TUE-PO1-113-04

Magnetic measurements of a full-scale prototype of the HL-LHC beam separation dipole

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27th International Conference on Magnet Technology (MT27)
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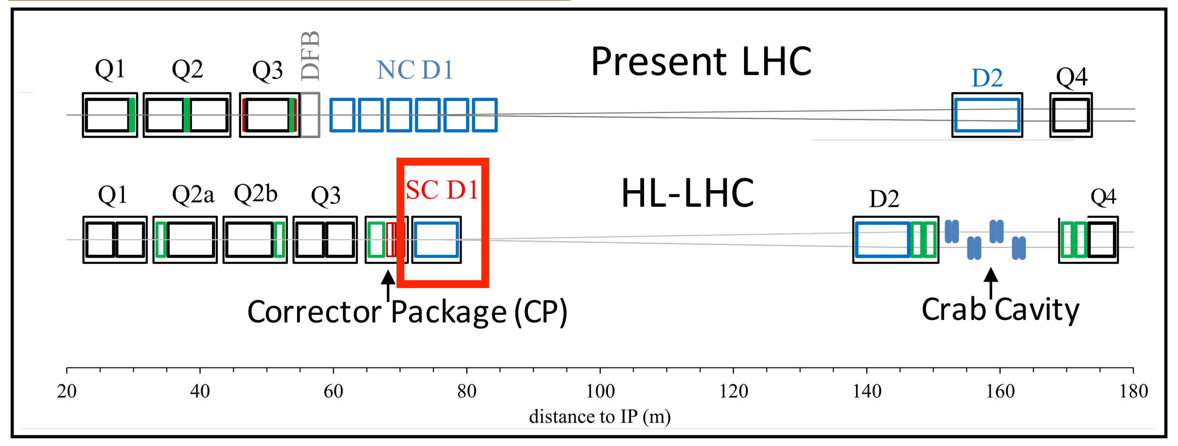
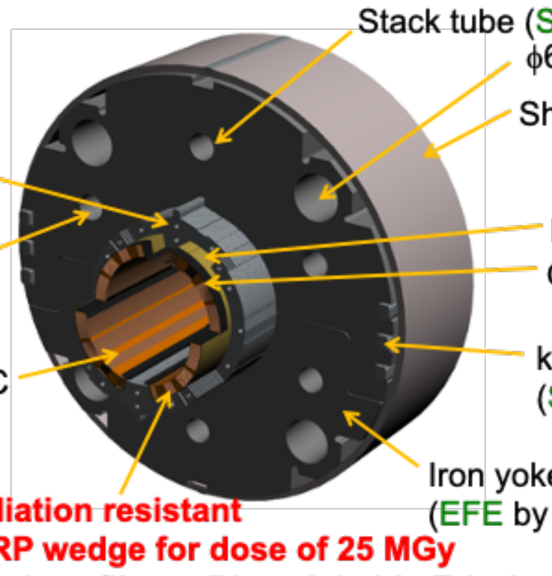
Abstract
High energy accelerator research organization, KEK, have engaged in development of the beam separation dipole toward the HL-LHC project. We have performed magnetic measurement for the first full-scale magnet (MBXFP) and validated our design methodology. We first review the design procedure for the prototype and then show data-calculation comparisons. Finally prospects for series magnet is described.

Introduction





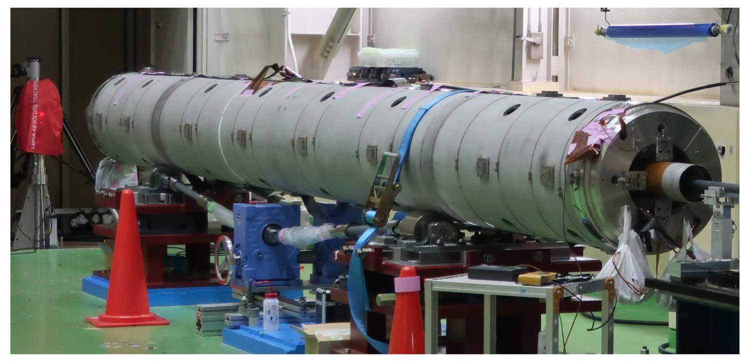
- The HL-LHC is planned to be constructed for further exploration of the physics beyond the Standard Model (BSM)
- The following targets can be achieved by reducing β^* :
  - Peak luminosity: 5x10^{-34} cm^{-2}s^{-1}
  - Total integrated luminosity: 3000 fb^{-1}
- **To reduce β^*:**
  - Aperture of inner triplets (Q1-Q3) : 70 mm → 150 mm,
  - Recover 10 m of the additional space for the triplet
  - New crab cavities will be installed between the recombination dipole (D2) and the two-in-one quadruple (Q4)

Design parameters of MBXF

Aperture (mm)	150
Find integral at 7 TeV (T·m)	35
Nominal field (T)	5.6
Magnetic length (m)	6.26
Stored energy (kJ/m)	340
Nominal current I_{nom} (kA)	12.11
Operation temperature (K)	1.9
| b_3 integral | (unit)	< 2.9
| b_5 integral | (unit)	< 1.5

Full-scale D1 magnet reception tests at KEK

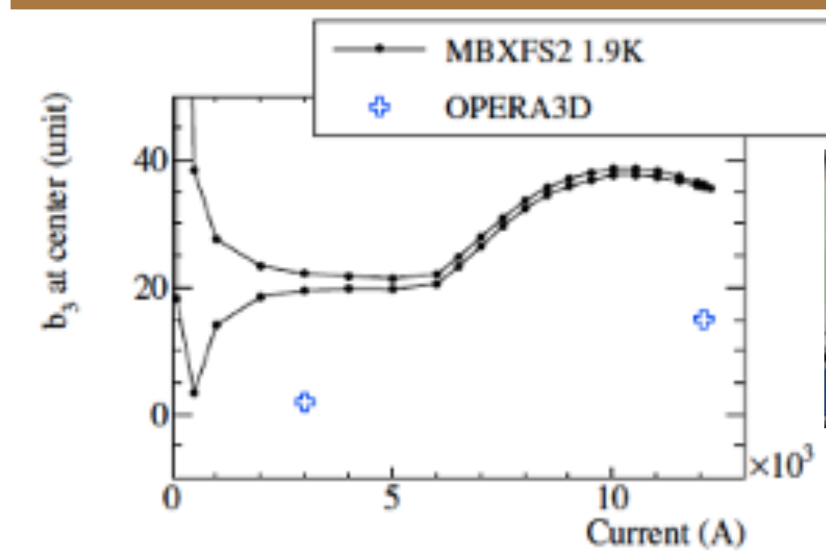
Yoked magnet with SS shell
1. Horizontal warm test
- magnetic measurement (MM)
2. Vertical cold test



