BRIEF REVIEW OF THE APPROACHES TO ELUCIDATE THE MECHANISM OF THE RADIATION-INDUCED DEMAGNETIZATION

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Abstract

Permanent magnets decrease their magnetic field under severe radiation environment. This radiation damage, radiation-induced demagnetization, is a great concern especially for the devices that requires very precise uniform magnetic field such as undulators. The evaluation of this field degradation is difficult because the mechanism of the radiation–induced demagnetization is not clear. Several approaches to clarify this mechanism have been made. For example, (1) the approach to examine the relations between the field degradation and the environmental factors like magnet shape, temperature and so on, (2) the approach to examine the changes of the microstructures and the properties of the magnet after irradiation, (3) the approach to compare and examine the experiments of the demagnetization and the computer simulations of the radiation. This paper reviews and summarizes these approaches and models briefly. The new point of view to consider the mechanism is presented as well.

INTRODUCTION

The magnetic field intensity of the permanent magnet decreases when the magnets are used in a strong radiation environment. This radiation damage is called radiation-induced demagnetization. The degradation of the magnetic field is a big problem for undulators and other devices with magnet that requires precise magnetic field. The changes of the magnetic field in the undulators were observed in the storage ring in APS[1]. For this reason, many studies have been done so far. In this paper, I review and summarize the typical studies and propose the new point of view to consider the mechanism of the radiation-induced demagnetization.

APPROACHES TO CLARIFY THE MECHANISM

Several approaches to clarify the mechanism of the radiation-induced demagnetization have been made. For example, (1) the approach to examine the relations between the field degradation and the environmental factors like magnet shape, temperature and so on, (2) the approach to examine the changes of the properties and the microstructures of the magnet after irradiation, (3) the approach to compare and examine the experiments of the demagnetization and the computer simulations of the radiation.

Environmental Factors

The radiation-induced demagnetization shows the dependencies of the following environmental factors; (a) material, chemical component, microstructure and manufacture, (b) coercivity, (c) temperature, (d) permeance coefficient that relate to magnet shape, outer magnetic field, inflection point (shape of B-H curve).

The relation of these factors looks uncertain, but these factors are similar to the factors that influence the demagnetization originated from the reversal magnetization. Especially, (b), (c), (d) are related to the coercivity decrease caused by the internal magnetic field that is described by permeance coefficient.

Properties and Microstructures after Irradiation

Several researchers have tried to observe the changes in the irradiated magnets. Cost[2], Kähkönen[3], Okuda[4], Ito[5], Chen[6], Klaffky[7], and Qiu[8] examined the magnetic properties change. The damaged magnets by irradiation were remagnetized and compared the magnetic properties before irradiation. Chen observed that the recovery intensity of the remanence changed depending on the flux of a 10 MeV neutron. Qiu observed the degradation of the remanence by a 2.5 GeV electron irradiation. However, others found no changes in the remanence. Cost observed the 20 % increase of the coercivity by fast neutron irradiation. Klaffky performed a thermal neutron irradiation, and Qiu performed a 2.5 GeV electron irradiation. Though both found no changes in coercivity.

Talvite[9] and Gao[10] could not observe any microstructural changes in the magnets after irradiation by using the positron annihilation measurement or the X-ray diffraction. Yang[11, 12] found some atomic local changes by using the XAS, Mössbauer spectrometry and XAFS.

These results indicate that the radiation-induced demagnetization can occur without clear changes of the magnetic properties and the structures. The change is extremely local even if existing. This implies that the cause of the radiation-induced demagnetization in early stage should be the magnetization reversal.

Experiments and Computer Simulation

Qiu, Asano and Leitner calculated the particle transport and interactions with matter using Monte Carlo simulation FLUKA, and compared the experimental results of the radiation-induced demagnetization.

Qiu[8] calculated the absorbed dose and the 1 MeV equivalent neutron fluence. "1 MeV equivalent neutron fluence, is widely used to characterize the displacement damage of the electronic devices in which the main material is Si when they are irradiated by neutrons." Qiu analysed the demagnetization caused by a 2.5 GeV electron irradiation, and proposed the fitted formula composed of two terms, the dose and the 1 MeV

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equivalent neutron fluence. This formula requires different coefficient of the term to the different target material.

