

Criteria for dynamic aperture limits and impact of the multipolar errors: summary of the simulations



High
Luminosity
LHC

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



The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. Work supported by the US LHC Accelerator Research Program (LARP) through the US Department of Energy contract DE-AC02-76SF00515.



Outline

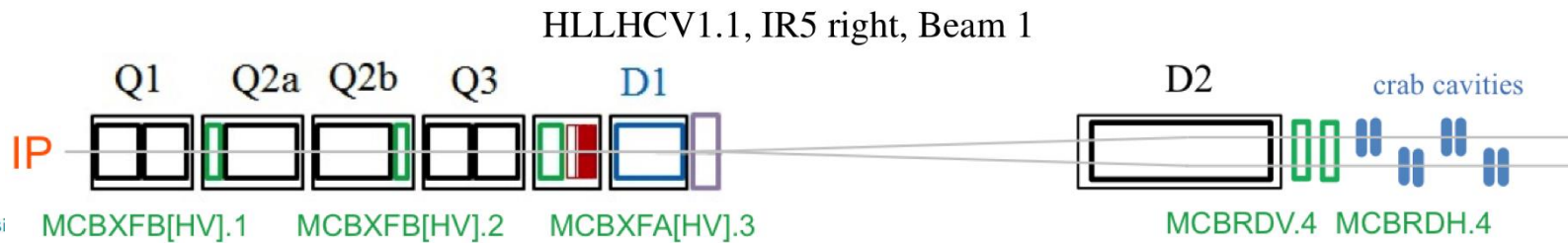
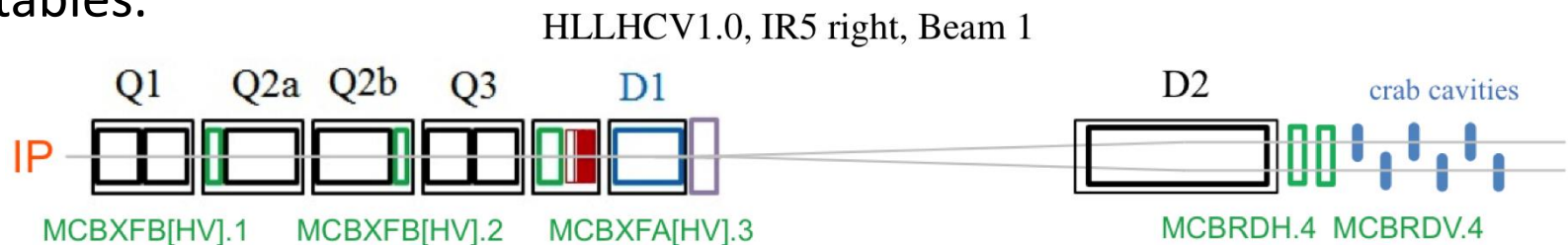
- Introduction
- D2 field quality status
- IT field quality status
- Q4 field quality status
- Summary and outlook

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Introduction

- **What is new since last HiLumi workshop:**
 - Layout used for DA simulations:
 - SLHCV31.b -> HLLHCV1.0
 - Updated expected error tables:
 - Nb-Ti 105 mm D2 separation dipoles
 - Nb₃Sn 150 mm aperture IT quadrupoles
 - Nb-Ti 90 mm Q4 quadrupoles
 - Complete analysis of injection and collision
 - Field quality data: classification as “specification” and “expected” tables.



Simulations set-up

- Lattice set-up:
 - **HLLHCV1.0 lattice layout**
 - collision optics with $\beta^* = 15$ cm at IP1, IP5 and $E = 7$ TeV
 - **injection optics** with $\beta^* = 5.5$ 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 = $3.75 \mu\text{m}$
 - 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
- Field coefficients:

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

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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 green: 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.

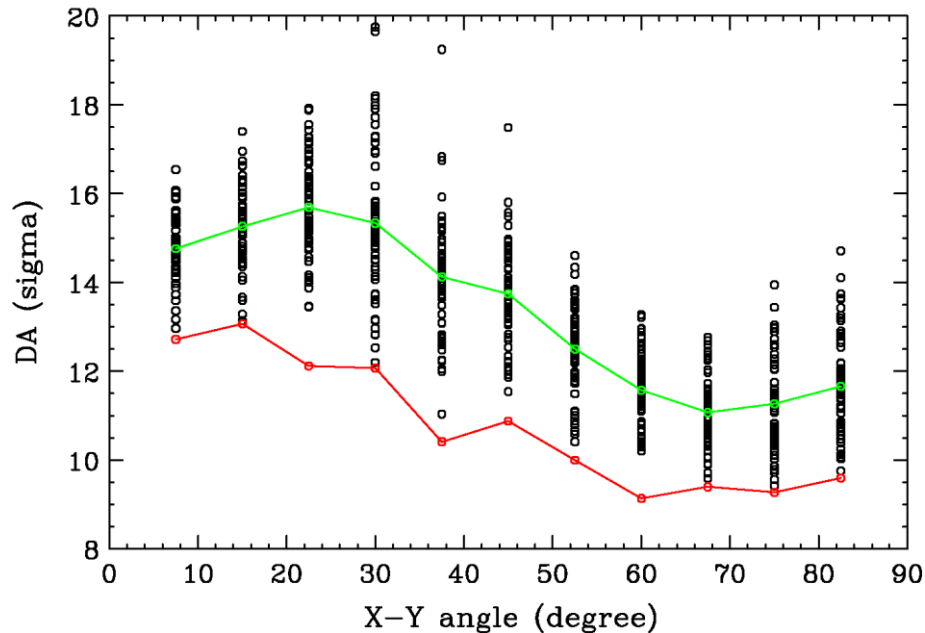
skew	mean	uncertainty	random	normal	mean	uncertainty	random
a2	0	0.679	0.679	b2	±1.00	1.000	1.000
a3	0	0.282	0.282	b3	1.00	1.667	1.667
a4	0	0.444	0.444	b4	±3.00	0.600	0.600
a5	0	0.152	0.152	b5	-1.00	0.500	0.500
a6	0	0.176	0.176	b6	±2.00	0.060	0.060
a7	0	0.057	0.057	b7	2.00	0.165	0.165
a8	0	0.061	0.061	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

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”.

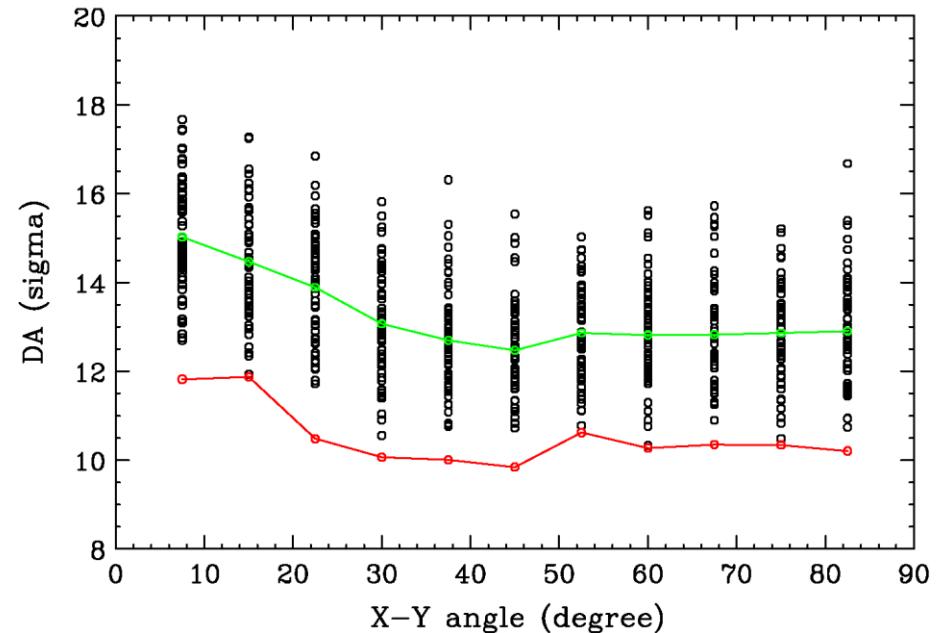
D2_errortable_v4_spec

DA_{ave} = 11.07σ, DA_{min} = 9.14σ, DA_{min1} = 9.42σ, DA_{min2} = 9.56σ



D2_errortable_v5

DA_{ave} = 12.47σ, DA_{min} = 9.85σ, DA_{min1} = 10.28σ, DA_{min2} = 10.34σ



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 green: 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.

