Measurement of magnetic fields with hysteresis effects in bending magnet for beam transport1

K.SUGAHARA, R.YASUTOMI (Kindai Univ.)
Y. ISHI, Y. KURIYAMA, T. UESUGI,
Y. FUWA, H. OKITA(KURRI)

FFAG 17 at Cornell Univ. , Sep. 10 2017

Contents of presentation

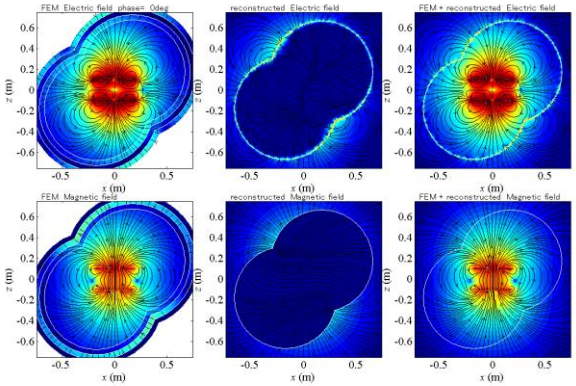
- Introduction
- Play model
- Research process(PLAN)
- A-Φ and TOSCA
- Summary

Self-introduction

2001. Mitsubishi Electric
Advanced Technology R&D Center

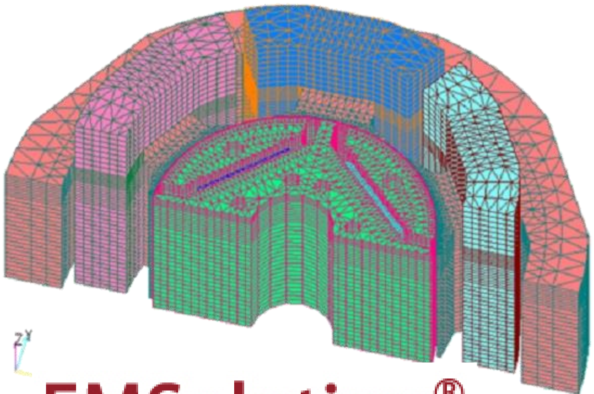
2008. Cell Phone Department <u>Withdrawal</u>

2010. Mitsubishi Electric (Kobe)
Proton Therapy Synchrotron



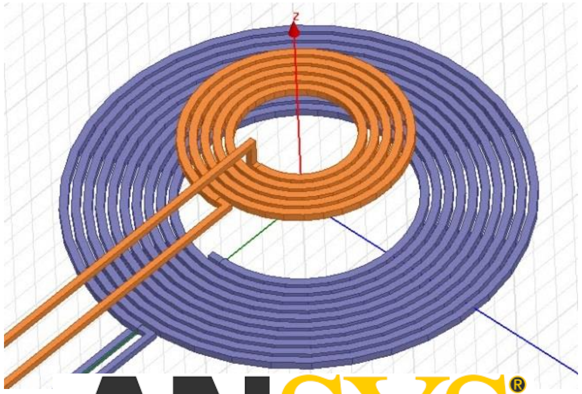
2014. Kindai University
IEEE Magnetics Society
(Electromagnetic Analysis)

