Magnetic measurements and analysis on 11-T models at CERN

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High Luminosity LHC

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Outline

- MM systems
  - ambient temperature tests
  - cryogenic temperature tests
- MM test strategy
- Tested magnets
- Results
  - TF
  - Multipoles
  - Comparison with ROXIE model
  - Cold/Warm correlation
  - Inverse analysis
  - Ramp-rate dependency
- Conclusions

Measurement system 300 K

- Motor + encoder + slip-ring unit (MRU)
- Fast Digital Integrator (FDI)
- FuG low voltage power supply (40 V, 20 A)
- DCCT Hitec MACC-plus
- Search coil shafts (radius 22 mm, length 1.2 m)
- Flexible software Framework for Magnetic Measurements (FFMM)

Number of turns	(-)	256
Inner width	(mm)	13.41
Inner length	(mm)	1195.6
Groove thickness	(mm)	1.4
Magnetic surface	(m2)	3.37
Center radius	(mm)	21.33

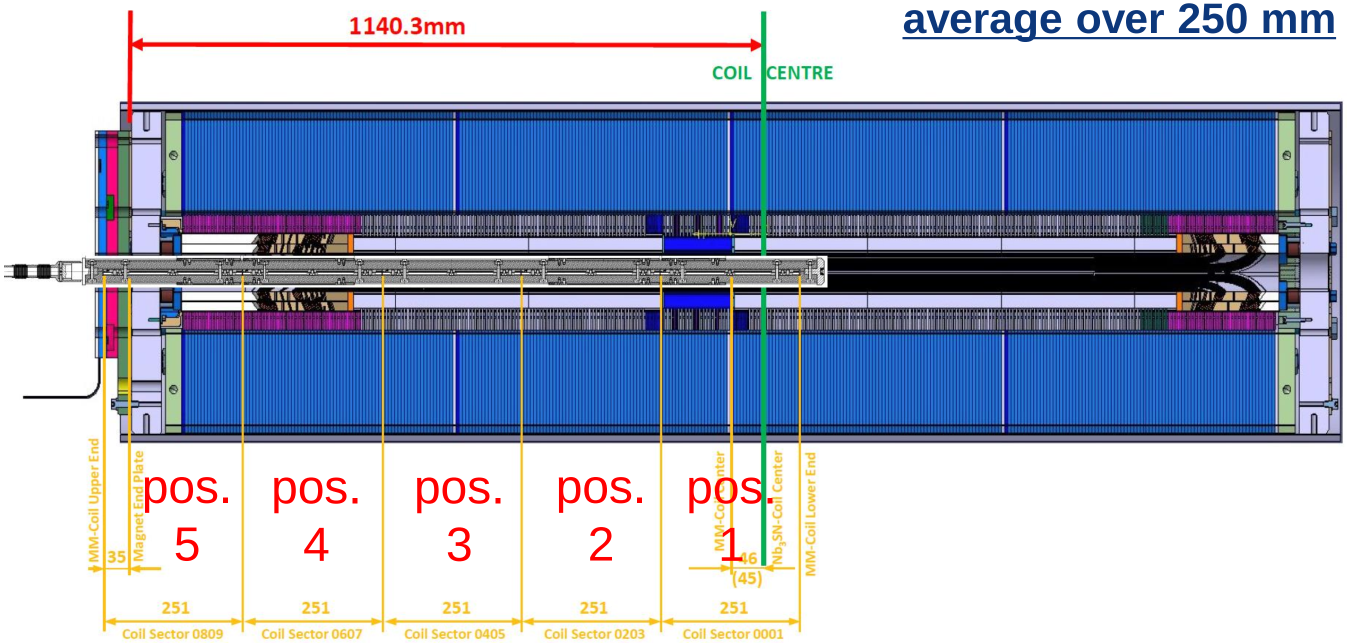
A measurement is an average over 1.2 m

Measurement system 1.9 K

- Flexible software Framework for Magnetic Measurements (FFMM)
- Fast Digital Integrators (FDI)
- Motor + encoder + slip-ring unit (MRU)
- <u>Vertical rotating shaft in liquid He</u>

Number of turns	(-)	150
Inner width	(mm)	6.43
Inner length	(mm)	250.00
Groove thickness	(mm)	0.80
Magnetic surface	(m^2)	0.28197
Center radius	(mm)	18.91

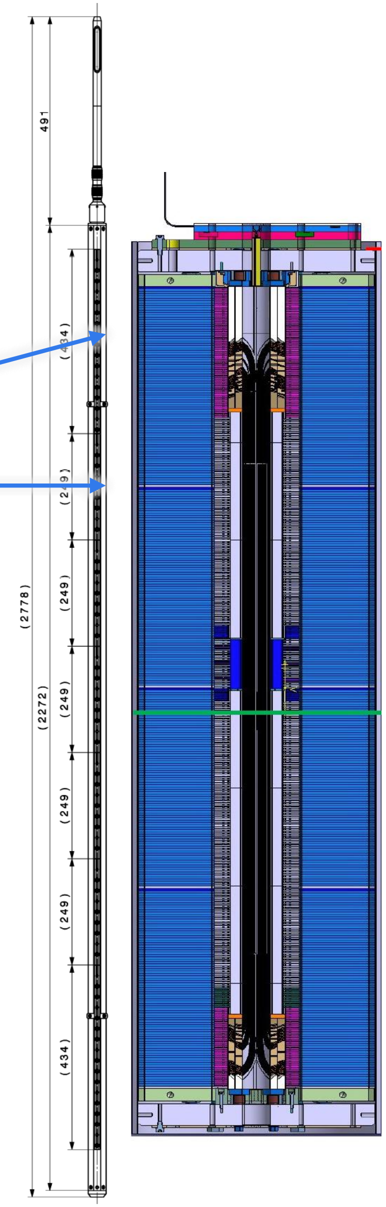
<u>A measurement is an average over 250 mm</u>



Measurement system 1.9 K

- Flexible software Framework for Magnetic Measurements (FFMM)
- Fast Digital Integrators (FDI)
- Motor + encoder + slip-ring unit (MRU)
- Vertical rotating shaft in liquid He

Number of turns	-	36	36
Inner width	mm	10.3	10.3
Inner length	mm	431.5	246.5
Groove thickness	mm	0.57	0.57
Magnetic surface	m^2	0.17	0.10
Center radius	mm	21.5	21.5



<u>A measurement is an average over 250 mm</u>

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MM test strategy

1) At ambient temperature
- Collared coil (CC) at ±20 A
- Cold mass (CM) at ±20 A

2) At cryogenic temperature
- CM with the following powering cycles
  - Stair-step cycle preceded by a quench
  - Machine cycle preceded by a quench
  - Ramp-rate study

  - Additional tests
    - Variable minimum current at 1.9 K and 4.5 K on MBHSP101
    - Long plateau (10 h) at nominal on MBHSP102