Asano[13] calculated the star densities owing to neutrons and photons. A star was defined by a hadronic inelastic interaction (spallation reaction) at energy higher than the threshold and excludes the spallation due to annihilating particles. In his calculation, the elastic scattering is included as well. He concluded, the "low-energy photoneutrons and bremsstrahlung photons are not involved in the demagnetization process, and suggest that the star density owing to the photoneutrons is strongly correlated with the demagnetization process."

Leitner[14] indicated that "the demagnetization grows significantly with the total dose, but it increases even faster with the non-electromagnetic dose," so the "neutrons are mostly identified as the cause of magnetization loss." He also presumed "more noxious impact of higher energy neutrons."

BASIC MODEL OF MAGNETIZATION REVERSAL

The basic process of the magnetization reversal in the nucleation-type magnet as represented by $Nd_2Fe_{14}B$ is following:

1. Heat and magnetic field decrease the coercivity.
2. Inverse magnetic moment domain nucleates where the anisotropy barrier is the lowest, such as near the grain boundary.
3. Domain wall expands in the grain immediately.

BRIEF REVIEW AND SUMMARIZE THE PAST MODELS

Typical models of the radiation-induced demagnetization that have been proposed so far are reviewed and summarized briefly in this chapter. Blackmore[15] pointed out the similarity between a radiation damage and "a thermal heating of the sample at elevated temperature." Cost[2] suggested that the high temperature generates the nucleus. "Collision cascade has a higher probability of nucleating a reverse domain when the temperature is closer to the Curie temperature."

Brown's Model

Brown[16] is unique for focusing on the magnetic interaction, though other researchers paid attention to the high temperature. He stated, "The decay of magnetic remanence during neutron irradiation is presumably caused by a combination of nucleation of reverse magnetic domains and depinning of domain walls, leading to domain wall motion and demagnetization." He assumed that the "magnetic interaction of the neutron's magnetic moment with the magnetization of the material" makes a "magnetic excitation in the magnetization of a grain, thereby nucleating a reverse domain, or an excitation at a magnetic domain wall pinning site causing depinning of the domain wall, which is then free to move." He also proposed the mechanism that the "inelastic collisions with the atoms, causing local disruption of the crystal structure and its magnetic anisotropy" "create additional pinning sites, which is seen as increased coercivity in sintered Nd-Fe-B magnets at very high doses."

Kähkönen's Model

The process of the Kähkönen's model[3] is the following:

1. Part of the energy of the incoming particle is transferred to the primary knock-on atom.
2. The energy is then diffused into the lattice raising the temperature of a spherical region.
3. If the temperature rises above the Curie temperature and if this sphere is large enough the demagnetizing field can turn the spins and nucleation of a new domain occurs.
4. The domain immediately grows to the size of the grain.

Zeller's Model

Zeller[17] pointed out that the loss of the coercivity is the reason of the demagnetization: "The sensitivity of NdFeB permanent magnet materials to radiation induced demagnetization is shown to be the result of loss of coercivity. This allows the magnet to demagnetize at locations which are subjected to the largest external and internal demagnetization fields."

Makita's Model

Makita[18] made clearer explanation of the origin of nucleation by focusing on the "decrease of the magnetic anisotropy" in place of the "loss of the coercivity". This is because the magnetic anisotropy is the origin of the coercivity. He made the experiments of using the different coercivity magnets with same Curie temperature and concluded that nucleation occurs below the Curie temperature: "Since all of the magnets have the same Curie temperature, the difference in the demagnetization rate can be attributed to the probability of nucleation of a reverse domain in a locally heated region located around a knock-on atom, which is analogous to the thermal demagnetization of the magnets that usually starts below their Curie points."

Gao's Model

Gao[19] declared "As an external energy source, γ-ray irradiation will decrease the ordering of magnetic moments by disturbing the electron spin of Fe and Co atoms in the ferromagnetic phase." and "The Curie temperature should be taken into account in high-energy particle irradiation conditions, but for γ-ray irradiation, coercivity mechanism is the dominant factor."

