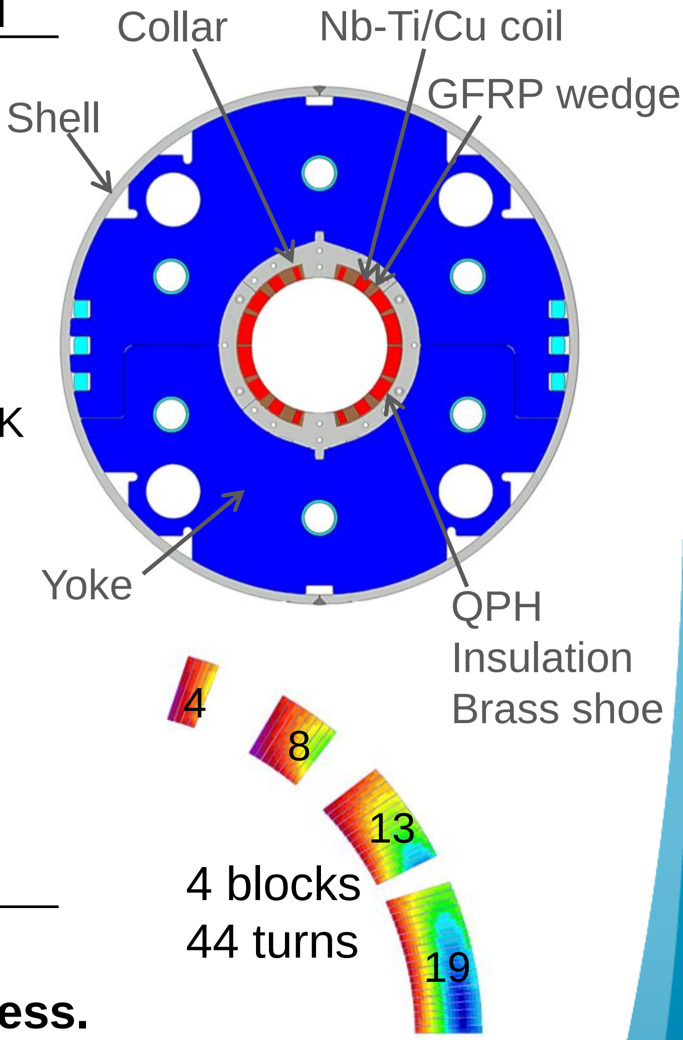
Results from the 1st cycle test of MBXFS2
- Quench Training & Field measurement -

Kento Suzuki

WP3 meeting -2018.11.20-

Design parameters of MBXFS2

	A series production	2 m model
Coil aperture	**150 mm**	
Field integral	**35 T m**	9.5 T m
Nominal field	5.57 T	
Peak field	6.45 T (SS), 6.58 T (coil end)	
Operating current	12.047 kA	
Operating temperature	1.9 K	
Field quality	O(10^{-4})w.r.t B_1 (R_{ref}=50 mm)	
Load line ratio	75.6%（SS）, 76.7%(coil end）at 1.9 K	
Differential inductance	4.0 mH/m	
Conductor	Nb-Ti: LHC-MB outer cable	
Stored energy	340 kJ/m	
Magnetic length	6.26 m	1.67 m
Coil mech. length	6.58 m	2.00 m
Magnet mech. length	6.73 m	2.15 m
Heat load	**135 W (Magnet total)** **2 mW/cm³ (Coil peak)**	
Radiation dose	**> 25 MGy**	



Technical challenges

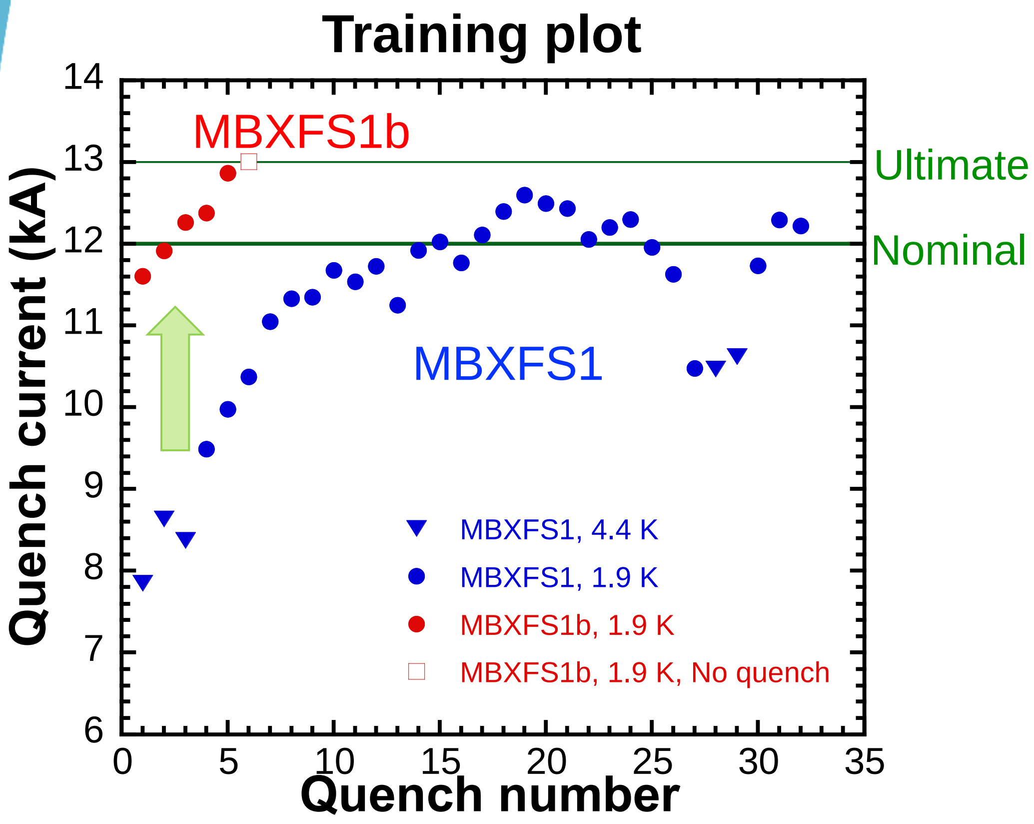
- **Large aperture**: **Management of coil size and pre-stress.**
- **Radiation resistance**: **Radiation resistant material for coil parts. Cooling capability.**
- **Iron saturation**: **Good field quality from injection to nominal current**

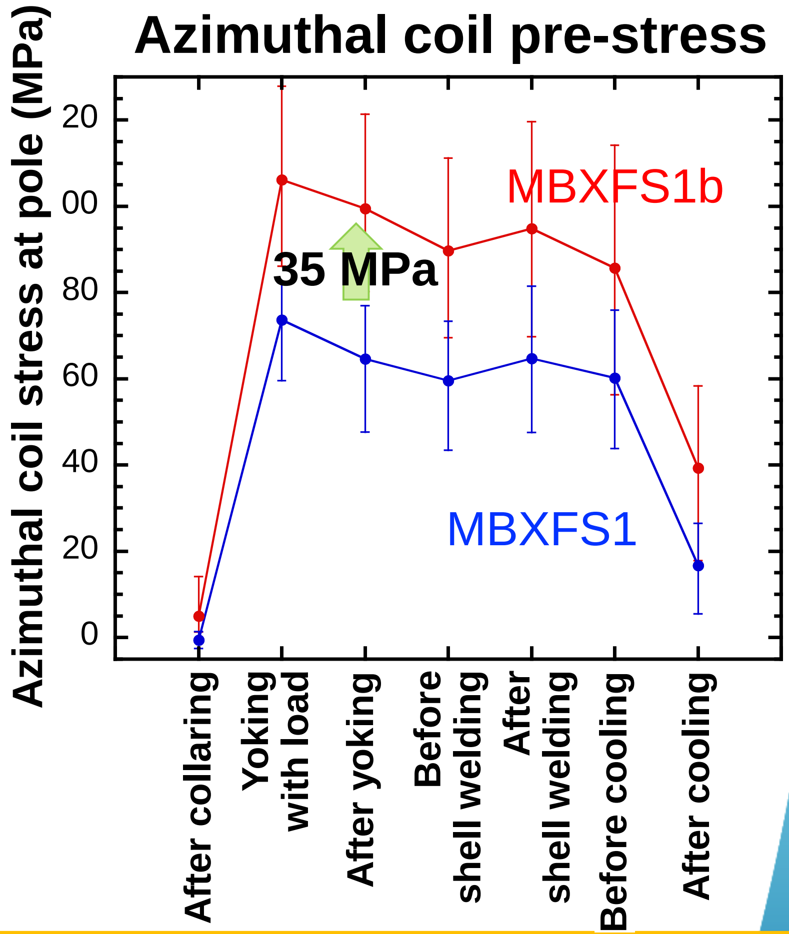
Training performance of MBXFS1/1b

Previous work

MBXFS1: First model magnet

MBXFS1b: Re-assembled first model magnet
with enhanced coil pre-stress





- Pre-stress control is a key factor for good training performance in D1 magnet.

Test Schedule

- **1st cycle: 2018.10.14 – 10. 26**
  - **10.14 : Z-scan at warm temperature, I=5 A**
  - **10.15-18 : Cool down to 1.9K,**
  - **10.18 : Z-scan before training, I=3 kA**
  - **10.18-22 : Training quench**
  - **10.22-26 : Field measurements**

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- 2nd cycle: 2018.12.10 – 12. 20
  - Training memory
  - New QPH performance
  - Reproducibility check of the 1st field measurement test

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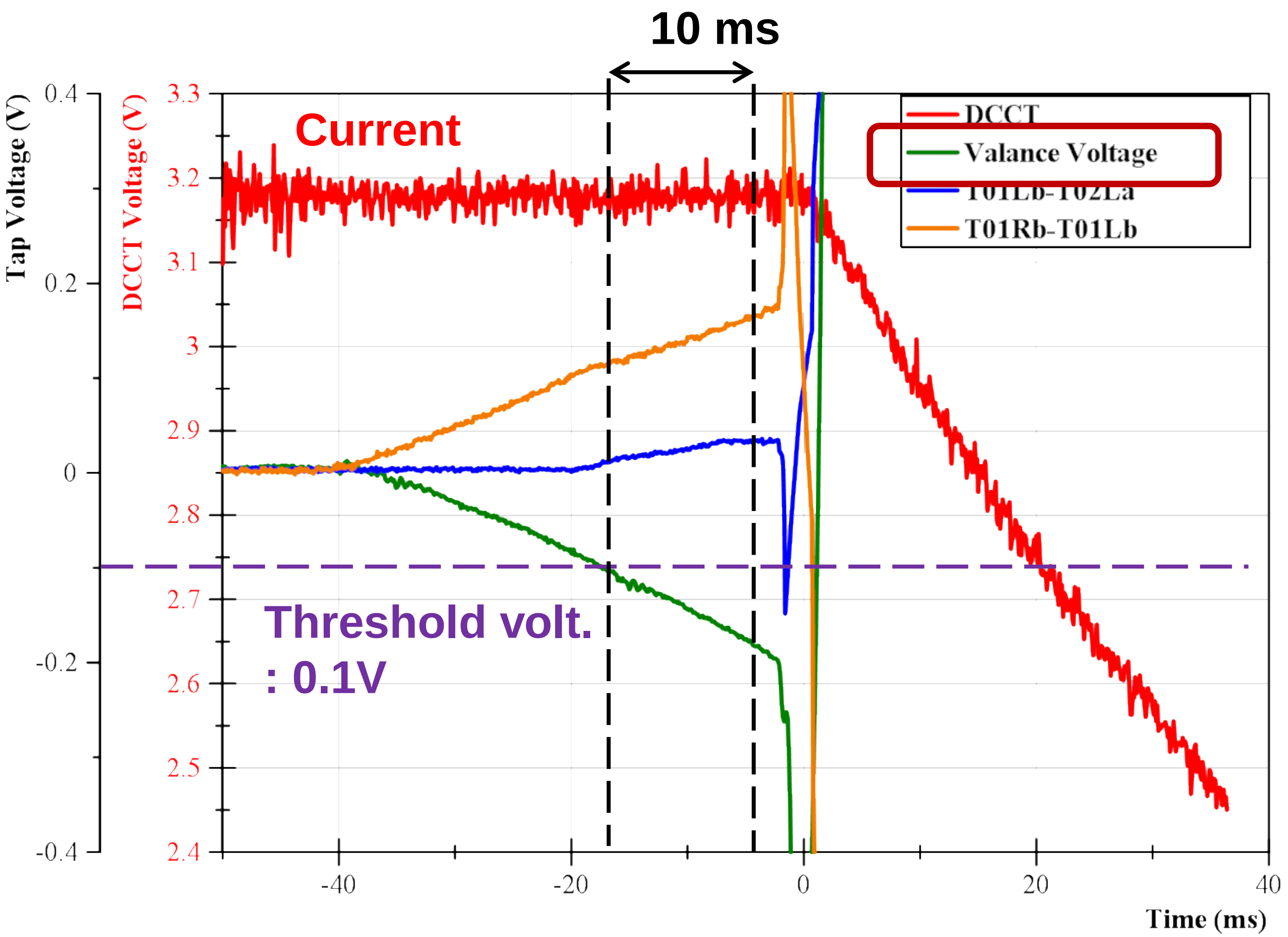
Training performance

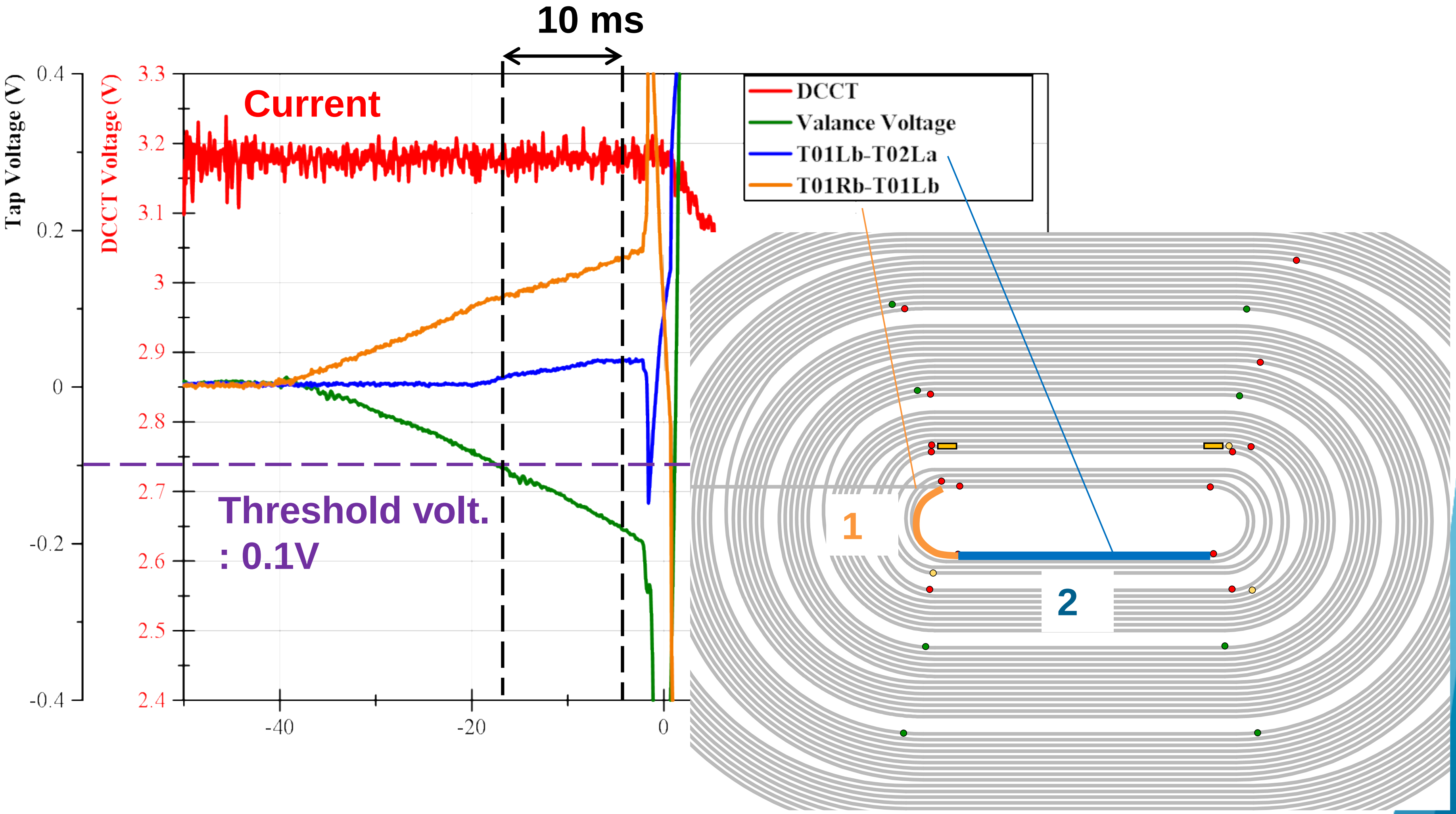
First quench signal (I=9.5 kA)


10 ms

Current

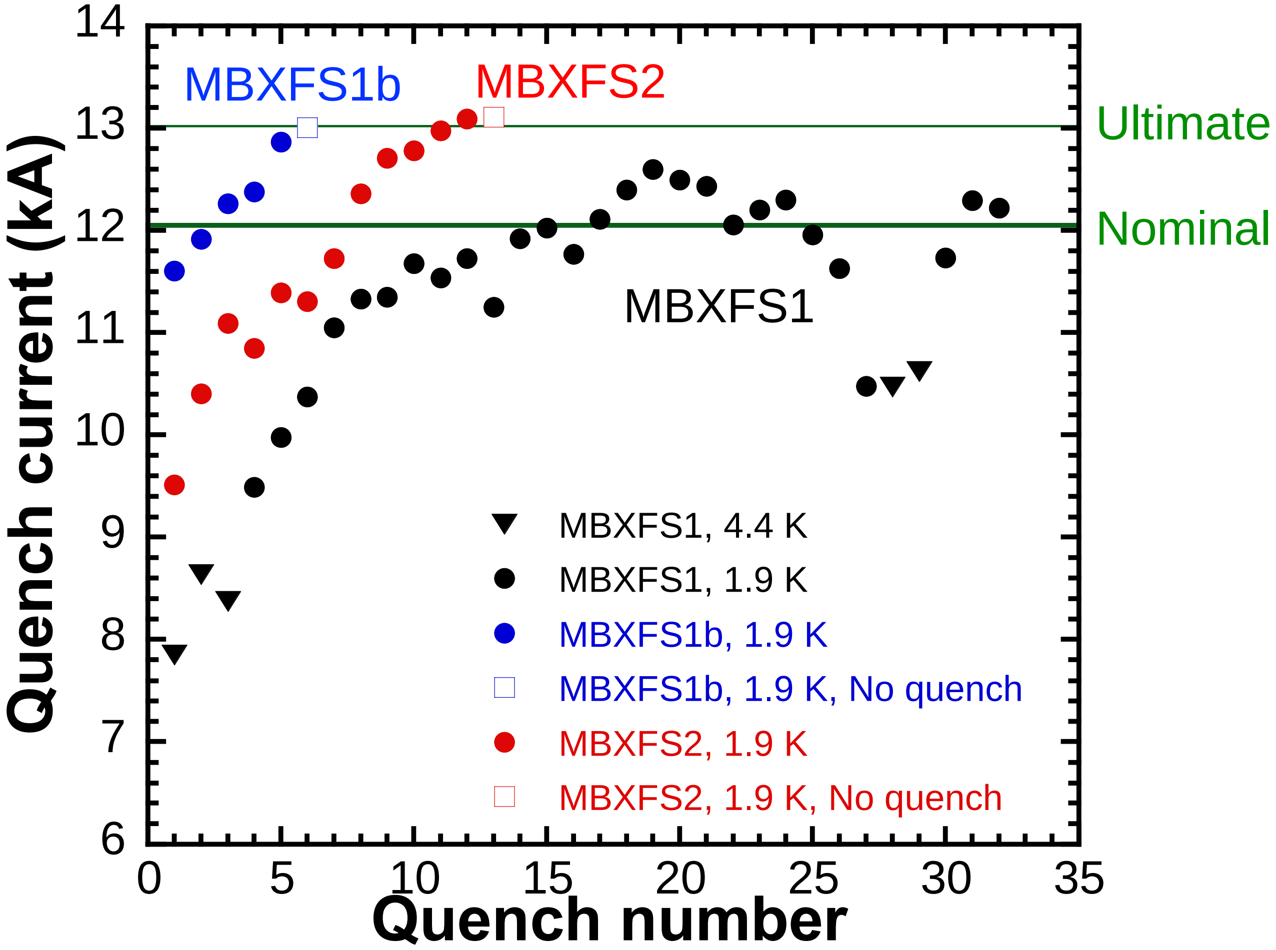
Threshold volt.
: 0.1V

First quench signal (I=9.5 kA)



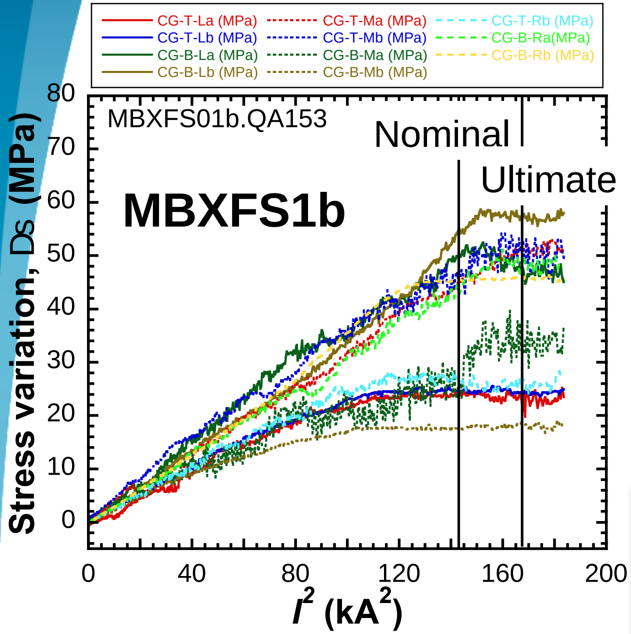
Quench signal appears in 1st turn of the top coil

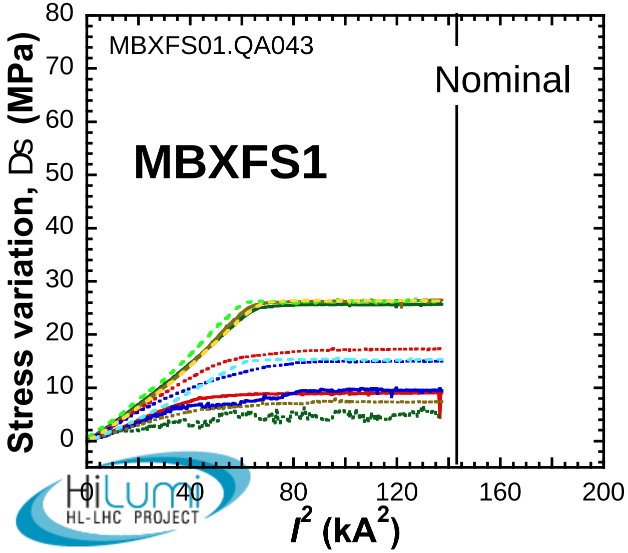
Training history

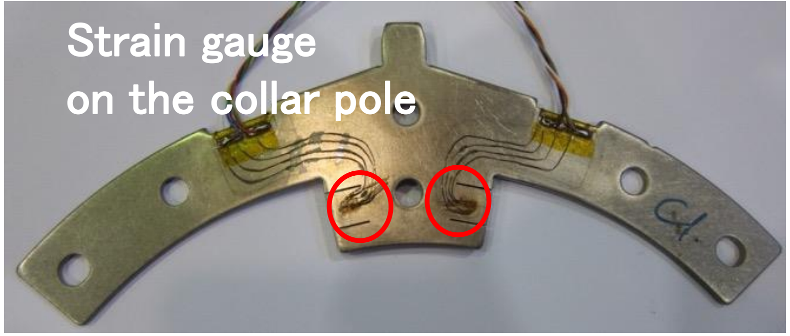


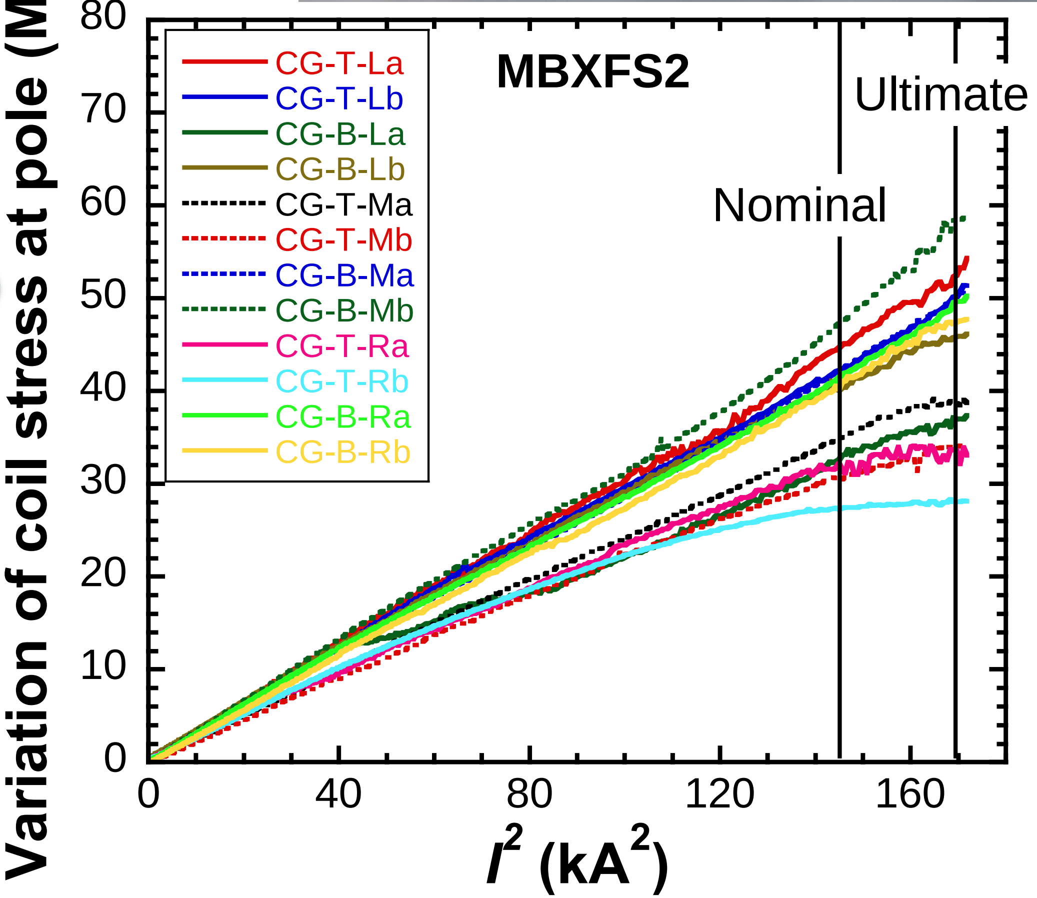
- 7 quenches to the nominal current (12.050 kA)
- 11 quenched to the ultimate current (13.020 kA)
- Quench current of MBXFS2 achieved acceptance criteria.

Azimuthal coil stress in the straight section



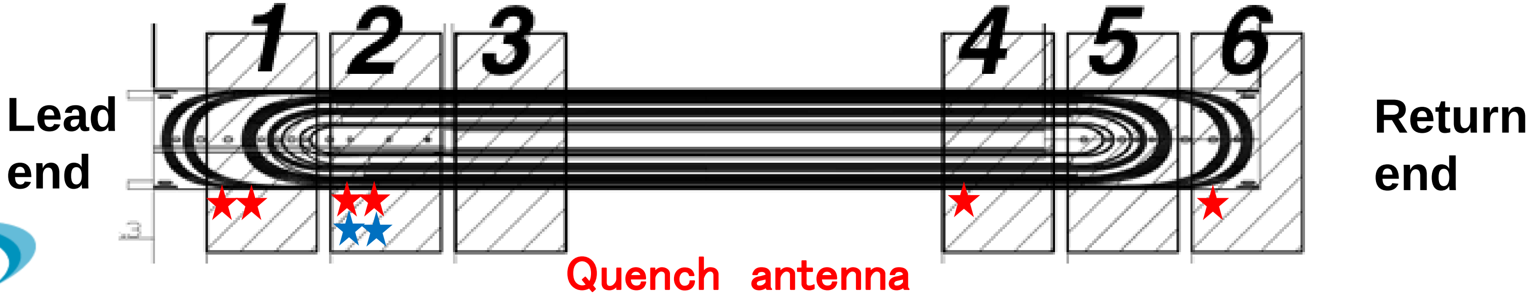



Strain gauge
on the collar pole



Quench location

Quench #	Quench Current (kA)	Quench start location	Quench antenna
1	9.517	Top, 1st turn	No signal
2	10.408	Bottom, 1st turn	QA2
3	11.098	Top, 26-27th turn	QA1
4	10.851	Top, 26-27th turn	QA1
5	11.393	Bottom, 2nd turn	QA2
6	11.309	Top, 2nd turn	QA2
7	11.727	Top, 13-14th turn	QA2
8	12.362	Top, 26th turn	QA6
9	12.710	Top, 5th turn	No signal
10	12.782	Top, 7-13th turn	No signal
11	12.977	Top, 5th turn	QA4
12	13.095	Bottom, 5th turn	No signal



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Quench #	Quench Current (kA)	Quench start location	Quench antenna
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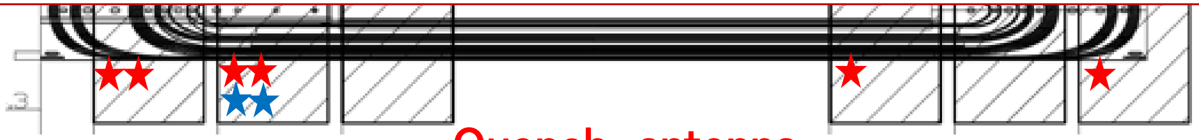
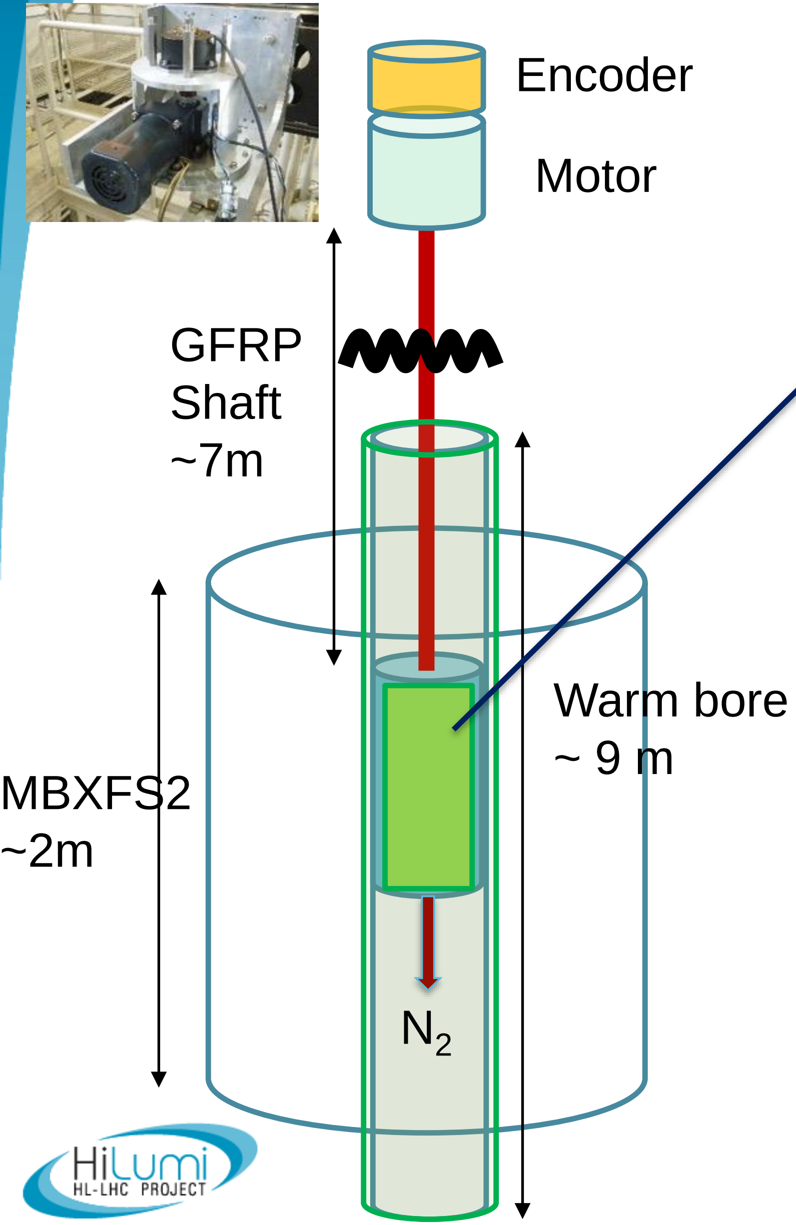
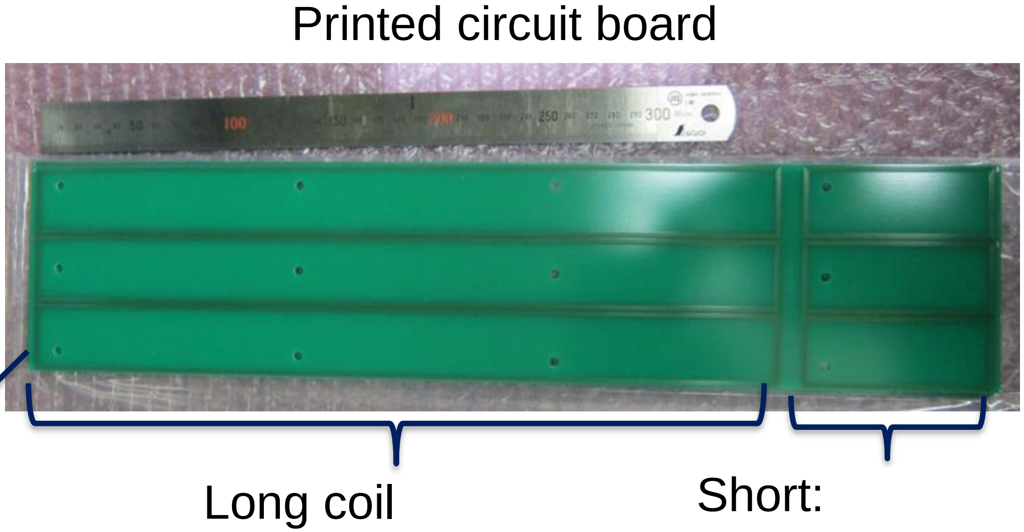
- Quench location
  - Mostly occurred at/near the coil end,
  - Signals from the quench antennas also help to identify the quench location in the Z direction, which is actually consistent with the result from the voltage tap analysis,
  - Not localized and widely distributed
- **Our magnet experiences good training**