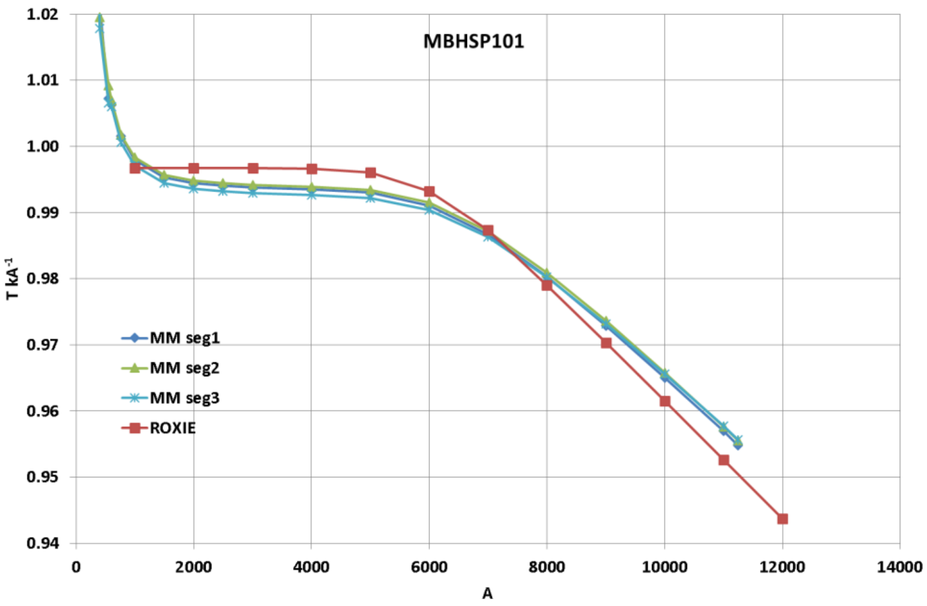
3) At ambient temperature
- CM at ±20 A

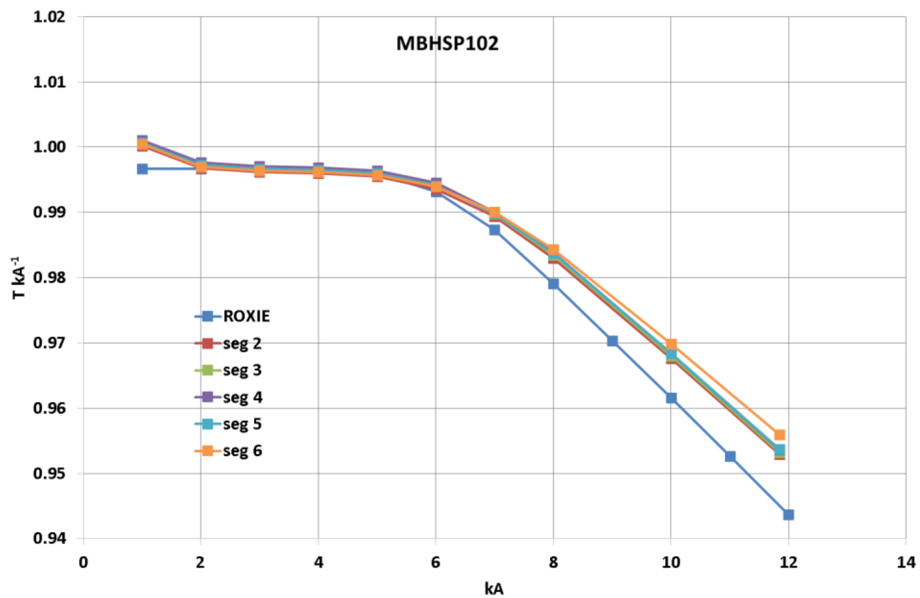
Tested magnets

2-m models with single aperture

- MBHSP101
  - CC and CM at 300 K
  - CM at 1.9 K
  - CM at 300 K
- MBHSP102
  - CC and CM at 300 K
  - CM at 1.9 K
  - CM at 300 K
- MBHSP103
  - CC and CM at 300 K

Transfer function





- Measurements and 2-D ROXIE model in agreement for geometric TF
  - -30 units on MBHSP101 probably due to shaft calibration
  - Perfect agreement on MBSP102
- Saturation overestimated by the model
  - +55 units measured on both magnet models

Transfer function

Possible sources of error:

Iron properties

Using data from LHC production the discrepancy decrease by 20 units (from ~70 to ~50 units)

Packing factor of the yoke laminations

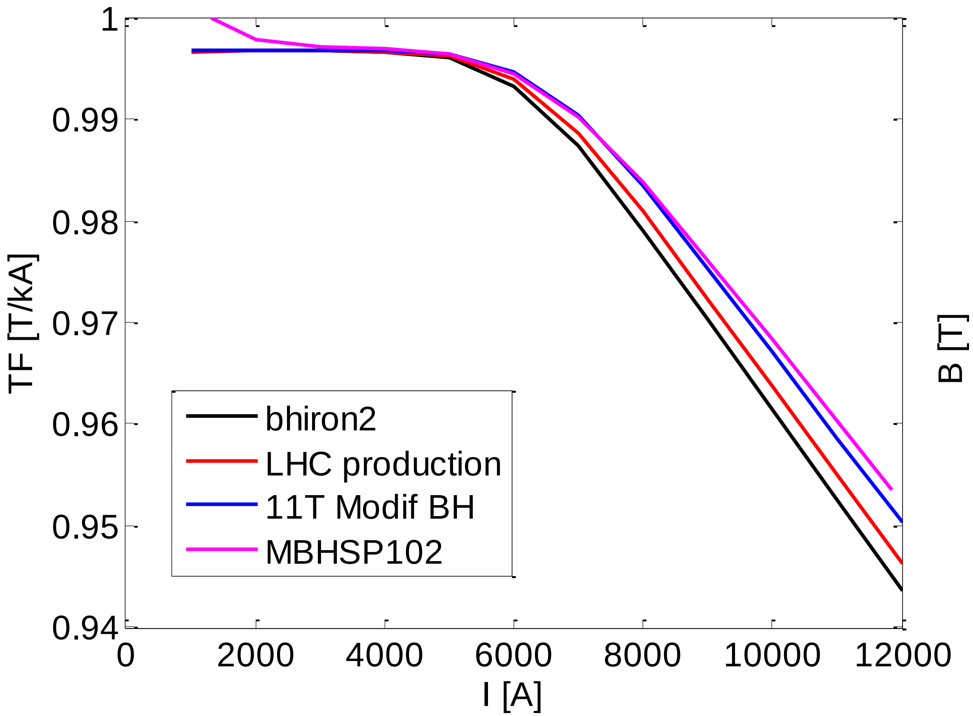
Its effect is up to ~15 units

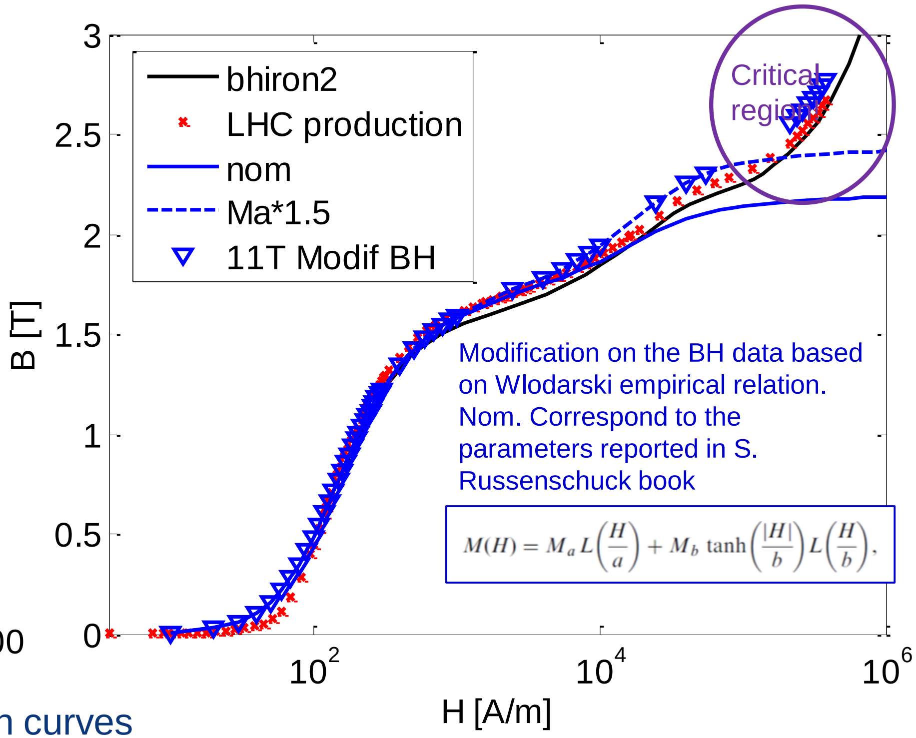
Geometric

Rather big displacements needed to explain 50 units (350 µm smaller coil gives ~15 units)

Transfer function

- The main source of error is the magnetic properties of the iron:
  - Discrepancy ~ 80 units using ROXIE bhdata2
  - Discrepancy ~ 55 units using LHC production data
  - Discrepancy ~ 15 units using a modified bh data based on [1]

