



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)

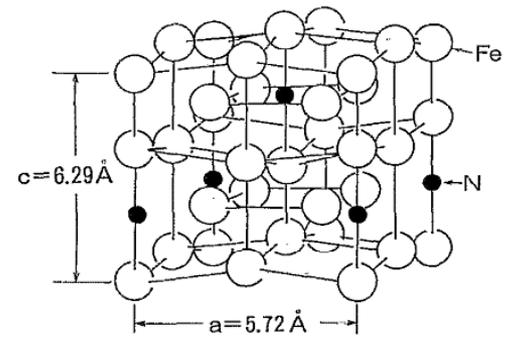
出身

滋賀県大津市



1997 Ph. D from Tohoku U

Fabrication of α'' -Fe₁₆N₂ phase and its magnetic properties



Data storage

2000 L1₀-FePt

2005 Graded media

2010 MAMR

2015 

2020

JST project

Permanent magnet



Thermally activated reversal process

FORC x μ -XMCD

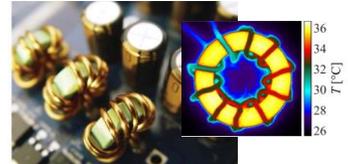
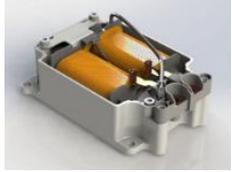
Magnetic tomography

Data science approach

ESICMM

DXMag

Soft magnetic materials

Passive device and materials for power electronics

INNOPEL

NEDO

1. Overview of Soft Magnet Application and History
2. Basics on Static Soft Magnetic Properties
3. Questions on Energy Losses in Soft Magnets
4. Various Loss Analysis Models
5. Accurate Loss Evaluation
6. Broadband Loss Analysis
7. Advanced Analyses

Categorization of Magnetic Materials and Their Applications

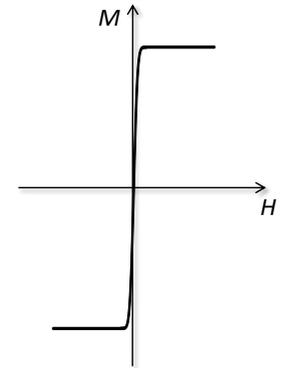
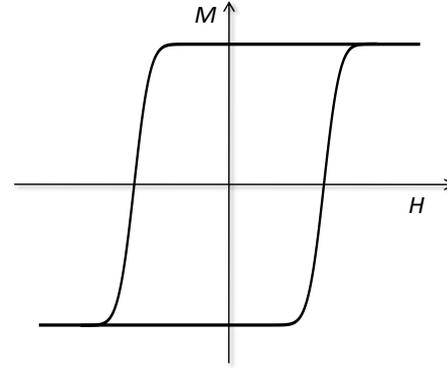
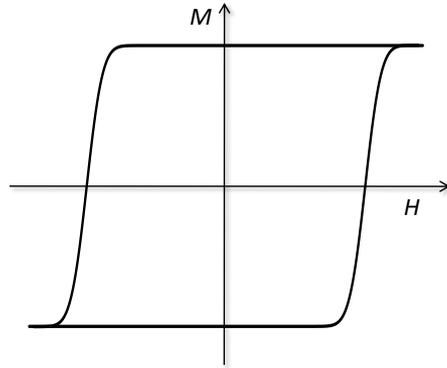
Category

Hard magnet

Semi-hard magnet

Soft magnet

Hysteresis



Coercivity H_c

Large

Middle

Small

Applications

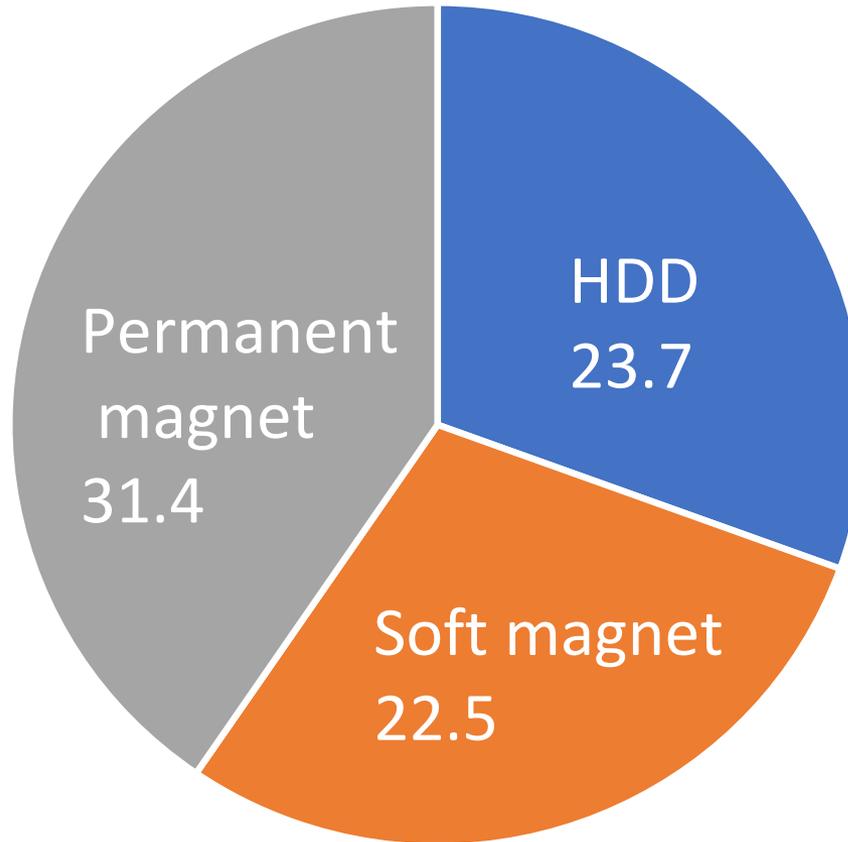
Permanent magnet (Motor)

Data Storage (HDD)

Too Many



Total 77.6 Billion USD



Billion USD
(2021)

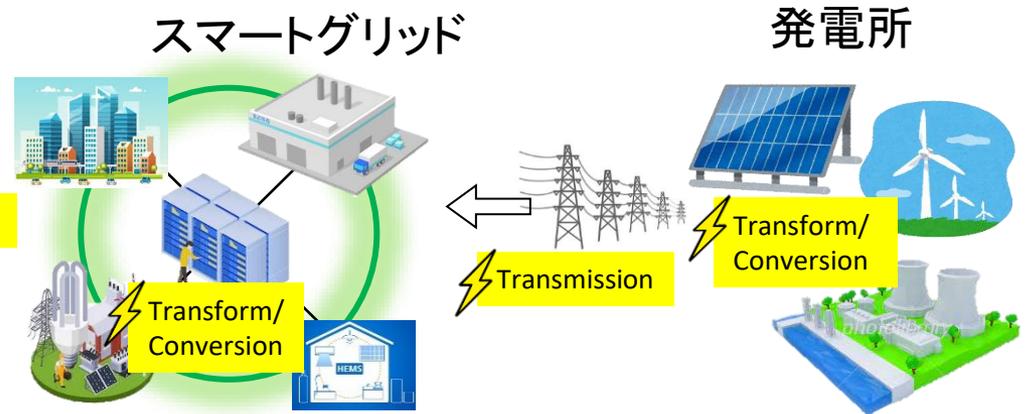
低損失軟磁性材料

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

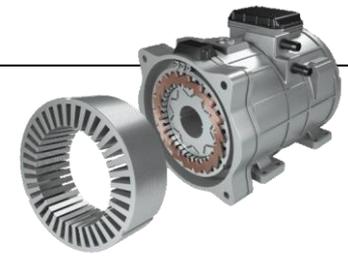
電源/電力制御



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



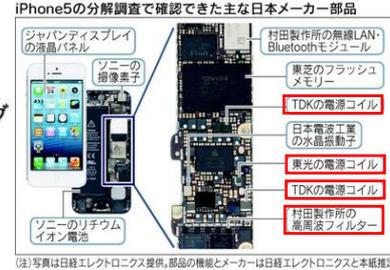
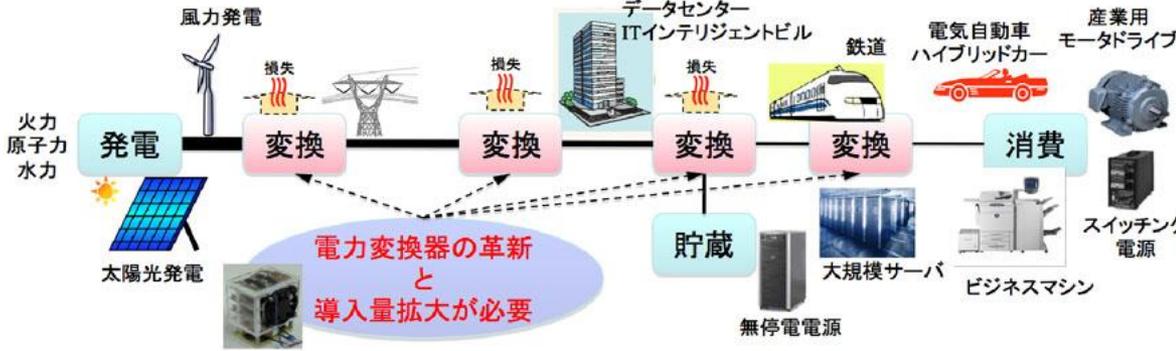
■ パワーエレクトロニクス

高性能パワー半導体
+ 低損失軟磁性材料

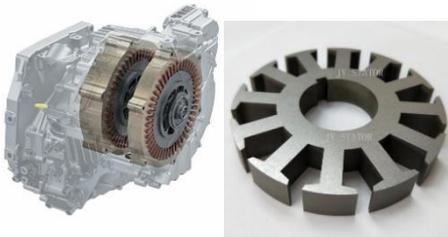


Various Applications of Soft Magnetic Materials

Passive devices of power electronics



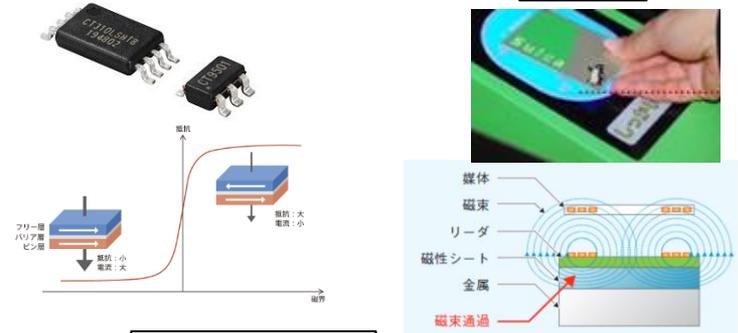
Motor core



Sensor



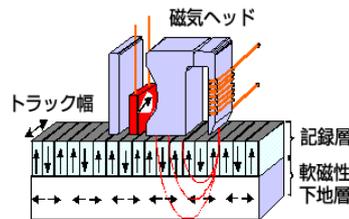
RFID



Electromagnet



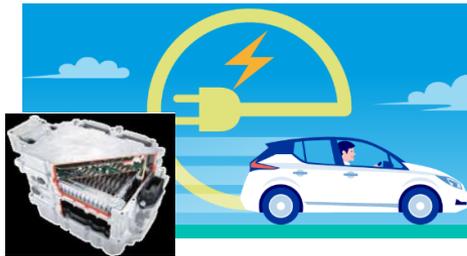
Recording head



Noise filter



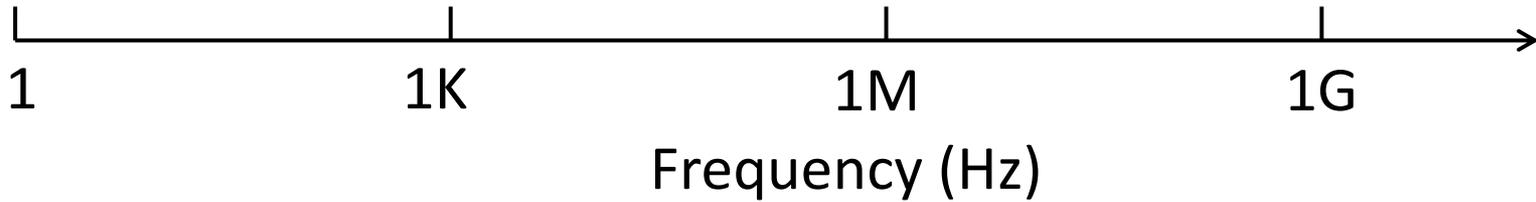
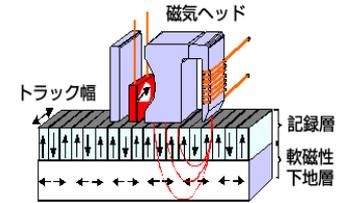
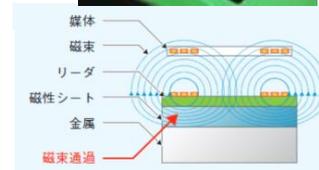
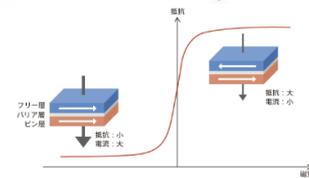
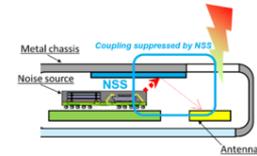
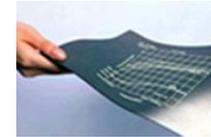
Operation Frequency of Soft Magnetic Materials



iPhone5の分解調査で確認できた主な日本メーカー部品

- ジャパンディスプレイの液晶パネル
- ソニーの撮像素子
- ソニーのリチウムイオン電池
- 村田製作所の無線LAN・Bluetoothモジュール
- 東芝のフラッシュメモリー
- TDKの電源コイル
- 日本電産工業の水晶振動子
- 東光の電源コイル
- TDKの電源コイル
- 村田製作所の高周波フィルター

(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



Electric mobility



Energy management

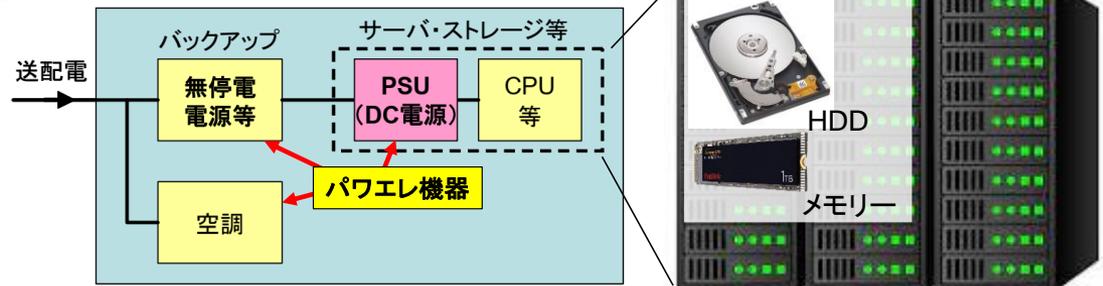
Stabilization, optimization, energy saving of power transmission & power distribution systems



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

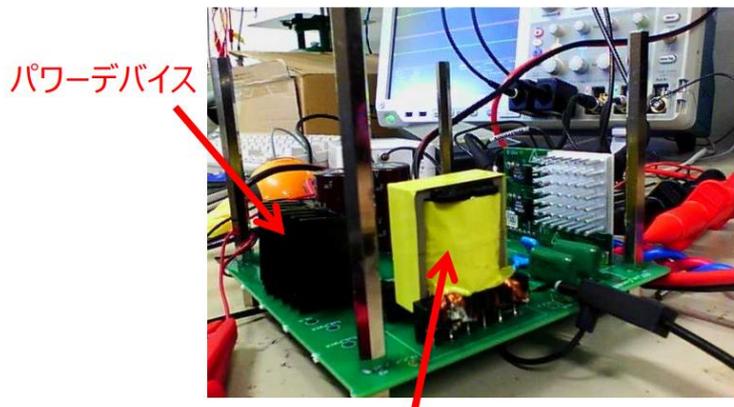
ICT

Data center

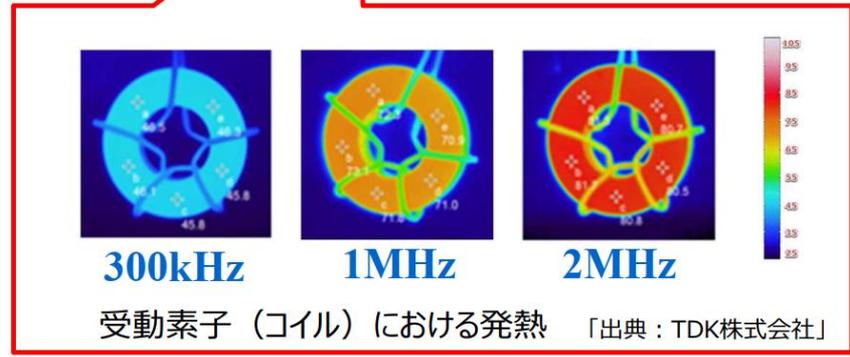
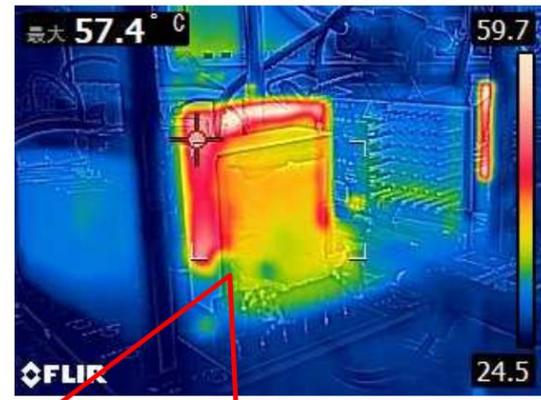


[NEDO 2021]

Loss in Magnetic Devices of Power Electronics



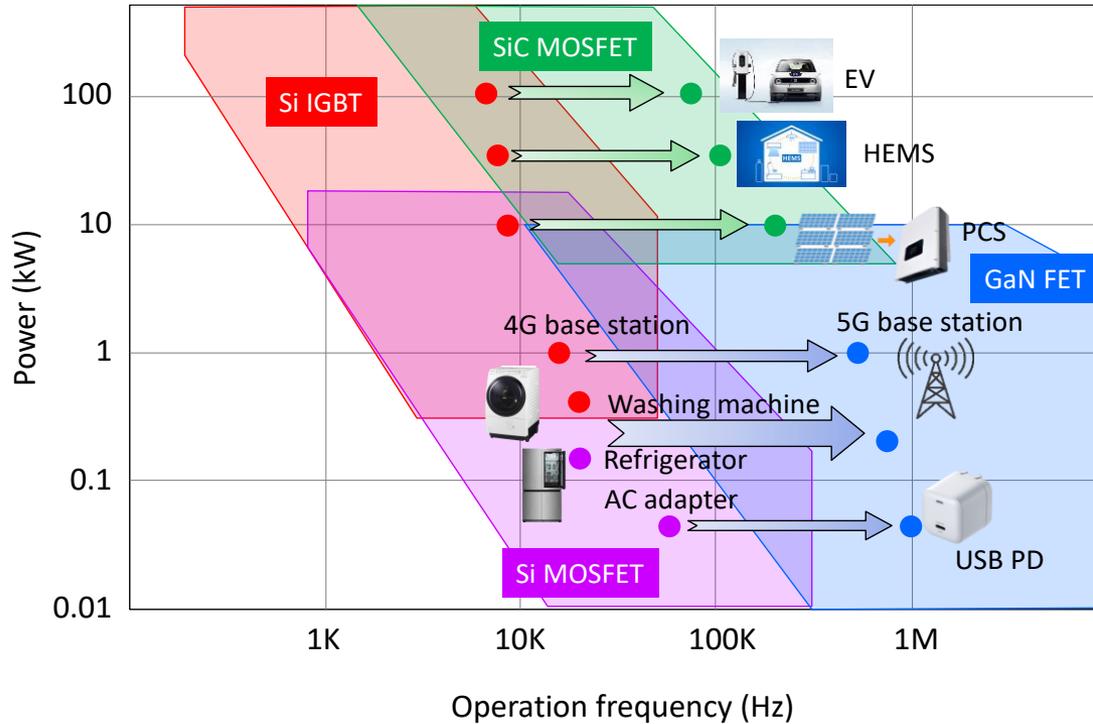
受動素子 (コイル)



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**

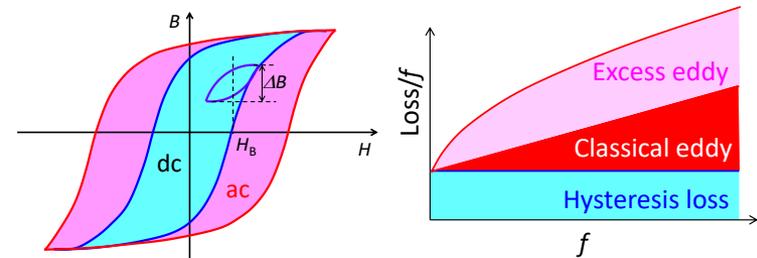
Soft Magnetic Materials in Advanced Power Electronics



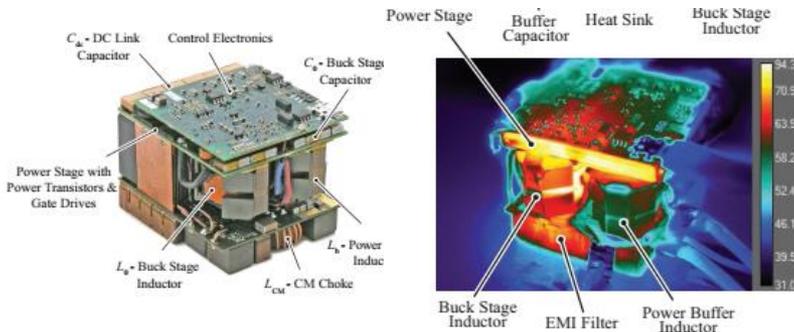
Next generation power semiconductors SiC, GaN