Bizen's Diagram

I propose the diagram of the process of the radiation-induced demagnetization shown in Fig. 1. If the energy from the particles supplied to the magnetic phase is sufficient, the magnetic anisotropy decreases and the nucleation occurs. There are two points to consider. The

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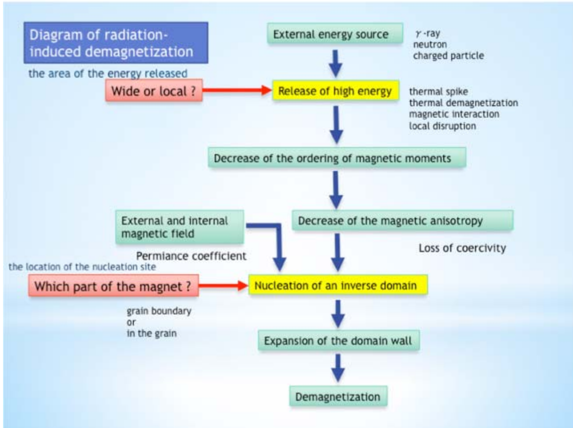

Figure 1: Diagram of the process of the radiation-induced demagnetization.

first is the area of the energy released from the particles. The second is the location of the nucleation site. From these points of view, two mechanisms were proposed [20]. These mechanisms are explained in the next chapter.

TWO POINTS OF VIEW TO CONSIDER THE MECHANISM

Wide Unstable Region (Magnetic Moment Instability)

Low energy radiation particles as γ ray, electron, and neutron transfer their energy in long range to the magnet. They act as an external energy sources like heat or magnetic field that make magnetic moment unstable in wide region. Therefore similar process of the magnetization reversal caused by heat and field would occur also in radiation (Fig. 2). The process is following:

1. Magnetic moment instability decreases the magnetic anisotropy, or coercivity in wide region.
2. Inverse magnetic moment domain nucleates at the grain boundary, where the anisotropy barrier is the lowest.
3. Domain wall expands immediately in the grain.

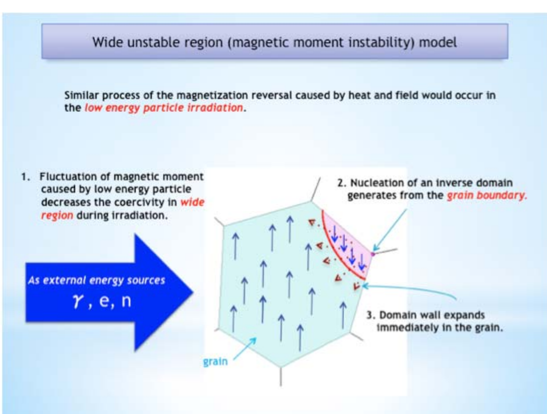

Figure 2: Wide unstable region model. Energy of γ, e and n is transferred in long range to the magnet atoms as ionization and excitation. This causes the instability of the magnetic spin in the region of over the grain size. Similar process of the magnetization reversal caused by heat and field occurs by radiation.

This radiation-induced demagnetization caused by the "wide unstable region (magnetic moment instability)" mechanism is similar to the magnetization reversal caused by the magnetic moment instability originated from thermal energy. For this similarity, the engineering technique for stabilization against high temperature is effective to the radiation damage as well. The method of this stabilization technique is a partial demagnetization of the magnet by heat or magnetic field. Figure 3 shows the improvement of the radiation resistance by this stabilization[21, 22].