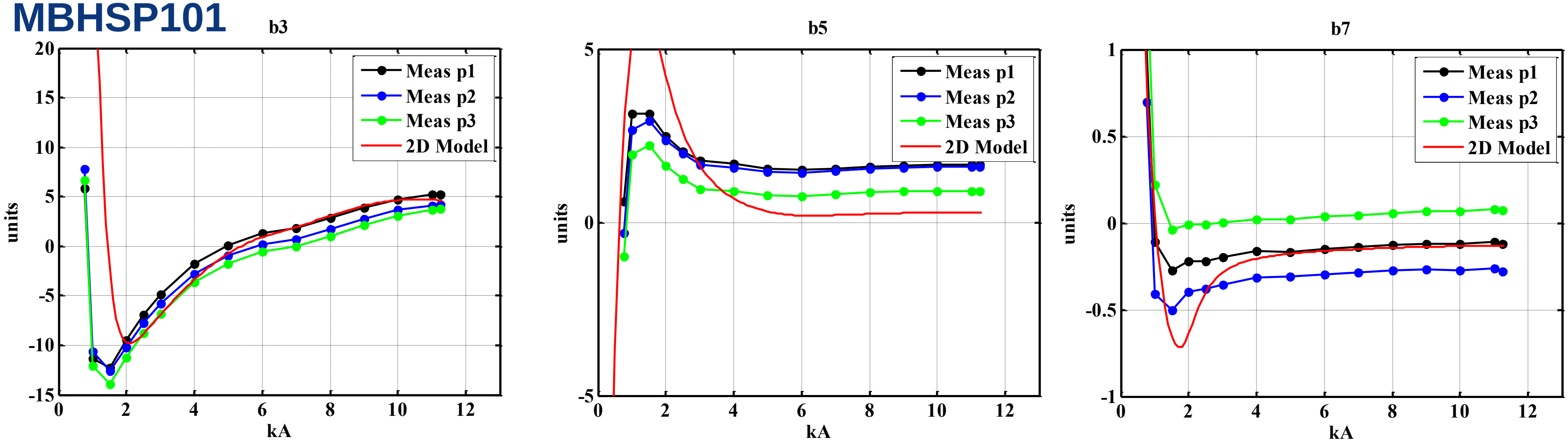




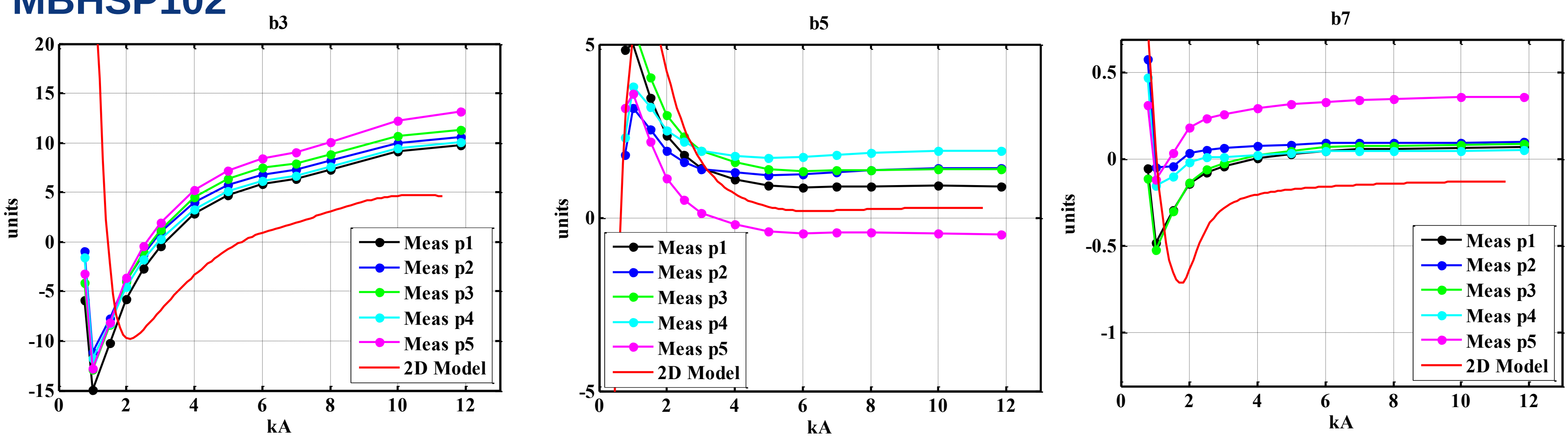
[1] Z. Wlodarki. Analytical description of magnetization curves

Allowed multipoles

MBHSP101



MBHSP102



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Reference radius 17 mm

Geometric multipoles MBHSP101

random block displacements of 60 μm

	pos 1		pos 2		pos 3						tolerances	
TF (T kA^{-1})	0.9930		0.9934		0.9922			6.23 units			-	
n	bn	an	bn	an	bn	an		σ bn	σ an		σ bn	σ an
2	0.86	5.47	-0.59	5.11	-2.14	4.66		1.50	0.41		1.70	1.82
3	6.35	-1.21	5.25	-0.78	4.60	-1.75		0.88	0.49		1.08	1.18
4	0.30	1.72	-0.51	0.99	-0.19	-0.26		0.41	1.00		0.62	0.67
5	1.49	0.01	1.43	0.43	0.72	0.48		0.43	0.26		0.35	0.39
6	0.01	0.49	-0.15	0.70	0.04	0.49		0.10	0.12		0.17	0.20
7	-0.06	-0.19	-0.22	-0.07	0.13	0.11		0.18	0.15		0.10	0.10
8	-0.01	0.10	-0.02	0.01	0.03	-0.01		0.03	0.06		0.06	0.05
9	0.89	-0.20	0.85	-0.32	0.80	-0.33		0.04	0.07		0.03	0.02
10	0.00	0.00	-0.01	0.00	-0.02	0.01		0.01	0.00		0.01	0.01
11	0.37	-0.06	0.37	-0.12	0.39	-0.14		0.01	0.05		0.01	0.01

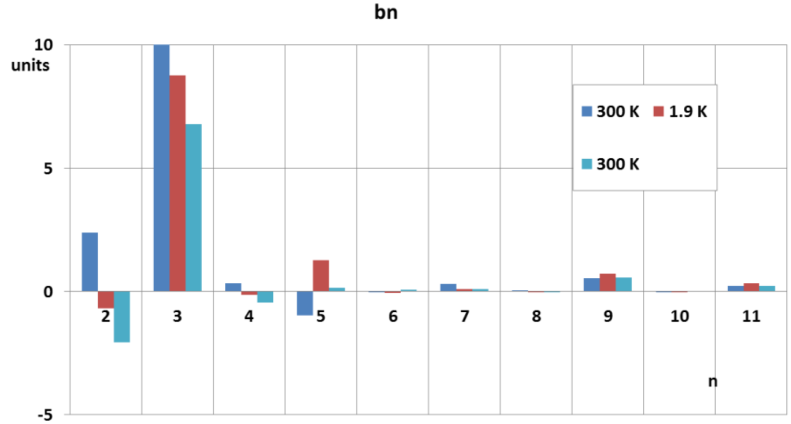
Reference radius 17 mm

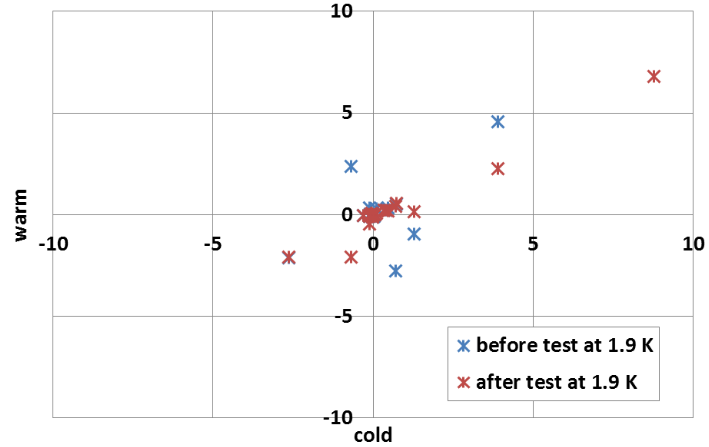
Cold/warm correlation MBHSP101 half magnet

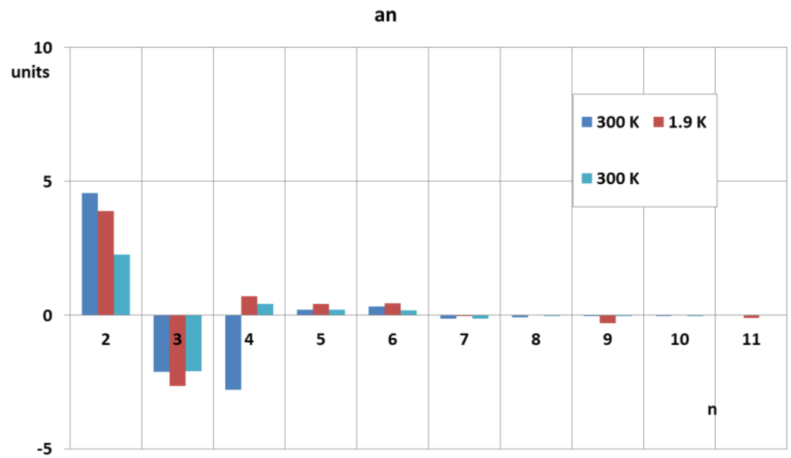
	half magnet			half magnet			half magnet	
Temp.	300 K before cold tests			1.9 K			300 K after cold tests	
TF	0.735			0.747			0.736	
n	**bn**	**an**		**bn**	**an**		**bn**	**an**
2	2.38	4.57		-0.68	3.89		-2.07	2.28
3	10.56	-2.12		8.77	-2.63		6.80	-2.08
4	0.33	-2.78		-0.12	0.70		-0.44	0.43
5	-0.96	0.22		1.28	0.43		0.15	0.22
6	-0.03	0.33		-0.05	0.46		0.07	0.18
7	0.30	-0.12		0.10	-0.01		0.09	-0.12
8	0.05	-0.08		-0.02	0.02		-0.01	-0.01
9	0.55	-0.02		0.72	-0.30		0.57	-0.03
10	0.00	0.00		-0.01	0.01		0.01	-0.02
11	0.23	0.02		0.33	-0.09		0.24	0.02

Reference radius 17 mm

Cold/warm correlation MBHSP101 half magnet







- Changes on multipoles before/after test at cold
- Better cold/warm correlation with measurements at warm **after** cold tests

Reference radius 17 mm

Geometric multipoles MBHSP102 central field

	300 K before tests at 1.9 K			1.9 K at 5 kA on three central segments							300 K after tests at 1.9 K	
	1.2 m			0.250 m		0.250 m		0.250 m			1.2 m	
n	bn	an		bn	an	bn	an	bn	an		bn	an
2	0.33	6.76		1.75	2.73	1.22	3.56	0.69	3.67		0.21	7.51
3	9.50	-0.84		11.32	-1.78	11.82	-1.38	10.75	0.25		10.05	-1.12
4	0.24	1.28		0.54	0.19	0.32	-0.33	-0.29	-0.20		0.23	1.50
5	1.56	-0.02		1.17	-0.59	1.39	0.20	1.65	0.58		1.42	0.01
6	0.00	0.03		-0.01	0.13	0.19	-0.42	0.09	-0.24		0.01	0.05
7	0.16	-0.02		0.16	-0.22	0.10	-0.07	0.12	-0.06		0.18	-0.01
8	0.08	0.03		0.03	-0.04	0.05	-0.09	0.03	0.05		0.05	0.03
9	0.83	0.00		0.63	-0.13	0.64	0.02	0.62	0.22		0.83	-0.02
10	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.01
11	0.40	0.02		0.22	-0.04	0.19	0.05	0.17	0.16		0.40	0.02
12	-0.06	0.01		-0.03	0.06	-0.06	0.04	-0.07	0.02		-0.01	0.01
13	-0.10	0.00		-0.11	-0.01	-0.11	0.00	-0.11	0.00		-0.09	0.00
14	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.01		0.00	0.00
15	-0.02	0.00		-0.02	0.00	-0.02	0.00	-0.02	-0.01		-0.02	0.00