Toward high frequency switching

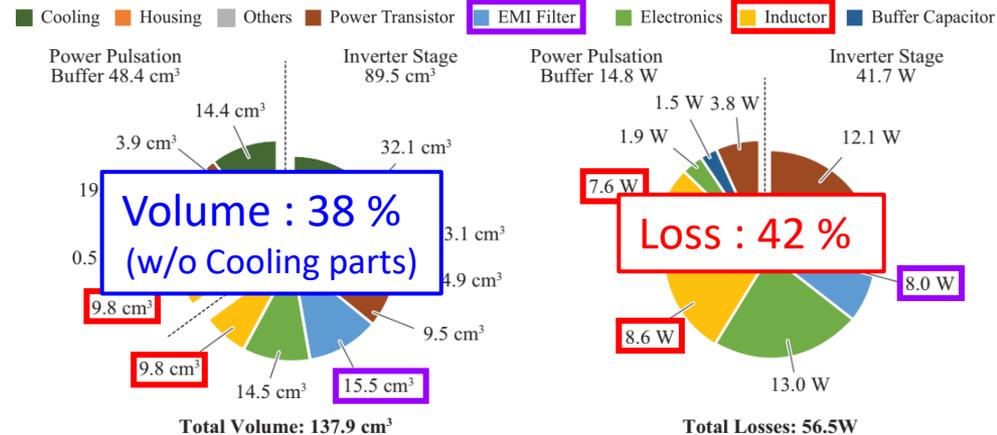
⇒ Significant iron loss in magnetic passive devices



Google Little Box Challenge (GLBC)



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



Magnetic passive devices



History of Soft Magnetic Studies

Materials

- 1889 Fe-Ni, Hopkinson
- 1900 Fe-Si, Hadfield
- 1916 Permalloy, Elmen
- 1932 Sendust (Fe₈₅Al₅Si₁₀), Masumoto
- 1934 Cold-rolled electrical steel, Goss
- 1947 Supermalloy, Boothby and Bozorth
- 1950 MnZn Ferrite, Guillaud and Barbezat
- 1957 NiZn Ferrite, Kornetzki
- 1967 Ferromagnetic amorphous, Duwez
- 1973 Metglas, AlliedSignal
- 1988 FINEMET(nc-Fe-Nb-Si-Cu-B), Yoshizawa
- 1990 nc-Fe-Zr-Cu-B, Suzuki
- 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

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

Present

Strong demand for high- M_s and low loss materials



Large gap

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

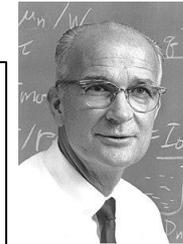
VOLUME 80, NUMBER 6

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, Schenectady, 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 Magnetism

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]



「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」

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

1. Overview of Soft Magnet Application and History
- 2. Basics on Static Soft Magnetic Properties**
3. Questions on Energy Losses in Soft Magnets
4. Various Loss Analysis Models
5. Accurate Loss Evaluation
6. Broadband Loss Analysis
7. Advanced Analyses

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 iron loss P up to high frequency

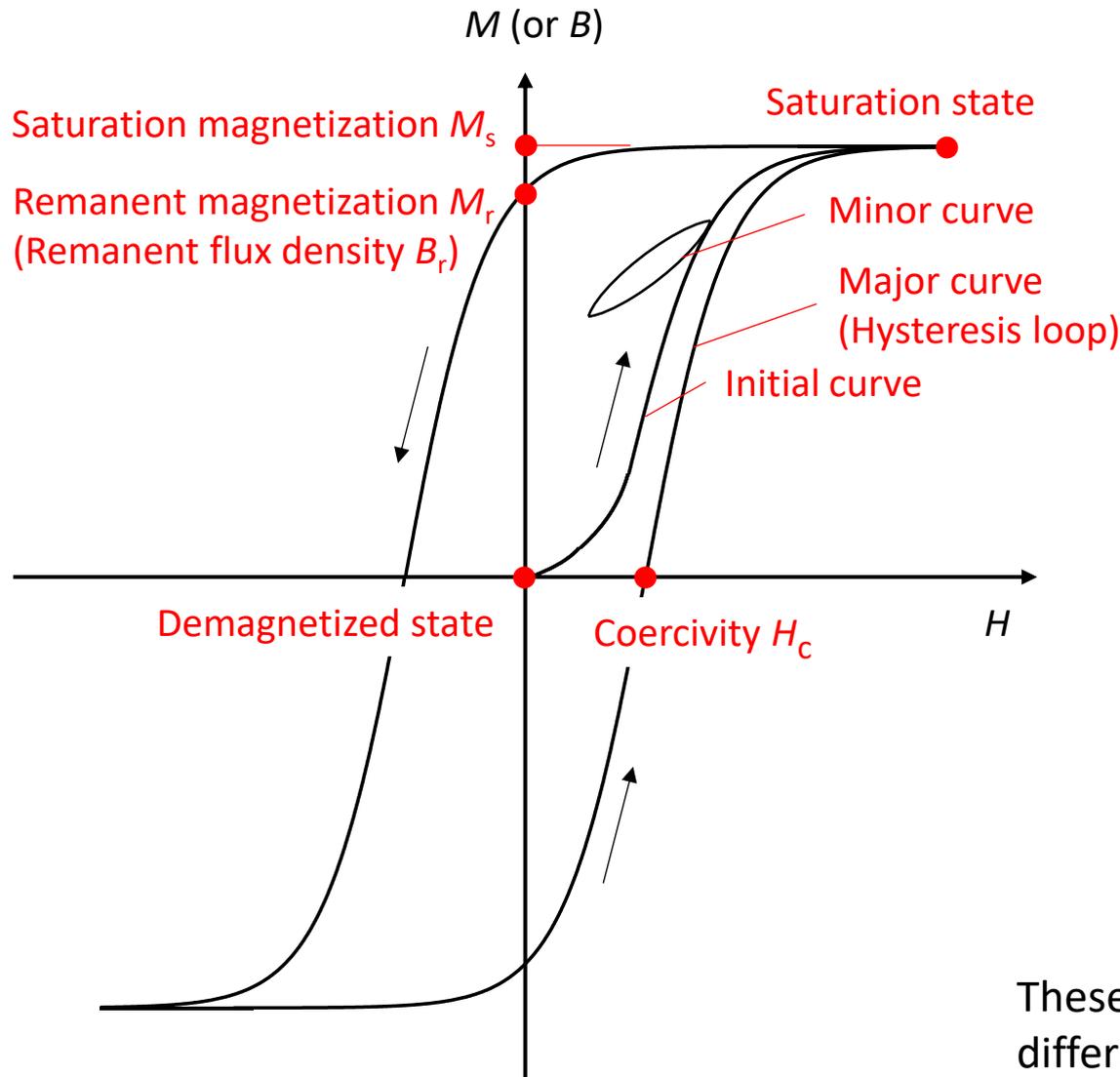
Q1

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

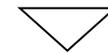


In SI unit,

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

Unit conversion

$$1 \text{ kA/m} : 1.254 \text{ mT}$$



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

$$M = \chi H \quad \chi [\text{no unit}]$$

$$B = \mu H \quad \mu [\text{H/m}]$$

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

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

Definitions of Permeability

電気専門用語集 (WEB版)

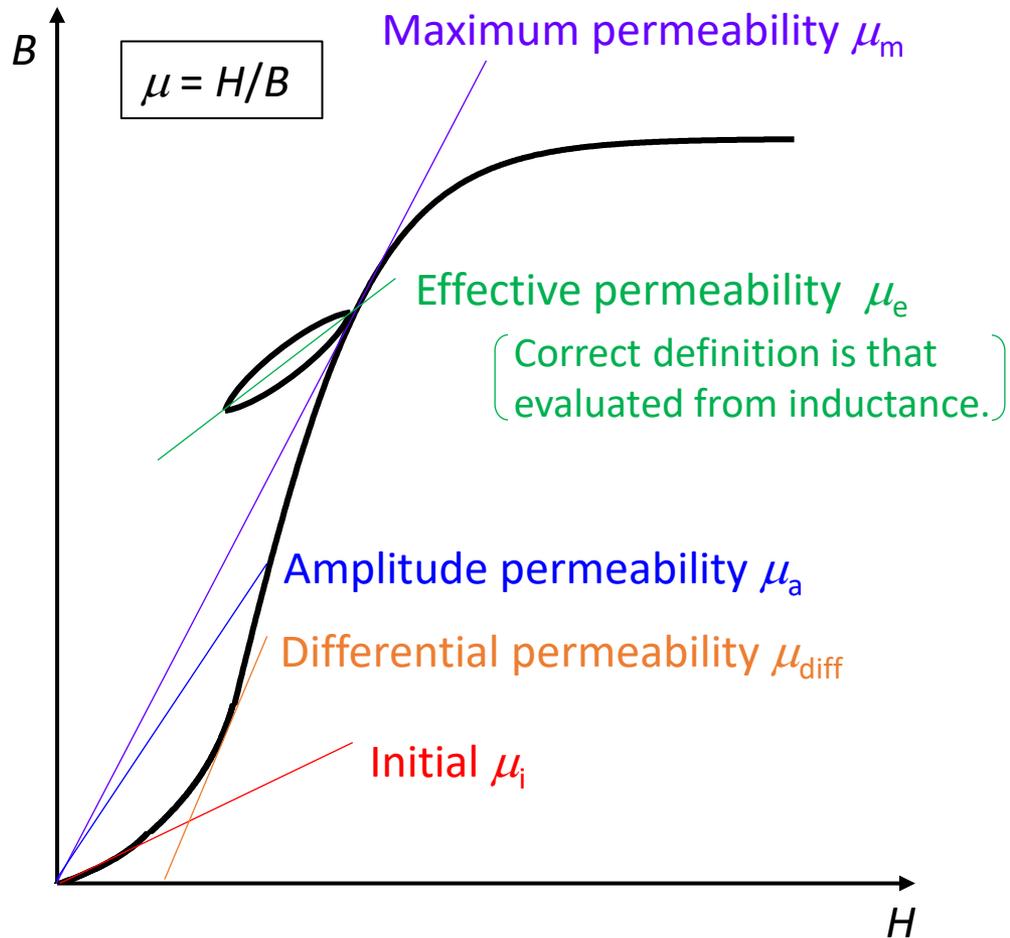
[https://jec-ieee.org/jec_ev/index_00.php]

「透磁率」で検索すると...

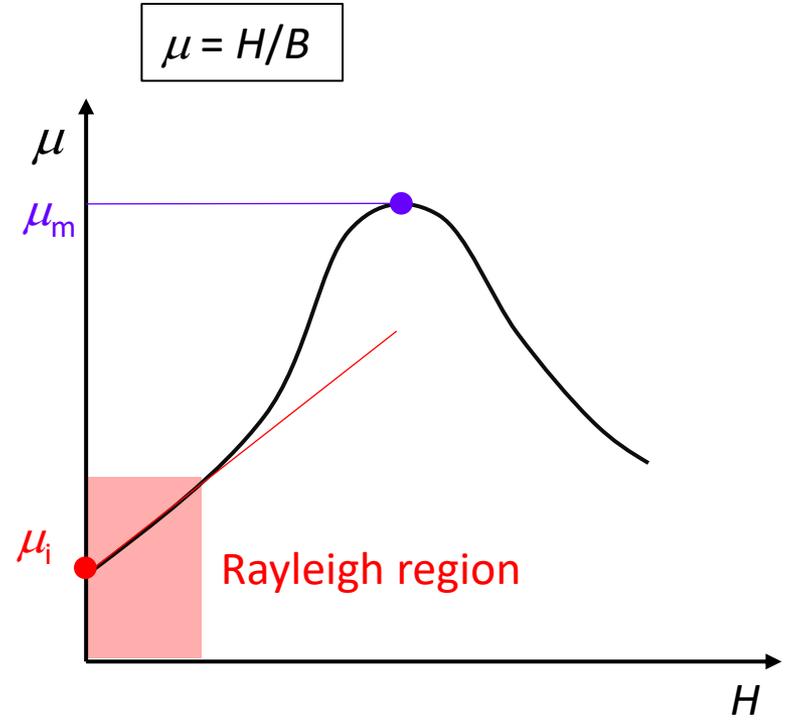
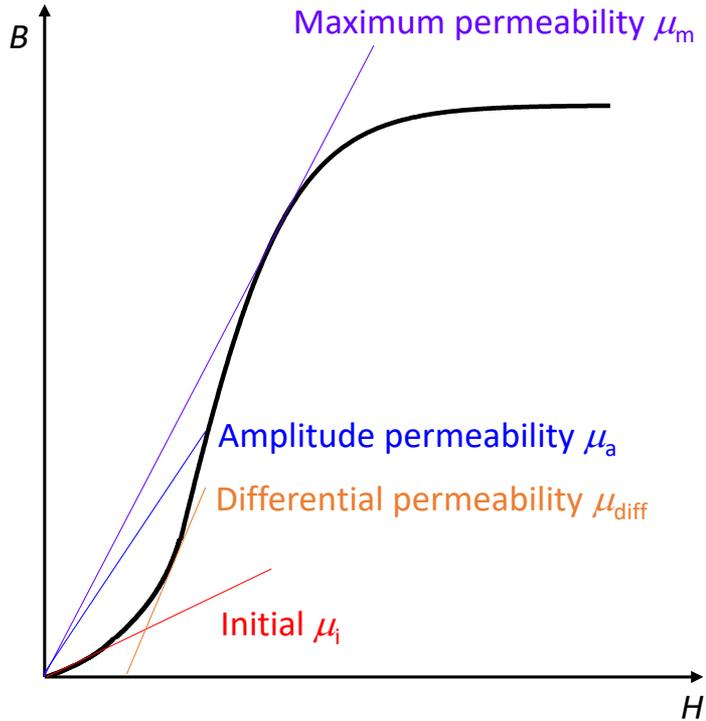


用語番号, 用語, 用語集No.

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



Rayleigh Region



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

$$\Rightarrow \mu = \underbrace{\mu_i}_{\text{Reversible component}} + \underbrace{\nu H}_{\text{Irreversible component}}$$

Reversible component (Magnetization rotation)
Irreversible component (Domain displacement)

Loop area (Hysteresis loss)

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

Coercivity (Coercive Force)

Why H_c is called as coercive force?

When 180° domain wall is assumed,

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

Non-uniformity increases H_c .

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

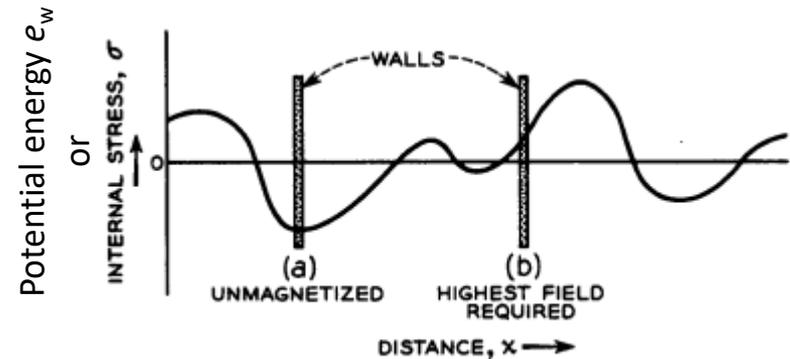
$$H_c \approx (\lambda_s \delta / 2M_s) (d\sigma/dx)_{\max}$$

λ_s : Saturation magnetostriction

δ : Wall thickness

λ_s affects H_c through non-uniform strain.

Spatial fluctuation of potential energy e_w



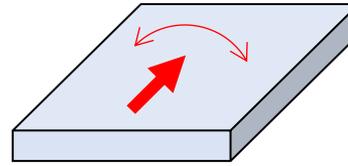
[Bozorth, Ferromagnetism (1951)]

In other words, H_c can decrease when uniformity improves.

Permeability

Magnetization rotation

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



ex) Fe ($\mu_0 M_s = 2.15$ T, $K = 42$ kJ/m³) $\mu_{ri} \approx 30$
 Fe 6.5wt.Si ($\mu_0 M_s = 1.8$ T, $K \approx 20$ kJ/m³) $\mu_{ri} \approx 40$

For $\mu_{ri} > 10,000$, $K < 10$ 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

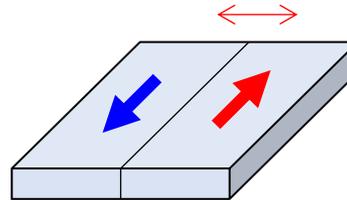
材料	板厚 (mm)	固有抵抗 ($\mu\Omega\cdot m$)	直流最大比透磁率	飽和磁化 (T)	磁束密度 B_s (T)	磁束密度 B_{25} (T)	磁歪 $\lambda_{10/400}$ ($\times 10^{-6}$)
JNEXコア	0.10	0.82	23,000	1.80	1.29	1.40	0.1
方向性けい素鋼板	0.05	0.48	—	2.03	1.75	—	—
	0.10		24,000		1.84	1.91	
	0.23		92,000		1.92	1.96	
	0.35		94,000		1.92	1.96	
無方向性けい素鋼板	0.10	0.57	12,500	2.05	1.58	—	7.8
	0.20		15,000	2.03	1.44	1.53	
	0.35		18,000	1.96	1.45	1.56	
	—		—	—	—	—	
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

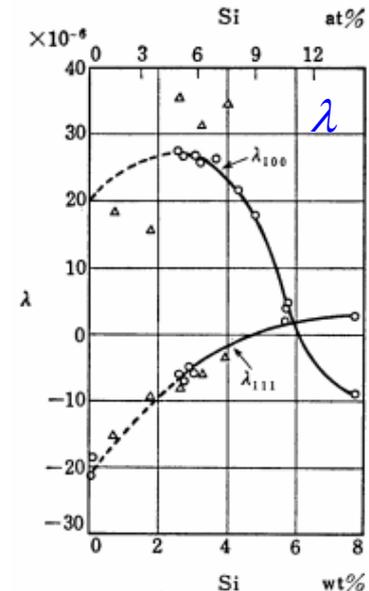
For 180° rigid wall, $\mu_{ri} \approx \frac{2\mu_0 M_s^2}{\pi^2 3\lambda\sigma_0} \frac{\ell}{\delta}$



σ_0 : internal stress amplitude,
 ℓ : stress wavelength, δ : domain wall thickness

ex) Fe ($\lambda \approx 20$ ppm) $\mu_{ri} \approx 10,000$
 Fe 6.5wt.Si ($\lambda \approx 1$ ppm) $\mu_{ri} \approx 170,000$

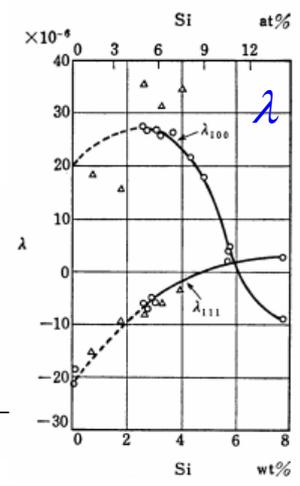
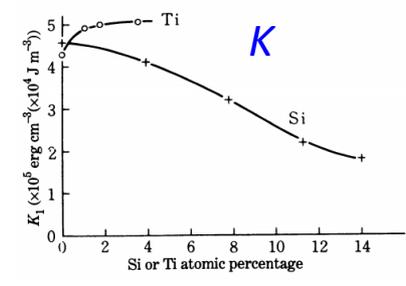
(for $\sigma_0 = 100$ MPa, $\ell/\delta = 100$)





Various Soft Magnetic Materials

Electrical steel (Fe-Si)



Permalloy (Ni₈₀Fe₂₀)

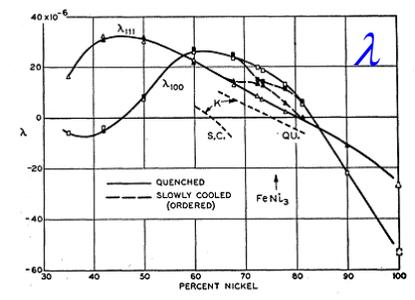
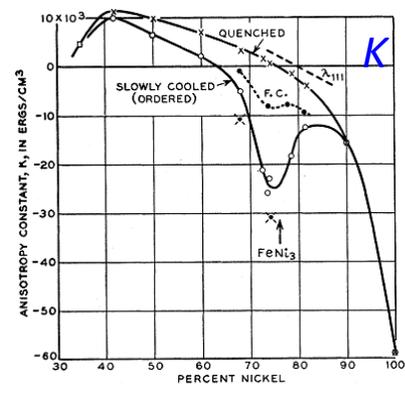
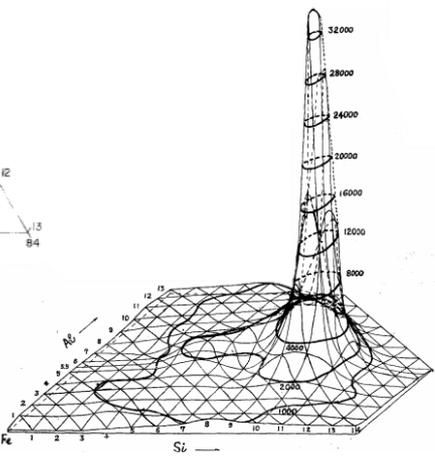
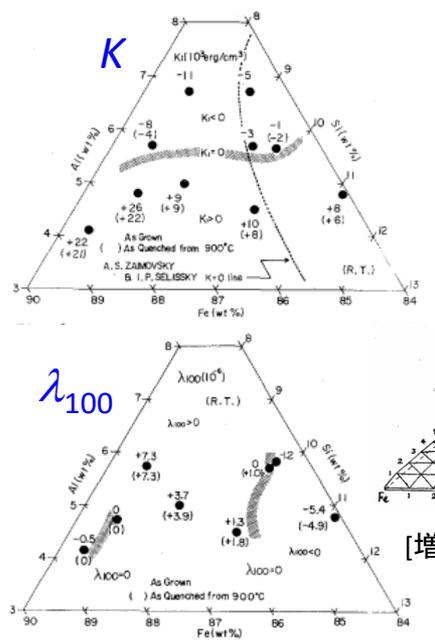


Fig. 5. Magnetostriction of quenched and of slowly cooled alloys. Broken lines show compositions at which anisotropy of quenched (QU.) and slowly cooled alloys (S.C.) goes through zero.

