Field quality of LHC corrector magnets

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Thanks to A. Lombardi, M. Giovannozzi and V. Remondino (AT-MEL)

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Outline

- **Short straight section correctors reminder**

- **Corrector field errors evaluation criteria**
  - ☐ Scaling with respect to main dipoles and quadrupoles
  - ☐ Orthogonality of knobs

- **Field quality results**
  - ☐ MCBH/V
  - ☐ MQT/S
  - ☐ MS(S)
  - ☐ MO

- **Summary**

SSS correctors

- Horizontal and vertical dipole correctors MCBH/V downstream of focusing and defocusing main quads MQ

- All modules equipped with normal (or skew) sextupole MS (MSS)

- Trim quadrupoles MQT or skew quadrupoles MQS or octupoles MO upstream of MQ
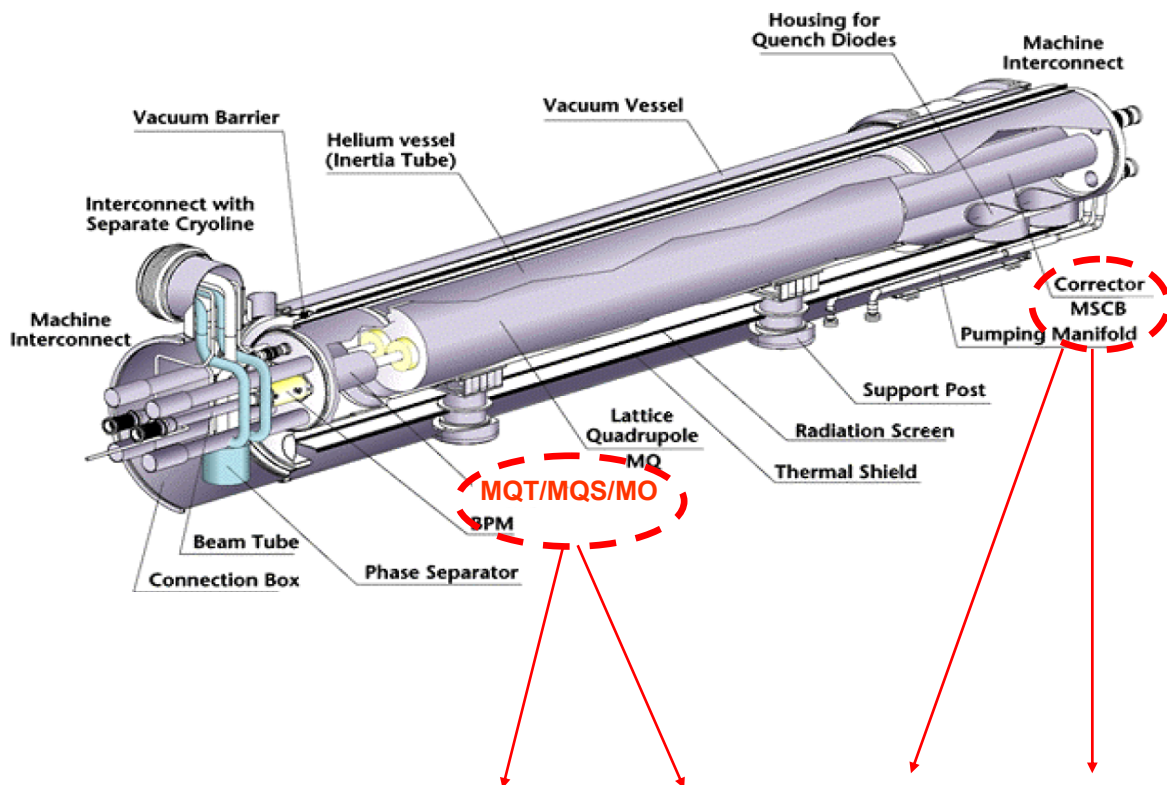
	MO	MQT/MQS	MSCB (A,B,C,D)	
			Sextupole	Dipole
Nominal strength	6.3×10^4 T/m^3	123 T/m	4430 T/m^2	2.9 T
Nominal current	550 A	550 A	550 A	55 A
Magnetic length	320 mm	320 mm	369 mm	647 mm
Overall length	395 mm	395 mm	1260 mm	
Diameter of aperture	56 mm	56 mm	56 mm	56 mm
Outer diameter	514 mm	514	452 mm	
Mass	~250 kg	~250 kg	1000 kg	
Number of magnets in arcs	168	160/32	360 (Type A: 146, B: 150, C: 32, D 32)	

