH PERMANENT MAGNETS FOR CRYOGENIC SPACE APPLICATIONS

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ABSTRACT

We present results of proton irradiation and performance tests on SmCo and NbFeB permanent magnets under ambient and cryogenic conditions carried out at the Proton Irradiation Facility (PIF) in Switzerland and at the Max-Planck-Institut für Astronomie. Such rare earth permanent magnets are commonly used in a variety of space mechanisms, e.g. in actuators and sensors. The qualification program reported here is performed in the context of the James Webb Space Telescope (JWST) mission. For JWST the magnets are used in an electromagnetic torque motor and a magnetoresistive position sensor for optical wheel mechanisms of the MIRI and NIRSpec science instruments. Sm_2Co_{17} and NeFeB magnets were irradiated with a 50 MeV proton beam with total ionising doses of 42.5 krad-Si and 760 krad-Si at cryogenic and room temperatures. No significant flux loss could be found.

Key words: Proton irradiation; SmCo and NbFeB magnets; JWST.

1. INTRODUCTION

The James Webb Space Telescope astronomical satellite mission is a joint ESA/NASA/CSA co-operation with unprecedented sensitivity and spatial resolution in the near and mid infrared wavelength range. This will allow viewing of the very distant universe and insight into the origin of the first stars. To reach this demanding goal there will be three main instruments on-board the JWST satellite: NIRCam – a near-infrared camera, NIRSpec – a near-infrared spectrograph and MIRI – a mid-infrared camera spectrograph.
Essential components in the NIRSpec and MIRI instruments are filter and grating wheel assemblies, see [8, 6]. The wheels are equipped with several different optical filters and dichroics. A wheel driving mechanism allows the positioning of different filters and dichroics into the light beam and thus observations in different wavelength ranges.
Within the MIRI and NIRSpec science instruments rare earth permanent magnets are used as parts of filter and grating wheel mechanisms.
On one hand the magnets are part of the electromagnetic motor that is driving the wheels. On the other hand the magnets are – together with small field-plates – part of the wheel position measurement system: The magnets are fixed on the instrument wheel. The field-plates are scanning the magnets giving a voltage readout signal which indicates precisely the position. The position sensor scheme consists of four stationary magnetoresistors arranged in a closed circuit which are biased by a moving magnet [1]. A position change of the sensing magnet translates into a magnetic flux switching through the individual magnetoresistors. The electrical signal is proportional to the displacement and is measured by connecting the pairs of mutually variable magnetoresistors in an electrical Wheatstone bridge circuit.
The precise positioning of the filters and gratings is essential for the quality of the astronomical observations. Due to the stringent science requirements all components have to be qualified and investigated w.r.t. possible degradation within the space environment.
From literature it is known that the performance of rare earth magnets depends on temperature and the presence of high radiation doses or large external magnetic fields, see e.g. [3], [4]. Since JWST will be orbiting the Lagrangian point L2 and the operating temperatures of the instruments are between 6 K and 42 K, the irradiation conditions differ from irradiation tests already published. Therefore the performance of different selected magnets under this special environmental conditions will be compared and the results will be discussed with respect to space applications.

2. IRRADIATION TESTS

From the MIRI and NIRSpec instrument design and shielding proportions it can be derived that the worst case proton dose the magnets will see over a 5.5 year mission (including a safety factor) will be 42.5 krad-Si for MIRI and 760 krad-Si for NIRSpec where krad-Si means Silicon equivalent total ionising dose (TID).

For the irradiation experiments two different kinds of rare earth magnets – Sm_2Co_{17} and NeFeB – were irradiated with different proton doses and under different temperatures. In order to take into account possible effects due to external magnetic fields different magnet geometries were investigated. Table 1 shows the different magnet types that were irradiated. For the Sm_2Co_{17} material

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Table 1. Magnet types used for proton irradiation experiments. The supplier for the Recoma magnets is 'Precision Magnetics' and the supplier for the Vacomax and Vacodym magnets is 'Vacuumschmelze'.