Sendust (Fe₈₅Al₅Si₁₀)



[増本, 日本金属学会誌(1937)]

Amorphous

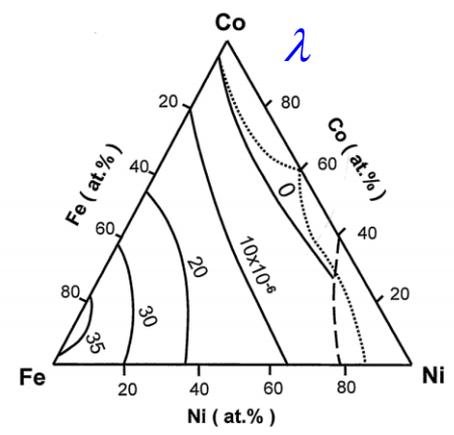


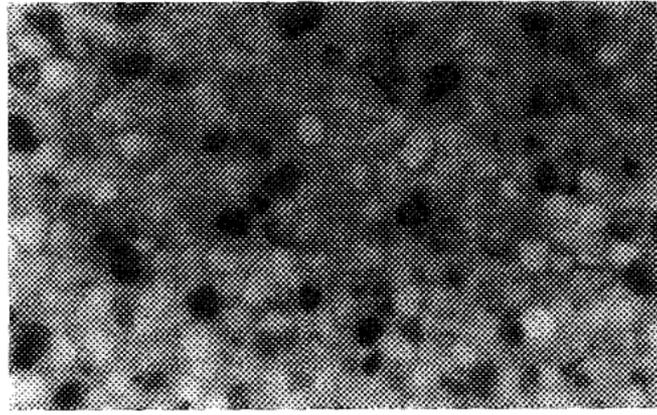
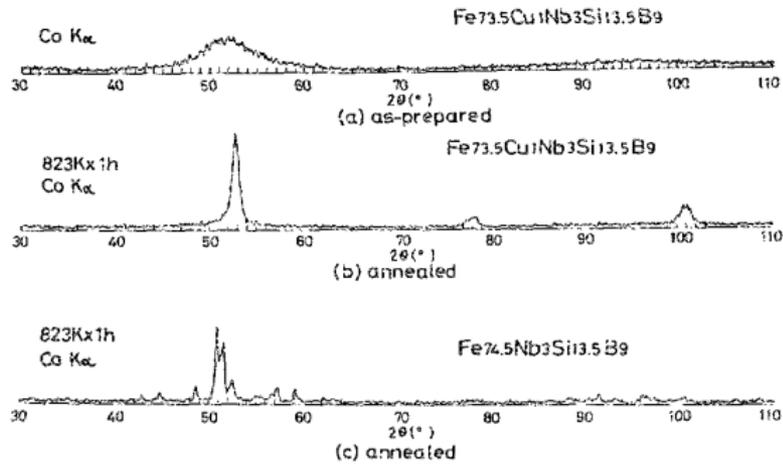
Fig. 6 Saturation magnetostriction of amorphous ribbons with composition (Fe-Co-Ni)₇₈Si₈B₁₄.

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

Fig. 1. Magnetic anisotropy constants of quenched and of slowly cooled alloys. Approximate rates of cooling, 10° 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.

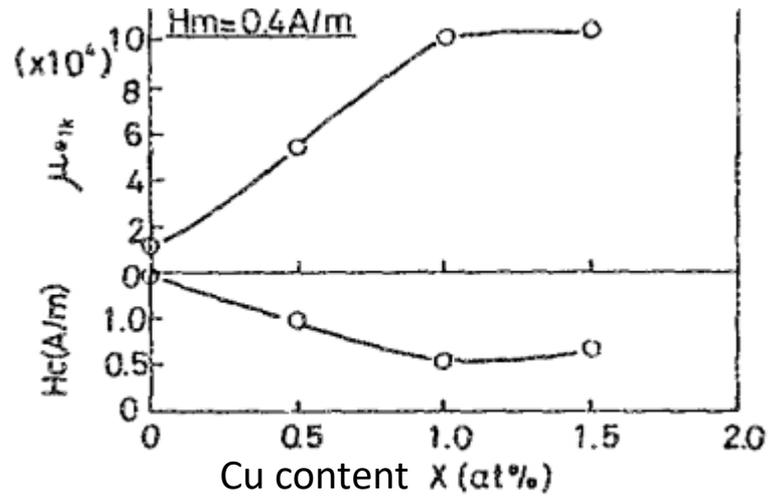
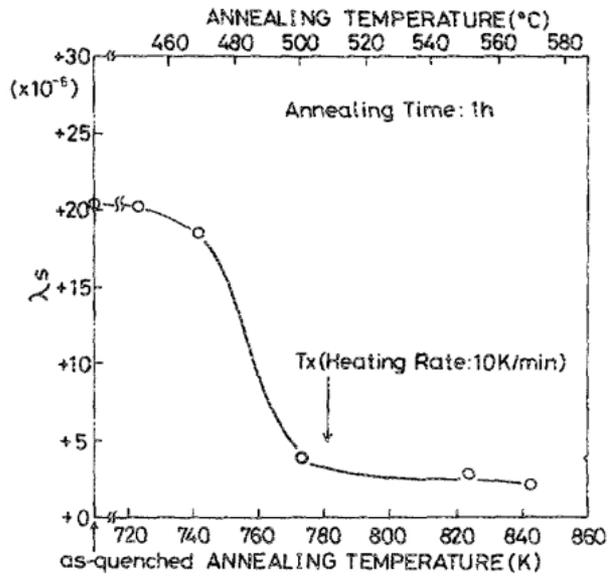
[Phys. Rev. 89, 624 (1953)]

FINEMET



50nm

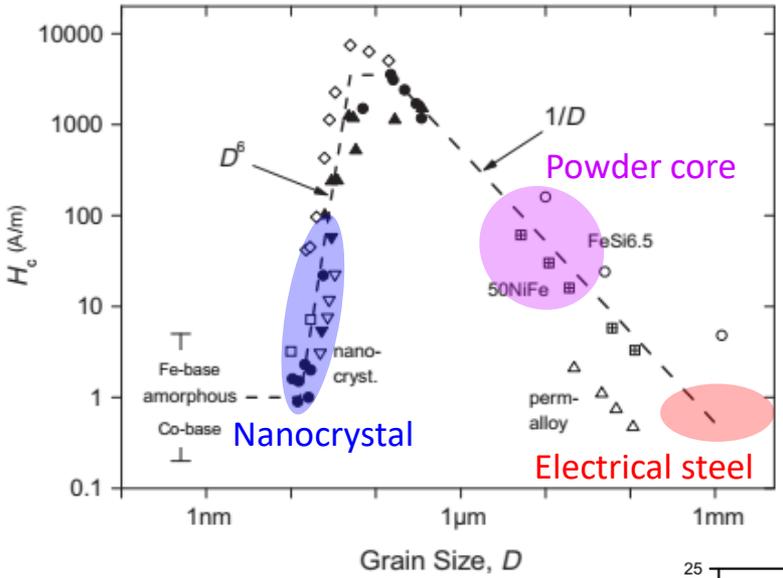
FIG. 2. X-ray diffraction patterns of Fe_{73.5}Cu₁Nb₃Si_{13.5}B₉ and Fe_{74.5}Nb₃Si_{13.5}B₉ alloys.



[Yoshizawa, JAP 64, 6044 (1988)]



Soft Magnetism of Nanocrystalline Alloys

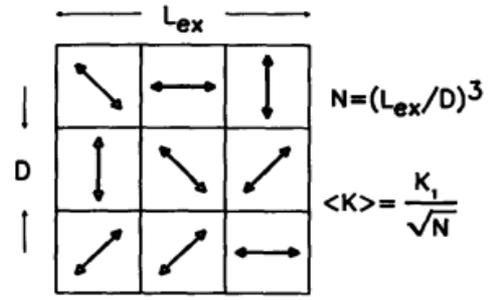


Random anisotropy model

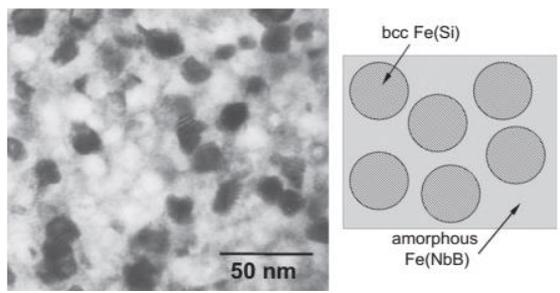
Exchange coupled averaging

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

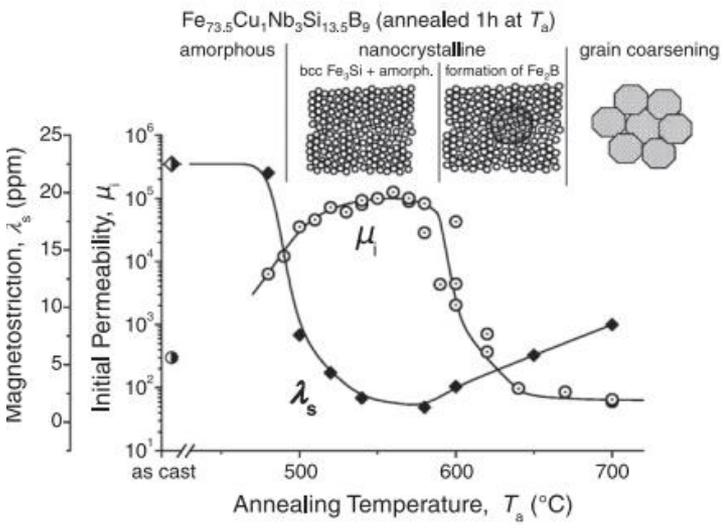
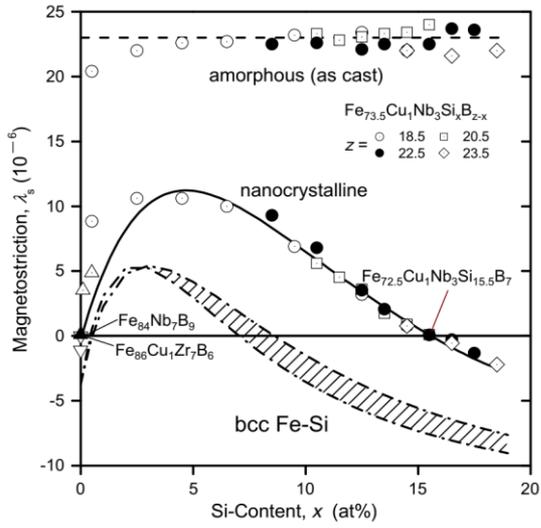
[Herzer, IEEE Trans Mag 26, 1397 (1990)]



Cancellation of λ



[Herzer, Acta Mater (2013)]

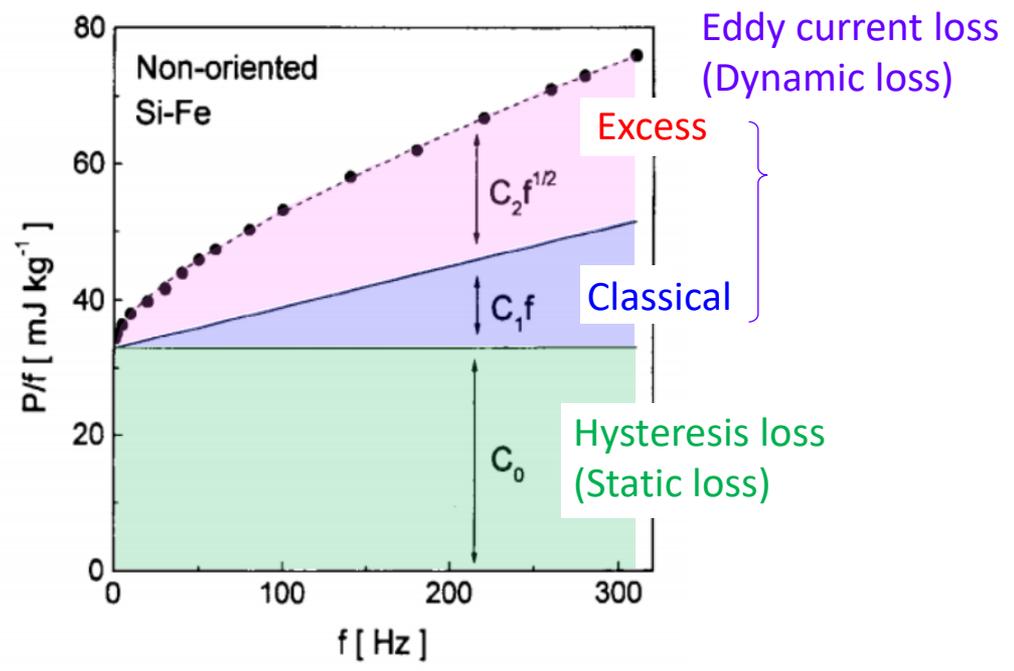
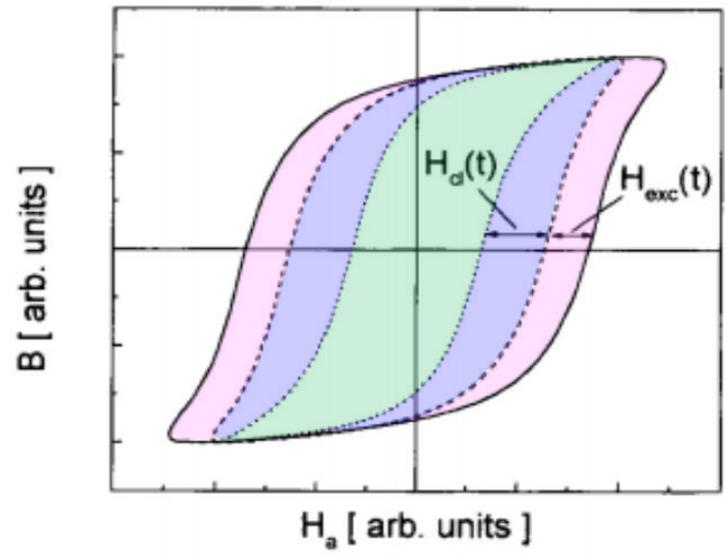


$$\lambda_s \approx x_{cr} \lambda_s^{Fe(Si)} + (1 - x_{cr}) \lambda_s^{am}$$

Negative Positive

1. Overview of Soft Magnet Application and History
2. Basics on Static Soft Magnetic Properties
- 3. Questions on Energy Losses in Soft Magnets**
4. Various Loss Analysis Models
5. Accurate Loss Evaluation
6. Broadband Loss Analysis
7. Advanced Analyses

Classical Intuitive Understanding of Iron Loss



Power loss

Work per cycle

Steinmetz eq. $P [W/m^3] = kf^\alpha B_m^\beta$ \Rightarrow $W [J/m^3] (P/f) = W_{hys} + W_{cl} + W_{exc}$
 [Steinmetz (1892)]

W_{hys} : constant

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

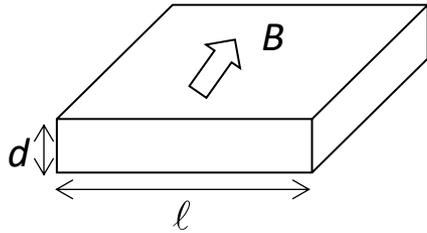
$W_{exc} = 8\sqrt{\sigma GSV_0} B_m^2 f^{0.5}$ from statistic theory for domain wall motion

[Bertotti (1985)]

Simple Estimation of Eddy Current Loss

Uniform flux change

Classical eddy current loss P_{cl}



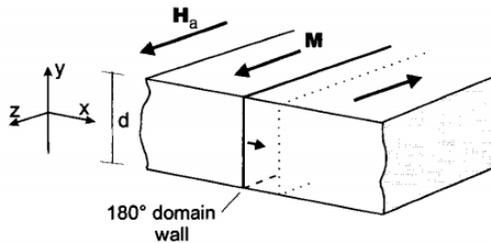
For a uniformly magnetized slab with $l \gg d$, eddy current j_{cl} flows along the slab edge.

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

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.

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

Maximum case of eddy current loss

For $l = 10 \text{ mm}$ and $d = 25 \mu\text{m}$

$$P_{exc}/P_{cl} \approx 200$$

Very important to control the magnetization reversal process

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

General requirements,

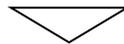
1. High saturation magnetization $\mu_0 M_s$
2. High permeability μ up to high frequency
3. Low iron loss P up to high frequency

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

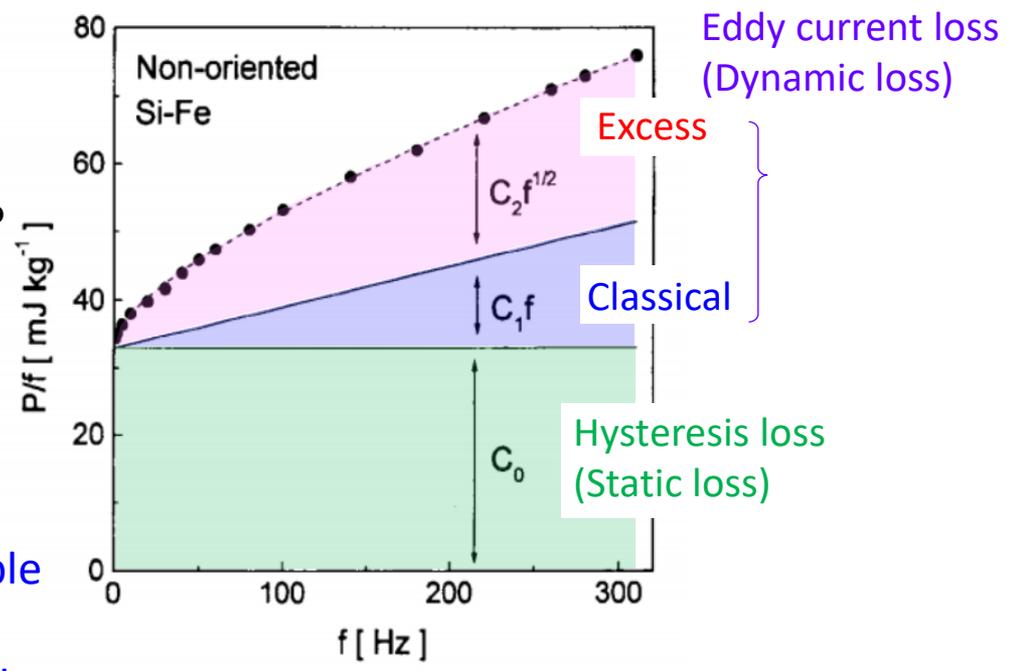
$$W \text{ [J/m}^3\text{]} = W_{\text{hys}} + W_{\text{cl}} + W_{\text{exc}}$$

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.



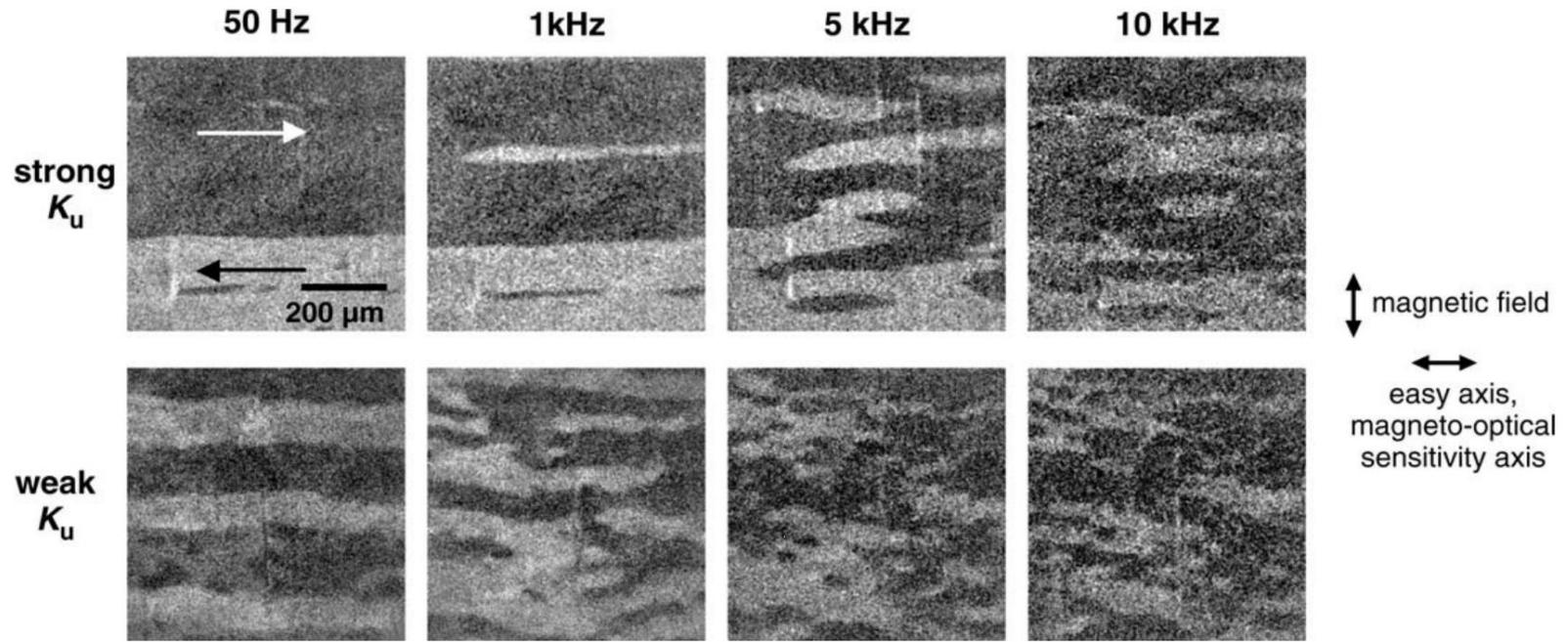
Q2 Is really W_h constant against f ? Do we really understand W_h ?