Field measurement

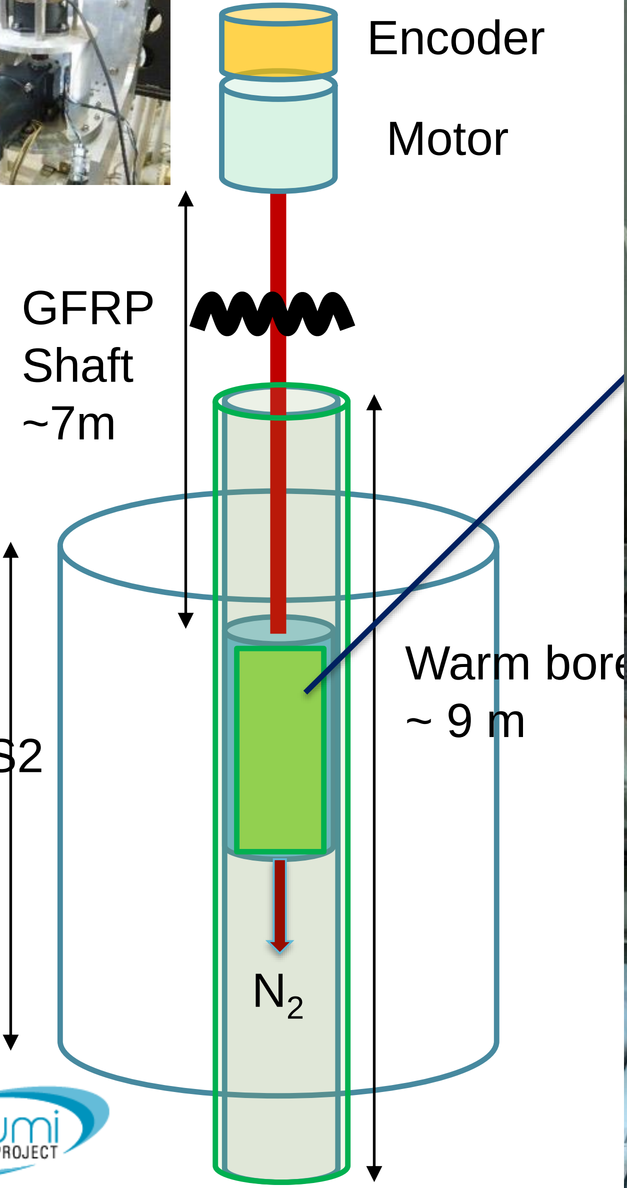
Rotating (Harmonic) coil system

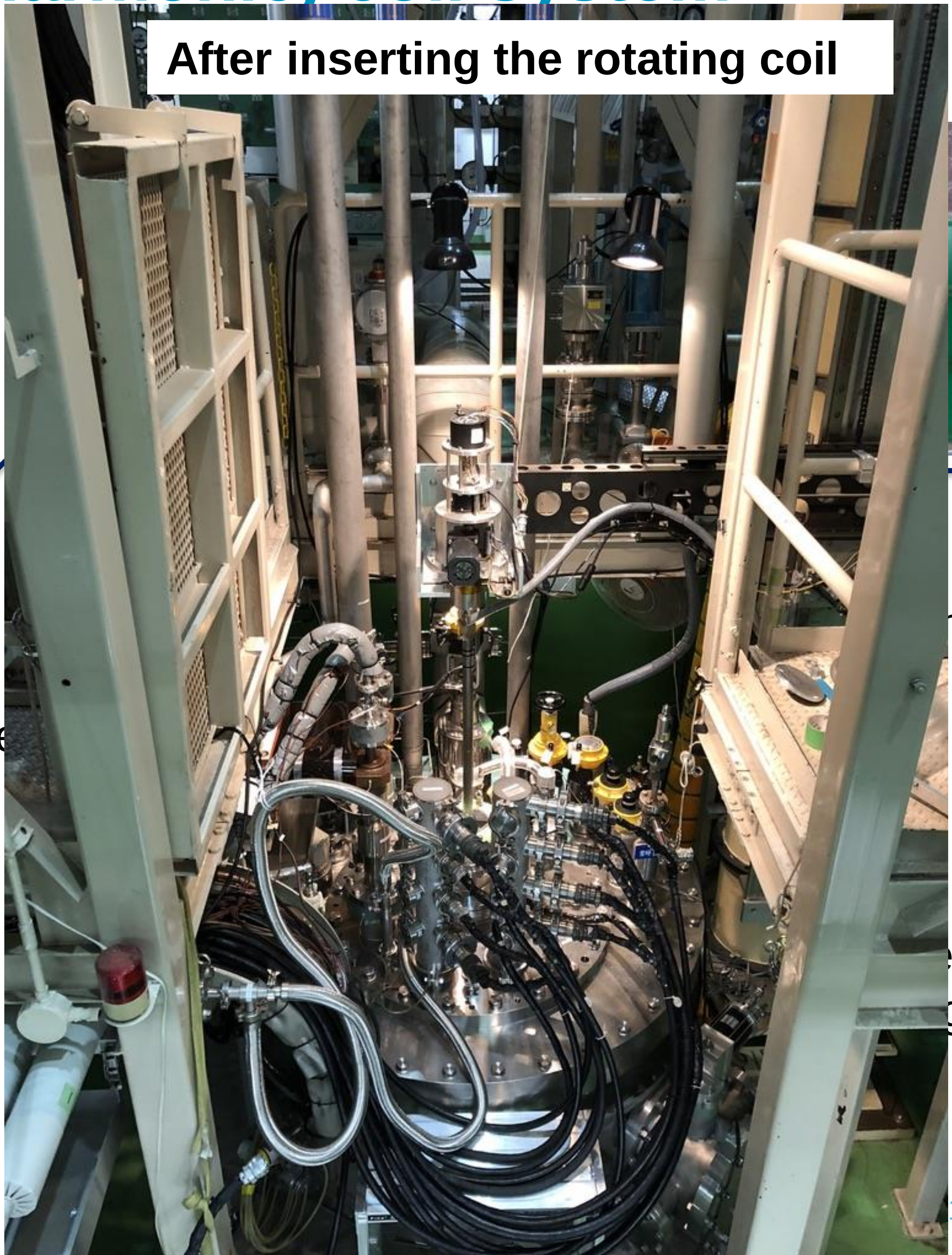




- Field quality is evaluated by means of the harmonics (rotating) coil
- Two types of the coil (PCB) :
  - Long coil: 350 x 30 mm^2
  - Short coil : 80 x 30 mm^2
  - Both have 20 turns
- N2 gas is flowed from the outlet into the warm bore to suppress thermal shrinkage of the pipe

Rotating (Harmonic) coil system





After inserting the rotating coil

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Method

- Harmonic coil rotates at 0.2 Hz, and measurement of the multipoles are repeated 5 times at each Z position / operating current

- Average of the multipoles is then calculated

- **<u>DC loop at Z=0 mm with the long coil (L=350 mm)</u>**

Skew: $a_n(z=0,I)=\frac{A_n(z=0,I)}{B_1(z=0,I)}\times 10^4$ Normal: $b_n(z=0,I)=\frac{B_n(z=0,I)}{B_1(z=0,I)}\times 10^4$

  - Current loop : 50A -> 12.2 kA -> 50A
  - Field angle is corrected at I=12.2 kA

- **<u>Z scan with the long / short coil (L=350 mm / 80 mm)</u>**

Skew: $a_n(z,I)=\frac{A_n(z,I)}{B_1(z=0,I)}\times 10^4$ Normal: $b_n(z,I)=\frac{B_n(z,I)}{B_1(z=0,I)}\times 10^4$

  - Field angle is corrected at Z=0 mm for every operating current

Schedule of MFM

- **10.14 : Z-scan at warm temperature, I=5 A**
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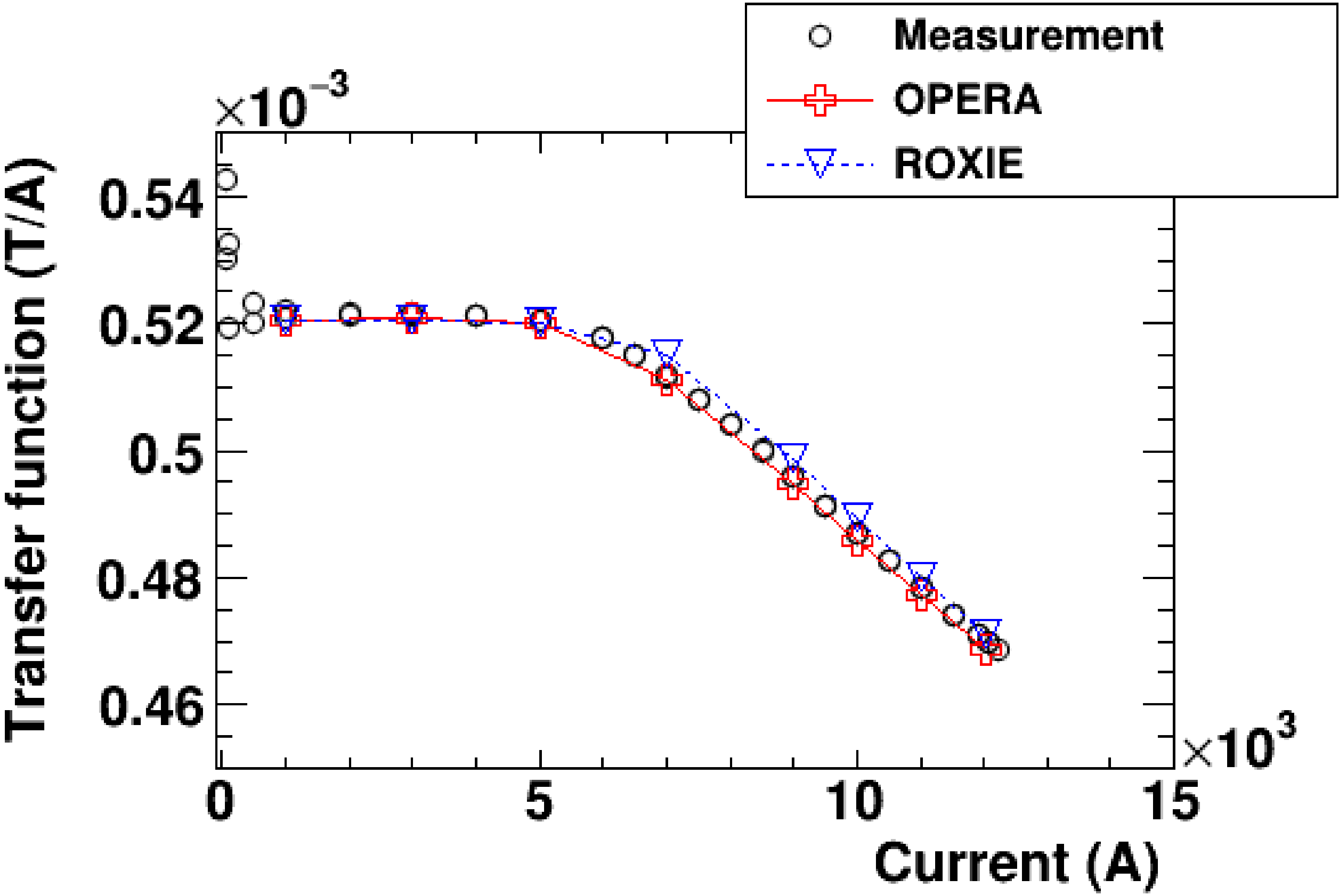
- **10.22 - 26 : Field measurements**

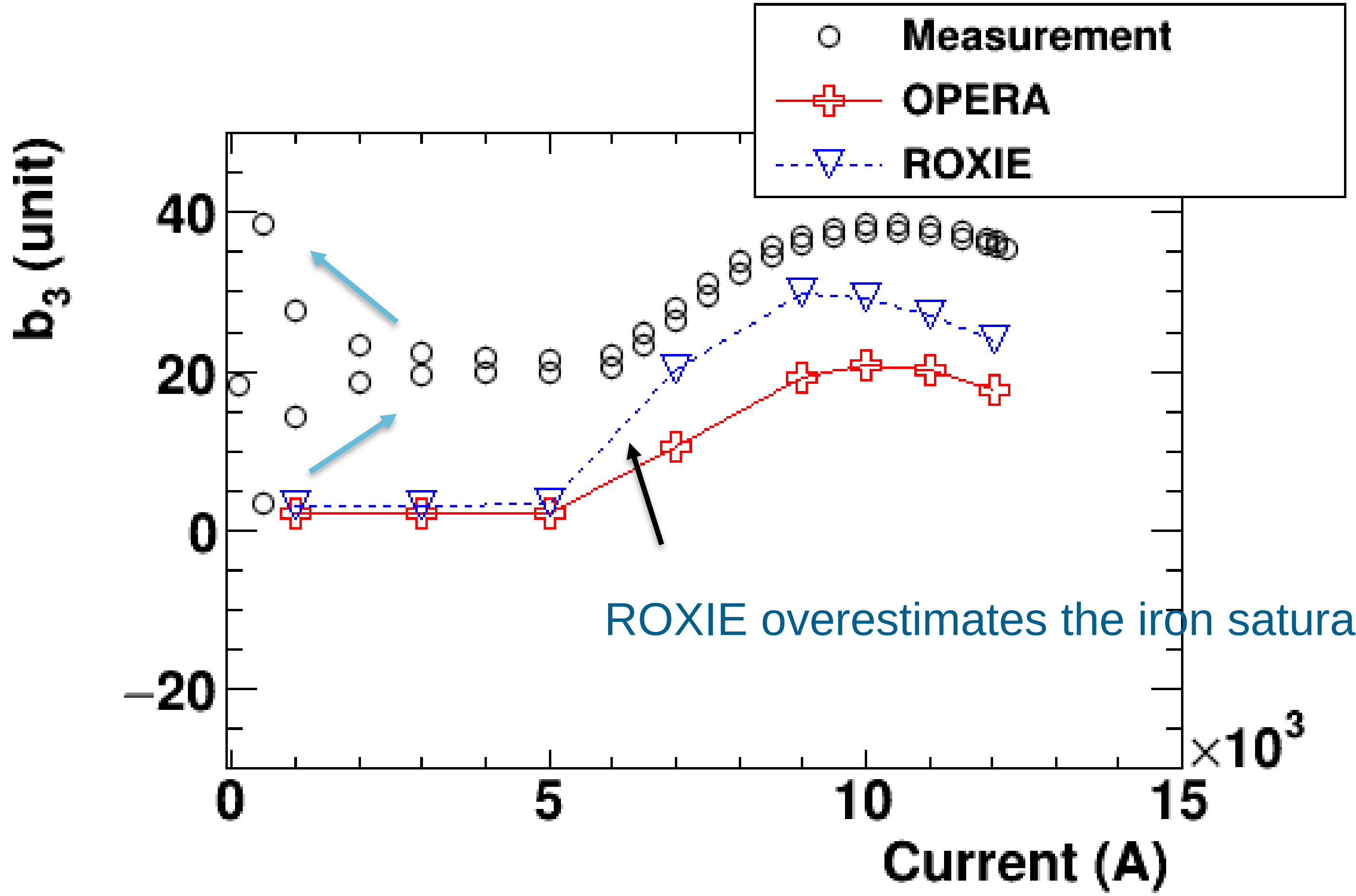
DC loop - Transfer function-



Consistent with the two calculations (OPERA, ROXIE)

Better agreement obtained when compared to OPERA

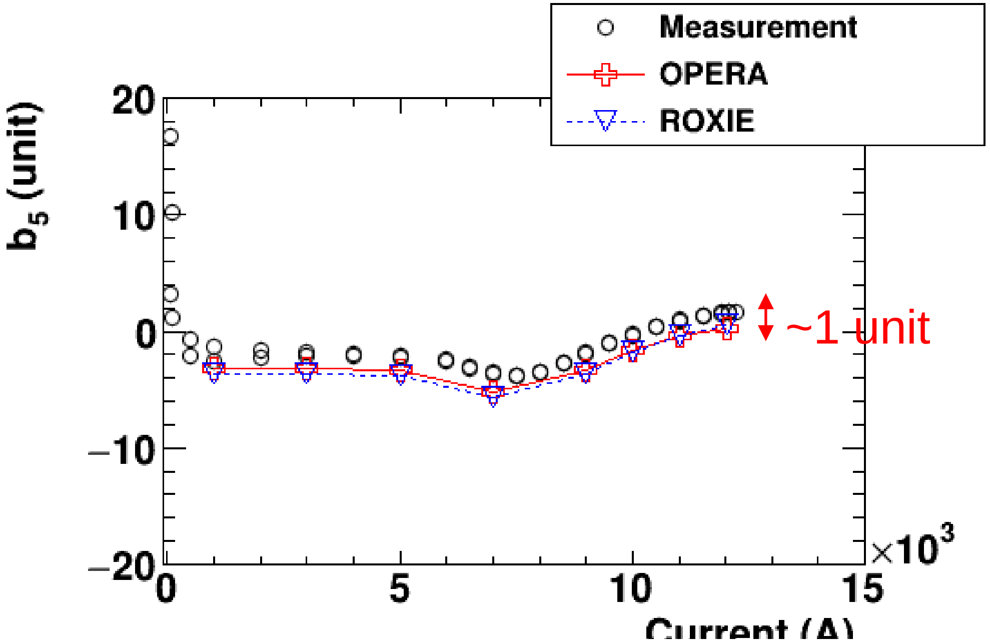
DC loop - b3 -



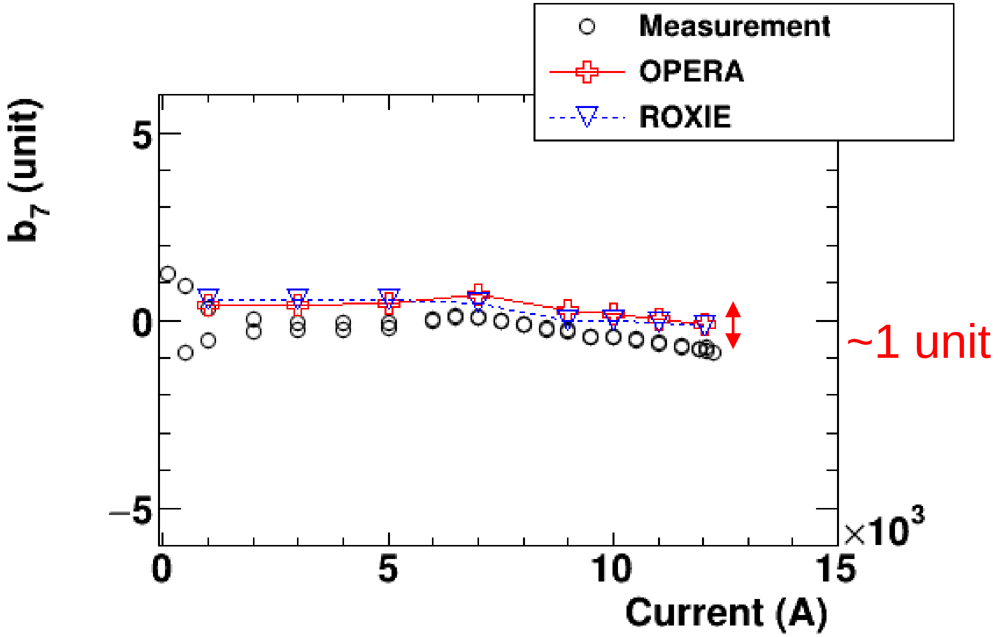
ROXIE overestimates the iron saturation effect

Observe 16 unit difference for I<3 kA between the measurement and calculations
If compared to OPERA, the difference is 18 unit at I = 12 kA.
=> 16-18 unit offset for every operating current

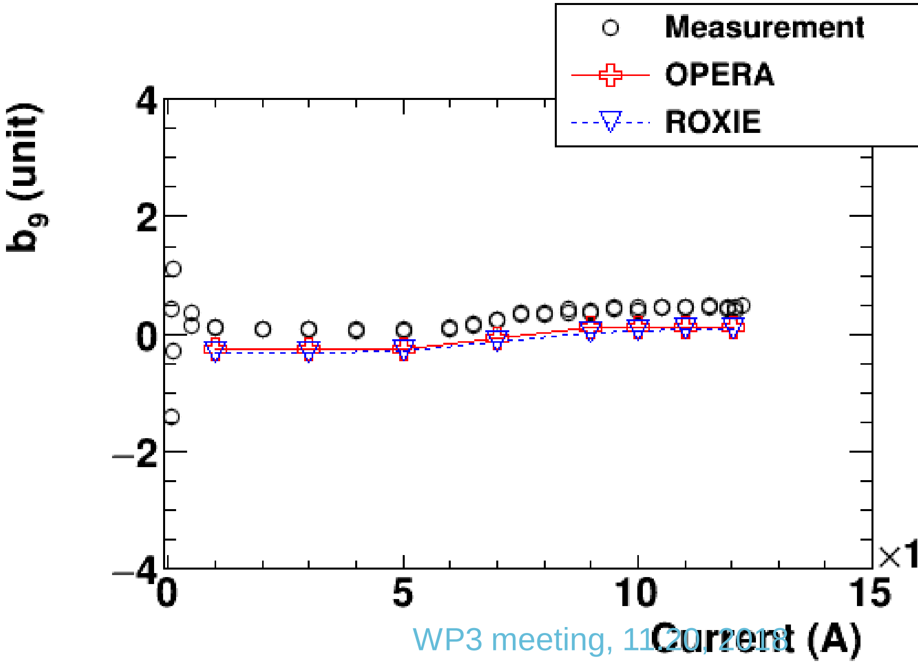
DC loop - b5, b7, b9 -



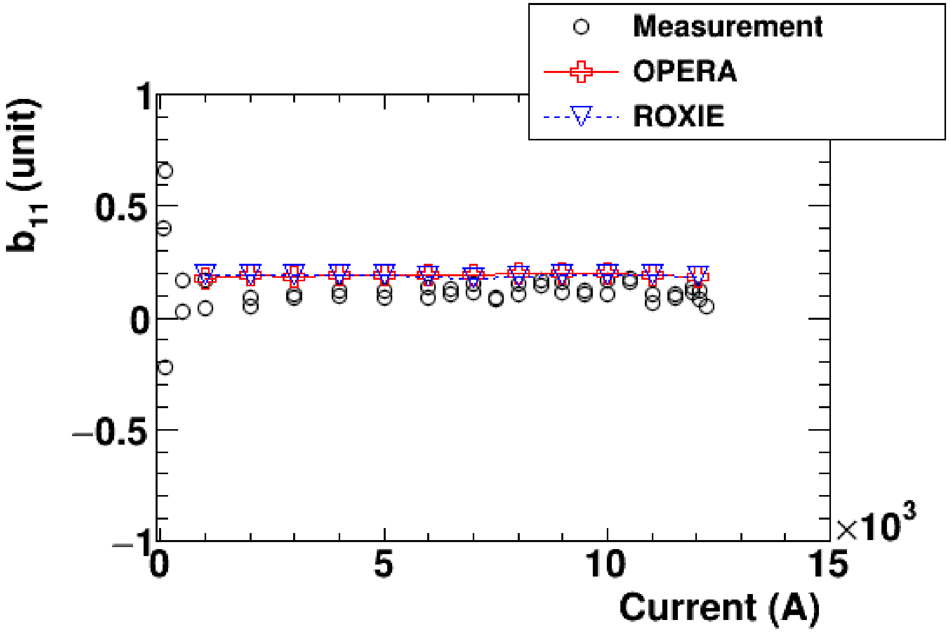
~1 unit

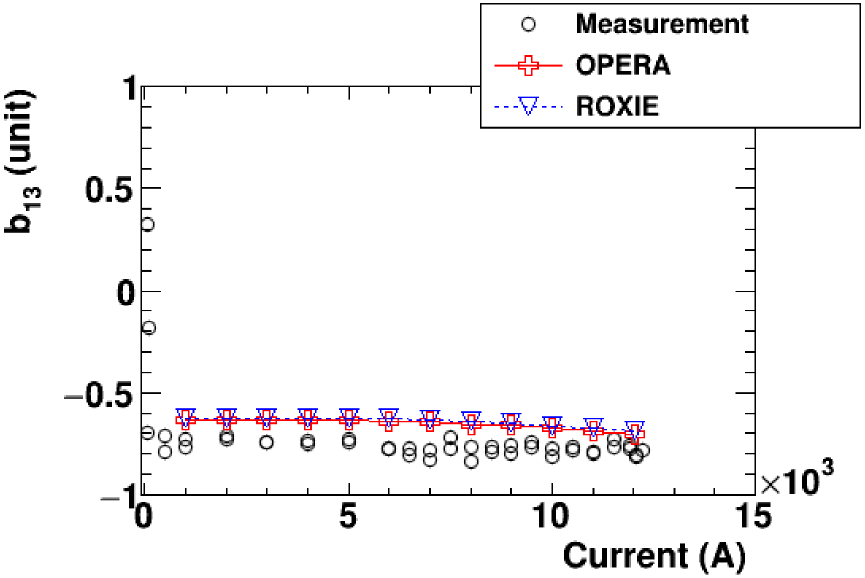


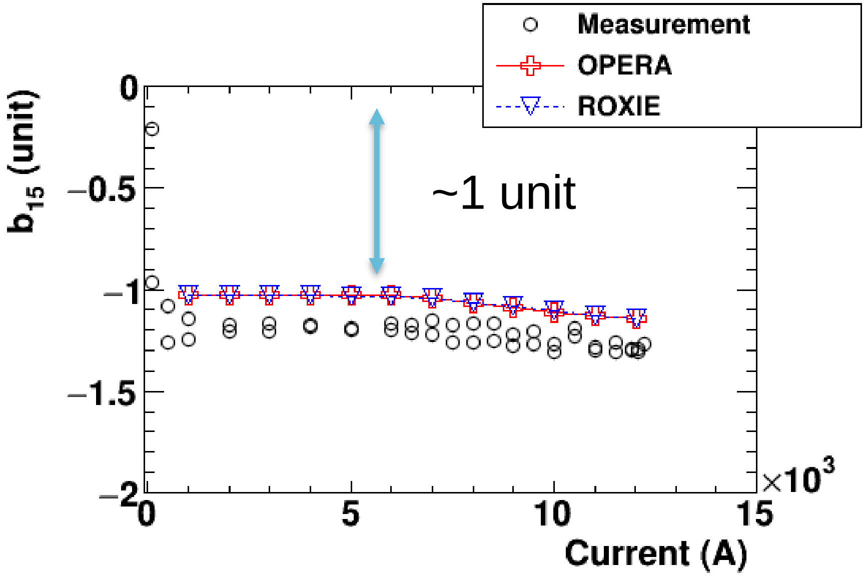
~1 unit



DC loop – b11, b13, b15 -





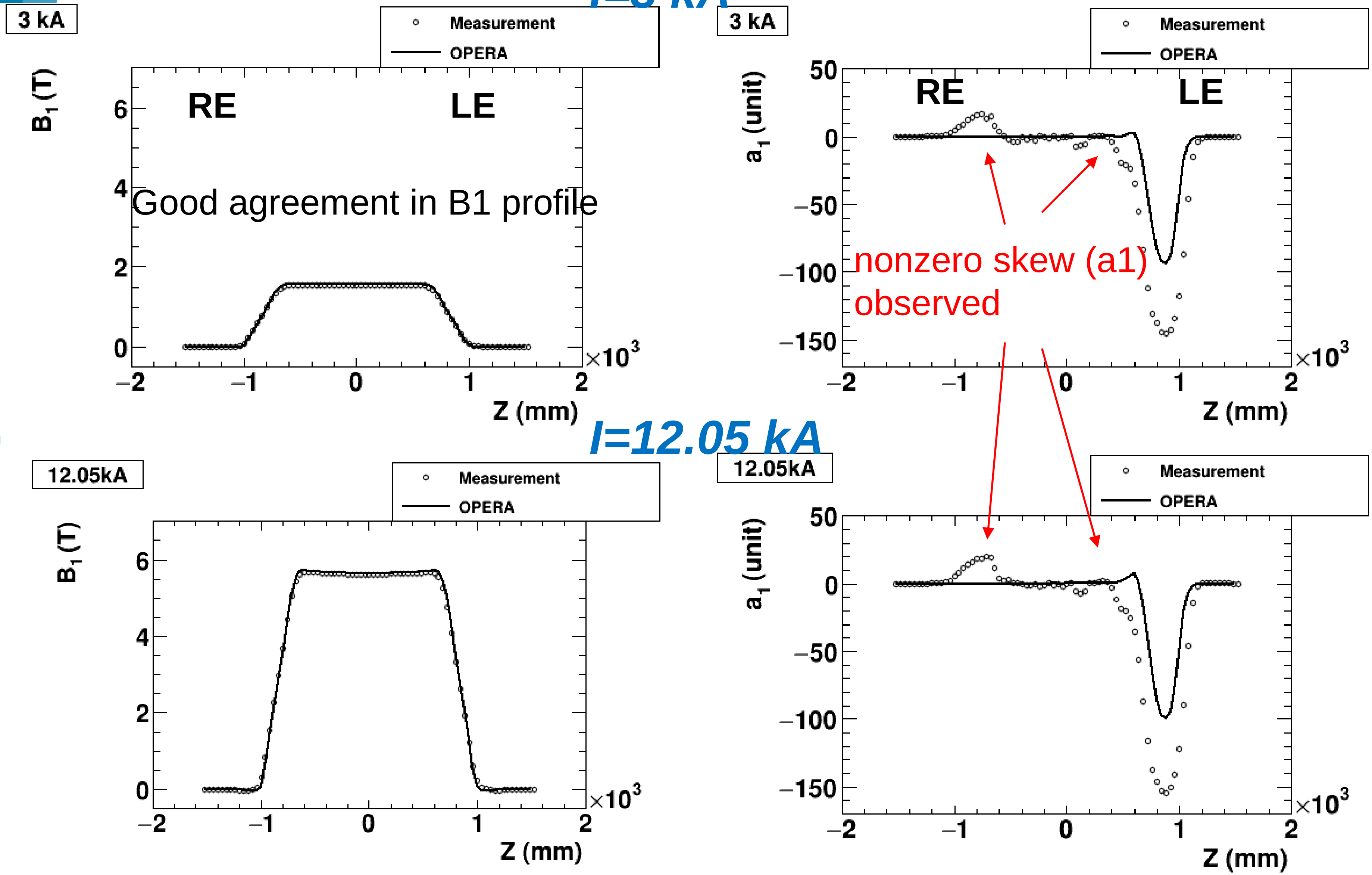


b15 is measured to be 1 unit , which is also reproduced in the calculation

Z scan w/ short coil ($B_{1,}$ a_1)

I=3 kA

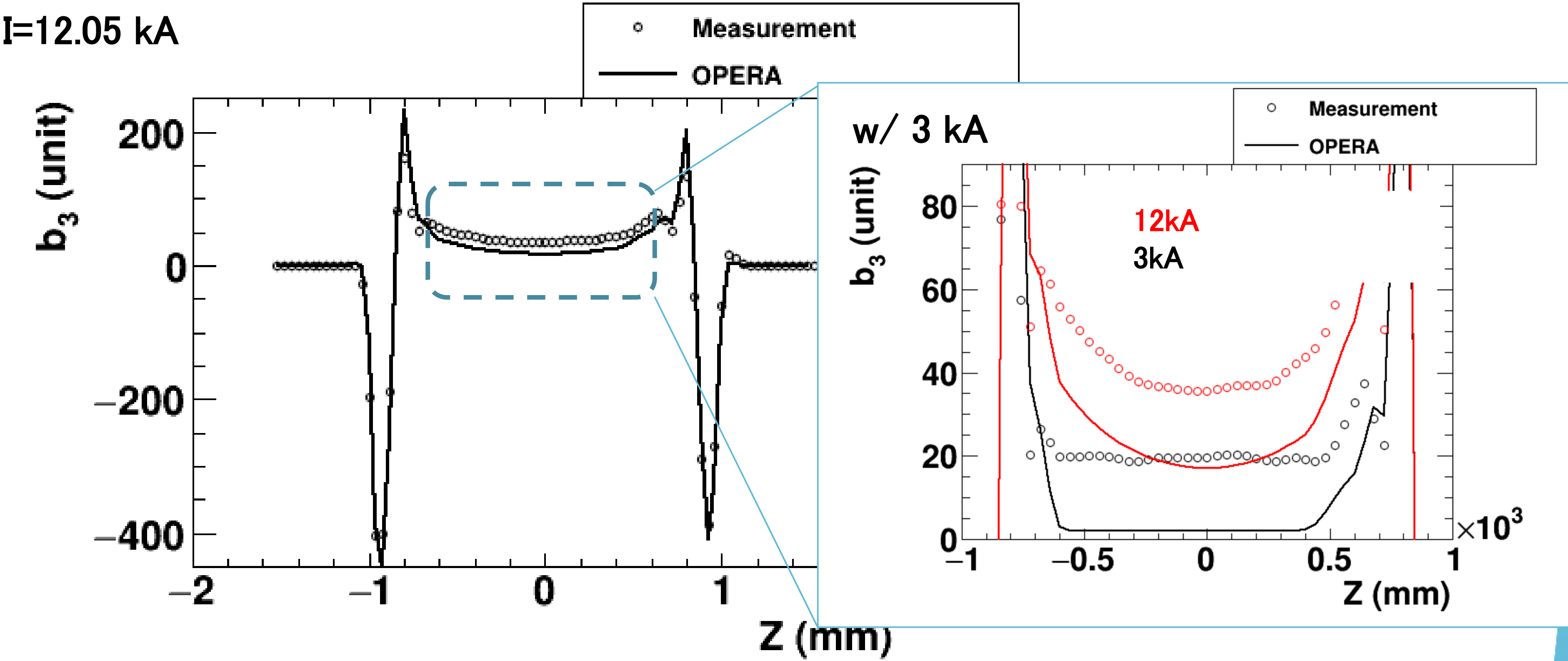
I=12.05 kA



Good agreement in B1 profile

nonzero skew (a1) observed

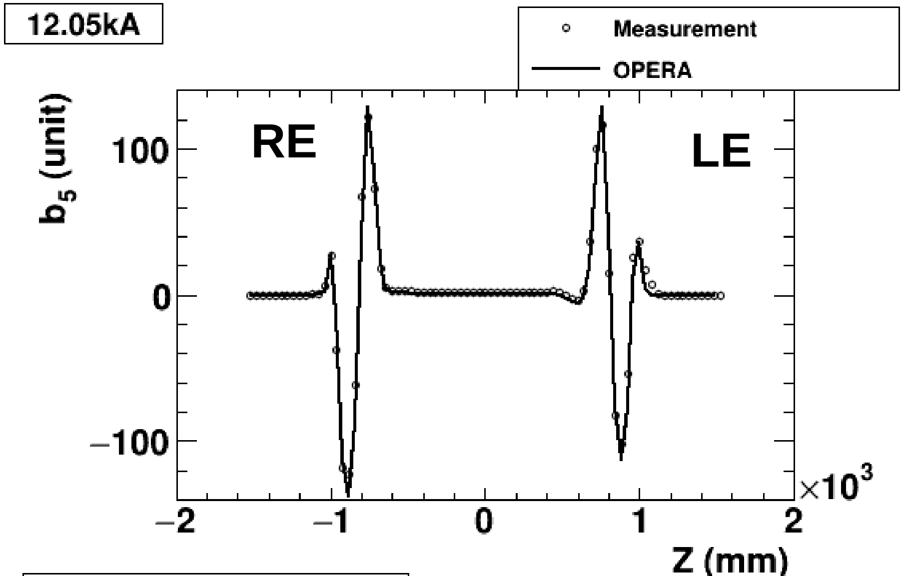
Z scan w/ short coil (b3)

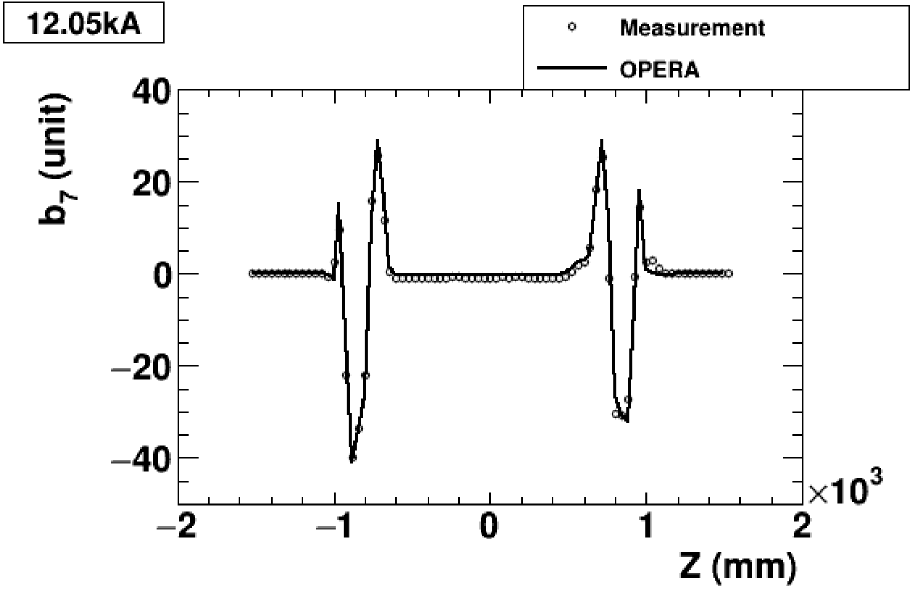


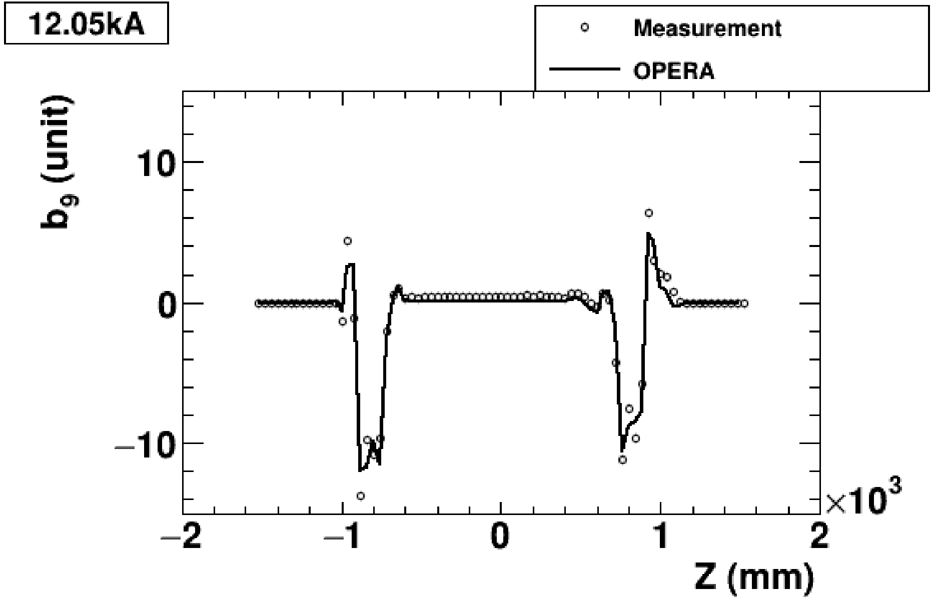
- We can see 16-18 unit offset along the straight section
- This might come from the imperfect coil geometry or unexpected magnetic material ?

