
Design and Experimental Study of a Model Magnet for Spiral-Sector FFAG Accelerators

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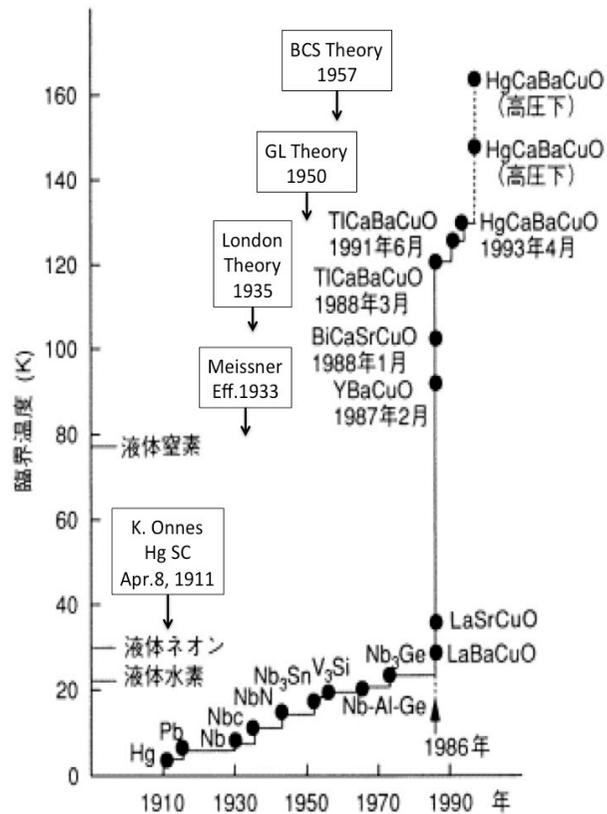
Outline

- **Introduction**
Background, Objective
- **Magnet Design**
- **Coil fabrication**
- **Dimensional accuracy of the model magnet**
Winding accuracy of the HTS coils
Dimensional deviations of the YBCO tape
Field calculation
- **Conclusion**

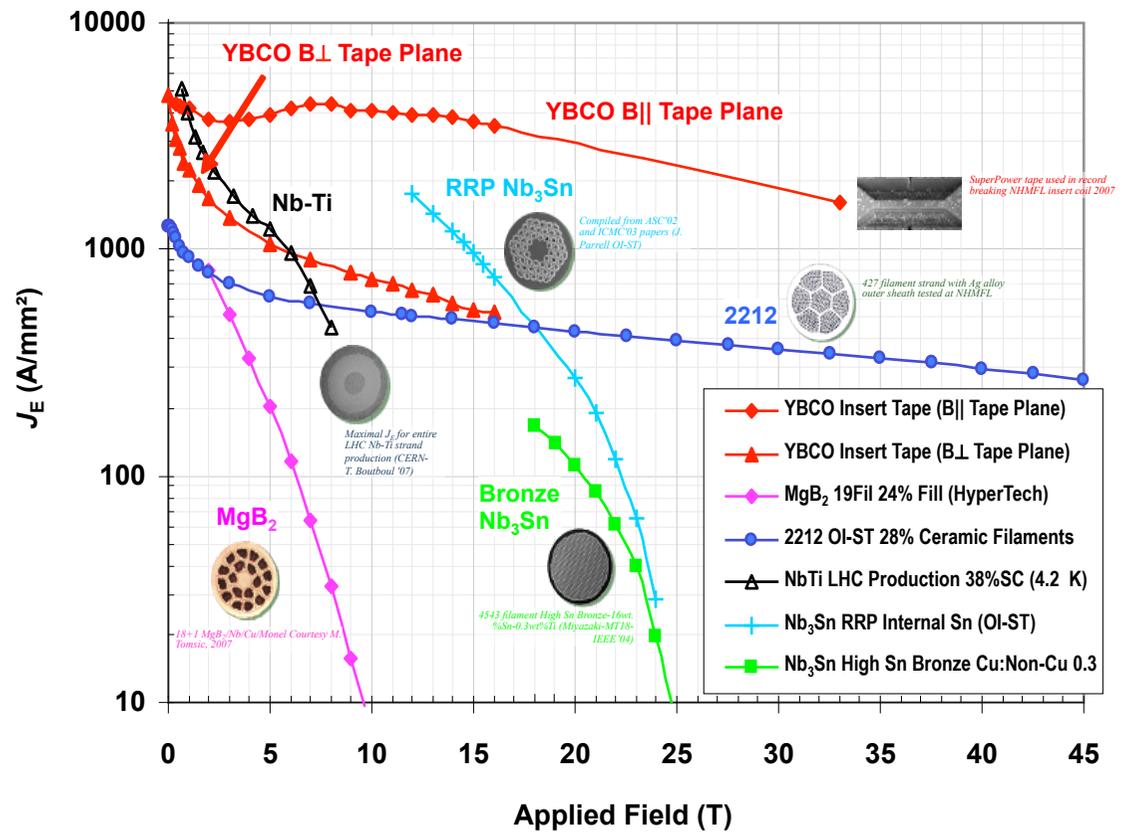
Introduction

Why High Temperature Superconductor (HTS)

- High temperature
 - High efficiency
 - High stability

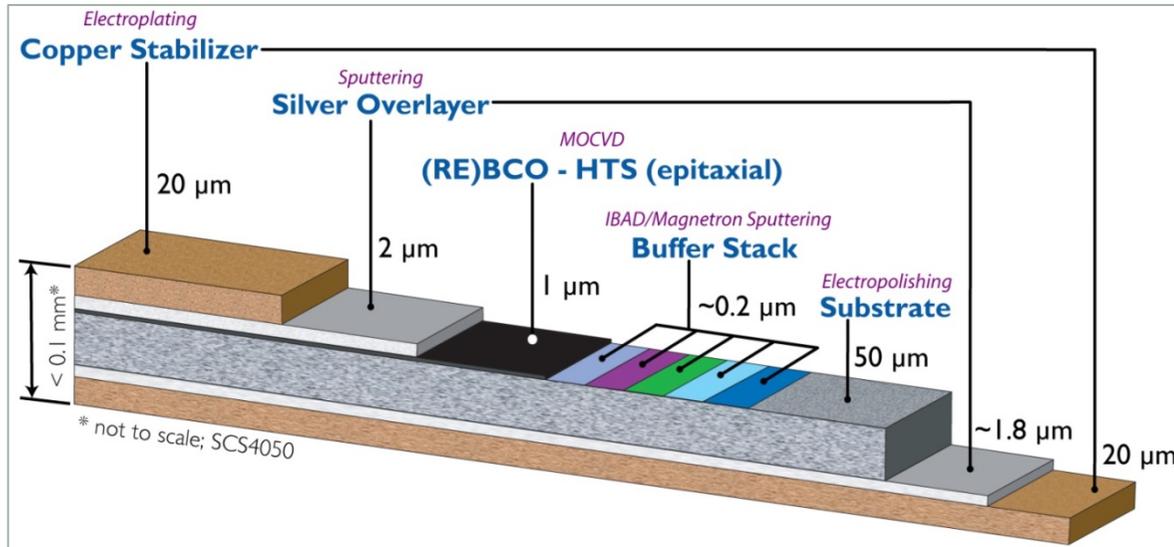


- High field



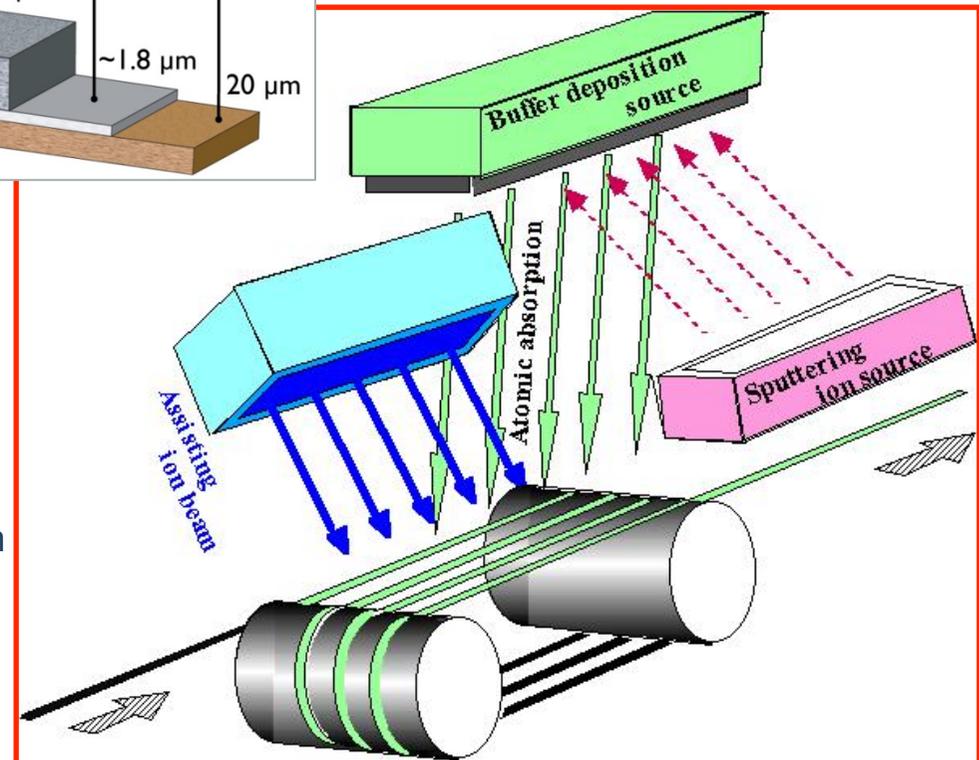
Introduction

ReBCO Coated Conductor



- ↑ High Performance
- ↑ High Strength
- ↑ React and Wind
- ↓ High Cost
- ↓ Large Shielding Current
- ↓ Anisotropy
- ↓ Exfoliation

- Hastelloy® C276 substrate
 - high strength
 - high resistance
 - non-magnetic
- Buffer layers with IBAD-MgO
 - Diffusion barrier to metal substrate
 - Ideal lattice matching from substrate through ReBCO
- MOCVD grown ReBCO layer with BZO nanorods
 - Flux pinning sites for high in-field I_c
- Silver and copper stabilization



Introduction

Background of the project

A research and development project of fundamental technologies for cryocooler-cooled accelerator magnets using coated conductors

Strategic Promotion of Innovative Research and Development Program (S-Innovation Program) funded by the Japan Science and Technology Agency (JST)

Medium field ~5T

10~20K operation for higher efficiency and stability

Target applications :

- **FFAG accelerator for Carbon cancer therapy**
- **Accelerator-driven subcritical reactor (ADSR)**

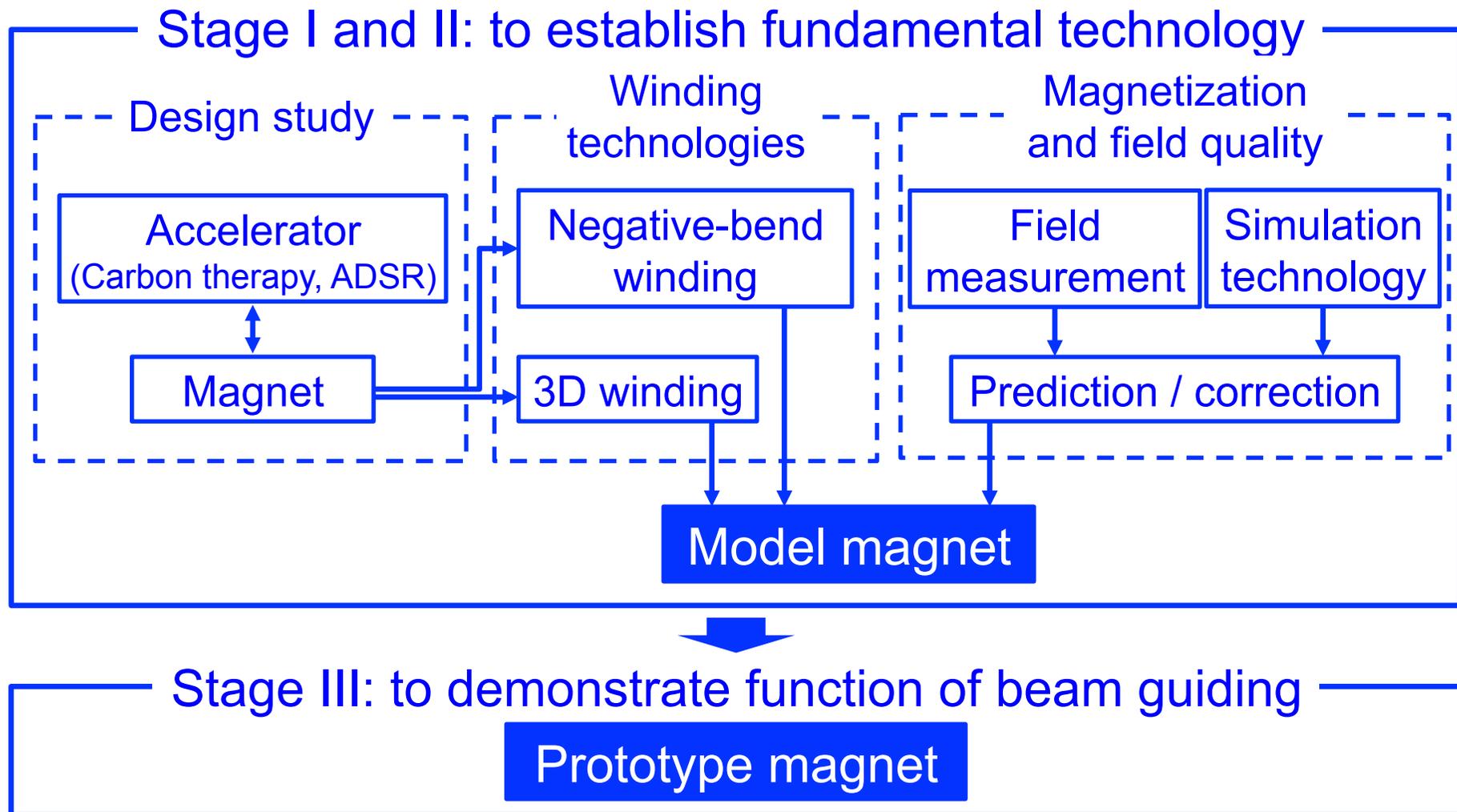
Introduction

Outline the project

Name of project	Challenge to functional, efficient, and compact accelerator system using high T_c superconductors
Objective	<ul style="list-style-type: none">•R&D of fundamental technologies for accelerator magnets using coated conductors•Constructing and testing prototype magnet
Future applications	<ul style="list-style-type: none">•Carbon cancer therapy•Accelerator-driven subcritical reactor
Project manager	Naoyuki Amemiya (Kyoto University)
Participating institutions	Kyoto University, Toshiba, KEK, NIRS (National Institute of Radiological Sciences), JAEA
Period	Stage I: 01/2010 – 03/2012 Stage II: 04/2012 – 03/2016 Stage III: 04/2016 – 03/2019
Funding program	Strategic Promotion of Innovative Research and Development (S-Innovation) Program by JST