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

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

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

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

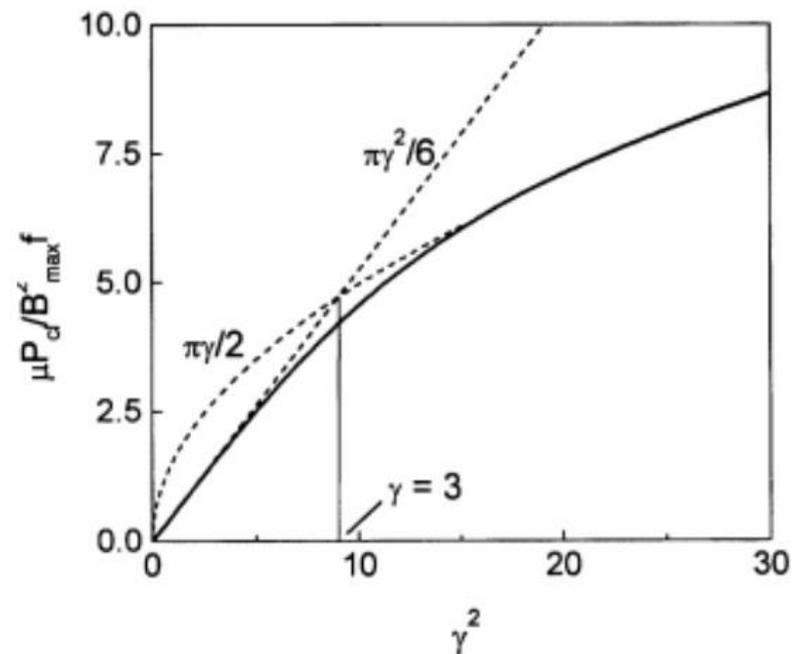
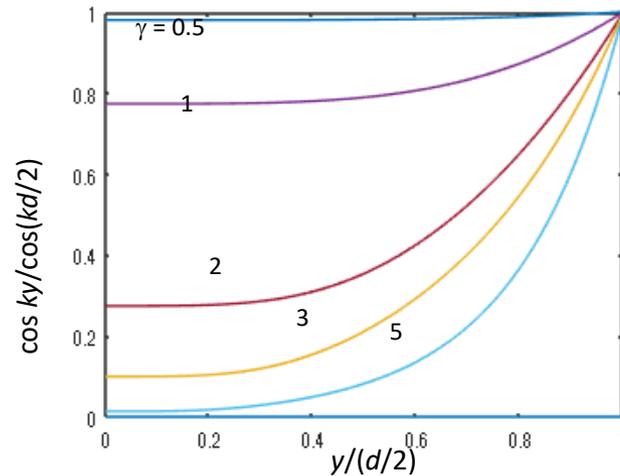


Classical Eddy Current Loss with Skin Effect

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

$$P_{cl} \approx \frac{\pi^2}{6} \sigma d^2 B_{\max}^2 f^2, \quad \gamma \ll 1$$

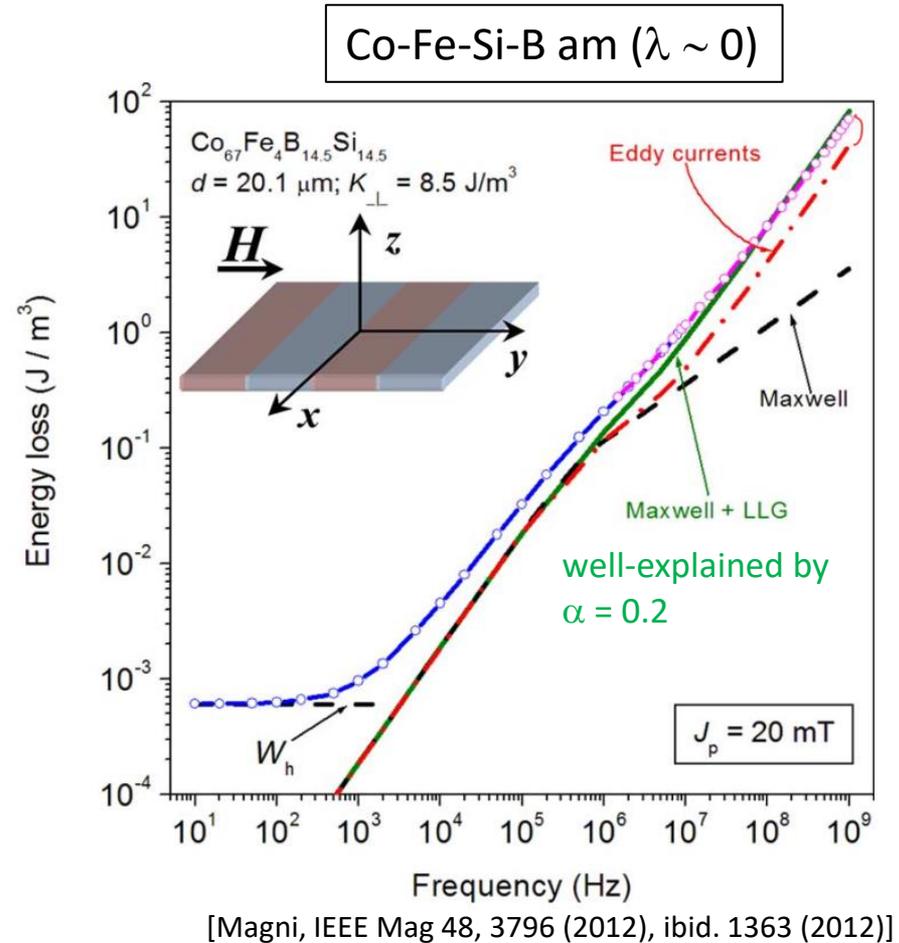
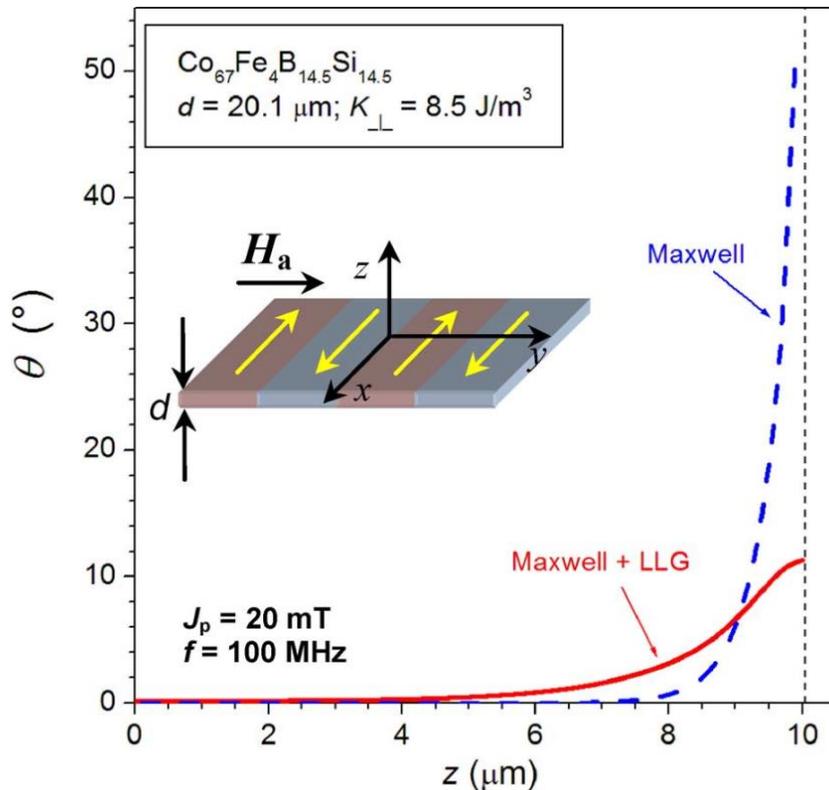
$$P_{cl} \approx \frac{\pi^{3/2}}{2} \sqrt{\frac{\sigma d^2}{\mu}} B_{\max}^2 f^{3/2}, \quad \gamma \gg 1$$



LLG & Maxwell Eqs. Coupled Calculation

$$\partial \mathbf{M} / \partial t = -\gamma \mu_0 \mathbf{M} \times [\mathbf{H}_{\text{eff}} + (\alpha / M_s) \mathbf{M} \times \mathbf{H}_{\text{eff}}]$$

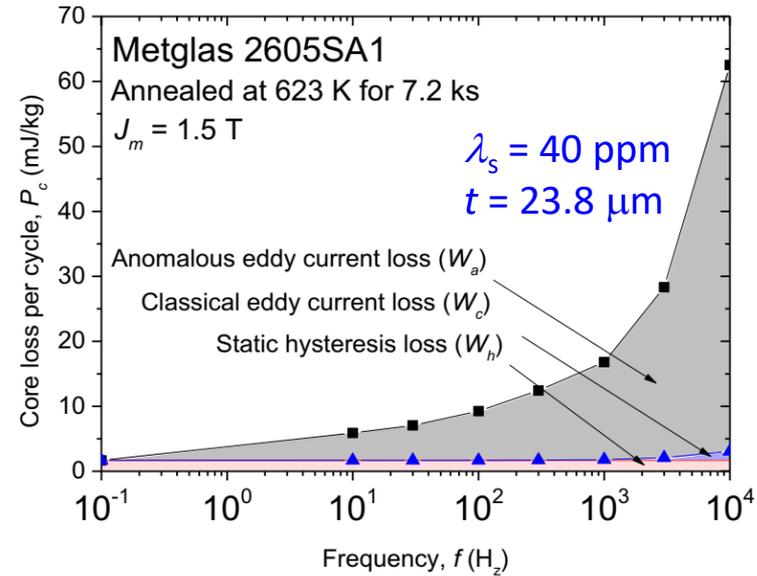
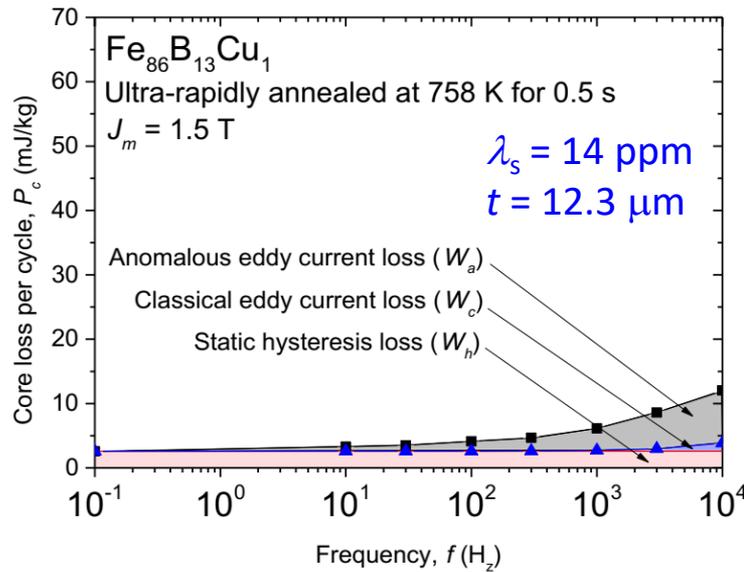
$$\partial^2 \mathbf{H}_{\text{eddy}} / \partial z^2 = \sigma \mu_0 \partial (\mathbf{M} + \mathbf{H}_{\text{eddy}} + \mathbf{H}_a) / \partial t$$



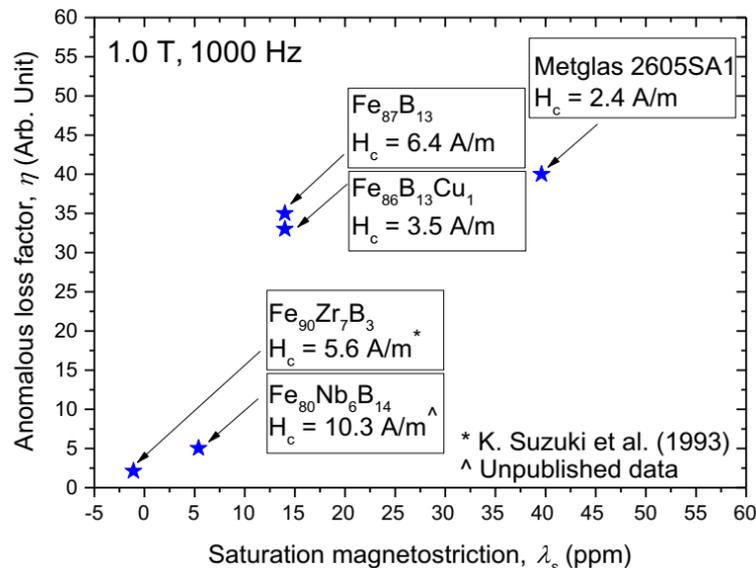
Maxwell + LLG well explain the experimental loss, but very large α is required.

⇒ 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

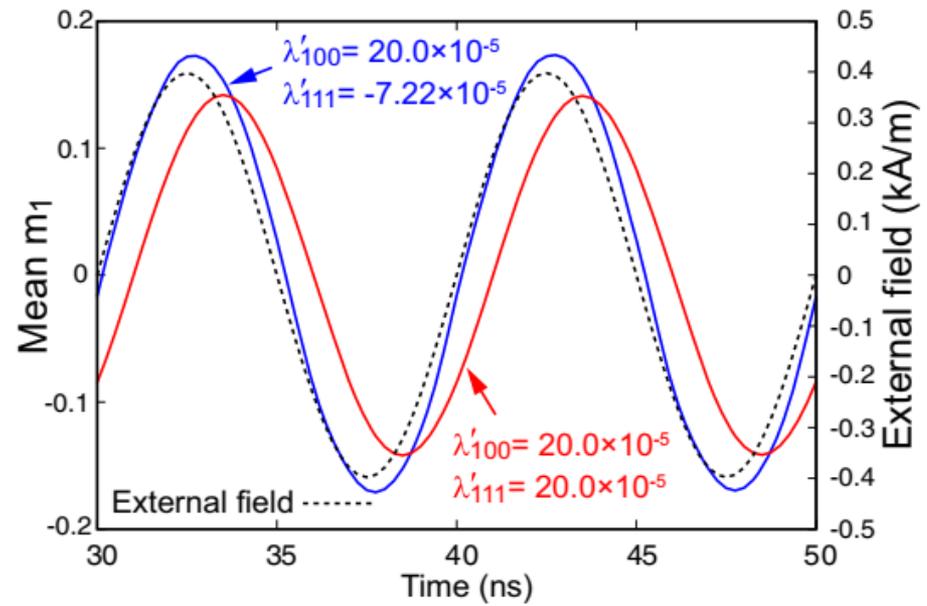
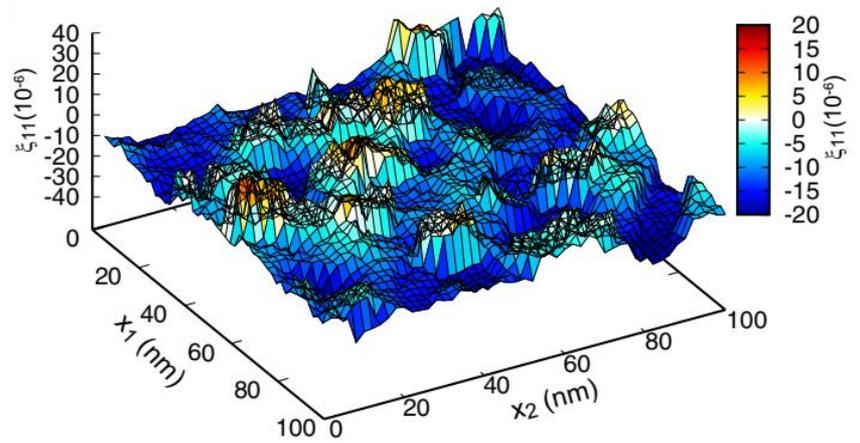
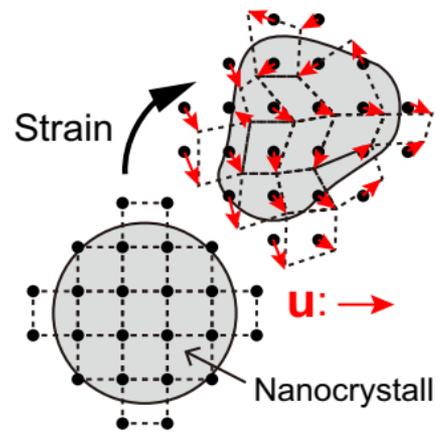
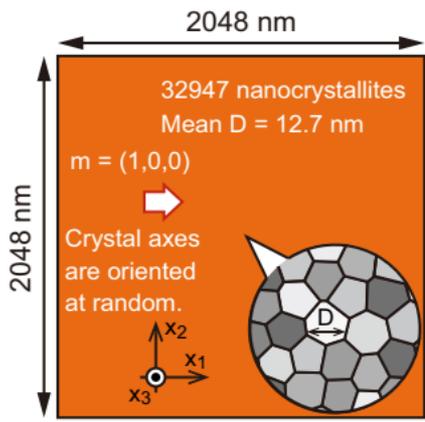


Possibility of λ origin loss

* 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)]



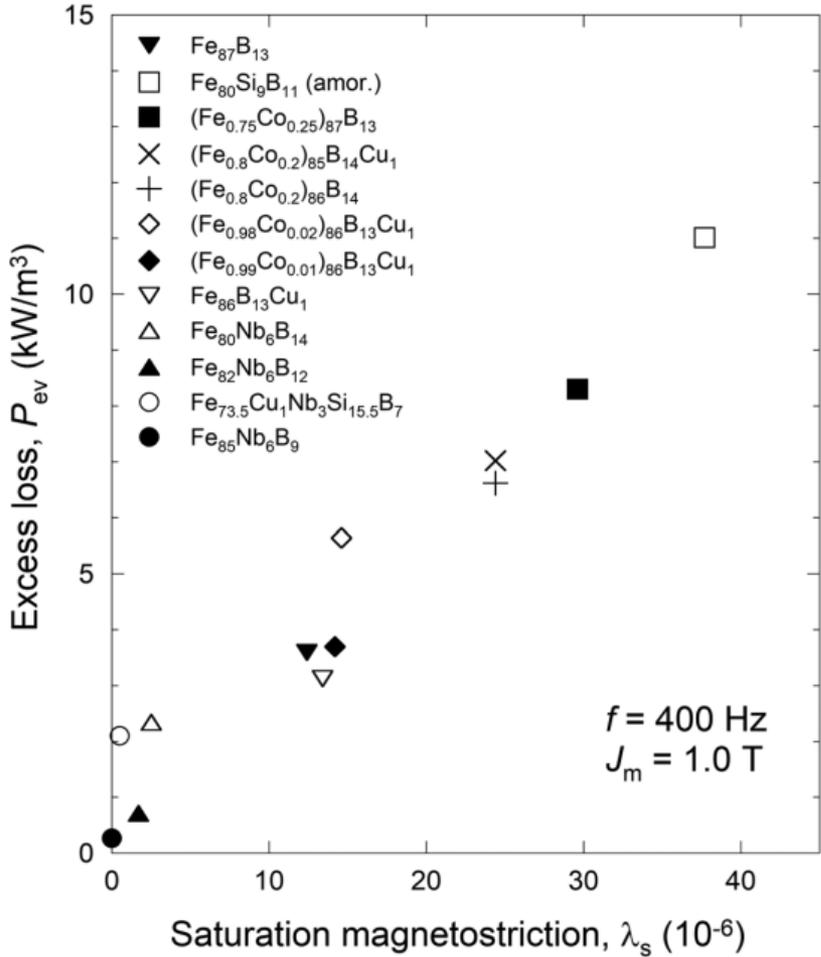
Excess Loss vs. Magnetostriction vs. Damping Constant



[Huang, PRB 109, 104408 (2024)]

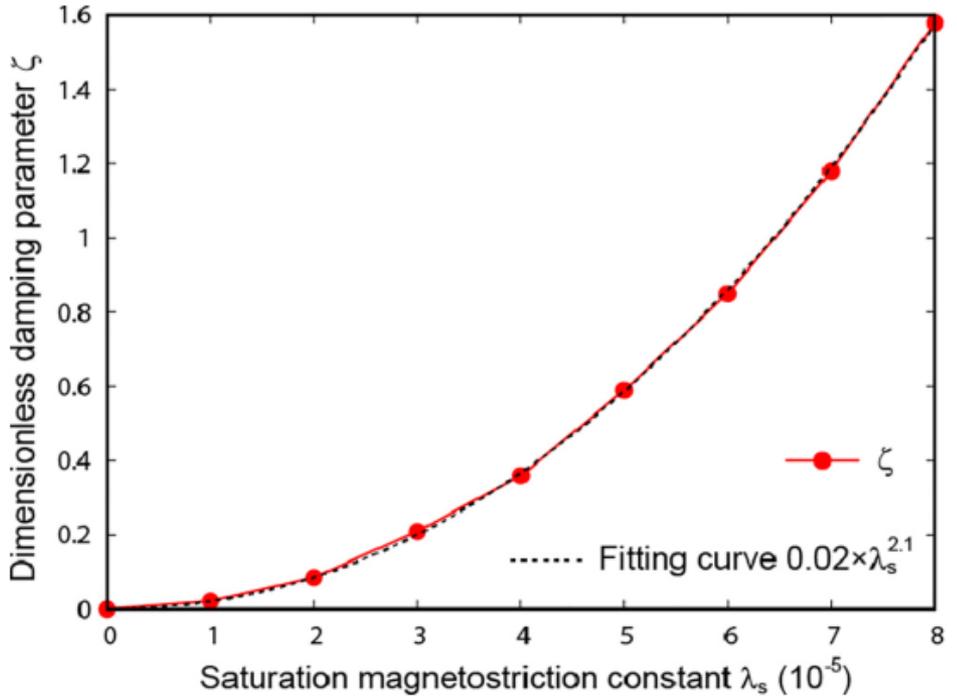
Experiments

Excess loss vs. Magnetostriction

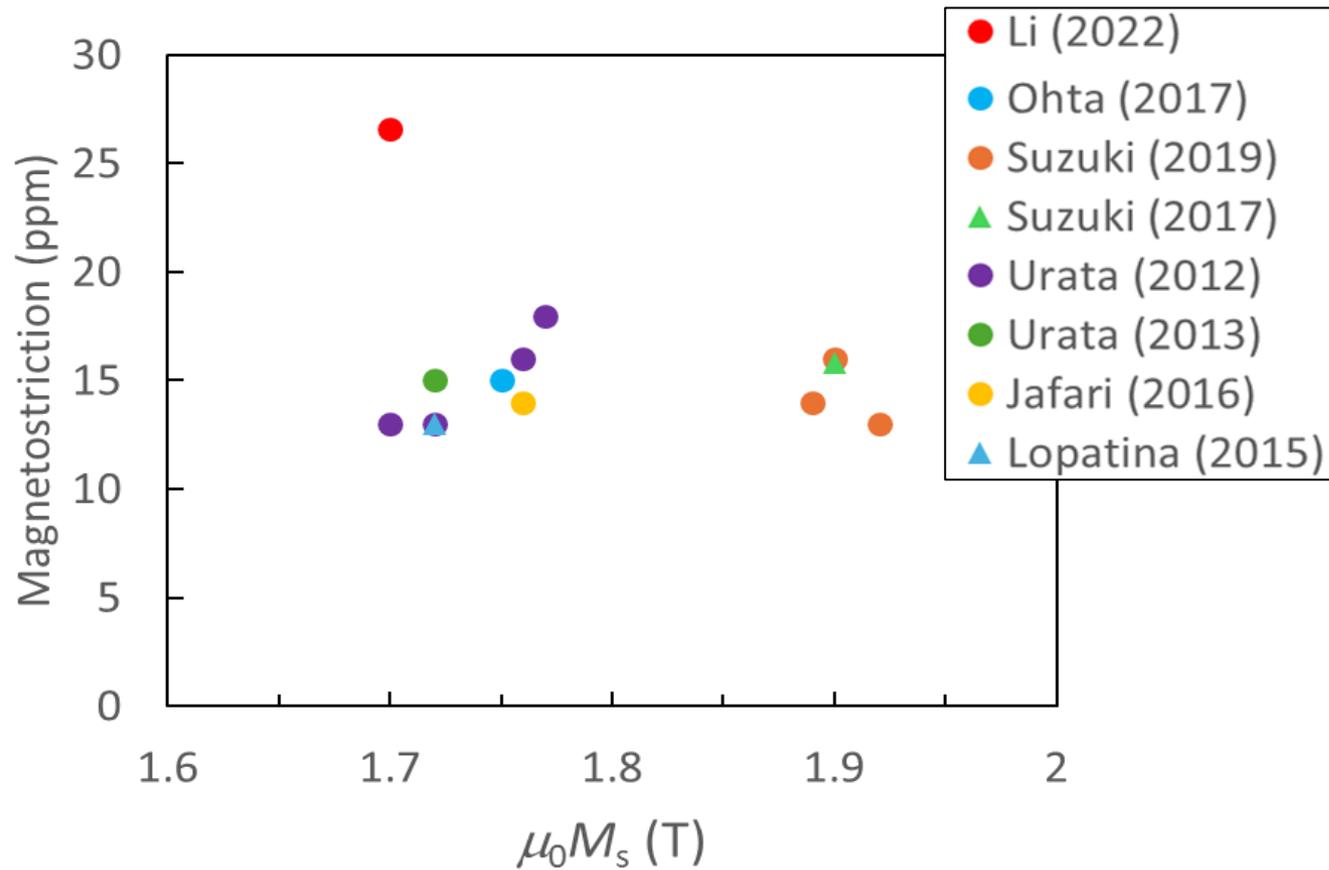


Theoretical calculation

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)]



