Brief Review of the Approaches to Elucidate the Mechanism of the Radiation-induced Demagnetization

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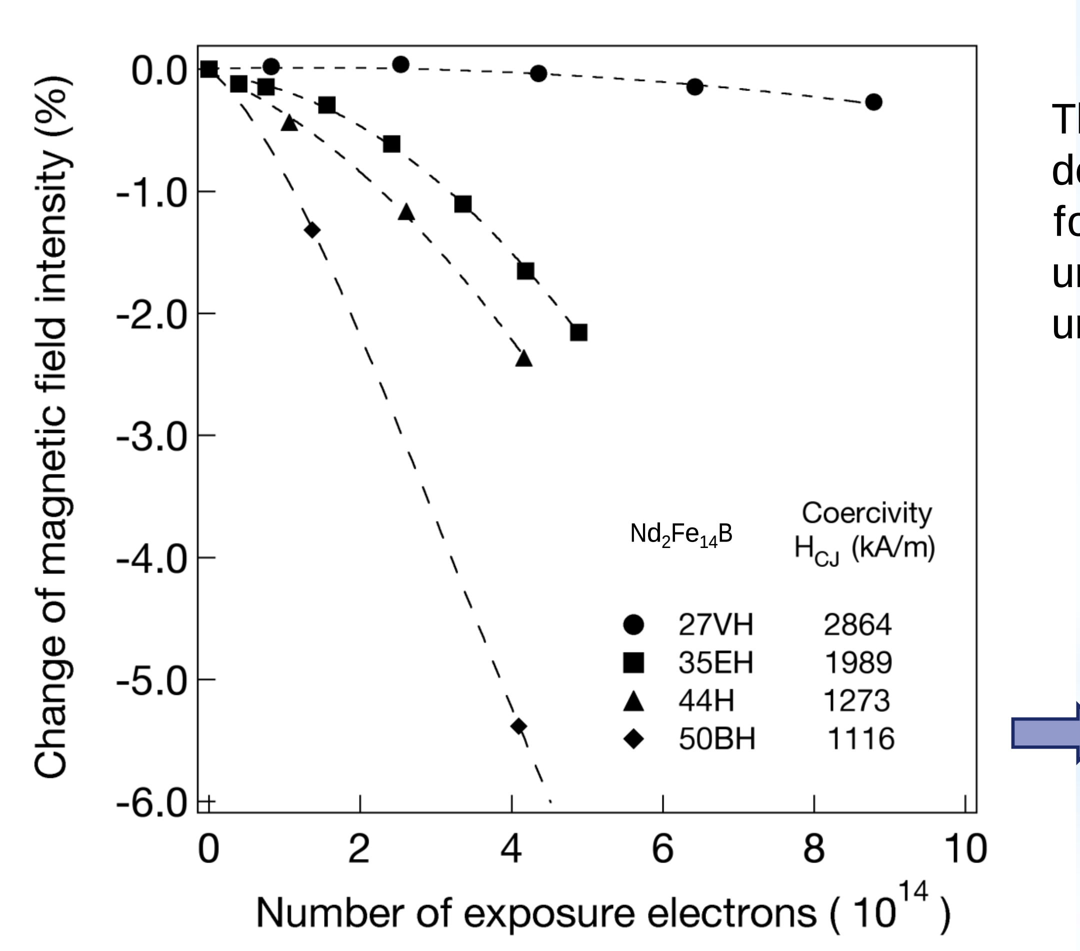
Contents

Radiation-induced demagnetization

The magnetic field intensity decreases when the magnets are put in a strong radiation environment.



2 GeV electron

This radiation-induced demagnetization is a great concern for devices that requires precise uniform magnetic field such as undulators.

Radiation-induced demagnetization shows coercivity dependence.

Several approaches to clarify the mechanism of the radiation-induced demagnetization that have been done so far.

(1) The approach to examine the relations between the field degradation and the environmental factors such as 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 experimental results and the computer simulations.

(1) The approach to examine the relations between the field degradation and the environmental factors.

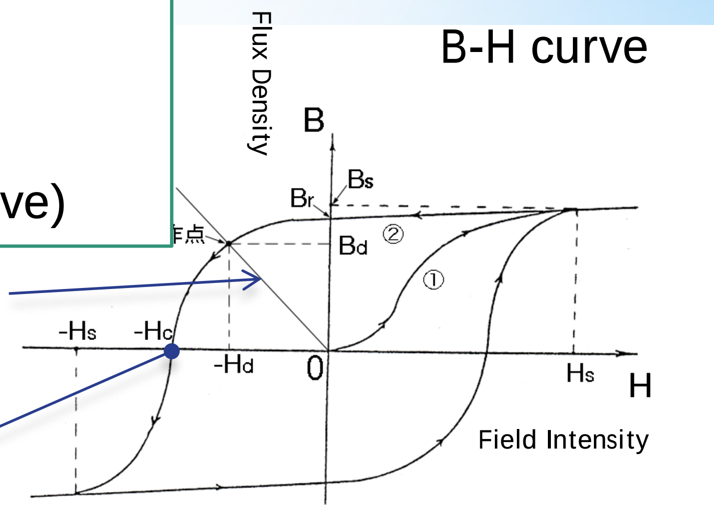
Radiation-induced demagnetization shows the following dependencies:

1 material
   - chemical component
   - microstructure
   - manufacture

2 coercivity

3 temperature

4 permeance coefficient (P_c)
   - magnet shape
   - outer magnetic field
   - inflection point (B-H curve)



(1) The approach to examine the relations between the field degradation and the environmental factors.

Radiation-induced demagnetization shows the following dependencies:

1 material
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- magnet shape
- outer magnetic field
- inflection point (B-H curve)

These factors are similar to the factors that influence the demagnetization originated from the reversal magnetization. Especially, 2, 3, and 4 are related to the coercivity decrease caused by the internal magnetic field that is described by permeance coefficient.

(2) The approach to examine the changes of the properties and the microstructures of the magnet after irradiation.

Remagnetization

The damaged magnets by irradiation were remagnetized and compared the magnetic properties before irradiation.

	Particle	Remanence	Coercivity
Cost 1988 [84]	Fast neutron	No change	*20 percent increased*
Kähkönen 1990 [3]	Proton 20 MeV	No change	
Okuda 1994 [90]	Electron 17 MeV	No change	
Ito 2002 [66]	Proton 200 MeV	No change	
Chen 2005 [264]	Neutron ~ 10 MeV	*Decreased (flux dependence)*	
Klaffky 2006 [266]	Thermal neutron	No change	No change
Qiu 2008 [270]	Electron 2.5 GeV	*Decreased*	No change

Microstructures change

	Particle	Methods	Results
Talvite 1991 [8]	Proton 20 MeV 20 Mrad	Positron annihilation measurement	no detectable vacancy concentration
Gao 2008 [262]	γ (^{60}Co) 200 Mrad	X-ray diffraction Positron annihilation spectroscopy	no phase changes the positron lifetime variations are all little
Yang 2009 [290] 2011 [245]	Proton 9 MeV 7×10^{14} p/cm^2	Soft X-ray absorption spectrometry (XAS) Mössbauer spectrometry X-ray diffraction (XRD) XAFS	the destruction of atomic symmetry and changes of bonding environment induce the change of atomic magnetic moment Proton irradiation has no effect on the long-range structure, but significantly affects the atomic local structure The alignment degree of the magnet decreases and the internal stress of the lattice increases. The coordination number of Fe–Nd in the first neighboring coordination shell of the Fe atoms decreases and the disorder degree increases.

Demagnetization occurs before clear structural changes.

↓

Demagnetization occurs by magnetization reversal in early stages.

(3) The approach to compare and examine the experimental results and the computer simulations.

	Code	Simulation	Particle
Qiu 2008 #270	FLUKA	Absorbed dose 1 MeV equivalent neutron fluence*	Electron 2.5 GeV
Asano 2009	FLUKA	Star density**	Electron 2, 4, 6, 8 GeV
Leitner 2010 #282	FLUKA	Total dose Non-electromagnetic dose Neutron fluence	Electron 13.7 GeV

They suggested the important role of neutron.

FLUKA is a Monte Carlo simulation code for the interaction and transport of particles and nuclei in matter.

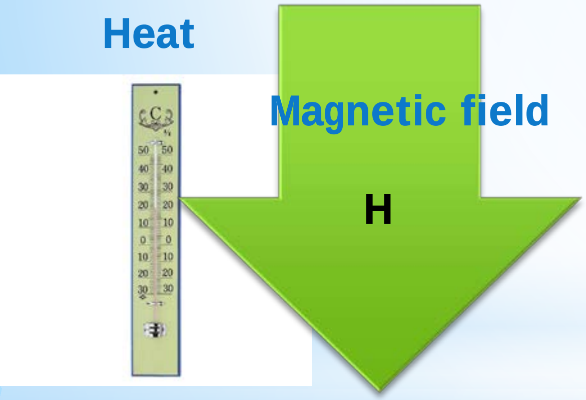
* 1MeV equivalent neutron fluence, is widely used to characterize the displacement damage of the electronic devices in which the main material is Si when they are irradiated by neutrons.

