2024/10/11 14:00-17:00
日本ボンド磁性材料協会(JABM)の寺子屋BM塾

軟磁性材料の基礎について

–パワエレ応用–

岡本 聡

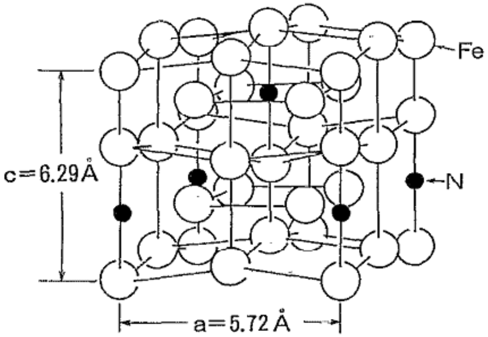
東北大学 多元物質科学研究所

自己紹介 : 岡本 聡 (おかもと さとし)

出身 滋賀県大津市

1997 Ph. D from Tohoku U

Fabrication of α''-$Fe_{16}N_2$ phase and its magnetic properties



2000
2005
2010
2015
2020

Data storage

L1_0-FePt

Graded media

MAMR

JST project

Permanent magnet

Thermally activated reversal process

FORC x μ-XMCD

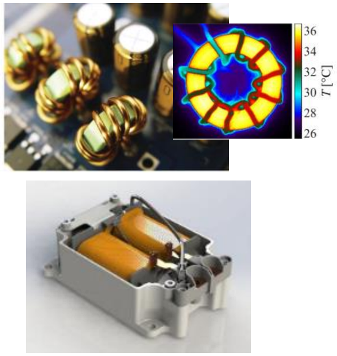
Magnetic tomography

Data science approach

ESICMM

DXMag

Soft magnetic materials



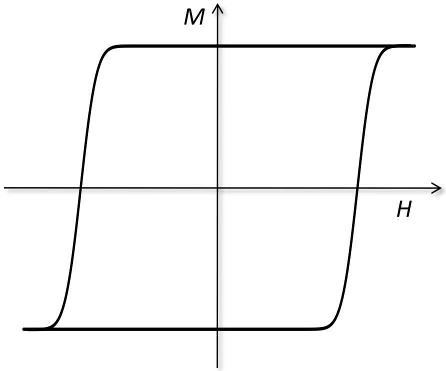
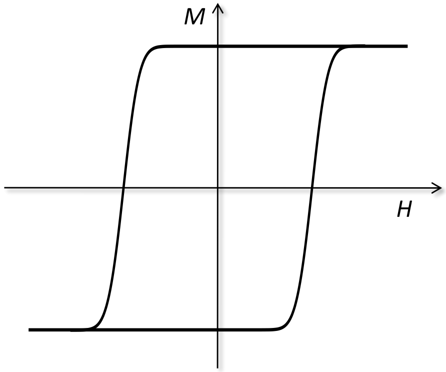
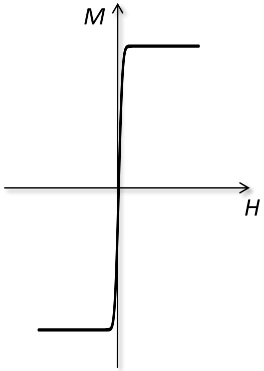
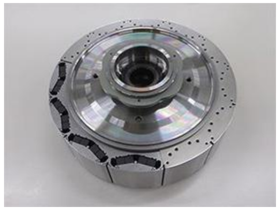
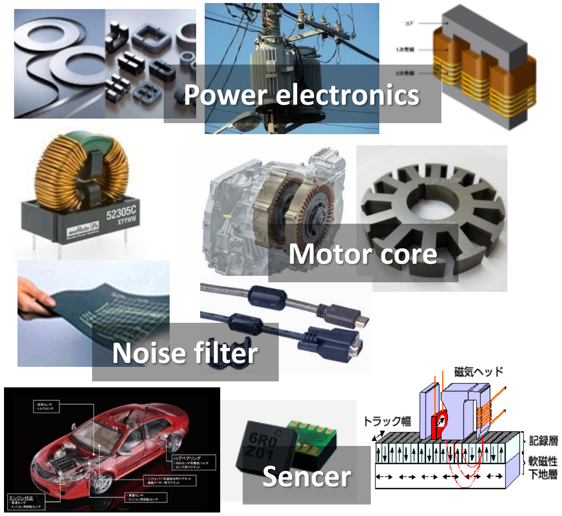
Passive device and materials for power electronics

INNOPEL

NEDO

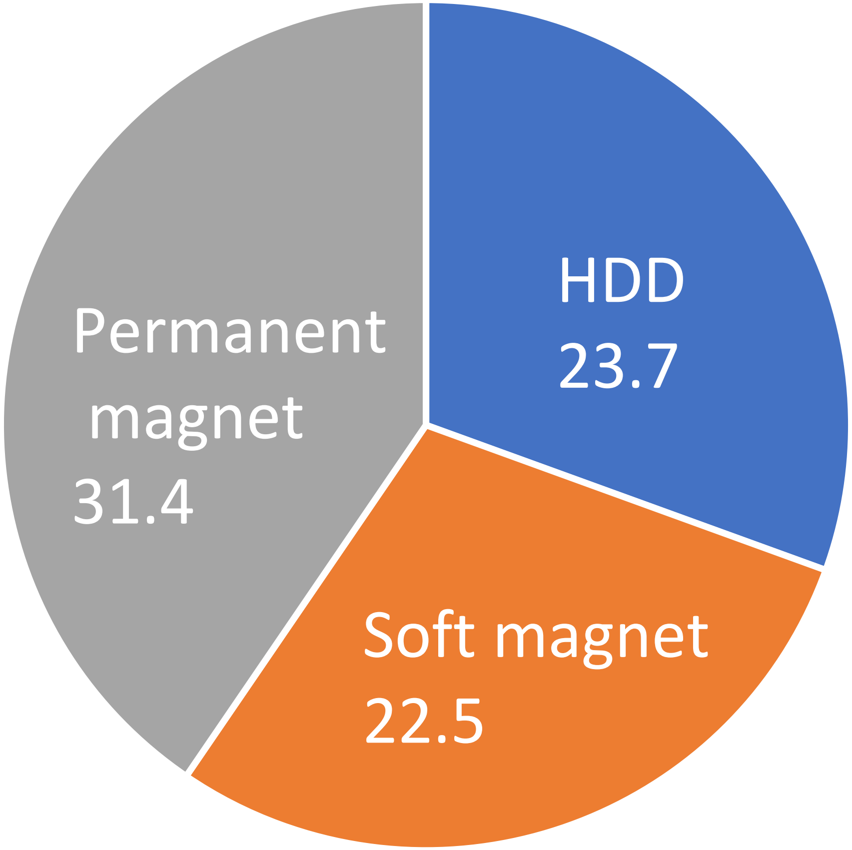
Contents

Categorization of Magnetic Materials and Their Applications

Category	Hard magnet	Semi-hard magnet	Soft magnet
Hysteresis			
Coercivity H_c	Large	Middle	Small
Applications	Permanent magnet (Motor)	Data Storage (HDD)	Too Many
	 	 	

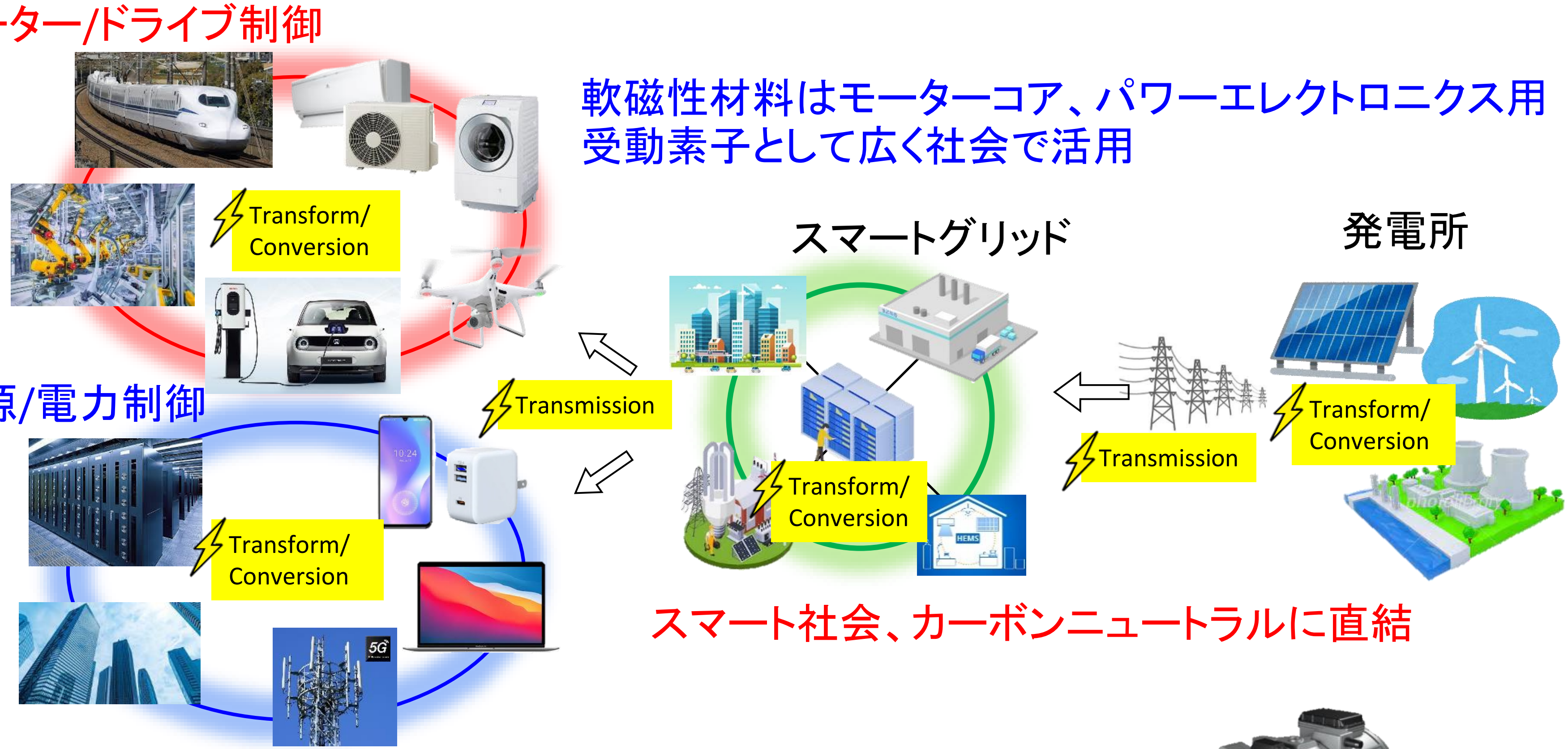
Market Size of Magnetic Materials and Devices

Total 77.6 Billion USD



Bilion USD
(2021)

低損失軟磁性材料



モーター/ドライブ制御

軟磁性材料はモーターコア、パワーエレクトロニクス用受動素子として広く社会で活用

Transform/
Conversion

電源/電力制御

Transform/
Conversion

Transmission

スマートグリッド

Transform/
Conversion

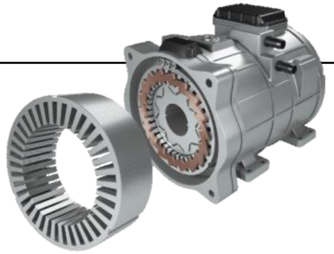
発電所

Transmission

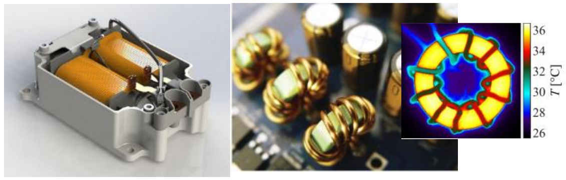
Transform/
Conversion

スマート社会、カーボンニュートラルに直結

- 高効率モーター　高性能永久磁石 ＋ インバータ駆動 ＋ 低損失軟磁性材料

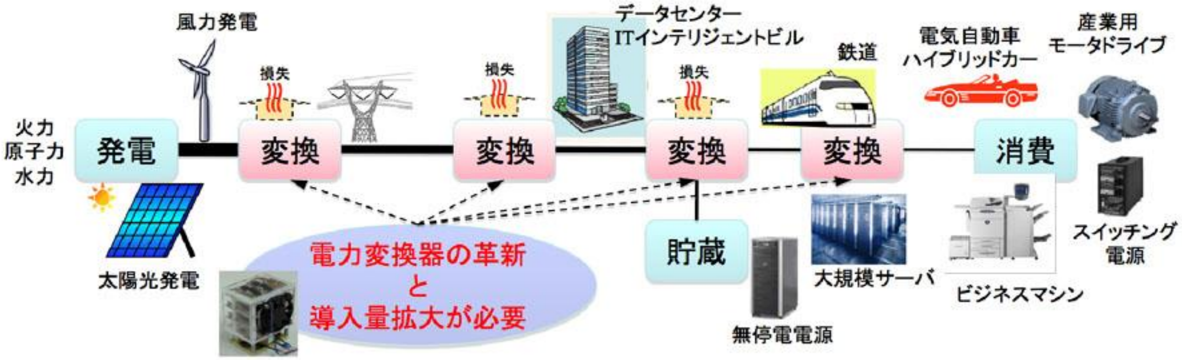


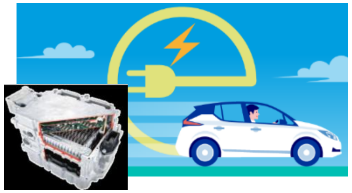
- パワーエレクトロニクス　高性能パワー半導体 ＋ 低損失軟磁性材料



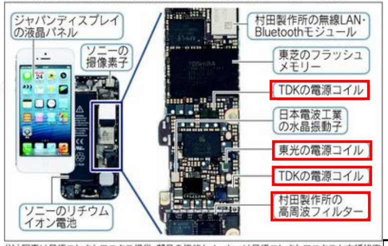
Various Applications of Soft Magnetic Materials

Passive devices of power electronics



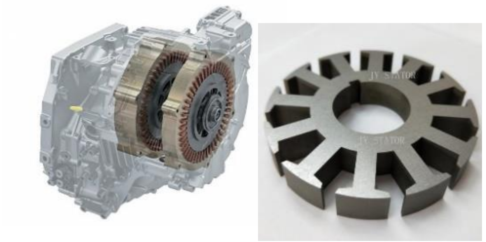


iPhone5の分解調査で確認できた主な日本メーカー部品

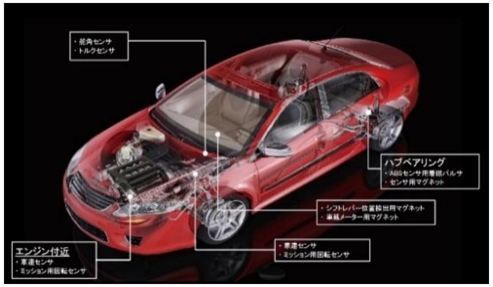


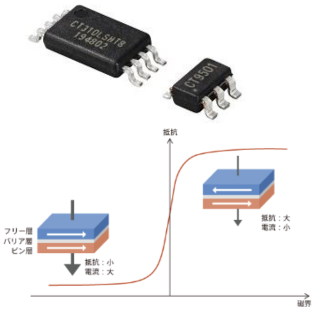
(注)写真は日経エレクトロニクス提供。部品の機能とメーカーは日経エレクトロニクスと本紙推定

Motor core



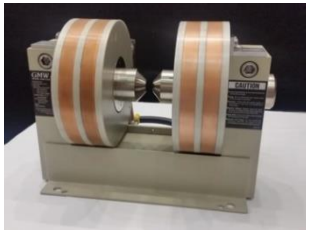
Sensor



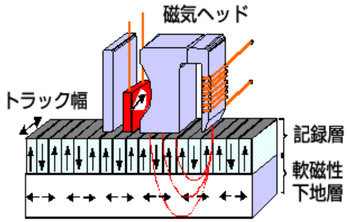


RFID

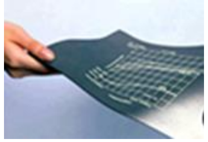
Electromagnet

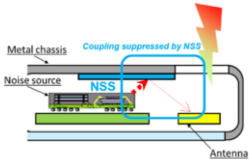


Recording head

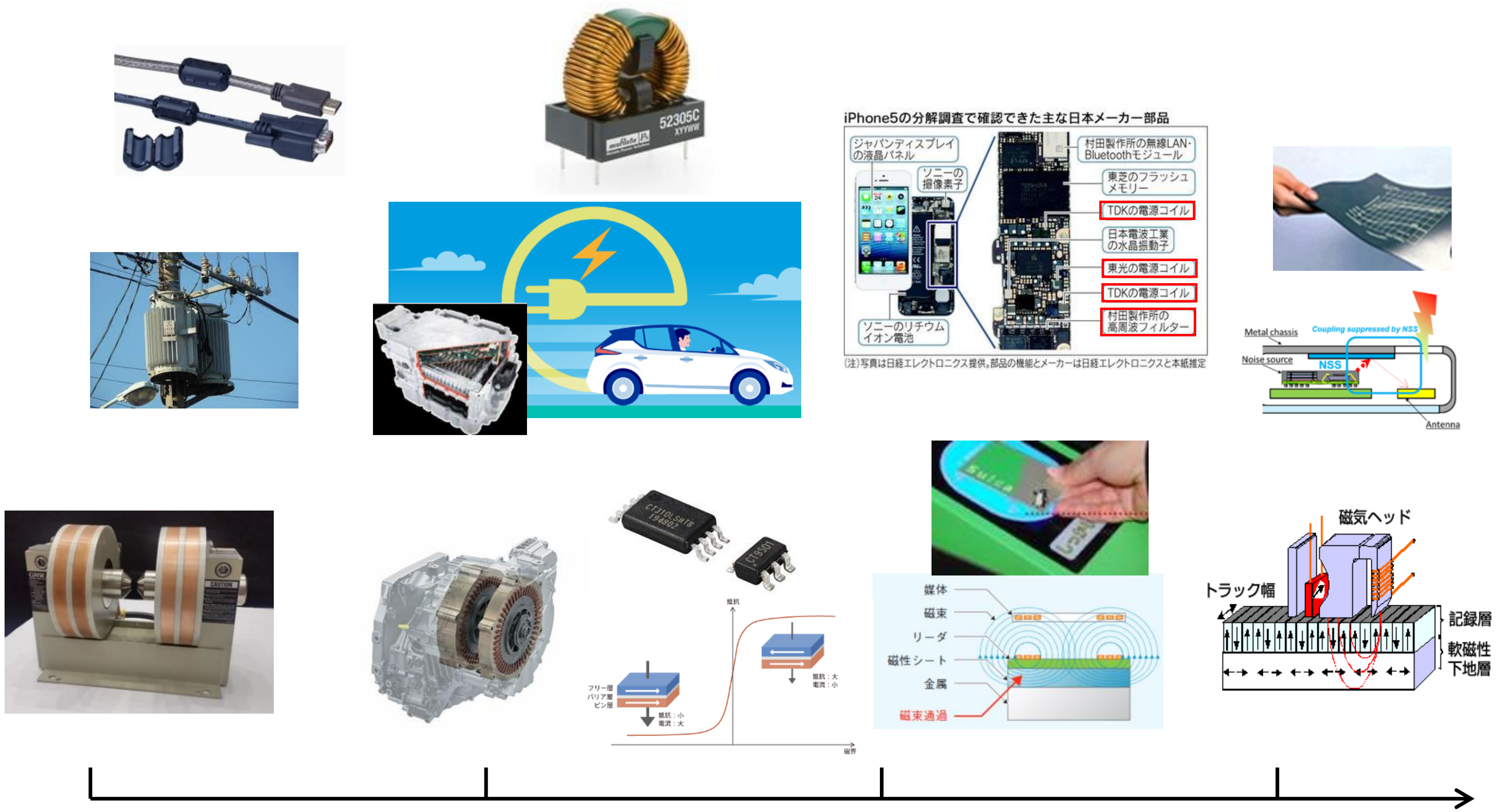


Noise filter





Operation Frequency of Soft Magnetic Materials



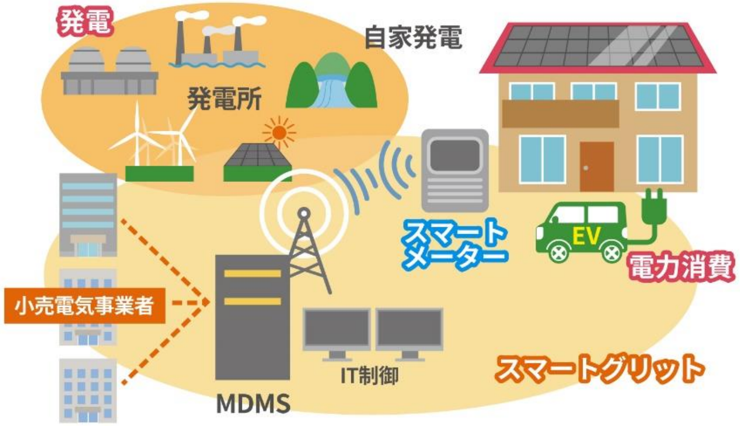
1 1K 1M 1G

Frequency (Hz)

Power Electronics

Energy management

Stabilization, optimization, energy saving of power transmission & power distribution systems

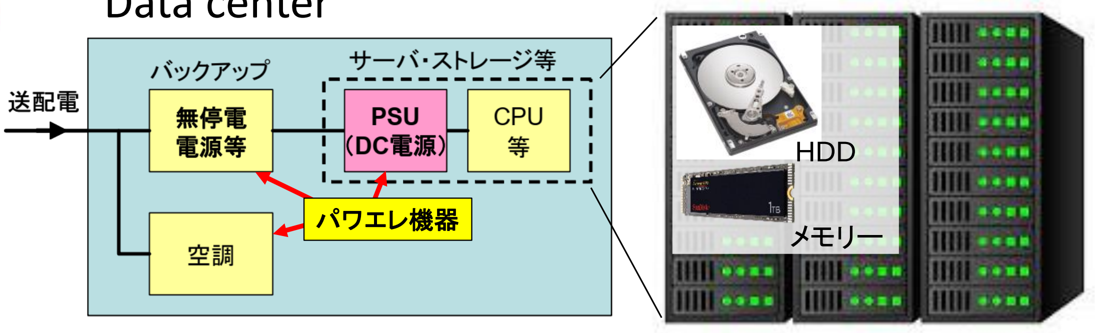


[https://www.upr-net.co.jp/info/iot/smart-grid.html]

Electric mobility

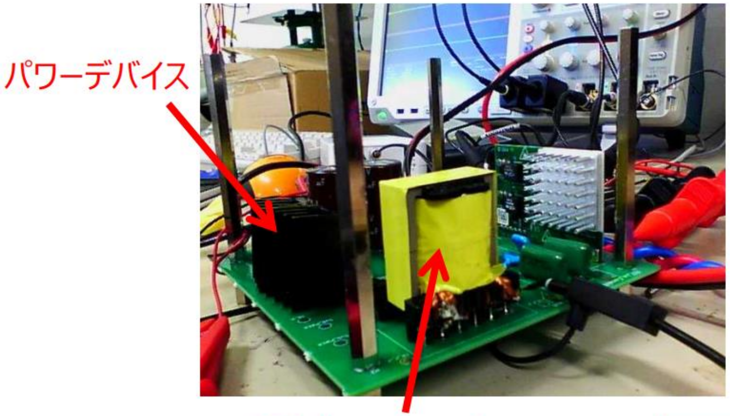
ICT

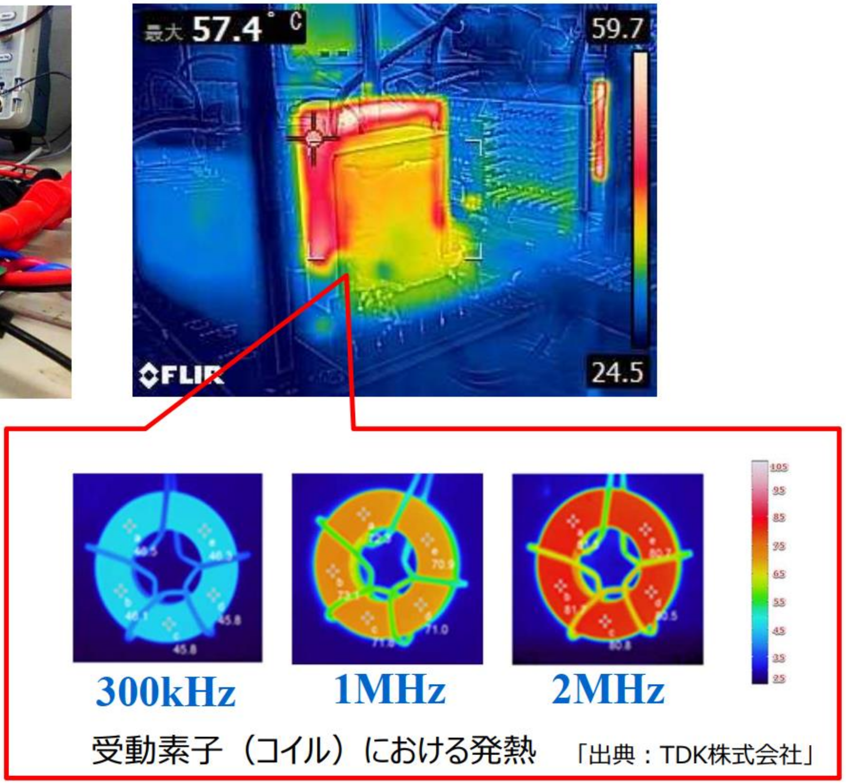
Data center



[NEDO 2021]