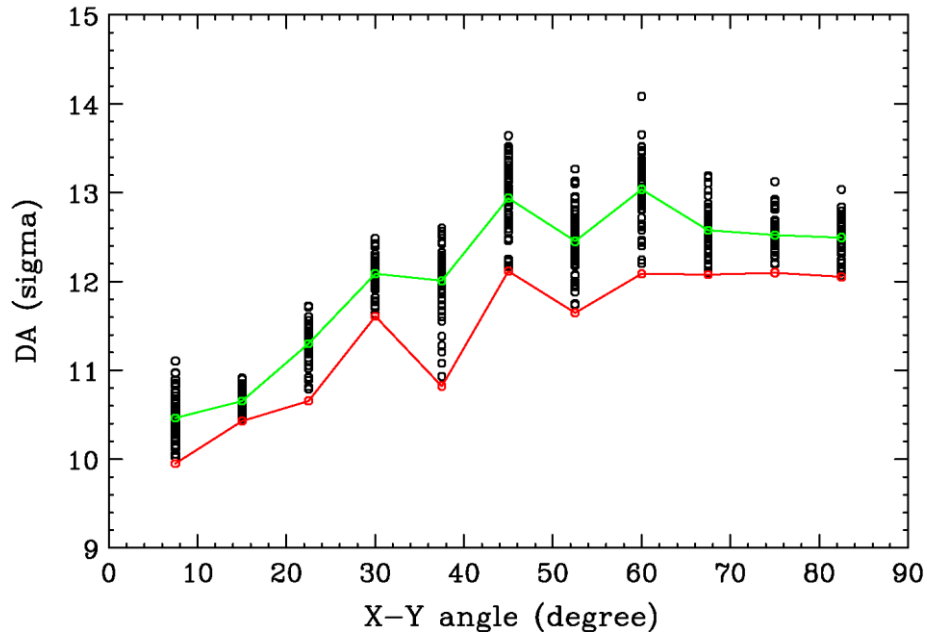
skew	mean	uncertainty	random	normal	mean	uncertainty	random
a2	0	0.679	0.679	b2	±5.00	0.200	0.200
a3	0	0.282	0.282	b3	-19.00	0.727	0.727
a4	0	0.444	0.444	b4	±2.00	0.126	0.126
a5	0	0.152	0.152	b5	3.00	0.365	0.365
a6	0	0.176	0.176	b6	±2.00	0.060	0.060
a7	0	0.057	0.057	b7	1.30	0.165	0.165
a8	0	0.061	0.061	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

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”.

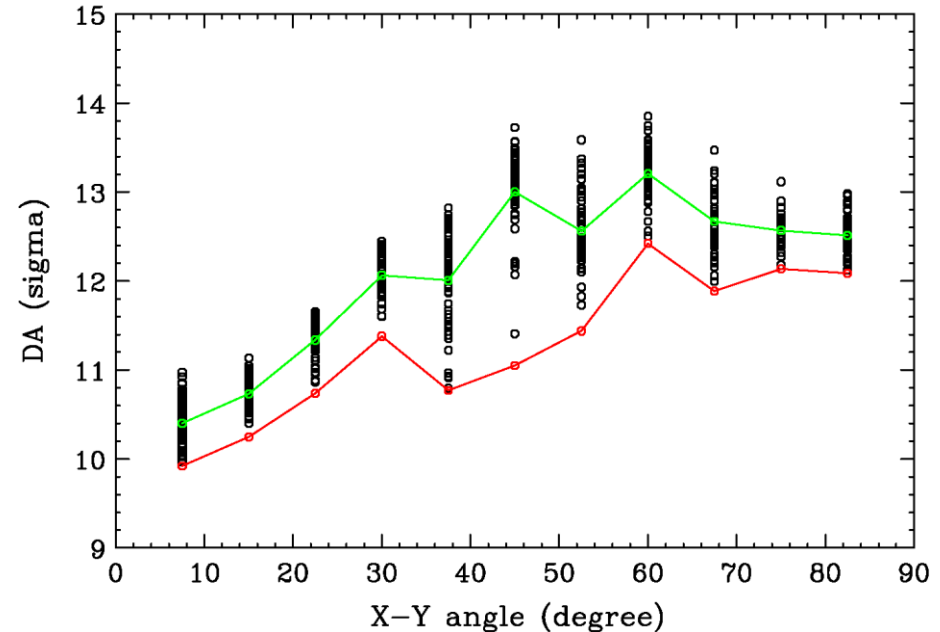
D2_errortable_v4_spec

DA_{ave} = 10.46σ, DA_{min} = 9.95σ, DA_{min1} = 10.02σ, DA_{min2} = 10.06σ



D2_errortable_v5

DA_{ave} = 10.40σ, DA_{min} = 9.92σ, DA_{min1} = 9.96σ, DA_{min2} = 9.99σ



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.

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- Introduction
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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 green. Reduced b6m (0.8 -> 0.4), but significantly increased **b10m** (0.075 -> -0.39) and **b14m** (-0.02 -> -0.67).

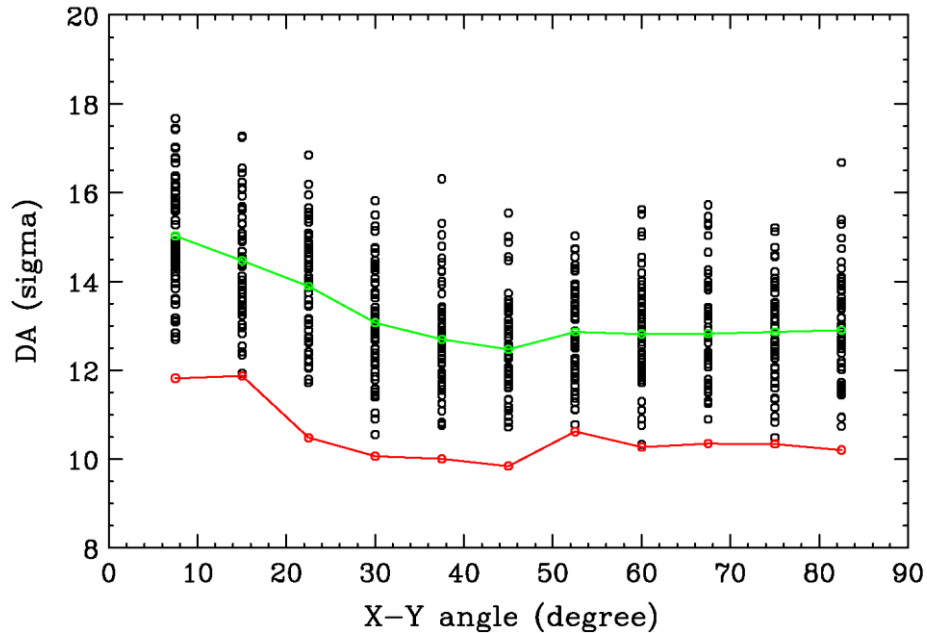
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	0.40	0.550	0.550
a7	0	0.152	0.095		b7	0	0.095	0.095
a8	0	0.088	0.055		b8	0	0.065	0.065
a9	0	0.064	0.040		b9	0	0.035	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

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”.