Cold mass to be delivered to CERN
Horizontal warm test only

- Deliverables for HL-LHC
  - **1 full-scale prototype cold mass (MBXFP)**
  - 6 series cold masses (MBXF1-6)
- **MBXFP is being fabricated by Hitachi Ltd**
  - The first vertical cold test / horizontal warm test were performed in this summer 2021

b3 issue in short models



Summary of measured/calculated b_3 and pre-loads

Aperture (mm)	MBXFS1	MBXFS2	MBXFS3
Measured b_3 at magnetic center for I=3 kA (unit)	6.23	20.89	24.05
Calculated b_3 (unit)	0.83	2.12	1.88
Measured pre-load (MPa)	65	111	114

- The first model (**MBXFS1**)
  - Unsatisfied training performance due to lack of pre-load (65 MPa)
- The second model (**MBXFS2**)
  - Pre-load was increased to ~115 MPa and the magnetic design was updated accordingly
  - **Good training performance**
  - **Large offset of b_3 (~20 units) was observed**
- The third model (**MBXFS3**)
  - **Reproduced model** of the 2nd one
  - **Similar offset b_3 was confirmed event at lower current (3 kA)**
    - **Ensured that this comes from geometrical reason**
- **Reason** :
  - Misunderstandings of the size of compression in the cable insulation thickness
  - **Actual coil cross section differs from designed one**

MBXFP magnetic design

Procedure

Detail : *IEEE TAS* vol. 30, no. 4, pp. 1-6, June 2020, Art no. 4002706,

- Goal
  - Target pre-load = 115 MPa
  - Target b_3 integral at I_{nom} = 0 unit
- Sensitivity study
  - Optimization is performed in the 2D computation (Roxie) at lower current
    - I) Determine the target b3 in Roxie2D (=b_3^{2D}) so that the b_3 integral at I_{nom} (= $\overline{b_3}^{12kA}$) becomes zero
    - II) Model the coil geometry (cross section, coil end) and perform the 3D computation (Opera3D) for crosschecking its field quality and integrals
    - III) Go back to I) and iterate this procedure if necessary so that $\overline{b_3}^{12kA}$ converges into 0

OPERA3D prediction — Return end — SS — Lead end

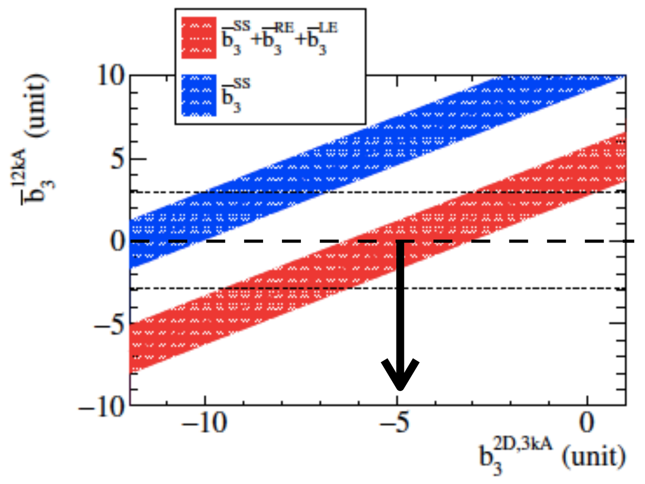
$$\bar{b}_3 = \frac{\int_{z=-4000}^{z=-2810} B_3(z)dz}{\int_{z=-4000}^{z=4000} B_1(z)dz}\times 10^4 + \frac{\int_{z=-2810}^{z=2810} B_3(z)dz}{\int_{z=-4000}^{z=4000} B_1(z)dz}\times 10^4 + \frac{\int_{z=2810}^{z=4000} B_3(z)dz}{\int_{z=-4000}^{z=4000} B_1(z)dz}\times 10^4$$

$$\int_{SS} B_3(z)dz \times 10^4 = B_{\rm ref}\int_{SS} b_3(z)dz$$
$$\simeq B_{\rm ref}\int_{SS} b_3(z=0)dz + \Delta\bar{b}_3^{\rm shape}$$
$$= B_{\rm ref}\cdot\left(b_3^{2D} + \Delta b_3^{\rm geom} + \Delta b_3^{3D} + \Delta b_3^{12kA}\right)\cdot\int_{SS} dz + \Delta\bar{b}_3^{\rm shape}$$

Input from ROXIE2D; Geometrical correction: 5.01 unit; Transition from 2D to 3D: 0 unit; Correction at 12 kA: 2.02 unit; 3D shape: 4.10 unit

3.51 unit + (b_3 difference between MBXFS2 and 3)

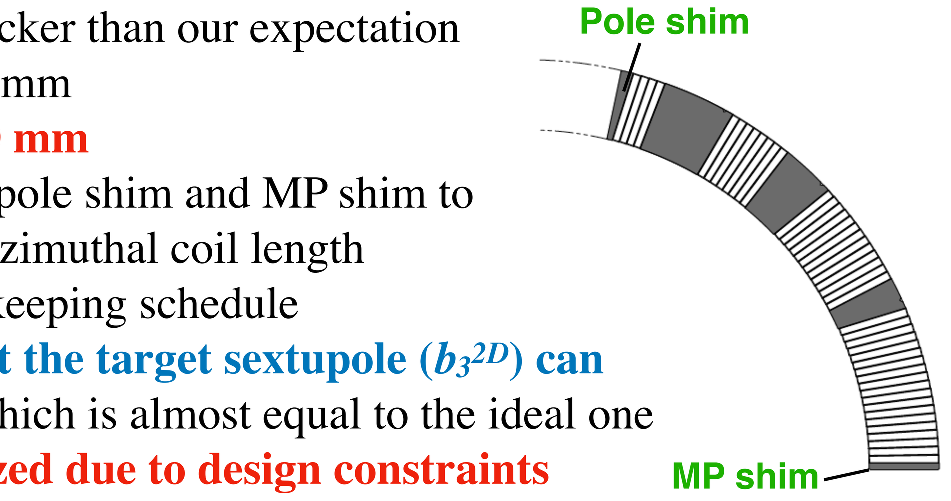
Confirmed by comparison of 2D and 3D



Given the formula above b_3^{2D} is set to **-5 unit** and a new cross section was proposed for prototype