Loss in Magnetic Devices of Power Electronics



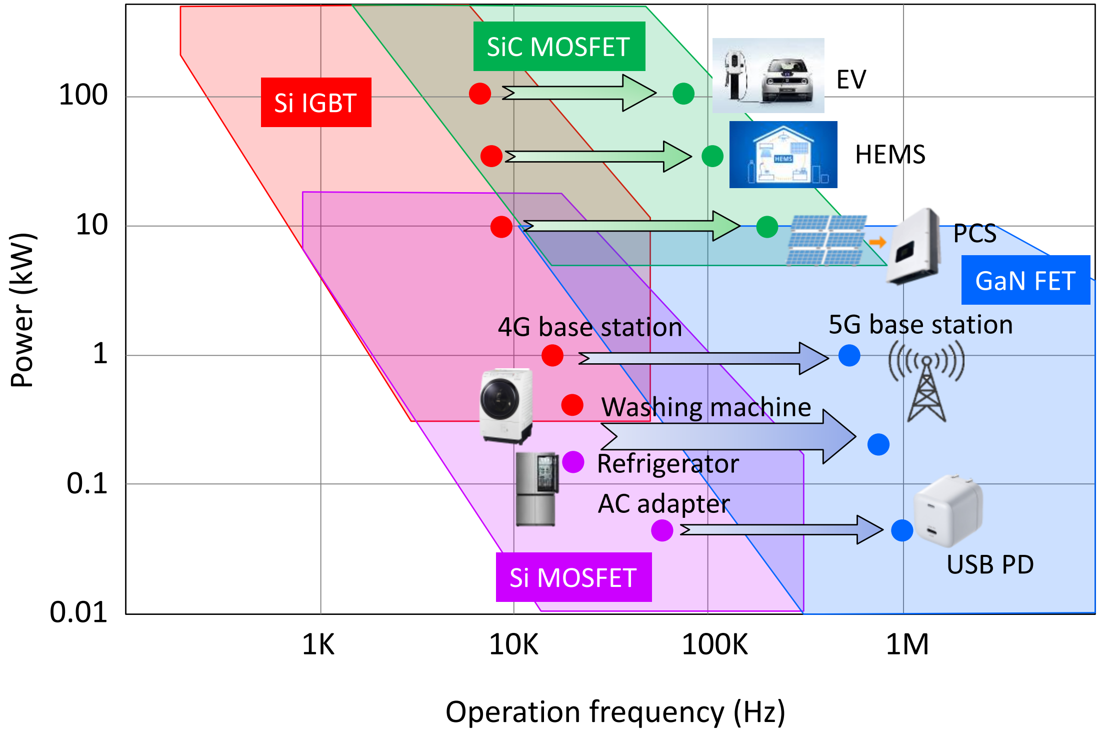


受動素子（コイル）における発熱 「出典：TDK株式会社」

https://product.tdk.com/info/ja/products/ferrite/ferrite/ferrite-core/technote/pov_pc200.html

- Loss in magnetic material Iron loss
- Loss in Cu winding Cu loss

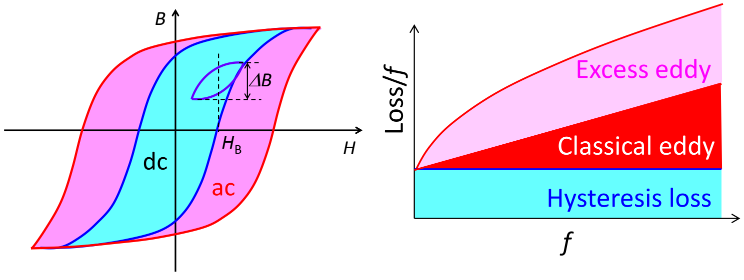
Soft Magnetic Materials in Advanced Power Electronics



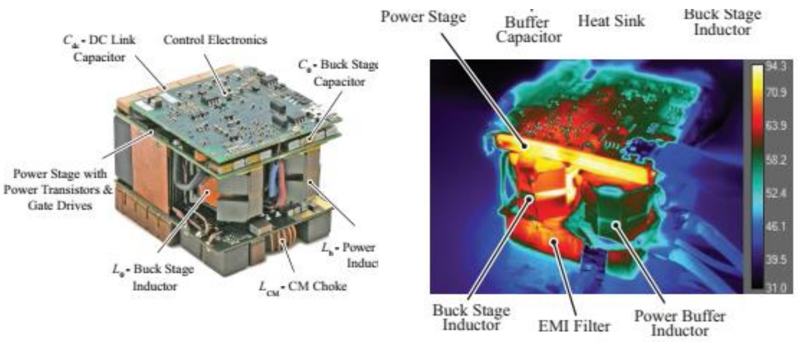
Next generation power semiconductors SiC, GaN

Toward high frequency switching

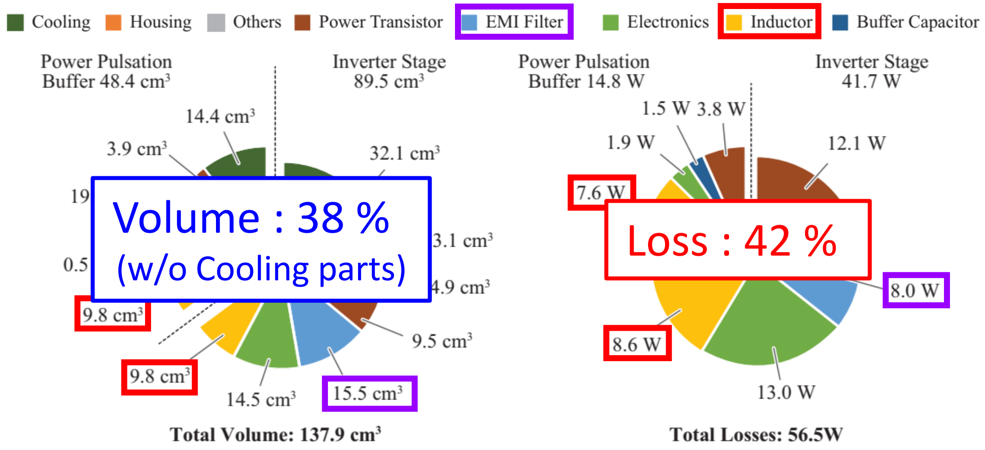
⇨ Significant iron loss in magnetic passive devices



■ Google Little Box Challenge (GLBC)



[Neumayr, CPSS Trans. Power Electro. Appl. 5, 251 (2020)]



Volume : 38 %
(w/o Cooling parts)

Loss : 42 %

Magnetic passive devices

TOHOKU UNIVERSITY

History of Soft Magnetic Studies

Materials

1889 Fe-Ni, Hopkinson

1900

1900 Fe-Si, Hadfield

1916 Permalloy, Elmen

1920

1932 Sendust ($Fe_{85}Al_5Si_{10}$), Masumoto
1934 Cold-rolled electrical steel, Goss

1940

1947 Supermalloy, Boothby and Bozorth
1950 MnZn Ferrite, Guillaud and Barbezat
1957 NiZn Ferrite, Kornetzki

1960

1967 Ferromagnetic amorphous, Duwez
1973 Metglas, AlliedSignal

1980

1988 FINEMET(nc-Fe-Nb-Si-Cu-B), Yoshizawa
1990 nc-Fe-Zr-Cu-B, Suzuki

2000

2007 nc-Fe-Si-B-Cu (1.84 T), Ohta
2011 nc-Fe-Si-B-P-Cu (1.80 T), Urata
2017 nc-Fe-B (1.9 T), Suzuki

2020

Present

Strong demand for high-M_s and low loss materials

⟺ Large gap

Theories on Soft Magnetics & Iron Loss

1892 Empirical loss model, Steinmetz
Steinmetz eq. $W = kf^{\alpha}B_m^{\beta}$

1935 Domain theory, Landau and Lifshitz

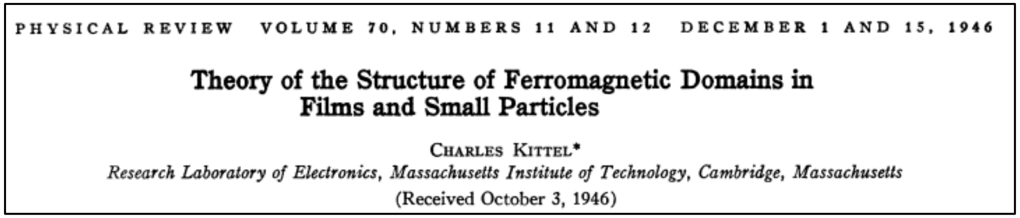
1946 Domain theory for film and particle, Kittel
1950 Anomalous eddy for single wall, Williams
1958 Anomalous eddy for periodic wall, Pry and Bean

1980 Effective domain wall model, Sakaki
1985 Statistic model for iron loss, Bertotti
1990 Random anisotropy model, Herzer

2006 Loss model on reversal process, Fiorillo

Theories and basic understandings are less updated during a couple of decades!

Researchers of Soft Magnet in 1940s-50s

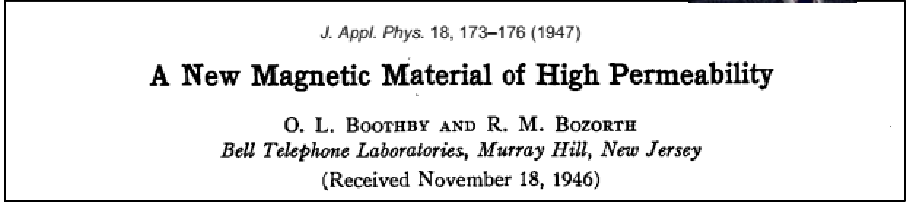


PHYSICAL REVIEW VOLUME 70, NUMBERS 11 AND 12 DECEMBER 1 AND 15, 1946

Theory of the Structure of Ferromagnetic Domains in Films and Small Particles

CHARLES KITTEL*
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 3, 1946)

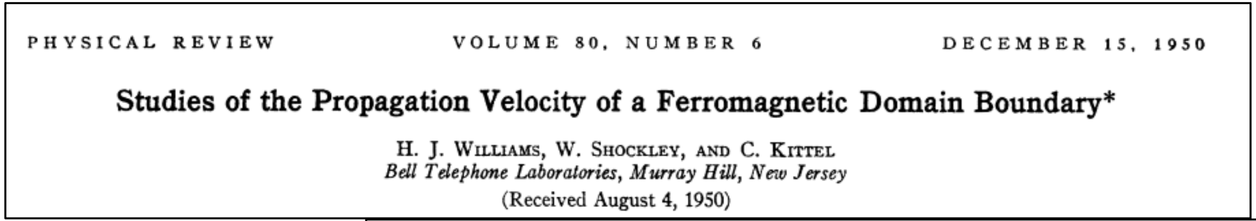
C. Kittel
[Wikipedia]



J. Appl. Phys. 18, 173–176 (1947)

A New Magnetic Material of High Permeability

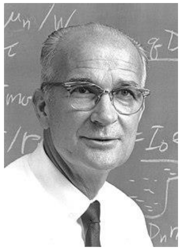
O. L. BOOTHBY AND R. M. BOZORTH
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received November 18, 1946)



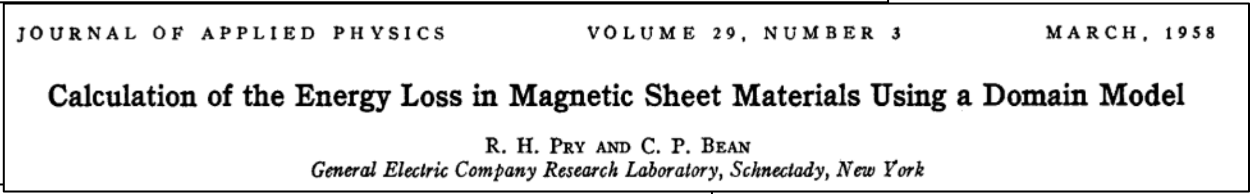
PHYSICAL REVIEW VOLUME 80, NUMBER 6 DECEMBER 15, 1950

Studies of the Propagation Velocity of a Ferromagnetic Domain Boundary*

H. J. WILLIAMS, W. SHOCKLEY, AND C. KITTEL
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received August 4, 1950)



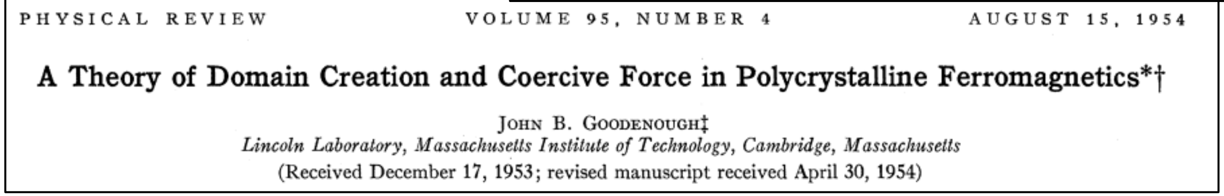
W. Shockley
[Wikipedia]



JOURNAL OF APPLIED PHYSICS VOLUME 29, NUMBER 3 MARCH, 1958

Calculation of the Energy Loss in Magnetic Sheet Materials Using a Domain Model

R. H. PRY AND C. P. BEAN
General Electric Company Research Laboratory, Schnectady, New York

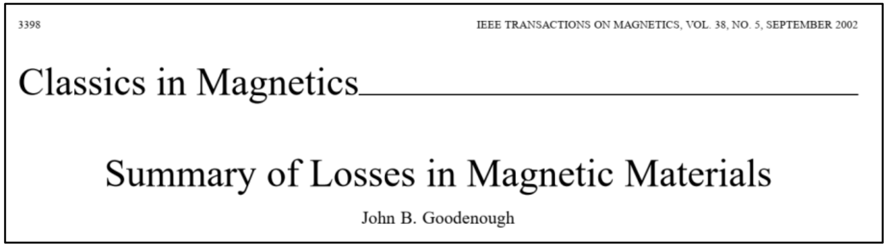


PHYSICAL REVIEW VOLUME 95, NUMBER 4 AUGUST 15, 1954

A Theory of Domain Creation and Coercive Force in Polycrystalline Ferromagnetics*†

JOHN B. GOODENOUGH‡
Lincoln Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received December 17, 1953; revised manuscript received April 30, 1954)

J. B. Goodenough
[Wikipedia]



3398 IEEE TRANSACTIONS ON MAGNETICS, VOL. 38, NO. 5, SEPTEMBER 2002

Classics in Magnetics

Summary of Losses in Magnetic Materials

John B. Goodenough

日本の磁性研究における基礎と応用の密接性

「産業は学問の道場なり」

本多光太郎
[Wikipedia]

物理学選書 4

強磁性体の物理(上)
—物質の磁性—
近角聰信著

裳華房

「強磁性体の物理」

著 近角聰信
[IEEE Trans. Magn. 53, 0500103 (2017)]

磁気工学の基礎 I
—磁気の物理—
太田恵造
著

ΣTAMΠ

共立全書
200

「磁気工学の基礎」

著 太田恵造

金森順次郎
[https://www.osaka-u.ac.jp/en/news/topics/2012/11/20121113_01]

佐川博士のNd-Fe-B磁石開発のすぐ後、Bが強磁性増強(FeのCo化)に寄与していることを指摘し、その後のSm-Fe-Nなどにつながる

Contents

Questions on Soft Magnetic Materials for Power Electronics

For power electronics applications, requirements for soft magnetic materials and devices strongly depend on the circuit type and power range.

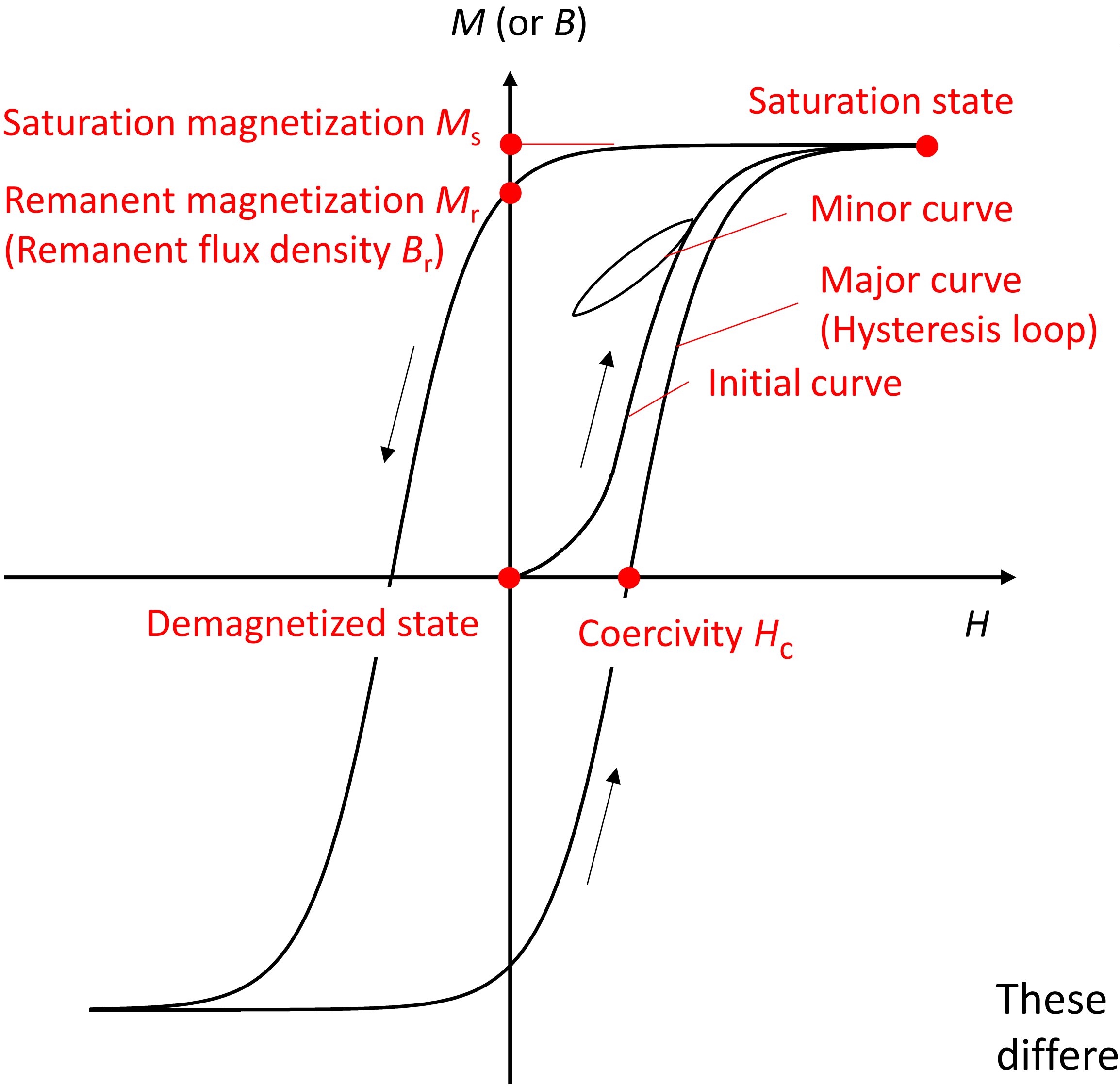
General requirements,

1. High saturation magnetization $\mu_0 M_s$
2. High permeability μ up to high frequency
3. Low ion loss P up to high frequency

Q1 Soft magnetic properties in textbooks are static properties. What is different for the modern high frequency applications?

Q2 Can be above 1 ~ 3 requirements satisfied concurrently?

How to See Hysteresis Loop



In SI unit,

$\boxed{B = \mu_0 H + \mu_0 M}$ B [T], H, M [A/m]

Unit conversion

1 kA/m : 1.254 mT

▽

Saturation flux density B_s is widely used. But this is not physically correct.

$\boxed{M = \chi H}$ χ [no unit]

$\boxed{B = \mu H}$ μ [H/m]

$\boxed{\mu/\mu_0 \ (= \mu_r) = \chi + 1}$

These relations become different in different unit systems, such as MKAS and CGS-Gauss Units.

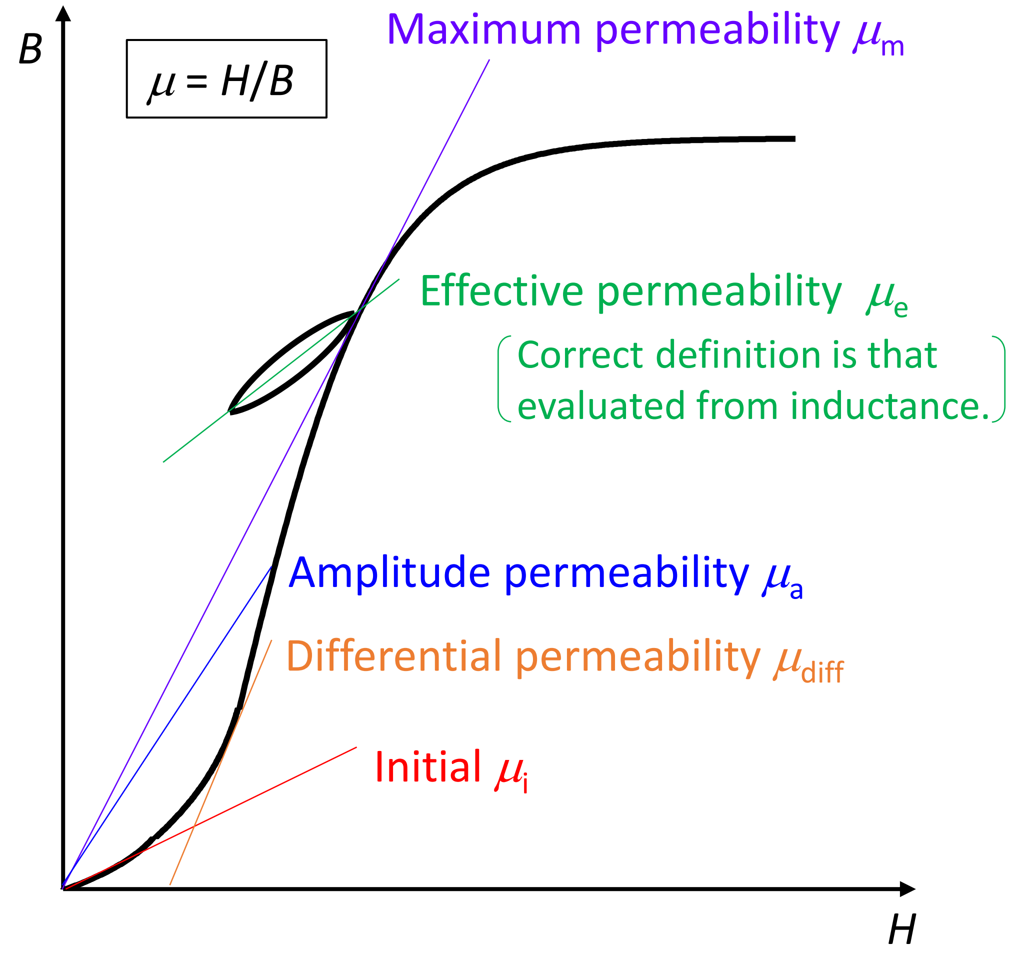
Definitions of Permeability

電気専門用語集（WEB版）

[https://jec-iee.org/jec_ev/index_00.php]

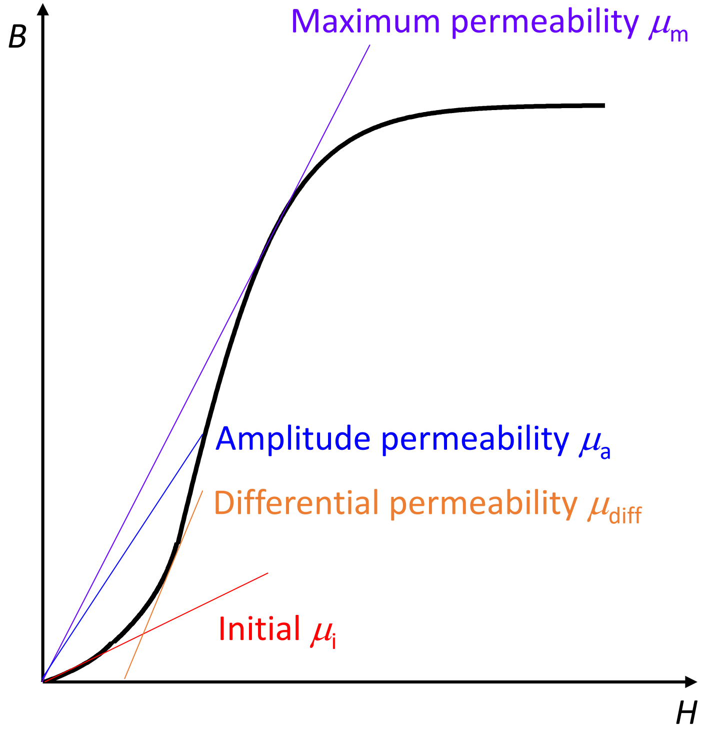
「透磁率」で検索すると…

用語番号	用語	用語集No.
4.08	可逆透磁率	24
4.20	最大透磁率	24
4.27	初透磁率	24
4.28	振幅透磁率	24
4.45	実効透磁率	24
4.56	絶対透磁率	24
4.67	透磁率	24
4.76	比透磁率	24
4.79	微分透磁率	24
4.83	複素透磁率	24



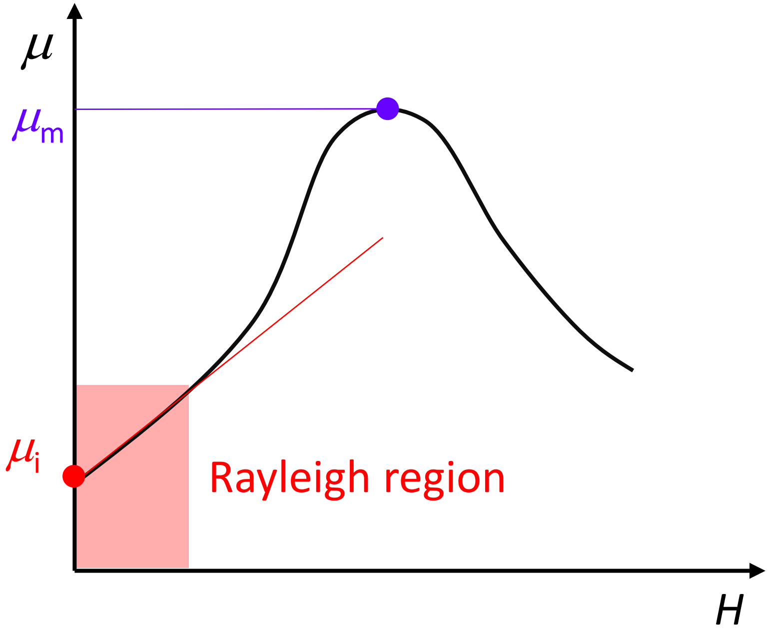
(Correct definition is that evaluated from inductance.)

Rayleigh Region



▷

$\mu = H/B$



When H is small, B follows as $B = \mu_i H + \nu H^2$

⇨ $\mu = \underbrace{\mu_i}_{\text{Reversible component (Magnetization rotation)}} + \underbrace{\nu H}_{\text{Irreversible component (Domain displacement)}}$

▷

Loop area (Hysteresis loss)

$W_{hys} \approx \nu H^3$

Coercivity (Coercive Force)

Why H_c is called as coercive force?

When 180° domain wall is assumed,

$$H_c = \underline{(de_w/dx)_{max}} /(2M_s)$$

Non-uniformity increases H_c.

If spatial fluctuation of e_w is given by nonuniform stress σ,

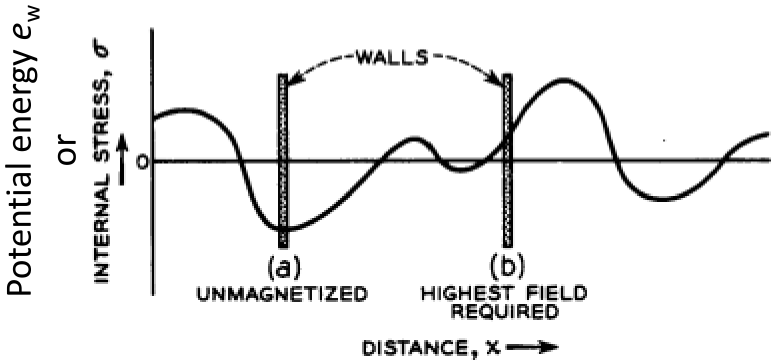
$$H_c \approx (\lambda_s\delta/2M_s)(de_w/dx)_{max}$$

λ_s : Saturation magnetostriction

δ : Wall thickness

λ_s affects H_c through non-uniform strain.