No:	Magnet Material	Shape	Dimension
M1	Recoma26He (Sm_2Co_{17})	cylinder	⊘ 3, height 5 mm
M2	Vacomax225HR (Sm_2Co_{17})	cylinder	⊘ 3, height 5 mm
M3	Recoma26He (Sm_2Co_{17})	cuboid	(7.5 x 7.5 x 6) mm^3
M3a	Recoma26He (Sm_2Co_{17})	slice	(7.5 x 7.5 x 1) mm^3
M4	Vacomax225HR (Sm_2Co_{17})	cylinder	⊘ 3, height 3 mm
M5	Vacodym655HR (NeFeB)	cylinder	⊘ 3, height 3 mm

Table 2. All magnet types were irradiated with different total ionising doses (TID) and under different temperatures (room temperature (RT) or cryogenic temperatures).

Temperature	TID [krad-Si]	Magnet types
RT	42.5	all
RT	760	all
42 K	42.5	all
42 K	760	M1, M3, M3a

magnets from two different suppliers were used. The magnet slice (number 3a in Table 1) can be considered as 'worst case' as this shape provides the largest external magnetic field. The magnets were irradiated with different total ionising doses and at different temperatures, see Table 2.

Although several papers have been published concerning proton irradiation of rare earth magnets [2], [3], [4], [5], [7] so far no irradiation experiments of Sm_2Co_{17} magnets under cryogenic temperature conditions and with space relevant radiation doses (42.5-760 krad-Si) have been published. In addition there are significant differences between the behaviour of Sm_2Co_{17} and $SmCo_5$ material as well as between the same magnet material from different suppliers, see e.g. [2]. NeFeB magnets are found to be more sensitive with respect to irradiation [3] but again this was only tested with doses in the Mrad range.

Therefore for the application of Sm_2Co_{17} or NeFeB magnets within space satellite projects like the JWST a detailed investigation within the relevant temperature and radiation range is necessary.

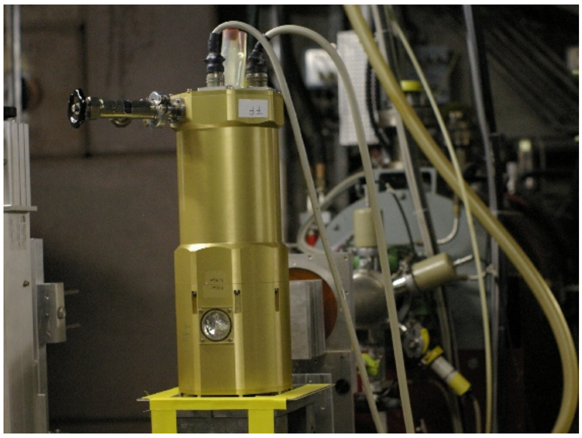

Figure 1. MPIA cryostat in the PIF laboratory. The magnet samples are inside the cryostat at cryogenic temperatures. The collimated proton beam enters the cryostat through plexiglass windows.

2.1. Experimental Set-up

The Proton Irradiation Facility (PIF) of the Paul Scherrer Institute (PSI) can provide monoenergetic proton beams up to 70 MeV proton energy. For the experiments described within this paper a proton beam of 50 MeV was used. As one can see from Table 2 some irradiation tests are performed at room temperature. These samples were simply fixed to the PIF sample holder and irradiated. For the sake of cold irradiation the samples were put into a cryostat, see Figures 1 and 2. The cryostat is approximately 50 cm in height and 13 cm in diameter with an aluminium wall thickness of 8 mm. Inside the cryostat is a nitrogen and helium shield underneath the magnet samples can be mounted. The cryostat was designed in such a way that two sample boards could be separateley placed inside. At two opposing sides of the cryostat plexiglass windows of 40 mm diameter and 4 mm thickness have been placed to allow the proton beam to enter the cryostat without too much energy degradation. So it was possible to irradiate first one sample board with a dose of 42.5 krad-Si from one side and then to rotate the cryostat by 180° and to irradiate the second sample board with a dose of 760 krad-Si through the second window. In addition temperature sensors and heaters were placed inside the cryostat in order to provide the correct temperatures. This cryostat was placed directly into the PIF proton beam. A calibration measurement was provided by PIF staff with a cryostat dummy in order to be sure about the exact dose at spot of the samples.

