AMED PROJECT

WAMHTS-4

2017.2.17

High Energy Accelerator Research Organization (KEK)

Kento Suzuki, Toru Ogitsu

CONTENTS

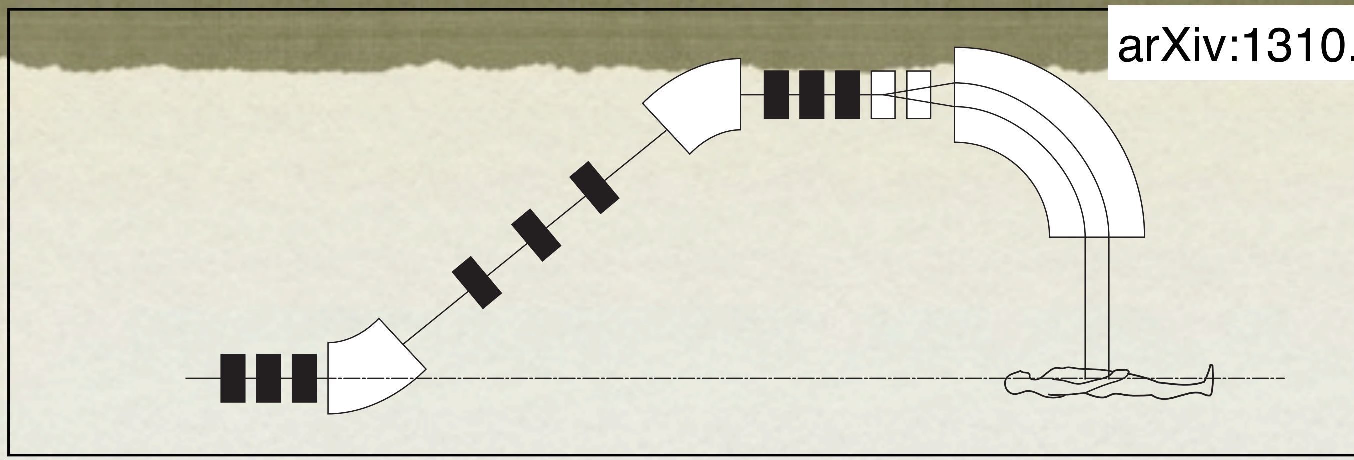
INTRODUCTION

AMED PROJECT

- KEK has engaged in “HTS” R&D program supported by “Japan Agency for Medical Research and Development (AMED)”

- R&D of **HTS-based** rotating gantry for Carbon-Ion Radiation Therapy
  - Collaboration w/ **Toshiba Co., Ltd**. and **Kyoto Univ.**

GANTRY FOR CIRT



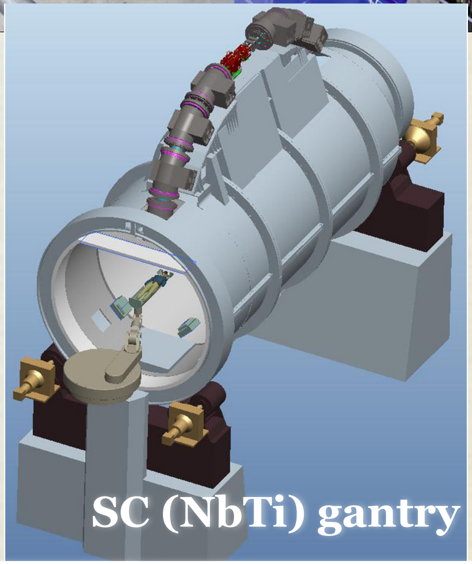
- Gantry:
  - Composed of group of magnets: **dipole**, quadrupole , scan magnets, etc
  - Can deliver beam to a tumor from a number of direction
    - Can avoid rotating a patient
- Carbon-ion (C^{6+}) Radiation Therapy (CIRT):
  - Good relative biological effectiveness (RBE) : **6 times larger** than that of proton beam
  - **Less multiple scattering** and **sharper Bragg peak** than those of proton beam
    - → Easily handle the size/local dose of the beam

Gantry+CIRT = Powerful & Effective tool

GANTRY FOR CIRT

- C^{6+} requires **larger** beam rigidity as compared to proton beam (T_{carbon}= 430MeV/u)
  - Beam rigidity : R_{carbon}=6.57 T•m
    - = **3 x** R_{proton} (=2.43 T•m)
    - ➡ "High field" or "Large acceptance" is essential
- Two CIRT gantries in the world at present
  - **NC gantry @ HIT in Gereman:**
    - B^{dipole}=1.8T, L_{gantry}=25m, M_{gantry}=600t
  - **SC gantry @ NIRS in Japan:**
    - B^{dipole}=2.9T, L_{gantry}=13m, M_{gantry}=210t

Heidelberg Ion-Beam Therapy Center (HIT)



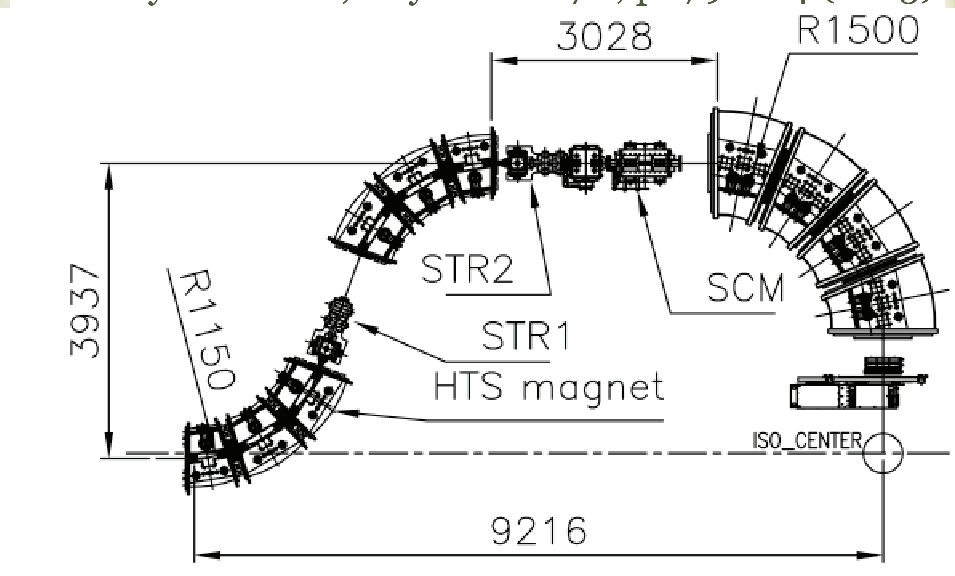
Y. Iwata *et al.*,
Phys. Rev. ST Accel. Beam **15** 0447701 (2012)

WHY HTS-BASED GANTRY ?

- Past study showed "HTS" could play an effective role in further reduction of the size:
  - Gantry length: 9.2 m
    - (ref. NC: 25 m, LTS: 13 m)
  - Total weight: 177 t
    - (ref. NC:600 t, LTS:210 t)

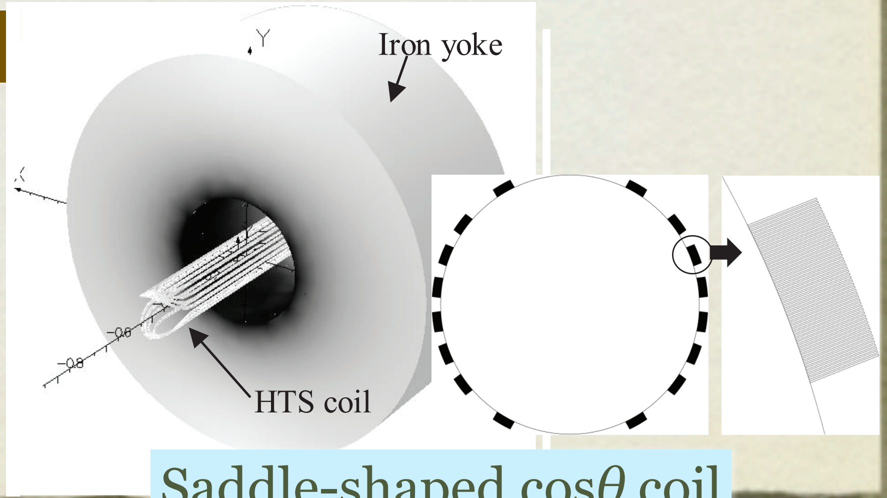
➡ **Promotion of the widespread adoption of CIRT gantry**

S. Takayama *et al.*, Phys. Proc. **76**, p879-884 (2015)



Design of the HTS (dipole) magnet for gantry:

