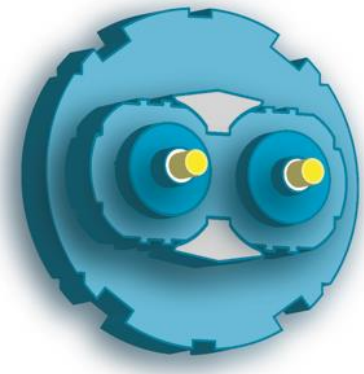

High Luminosity LHC

Update on field quality requirements for HL-LHC new magnets

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Acknowledgements: G. Arduini, S. Fartoukh, E. Todesco

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Simulations set-up

- Lattice set-up:
  - **HLLHCV1.0 lattice layout**
  - collision optics with β^*= 15 cm at IP1,IP5 and E = 7 TeV
  - **injection optics** with β^*= 6 m and E = 450 GeV

- Tracking simulations set-up:
  - 10^5 turns, 60 random error seeds, 30 particle pairs per amplitude step (2σ), 11 x-y angles
  - Beam energy: 7 TeV (collision), 450 GeV (injection)
  - Initial $\Delta p/p$: 2.7e-4 (collision), 7.5e-4 (injection)
  - Nominal tune: 62.31, 60.32 (collision), 62.28, 60.31 (injection)
  - Normalized emittance = 3.75 μm
  - Arc errors and the standard correction systems are always included
  - IT non-linear correctors of order n=3-6 are used in the collision optics
  - No beam-beam effects

- Field coefficients:

$$B_y + iB_x = 10^{-4} B_{ref} \times \sum_{n=1}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

Field quality specifications for D1 separation dipoles at collision energy (r_0 = 50 mm)

Two multipoles optimised

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	0	0.200	0.200
a3	0	0.282	0.282		b3	-0.900	0.727	0.727
a4	0	0.444	0.444		b4	0	0.126	0.126
a5	0	0.152	0.152		b5	0	0.365	0.365
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	0.4→0.2	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	-0.59→-0.295	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.470	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	-0.040	0.002	0.002

Red values represent requests from WP2

Field quality specifications for D1 separation dipoles at injection energy (r_0 = 50 mm)

No changes requested

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	0	0.200	0.200
a3	0	0.282	0.282		b3	-16.0	0.727	0.727
a4	0	0.444	0.444		b4	0	0.126	0.126
a5	0	0.152	0.152		b5	-0.500	0.365	0.365
a6	0	0.176	0.176		b6	0	0.060	0.060
a7	0	0.057	0.057		b7	0.900	0.165	0.165
a8	0	0.061	0.061		b8	0	0.027	0.027
a9	0	0.020	0.020		b9	-0.660	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.440	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	-0.040	0.002	0.002

Red values represent requests from WP2

Field quality specifications for Q5 matching quadrupoles at collision energy (r_0 = 17 mm)

No changes requested

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.500	0.900		b3	0	0.940	1.100
a4	0	0.230	0.480		b4	0	0.260	0.250
a5	0	0.070	0.160		b5	0	0.080	0.170
a6	0	0.140	0.080		b6	0	1.500	0.430
a7	0	0.020	0.040		b7	0	0.020	0.040
a8	0	0.030	0.040		b8	0	0.030	0.040
a9	0	0.010	0.010		b9	0	0.010	0.010
a10	0	0.010	0.010		b10	0	0.300	0.080
a11	0	0.020	0.030		b11	0	0.020	0.030
a12	0	0.020	0.010		b12	0	0.020	0.010
a13	0	0.020	0.010		b13	0	0.020	0.010
a14	0	0.020	0.010		b14	0	0.050	0.010
a15	0	0.020	0.010		b15	0	0.020	0.010

Red values represent requests from WP2

Field quality specifications for Q5 matching quadrupoles at injection energy (r_0 = 17 mm)

No changes requested

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.500	0.900		b3	0	0.940	1.100
a4	0	0.230	0.480		b4	0	0.260	0.250
a5	0	0.070	0.160		b5	0	0.080	0.170
a6	0	0.140	0.080		b6	-3.000	3.000	0.860
a7	0	0.020	0.040		b7	0	0.020	0.040
a8	0	0.030	0.040		b8	0	0.030	0.040
a9	0	0.010	0.010		b9	0	0.010	0.010
a10	0	0.010	0.010		b10	0	0.300	0.080
a11	0	0.020	0.030		b11	0	0.020	0.030
a12	0	0.020	0.010		b12	0	0.020	0.010
a13	0	0.020	0.010		b13	0	0.020	0.010
a14	0	0.020	0.010		b14	0	0.050	0.010
a15	0	0.020	0.010		b15	0	0.020	0.010

Red values represent requests from WP2

Updated estimate of D2 field quality at collision energy (r_0 = 35 mm)

Previous specification: "D2_errortable_v4_spec".

New estimate: "D2_errortable_v5". New estimates are indicated in blue: b3m (1.5 -> 1.0), b3u,b3r (1.5 -> 1.667), b4m (1.0 -> -3.0), b4u,b4r (0.2-> 0.6), b6m (0 -> 2.0), b7m (-0.2 -> 2.0), b8m (0 -> 1.0), b9m (0.09 -> 0.5). In tracking b2 = 0.