IEEE MAGNETICS



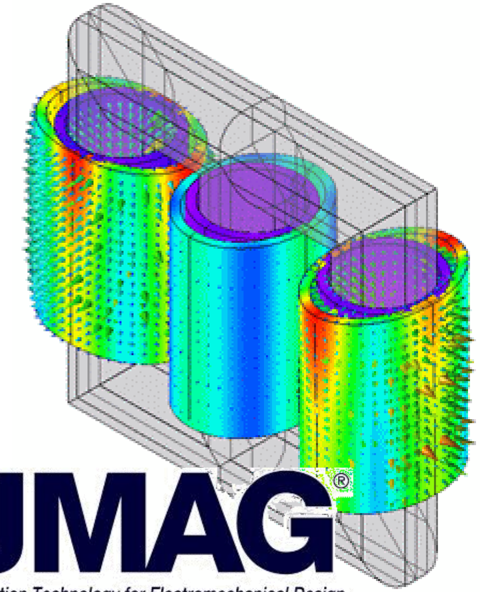
EMSolution®

IPMSM model



ANSYS®

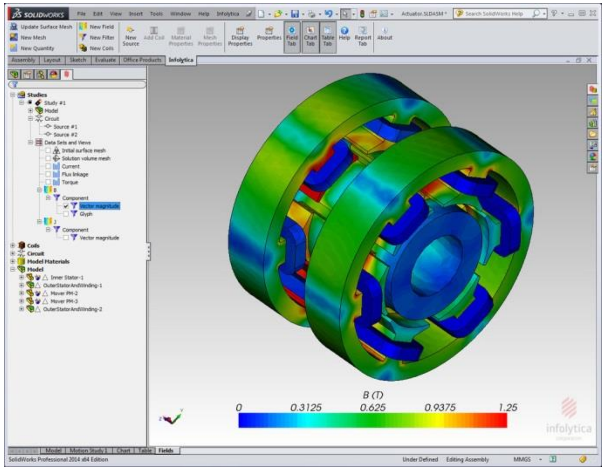
Wireless PT



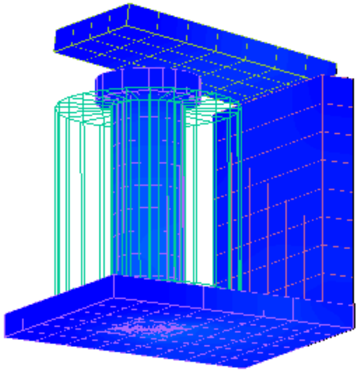
JMAG®

Simulation Technology for Electromechanical Design

Transformer



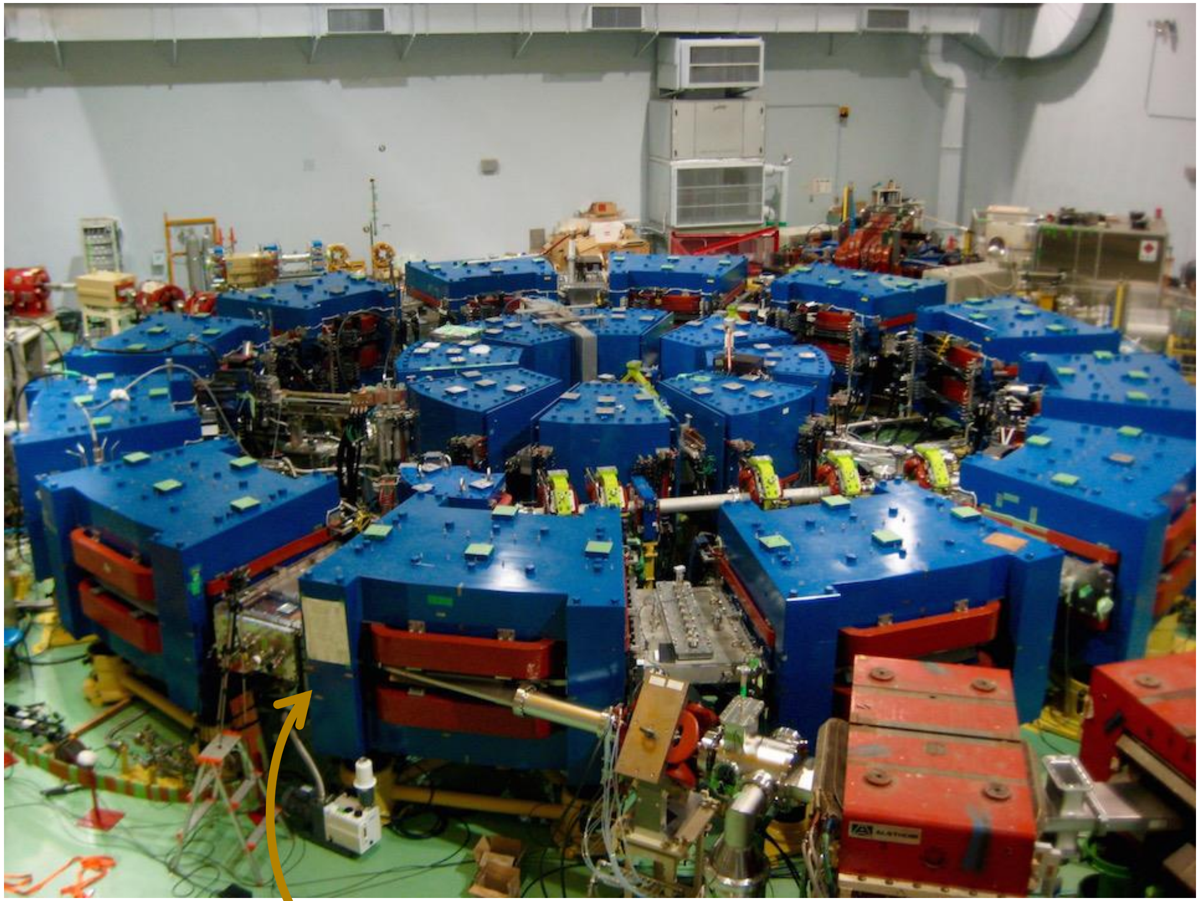
infolytica
corporation



ELF/magic

magnetic relay

Collaboration with FFAG@KURRI



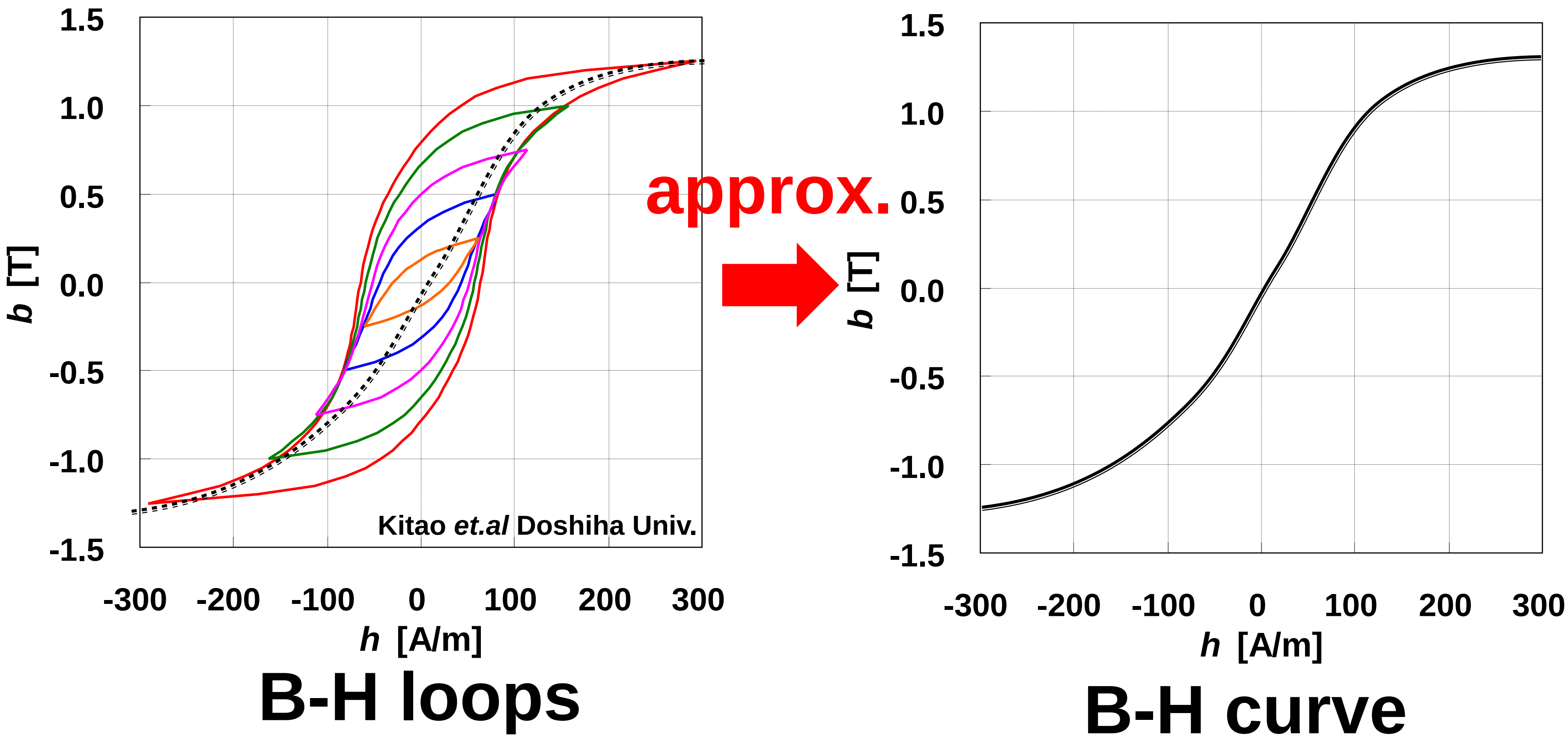
Electric apparatus

Yoshihiro Ishi

MITSUBISHI ELECTRIC

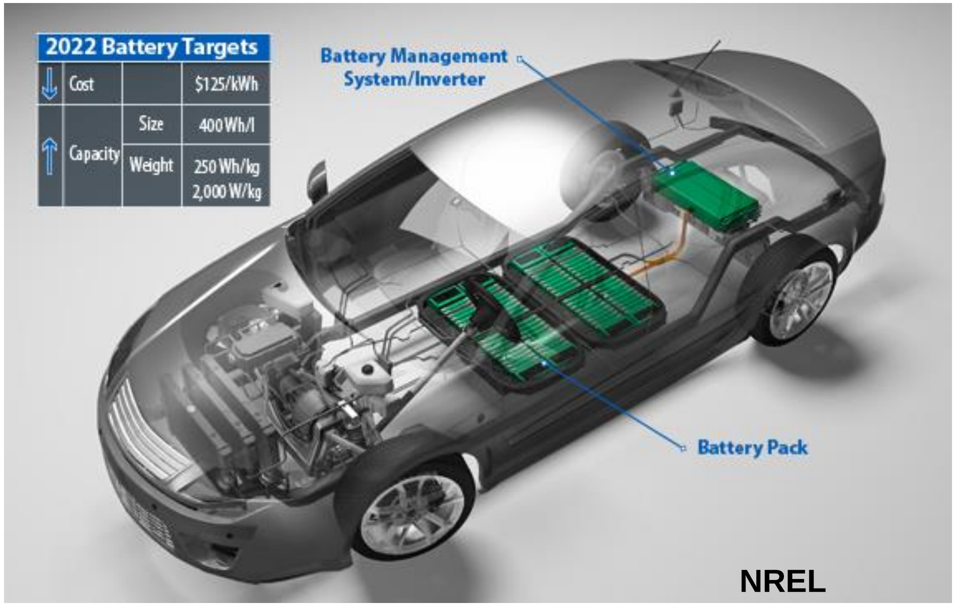
My background is not 100% accelerator.

BH-loops in Electric Apparatus

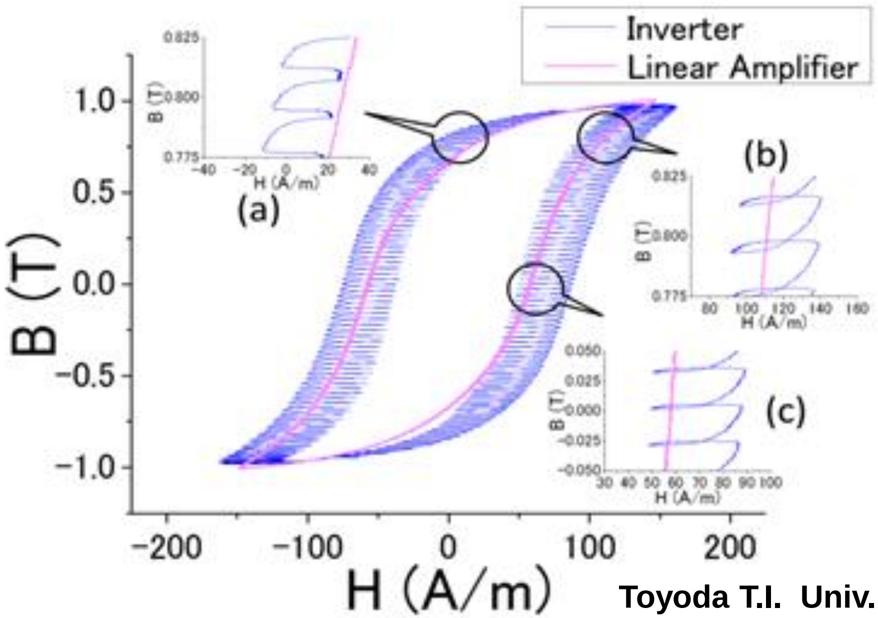


Most of EM software (e.g. TOSCA) uses B-H curve, instead of B-H loops.

Hysteresis Effects in Iron Loss



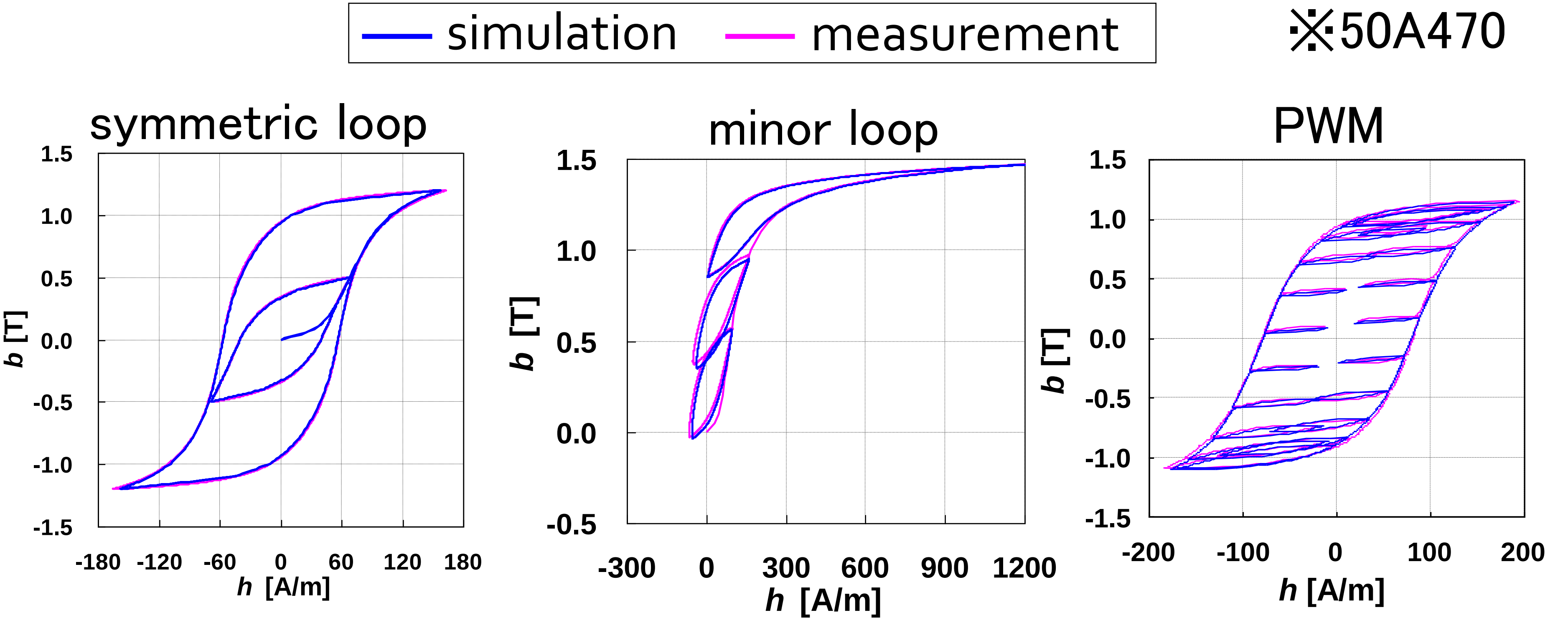
electric vehicle



inverter driven

Iron loss is important in electric vehicles.