** 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.

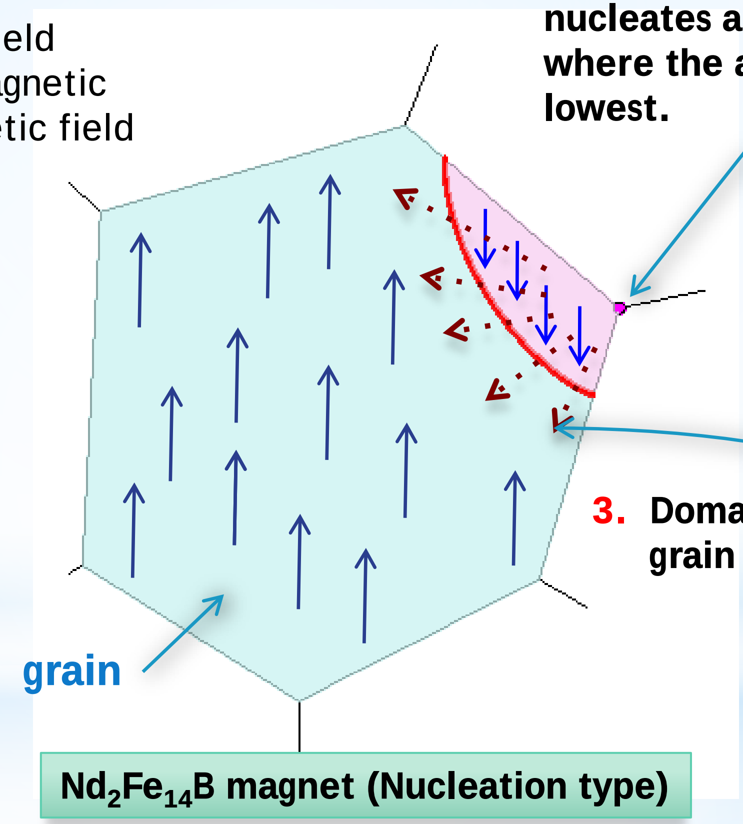
Basic model of magnetization reversal

Process of magnetization reversal by heat and field

1. When the magnet **is put** in a high temperature or reverse magnetic field environment, the fluctuation of magnetic moment caused by heat and magnetic field **decreases** its coercivity.



2. Inverse magnetic moment domain nucleates at the grain boundary, where the anisotropy barrier is the lowest.



3. Domain wall expands in the grain immediately.

Brief review and summarize the past models

	Model
Blackmore 1985 #85	It appears to be similar to a thermal heating of the sample at elevated temperature.
Cost 1988 #84	Collision cascade has a higher probability of nucleating a reverse domain when the temperature is closer to the Curie temperature.
Brown 1988 #52	
Kähkönen 1990 #3	
Zeller 1990 #139	
Makita 2004 #208	
Gao 2006 #246	

Brown's model

Brown focused on the magnetic interaction.

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.

Magnetic interaction of the neutron's magnetic moment with the magnetization of the material

→

Magnetic excitation in the magnetization of a grain

Nucleating a reverse domain

Excitation at a magnetic domain wall pinning site

Depinning of the domain wall, which is then free to move

Inelastic collisions with the atoms

Local disruption
crystal structure
magnetic anisotropy

→

Creation of additional pinning sites

Increasing the coerecivity

* J. Appl. Phys. 64 (10), (1988), 5305-5307

Kähkönen’s model

(1)

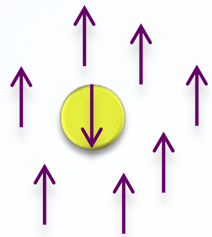
Part of the energy of the incoming particle is transferred to the primary knock-on atom.

(2)

The energy is then diffused into the lattice raising the temperature of a spherical region.

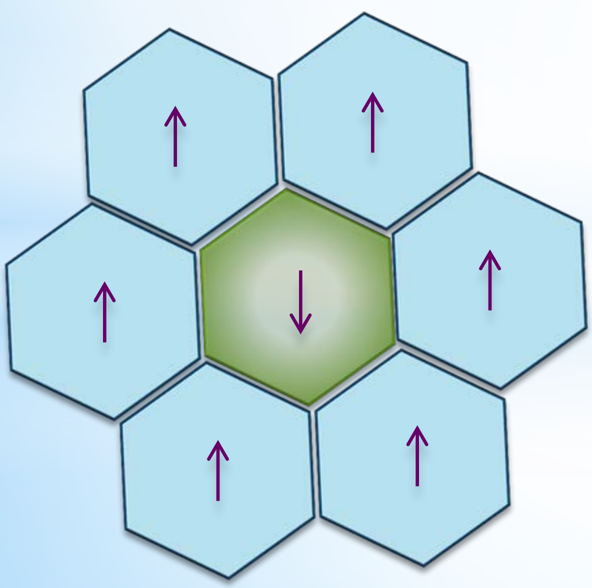
Thermal spike

(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.

* J. Phys. Condens. Mater 4 (1992) 1007-1014

** Graphic image is added by Bizen.

Zeller's model

Zeller pointed out the loss of the coercivity in the magnet.

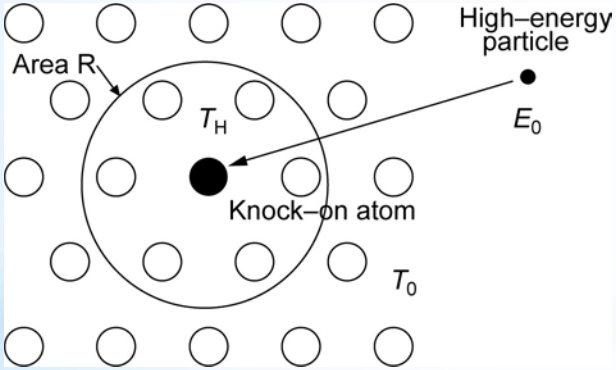
The sensitivity of NdFeB permanent magnet materials to radiation induced demagnetization is shown to be the result of loss of coercivity. This allows the magnet to demagnetize at locations which are subjected to the largest external and internal demagnetization fields.

* 9th International Workshop on Rare-Earth Magnets and their Applications, (1987)

Makita's model

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.

Makita made clearer explanation of the origin of the 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.



(1) Temperature rise (below Curie temperature)

(2) Magnetic anisotropy decreases

(3) Nucreation and reversal magnetization

* J. Magn. Soc. Jpn.28, (2004), 326-329

Gao's model

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.

γ-ray (^{60}Co)