No changes requested

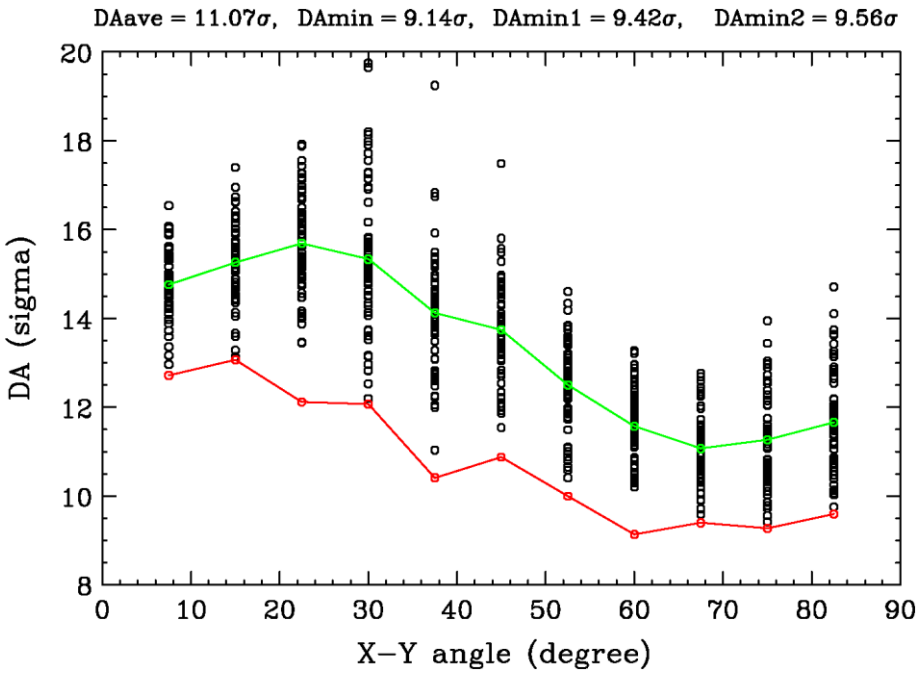
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	±1.00	1.000	1.000
a3	0	0.282	0.282		b3	**1.00**	**1.667**	**1.667**
a4	0	0.444	0.444		b4	**±3.00**	**0.600**	**0.600**
a5	0	0.152	0.152		b5	-1.00	0.500	0.500
a6	0	0.176	0.176		b6	**±2.00**	0.060	0.060
a7	0	0.057	0.057		b7	**2.00**	0.165	0.165
a8	0	0.061	0.061		b8	**±1.00**	0.027	0.027
a9	0	0.020	0.020		b9	**0.50**	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0.03	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	0	0.002	0.002

Red values represent requests from WP2

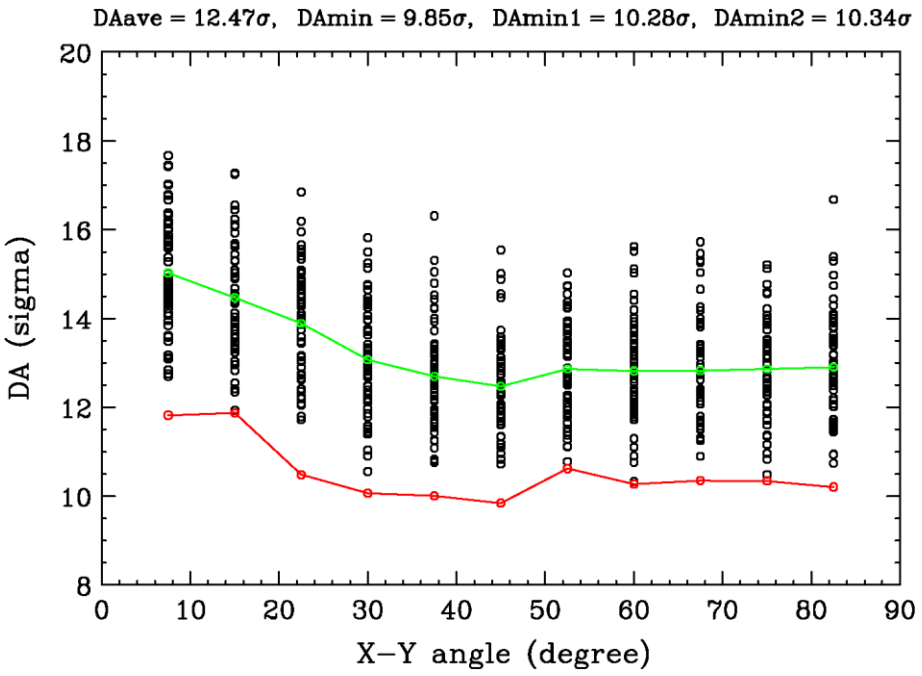
DA at collision energy with updated D2 field quality

The other magnets: “IT_errortable_v3_spec”, D1_errortable_v1_spec”, “Q4_errortable_v1_spec”, “Q5_errortable_v0_spec”.

D2_errortable_v4_spec



D2_errortable_v5



The field quality of “D2_errortable_v5” at collision is acceptable.

Here, DA_{ave} is minimum average DA over 11 angles, DA_{min} is absolute minimum DA, DA_{min1} is minimum DA when the worst seed is removed, DA_{min2} is the minimum DA when two worst seeds are removed.

Updated estimate of D2 field quality at injection energy (r_0 = 35 mm)

Previous specification: "D2_errortable_v4_spec".

New estimate: "D2_errortable_v5". New estimates are indicated in blue: b2m (0 -> -5.0), b3m (3.8 -> -19.0), b4m (-8.0 -> 2.0), b6m (0-> 2.0), b6m (0 -> 2.0), b7m (0.1 -> 1.3), b8m (0 -> 1.0), b9m (0.02 -> 0.52). In tracking b2 = 0.