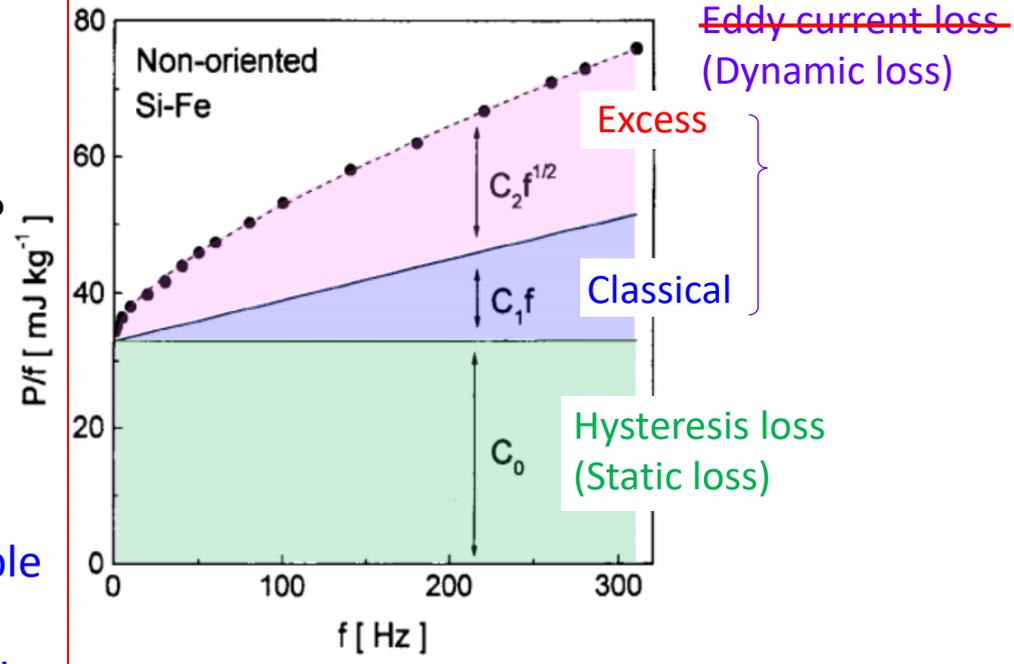
- The statistic model can be only applicable for low frequency range.
- Physics based loss analyses are required.

Today's topics

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

1. Overview of Soft Magnet Application and History
2. Basics on Static Soft Magnetic Properties
3. Questions on Energy Losses in Soft Magnets
- 4. Various Loss Analysis Models**
5. Accurate Loss Evaluation
6. Broadband Loss Analysis
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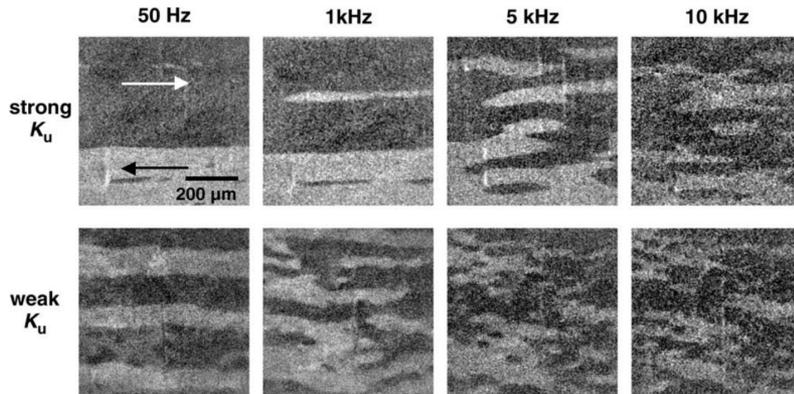
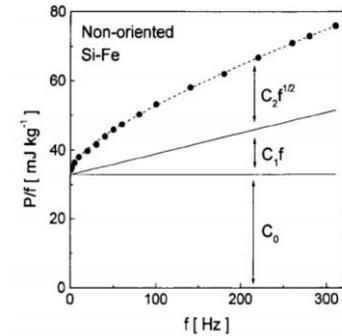
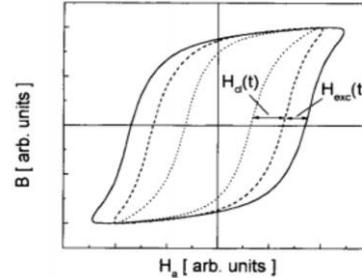
Physic Based Iron Loss Analysis

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

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

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 $\mu = \mu_i + \nu H$

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

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

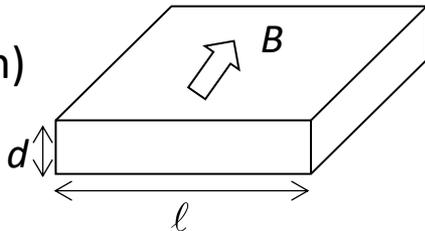
In many text books and review papers,

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

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

Classical Eddy Current Loss W_{hys}

Uniform flux change
(Magnetization rotation)



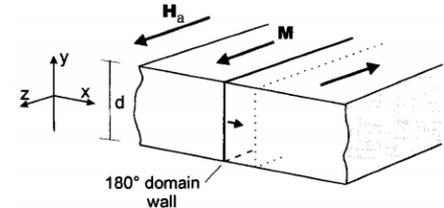
$$P_{\text{cl}} \approx \rho j_m^2 \approx \frac{d^2}{\rho} \left(\frac{\partial B}{\partial t} \right)^2 \propto B_m^2 f^2$$

$$W_{\text{cl}} \propto B_m^2 f$$

Excess (Anomalous Eddy Current) Loss W_{exc}

Single domain wall

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

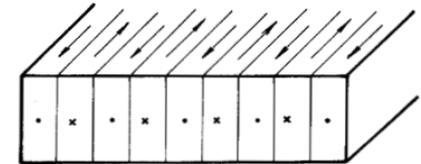


$$P_{\text{exc}} \approx \rho j_m^2 \frac{2d^2}{lt} \approx \frac{ld}{8\rho} \left(\frac{\partial B}{\partial t} \right)^2 \propto B_m^2 f^2$$

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

Multidomain

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



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

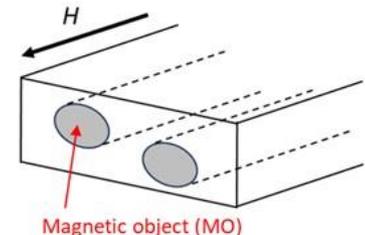
$$W_{\text{exc}} \propto \frac{B_m^2 f}{n}$$

Correlated multidomain (Bertotti's Statistic theory)

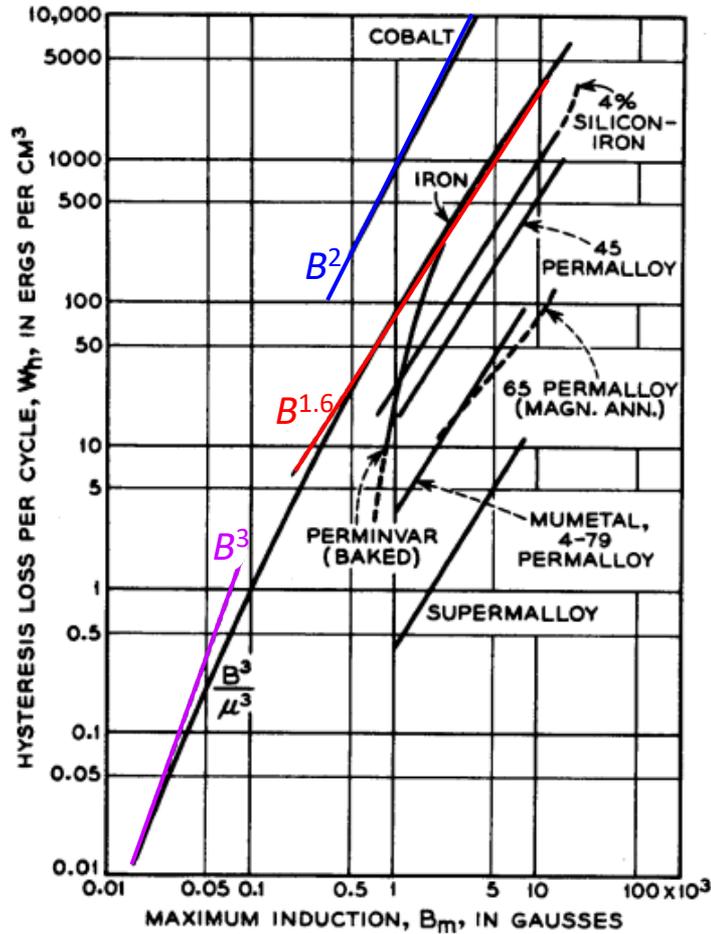
[Bertotti, JAP 57, 2110 (1985)]

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

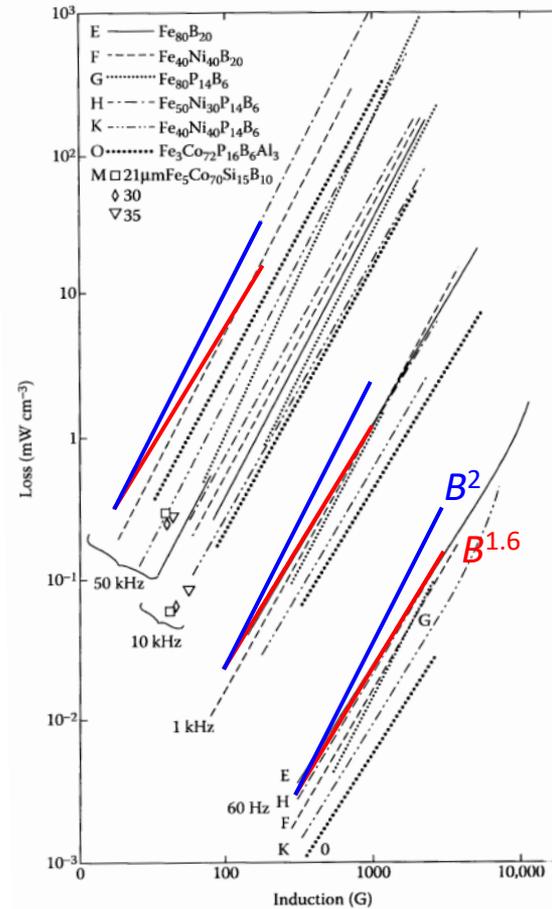
$$W_{\text{exc}} \propto B_m^{1.5} f^{0.5}$$



Power Law of Hysteresis Loss



[Bozorth, Ferromagnetism]

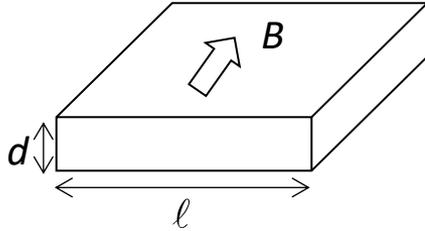


[Jiles, Introduction to Magnetism and Magnetic Materials]

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

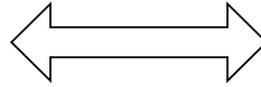
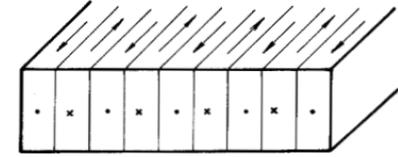
W_{cl} and W_{exc} can exist concurrently?

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

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

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

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

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

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

[Bertotti, JAP 57, 2110 (1985)]

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

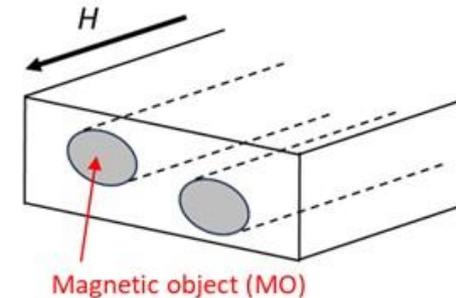
Number of MO $n_{\text{MO}}(H_{\text{exc}}) = n_{\text{MO}}(0) + \frac{H_{\text{exc}}}{V_0}$

for $\frac{4H_w}{n_{\text{MO}}(0)^2 V_0} \ll 1$ (Low f limit), $H_{\text{exc}} = \frac{\sigma GS}{n_{\text{MO}}(0)} \langle \partial B / \partial t \rangle$

$\Rightarrow P_{\text{exc}} = \frac{4\sigma GS}{n_{\text{MO}}(0)} B_m^2 f^2$ **Same with Pry and Bean model**

for $\frac{4H_w}{n_{\text{MO}}(0)^2 V_0} \gg 1$ (high f region), $H_{\text{exc}} = \sqrt{\sigma GS V_0} \langle \partial B / \partial t \rangle^{1/2}$

$\Rightarrow P_{\text{exc}} = 8 \sqrt{\sigma GS V_0} B_m^{1.5} f^{1.5}$ **Same power law with experiments**

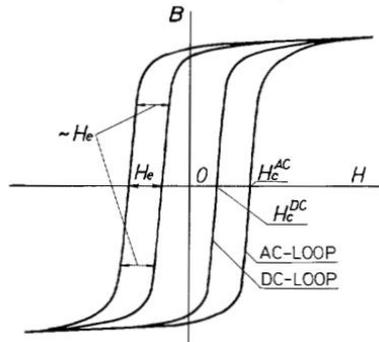


H_w : Effective field of single domain wall

V_0 : Related to pinning field distribution with unit of field (A/m)

G : Geometrical factor, S : Cross sectional area

Effective Domain Wall Model



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

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

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

- 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)]

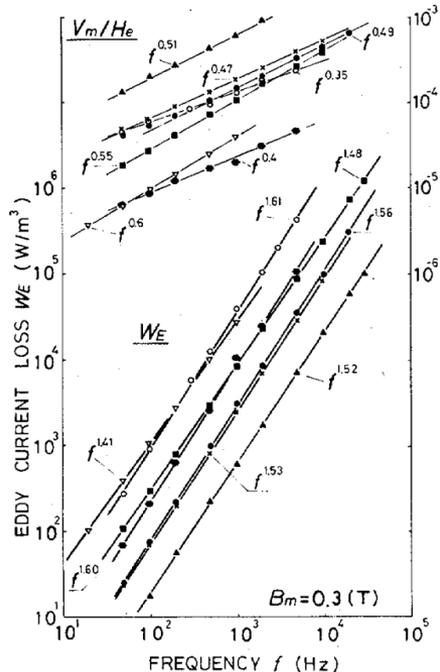
Experimentally, $v \approx 1.5$

Assuming effective wall number n

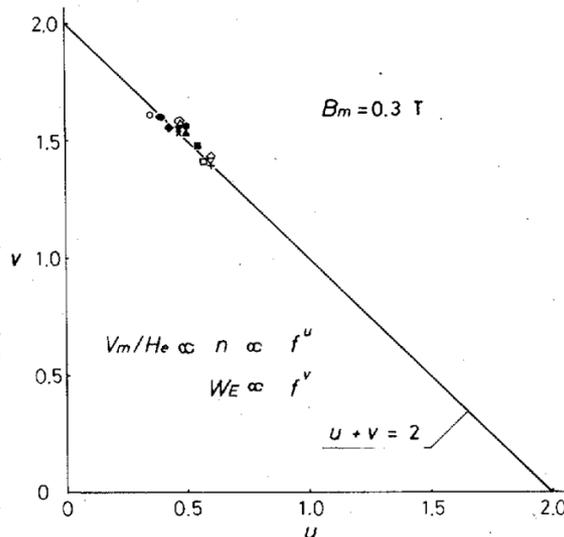
$$V_m/H_{c, dyn} = 2B_s n d / \beta \propto f^u$$

Experimentally, $u \approx 0.5$

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



- Grain oriented
- △ 3% Si-Fe
- Square Loop
- ▽ 50% Ni-Fe
- ◇ Supermalloy,
- (5% Mo-79% Ni-16% Fe)
- Fe₄₇Co₇Q₃Si₁₅B₁₀
- ▲ Fe₄Co₆₆Si₁₇B₁₃
- Fe₄₀Ni₄₀P₁₄B₆
- ▼ Fe₈₁B₁₃Si₃₅C₂
- Fe₆₇Co₁₈B₁₄Si₁
- Fe₇₀Ni₈Si₁₀B₁₂



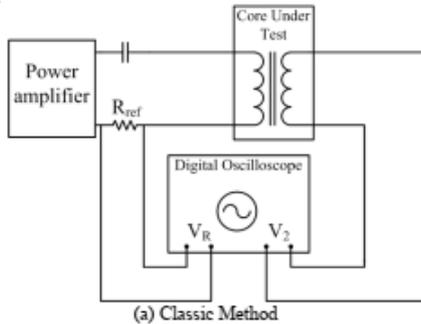
Modified Pry and Bean model,

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

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Capacitance Cancellation Method

Standard method (Two-coil method)



IWATSU, B-H analyzer



Magnetic Device Laboratory Ltd.

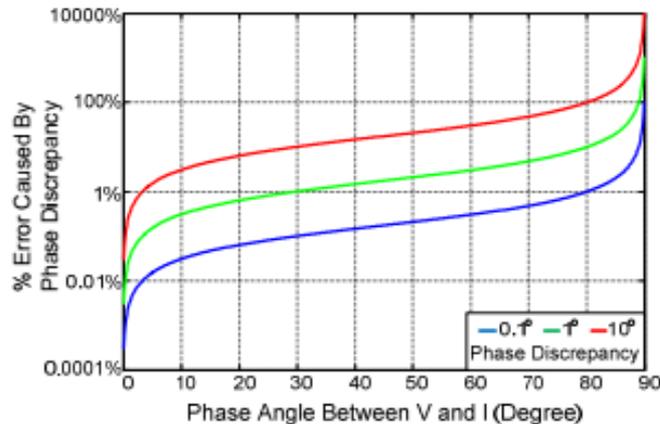
$$P = VA \cos \theta$$

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

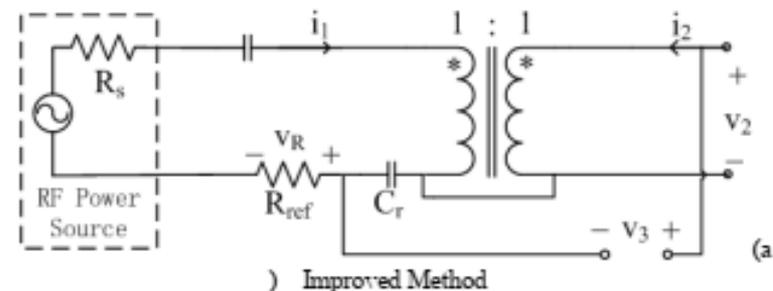
■ Error of core loss measurement

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

[Tan, IEEE Power Ele (1995)]



Capacitance Cancellation Method



[Mu, IEEE Power Ele (2014)]