Design adapted for prototype

- During fabrication thickness of cable insulation, used in MBXFP, was found to be thicker than our expectation
  - designed thickness : 0.155 mm
  - measured thickness : **0.160 mm**
- **Action:** reduce thickness of pole shim and MP shim to compensate increase of the azimuthal coil length
  - Minimal modification for keeping schedule
- Not perfect optimization, **but the target sextupole (b_3^{2D}) can be tuned around -5 units** which is almost equal to the ideal one
  - **b_5 cannot be fully optimized due to design constraints**



Two dimensional field quality (b_3^{2D} in Roxie2D)

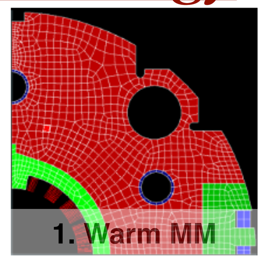
	Ideal mode	Adapted
b_3	-5.00	**-5.16**
b_5	-3.00	**1.25**
b_7	0.18	**0.97**
b_9	-0.10	**0.48**
b_{11}	-0.06	**0.06**

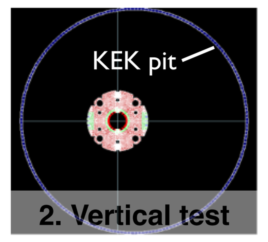
Cable layout for MBXFP

Block	MBXFP Φ	MBXFP α
1	1.1600	0.0000
2	28.0040	27.4005
3	50.6138	52.3400
4	71.0417	68.9141

Magnetic measurement of MBXFP

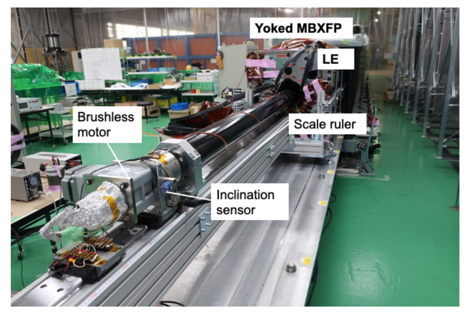
Strategy

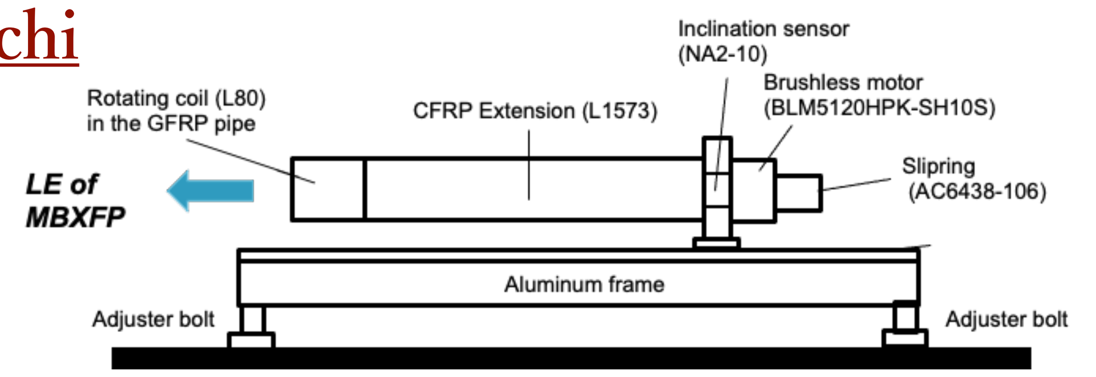




1. Warn MM during magnet assembly
   - → Warm MM at the Hitachi premise (after yoking)
   - → First validation of our methodology (b3 reduction)
   - → Feedback to design of series magnet (MBXF1-6)
2. MM during vertical cold test
   - → Cold MM at the KEK pit to check field quality (FQ) at nominal operating condition
   - → Reproducibility check of results from 1 (MM at Hitachi)
3. MM during horizontal warm test
   - → Measurement of the XY-magnetic center
   - → Measurement of the absolute field angle
   - → Analyses are ongoing

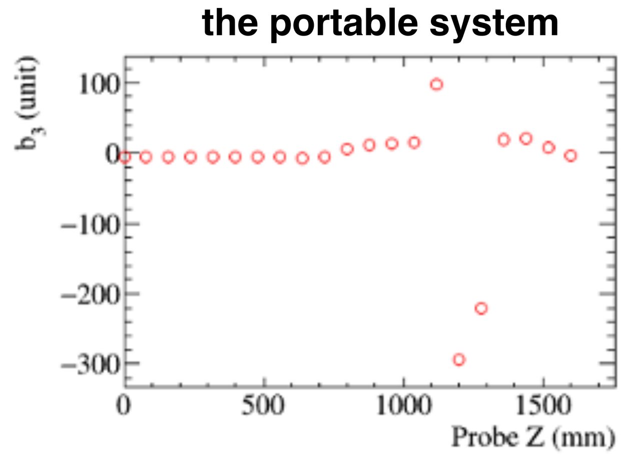
1. Warm MM at Hitachi





- Development of the portable MM system (rotating coil) to be easily delivered to the Hitachi premise
- The 1.6-m shaft can cover a straight section of the 7m magnet and verify field quality (FQ) of the new magnetic design (i.e. coil cross section)
- Result of FQ at the straight section
  - **Large b_3 offset disappears (20 units -> -4.9 units)**
    - ✓Expectation : -2.3 unit at warm
    - **✓Measured b_3 is 2.6 units lower than expectation**
    - ✓This is because lack of understandings for mechanism of cable compression (insulation)
  - **Fine tunings will be applied to the first series magnet**

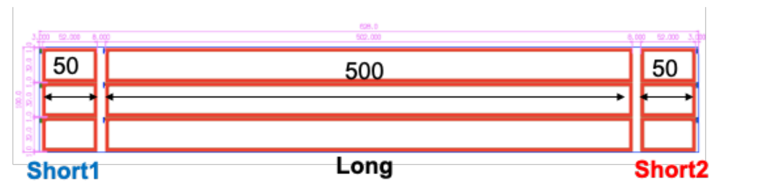
b_3 profile measured by the portable system

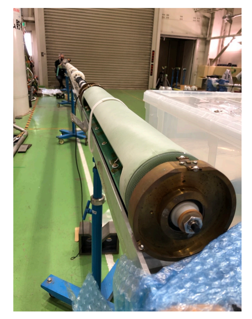


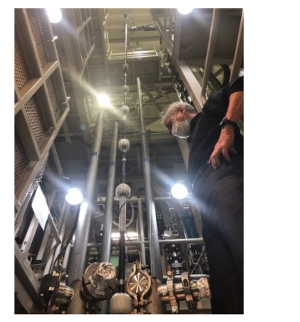
2. Cold MM at KEK pit

Overview of MM system : *IEEE TAS*, vol. 27, no. 4, pp. 1-5, June 2017, Art no. 0600705,