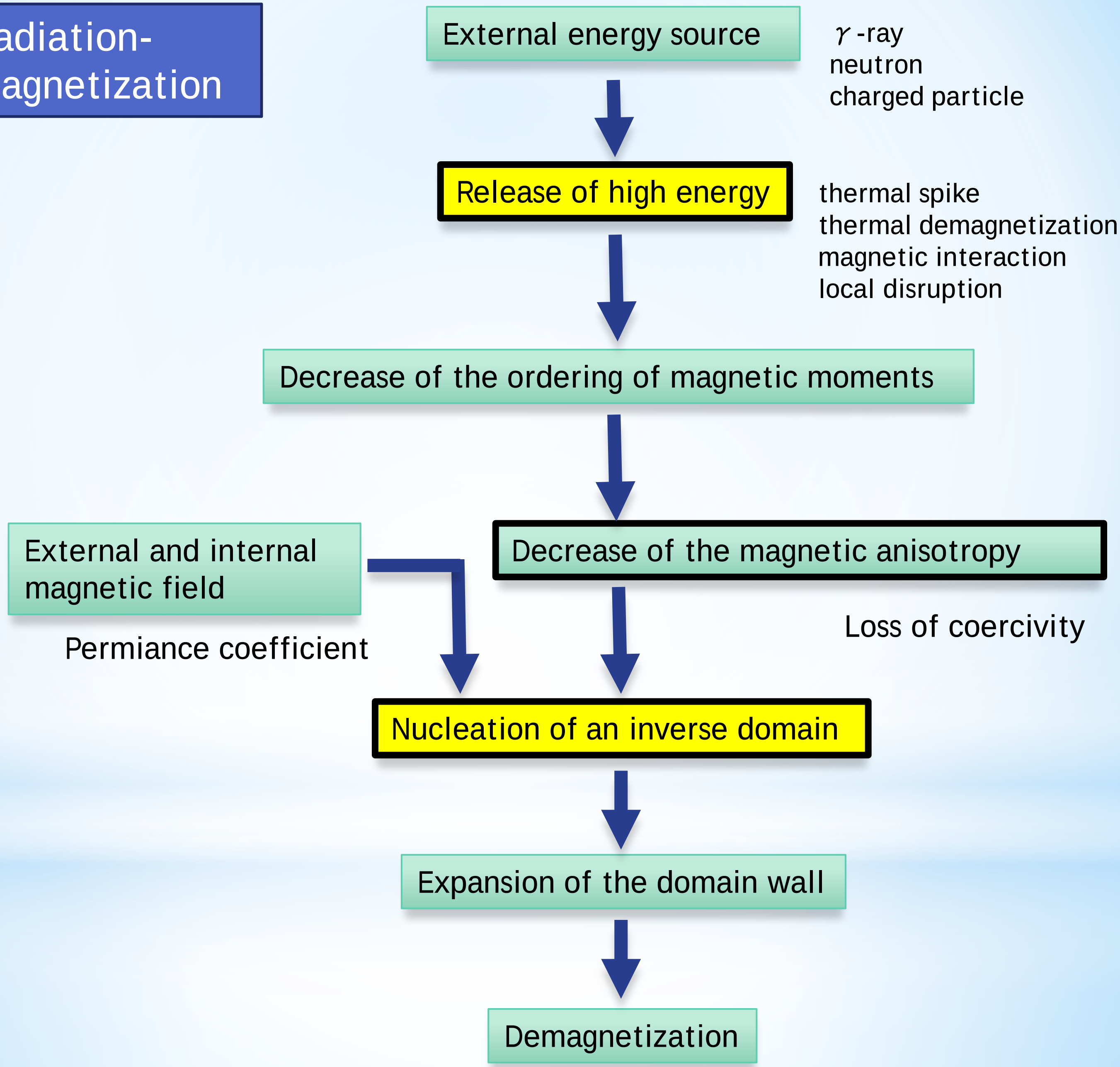
Fe-Cr-Co and $Nd_2Fe_{14}B$ magnet

	Fe-Cr-Co		$Nd_2Fe_{14}B$
Curie temperature	**945 K**	**>**	**700 K**
Demagnetization	**16.5 %**	**>**	**2.5 %**

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*.

J. Magn. Magn. Mater. 302 (2006)

Diagram of radiation-induced demagnetization



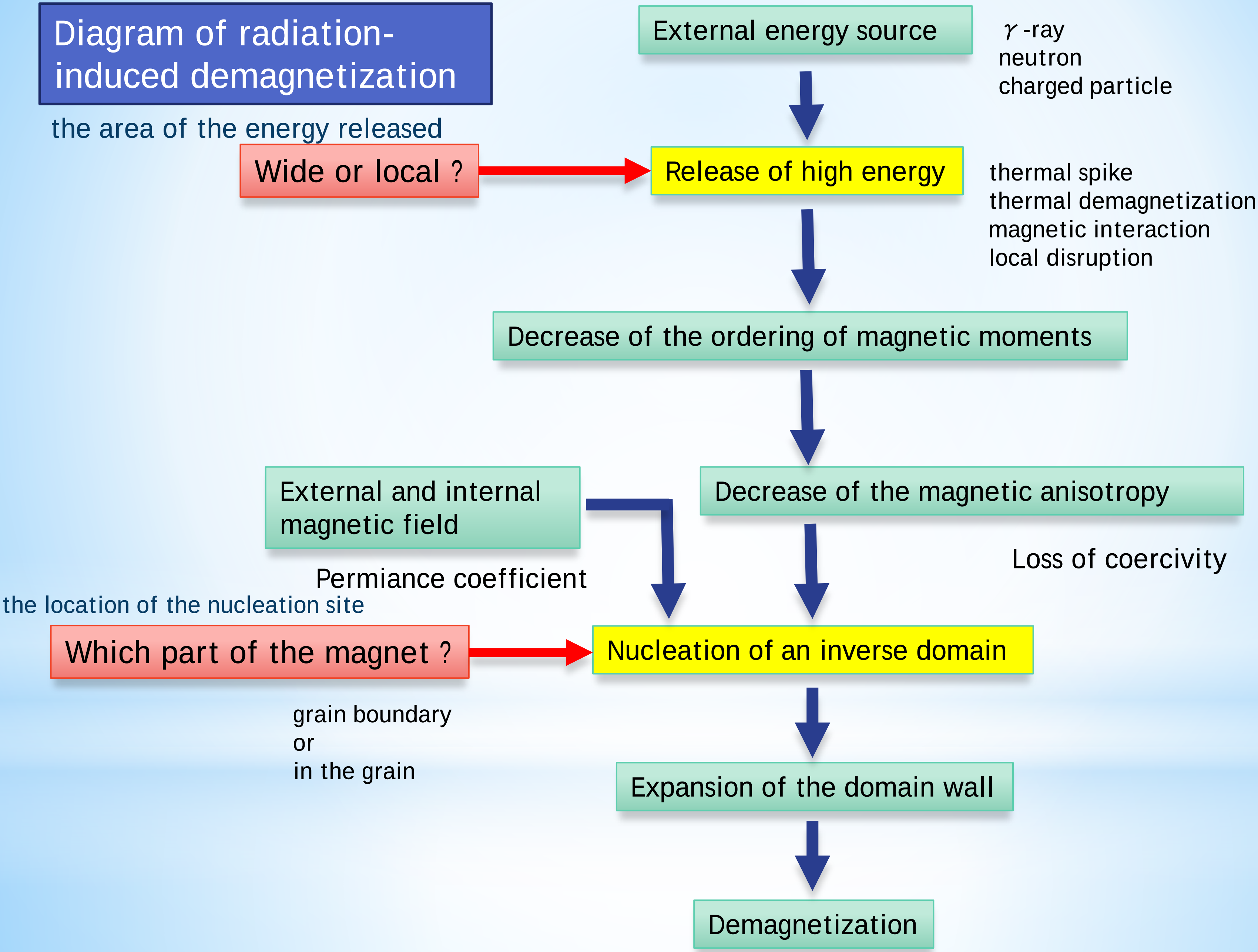


Diagram of radiation-induced demagnetization
the area of the energy released
Wide or local ?
External energy source
γ-ray
neutron
charged particle
Release of high energy
thermal spike
thermal demagnetization
magnetic interaction
local disruption
Decrease of the ordering of magnetic moments
External and internal magnetic field
Decrease of the magnetic anisotropy
Loss of coercivity
Permiance coefficient
the location of the nucleation site
Which part of the magnet ?
Nucleation of an inverse domain
grain boundary
or
in the grain
Expansion of the domain wall
Demagnetization

Two points of view to consider the mechanism

Wide effect and local effect

1. **Wide unstable region (magnetic moment instability)**
2. **Local hot spot (quasi-thermal spike)**

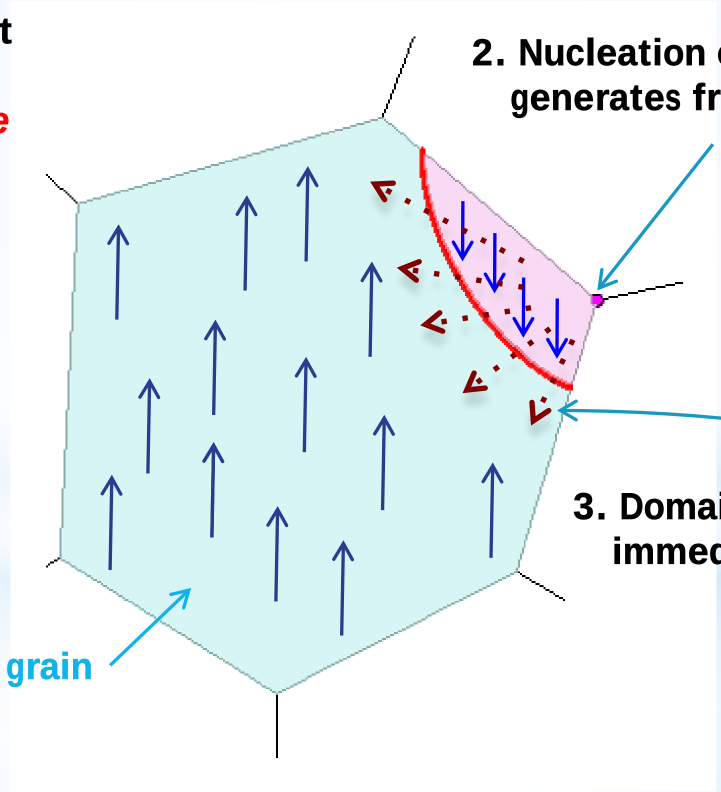
1. Wide unstable region (magnetic moment instability) model

Similar process of the magnetization reversal caused by heat and field would occur in the *low energy particle irradiation*.

1. **Fluctuation of magnetic moment caused by low energy particle decreases the coercivity in *wide region* during irradiation.**

As external energy sources

γ, e, n



2. Nucleation of an inverse domain generates from the *grain boundary.*

3. Domain wall expands immediately in the grain.

T. Bizen et. al. Particle Accelerator Society Meeting. (2009)

Similar process of the magnetization reversal caused by heat and field would occur in the *low energy particle irradiation*.