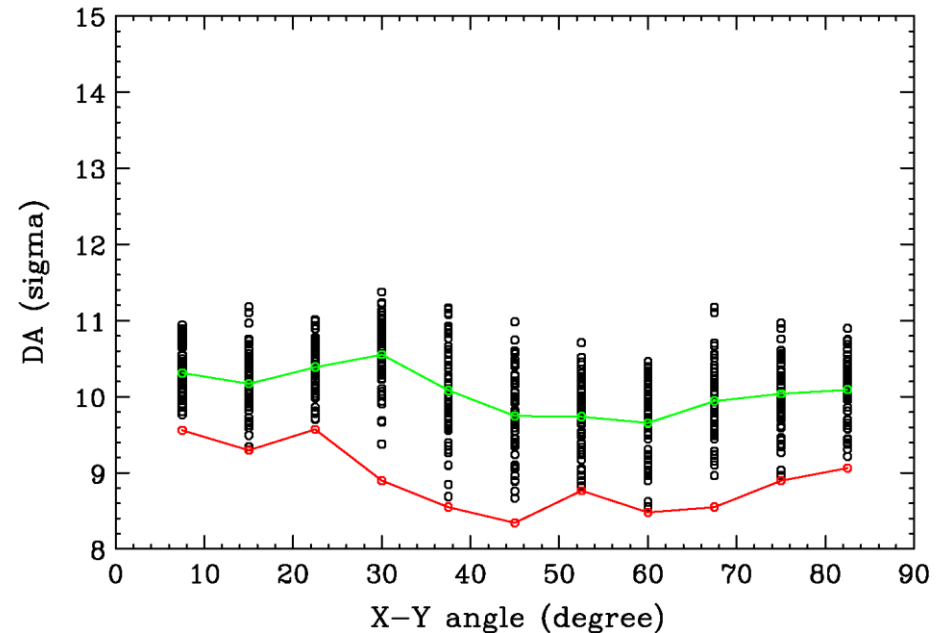
IT_errortable_v3_spec

DA_{ave} = 12.47σ, DA_{min} = 9.85σ, DA_{min1} = 10.28σ, DA_{min2} = 10.34σ



IT_errortable_v66_4

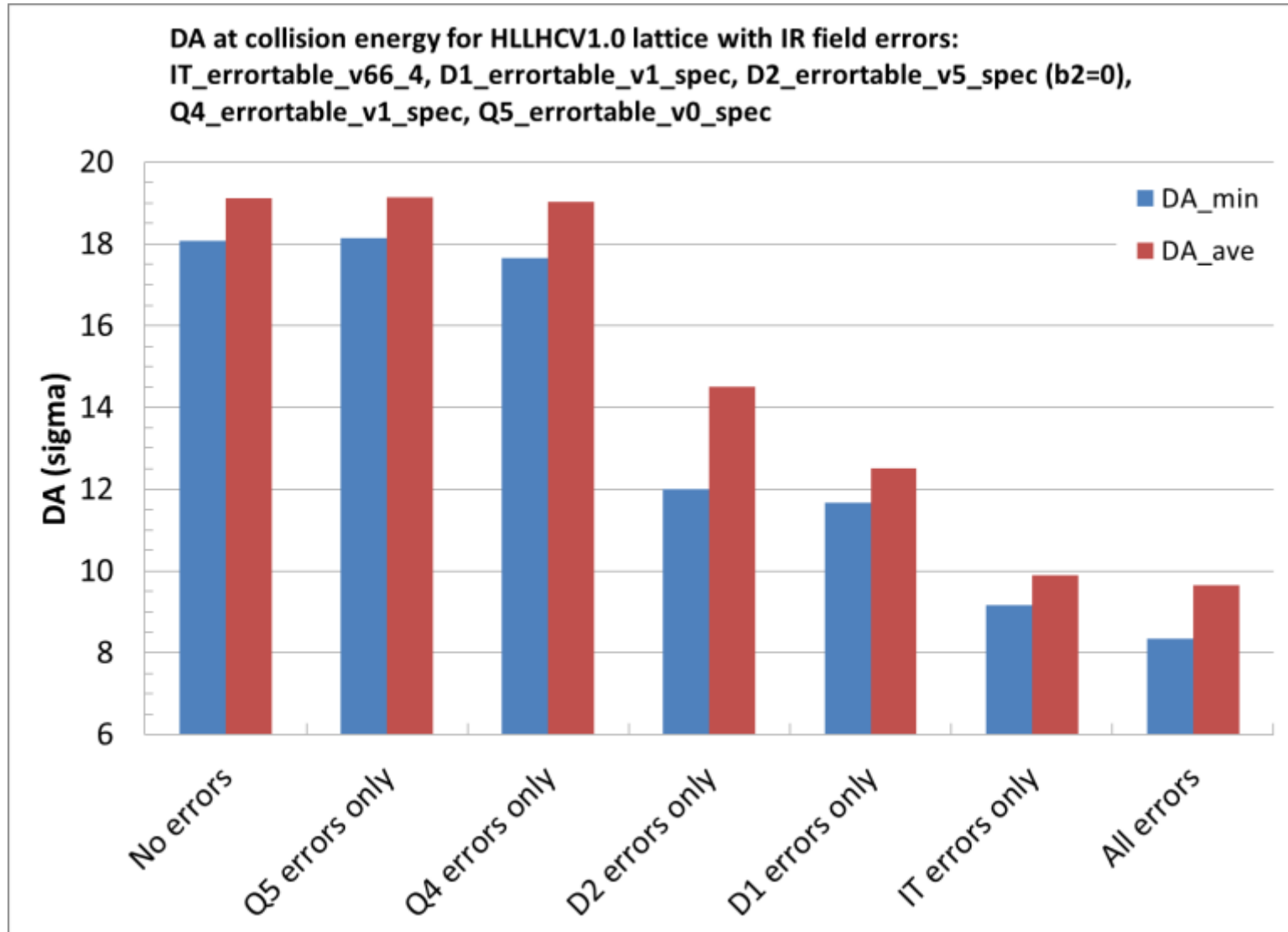
DA_{ave} = 9.65σ, DA_{min} = 8.34σ, DA_{min1} = 8.48σ, DA_{min2} = 8.62σ