Coil mechanical length	540 mm
Dipole field	5.8 T
Bore radius	30 mm
# of layers	4
Field quality	<0.1%
Reference radius	20 mm

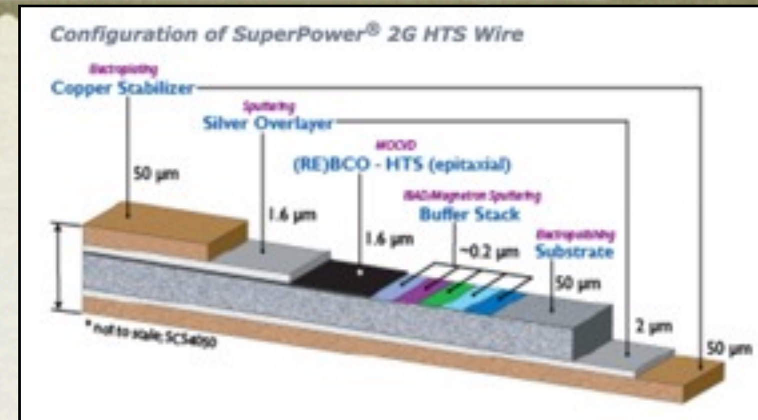


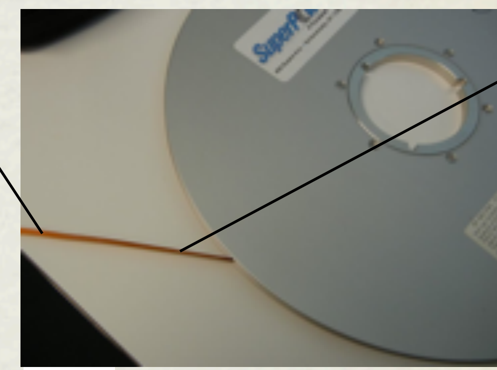
Saddle-shaped cosθ coil

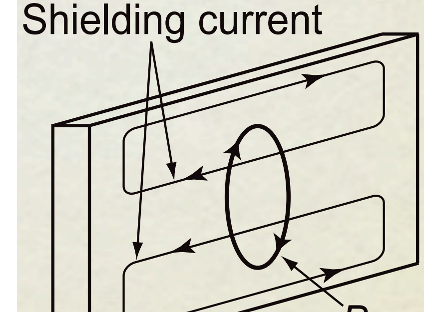
OUR TASK

Investigation of feasibility of HTS magnet for CIRT gangry

- Establish the winding technology for the HTS dipole magnet using ReBCO coated conductor (4mm wide)
- Estimation of effect from the shielding current on the field uniformity
- Fabricate the model magnet @ Toshiba
    - Make coils based on the established technology
    - Check its performance and healthiness after the winding process
    - Check its field quality using harmonic coil system







N. Amemiya *et al*.,
Supercond. Sci. Technol. **21** 095001 (2008)

Prospect:

- Development of quench protection

OUR TASK

Investigation of feasibility of HTS magnet for CIRT gangry

- Establish the winding technology for the HTS dipole magnet using ReBCO coated conductor (4mm wide)

K. Koyanagi *et al.*, IEEE Trans. Appl. Supercond. **25**, 4003104 (2015)

- Estimation of effect from the shielding current on the field uniformity

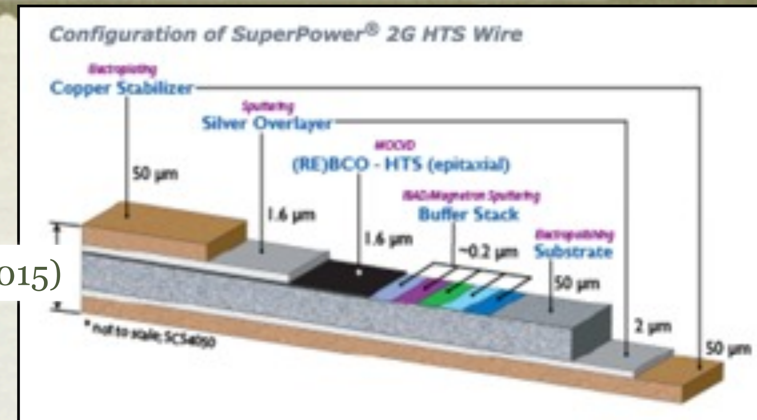
A. Amemiya *et al.*, Supercond. Sci. Technol. **28** 035003 (2015)

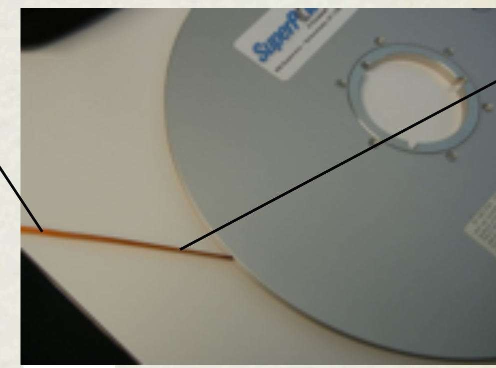
- Fabricate the model magnet @ Toshiba
  - Make coils based on the established technology
  - Check its performance and healthiness after the winding process
  - Check its field quality using harmonic coil system

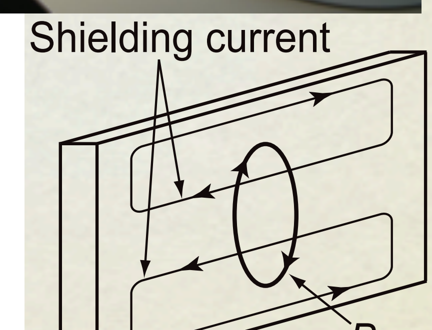
K. Suzuki *et al.*, IEEE Trans. Appl. Supercond. **27**, 4600405 (2017)

Prospect:

- Development of quench protection





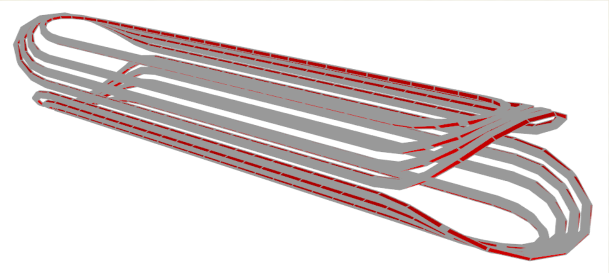


N. Amemiya *et al.*, Supercond. Sci. Technol. **21** 095001 (2008)

FABRICATION

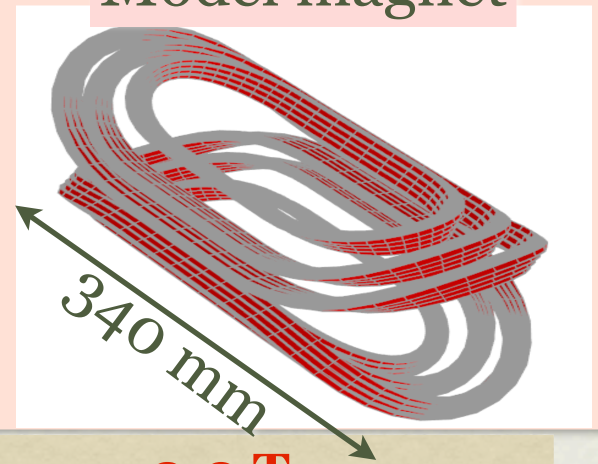
MODEL MAGNET DESIGN

Benchmark



Straight part is reduced to 1/3

Model magnet



Dipole field	**3.0 T**
Rated current	366 A
Load line ratio	~60% @ 20K
Bore radius	30 mm
Num. of HTS coils	24
Num. of coil turns	50
Coil inductance	288.9 mH
Reference radius	**20 mm**
Field quality	**0.2%**