Introduction

Project overview and key R&D issues at stage I & II



Introduction

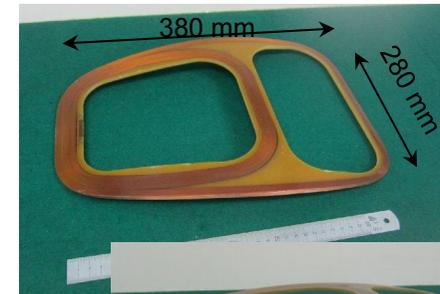
Prototyping of non-circular REBCO-CC coils



K Koyanagi, et al.: *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Art. No. 4101904, 2012.



K Koyanagi, et al.: *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Art. No. 4100904, 2013.



Takayama, et al., *Abstracts of CSJ Conference*, Vol. 87 (2013) p.142

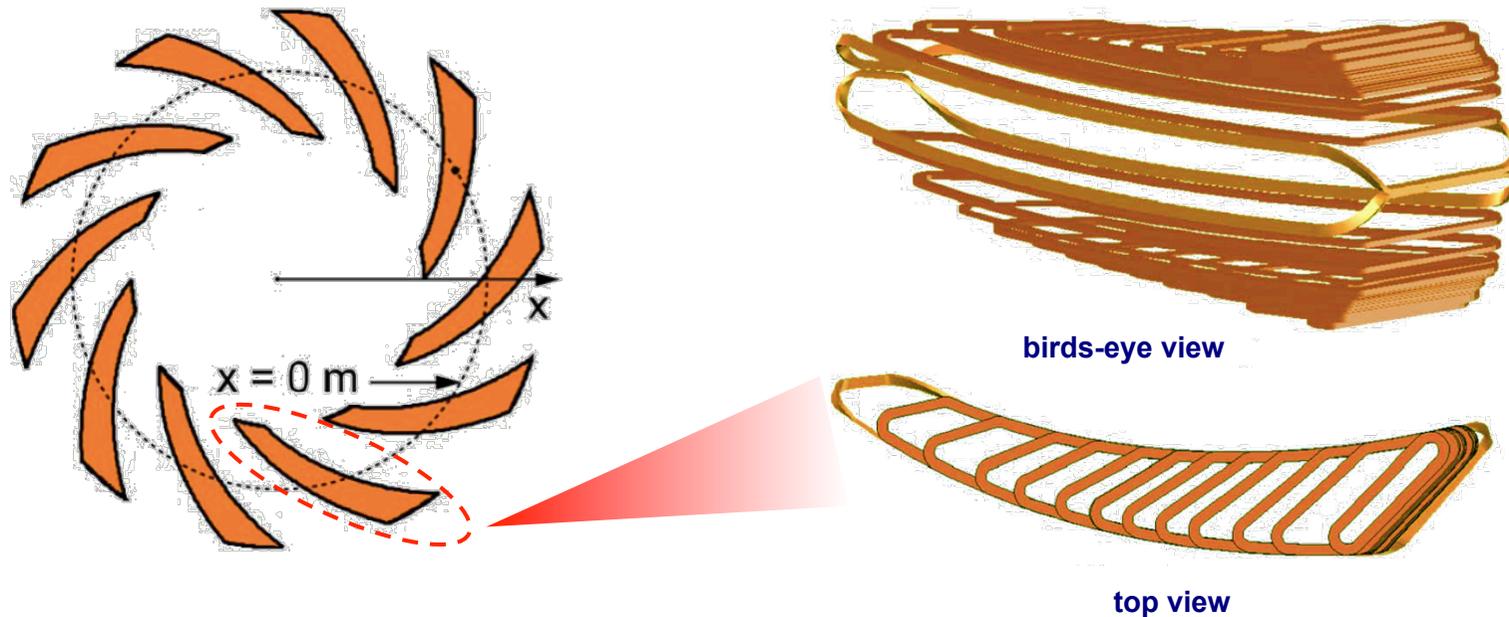


Takayama, et al., *IEEJ Conference*. Vol. 5. P.179 2012.

Complicated shaped coils are needed for FFAG in order to ensure a precise magnetic field distribution

Introduction

Coil design for the Spiral-sector FFAG accelerator magnet



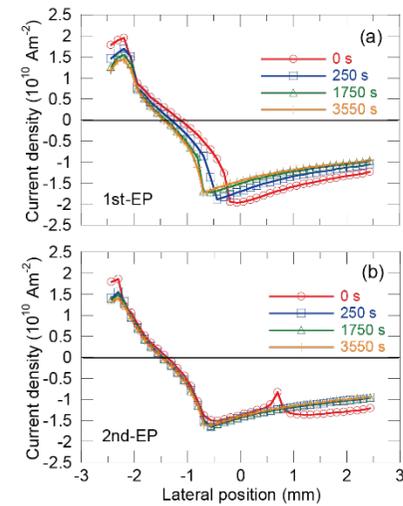
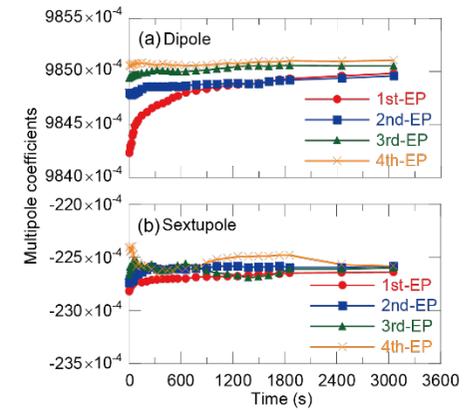
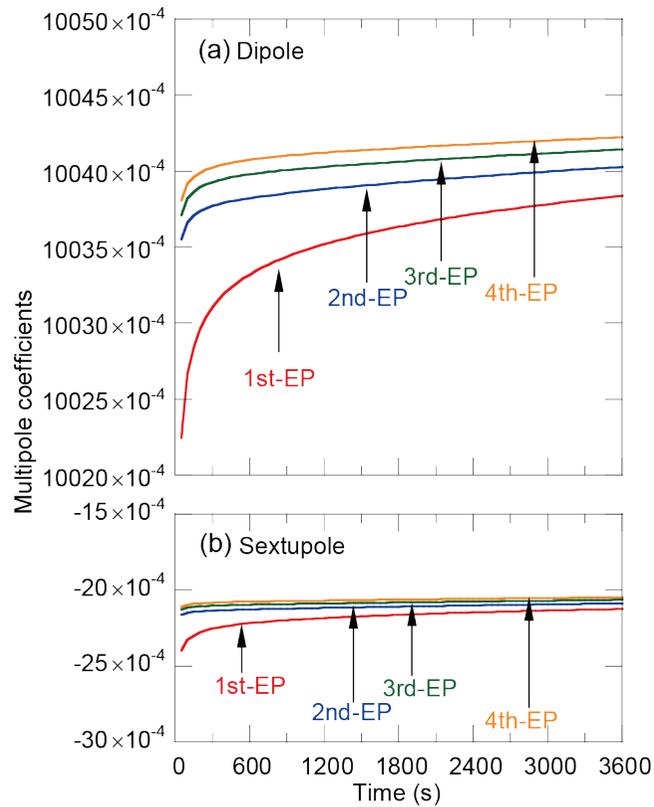
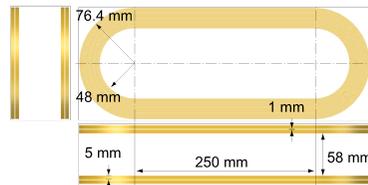
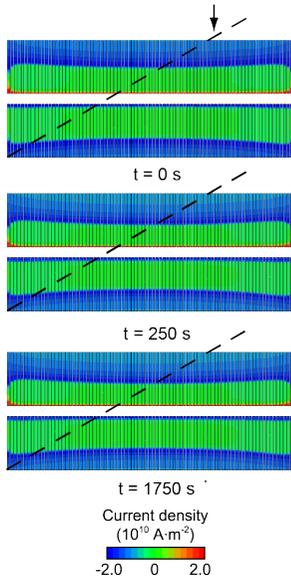
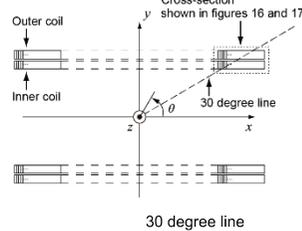
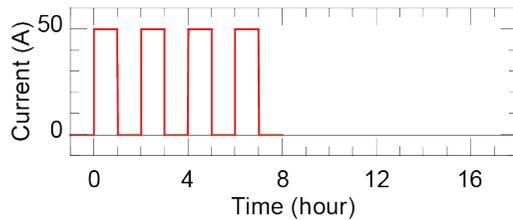
K Goda, *et al.*: *IEEE Trans. Appl. Supercond.*,” vol. 24, no. 3, Art. No. 4402605, 2014.
Update result will be presented MT24 Oct18~23 2015

The characteristic parts of this design:

- Negative-bend part
- Three dimensional bending part

Introduction

Influence of Shielding Current

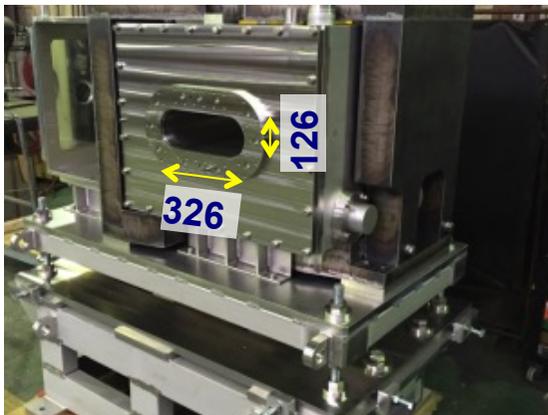
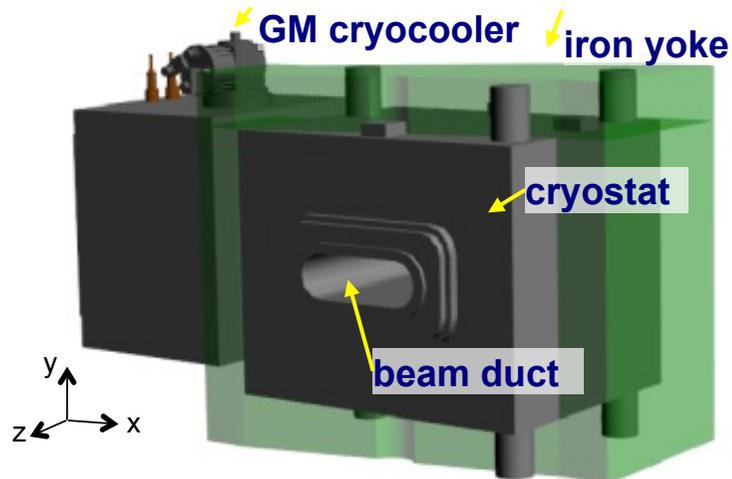


Objective

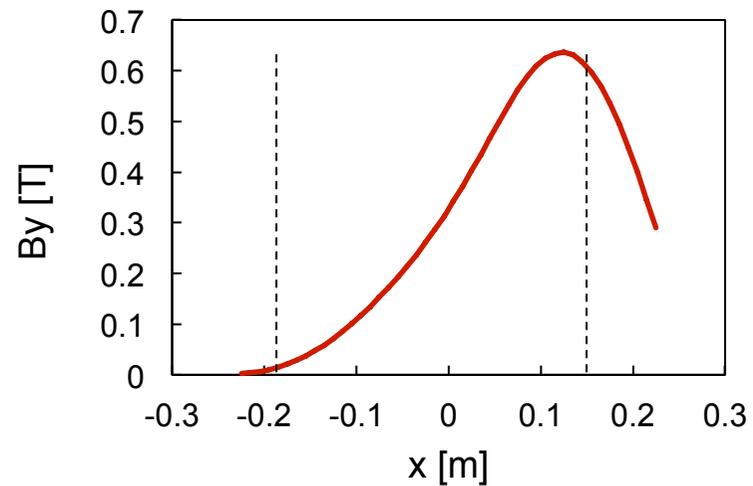
- **Design of the Model Magnet**
 - To generate a nonlinear magnetic field within a racetrack cross-sectional beam duct, similarly to the actual FFAG magnet
- **Demonstration of winding technology for YBCO coils with complicated three-dimensional winding shapes**
- **Confirmation of the dimensional accuracy of the YBCO coils and the influence of this accuracy on the magnetic field**