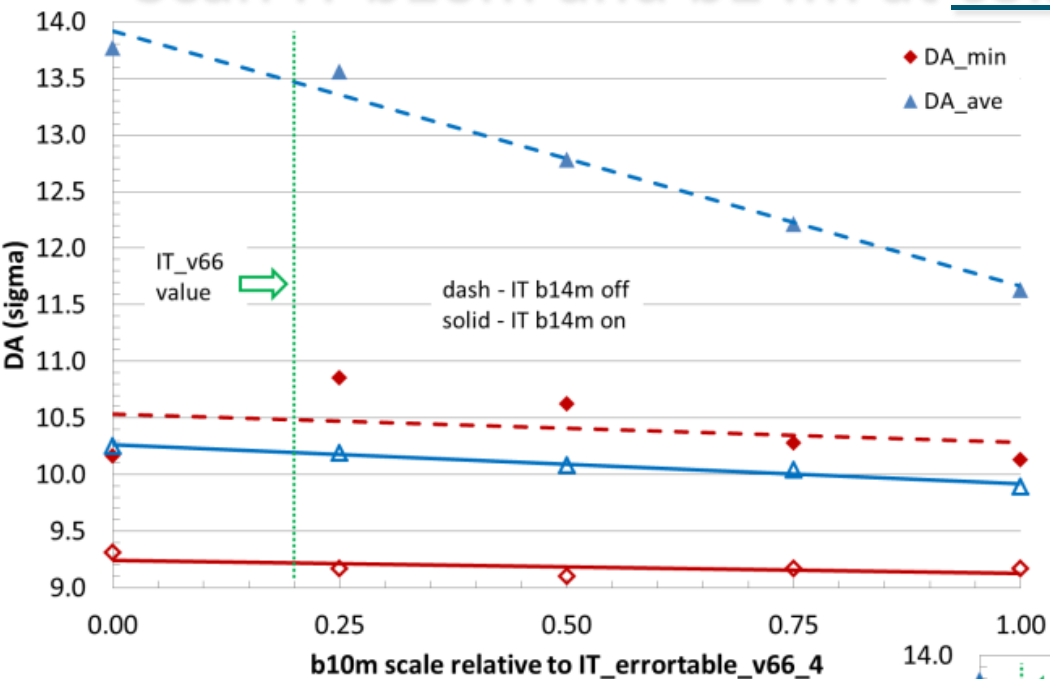
Significantly reduced DA at collision with the field quality of “IT_errortable_v66_4”.

Next step: scan and adjust the b10m and b14m terms.

Impact of “IT_errortable_v66_4” at collision compared to impact of the other IR magnets

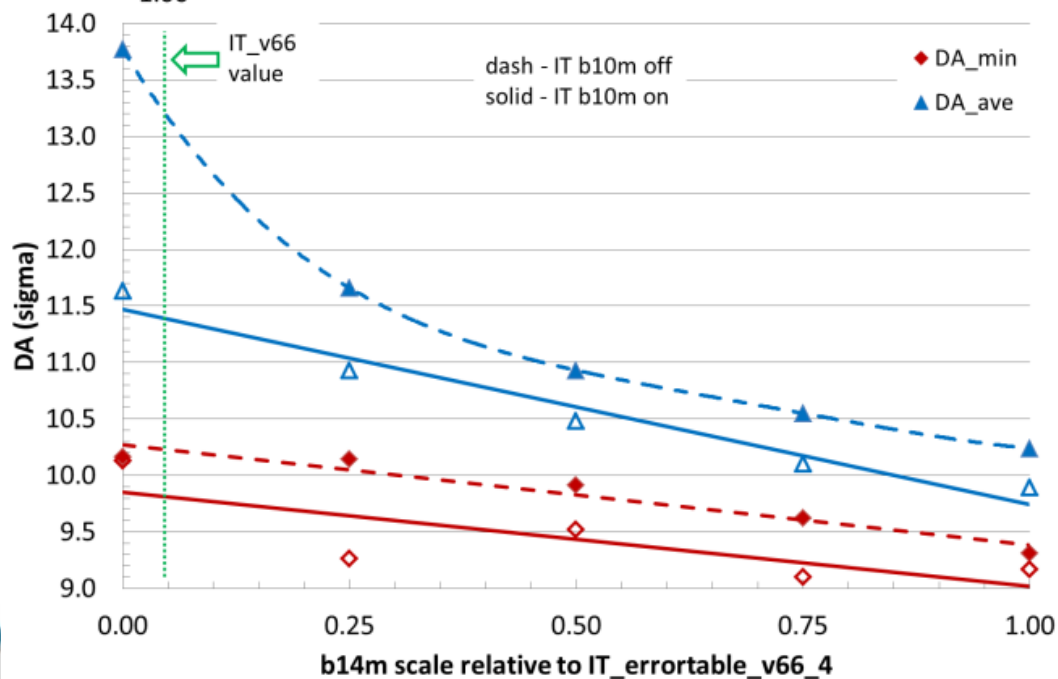


Scan IT b10m and b14m at collision (other IR errors off)



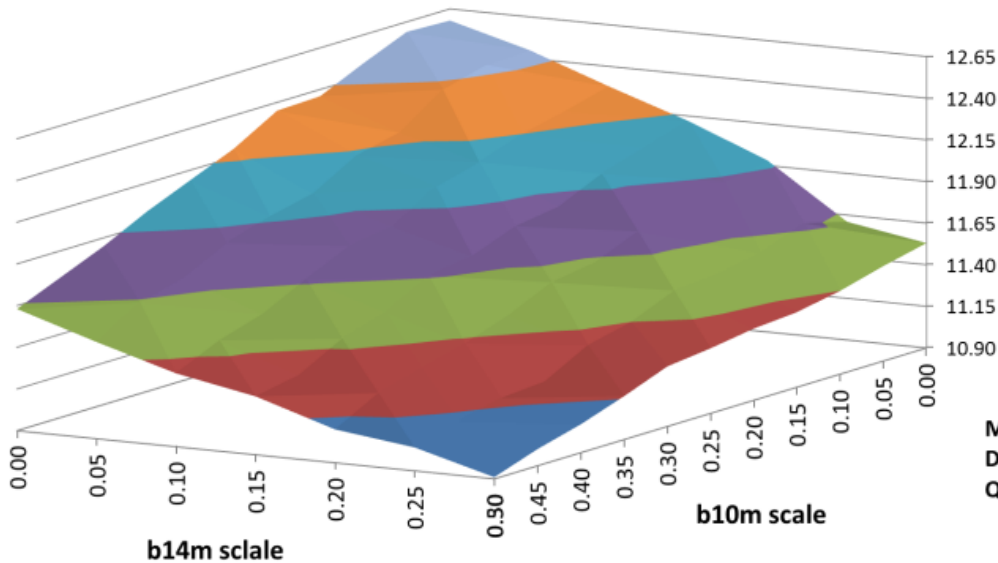
Minimum DA is not strongly dependent on b10m.

Strong DA sensitivity to b14m.



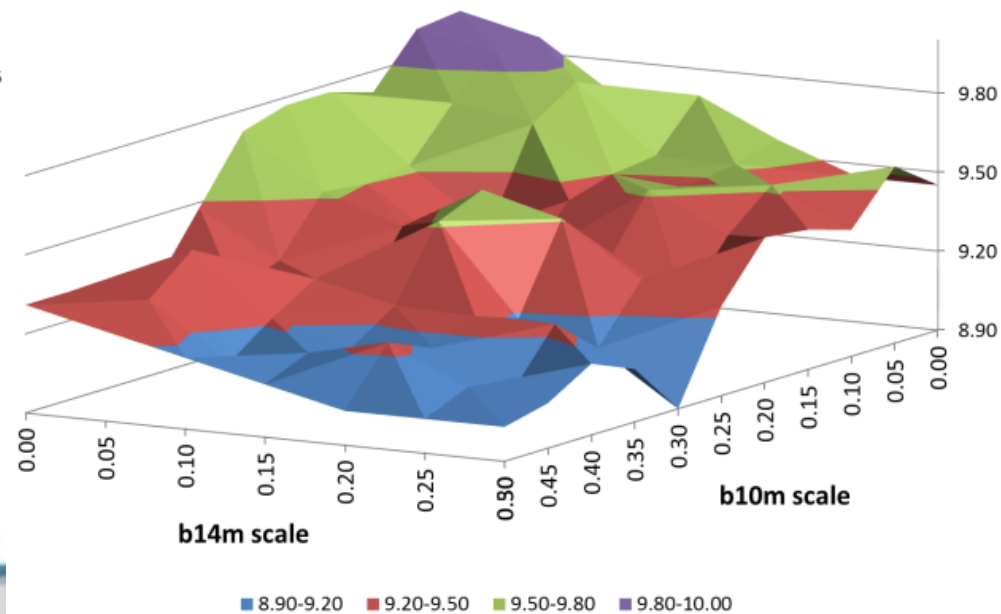
2D scan of DA at collision versus IT b10m, b14m

Average DA [σ] for 60 seeds with IR field errors: IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0), Q4_errortable_v1_spec, Q5_errortable_v0_spec



The average DA is monotonically reduced with both b10m and b14m. Stronger DA dependence on b14m than on b10m.