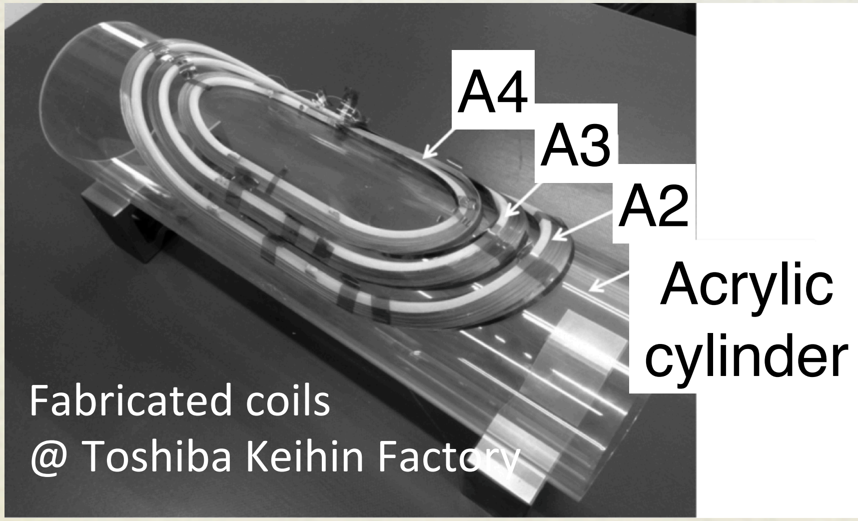
Magnet is designed to be cooled down to 4K by means of conduction-cooling method

MODEL MAGNET ASSEMBLY

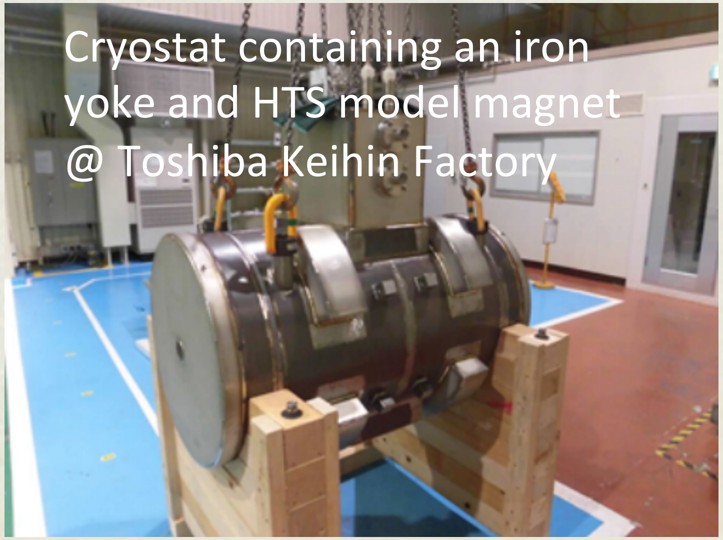
- Coil was wound through the automated winding machine developed by Toshiba
  - Turn-to-turn insulation : prepreg tape inserted in-between ReBCO tapes
- Winding accuracy was measured to be <**0.2mm**
  - Effect on the field uniformity was confirmed be negligible according to 3D FEM calculation

S. Takayama *et al*., IEEE Trans. Appl. Supercond **26**, 4402304 (2016)

- Healthiness of each coil was confirmed by checking its I-V characteristics at 77K
- Each coil is connected to a refrigerator through a high-purity aluminum sheet which is attached to a surface of the coil

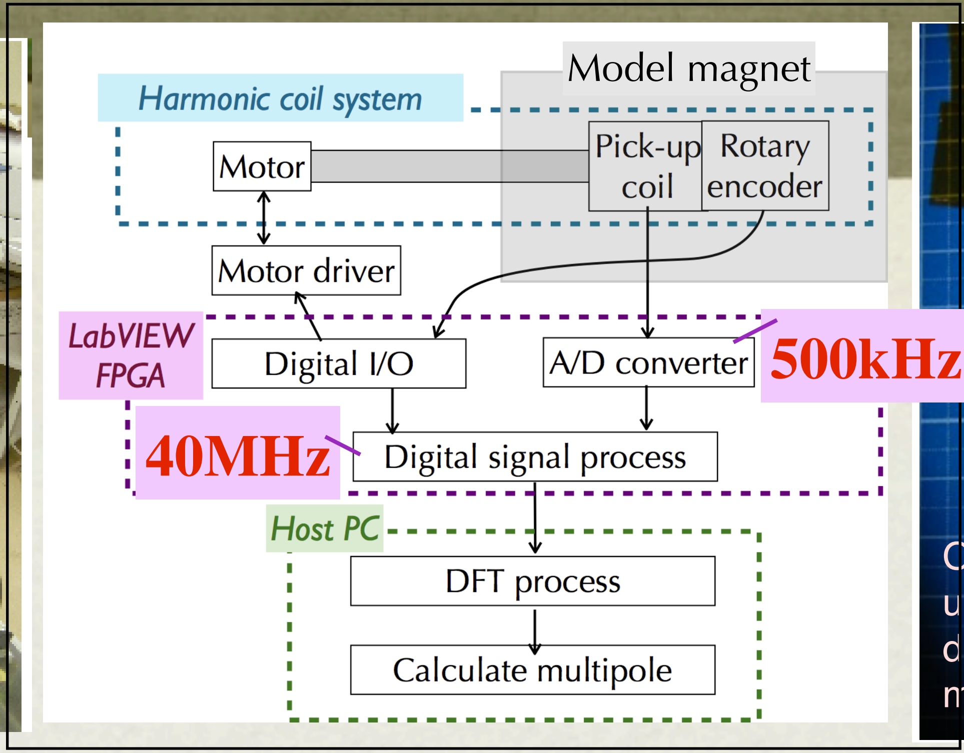


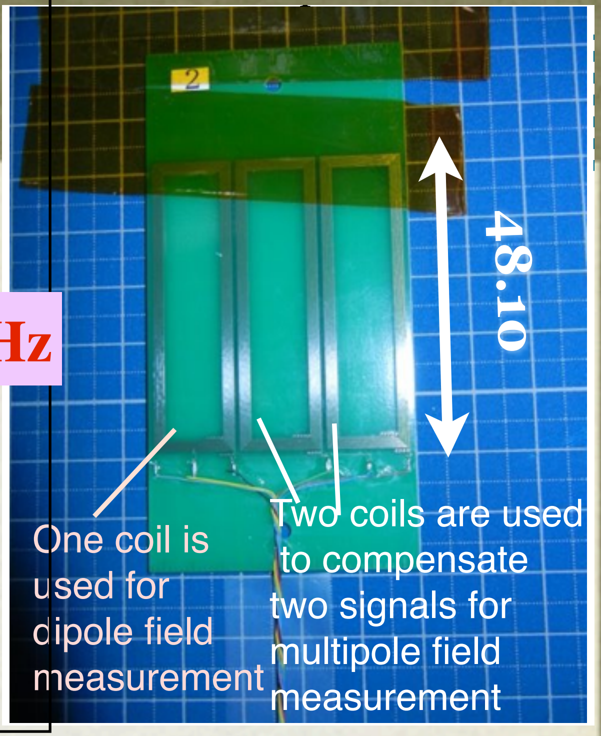
Fabricated coils
@ Toshiba Keihin Factory