No changes requested

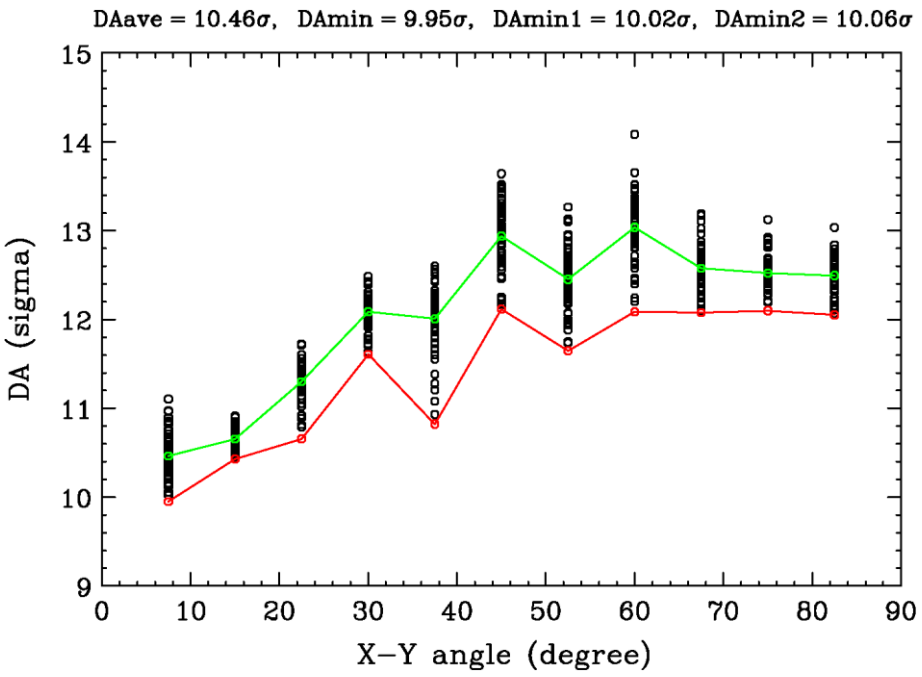
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.679		b2	**±5.00**	0.200	0.200
a3	0	0.282	0.282		b3	**-19.00**	0.727	0.727
a4	0	0.444	0.444		b4	**±2.00**	0.126	0.126
a5	0	0.152	0.152		b5	3.00	0.365	0.365
a6	0	0.176	0.176		b6	**±2.00**	0.060	0.060
a7	0	0.057	0.057		b7	**1.30**	0.165	0.165
a8	0	0.061	0.061		b8	**±1.00**	0.027	0.027
a9	0	0.020	0.020		b9	**0.52**	0.065	0.065
a10	0	0.025	0.025		b10	0	0.008	0.008
a11	0	0.007	0.007		b11	0	0.019	0.019
a12	0	0.008	0.008		b12	0	0.003	0.003
a13	0	0.002	0.002		b13	0	0.006	0.006
a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	0	0.002	0.002

Red values represent requests from WP2

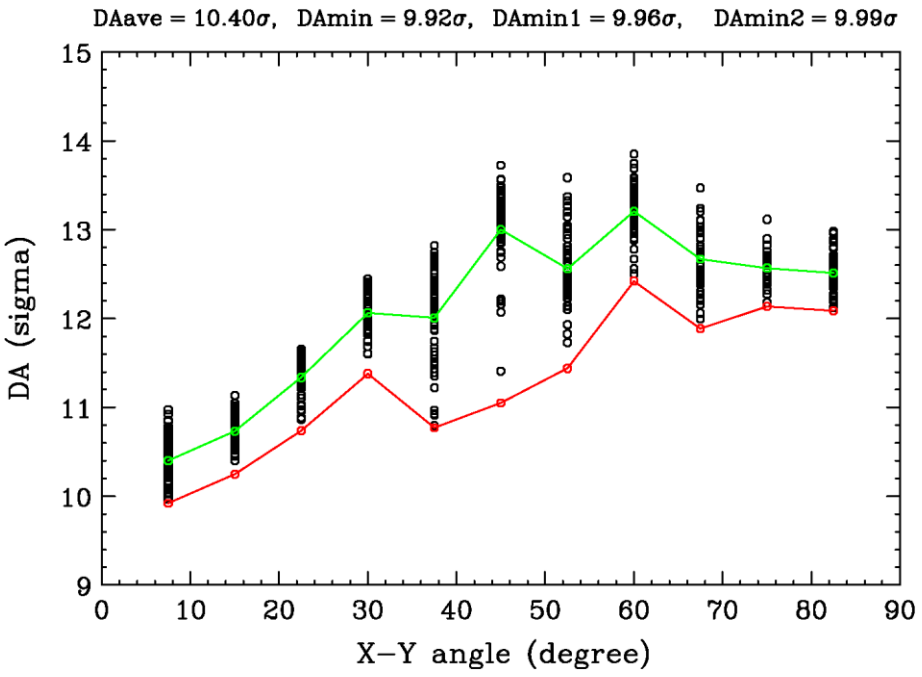
DA at injection energy with updated D2 field quality

The other magnets: “IT_errortable_v3_spec”, D1_errortable_v1_spec”, “Q4_errortable_v1_spec”, “Q5_errortable_v0_spec”.

D2_errortable_v4_spec



D2_errortable_v5



The field quality of “D2_errortable_v5” at injection is acceptable.
Hence, the updated estimate of D2 field quality becomes the specification table “D2_errortable_v5_spec” for both collision and injection energies.

Updated estimate of IT field quality at collision energy (r_0 = 50 mm)

Previous specification: "IT_errortable_v3_spec" (same as "IT_errortable_v66").
New reference: "IT_errortable_v66_4" (based on the new estimate in "IT_errortable_v4" combined with previously optimized terms (in red below) in "IT_errortable_v3_spec"). New estimates are indicated in blue. Reduced b6m (0.8 -> 0.4), but significantly increased b10m (0.075 -> -0.39) and b14m (-0.02 -> -0.67).