Field errors evaluation criteria

■ Scaled field errors of correctors compared to the errors of the main dipoles or quadrupoles (A. Lombardi, FQWG 02/03/04, 16/11/04)

☐ Integrated kick of the scaled corrector field error should be less than 10% of either the corresponding quadrupole or dipole error effect

$$b_n^{c,\,scaled} = |b_n^c| \left(\frac{\beta_{x,y}^c}{\beta_{x,y}^M} \right)^{n/2} \frac{B^c l^c}{B^M l^M} < a_{sc}\, |b_n^M|$$

☐ a_{sc} equals **0.1** for the systematic errors and **0.46** for the random (imposed by the quadratic sum of random errors)

☐ Special attention addressed to skew correctors (MCBV, MQS and MSS), where multipole harmonics are measured in referential rotated anti-clockwise by angle **φ**. In that case, the "real" multipoles are (A. Jain, CERN academic training lectures, April 2003)

$$b_n + i a_n = (b_n' + i a_n') e^{-in\phi}$$

where **φ** equals **π/2** for the MCBV, MSS and **π/4** for the MQS

Field errors evaluation criteria (cont)

- Especially for the random b_1, a_1 and systematic b_2, a_2 and b_3, the correctors should **also** have negligible effect on orbit, tune, coupling and chromaticity, respectively.

  - Taking into account orbit distortion of less than 0.1σ, the random b_1, a_1 should be
  $$\sigma_{b_1,a_1}^{scaled} < \min(0.46\sigma_{b_1,a_1}^{dip}, \frac{0.5}{\sqrt{N_c}})$$

  - For tune-shift of less than 10^{-3}, the systematic b_2 should be
  $$<b_2>^{scaled} < \min(0.1<b_2>^{dip}, \frac{5}{N_c})$$

  - For coupling coefficient c_ of less than 10^{-3}, the systematic a_2 should be
  $$<a_2>^{scaled} < \min(0.1<a_2>^{dip}, \frac{5}{N_c})$$

  - For chromaticity of less than 1 unit, the systematic b_3 should be
  $$<b_3>^{scaled} < \min(0.1<b_3>^{dip}, \frac{20}{N_c})$$

- Dipole correctors powered to **any** value for efficient orbit correction, the quadratic sum of their systematic and random errors also compared to scaled random values of MB and MQ

- When corrector error is beyond imposed limits with respect to **both** MB or MQ, it is considered **out of specs**

Reference errors for dipoles and quads

- Taken from LHC Pr. Rep. 501

- The random errors are based on the uncertainty values of the tables

- The β-functions are the average values for the dipoles and the value at the center of the quadrupole

Multipoles		MB		MQ	
		Systematic	Random	Systematic	Random
Normal	b1	0.00	8.00	0.00	0.00
	b2	0.50	0.70	-2.80	10.01
	b3	3.00	1.40	-1.00	1.35
	b4	0.20	0.50	-0.50	0.30
	b5	1.10	0.40	-0.50	0.52
	b6	0.00	0.04	-1.00	0.60
	b7	0.10	0.24	0.20	0.14
	b8	0.01	0.02	0.02	0.24
	b9	0.77	0.12	0.04	0.41
	b10	0.00	0.02	-0.29	0.35
	b11	0.59	0.03	0.02	0.24
Skew	a1	0.00	8.00	0.00	0.00
	a2	0.45	1.60	0.00	0.00
	a3	0.75	0.70	-2.00	1.45
	a4	0.10	0.50	-0.50	1.36
	a5	0.20	0.40	-0.50	0.52
	a6	0.00	0.08	-1.00	0.42
	a7	0.04	0.04	-0.20	0.14
	a8	0.00	0.03	0.02	0.24
	a9	-0.01	0.03	0.04	0.41
	a10	0.00	0.01	0.04	0.35
	a11	0.04	0.04	0.02	0.24
Length [m]		14.312		3.1	
Nominal field [T]		8.33		3.79	
Number		1232		392	
βx [m]		135.5		176.9	
βy [m]		139.1		180.2	