Magnet Design

"Model magnet" - reduced-size test magnet -



Outer view of the model magnet

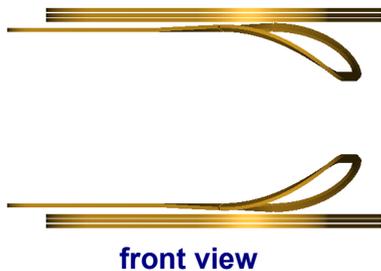
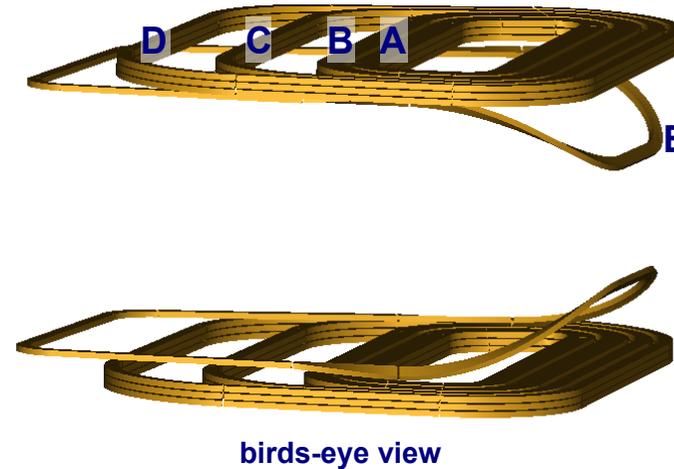
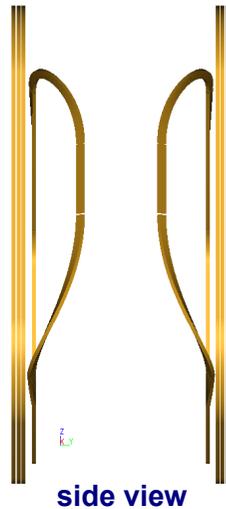
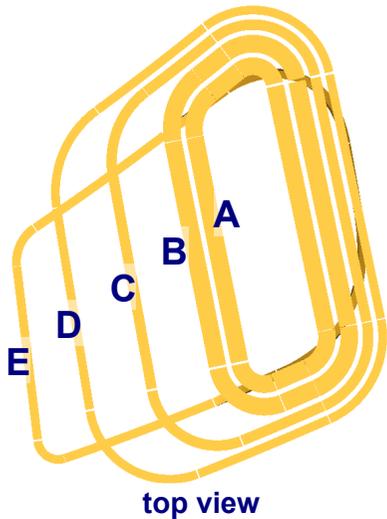


Calculated field distribution of the model magnet on the midplane

The magnet was designed to generate asymmetric, non-linear field

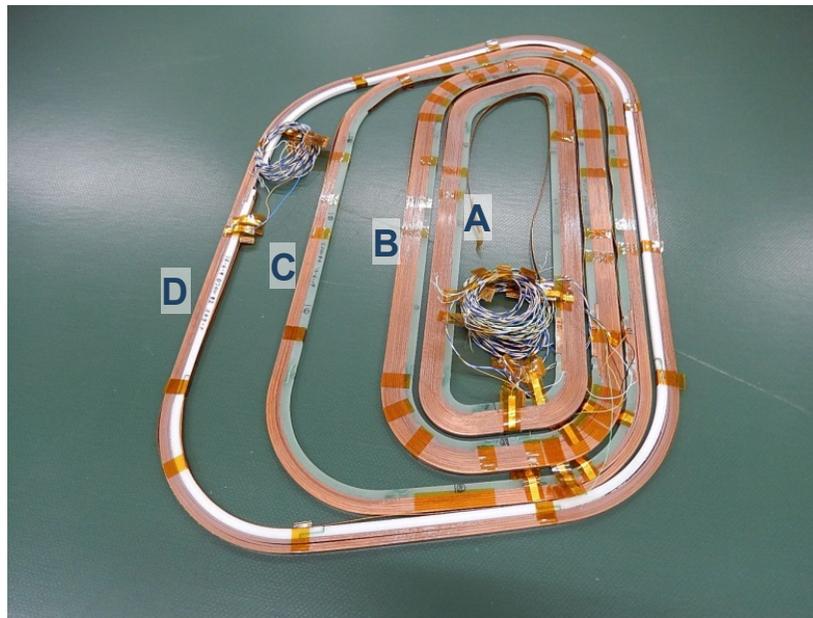
Magnet Design

Specifications of the YBCO coils

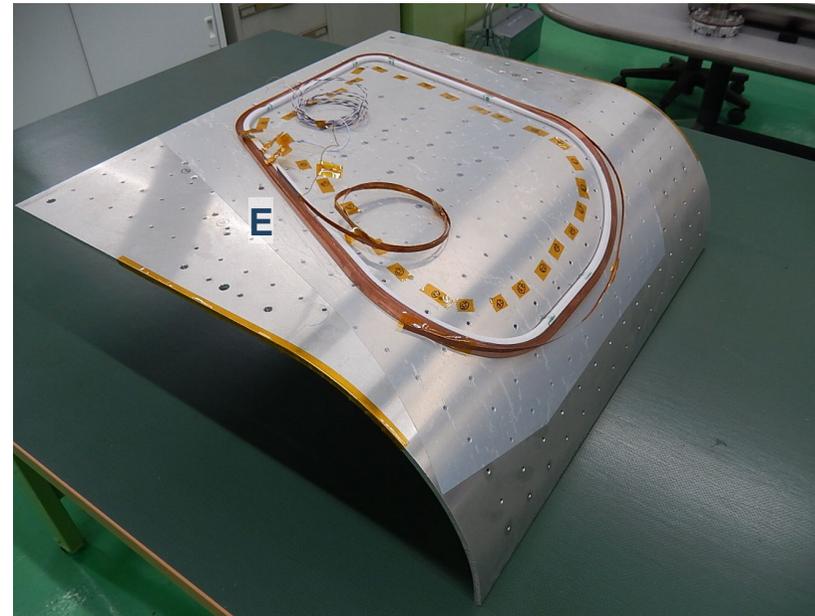


parameter	coil	A	B	C	D	E
Outside dimension, x-axis, mm		93	139	228	308	250
Outside dimension, y-axis, mm		100	146	185	215	100
Minimum bending radius, mm		20	58	98	130	26
negative-bend radius, mm		3262	3186	3035	2884	2700
Radius of the duct curvature, mm		-	-	-	-	150
Number of turns		100	100	60	50	50
Total tape length / coil, m		79.5	94.0	70.6	68.4	75.0
Number of coil		6	6	6	6	2

Coil fabrication



coil A, B, C, D
(deformed flat pancake coils
with negative bend)

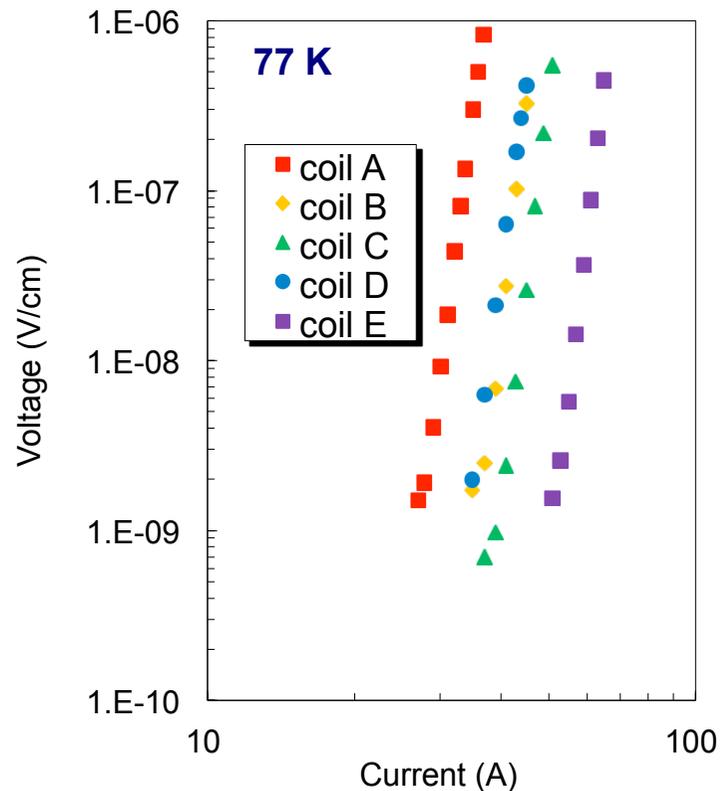


coil E
(including a negative-bend part and
a three-dimensional bent part)

**Fabrication of these coils is underway using YBCO coated
conductors (width: 4 mm, thickness: 0.1 mm)**

Coil fabrication

Measurement of V-I characteristics



	A	B	C	D	E
I_c	37.1	47.8	52.7	46.6	67.3
n-value	21.5	21.9	22.1	21.4	24.2

- From the $V-I$ characteristics in an electric field in the region of 10^{-8} V/m, index values of above 20 were obtained
- Degradation-free superconducting properties were confirmed

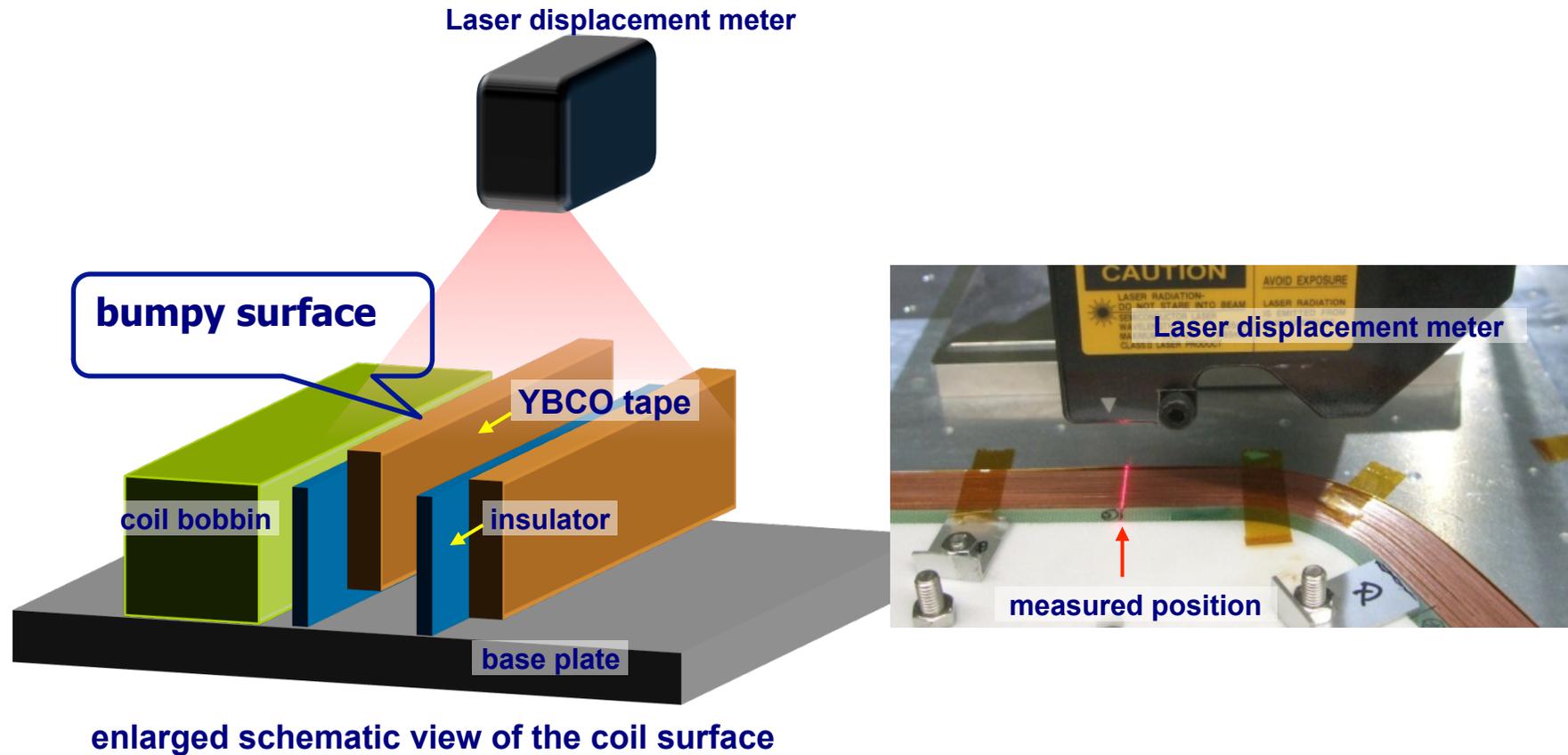
Dimensional accuracy of the HTS coils

A number of factors are considered to cause a deviation between the generated and designed fields of the HTS accelerator magnet ;

