List of machine and beam parameters

A. List of machine and beam parameters

A.1. Main machine parameters

Table A-1: HL-LHC nominal machine parameters for proton operation [1]

		Injection	**Collision**
Geometry			
Ring circumference	(m)	26658.883	26658.883
Ring separation in arcs	(mm)	194	194
Bare inner vacuum screen height in arcs	(mm)	46.5	46.5
Effective vacuum screen height (incl. tol.)	(mm)	44.04	44.04
Bare inner vacuum screen width in arcs	(mm)	36.9	36.9
Effective vacuum screen width (incl. tol.)	(mm)	34.28	34.28
Main magnets			
Number of main bends		1232	1232
Length of main bends	(m)	14.3	14.3
Field of main bends	(T)	0.535	8.33
Bending radius	(m)	2803.95	2803.95
Lattice			
Maximum dispersion in arc (H/V)	(m)	2.42/0.28	2.72/0.80
Minimum dispersion in arc (H/V)	(m)	0.96/−0.28	0.56/−0.50
Maximum β in arc (H/V)	(m)	178/179	592/593
Minimum β in arc (H/V)	(m)	31.2/31.7	24.1/25.1
Minimum β in IP1/2/5/8*	(m)	6/10/6/10	0.15/10/0.15/1.5
Horizontal tune		62.27	62.31
Vertical tune		60.295	60.32
Momentum compaction (B1/B2)	[10^{-4}]	3.478/3.476	3.485/3.480
Slip factor η (B1/B2)	[10^{-4}]	3.435/3.432	3.485/3.480
Gamma transition γ_{tr} (B1/B2)		53.62/53.64	53.56/53.61
RF System			
Revolution frequency	(kHz)	11.2455	11.2455
RF frequency	(MHz)	400.789	400.790
Harmonic number		35640	35640
Total RF voltage**	(MV)	8	16
Synchrotron frequency	(Hz)	66.0	23.8
Bucket area	(eVs)	1.38	7.63
Bucket half height ($\Delta E/E$)	[10^{-3}]	0.965	0.343
Crab Cavities			
RF frequency	(MHz)	400.789	400.790
Max. Total RF voltage (per IP)	(MV)	6.8	6.8

*The horizontal and vertical β functions are equal at the IP.

** Injection requires the so-called half-detuning scheme while energy ramp, flattop, and collision require full detuning scheme (see chapter 4).

Table A-2: HL-LHC nominal machine parameters at the collision points for proton operation. The crossing angle and separation refer to Beam 1 if not specified otherwise [1].

		Injection	**Collision**
Interaction data			
Number of collision points		NA	4
Half crossing angle at the IP for ATLAS (IP1)[a]	(μrad)	+295 (H)	+250 (H)
Half parallel separation at the IP for ATLAS (IP1)[b]	(mm)	+2.0 (V)	0.0 (V)
Half external crossing angle at IP for ALICE (IP2)[b,c]	(μrad)	-170 (V)	-170 (V)
Half crossing angle at the IP for ALICE (IP2)[b,c,d]	(μrad)	-170 ∓ 1089 (V)	-170∓70 (V)
External parallel angle at the IP for ALICE (IP2)[e]	(μrad)	-40 (H)	0 (H)
Angle at the IP for ALICE (IP2)	(μrad)	-40∓4.5(B1H)//40±4.5(B2H)	∓0.3(B1H)//±0.3(B2H)
Half parallel separation at the IP for ALICE (IP2)[e]	(mm)	+3.5 (H)	+0.138[f] (H)
Half crossing angle at the IP for CMS (IP5)[b]	(μrad)	+295 (V)	+250 (V)
Half parallel separation at the IP for CMS (IP5)[b]	(mm)	-2.0 (H)	0.0 (H)
Half external crossing angle at the IP for LHCb (IP8)[a]	(μrad)	-170 (H)	-200 (H)
Half crossing angle at the IP for LHCb (IP8)[c,d]	(μrad)	-170∓2100 (H)	-200∓135 (H)
External parallel angle at the IP for LHCb[e] (IP8)[e] [4]	(μrad)	-40 (V)	0
Angle at the IP for LHCb (IP8) [4]	(μrad)	-40∓28(B1V)//40±28(B2V)	∓1.8(B1V)//±1.8(B2V)
Half parallel separation at IP for LHCb (IP8)[e] [4]	(mm)	-3.5 (V)	-0.031/-0.035[g] (V)
Minimum β at IP1 and IP5 (H/V)	(m)	6/6	0.15/0.15
β at IP2 (H/V)	(m)	10/10	10/10
β at IP8 (H/V)	(m)	10/10	1.5/1.5

[a] The sign is defined by the LHC geometry.

[b] The other sign is possible and not correlated with other sign choices.