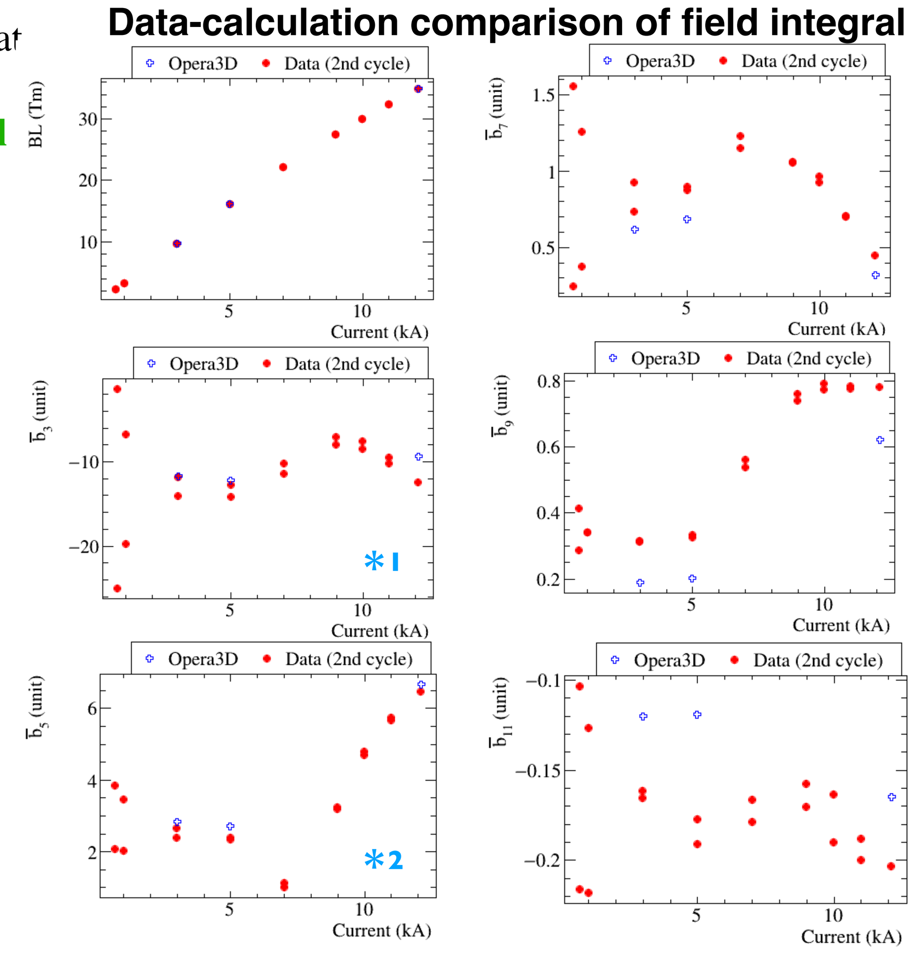
- Magnet inserted into the 9-m deep vertical cryostat
- Rotating coil upgrade :
  - **New Printed Circuit Board for harmonic coil**
    - ✓Long (500) x 1 + short (50) x 2
  - **10 m long shaft to fully cover the magnet**
- Modified computation model
  - **Developed after the Hitachi MM**
  - Shows an excellent agreement with the data !!
  - Possible for precise prediction of FQ for series





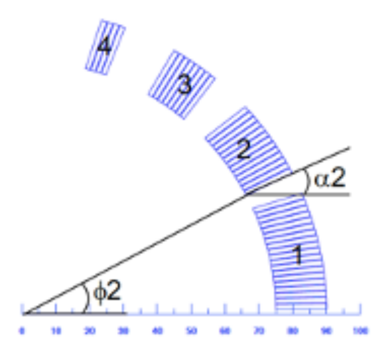


Data-calculation comparison of field integral



(*1,2) In Opera3D geometrical/saturation corrections are applied to FQ in the straight section:
- $\Delta b_3 = \Delta b_3^{geom} + \Delta b_3^{12kA}$ =4.13 + 2.02 units ,
- Δb_5 = 1.02 units (geom. correction only)

Conclusion and Prospects



Cable layout for series (MBXF)

Block	MBXF Φ	MBXF α
1	1.1680	0.0000
2	27.8471	27.5527
3	50.3830	52.5639
4	70.7157	70.3048

- Succeed in substantial reduction of b_3 but find tunings are necessary for series
- Horizontal warm test was done and analyses are ongoing
- The new magnetic design have been studied after the Hitachi MM and validated through 3D computation
- With the new model one can expect :
  - b_3 integral : -1.5 units
  - b_5 integral : 1.4 units

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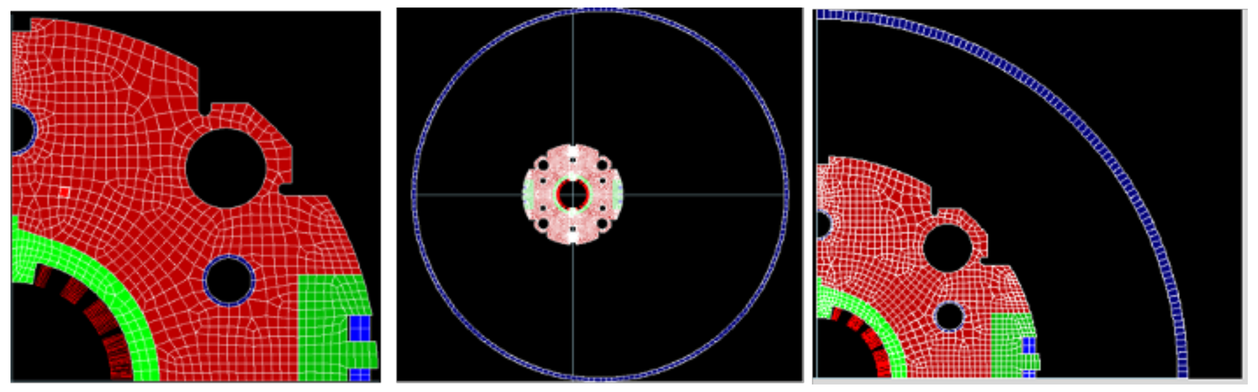
Summary of KEK MM system