- **Positional misalignment of each turn within the coil cross-section**
- **Dimensional deviations of the YBCO tape and other winding materials**
- **Displacement of the relative positions of multiple coils**
- **Misalignment between the coil unit and the cryostat or iron yoke**
- **Magnetization of the tape conductor,
etc.**

Dimensional accuracy of the HTS coils

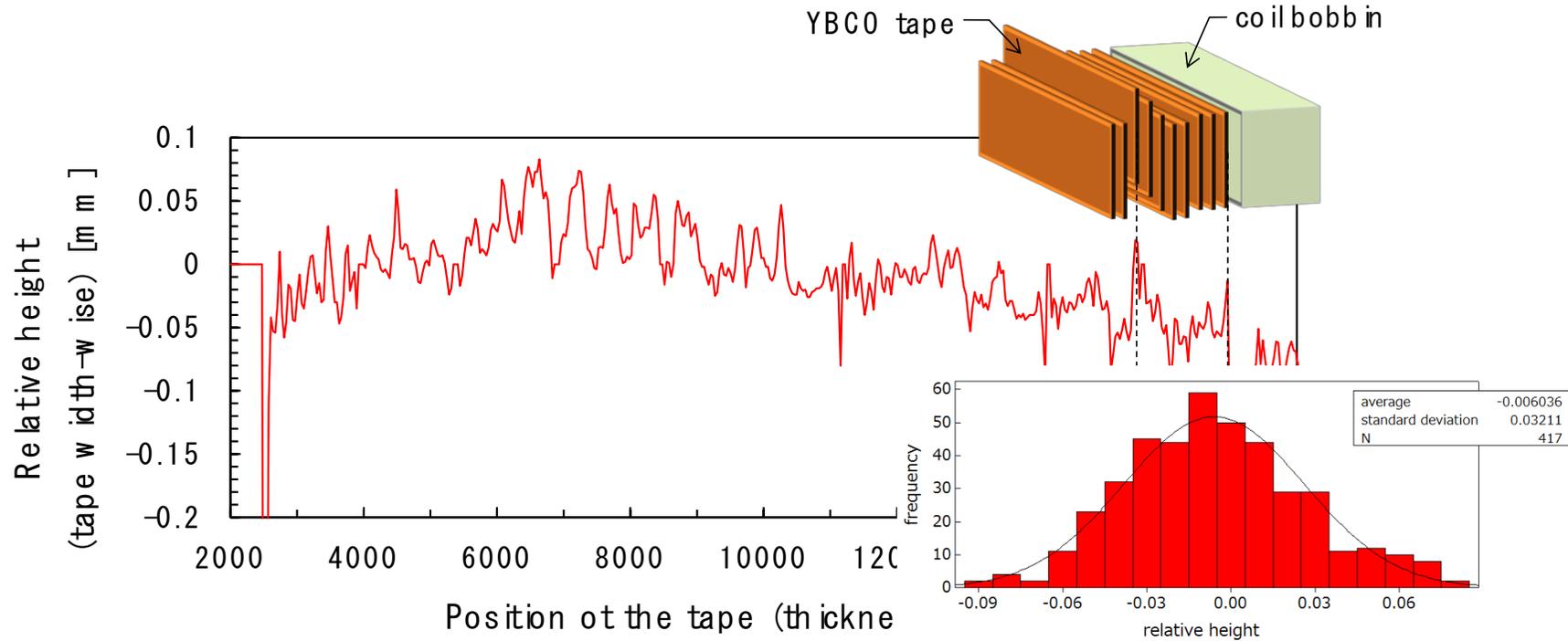
Roughness of the YBCO coil surface



To confirm the positional displacement of each turn in the YBCO coil quantitatively, the roughness of the YBCO coil surface was measured

Dimensional accuracy of the HTS coils

Roughness of the YBCO coil surface

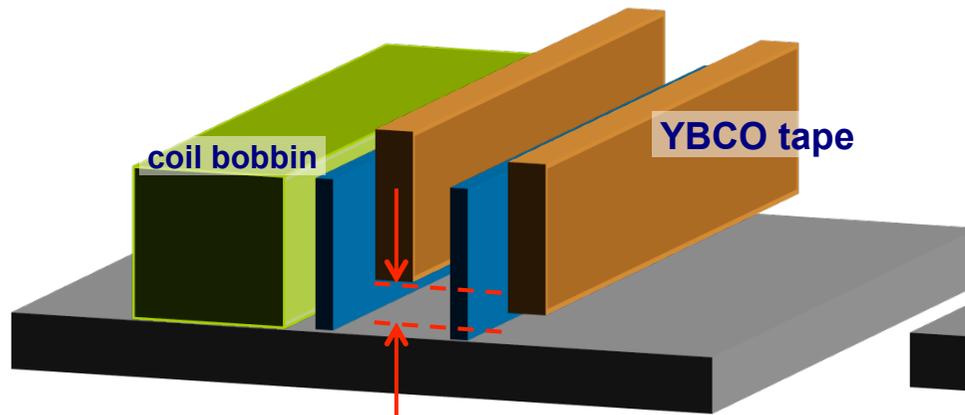


From this measurement, a positional misalignment of 32.1 μm in the tape edge direction was obtained

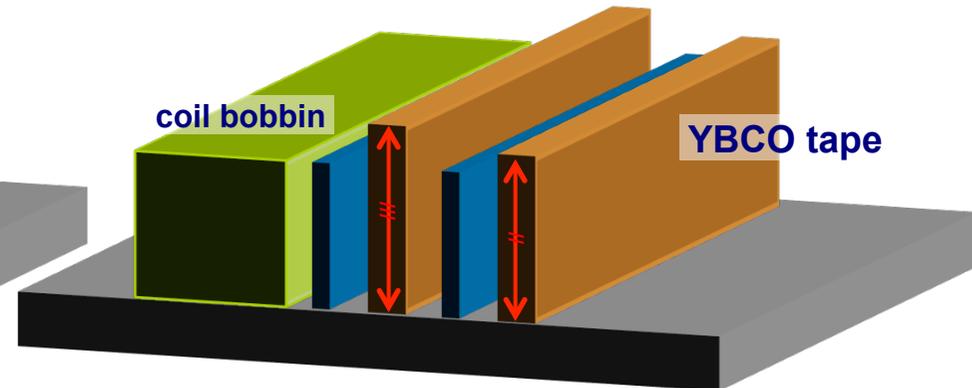
Dimensional accuracy of the HTS coils

Causes of the positional misalignment of each turn

Deterioration of the positional accuracy in a coil winding process



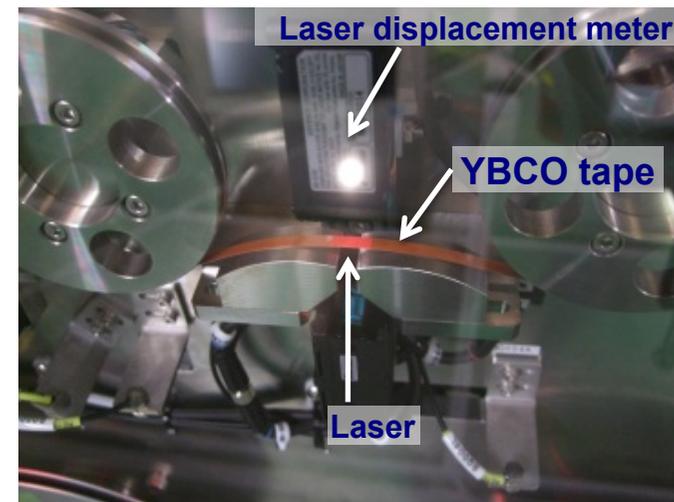
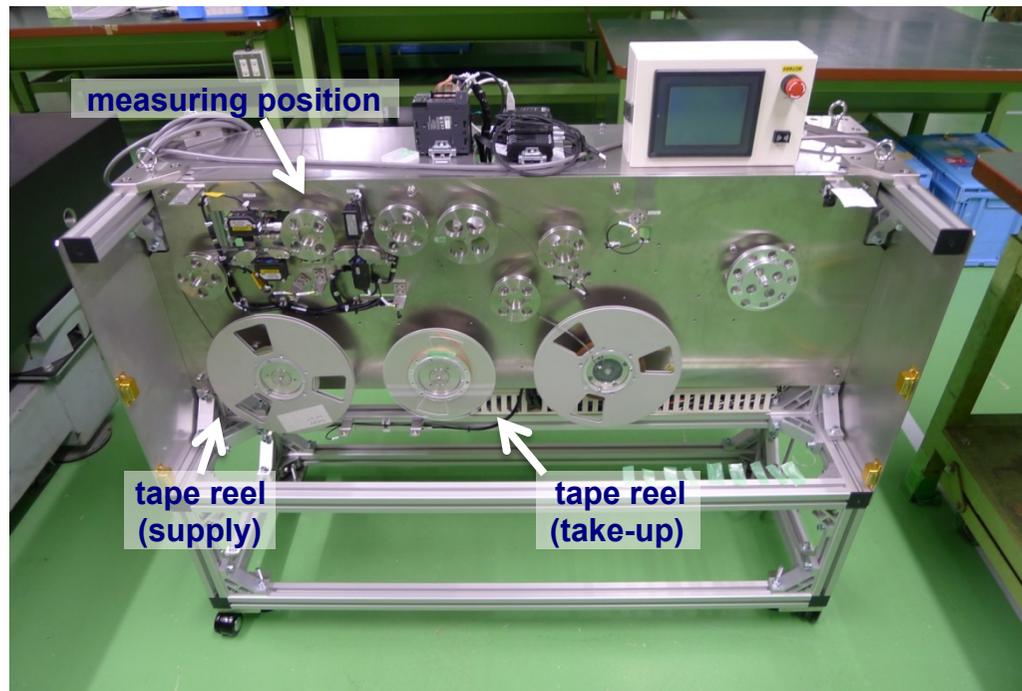
Dimensional deviations of the YBCO tape



Roughness of the YBCO coil surface was due to both the winding accuracy and the deviations of the YBCO tape itself

Dimensional accuracy of the HTS coils

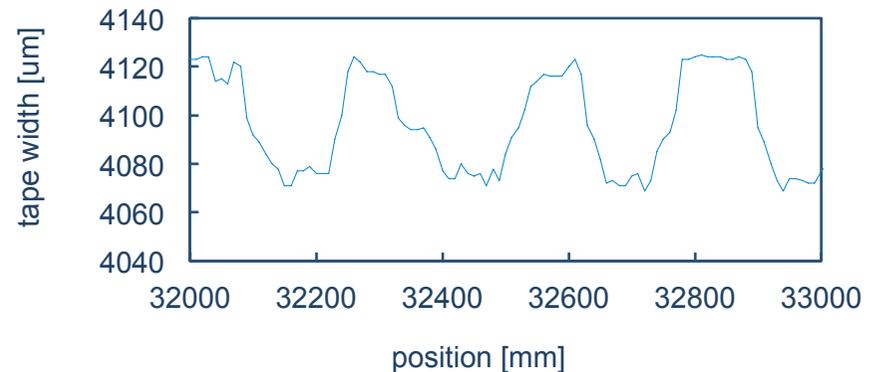
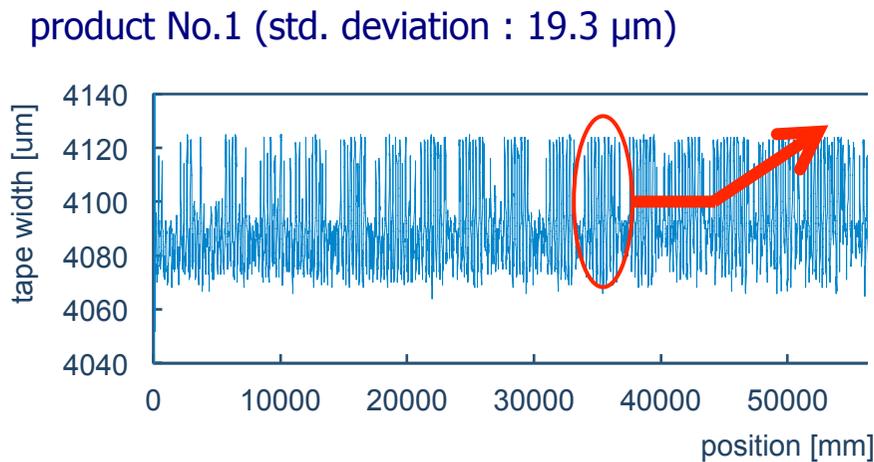
Measurement of tape width and thickness



A prototype apparatus for continuously measuring the width and thickness of the tape was newly developed