[c] The crossing angle in IP2 and IP8 is the sum of an external crossing angle bump and an ‘internal’ spectrometer compensation bump and it depends on the spectrometer polarity [2]. The external bump extends over the triplet and D1 and D2 magnets. The internal spectrometer compensation bump extends only over the long drift space between the two triplet assemblies left and right from the IP. For IP2 the vertical external crossing angle sign can be changed (but it is not strictly necessary) and therefore the sign of the internal and external angle can be chosen to be the same. This is not possible for IP8 as the sign of the crossing angle must be compatible with the recombination scheme. For IP2 and IP8 the value of the external crossing angle is given to provide the maximum crossing angle at the IP for the so-called “positive” polarity of the spectrometer [3]. The convention for the spectrometer polarity sign is that it is positive for a negative sign of the “internal” crossing angle at the IP.

[d] The first value corresponds to the so-called “positive” polarity of the spectrometers [3].

[e] The other sign is possible but the sign of the parallel angle and separation are correlated for the same IP.

[f] This corresponds to a full separation of 4.8 σ required to reduce the luminosity down to 10^{31} cm^{-2} s^{-1} for the nominal bunch population at the beginning of the stable beam period both for the positive and negative polarity of the spectrometer. The standard filling scheme has been considered.

[g] This corresponds to a full separation of 2.8/3.1 σ required to reduce the luminosity down to 2×10^{33} cm^{-2} s^{-1} for the nominal bunch population at the beginning of the stable beam period for the positive and negative polarity of the spectrometer, respectively. The standard filling scheme has been considered.

A.2. Proton-beam parameters in collision

Table A-3: HL-LHC nominal parameters for 25 ns operation [5][6] for two production modes of the LHC beam in the injectors described in Ref. [7] and for the alternative scenario 8b+4e [7] [8] [9].

Parameter	**HL-LHC (standard)**	**HL-LHC (BCMS)[#]**	**HL-LHC (8b+4e)[@]**
Beam energy in collision (TeV)	7	7	7
Particles per bunch, N [10^{11}]	2.2	2.2	2.2
Number of bunches per beam	2760	2744	1972
Number of collisions in IP1 and IP5[*]	2748	2736	1960
N_{tot} [10^{14}]	6.1	6.0	4.3
Beam current (A)	1.10	1.10	0.78
Half-crossing angle in IP1 and IP5 (μrad)	250	250	250
Minimum norm. long-range beam–beam separation (σ)	10.5	10.5	10.5
Minimum β^* (m)	0.15	0.15	0.15
ε_{n} (μm)	2.50	2.50	2.50
ε_{L} (eVs)	3.03	3.03	3.03
R.M.S. energy spread [10^{-4}] (q-Gaussian distribution)	1.1	1.1	1.1
R.M.S. energy spread [10^{-4}] (FWHM equiv. Gaussian)	1.29	1.29	1.29
R.M.S. bunch length (cm) (q-Gaussian distribution)	7.61	7.61	7.61
R.M.S. bunch length (cm) (FWHM equivalent Gaussian)	9.0	9.0	9.0
IBS horizontal (h)	16.5	16.5	16.5
IBS longitudinal (h)	19.2	19.2	19.2
Radiation Damping time (h)	26	26	26
Piwinski parameter	2.66	2.66	2.66
Total reduction factor R_0 without crab cavities at min. β^*	0.342	0.342	0.342
Total reduction factor R_1 with crab cavities at min. β^*	0.716	0.716	0.716
Beam–beam tune shift/IP [10^{-3}]	8.6	8.6	8.6
Peak luminosity without crab cavities L_{peak} [10^{34} cm^{-2} s^{-1}]	8.11	8.07	5.78
Peak luminosity with crab cavities $L_{\mathrm{peak}} \times R_1/R_0$ [10^{34} cm^{-2} s^{-1}]	17.0	16.9	12.1
Events/crossing w/o levelling and without crab cavities	212	212	212
Levelled luminosity [10^{34} cm^{-2} s^{-1}]	5.0	5.0	3.8
Events/crossing μ (with levelling and crab cavities)[‡]	131	132	140
Max. line density of pile-up events during fill [evts/mm]	1.28	1.29	1.37
Levelling time (h) (assuming no emittance growth)[‡]	7.2	7.2	6.4
Number of collisions in IP2/IP8	2492/2574[**]	2246/2370[**]	1178/1886[**]
N at injection [10^{11}][††]	2.30	2.30	2.30
Maximum number of bunches per injection	288	240	224
N_{tot}/injection [10^{13}]	6.62	5.52	5.15
ε_{n} at SPS extraction (μm)[‡‡]	2.10	1.70	1.70

[#] BCMS parameters are only considered as a backup scenario set in case one encounters larger-than-expected emittance growth in HL-LHC during injection, ramp, and squeeze

[@] The 8b+4e variant represents a back-up scenario for the baseline 25ns operation in case of electron cloud limitations.