Cryostat containing an iron yoke and HTS model magnet
@ Toshiba Keihin Factory

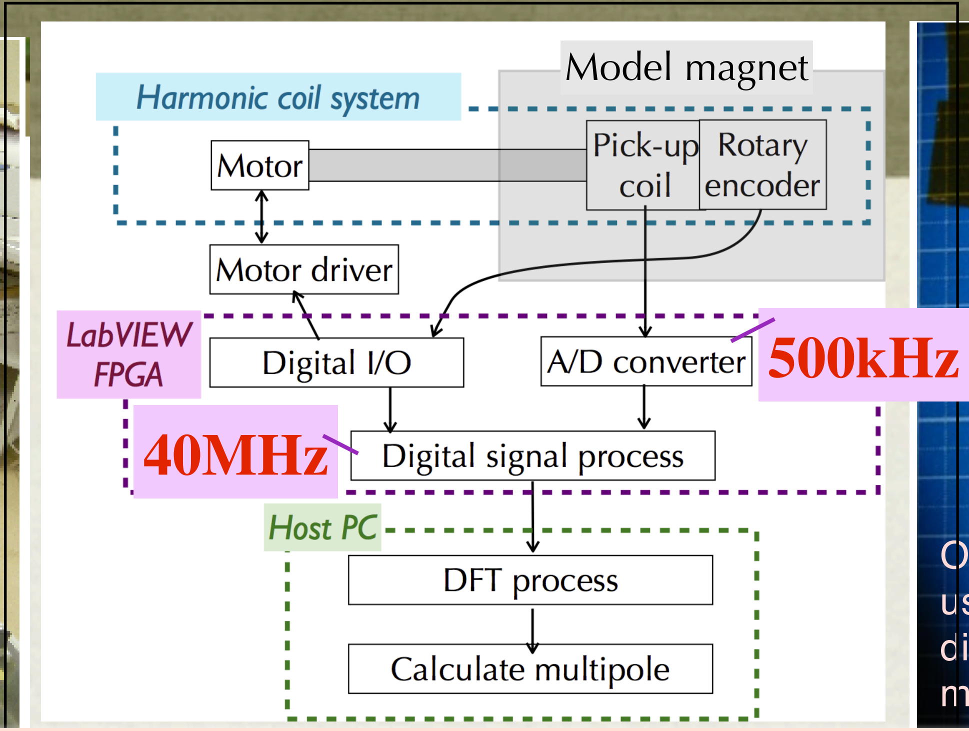
HARMONIC COIL SYSTEM

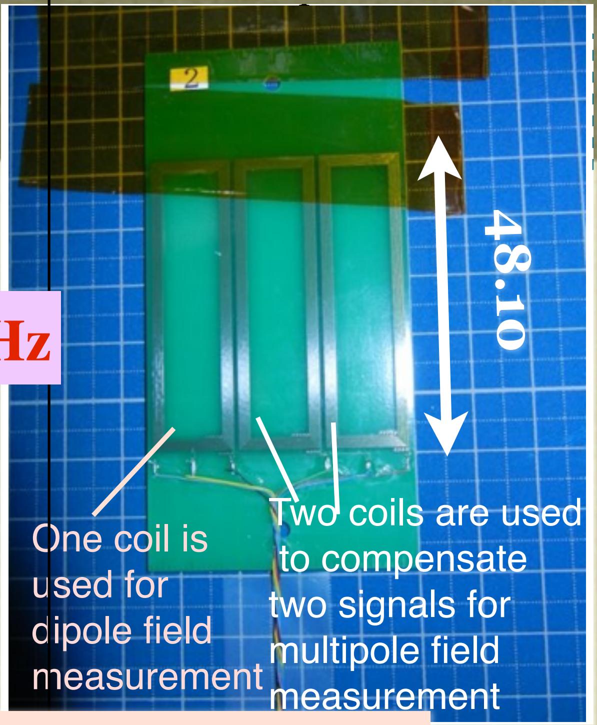




- Requirements:
  - Sampling rate for multipole measurement is **10 Hz**
    - i.e. Maximum rotation speed of the coil is **10 rot/s**
  - Measure multipole coefficients with a precision better than **0.1%** to confirm good filed uniformity of <0.1% @ **10 Hz** samples/s
  - Enable to measure coefficient on the **on-line basis**

HARMONIC COIL SYSTEM



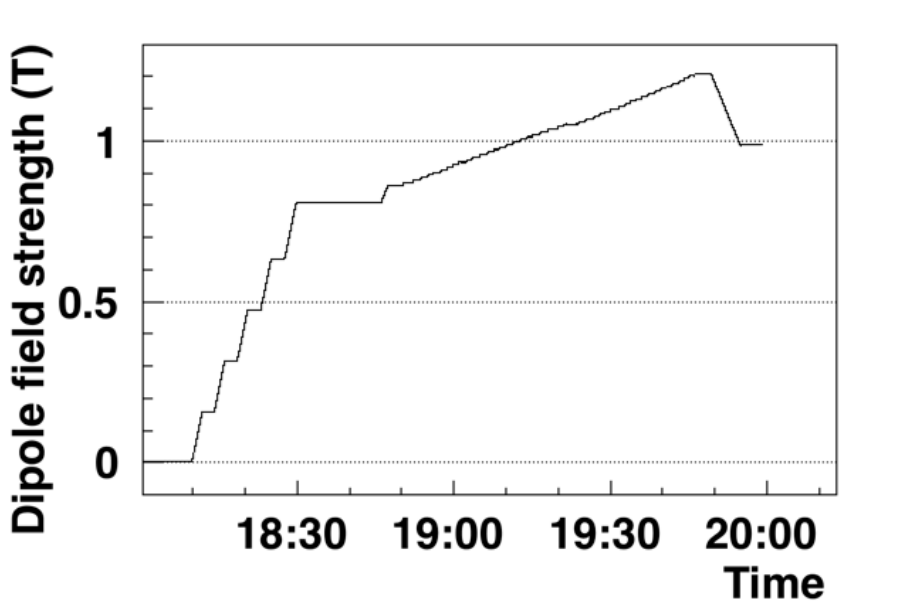


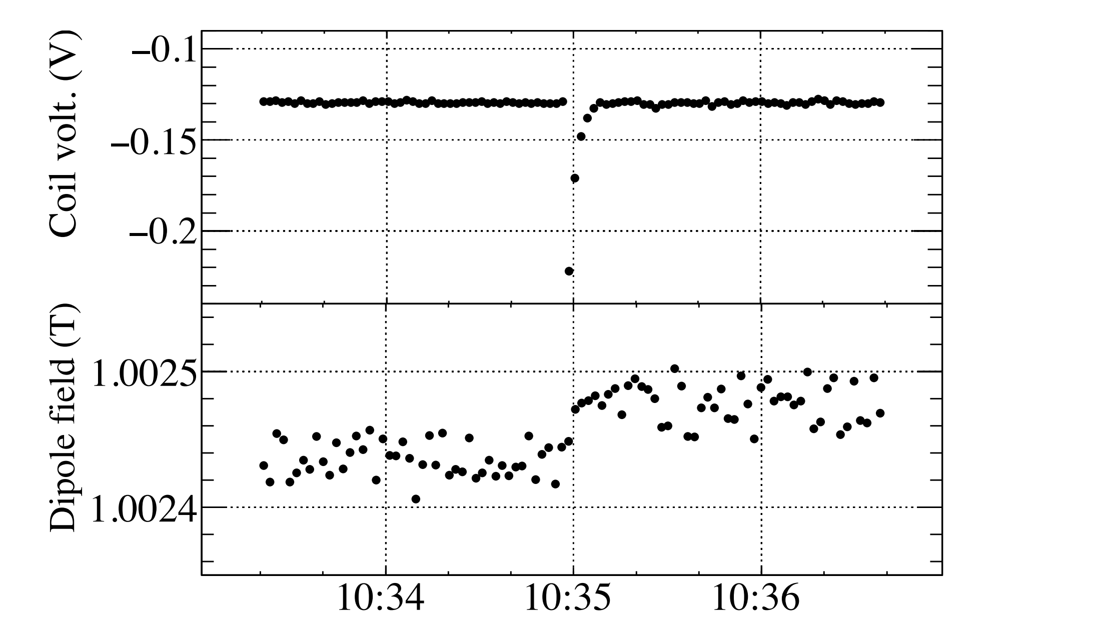
- **Check its performance using KEKB accelerator magnet**
  - Sampling rate for multipole measurement is **10 Hz** → **7Hz**
    - i.e. Maximum rotation speed of the coil is **10 rot/s** →**7 rot/s**
  - Measure multipole coefficients with a precision better than **0.1%** to confirm good filed uniformity of <0.1% @ **10 Hz** samples/s → **OK but at 7 Hz**
  - Enable to measure coefficient on the **on-line basis** → **OK**