Minimum DA [σ] for 60 seeds with IR field errors: IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0), Q4_errortable_v1_spec, Q5_errortable_v0_spec

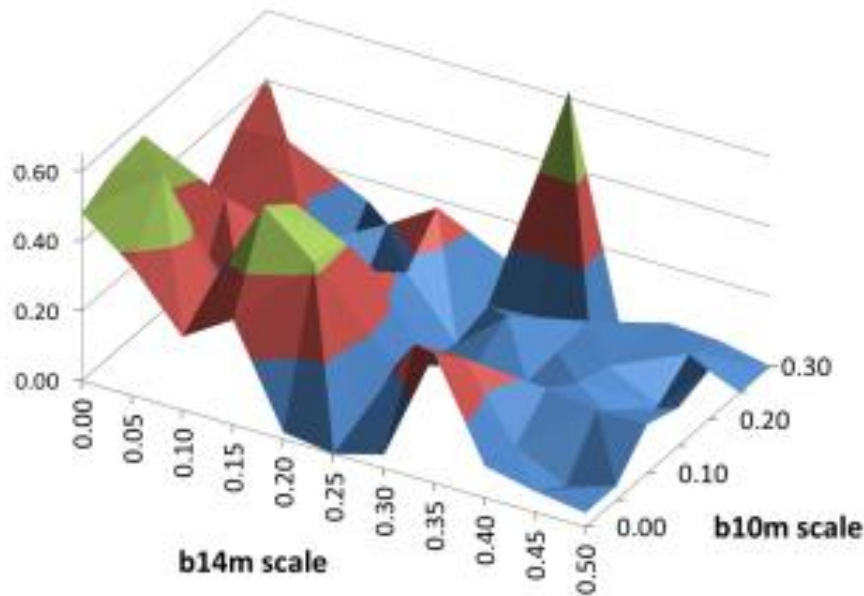


The minimum DA is fluctuating versus b10m and b14m.

Impact of worst seeds on minimum DA versus b10m, b14m of the “IT_errortable_v66_4” at collision energy

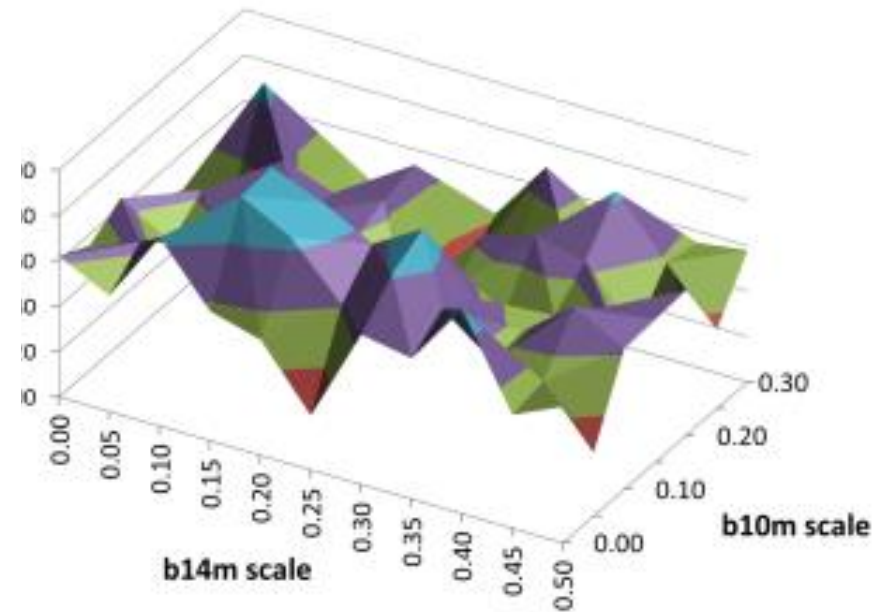
$$DA_{\min 1} - DA_{\min}$$

Increase of minimum DA [σ] with the worst seed removed and with IR field errors: IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0), Q4_errortable_v1_spec, Q5_errortable_v0_spec



$$DA_{\min 2} - DA_{\min}$$

Increase of minimum DA [σ] with two worst seeds removed and with IR field errors: IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0), Q4_errortable_v1_spec, Q5_errortable_v0_spec



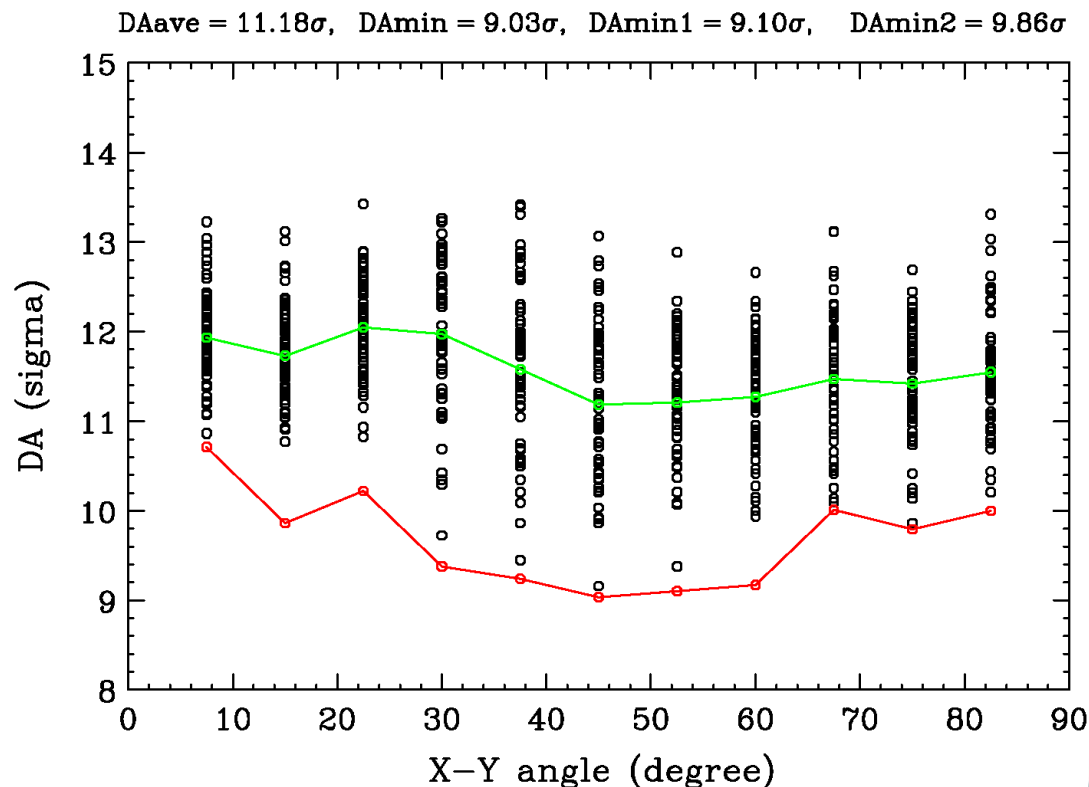
Removing the worst seed increases minimum DA (for 98.3% remaining seeds) in the range from 0 to 0.5σ .