Spatial fluctuation of potential energy e_w



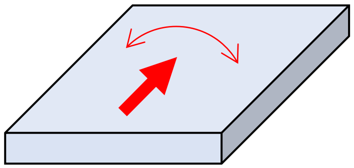
[Bozorth, Ferromagnetism (1951)]

In other words, H_c can decreases when uniformity improves.

Permeability

Magnetization rotation

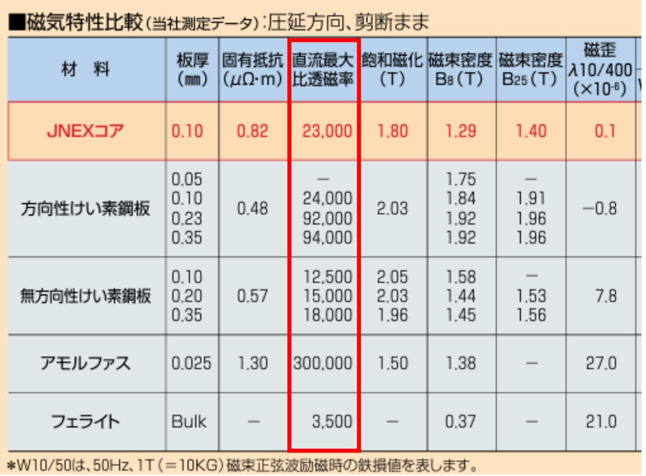
For randomly oriented crystal, $\mu_{\mathrm{ri}} \approx \dfrac{\mu_0 M_s^{\,2}}{3K}$



ex) Fe ($\mu_0 M_s$ = 2.15 T, K = 42 KJ/m³) $\mu_{\mathrm{ri}} \approx 30$

Fe 6.5wt.Si ($\mu_0 M_s$ = 1.8 T, $K \approx$ 20 kJ/m³) 40

For μ_{ri} > 10,000, K < 10 J/m³ is required.



■磁気特性比較（当社測定データ）：圧延方向、剪断まま

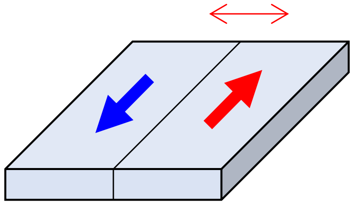
材　料	板厚（㎜）	固有抵抗（μΩ·m）	直流最大比透磁率	飽和磁化（T）	磁束密度 B8（T）	磁束密度 B25（T）	磁歪 λ10/400（×10⁻⁶）
JNEXコア	0.10	0.82	23,000	1.80	1.29	1.40	0.1
方向性けい素鋼板	0.05 0.10 0.23 0.35	0.48	– 24,000 92,000 94,000	2.03	1.75 1.84 1.92 1.92	– 1.91 1.96 1.96	–0.8
無方向性けい素鋼板	0.10 0.20 0.35	0.57	12,500 15,000 18,000	2.05 2.03 1.96	1.58 1.44 1.45	– 1.53 1.56	7.8
アモルファス	0.025	1.30	300,000	1.50	1.38	–	27.0
フェライト	Bulk	–	3,500	–	0.37	–	21.0

＊W10/50は、50Hz、1T（＝10KG）磁束正弦波励磁時の鉄損値を表します。

[JFE catalog]

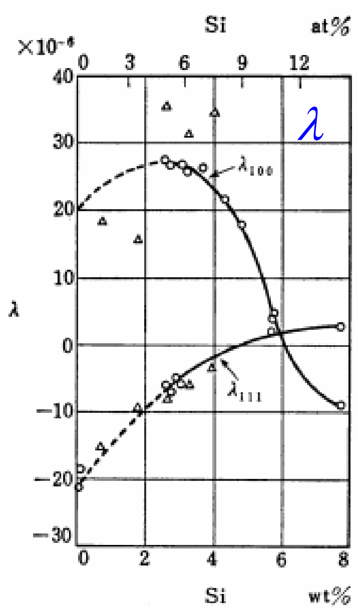
Domain wall motion

For 180° rigid wall, $\mu_{\mathrm{ri}} \approx \dfrac{2\mu_0 M_s^{\,2}}{\pi^2 3\lambda\sigma_0}\,\dfrac{\ell}{\delta}$



σ_0 : internal stress amplitude,

ℓ : stress wavelength, δ : domain wall thickness



ex) Fe ($\lambda \approx$ 20 ppm) $\mu_{\mathrm{ri}} \approx 10{,}000$

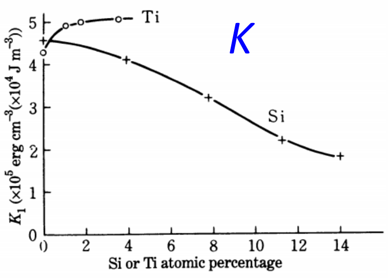
Fe 6.5wt.Si ($\lambda \approx$ 1 ppm) 170,000

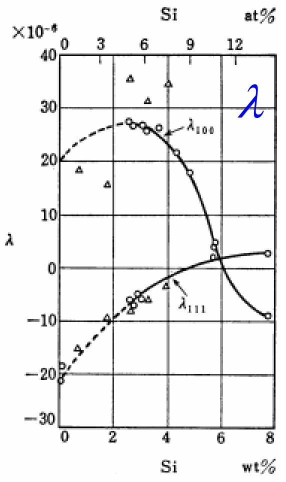
(for σ_0 = 100 MPa, ℓ/δ = 100)

[Chikazumi, Physics of Ferromagnetism]

Various Soft Magnetic Materials

Electrical steel (Fe-Si)





Permalloy ($Ni_{80}Fe_{20}$)

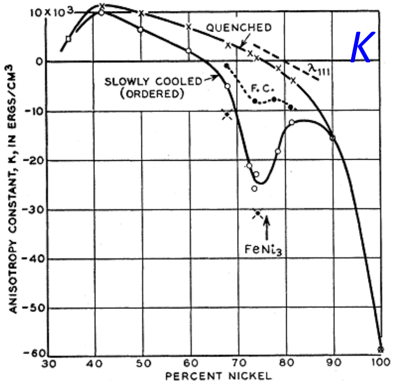


FIG. 1. Magnetic anisotropy constants of quenched and of slowly cooled alloys. Approximate rates of cooling, 10^5 and 2.5°C/hr, respectively, from 600 to 300°C. Broken line F.C. shows values for 55°C/hr. Line λ_{111} shows composition at which magnetostriction in [111] direction goes through zero. Single low points at 68 and 74 percent nickel are for cooling rate of about 1.5°C/hr.

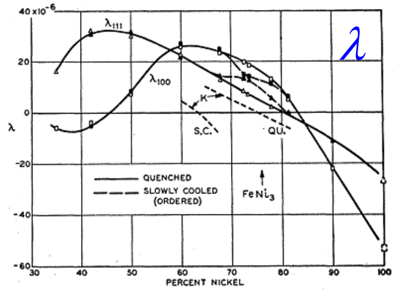
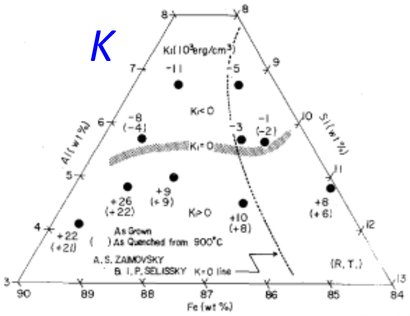
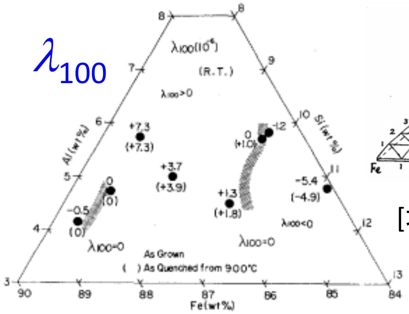


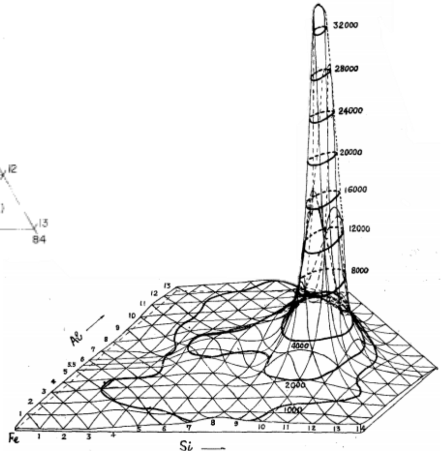
FIG. 5. Magnetostriction of quenched and of slowly cooled alloys. Broken lines show compositions at which anisotropy of quenched (QU.) and slowly cooled alloys (S.C.) goes through zero.

[Phys. Rev. 89, 624 (1953)]

Sendust ($Fe_{85}Al_5Si_{10}$)







[増本, 日本金属学会誌(1937)]

Amorphous

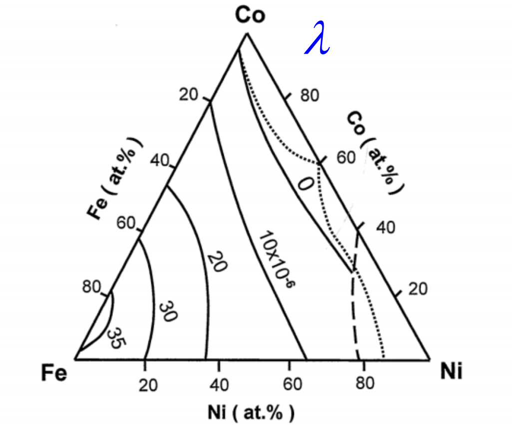


Fig. 6 Saturation magnetostriction of amorphous ribbons with composition $(Fe\text{–}Co\text{–}Ni)_{78}Si_8B_{14}$.

Fe based amorphous has $\lambda \sim 30$ ppm.

FINEMET

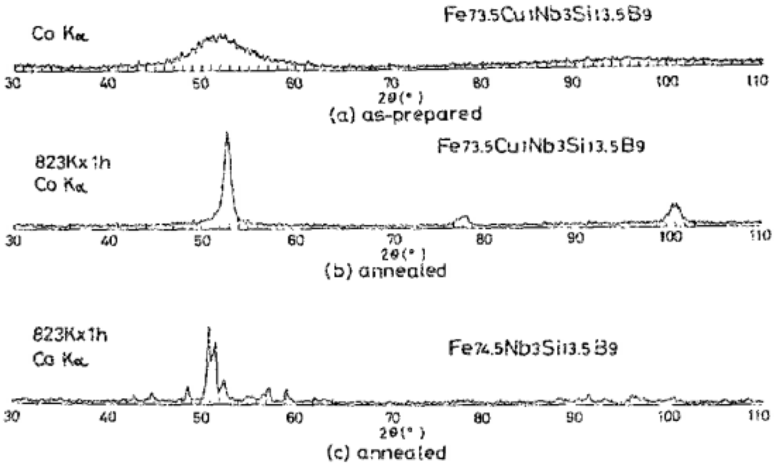
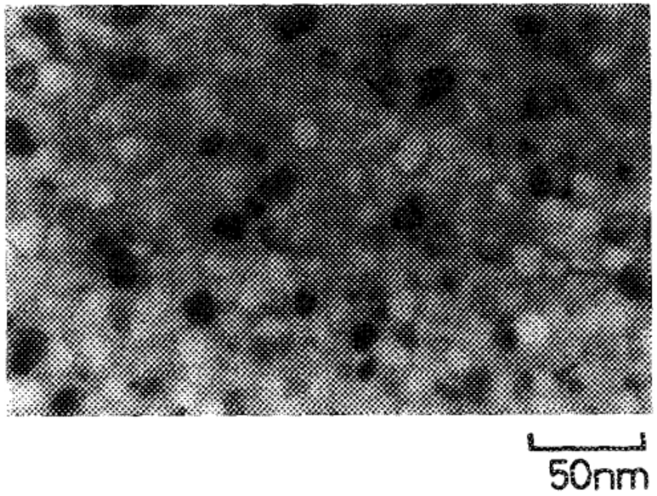
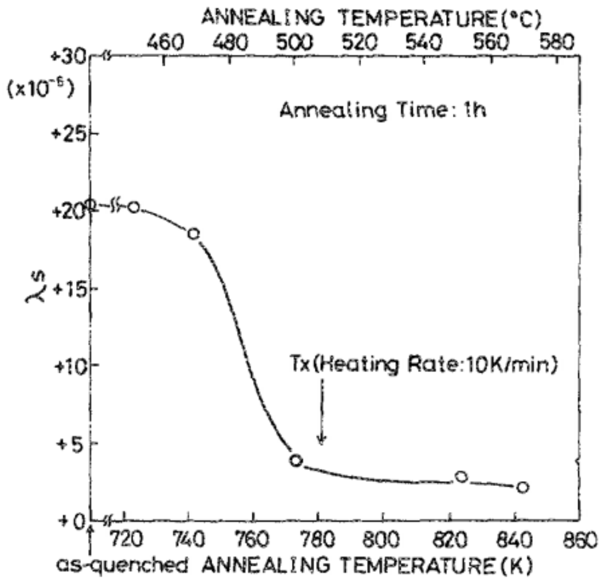
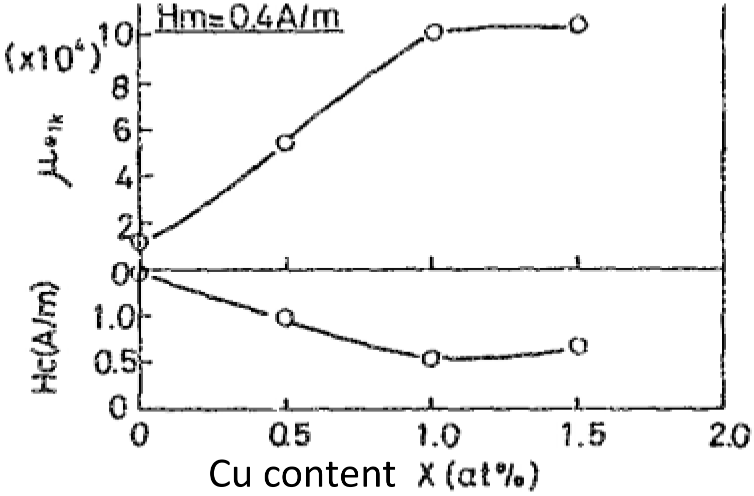


FIG. 2. X-ray diffraction patterns of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ and $Fe_{74.5}Nb_3Si_{13.5}B_9$ alloys.

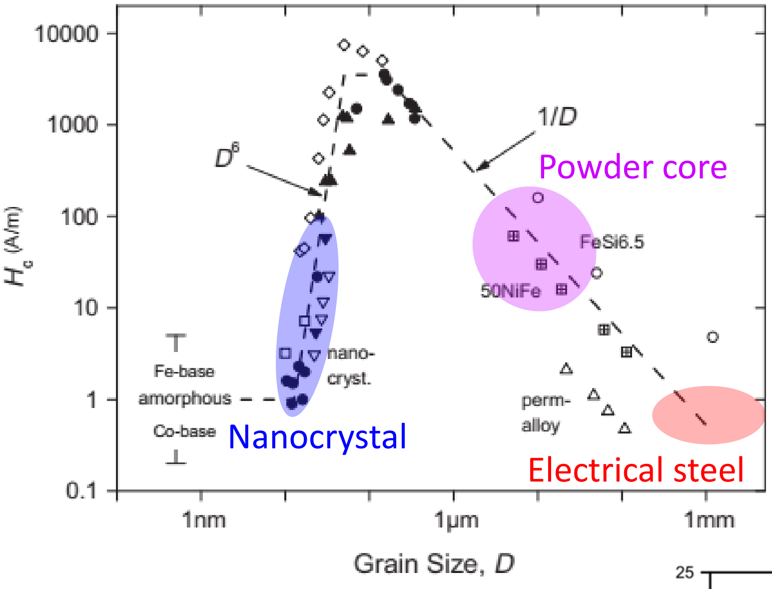






[Yoshizawa, JAP 64, 6044 (1988)]

Soft Magnetism of Nanocrystalline Alloys

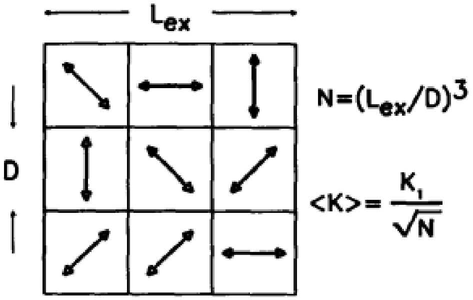


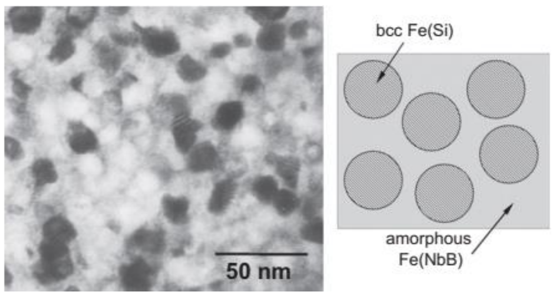
Random anisotropy model

Exchange coupled averaging

$$K_{av} \approx (K^4/A_{ex}^3)D^6$$

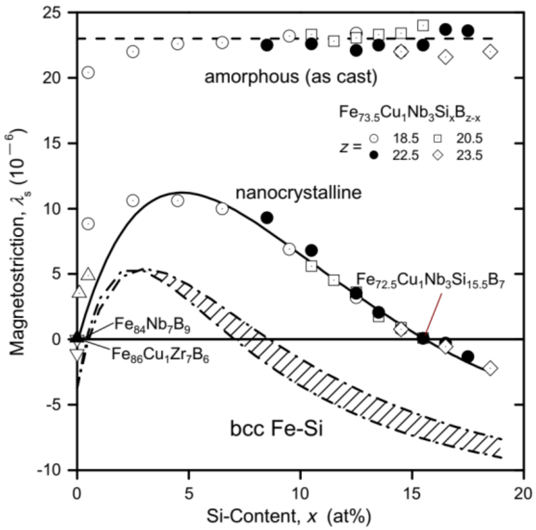
[Herzer, IEEE Trans Mag 26, 1397 (1990)]

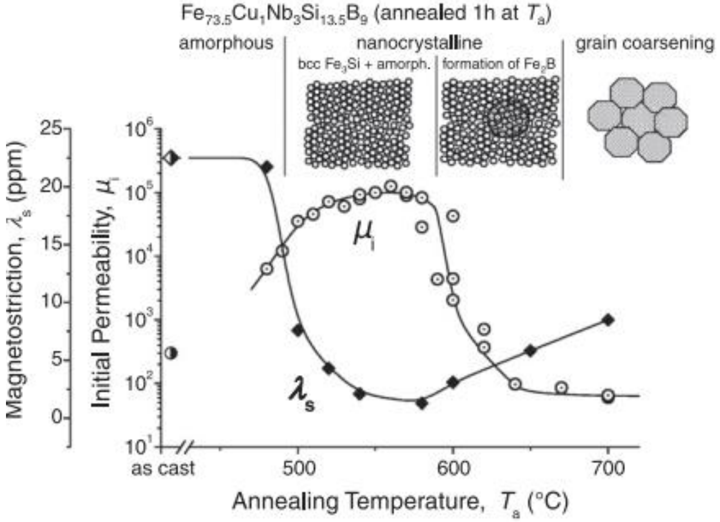




[Herzer, Acta Mater (2013)]

Cancellation of λ



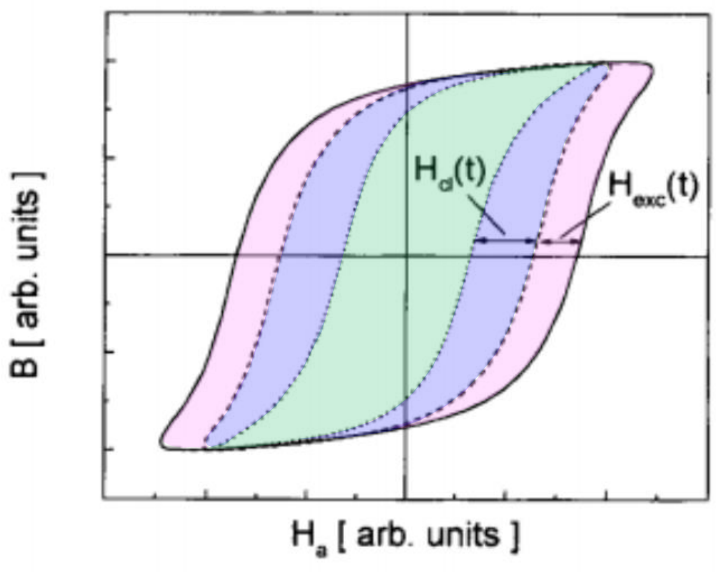


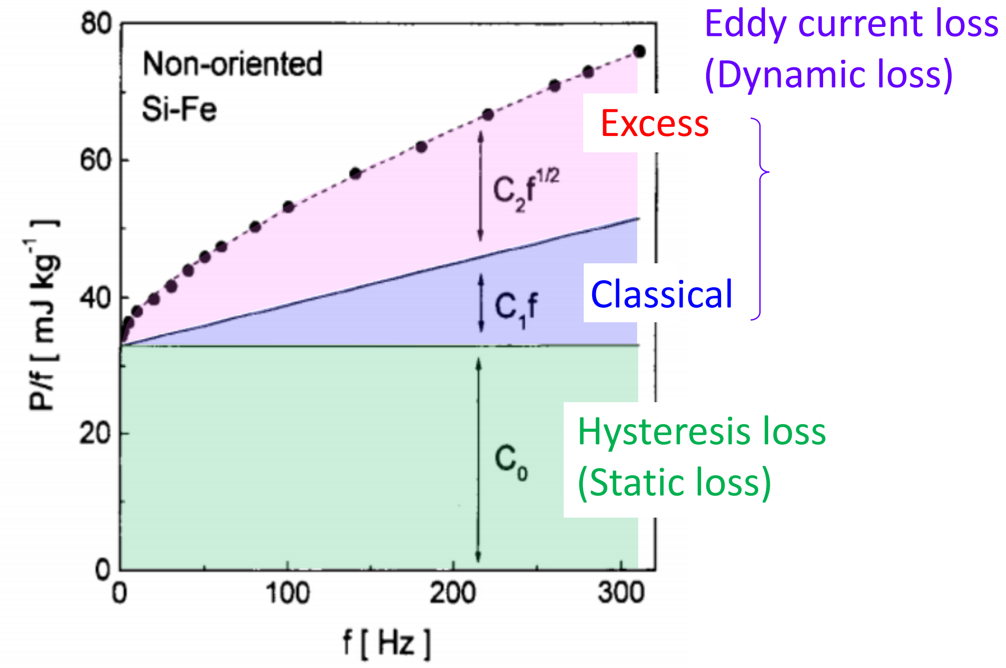
$$\lambda_s \approx x_{cr}\underline{\lambda_s}^{Fe(Si)} + (1 - x_{cr})\underline{\lambda_s}^{am}$$

Negative Positive

Contents

Classical Intuitive Understanding of Iron Loss





Power loss

Steinmetz eq. P [W/m^3]= $kf^{\alpha}B_m{}^{\beta}$ ⇨

[Steinmetz (1892)]

Work per cycle

W [J/m^3] (P/f) = W_{hys} + W_{cl} + W_{exc}

W_{hys} : constant

$W_{cl} = \dfrac{\pi^2}{6}\sigma d^2 B_m{}^2 f$ from Maxwell eqs. for uniform flux change

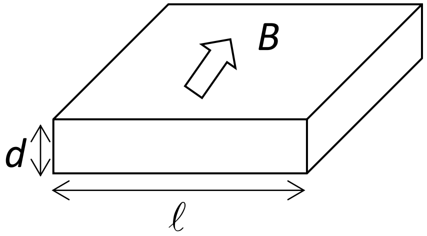
$W_{exc} = 8\sqrt{\sigma G S V_0} B_m{}^2 f^{0.5}$ from statistic theory for domain wall motion

[Bertotti (1985)]

Simple Estimation of Eddy Current Loss

Uniform flux change

Classical eddy current loss P_{cl}



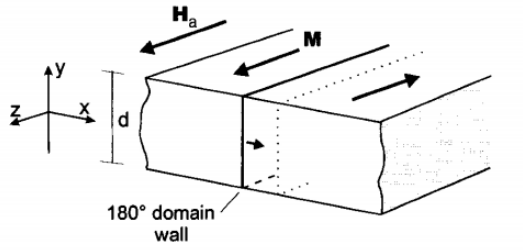
For a uniformly magnetized slab with $\ell >> d$, eddy current j_{cl} flows along the slab edge.

$$2\ell j_{cl} \approx \frac{1}{\rho}\frac{\partial \phi}{\partial t} = \frac{\ell d}{\rho}\frac{\partial B}{\partial t} \Rightarrow P_{\mathrm{cl}} \approx \rho j_{cl}^{\,2} \approx \frac{d^2}{4\rho}\left(\frac{\partial B}{\partial t}\right)^2 \propto f^2$$

Minimum case of eddy current loss

Single domain wall flux change

Excess (Anomalous eddy current) loss P_{exc}



Large dB/dt occurs at domain wall displacement.

$$4dj_{exc} \approx \frac{1}{\rho}\frac{\partial \phi}{\partial t} = \frac{\ell d}{\rho}\frac{\partial B}{\partial t} \Rightarrow P_{exc} \approx \rho j_{exc}^{\,2}\left(\frac{2d^2}{\ell d}\right) \approx \frac{\ell d}{8\rho}\left(\frac{\partial B}{\partial t}\right)^2 = P_{\mathrm{cl}}\left(\frac{\ell}{2d}\right)$$

Maximum case of eddy current loss

For ℓ = 10 mm and d = 25 μm $P_{\mathrm{exc}}/P_{\mathrm{cl}} \approx 200$

Very important to control the magnetization reversal process

Questions on Soft Magnetic Materials for Power Electronics

For power electronics applications, requirements for soft magnetic materials and devices strongly depend on the circuit type and power range.

General requirements,

1. High saturation magnetization $\mu_0 M_s$
2. High permeability μ up to high frequency
3. Low ion loss P up to high frequency

Q1 Soft magnetic properties in textbooks are static properties. What is different for high frequency applications?

Ans Excellent static soft magnetic properties are obtained by improvement of uniformity and domain wall displacement. But these conditions will cause significant loss in high frequency region. Lowest energy loss state is magnetization rotation, but this cause low permeability.