Resolution of dipole field measurement → < 100 ppm

FIELD MEASUREMENT

MODEL MAGNET RAMP-UP TEST

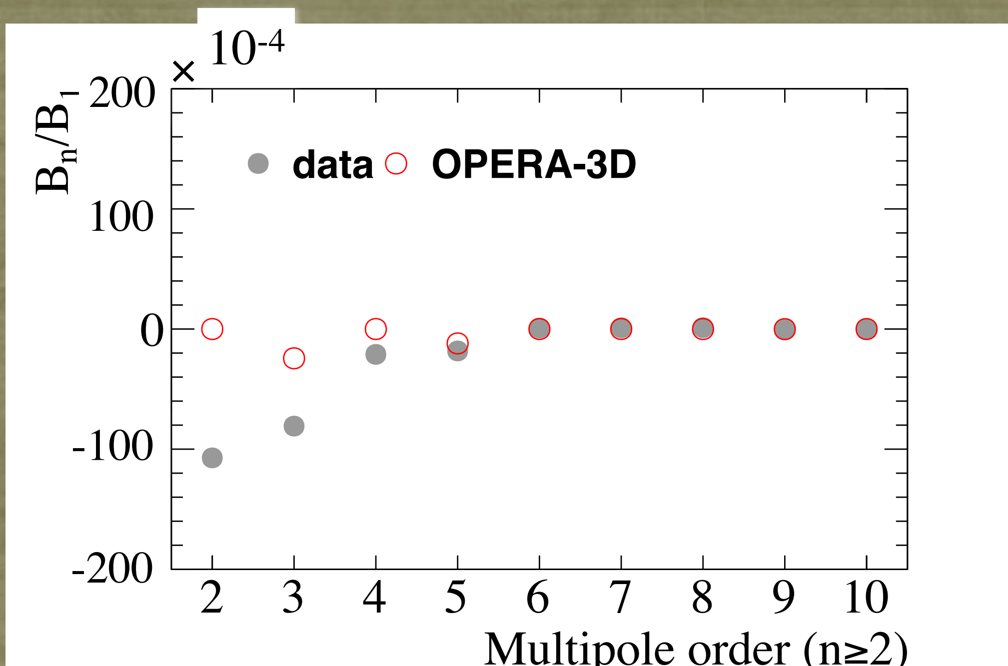


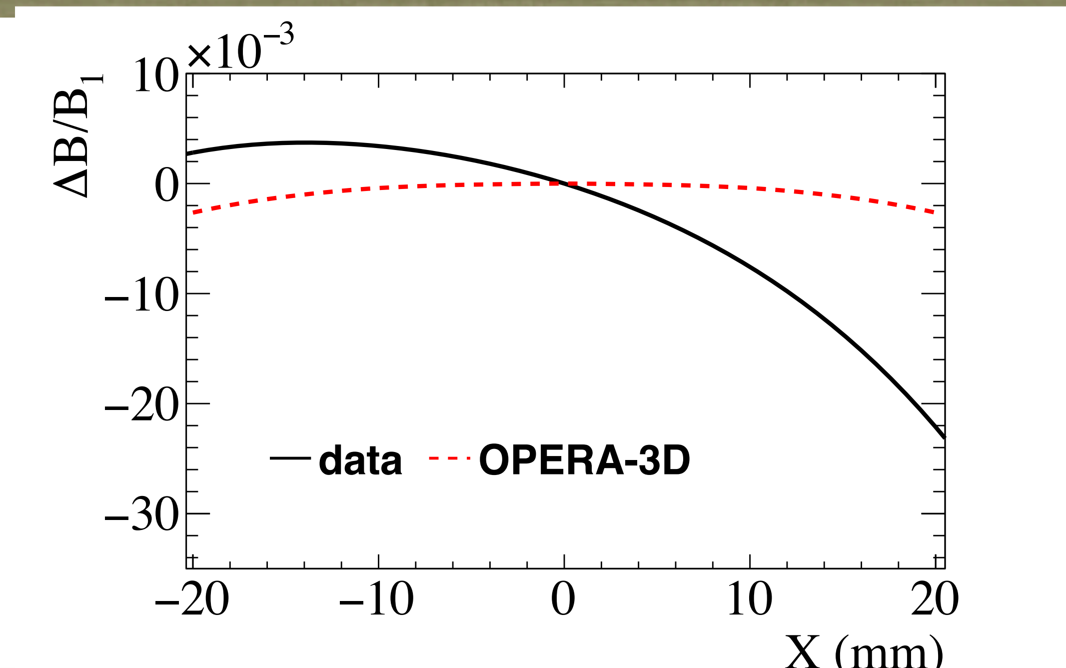


- Ramp-rate was set to <5A/min
- Maximum field of **1.2T** was achieved at I=**153A** so far (see left fig.)
- Operation was suspended at B=1.2T since spikes of coil voltages were observed
  - One of the examples is shown on right fig., where a coincidental field jump (~100 ppm) is also seen (**Flux jump?**)
- **Effect from this jump could be significant when increasing operation current.**
- **In addition, 100 ppm change is already critical for particle accelerator application (~10^{-4})**

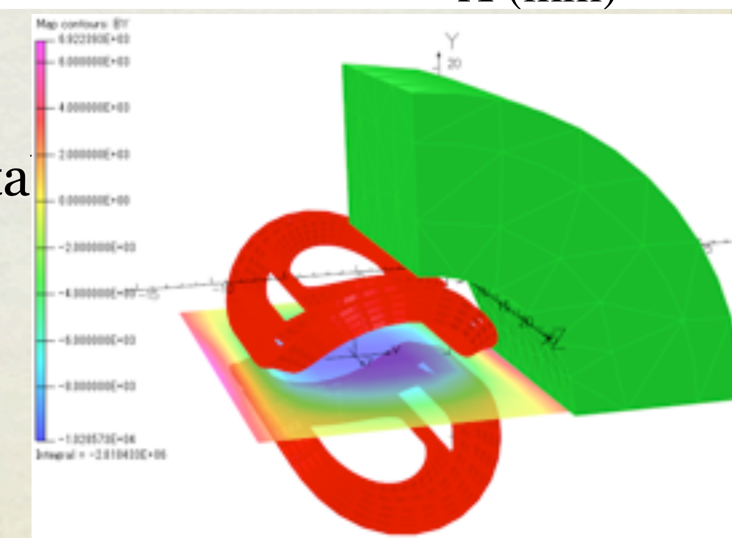
Need some countermeasures

MODEL MAGNET FIELD MEASUREMENT



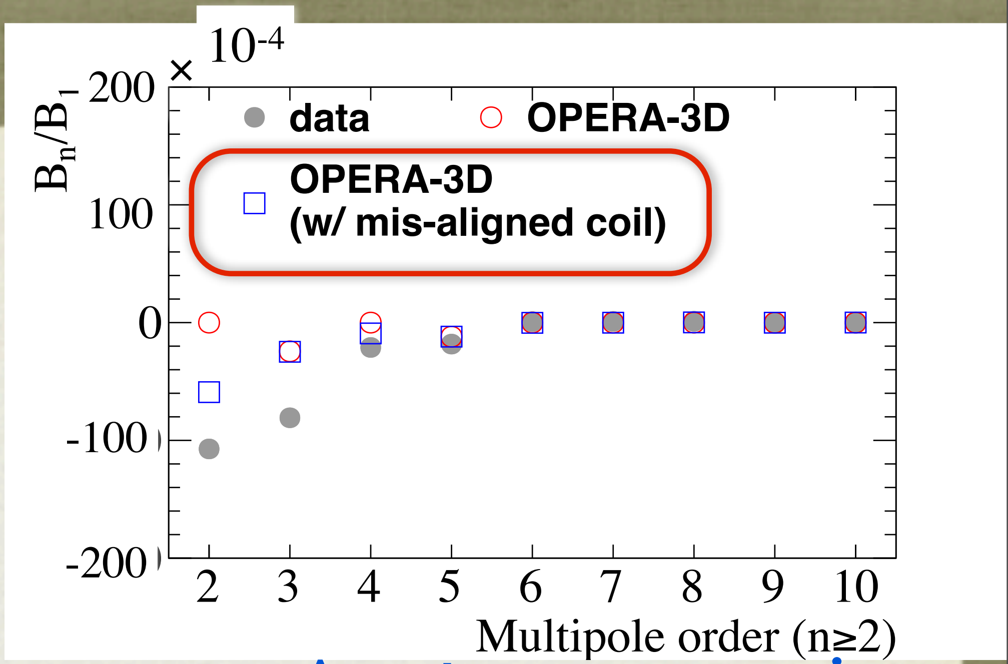


- Left: Field harmonics (normal) at R_{ref}=20mm
- Right: Deviation from the center field along horizonta direction
  - Operating current was fixed at 120A (B=1.0T)
  - Large contribution from b_2 and b_3 : $O(10^{-2})$
  - Field non-uniformity is limited to **2**%

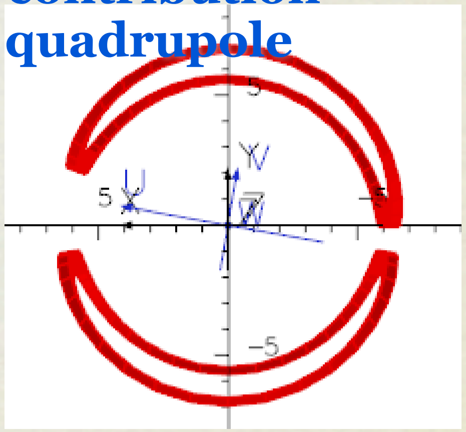


MIS-ALIGNMENT ISSUE

- Why observed large non-uniformity?
  - Mis-alignment during the fabrication process, especially “coil layering”
  - The mis-alignments of the coils were reproduced in the 3D calculation, showing similar trend in deviation of quadrupole
  - Allowed multipoles, however, do not show any deviation, indicating our understanding on the mis-alignment is not perfect