Accuracy Evaluation of Core Loss – R_0 Plot –

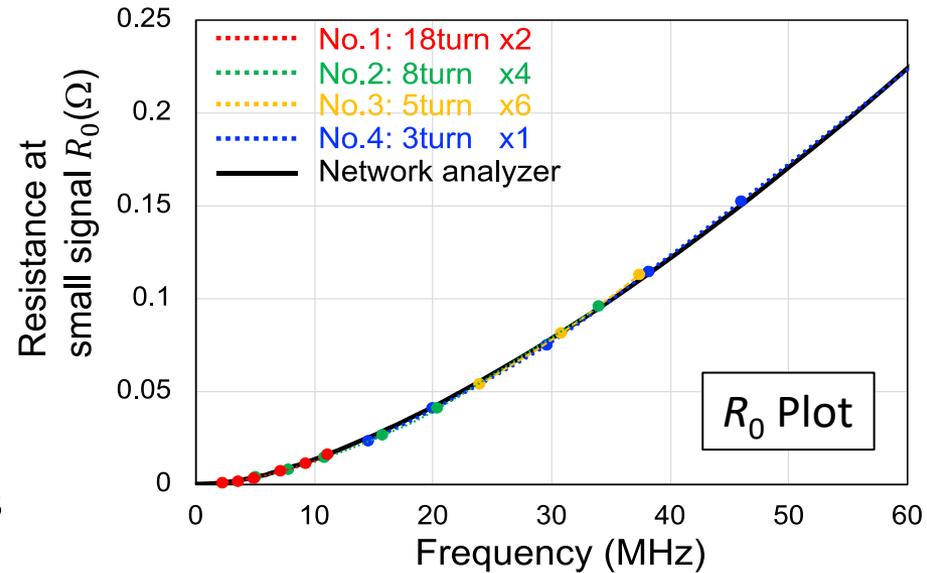
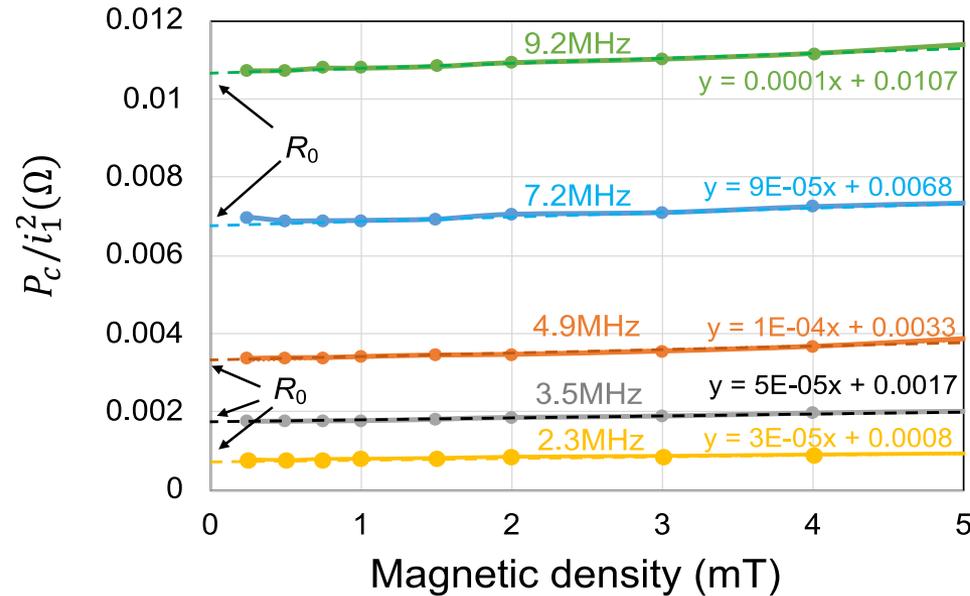
Equivalent Resistance $R [\Omega] = P [W] / I^2$

R_0 : Extrapolation to zero B_m

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



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	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

Windings and Self-Resonance for Low Permeability Device

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



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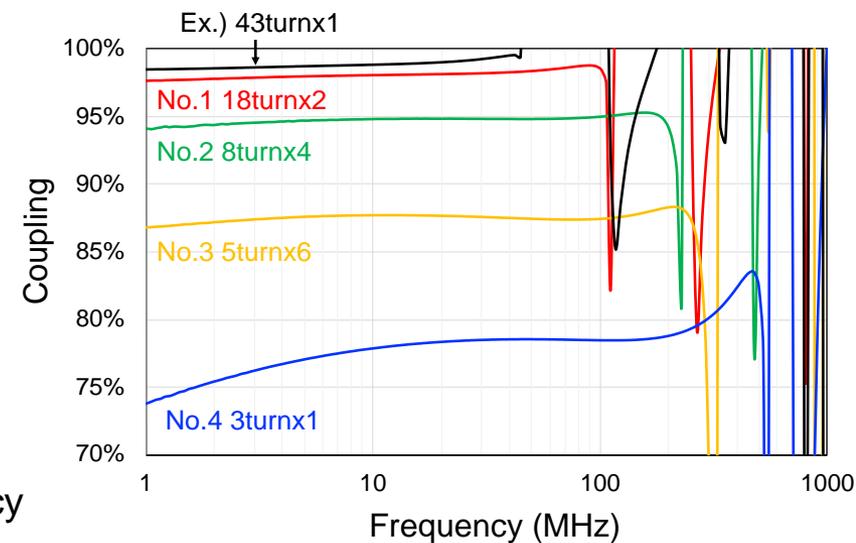
- The coupling must be 100% for high-accuracy measurements.
- For low-permeability material, many number of turns cannot be wound because the resonant frequency goes down. → Parallel windings were employed for the investigation.

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.

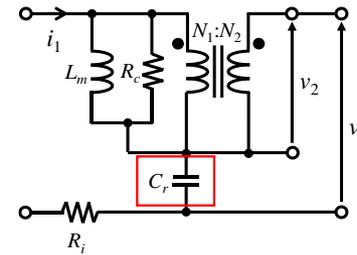
Coupling vs Frequency



Iron Loss Measurement for Low Permeability Core

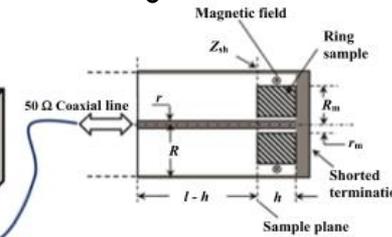
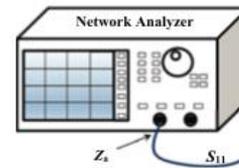
[Sato, SO, IEEE Trans. Magn. 59, 6301105 (2023)]

- 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.



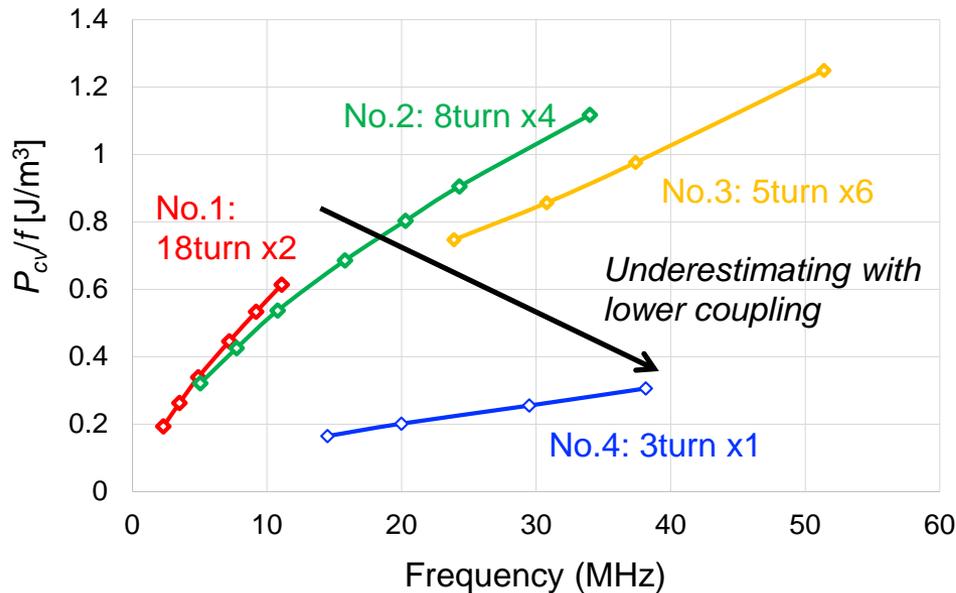
Magnetic Device Laboratory Ltd.

[Mu, IEEE Power Elec. (2014)]

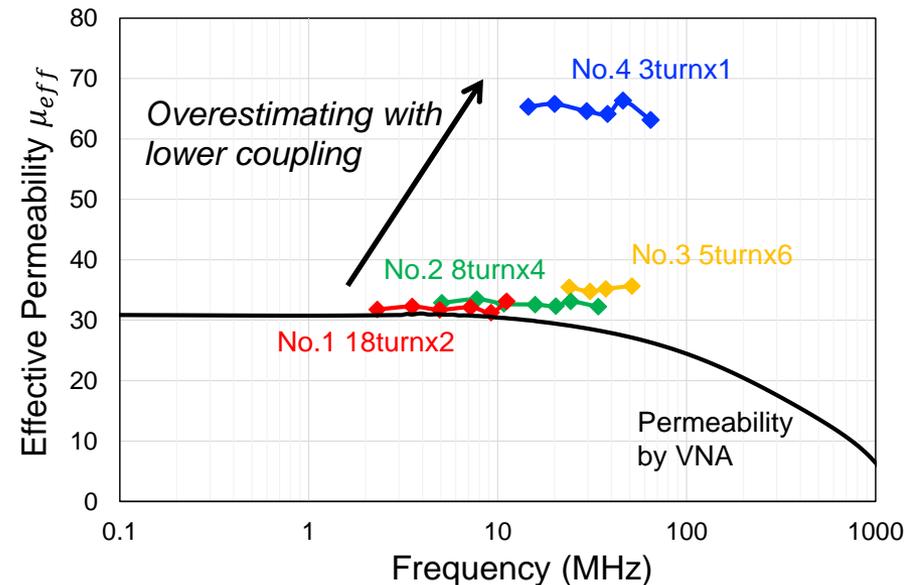


[Ferrara, J. Mater. Res. (2018)]

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



Permeability vs Frequency at $B_m=0.25\text{mT}$

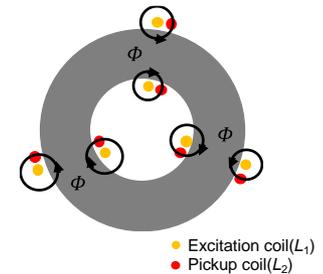
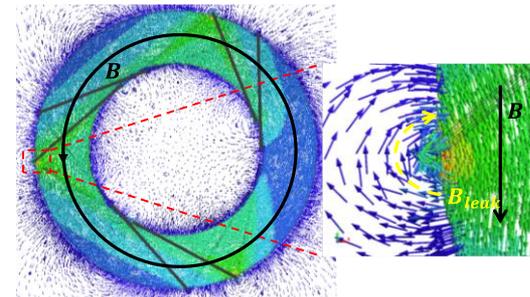
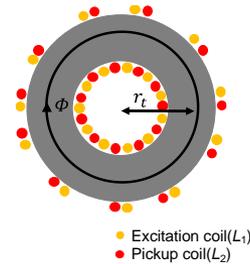
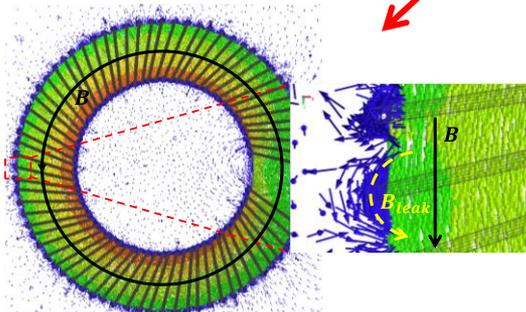
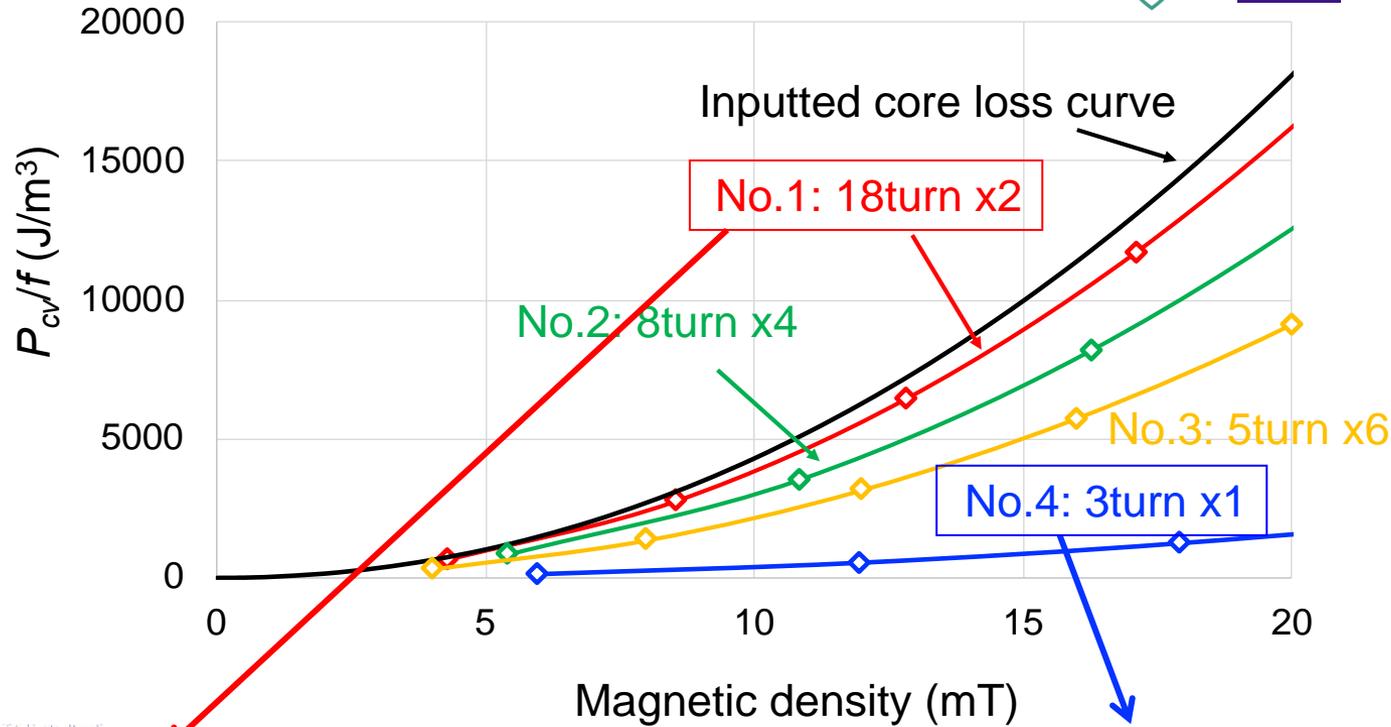


Simulations for Low Permeability Cores

[Sato, SO, IEEE Trans. Magn. 59, 6301105 (2023)]



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➤ Less leakage flux

➤ Very large leakage flux

Correction Method for Low Permeability Cores

[Sato, SO, IEEE Trans. Magn. 59, 6301105 (2023)]

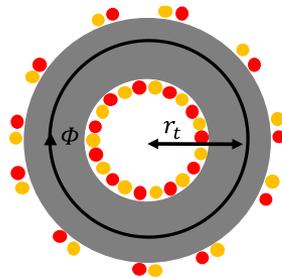
■ Magnetic flux density

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



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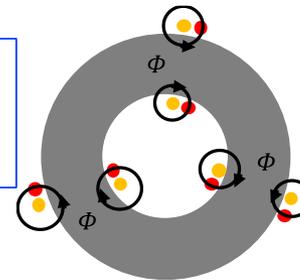
Dense winding : High coupling



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

$$\mu_r \approx \mu_{eff}$$

Coarse winding : Low coupling



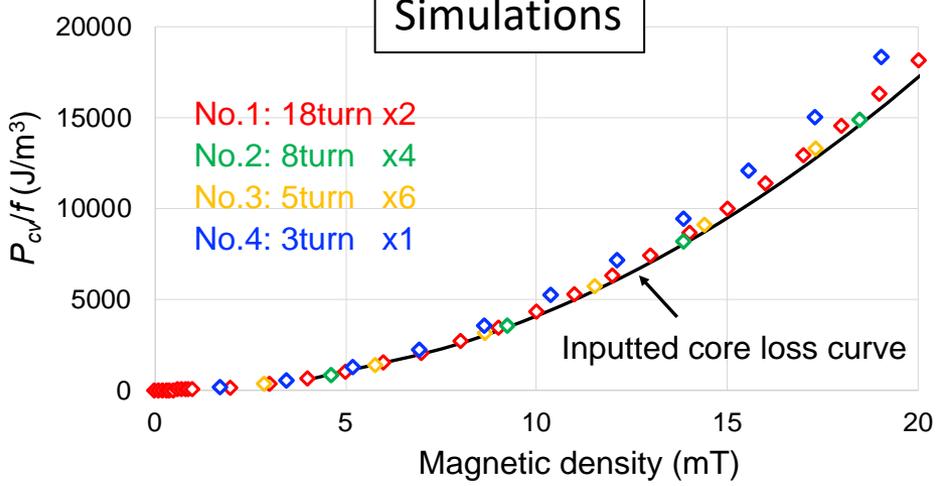
$$l \neq 2\pi r_t \gg l_{eff}$$

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

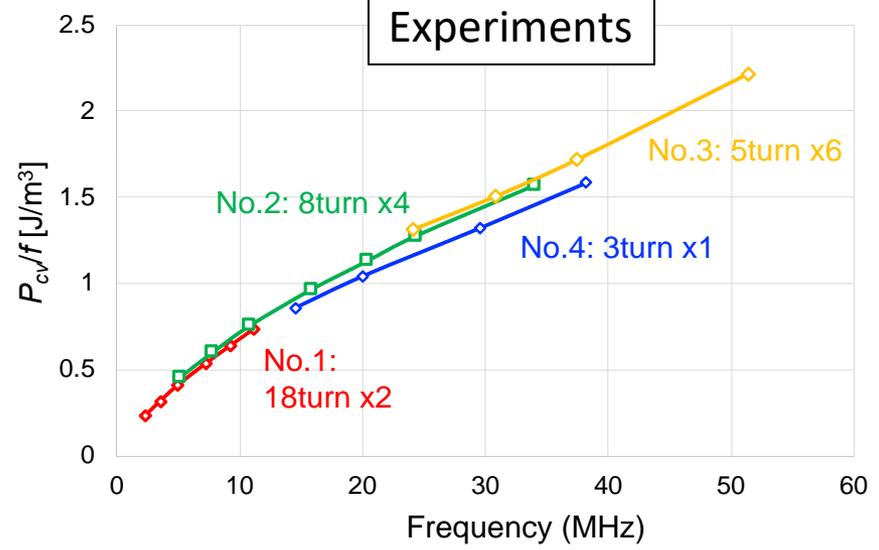
Proposed correction:

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

Simulations

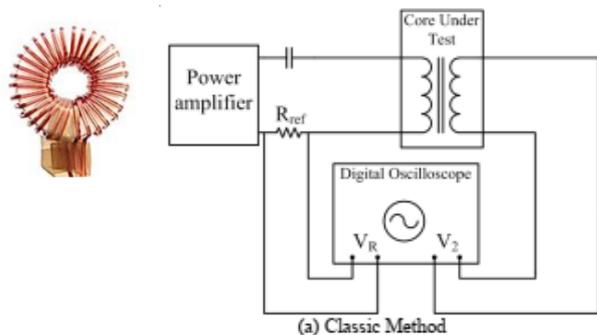


Experiments

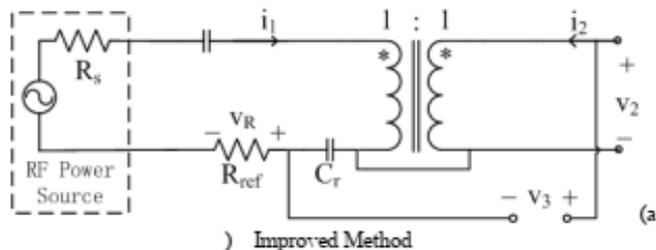


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Standard method(Two-coil method)

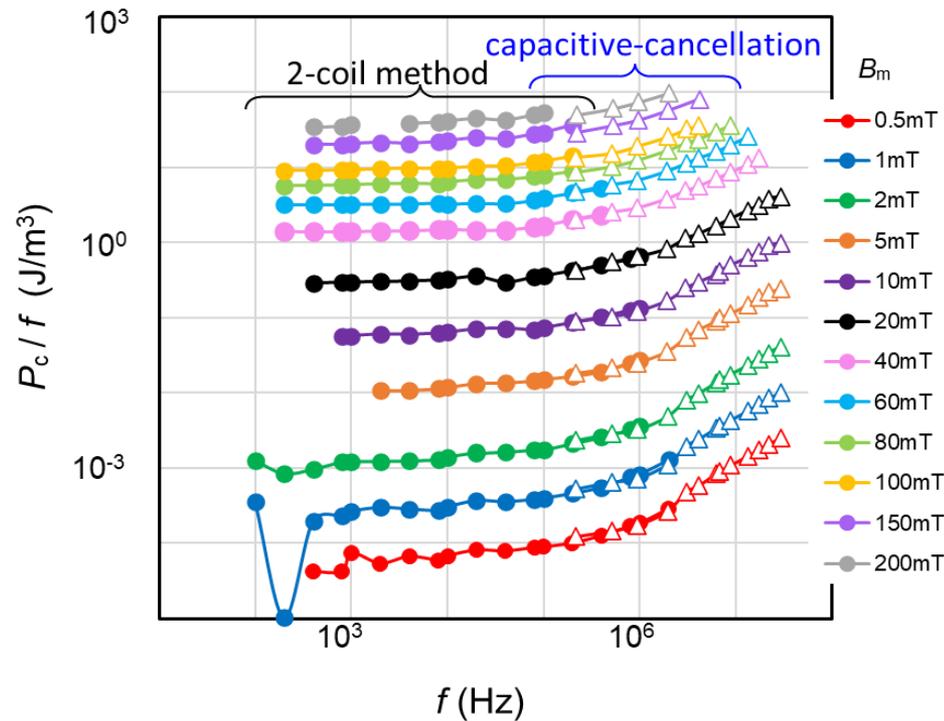


Capacitance Cancellation Method



[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

Developed by Fiorillo Gr. for analysis of Ferrite core

[Beatrice, JMMM 429, 129 (2017)]