Understanding loss mechanism is important

Q2 Can be above 1 ~ 3 requirements satisfied concurrently?

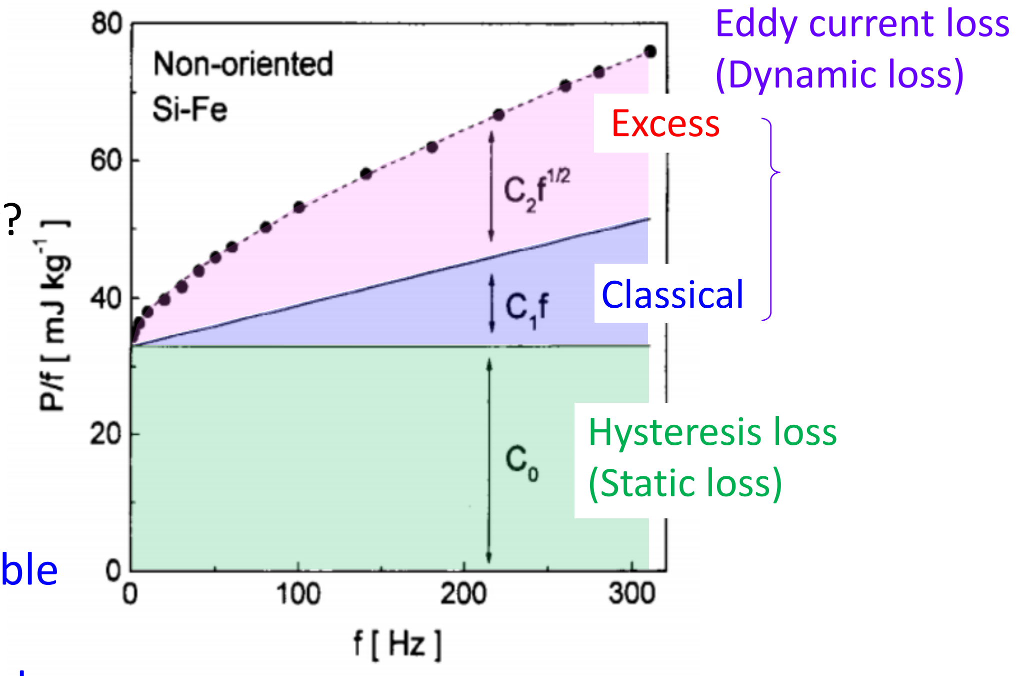
Ans It is difficult physically, and optimization is very important. But there are too many variables for optimization.

Questions on Classical Understanding of Iron Loss

$W\,[\mathrm{J/m^3}] = W_{\mathrm{hys}} + W_{\mathrm{cl}} + W_{\mathrm{exc}}$

Q1 W_{cl} and W_{exc} can exist concurrently?

Ans Physically No. But the statistic theory mathematically deals this issue. [Bertotti (1985)]



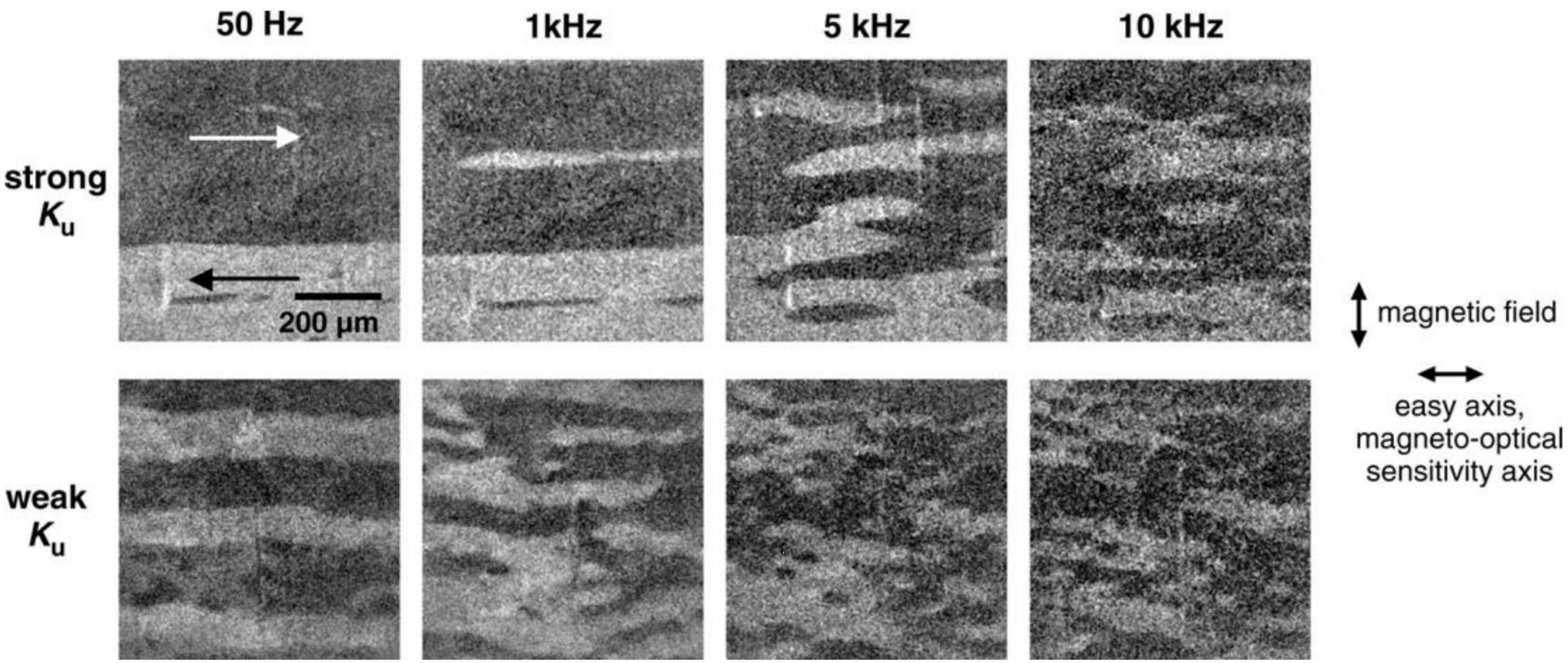
- The statistic model can be only applicable for low frequency range.
- Physics based loss analyses are required.

Q2 Is really W_{h} constant against f ? Do we really understand W_{h} ?

Q3 Do we really understand W_{cl} ?

Q4 Do we really understand W_{exc} ?

Q2: Do we really understand W_h ?



[Flohere, Acta Mater (2006)]

Magnetic domain structure strongly depends on frequency

⇩

Change in magnetization reversal process

W_h is not a constant for higher frequency range

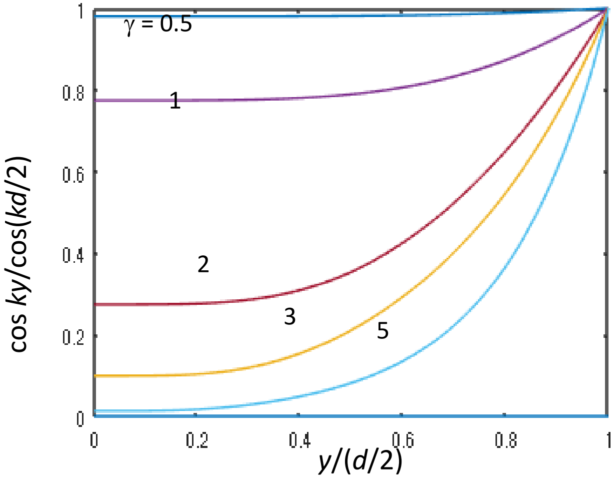
Q3: Do we really understand W_{cl} ?

Skin Effect

$$H(y,t) = H_{\max}\frac{\cos ky}{\cos(kd/2)}\exp(-i\omega t)$$

$$kd = \gamma(1+i),\ \gamma = d/\delta$$

$$\delta = \sqrt{2/\sigma\mu\omega}$$

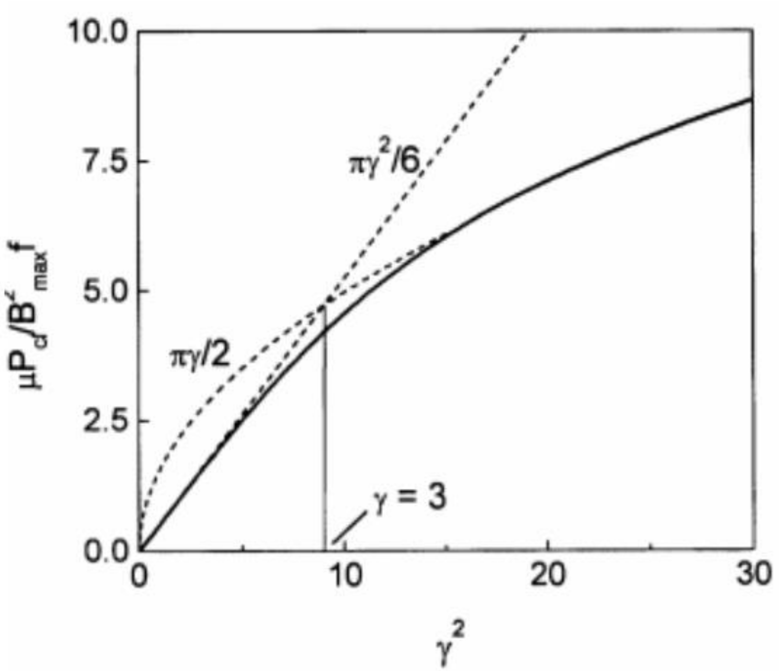


Classical Eddy Current Loss with Skin Effect

$$P_{\mathrm{cl}} = \frac{\pi}{2}\frac{\gamma B_{\max}{}^2 f}{\mu}\frac{\mathrm{sh}\gamma - \sin\gamma}{\mathrm{ch}\gamma - \cos\gamma}$$

$$P_{\mathrm{cl}} \simeq \frac{\pi^2}{6}\sigma d^2 B_{\max}{}^2 f^2,\ \gamma << 1$$

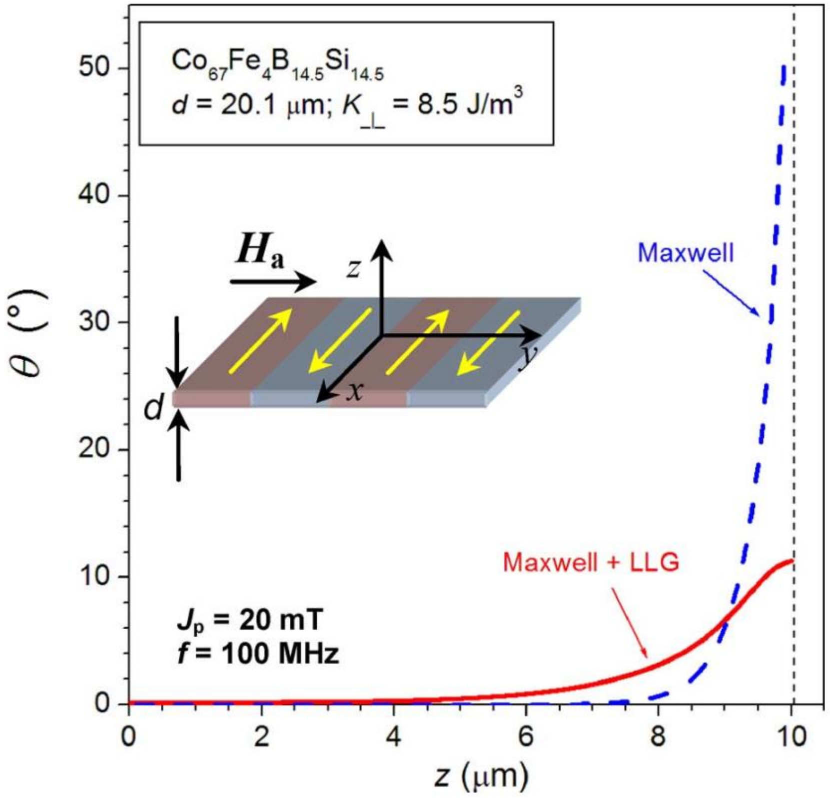
$$P_{\mathrm{cl}} \simeq \frac{\pi^{3/2}}{2}\sqrt{\frac{\sigma d^2}{\mu}}B_{\max}{}^2 f^{3/2},\ \gamma >> 1$$



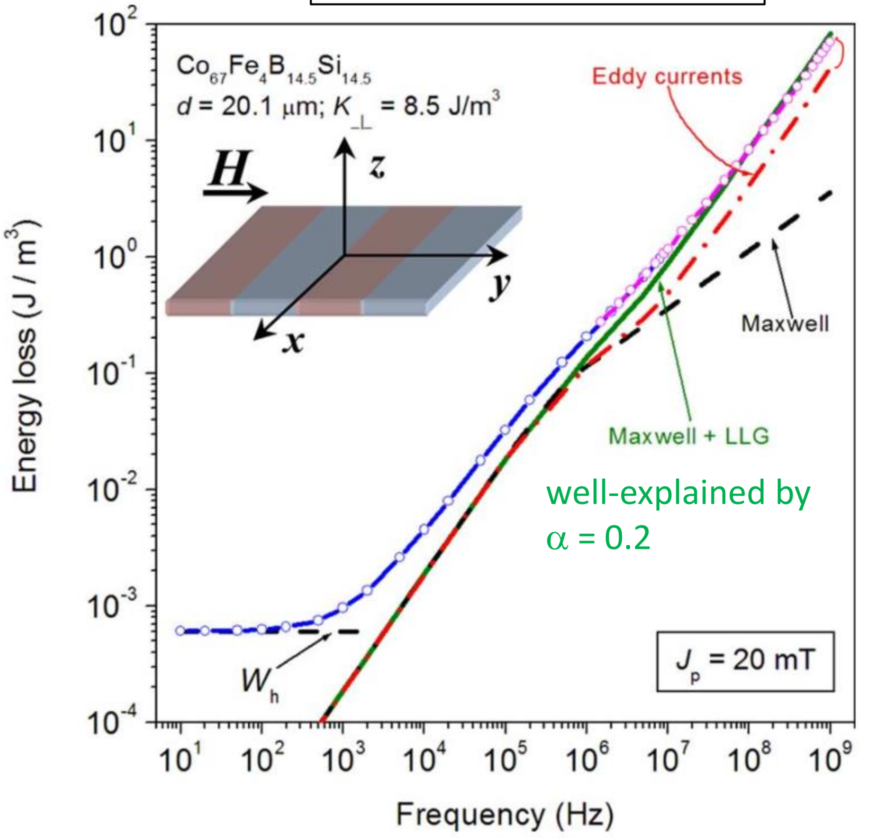
LLG & Maxwell Eqs. Coupled Calculation

$$\partial \boldsymbol{M}/\partial t = -\gamma\mu_0 \boldsymbol{M} \times \left[\boldsymbol{H}_{\mathrm{eff}} + (\alpha/M_{\mathrm{s}})\,\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}}\right]$$

$$\partial^2 \boldsymbol{H}_{\mathrm{eddy}}/\partial z^2 = \sigma\mu_0 \partial\left(\boldsymbol{M} + \boldsymbol{H}_{\mathrm{eddy}} + \boldsymbol{H}_{\mathrm{a}}\right)/\partial t$$



Co-Fe-Si-B am ($\lambda \sim 0$)



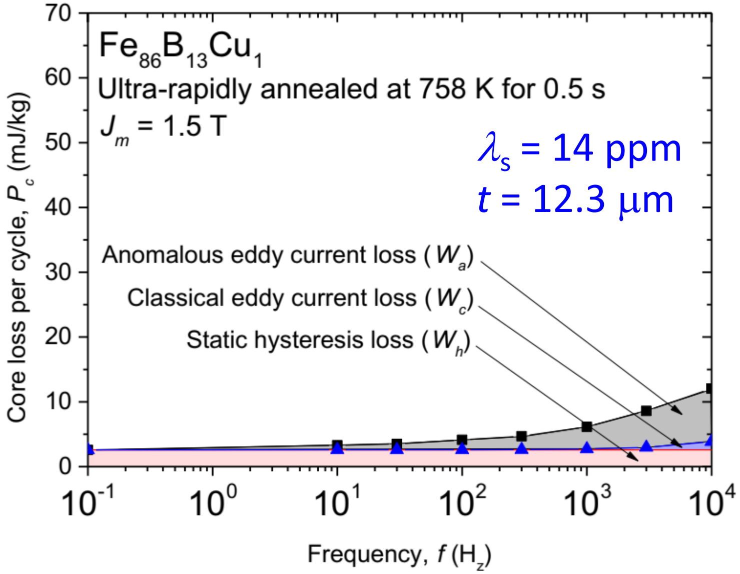
well-explained by
α = 0.2

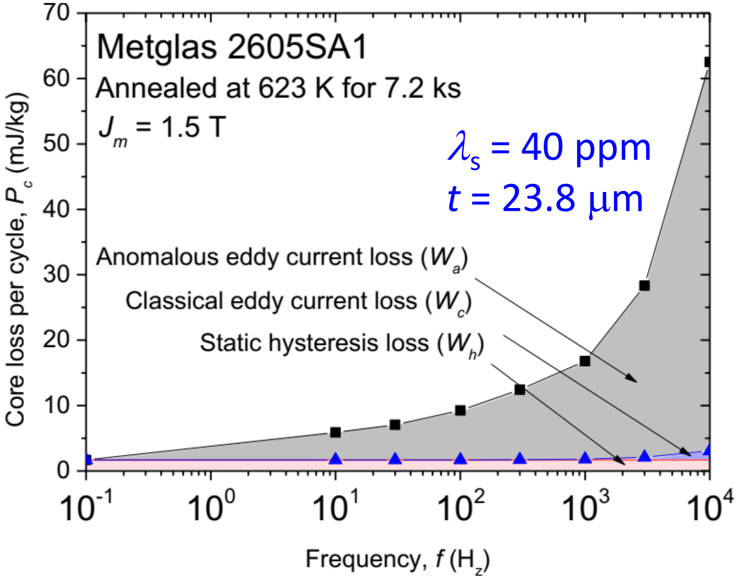
[Magni, IEEE Mag 48, 3796 (2012), ibid. 1363 (2012)]

Maxwell + LLG well explain the experimental loss, but very large α is required.

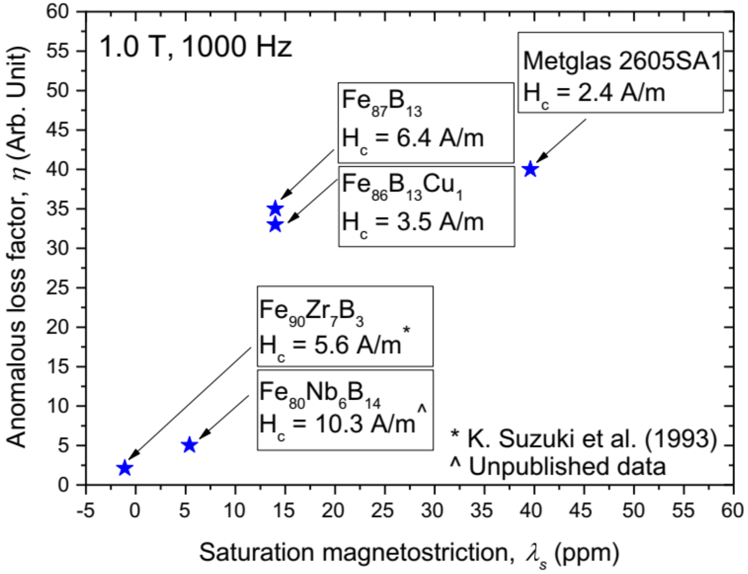
⇨ Eddy current origin loss + Damping origin loss

Q4: Do we really understand W_{exc} ?





[Parsons, JMMM 476, 142 (2019)]



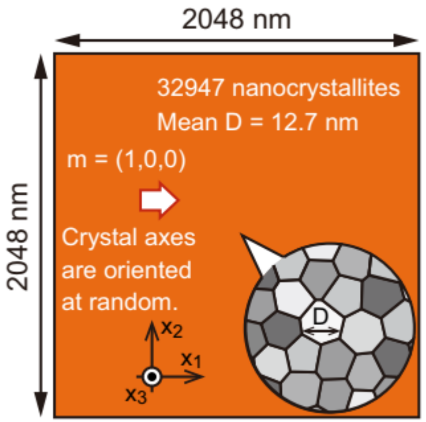
- It is hard to explain W_{exc} by eddy current origin.
- W_{exc} has strong relation with λ

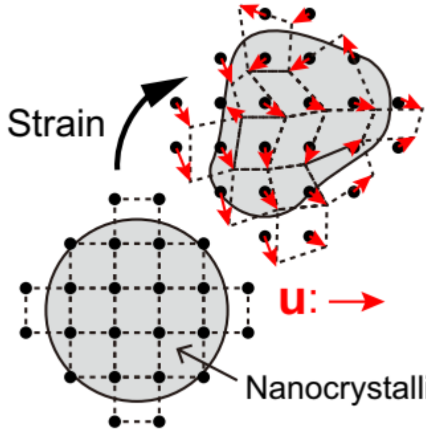
⇨ Possibility of λ origin loss

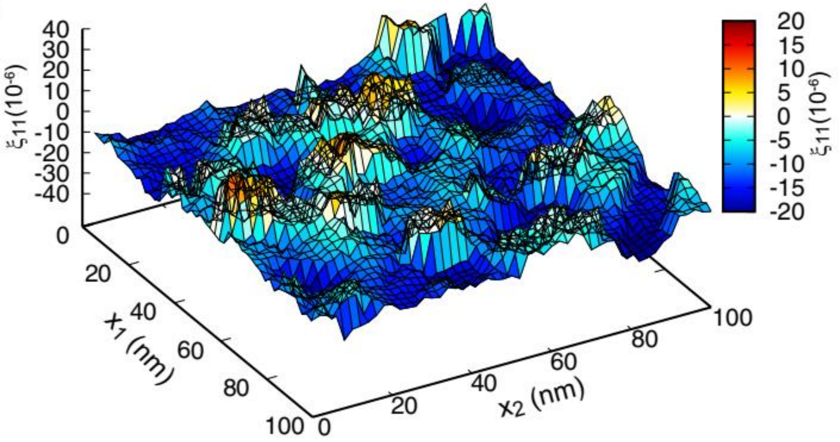
* This is not static effect such as inverse λ effect but the dynamic effect.

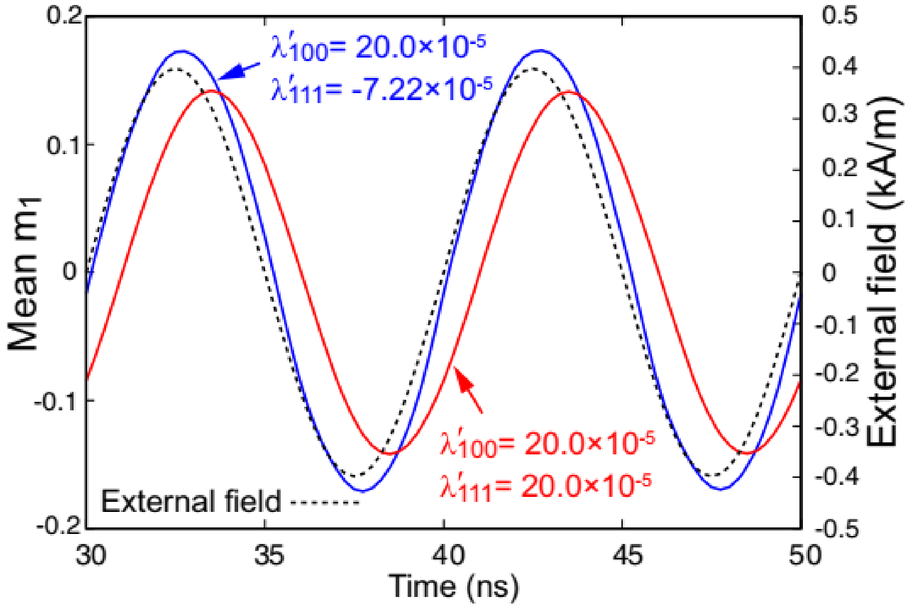
"Anomalous eddy" is not appropriate term. Excess loss is better.

Magnetostriction Origin Excess Loss









Magnetostriction cause phase lag through friction of lattice deformation.