2.2. Magnetic Measurements

The parameter under investigation for the magnets is a possible flux loss due to irradiation. All magnets that were irradiated under cryogenic temperatures had to undergo one cryo-cycle before the irradiation. The magnetic flux was measured before and after the cryo-cycle

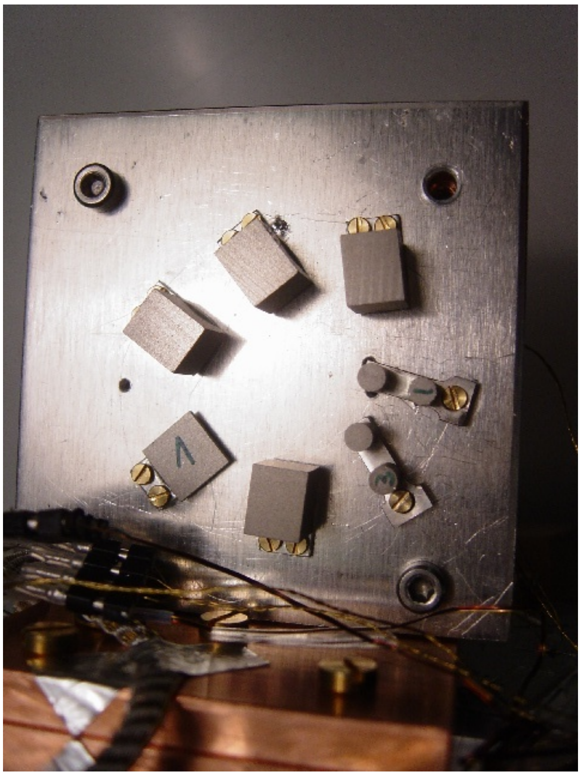

Figure 2. Different magnet samples (type M3, M3a, M1 in Table 1) on a base-plate which is fixed inside the cryostat.

to make sure that a possible flux loss due to the subsequent irradiation would not originate from the cold temperatures. Afterwards the magnets were irradiated and again the magnetic flux of the magnets was measured before and after the irradiation. For each magnet measurements were taken using a fluxmeter and a Helmholtz coil (MS 75). The fluxmeter (EF 5, supplier Magnet-Physik) has a measurement accuracy of 0.3% w.r.t. the measured value. The measurements are taken in two steps: First the magnet is fed into the centre of the Helmholtz coil with its magnetic axis parallel to the coil axis and the fluxmeter is set to zero. Then the magnet is rotated by 180°. The signal shown in the fluxmeter display is then twice the flux. Afterwards the magnet is turned into its original position and a cross-check measurement is taken which should be zero.

3. RESULTS

3.1. Proton Irradiation at 42 K with 760 krad-Si Dose

Four samples each of the Sm_2Co_{17} magnet type M1 (cylinder shape) and M3 (cuboid), see Table 1, were irradiated at a temperture of 42 K within the cryostat. The magnets were fixed to a base plate as can be seen in Figure 2. To reach the 760 krad Silicon equivalent total ionising dose with the 50 MeV proton beam provided by PIF a fluence of $4.2 \cdot 10^{12}$ protons/cm^2 was necessary. As mentioned before the magnets underwent one cryo-cycle (cool-down to < 22 K starting from RT and heating up again) before the irradiation. A fifth sample of each magnet type M1 and M3 was hold back as radiation control sample that means it was neither cycled nor irradiated. Table 3 shows the magnetic measurements of the 4 cylindric and cubic Sm_2Co_{17} magnets (type M1 and M3 in Table 1) as well as of the control samples.

Tables 3 and 4 give the results for the cylindric M1-type and the cubic M3-type magnets.

One can see the starting values of the M1 type magnets are not the same although all magnets are from the same batch. The maximal difference is 1.3% between the samples 4 and 5. After cryo-cycling the measurement value of all samples decreases, see column 5 of Table 3. Nevertheless comparing the values with the (non-cycled) control sample (M1-5) and taking into account that the measurement accuracy of the fluxmeter is 0.3% of the measured value one sees that their is no significant flux change of the small cylindric magnets due to the cryo-cycling. After the irradiation the flux measurements are approximately 0.6% smaller (column 6 of Table 3). The value of the control sample is the same when taking into account the measurement accuracy. Therefore one can conclude that at most the M1-type magnets show a small flux loss of approximately 0.3% after proton irradiation with 760 krad-Si at 42K.

