Neutron radiation damage study and cost estimate of a hybrid magnet for the XFEL

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MSL-08-1
8 September 2008

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1 Introduction

After the undulator section of the XFEL the electron beam is bent away from the photon beam with a 2×5 m long bending magnet and directed towards the beam dump [1]. Instead of using conventional electromagnets proposals for using a hybrid magnet design have been presented [2, 3]. This hybrid magnet contains permanent magnet material (PMM) integrated in an iron core to obtain 1 T bias field in the air gap of the magnet. The magnetic field can be increased or decreased by magnet coils.

The permanent magnet material can lose part of the magnetization after being exposed to radiation. The hierarchy of radiation damage is: $p>d>n>e>\gamma$ [4]. The main concern for the bending magnets is the radiation damage from neutrons with energies 0-100 MeV backscattered from the beam dump [5]. Rough estimates show that the magnets will be exposed to a neutron fluence (time integrated flux) of $7 \times 10^{10} - 7 \times 10^{13}$ neutrons/cm^2 per year of operation (5000 hours) and the neutrons have energies 0-100 MeV [5]. From more detailed calculations the absorbed dose in the region of the second 5 m long dipole magnet is 10-100 Gy per year (5000 hours). Assuming that the XFEL will operate for 15 years the permanent magnet material has to withstand a maximum dose of 1500 Gy (or 1×10^{15}neutrons/cm^2).

This report presents a short summary of some results found in literature concerning the demagnetization of permanent magnets due to neutron radiation.

2 Neutron radiation damage

2.1 Processes causing demagnetization

The process or processes causing demagnetization of permanent magnet materials are not completely known and therefore it is difficult to predict the damage as function of neutron flux and energy. Possible processes are transmutation, dislocation of atoms and localized heating. Transmutation is most efficient at low neutron energies and it is not believed to be a dominant process at high energies. For dislocation a high energy neutron colliding with an atom transfers part of its energy, enough to displace the atom from the lattice and damage the atomic structure. Alderman *et al.* [6] suggests the damage is permanent and caused by dislocation of atoms or by transmutation, because the damage does not cure itself over time. Other works claim the opposite. Since permanent magnet material can be remagnetized after irradiation by neutrons, dislocation of lattice atoms seems unlikely to be the responsible process for demagnetization [7].

Kähkönen *et al.* [8, 10] presented a theoretical model based on the assumption that part of the energy of the incoming particle (proton) is transferred to a primary atom. The energy is then diffused into the lattice increasing the temperature in a spherical region by diffusion of heat. If the temperature increases above the Curie temperature the spins lose their fixed orientation. When the temperature returns below the Curie temperature the demagnetization field can turn the spins opposite to the direction they pointed in before the heating. The nucleation of a new domain is possible and if the direction of magnetization of this new domain is directed against the direction of the total magnetization part of the total magnetization is lost. Measurements have shown that the demagnetization depends on the temperature of the sample. The flux loss is greater at high temperatures. Chen *et al.* [7] measured the temperature of a sample as function of neutron flux and showed that the temperature of the material increases as the neutron flux increases. J. R. Cost *et al.* [13] measured the demagnetization at 77°C and 153°C and showed that the demagnetization is greater at high temperatures. Chen *et al.* [7] concluded that the demagnetization is not only a function of the dose, but also a function of neutron flux.

Kähkönen *et al.* [8] measured the demagnetization of a cubic sample and found that it was low when the proton beam was passing through the sample perpendicular to the direction of magnetization compared to when the beam was going parallel to the direction of magnetization. A particle going through a sample perpendicular to the direction of magnetization first enters a region with low demagnetization field. The demagnetization field is larger at the entrance of the sample moving parallel to the magnetization of the material (to visualize this see figure 1 (I). The flux lost after being exposed to a 10 MGy dose was about 70% when the direction of magnetization was parallel to the proton beam and 30% when the direction of magnetization was perpendicular to the beam. The discovery that the damage is worse at the part closest to the entrance of the beam was experimentally investigated by Brown *et al.* [9] who measured the demagnetization of a sample composed of several parts. After irradiation the part closest to the neutron source showed most decrease in magnetization.