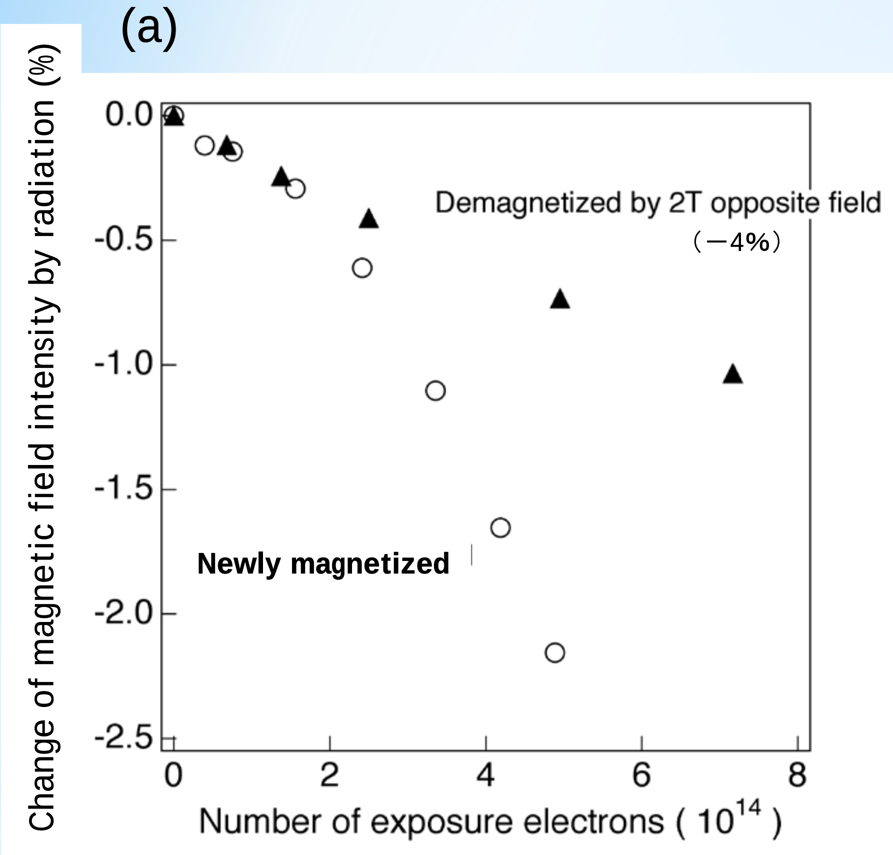
Similar stabilizing effect is observed in radiation-induced demagnetization.

Magnets using in high temperature can be *stabilized* against irreversible losses by *partial demagnetization* induced by *external magnetic fields* or by *heat*.

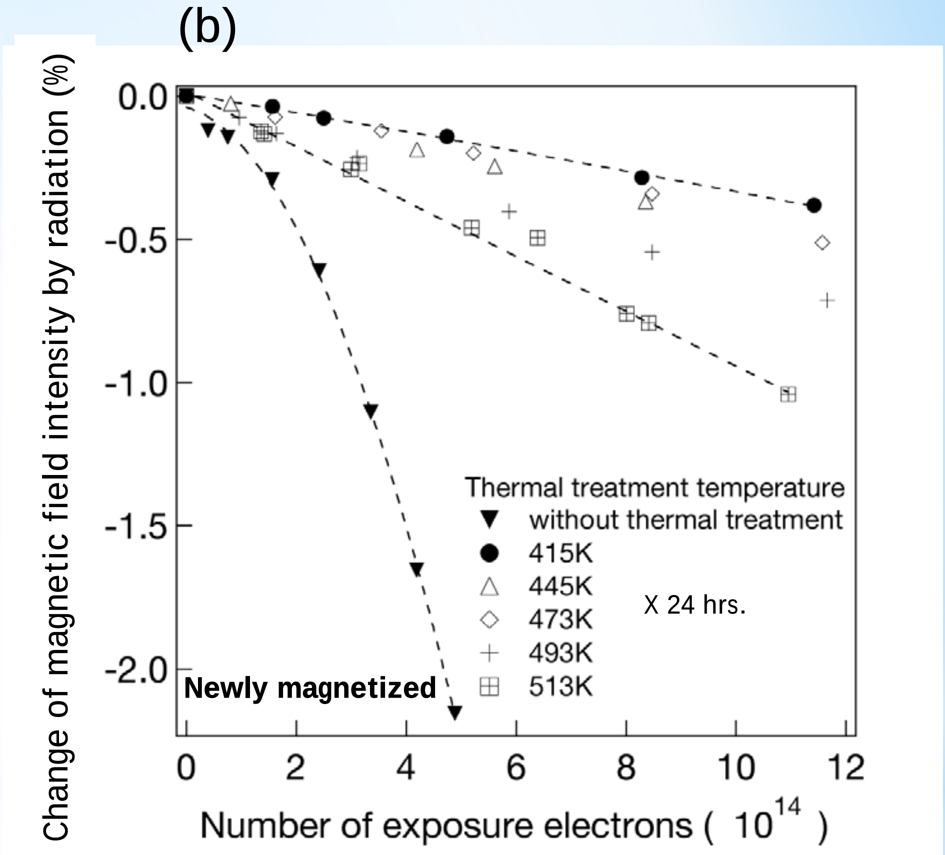
This technique is a stabilization against the after-effect that is associated with the fluctuations of magnetic moment in thermal or magnetic energy.

Effect of the partial demagnetization induced by external magnetic field

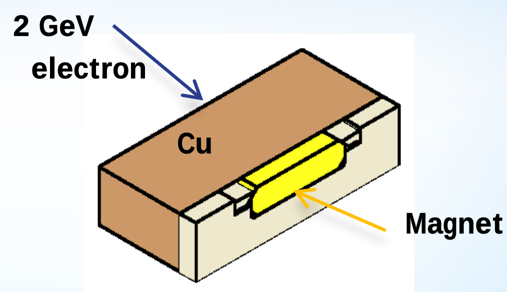
Effect of the partial demagnetization induced by heat



Bizen et. al. Radiat. Meas. (2007)



Bizen et. al. Radiat. Meas. (2007)



$Nd_2Fe_{14}B$: NEOMAX35EH

2. Local hot spot (quasi-thermal-spike) model

Local hot spot is generated by high energy photoneutron

Thermal spike generates very high temperature in very small area.

The energy of the knock-on atom transfers to the magnet atom by the process similar to the thermal spike (quasi-thermal-spike*).