Z scan w/ short coil (b_5, b_7, b_9)

I=12.05 kA



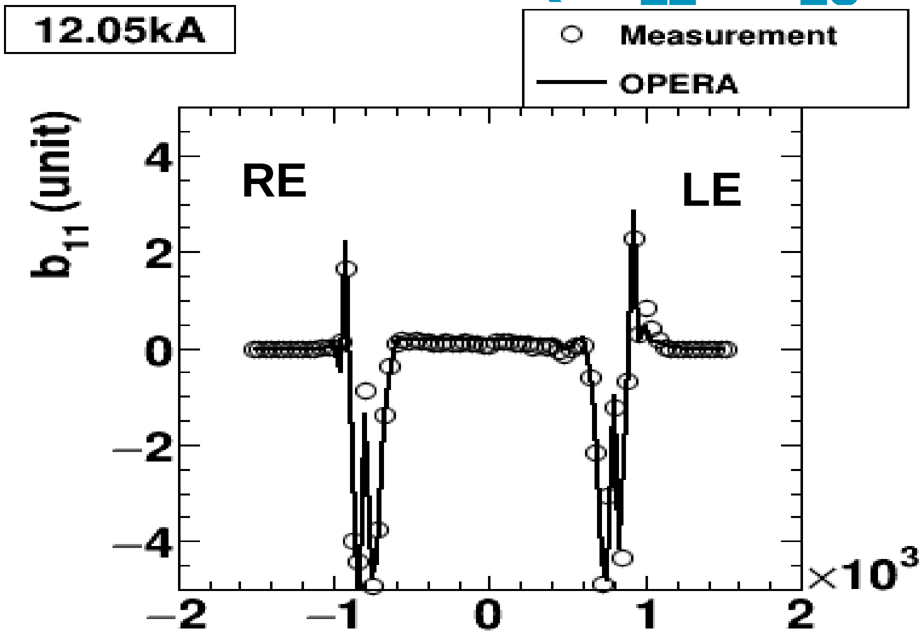


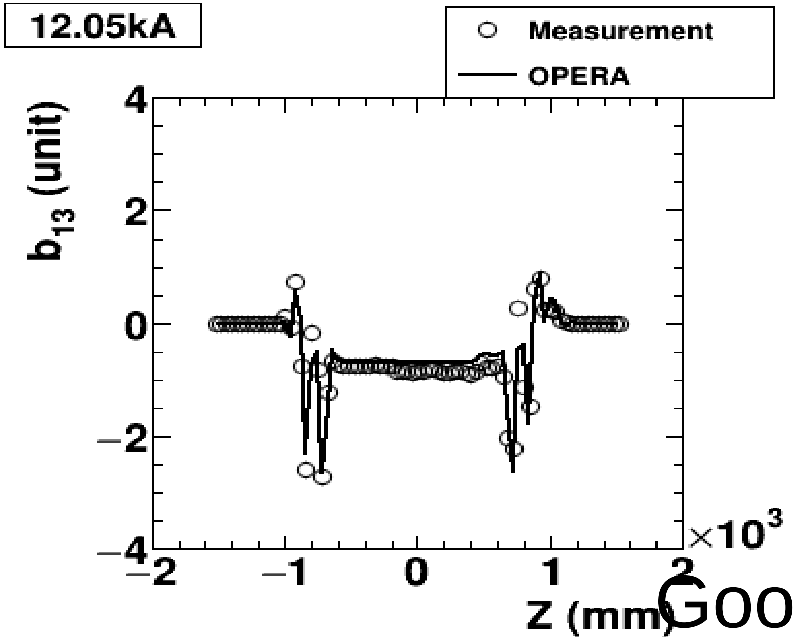


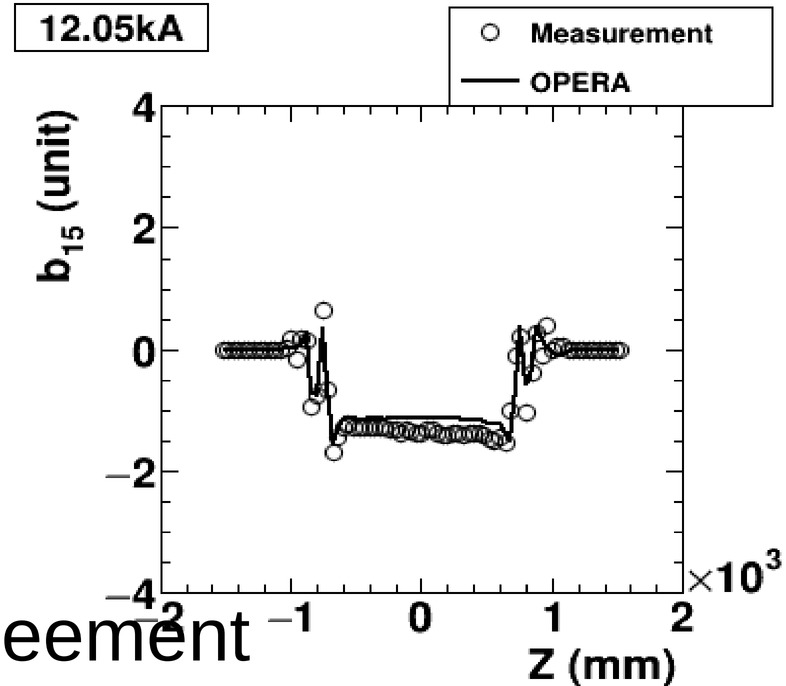
Good agreement

Z scan w/ short coil (b_{11}, b_{13}, b_{15})

I=12.05 kA



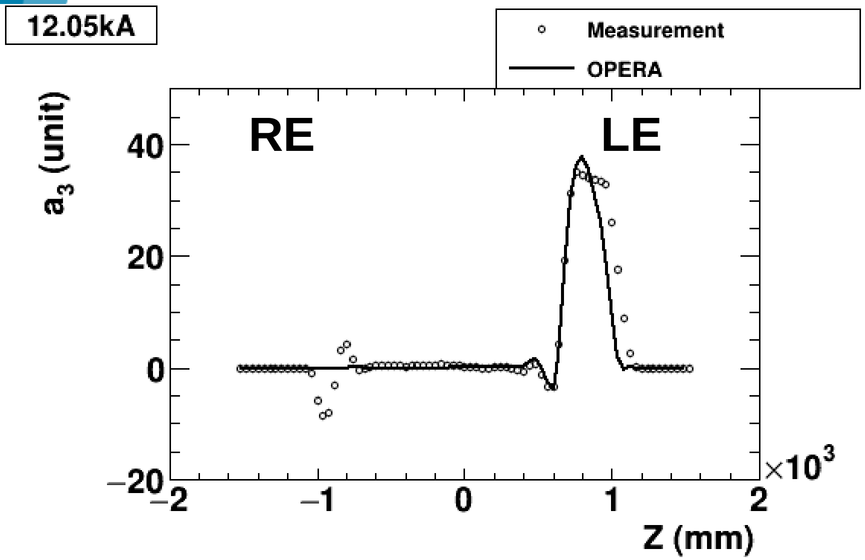


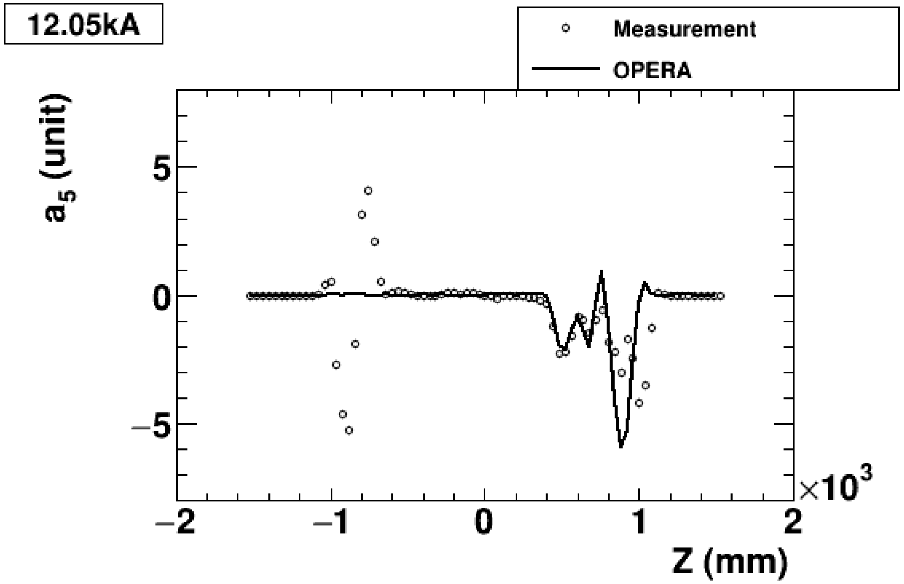


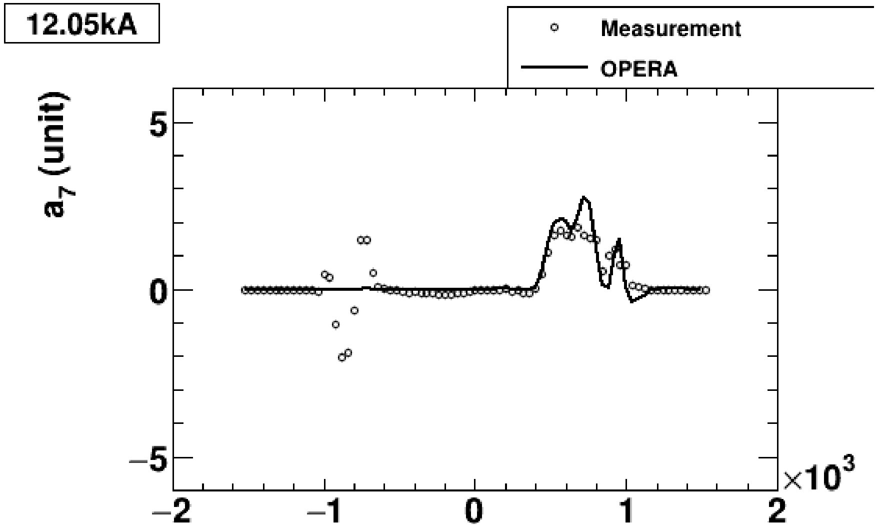
Good agreement

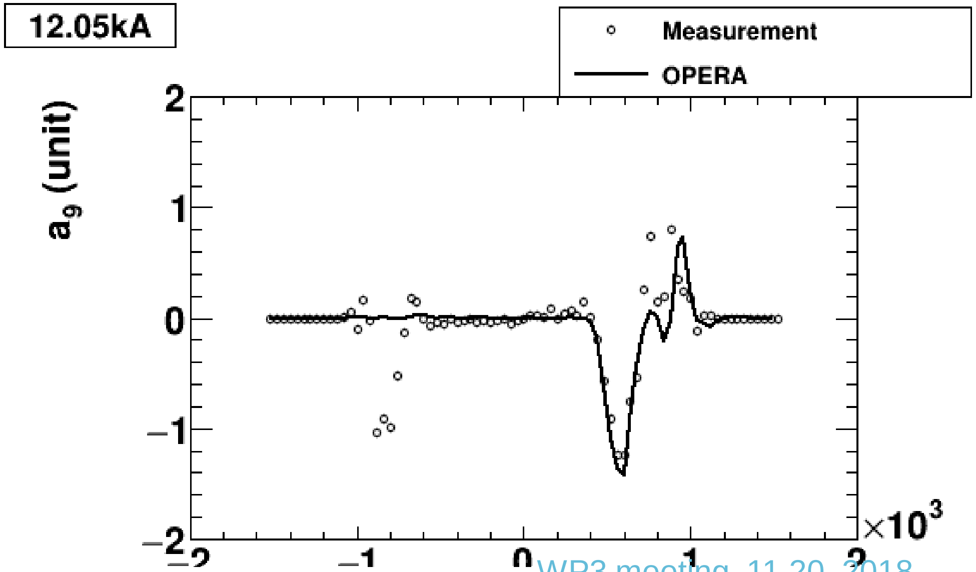
Z scan w/ short coil (a_3, a_5, a_7, a_9)

I=12.05 kA









Observe nonzero skew in RE, which is due to the winding inaccuracy?

Field integral (I=12.047kA)

$$\bar{b}_n(I) = \frac{\int_{z1}^{z2} B_n(I,z)dz}{\int_{-1750}^{1750} B_1(I,z)dz} \times 10^4$$

(): OPERA

n	RE (-1750 ~ -525)		SS (-525 ~ 525)		LE (525 ~ 1750)		Total (-1750~1750)	
	bn	an	bn	an	bn	an	bn	an
1	1925 (1871)	0.61 (0.00)	6259 (6267)	-0.20 (0.03)	1816 (1862)	**-6.01** **(-2.73)**	10000 (10000)	**-5.60** **(-2.69)**
2	1.18 (0.00)	-1.05 (-0.01)	-2.52 (-0.01)	0.16 (0.01)	1.03 (-0.03)	-3.66 (-0.08)	-0.31 (-0.04)	-4.55 (-0.08)
3	-14.11 (-12.27)	-0.45 (0.00)	**24.81** **(13.76)**	0.15 (0.11)	-9.74 (-9.61)	7.30 (5.73)	**0.95** **(-8.12)**	7.01 (5.84)
4	0.02 (0.00)	-0.30 (0.00)	-0.40 (0.01)	0.16 (0.00)	-0.63 (-0.11)	-0.01 (0.05)	-1.00 (-0.11)	-0.14 (0.05)
5	-0.40 (-0.90)	-0.02 (0.00)	1.09 (0.26)	-0.14 (-0.10)	**2.62** **(1.03)**	-0.66 (-0.59)	**3.30** **(0.39)**	-0.82 (-0.69)
6	0.22 (0.00)	-0.02 (0.00)	0.13 (0.00)	0.09 (0.00)	0.06 (-0.10)	-0.12 (0.04)	0.41 (-0.10)	-0.05 (0.04)
7	-1.25 (-1.05)	-0.04 (0.00)	-0.50 (-0.06)	0.02 (0.07)	-0.39 (-0.26)	0.42 (0.41)	-2.14 (-1.37)	0.40 (0.48)
8	0.29 (0.00)	0.05 (0.00)	-0.15 (0.00)	0.07 (0.00)	0.26 (-0.07)	0.02 (0.06)	0.40 (-0.07)	0.14 (0.05)
9	-0.98 (-0.99)	-0.06 (0.00)	0.28 (0.07)	-0.05 (-0.03)	-0.50 (-0.64)	-0.04 (-0.08)	-1.19 (-1.56)	-0.15 (-0.12)
10	0.14 (0.00)	0.01 (0.00)	-0.05 (0.00)	0.01 (0.00)	0.13 (-0.05)	0.01 (0.04)	0.21 (-0.05)	0.03 (0.04)
11	-0.37	0.01	0.06	0.02	-0.29	0.03	-0.60	0.06

Field integral (I=12.047kA)

$$\bar{b}_n(I) = \frac{\int_{z1}^{z2} B_n(I,z)dz}{\int_{-1750}^{1750} B_1(I,z)dz} \times 10^4$$

(): OPERA

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2	1.18 (0.00)	-1.05 (-0.01)	-2.52 (-0.01)	0.16 (0.01)	1.03 (-0.03)	-3.66 (-0.08)	-0.31 (-0.04)	-4.55 (-0.08)
3	-14.11 (-12.27)	-0.45 (0.00)	**24.81** **(13.76)**	0.15 (0.11)	-9.74 (-9.61)	7.30 (5.73)	**0.95** **(-8.12)**	7.01 (5.84)
4	0.02 (0.00)	-0.30 (0.00)	-0.40 (0.01)	0.16 (0.00)	-0.63 (-0.11)	-0.01 (0.05)	-1.00 (-0.11)	-0.14 (0.05)
5	-0.40 (-0.90)	-0.02 (0.00)	1.09 (0.26)	-0.14 (-0.10)	**2.62** **(1.03)**	-0.66 (-0.59)	**3.30** **(0.39)**	-0.82 (-0.69)
6	0.22	-0.02	0.13	0.09	0.06	-0.12	0.41	-0.05
	(0.00)	(0.00)	(0.00)	(0.00)	(-0.07)	(0.06)	(-0.07)	(0.05)
9	-0.98 (-0.99)	-0.06 (0.00)	0.28 (0.07)	-0.05 (-0.03)	-0.50 (-0.64)	-0.04 (-0.08)	-1.19 (-1.56)	-0.15 (-0.12)
10	0.14 (0.00)	0.01 (0.00)	-0.05 (0.00)	0.01 (0.00)	0.13 (-0.05)	0.01 (0.04)	0.21 (-0.05)	0.03 (0.04)
11	-0.37	0.01	0.06	0.02	-0.29	0.03	-0.60	0.06

Dominated by contributions from the end regions, which could be negligible for 7m magnets

Field integral (I=12.047kA)

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1	1925 (1871)	0.61 (0.00)	6259 (6267)	-0.20 (0.03)	1816 (1862)	**-6.01** **(-2.73)**	10000 (10000)	**-5.60** **(-2.69)**
2	1.18 (0.00)	-1.05 (-0.01)	-2.52 (-0.01)	0.16 (0.01)	1.03 (-0.03)	-3.66 (-0.08)	-0.31 (-0.04)	-4.55 (-0.08)
3	-14.11 (-12.27)	-0.45 (0.00)	**24.81** **(13.76)**	0.15 (0.11)	-9.74 (-9.61)	7.30 (5.73)	**0.95** **(-8.12)**	7.01 (5.84)
4	0.02 (0.00)	-0.30 (0.00)	-0.40 (0.01)	0.16 (0.00)	-0.63 (-0.11)	-0.01 (0.05)	-1.00 (-0.11)	-0.14 (0.05)
5	-0.40 (-0.90)	-0.02 (0.00)	1.09 (0.26)	-0.14 (-0.10)	**2.62** **(1.03)**	-0.66 (-0.59)	**3.30** **(0.39)**	-0.82 (-0.69)
6	0.22	-0.02	0.13	0.09	0.06	-0.12	0.41	-0.05 (0.04)
7								.40 (0.48)
8	(0.00)	(0.00)	(0.00)	(0.00)	(-0.07)	(0.06)	(-0.07)	.14 (0.05)
9	-0.98 (-0.99)	-0.06 (0.00)	0.28 (0.07)	-0.05 (-0.03)	-0.50 (-0.64)	-0.04 (-0.08)	-1.19 (-1.56)	-0.15 (-0.12)
10	0.14 (0.00)	0.01 (0.00)	-0.05 (0.00)	0.01 (0.00)	0.13 (-0.05)	0.01 (0.04)	0.21 (-0.05)	0.03 (0.04)
11	-0.37	0.01	0.06	0.02	-0.29	0.03	-0.60	0.06

Integral of b3:
Large contribution from the straight section

Field integral (I=12.047kA)

$$\bar{b}_n(I) = \frac{\int_{z1}^{z2} B_n(I,z)dz}{\int_{-1750}^{1750} B_1(I,z)dz} \times 10^4$$

(): OPERA

D1 acceptance criteria given by Ezio
(Field integral at nominal operation)

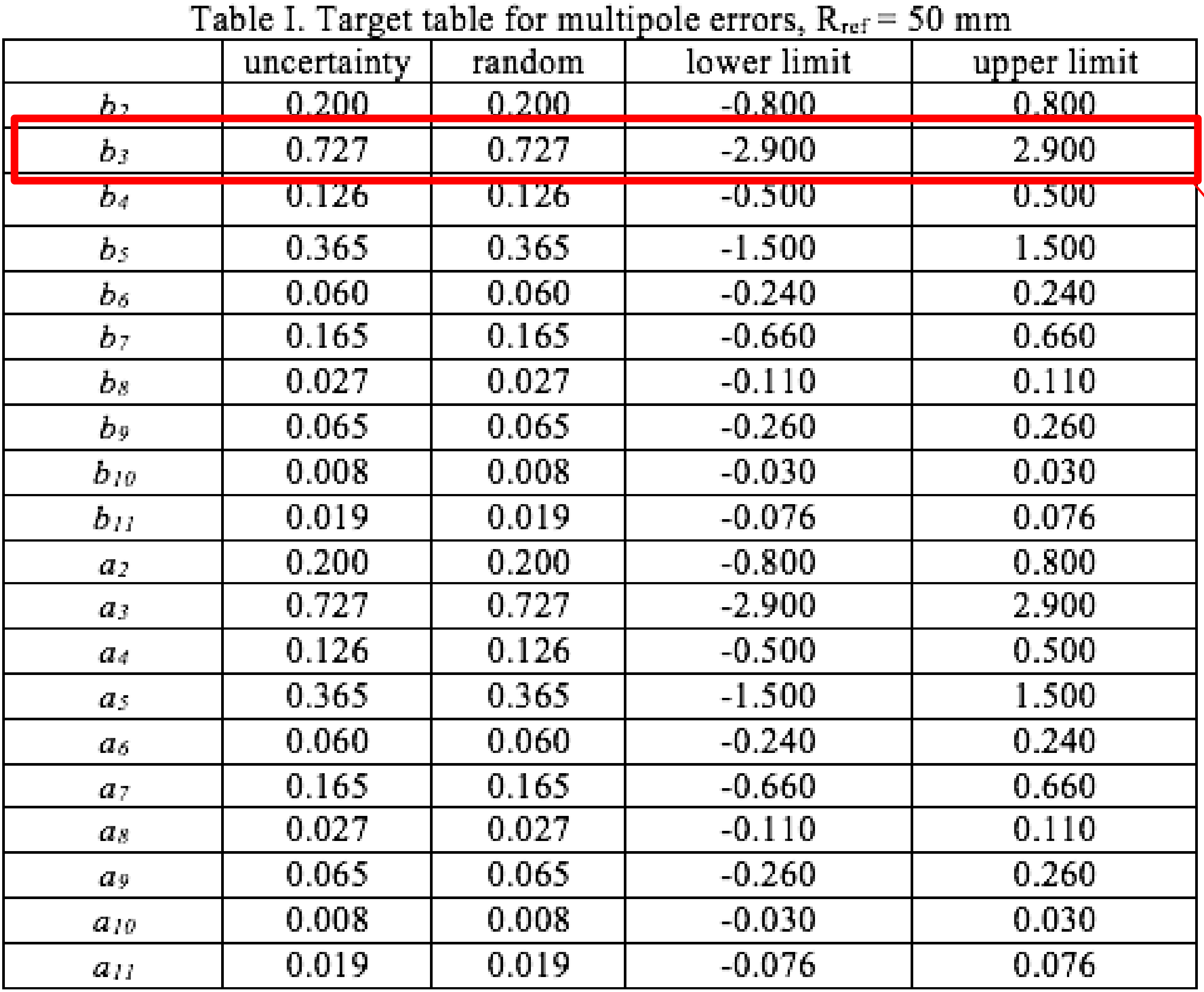


Table I. Target table for multipole errors, R_{ref} = 50 mm

	uncertainty	random	lower limit	upper limit
b_2	0.200	0.200	-0.800	0.800
b_3	0.727	0.727	-2.900	2.900
b_4	0.126	0.126	-0.500	0.500
b_5	0.365	0.365	-1.500	1.500
b_6	0.060	0.060	-0.240	0.240
b_7	0.165	0.165	-0.660	0.660
b_8	0.027	0.027	-0.110	0.110
b_9	0.065	0.065	-0.260	0.260
b_{10}	0.008	0.008	-0.030	0.030
b_{11}	0.019	0.019	-0.076	0.076
a_2	0.200	0.200	-0.800	0.800
a_3	0.727	0.727	-2.900	2.900
a_4	0.126	0.126	-0.500	0.500
a_5	0.365	0.365	-1.500	1.500
a_6	0.060	0.060	-0.240	0.240
a_7	0.165	0.165	-0.660	0.660
a_8	0.027	0.027	-0.110	0.110
a_9	0.065	0.065	-0.260	0.260
a_{10}	0.008	0.008	-0.030	0.030
a_{11}	0.019	0.019	-0.076	0.076

n

LE (525 ~ 1750)

Total (-1750~1750)	
bn	an
10000 (10000)	**-5.60** **(-2.69)**
-0.31 (-0.04)	-4.55 (-0.08)
0.95 **(-8.12)**	7.01 (5.84)
-1.00 (-0.11)	-0.14 (0.05)
3.30 **(0.39)**	-0.82 (-0.69)
0.41 (-0.10)	-0.05 (0.04)
-2.14 (-1.37)	0.40 (0.48)
0.40 (-0.07)	0.14 (0.05)
-1.19 (-1.56)	-0.15 (-0.12)
0.21 (-0.05)	0.03 (0.04)
-0.60	0.06

Field integral (I=12.047kA)

$$\bar{b}_n(I) = \frac{\int_{z1}^{z2} B_n(I,z)dz}{\int_{-1750}^{1750} B_1(I,z)dz} \times 10^4$$

(): OPERA

D1 acceptance criteria given by Ezio
(Field integral at nominal operation)

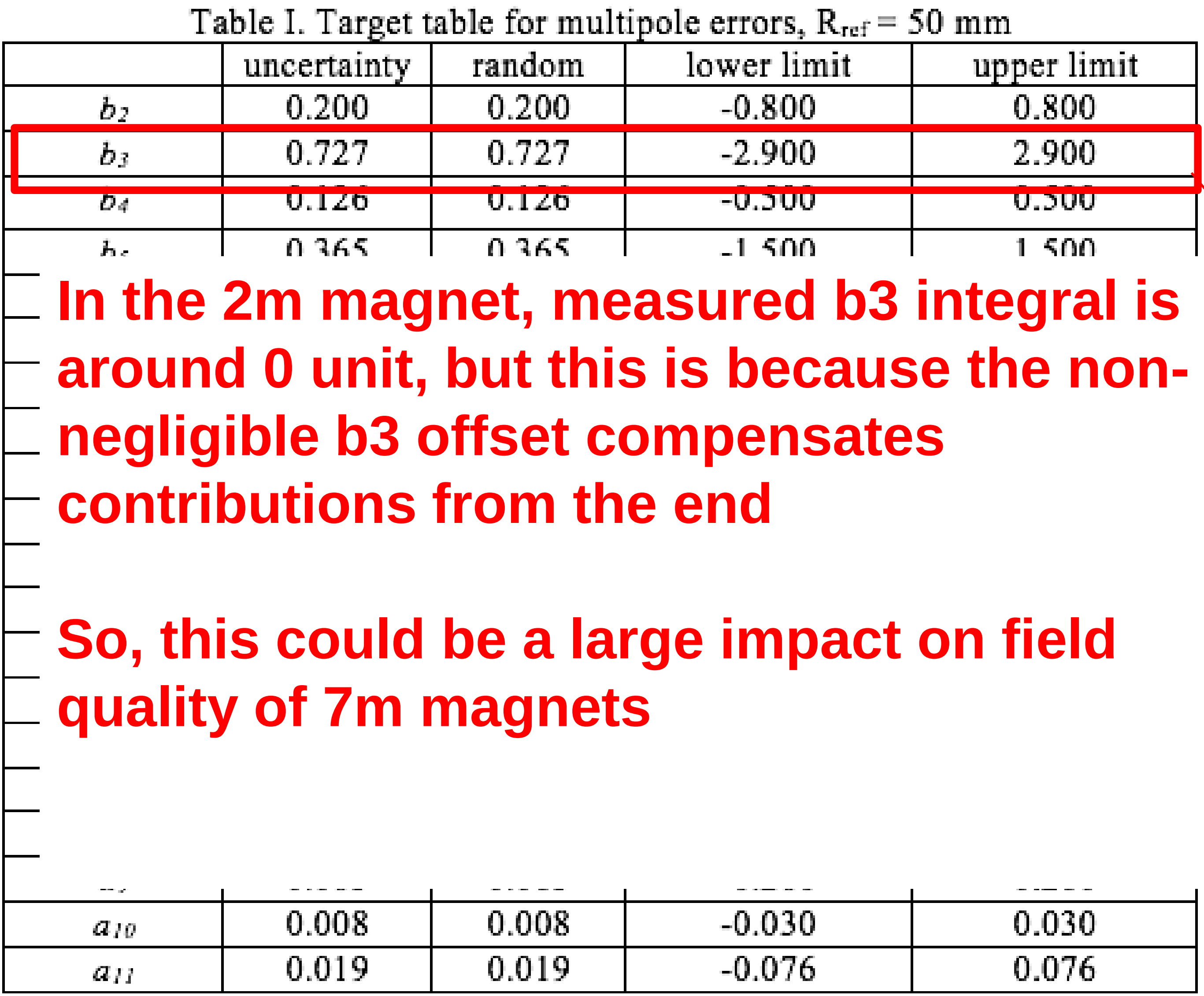


Table I. Target table for multipole errors, R_{ref} = 50 mm

	uncertainty	random	lower limit	upper limit
b_2	0.200	0.200	-0.800	0.800
b_3	0.727	0.727	-2.900	2.900
b_4	0.126	0.126	-0.300	0.300
b_5	0.365	0.365	-1.500	1.500
a_{10}	0.008	0.008	-0.030	0.030
a_{11}	0.019	0.019	-0.076	0.076

In the 2m magnet, measured b3 integral is around 0 unit, but this is because the non-negligible b3 offset compensates contributions from the end

So, this could be a large impact on field quality of 7m magnets

Total (-1750~1750)	
bn	an
10000 (10000)	**-5.60** **(-2.69)**
-0.31 (-0.04)	-4.55 (-0.08)
0.95 **(-8.12)**	7.01 (5.84)
-1.00 (-0.11)	-0.14 (0.05)
3.30 **(0.39)**	-0.82 (-0.69)
0.41 (-0.10)	-0.05 (0.04)
-2.14 (-1.37)	0.40 (0.48)
0.40 (-0.07)	0.14 (0.05)
-1.19 (-1.56)	-0.15 (-0.12)
0.21 (-0.05)	0.03 (0.04)
-0.60	0.06

Field integral (n>12) not covered by the acceptance criteria

(): OPERA

n	RE (-1750 ~ -525)		SS (-525 ~ 525)		LE (525 ~ 1750)		Total (-1750~1750)	
	bn	an	bn	an	bn	an	bn	an
12	0.08 (0.00)	0.01 (0.00)	0.23 (0.00)	0.03 (0.00)	0.09 (-0.01)	0.03 (0.00)	0.40 (-0.02)	0.06 (0.01)
13	-0.22 (-0.23)	-0.01 (0.00)	-0.49 (-0.43)	-0.05 (0.00)	-0.15 (-0.16)	-0.01 (-0.02)	-0.86 (-0.82)	-0.07 (-0.02)
14	0.10 (0.00)	-0.01 (0.00)	0.53 (0.00)	0.04 (0.00)	0.10 (0.01)	0.00 (0.00)	0.72 (0.01)	0.03 (0.00)
15	-0.17 (-0.17)	-0.01 (0.00)	-0.80 (-0.72)	-0.07 (0.00)	-0.14 (-0.17)	0.02 (0.00)	-1.11 (-1.05)	-0.06 (0.00)
16	0.04 (0.00)	0.00 (0.00)	0.39 (0.00)	0.05 (0.00)	0.08 (0.00)	-0.02 (0.00)	0.51 (0.00)	0.03 (0.00)
17	-0.06 (-0.07)	-0.01 (0.00)	-0.40 (-0.50)	-0.03 (0.00)	-0.06 (-0.07)	-0.01 (0.00)	-0.52 (-0.64)	-0.05 (0.00)
18	-0.01 (0.00)	0.00 (0.00)	-0.21 (0.00)	-0.03 (0.00)	-0.02 (-0.01)	-0.01 (0.00)	-0.24 (-0.01)	-0.04 (0.00)
19	0.05 (0.03)	0.00 (0.00)	0.23 (0.24)	0.01 (0.00)	0.02 (0.04)	0.00 (0.00)	0.30 (0.31)	0.01 (0.00)
20	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

For the multipoles (n>12), all the results are consistent with the calculations

Field integral (n>12) not covered by the acceptance criteria

(): OPERA

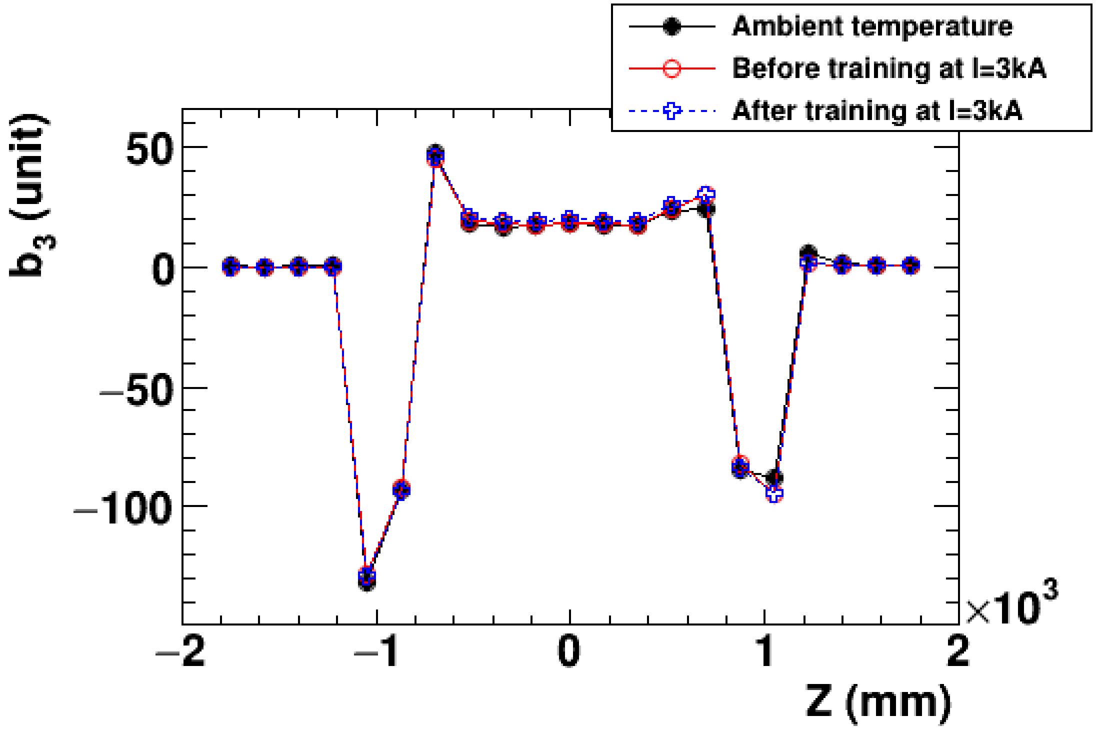
n	RE (-1750 ~ -525)		SS (-525 ~ 525)		LE (525 ~ 1750)		Total (-1750~1750)	
	bn	an	bn	an	bn	an	bn	an
12	0.08 (0.00)	0.01 (0.00)	0.23 (0.00)	0.03 (0.00)	0.09 (-0.01)	0.03 (0.00)	0.40 (-0.02)	0.06 (0.01)
13	-0.22 (-0.23)	-0.01 (0.00)	-0.49 (-0.43)	-0.05 (0.00)	-0.15 (-0.16)	-0.01 (-0.02)	-0.86 (-0.82)	-0.07 (-0.02)
14	0.10 (0.00)	-0.01 (0.00)	0.53 (0.00)	0.04 (0.00)	0.10 (0.01)	0.00 (0.00)	0.72 (0.01)	0.03 (0.00)
15	-0.17 (-0.17)	-0.01 (0.00)	-0.80 (-0.72				-1.11 (-1.05)	-0.06 (0.00)
16	0.04 (0.00)	0.00 (0.00)	0.39 (0.00)	(0.00)	(0.00)	(0.00)	0.51 (0.00)	0.03 (0.00)
17	-0.06 (-0.07)	-0.01 (0.00)	-0.40 (-0.50)	-0.03 (0.00)	-0.06 (-0.07)	-0.01 (0.00)	-0.52 (-0.64)	-0.05 (0.00)
18	-0.01 (0.00)	0.00 (0.00)	-0.21 (0.00)	-0.03 (0.00)	-0.02 (-0.01)	-0.01 (0.00)	-0.24 (-0.01)	-0.04 (0.00)
19	0.05 (0.03)	0.00 (0.00)	0.23 (0.24)	0.01 (0.00)	0.02 (0.04)	0.00 (0.00)	0.30 (0.31)	0.01 (0.00)
20	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

b15 : ~1unit
Is this acceptable?