Horizontal Dipole correctors - MCBH

Length [m]	0.65
Nominal field [T]	2.9
Number	376
βx [m]	170.7
βy [m]	174.2
Scaling MB	63.2
Scaling MQ	6.2

- **Systematic b_3** 4 times higher than spec (chromaticity of 4 units if all correctors powered to nominal value)

- Systematic a_3 slightly out of spec (0.08 units in MB)

- All other errors insignificant

Multipoles		MCBM		MCBH/MB			MCBH/MQ		
		Systematic	Random	Systematic	Random	Syst + Rand.	Systematic	Random	Syst + Rand.
Normal	b1	10000.00	0.00						
	b2	-0.59	4.94	0.01	0.10	0.10	0.09	0.79	0.80
	b3	-8.82	7.29	0.20	0.16	0.25	1.42	1.17	1.84
	b4	-0.05	0.89	0.00	0.02	0.02	0.01	0.14	0.14
	b5	-2.66	1.17	0.07	0.03	0.08	0.43	0.19	0.47
	b6	0.01	0.24	0.00	0.01	0.01	0.00	0.04	0.04
	b7	0.86	0.27	0.03	0.01	0.03	0.14	0.04	0.14
	b8	0.00	0.07	0.00	0.00	0.00	0.00	0.01	0.01
	b9	0.97	0.09	0.04	0.00	0.04	0.15	0.01	0.16
	b10	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
	b11	0.04	0.06	0.00	0.00	0.00	0.01	0.01	0.01
Skew	a1	0.00	0.00						
	a2	0.11	6.67	0.00	0.13	0.13	0.02	1.07	1.07
	a3	-4.41	2.01	0.10	0.04	0.11	0.71	0.32	0.78
	a4	-0.01	1.86	0.00	0.05	0.05	0.00	0.30	0.30
	a5	-0.23	0.47	0.01	0.01	0.01	0.04	0.08	0.08
	a6	0.00	0.46	0.00	0.01	0.01	0.00	0.07	0.07
	a7	-0.23	0.14	0.01	0.00	0.01	0.04	0.02	0.04
	a8	0.01	0.14	0.00	0.01	0.01	0.00	0.02	0.02
	a9	0.00	0.05	0.00	0.00	0.00	0.00	0.01	0.01
	a10	0.00	0.05	0.00	0.00	0.00	0.00	0.01	0.01
	a11	-0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00