[*] Assuming one less batch from the PS for machine protection (pilot injection, transfer line steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies, etc.). Note that due to RF beam loading the abort gap length must not exceed the 3 μs design value.

[‡] The total number of events/crossing is calculated with an inelastic cross-section of 81 mb, while 111 mb is assumed as a pessimistic value for calculating the proton burn off and the resulting levelling time [10][11].

[**] The lower number of collisions in IR2/8 compared to the general-purpose detectors is a result of the agreed filling scheme, aiming as much as possible at an equal sharing of collisions between the experiments.

[††] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.

[‡‡] A transverse emittance blow-up of 10–15% on the average H/V emittance in addition to that expected from intra-beam scattering (IBS) is assumed (to reach 2.5 μm of emittance in collision for 25 ns operation).

A.3. Proton-beam parameters at LHC injection (after capture)

Table A-4: HL-LHC nominal parameters at injection (after capture) for 25 ns operation [5][6]for two production modes of the LHC beam in the injectors described in [7] and for the alternative scenario 8b+4e [7][8][9]. The longitudinal parameters have been revised with respect to previous documents.

Parameter	**HL-LHC (standard)**	**HL-LHC (BCMS)#**	**HL-LHC (8b+4e)@**
Beam energy (TeV)	0.45	0.45	0.45
Relativistic gamma	479.6	479.6	479.6
Particles per bunch, N [10^{11}]	2.30	2.30	2.30
Number of bunches per beam	2760	2744	1972
N_{tot} [10^{14}]	6.3	6.3	4.5
Beam current (A)	1.14	1.14	0.82
Stored energy per beam (MJ)	46	46	33
ε_n (μm)	2.1	1.7	1.7
ε_L (eVs)	0.57	0.57	0.57
R.M.S. energy spread [10^{-4}] (q-Gaussian distribution)**	3.1	3.1	3.1
R.M.S. energy spread [10^{-4}] (FWHM equiv. Gaussian)**	3.4	3.4	3.4
R.M.S. bunch length (cm) (q-Gaussian distribution)**	7.8	7.8	7.8
R.M.S. bunch length (cm) (FWHM equivalent Gaussian)**	9.2	9.2	9.2
IBS horizontal (h)	4.7	3.0	3.0
IBS longitudinal (h)	3.5	2.7	2.7

[#] BCMS parameters are only considered for injection and as a backup parameter set in case one encounters larger-than-expected emittance growth in the HL-LHC during injection, ramp and squeeze.

[@] The 8b+4e variant represents a back-up scenario for the baseline 25ns operation in case of electron cloud limitations.

[**] Before IBS emittance blow-up takes place.

A.4. Required proton beam parameters at SPS extraction

Table A-5: Required beam parameters at SPS extraction for 25 ns operation [5][6] for two production modes of the LHC beam in the injectors described in [7] and for the alternative scenario 8b+4e [8][9].

Parameter	**HL-LHC (standard)**	**HL-LHC (BCMS)#**	**HL-LHC (8b+4e)@**
Beam energy (TeV)	0.45	0.45	0.45
Particles per bunch, N [10^{11}]††	2.30	2.30	2.30
Maximum number of bunches per injection	288	240	224
Max N_{tot}/extraction [10^{13}]	6.62	5.52	5.15
ε_n (μm)‡‡	2.1	1.7	1.7
ε_L (eVs)a	0.57	0.57	0.57
R.M.S. energy spread [0.0001] a	2.5	2.5	2.5
R.M.S. bunch length (cm) a	12.4	12.4	12.4

[#] BCMS parameters are only considered as a backup scenario set in case one encounters larger-than-expected emittance growth in the HL-LHC during injection, ramp and squeeze.

[@] The 8b+4e variant represents a back-up scenario for the baseline 25ns operation in case of electron cloud limitations.

[††] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.

[‡‡] A transverse emittance blow-up of 10–15% on the average H/V emittance in addition to that expected from intra-beam scattering (IBS) is assumed (to reach 2.5 μm of emittance in collision for 25 ns operation).

[a] These represent the average values including 10% voltage of 4th harmonic system. Calculations are performed without including intensity effects. A spread of ±10% in longitudinal bunch length and of ±10% in R.M.S. energy spread has to be expected, resulting in a ±20% spread in longitudinal emittance.

A.5. Ion-beam parameters in collision

Table A-6: Key LHC design parameters for Pb operation from [12] compared with the achieved parameters in 2018 and the HL-LHC design values [13].