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

Key points of this model

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

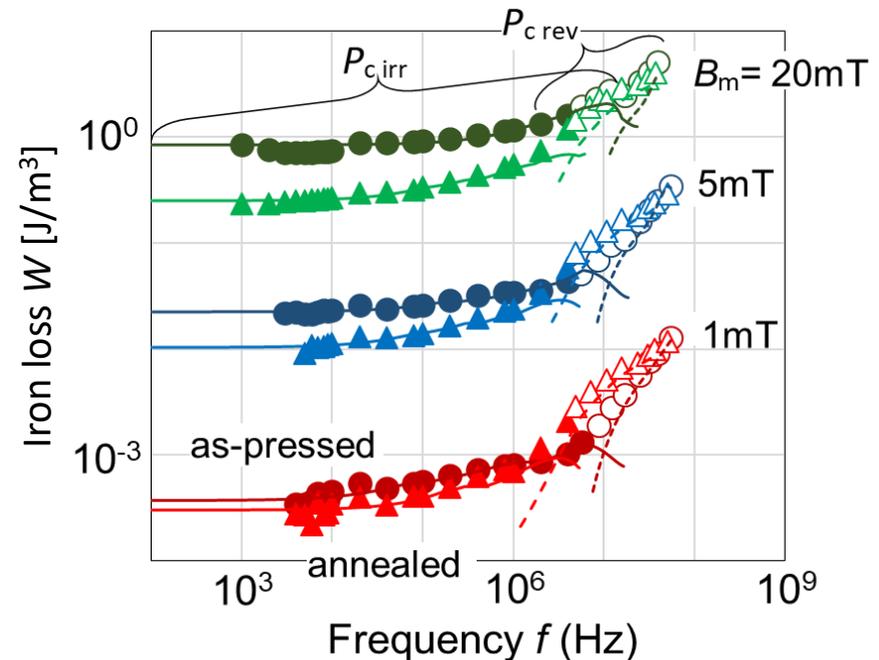
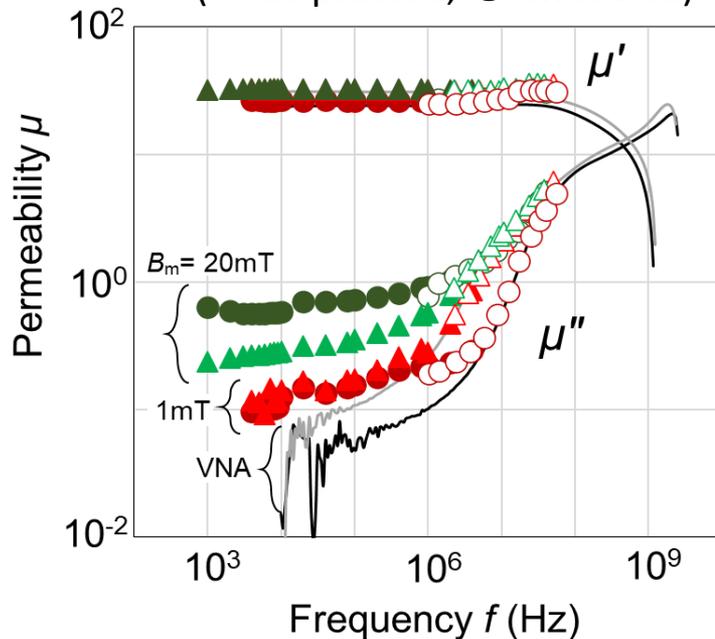
$$\mu = \mu_{\text{rev}} + \mu_{\text{irr}} \quad (\mu_{\text{rev}} : \text{constant}, \mu_{\text{irr}} \propto H)$$



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

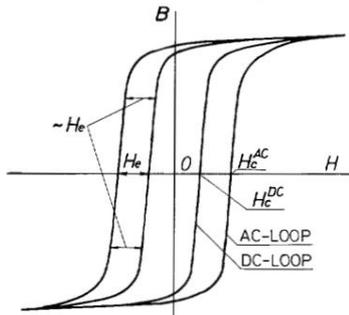
Sendust dust core

(▲ as-pressed, ● annealed)



Effective Domain Wall Model

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



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

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

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

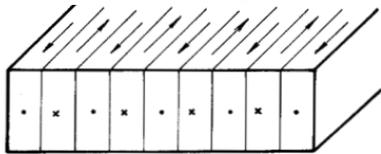
Assuming effective wall number n

$$V_m / H_{c, dyn} = 2B_s nd / \beta \propto f^u$$

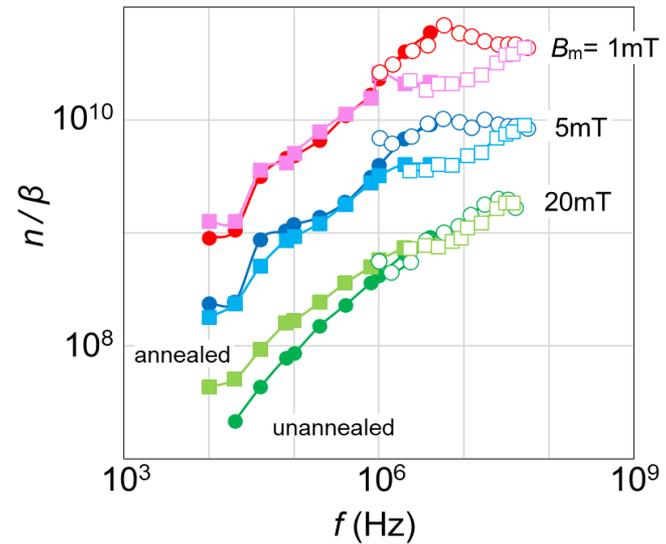
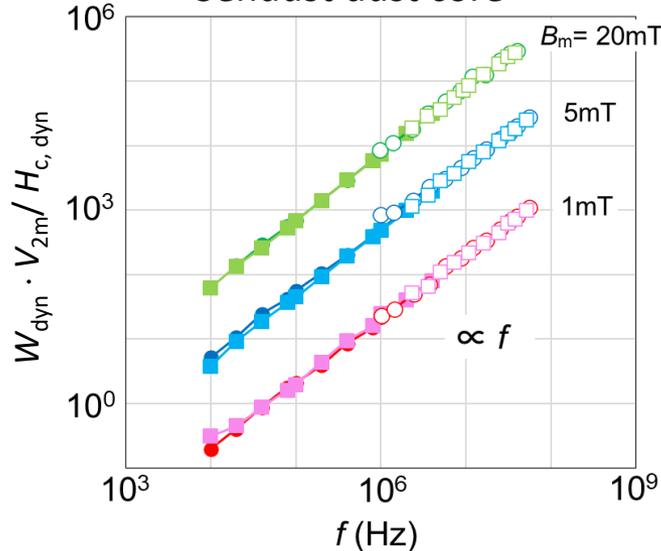
$$P_{c, dyn} \cdot V_m / H_{c, dyn} \propto f^{(u+v)}, u+v = 2$$

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

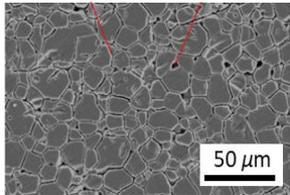
Permeability Analysis for Various Materials

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

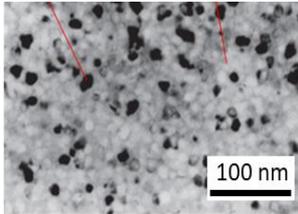
Sample	d (μm)*	h (mm) *	ρ_{AC} (Ωm)**	J_s (T) *	μ_{ri} **
Mn-Zn ferrite sintered core	11	4.9	7.8	0.51	2,900
FINEMET wound core	18	4.4	0.068	0.90	50,000
Sendust powder core	11	1.0	0.39	0.73	30

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

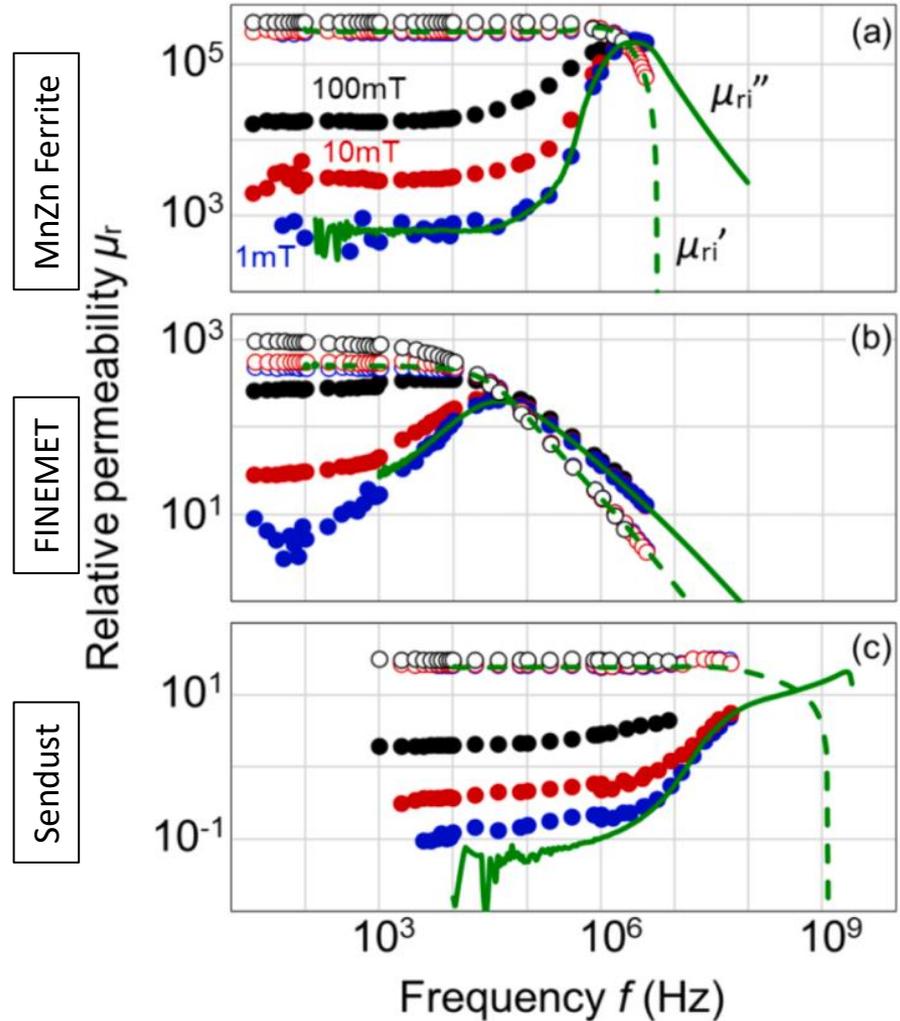
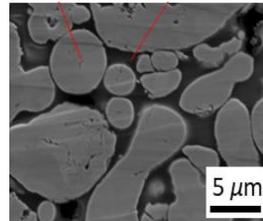
Mn-Zn ferrite



FINEMET



Sendust



MnZn Ferrite

FINEMET

Sendust

Relative permeability μ_r

Frequency f (Hz)

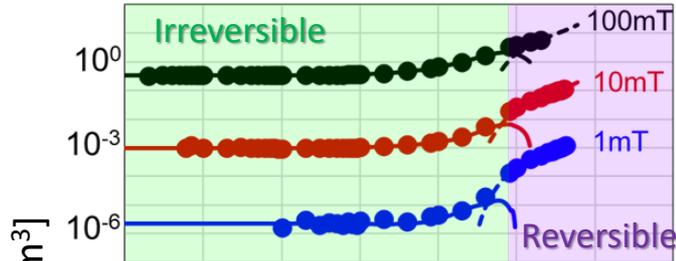
Broadband Iron Loss Analyses for Various Materials

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

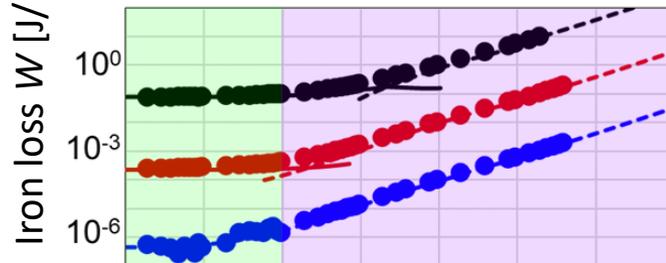
Magnetization process decomposition

Effective Domain Wall Number

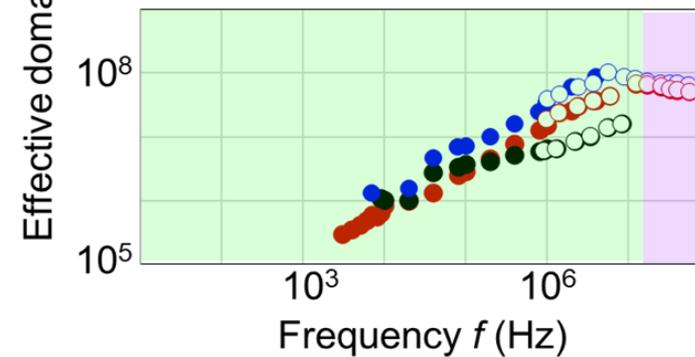
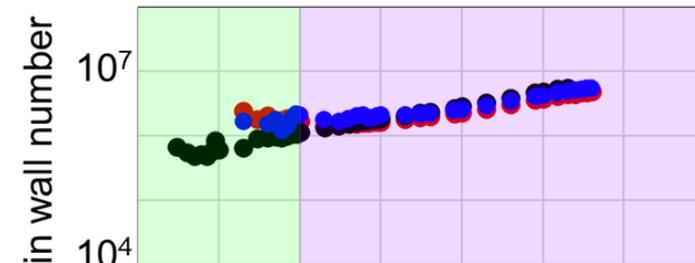
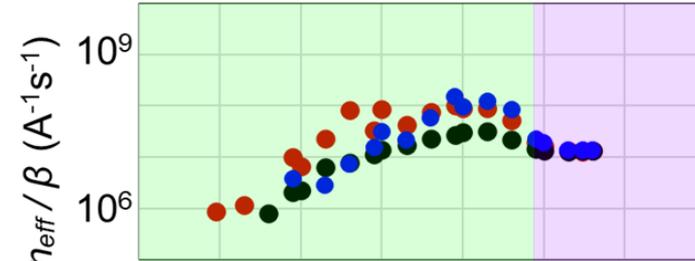
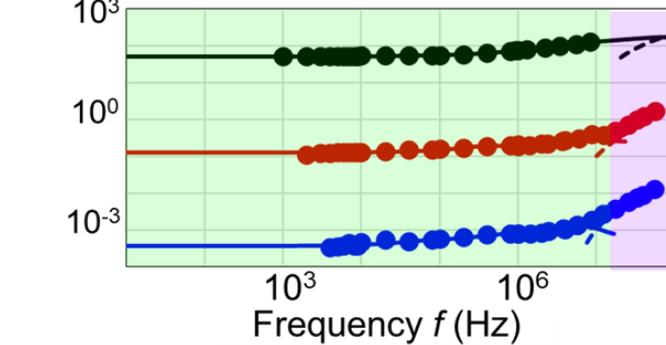
Mn-Zn Ferrite



FINEMET

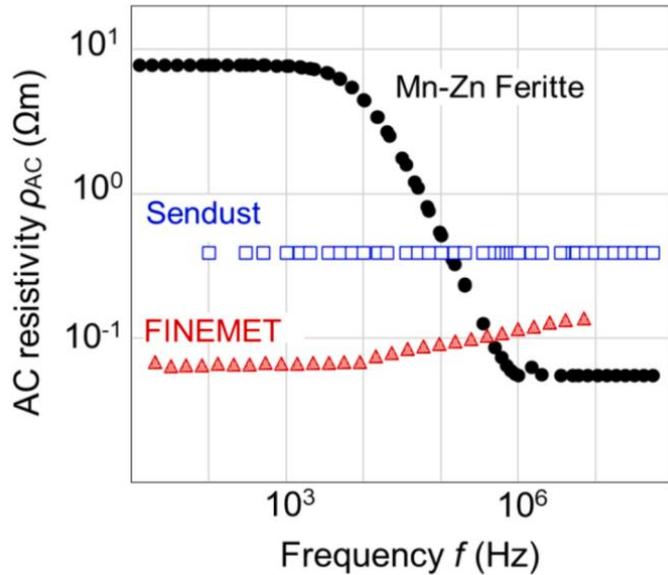
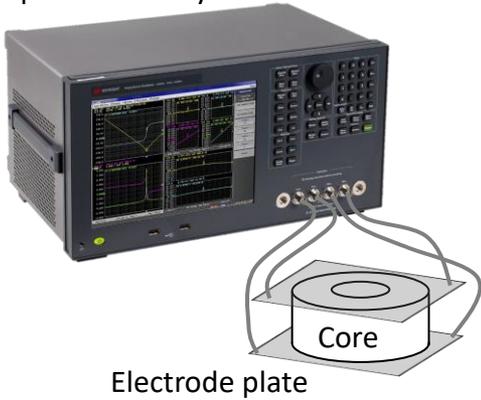


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Low frequency : Wall displacement
High frequency : Rotation

Impedance analyzer



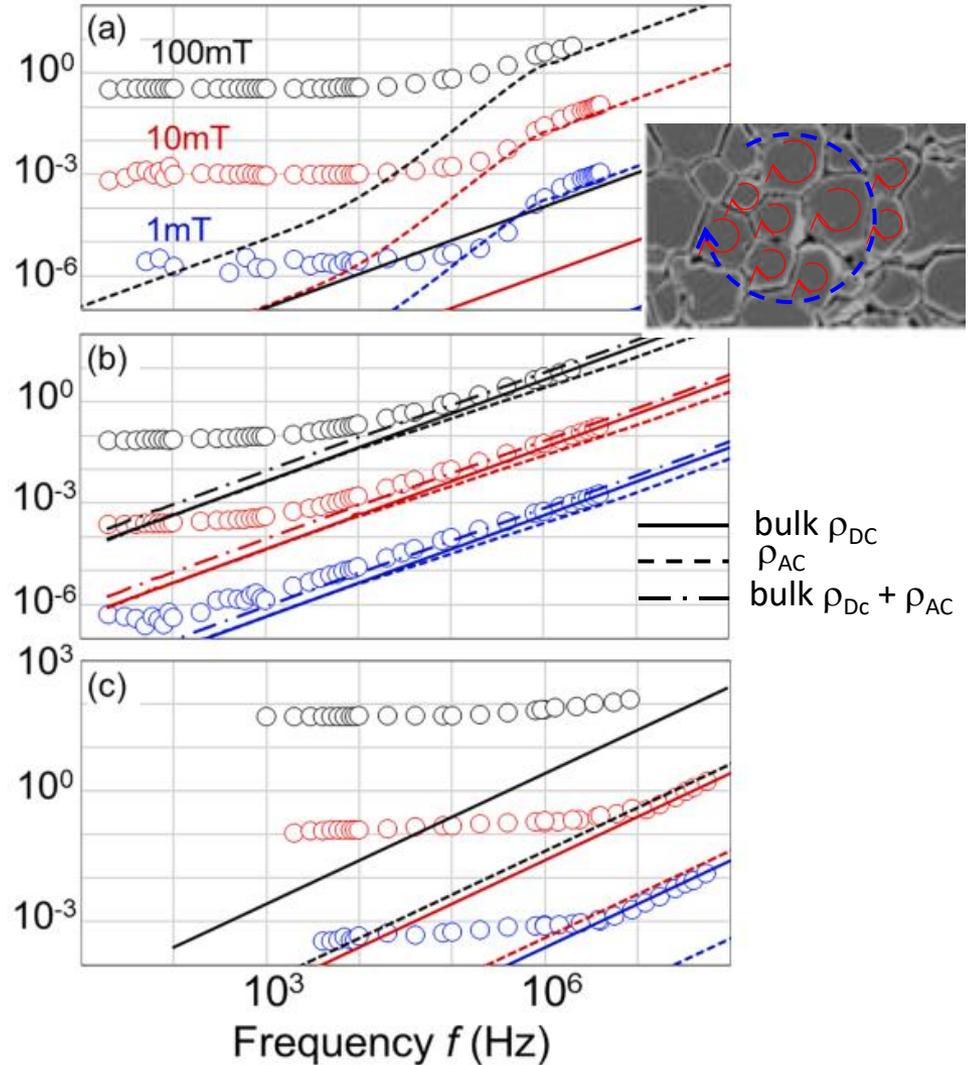
Classical eddy current loss evaluation

MnZn Ferrite

FINEMET

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Calculated W_{cl} (J/m^3)

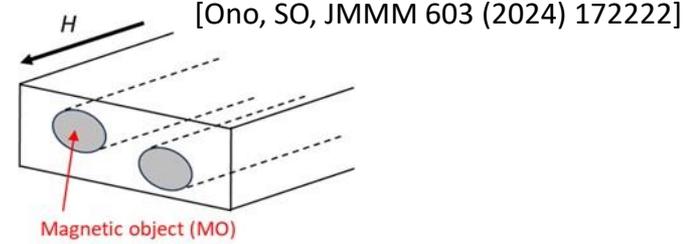


Comparison with Statistic and Steinmetz Analyses

Statistic Model Standard theory for excess loss

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

[Bertotti, JAP 57, 2110 (1985)]

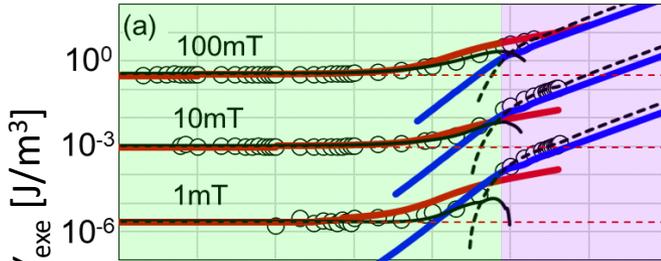


— $W_h + W_{exe}$ — W_{cl}

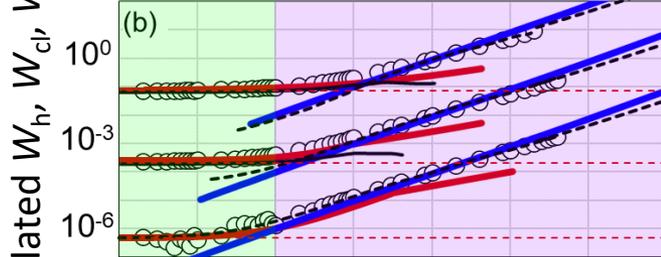
Magnetization process decomposition

Effective Domain Wall Number

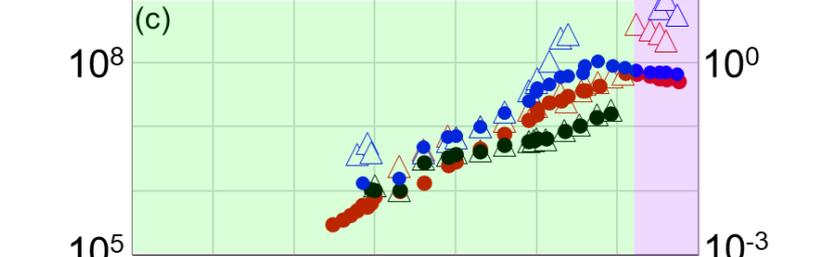
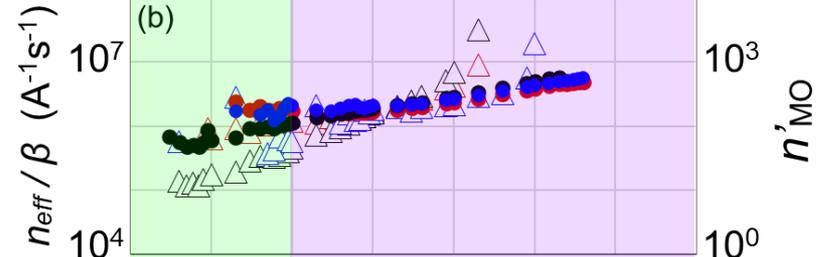
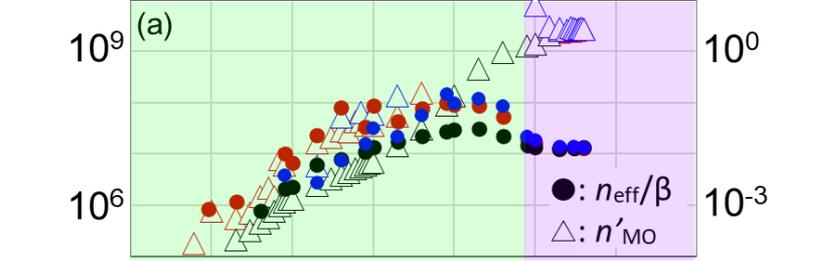
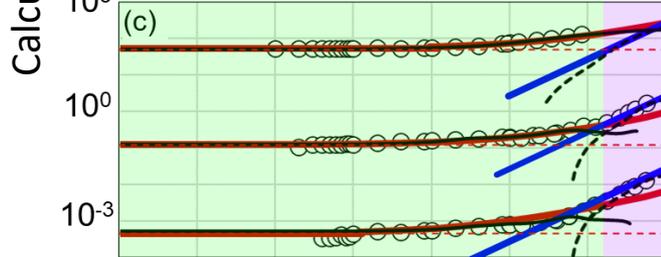
Mn-Zn Ferrite