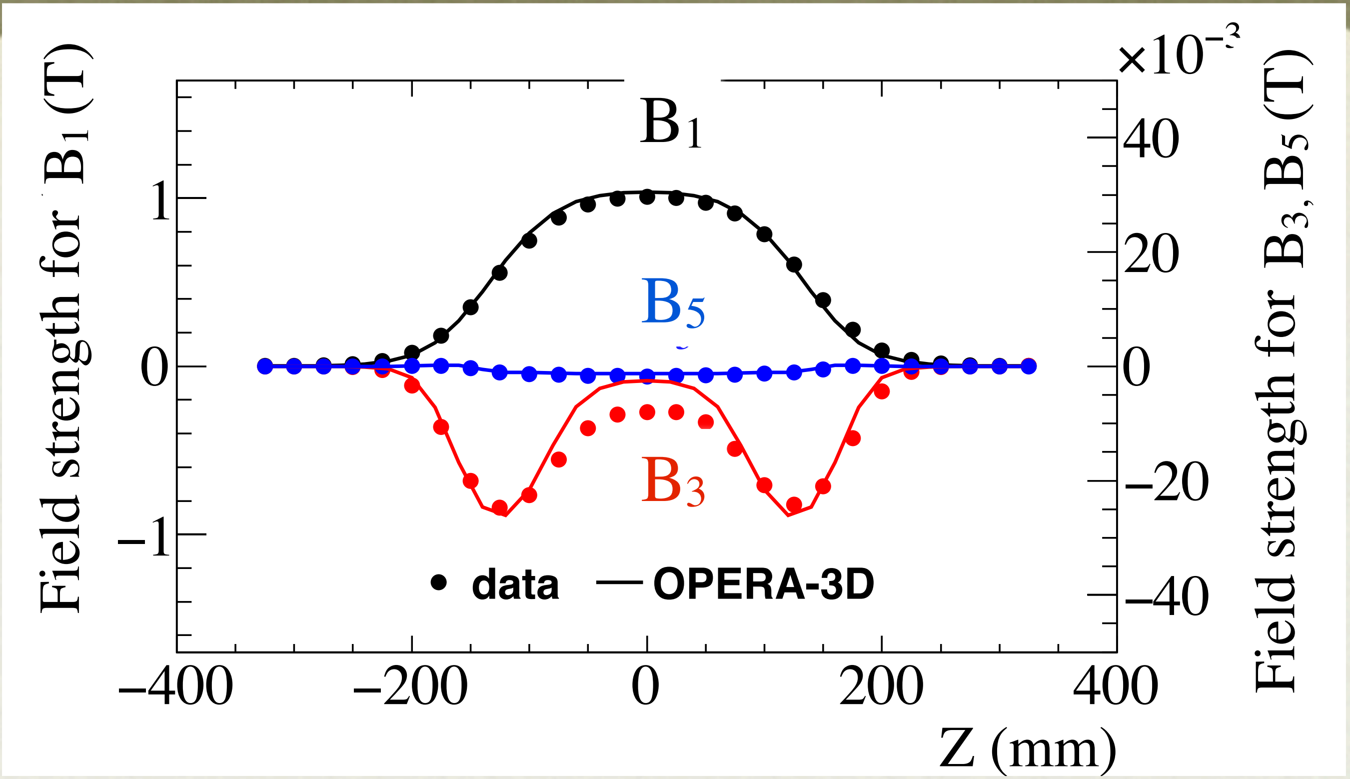


An extreme case causing large contribution from quadrupole



Further investigation needs to be made,
but this result provides useful information for the next design study

MODEL MAGNET LONGITUDINAL FIELD



- Harmonics (allowed multipoles) along the longitudinal direction
- Effective length
  - Data: **286.6** mm
  - Calculation: **274.4** mm
  - Agree within **2%** level
- Although large discrepancy is observed in b_3 around the magnet center (Z~0), overall profile is consistent with the calculation

PROSPECT

TEST AT KEK

- We plan to continue the ramp-up test at KEK
  - The magnet was delivered from the Toshiba Factory
  - Ready to start the operation

- Investigation of the flux-jump like events
- Investigation of the large non-uniformity
- Temporal evolution of the screening current
- etc...

SUMMARY

- Collaboration project for R&D of HTS-based gantry
- Model magnet was fabricated at Toshiba, and its performance was measured using the harmonic coil system
- Flux-jump like event, which could be a critical issue for application, was observed during the ramp-up test
- Non-uniformity was limited to 2%, the reason of which partially be explained by mis-alignment of the coils
- We plan to continue the measurement

SUPPLEMENT

KEK "HTS" ACTIVITY

- KEK has engaged in "HTS" R&D program supported by "Japan Agency for Medical Research and Development (AMED)"
- Brief introduction to AMED

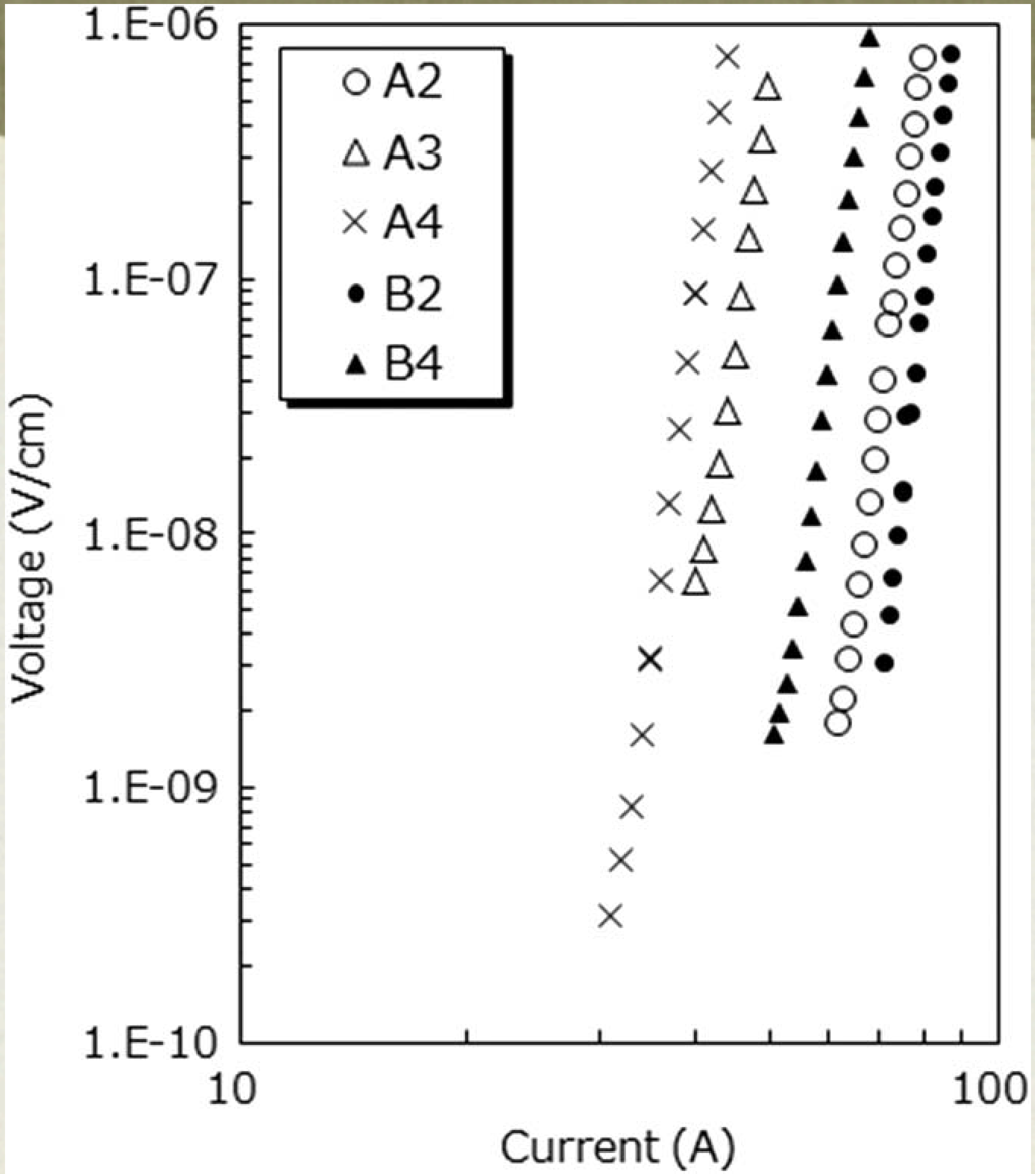
Japan Agency for Medical Research and Development aims to act as a 'control tower' that directs integrated research, from basic research to practical application. And since Japan is projected to become the world's first ultra-aging society, AMED aims to achieve the world's healthiest and longest-living people by creating the world's most advanced medical technologies and services, and also aims to become a pillar of Japan's economy by fostering medicine, drugs, and medical devices as strategic industries.