Vertical Dipole correctors - MCBV

Multipoles		MCBM		MCBV/MB			MCBV/MQ		
		Systematic	Random	Systematic	Random	Syst + Rand.	Systematic	Random	Syst + Rand.
Normal	b1	10000.00	0.00						
	b2	-0.59	4.94	0.01	0.10	0.10	0.09	0.79	0.80
	b3	-8.82	7.29	0.10	0.04	0.11	0.71	0.32	0.78
	b4	-0.05	0.89	0.00	0.02	0.02	0.01	0.14	0.14
	b5	-2.66	1.17	0.01	0.01	0.01	0.04	0.08	0.08
	b6	0.01	0.24	0.00	0.01	0.01	0.00	0.04	0.04
	b7	0.86	0.27	0.01	0.00	0.01	0.04	0.02	0.04
	b8	0.00	0.07	0.00	0.00	0.00	0.00	0.01	0.01
	b9	0.97	0.09	0.00	0.00	0.00	0.00	0.01	0.01
	b10	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
	b11	0.04	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Skew	a1	0.00	0.00						
	a2	0.11	6.67	0.00	0.13	0.13	0.02	1.07	1.07
	a3	-4.41	2.01	0.20	0.16	0.25	1.42	1.17	1.84
	a4	-0.01	1.86	0.00	0.05	0.05	0.00	0.30	0.30
	a5	-0.23	0.47	0.07	0.03	0.08	0.43	0.19	0.47
	a6	0.00	0.46	0.00	0.01	0.01	0.00	0.07	0.07
	a7	-0.23	0.14	0.03	0.01	0.03	0.14	0.04	0.14
	a8	0.01	0.14	0.00	0.01	0.01	0.00	0.02	0.02
	a9	0.00	0.05	0.04	0.00	0.04	0.15	0.01	0.16
	a10	0.00	0.05	0.00	0.00	0.00	0.00	0.01	0.01
	a11	-0.01	0.03	0.00	0.00	0.00	0.01	0.01	0.01

- **Systematic b_3** 2 times higher than spec (a_3 value of MCBH) giving chromaticity of 2 units if all correctors powered to maximum value.
- Systematic a_3 (b_3 value of MCBH) out of spec (0.08 units in MB)
- All other errors insignificant

Trim quadrupole correctors - MQT

Length [m]	0.32
Nominal field [T]	2.04
Number	160
βx [m]	175.5
βy [m]	177.9
Scaling MB	182.6
Scaling MQ	18.0

Multipoles		MQT		MQT/MB		MQT/MQ	
		Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1	0.00	0.00				
	b2	10000.00	0.00				
	b3	2.56	20.33	0.02	0.16	0.14	1.13
	b4	-1.60	6.67	0.01	0.06	0.09	0.37
	b5	-0.47	3.13	0.00	0.03	0.03	0.17
	b6	-6.48	4.70	0.08	0.05	0.36	0.26
	b7	0.00	1.02	0.00	0.01	0.00	0.06
	b8	0.00	0.57	0.00	0.01	0.00	0.03
	b9	0.07	0.33	0.00	0.01	0.00	0.02
	b10	-15.18	0.69	0.29	0.01	0.84	0.04
	b11	0.00	0.11	0.00	0.00	0.00	0.01
Skew	a1	0.00	0.00				
	a2	0.00	0.00				
	a3	-0.08	16.67	0.00	0.13	0.00	0.93
	a4	-1.84	6.86	0.02	0.06	0.10	0.38
	a5	0.21	3.42	0.00	0.04	0.01	0.19
	a6	-0.26	0.92	0.00	0.01	0.01	0.05
	a7	-0.17	0.97	0.00	0.01	0.01	0.05
	a8	-0.20	0.82	0.00	0.01	0.01	0.05
	a9	0.03	0.34	0.00	0.01	0.00	0.02
	a10	-0.21	0.12	0.00	0.00	0.01	0.01
	a11	-0.03	0.10	0.00	0.00	0.00	0.01

- **Systematic b_6 out of spec by a small amount (0.10 for MQ)**

- **Systematic b_{10} out of spec by a large amount (0 for MQ).**
  - Studied in tracking by A. Lombardi and found that the effect in DA is small.
  - To be included in MADX error tables

Skew quadrupole correctors - MQS

- **Systematic a_6** out of spec by a small amount (0.1 for MQ)

- **Systematic a_{10}** out of spec by a large amount (0 in MQ). To be included in tracking error tables