FINEMET

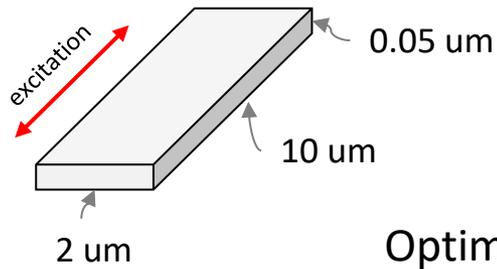


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Micromagnetics Simulation



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

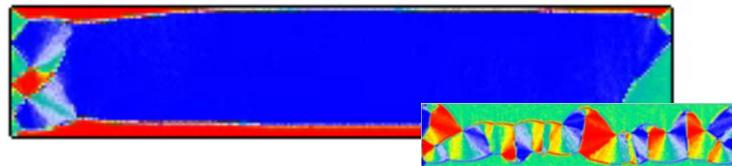
Steady state (Quasi-static)



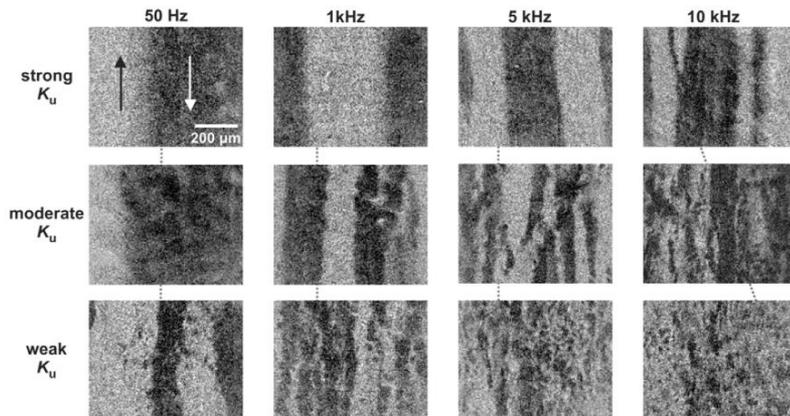
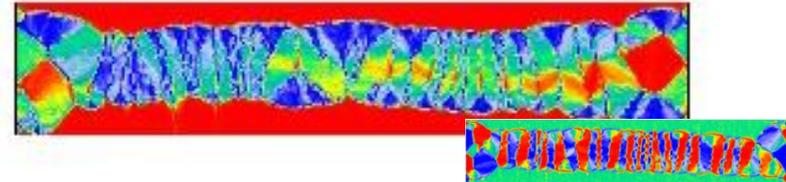
1 MHz



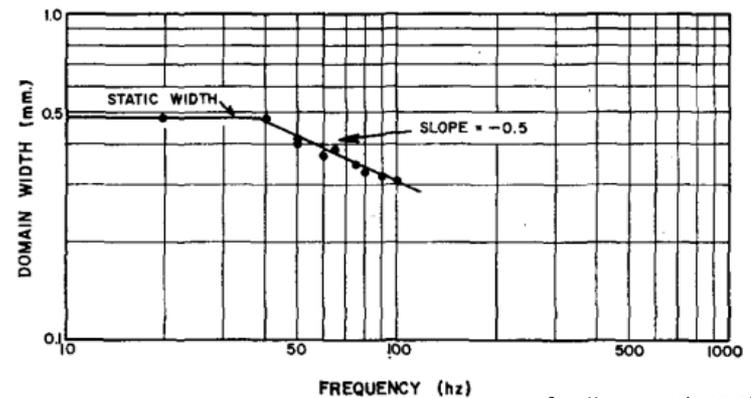
100 kHz



10 MHz



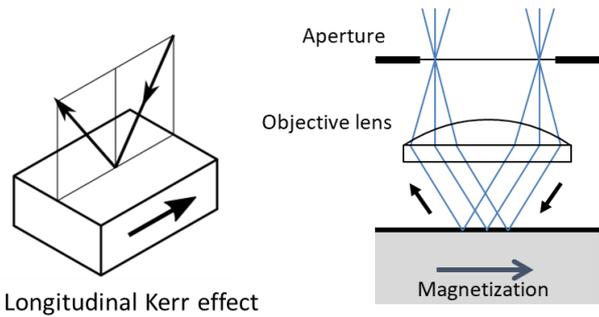
[Flohrer, Acta Mater (2006)]



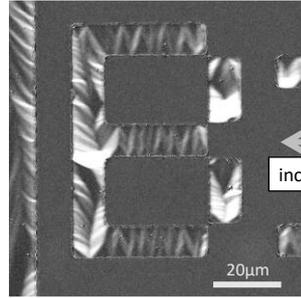
[Haller, JAP (1970)]

Vector MOKE Microscopy

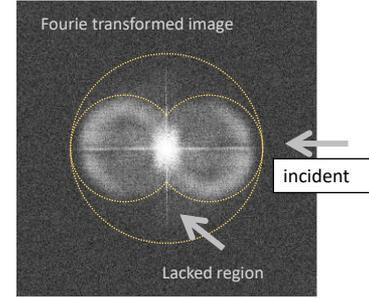
Conventional μ -MOKE



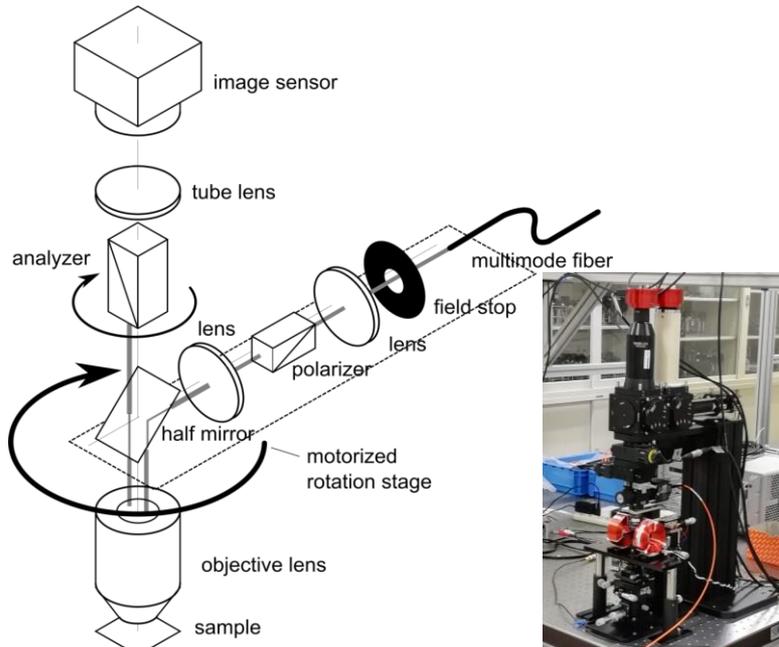
MOKE image



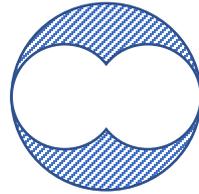
FFT



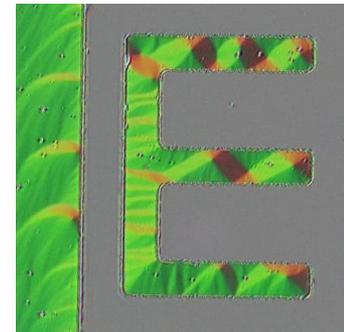
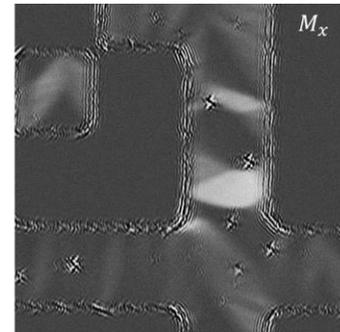
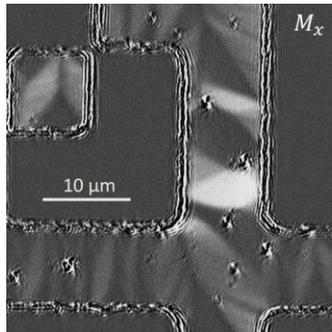
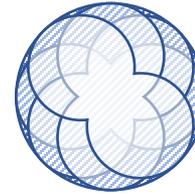
Newly developed Vector μ -MOKE



Conventional



This method



High resolution and vector magnetization

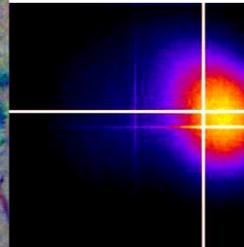
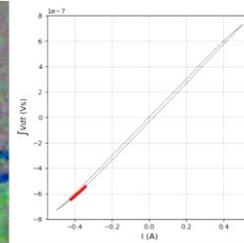
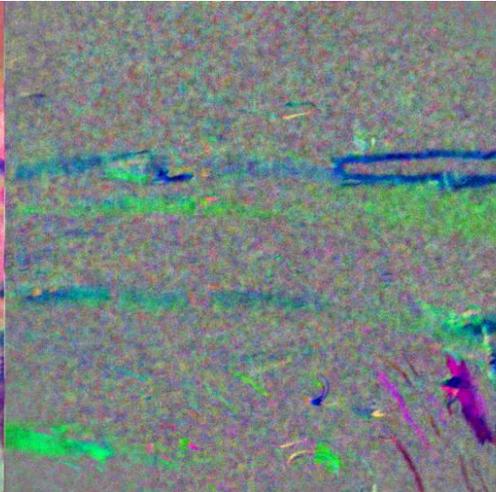
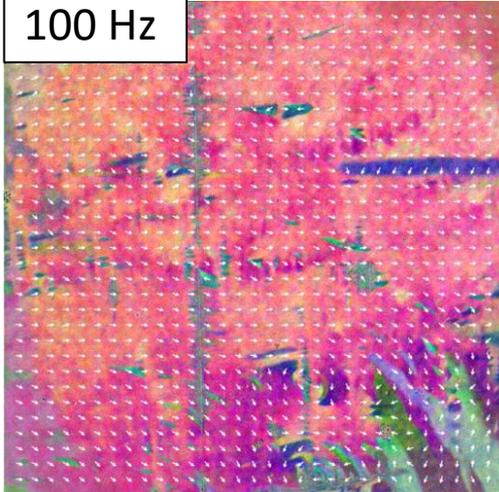
T. Ogasawara, Jpn. J. Appl. Phys. 56, 108002 (2017).

Time-Resolved Vector MOKE Microscopy

NANOMET ribbon

Differential

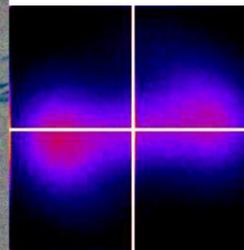
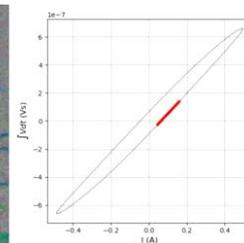
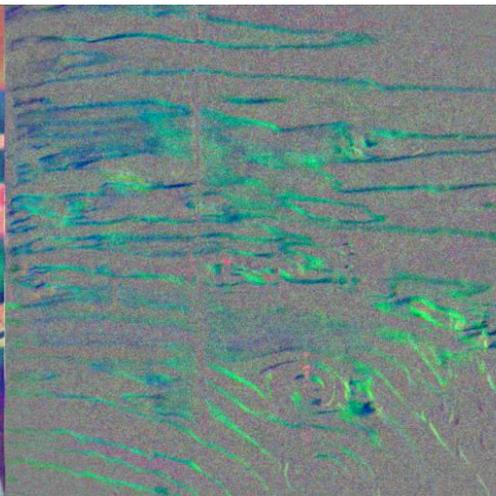
100 Hz



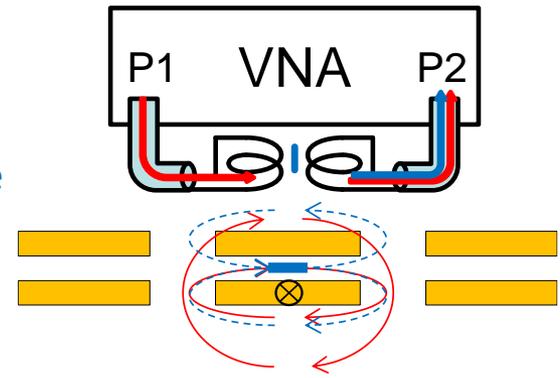
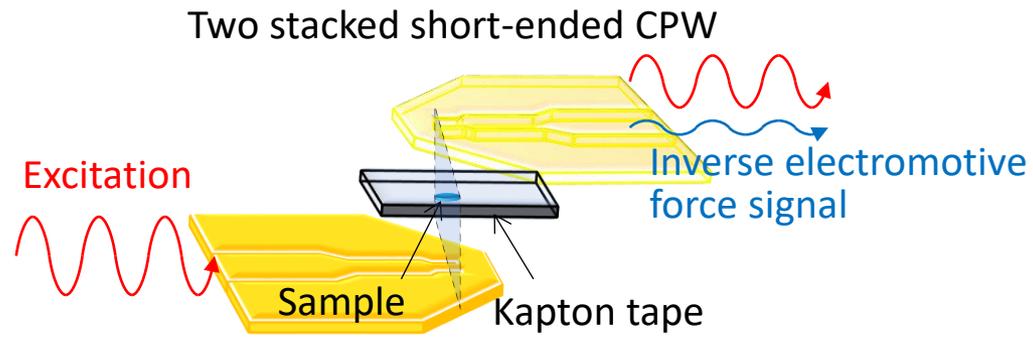
B-H

Vector histogram

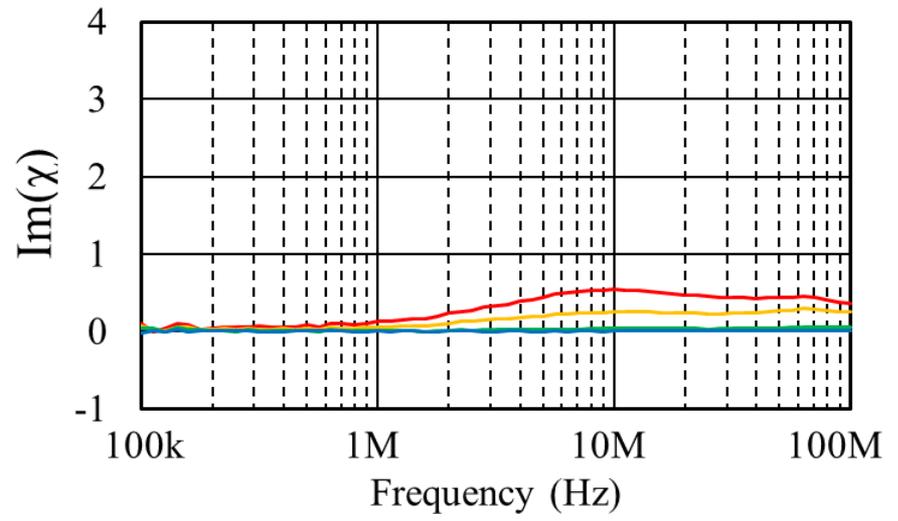
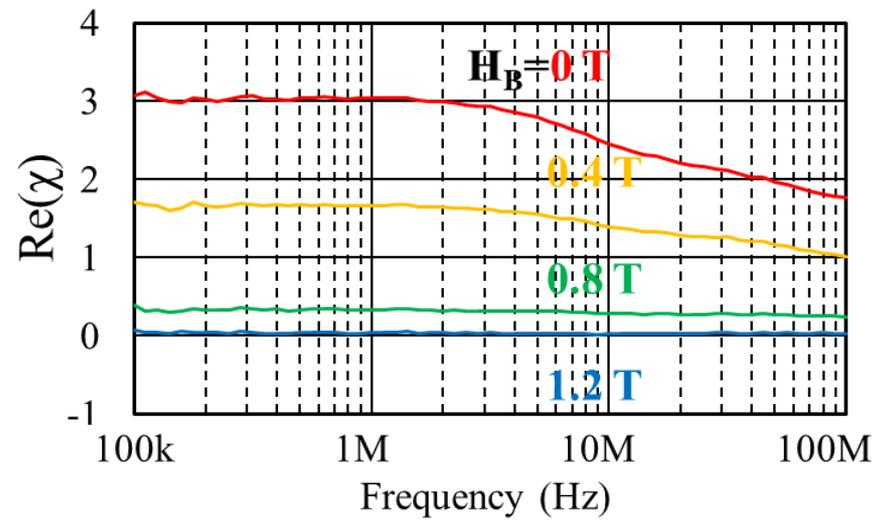
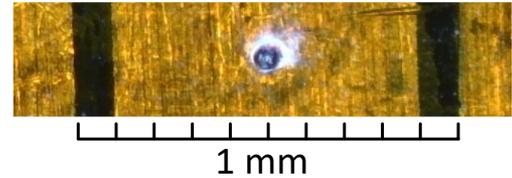
100 kHz



Permeability Measurement for a Single Particle



Fe₂B atomized particle
 $B_s \sim 1.6$ T
 Diameter ~ 50 μ m



Loss Mechanism

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

Measurements

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

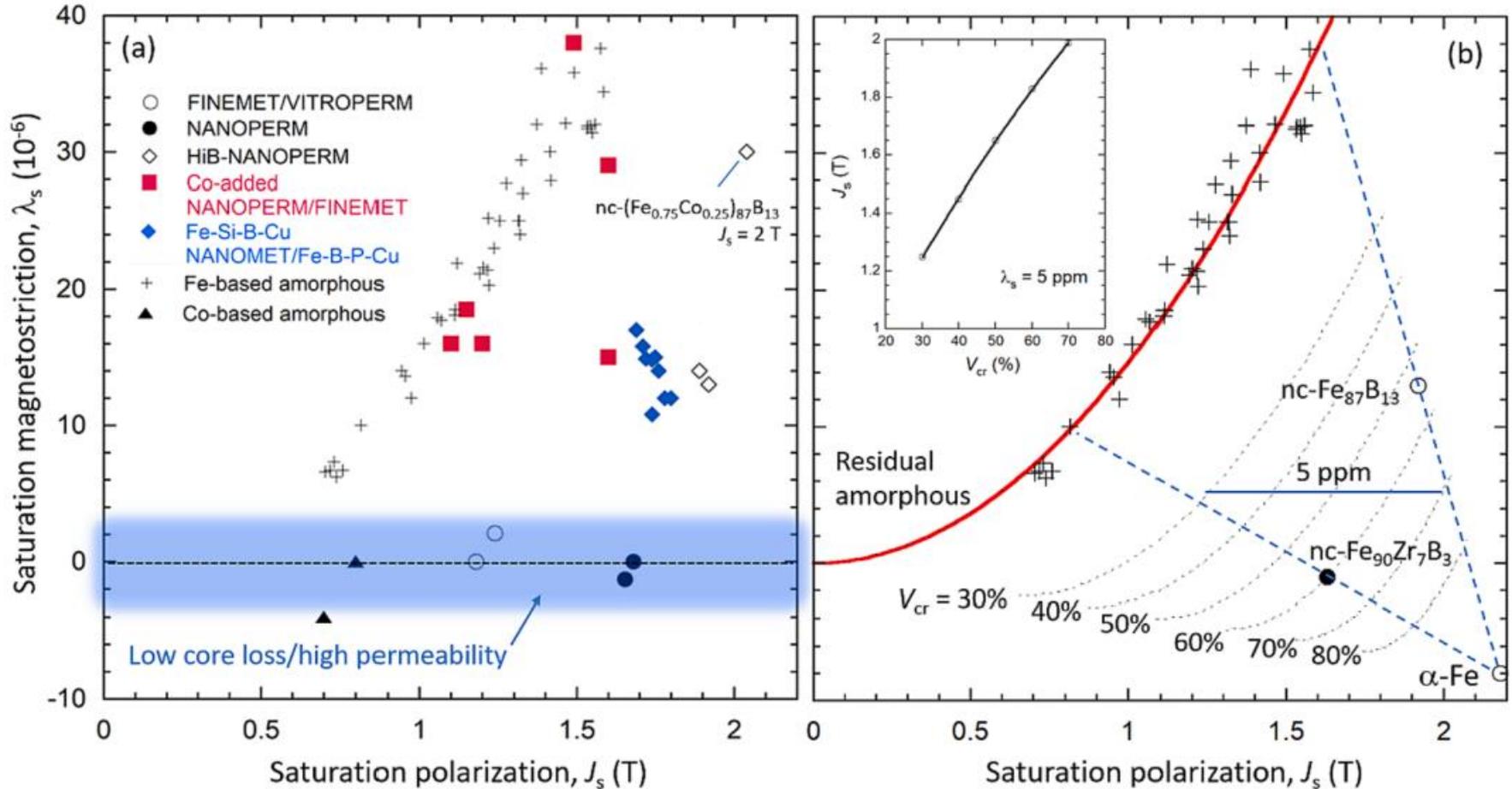
Material Design and Developments

- 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





Acknowledgments

Collaborators



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



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



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MEXT