Parameters	**Nominal LHC (design report)**	**2018 achieved**	**HL-LHC (LIU baseline)**
Beam energy in collision (Z TeV)	7	6.37	7
Particles per bunch, N [10^7]	7	23	18
Number of bunches per beam	592	733	1240
Colliding pairs at IP1/5	< 592	733	976-1240[1]
Colliding pairs at IP2	592	702	976-1200[1]
Colliding pairs at IP8	0	468	0-716[1]
Total intensity N_{tot} [10^9]	41.4	169	223
Beam current (mA)	6.12	24.9	33.0
Stored beam energy (MJ)	3.8	13.9	20.5
Minimum β^* (m)	0.5	0.5	0.5
Normalized emittance ε_{n} (μm)	1.5	2.3	1.65
Longitudinal emittance ε_{L} [eVs/charge]	2.50	2.33	2.42
RMS energy spread [10^{-4}]	1.08	1.06	1.02
RMS bunch length (cm)	8.07	8.24	8.24
Half-crossing angle at IP2 (μrad) (external,net)	110,40	137,60	170,100
Peak luminosity [10^{27} cm^{-2} s^{-1}]	1.0	-	-
Levelled luminosity IP1/5 [10^{27} cm^{-2} s^{-1}]	-	6.13	6.4
Levelled luminosity IP2 [10^{27} cm^{-2} s^{-1}]	-	1.0	6.4
Levelled luminosity IP8 [10^{27} cm^{-2} s^{-1}]	-	1.0	1.0
Typical levelling time IP2 (h)	-	7	1.5
Maximum number of bunches per injection	54	42	56

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[1] The values give the range over the filling schemes considered in Ref. [13].

A.6. Main insertion region magnet parameters

Table A-7: New or refurbished quadrupoles for the HL-LHC in IR1 and 5. "Beam stay clear" indicates the minimum aperture available for the beam considering the tolerance on the mechanical deformations of the nominal beam screen inner shape.

	Inner triplet (single aperture)			Matching section (two-in-one)	
Magnet	Q1	Q2	Q3	Q4	Q5
Number per side per insertion	2			1	
Type	MQXFA	MQXFB	MQXFA	MQY	MQML
Magnetic length (m)	4.2	7.17	4.2	3.4	4.8
Maximum Gradient	132.2			160	160
Coil aperture (mm)	150			70	56
Aperture separation	NA			194	
Operating temperature	1.9			4.5	
Beam screen shape	Octagon			Rectellipse	
Nominal beam screen aperture (mm)	99.7 (H/V)/ 99.7 (45°)	119.7 (H/V)/ 110.7 (45°)		60.2 (d)/50.4 (g)	47.5 (d)/37.7 (g)
Beam stay clear (mm)	94.94 (H/V)/ 94.94 (45°)	115.3 (H/V)/ 106.3 (45°)		57.8 (d)/48 (g)	45.1 (d)/35.3 (g)
Alignment tolerances (R/H/V) (mm)	0.6/1.0/1.0			0.84/1.26/0.6	
Beam screen orientation (plane of smaller gap)				L.B1: V L.B2: H R.B1: H R.B2: V	

The description of the shapes is made by providing the dimensions corresponding to the horizontal (H)/vertical (V) and 45° cuts for octagons; diameter (d) and gap (g) for rectellipse [12]; radius for circles. The orientation of the rectellipse cross section depends on the IP side and beam type and it has been chosen to optimise the beam aperture in collision. The alignment tolerances are represented as a racetrack shape of radius (R), horizontal (H), vertical (V) extent, respectively. The values provided include ground motion and fiducialization tolerances [1], although they are going to be reviewed in the context of the full remote alignment system.

Table A-8: Separation and corrector dipole magnets for the HL-LHC in IR1 and 5. The order of the correctors has to be considered starting from the IP towards the arcs.

	Separation/recombination dipoles		**Orbit correctors**				
Assembly	D1	D2	Corrector Package	Q2	D2	Q4	Q5
Number per side per insertion	1	1	1	2	2	3	1
Configuration			HV nested	HV nested	L.B1: VH L.B2: HV R.B1: VH R.B2: HV consecutive	L.B1: VHV L.B2: HVH R.B1: HVH R.B2: VHV consecutive	L.B1: V L.B2: H R.B1: H R.B2:V
Type	MBXF	MBRD	MCBXFA	MCBXFB	MCBRD	MCBY	MCBC
Magnetic length (m)	6.27	7.78	2.2	1.2	1.89	0.9	0.9
Integrated field (Tm)	35.08	35.08	4.5	2.5	5.0	2.5	2.33
Coil aperture (mm)	150	105	150	150	105	70	56
Aperture separation (mm)	NA	188	NA	NA	188	194	194
Operating temperature (K)	1.9					4.5	
Beam screen shape	Octagon	Octagon	Octagon	Octagon	Octagon	Rectellipse	Rectellipse
Nominal beam screen aperture (mm)	119.7 (H/V)/ 110.7 (45°)	87.45 (H/V)/ 77.55 (45°)	119.7 (H/V)/ 110.7 (45°)	119.7 (H/V)/ 110.7 (45°)	87.45 (H/V)/ 77.55 (45°)	60.2 (d)/ 50.4 (g)	47.5 (d)/ 37.7 (g)
Beam stay clear	115.3 (H/V)/ 106.3 (45°)	82.7 (H/V)/ 72.5 (45°)	115.3 (H/V)/ 106.3 (45°)	115.3 (H/V)/ 106.3 (45°)	82.7 (H/V)/ 72.5 (45°)	57.8 (d)/ 48 (g)	45.1 (d)/ 35.3 (g)
Alignment tolerances (R/H/V) (mm)	0.6/1.0/1.0	0.84/1.36/1.0	0.6/1.0/1.0	0.6/1.0/1.0	0.84/1.36/1.0	0.84/1.26/0.6	
Beam screen orientation (plane of smaller gap)						L.B1: V L.B2: H R.B1: H R.B2: V	