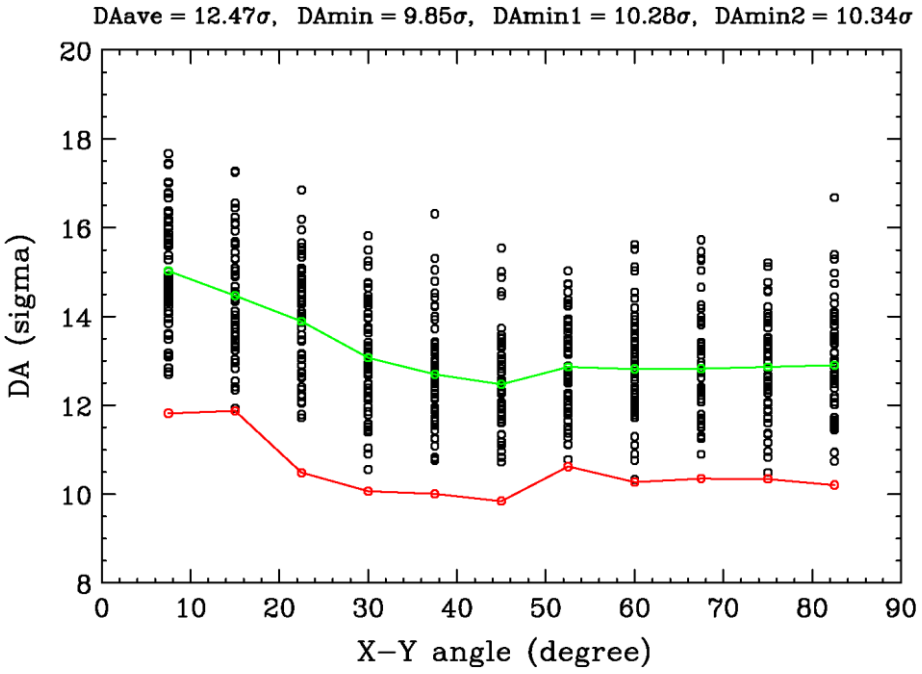
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	**0.40**	0.550	0.550
a7	0	0.152	0.095		b7	0	0.095	0.095
a8	0	0.088	0.055		b8	0	0.065	0.065
a9	0	0.064	0.040		b9	0	0.035	0.035
a10	0	0.040	0.032		b10	**-0.39**	0.100	0.100
a11	0	0.026	0.0208		b11	0	0.0208	0.0208
a12	0	0.014	0.014		b12	0	0.0144	0.0144
a13	0	0.010	0.010		b13	0	0.0072	0.0072
a14	0	0.005	0.005		b14	**-0.67**	0.0115	0.0115

Red values represent requests from WP2

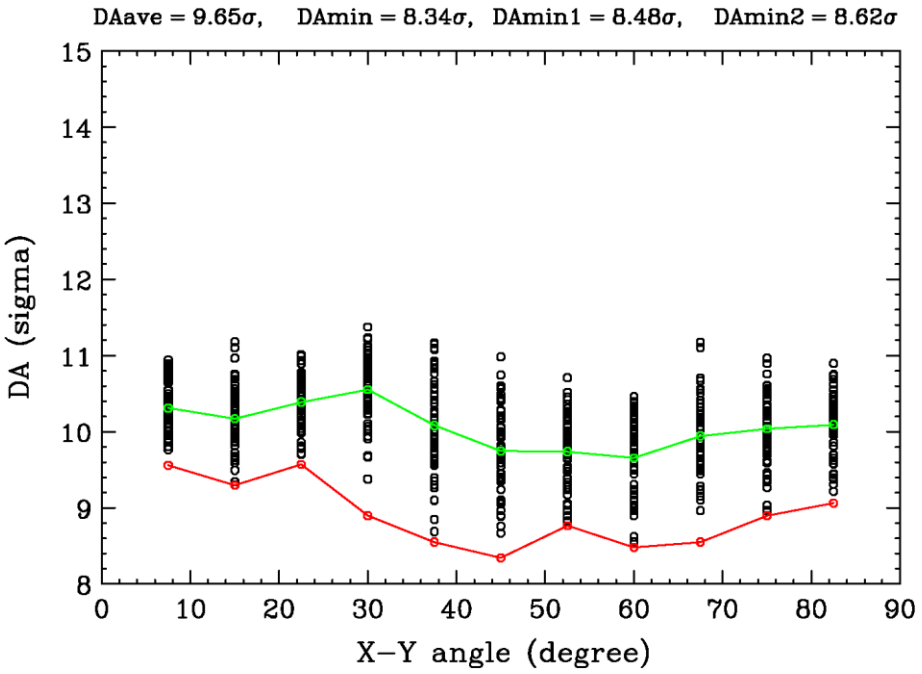
DA at collision energy with updated IT field quality

The other magnets: D1_errortable_v1_spec", "D2_errortable_v5_spec", "Q4_errortable_v1_spec", "Q5_errortable_v0_spec".

IT_errortable_v3_spec



IT_errortable_v66_4



Significantly reduced DA at collision with the field quality of "IT_errortable_v66_4".

Updated IT field quality at collision energy with adjusted b10m (*0.4) and b14m (*0.25) (r_0 = 50 mm)

Several changes requested, two new

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	**0.40**	0.550	0.550
a7	0	0.152	0.095		b7	0	0.095	0.095
a8	0	0.088	0.055		b8	0	0.065	0.065
a9	0	0.064	0.040		b9	0	0.035	0.035
a10	0	0.040	0.032		b10	**-0.156**	0.100	0.100
a11	0	0.026	0.0208		b11	0	0.0208	0.0208
a12	0	0.014	0.014		b12	0	0.0144	0.0144
a13	0	0.010	0.010		b13	0	0.0072	0.0072
a14	0	0.005	0.005		b14	**-0.1675**	0.0115	0.0115

Red values represent requests from WP2

Updated estimate of IT field quality at injection energy (r_0 = 50 mm)

Previous specification: "IT_errortable_v3_spec".
New estimate: "IT_errortable_v4" or "IT_errortable_v66_4" (same injection terms).
New estimates are indicated in blue below. Slightly reduced b6m (-16 -> -15.8) and b10m (4.15 -> 3.63), but significantly increased b14m: -0.04 -> -0.6.