http://www.amed.go.jp/en/aboutus/gaiyou.html

MODEL MAGNET PARAMETERS

Main parameter of the model magnet	
Dipole field strength	3 T
Rated current	366 A
Bore radius	30 mm
Inner radius of iron yoke	95 mm
Outer radius of iron yoke	205 mm
Num. of HTS coils	24
Num. of turn for each coil	50
Magnet mechanical length	1200 mm
Coil mechanical length	340 mm
Coil inductance	288.9 mH
Sum of Lorentz force per quadrant	
Horizontal (ΣF_x)	349.4 kN/m
Vertical (ΣF_y)	-74.7 kN/m

I-V CHARACTERISTICS

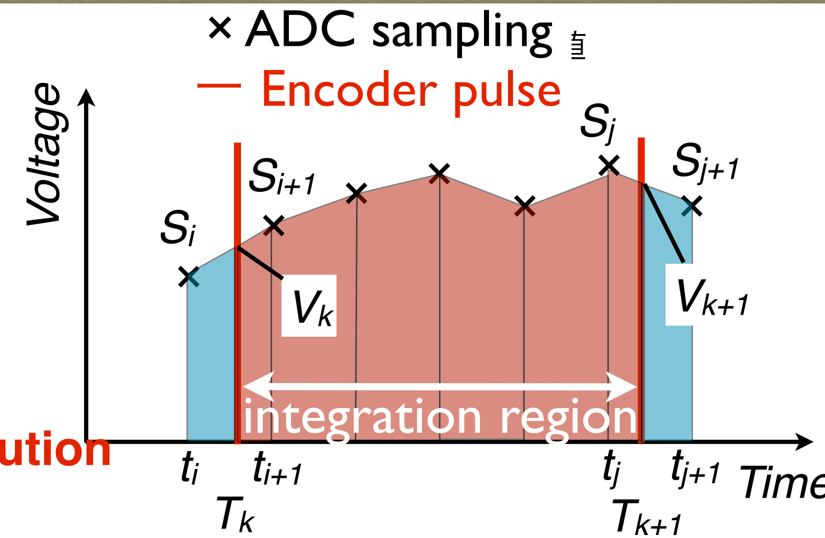


S. Takayama et. al.,
IEEE Trans. Appl. Supercond ***26****, 4402304 (2016)*

DIGITAL SIGNAL PROCESS

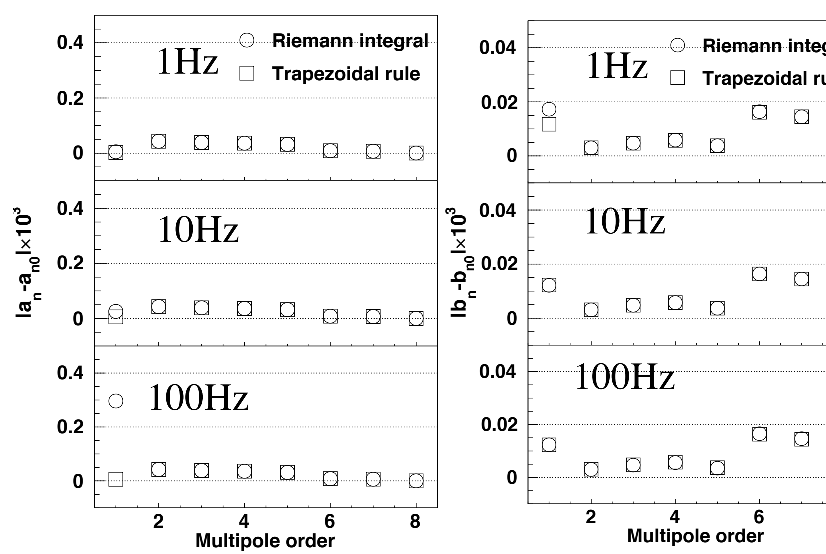
- Coil voltage is integrated during an interval between the arrival time of the encoder pulses (T_k, T_{k+1}) (see right picture)
- Two integration methods are possible
  - Riemann integral
  - Trapezoidal rule

→ Adopt "trapezoidal rule" for better resolution

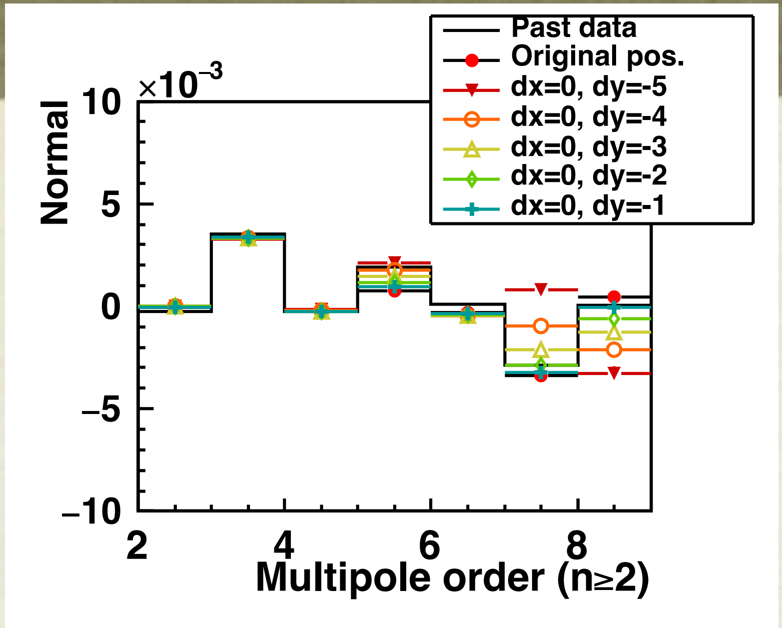


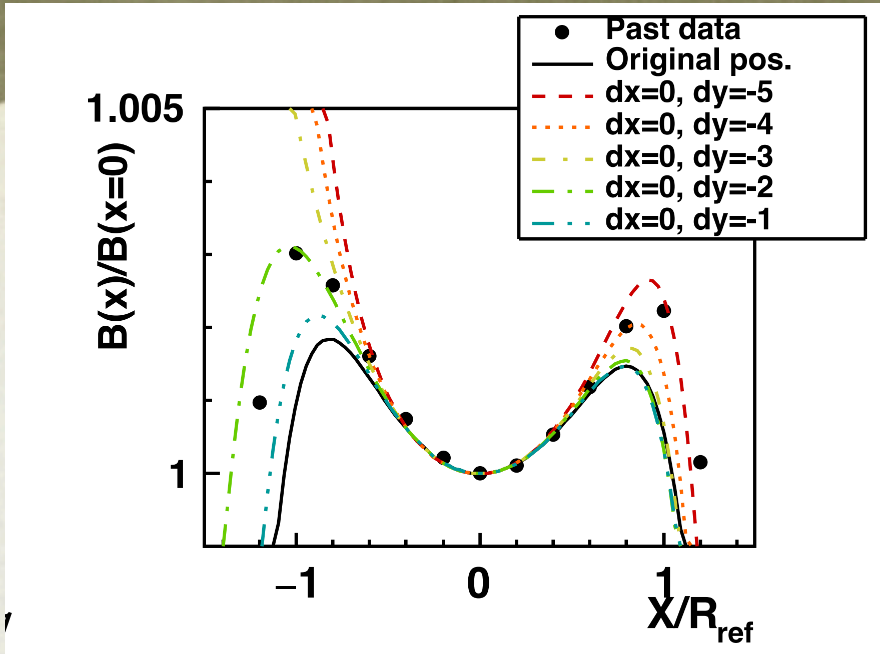
- Coil voltage at the arrival time of the encoder pulse (V_k) is determined from a linear interpolation between two neighboring voltages (S_i, S_{i+1})
  - $V_k = S_i + (S_{i+1} - S_i)/(t_{i+1} - t_i) \times (T_k - t_i)$
- According to simulation:
  - Confirmed a precision better than 0.1% is achievable for multipole measurement if DAQ device has:
    - >500kHz for ADC sampling rate
    - >16bit for ADC resolution
    - >40MHz clock Hz (for encoder pulse)

Simulation



EFFECT FROM "FEED DOWN"