For the multipoles (n>12), all the results are consistent with the calculations

Study on b3

History of b3 incl. the RT measurement

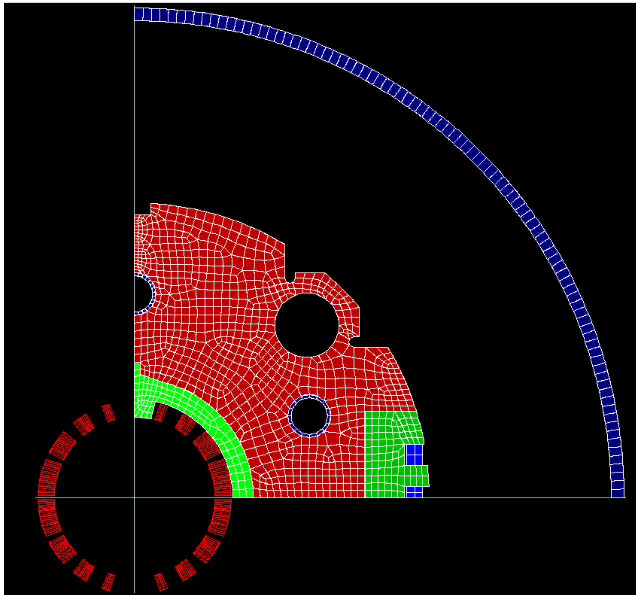


18 unit offset can be seen even in the RT measurement
Surprisingly, 1unit increase is observed in b3 after the training

Condition	b_3 (unit) at the magnet center
Room temp. (I=5 A)	18.14
Before training (I=3 kA)	18.31 + 1unit
After training (I=3 kA)	19.53

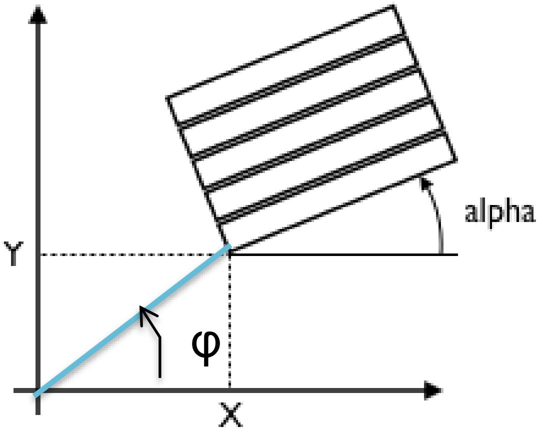
Inverted field calculation w/ ROXIE 2D

- Purpose:
  - find out the best coil position (phi, alpha) so that the resultant multipoles matches the measurement
  - **Target values : (b3, b5) =(18, -2)**

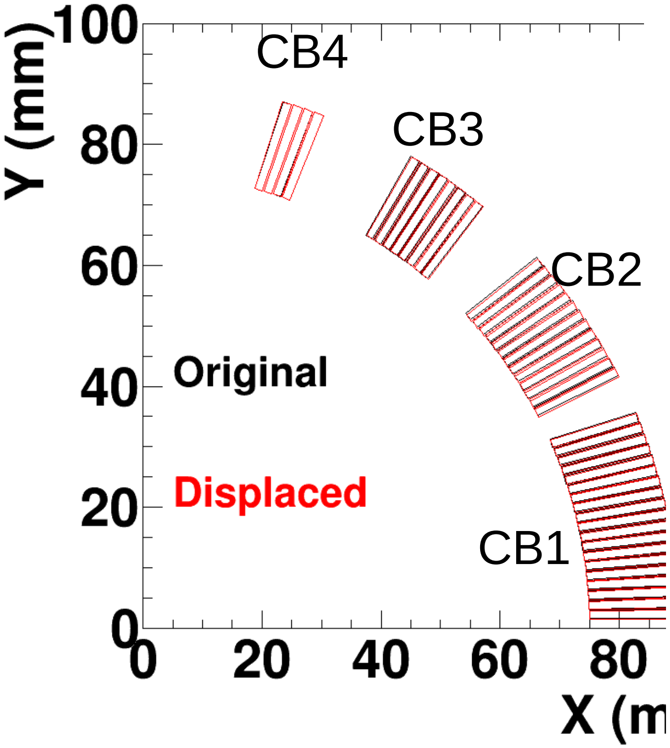


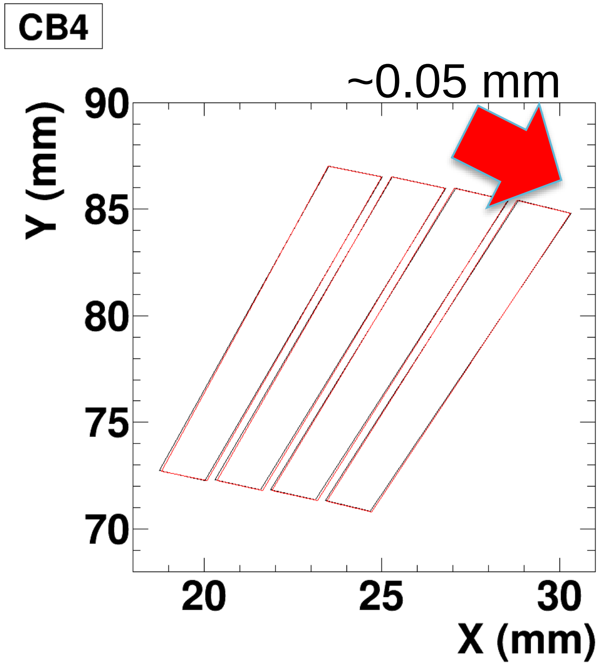
After conducting inverted field calc.

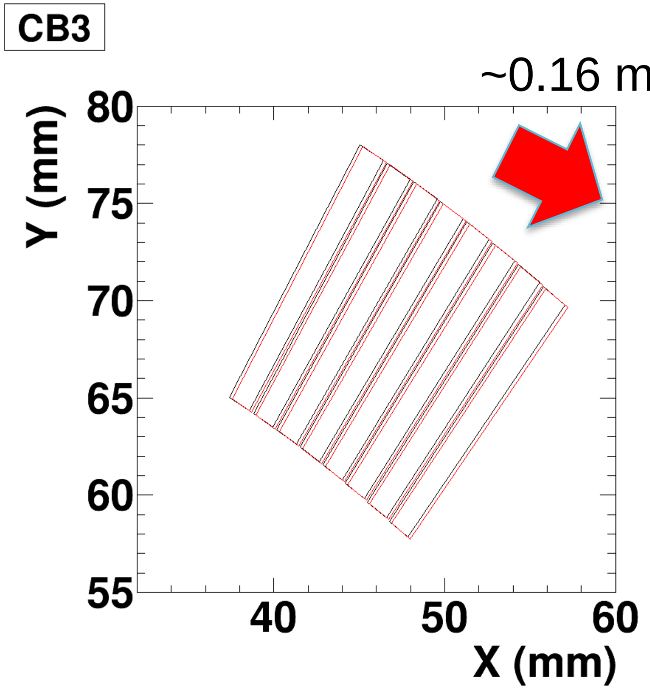
Normal	Measurement	ROXIE2D	
		Original	Displaced
3	18.31 (19.53)	1.92	18.02
5	-2.27 (-2.09)	-3.21	-2.00
7	-0.21 (-0.24)	0.40	-0.25
9	0.011 (0.079)	-0.27	-0.22

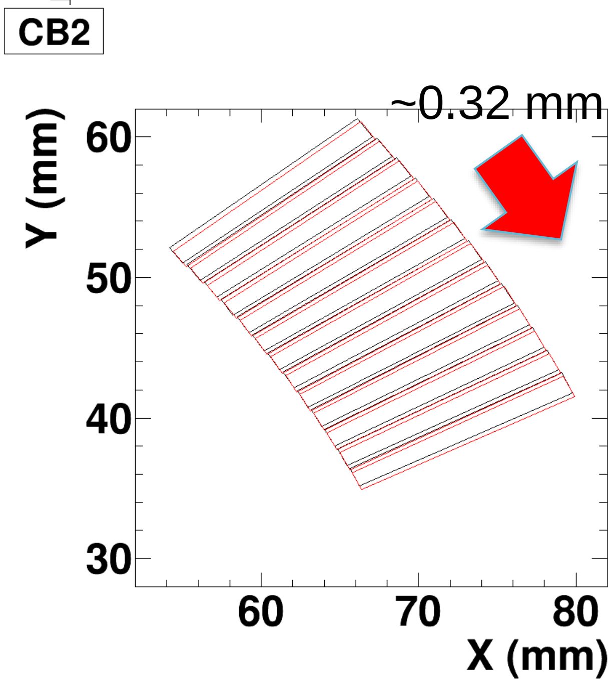


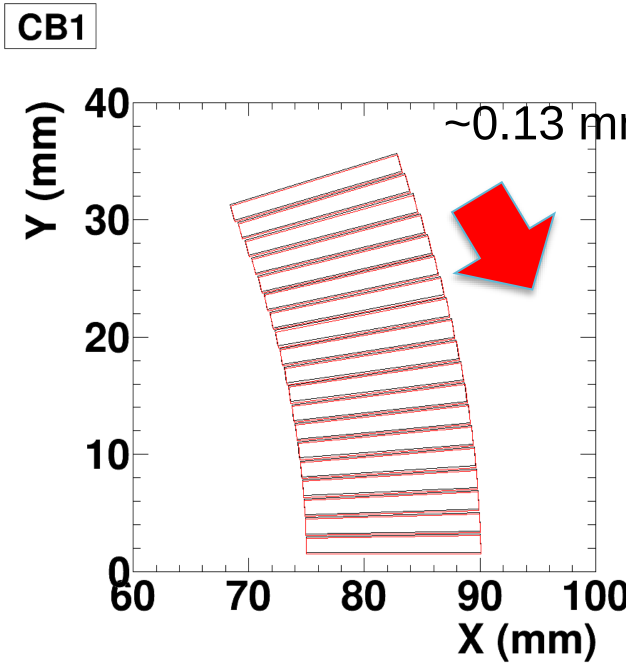
Inverted Field Calc. : Result











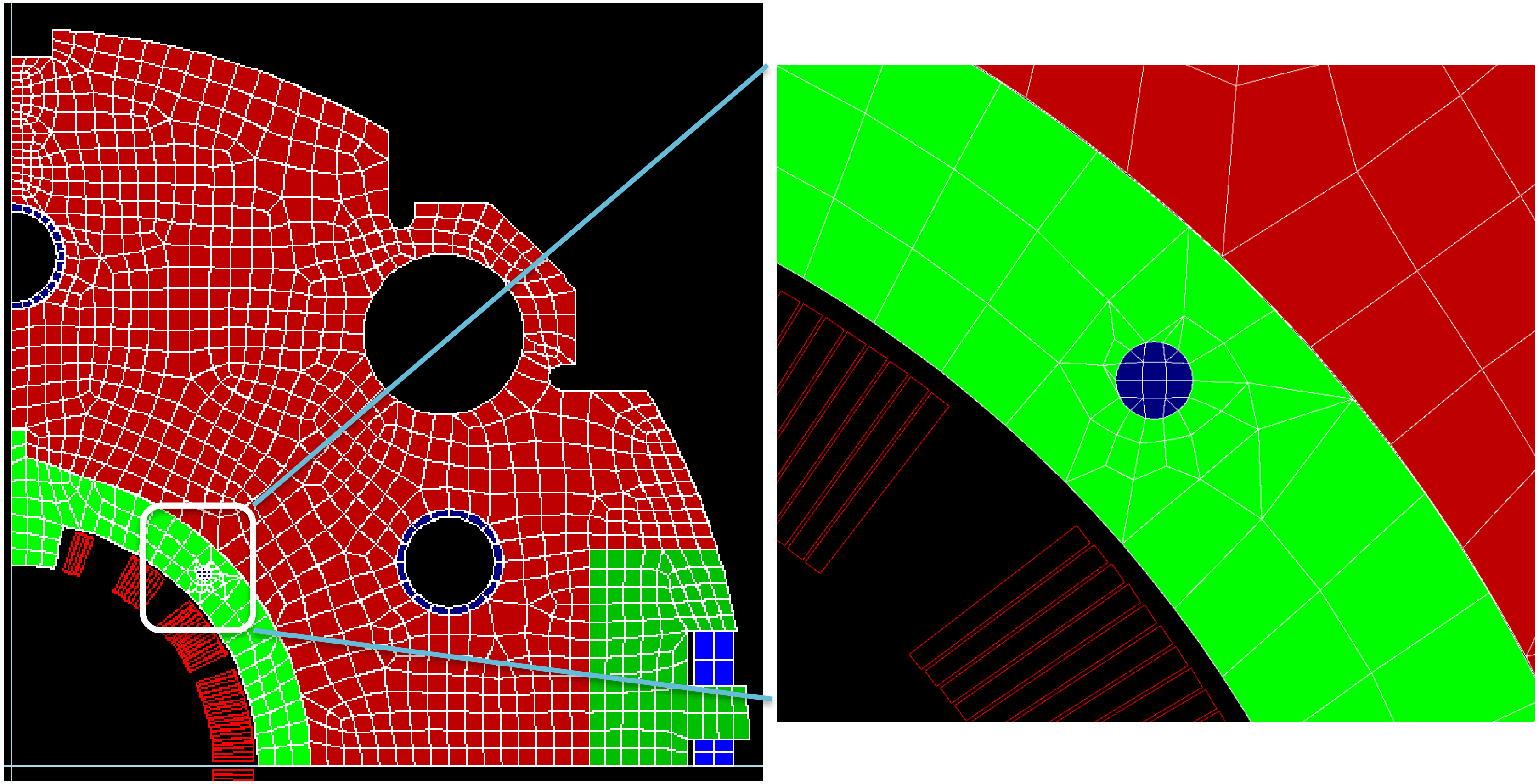
Summary of Cable displacement

Coil block position

CB	Original		Displaced		Delta	
	Phi (degree）	Alpha (degree)	Phi	Alpha	Phi	Alpha
1	1.1358	0	1.0332	0	-0.1026	0
2	27.8743	26	27.6322	26.1464	-0.2421	-0.1464
3	50.2988	52.4205	50.1761	52.2924	-0.1227	-0.1281
4	70.6996	68.0007	70.6587	68.2953	-0.0409	0.2946

The study indicates that the cable has to be displaced O(100 um) toward MP

Other possibility: magnetic material?



- Concern about effects from permeability of the collar pins
- Now we are investigating by introducing a BH curve of this material

Summary

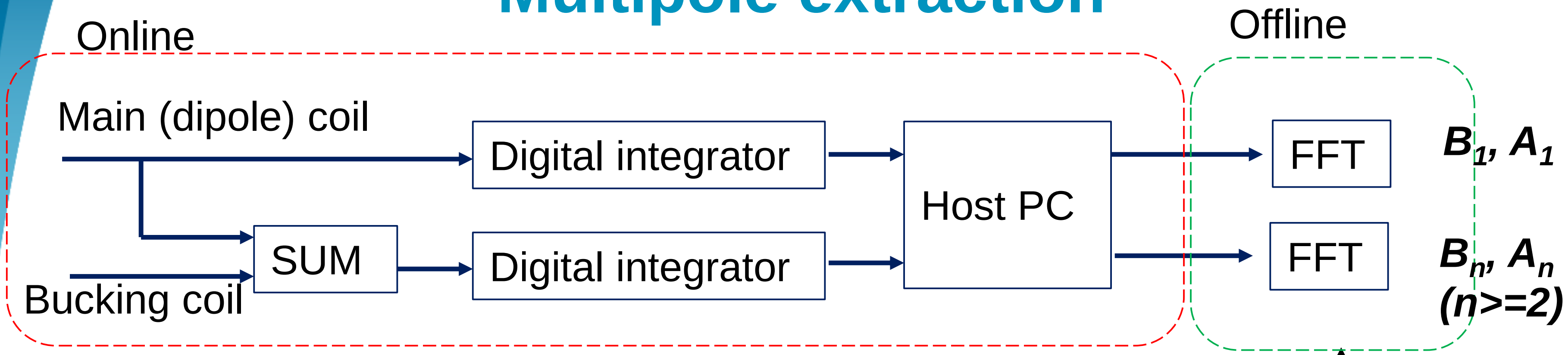
- Quench training
    - Good training result thanks to a increase of the pre-stress
- Field measurement
    - Measured higher multipoles are at the satisfactory level
    - However, we get the big offset in b3, reason of which is still not revealed yet
    - Further investigation is ongoing

Prospect for the 2nd cycle

- We will start the 2nd cycle from 12th Dec.
  - Purpose:
    - Training memory
    - New QPH performance
    - MFM reproducibility
- Fabrication of the 3rd short model, MBXFS3, will be started from 26th Nov.
  - Same cross section as that of the 2nd model
  - Need to establish correction of the b3, if this is reproduced

Supplement

Multipole extraction



Online

Main (dipole) coil

Bucking coil

SUM

Digital integrator

Digital integrator

Host PC

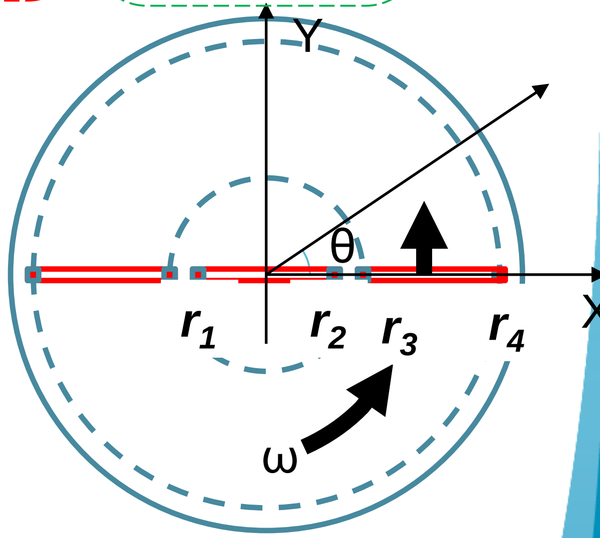
Offline

FFT

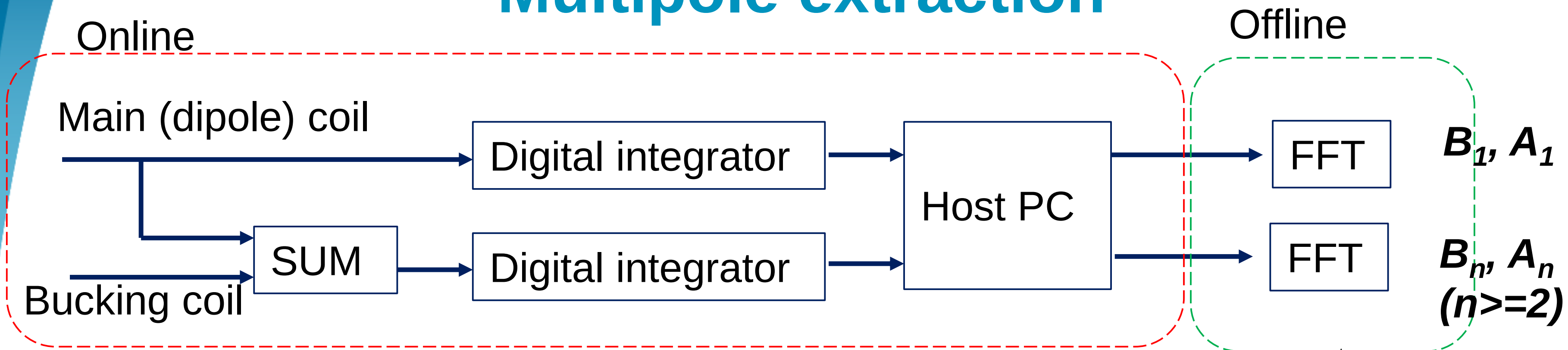
FFT

B_1, A_1

B_n, A_n
$(n>=2)$



Multipole extraction



Online

Main (dipole) coil

Bucking coil

SUM

Digital integrator

Digital integrator

Host PC

Offline

FFT

FFT

***B*$_1$*, A*$_1$**

***B*$_n$*, A*$_n$**

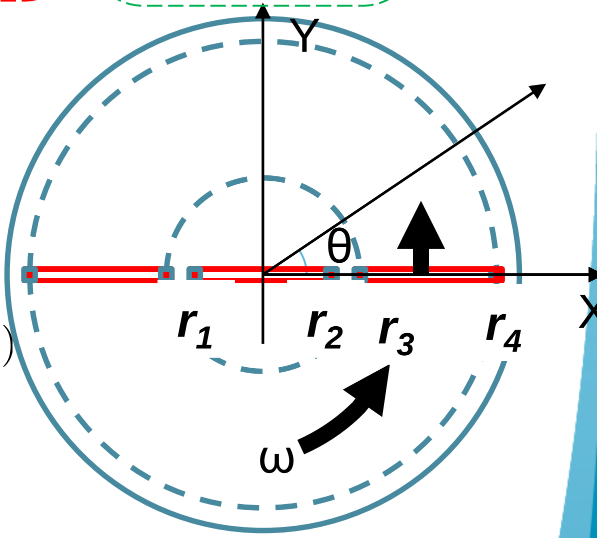
(n>=2)

Induced voltage:

Normal **Skew**

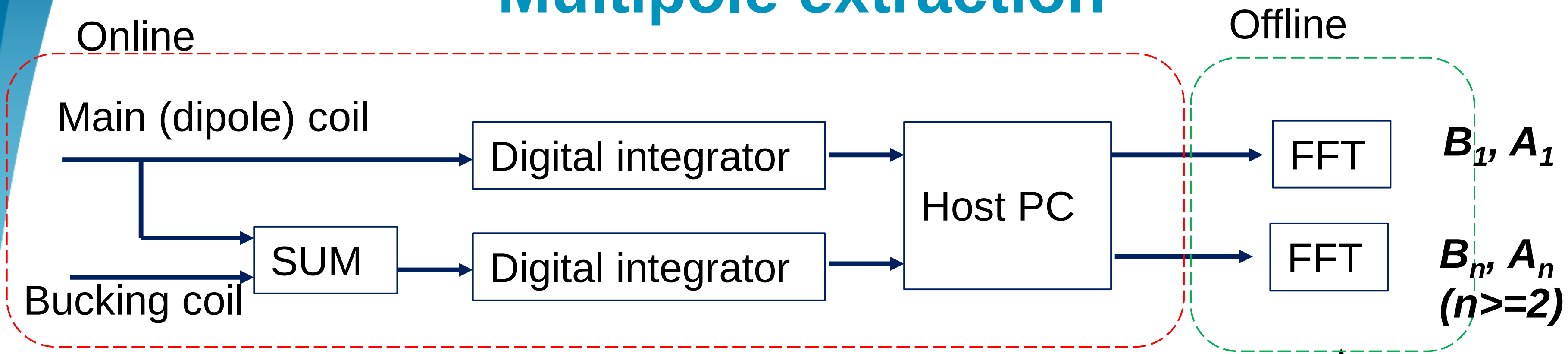
$$V(t) = NL\omega r_{\mathrm{ref}} \left[\sum_{n=1}^{\infty} \frac{1}{n} K_n \left\{ \bigcirc\!\!\!\!\!\!\! B_n (r_{\mathrm{ref}}) \sin \omega t - \bigcirc\!\!\!\!\!\!\! A_n (r_{\mathrm{ref}}) \cos \omega t \right\} \right]$$

$$K_n = \begin{cases} \left(\frac{r_2}{r_{\mathrm{ref}}}\right)^2 - \left(\frac{r_1}{r_{\mathrm{ref}}}\right)^2 & \text{(for dipole signal)} \\ \left\{ \left(\frac{r_2}{r_{\mathrm{ref}}}\right)^2 - \left(\frac{r_1}{r_{\mathrm{ref}}}\right)^2 \right\} - \left\{ \left(\frac{r_4}{r_{\mathrm{ref}}}\right)^2 - \left(\frac{r_3}{r_{\mathrm{ref}}}\right)^2 \right\} & \text{(for bucked signal)} \end{cases}$$



N: # of turns, ***L***: Coil length ***r***$_{ref}$: reference rad. (50mm)

Multipole extraction



Online

Main (dipole) coil

Bucking coil

SUM

Digital integrator

Digital integrator

Host PC

Offline

FFT

FFT

B_1, A_1

B_n, A_n (n>=2)

Induced voltage:

Normal **Skew**

$$V(t) = NL\omega r_{\mathrm{ref}} \left[\sum_{n=1}^{\infty} \frac{1}{n} K_n \left\{ B_n(r_{\mathrm{ref}}) \sin \omega t - A_n(r_{\mathrm{ref}}) \cos \omega t \right\} \right]$$

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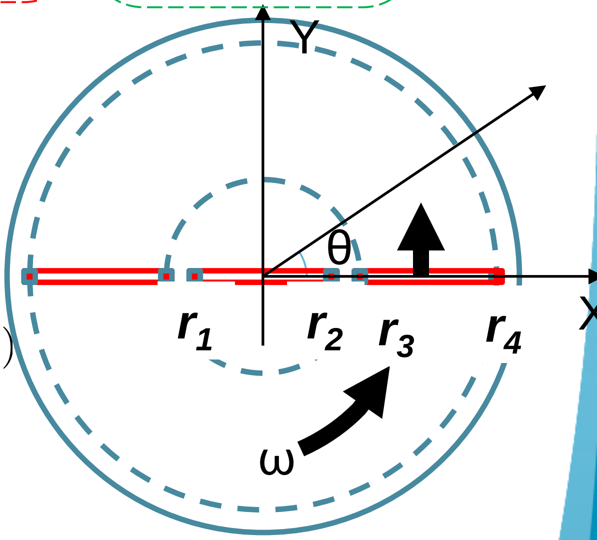
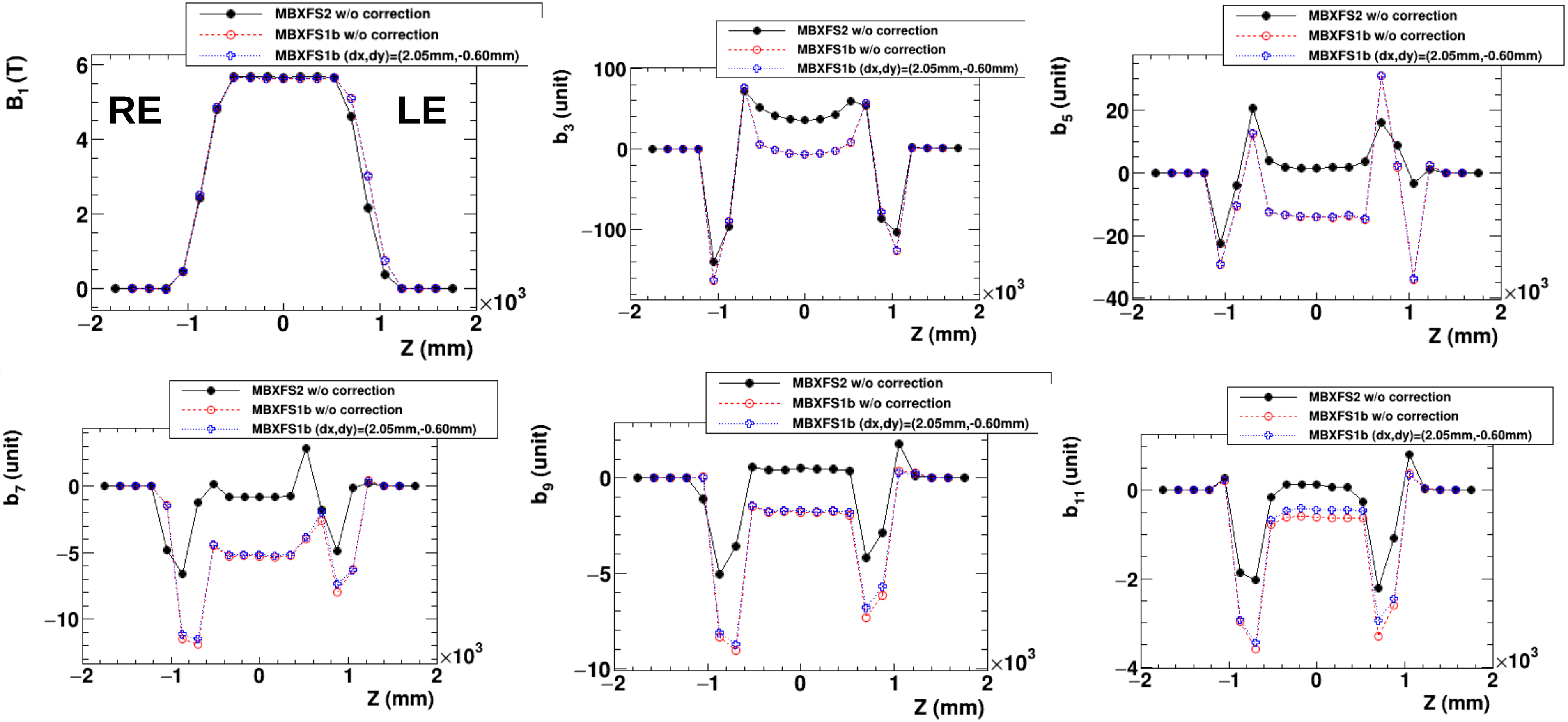


N: # of turns, ***L***: Coil length ***r_{ref}*** : reference rad. (50mm)

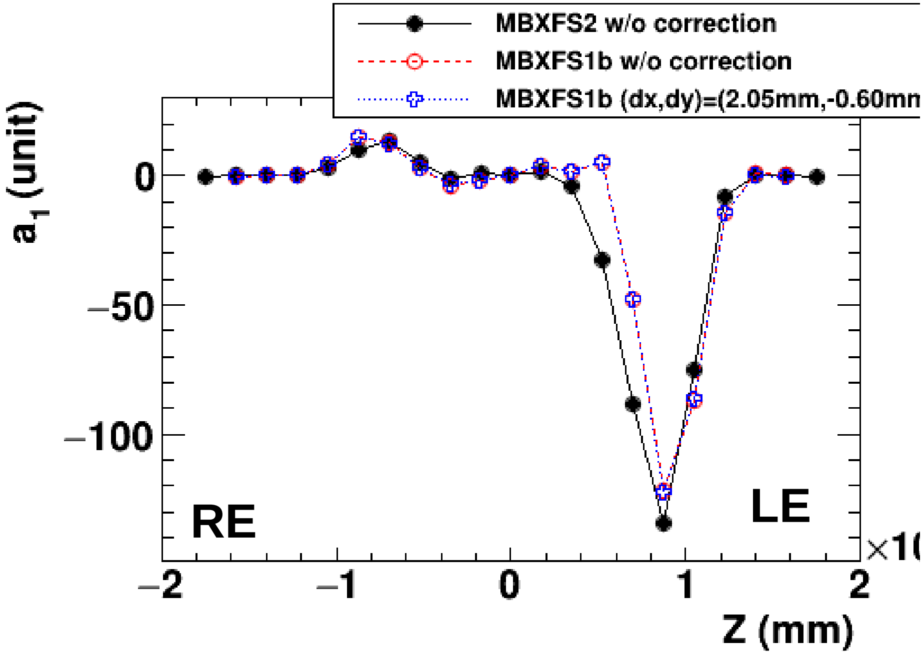
Integrating ***V(t)*** over the given rotation angle
→ vanish ***ω*** (avoid effects from instability in the rotation)