No changes requested

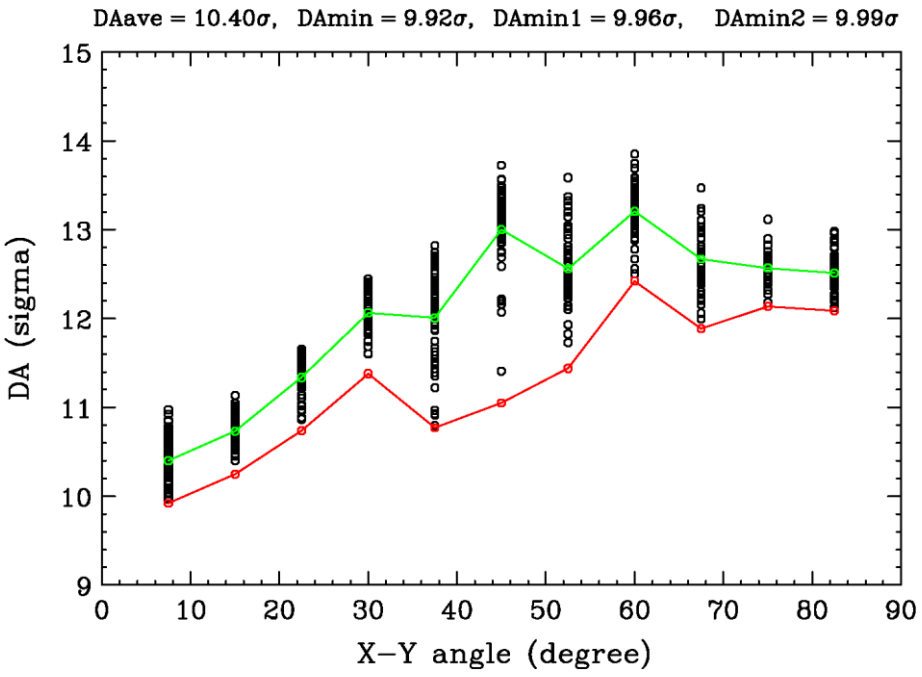
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	**-15.8**	1.100	1.100
a7	0	0.190	0.190		b7	0	0.190	0.190
a8	0	0.110	0.110		b8	0	0.130	0.130
a9	0	0.080	0.080		b9	0	0.070	0.070
a10	0	0.040	0.040		b10	**3.63**	0.200	0.200
a11	0	0.026	0.026		b11	0	0.026	0.026
a12	0	0.014	0.014		b12	0	0.018	0.018
a13	0	0.010	0.010		b13	0	0.009	0.009
a14	0	0.005	0.005		b14	**-0.6**	0.023	0.023

Red values represent requests from WP2

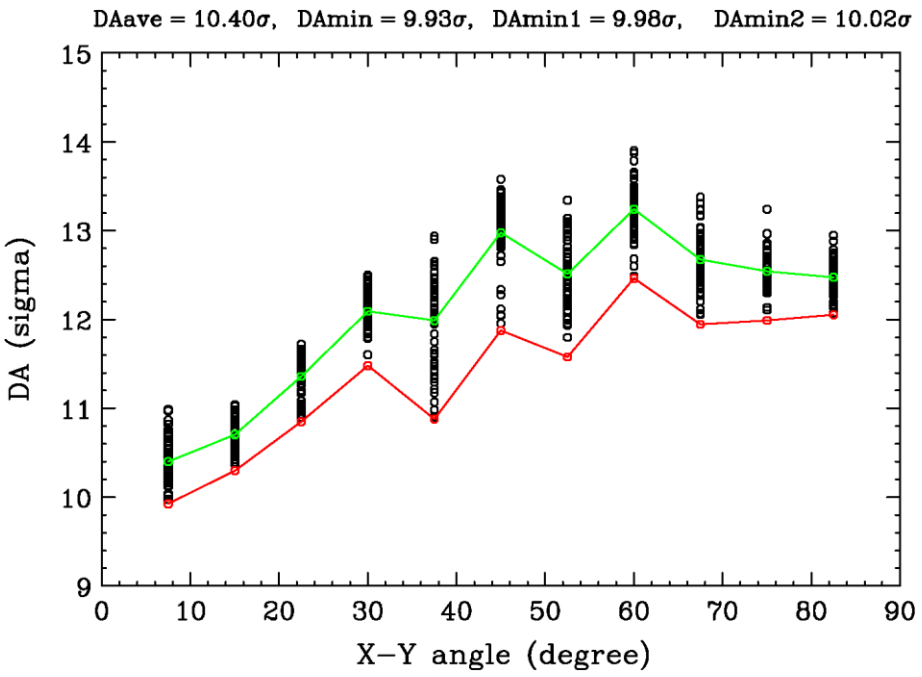
DA at injection energy with updated IT field quality

The other magnets: D1_errortable_v1_spec", "D2_errortable_v5_spec", "Q4_errortable_v1_spec", "Q5_errortable_v0_spec".

IT_errortable_v3_spec



IT_errortable_v66_4



The field quality of "IT_errortable_v4" ("IT_errortable_v66_4") at injection is acceptable.

Updated estimate of Q4 field quality at collision energy (r_0 = 30 mm)

Previous specification: "Q4_errortable_v1_spec". New estimate: "Q4_errortable_v2". All coefficients are updated. Most of the low order terms are increased, while the high order terms (n > 9) are significantly reduced. New non-zero b6m and b14m. Cancellation of b6u,b6r, b10u,b10r, and b14u,b14r.

No changes requested

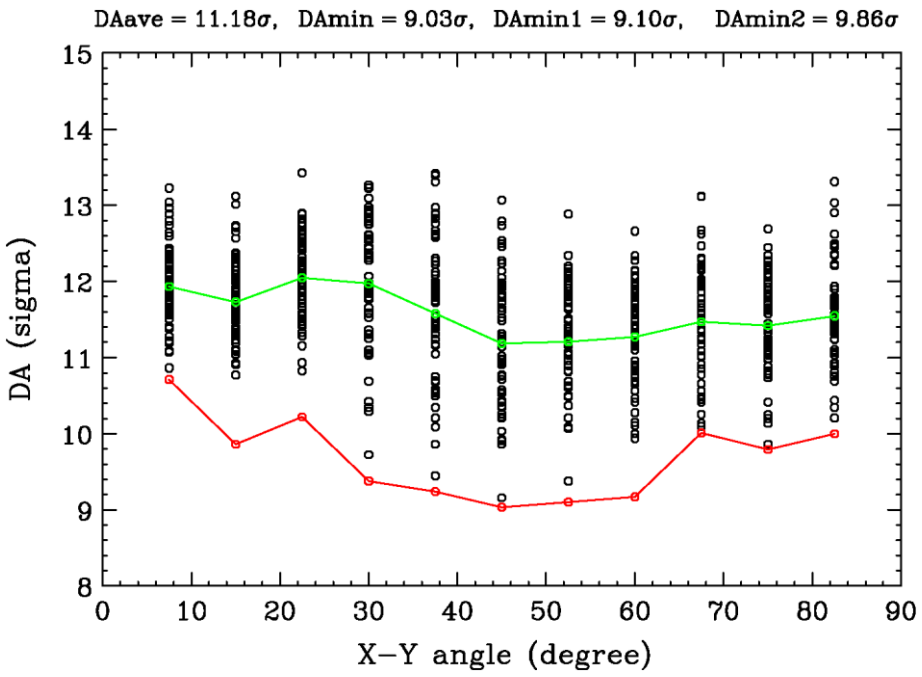
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	**1.793**	**1.793**		b3	0	**1.793**	**1.793**
a4	0	**1.158**	**1.158**		b4	0	**1.158**	**1.158**
a5	0	**0.748**	**0.748**		b5	0	**0.748**	**0.748**
a6	0	**0.483**	**0.483**		b6	**-0.05**	**0**	**0**
a7	0	**0.312**	**0.312**		b7	0	**0.312**	**0.312**
a8	0	**0.202**	**0.202**		b8	0	**0.202**	**0.202**
a9	0	**0.130**	**0.130**		b9	0	**0.130**	**0.130**
a10	0	**0.084**	**0.084**		b10	0	**0**	**0**
a11	0	**0.054**	**0.054**		b11	0	**0.054**	**0.054**
a12	0	**0.035**	**0.035**		b12	0	**0.035**	**0.035**
a13	0	**0.023**	**0.023**		b13	0	**0.023**	**0.023**
a14	0	**0.015**	**0.015**		b14	**1.50**	**0**	**0**
a15	0	**0**	**0**		b15	0	**0**	**0**