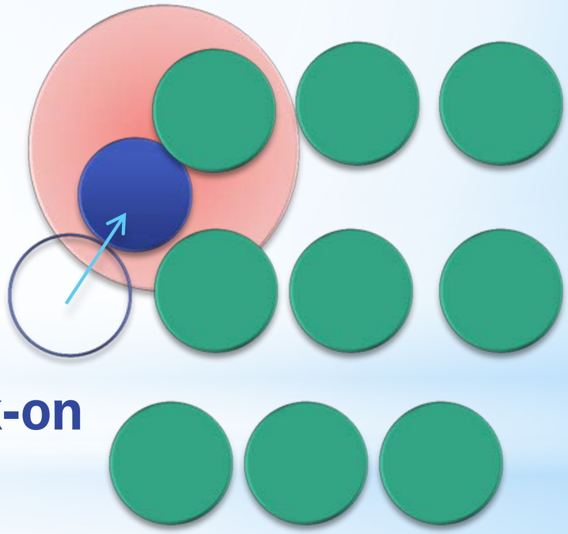
High energy photoneutron

n

Over tens of MeV

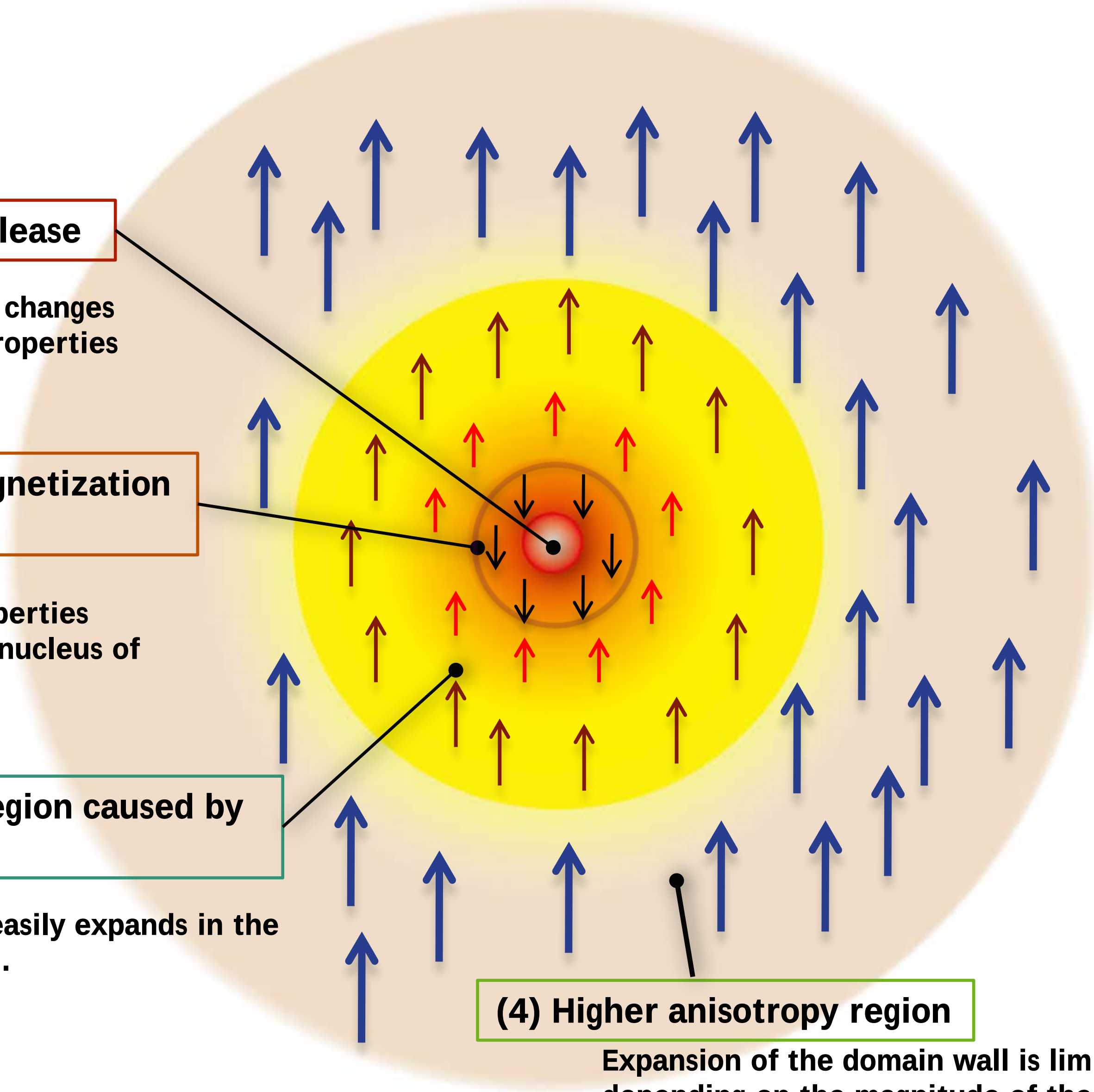
Atom of the magnet

Knock-on



** Temperature generated by the thermal spike is higher than the melting point, however, as Makita stated, demagnetization can occur below Curie temperature much lower than the thermal spike temperature.*

Inverse magnetic domain is formed in local hot spot



(1) Core of energy release

Melting and structural changes make the magnetic properties different.

(2) Nucleation of magnetization reversal

Heat and intense properties change generates the nucleus of inverse domain.

(3) Low anisotropy region caused by temperature rise

Inverse domain wall easily expands in the low anisotropy region.

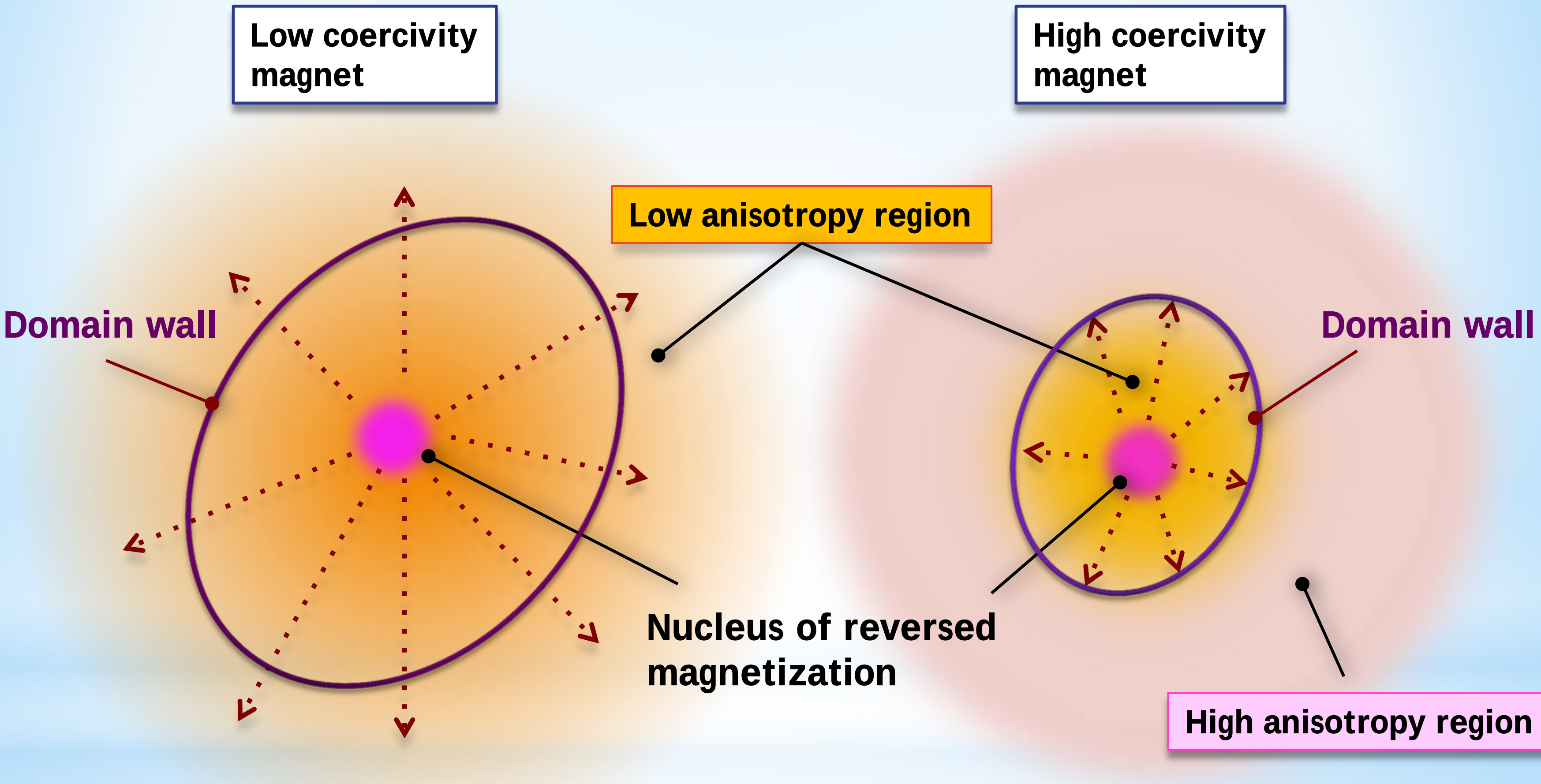
(4) Higher anisotropy region

Expansion of the domain wall is limited depending on the magnitude of the anisotropy.

T. Bizen et. al. Particle Accelerator Society Meeting. (2009)

Inverse domain expands against anisotropy field

This is the reason of coercivity dependence though the nucleation is inevitable.



Inverse domain wall easily expands in the low anisotropy region.

Expansion is regulated in the high anisotropy region.

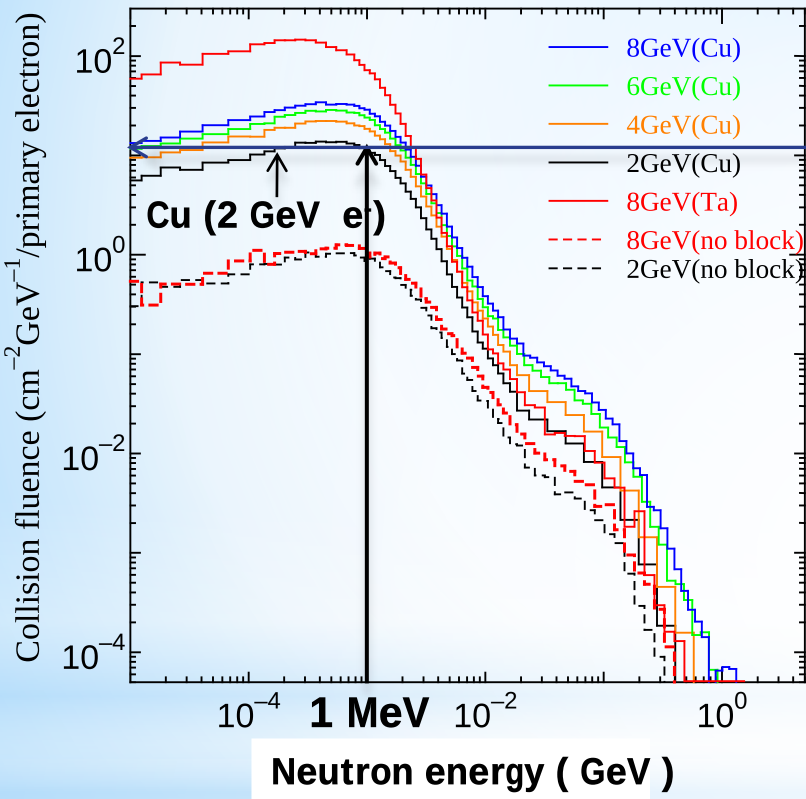
T. Bizen et. al. Particle Accelerator Society Meeting.(2009)

High-energy electron irradiation will cause the local hot spot.