Reference radius 17 mm

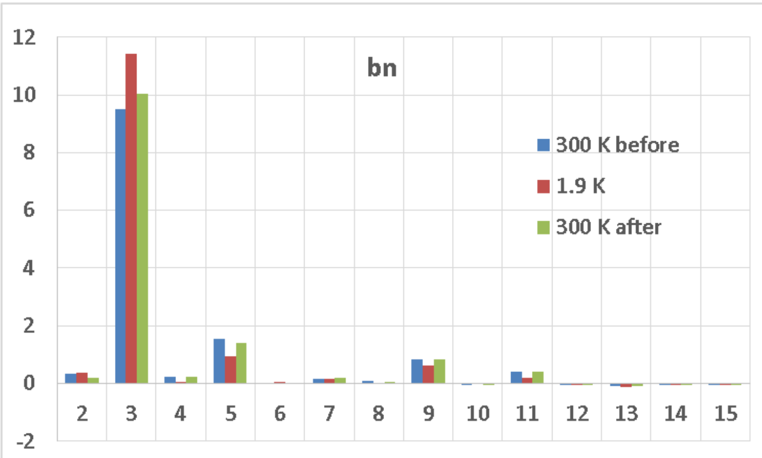
Geometric multipoles MBHSP102 integral field

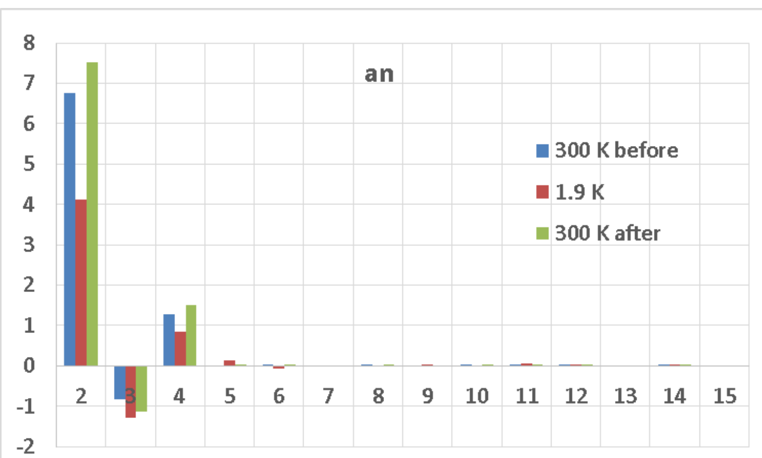
	300 K before tests at 1.9 K			1.9 K			300 K after tests at 1.9 K	
n	**bn**	**an**		**bn**	**an**		**bn**	**an**
2	0.41	3.23		0.51	2.33		0.83	4.15
3	14.20	-1.81		14.54	-1.02		14.26	-1.80
4	0.39	0.75		0.03	0.69		0.34	1.11
5	3.13	0.50		1.69	0.33		3.36	0.39
6	-0.06	-0.03		0.06	-0.07		-0.09	0.06
7	0.07	0.06		0.22	0.06		0.02	0.10
8	0.07	0.00		0.02	0.00		0.07	-0.02
9	0.70	0.00		0.63	0.05		0.71	-0.02
10	-0.01	-0.01		0.00	0.00		0.01	0.01
11	0.35	0.05		0.22	0.07		0.34	0.05
12	-0.06	0.00		-0.02	0.01		-0.02	0.00
13	-0.09	0.00		-0.11	0.00		-0.09	0.00
14	0.00	0.01		0.00	0.00		0.00	0.01
15	-0.02	0.00		-0.02	0.00		-0.02	0.00

Reference radius 17 mm

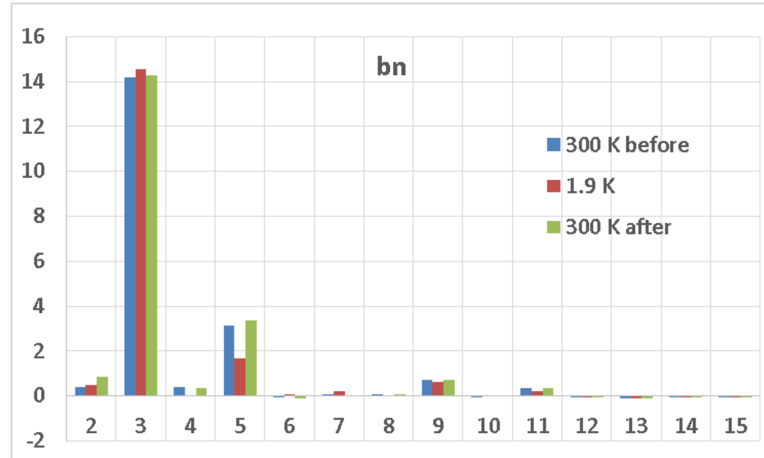
Cold/warm correlation MBHSP102

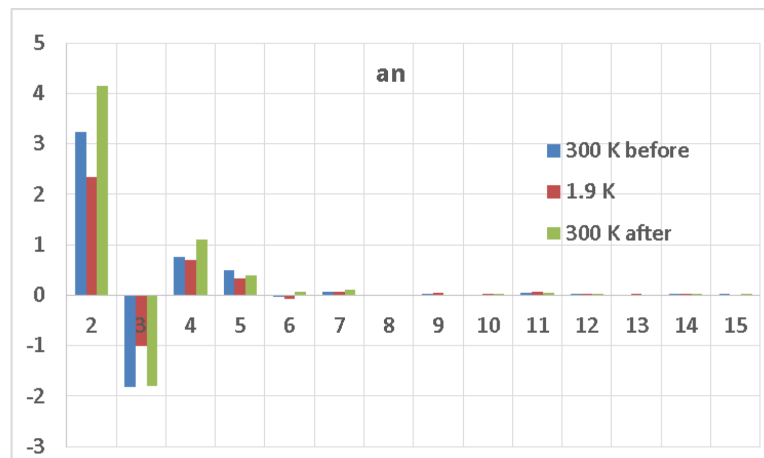
Central field





Integral field





- No changes on multipoles before/after test at 1.9 K

Reference radius 17 mm

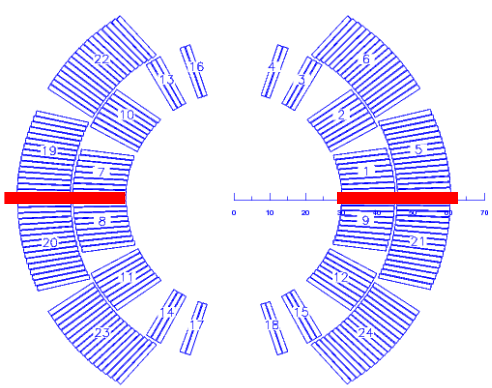
Inverse Analysis

MBHSP101* (mid plane 125 um off)		After collaring	After shell welding	1.9K 5 kA	1.9K I_{nom}
b3			7.00	5.25	5.25
b5			0.14	1.43	1.43
b7			0.18	-0.22	-0.22
b9			0.76	0.85	0.85

* Inom 11.25 instead of 11.85

MBHSP102 (mid plane OK)		After collaring	After shell welding	1.9K 5 kA	1.9K I_{nom}
b3		1.71	9.50	11.82	11.82
b5		2.24	1.56	1.39	1.39
b7		0.11	0.16	0.10	0.10
b9		0.88	0.83	0.64	0.64

- Shift on b_3 of 6.5 units between the first and second model.
- The main difference among them is the mid-plane shim:
    - MBHSP101 : 250 µm excess (0.125 µm per coil)
    - MBHSP102 : nominal
- ROXIE-ANSYS interface to evaluate the impact of the actual coil geometry on the harmonics.