Red values represent requests from WP2

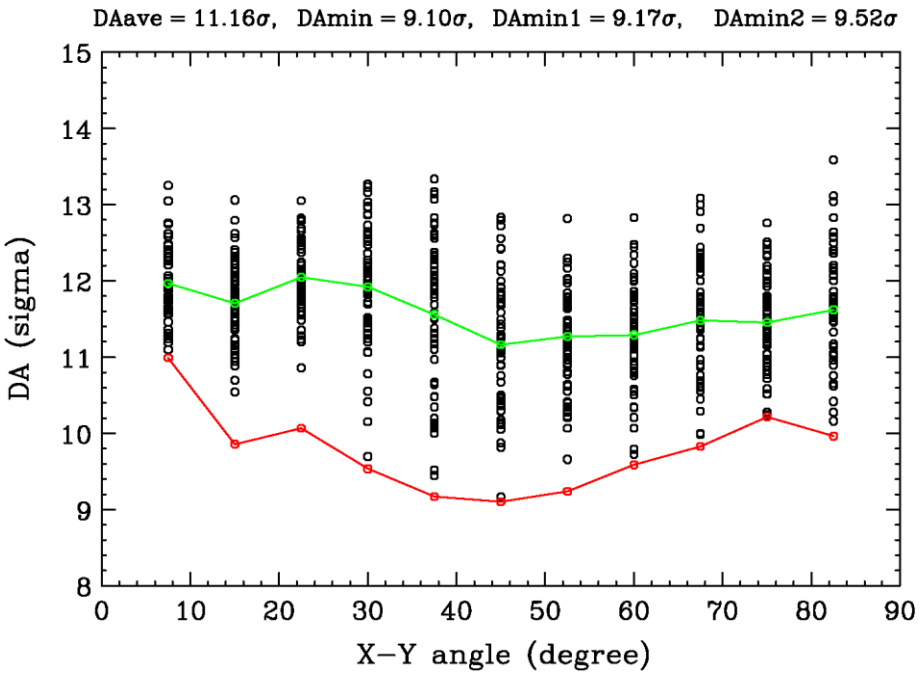
DA at collision energy with updated Q4 field quality

The other magnets: “IT_errortable_v66_4” (b10m*0.4, b14m*0.25), “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q5_errortable_v0_spec”.

Q4_errortable_v1_spec



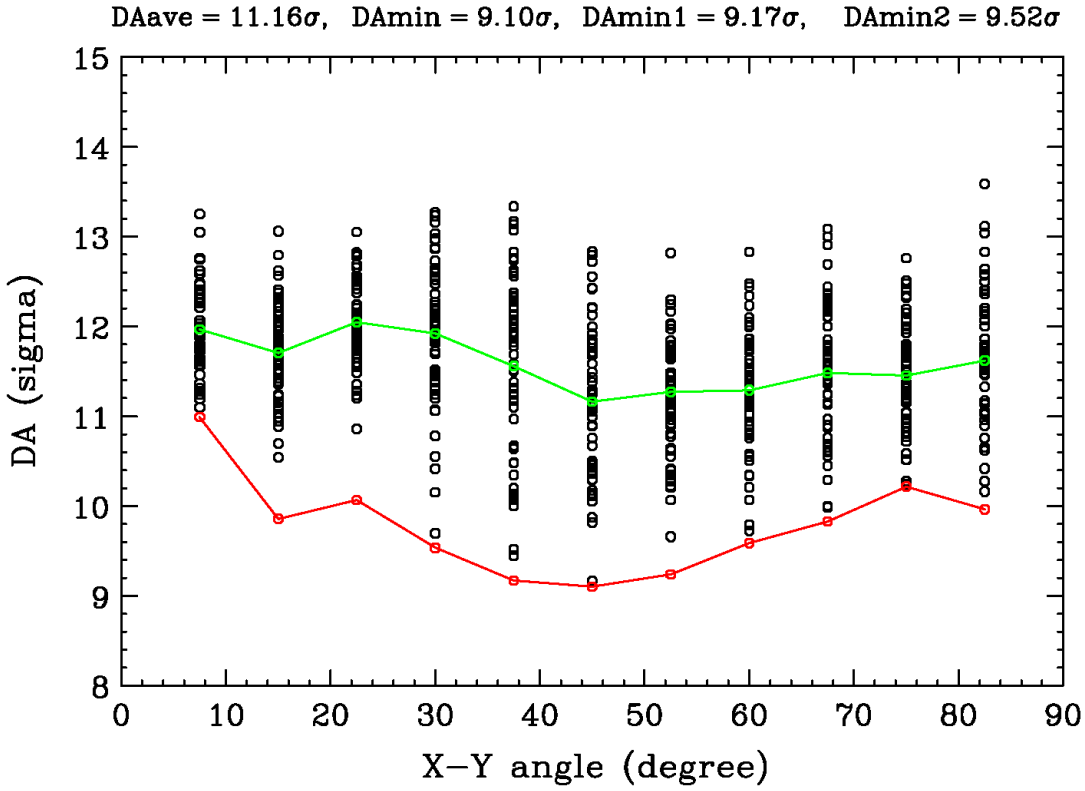
Q4_errortable_v2



Impact of the “Q4_errortable_v2” at collision energy is relatively small. It appears acceptable.