Kähkönen *et al.* [10] measured the demagnetization as function of proton energy (14-20 MeV) and found that the energy dependence was small. They also measured the flux loss as function of an applied external magnetic field and concluded that the flux loss depends on the intrinsic field of the material. This has also been investigated by several groups where they have measured flux loss as function of $P_c = B/\mu_0 H$ [11, 12] or L/D where L is the length and D the diameter of the sample [9]. The shape of the sample determines the magnet working point on the load line.

2.2 Thermal neutrons

Since the processes of demagnetization are not fully understood conclusions have to be made from experiments. Unfortunately all measurements are done at nuclear reactors where the maximum energy is about 15 MeV with a peak in the energy distribution around 1 MeV. Some experiments stopped the thermal neutrons before the magnets were exposed to radiation, but only one paper present results from experiments where PMM was exposed to mainly thermal neutrons (NeFeB) [6]. That measurement showed no detectable decrease of the remanence field (B_r) after being exposed to 10^{12} neutrons/cm^2 (see table 1). It should be noted that fast neutrons did not cause any detectable damage after a similar dose. In this experiment it was too time consuming to expose the sample to a higher dose of thermal neutrons.

Other experiments have reduced thermal neutrons to avoid the reaction between thermal neutrons and ^{10}B [14].

Type	Thermal ($n/cm^2/s$)	Intermediate ($n/cm^2/s$)	Fast >0.1 MeV ($n/cm^2/s$)	Neutron fluence (n/cm^2)	Flux loss (%)
NdFeB	1×10^6	2.1×10^7	4.8×10^5	3.34×10^{12}	< 0.25
NdFeB	7.3×10^5	2.5×10^7	4.9×10^8	1.61×10^{14}	> 10

Table 1: Results from J. Alderman *et al.* [6].

2.3 Nuclear reactors

Several experiments performed in nuclear reactors are found in literature. Mainly two types of PMM have been tested, NdFeB and SmCo. SmCo compounds have higher Curie temperature (T_c) and are more radiation resistant, but they are also more expensive and tend to have lower remanence field than NdFeB compounds. Another disadvantage of SmCo is that it becomes radioactive through the large neutron capture cross section, forming Co^{60} and Sm^{151} with 5.3 and 93 years lifetime, respectively [15]. Experimental results of SmCo compounds all show similar results, SmCo lose less than 10% remanence field after exposure of a neutron fluence of 10^{19} n/cm^2.

Brown and Cost [9, 14, 13] have done several measurements on *NdFeB* samples and they found that the loss of magnetic flux depends on type of magnet and even manufacturer. A melt-spun NdFeB magnet material lost less than 2% remanent field while the best sintered materials lost nearly 5% at a fluence of 1.4×10^{16} n/cm^2. Kähkönen *et al.* [8, 10] claim that the size of the grain is a key factor for better resistance. A small grain size prevents the growth of a new domain with magnetization opposite the total magnetization.

The radiation resistance can also be better controlled using doped materials. Commercially avaliable NdFeB materials contain dysprosium (Dy) in order to increase the intrinsic coercivity and it is found that a high Dy content results in greater resistance against radiation [9]. It is also possible to dope the magnet material with terbium (Tb) to increase the intrinsic coercivity. This also results in greater resistance against radiation. The drawback of changing Nd for other rare earth compounds is that the initial magnetization is reduced.

Results from experiments carried out in nuclear reactors are presented in table 2. The demagnetization after maximum dose is presented together with the demagnetization after 10^{15} n/cm^2 which is the estimated maximum dose of the hybrid magnet after 15 years of operation.

2.4 Fast neutrons

There are no results from experiments with neutron energies higher than the maximum energy reached in nuclear reactors. A way to estimate the upper limit for demagnetization at energies higher than 15 MeV is to study radiation damage caused by protons if one assumes that protons cause greater damage than neautrons [4]. Another possibility is to use a cyclotron, accelerated protons colliding with a Li target produce free neutrons. The neutron flux is lower than in a nuclear reactor and therefore time consuming, but it is not impossible if studies with energies up to 100 MeV are needed.