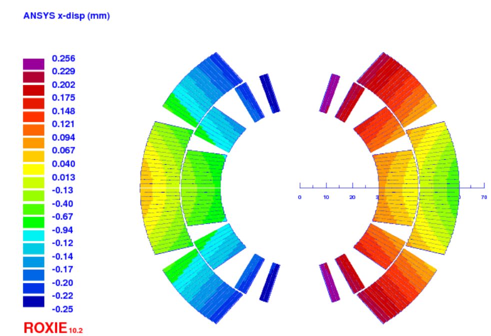
ANSYS displacements

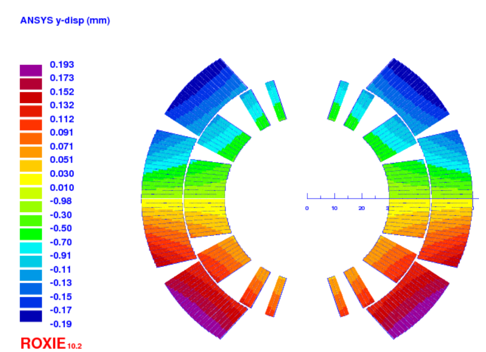
↓

Apply displacement in ROXIE strands

↓

Study impact of the displacements on field quality in ROXIE





MBHSP101

- reasonable for b3
- Still a discrepancy on b5

MBHSP101* (mid plane 125 um off)		After collaring	After shell welding	1.9K 5 kA	1.9K I_{nom}
b3			7.00	5.25	5.25
b5			0.14	1.43	1.43
b7			0.18	-0.22	-0.22
b9			0.76	0.85	0.85

* Inom 11.25 instead of 11.85

	ROXIE		ROXIE + ANSYS		ROXIE		ROXIE + ANSYS	
Midplane 125 um off	After collaring	After shell welding	After collaring	After shell welding	1.9 K 5 kA	1.9 K Inom	1.9K 5 kA	1.9K I_{nom}
b3	-5.58	2.57			2.55	1.79		5.04
b5	-1.41	-1.45			-1.49	-1.25		-0.78
b7	-0.64	-0.50			-0.52	-0.55		-0.21
b9	1.00	0.42			0.82	0.87		0.81

MBHSP102

- reasonable for b3
- Still a discrepancy on b5

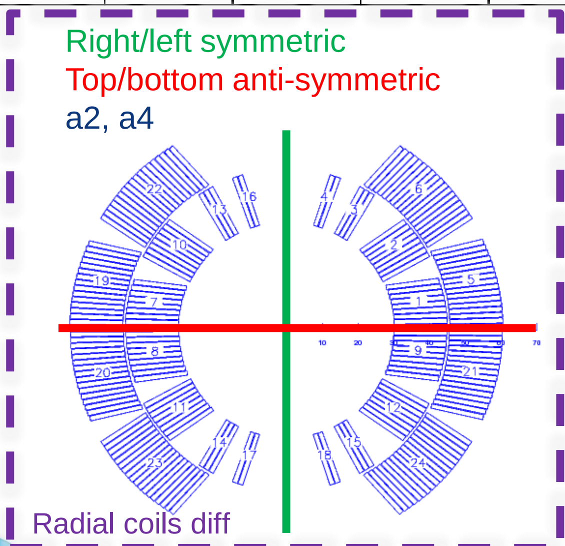
MBHSP102 (mid plane OK)	RT	After collaring	After shell welding	1.9K 5 kA	1.9K I_{nom}
b3		1.71	9.50	11.82	11.82
b5		2.24	1.56	1.39	1.39
b7		0.11	0.16	0.10	0.10
b9		0.88	0.83	0.64	0.64

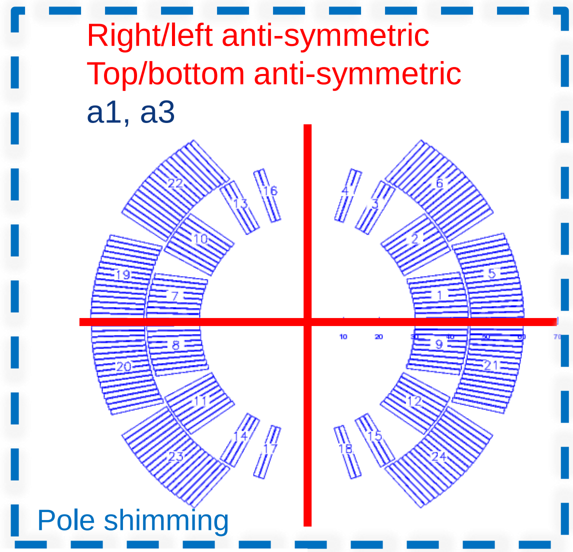
	ROXIE		ROXIE + ANSYS		ROXIE		ROXIE + ANSYS	
Midplane OK	After collaring	After shell welding	After collaring	After shell welding	1.9 K 5 kA	1.9 K Inom	1.9K 5 kA	1.9K I_{nom}
b3	-0.40	6.76			6.77	6.22		12.70
b5	0.49	0.08			0.06	0.38		-0.05
b7	-0.12	-0.09			-0.10	-0.10		0.04
b9	1.11	0.89			0.91	0.96		0.84

MBHSP102 non-allowed

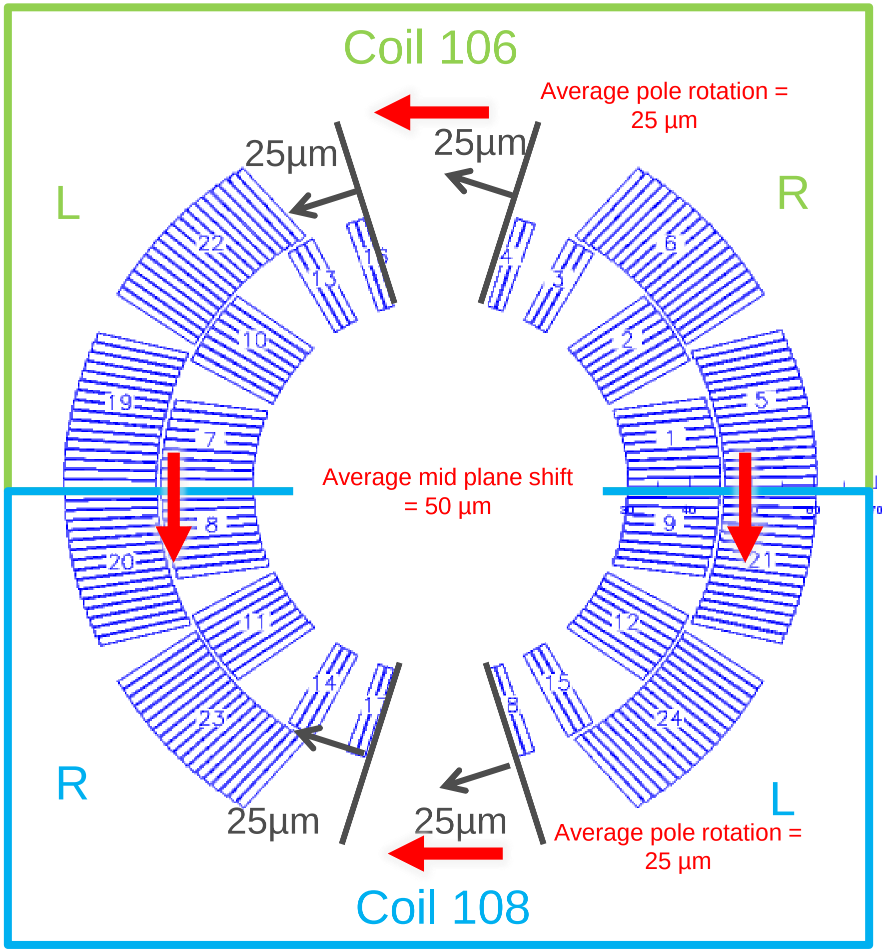
- For the non-allowed, only a_2 is not within the boundaries set by the manufacturing tolerances.
- It can be easily explained by the differences in coil outer radial insulation

	300 K at 20 A		300 K at 20 A		1.9 K at 5 kA						Manufacturing tolerance	
	Collared coil		Cold mass		seg3		seg4		seg5			
n	**bn**	**an**	**bn**	**an**	**bn**	**an**	**bn**	**an**	**bn**	**an**	**bn**	**an**
2	0.00	8.72	0.33	6.76	1.75	2.73	1.22	3.56	0.69	3.67	1.93	2.87
3	1.71	-0.93	9.50	-0.84	11.32	-1.78	11.82	-1.38	10.75	0.25	1.24	1.66
4	0.21	1.66	0.24	1.28	0.54	0.19	0.32	-0.33	-0.29	-0.2	0.6	1
5	2.24	-0.01	1.56	-0.02	1.17	-0.59	1.39	0.2	1.65	0.58	0.31	0.64





MBHSP102 Coil Geometry

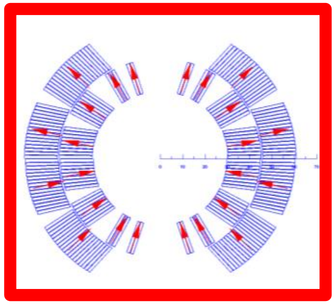


Pole shimming	SS-316	Kapton
Nominal	0.125	3x0.125
106 right	0.1	3x0.125
106 left	0.15	3x0.125
108 right	0.15	3x0.125
108 left	0.1	3x0.125