DA at collision energy with updated field of D2 and Q4 magnets and adjusted updated field of IT quadrupoles

Magnet errors: “IT_errortable_v66_4” (b10m*0.4, b14m*0.25), “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q4_errortable_v2”, “Q5_errortable_v0_spec”.



The minimum DA at collision energy is influenced by two bad seeds. Without these two seeds, the DA appears acceptable.

Updated estimate of Q4 field quality at injection energy (r_0 = 30 mm)

Previous specification: "Q4_errortable_v1_spec". New estimate: "Q4_errortable_v2". All coefficients are updated. Most of the low order terms are increased, while the high order terms (n > 9) are significantly reduced. New non-zero b10m and b14m. Cancellation of b6u,b6r, b10u,b10r, and b14u,b14r.

No changes requested

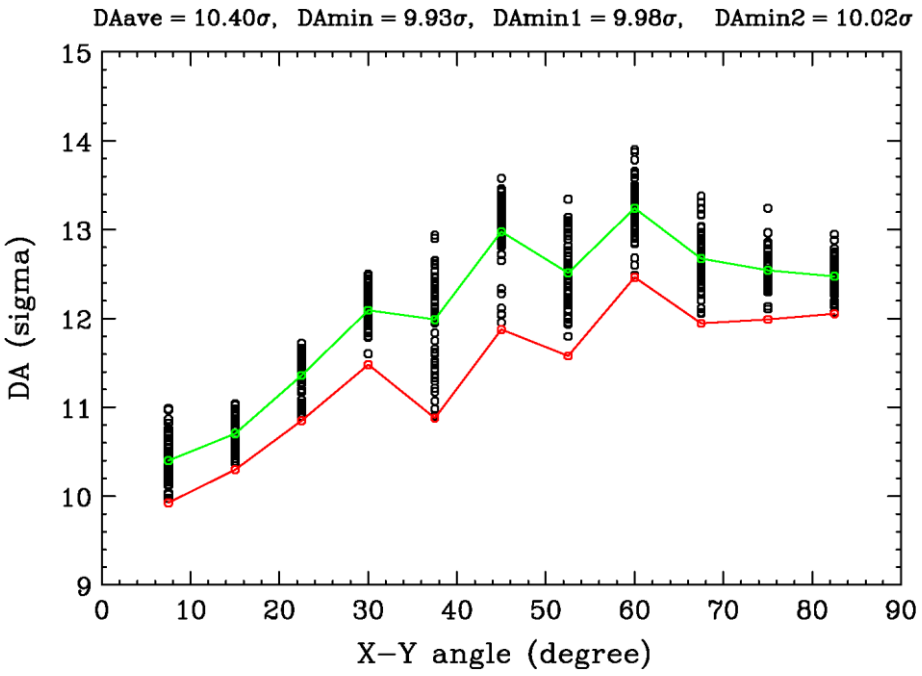
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	**1.793**	**1.793**		b3	0	**1.793**	**1.793**
a4	0	**1.158**	**1.158**		b4	0	**1.158**	**1.158**
a5	0	**0.748**	**0.748**		b5	0	**0.748**	**0.748**
a6	0	**0.483**	**0.483**		b6	**-11.45**	**0**	**0**
a7	0	**0.312**	**0.312**		b7	0	**0.312**	**0.312**
a8	0	**0.202**	**0.202**		b8	0	**0.202**	**0.202**
a9	0	**0.130**	**0.130**		b9	0	**0.130**	**0.130**
a10	0	**0.084**	**0.084**		b10	**1.00**	**0**	**0**
a11	0	**0.054**	**0.054**		b11	0	**0.054**	**0.054**
a12	0	**0.035**	**0.035**		b12	0	**0.035**	**0.035**
a13	0	**0.023**	**0.023**		b13	0	**0.023**	**0.023**
a14	0	**0.015**	**0.015**		b14	**1.50**	**0**	**0**
a15	0	**0**	**0**		b15	0	**0**	**0**

Red values represent requests from WP2

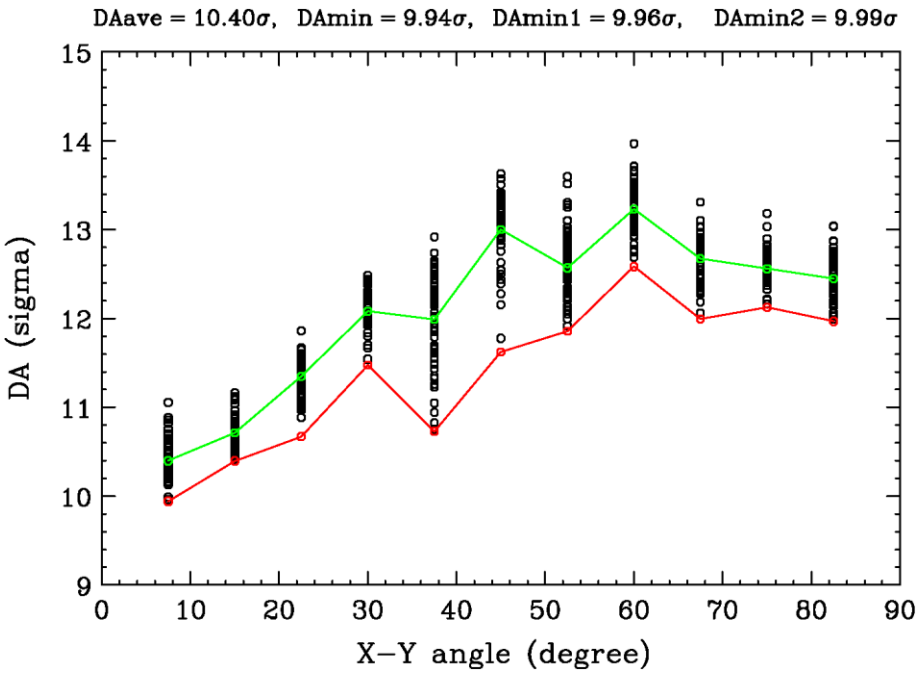
DA at injection energy with updated Q4 field quality

The other magnets: “IT_errortable_v66_4”, “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q5_errortable_v0_spec”.