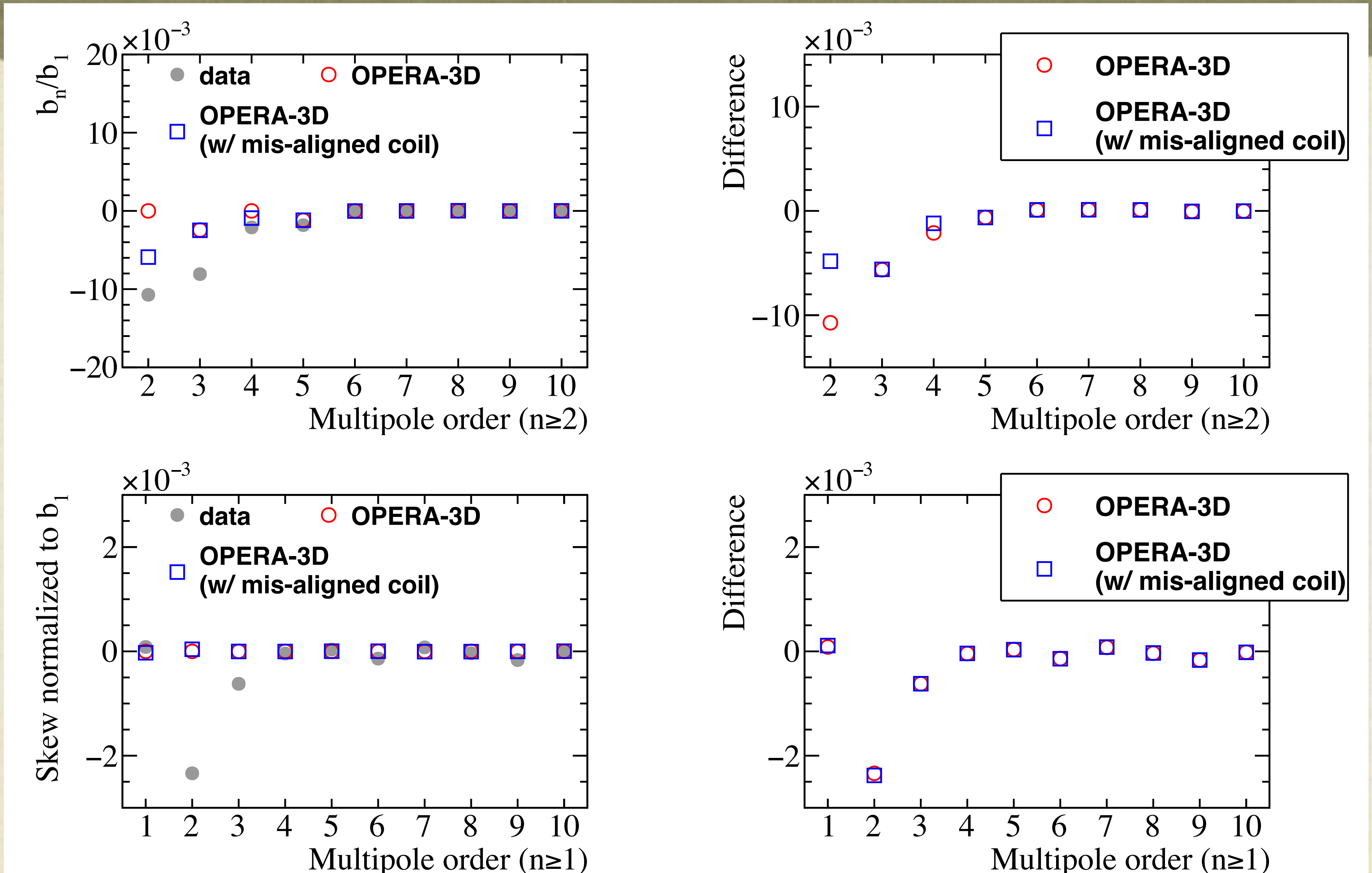




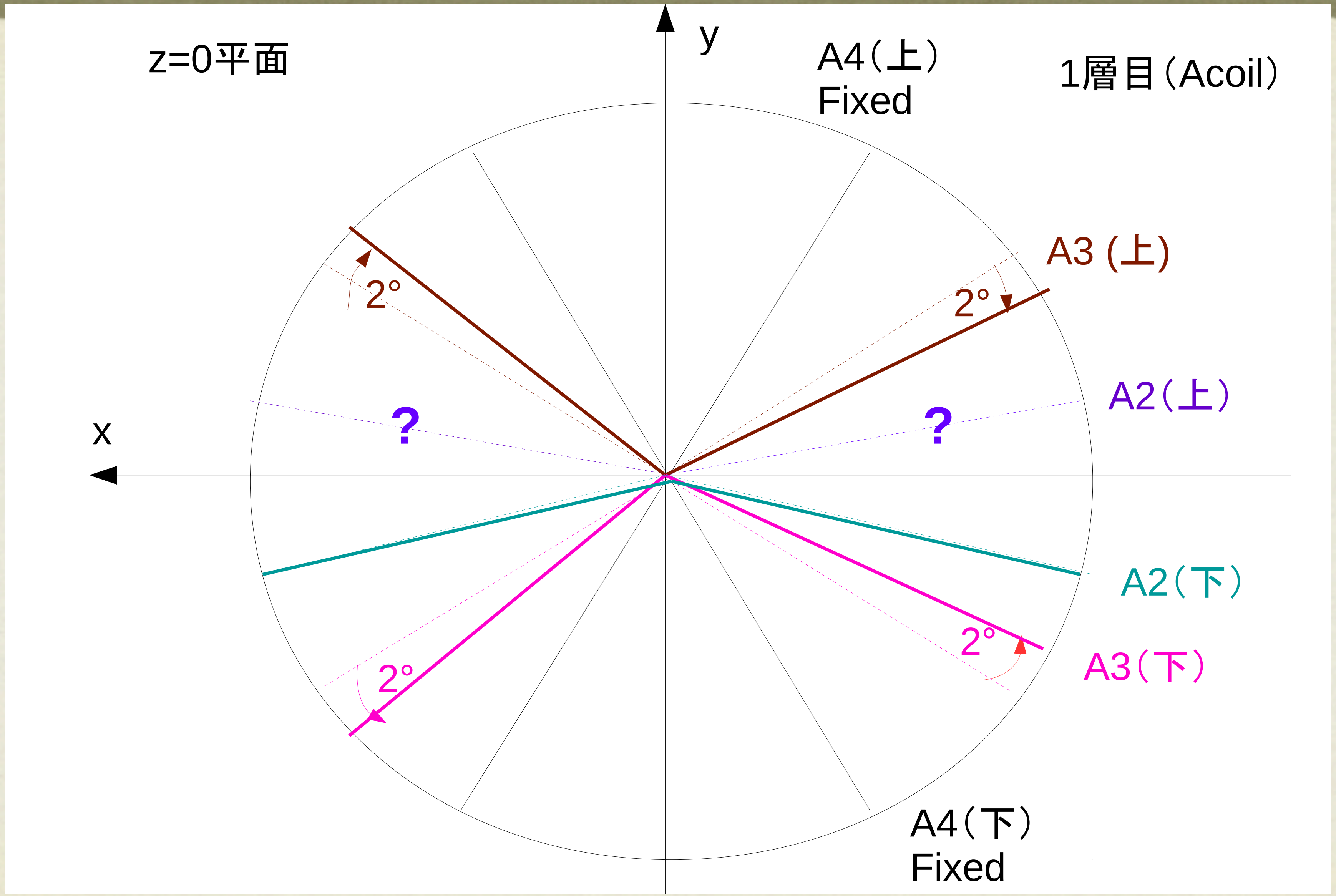
- Further investigated if the inconsistency in the x-mapping are due to 'mis-alignment' of the rotating coil
- Assume the coil was mis-alined by 0-5mm
  - Best agreement was found at (dx, dy)=(0mm, -2mm)
  - Inconsistency in x-mapping is considered to be due to mis-alignment

In summary,we ensured our measurement system has a measurement precision (<0.1%) for multipoles with a fast (7Hz) sampling rate

HARMONICS


×10⁻³
b_n/b_1
data
OPERA-3D
OPERA-3D
(w/ mis-aligned coil)
Multipole order (n≥2)
×10⁻³
Difference
OPERA-3D
OPERA-3D
(w/ mis-aligned coil)
Multipole order (n≥2)
×10⁻³
Skew normalized to b_1
data
OPERA-3D
OPERA-3D
(w/ mis-aligned coil)
Multipole order (n≥1)
×10⁻³
Difference
OPERA-3D
OPERA-3D
(w/ mis-aligned coil)
Multipole order (n≥1)

COIL MISALIGNMENT



PROSPECT

Understand E-J characteristics for ReBCO tape