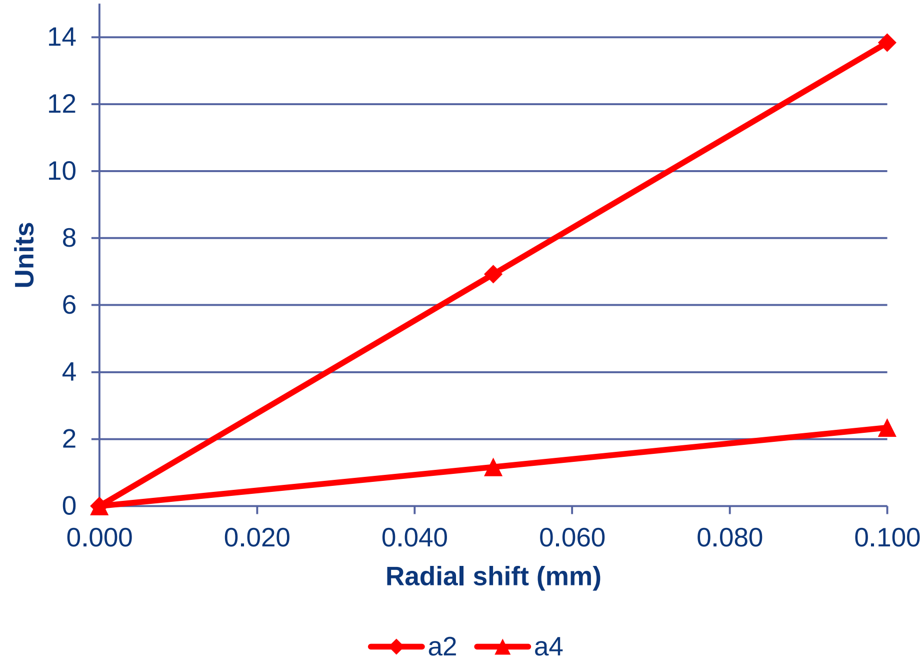
Radial Insulation	S2-Wrap	Kapton
Nominal	0.2	0.5
106 inner	0.0	0.5
106 outer	0.0	0.5
108 inner	0.1	0.5
108 outer	0.1	0.5

MBHSP102 a2, a4

A radial shift of 50 µm explain a2 and a4, which is reasonable considering that coil 106 has 100 µm less of radial insulation

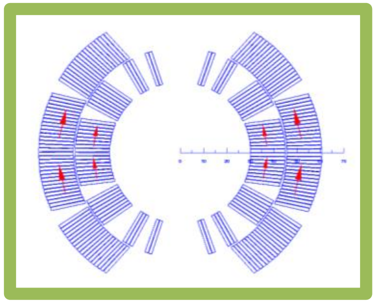


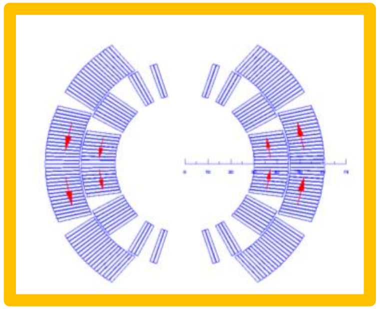
CC	R22		ROXIE	
	0.795		0.798	
n	bn	an	bn	an
2	0.00	8.72	0.00	0.00
3	1.71	-0.93	-0.40	0.00
4	0.21	1.66	0.00	0.00
5	2.24	-0.01	0.49	0.00



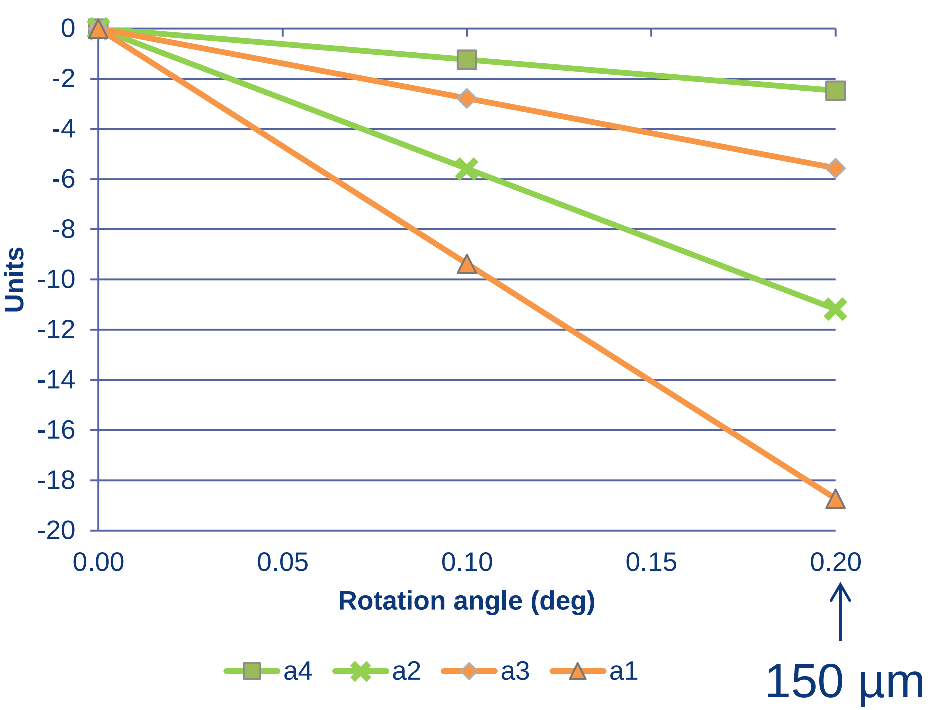
MBHSP102 a3, a5

- To explain a3/a5 we need anti-symmetry in both axis
- 20 µm of rotation on the mid-plane is enough to justify a_3,
- But from mechanical measurements it seems that the mid-plane is shifted (i.e. a_2 a_4) and not rotated. 70 µm of rotation in the mid-plane explains the measured a2 and a4 (which can be also explain with the differences in coil radial shimming).





CC	R22		ROXIE	
	0.795		0.798	
n	bn	an	bn	an
2	0.00	8.72	0.00	0.00
3	1.71	-0.93	-0.40	0.00
4	0.21	1.66	0.00	0.00
5	2.24	-0.01	0.49	0.00



Ramp-rate dependence

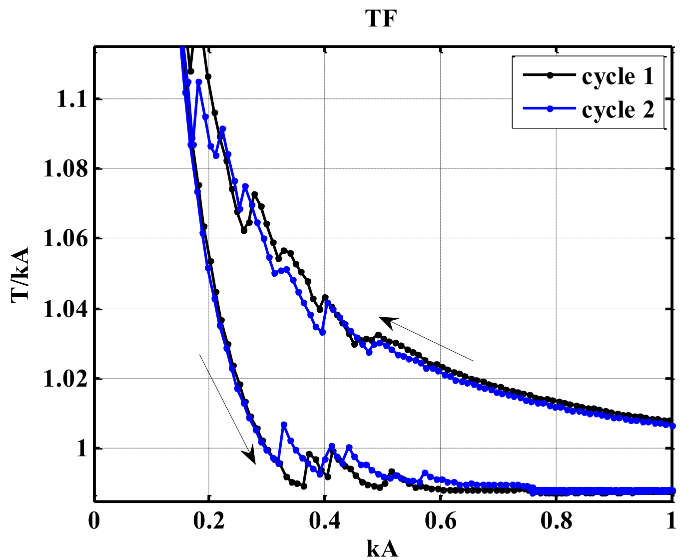
MBHSP101										
A s^{-1}	0	10	20	40	80	0	10	20	40	80
	Δ b_n at 5 kA (units)					Δ a_n at 5 kA (units)				
2	0.00	0.10	0.05	-0.03	-0.20	0.00	-0.05	-0.11	-0.12	-0.13
3	0.00	0.03	0.05	0.06	0.16	0.00	0.02	-0.04	-0.15	-0.30
4	0.00	0.02	0.05	0.09	0.21	0.00	0.01	0.02	0.04	0.10
5	0.00	-0.04	-0.05	-0.10	-0.17	0.00	0.00	0.00	-0.01	-0.01
6	0.00	0.00	0.00	0.05	0.10	0.00	0.01	0.02	0.02	0.01
7	0.00	0.02	0.00	0.01	0.00	0.00	-0.03	-0.01	-0.03	-0.01
8	0.00	0.03	0.03	0.04	0.05	0.00	0.01	0.00	0.02	0.01
9	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.04

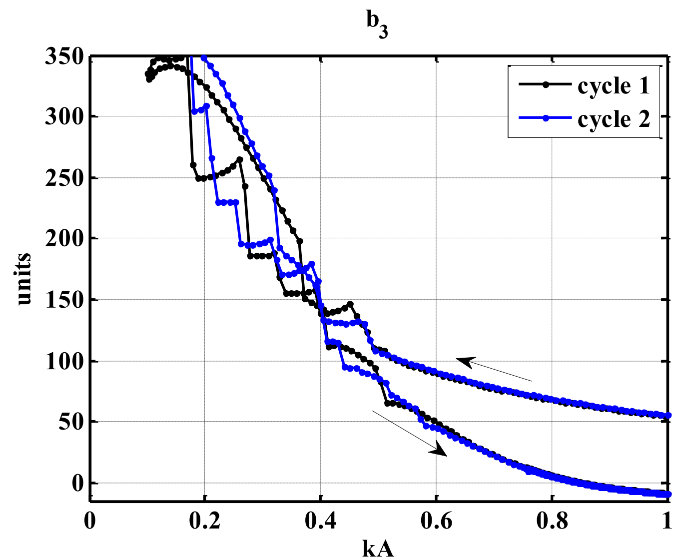
MBHSP102										
A s^{-1}	0		20	50	100	0		20	50	100
	Δ b_n at 5 kA (units)					Δ a_n at 5 kA (units)				
2	0.00		-0.02	-0.14	-0.12	0.00		-0.26	-0.62	-0.84
3	0.00		0.16	0.32	0.54	0.00		-0.04	0.04	0.12
4	0.00		0.02	0.04	0.08	0.00		-0.16	-0.28	-0.38
5	0.00		-0.14	-0.08	0.02	0.00		-0.06	-0.02	-0.02
6	0.00		0.00	0.02	0.06	0.00		0.02	-0.02	-0.06
7	0.00		0.02	0.02	0.04	0.00		0.00	0.00	0.00
8	0.00		0.00	0.02	0.08	0.00		0.00	-0.02	0.00
9	0.00		0.02	0.00	-0.02	0.00		0.00	0.02	0.02