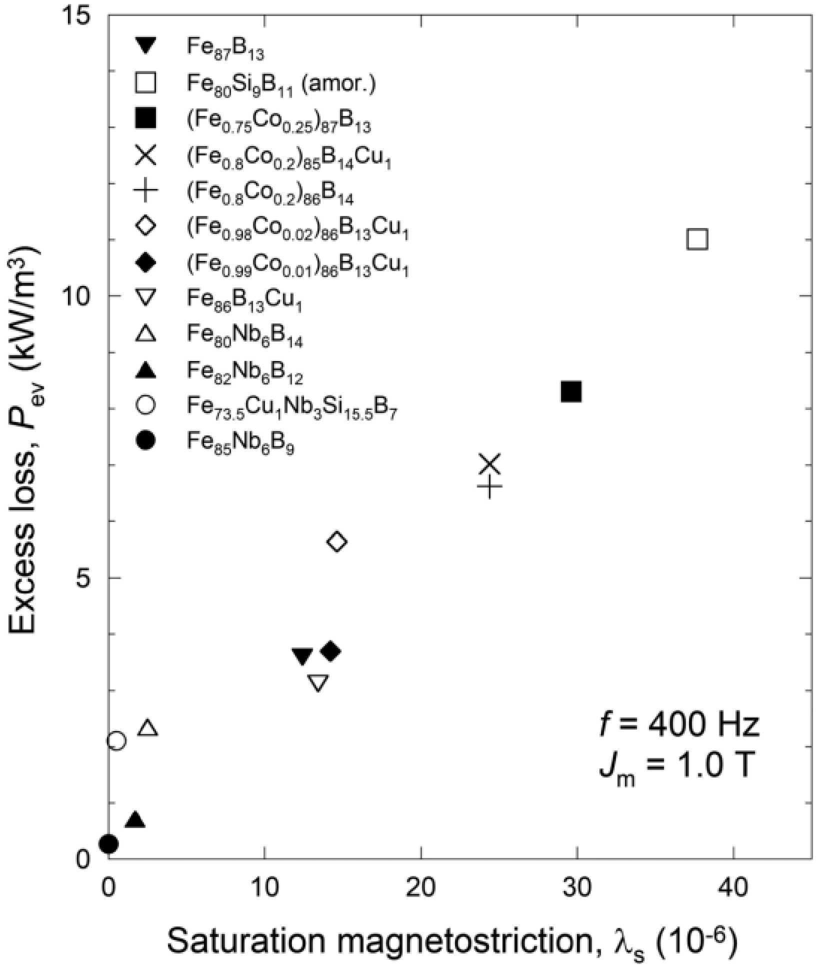
[Tsukahara, NPG Asia 476, 142 (2019)]

Excess Loss vs. Magnetostriction vs. Damping Constant

[Huang, PRB 109, 104408 (2024)]

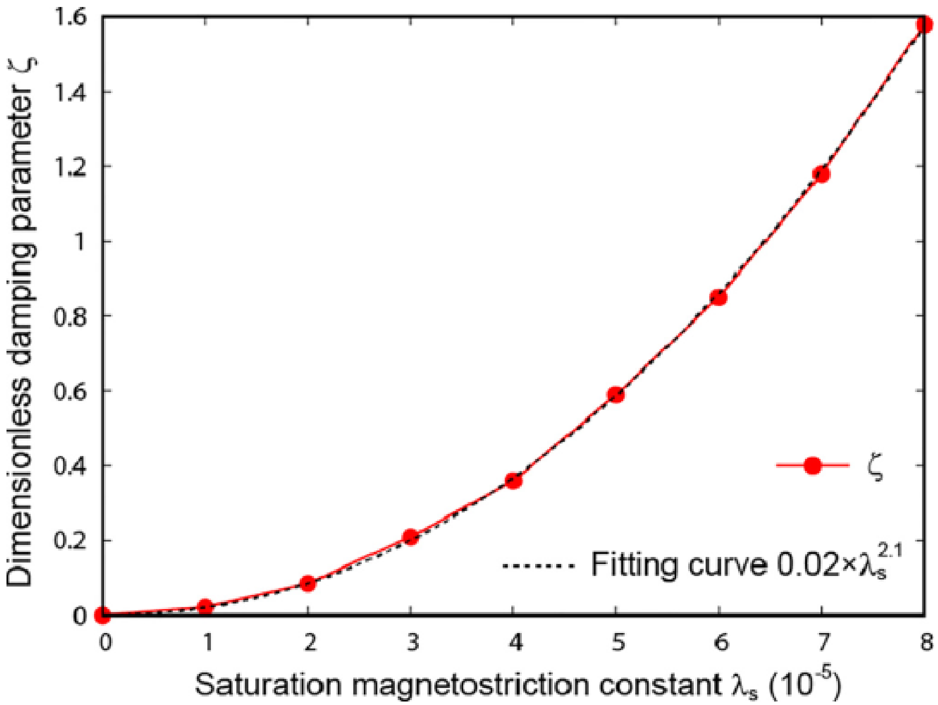
Experiments

Excess loss vs. Magnetostriction

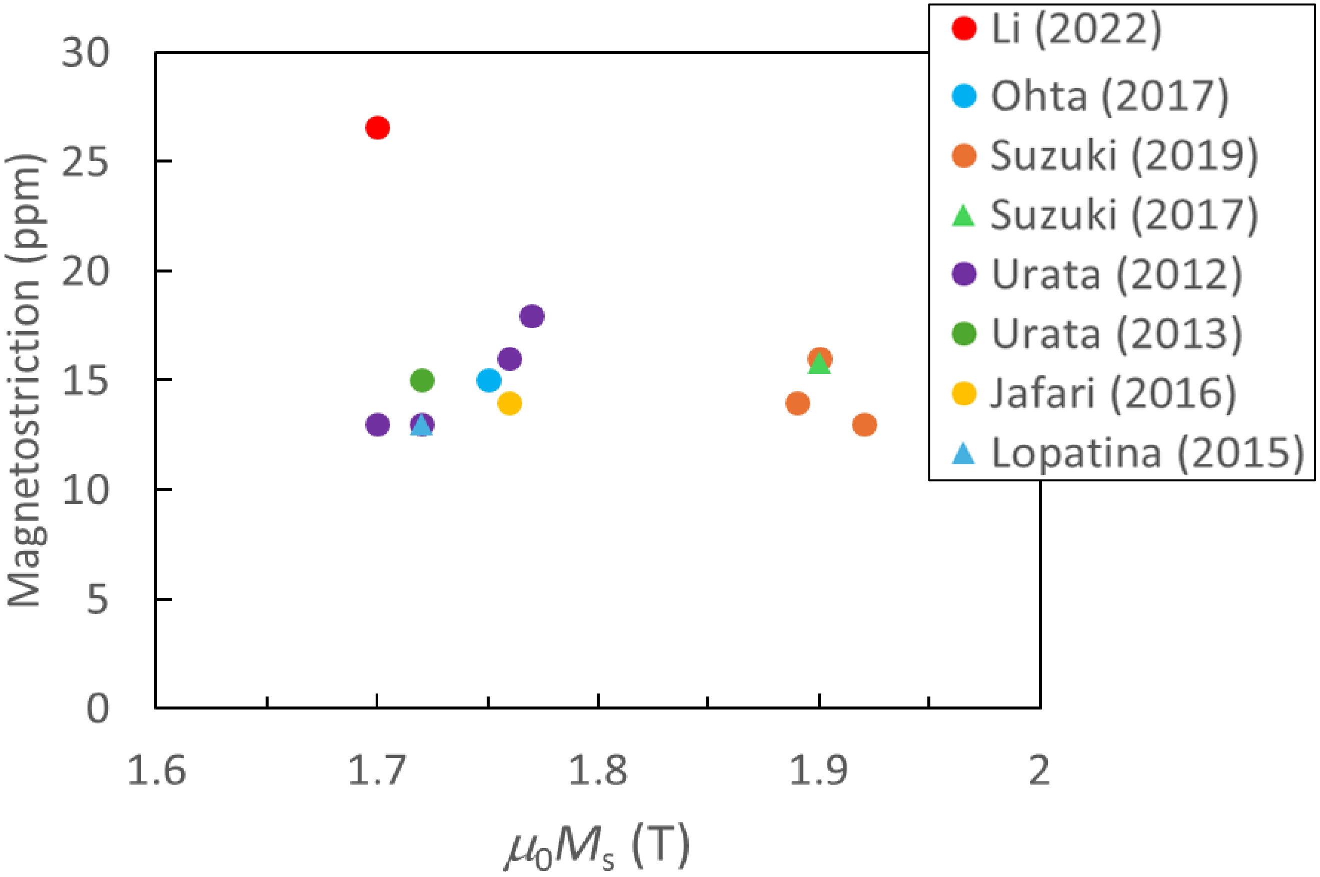


Theoretical calculation

Damping constant vs. Magnetostriction



Recent High-M_s nc-Ribbons



Questions on Classical Understanding of Iron Loss

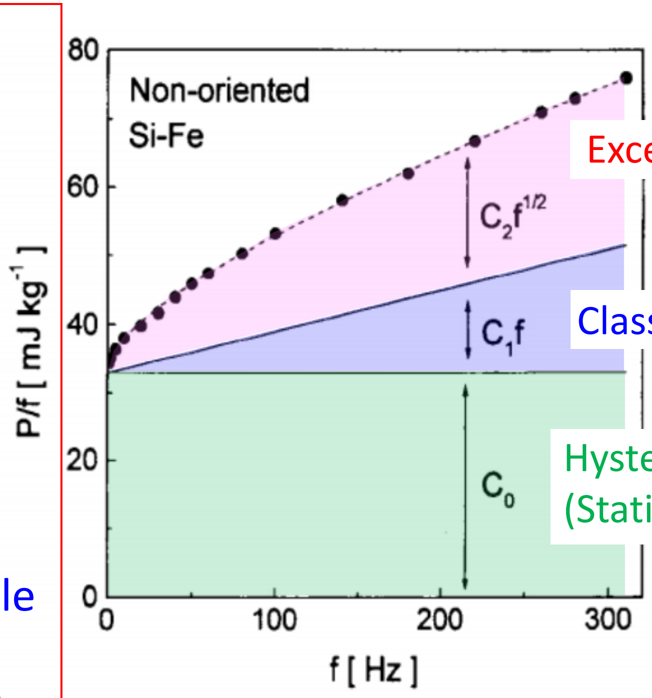
W [J/m^3] = W_{hys} + W_{cl} + W_{exc}

Q1 W_{cl} and W_{exc} can exist concurrently?

Ans Physically No. But the statistic theory mathematically deals this issue. [Bertotti (1985)]

- The statistic model can be only applicable for low frequency range.
- Physics based loss analyses are required.

Today's topics



Eddy current loss (Dynamic loss)

Excess

Classical

Hysteresis loss (Static loss)

Q2 Is really W_h constant against f ? Do we really understand W_h ?

Q3 Do we really understand W_{cl} ?

Q4 Do we really understand W_{exc} ?

Ans For high f region

On-going topics

Contents

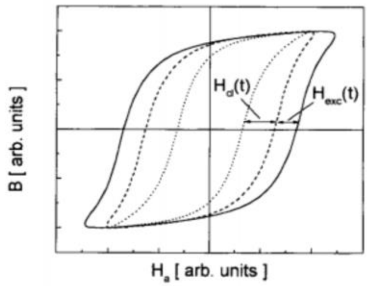
Physic Based Iron Loss Analysis

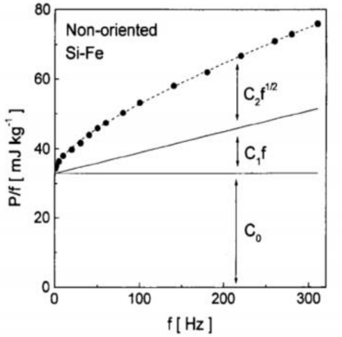
Steinmetz eq. $W = kf^{\alpha}B_m^{\beta}$ [Steinmetz, American Inst. Elec. Eng. Trans. 9, 344 (1892)]

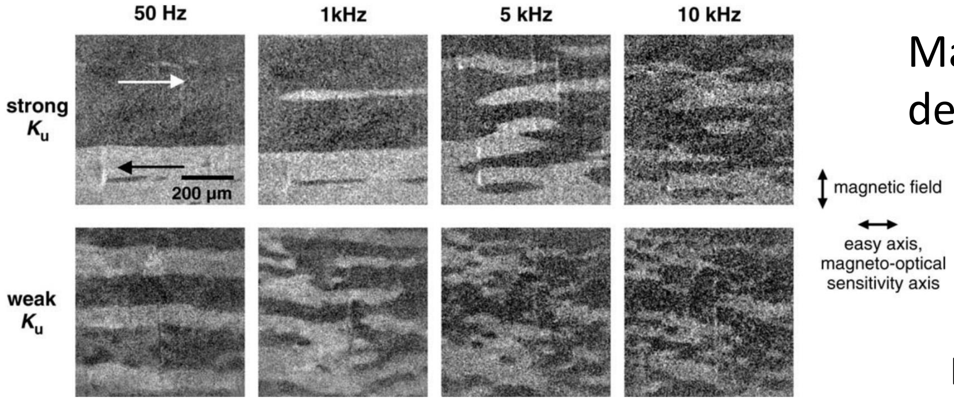
⇨ $W = W_h + W_{cl} + W_{exc}$

- ✓ W_h is constant for even high frequency
- ✓ W_{exc} is residual component from W_{cl}

Physically correct?







Magnetic domain structure strongly depends on frequency

⇨ Change in magnetization reversal process

[Flohere, Acta Mater (2006)]

$W = W_h + W_{cl} + W_{exc}$ Steinmetz based model

$= \underbrace{W_{rev} + W_{irr}}$ $= W_{rev,\ eddy} + \underbrace{(W_{irr,\ h} + W_{irr,\ eddy})}$ $= \underbrace{W_{static} + W_{dyn}}$

Magnetization reversal decomposition model [Fiorillo (2017)]

Statistic model [Bertotti (1985)]

Effective domain wall model [Sakaki (1980)]

Power Laws in Loss Components

Hysteresis Loss W_{hys}

Rayleigh Region $\mu = \mu_i + \nu H$

⇨ $$W_{hys} \approx \nu H^3 \approx \frac{\nu}{\mu^3} B_m^{\ 3}$$

$$P_{hys} \approx \frac{\nu}{\mu^3} B_m^{\ 3} f$$

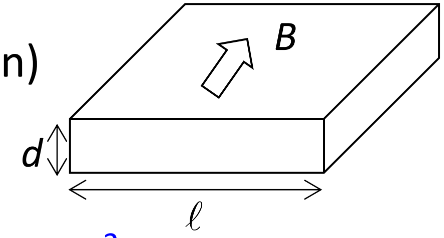
In many text books and review papers,

$$W_{hys} \approx B_m^{\ 1.6}$$

$$P_{hys} \approx B_m^{\ 1.6} f$$

Classical Eddy Current Loss W_{hys}

Uniform flux change
(Magnetization rotation)



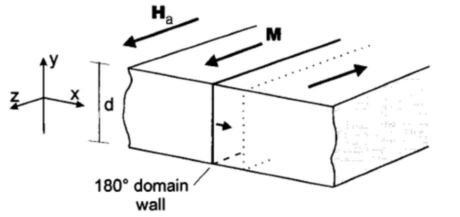
$$P_{hys} \approx \rho j_m^{\ 2} \approx \frac{d^2}{\rho} \left(\frac{\partial B}{\partial t} \right)^2 \propto B_m^{\ 2} f^2$$

$$W_{hys} \propto B_m^{\ 2} f$$

Excess (Anomalous Eddy Current) Loss W_{exc}

Single domain wall

[Williams, Phys. Rev. 80, 1090 (1950)]

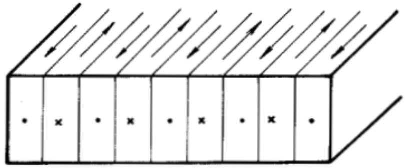


$$P_{exc} \approx \rho j_m^{\ 2} \frac{2d^2}{\ell t} \approx \frac{\ell d}{8\rho} \left(\frac{\partial B}{\partial t} \right)^2 \propto B_m^{\ 2} f^2$$

$$W_{exc} \propto B_m^{\ 2} f$$

Multidomain

[Pry and Bean, JAP 29, 532 (1958)]

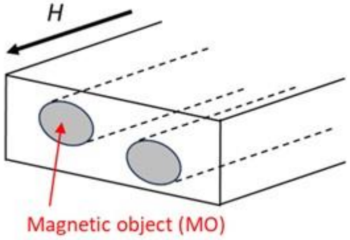


$$P_{exc} \propto \frac{B_m^{\ 2} f^2}{n}$$

$$W_{exc} \propto \frac{B_m^{\ 2} f}{n}$$

Correlated multidomain (Bertotti's Statistic theory)

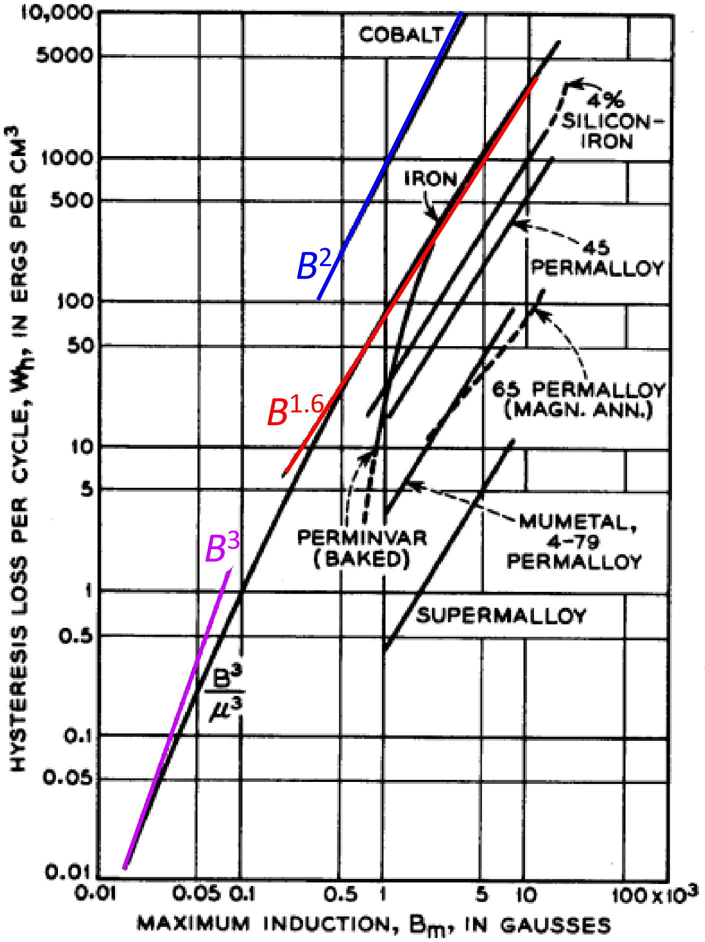
[Bertotti, JAP 57, 2110 (1985)]



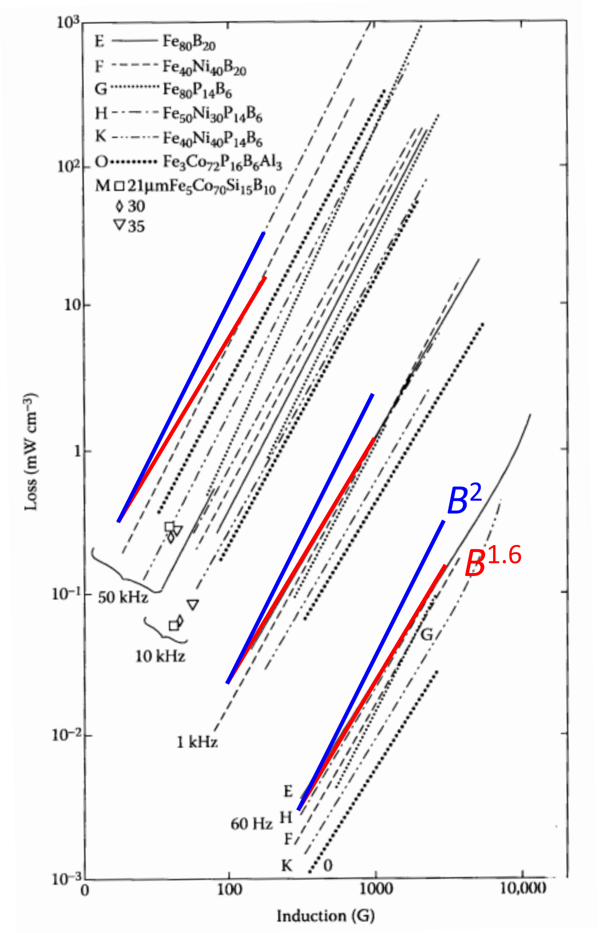
$$P_{exc} \propto \left(\frac{\partial B}{\partial t} \right)^{1.5} \propto B_m^{\ 1.5} f^{1.5}$$

$$W_{exc} \propto B_m^{\ 1.5} f^{0.5}$$

Power Law of Hysteresis Loss



[Bozorth, Ferromagnetism]

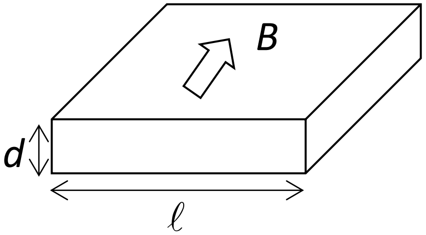


[Jiles, Introduction to Magnetism and Magnetic Materials]

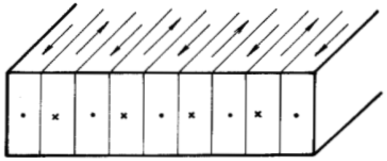
There are many cases deviating from empirical model of $W_{hys} \approx B_m^{1.6}$.
There is no theory on $W_{hys} \approx B_m^{\beta}$.

W_{cl} and W_{exc} can exist concurrently?

W_{cl} Magnetization rotation



W_{exc} Domain wall displacement



Can not exist concurrently !!

Bertotti's explanation

[Bertotti, Hysteresis on Magnetism]

Hysteresis contains numerous number of Barkhausen jumps.

Eddy current throughout hysteresis $\boldsymbol{i} = \sum \boldsymbol{i}_i$, $\boldsymbol{i}_i$: Eddy current of single Barkhausen jump

From $P \propto |\boldsymbol{i}|^2$, $|\boldsymbol{i}|^2 = \sum_{i}^{N} |\boldsymbol{i}_i|^2 + \sum_{i \neq j} \boldsymbol{i}_i \cdot \boldsymbol{i}_j = N\langle |\boldsymbol{i}_i|^2 \rangle + N^2 \langle \boldsymbol{i}_i \cdot \boldsymbol{i}_j \rangle$

For the case of non-correlated Barkhausen jumps, $N^2 \langle \boldsymbol{i}_i \cdot \boldsymbol{i}_j \rangle = \langle N\boldsymbol{i}_i \rangle^2$

$N\langle |\boldsymbol{i}_i|^2 \rangle$ and $\langle N\boldsymbol{i}_i \rangle^2$ correspond to sum of each Barkhausen jump and uniform eddy current, respectively.

Thus,
$$|\boldsymbol{i}|^2 = \underbrace{N\langle |\boldsymbol{i}_i|^2 \rangle}_{P_{hys}} + \underbrace{\langle N\boldsymbol{i}_i \rangle^2}_{P_{cl}} + \underbrace{N^2(\langle \boldsymbol{i}_i \cdot \boldsymbol{i}_j \rangle - \langle \boldsymbol{i}_i \rangle^2)}_{P_{exc}}$$

Statistic Theory for W_{exc}

Cluster of correlated domain walls was treated as Magnetic Object (MO).

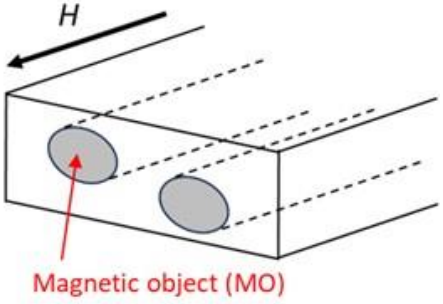
[Bertotti, JAP 57, 2110 (1985)]

Effective field $H_{\mathrm{exc}} = P_{\mathrm{exc}} / \langle \partial B / \partial t \rangle$

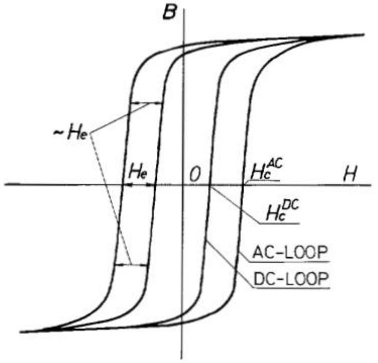
Number of MO $n_{\mathrm{MO}}(H_{\mathrm{exc}}) = n_{\mathrm{MO}}(0) + \dfrac{H_{\mathrm{exc}}}{V_0}$

$$\Rightarrow \quad H_{\mathrm{exc}} = \sqrt{\sigma G S V_0}\, \langle \partial B / \partial t \rangle^{1/2}$$

$$\Rightarrow \quad P_{\mathrm{exc}} = 8 \sqrt{\sigma G S V_0}\, B_{\mathrm{m}}^{1.5} f^{1.5}$$



Effective Domain Wall Model



Dynamic effective field H_{dyn} and dynamic loss $P_{\mathrm{c,\,dyn}}$

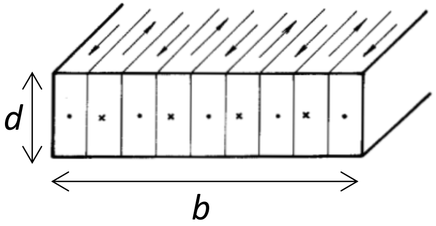
$$H_{\mathrm{c\,dyn}} = H_{\mathrm{c}}^{\mathrm{ac}} - H_{\mathrm{c}}^{\mathrm{dc}}$$

$$P_{\mathrm{dyn}} = P - P_{\mathrm{hys}} \propto f^{v}$$

Experimentally, $v \approx 1.5$

V_{m}: Output voltage amplitude
B_{s}: Saturation magnetic flux density
d: Sample thickness
β: Domain wall damping

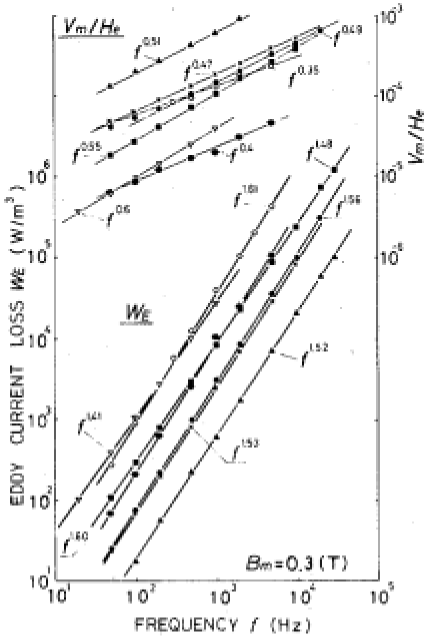
[Sakaki, IEEE Trans Magn MAG-16, 569 (1980)]
[Sakaki, IEEE Trans Magn MAG-17, 1478 (1981)]
[Sakaki, IEEE Trans Magn MAG-20, 1487 (1984)]

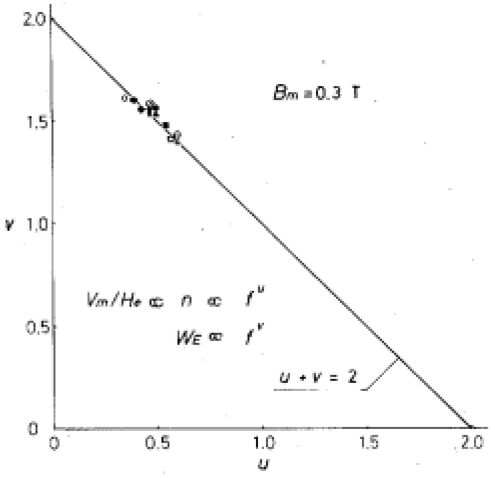


Assuming effective wall number n

$$V_{\mathrm{m}}/H_{\mathrm{c\,dyn}} = 2B_{\mathrm{s}}nd/\beta \propto f^{u}$$

Experimentally, $u \approx 0.5$ ⇨ $P_{\mathrm{dyn}} \cdot V_{\mathrm{m}}/H_{\mathrm{c\,dyn}} \propto f^{(u+v)}$, $u+v = 2$





Modified Pry and Bean model,

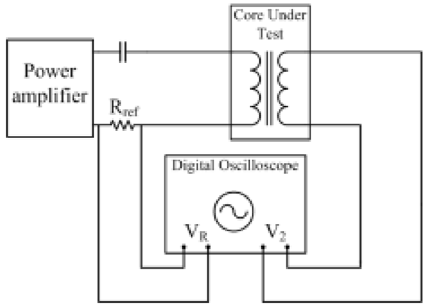
$$P_{\mathrm{dyn}} = \frac{8.4\sigma d b}{\pi n} B_{\mathrm{m}}^{2} f^{2}$$

Contents

Capacitance Cancellation Method

Magnetic Device
Laboratory Ltd.