Dimensional accuracy of the HTS coils

Measurement of tape width and thickness



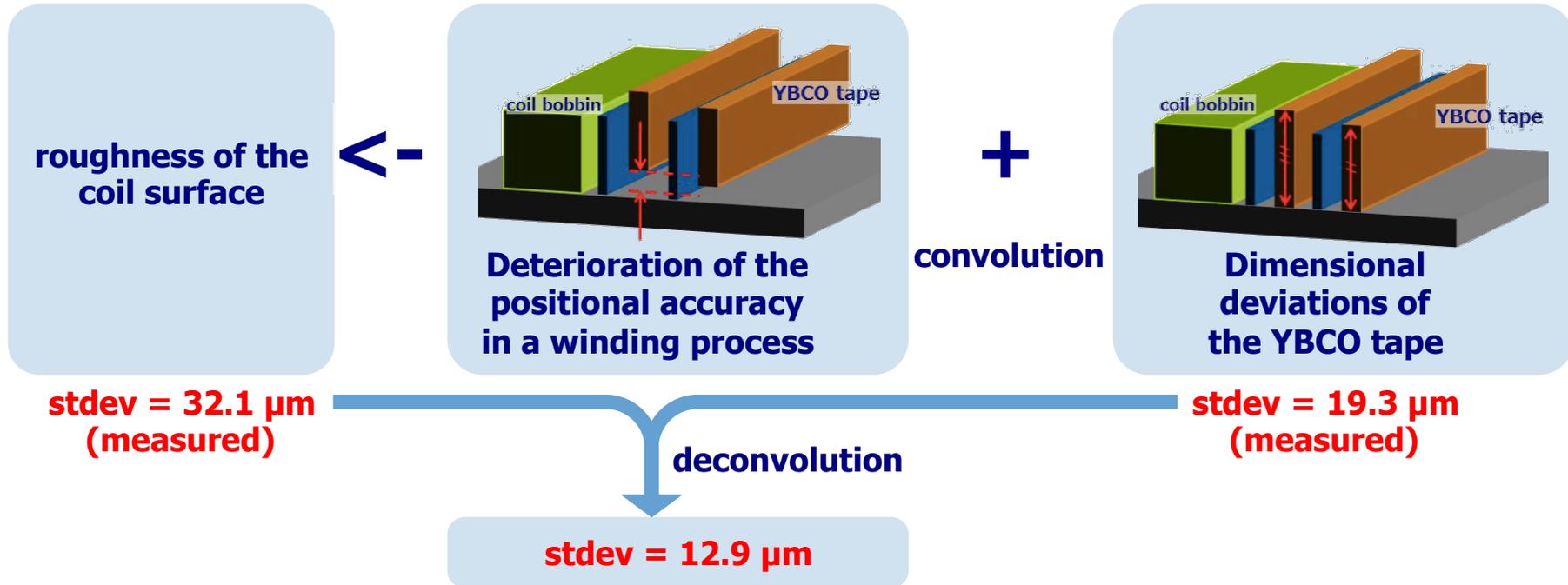
product No.	width (avg.) [mm]	std. deviation [μm]	cycle [mm] (*)
#1	4.0944	19.3	275
#2	4.0865	46.0	279
#3	3.9711	8.47	277
#4	4.1231	12.4	256
#5	4.0627	43.2	320

(*) Cycles were calculated using FFT.

- The width were measured every 10 mm for the longitudinal direction
- Standard deviation of 19.3 μm in the tape width was obtained

Dimensional accuracy of the HTS coils

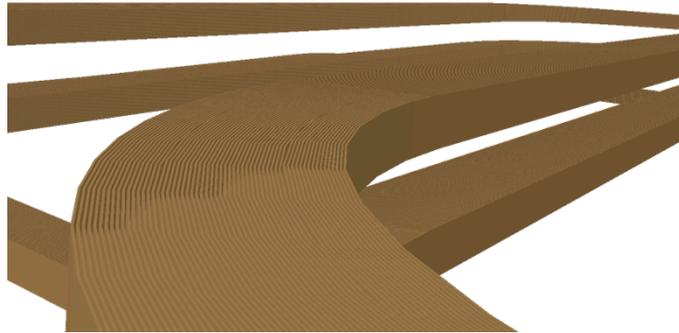
Separation of the causes due to the winding accuracy



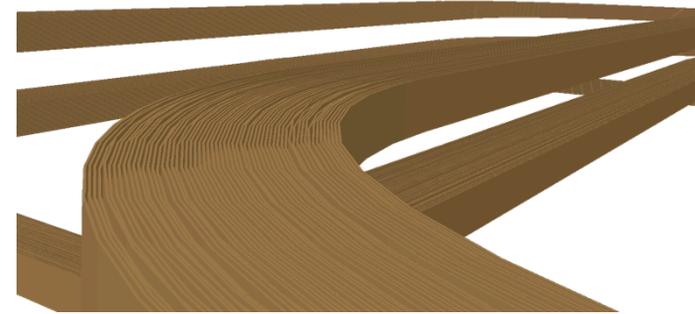
The deterioration of the positional accuracy in the coil winding process was calculated to be $12.9 \mu\text{m}$ via deconvolution

Field calculation

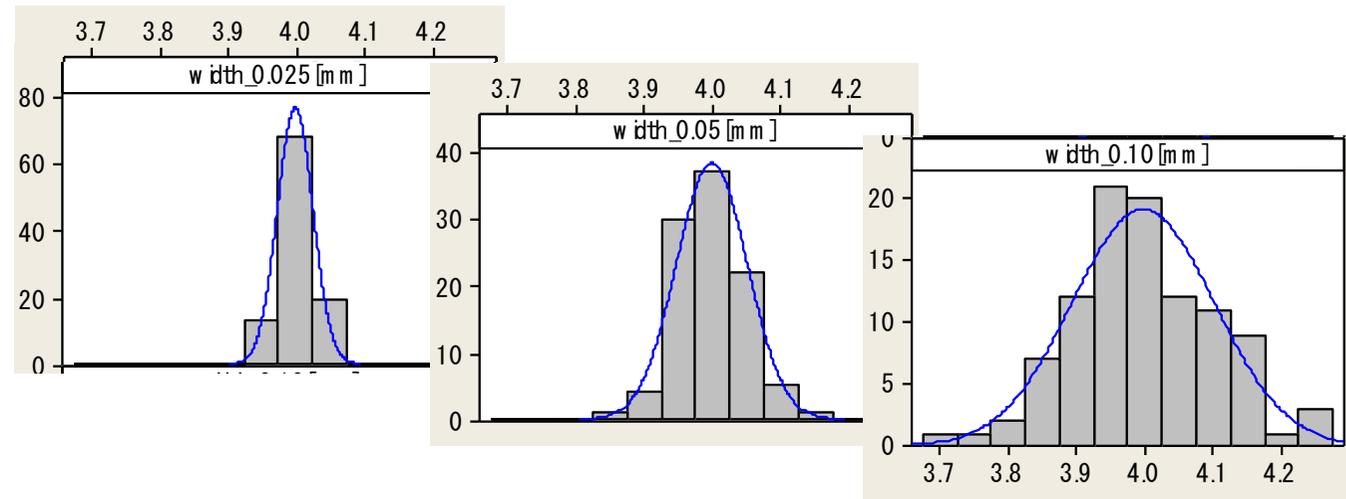
Field analysis model with the dimensional error



**Coil surface with no deviations
(Reference)**

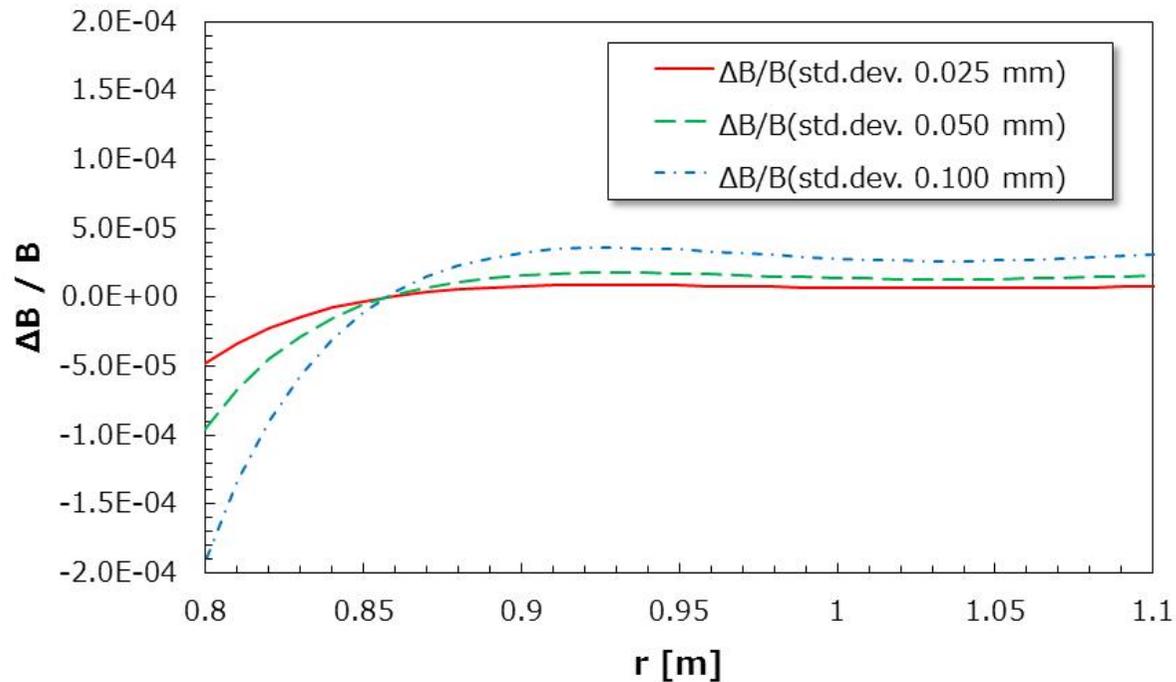


positional deviations of 100 μm



Field calculation

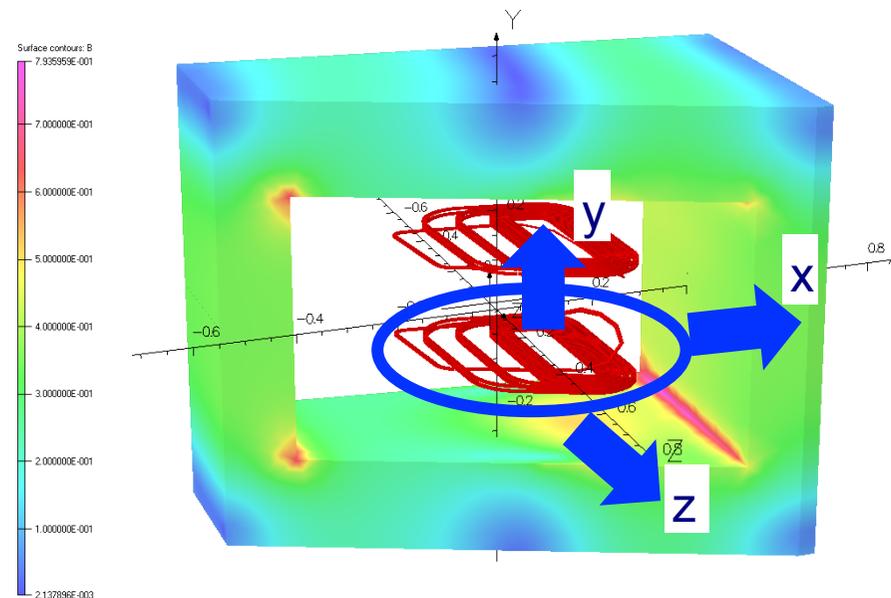
Influence of the dimensional errors of the YBCO coil on the magnetic field



- Magnetic field accuracy was defined as the field difference between the original and the deviated model
- Influence of the dimensional deviations of the YBCO tape within the coil was sufficiently small

Field calculation

Field analysis model with the coil alignment error

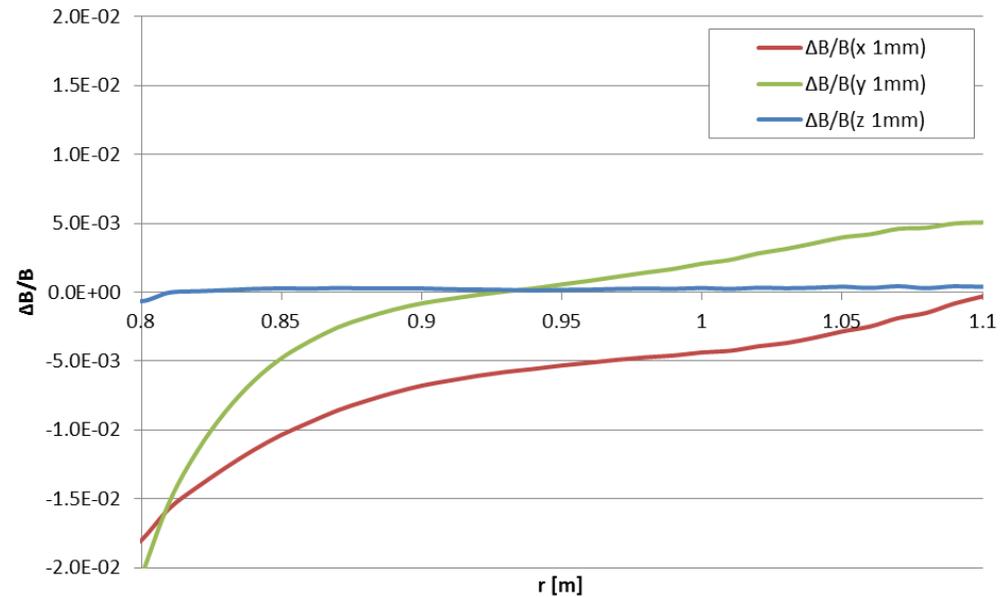
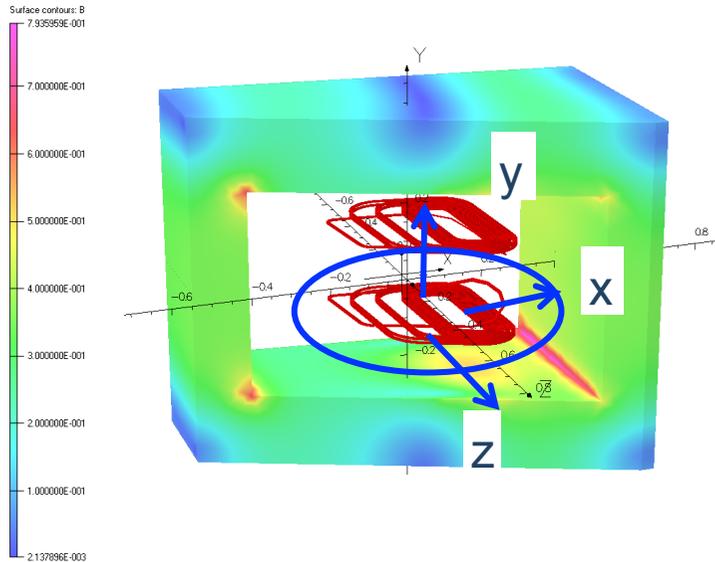


Bottom coil alignment error



Field calculation

Field analysis model with the coil alignment error



Bottom coil mis-alignment of 1mm for x、y、z direction each

x: 1.04%, y: 0.48%, z: 0.04%

Accuracy better than 0.1mm is required to achieve 0.1%



TOSHIBA
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Conclusion

- A YBCO model magnet was designed to demonstrate winding technology for producing YBCO coils for FFAG accelerator magnets.
- YBCO coils with complicated three-dimensional winding shapes were fabricated, and degradation-free superconducting properties were confirmed.
- The dimensional accuracy of the YBCO coils and the influence of the accuracy on the magnetic field were investigated. From measurement of the dimensional deviations and the field analysis, the effect of the dimensional deviations was found not to be a serious issue for the magnetic field.
 - except for error associated with conductor thickness...