For the cubic M3-type magnets the magnetisation direction is different from the M1-type magnets and thus the flux values are negative. Again the starting values of the M3 type magnets are not the same although all magnets are from the same batch. For the M3-type magnets the maximal difference is 2% between the samples 2 and 4. After cryo-cycling the measurement value of all samples decreases by approximately 0.7%, see column 5 of Table 3. On the other hand the (non-cycled) control sample (M3-5) shows only a change in the order of the measurement accuracy of the fluxmeter. After the irradiation the flux measurements are only 0.1 to 0.2 % larger than after the cryo-cycle. This change lays fully within measurement accuracy. Therefore for the large magnetic cuboids no significant change due to irradiation can be found. Nevertheless a flux change after the cryo-cycle of approximately 0.4% is visible which was not found in the data of the smaller cylindric magnet type M1 samples. Therefore in a second part of the JWST magnet qualification programme the magnets will undergo several cryo-cycles and their magnetic flux change will be investigated.

3.2. Proton Irradiation at RT with 42.5 krad-Si Dose

Four samples each of the Sm_2Co_{17} magnet type M1, M2, M4 and of the NeFeB material (M5 type), see Table 1, were irradiated at room temperature. The magnets were fixed to a base plate which was simply hung into the proton beam of the PIF. To reach the 42.5 krad Silicon equivalent total ionising dose with the 50 MeV proton beam provided by PIF a fluence of $2.3 \cdot 10^{11}$ protons/cm^2 was necessary.

Tables 5 and 6 show the magnetic measurements of the four samples of type M1, M2, M4 and M5 (in Table 1). In addition the measurements of the radiation control samples which were not irradiated (M1-5, M2-5, M4-5, M4-5) are given for comparison. Column 3 shows the flux values measured after the irradiation at PSI. Column 5 shows the values of the same magnets measured again a few weeks later. The difference between the two measurement after the irradiation w.r.t. the measurement before (columns 4 and 6) lie both within the measurement accuracy of 0.3% of the fluxmeter. So one can conclude that there is no significant flux loss of the Sm_2Co_{17} and NeFeB magnet cylinders after an exposure to 42.5-krad-Si proton dose.

3.3. Sm_2Co_{17} Magnet Slice

The thin Sm_2Co_{17} magnet slice of dimensions 7.5 mm x 7.5 mm x 1 mm (type M3a in Table 1) has the most extreme geometry of all magnets under investigation and thus represents the worst case w.r.t. the external magnetic field. Tables 7 and 8 show the results of the proton irradiation at room temperature and at 42 K within the cryostat at different total ionising doses.

From Table 7 one can see that there is no flux loss (taking into account the measurement accuracy of 0.3%) when irradiating the slices at room temperature – neither when using a proton dose of 42.5 krad-Si nor 760 krad-Si. Table 8 shows the data from the cold irradiation at 42 K. One can again see that there is a small flux change after the cryo-cycle but no further flux change after the irradiation. This is the same effect as already found with the M3 Type samples, see Table 3.

3.4. Sm_2Co_{17} Magnet Cube

This subsection summarises the results of the proton irradiation of the Sm_2Co_{17} magnet cuboids of dimensions 7.5 mm x 7.5 mm x 6 mm (type M3 in Table 1). Tables 9 and 10 show the results of the proton irradiation at room temperature and at 42 K within the cryostat at different total ionising doses.

Unfortunately one M3 sample was damaged during the deintegration from the cryostat and thus there are no measurement values for a M3 magnet irradiated at 42 krad with a dose of 42.5 krad-Si. Nevertheless the results of the other measurements are similar to the ones of the magnetic slices: Taking into account the measurement accuracy of 0.3% of the fluxmeter there is no flux change when irradiating the M3 magnets at room temperature. The cold irradiation sample (corresponds to M3-2 in Table 3) shows a flux loss of approximately 0.3% after the cryo-cycle but no further flux loss after the irradiation.

3.5. Magnet Cylinders of Types M1, M2, M4, M5

For the Sm_2Co_{17} and NeFeB magnet cylinders no significant flux loss was found neither after irradiation with 42.5 or 760 krad-Si proton dose at 42 K nor at room temperature.

4. SUMMARY

In this paper we presented the results of irradiation experiments for the qualification program of rare earth magnets for the James Webb Space Telescope mission. Sm_2Co_{17} and NeFeB magnets were irradiated with a 50 MeV proton beam with total ionising doses of 42.5 krad-Si and 760 krad-Si at cryogenic and room temperatures. The change in the magnetic flux of the magnets due to the irradiation was measured. No significant flux loss of the magnets could be found which agrees well with the expectations and makes them applicable for use in the JWST mission. For the cubic magnets and slices under investigation (type M3 and M3a in Table 1) a small flux change after one cryo-cycle was found. This effect will be further investigated in a second part of the JWST magnet qualification programme.