Standard method (Two-coil method)



(a) Classic Method

IWATSU, B-H analyzer

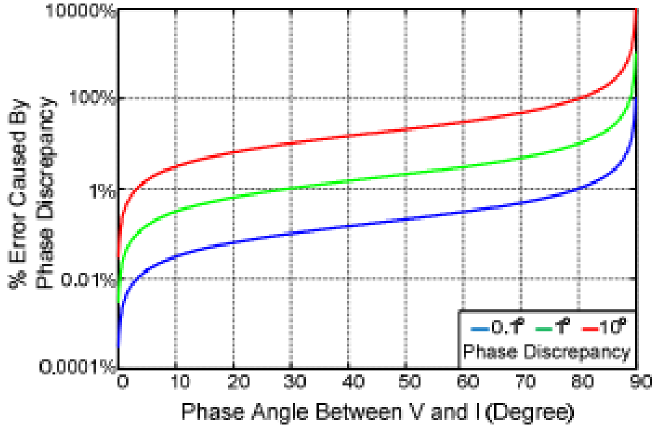
$P = VA \cos\theta$

V : output voltage, A : Input current, θ : phase lag between V and A

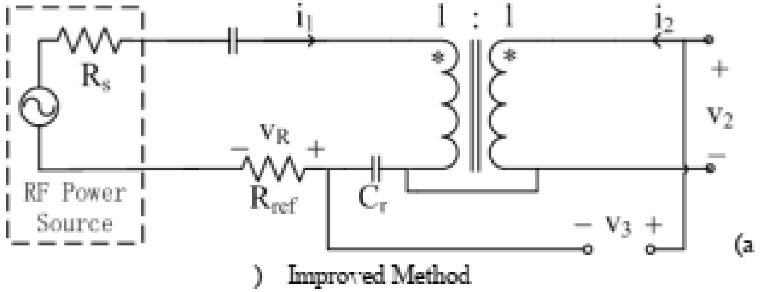
- Error of core loss measurement

$$\left|\frac{\Delta P}{P}\right| = |tan\theta\Delta\theta|$$

[Tan, IEEE Power Ele (1995)]



Capacitance Cancellation Method



[Mu, IEEE Power Ele (2014)]

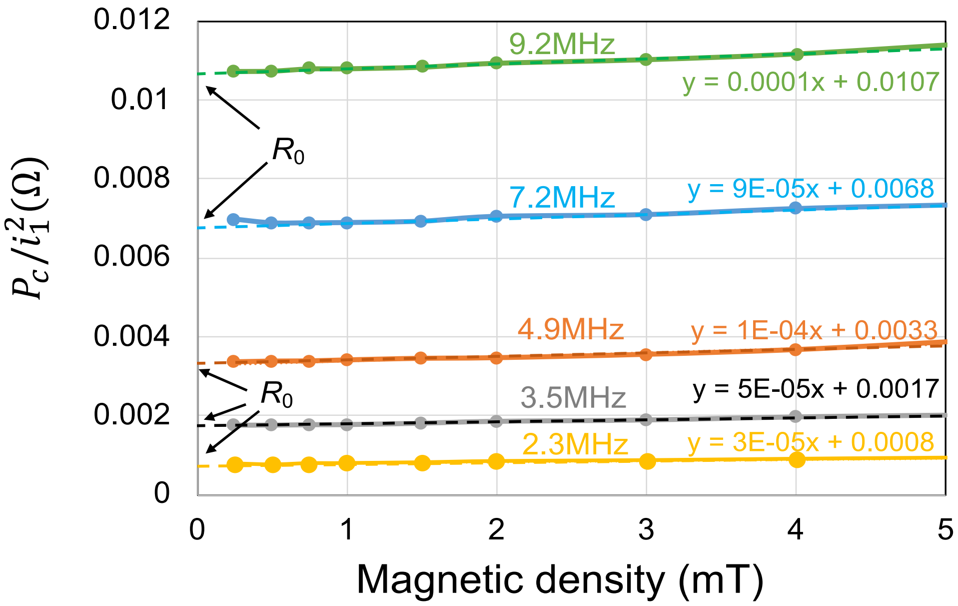
Accuracy Evaluation of Core Loss – R_0 Plot –

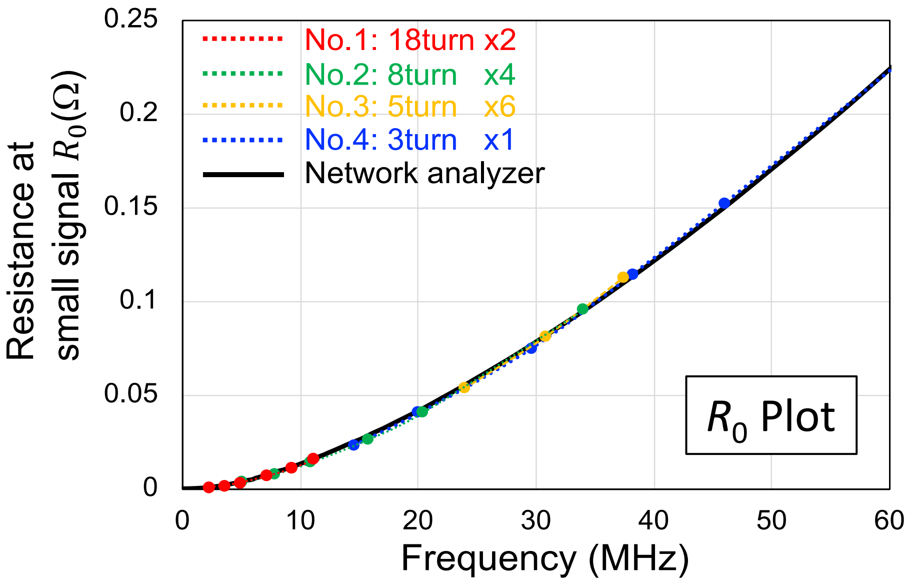
Magnetic Device Laboratory Ltd.

Equivalent Resistance R [Ω] = P [W] /I^2

R_0 : Extrapolation to zero B_m

⇨ R_0 is also measured by using well-calibrated method such as VNA





	No.1	No.2	No.3	No.4
Pics				
# of turns	18turn	8turn	5turn	3turn
# of parallels	2	4	6	1
N_1:N_2	1:1	1:1	1:1	1:1
Coupling	~97%	~95%	~87%	~78%

Accuracy evaluation method of iron loss

[Sato and SO, IEEE Trans Mag/DOI: 10.1109/TMAG.2023.3283955]

Wingdings and Self-Resonance for Low Permeability Device

Magnetic Device Laboratory Ltd.

- Power converters for frequency more than MHz range requires low-permeability devices
  → Accurate evaluation of iron loss is very difficult

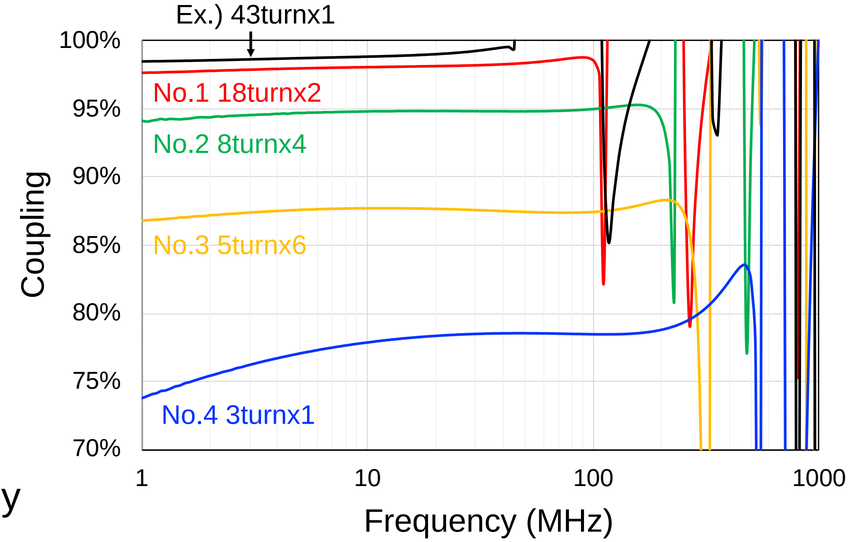
- The coupling must be 100% for high-accuracy measurements.
- For low-permeability material, many number of turns cannot be wound because the resonant frequency goes down. → Parallel windings were employed for the investigation.

Prepared Samples

	No.1	No.2	No.3	No.4
Pics				
# of turns	18turn	8turn	5turn	3turn
# of parallels	2	4	6	1
N_1:N_2	1:1	1:1	1:1	1:1
Coupling	~97%	~95%	~87%	~78%

With 4 samples, we investigate the effect on the accuracy of core loss measurement.

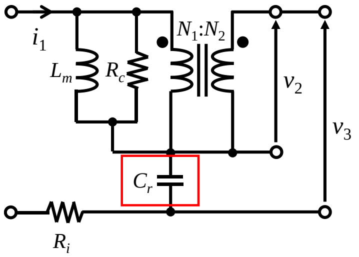
Coupling vs Frequency



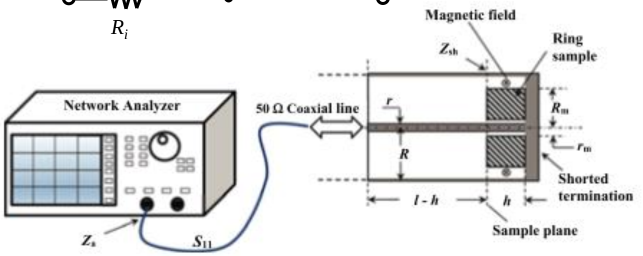
Iron Loss Measurement for Low Permeability Core

Magnetic Device Laboratory Ltd.

- Sendust dust core (OD/ID/H = 13/8/1mm)
- The iron loss was measured using a capacitive cancellation method.
- The permeability during the iron loss measurements was measured.
- The permeability of low excitation limit was also measured by a transmission method.

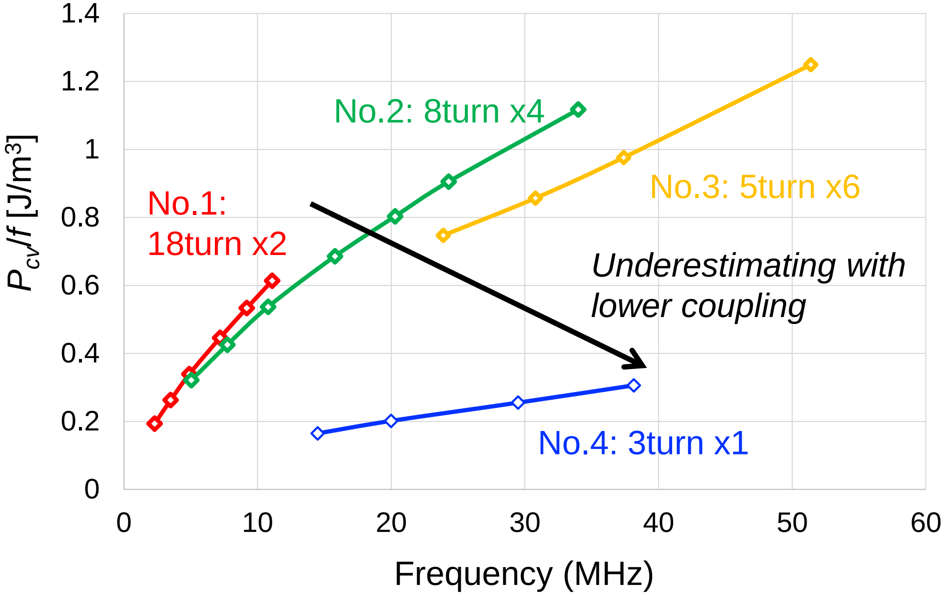


[Mu, IEEE Power Elec. (2014)]

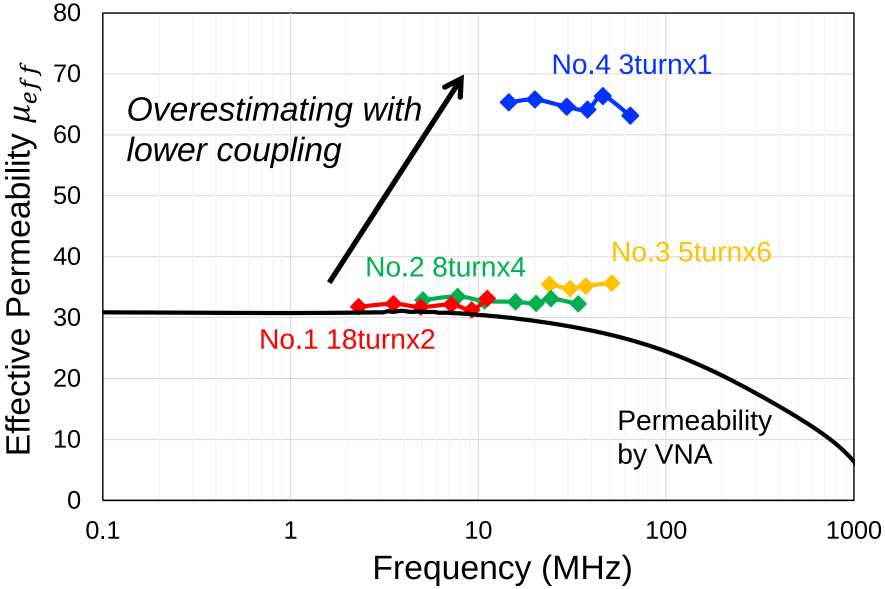


[Ferrara, J. Mater. Res. (2018)]

P_{cv}/f vs Frequency at B_m=10mT

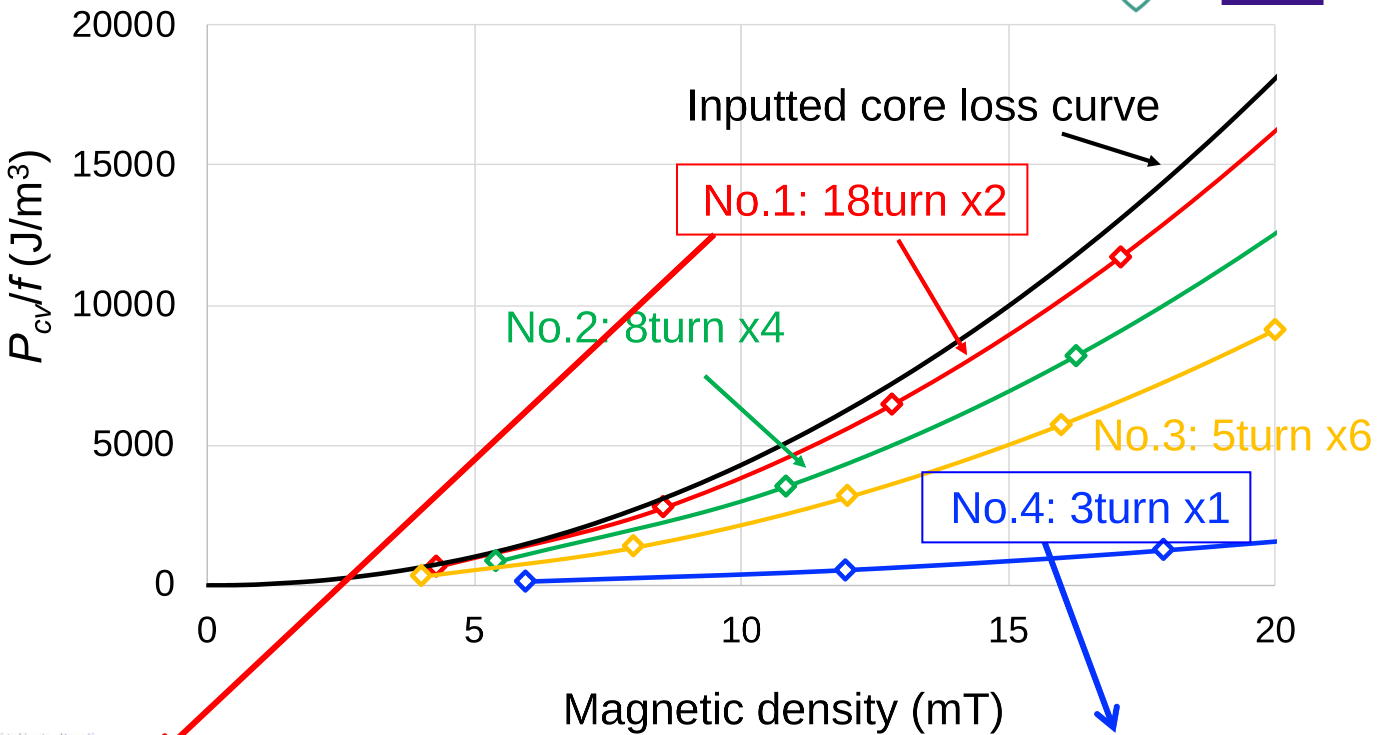


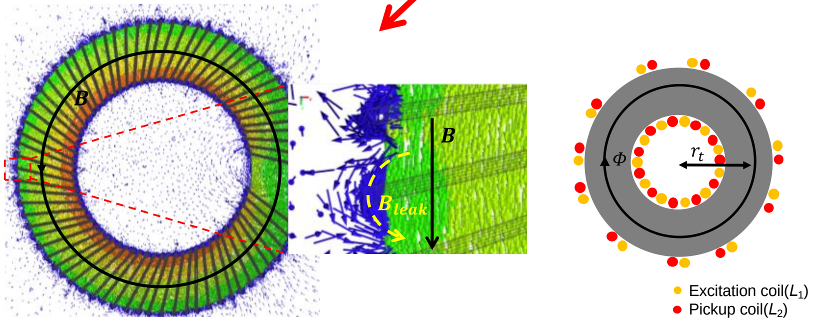
Permeability vs Frequency at B_m=0.25mT

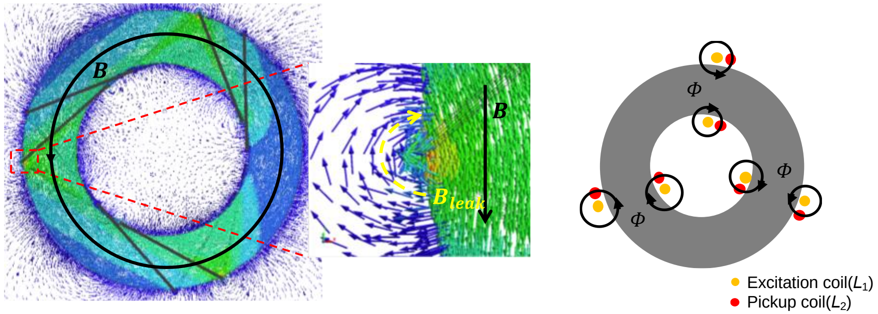


Simulations for Low Permeability Cores

Magnetic Device
Laboratory Ltd.







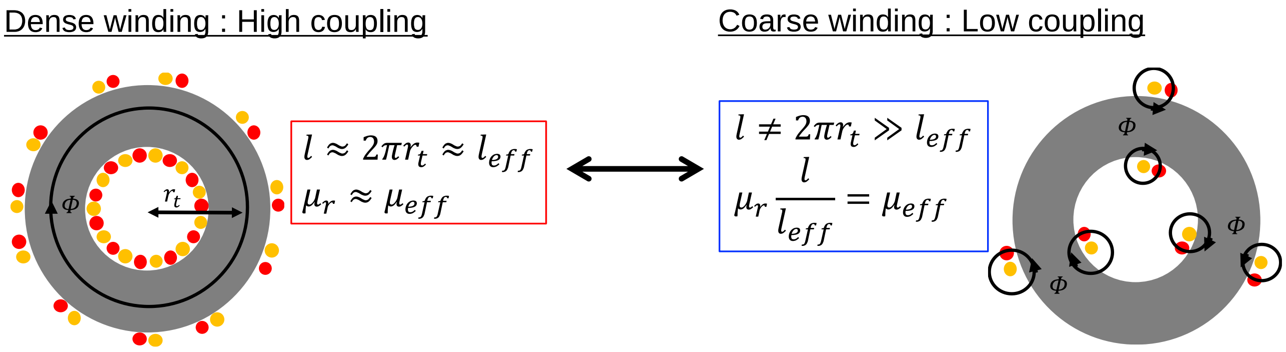
- ➢ Less leakage flux
- ➢ Very large leakage flux

Correction Method for Low Permeability Cores

Magnetic Device Laboratory Ltd.

- Magnetic flux density

$$B_m = \mu_0\mu_r H = \mu_0\mu_r \frac{N_1 i_1}{l} = \mu_0\mu_r \frac{l}{l_{eff}} \frac{N_1 i_1}{l} = \mu_{eff} \frac{N_1 i_1}{l}$$



$l \approx 2\pi r_t \approx l_{eff}$

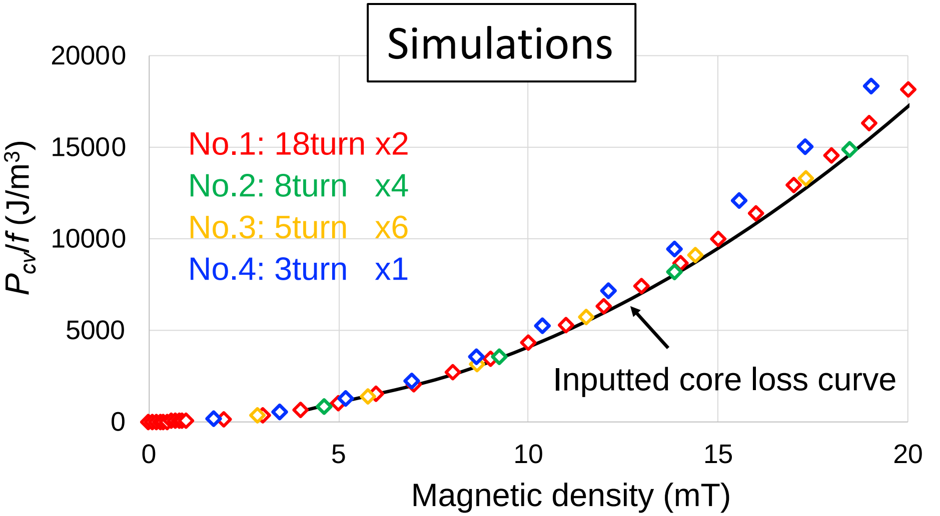
$\mu_r \approx \mu_{eff}$

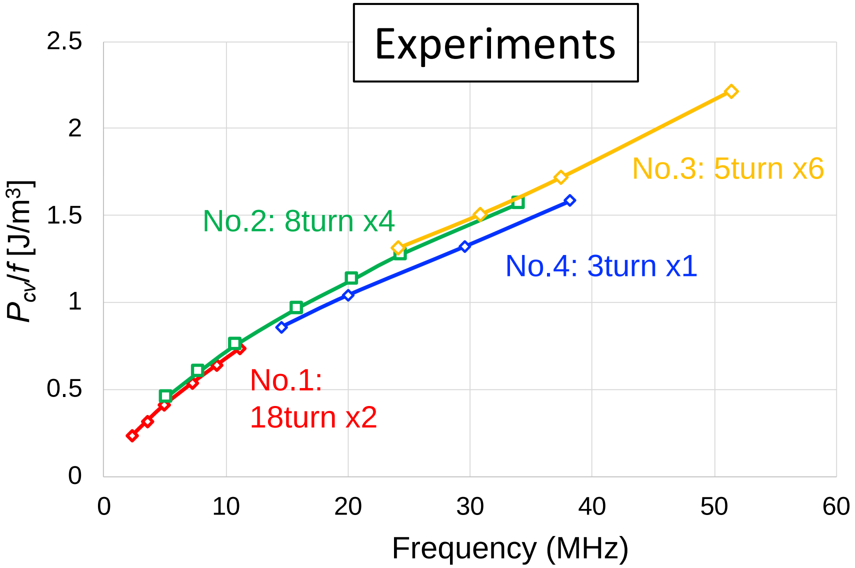
$l \neq 2\pi r_t \gg l_{eff}$

$\mu_r \frac{l}{l_{eff}} = \mu_{eff}$

Proposed correction:

$$B_{cor} = \frac{\mu_r}{\mu_{eff}} B_m$$



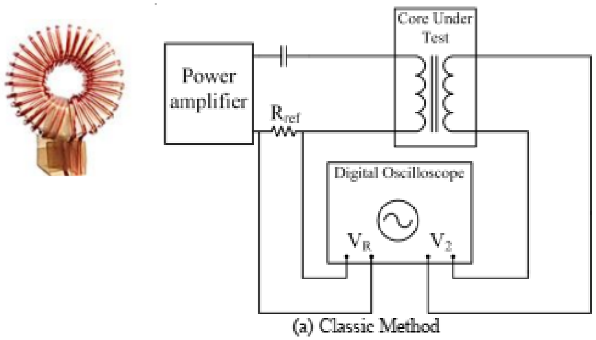


Contents

Broadband Iron Loss Measurement

[Ono, SO, JMMM 603 (2024) 172222]

Standard method(Two-coil method)



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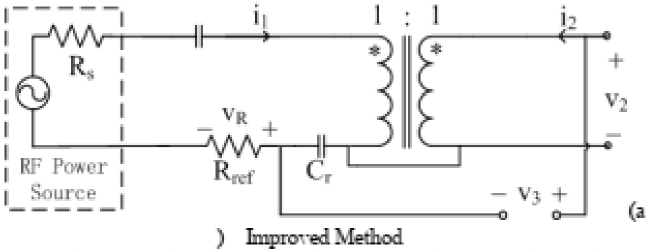
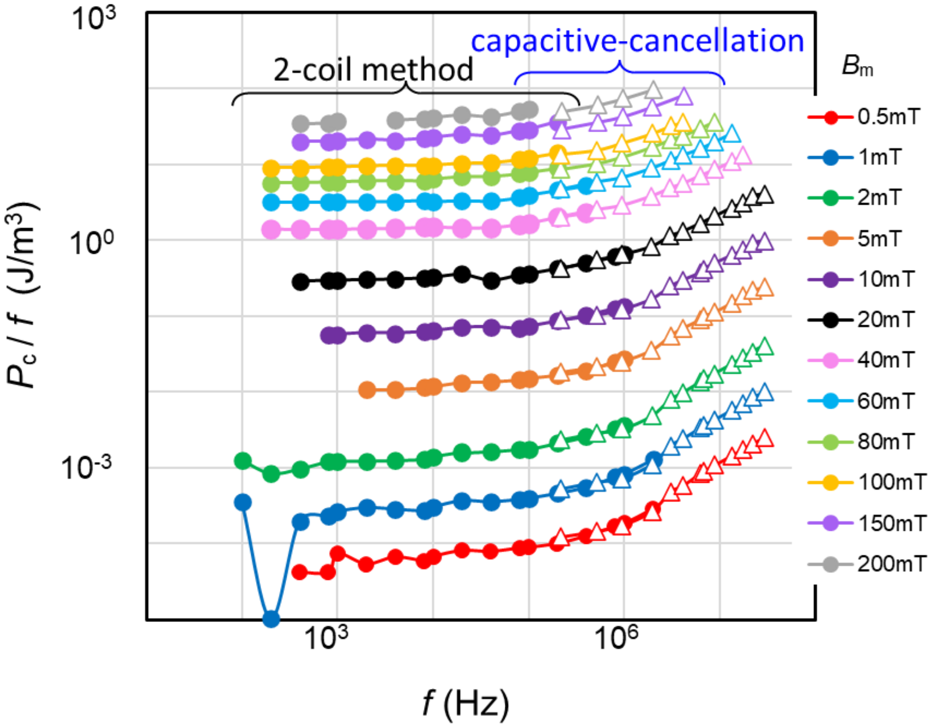
Capacitance Cancellation Method