	Vertical stand		Horizontal stand	Portable system
	-2020 (MBXFS1-3)	2021- (MBXFP-)		
Site	KEK	KEK	KEK	Hitachi
Temp. Condition	Warm / Cold	Warm / Cold	Warm	Warm
Coil (Length)	Long (350) Short (80)	Long(500) Short x 2 (50)	Long (500) Short x 2 (50)	Short (80)
Integrator	Metrolab PDI5025	Metrolab PDI5025	NI PXIe multimeter sys. / FDI2056	NI PXIe Multimeter system
Z scan	Automation (Stepping motor & Magnescale)	Automation (Stepping motor & Magnescale)	Automation (Stepping motor & Magnescale)	Manual / limited range (1000mm of SS)

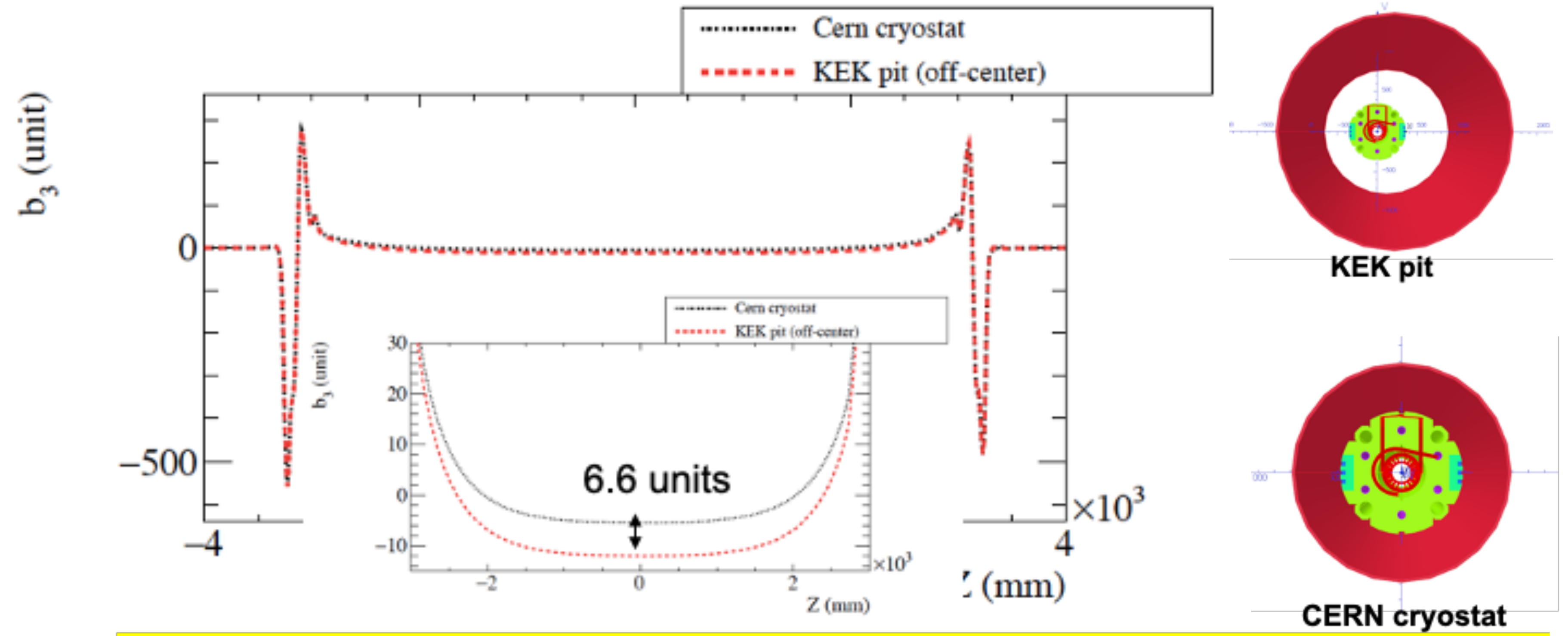
Simulation models

Two dimensional cross section



w/o Cryostat	KEK pit	CERN cryostat
Horizontal warm test	Vertical cold test - Off-centered by 150mm	Used for design - Centered*

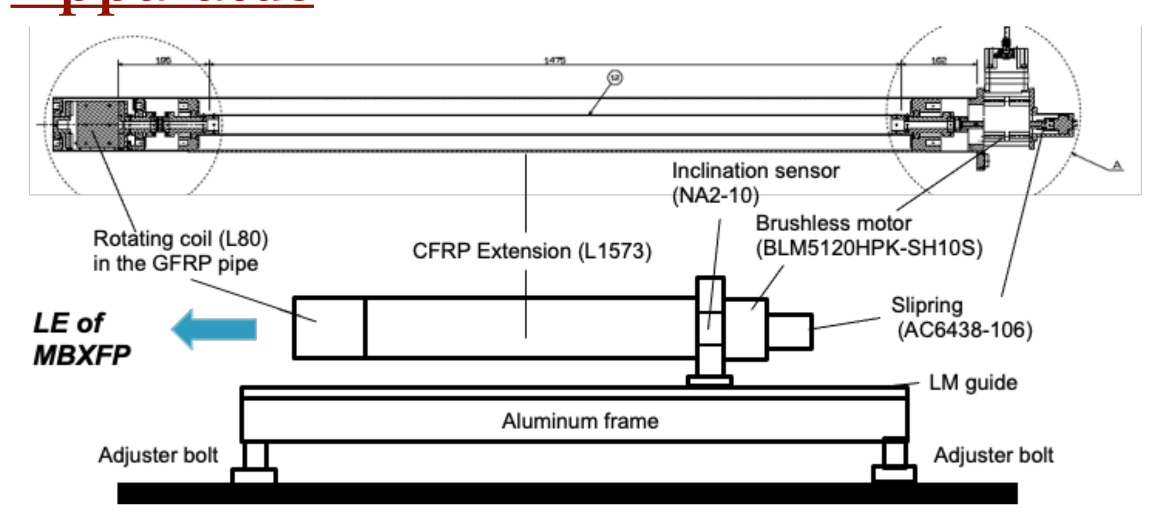
Geometrical effect (KEK pit vs. CERN cryostat)