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Table 3. Magnetic flux measurement of cylindric and cubic Sm_2Co_{17} magnets (type M1 and M3 in Table 1). Column 1: magnet type and number, column 2: magnetic flux at start, column 3: magnetic flux after one cryo-cycle, column 4: magnetic flux after irradiation, column 5: flux difference between start value and value measured after one cryo-cycle, column 6: flux difference between start value and value measured after the irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

No:	flux at start Φ_0 [Vs]	flux after cryo-cycle Φ_c [Vs]	flux after irradiation Φ_i [Vs]	$\frac{\Phi_c - \Phi_0}{\Phi_0}$ [%]	$\frac{\Phi_i - \Phi_0}{\Phi_0}$ [%]
M1-1	$4.903 \cdot 10^{-4}$	$4.889 \cdot 10^{-4}$	$4.871 \cdot 10^{-4}$	-0.28	-0.66
M1-2	$4.904 \cdot 10^{-4}$	$4.880 \cdot 10^{-4}$	$4.875 \cdot 10^{-4}$	-0.47	-0.58
M1-3	$4.875 \cdot 10^{-4}$	$4.859 \cdot 10^{-4}$	$4.854 \cdot 10^{-4}$	-0.32	-0.42
M1-4	$4.854 \cdot 10^{-4}$	$4.849 \cdot 10^{-4}$	$4.825 \cdot 10^{-4}$	-0.10	-0.60
M3-1	$-4.590 \cdot 10^{-3}$	$-4.556 \cdot 10^{-3}$	$-4.550 \cdot 10^{-3}$	-0.75	-0.88
M3-2	$-4.594 \cdot 10^{-3}$	$-4.564 \cdot 10^{-3}$	$-4.553 \cdot 10^{-3}$	-0.64	-0.87
M3-3	$-4.590 \cdot 10^{-3}$	$-4.556 \cdot 10^{-3}$	$-4.548 \cdot 10^{-3}$	-0.75	-0.91
M3-4	$-4.500 \cdot 10^{-3}$	$-4.467 \cdot 10^{-3}$	$-4.462 \cdot 10^{-3}$	-0.73	-0.86

Table 4. Magnetic flux measurement of the radiation control samples of the cylindric and cubic Sm_2Co_{17} magnets (type M1 and M3 in Table 1). The radiation control samples were neither cycled nor irradiated. Their values correspond only to a second and third control measurement. Column 1: magnet type and number, column 2: magnetic flux measurement 0, column 3: magnetic flux measurement 1, column 4: magnetic flux measurement 2, column 5: flux difference between measurement 0 and 1, column 6: flux difference between measurement 1 and 2. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

No:	flux Φ_0 [Vs]	flux Φ_1 [Vs]	flux Φ_2 [Vs]	$\frac{\Phi_1 - \Phi_0}{\Phi_0}$ [%]	$\frac{\Phi_2 - \Phi_0}{\Phi_0}$ [%]
M1-5	$4.917 \cdot 10^{-4}$	$4.901 \cdot 10^{-4}$	$4.899 \cdot 10^{-4}$	-0.33	-0.37
M3-5	$-4.576 \cdot 10^{-3}$	$-4.560 \cdot 10^{-3}$	$-4.560 \cdot 10^{-3}$	-0.35	-0.36

Table 5. Magnetic flux measurement of Sm_2Co_{17} and NeFeB magnets (type M1, M2, M4 and M5 in Table 1). Column 1: magnet type and number, column 2: magnetic flux at start, column 3: magnetic flux after irradiation, column 4: flux difference between start value and value measured after irradiation, column 5: magnetic flux of a second measurement, column 6: flux difference between start value and the 2nd measurement after irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