Table A-9: New superferric correctors for the HL-LHC [15][16]. The order (from left to right) follows the order of installation from the IP.

Number	1	1	1	1	1	1	1	1	1
Number of poles	4	12	12	10	10	8	8	6	6
Normal/skew	Skew	Normal	Skew	Normal	Skew	Normal	Skew	Normal	Skew
Name	MQSXF	MCTXF	MCTSXF	MCDXF	MCDSXF	MCOXF	MCOSXF	MCSXF	MCSSXF
Magnetic length (m)	0.401	0.470	0.099	0.146	0.146	0.145	0.145	0.167	0.167
Integrated field (mT m) at 50 mm	700	86	17	37	37	69	69	95	95
Aperture (mm)	150								
Operating temp.(K)	1.9								
Beam screen shape	Octagon								
Nominal beam screen aperture (H/V) (mm)	119.7 (H/V)/ 110.7 (45°)								
Beam stay clear (mm)	115.3 (H/V)/ 106.3 (45°)								
Alignment tolerances (R/H/V) (mm)	0.6/1.0/1.0								

A.7. Expected field quality for the new insertion-region magnets

In this section the error tables used in the tracking simulations (as described in Chapter 2, Section 2.3.2) for the various classes of new magnets are collected. The error tables can be found under /afs/cern.ch/eng/lhc/optics/HLLHCV1.0/errors2.

The expected field quality of each of the triplet magnets MQXFA and MQXFB at injection and top energy is presented in Table A-10 and Table A-11, respectively. The contributions from the body of the magnets and of the fringe fields at the Connection Side (CS) and Non-Connection Side (NCS) are indicated. The magnetic lengths of the magnets body and of the fringe fields are listed in

Table A-12.

Table A-10: Expected field quality (Systematic – S, Uncertainty – U, Random – R) at injection energy for the IT magnets (r_0 = 50 mm).

	Body			CS	NCS		Body			CS	NCS
	S	U	R	S	S		S	U	R	S	S
a_2	0.000	0.000	0.000	-31.342	0.000	b_2	0.000	0.000	10.000	0.000	0.000
a_3	0.000	0.650	0.650	0.000	0.000	b_3	0.000	0.820	0.820	0.000	0.000
a_4	0.000	0.650	0.650	0.000	0.000	b_4	0.000	0.570	0.570	0.000	0.000
a_5	0.000	0.430	0.430	0.000	0.000	b_5	0.000	0.420	0.420	0.000	0.000
a_6	0.000	0.310	0.310	2.209	0.000	b_6	-21.300	1.100	1.100	8.943	-0.025
a_7	0.000	0.190	0.190	0.000	0.000	b_7	0.000	0.190	0.190	0.000	0.000
a_8	0.000	0.110	0.110	0.000	0.000	b_8	0.000	0.130	0.130	0.000	0.000
a_9	0.000	0.080	0.080	0.000	0.000	b_9	0.000	0.070	0.070	0.000	0.000
a_{10}	0.000	0.040	0.040	0.065	0.000	b_{10}	3.890	0.200	0.200	-0.189	-0.821
a_{11}	0.000	0.026	0.026	0.000	0.000	b_{11}	0.000	0.026	0.026	0.000	0.000
a_{12}	0.000	0.014	0.014	0.000	0.000	b_{12}	0.000	0.018	0.018	0.000	0.000
a_{13}	0.000	0.010	0.010	0.000	0.000	b_{13}	0.000	0.009	0.009	0.000	0.000
a_{14}	0.000	0.005	0.005	-0.222	0.000	b_{14}	0.210	0.023	0.023	-0.545	-1.083
a_{15}	0.000	0.000	0.000	0.000	0.000	b_{15}	0.000	0.000	0.000	0.000	0.000

Table A-11: Expected field quality (Systematic – S, Uncertainty – U, Random – R) at top energy for the IT magnets (r_0 = 50 mm).