Recent Progress in hysteresis analysis



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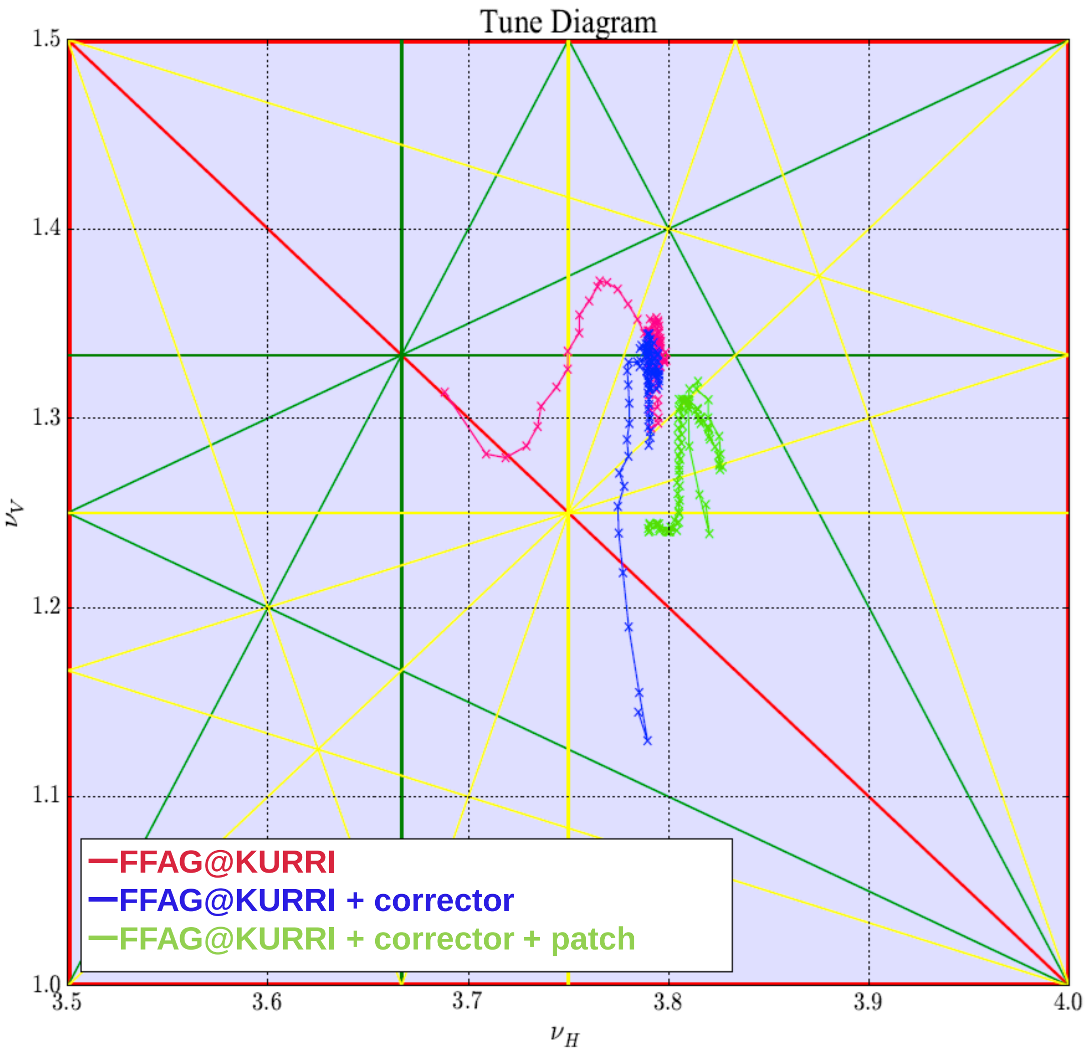
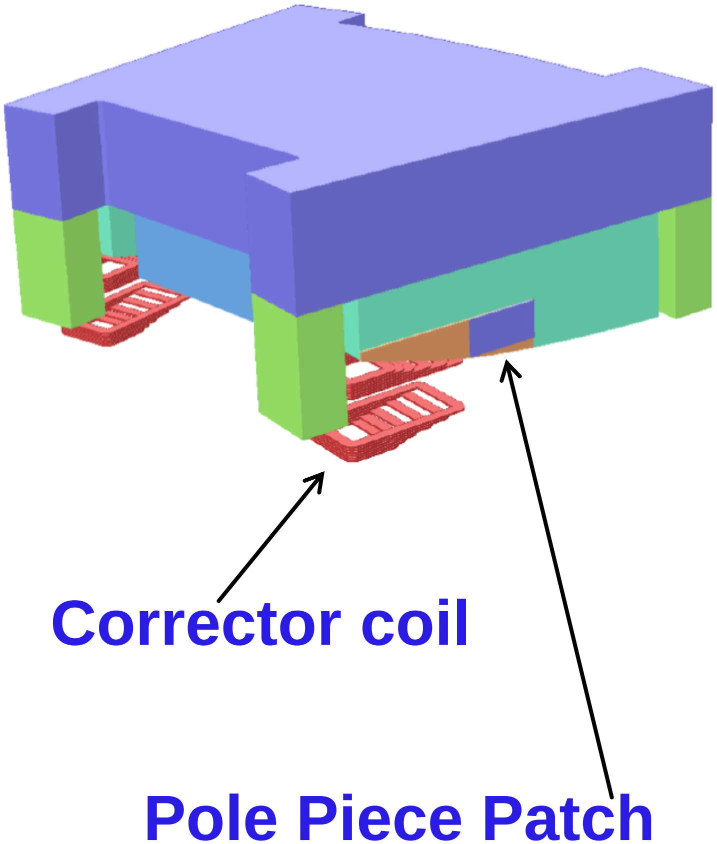
Hysteresis models can reproduce BH-loops pretty well.

Objective of our Research

Prior research: tune corrections

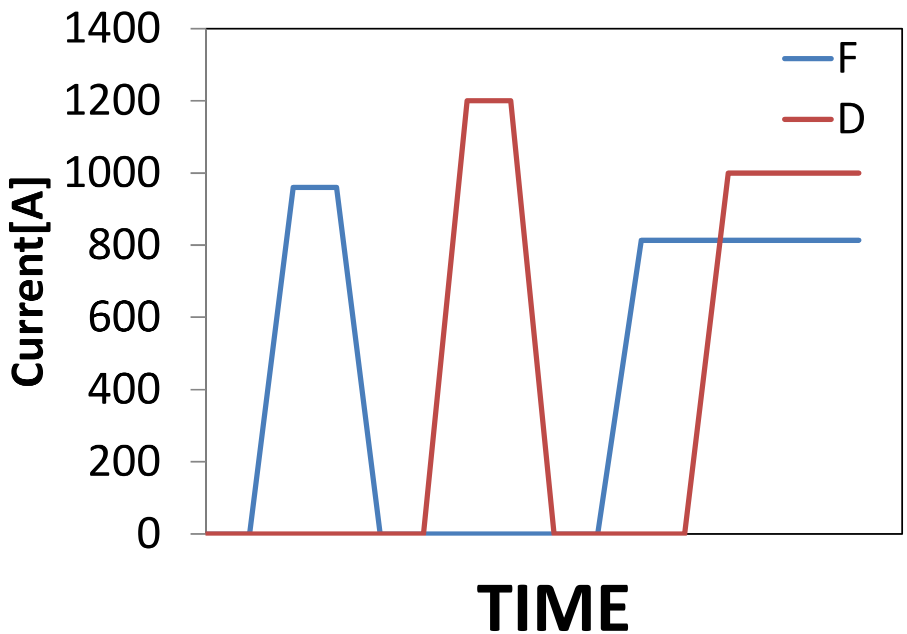




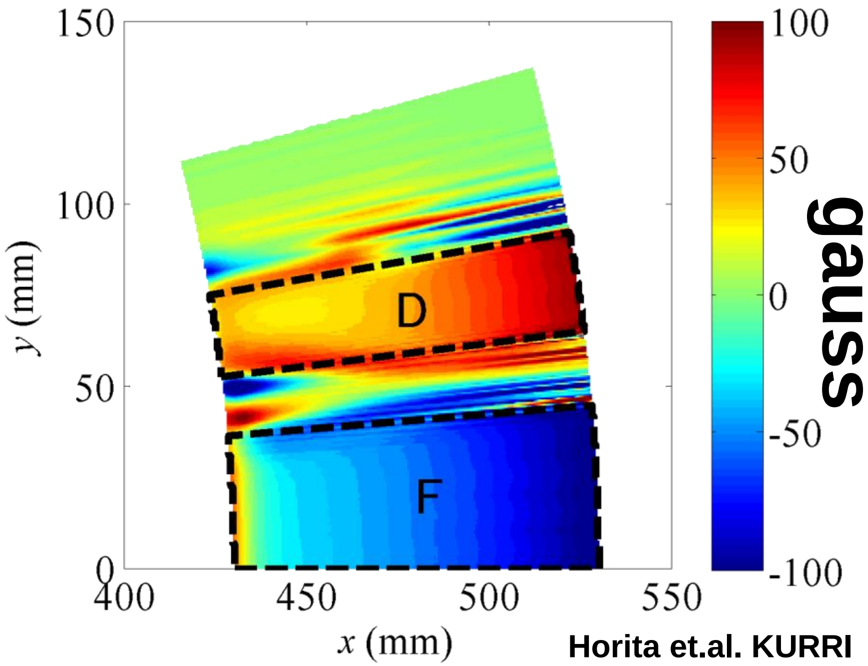
Motohasi et.al. Kyushu Horita et.al. KURRI

Objective of our Research

Optimization of initial current pattern



initial current pattern



Horita et.al. KURRI

target ΔB map

$$\Delta B = B_{\mathrm{horita}} - B_{\mathrm{orig}}$$

By optimizing the initial current pattern, tune corrections will be performed without any additional components.

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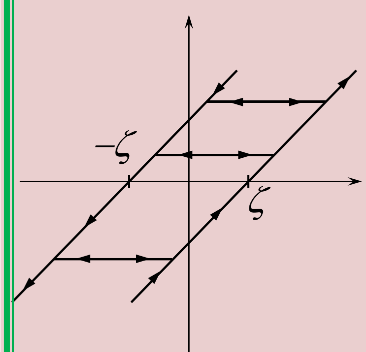
Hysteresis model benchmark

Phenomelogical model ⟷ **Physics-based model**

	Play model	Jiles–Atherton	Stoner–Wohlfarth	Micromagnetics
Theory		$M = M_{irr} + M_{rev}$ $M_{rev} = c(M_{an} - M_{irr})$ $\frac{dM_{rev}}{dH} = \frac{M_{an} - M_{irr}}{\delta k - \alpha(M_{an} - M_{irr})}$ $M_{an} = M_s\left(\coth\frac{H_e}{a} - \frac{a}{H_e}\right)$	$E = K\sin^2\theta - MH\cos\varphi$ K: Anisotropy param. θ: easy axis angle φ: magnetization angle	$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M}\times\boldsymbol{H} - \frac{\alpha\gamma}{M}\boldsymbol{M}\times(\boldsymbol{M}\times\boldsymbol{H})$ $\boldsymbol{H} = -\frac{\partial E_{ani}}{\partial \boldsymbol{M}} - \frac{\partial E_{mag}}{\partial \boldsymbol{M}} - \frac{\partial E_{exc}}{\partial \boldsymbol{M}} - \frac{\partial E_{ext}}{\partial \boldsymbol{M}}$
Accuracy	good	difficulty in minor loop	difficulty in minor loop	excellent
Identification	reasonable	not easy	not easy	reasonable
Computation time	fast	fast	slow	very slow
Number of parameters	20–80	5 (scalar) 15 (vector)	4N	too many

Mathematically equivalent to Preisach

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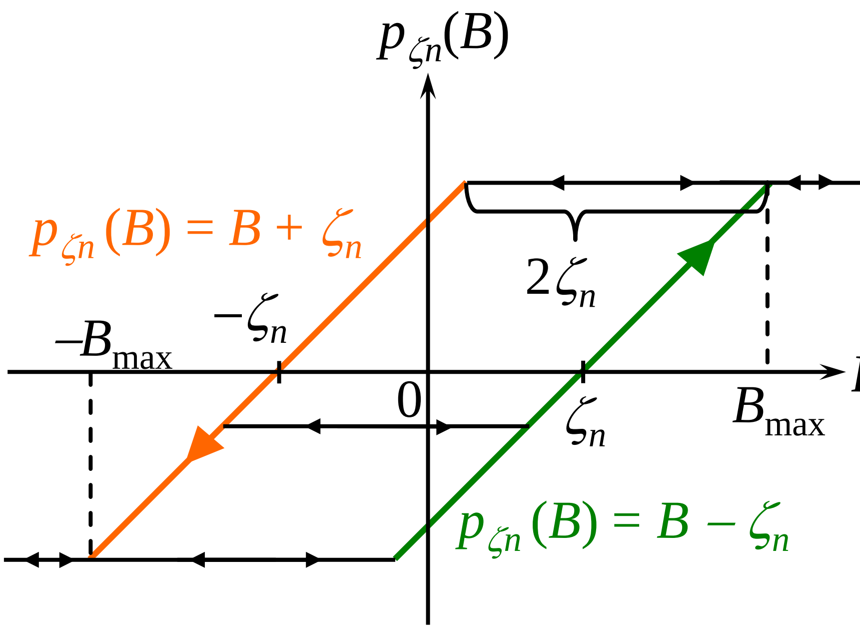
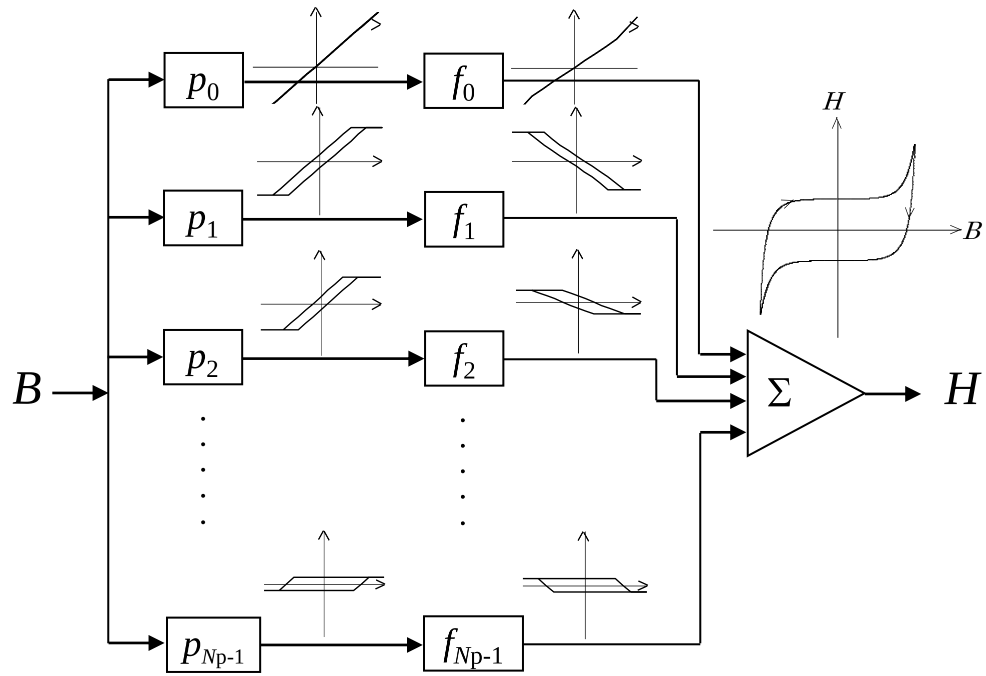
Theory of Play model