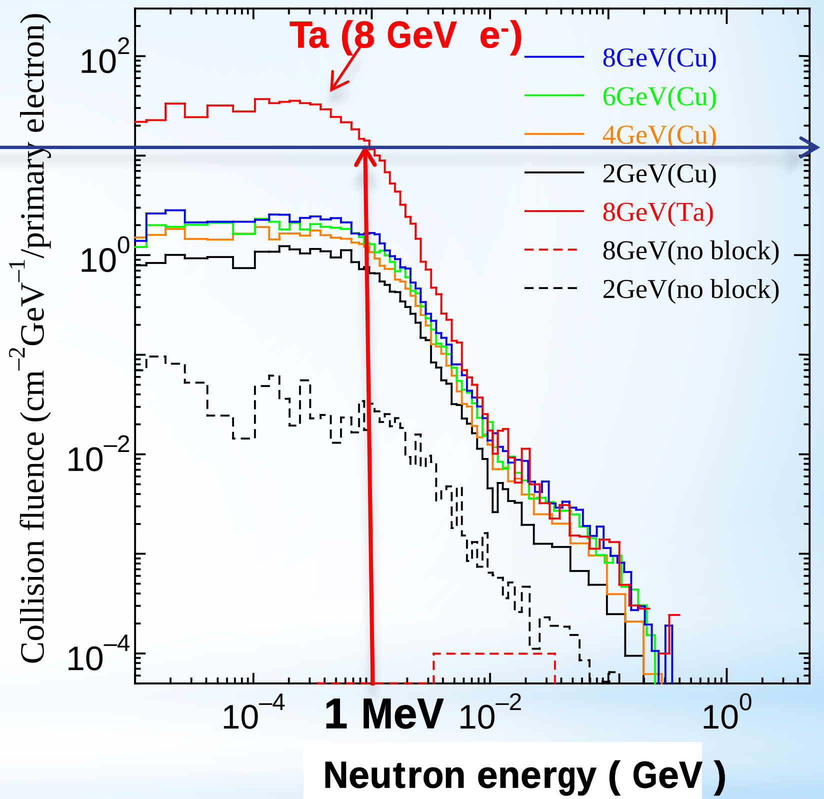
The experimental results of the demagnetization caused by the high-energy electron irradiation were compared to the computer simulations.

Neutron collision density distribution
[Energy and target dependence]

(a) Center of the magnet

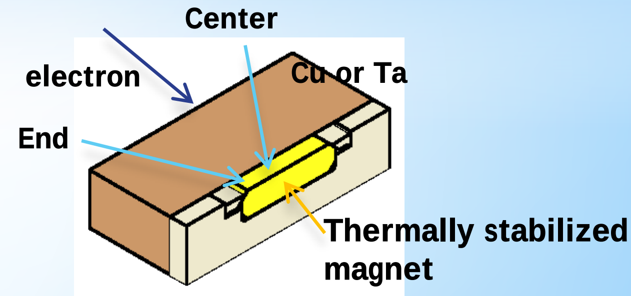


(b) End of the magnet



Collision density of the neutron energy below 1 MeV

Center of the magnet Cu (2 GeV e$^-$)	<	End of the magnet Ta (8 GeV e$^-$)

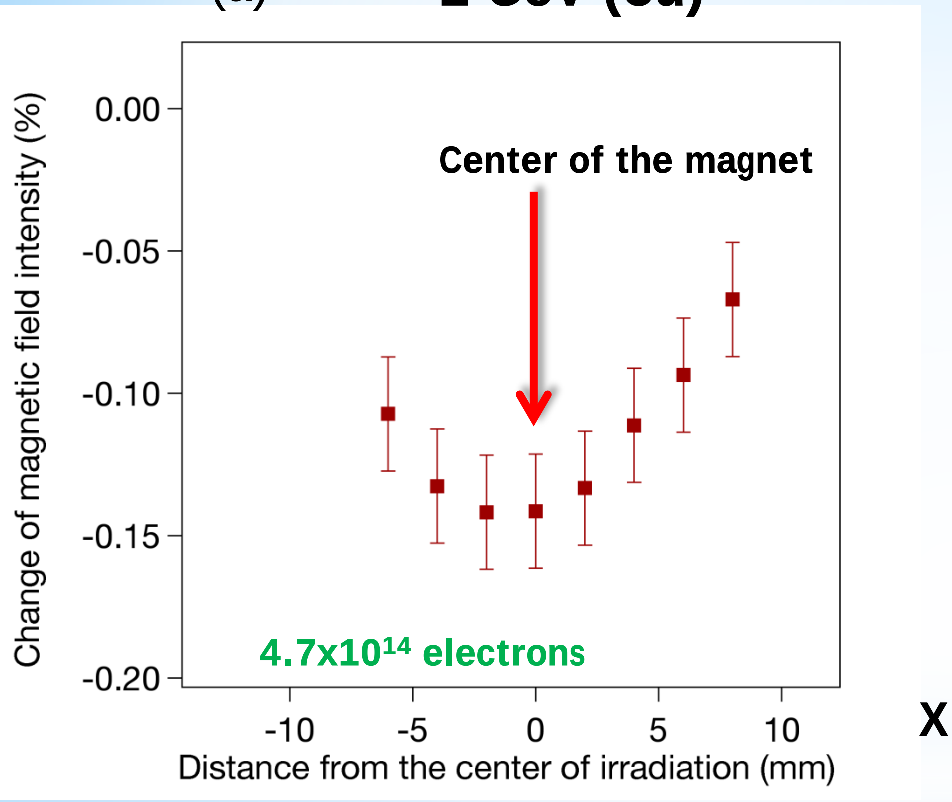


Calculated by FLUKA

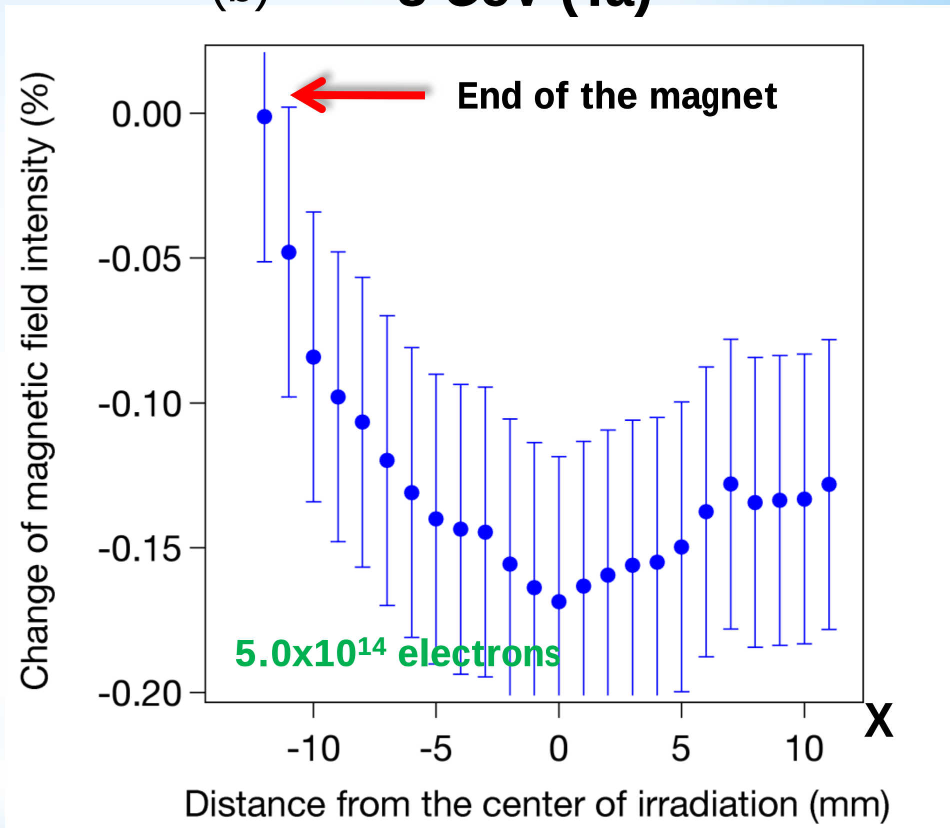
Y. Asano et. al. J. Synchrotron Rad. (2009)

Distribution of the magnetic field change
(Experimental result)