	Body			CS	NCS		Body			CS	NCS
	S	U	R	S	S		S	U	R	S	S
a_2	0.000	0.000	0.000	-31.342	0.000	b_2	0.000	0.000	10.000	0.000	0.000
a_3	0.000	0.650	0.650	0.000	0.000	b_3	0.000	0.820	0.820	0.000	0.000
a_4	0.000	0.650	0.650	0.000	0.000	b_4	0.000	0.570	0.570	0.000	0.000
a_5	0.000	0.430	0.430	0.000	0.000	b_5	0.000	0.420	0.420	0.000	0.000
a_6	0.000	0.310	0.310	2.209	0.000	b_6	-0.640	1.100	1.100	8.943	-0.025
a_7	0.000	0.190	0.190	0.000	0.000	b_7	0.000	0.190	0.190	0.000	0.000
a_8	0.000	0.110	0.110	0.000	0.000	b_8	0.000	0.130	0.130	0.000	0.000
a_9	0.000	0.080	0.080	0.000	0.000	b_9	0.000	0.070	0.070	0.000	0.000
a_{10}	0.000	0.040	0.040	0.065	0.000	b_{10}	-0.110	0.200	0.200	-0.189	-0.821
a_{11}	0.000	0.026	0.026	0.000	0.000	b_{11}	0.000	0.026	0.026	0.000	0.000
a_{12}	0.000	0.014	0.014	0.000	0.000	b_{12}	0.000	0.018	0.018	0.000	0.000
a_{13}	0.000	0.010	0.010	0.000	0.000	b_{13}	0.000	0.009	0.009	0.000	0.000
a_{14}	0.000	0.005	0.005	-0.222	0.000	b_{14}	-0.870	0.023	0.023	-0.545	-1.083
a_{15}	0.000	0.000	0.000	0.000	0.000	b_{15}	0.000	0.000	0.000	0.000	0.000

Table A-12: Estimated magnetic lengths of the triplet magnets' body and fringe fields at the connection (CS) and non-connection (NCS) sides.

	Magnetic length		
Magnet	Body	CS	NCS
MQXFA	3.459	0.4	0.341
MQXFB	6.409	0.4	0.341

The expected field quality of the MBXF magnet at injection and top energy is presented in Table A-13 and Table A-14, respectively.

Table A-13: Expected field quality errors (Systematic – S, Uncertainty – U, Random – R) at injection energy for the MBXF magnets (r_0 = 50 mm).

	S	U	R		S	U	R
a_2	0.000	0.679	0.679	b_2	0.000	0.200	0.200
a_3	0.000	0.282	0.282	b_3	-16.000	0.727	0.727
a_4	0.000	0.444	0.444	b_4	0.000	0.126	0.126
a_5	0.000	0.152	0.152	b_5	-0.500	0.365	0.365
a_6	0.000	0.176	0.176	b_6	0.000	0.060	0.060
a_7	0.000	0.057	0.057	b_7	0.900	0.165	0.165
a_8	0.000	0.061	0.061	b_8	0.000	0.027	0.027
a_9	0.000	0.020	0.020	b_9	-0.660	0.065	0.065
a_{10}	0.000	0.025	0.025	b_{10}	0.000	0.008	0.008
a_{11}	0.000	0.007	0.007	b_{11}	0.440	0.019	0.019
a_{12}	0.000	0.008	0.008	b_{12}	0.000	0.003	0.003
a_{13}	0.000	0.002	0.002	b_{13}	0.000	0.006	0.006
a_{14}	0.000	0.003	0.003	b_{14}	0.000	0.001	0.001
a_{15}	0.000	0.001	0.001	b_{15}	-0.040	0.002	0.002

Table A-14: Expected field quality errors (Systematic – S, Uncertainty – U, Random – R) at top energy for the MBXF magnets (r_0 = 50 mm).

	S	U	R		S	U	R
a_2	0.000	0.679	0.679	b_2	0.000	0.200	0.200
a_3	0.000	0.282	0.282	b_3	-0.900	0.727	0.727
a_4	0.000	0.444	0.444	b_4	0.000	0.126	0.126
a_5	0.000	0.152	0.152	b_5	0.000	0.365	0.365
a_6	0.000	0.176	0.176	b_6	0.000	0.060	0.060
a_7	0.000	0.057	0.057	b_7	0.400	0.165	0.165
a_8	0.000	0.061	0.061	b_8	0.000	0.027	0.027
a_9	0.000	0.020	0.020	b_9	-0.590	0.065	0.065
a_{10}	0.000	0.025	0.025	b_{10}	0.000	0.008	0.008
a_{11}	0.000	0.007	0.007	b_{11}	0.470	0.019	0.019
a_{12}	0.000	0.008	0.008	b_{12}	0.000	0.003	0.003
a_{13}	0.000	0.002	0.002	b_{13}	0.000	0.006	0.006
a_{14}	0.000	0.003	0.003	b_{14}	0.000	0.001	0.001
a_{15}	0.000	0.001	0.001	b_{15}	-0.040	0.002	0.002

The Expected field quality of the MBRD magnets at injection and top energy is presented in Table A-15 and Table A-16, respectively.