Multipoles		MQS		MQS/MB		MQS/MQ	
		Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1	0.00	0.00				
	b2	10000.00	0.00				
	b3	3.67	20.70	0.01	0.18	0.09	**1.26**
	b4	-2.43	7.78	**0.02**	0.07	**0.13**	**0.43**
	b5	-0.58	3.25	0.00	0.03	0.01	0.17
	b6	-6.53	4.84	**0.00**	0.01	0.01	0.06
	b7	-0.06	0.93	0.00	0.01	0.01	0.05
	b8	-0.20	0.57	**0.00**	0.01	**0.01**	0.03
	b9	0.03	0.39	0.00	0.01	0.00	0.02
	b10	-14.99	0.65	**0.00**	0.00	0.01	0.01
	b11	-0.01	0.12	0.00	0.00	0.00	0.01
Skew	a1	0.00	0.00				
	a2	0.00	0.00				
	a3	-1.46	24.44	0.03	0.18	**0.20**	**1.26**
	a4	-1.29	6.66	**0.01**	0.06	**0.07**	0.37
	a5	-0.81	2.75	0.01	0.03	**0.05**	0.17
	a6	-0.22	1.10	**0.08**	**0.06**	**0.36**	**0.27**
	a7	-0.17	0.95	0.00	0.01	0.00	0.05
	a8	0.02	1.12	**0.00**	**0.02**	0.00	0.06
	a9	-0.04	0.41	0.00	0.01	0.00	0.02
	a10	-0.24	0.09	**0.29**	**0.01**	**0.83**	0.04
	a11	-0.01	0.17	0.00	0.00	0.00	0.01

Sextupole correctors - MS

Length [m]	0.369
Nominal field [T]	1.28
Number	344
βx [m]	174.3
βy [m]	177.7
Scaling MB	252.4
Scaling MQ	24.9

Multipoles		MSM		MS/MB		MS/MQ	
		Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1	3.10	17.91	**0.01**	**0.08**	**0.12**	**0.72**
	b2	0.00	0.00	0.00	0.00	0.00	0.00
	b3	10000.00	0.00				
	b4	3.03	12.07	0.02	0.08	**0.12**	**0.49**
	b5	0.23	5.02	0.00	0.04	0.01	0.20
	b6	-0.35	1.98	**0.00**	0.02	0.01	0.08
	b7	0.12	0.98	0.00	0.01	0.00	0.04
	b8	-0.05	0.53	0.00	0.01	0.00	0.02
	b9	-3.94	0.76	0.05	0.01	**0.16**	0.03
	b10	0.01	0.21	**0.00**	0.00	0.00	0.01
	b11	-0.01	0.13	0.00	0.00	0.00	0.01
Skew	a1	-1.10	18.55	**0.00**	**0.08**	**0.04**	**0.75**
	a2	0.00	0.00	0.00	0.00	0.00	0.00
	a3	0.00	0.00				
	a4	2.20	12.28	**0.01**	0.08	**0.09**	0.49
	a5	-0.43	4.92	0.00	0.04	0.02	0.20
	a6	0.05	1.98	**0.00**	0.02	0.00	0.08
	a7	-0.04	0.96	0.00	0.01	0.00	0.04
	a8	-0.01	0.53	**0.00**	0.01	0.00	0.02
	a9	0.05	0.21	0.00	0.00	0.00	0.01
	a10	-0.01	0.21	**0.00**	0.00	0.00	0.01
	a11	0.01	0.13	0.00	0.00	0.00	0.01

- **Random b_1** and **a_1** out of spec (equivalent to an orbit distortion of 0.3σ)
- All other errors within specs or insignificant

Skew sextupole correctors - MSS

Length [m]	0.369
Nominal field [T]	1.28
Number	32
βx [m]	174.3
βy [m]	177.7
Scaling MB	252.4
Scaling MQ	24.9