(a) **2 GeV (Cu)**

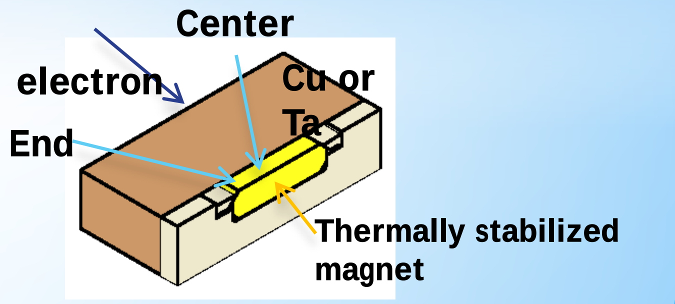


(b) **8 GeV (Ta)**



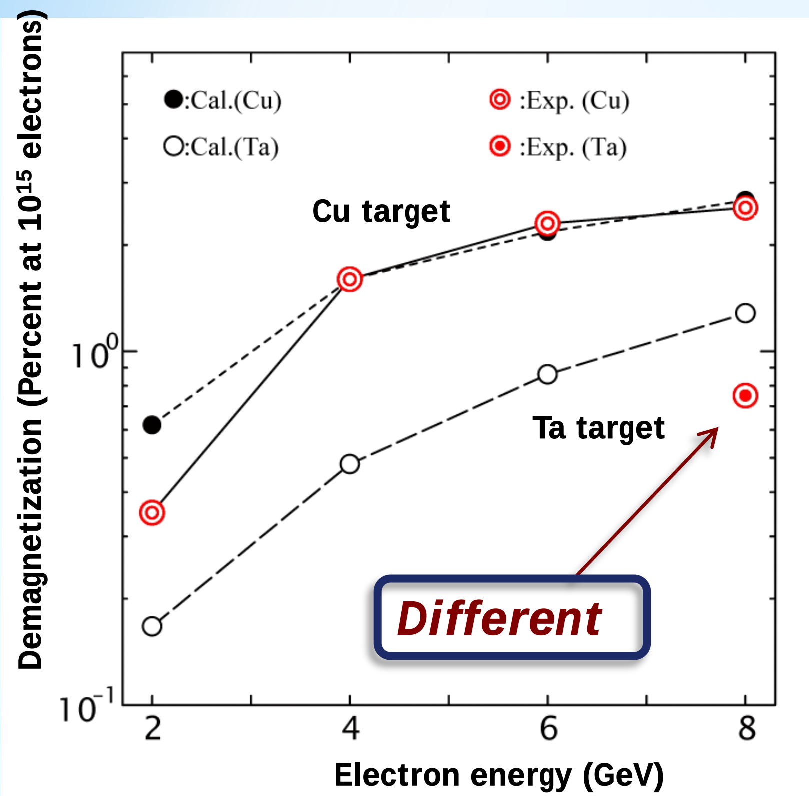
Experimental result is opposite!

Neutron in the low energy region is not effective to the demagnetization.

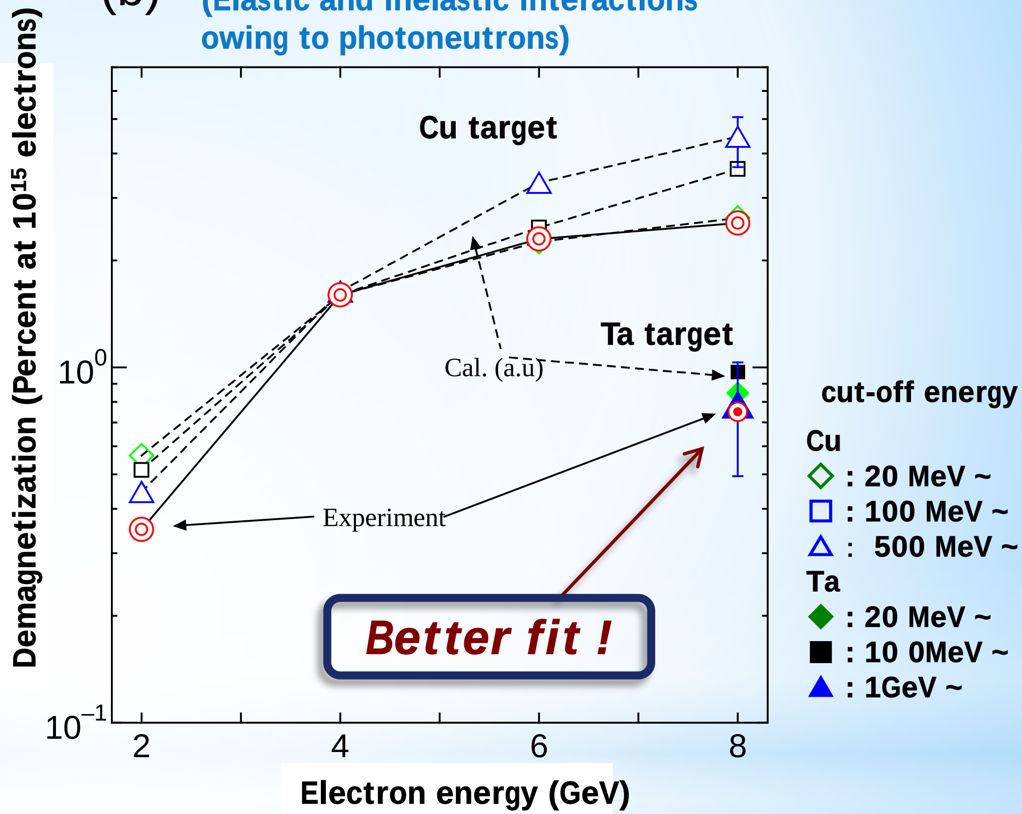


Energy and target dependence (Experiment and calculation)

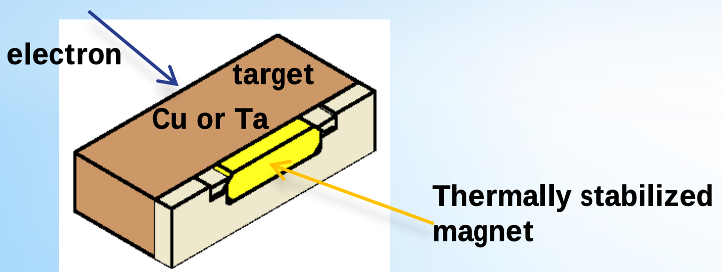
(a) **Absorbed dose**



(b) **Star densities**
(Elastic and inelastic interactions owing to photoneutrons)



The calculation results are normalized to the 4 GeV experimental results.

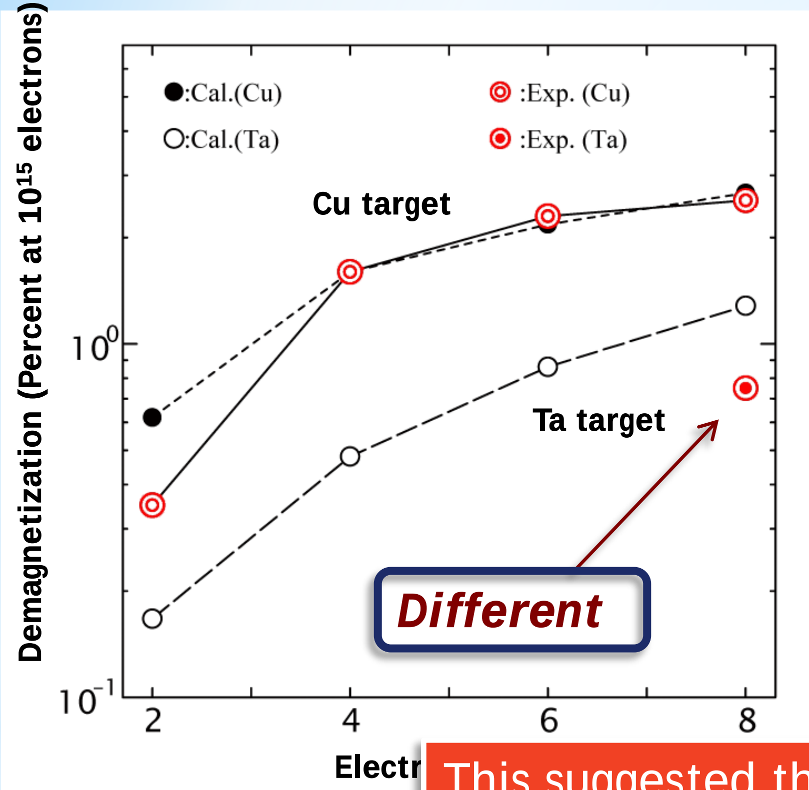


Calculated by FLUKA

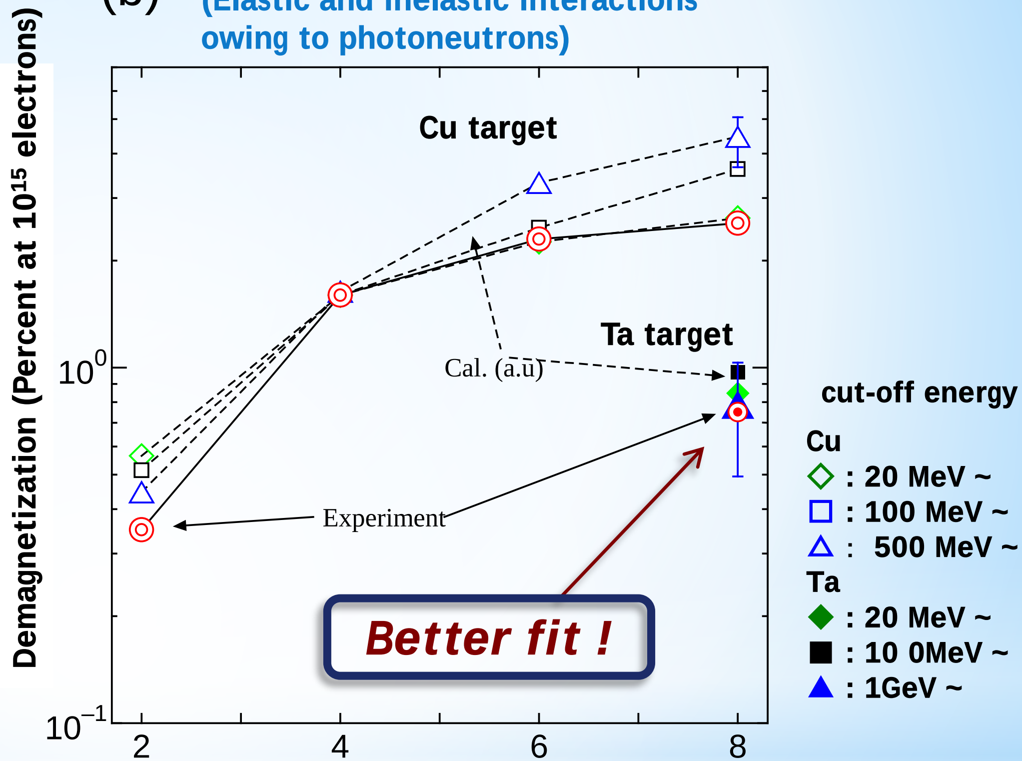
Y. Asano et. al. J. Synchrotron Rad. (2009)