Ito *et al.* [11] have investigated the change in magnetic flux for both NdFeB and SmCo compounds after irradiation with 200 MeV protons. They concluded after comparing the results with the neutron radiation experiments presented in

Material	Type	Temp [K]	Energy	Flux [n/cm^{2}s]	L/D	Fluence [n/cm^2]	Flux loss [%]	Flux loss at 10^{15}n/cm^2 [%]	Reference
NdFeB	NeIGT 27H	350	$>$ 5 eV	4×10^{12}		6×10^{16}	60	5	[13]
NdFeB	NeIGT 27H	426	$>$ 5 eV	4×10^{12}		5×10^{16}	90	10	[13]
NdFeB	Magnequench	350	$>$ 5 eV	4×10^{12}		7.6×10^{16}	3	1	[14]
NdFeB	Sumitomo 30H	350	$>$ 5 eV	4×10^{12}		1.5×10^{16}	5	1	[14]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	8.9	7×10^{15}	7	2	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	4.8	7×10^{15}	10	3	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	4.4	7×10^{15}	16	4	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	3.1	7×10^{15}	23	6	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	2	7×10^{15}	31	10	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	0.9	7×10^{15}	61	24	[9]
NdFeB	NeIGT 27H	350	$>$ 0.1 MeV	4×10^{12}	0.4	7×10^{15}	80	63	[9]
NdFeB	Neomax30H	350	$>$ 0.1 MeV	4×10^{12}	6.1	15×10^{15}	3	1	[9]
NdFeB	Neomax30H	350	$>$ 0.1 MeV	4×10^{12}	4.3	15×10^{15}	4	1	[9]
NdFeB	Neomax30H	350	$>$ 0.1 MeV	4×10^{12}	3	15×10^{15}	7	3	[9]
NdFeB	Neomax30H	350	$>$ 0.1 MeV	4×10^{12}	1.4	15×10^{15}	24	4	[9]
NdFeB	Neomax30H	350	$>$ 0.1 MeV	4×10^{12}	0.5	7.5×10^{15}	60	31	[9]
NdFeB		539	$<$ 10 MeV	$4.7 \times 10^{10} - 2.1 \times 10^{13}$	1.25	1×10^{16}	100	0	[7]
Sm_2Co_{17}	T500C	480	$<$ 10 MeV	$4.7 \times 10^{10} - 2.1 \times 10^{13}$	1.25	1×10^{20}	0	0	[7]
$SmCo_5$						1×10^{18}	<2		[16]

Table 2: Magnetic loss for different permanent magnet samples. The values of magnetic loss have been estimated from graphs in references.

Magnet type	P_c	Absorbed dose (10^3 Gy)	Flux loss (%)
NdFeB(N48)	0.5	1.5	40
NdFeB(N48)	1.0	1.5	20
NdFeB(N48)	2.0	1.5	4
NdFeB(N32Z)	0.5	7	6
NdFeB(N32Z)	2.0	40	2
SmCo(R26H)	0.5	100	0

Table 3: Results from samples irradiated with 200 MeV protons. The values are taken from figure 2 of reference [11].

reference [9], that NdFeB is more resistant to neutron radiation (1 MeV) than 200 MeV protons. Ito *et al.* measured the flux loss for a dose of $10^2 - 10^5$ Gy. The hybrid dipole magnet in the XFEL beam dump is estimated to be exposed to maximum 1.5×10^3 Gy after 15 years of operation. For SmCo there is no loss of magnetic flux even after 10^5 Gy. The *NdFeB* compounds show similar behaviour for 200 MeV protons as for fast neutrons (1 MeV), the loss of magnetic flux depends on the geometry of the magnet and it is between 2 and 40 percent at 1.5×10^3 Gy (see table 3).

3 Neutron damage of a hybrid dipole

3.1 Magnet geometry dependence

Magnetic properties important to resist radiation damage is high T_c, and high intrinsic coercivity. For a permanent magnet surrounded by air the geometry of the sample has shown to be important [9] and it is determined by the magnet working point on the load line, which can be described by the permeance coefficient ($P_c = B/\mu_0 H$). A higher value of P_c corresponds to a weaker demagnetization field. For a dipole configuration shown in figure 1 (III) the field lines are guided through a steel core and therefore the situation is better than for the magnet surrounded only by air shown in figure 1 (I). For a dipole configuration shown in figure 1 (II) the field from each block is not guided in one direction through the air gap, part of the field from each block passes through the other blocks in the opposite direction to the magnetization. The total effect is a lower B-field inside all blocks compared with a block in configuration III.

3.2 Beam energy dependence

Since the hybrid magnet in figure 1 uses magnet coils to decrease or increase the magnetic field in the gap the damage depends on the magnitude and direction of the current through the coils. For low beam energies the field from the coils is in the opposite direction to the field inside the blocks and therefore the blocks are also less resistant to radiation. On the other hand the flux of neutrons is lower for low beam energies. In the estimate of the maximum neutron flux at the XFEL it was assumed to be linear with respect to beam energy.