Q4_errortable_v1_spec



Q4_errortable_v2

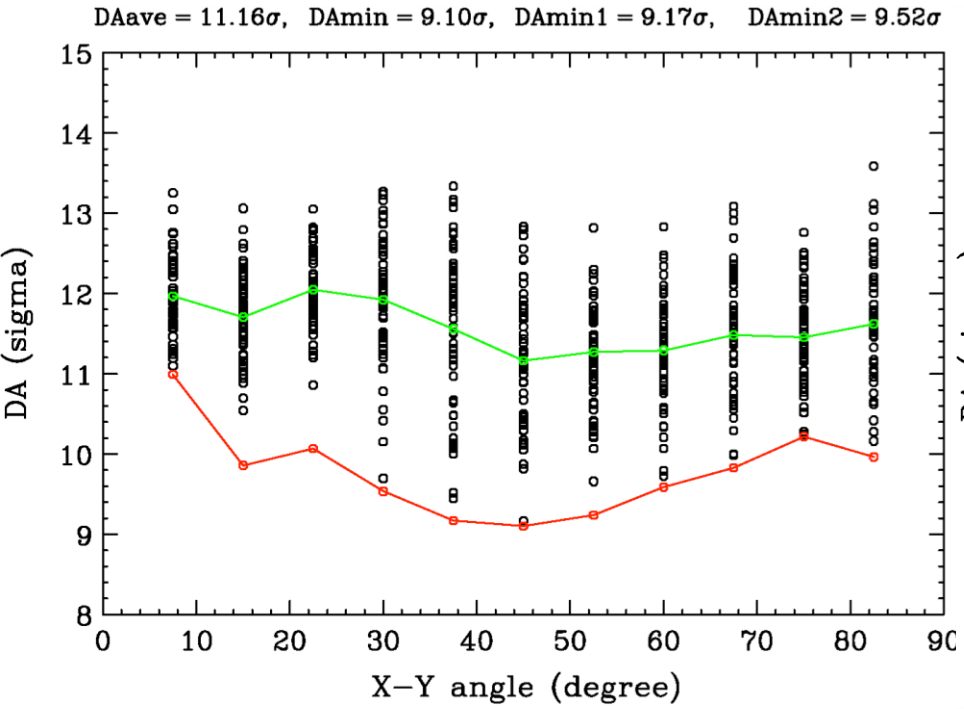


Impact of the “Q4_errortable_v2” at injection energy is negligible.
Hence, this field quality should be acceptable.

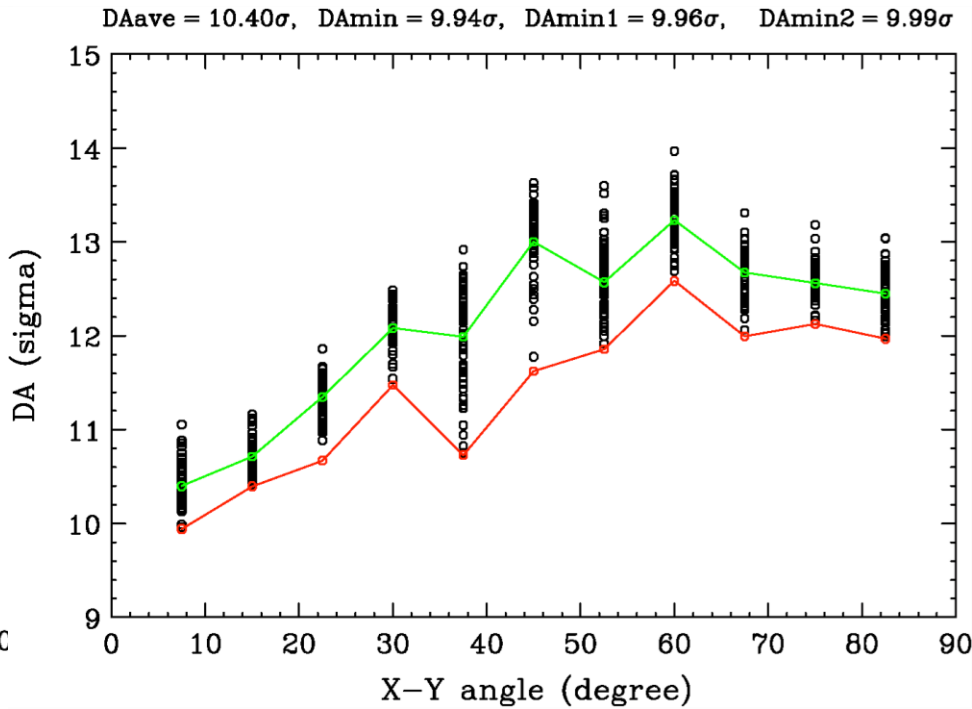
Putting all together

The other magnets: “IT_errortable_v66_4”, “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q4_errortable_v2_spec”, “Q5_errortable_v0_spec”.

DA in collision



DA at injection



Summary and outlook

DA_{min} in collision is dangerously approaching the value of 9 σ without beam-beam!

- Review impact of latest IT FQ estimates (see next presentation by Ezio).
- Start analysis of impact of IT fringe fields on DA.
- Initial approach will be based on installing two additional kicks (entry and exit of magnets) to represent the effect of heads.
- Some tools to be developed, such as error routines for new kicks, installation of additional kicks.
- Consider impact of FQ of dipole correctors in IT.