Many thanks for your attention

This work was supported by Japan Science and Technology Agency under Strategic Promotion of Innovative Research and Development Program.

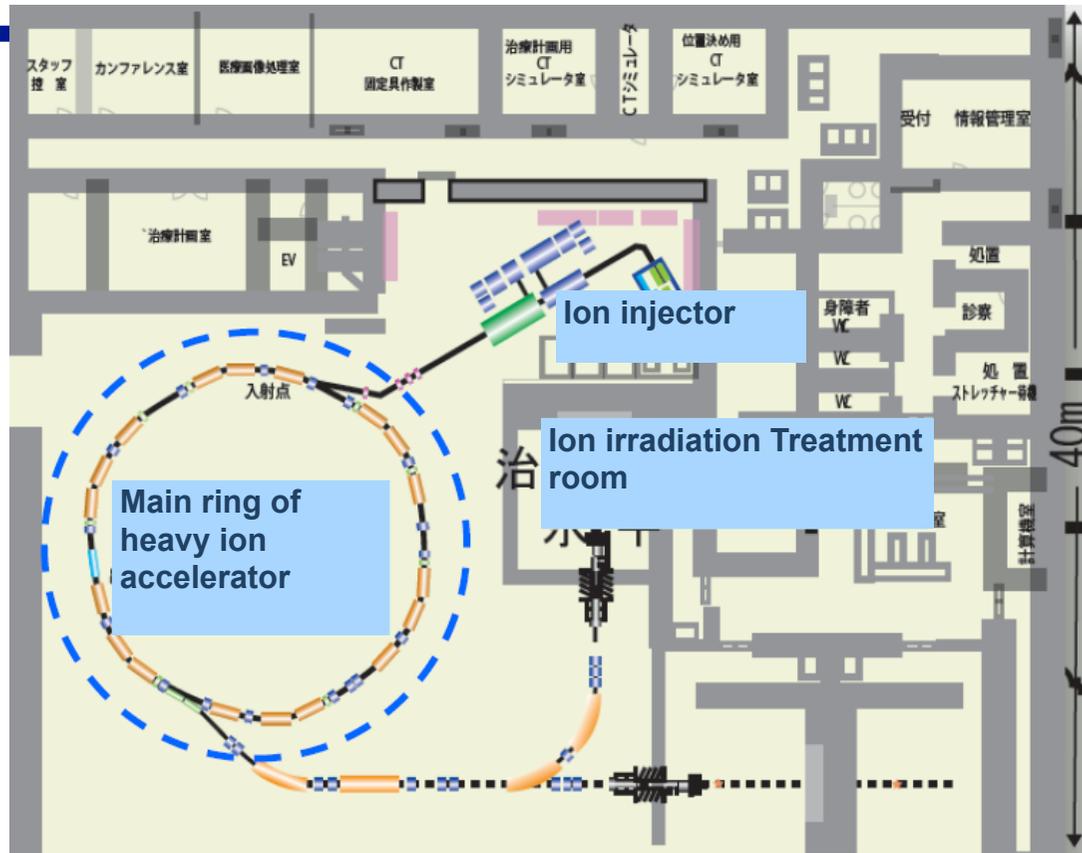


(appendix)

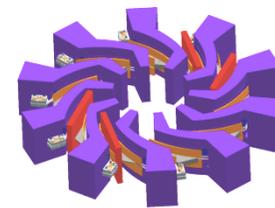


Introduction

Development of HTS magnets aiming to miniaturization of a main ring



Schematic view of heavy ion cancer treatment device



Schematic view of main ring (Spiral-sector FFAG accelerator)

High magnetic field

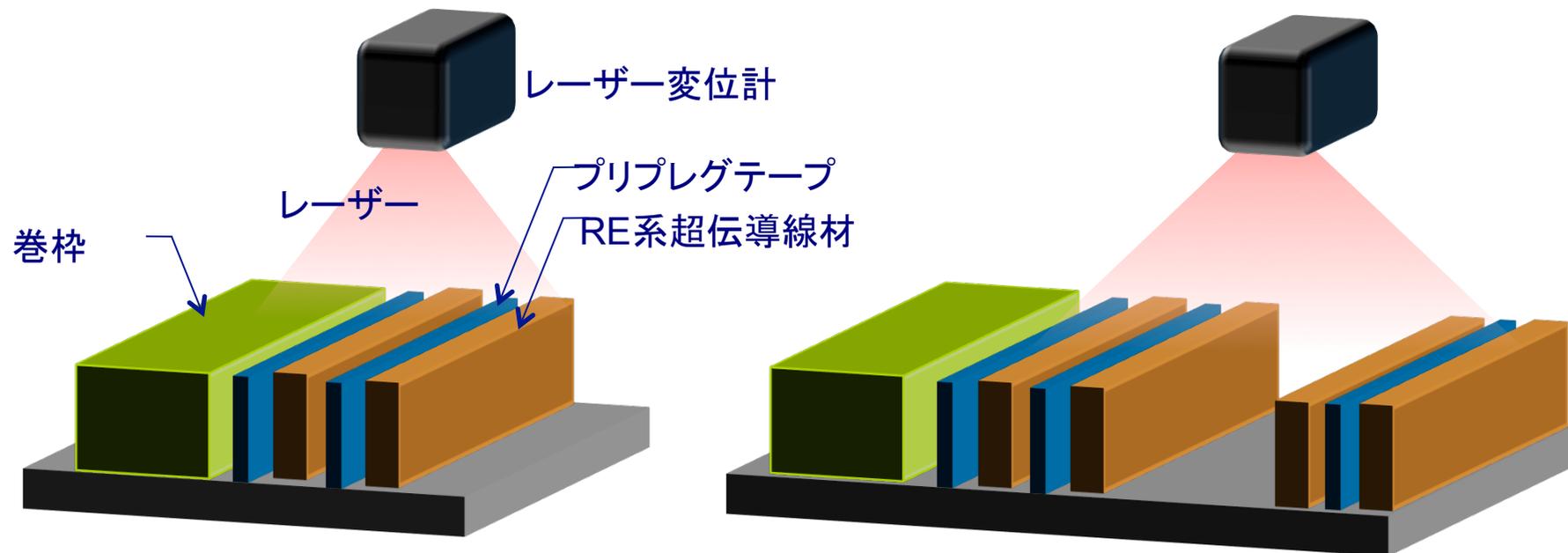
possible to reduce curvature radius of beam orbit

ring radius: 10 m -> 5m

FFAG accelerator would be suitable for superconducting magnet for a heavy ion cancer treatment apparatus

線材厚さ方向巻線精度の測定方法

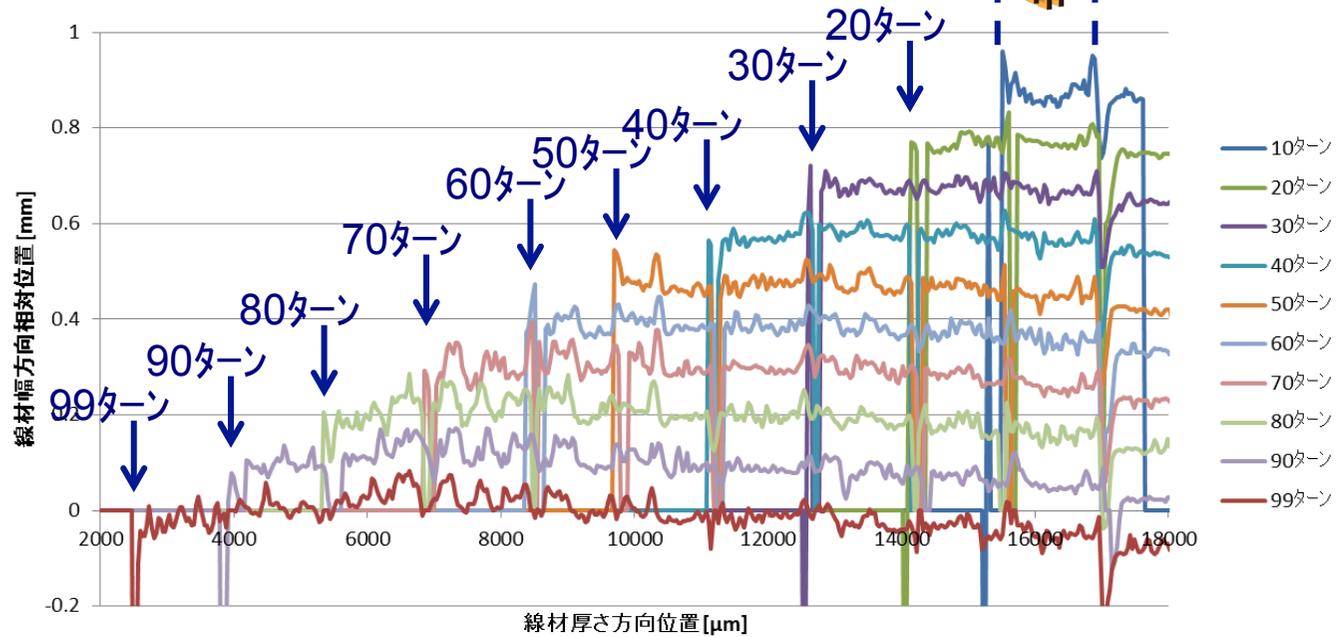
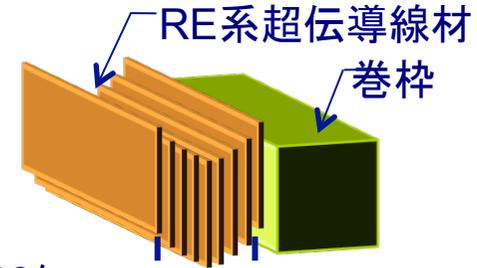
モデルコイルを10ターン巻線する毎にレーザー変位計でコイル表面の凹凸を測定し、そこから巻厚を求めることで、線材厚さ方向の巻線精度を評価した。



巻厚測定の様式図

Dimensional deviations of the YBCO coils

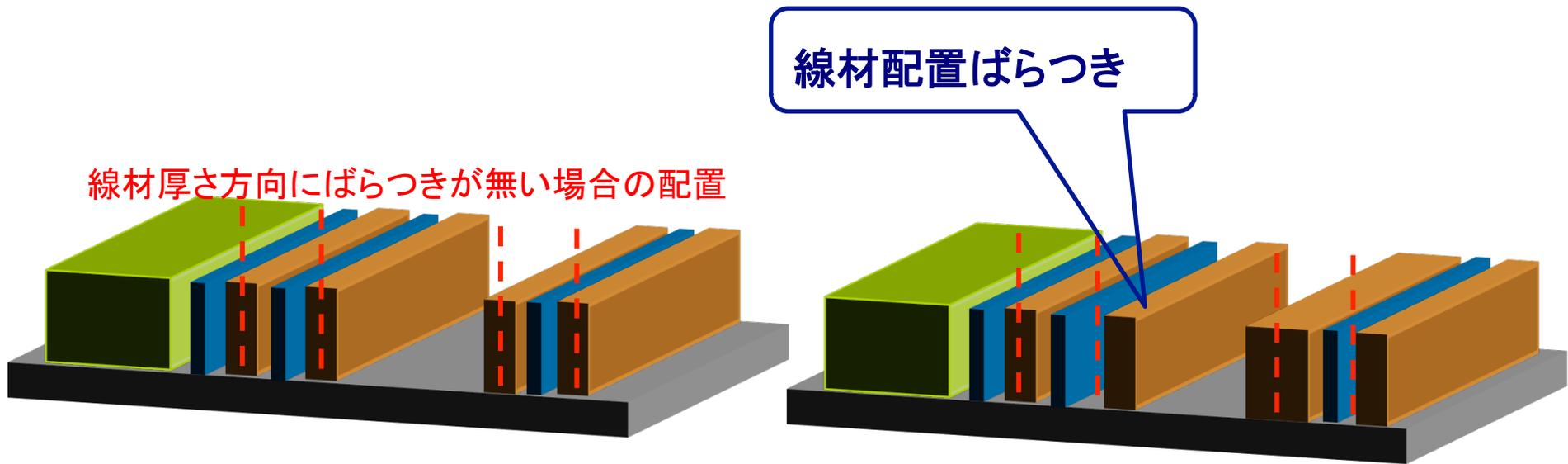
巻線時、10ターンごとに巻線部厚さの測定を実施



巻線部厚さ(線材厚さ方向)測定結果

モデルコイル巻厚測定結果

コイル巻厚は線材厚さ方向にばらつきが無ければ線形に増加する。
実際には線材厚さ方向のばらつきを反映して線形近似位置からずれる。
このずれ量が線材厚さ方向の巻線精度となる。