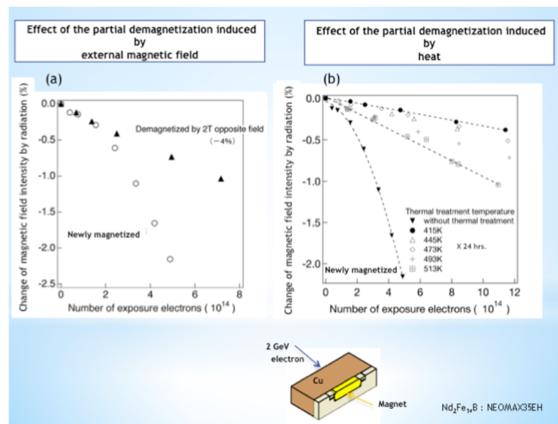

Figure 3: The effect of the engineering technique for stabilization against radiation was tested. The magnet is put behind the copper block and is irradiated with a 2 GeV electron. (a): The effect of the partial demagnetization induced by external magnetic field. The sample of partially demagnetized by magnetic field shows less demagnetization. (b): The effect of the partial demagnetization induced by heat. Black triangle is newly magnetized magnet. The others are partially demagnetized by different temperature. The samples of partially demagnetized by heat show less demagnetization.

Both different engineering stabilizing techniques are effective to the radiation.

Local Hot Spot (Quasi-thermal Spike)

When a high-energy electron interacts with a material, high-energy photoneutrons are generated. High-energy photoneutron collides with an atom of the magnet and kicks out from the lattice. The energy of the knock-on atom transfers to the magnet atom by the process similar to the thermal spike. Thermal spike generates very high temperature over melting point instantaneously in a very small region. However, as Makita stated, demagnetization can occur below the Curie temperature of much lower

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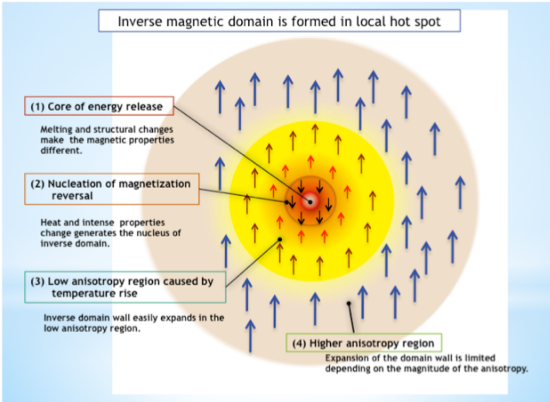

Figure 4: High-energy release point produced by the quasi-thermal-spike is made anywhere in the magnet independently of the anisotropy. This instantaneous large energy transfer generates the melted core or the structural change. The intense magnetic change in the core causes the instability of the magnetic spin around the core and produces the nucleus of inverse magnetization. Low coercivity region is generated around the core as well. The inverse domain wall of the nuclei easily expands in this region, but this expansion is limited when it enters into the high coercivity region.

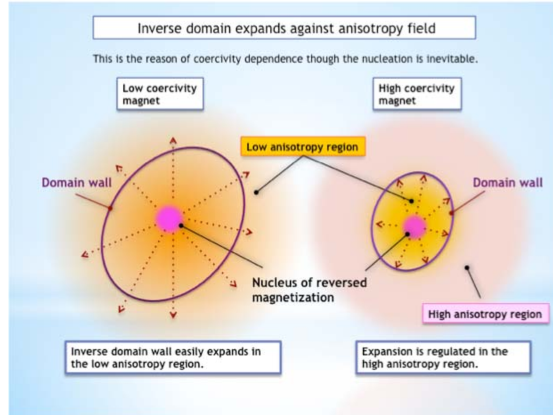

Figure 5: Temperature generated by the quasi-thermal-spike is extremely high so that the nuclei are produced in any magnet. In contrast, the easiness of the expansion of the inverse domain wall depends on the properties of the magnet. In the low coercivity magnets, the domain wall expands easily and the inverse domain grows to the whole grain, consequently this leads large demagnetization. In the large coercivity magnets, the coercivity around the nucleus is so large that the domain wall can hardly expand therefore the demagnetization is small.

than the thermal spike temperature. Therefore, the term of "quasi-thermal-spike" is used here instead of the "thermal spike". Quasi-thermal spike generates hot spots everywhere, such as near the grain boundary where the anisotropy barrier is low, and in the grain where the anisotropy barrier is high. Figure 4 shows the image of the local hot spot. The process is following:

1. In the center of the hot spot, there is a core of energy release where the temperature is very high. If the released energy is very high, the temperature rises over the melting point. Melting and structural changes make the magnetic properties different.
2. Around the core, heat and intense properties change decreases the magnetic anisotropy and generates the nucleus of inverse domain.
3. Inverse domain wall easily expands in the low anisotropy region caused by the temperature rise.
4. In the higher anisotropy region, expansion of the domain wall is limited depending on the magnitude of the anisotropy.