Removing two worst seeds increases the minimum DA (for 96.7% remaining seeds) for most points from 0.5σ to 1σ .

DA at collision energy with adjusted b10m (*0.4) and b14m (*0.25) of the “IT_errortable_v66_4”

The other magnets: “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q4_errortable_v1_spec”, “Q5_errortable_v0_spec”.

Realistically, the b10m, b14m cannot be too small. We scale them to b10m*0.4 and b14m*0.25. The minimum DA is strongly influenced by two bad seeds (number 60 and 46). Without these two seeds, the minimum DA is acceptable.



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

The adjusted coefficients are shown in blue.

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

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 green below. Slightly reduced b6m (-16 -> -15.8) and b10m (4.15 -> 3.63), but significantly increased **b14m**: -0.04 -> -0.6.

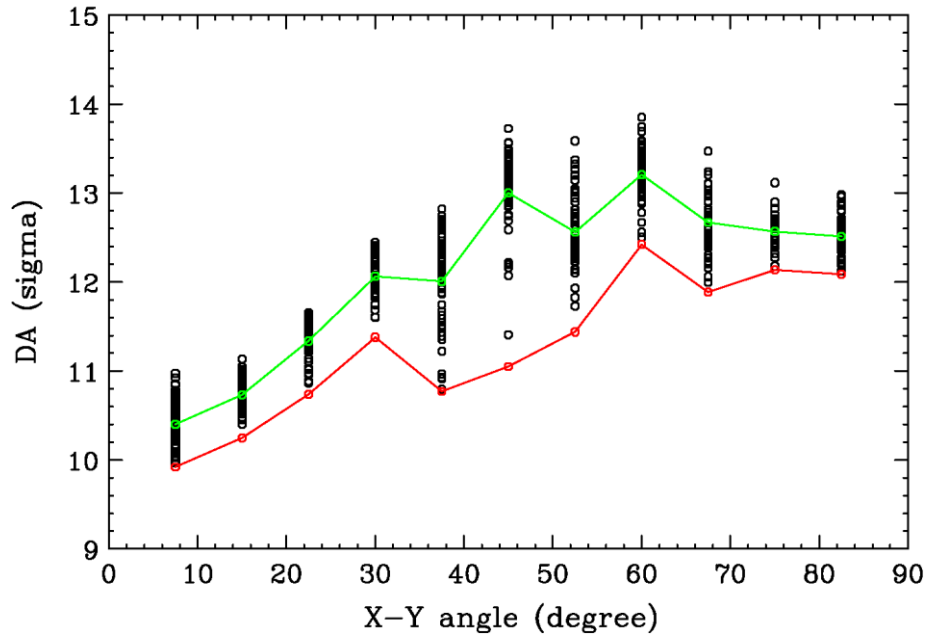
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	0.800	0.800		b3	0	0.820	0.820
a4	0	0.650	0.650		b4	0	0.570	0.570
a5	0	0.430	0.430		b5	0	0.420	0.420
a6	0	0.310	0.310		b6	-15.8	1.100	1.100
a7	0	0.190	0.190		b7	0	0.190	0.190
a8	0	0.110	0.110		b8	0	0.130	0.130
a9	0	0.080	0.080		b9	0	0.070	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

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".

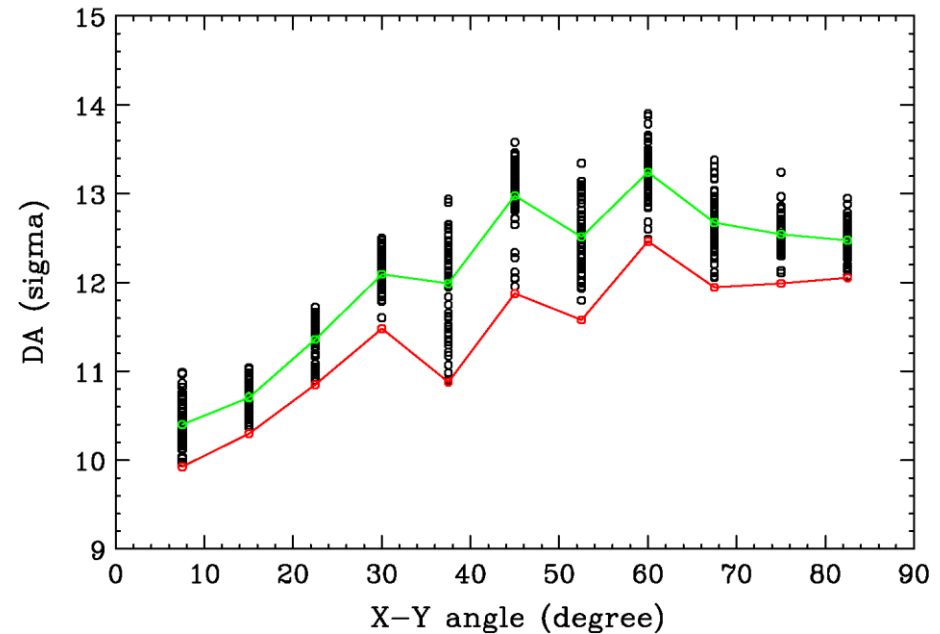
IT_errortable_v3_spec

DAave = 10.40 σ , Damin = 9.92 σ , Damin1 = 9.96 σ , Damin2 = 9.99 σ



IT_errortable_v66_4

DAave = 10.40 σ , Damin = 9.93 σ , Damin1 = 9.98 σ , Damin2 = 10.02 σ



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

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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.

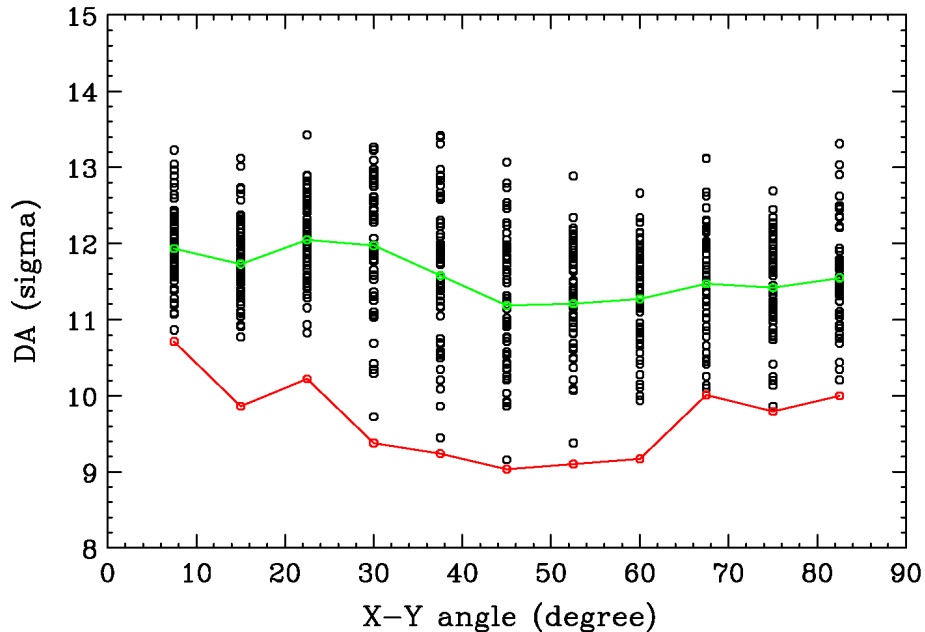
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	1.793	1.793		b3	0	1.793	1.793
a4	0	1.158	1.158		b4	0	1.158	1.158
a5	0	0.748	0.748		b5	0	0.748	0.748
a6	0	0.483	0.483		b6	-0.05	0	0
a7	0	0.312	0.312		b7	0	0.312	0.312
a8	0	0.202	0.202		b8	0	0.202	0.202
a9	0	0.130	0.130		b9	0	0.130	0.130
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

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”.