Play hysteron

$$0 \le \zeta_n \le B_{\max}$$

$$-B_{\max} + \zeta_n \le p_{\zeta n}(B) \le B_{\max} - \zeta_n$$

$$f_{\zeta_n}(p_{\zeta_n}) = f_{\zeta_n}(p_{\zeta_n,j}) + \mu_{n,j}(p_{\zeta_n} - p_{\zeta_n,j})$$

Shape functions

$$H(B) = \sum_{n=0}^{N_p-1} f_{\zeta_n}(p_{\zeta_n}(B))$$

$$\zeta_n = nB_{\max}/N_p \quad (n = 0, 1, \ldots, N_p-1)$$

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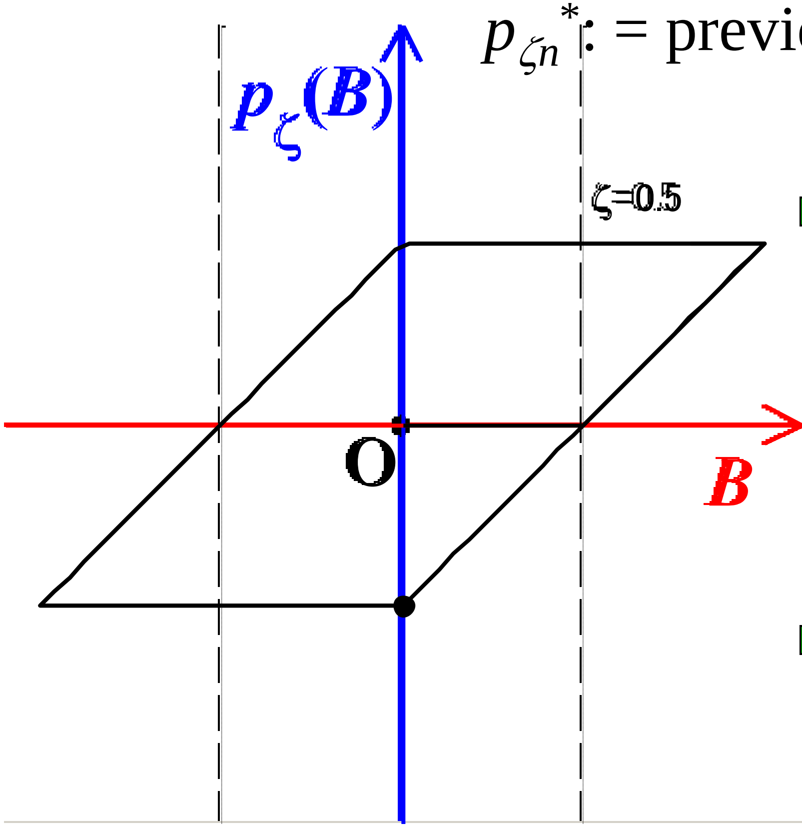
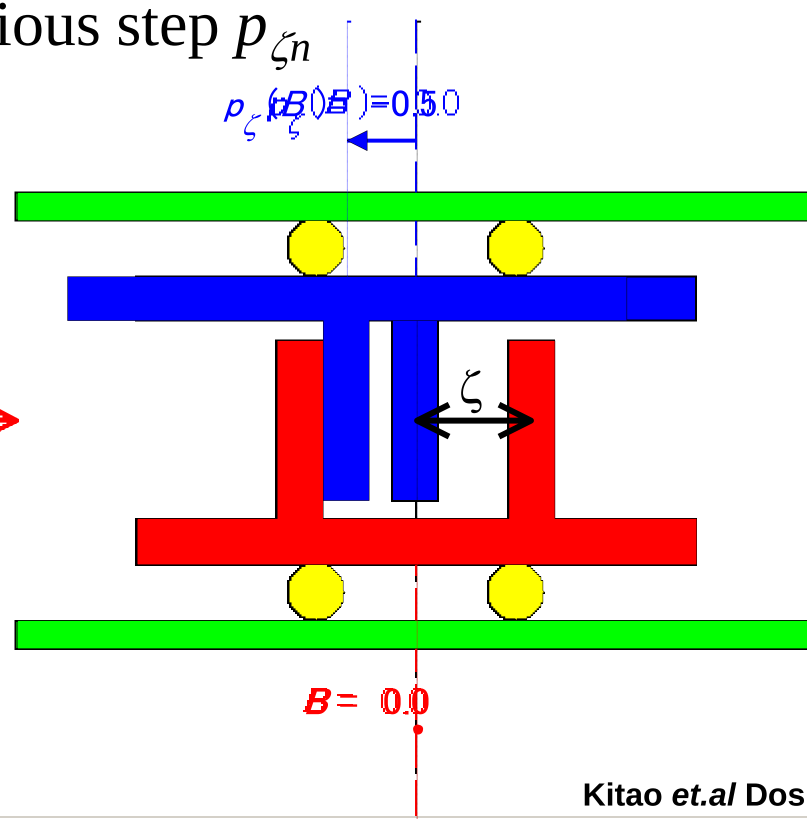
shape functions are different in each material

Play hysteron ζ = 0.5

$$p_\zeta(B) = B - \frac{B - p_\zeta^{\ *}}{\max(\left|B - p_\zeta^{\ *}\right|, \zeta)}\zeta$$

$p_{\zeta n}^{\ *}$: = previous step $p_{\zeta n}$





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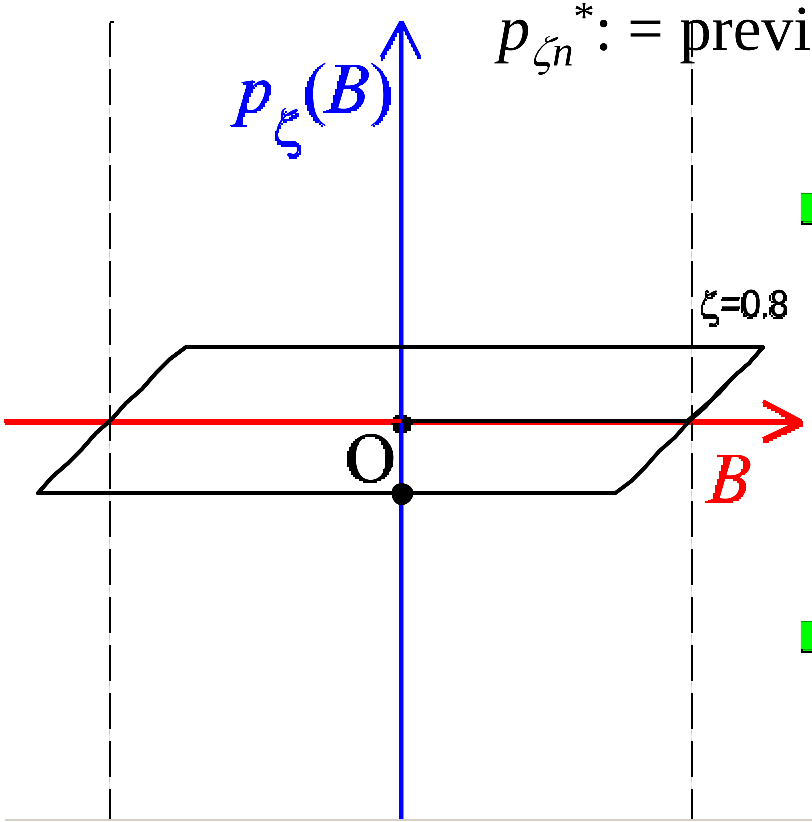
Play hysteron

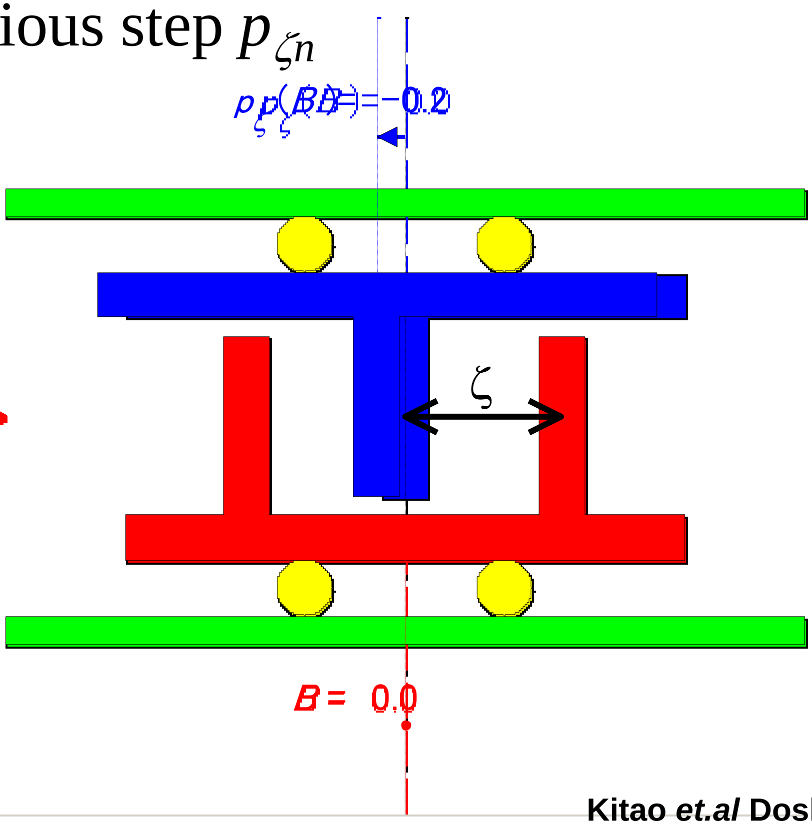
Cart model

Play hysteron ζ = 0.8

$$p_\zeta(B) = B - \frac{B - p_\zeta^{\,*}}{\max(\left|B - p_\zeta^{\,*}\right|, \zeta)}\zeta$$