[Mu, IEEE Power Ele (2014)]

Sendust dust core



Combination of 2-coil and capacitive-cancellation methods expands dynamic range of 10^6 Hz

Iron Loss Decomposition based on Magnetization Process

[Ono, SO, JMMM 603 (2024) 172222]

Developed by Fiorillo Gr. for analysis of Ferrite core

[Beatrice, JMMM 429, 129 (2017)]

Key points of this model

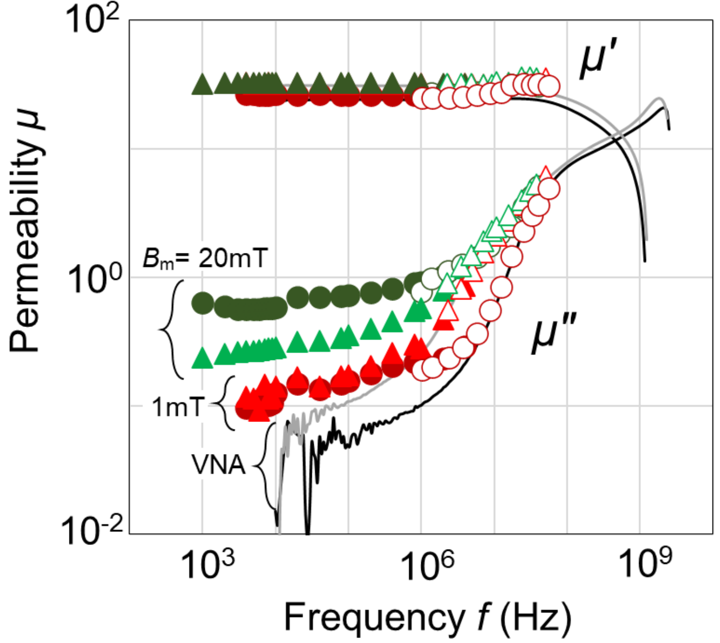
- Broadband iron loss and permeability measurements (dc~)
- Rayleigh region (linear region of susceptibility)

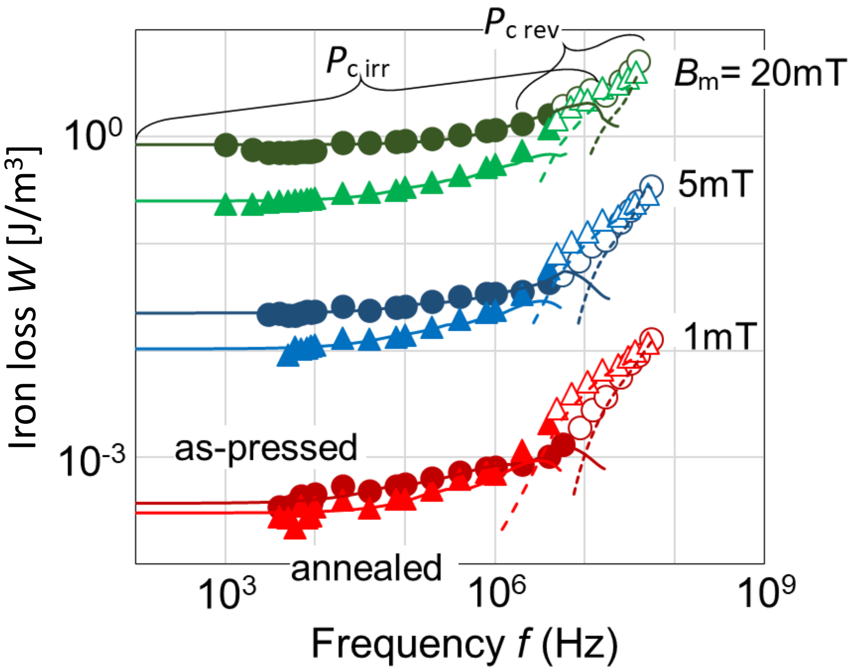
$\mu = \mu_{rev} + \mu_{irr}$ (μ_{rev} : constant, $\mu_{irr} \propto H$) ⇨

$$W = \frac{\pi B_m{}^2 \mu''}{\mu_0 \mu''^2}$$

Sendust dust core

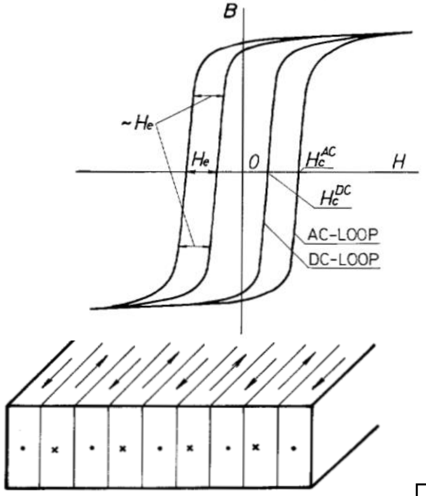
(▲ as-pressed, ● annealed)





Effective Domain Wall Model

[Ono, SO, JMMM 603 (2024) 172222]



Dynamic effective field H_{dyn} and dynamic loss $P_{\mathrm{c,\ dyn}}$

$$H_{\mathrm{c\ dyn}} = H_{\mathrm{c}}^{\mathrm{ac}} - H_{\mathrm{c}}^{\mathrm{dc}}$$

$$P_{\mathrm{c\ dyn}} = P_{\mathrm{c}} - P_{\mathrm{c\ hys}} \propto f^{v}$$

Assuming effective wall number *n*

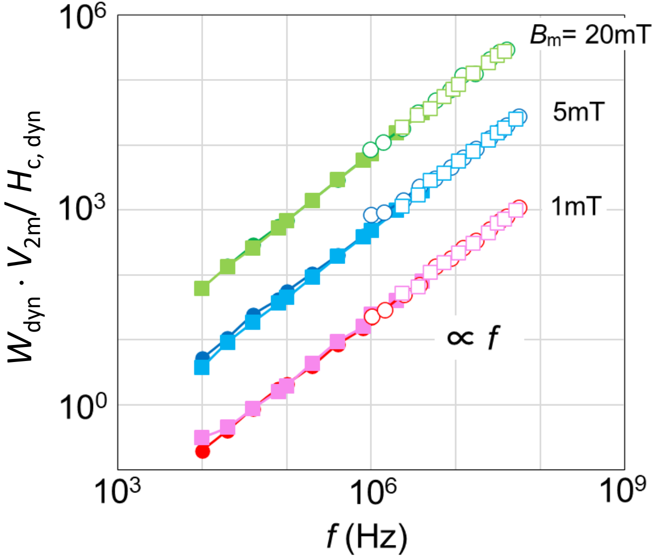
$$V_{\mathrm{m}}/H_{\mathrm{c\ dyn}} = 2B_{\mathrm{s}}nd/\beta \propto f^{u}$$

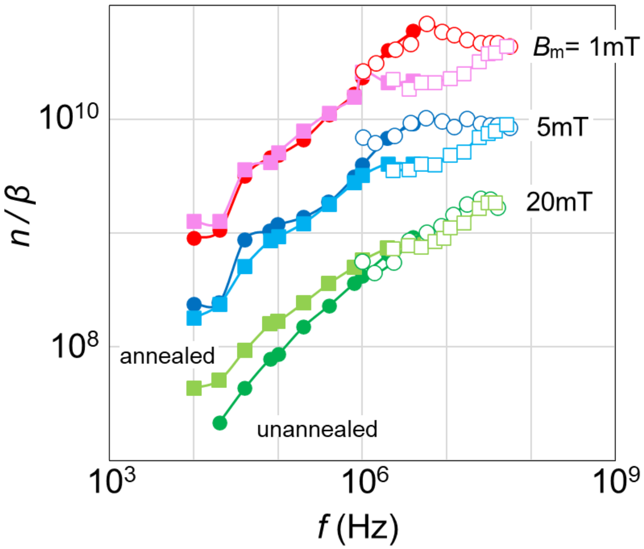
$$\boxed{P_{\mathrm{c\ dyn}} \cdot V_{\mathrm{m}}/H_{\mathrm{c\ dyn}} \propto f^{(u+v)},\ u+v = 2}$$

V_{m}: Output voltage amplitude
B_{s}: Saturation magnetic flux density
d: Sample thickness
β: Domain wall damping

[Sakaki, IEEE Trans Magn MAG-16, 569 (1980)]
[Sakaki, IEEE Trans Magn MAG-17, 1478 (1981)]
[Sakaki, IEEE Trans Magn MAG-20, 1487 (1984)]

Sendust dust core





Frequencies for saturation of *n* is the same with that of magnetization reversal change

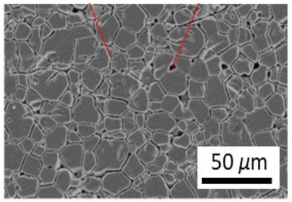
Permeability Analysis for Various Materials

[Ono, SO, JMMM 603 (2024) 172222]

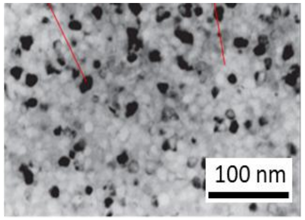
Sample	d (μm)*	h (mm) *	ρ_{AC} (Ωm)**	J_s (T) *	μ_{ri}**
Mn-Zn ferrite sintered core	11	4.9	7.8	0.51	2,900
FINEMET wound core	18	4.4	0.068	0.90	50,000
Sendust powder core	11	1.0	0.39	0.73	30

*: from data sheets. **: from measurements.

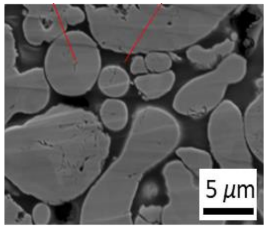
Mn-Zn ferrite

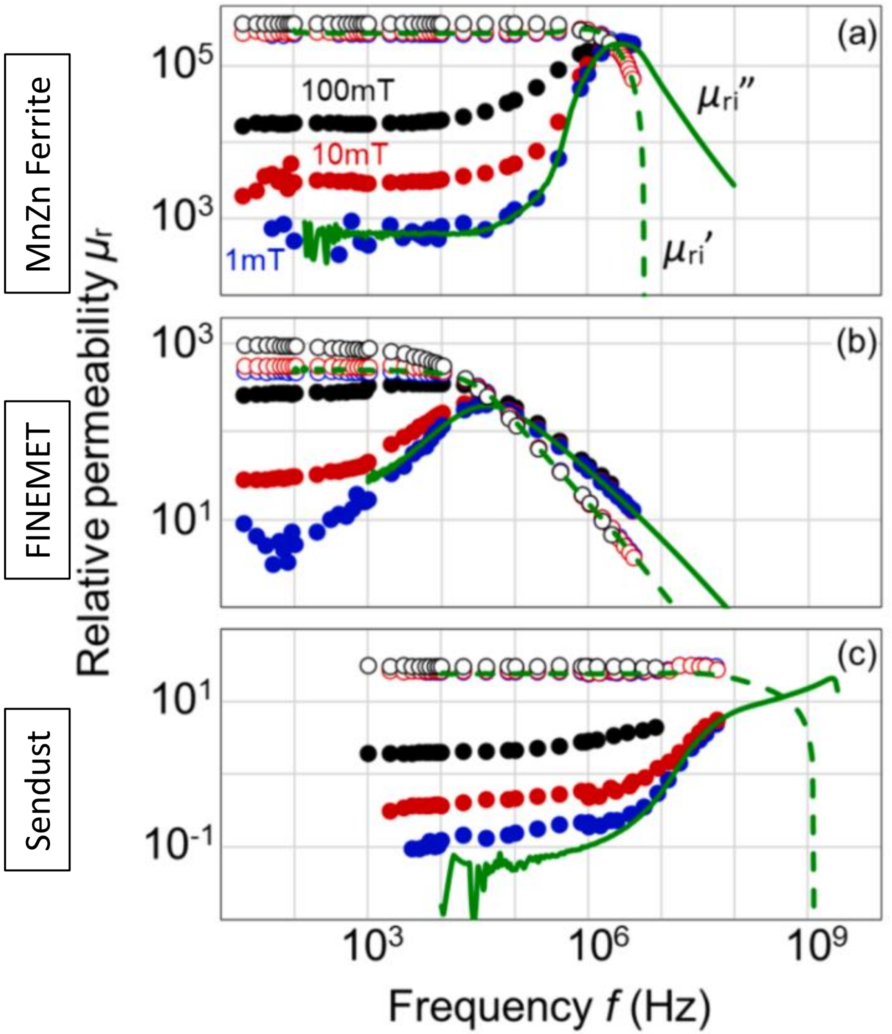


FINEMET



Sendust

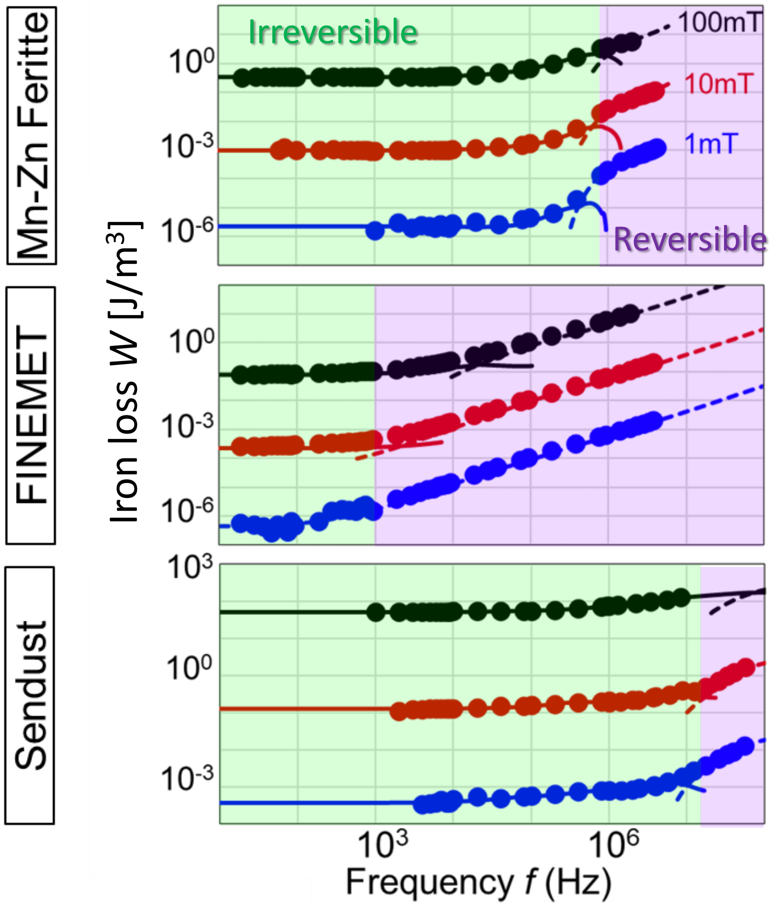




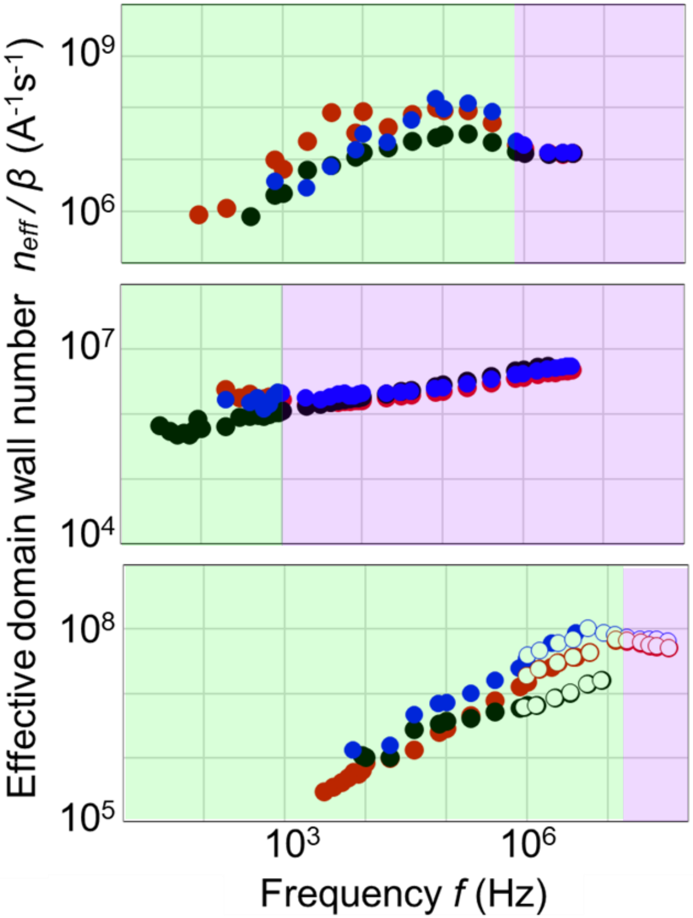
Broadband Iron Loss Analyses for Various Materials

[Ono, SO, JMMM 603 (2024) 172222]

Magnetization process decomposition



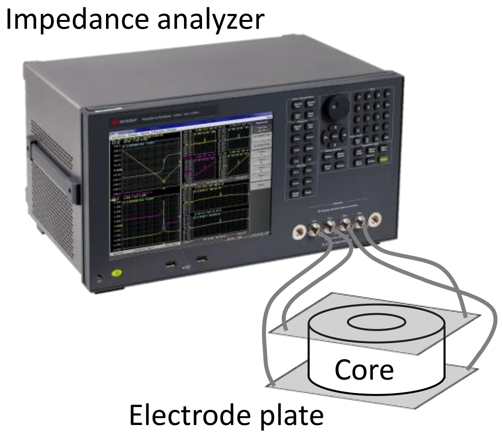
Effective Domain Wall Number

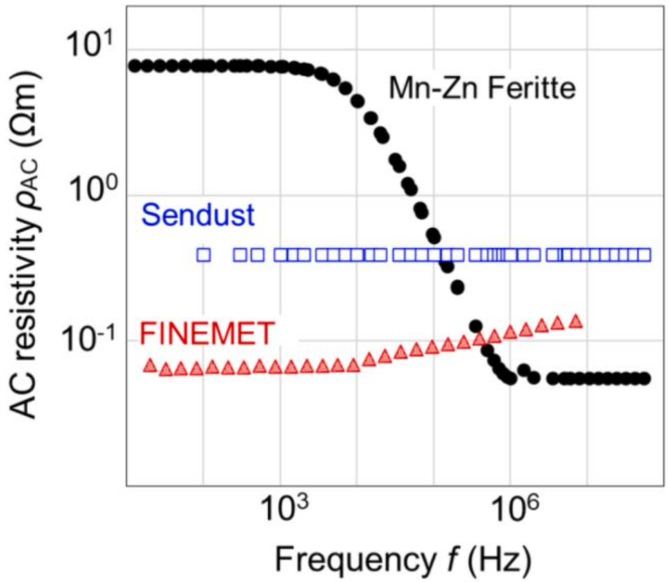


Low frequency : Wall displacement
High frequency : Rotation

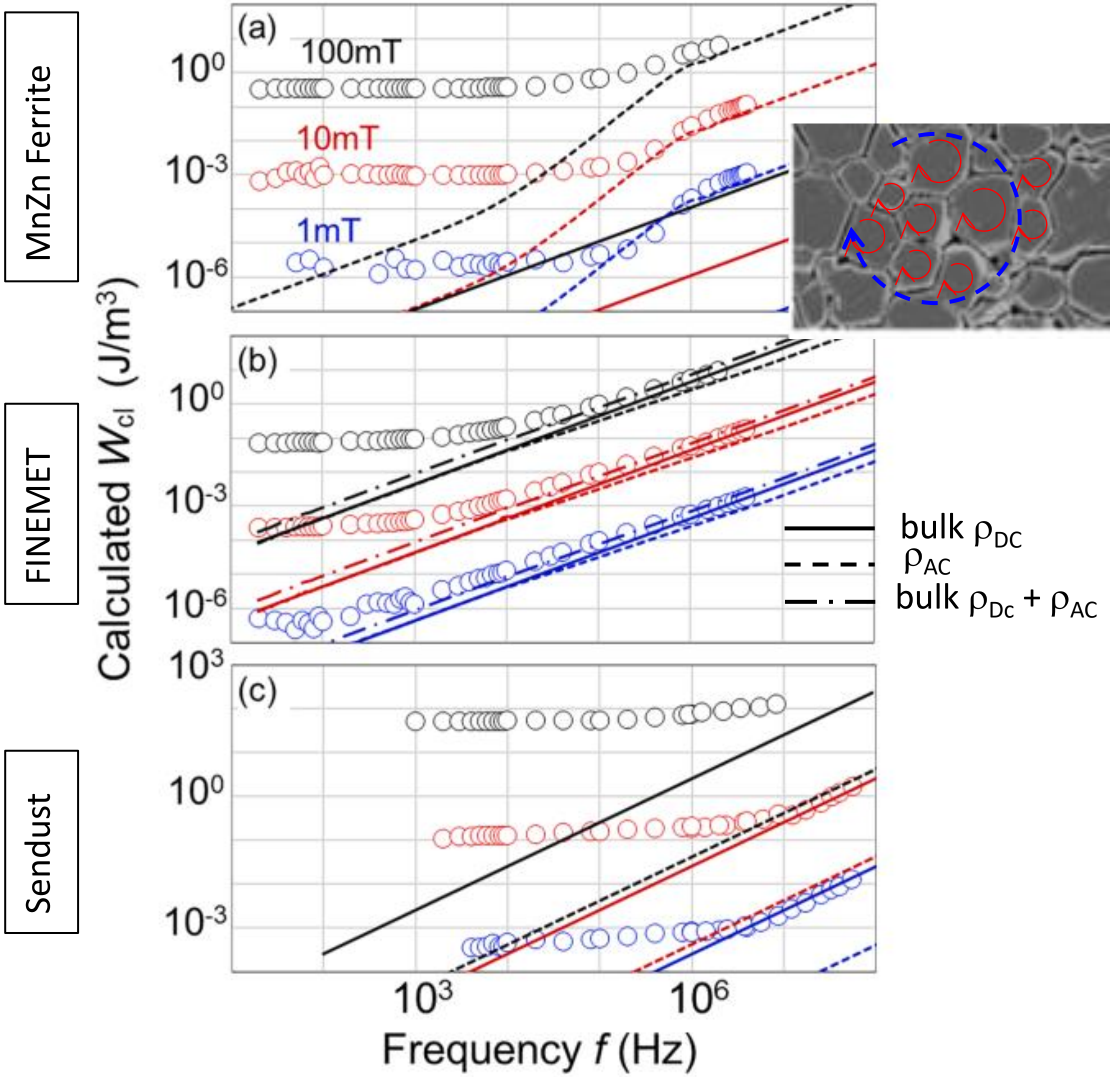
Comparison with Classical Models (Classical Eddy Current Loss)

[Ono, SO, JMMM 603 (2024) 172222]





Classical eddy current loss evaluation



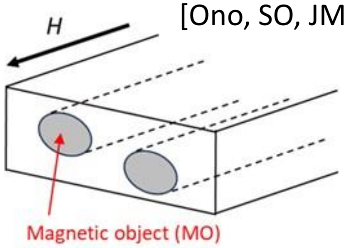
Comparison with Statistic and Steinmetz Analyses

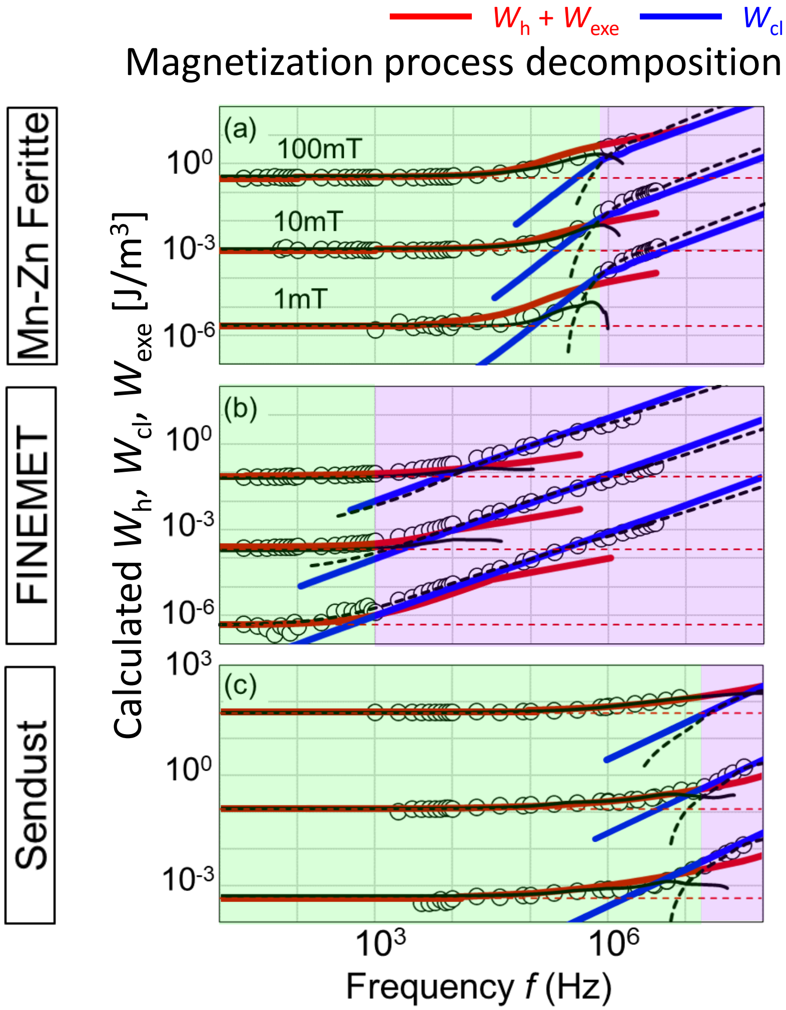
Statistic Model Standard theory for excess loss

[Ono, SO, JMMM 603 (2024) 172222]