Energy and target dependence (Experiment and calculation)

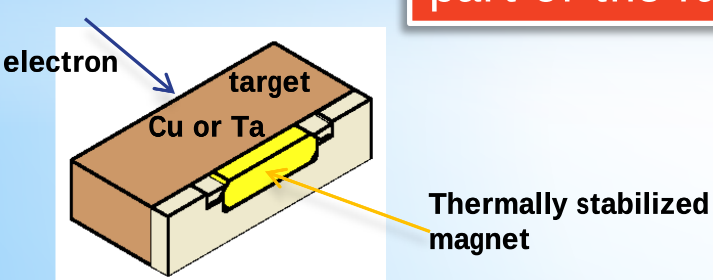
(a) **Absorbed dose**



(b) **Star densities**
(Elastic and inelastic interactions owing to photoneutrons)



This suggested that the absorbed dose can explain only the part of the radiation-induced demagnetization.



Calculated by FLUKA

Y. Asano et. al. J. Synchrotron Rad. (2009)

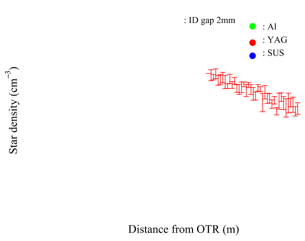
Application case

Fig.1 Geometry of simulations. (unit: mm)

Stainless steel, aluminium, and YAG ($Y_3Al_5O_{12}$: density 4.6 g·cm^{-3}) are usually use for the material of OTR. Figure 4 shows the results of the star density distributions for each OTR materials with 0.1 mm thick. The OTR made of aluminium produce the lowest star density in the same thickness of 0.1 mm. In the case of aluminium OTR with 1 mm thick, the peak position of the star density moves to almost 7.2 m distance from the OTR and the density increases from about 2.4 x 10^{-7} to about 7.8x10^{-7} star·cm^{-3}·electron^{-1} so that the thickness of the OTR is also important to reduce the star density.

Table 1 Comparison of maximum star density and peak position between the 2 mm and 4 mm ID gap width. (*Density unit: star·cm^{-3}·electron^{-1})

ID gap width



ESTIMATIONS FOR DEMAGNETIZATION OF ID PERMANENT MAGNETS DUE TO INSTALLATION OF OTR

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T. Bizen, JASRI/SPring-8, 1-1 Koto Sayo Hyogo, 679-5198, Japan

The estimation of the demagnetization has been performed quantitatively as functions of the electron energy, the gap width of the ID, and the dependence on material of the OTR.

Y. Asano, Proceedings of 2nd International Particle Accelerator Conference 2011, San Sebastian, Spain, THPC165, (2011).

Effective protection

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

1. Designing the magnetic circuit of higher permeance coefficient

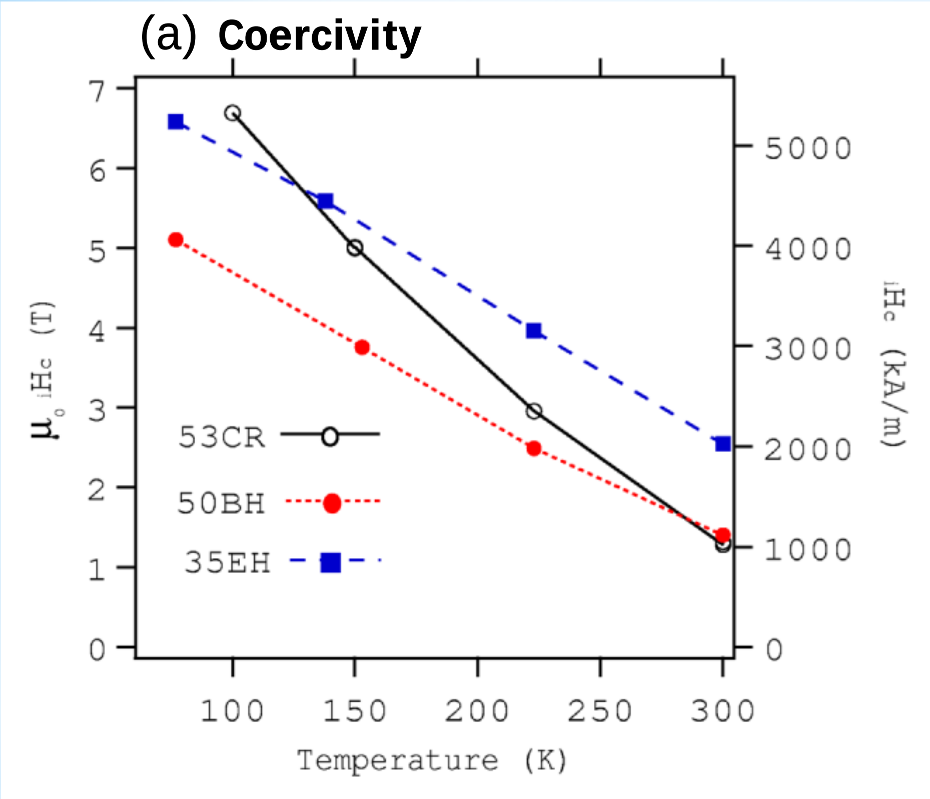
2. Selecting the magnets with high coercivity

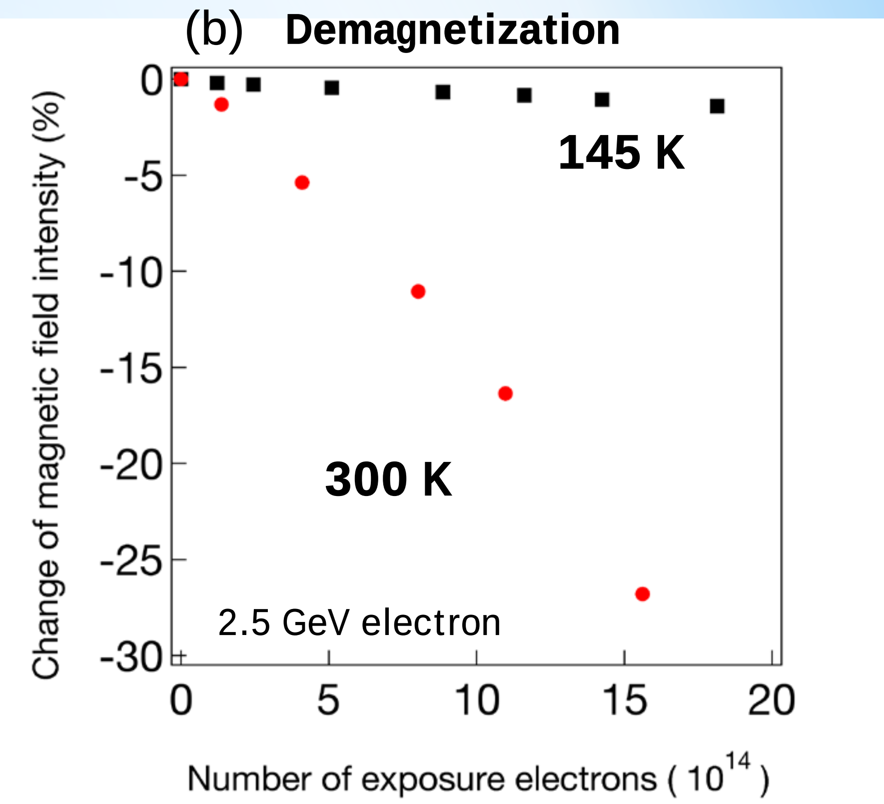
3. Selecting the magnets with high temperature-stability

4. Applying the stabilization technique to the magnets

5. Using the magnets at very low temperature

Using the magnets at very low temperature





To increase the coercivity in the grain, the best way is to decrease the magnet temperature.

Resistance against the radiation increases at low temperature.

T. Hara et. al. Phys. Rev. ST Accel. Beams. (2004)

T. Bizen et. al. Radiat. Meas. (2007)

Summary

Typical past experiments and models of radiation-induced demagnetization are reviewed and summarized.

If the nucleation is the origin of the radiation-induced demagnetization, two types of demagnetization should be considered.

The demagnetization cannot be estimated sufficiently by a simulation of the dose alone, because the mechanism of the demagnetization depends on the particle energy.

The simulation of the star density was in good agreement with the demagnetization. The star density can be used for estimation of the radiation-induced demagnetization.

Thank you for your attention.