- Small effects on both magnets

Reference radius 17 mm

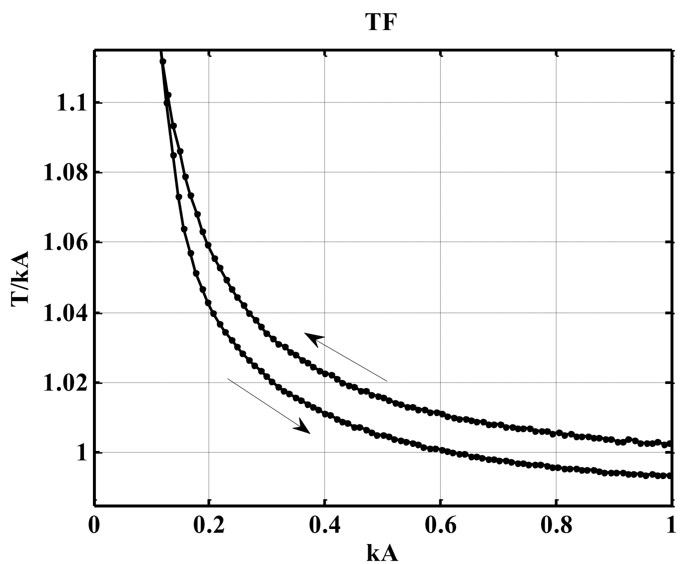
Noise at low current MBHSP101

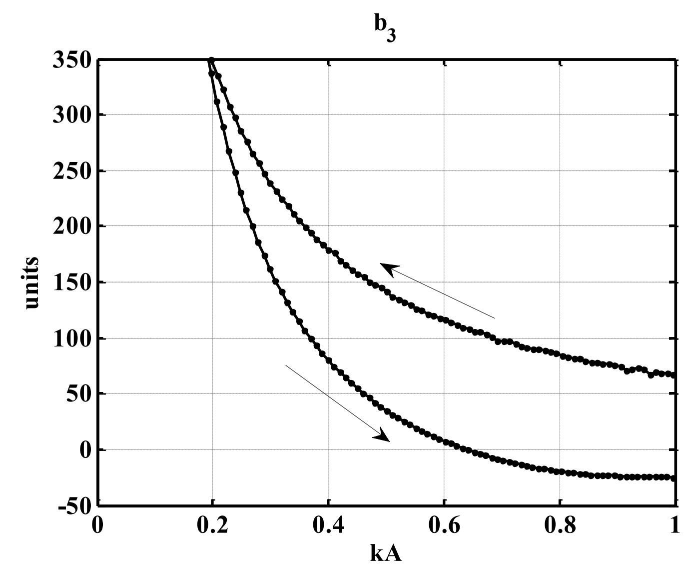




At 1.9 K

- Noise up to 600 A
- Visible on TF and multipoles





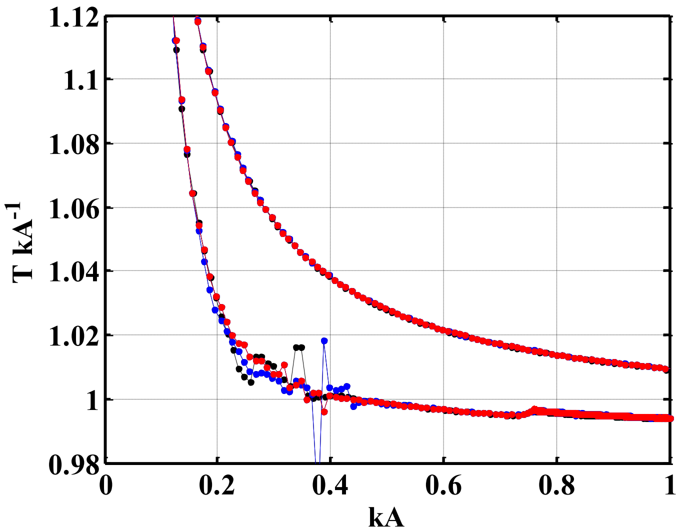
At 4.5 K

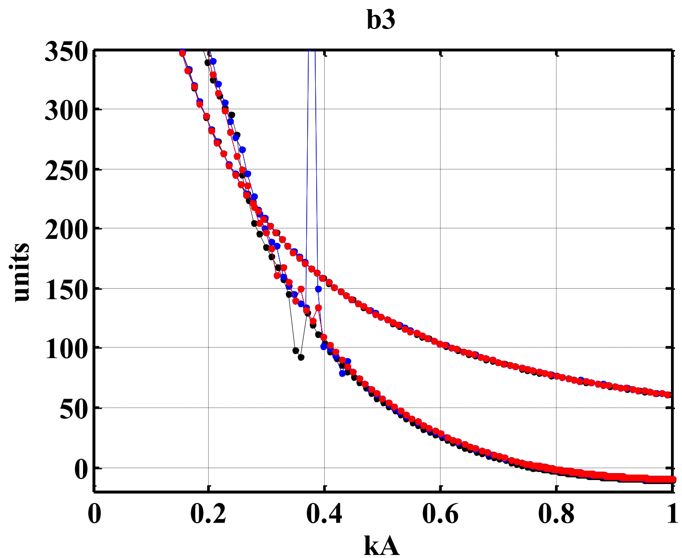
- No noise at low current
- Noise of smaller amplitude at higher current