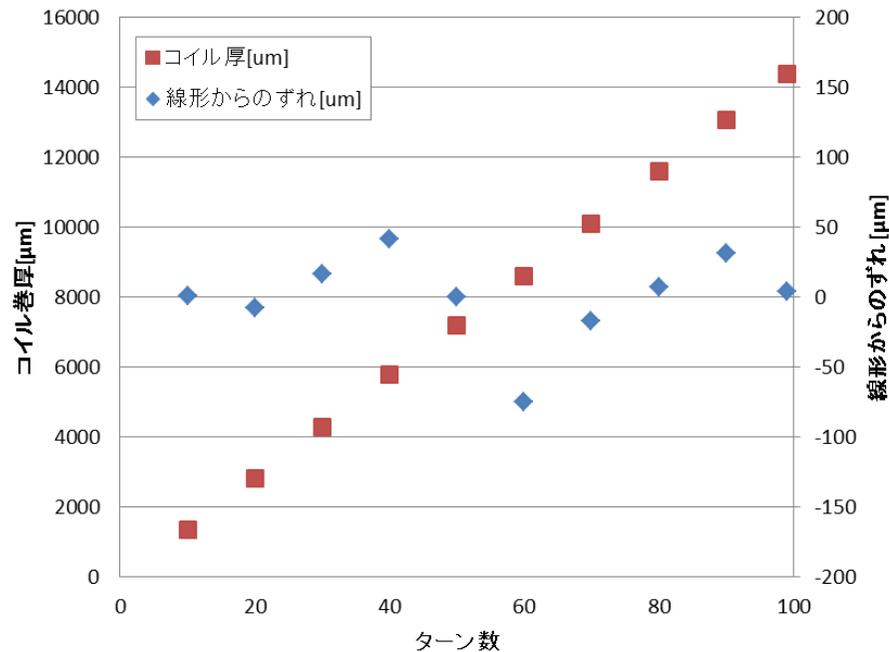


線材厚さ方向配置ずれ模式図

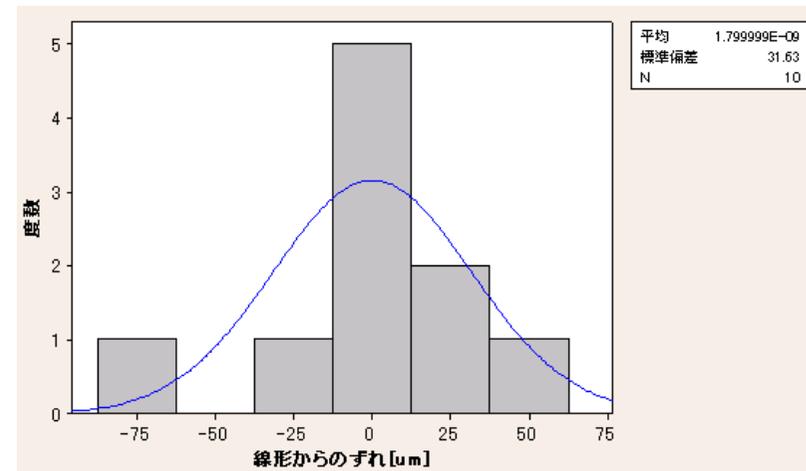
モデルコイル巻厚測定結果

線形近似からのずれ量を度数分布で評価

標準偏差 : 31.63 μm



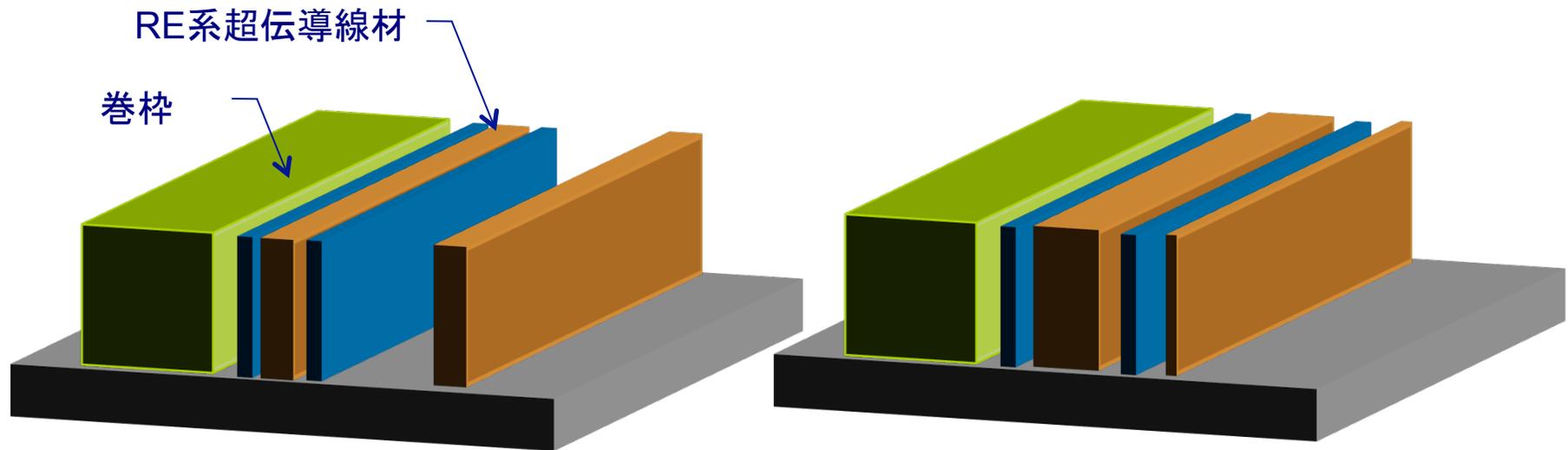
線材厚さ方向コイル厚測定結果



コイル巻厚の線形近似からのずれの
ヒストグラム

モデルコイル厚さ寸法精度の確認

一方で、線材幅方向と同様本測定では以下の二つのばらつきが混在して測定されている。



線材厚さ方向配置のばらつき
(線材厚さ方向巻線精度)

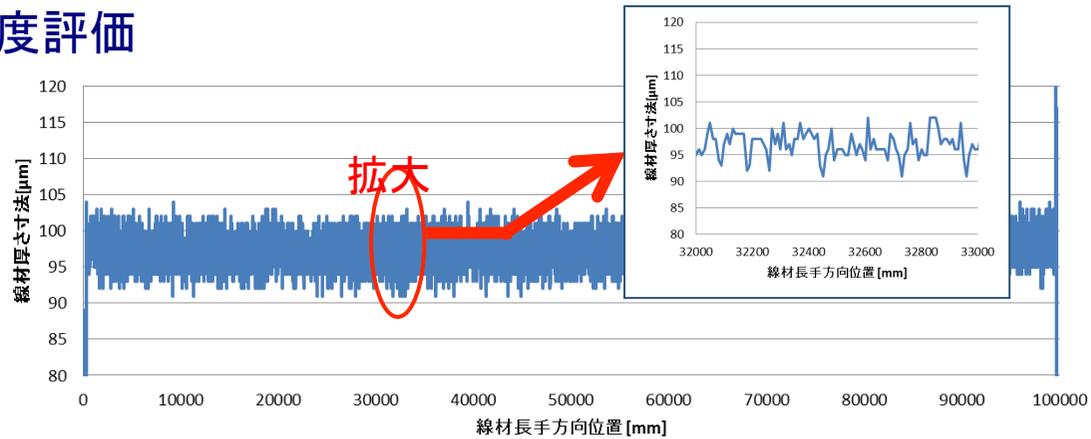
線材厚さ寸法のばらつき

線材厚さ方向配置ずれ模式図

Dimensional deviations of the YBCO tape

線材そのものの寸法精度評価

<ロット#1>
 線材厚さ寸法
 標準偏差 : 2.30 μ m



線材厚さ寸法連続測定

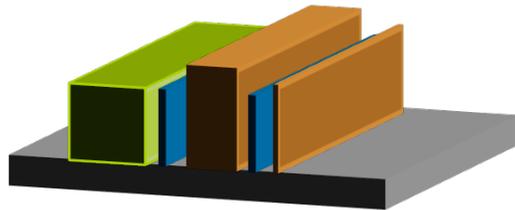
ロットNo.	平均厚さ [μ m]	厚さ寸法 標準偏差 [μ m]	周期 [mm] (*1)
#1	97.2	2.3	-
#2	77.9	1.7	251.3
#3	73.4	1.7	251.3
#4	95.6	1.7	-
#5	92.3	1.6	-

(*1:FFTによって周期を計算。ハイフンは周期性無し)

モデルコイル線材厚さ方向巻線精度の評価

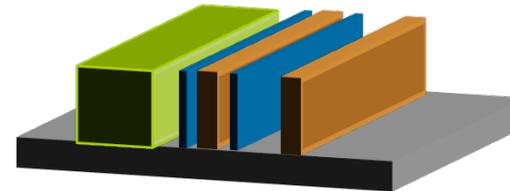
逆畳み込み*で分離することで線材厚さ方向の巻線精度が求められ、
標準偏差で29.326 μm であることが明らかとなった。

(*線材厚さ方向配置の精度は正規分布していると仮定)



線材厚さ寸法精度

標準偏差: 2.304 μm (畳み込み)



線材厚さ方向配置の精度
(線材厚さ方向巻線精度)



コイル巻厚の線形近似からのずれ

標準偏差: 31.63 μm

実機コイル巻線に要求される精度0.1mm以下となっている。

ばらつきを加えた場合の解析結果

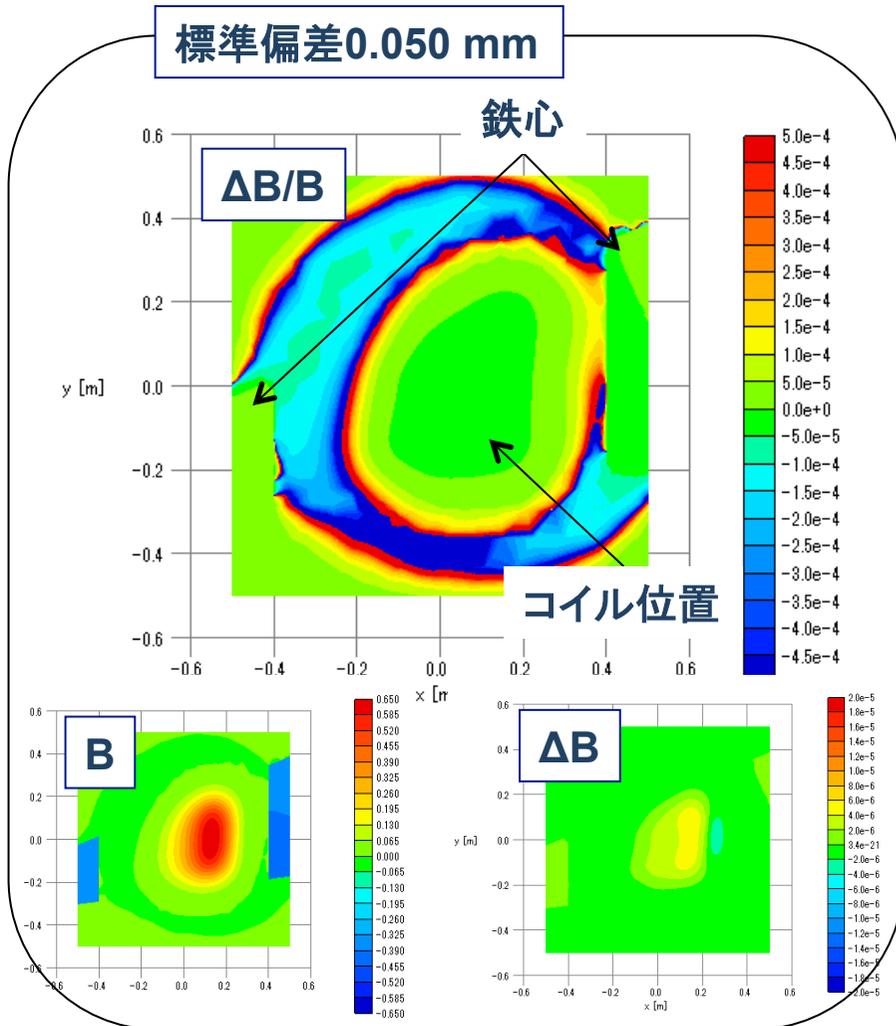
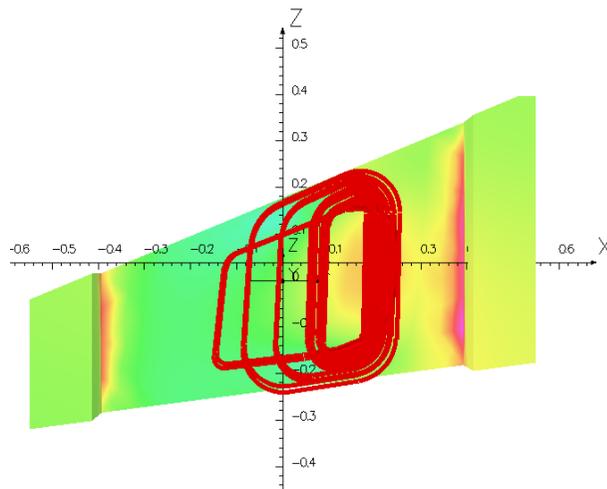
線材寸法にばらつきを加えたものと、ばらつきを加えていないものとのミッドプレーンでの磁場分布を比較した。