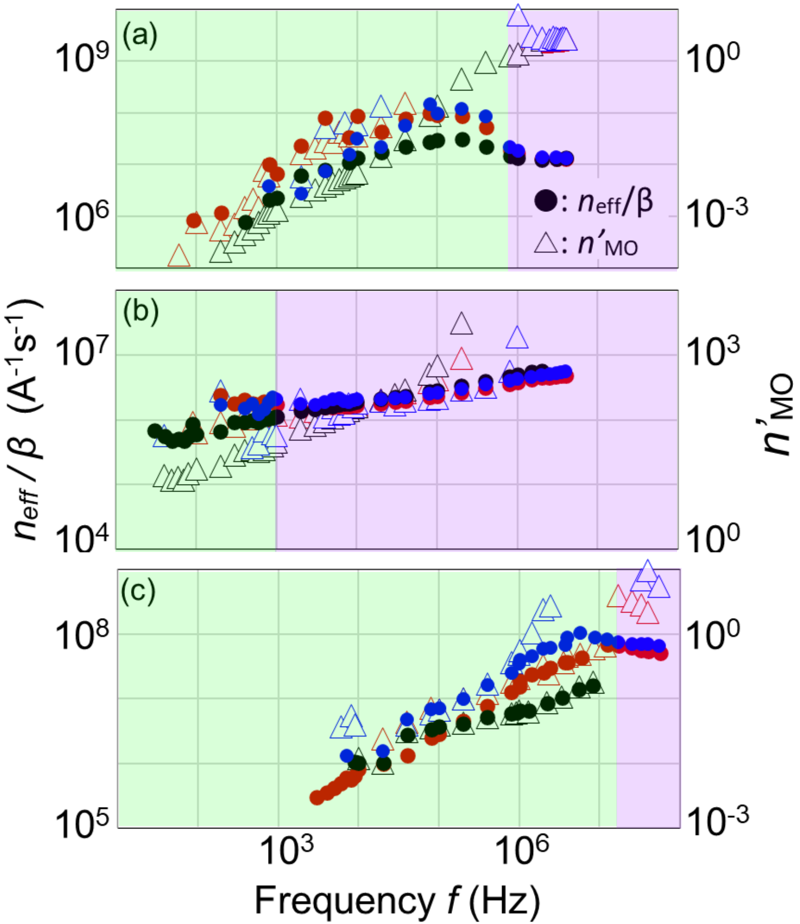
$$n_{\mathrm{MO}}(H_{\mathrm{exc}}) = n_{\mathrm{MO}}(0) + \frac{H_{\mathrm{exc}}}{V_0}, \; W_{\mathrm{exc}} = 8\sqrt{\sigma G S V_0}\, B_{\mathrm{m}}^{1.5} f^{0.5}$$

[Bertotti, JAP 57, 2110 (1985)]




Magnetization process decomposition

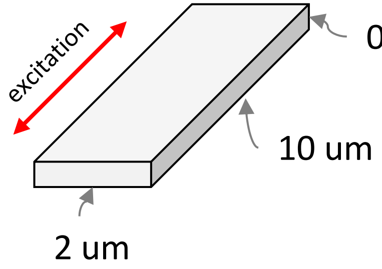
Effective Domain Wall Number



Contents

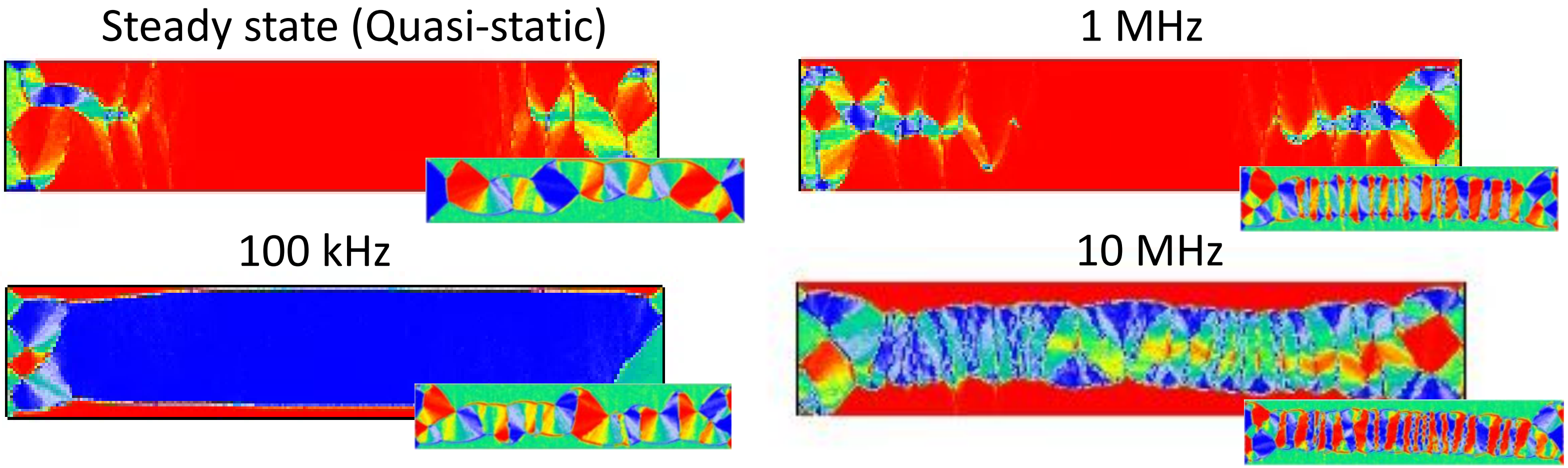
Contents

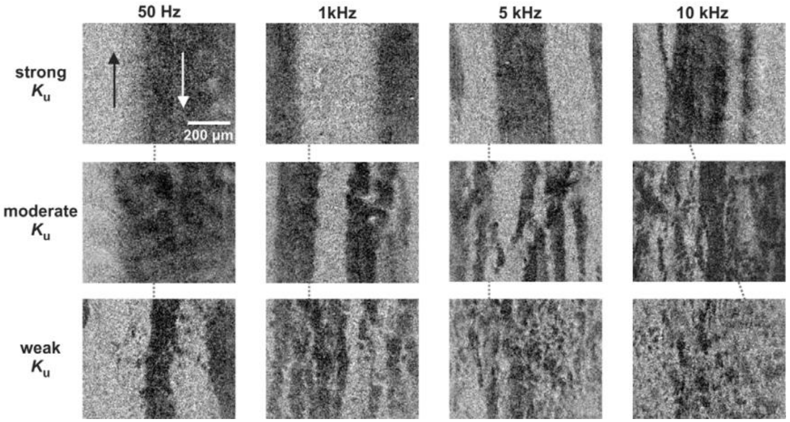
Micromagnetics Simulation



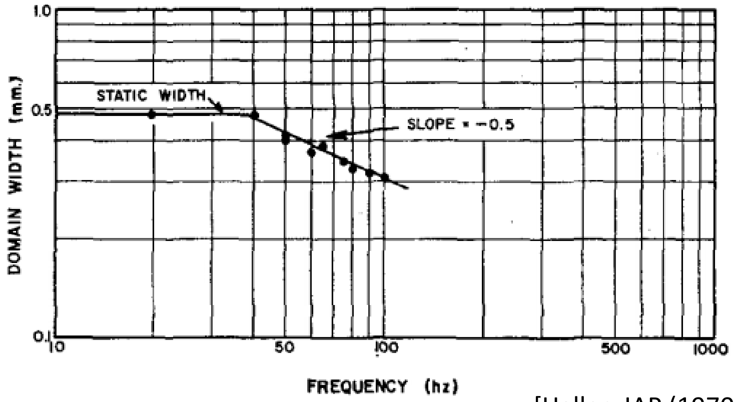
Mesh cell size : 10nm (1 mesh correspond as one grain)
Ribbon : 10^6 elements
Air : 1.8×10^7 elements

Optimizations of calculation condition and algorism





[Flohrer, Acta Mater (2006)]

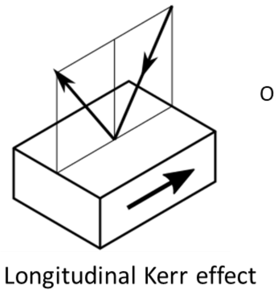


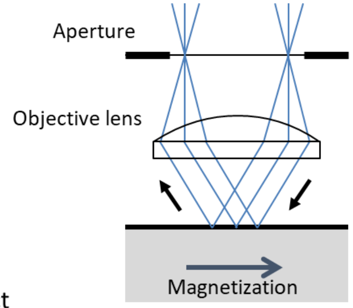
[Haller, JAP (1970)]

Vector MOKE Microscopy

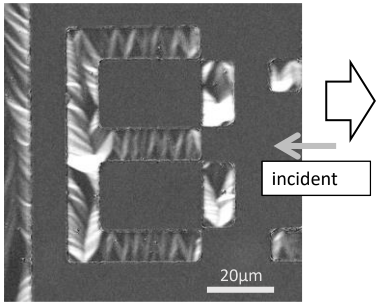
Dr. Ogasawara

Conventional μ-MOKE

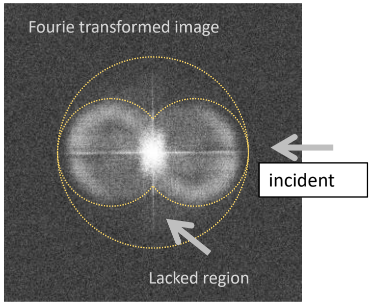

Longitudinal Kerr effect



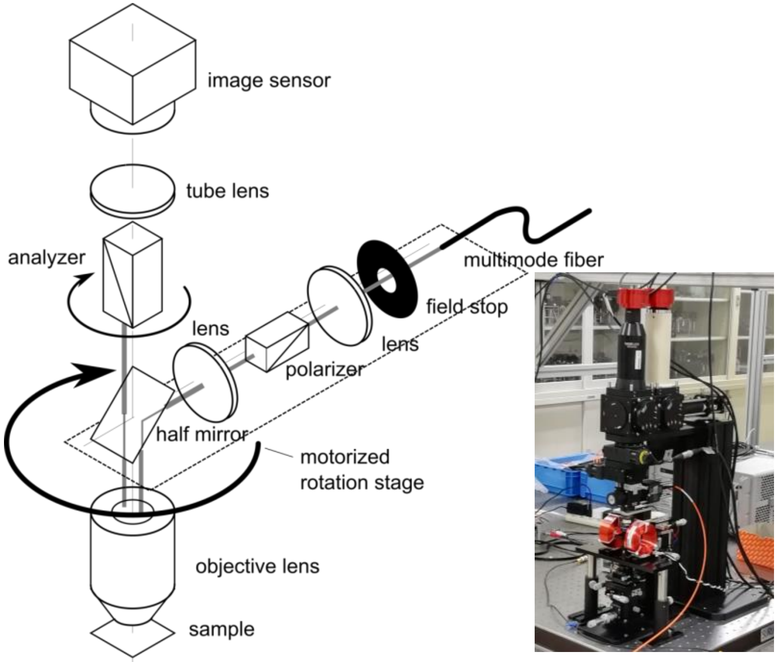
MOKE image



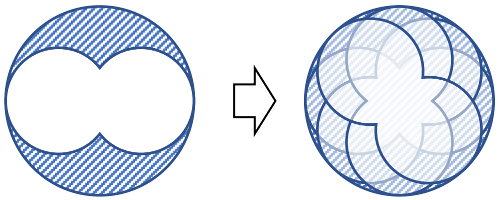
FFT

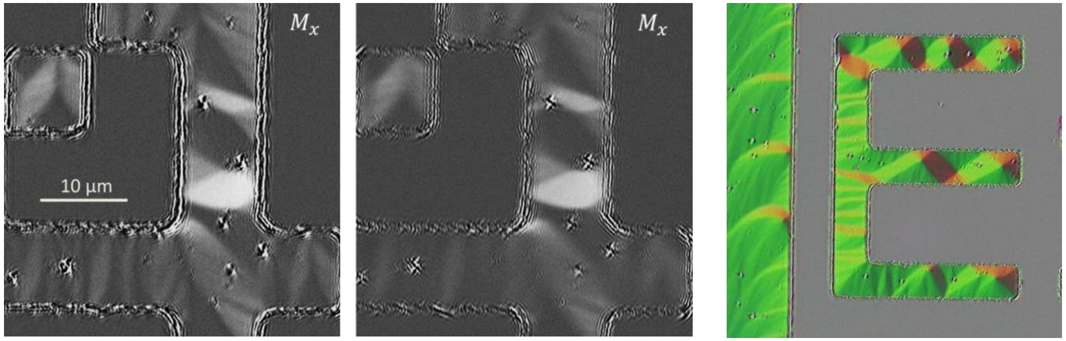


Newly developed Vector μ-MOKE



Conventional This method





High resolution and vector magnetization

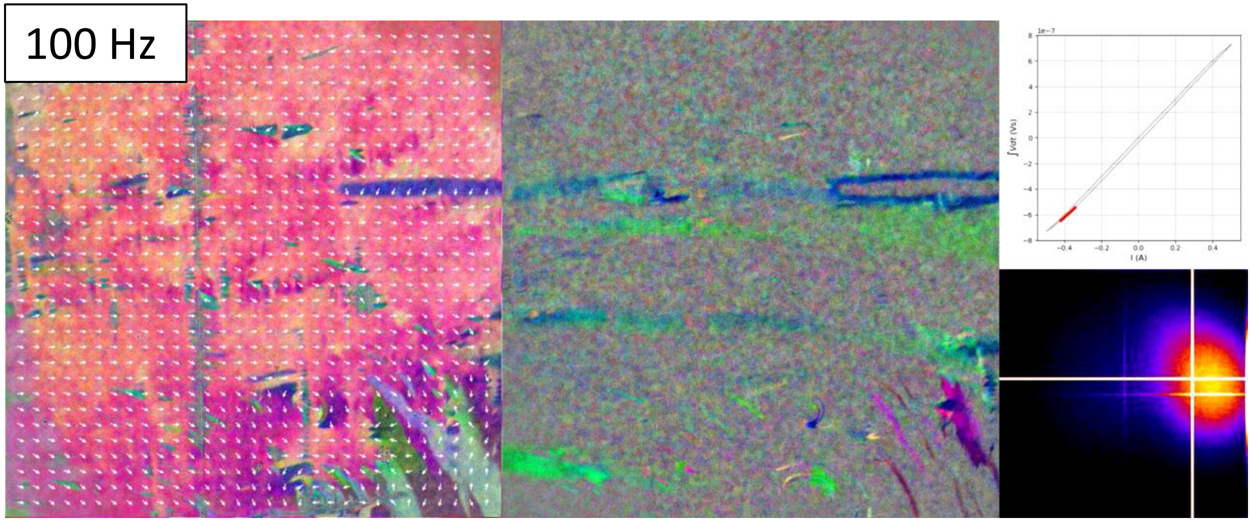
T. Ogasawara, Jpn. J. Appl. Phys. 56, 108002 (2017).

Time-Resolved Vector MOKE Microscopy

Dr. Ogasawara

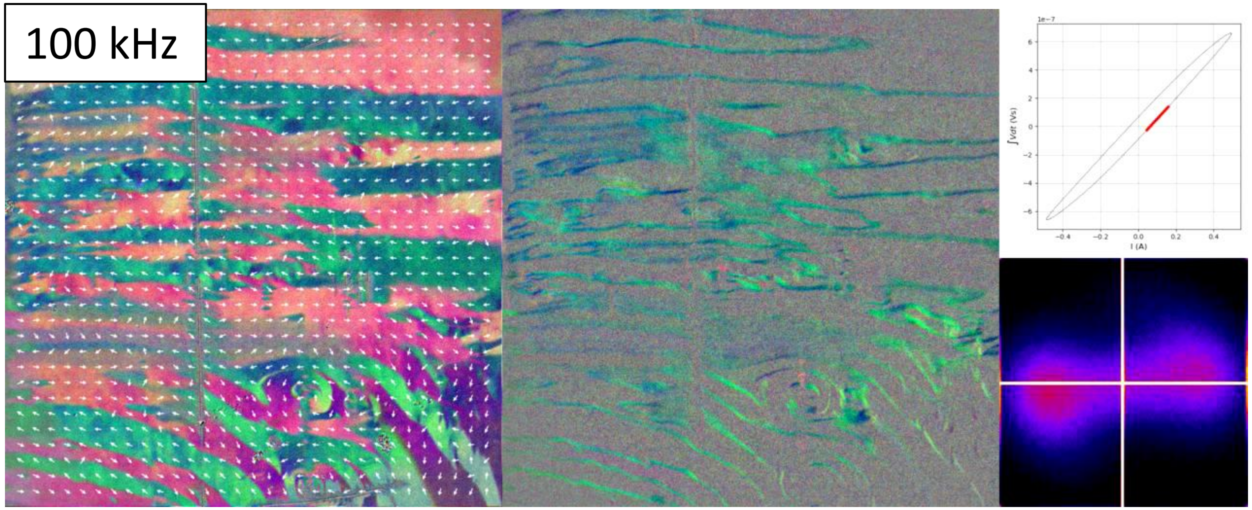
NANOMET ribbon

Differential

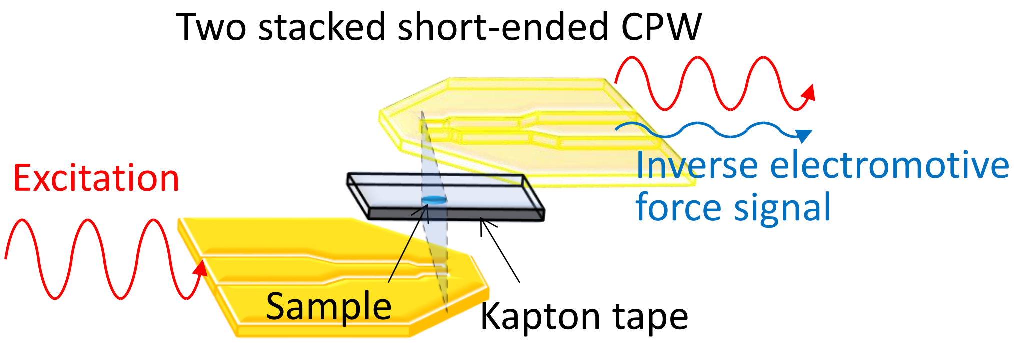


B-H

Vector histogram



Permeability Measurement for a Single Particle



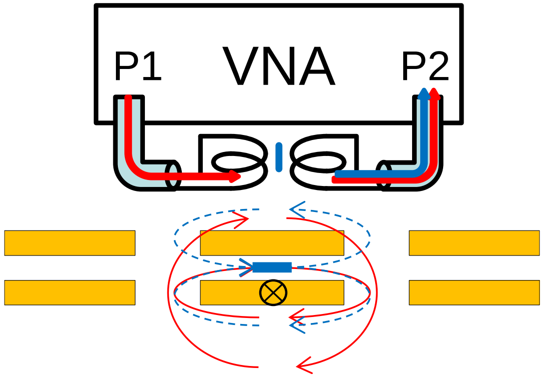
Two stacked short-ended CPW

Excitation

Inverse electromotive force signal

Sample

Kapton tape

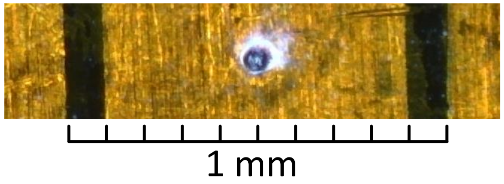


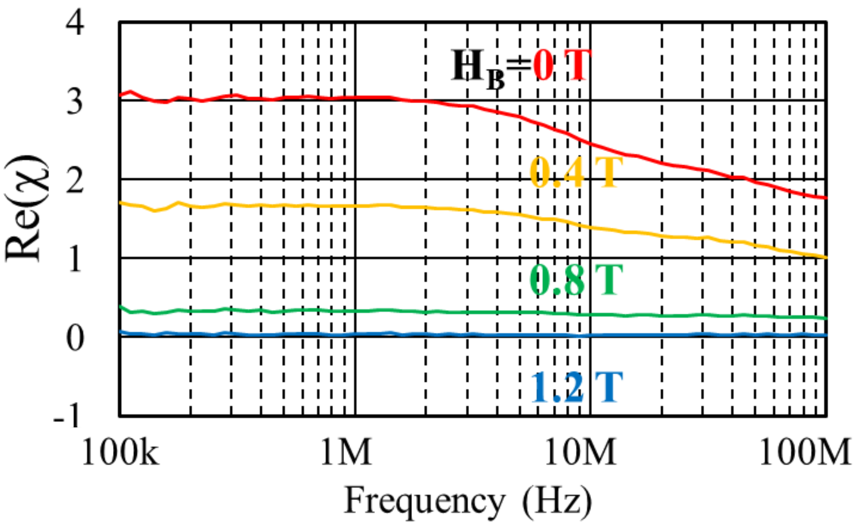
Dr. Tamaru

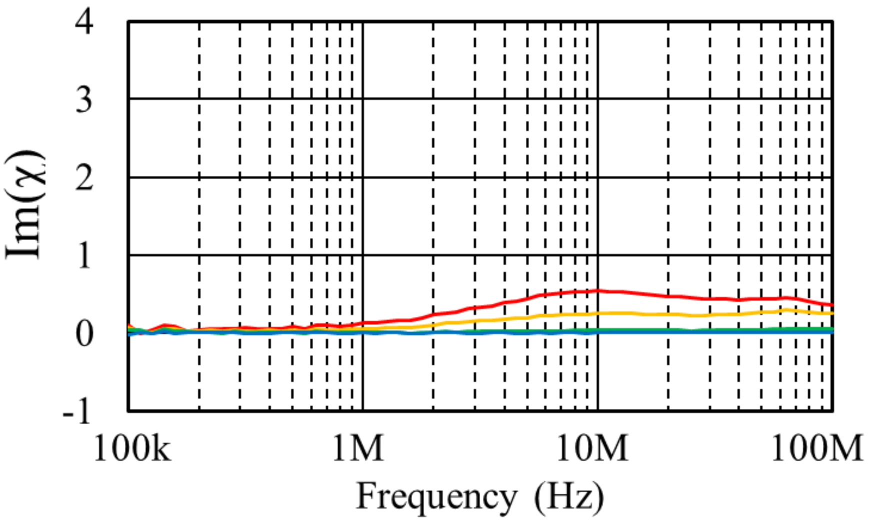
Fe$_2$B atomized particle

B_s ~ 1.6 T

Diameter ~ 50 μm







Prospects and Future Works

Loss Mechanism

- Magnetization dynamics including energy dissipation mechanism
- Non-eddy current origin loss mechanism

Measurements

- Accurate loss measurement under triangular wave
- High-throughput measurements

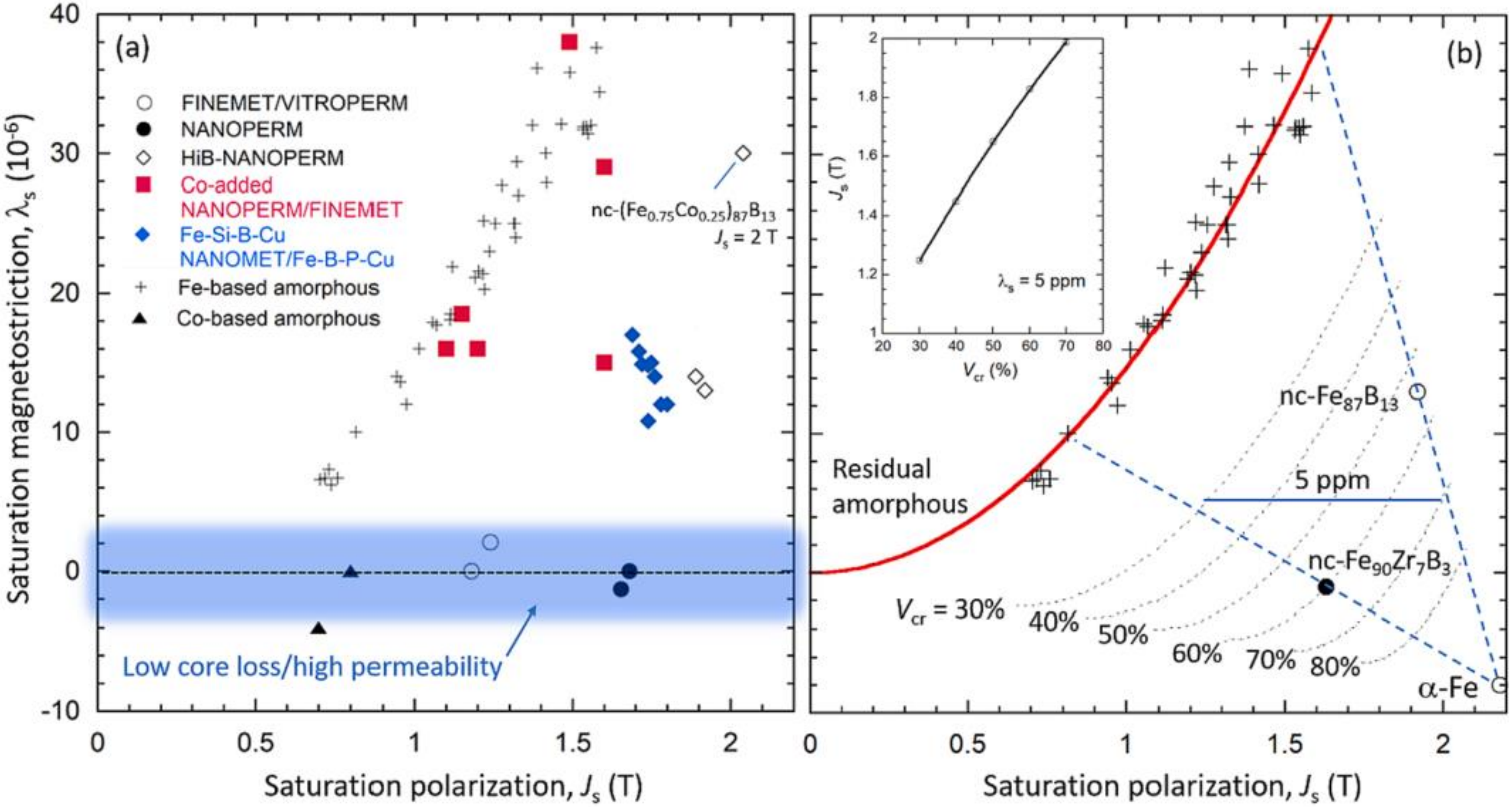
Material Design and Developments

- Multivariable optimization of nc-material
- Point focused optimization, ex. lowering core loss for specific frequency range

Optimization for Power-Electronics Circuit

- Total optimization of power-electronics circuit
- Inverse problem of magnetic core design

Material Design Prospect for High-M_s nc-Ribbons



[Suzuki, JMMM (2024)]

TOHOKU UNIVERSITY

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Collaborators

TOHOKU UNIVERSITY
Mr. N. Ono, Mr. T. Onuma, Dr. H. Tsukahara, Prof. T. Taniguchi,
Prof. Y. Endo, Prof. S. Yoshida

NIMS
Dr. G. Ravi, Dr. H.Sepehri-Amin, Dr. T. Ohkubo

Prof. K. Wada

Magnetic Device Laboratory Ltd.
Dr. Y. Uehara

Prof. Y. Sato

Prof. H. Matsumori

Prof. M. Kotsugi

KYOTO UNIVERSITY FOUNDED 1897
Prof. T. Matsuo

FUJITSU
Dr. T. Tanaka

AIST
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)
Dr. Tamaru, Dr. Ogasawara

TMI
Tohoku Magnet Institute
Mr. S. Hiramoto, Mr. T. Miyatake

TOKIN
Dr. A. Urata, Mr. H. Oikawa

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Prof. K. Suzuki

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