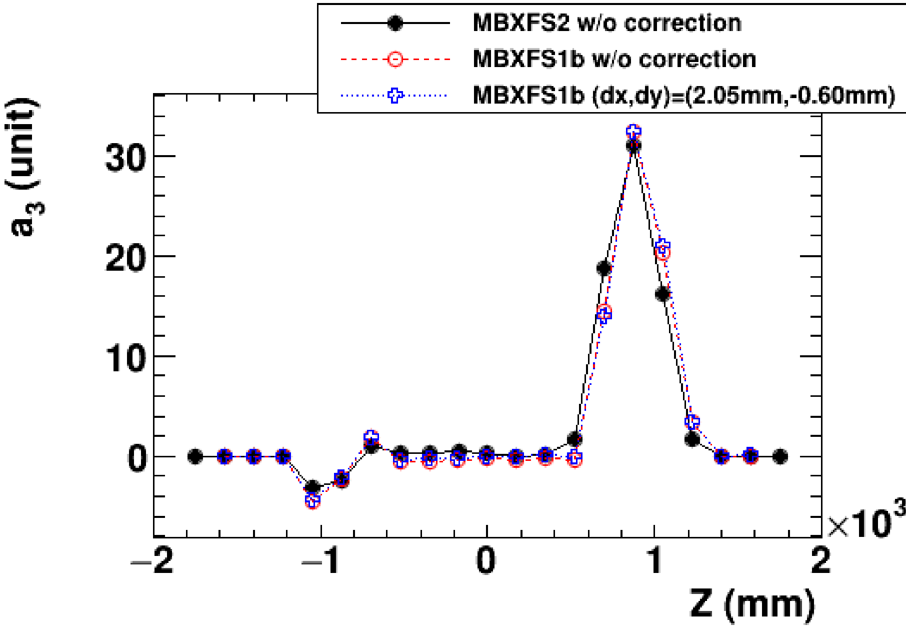
$$\phi(\theta) = \sum_{n=1}^{\infty} \frac{NLr_{\mathrm{ref}}}{n} K_n \left\{ B_n \cos n\theta + A_n \sin n\theta \right\}$$

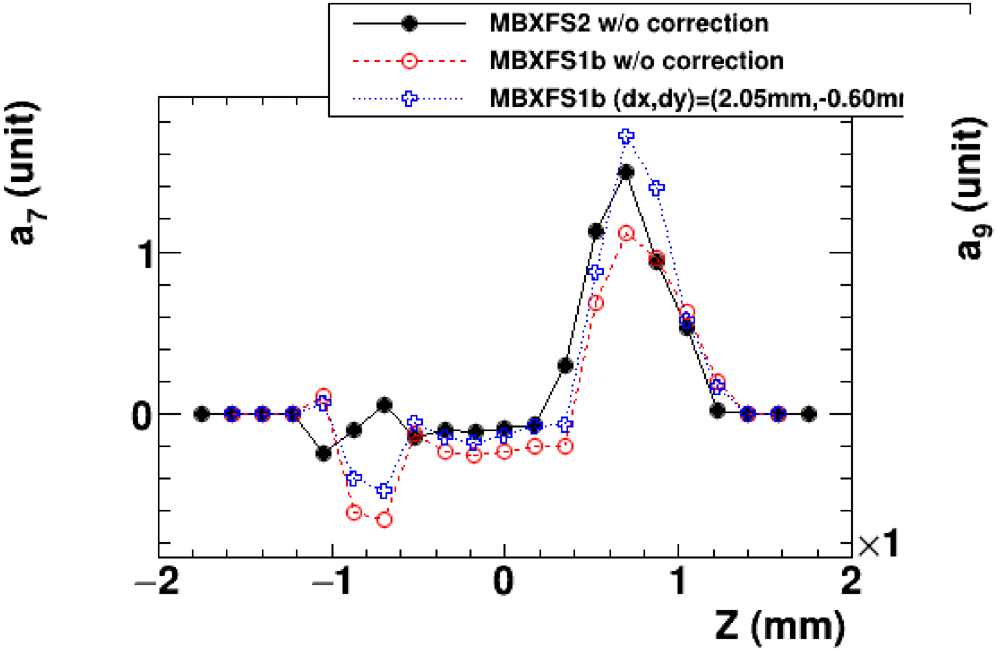
Comparison w/ 1b

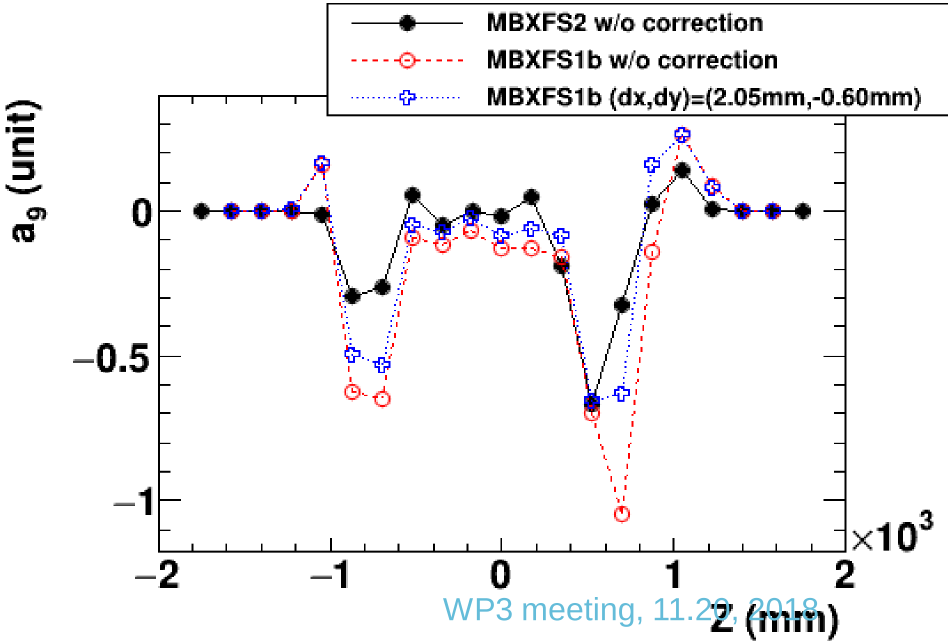


Comparison w/ 1b

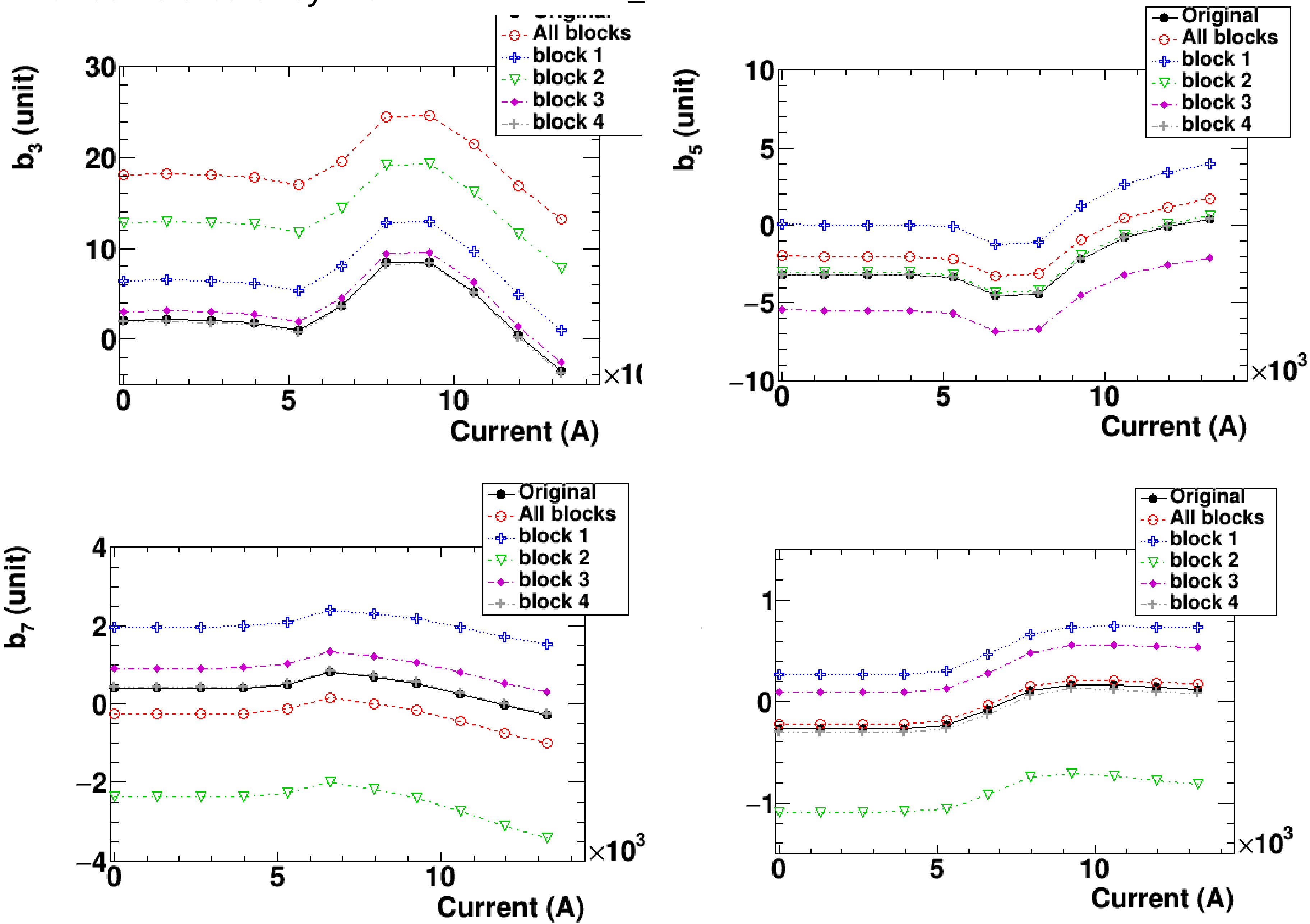




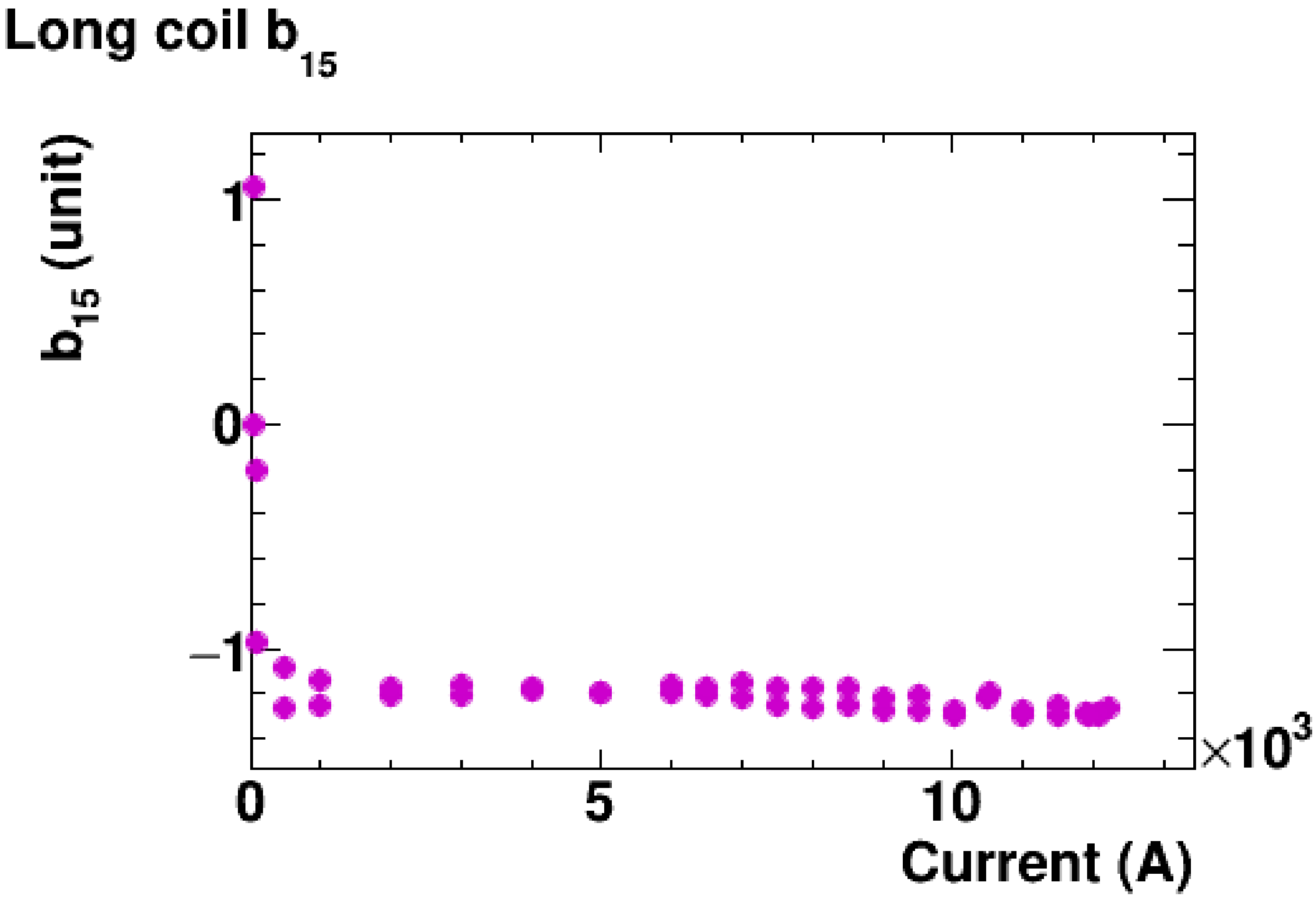




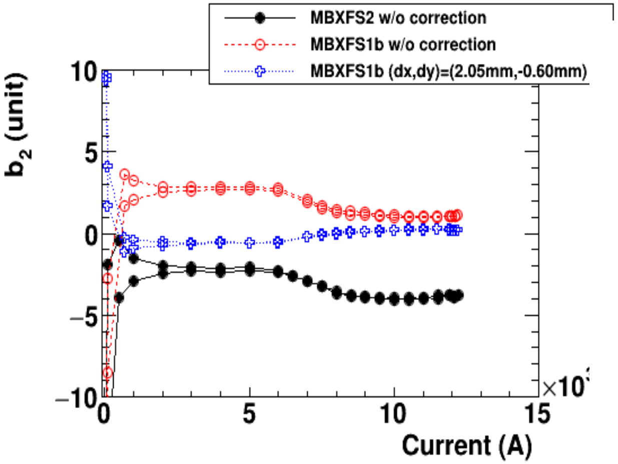
Inverted field calc. by ROXIE

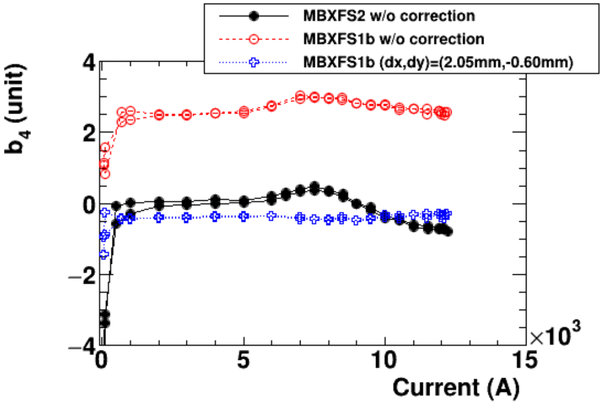


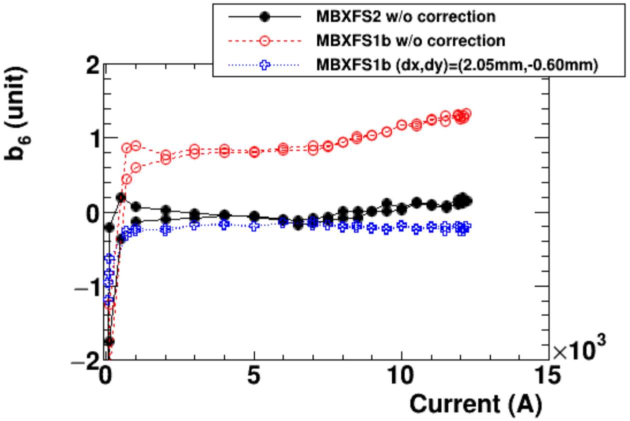
b_{15} : DC loop

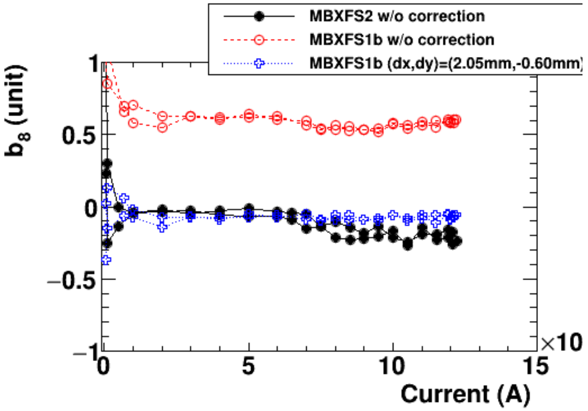


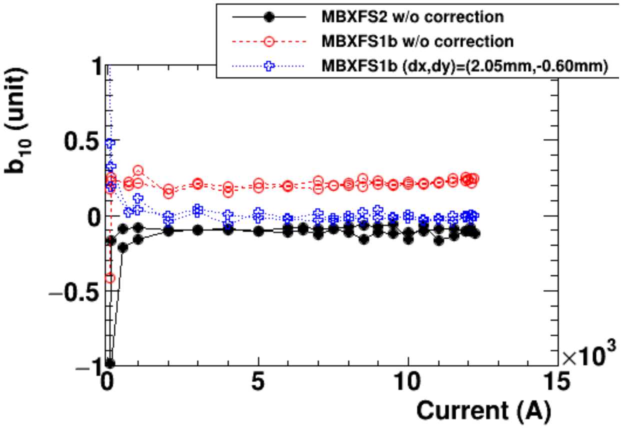
DC loop (non-allowed normal)

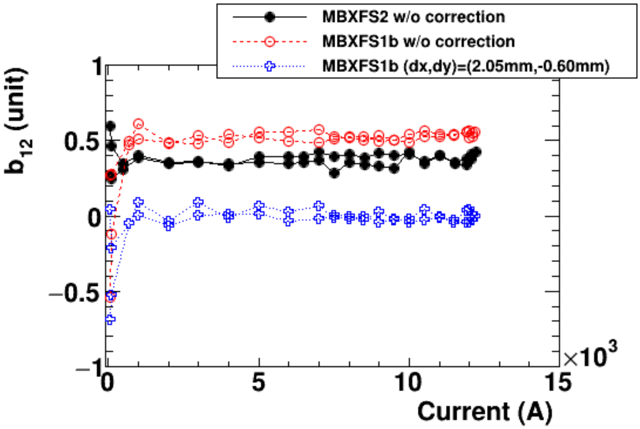




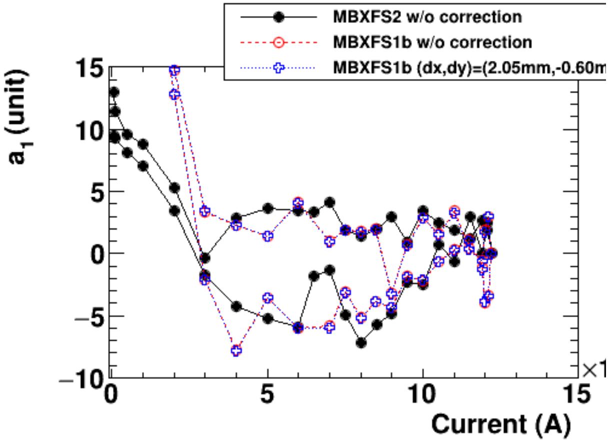


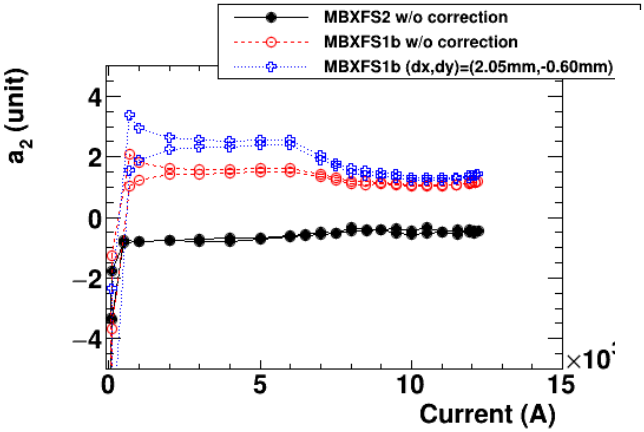


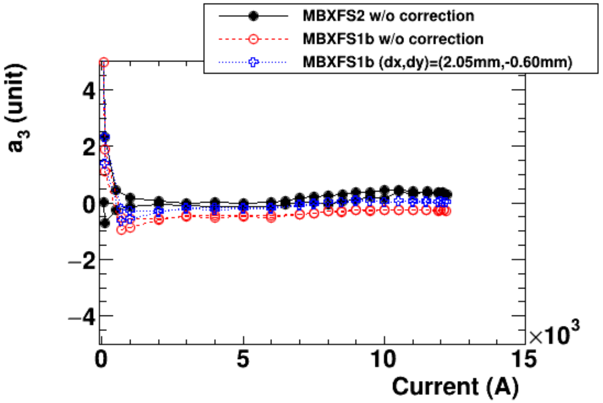


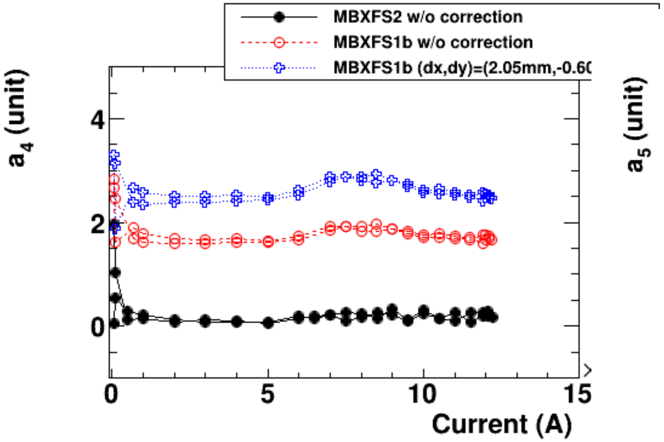


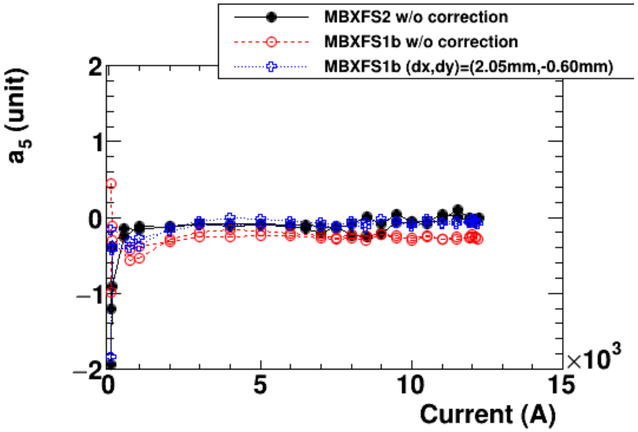
DC loop (Skew, a_1-a_6)

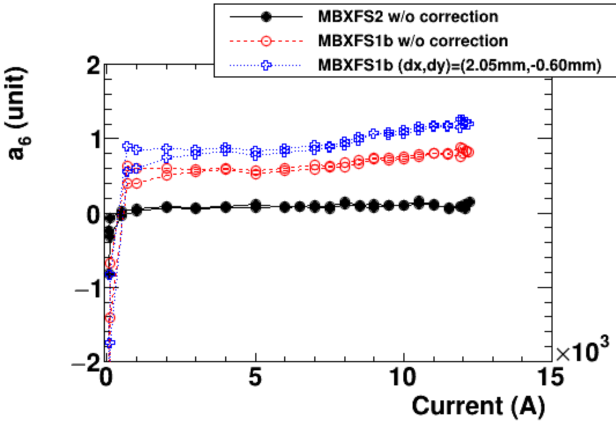




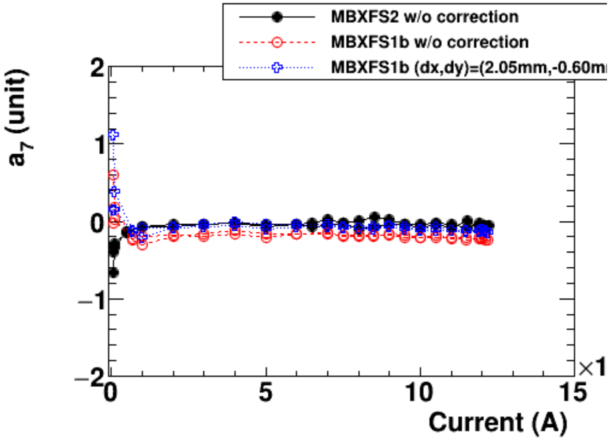


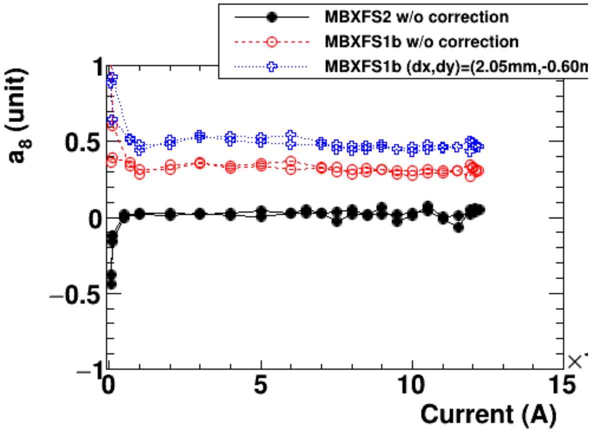


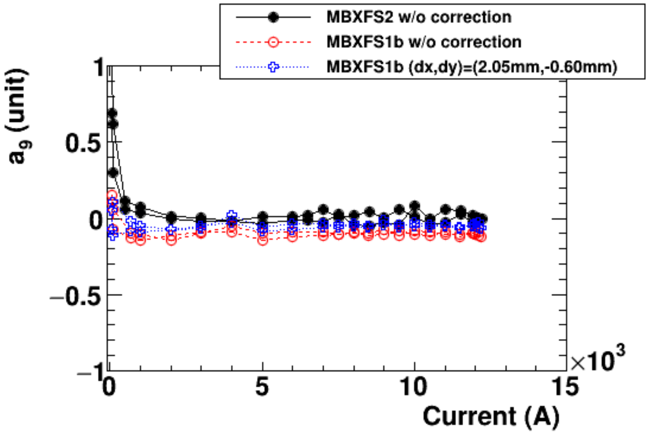


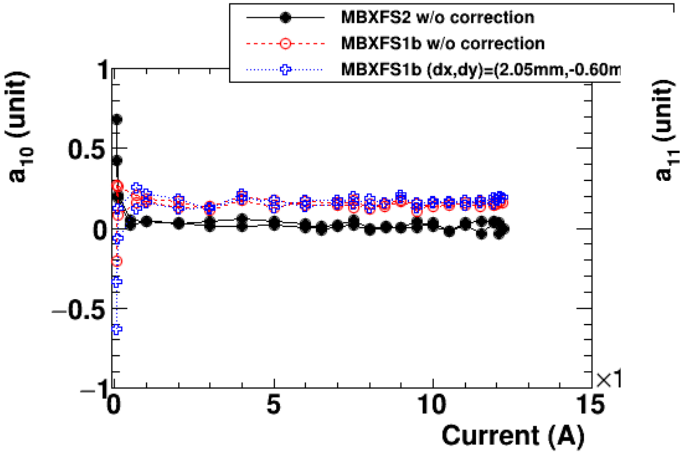


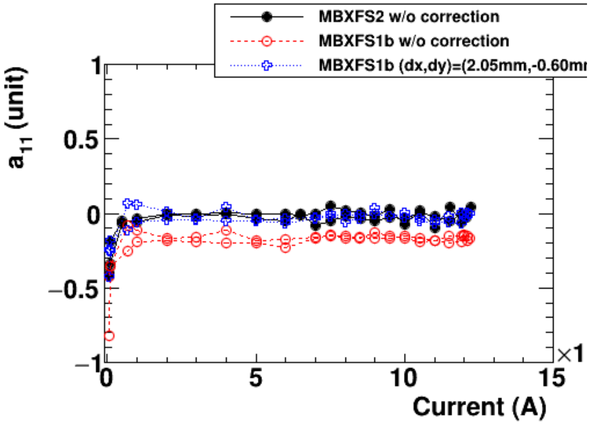
DC loop (Skew, a_7-a_{12})

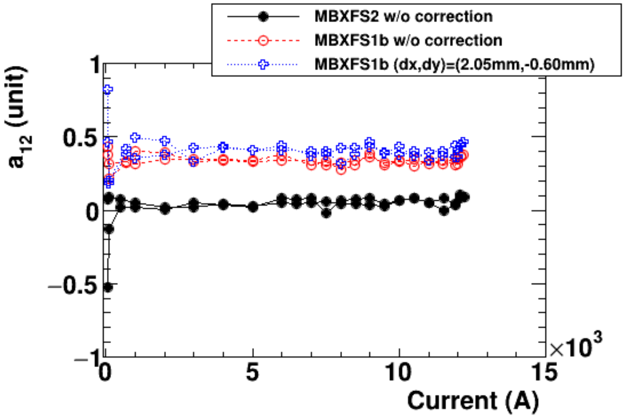




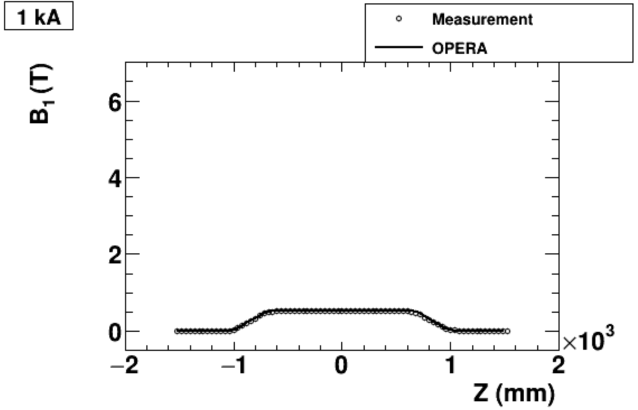


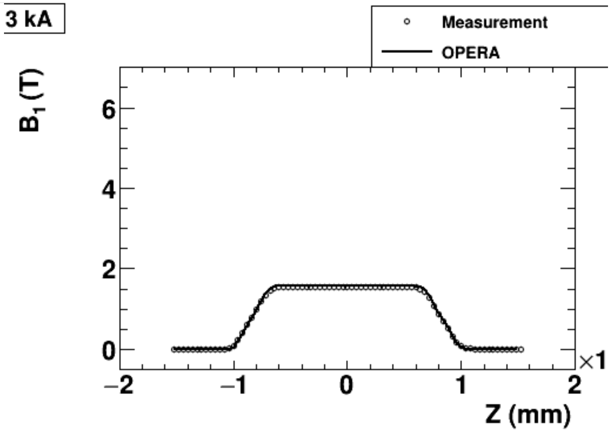


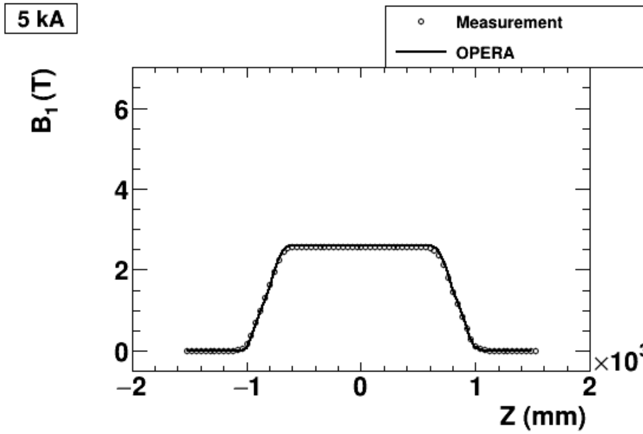


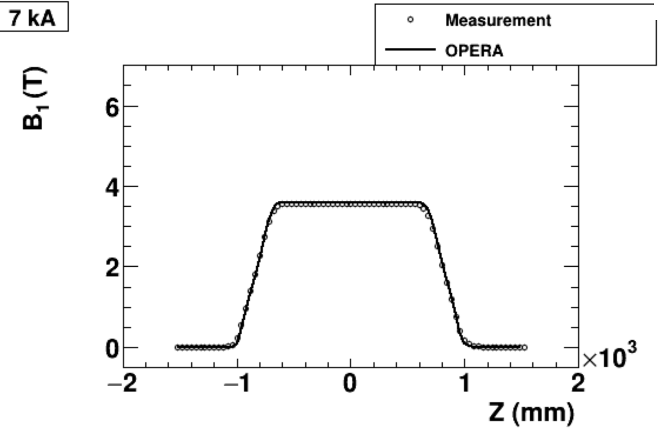


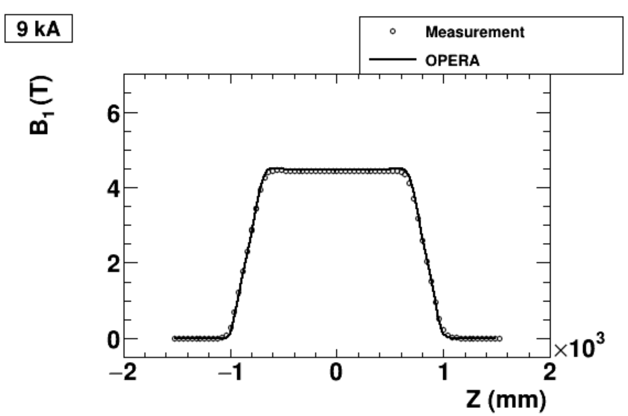
Z scan w/ short coil (B_1)