ここで

$$\Delta B = B(\text{ばらつき有}) - B(\text{ばらつき無})$$

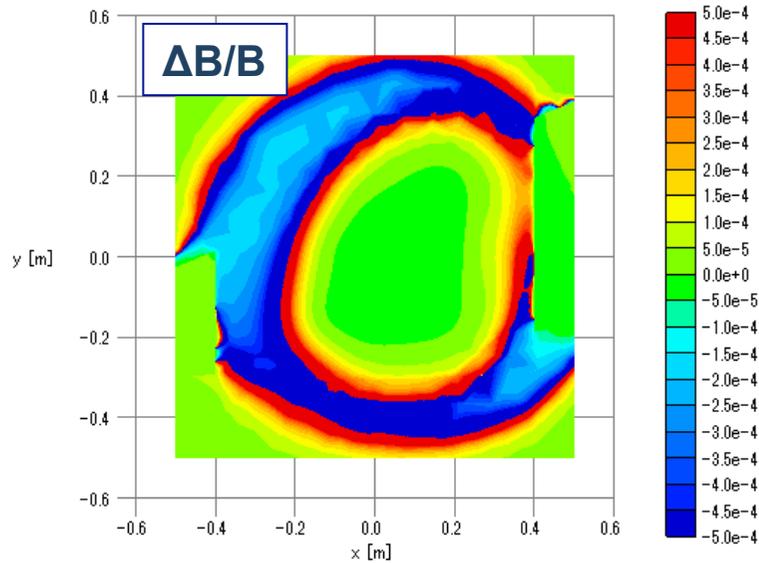
$$\Delta B/B = \Delta B/B(\text{ばらつき有})$$

とした

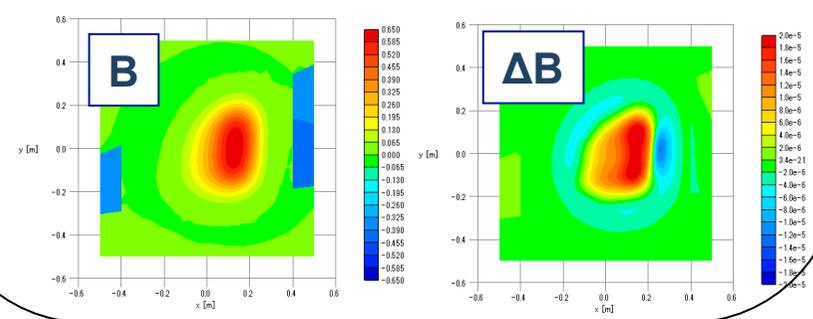
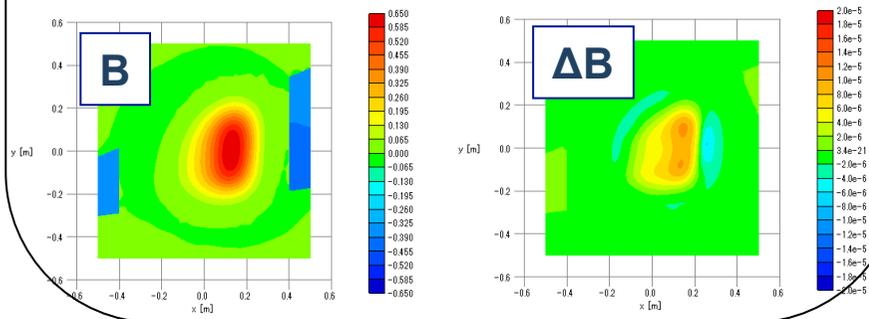
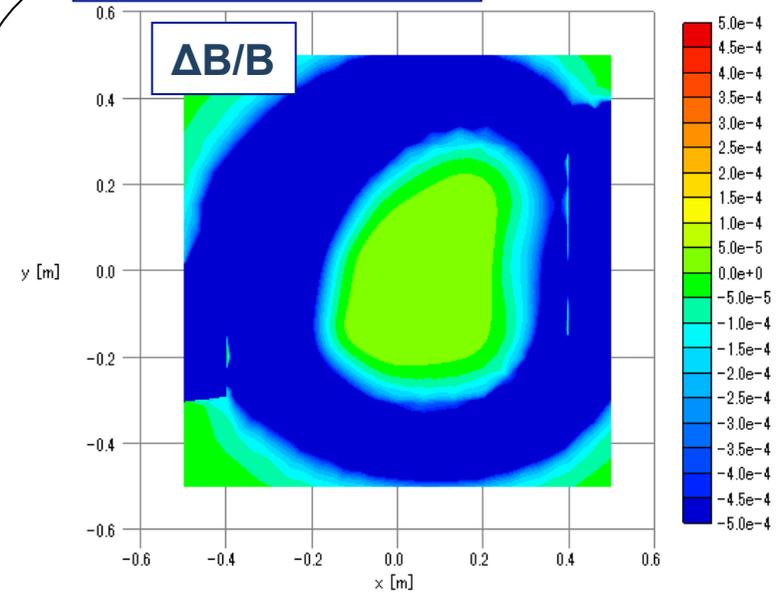


ばらつきを加えた場合の解析結果

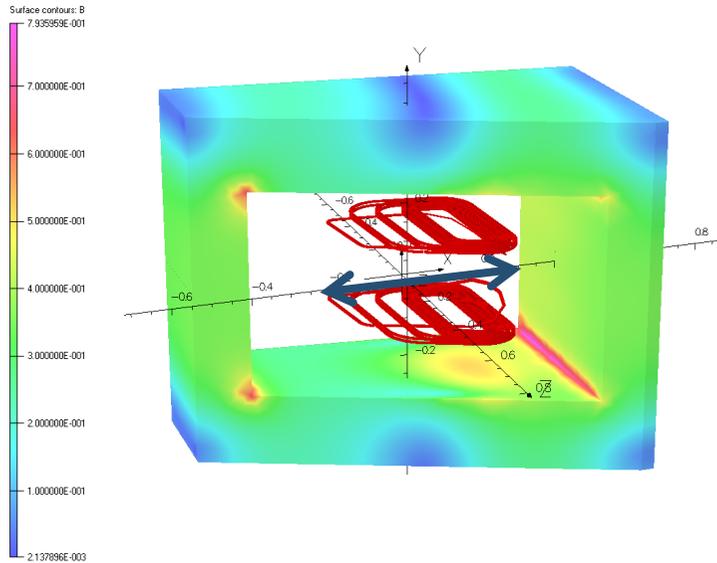
標準偏差0.050 mm



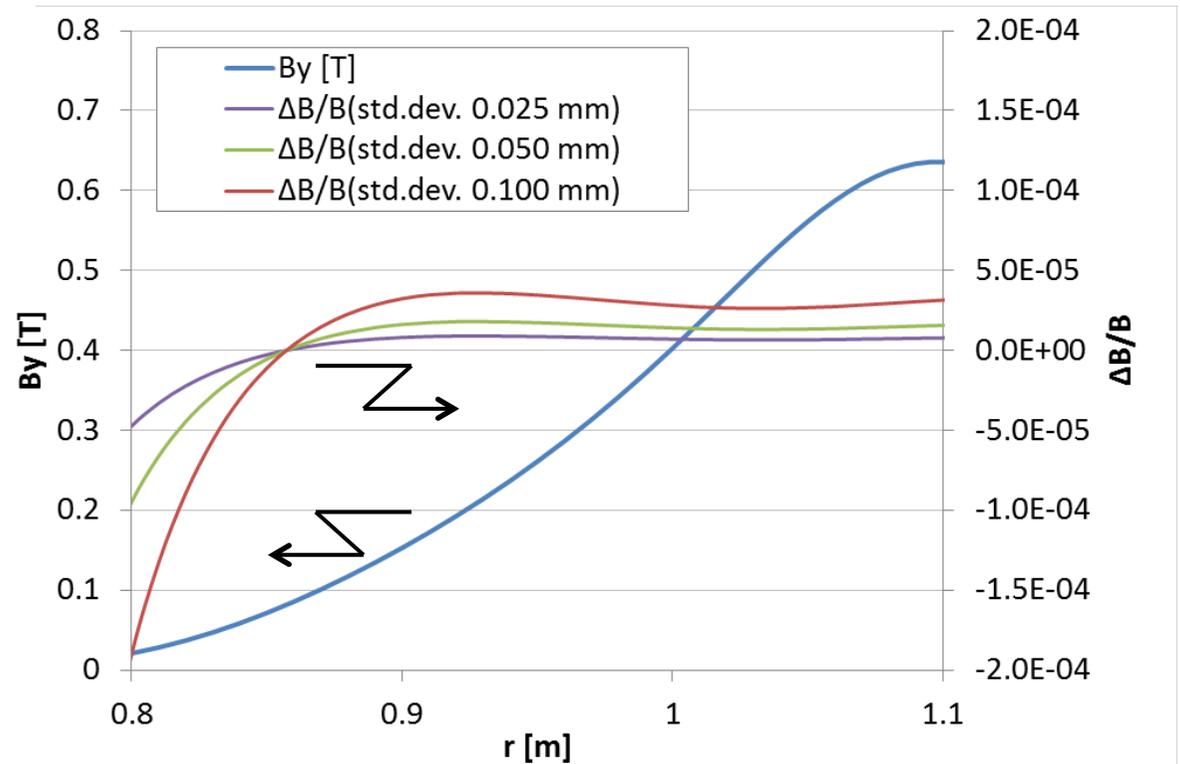
標準偏差0.100 mm

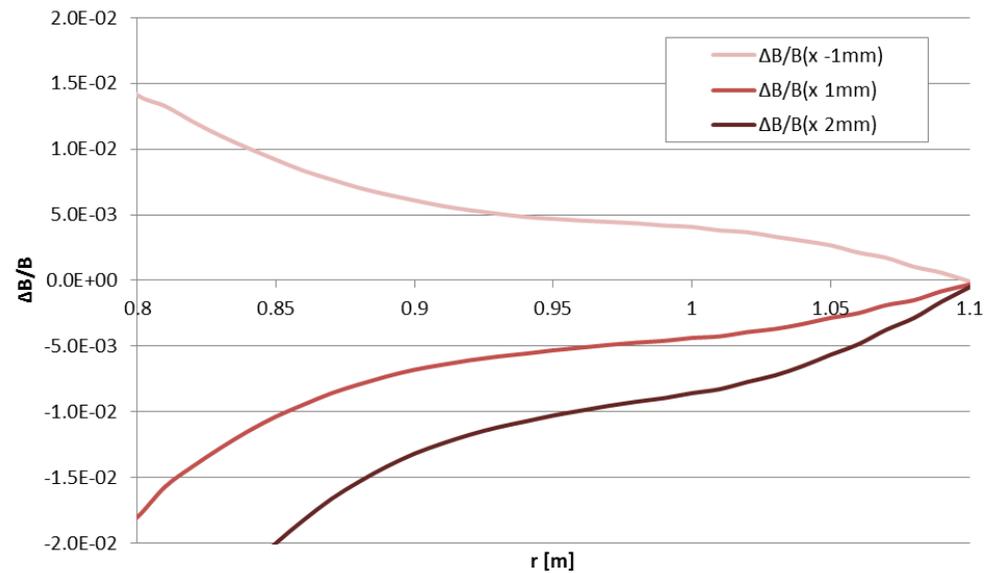
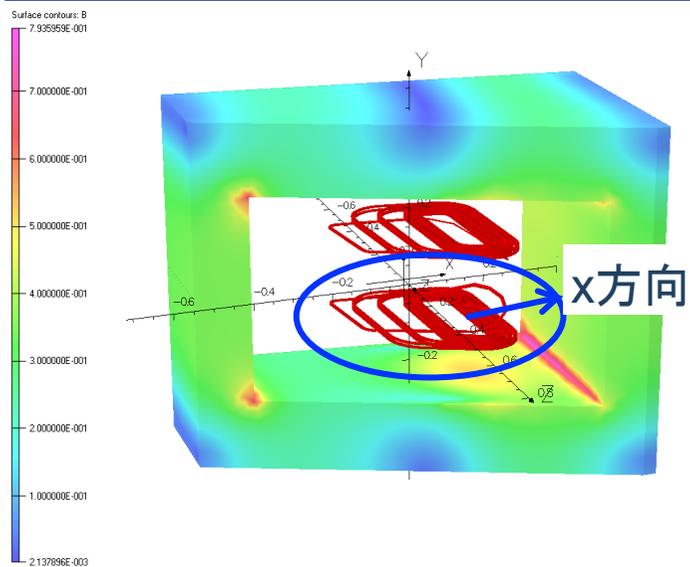


ばらつきを加えた場合の解析結果



幅寸法のばらつきが磁場分布に与える影響は小さく、現状の巻線精度で巻線出来た場合、 5×10^{-5} 以下程度となった。





特にx方向への変位量を変更した場合の解析を実施。

変位量に対し、相対磁場精度に線形性がみられる結果となった。