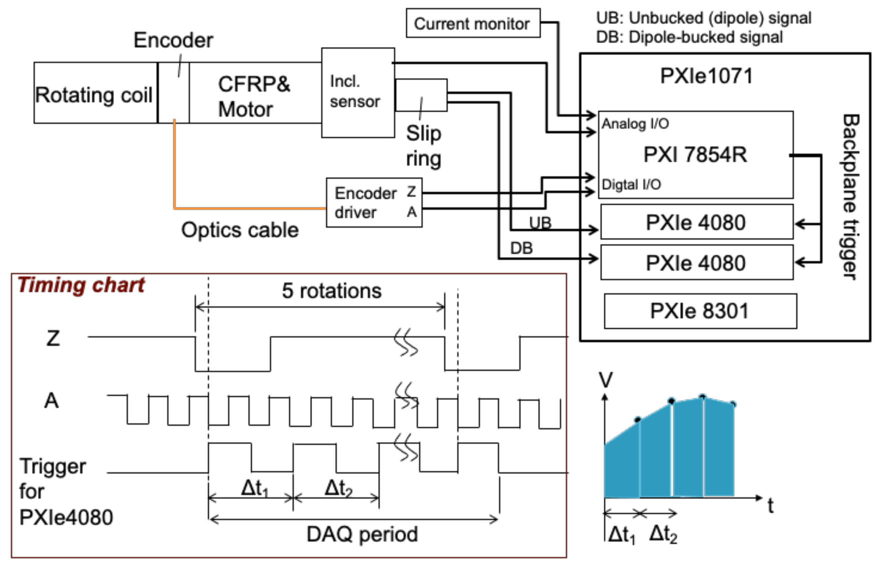


NOTE: **6.6 units** difference in b_3 between two models even x-section is same

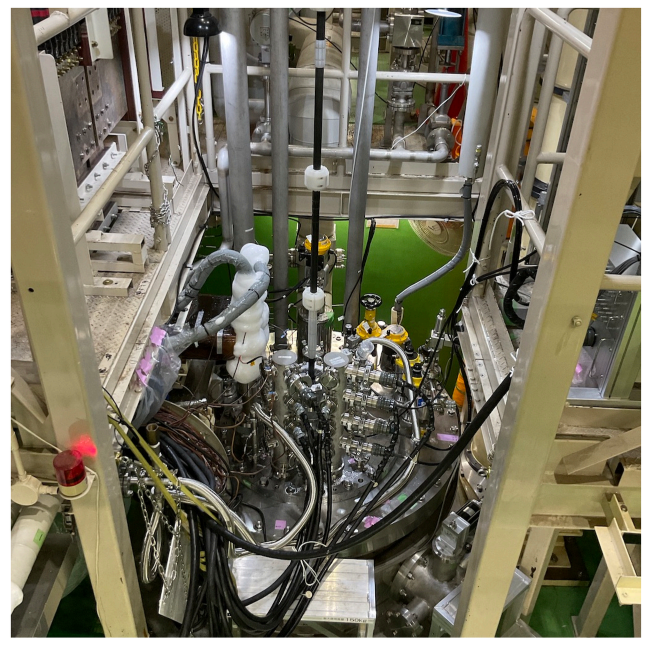
Warm MM at the Hitachi premise

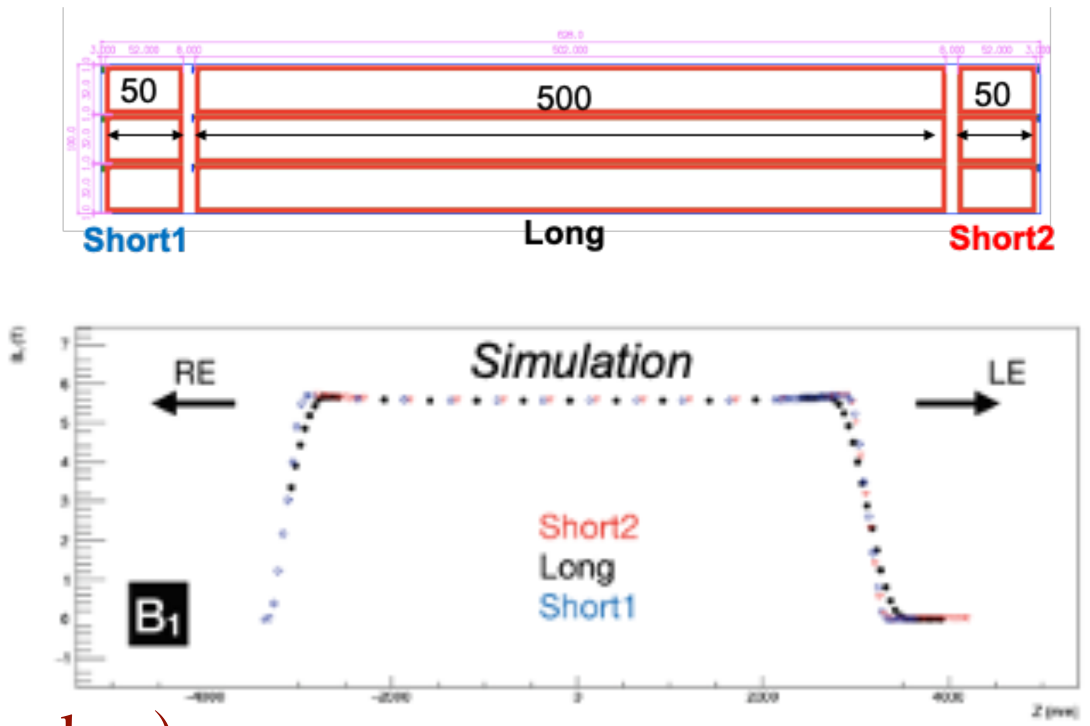
Apparatus





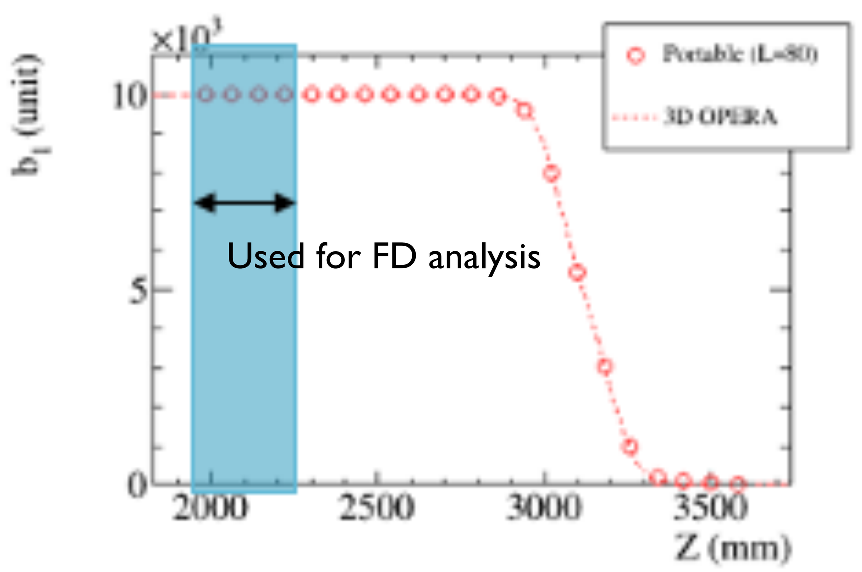
Vertical MM at the KEK cryostat



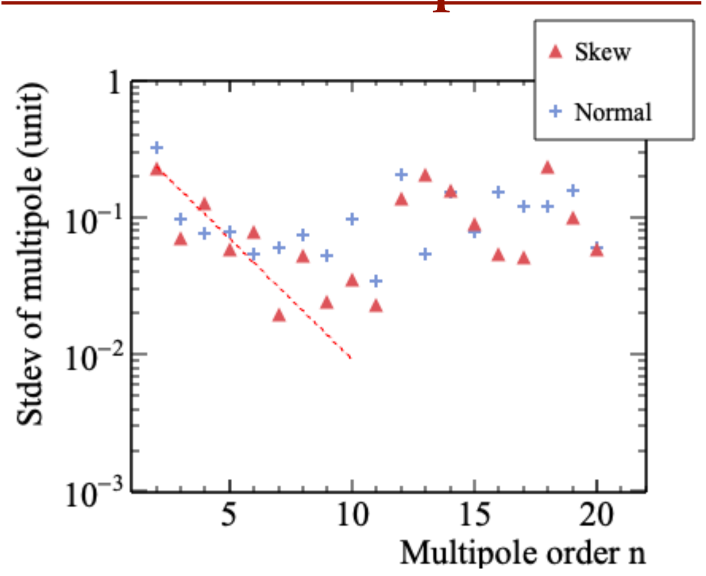


- PCB
  - One long coil sandwiched by 2 short ones
  - Long coil is for integral measurement
  - Short coils are for profile measurement
- Data coverage
  - 10m-long shaft to entirely cover the magnet

Data coverage



Measurement precision



Feeddown (FD) analysis

- Two algorithms
  1. Minimize c_{14} by c_{15}
     - ✓ c_n = sqrt($b_n^2 + a_n^2$)