$p_{\zeta n}^{\,*} :=$ previous step $p_{\zeta n}$





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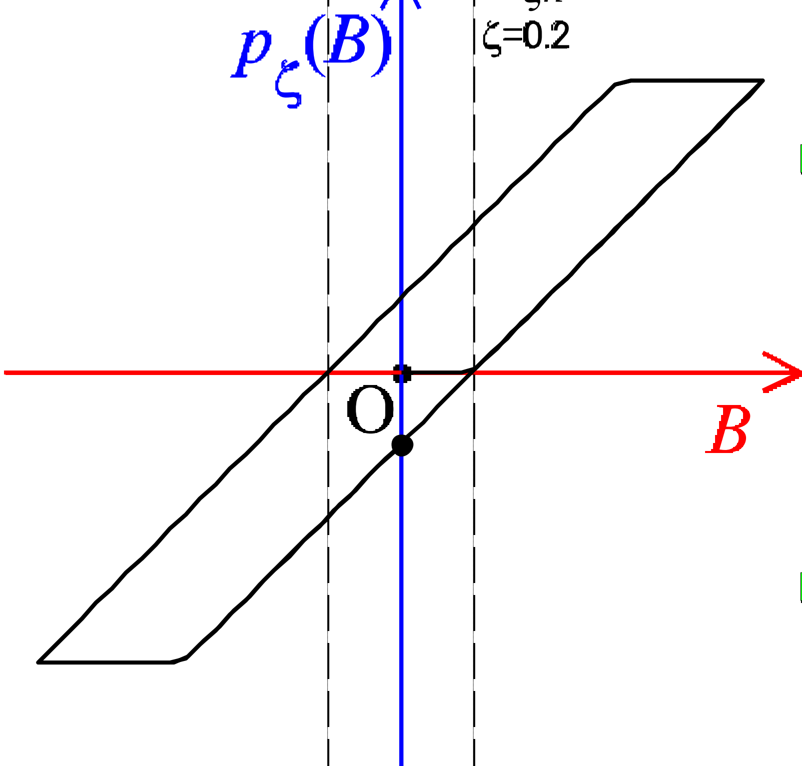
Play hysteron **Cart model**

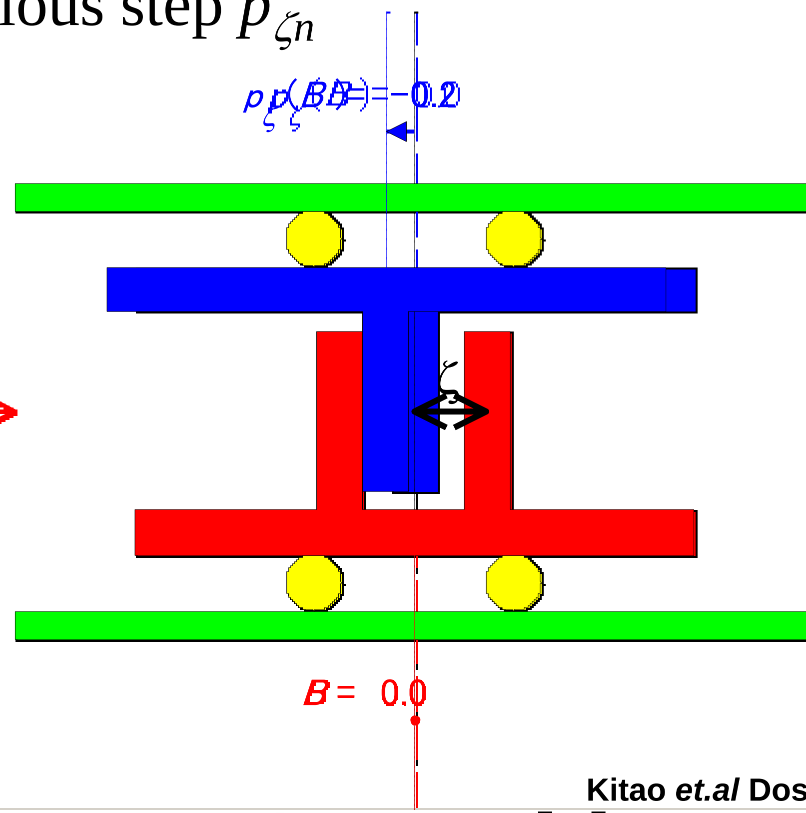
Play hysteron $\zeta = 0.2$

$$p_\zeta(B) = B - \frac{B - p_\zeta^{\ *}}{\max\left(\left|B - p_\zeta^{\ *}\right|, \zeta\right)}\zeta$$

$p_{\zeta n}^{\ *} :=$ previous step $p_{\zeta n}$



Play hysteron



Cart model

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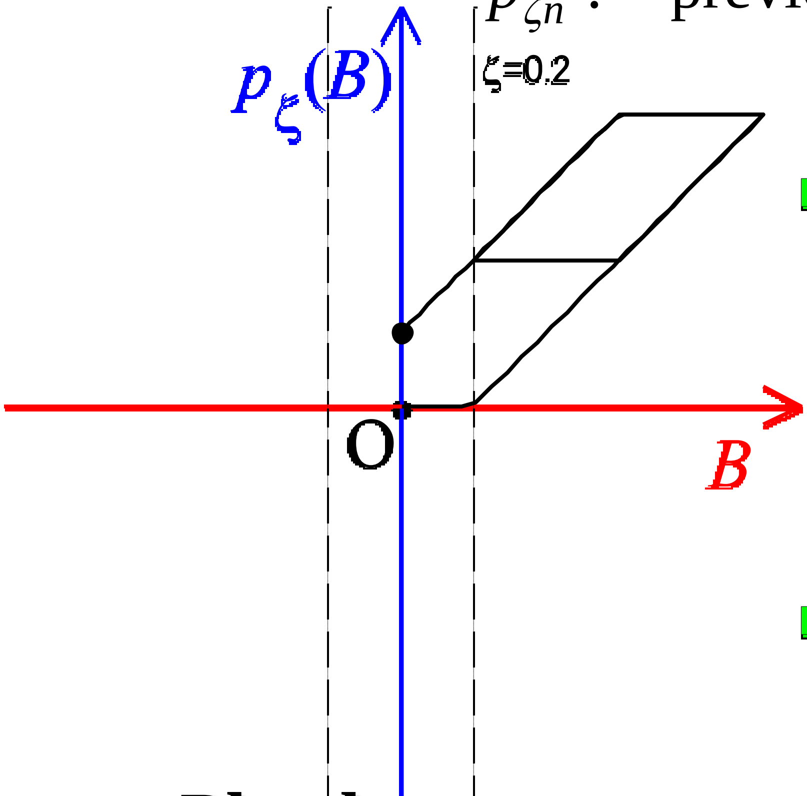
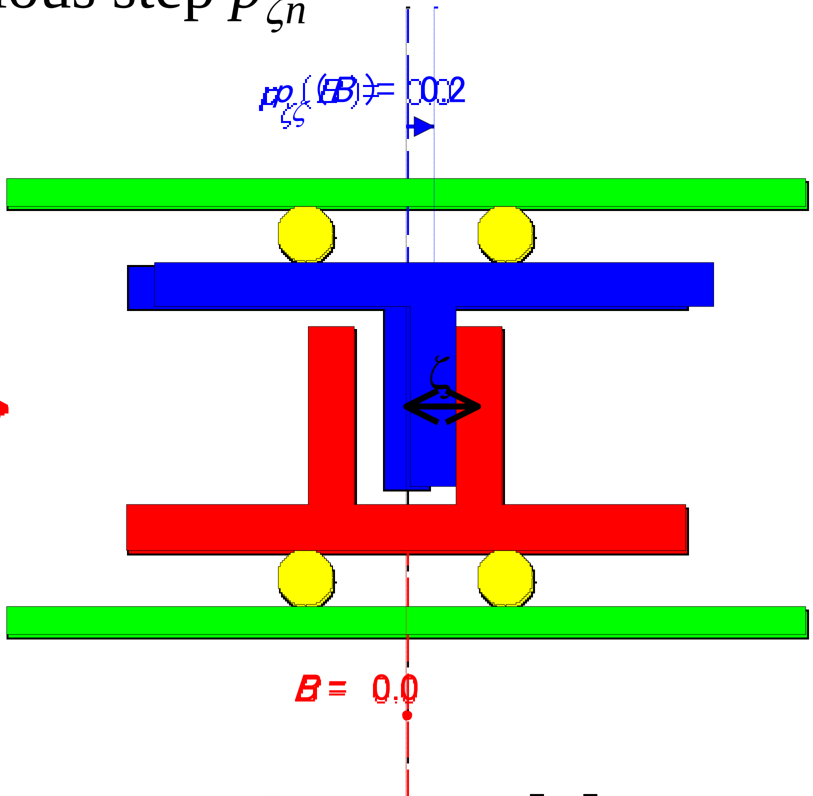
Play hysteron ζ = 0.2

$$p_\zeta(B) = B - \frac{B - p_\zeta^*}{\max(\left|B - p_\zeta^*\right|, \zeta)}\zeta$$