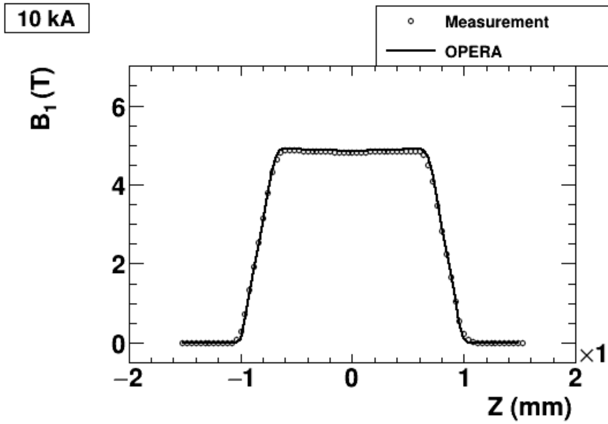

1 kA

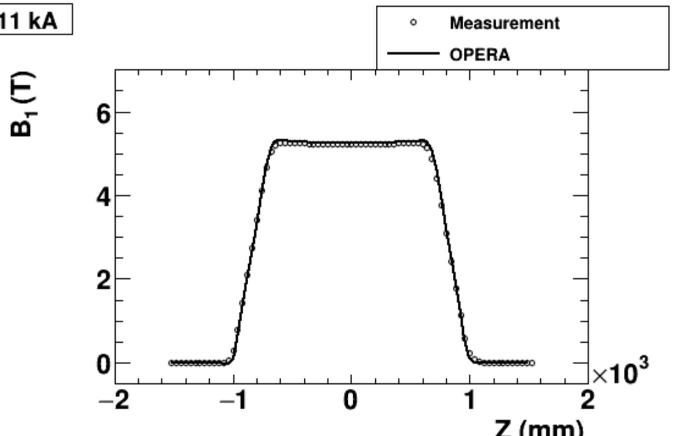

3 kA

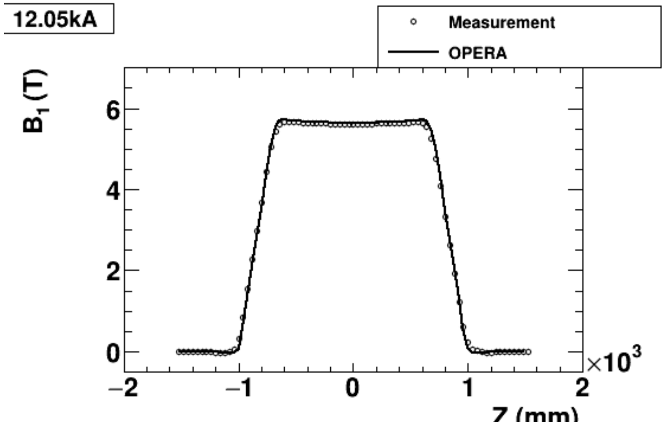

5 kA


7 kA

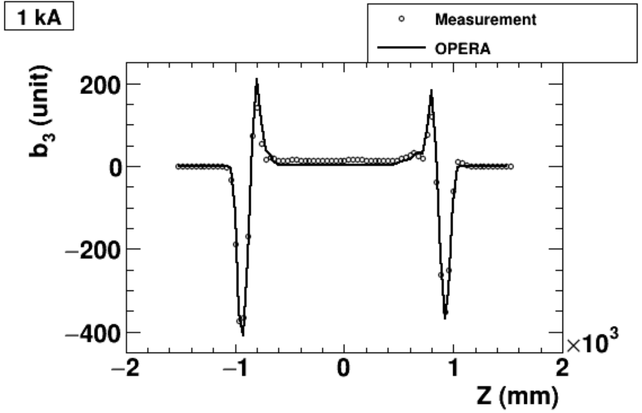

9 kA


10 kA

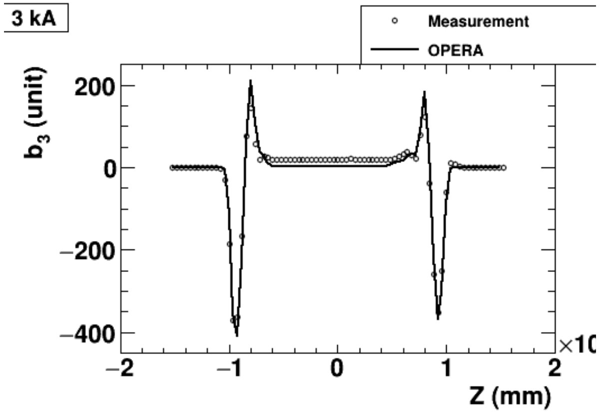

11 kA


12.05kA

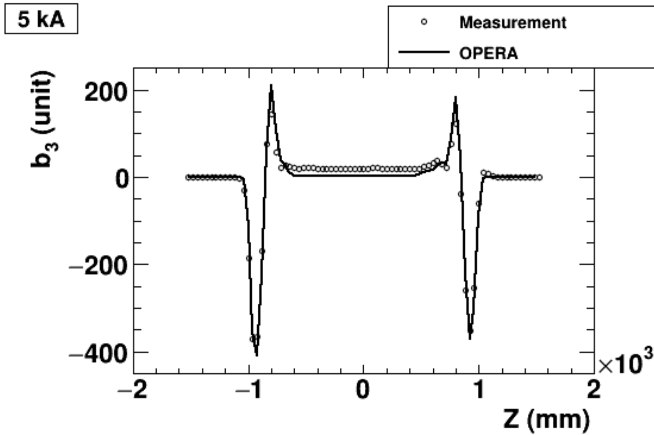
Z scan (b_3)



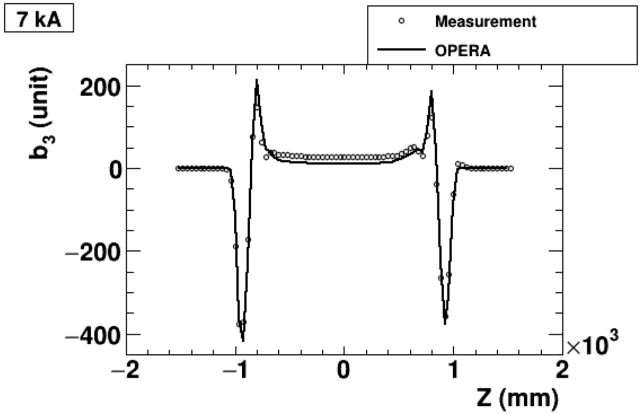
1 kA



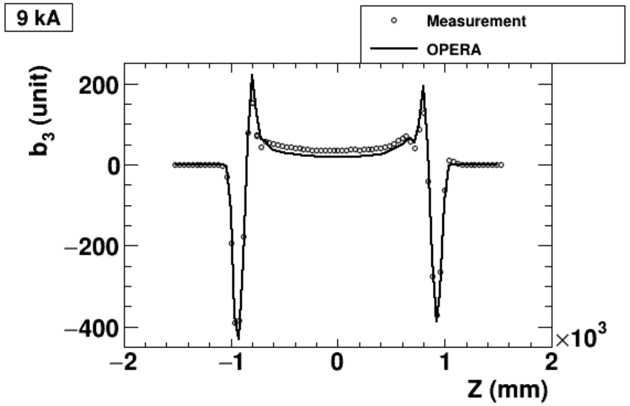
3 kA



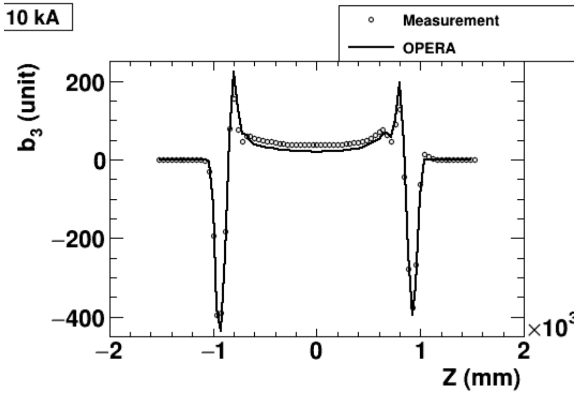
5 kA



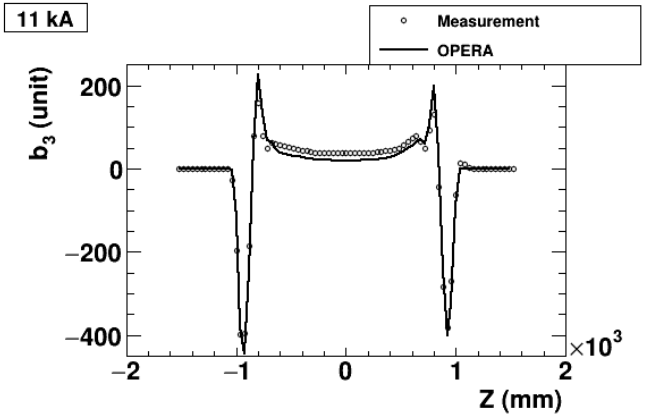
7 kA



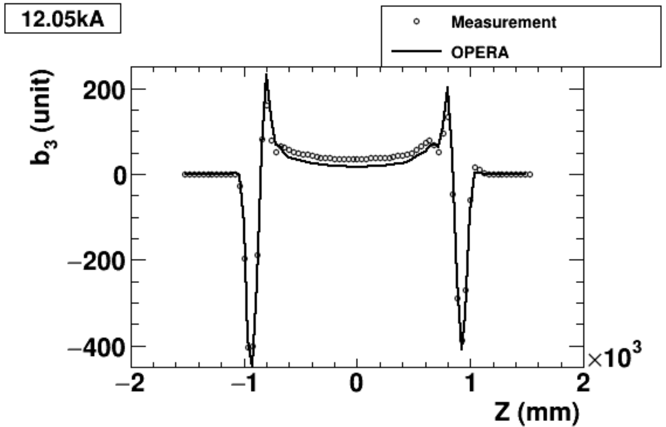
9 kA



10 kA

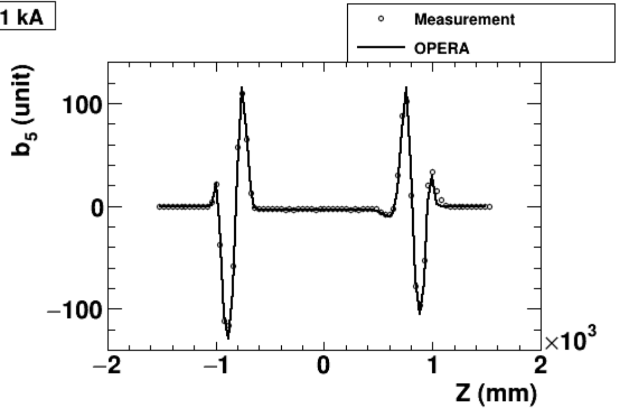


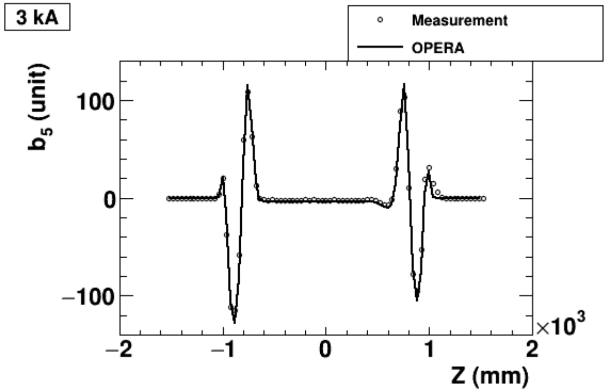
11 kA

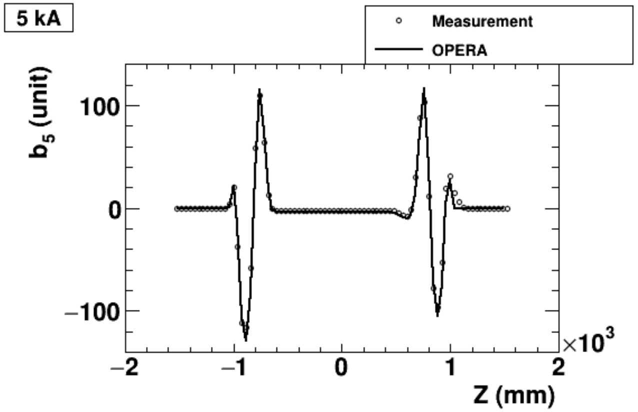


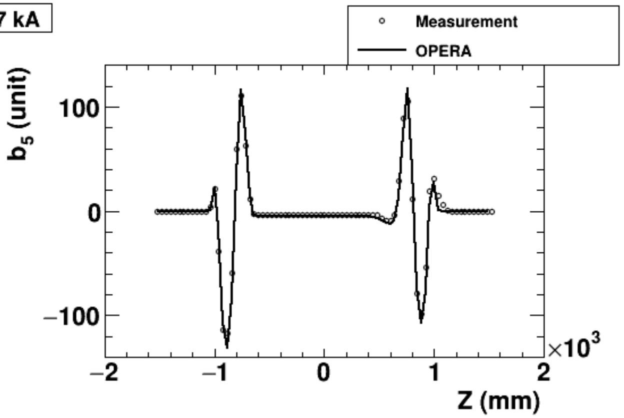
12.05kA

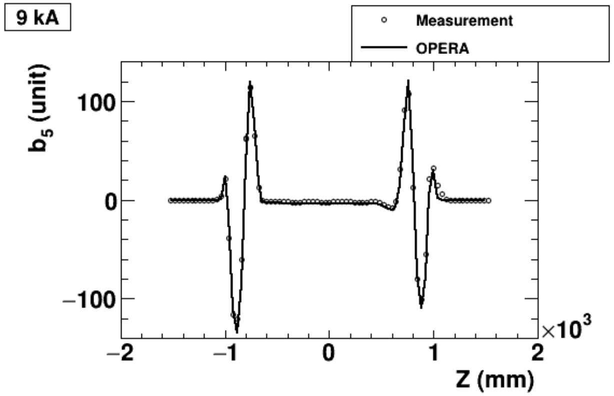
Z scan (b_5)

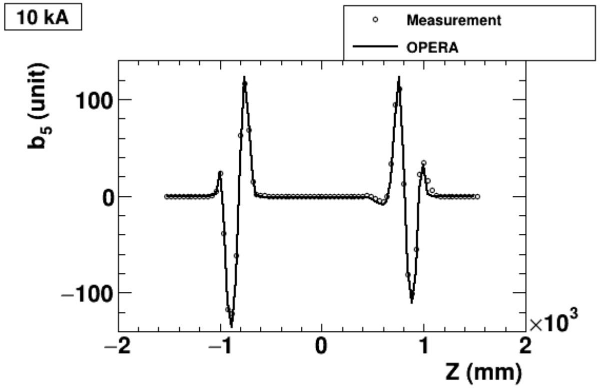

1 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

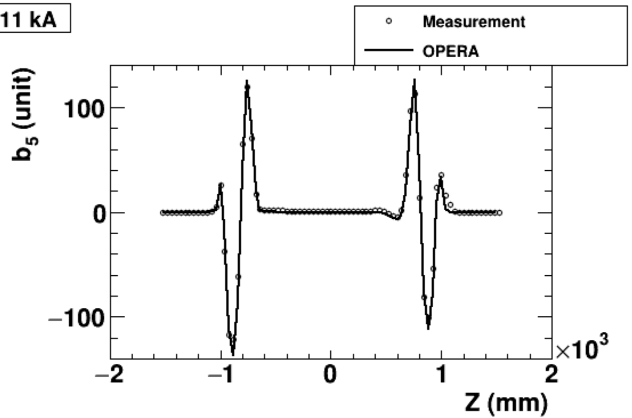

3 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

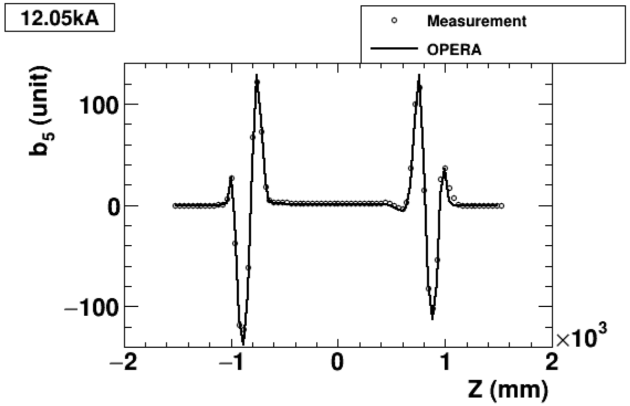

5 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)


7 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

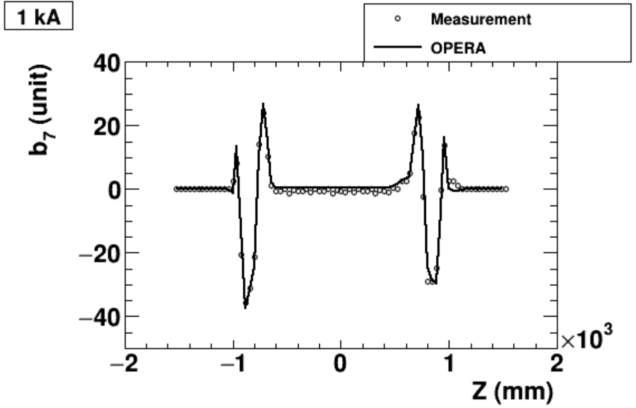

9 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

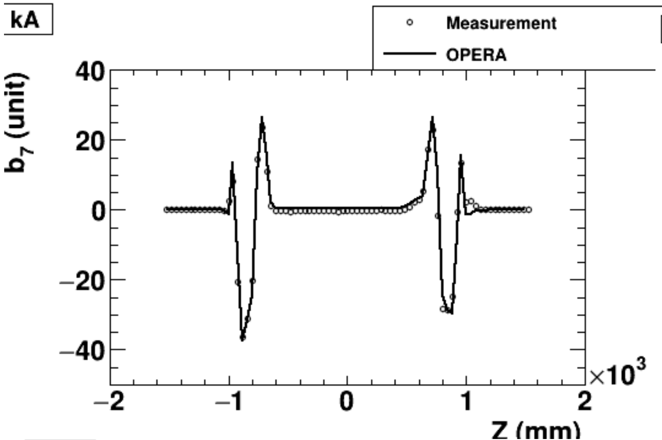

10 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

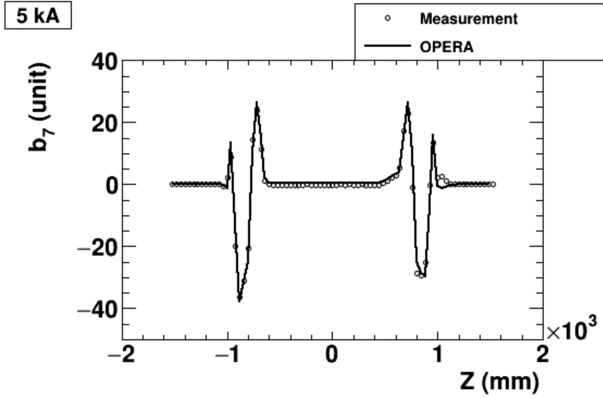

11 kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

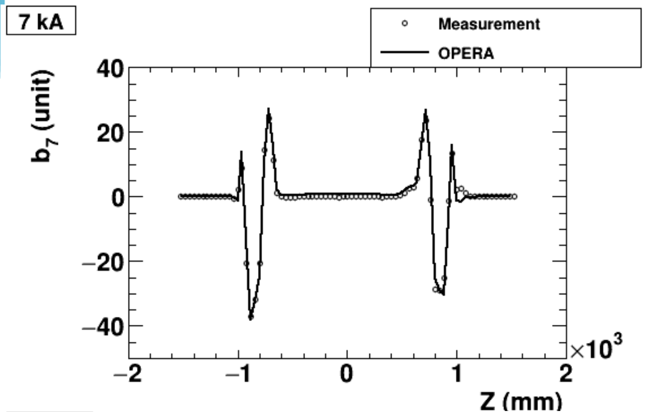

12.05kA
Measurement
OPERA
b_5 (unit)
100
0
−100
−2
−1
0
1
2
×10³
Z (mm)

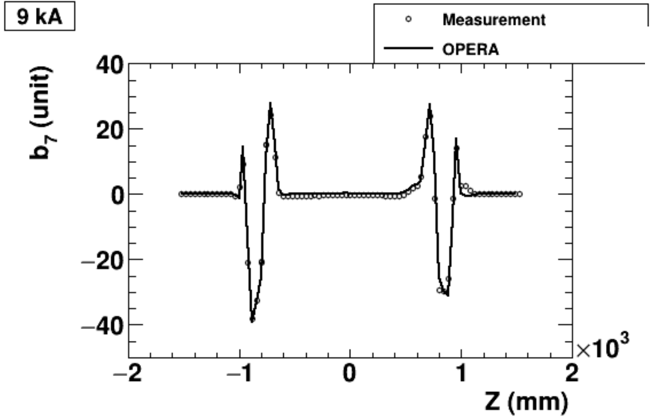
Z scan (b_7)

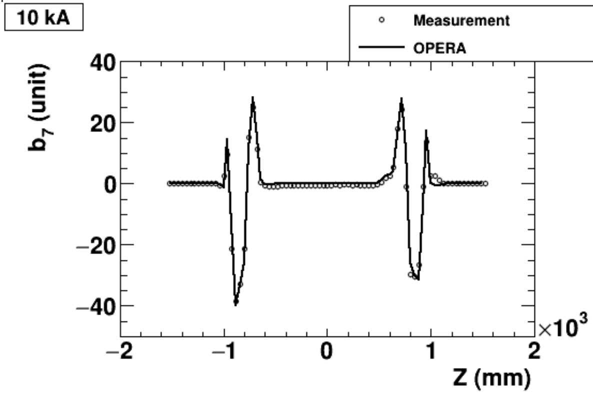

1 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

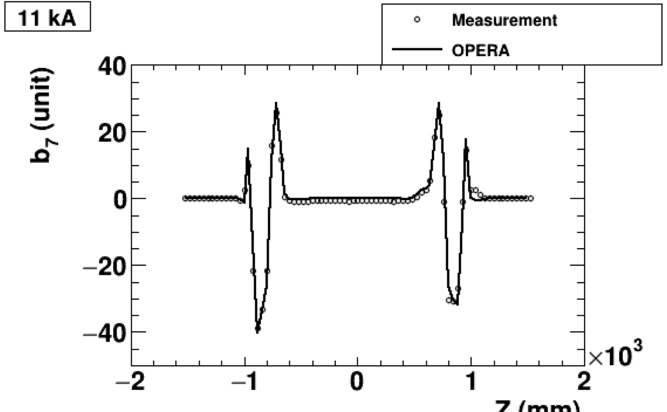

kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

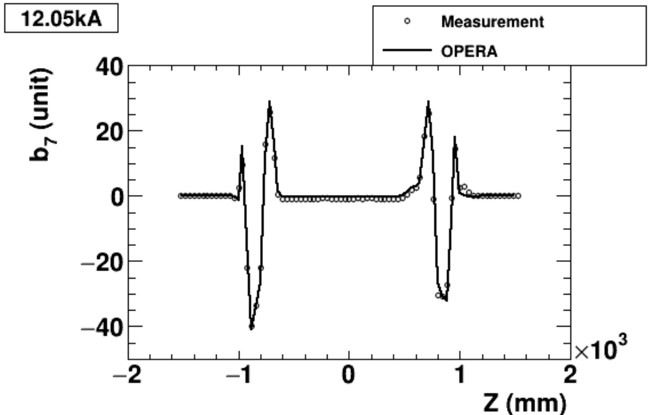

5 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)


7 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

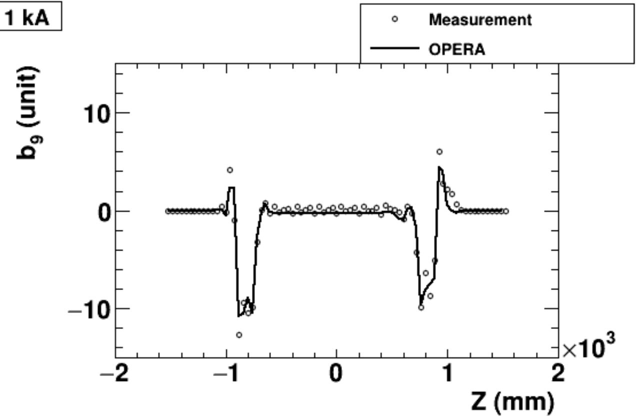

9 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

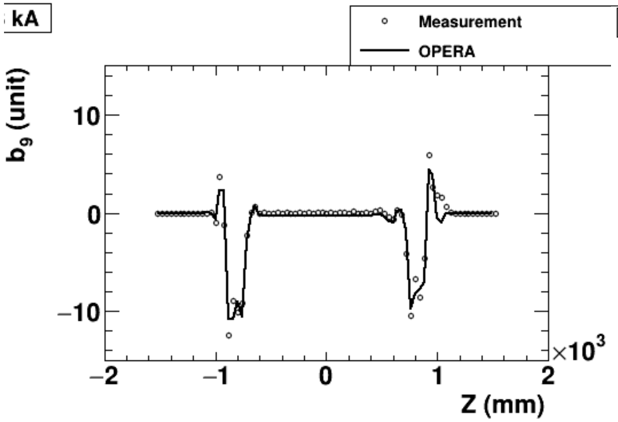

10 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

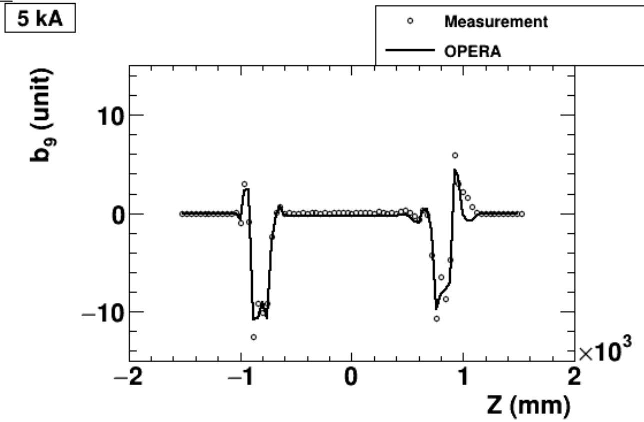

11 kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

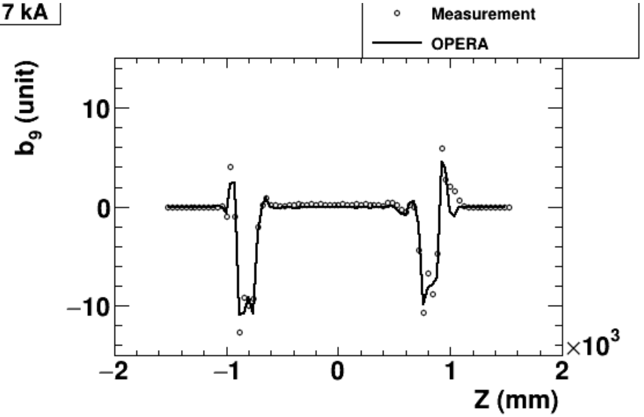

12.05kA
Measurement
OPERA
b7 (unit)
40
20
0
−20
−40
−2
−1
0
1
2
×10³
Z (mm)

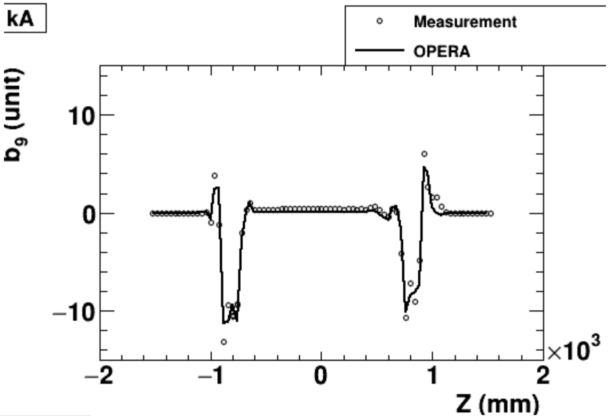
Z scan (b_9)

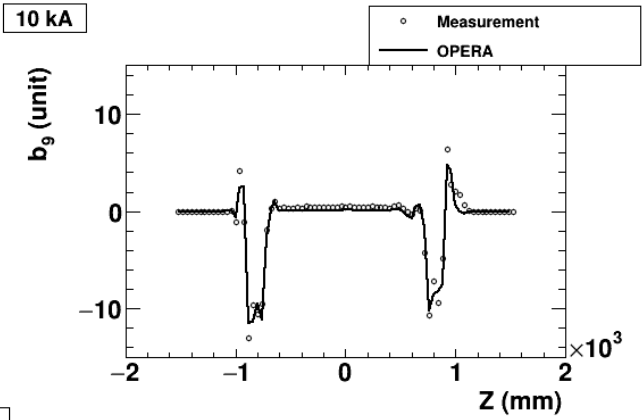

1 kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

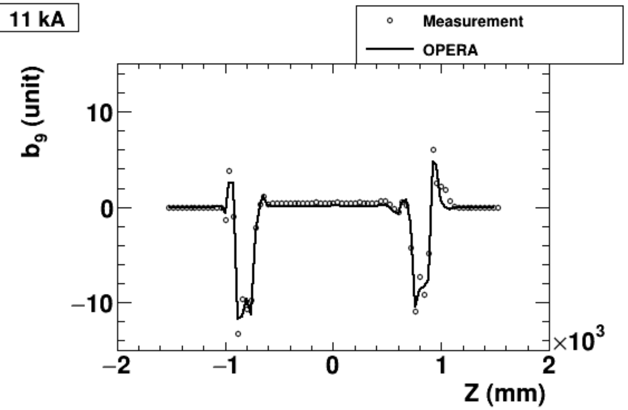

kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

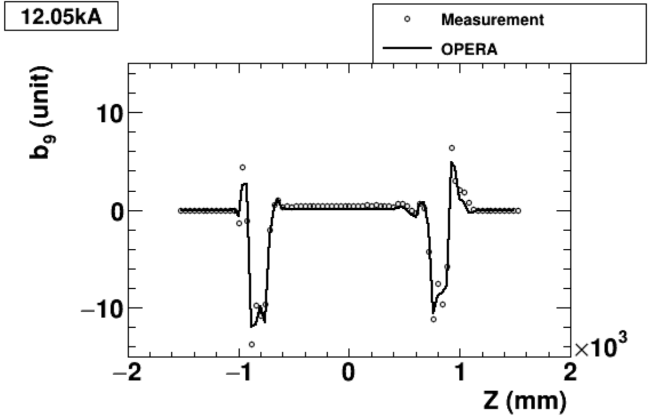

5 kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)


7 kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

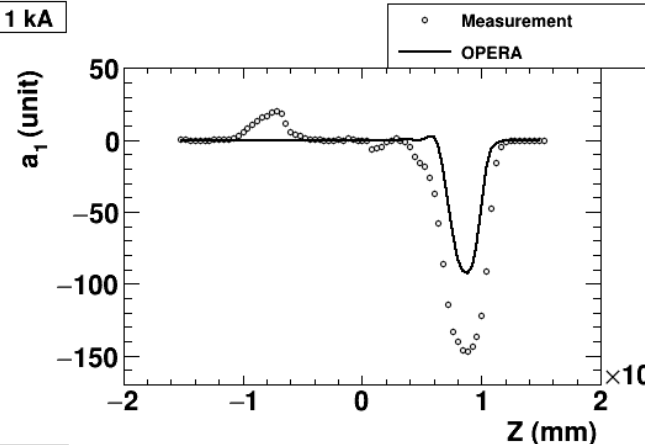

kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

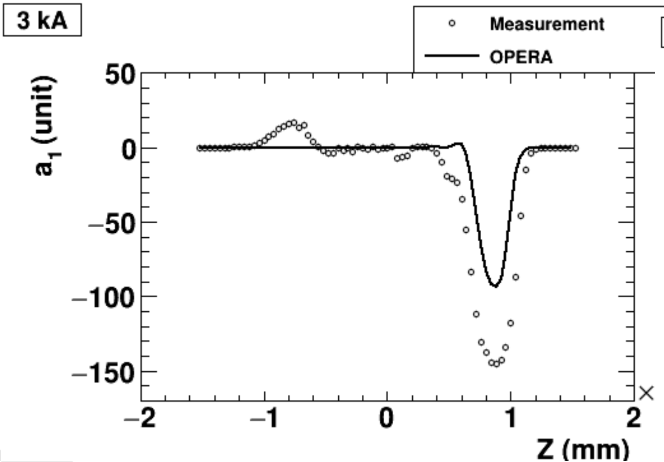

10 kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

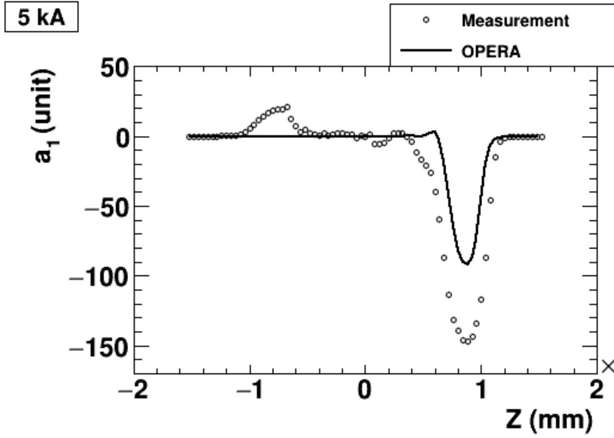

11 kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

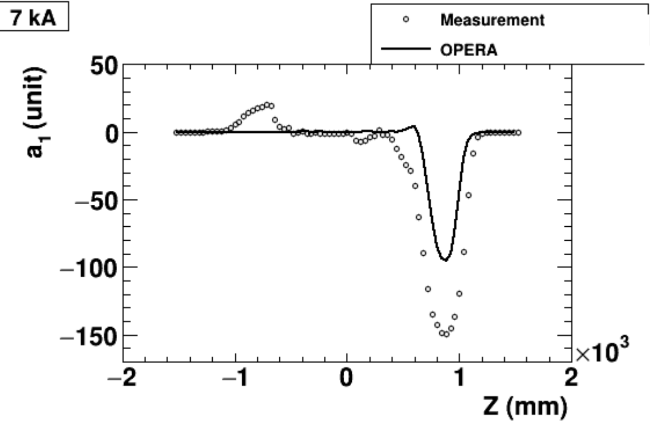

12.05kA
Measurement
OPERA
b9 (unit)
10
0
−10
×10^3
−2
−1
0
1
2
Z (mm)

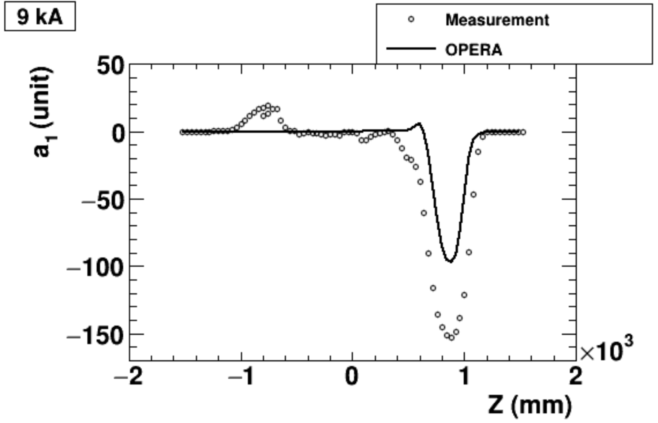
Z scan (a_1)