Multipoles		MSM		MSS/MB		MSS/MQ	
		Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1	3.10	17.91	0.00	0.08	0.04	0.75
	b2	0.00	0.00	0.00	0.00	0.00	0.00
	b3	10000.00	0.00				
	b4	3.03	12.07	0.02	0.08	0.12	0.49
	b5	0.23	5.02	0.00	0.04	0.02	0.20
	b6	-0.35	1.98	0.00	0.02	0.01	0.08
	b7	0.12	0.98	0.00	0.01	0.00	0.04
	b8	-0.05	0.53	0.00	0.01	0.00	0.02
	b9	-3.94	0.76	0.00	0.00	0.00	0.01
	b10	0.01	0.21	0.00	0.00	0.00	0.01
	b11	-0.01	0.13	0.00	0.00	0.00	0.01
Skew	a1	-1.10	18.55	0.01	0.08	0.12	0.72
	a2	0.00	0.00	0.00	0.00	0.00	0.00
	a3	0.00	0.00				
	a4	2.20	12.28	0.01	0.02	0.09	0.49
	a5	-0.43	4.92	0.00	0.04	0.01	0.20
	a6	0.05	1.98	0.00	0.01	0.00	0.08
	a7	-0.04	0.96	0.00	0.01	0.00	0.04
	a8	-0.01	0.53	0.00	0.01	0.00	0.02
	a9	0.05	0.21	0.05	0.01	0.16	0.03
	a10	-0.01	0.21	0.00	0.01	0.00	0.01
	a11	0.01	0.13	0.00	0.00	0.00	0.01

■ **Random b_1 and a_1** in spec due to smaller amount of correctors (32)

■ **Systematic a_9** out of spec but effect should be small

Octupole correctors – MO

Length [m]	0.32
Nominal field [T]	0.29
Number	168
βx [m]	175.4
βy [m]	178.7
Scaling MB	1284.7
Scaling MQ	126.6

- **Systematic b$_2$** out of spec by a small amount (0.03 for MB), equivalent to tune-shift of 2 x 10^{-3} if powered to maximum current

Multipoles		MO		MO/MB		MO/MQ	
		Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1	19.99	42.81	0.02	0.04	0.16	0.34
	b2	40.80	58.96	0.04	0.06	0.32	0.47
	b3	0.00	0.00	0.00	0.00	0.00	0.00
	b4	10000.00	0.00				
	b5	-6.42	32.05	0.01	0.05	0.05	0.25
	b6	-3.04	9.11	0.01	0.02	0.02	0.07
	b7	-2.78	4.49	0.01	0.01	0.02	0.04
	b8	1.57	2.02	0.00	0.00	0.01	0.02
	b9	0.68	1.11	0.00	0.00	0.01	0.01
	b10	0.13	0.53	0.00	0.00	0.00	0.00
	b11	0.08	0.33	0.00	0.00	0.00	0.00
Skew	a1	1.05	42.75	0.00	0.04	0.01	0.34
	a2	-3.61	55.87	0.00	0.06	0.03	0.44
	a3	0.00	0.00	0.00	0.00	0.00	0.00
	a4	0.00	0.00				
	a5	-26.07	33.47	0.04	0.05	0.21	0.26
	a6	-1.30	9.69	0.00	0.02	0.01	0.08
	a7	-0.62	4.50	0.00	0.01	0.00	0.04
	a8	0.21	4.83	0.00	0.01	0.00	0.04
	a9	-0.23	1.11	0.00	0.00	0.00	0.01
	a10	-0.19	0.52	0.00	0.00	0.00	0.00
	a11	-0.17	0.31	0.00	0.00	0.00	0.00

Summary

Multipoles		MCBH (spec)		MCBV (spec)		MQT (spec)		MQS (spec)		MS (spec)		MSS (spec)		MO (spec)	
		Systematic	Random	Systematic	Random	Systematic	Random	Systematic	Random	Systematic	Random	Systematic	Random	Systematic	Random
Normal	b1										0.08 (0.03)				
	b2													0.04 (0.03)	
	b3	0.20 (0.05)		0.10 (0.05)											
	b4														
	b5														
	b6					0.36 (0.10)									
	b7														
	b8														
	b9														
	b10					0.84 (0.03)									
	b11														
Skew	a1										0.08 (0.03)				
	a2														
	a3														
	a4														
	a5														
	a6							0.36 (0.10)							
	a7														
	a8														
	a9												0.16 (0.00)		
	a10							0.83 (0.00)							
	a11														

*** All errors are referred with respect to the MQ, except of random a_1, b_1, and systematic a_2, b_2 and b_3