$p_{\zeta n}^*$: = previous step $p_{\zeta n}$

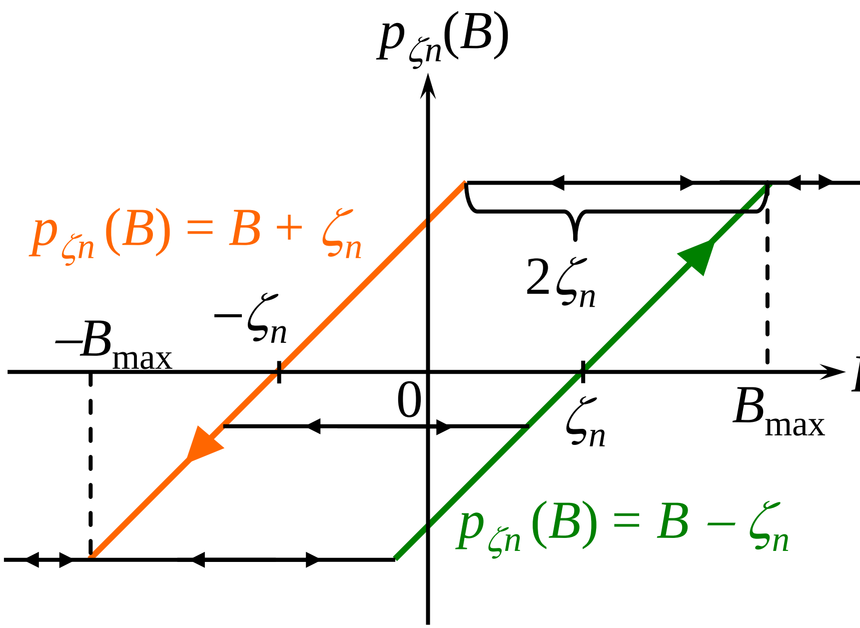




Play hysteron

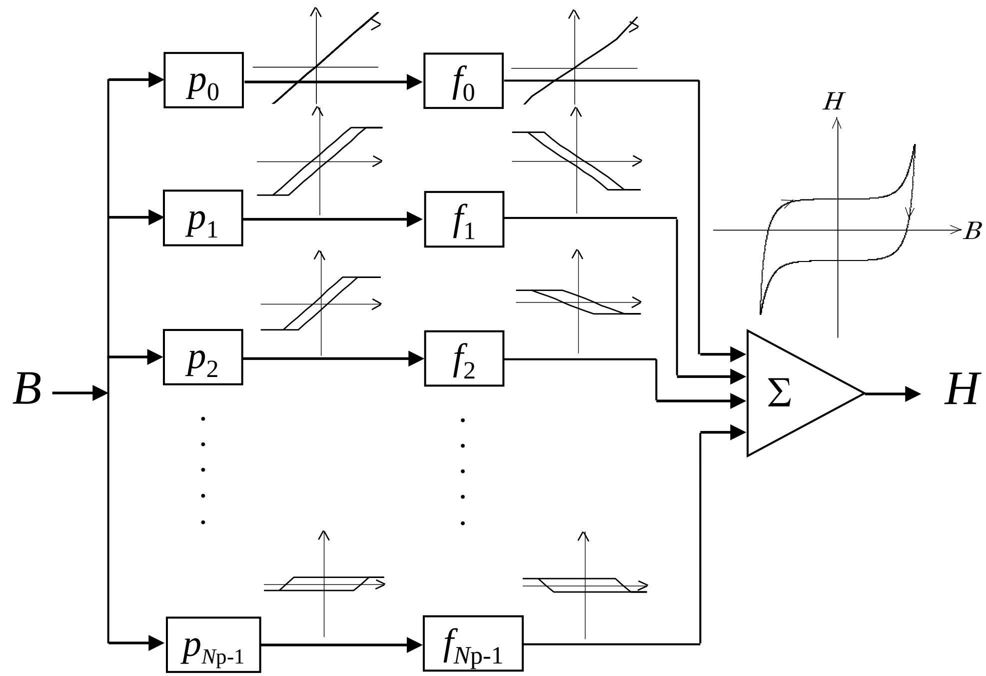
Cart model

Theory of Play model



Play hysteron

$$0 \le \zeta_n \le B_{max}$$
$$-B_{max} + \zeta_n \le p_{\zeta n}(B) \le B_{max} - \zeta_n$$
$$f_{\zeta_n}(p_{\zeta_n}) = f_{\zeta_n}(p_{\zeta_n,j}) + \mu_{n,j}(p_{\zeta_n} - p_{\zeta_n,j})$$



Shape functions

$$H(B) = \sum_{n=0}^{N_p-1} f_{\zeta_n}(p_{\zeta_n}(B))$$
$$\zeta_n = nB_{max}/N_p \quad (n = 0, 1, \ldots, N_p-1)$$

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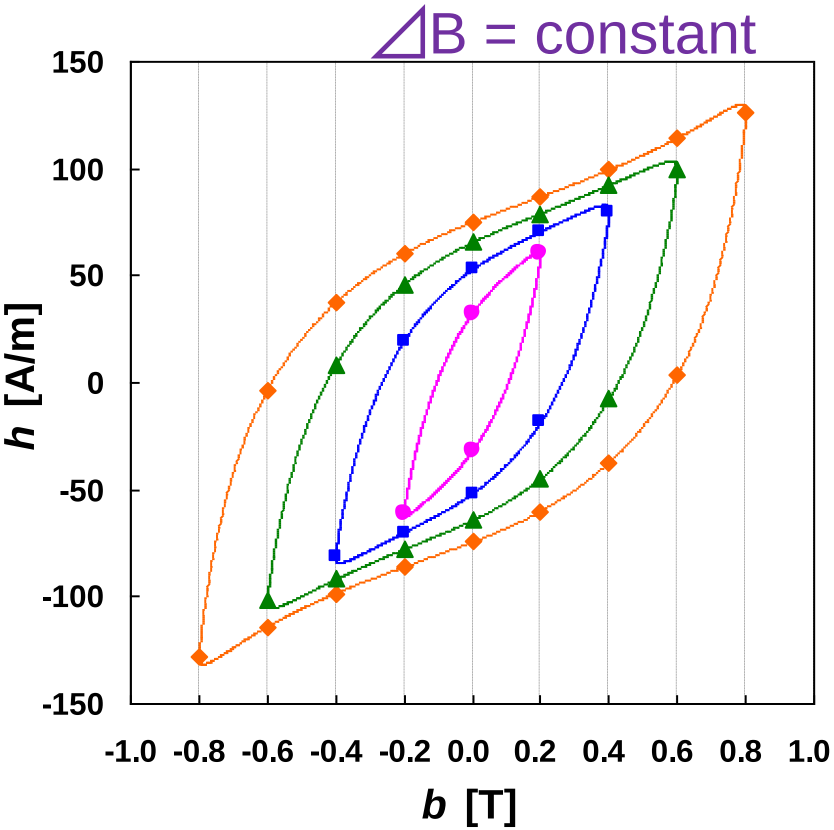
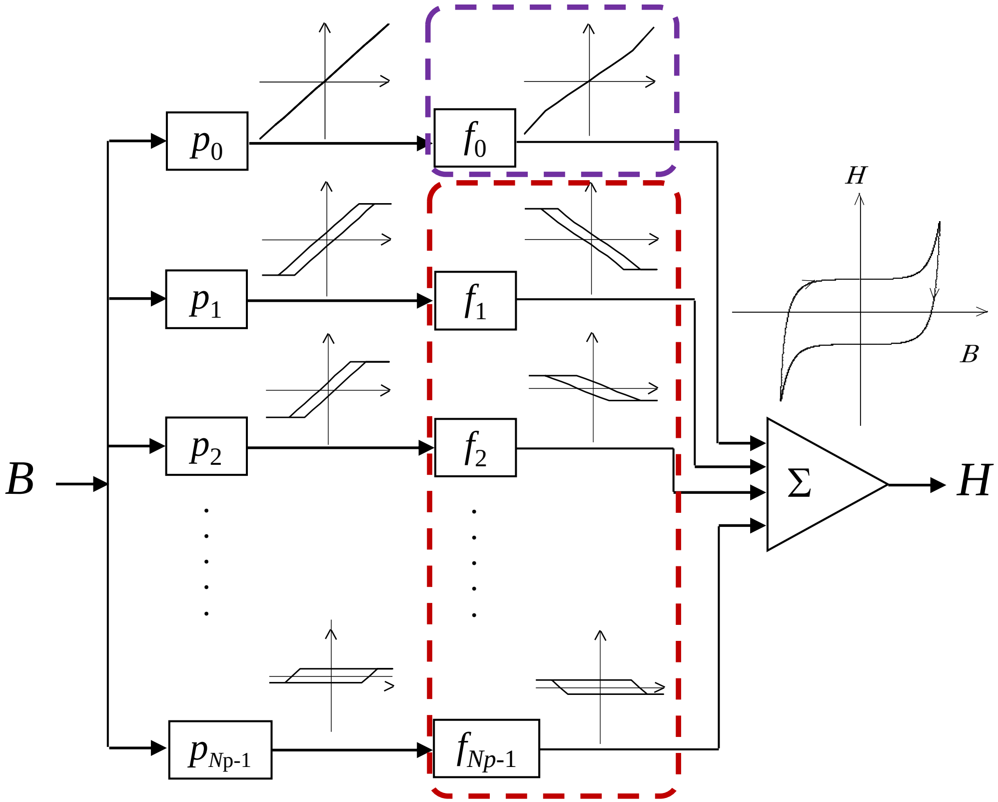
H **(*B*) is given as sum of play hysteron operated by shape functions**

Identification of the shape functions



measured B-H loops



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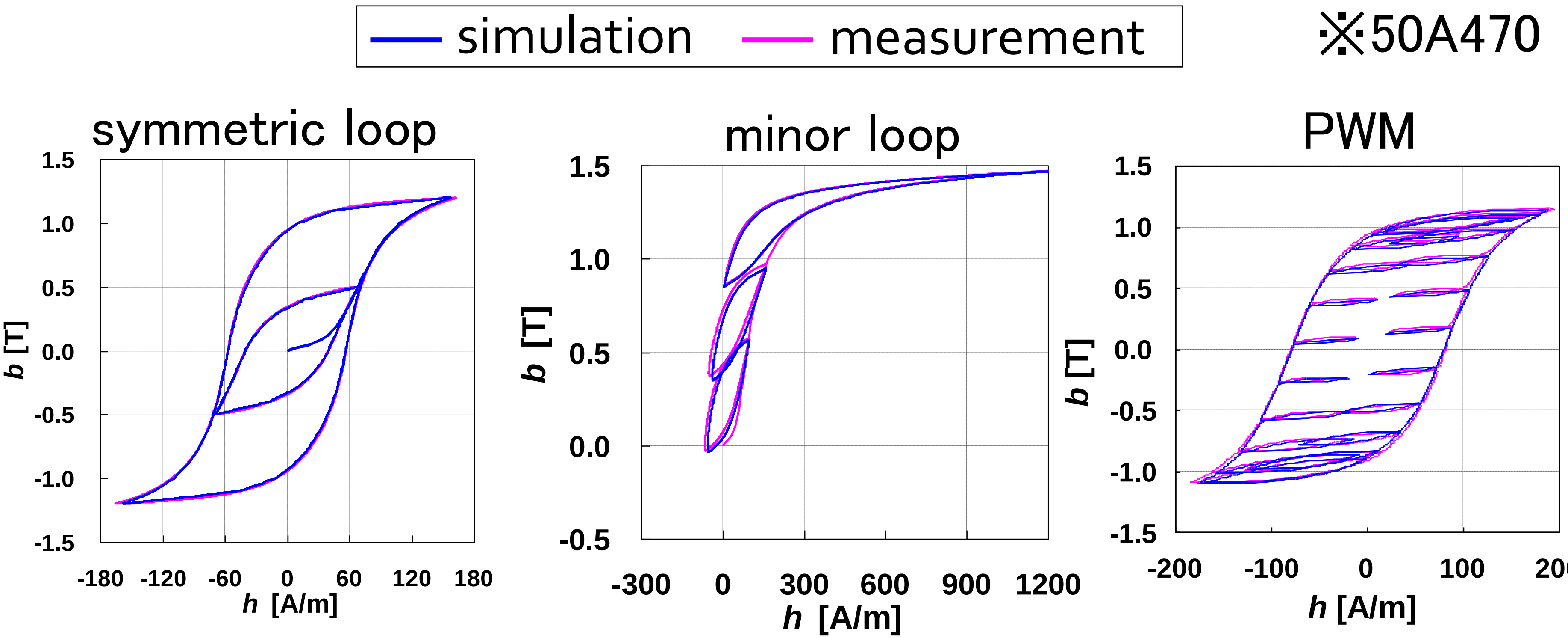
Identification of shape functions form measured B-H loops

Performance of the Play model



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Play model can reproduce BH-loops pretty well.