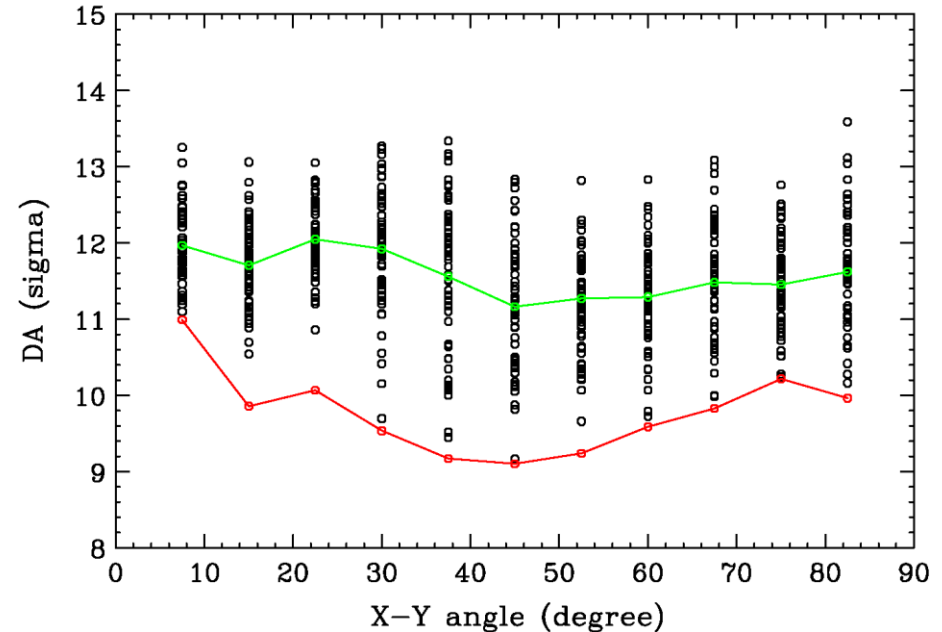
Q4_errortable_v1_spec

DAave = 11.18 σ , DAmIn = 9.03 σ , DAmIn1 = 9.10 σ , DAmIn2 = 9.86 σ



Q4_errortable_v2

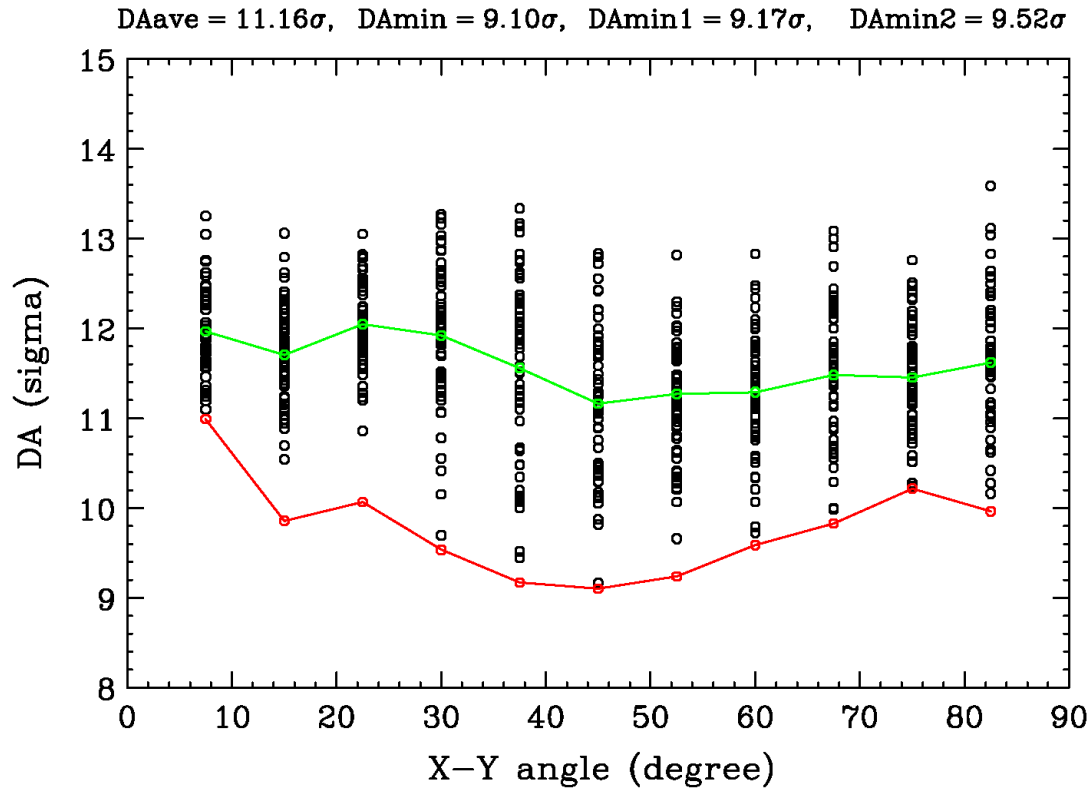
DAave = 11.16 σ , DAmIn = 9.10 σ , DAmIn1 = 9.17 σ , DAmIn2 = 9.52 σ



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.

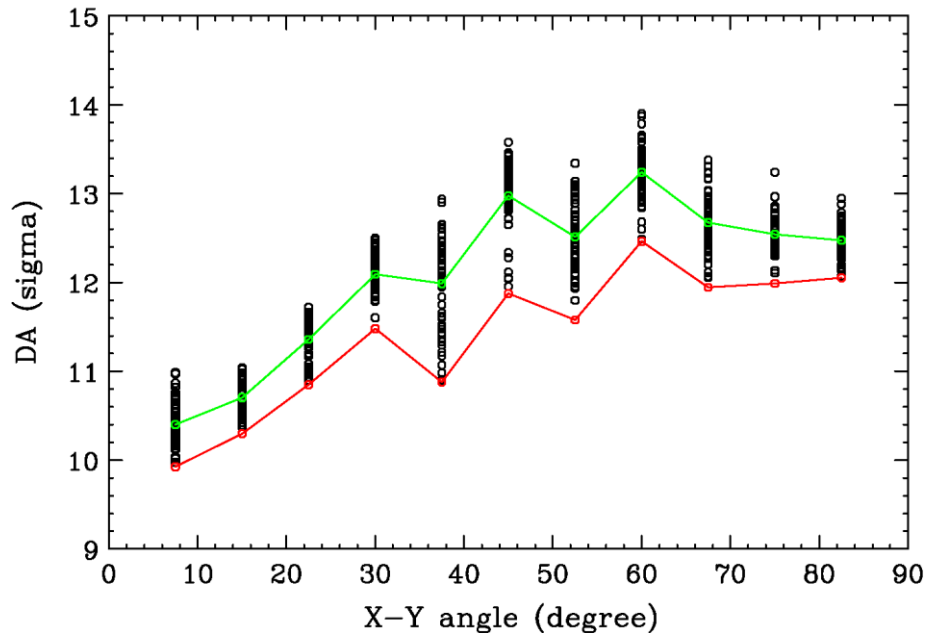
skew	mean	uncertainty	random		normal	mean	uncertainty	random
a3	0	1.793	1.793		b3	0	1.793	1.793
a4	0	1.158	1.158		b4	0	1.158	1.158
a5	0	0.748	0.748		b5	0	0.748	0.748
a6	0	0.483	0.483		b6	-11.45	0	0
a7	0	0.312	0.312		b7	0	0.312	0.312
a8	0	0.202	0.202		b8	0	0.202	0.202
a9	0	0.130	0.130		b9	0	0.130	0.130
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

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”.