     - ✓ b_{15} has an intrinsic offset (~ -1unit) which can be used to minimize b_{14}
  2. Minimize multi c_{2n} simulatenously
     - ✓ Find a pair of (dx,dy) which maximize a probability :

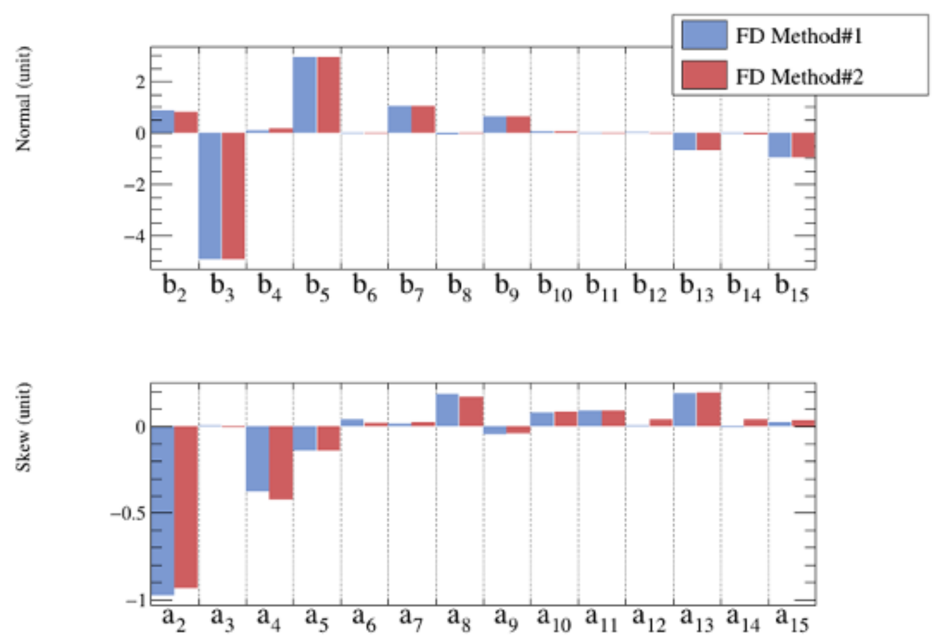
$$P = \prod_i \exp\left[-w_i \frac{\{c_i(dx,dy) - c_i^t\}^2}{\sigma_{c_i}^2}\right]$$

     - ✓ i.e. minimize a log likelihood :

$$-\ln P = \sum_i \left[w_i \frac{\{c_i(dx,dy) - c_i^t\}^2}{\sigma_{c_i}^2}\right]$$

W_i: weight
c_i^t = true c_i (ideally 0 for i=2n)
σ_{ci} = Standard error of c_i (50 sample)

Minimization is performed only for higher order (n>=3) : $w_i = \begin{cases} 1 \text{ (for i=2n, n>=3)} \\ 0 \text{ (for others)} \end{cases}$