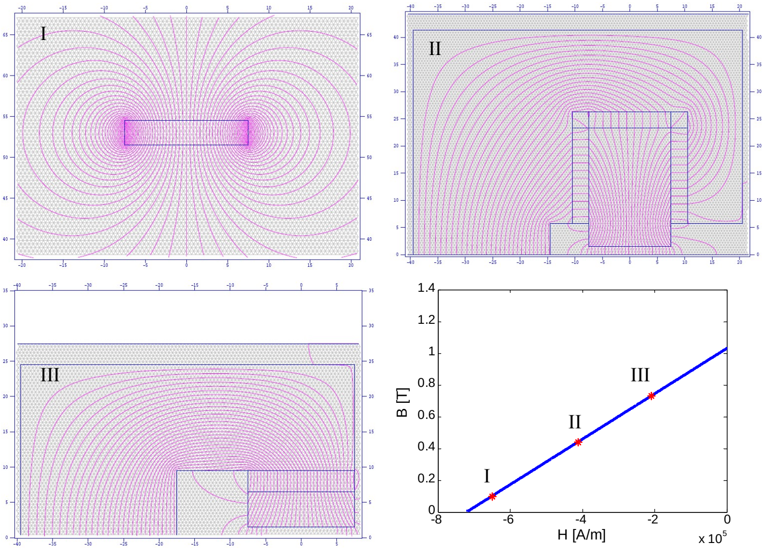

Figure 1: Comparison of working point on the demagnetization curve for a PMM block in air (I), in a six block configuration inside a C-shaped iron core (II), and in a double block configuration inside a C-shaped iron core (III).

4 Cost of a hybrid dipole

Although the hybrid magnet has several advantages, the high cost of permanent magnet material has to be considered. Vacuumschmeltze, a manufacturer of magnetic materials and magnetic systems, has estimated the cost of buildinig a hybrid magnet. A rough estimate of the price of suitable blocks ($50 \times 50 \times 30$ mm, tolerances $\pm$ 0.1mm) of NdFeB materials is 80-100 €/kg. The price of SmCo blocks is approximately the double. Vacuumschmeltze recommended to use NdFeB materials like VACODYM 863AP or VACODYM 655A which have high $\mathrm{H_{ci}}$, since they are more resistant against radiation. Additional costs for mounting and tooling is 30-50 k€.

The electromagnet presented in the XFEL technical design report [1] has a 6 cm pole gap. This was used as input in the calculations for designs presented in the first report [2]. In the second report [3] a 3 cm pole gap was used in the calculations since DESY hoped to reduce the gap to 3 cm. This improvement would have reduced the amount of permanent magnet material significantly in the design and therefore the extra cost due to permanent magnet material would have been smaller. At the time of this report the pole gap is 5 cm. In the new design the number of coil turns has increased from 2×42 to 2×64. Compared with the initial design, the reduced gap and increased number of turns reduce the power consumption from maximum 71 kW to 27 kW at 25 GeV (1.46 T), and now the magnet consumes 13.2 kW at the nominal energy, 17.5 GeV (1.02 T).

Using Vacodym 863AP with $\mathrm{B_r} = 1.21$ T, $\mathrm{H_{cB}} = 925$ kA/mT and $\mathrm{H_{ci}} = 2000$ kA/mT each 2.5 m long magnet contains approximately 823 kg of magnet material, estimated from calculations similar to the ones presented in the second rapport [3]. The dimensions of the blocks are a=d=5 cm, b=15 cm and c=14 cm (see figure 6 in [3]). The price of the magnet can be estimated to $90 \cdot 823 + 40000 = 114000$ €. The price does not include costs of steel core and coils, and it can be regarded as an approximate additional cost to a conventional electromagnet.

5 Discussion

The rare earth permanent magnets NdFeB and SmCo are both possible materials for implementation in particle accelerators. The raw material of NdFeB is relatively abundant and less expensive. The remanent field is typacilly higher for NdFeB, but SmCo has the advantage of having higher Curie temperature, possibly one reason why it is more resistant to radiation. A disadvantage is that SmCo becomes radioactive through the relatively large neutron capture cross section forming ^{60}Co and ^{151}Sm with 5.3 and 93 years lifetime, respectively. All results points at that SmCo compounds are enough resistant to radiation, even to neutron fluence orders of magnitude higher than what has been estimated to be the total neutron fluence at the XFEL dipole magnets. This conclusion is based on both 1 MeV neutrons and 200 MeV protons.