In this "local hot spot (quasi-thermal spike)" mechanism, the nucleation can occur in the middle of the grain where the magnetic anisotropy is high, because the temperature of the hot spot is very high with the high-energy electron irradiation. Under the same irradiation condition, the amount of the nucleation should be same in all magnets, though the demagnetization shows the coercivity dependence. This is because the expansion of the inverse domain wall is regulated especially in the high coercivity magnet (Fig. 5).

The experimental results of the demagnetization caused by the high-energy electron irradiation were compared to the computer calculation. Asano calculated the neutron collision density distribution by using FLUKA code as shown in Fig.6 [13]. In the neutron energy below 1 MeV, the collision density at the center of the magnet irradiated with a 2 GeV electrons to the copper target is smaller than that at the end of the magnet with an 8 GeV to the tantalum target. But the demagnetization experiment shows opposite result as shown in Fig.7. Little demagnetization is observed at the end of the magnet irradiated with an 8 GeV electrons to the tantalum target. This implies that the neutron in the low energy region is not effective to demagnetization of the thermally stabilized magnet.

The calculation results of the absorbed doses are shown in (a) of Fig. 8. Experimental result of the tantalum target is different from the calculation. The right hand graph is the star densities that include elastic and inelastic interactions owing to high-energy photoneutrons. Both experimental results of copper and tantalum target are better fit to the calculation. This indicates that the absorbed dose is not strongly connected to the demagnetization of the thermally stabilized magnet. On the contrary, the interactions owing to high-energy photoneutrons are strongly correlated with the demagnetization process. These results could be explained by the mechanism of the local hot spot. The demagnetization caused by the high-energy electron is well indicated by the star densities than the dose. For the example of this application, Asano performed the estimation of the demagnetization quantitatively as

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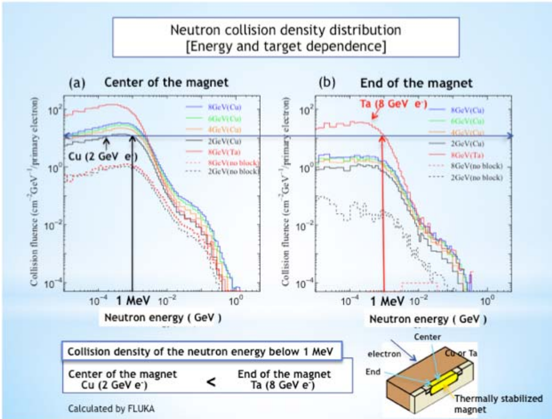

Figure 6: Calculated neutron collision density distribution. In the neutron energy below 1 MeV, the collision density at the center of the magnet irradiated with a 2 GeV electrons to the copper target is smaller than that at the end of the magnet with an 8 GeV to the tantalum target.

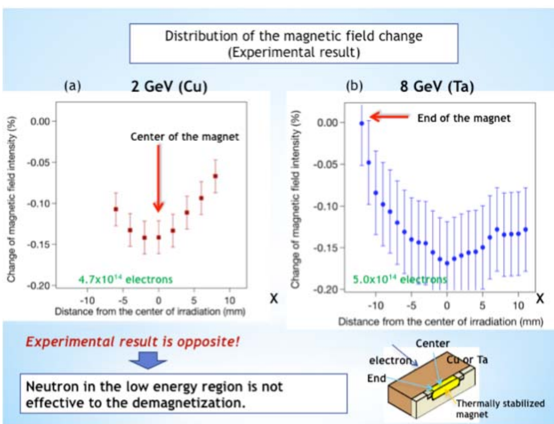

Figure 7: The experimental results of the distribution of the magnetic field change. The demagnetization shows opposite of the calculation result. Little demagnetization is shown at the end of the thermally stabilized magnet irradiated with an 8 GeV electrons to the tantalum target. This discrepancy implies that the neutron in the low energy region is not effective to the demagnetization.

functions of the electron energy, the gap width of the ID, and the dependence on material of the OTR[23].