No:	flux at start Φ_0 [Vs]	flux after irradiation Φ_{i1} [Vs]	$\frac{\Phi_{i1}-\Phi_0}{\Phi_0}$ [%]	flux after irradiation Φ_{i2} [Vs]	$\frac{\Phi_{i2}-\Phi_0}{\Phi_0}$ [%]
M1-1	$4.790 \cdot 10^{-4}$	$4.802 \cdot 10^{-4}$	0.25	$4.811 \cdot 10^{-4}$	0.43
M1-2	$4.864 \cdot 10^{-4}$	$4.851 \cdot 10^{-4}$	-0.27	$4.866 \cdot 10^{-4}$	0.04
M1-3	$4.895 \cdot 10^{-4}$	$4.889 \cdot 10^{-4}$	-0.12	$4.896 \cdot 10^{-4}$	0.01
M1-4	$4.795 \cdot 10^{-4}$	$4.796 \cdot 10^{-4}$	0.03	$4.805 \cdot 10^{-4}$	0.22
M2-1	$4.898 \cdot 10^{-4}$	$4.898 \cdot 10^{-4}$	0.00	$4.909 \cdot 10^{-4}$	0.22
M2-2	$4.918 \cdot 10^{-4}$	$4.920 \cdot 10^{-4}$	0.04	$4.925 \cdot 10^{-4}$	0.14
M2-3	$4.940 \cdot 10^{-4}$	$4.928 \cdot 10^{-4}$	-0.25	$4.940 \cdot 10^{-4}$	0.00
M2-4	$4.937 \cdot 10^{-4}$	$4.928 \cdot 10^{-4}$	-0.18	$4.935 \cdot 10^{-4}$	-0.04
M4-1	$2.937 \cdot 10^{-4}$	$2.936 \cdot 10^{-4}$	-0.03	$2.940 \cdot 10^{-4}$	0.10
M4-2	$2.905 \cdot 10^{-4}$	$2.915 \cdot 10^{-4}$	0.36	$2.920 \cdot 10^{-4}$	0.53
M4-3	$2.933 \cdot 10^{-4}$	$2.925 \cdot 10^{-4}$	-0.26	$2.925 \cdot 10^{-4}$	-0.26
M4-4	$2.945 \cdot 10^{-4}$	$2.940 \cdot 10^{-4}$	-0.17	$2.945 \cdot 10^{-4}$	0.00
M5-1	$3.348 \cdot 10^{-4}$	$3.335 \cdot 10^{-4}$	-0.37	$3.345 \cdot 10^{-4}$	-0.07
M5-2	$3.365 \cdot 10^{-4}$	$3.350 \cdot 10^{-4}$	-0.45	$3.355 \cdot 10^{-4}$	-0.30
M5-3	$3.355 \cdot 10^{-4}$	$3.347 \cdot 10^{-4}$	-0.25	$3.350 \cdot 10^{-4}$	-0.15
M5-4	$3.345 \cdot 10^{-4}$	$3.350 \cdot 10^{-4}$	0.15	$3.355 \cdot 10^{-4}$	0.30

Table 6. Magnetic flux measurement of the radiation control samples of of Sm_2Co_{17} and NeFeB magnets (type M1, M2, M4 and M5 in Table 1). The radiation control samples were neither cycled nor irradiated. Their values correspond only to a second control measurement. Column 1: magnet type and number, column 2: magnetic flux measurement 0, column 3: magnetic flux measurement 1, column 4: flux difference between measurement 0 and 1. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

No:	flux Φ_0 [Vs]	flux Φ_1 [Vs]	$\frac{\Phi_1-\Phi_0}{\Phi_0}$ [%]
M1-5	$4.820 \cdot 10^{-4}$	$4.82600 \cdot 10^{-4}$	0.12
M2-5	$4.921 \cdot 10^{-4}$	$4.920 \cdot 10^{-4}$	-0.02
M4-5	$2.940 \cdot 10^{-4}$	$2.940 \cdot 10^{-4}$	0.00
M5-5	$3.360 \cdot 10^{-4}$	$3.350 \cdot 10^{-4}$	-0.30

Table 7. Magnetic flux measurement of Sm_2Co_{17} slices (type M3a in Table 1). Column 1: irradiation temperature T, column 2: total ionising dose, column 3: magnetic flux at start, column 4: magnetic flux after irradiation, column 5: flux difference between start value and value measured after irradiation, column 6: magnetic flux of a second measurement, column 7: flux difference between start value and the 2nd measurement after irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