Although NdFeB type magnets are less radiation resistant, they are stronger and cheaper and might therefore be preferred. Many types of NdFeB magnets have been tested and the radiation resistance seems to depend on the temperature and shape of the sample. Well designed NdFeB compounds ($\mathrm{P_c} = 0.5, \mathrm{H_c} = 2.5$ [11]) lose approximately 10% of the magnetization at 10^4 Gy of 200 MeV protons. Assuming that protons cause more damage than neutrons and that the damage is greater at higher energies, the magnetic flux loss will be less than 10% at 10 times the estimated dose at XFEL.

$\mathrm{Sm_2Co_{17}}$ (Vacoomax 225 HR) was used in the calculations shown in figure 1 and has minimum $\mathrm{B_r} = 1.04$ T and $\mathrm{H_c} = 680000$ A/m. The hybrid magnet is designed to operate at 10-25 GeV (0.58-1.46 T) and for Vacoomax 225 HR $P_c = 0.5 - 1.48$. At the nominal energy 17.5 GeV (1.01 T) $P_c = 0.9$. The hybrid magnet will be less resistant against radiation at low electron beam energies than at high beam energies. In reference [3] the hybrid magnet is compared with a segmented dipole configuration. The principle is that 3×1 meter long permanent magnets bend the 17.5 GeV electrons 5°. For other beam energies the electron trajectory is corrected using 2×1 meter electromagnets. This type of configuration might be preferred from the perspective of radiation damage since $\mathrm{P_c}$ will be the same in the permanent magnet material for all beam energies.

For the hybrid magnet to be an attractive alternative to an electromagnet the additional cost of the permanent magnet material has to be returned by a reduced electricity bill. It is difficult to predict future electricity prices, but the current price is approximately 0.1€/kWh. Assuming 5000 running hours per year, the additional cost of magnet material and mounting is returned after 17 years of operation running at the nominal energy. If a conventional electromagnet is used instead, an additional permanent magnet system is needed further down the photon beam line, working as a passive safety system in case of power failure. If the hybrid magnet can be considered a reliable safety system it becomes more favourable.

Although the hybrid magnet causes additional costs in the construction phase it has many advantages. The operational cost will be reduced by the low power consumption and it can be regarded as an insurance against possible increased price for electricity in the future. Also, working as a passive safety system the number of magnet parts in the beam line are reduced.

References

[1] XFEL Technical Design Report, Edited by M. Altarelli *et al.*, DESY 2006.

[2] F. Hellberg, Investigating the possibility of a hybrid magnet design for BV/BW dipole magnets at the XFEL, MSL-06-1, 2006.

[3] F. Hellberg, Comparison of two hybrid magnet designs, MSL-07-1, 2007.

[4] J. Spencer and J. Volk, "Permanent magnets for radiation damage studies", PAC'03, Portland,(2003).

[5] M. Schmitz, private communication.

[6] J. Alderman *et al.*, Nucl. Instr. Meth. in Phys. Res. A 481, 9 (2002).

[7] C. H. Chen *et al.*, IEEE Trans. on Magn. 41, 3832 (2005).

[8] O-P. Kähkönen *et al.*, J. Phys. Condensed Matter 4, 1007 (1992).

[9] R. D. Brown and J. R. Cost, IEEE Trans. on Magn. 25, 3117 (1989).

[10] O-P. Kähkönen *et. al.*, Phys. Rev. B 49, 6052 (1994).

[11] Y. Ito *et al.*, Nucl. Instr. Meth. in Phys. Res. B 183, 323 (2001).

[12] J. Allen *et al.*, SLAC-PUB-10534 (2004).

[13] J. R. Cost *et al.*, IEEE Trans. on Magn. 24, 2016 (1988).

[14] R. D. Brown *et al.*, J. Appl. Phys. 64, 5305 (1988).

[15] S. Anderson *et al.*, "Fast neutron radiactivity and damage studies on materials", SLAC-PUB-12574, (2007).

[16] R. D. Brown *et al.*, "Radiation effects on samarium-cobalt permanent magnets", LA-9437-MS, (1982).