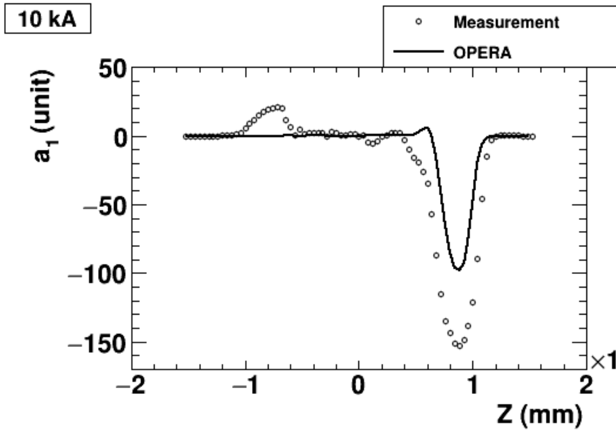

1 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×10

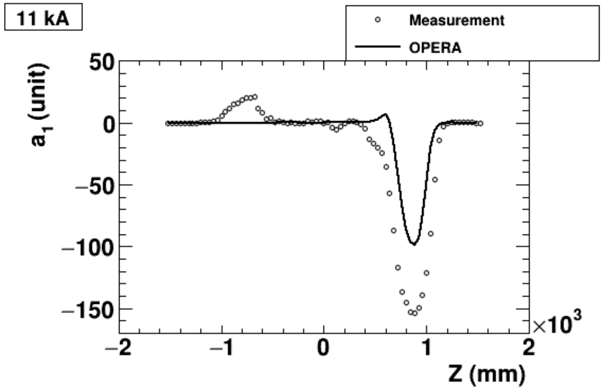

3 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×

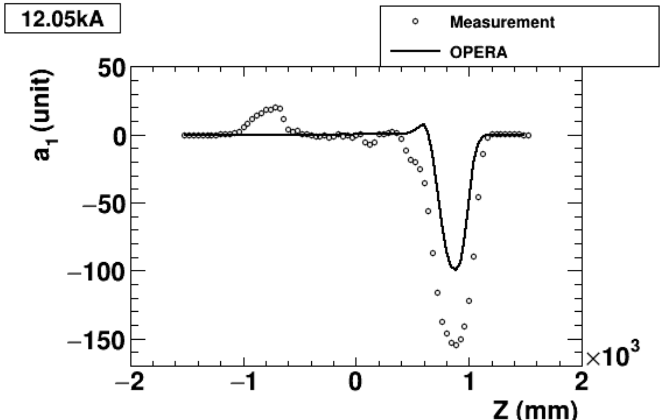

5 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×


7 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×10^3

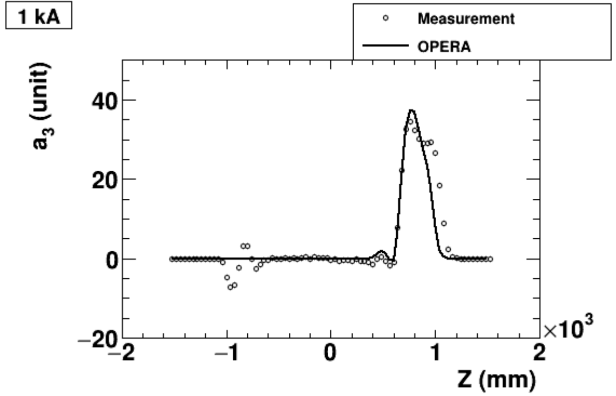

9 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×10^3

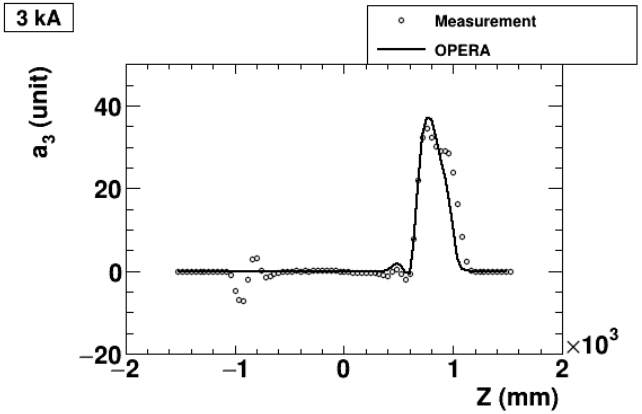

10 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×1

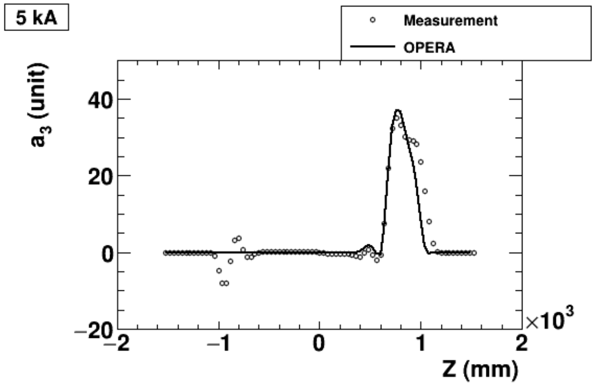

11 kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×10^3

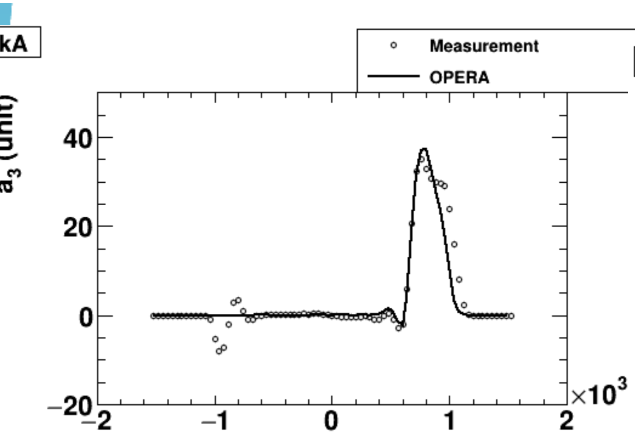

12.05kA
Measurement
OPERA
a1 (unit)
50
0
−50
−100
−150
−2
−1
0
1
2
Z (mm)
×10^3

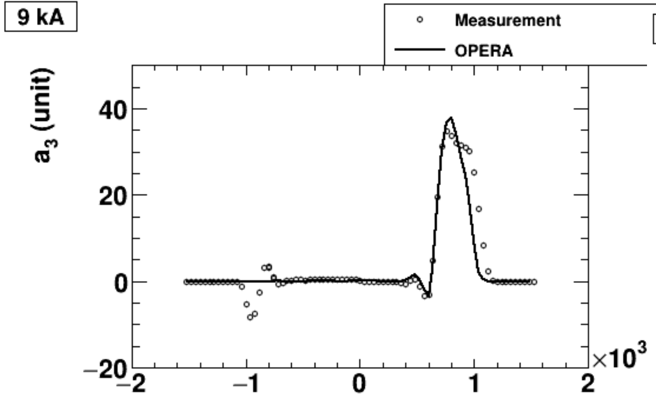
Z scan (a_3)

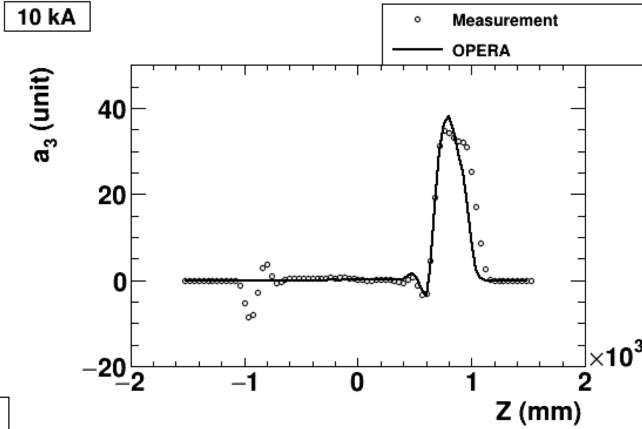

1 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3
Z (mm)

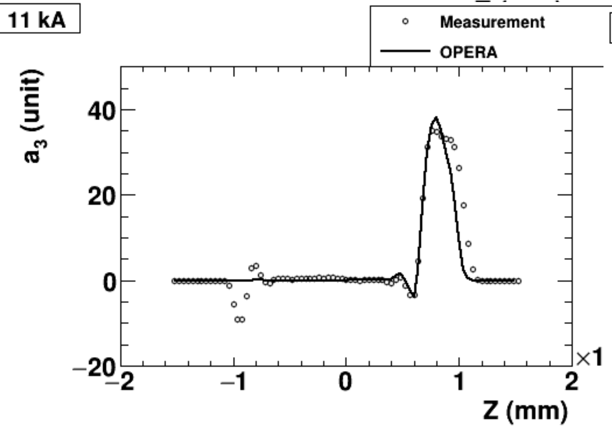

3 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3
Z (mm)

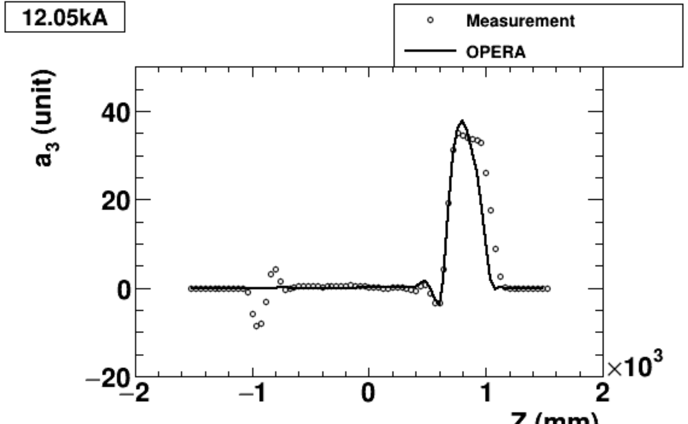

5 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3
Z (mm)


kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3

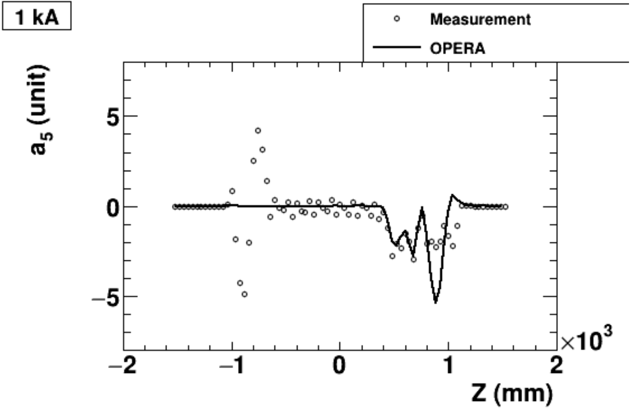

9 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3

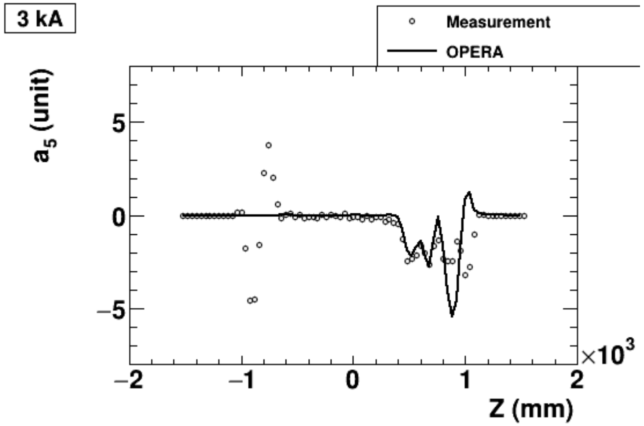

10 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3
Z (mm)

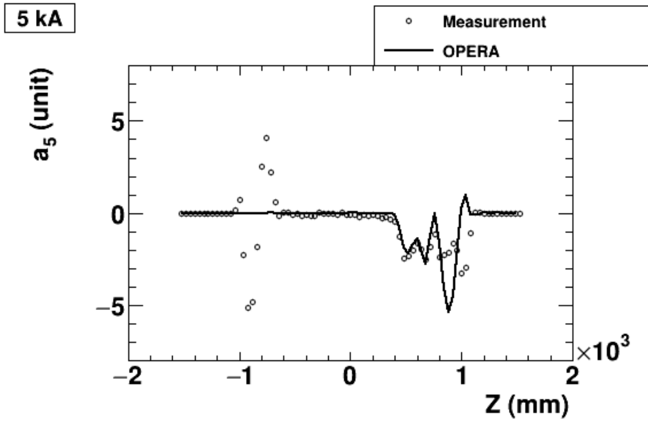

11 kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×1
Z (mm)

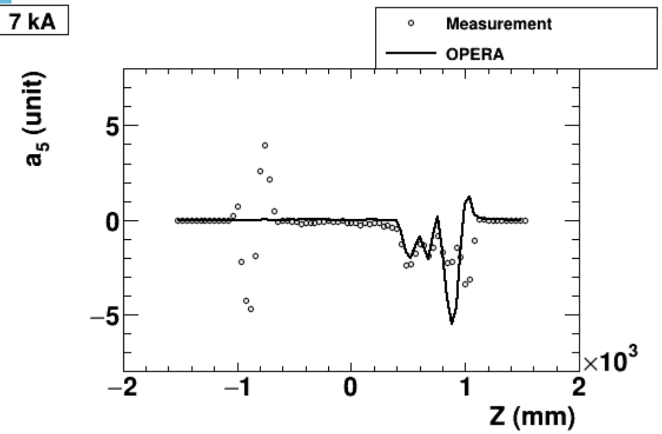

12.05kA
Measurement
OPERA
a3 (unit)
40
20
0
−20
−2
−1
0
1
2
×10^3
Z (mm)

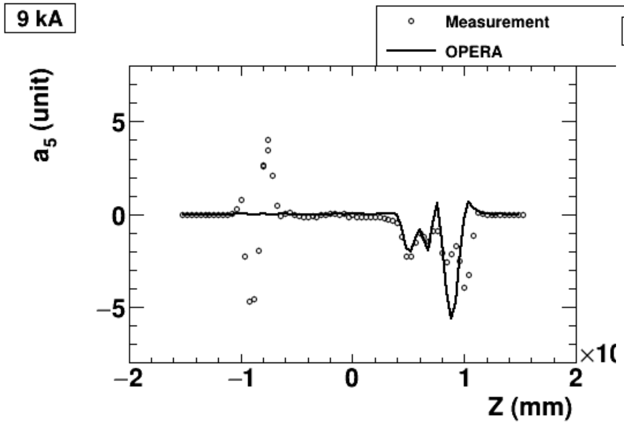
Z scan (a_5)

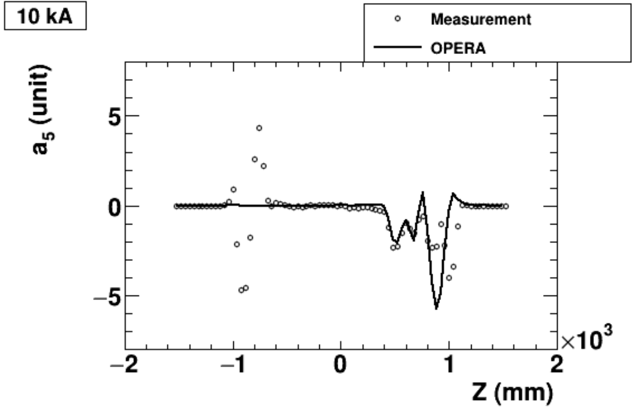

1 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

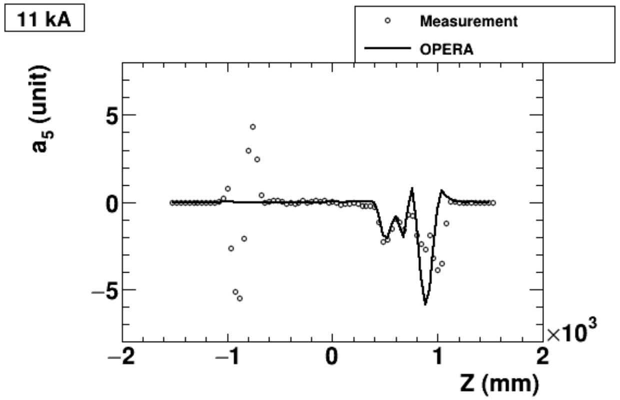

3 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

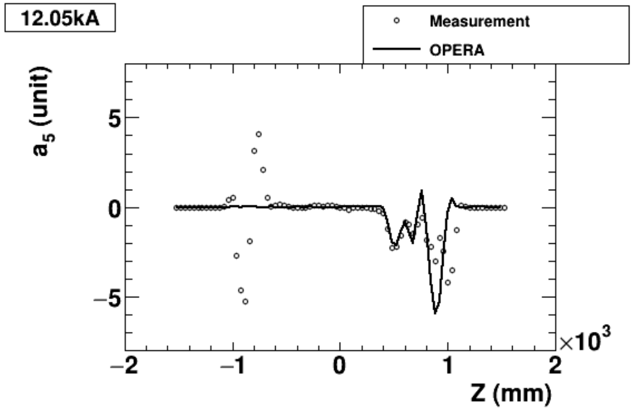

5 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)


7 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

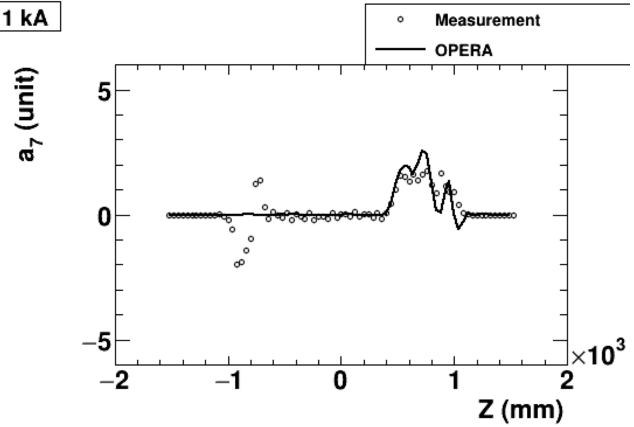

9 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×1(
Z (mm)

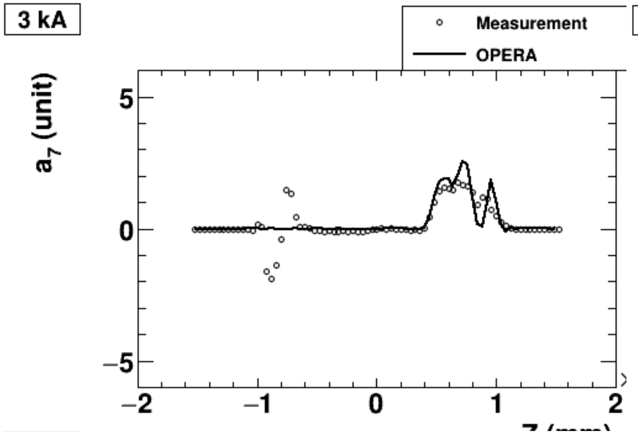

10 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

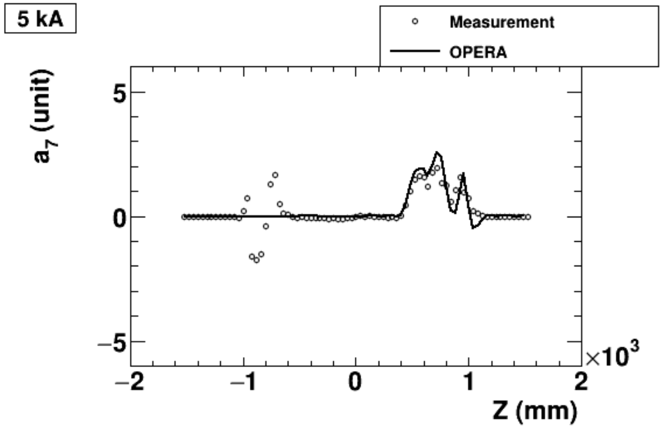

11 kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

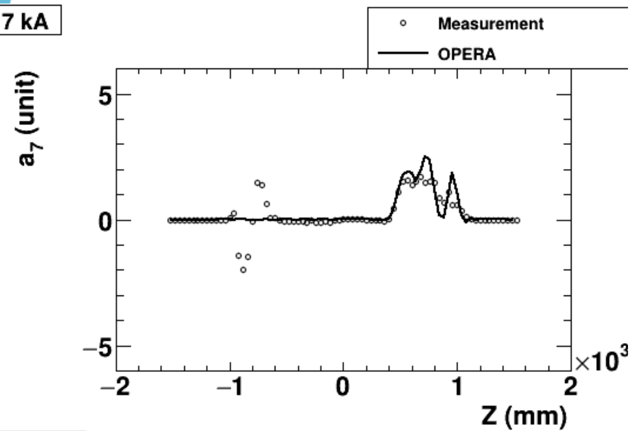

12.05kA
Measurement
OPERA
a5 (unit)
5
0
−5
−2
−1
0
1
2
×10^3
Z (mm)

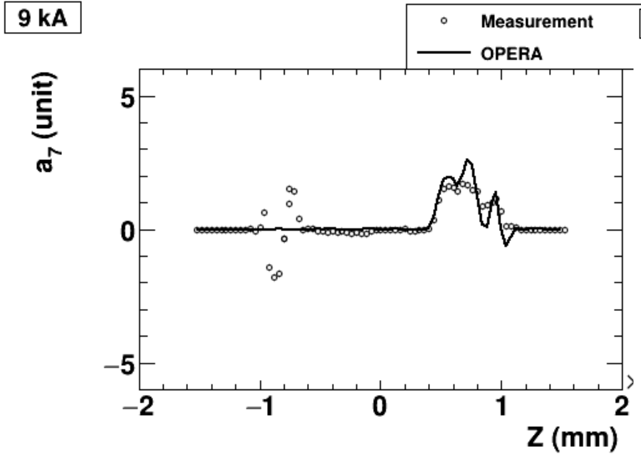
Z scan (a_7)

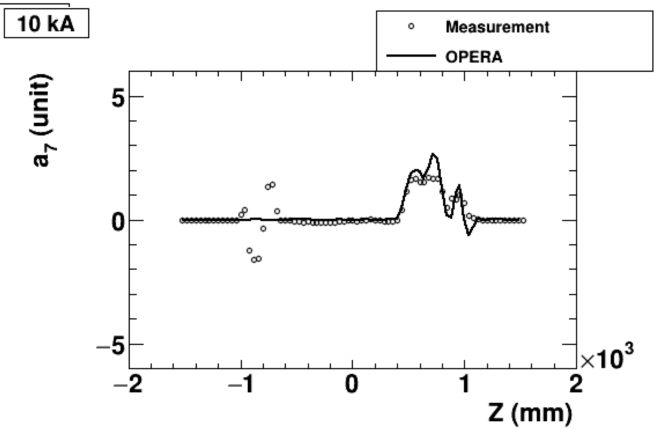

1 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10³
Z (mm)

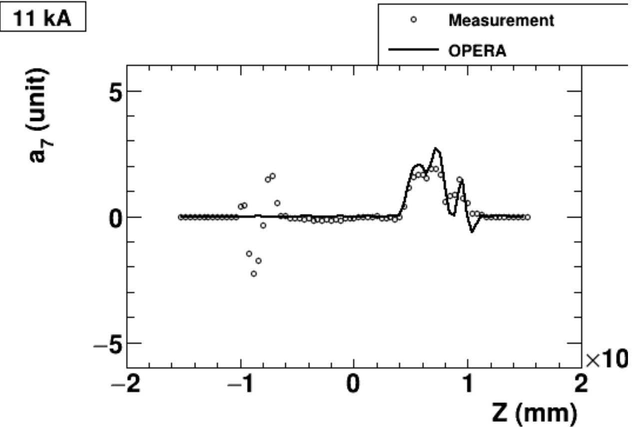

3 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2

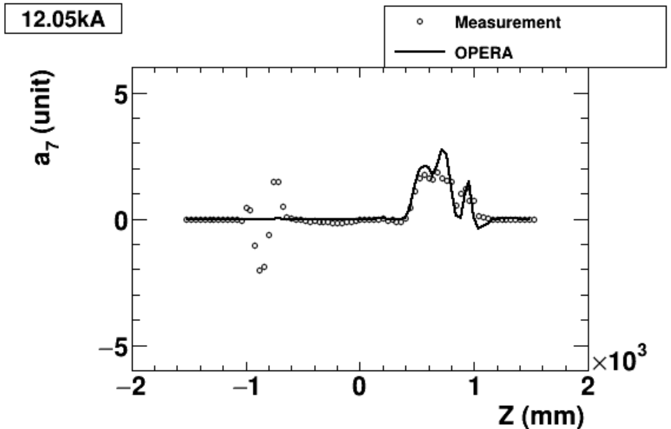

5 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10³
Z (mm)


7 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10³
Z (mm)

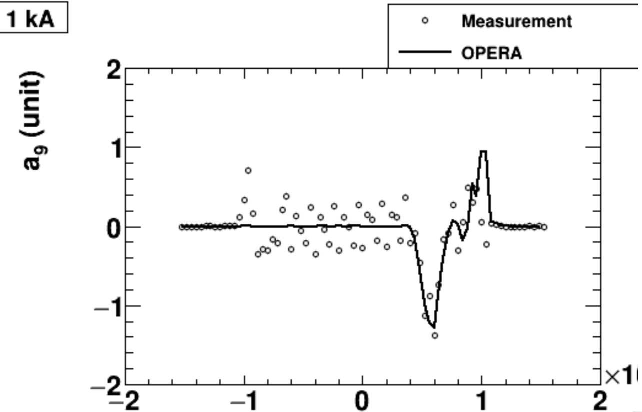

9 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
Z (mm)

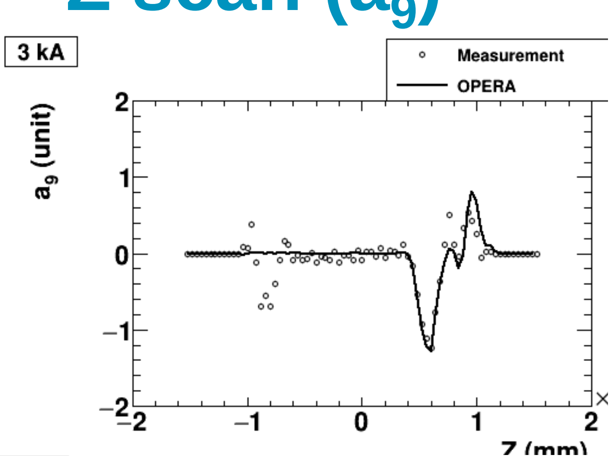

10 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10³
Z (mm)

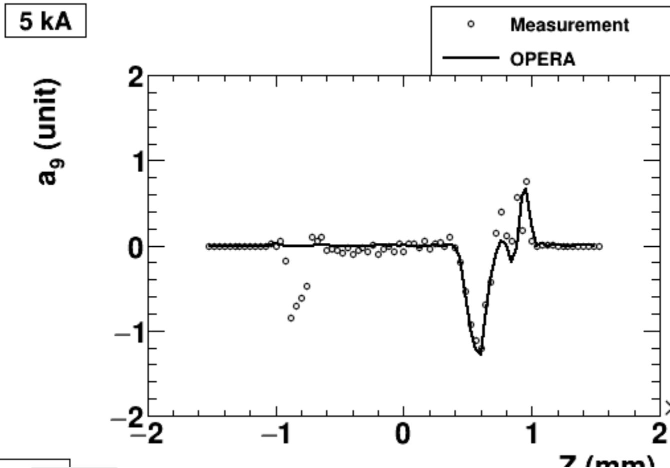

11 kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10
Z (mm)

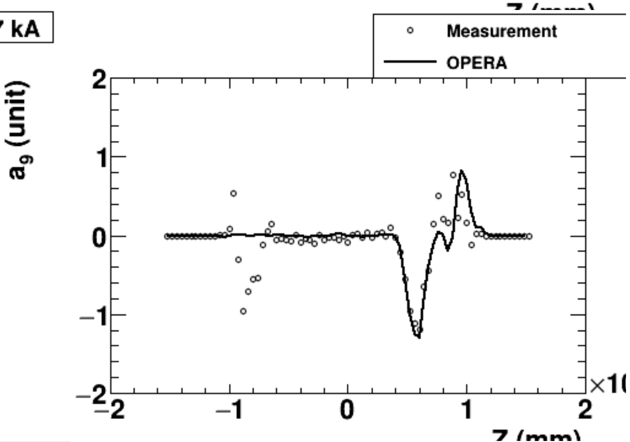

12.05kA
Measurement
OPERA
a7 (unit)
5
0
−5
−2
−1
0
1
2
×10³
Z (mm)

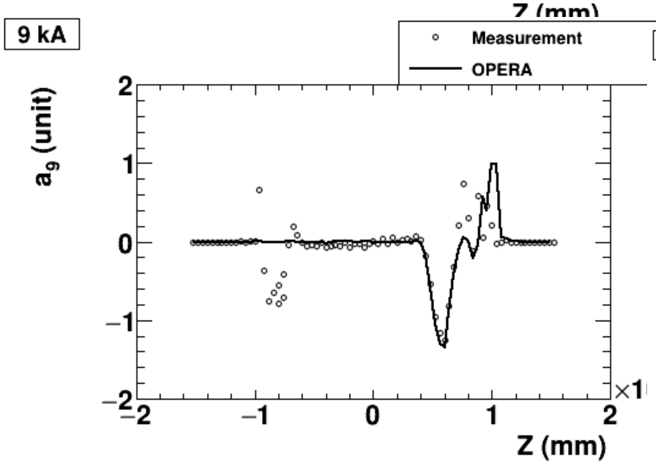
Z scan (a_9)

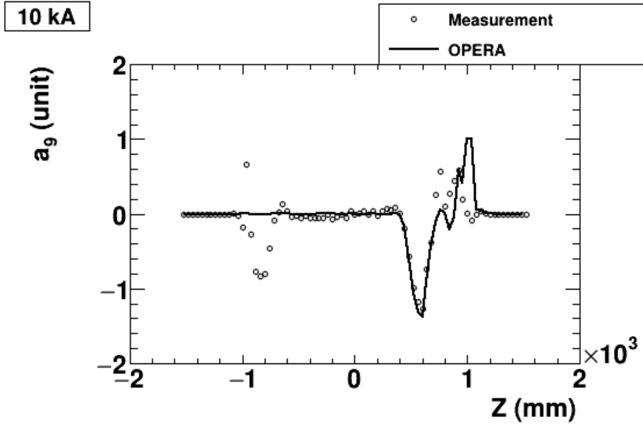

1 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
×1

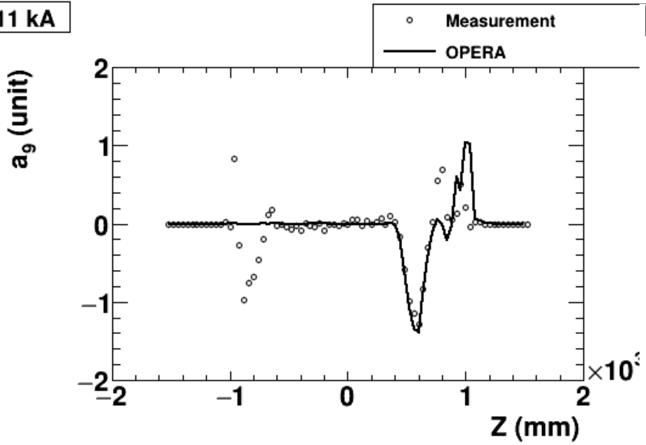

3 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×

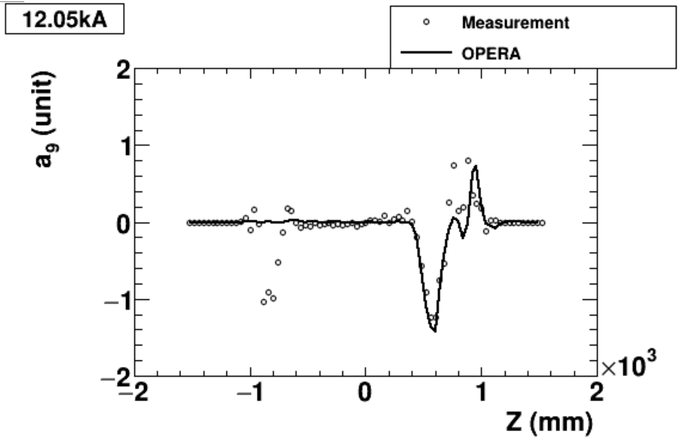

5 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)