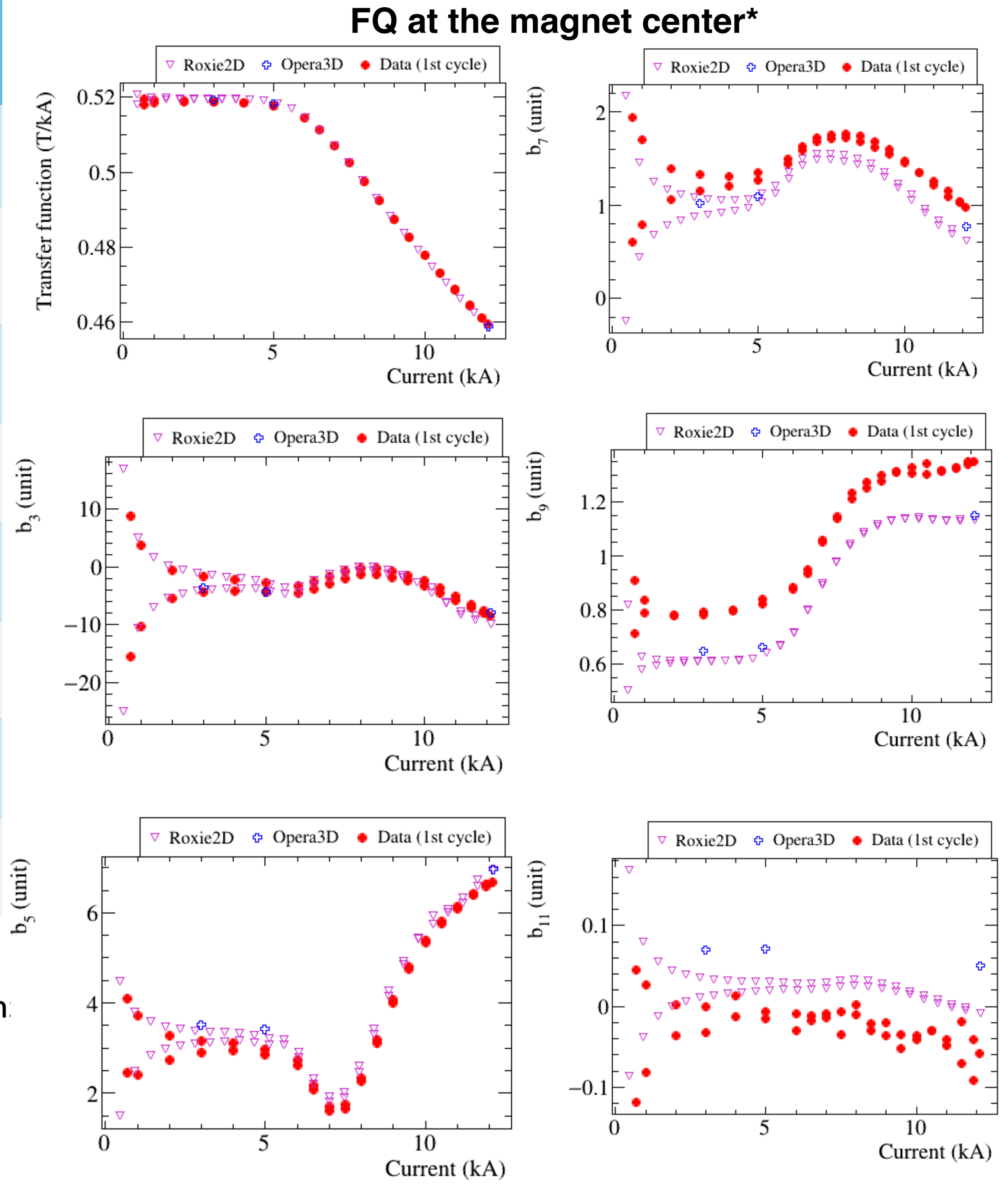


FQ summary (feeddown is not applied to data)

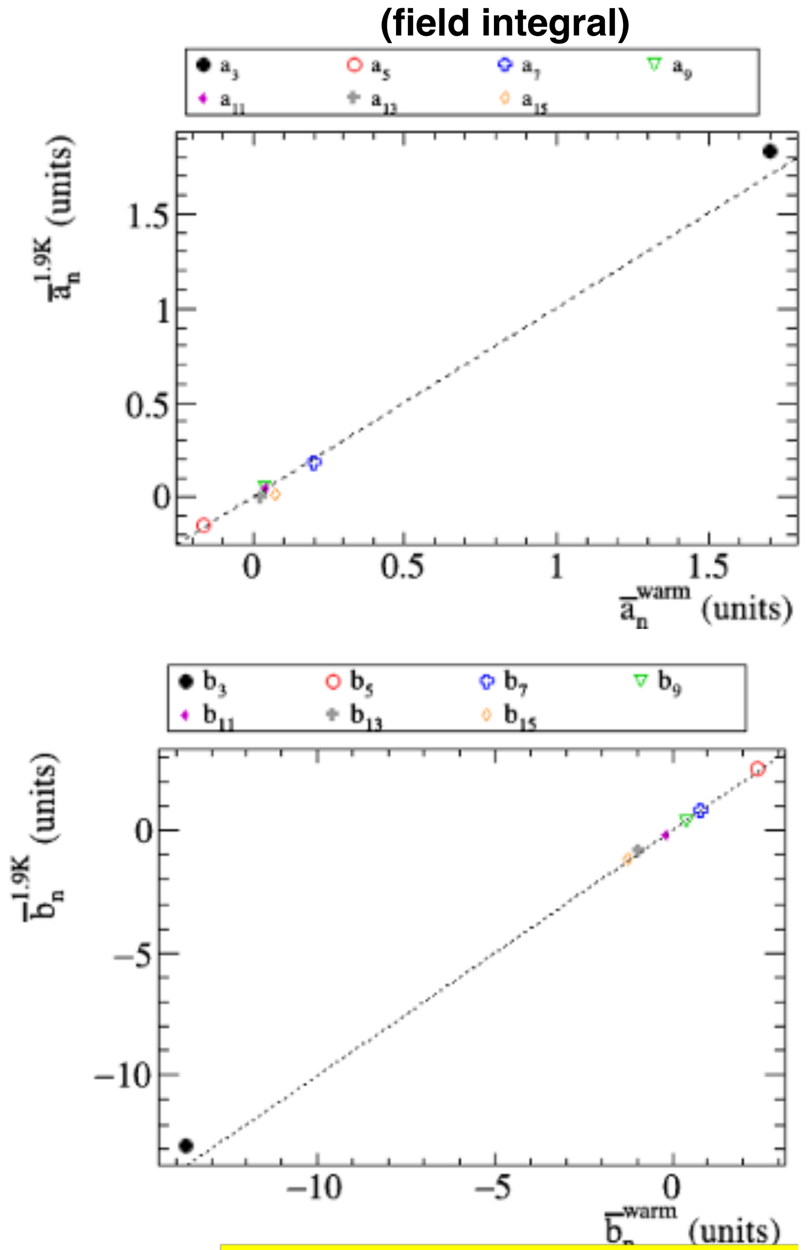
	Magnetic center (Z=-250 to +250 mm)		Integral	
	Opera3D calc.*	Data	Opera3D calc.*	Data
b_3 (units)	-7.97	-8.51	-9.36	-12.66
b_5	6.96	6.68	6.67	6.45
b_7	0.77	0.98	0.32	0.50
b_9	1.15	1.35	0.62	0.75
b_{11}	0.05	-0.06	-0.17	-0.24
b_{13}	-0.74	-1.03	-0.80	-0.96
b_{15}	-1.34	-1.52	-1.31	-1.38

(*)Modified model developed after the Hitachi MM (v11.2.0)
Geometrical + saturation corrections applied to the straight section
- Δb_3 = 4.13 + 2.02 units (Δb_3^{geom}+Δb_3^{12kA})
- Δb_5 = 1.02 units (Δb_5^{geom} : oval correction)
- No correction applied to higher order (n≥7)

Data-calculation comparison of FQ at the magnet center*



Cold** vs warm correlation (field integral)



Good correlation observed !!

(**) Average of up/down at 3kA