LHC

Reference radius 17 mm

Noise at low current MBHSP102





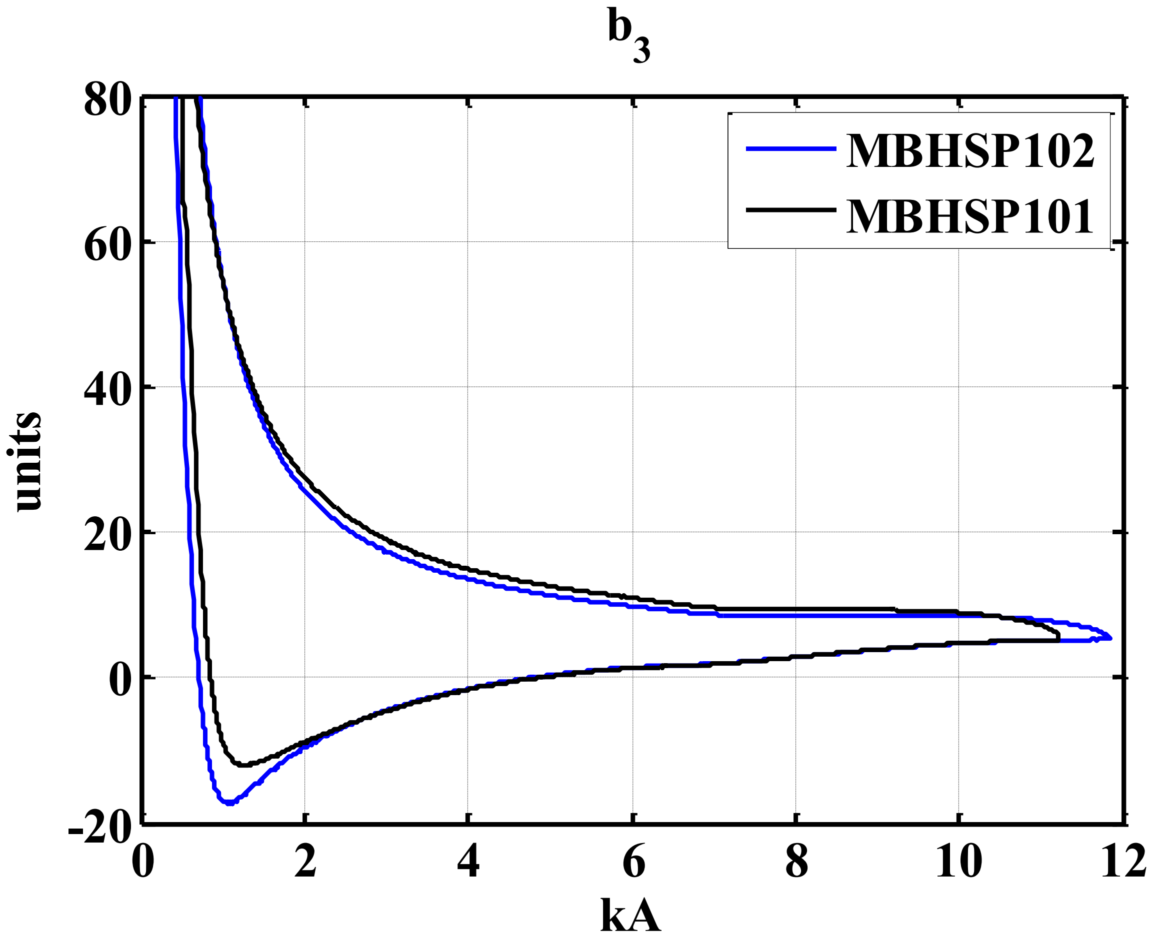
At 1.9 K

- Noise up to 500 A
- Visible on TF and multipoles

No tests at 4.5 K

Reference radius 17 mm

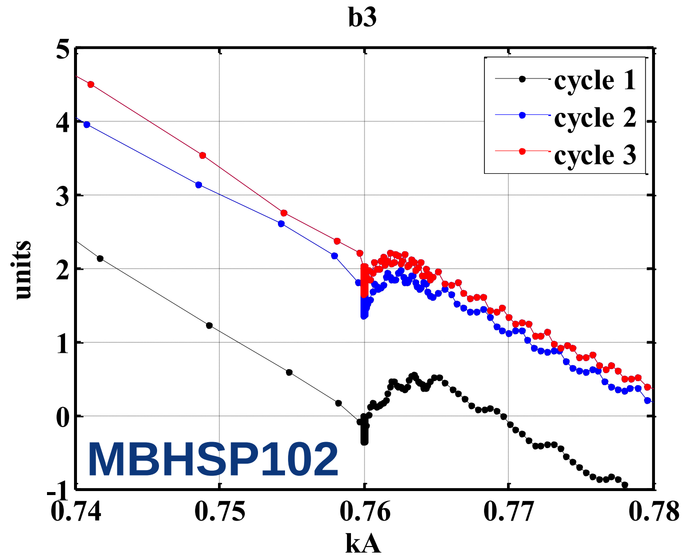
Persistent currents

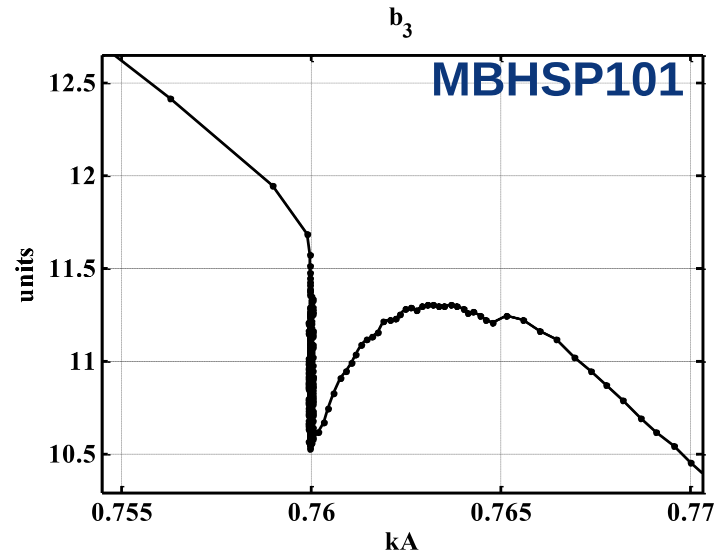


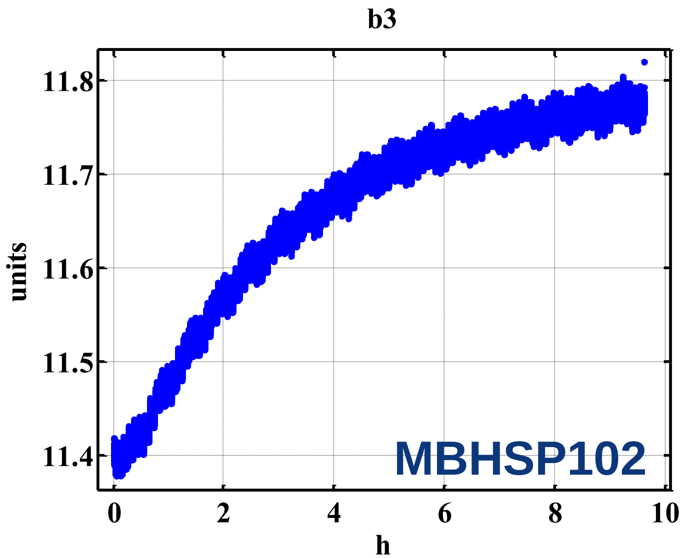
- Differences on measured b3 magnetization cycle

Reference radius 17 mm

Other measurements



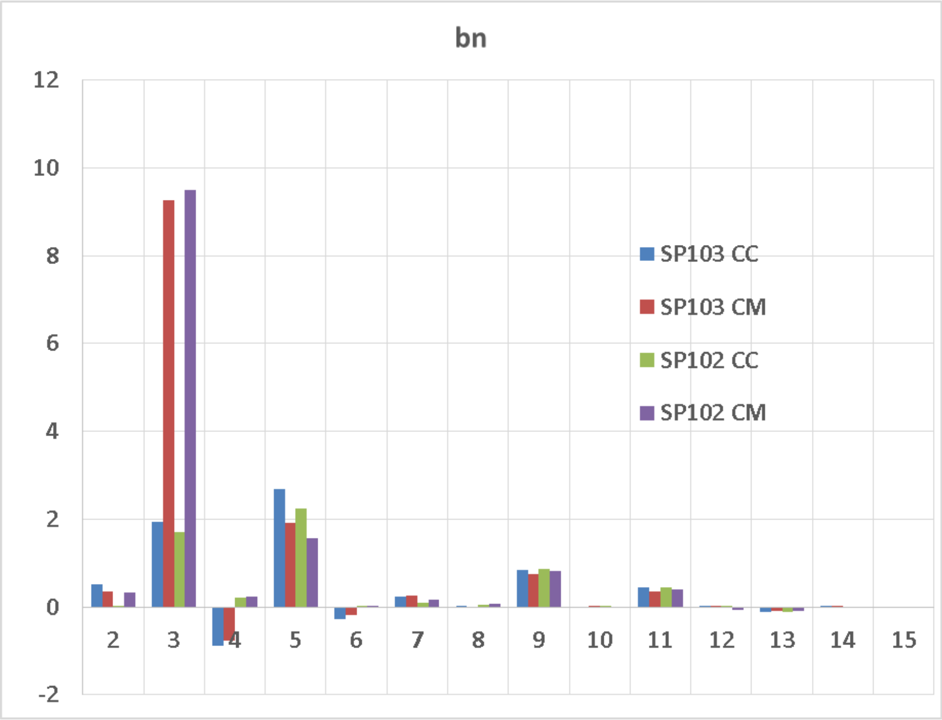


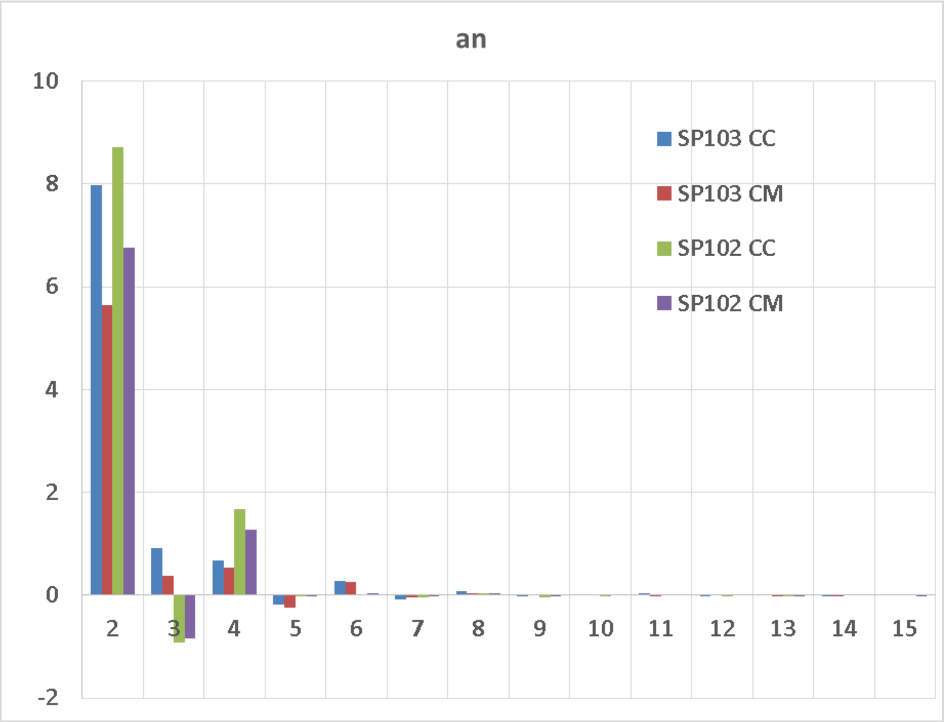


- Settling of b3 after 3 cycles
- Decay at injection of 1.2 units observed on SP101
- Decay of 0.4 units on b3 during a 10-h long plateau at nominal current

Reference radius 17 mm

MBHSP103





- Results of measurements at 300 K on MBHSP103 are very similar to those on MBHSP102

Reference radius 17 mm

Conclusions

3 short models tested (2 warm and cold, and 1 warm)

Transfer function

- Geometric in agreement with the model
- Saturation overestimated by the model

Multipoles

- Geometric in general agreement with the model
- Discrepancies on persistent current effects

Ramp-rate dependency

- Relatively small effects

Cold/Warm correlation

- Change before/after cold tests on MBHSP101
- Better correlation on MBHSP102