T	TID [krad-Si]	flux at start Φ_0 [Vs]	flux after irradiation Φ_{i1} [Vs]	$\frac{\Phi_{i1}-\Phi_0}{\Phi_0}$ [%]	flux after irradiation Φ_{i2} [Vs]	$\frac{\Phi_{i2}-\Phi_0}{\Phi_0}$ [%]
RT	42.5	-7.035$\cdot 10^{-4}$	-7.050$\cdot 10^{-4}$	0.21	-7.052$\cdot 10^{-4}$	0.23
RT	760	-7.235$\cdot 10^{-4}$	-7.233$\cdot 10^{-4}$	-0.03	-7.212$\cdot 10^{-4}$	-0.03

Table 8. Magnetic flux measurement of Sm_2Co_{17} slices (type M3a in Table 1). Column 1: irradiation temperature T, column 2: total ionising dose, column 3: magnetic flux at start, column 4: magnetic flux after one cryo-cycle, column 5: magnetic flux after irradiation, column 6: flux difference between start value and value measured after one cryo-cycle, column 7: flux difference between start value and value measured after irradiation, column 8: magnetic flux of a second measurement after irradiation, column 9: flux difference between start value and the 2nd measurement after irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

T $[K]$	TID [krad-Si]	flux at start Φ_0 [Vs]	flux after cryo-cycle Φ_c [Vs]	flux after irrad-iation Φ_{i1} [Vs]	$\frac{\Phi_c-\Phi_0}{\Phi_0}$ [%]	$\frac{\Phi_{i1}-\Phi_0}{\Phi_0}$ [%]	flux after irrad-iation Φ_{i2} [Vs]	$\frac{\Phi_{i2}-\Phi_0}{\Phi_0}$ [%]
42	42.5	-7.278$\cdot 10^{-4}$	-7.222$\cdot 10^{-4}$	-7.228$\cdot 10^{-4}$	-0.76	-0.68	-7.221$\cdot 10^{-4}$	-0.78
42	760	-7.045$\cdot 10^{-4}$	-7.000$\cdot 10^{-4}$	-7.013$\cdot 10^{-4}$	-0.64	-0.46	-7.000$\cdot 10^{-4}$	-0.64

Table 9. Magnetic flux measurement of Sm_2Co_{17} cuboids (type M3 in Table 1). Column 1: irradiation temperature T, column 2: total ionising dose, column 3: magnetic flux at start, column 4: magnetic flux after irradiation, column 5: flux difference between start value and value measured after irradiation, column 6: magnetic flux of a second measurement, column 7: flux difference between start value and the 2nd measurement after irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

T	TID [krad-Si]	flux at start Φ_0 [Vs]	flux after irradiation Φ_{i1} [Vs]	$\frac{\Phi_{i1}-\Phi_0}{\Phi_0}$ [%]	flux after irradiation Φ_{i2} [Vs]	$\frac{\Phi_{i2}-\Phi_0}{\Phi_0}$ [%]
RT	42.5	-4.528$\cdot 10^{-3}$	-4.533$\cdot 10^{-3}$	0.12	-4.529$\cdot 10^{-3}$	0.02
RT	760	-4.598$\cdot 10^{-3}$	-4.580$\cdot 10^{-3}$	-0.40	-4.579$\cdot 10^{-3}$	-0.42

Table 10. Magnetic flux measurement of Sm_2Co_{17} cuboids (type M3 in Table 1). Column 1: irradiation temperature T, column 2: total ionising dose, column 3: magnetic flux at start, column 4: magnetic flux after one cryo-cycle, column 5: magnetic flux after irradiation, column 6: flux difference between start value and value measured after one cryo-cycle, column 7: flux difference between start value and value measured after irradiation, column 8: magnetic flux of a second measurement after irradiation, column 9: flux difference between start value and the 2nd measurement after irradiation. The measurement accuracy of the fluxmeter is 0.3% of the measured value.

T $[K]$	TID [krad-Si]	flux at start Φ_0 [Vs]	flux after cryo-cycle Φ_c [Vs]	flux after irrad-iation Φ_{i1} [Vs]	$\frac{\Phi_c-\Phi_0}{\Phi_0}$ [%]	$\frac{\Phi_{i1}-\Phi_0}{\Phi_0}$ [%]	flux after irrad-iation Φ_{i2} [Vs]	$\frac{\Phi_{i2}-\Phi_0}{\Phi_0}$ [%]
42	760	-4.594$\cdot 10^{-3}$	-4.564$\cdot 10^{-3}$	-4.553$\cdot 10^{-3}$	-0.64	-0.87	-4.558$\cdot 10^{-3}$	-0.76