Table A-15: Expected field quality errors (Systematic – S, Uncertainty – U, Random – R) at injection energy for the MBRD magnets (r_0 = 35 mm). The systematic error represents the value of the multipole for the V1 aperture and that for V2 can be derived from the well-known symmetries for 2-in-1 magnets.

	S	U	R		S	U	R
a_2	0.000	0.679	0.679	b_2	-5.000	0.200	0.200
a_3	0.000	0.282	0.282	b_3	-19.000	0.727	0.727
a_4	0.000	0.444	0.444	b_4	2.000	0.126	0.126
a_5	0.000	0.152	0.152	b_5	3.000	0.365	0.365
a_6	0.000	0.176	0.176	b_6	2.000	0.060	0.060
a_7	0.000	0.057	0.057	b_7	1.300	0.165	0.165
a_8	0.000	0.061	0.061	b_8	1.000	0.027	0.027
a_9	0.000	0.020	0.020	b_9	0.520	0.065	0.065
a_{10}	0.000	0.025	0.025	b_{10}	0.000	0.008	0.008
a_{11}	0.000	0.007	0.007	b_{11}	0.000	0.019	0.019
a_{12}	0.000	0.008	0.008	b_{12}	0.000	0.003	0.003
a_{13}	0.000	0.002	0.002	b_{13}	0.000	0.006	0.006
a_{14}	0.000	0.003	0.003	b_{14}	0.000	0.001	0.001
a_{15}	0.000	0.001	0.001	b_{15}	0.000	0.002	0.002

Table A-16: Expected field quality errors (Systematic – S, Uncertainty – U, Random – R) at top energy for the MBRD magnets (r_0 = 35 mm).

	S	U	R		S	U	R
a_2	0.000	0.679	0.679	b_2	1.000	1.000	1.000
a_3	0.000	0.282	0.282	b_3	1.000	1.667	1.667
a_4	0.000	0.444	0.444	b_4	-3.000	0.600	0.600
a_5	0.000	0.152	0.152	b_5	-1.000	0.500	0.500
a_6	0.000	0.176	0.176	b_6	2.000	0.060	0.060
a_7	0.000	0.057	0.057	b_7	2.000	0.165	0.165
a_8	0.000	0.061	0.061	b_8	1.000	0.027	0.027
a_9	0.000	0.020	0.020	b_9	0.500	0.065	0.065
a_{10}	0.000	0.025	0.025	b_{10}	0.000	0.008	0.008
a_{11}	0.000	0.007	0.007	b_{11}	0.030	0.019	0.019
a_{12}	0.000	0.008	0.008	b_{12}	0.000	0.003	0.003
a_{13}	0.000	0.002	0.002	b_{13}	0.000	0.006	0.006
a_{14}	0.000	0.003	0.003	b_{14}	0.000	0.001	0.001
a_{15}	0.000	0.001	0.001	b_{15}	0.000	0.002	0.002

The expected field quality of the MCBXFA and MCBXFB magnets at nominal field is presented in Table A-17.

Table A-17: Expected field quality errors for the MCBXFA and MCBXFB magnets (r_0 = 50 mm) for the two orientations (horizontal and vertical) at top energy.

	MCBXFA		MCBXFB			MCBXFA		MCBXFB	
	H	V	H	V		H	V	H	V
a_2	0.00	0.00	0.00	0.00	b_2	0.00	0.00	0.00	0.00
a_3	0.00	20.12	0.00	-10.33	b_3	-16.65	0.00	17.37	0.00
a_4	0.00	0.00	0.00	0.00	b_4	0.00	0.00	0.00	0.00
a_5	0.00	-3.04	0.00	-3.60	b_5	-0.35	0.00	2.49	0.00
a_6	0.00	0.00	0.00	0.00	b_6	0.00	0.00	0.00	0.00
a_7	0.00	-3.98	0.00	-3.26	b_7	0.98	0.00	0.62	0.00
a_8	0.00	0.00	0.00	0.00	b_8	0.00	0.00	0.00	0.00
a_9	0.00	-0.62	0.00	-0.58	b_9	0.07	0.00	-0.75	0.00
a_{10}	0.00	0.00	0.00	0.00	b_{10}	0.00	0.00	0.00	0.00
a_{11}	0.00	0.02	0.00	0.12	b_{11}	4.30	0.00	3.60	0.00
a_{12}	0.00	0.00	0.00	0.00	b_{12}	0.00	0.00	0.00	0.00
a_{13}	0.00	0.00	0.00	0.00	b_{13}	0.00	0.00	0.00	0.00
a_{14}	0.00	0.00	0.00	0.00	b_{14}	0.00	0.00	0.00	0.00
a_{15}	0.00	0.00	0.00	0.00	b_{15}	0.00	0.00	0.00	0.00

The expected field quality for the MCBRD correctors is being evaluated.