Characteristic of Play model

➢ (3) Reproducibility of the minor loops

➢ (1) time independent

DC hysteresis.
not dependent on time but history

➢ (2) equivalent minor loops

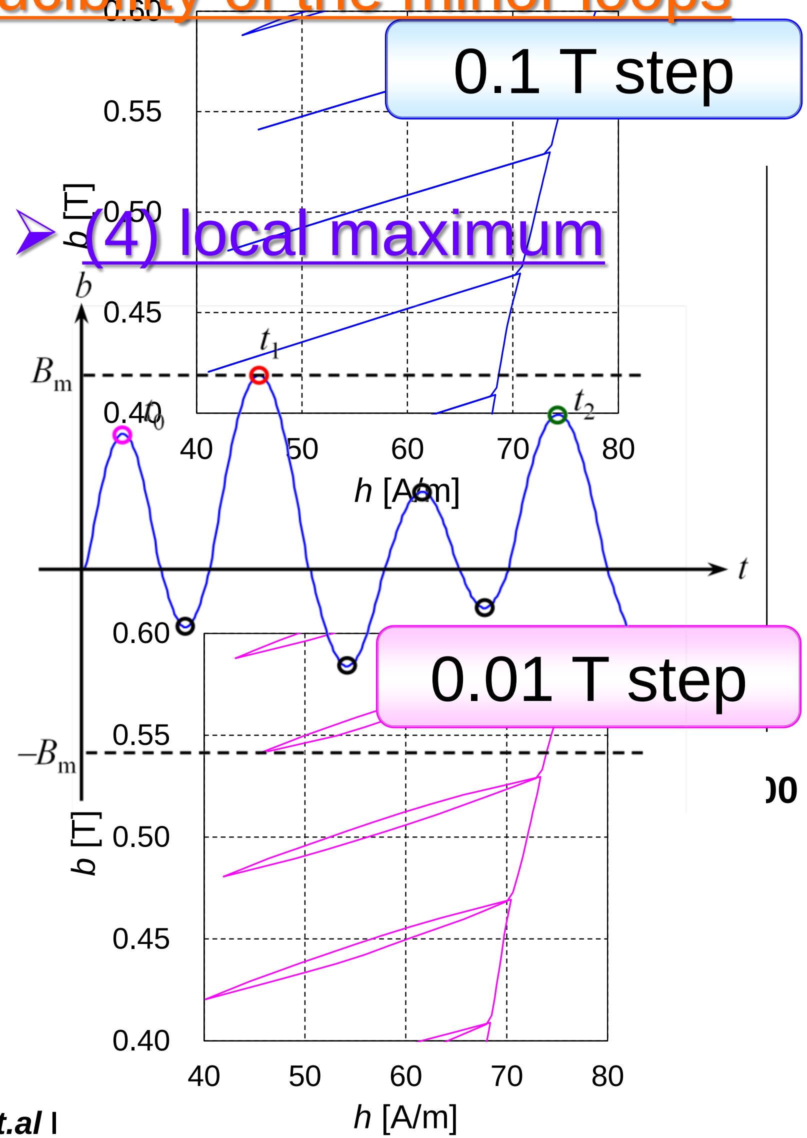
When the input b is ($b_1 \le b \le b_2$), the output Δh *is the same.*

➢ (3) Reproducibility of the minor loo

Minor loops whose Δb is smaller than the measurement step can not be reproduced.

➢ (4) local maximum

Play model is independent before the local minimum



➢ (4) local maximum

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Vector Play model

Scalar model

$$p_{\zeta_n}(B) = B - \frac{B - p^*_{\zeta_n}}{\max\left(\left|B - p^*_{\zeta_n}\right|, \zeta_n\right)}\zeta_n$$

$$H(B) = \sum_{n=0}^{N_p - 1} f_{\zeta_n}(p_{\zeta_n}(B))$$

B: scalar, H: scalar

$p_{\zeta_n}{}^*$: scalar, f_{ζ_n} : scalar

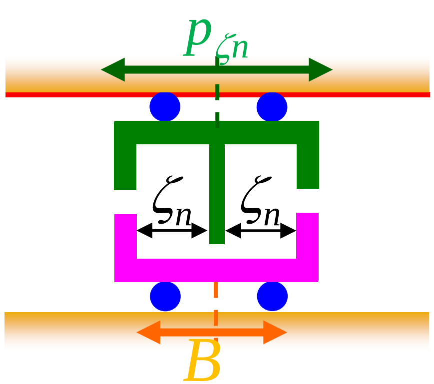
Vector model

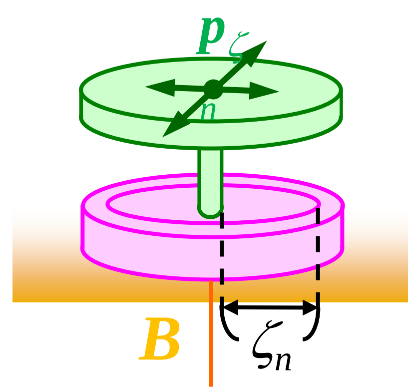
$$\boldsymbol{p}_{\zeta_n}(\boldsymbol{B}) = \boldsymbol{B} - \frac{\boldsymbol{B} - \boldsymbol{p}^*_{\zeta_n}}{\max\left(\left|\boldsymbol{B} - \boldsymbol{p}^*_{\zeta_n}\right|, \zeta_n\right)}\zeta_n$$

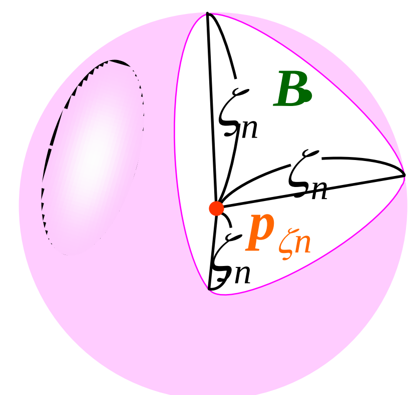
$$\boldsymbol{H}(\boldsymbol{B}) = \sum_{n=0}^{N_p - 1} f_{\zeta_n}\left(\left|\boldsymbol{p}_{\zeta_n}(\boldsymbol{B})\right|\right)\frac{\boldsymbol{p}_{\zeta_n}(\boldsymbol{B})}{\left|\boldsymbol{p}_{\zeta_n}(\boldsymbol{B})\right|}$$

$\boldsymbol{B}$: vector, $\boldsymbol{H}$: vector

$\boldsymbol{p}_{\zeta_n}{}^*$: vector, f_{ζ_n}: scalar







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Vectorization of Play model is rather simple.

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Magnetic field solver

	Software	Variables
TOSCA	Accelerator magnets	Reduces magnetic scalar potential Total magnetic scalar potential
T−Ω	**U.S.** Ansys Infolytica	T: current vector potential Ω : magnetic scalar potentail
A−Φ	**Japan** JMAG EMSolution	A: magnetic vector potential Φ : electric scalar potential

Research process (PLAN)

Step 1:

A-Φ + play model (Hysteresis model)
commercial software available
(e.g. JMAG Simulation Technology for Electromechanical Design, EMSolution®)

Question 1
A-Φ VS TOSCA, similar performance?
(without hysteresis effects)

Staff: B4 student@ Kindai Univ.
Status: Now on going.

Research process (PLAN)

Step 2:

TOSCA + play model
no source code distributed

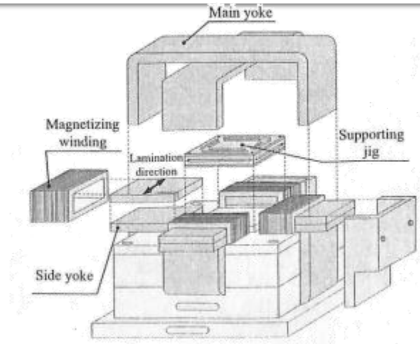
Question 2
How can we incorporate?

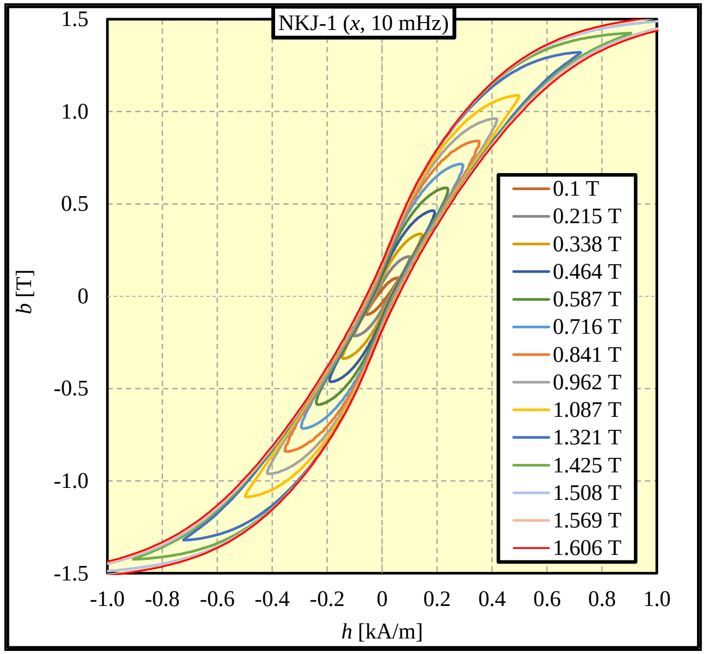
With python scripts,
TOSCA + play model work?

Stuff: Me
Status: Need grant to purchase TOSCA

Research process (PLAN)

Step 3:





B-H loop measurement

Question 2

How low the frequency can be?

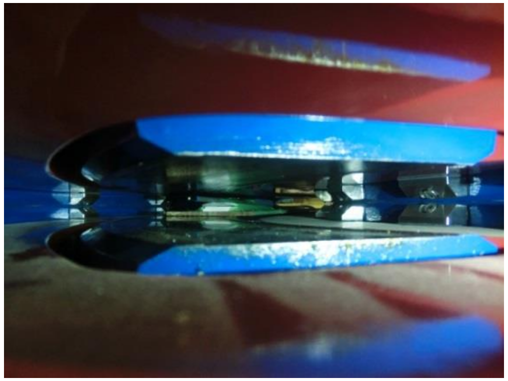
Stuff: Prof. K. Fujiwara@ Doshisa Univ.

Status:1st data obtained.

Research process (PLAN)

Step 4:

play model VS B-map measurement
in accelerator magnets



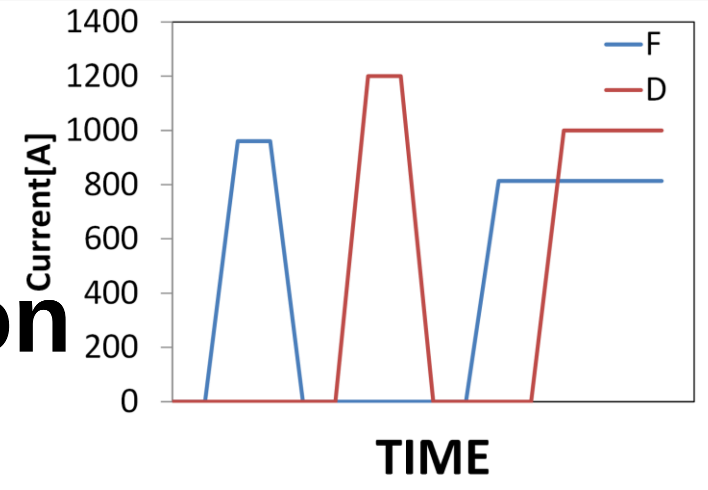
Question 3

Accuracy is OK?
DC hysteresis (time independent) ok?