EFFICIENT METHODS FOR INCREASE THE RADIATION RESISTANCE

The efficient methods to increase the radiation resistance of the magnet is following:

1. Designing the magnetic circuit of higher permeance coefficient
2. Selecting the magnets with high coercivity
3. Selecting the magnets with high temperature-stability
4. Applying the stabilization technique to the magnets

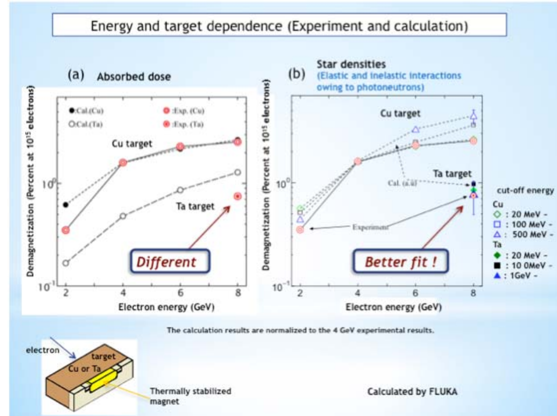

Figure 8: Comparison between the calculations and the experimental results of the demagnetization irradiated with different energy of electrons. The calculation results are normalized to the 4GeV experimental results.
(a): The absorbed dose: Experimental result of the tantalum target is different from calculation.
(b): The star densities: Both experimental results of copper and tantalum target are better fit to the calculation.
This indicates that the absorbed dose is not strongly connected to the demagnetization. On the contrary, the star density is strongly correlated with the demagnetization process.

5. Using the magnets at very low temperature

Figure 9 (b) shows the increase of the radiation resistance of the magnet uses at low temperature[24]. The coercivity increases with decrease the temperature as shown in (a)[25].

The coercivity can be increased by the partial substitution of dysprosium (Dy) for Nd in $Nd_2Fe_{14}B$ phase as well. The Dy distributes mainly near grain boundary especially in recent magnet. In the case of the high-energy particle irradiation, the nucleation in the grain should be concern. That is, the higher magnetic anisotropy in the grain is important. It is very effective to decrease the magnet temperature to increase the coercivity in whole grain.

SUMMARY

Typical past experiments and models of radiation-induced demagnetization are reviewed and summarized. The demagnetization can occur without clear changes of the magnetic properties and the structures. This implies that the cause of the radiation-induced demagnetization in early stage should be the magnetization reversal. The energy from the particles decreases the magnetic anisotropy of the magnet, and nucleation occurs. If the nucleation is the origin of the radiation-induced demagnetization, two types of demagnetization mechanism should be considered. One is the "wide unstable region (magnetic moment instability)"

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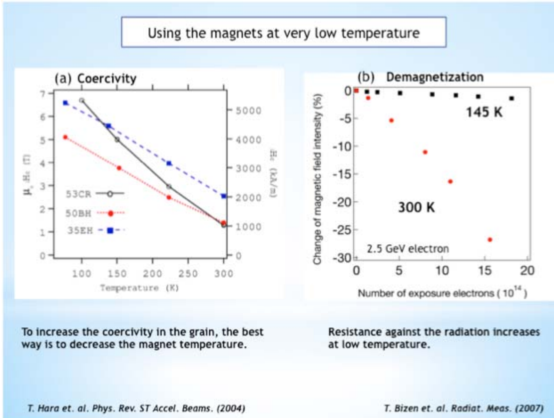

Figure 9: To increase the coercivity in the grain, the best way is to decrease the magnet temperature. (a) The coercivity increases with the temperature decrease. (b) Resistance against the radiation remarkably increases at low temperature.

mechanism, and the second is the "local hot spot (quasi-thermal spike)" mechanism.

The demagnetization cannot be estimated sufficiently by a calculation of the dose alone, because the mechanism of the demagnetization depends on the particle energy. The simulation of the star density is in good agreement with the demagnetization of the stabilized magnet with high-energy electron irradiation. The star density can be used for estimation of the radiation-induced demagnetization.

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