A.8. Expected field errors for the crab cavities

The expected RF multipoles for the DQW (providing vertical kick) and RFD (providing horizontal kicks) cavities normalized to a RF voltage of 10 MV are listed in Table A-18 and Table A-19, respectively.

Table A-18: Expected integrated RF multipoles normalized to a RF voltage of 10 MV for the DQW crab cavities (r_0 = 30 mm) in mT m/m^{n-1} as defined in [17] and updated in [18].

	Re	Im		Re	Im
a_2	0	0	b_2	6	-2
a_3	1506	27	b_3	0	0
a_4	0	0	b_4	2106	-539
a_5	N/A	N/A	b_5	N/A	N/A
a_6	N/A	N/A	b_6	N/A	N/A

Table A-19: Expected integrated RF multipoles normalized to a RF voltage of 10 MV for the RFD crab cavities (r_0 = 30 mm) in mT m/m^{n-1} as defined in [17] and updated in [18].

	Re	Im		Re	Im
a_2	0	0	b_2	0	0
a_3	0	0	b_3	-522	-56
a_4	0	0	b_4	-914	-36
a_5	N/A	N/A	b_5	N/A	N/A
a_6	N/A	N/A	b_6	N/A	N/A

The expected RF integrated normal and skew decapolar and dodecapolar components are not available yet.

A.9. References

[1] E. Métral *et al.*, Update of the HL-LHC operational Scenarios for Proton Operation, CERN-ACC-NOTE-2018-0002.

[2] O. Brüning and W. Herr, R. Ostojic, A beam separation and collision scheme for IP2 and IP8 at the LHC for optics version 6.1, LHC Project Report 367.

[3] Spectrometer bumps and polarities Guide.

[4] S. Fartoukh, LHCb crossing scheme for Run II & III, LHC Machine Committee Meeting n. 167, 19/6/2013.

[5] R. Tomás Garcia, Update of HL-LHC parameters and operational scenarios (protons), 104th Technical Coordination Committee, 28th May 2020, INDICO: 921722.

[6] HL-LHC Technical Coordination Committee Parameter Table v. 7.1.1 (29/07/2020), TCC Web page

[7] G. Arduini, O. Brüning, R. De Maria, R. Garoby, S. Gilardoni, B. Goddard, B. Gorini, M. Meddahi, G. Rumolo and R. Tomás, Beam parameters at LHC injection, CERN-ACC-2014-0006.

[8] R. Tomás *et al.*, HL-LHC: Exploring alternative ideas, Proc. Review of LHC and Injector Upgrade Plans Workshop (RLIUP), Archamps, France, 29–31 October 2013, CERN–2014–006, pp. 119-126 DOI: 10.5170/CERN-2014-006.119.

[9] H. Damerau *et al.*, LIU: Exploring Alternative Ideas, Proc. Review of LHC and Injector Upgrade Plans Workshop (RLIUP), Archamps, France, 29–31 October 2013, CERN–2014–006, pp. 127-137, DOI: 10.5170/CERN-2014-006.127

[10] The ATLAS and CMS Collaborations, Expected pile-up values at HL-LHC, ATL-UPGRADE-PUB-2013-014, CERN (30 September 2013).

[11] D. Contardo, private communication, 3 December 2014.

[12] O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole and P. Proudlock (Eds.), LHC Design Report , v.1: the LHC Main Ring, 2012, CERN-2004-003-V-1.

[13] R. Bruce et al., HL-LHC operational scenario for Pb-Pb and p-Pb operation, CERN-ACC-2020-0011.

[14] J.-B. Jeanneret, Geometrical tolerances for the qualification of LHC magnets, LHC-PROJECT-Report-1007.

[15] E. Todesco, M. Sorbi, HL-LHC ECR - WP3 Change Of Quadrupole, Sextupole, Octupole And Decapole Correctors Integrated Field - LHC-M-EC-0002, EDMS: 1963788.

[16] J. Oliveira, M. Amparo Gonzalez De La Aleja Cabana, Final confirmation of dimension of magnetic length of Corrector Package, INDICO: 774098.

[17] A. Grudiev, J. Barranco, R. Calaga, R. De Maria, M. Giovannozzi, and R. Tomas, “Study of Multipolar RF Kicks from the Main Deflecting Mode in Compact Crab Cavities for LHC”, in Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12), New Orleans, LA, USA, May 2012, paper TUPPR027, pp. 1873-1875.

[18] R. Calaga, “Latest info on field quality for crab cavities”, Presentation in the 152nd HL-LHC WP2 Meeting, 02/07/2019, INDICO: 826475.