Stuff: M1 student @ Kindai Univ.
under Dr. Kuriyama@ KURRI

Research process (PLAN)

Step 5:



initial pattern optimization

Question 4

Predicted tunes be reproduced?

Stuff: All of the authors.
Status: not yet

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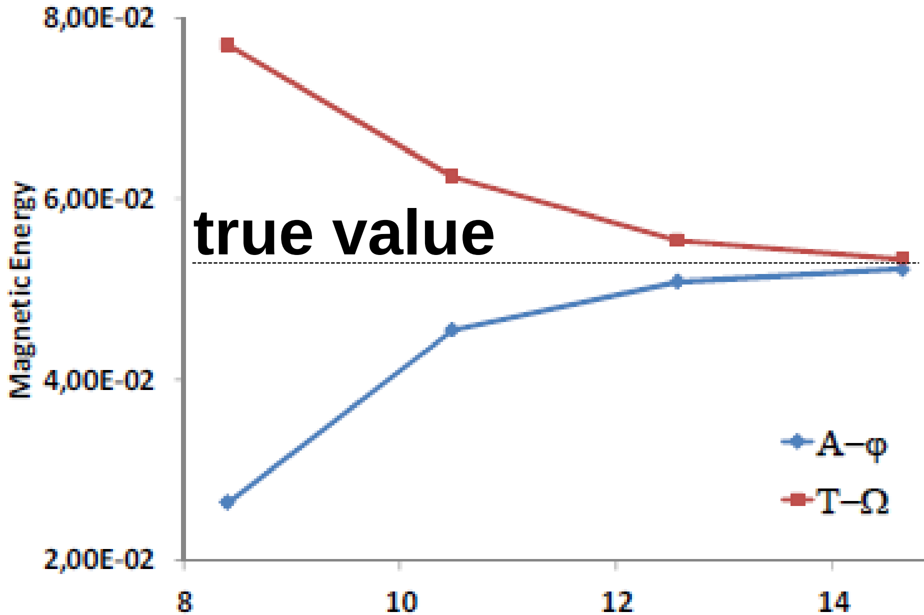
A-Φ and T-Ω

TABLE I
PROPERTIES OF FIELDS

Properties of fields	Formulations	
	A-φ	T-Ω
$[\mathbf{E}_h \wedge \mathbf{n}]_F = 0$	Strong sense	Weak sense
$[\mathbf{H}_h \wedge \mathbf{n}]_F = 0$	Weak sense	Strong sense
$[\mathbf{B}_h . \mathbf{n}]_F = 0$	Strong sense	Weak sense
$[\mathbf{J}_h . \mathbf{n}]_F = 0$	Weak sense	Strong sense

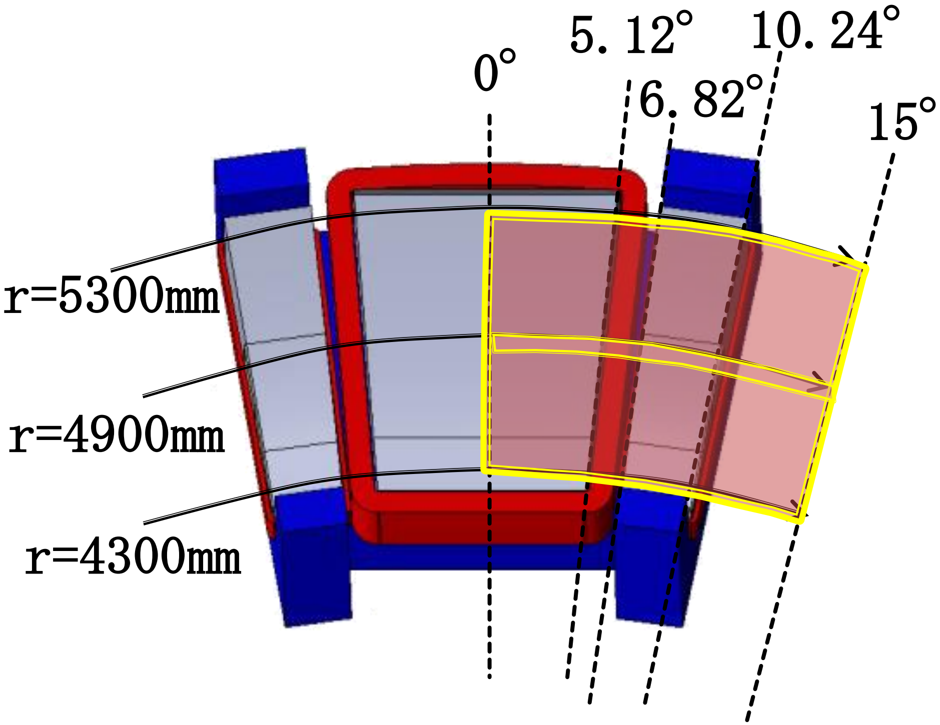


Tittarelli *et.al.* Univ. Lilli

True values are in between A-Φ and T-Ω.

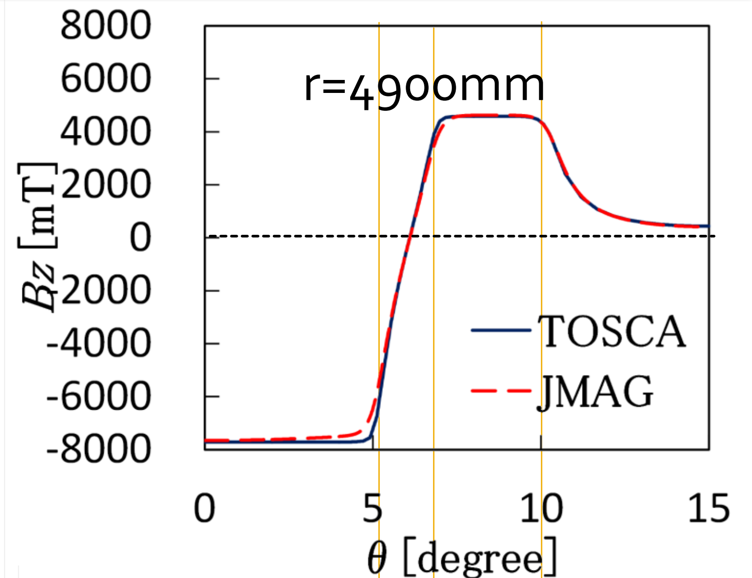
T-Ω has similar characteristics to TOSCA.

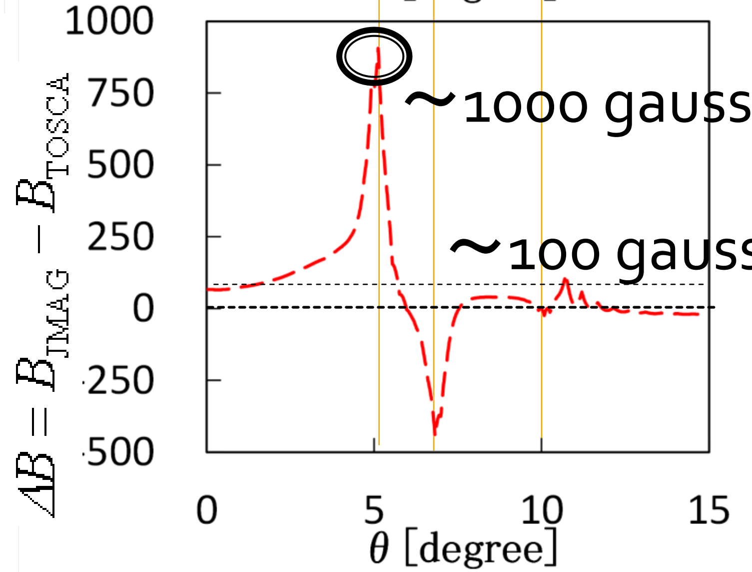
Comparison between TOSCA and JMAG



F magnet : 814 A 50 T

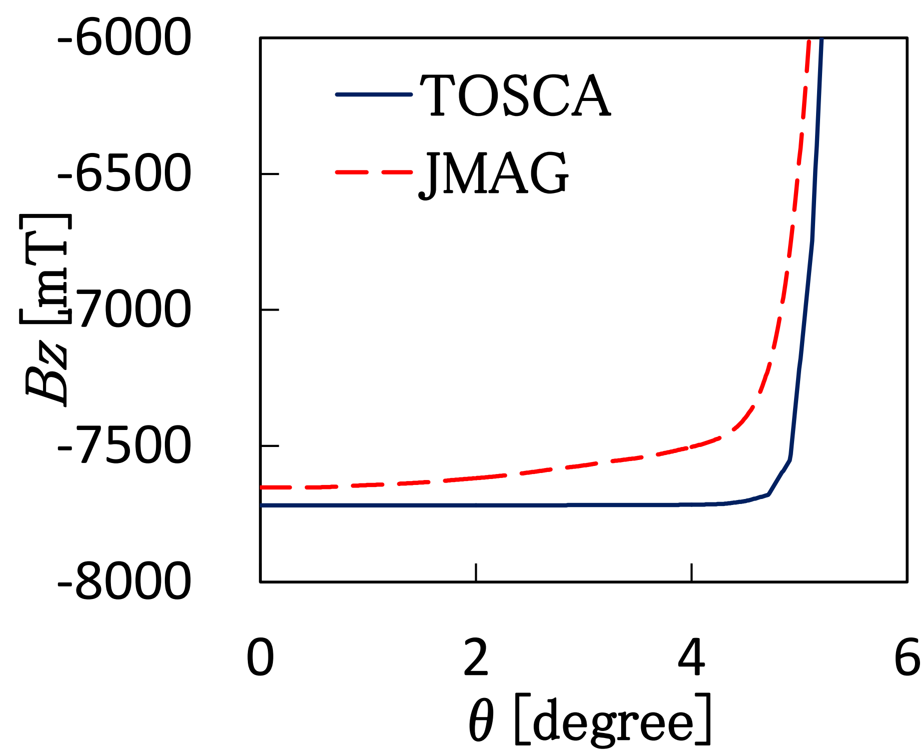
D magnet : 980 A 5 T





Current Issue

Shoulder problem



We tried to use finer mesh but did not work out.

One idea is to solve 2D-problem to check
if this is a meshing problem.

Next step: EMSolution

	TOSCA	JMAG	EMSolution
Vendor	Cobham (U.K.)	JSOL (Japan)	SSIL (Japan)
Typical application	accelerator magnets	motor	motor
Hysteresis	generate from upper and lower	play model	play model
Mesh generation	1) preprocessor 2) Mosaic mesh 3) tetrahedron	1) tetrahedron	1) import only 2) hex/tetra
Element order	1^{st} and 2^{nd}	1^{st}	1^{st} and 2^{nd}
Coil	external	to be meshed	external
Speed	fast	slower	slower

Following strategy

(a) Hybrid method

$$\left| B_{\text{TOSCA}} - B_{\text{JMAG}} \right| < 100\text{gauss}$$

almost impossible

TOSCA

$$B_{\text{hys}} = \boxed{B_{\text{TOSCA}}} + \Delta B$$

$$\Delta B = \boxed{B_{\text{pattern1}} - B_{\text{pattern0}}}$$

JMAG or EMSolution

(b) Python Script based Play model

(c) Collaborate with Cobham

We have not tried yet.

Summary

- **We have just started our project.**
  (Please watch with warm eyes)

1. **Recent progress of hysteresis model**

2. **Our research plan**

3. **A-Φ and TOSCA benchmark**