7 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×1

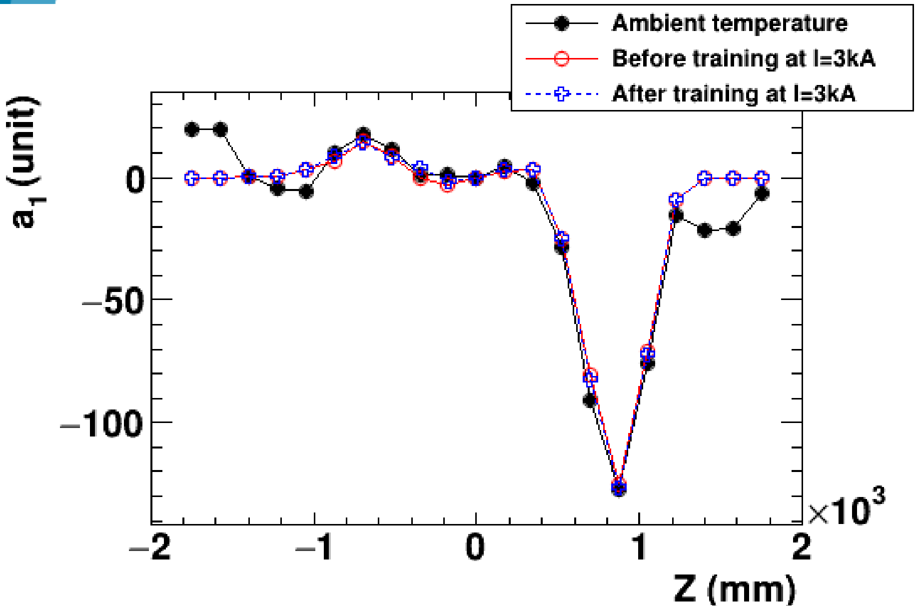

9 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×1

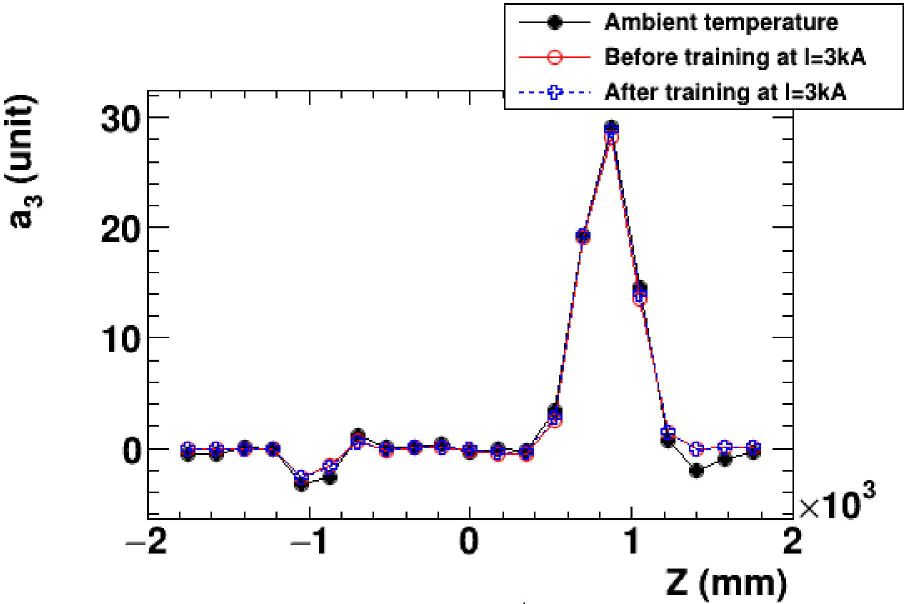

10 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×10^3

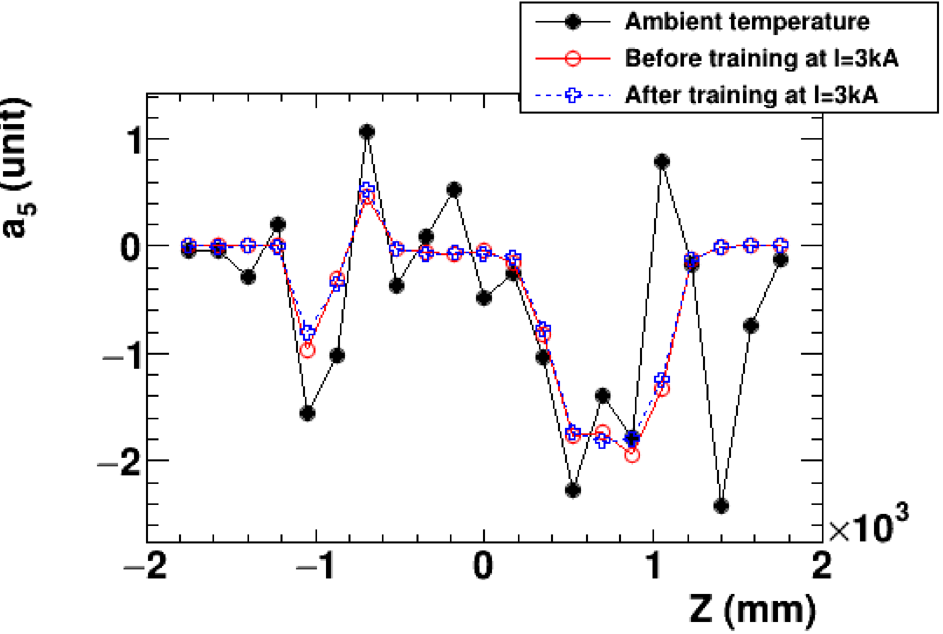

11 kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×10

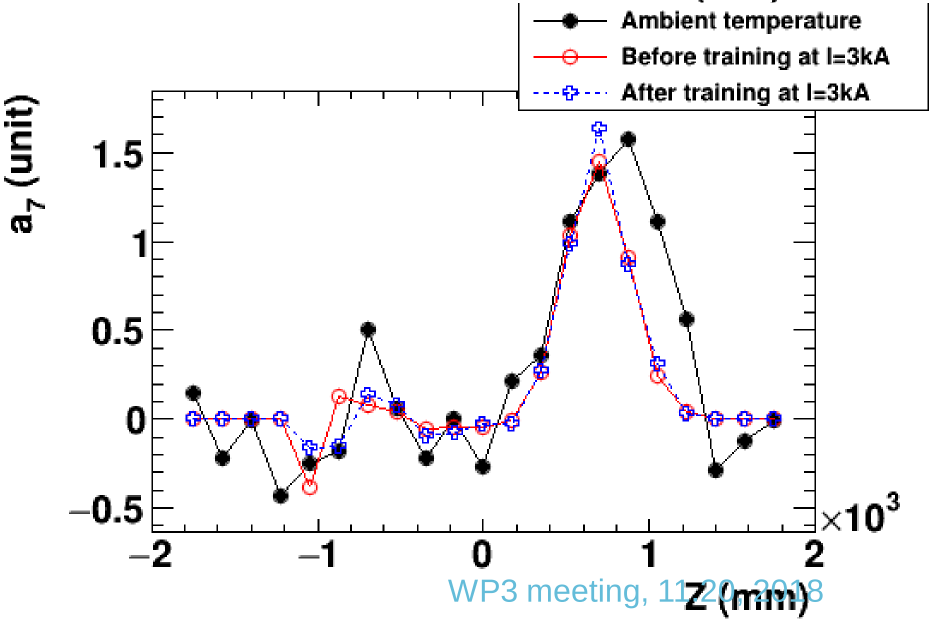

12.05kA
Measurement
OPERA
a9 (unit)
2
1
0
−1
−2
−2
−1
0
1
2
Z (mm)
×10^3

RT -> before training -> after training

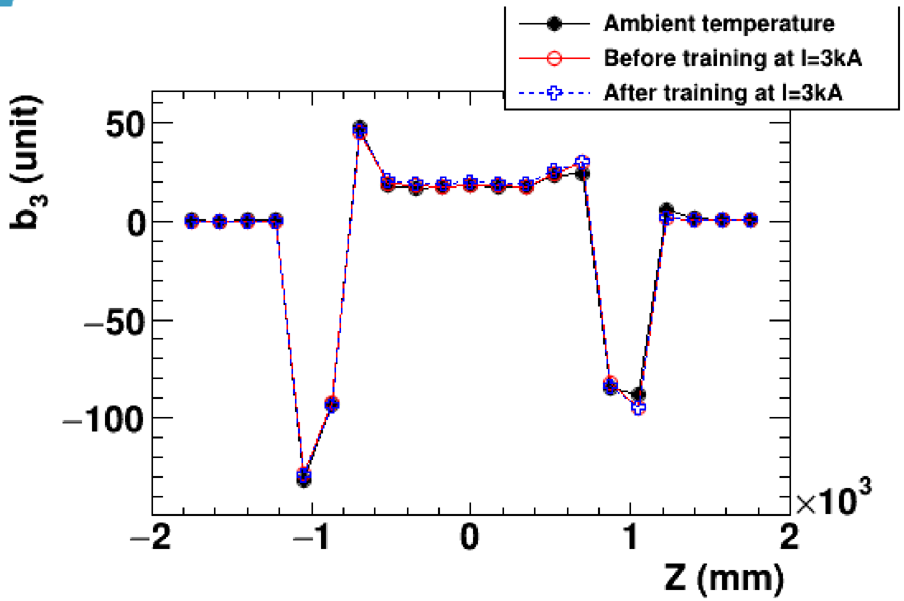


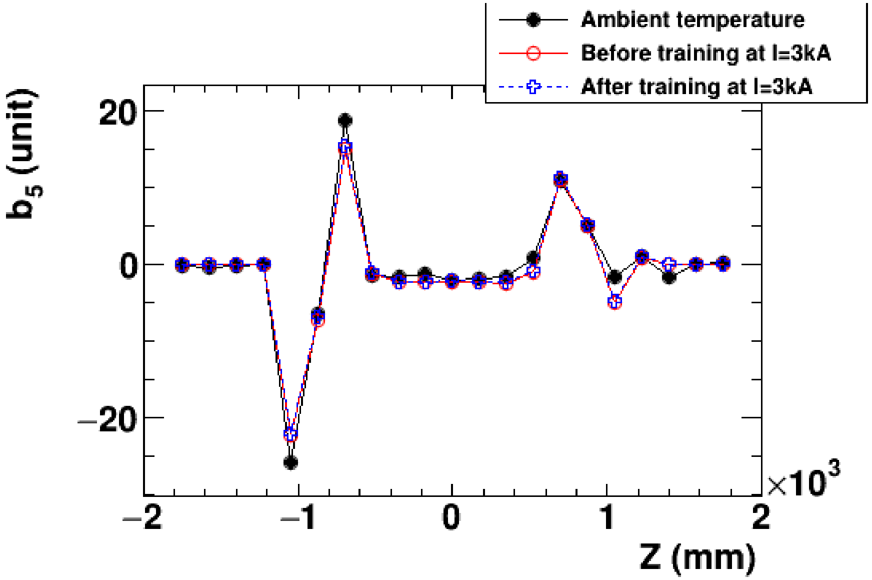


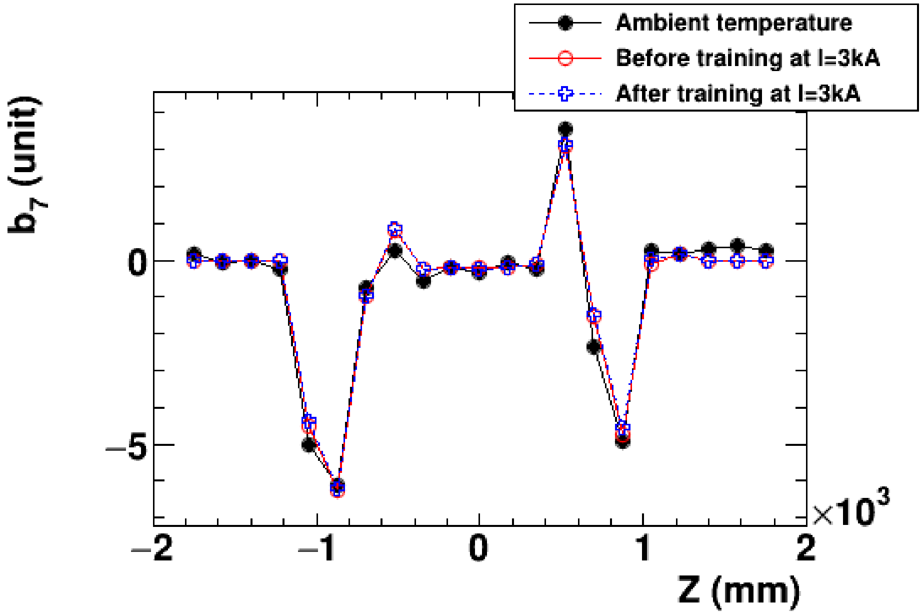


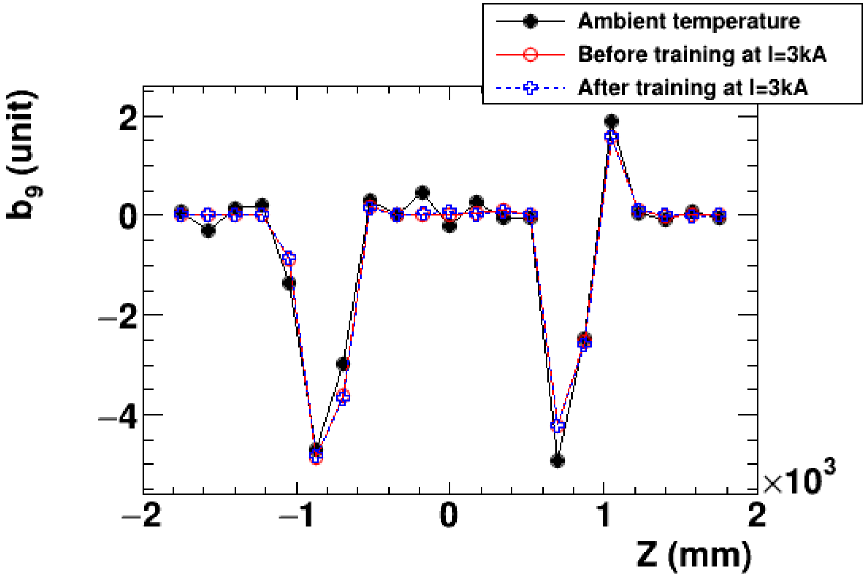


RT -> Before training -> After training









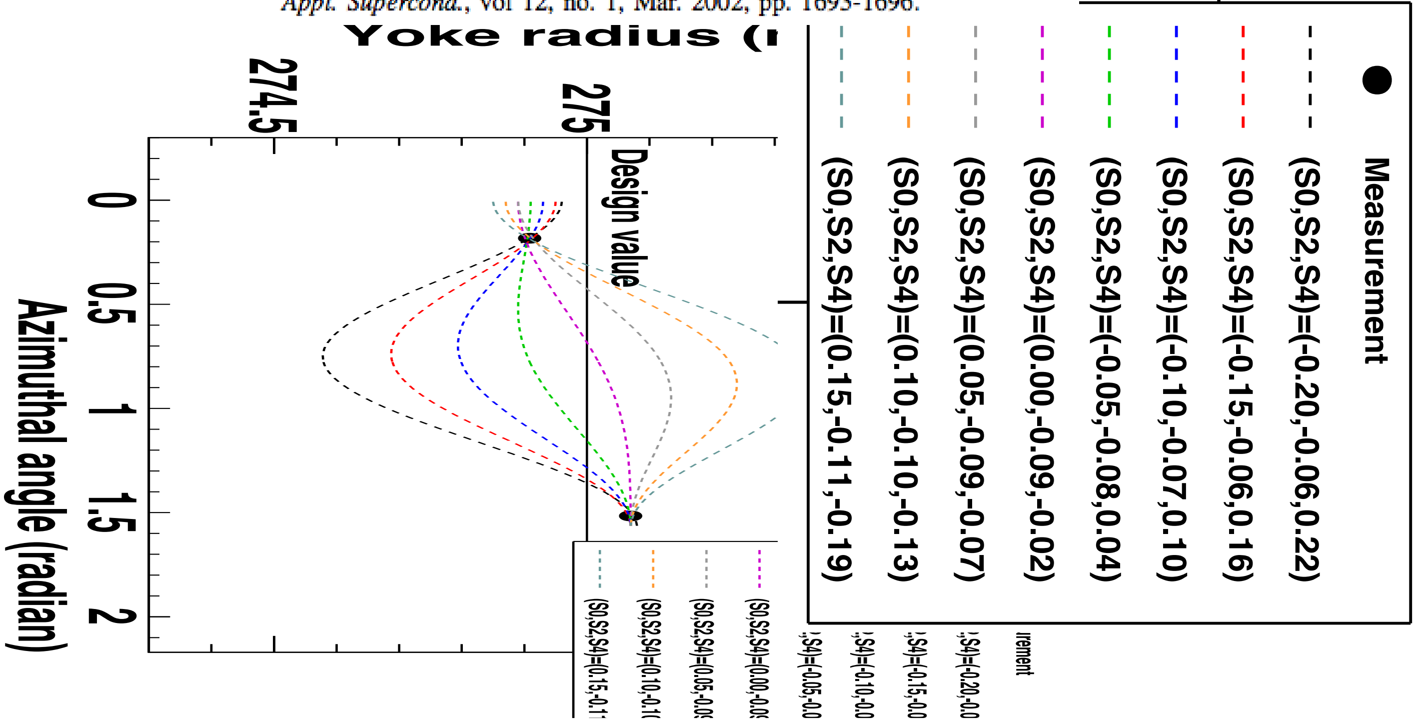
Investigation w/ OPERA2D

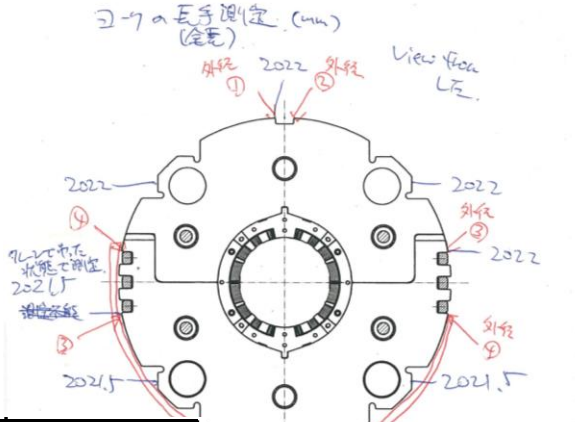
Coil distortion model

$$r = a_0 + \sum_m (S_m \cos m\phi + T_m \sin m\phi) \qquad (1)$$

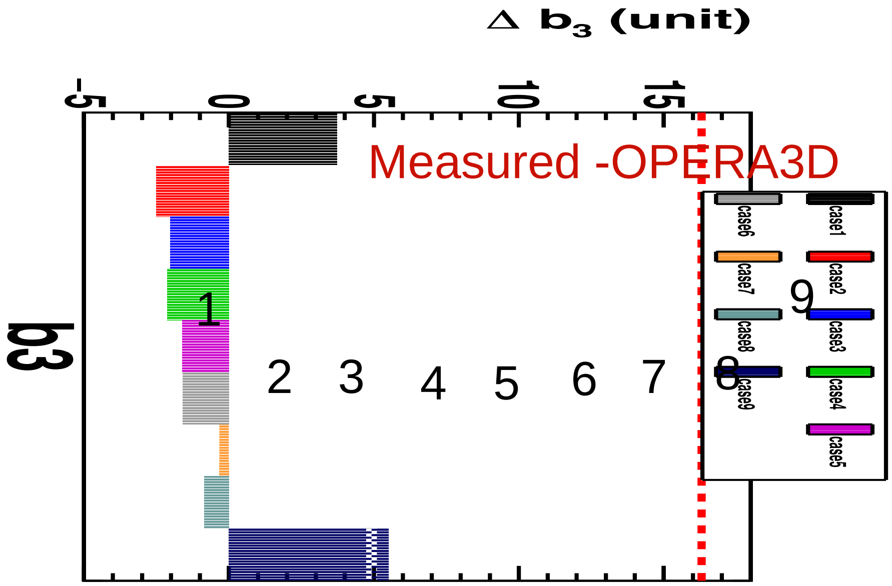
a_0 : original rad., S_m and T_m : distortion amplitude

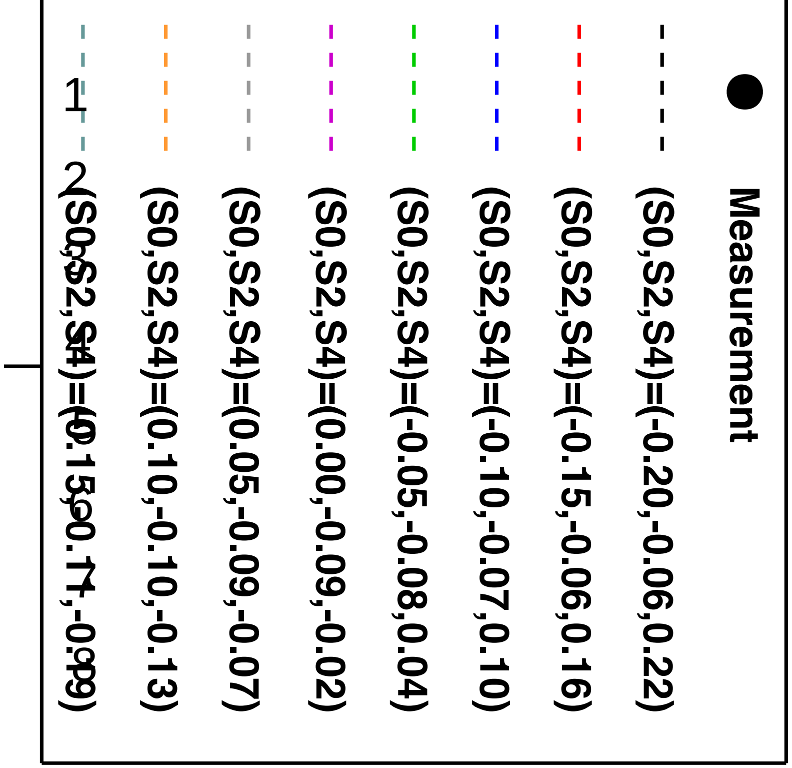
[16] K. Sugita *et al.*, "Analytical Calculation of Field Error Due to Radial Coil Distortion of the LHC Low-Beat Quadrupole Magnets," *IEEE Trans. Appl. Supercond.*, vol 12, no. 1, Mar. 2002, pp. 1693-1696.

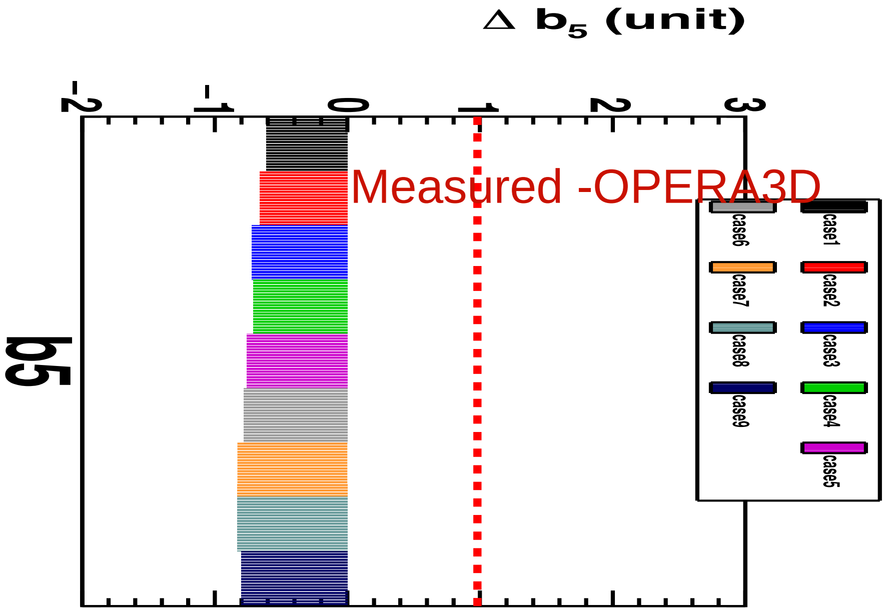




Result

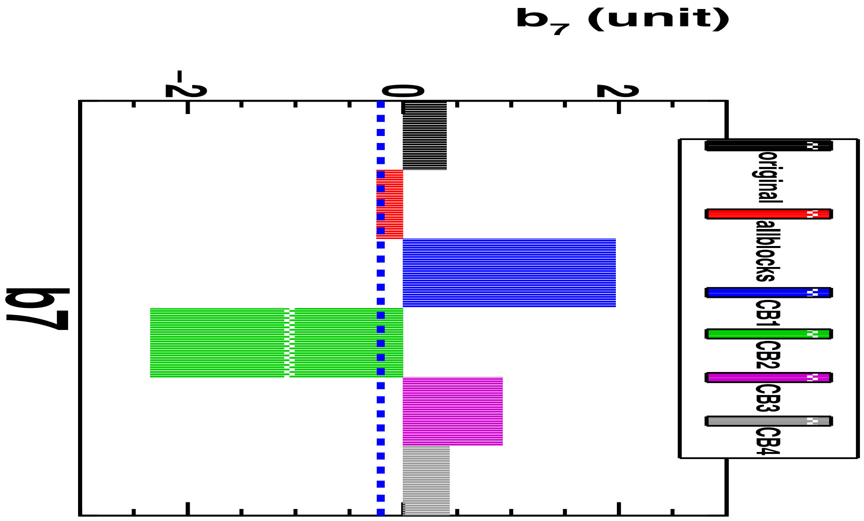


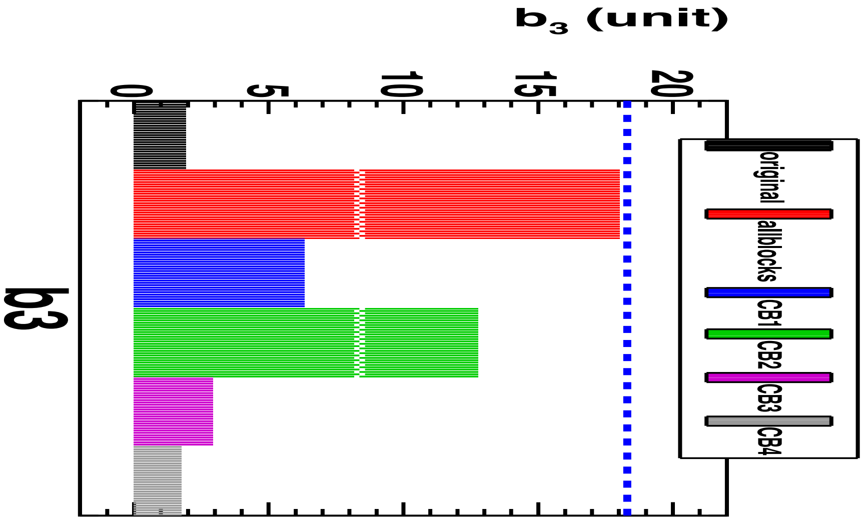


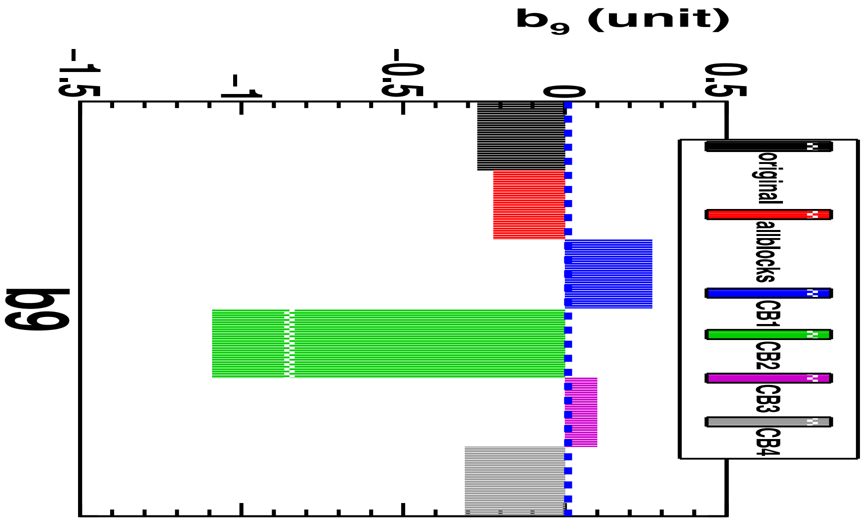


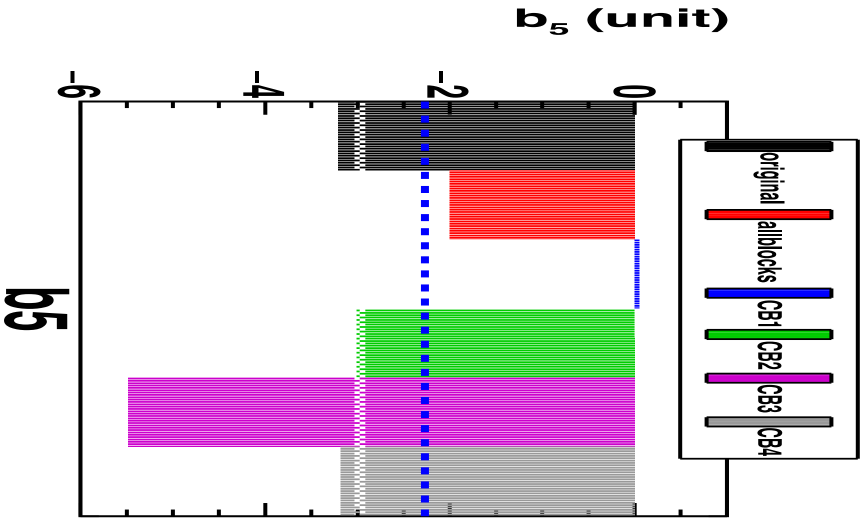
- Cannot explain 18 unit difference of b3 even considering the oval coild deformation

Breakdown

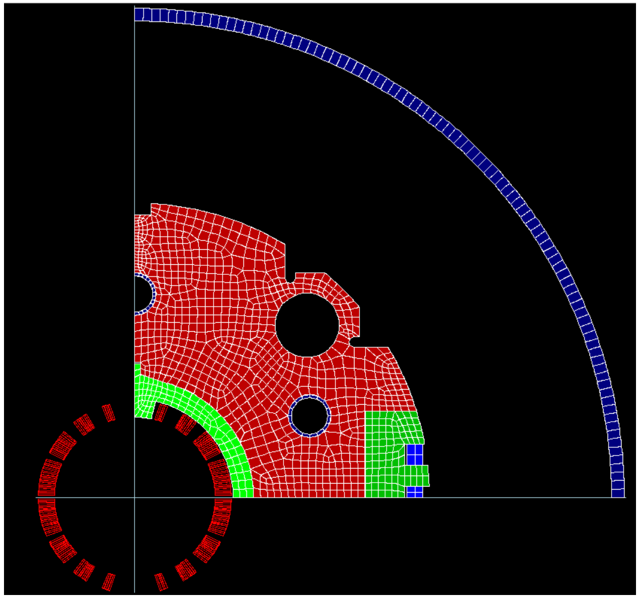

b7
b_7 (unit)
-2
0
2
original
allblocks
CB1
CB2
CB3
CB4


b3
b_3 (unit)
0
5
10
15
20
original
allblocks
CB1
CB2
CB3
CB4


b9
b_9 (unit)
-1.5
-1
-0.5
0
0.5
original
allblocks
CB1
CB2
CB3
CB4


b5
b_5 (unit)
-6
-4
-2
0
original
allblocks
CB1
CB2
CB3
CB4

Inverted field calculation w/ ROXIE 2D



- Purpose:
  - find out the best coil position (phi, alpha) so that the resultant multipoles matches the measurement
  - **Target values : (b3, b5) =(18, -2)**
  - Not only ideal coil form, but also its deformation is taken into account in this optimization:

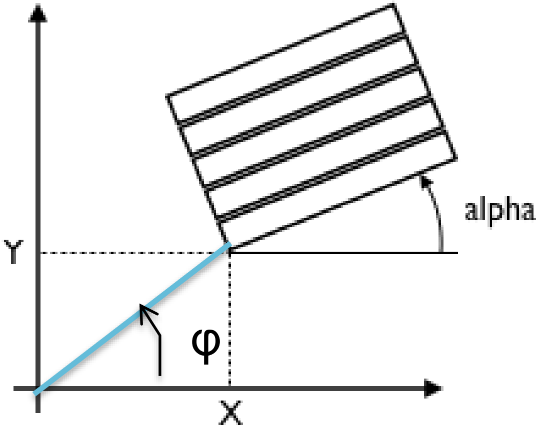
$$r = a_0 + \sum_m (S_m \cos m\phi + T_m \sin m\phi) \qquad (1)$$

a_0 : original rad., S_m and T_m : distortion amplitude

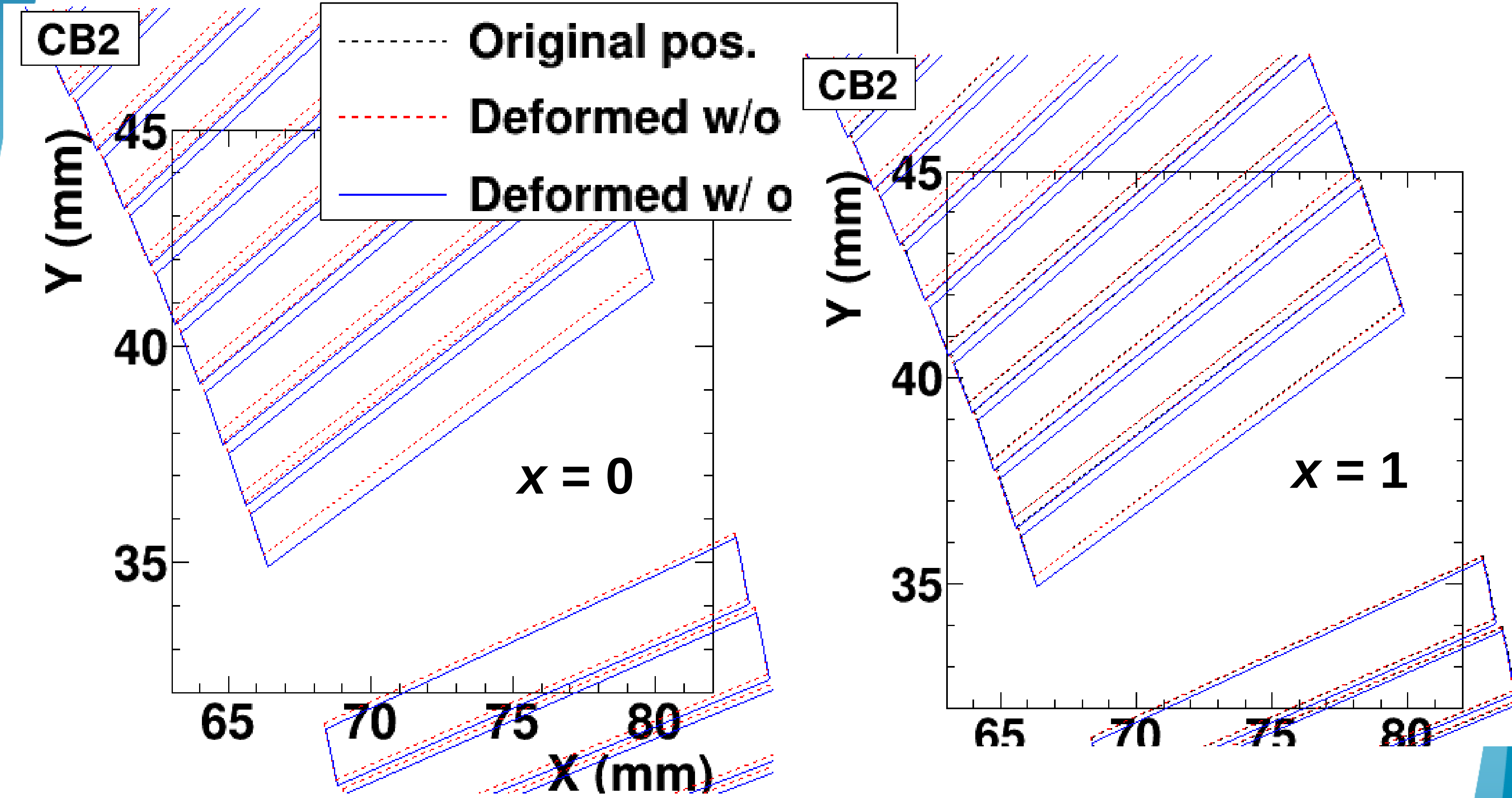
=> We only consider the 'oval' form

$$r = a_0 + xS_2 \cos 2\theta$$

S2 : 0.075 mm (from the measurement)
x : scale variable (0 – 2)



Displacement of the cable



Original pos. : Designed phi and alpha
Deformed w/o opt. : Just deform the coil (not execute ROXIE2D optimization)
Deformed w/ opt. : ROXIE2D optimization is executed after deforming the coil

Acceptance criteria

Field integral at the nominal current

From the first draft

	uncertainty	random	lower limit	upper limit
b_2	0.200	0.200	-0.800	0.800
b_3	0.727	0.727	-2.900	2.900
b_4	0.126	0.126	-0.500	0.500
b_5	0.365	0.365	-1.500	1.500
b_6	0.060	0.060	-0.240	0.240
b_7	0.165	0.165	-0.660	0.660
b_8	0.027	0.027	-0.110	0.110
b_9	0.065	0.065	-0.260	0.260
b_{10}	0.008	0.008	-0.030	0.030
b_{11}	0.019	0.019	-0.076	0.076
a_2	0.200	0.200	-0.800	0.800
a_3	0.727	0.727	-2.900	2.900
a_4	0.126	0.126	-0.500	0.500
a_5	0.365	0.365	-1.500	1.500
a_6	0.060	0.060	-0.240	0.240
a_7	0.165	0.165	-0.660	0.660
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a_9	0.065	0.065	-0.260	0.260
a_{10}	0.008	0.008	-0.030	0.030
a_{11}	0.019	0.019	-0.076	0.076

Summary of allowed multipoles at I=3kA

Normal multipoles	Measure	ROXIE 3D	OPERA 3D	ROXIE 2D
3	18.31 (19.53)	2.97	2.01	1.92
5	-2.27 (-2.09)	-3.59	-3.25	-3.21
7	-0.21 (-0.24)	0.53	0.39	0.40
9	0.011 (0.079)	-0.32	-0.25	-0.27

(): After training