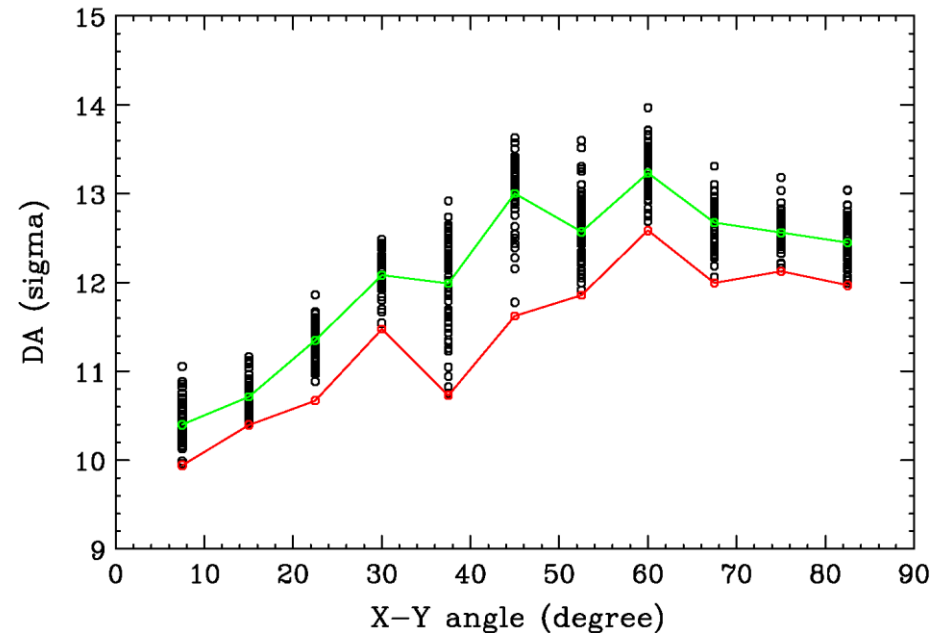
Q4_errortable_v1_spec

DA_{ave} = 10.40σ, DA_{min} = 9.93σ, DA_{min1} = 9.98σ, DA_{min2} = 10.02σ



Q4_errortable_v2

DA_{ave} = 10.40σ, DA_{min} = 9.94σ, DA_{min1} = 9.96σ, DA_{min2} = 9.99σ



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

Outline

- Introduction
- D2 field quality status
- IT field quality status
- Q4 field quality status
- Summary and outlook

Summary and outlook - I

- The latest estimate of field quality of **D2 magnets** (“D2_errortable_v5”) improves DA at collision energy while having no impact at injection energy. **Hence, it is acceptable and becomes a new specification table.**
- The updated estimate of **IT field quality** (“IT_errortable_v66_4”) **required adjustment of b10m, b14m terms at collision energy.** The minimum DA at collision was also found to be sensitive to bad seeds. With the above adjustment and without two bad seeds, the DA at collision appears **barely acceptable.** **At injection energy, the impact of the “IT_errortable_v66_4” is negligible and therefore this field quality at injection is acceptable.**
- The updated estimate of **Q4 field quality** (“Q4_errortable_v2”) has minor impact on the DA. **Hence, it is acceptable and it becomes a new specification table.**

Globally, DA_{\min} is dangerously approaching the value of 8σ !

Summary and outlook - II

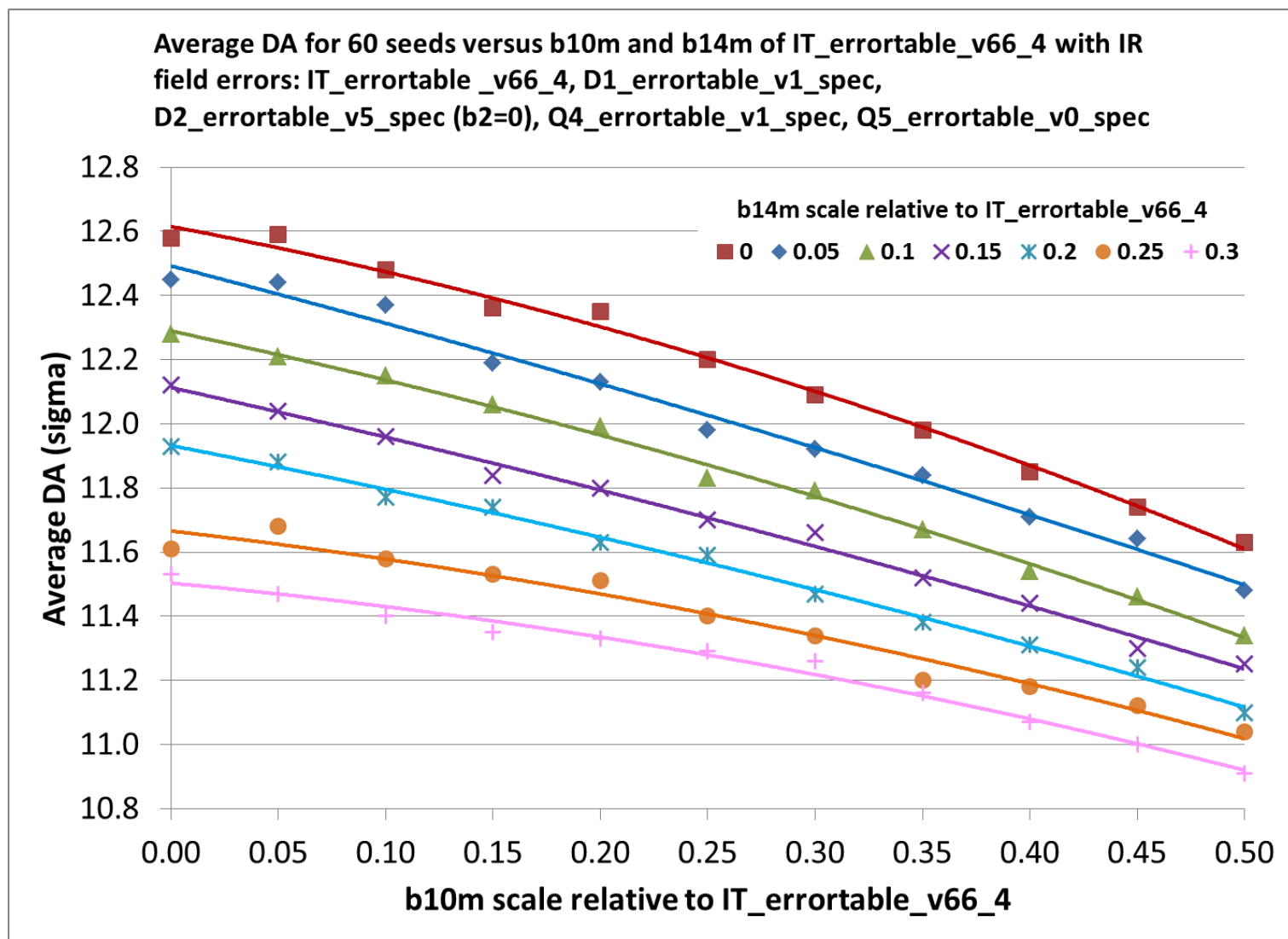
- These studies should take into account any future evolution of the situation of field quality estimates (magnet design, magnetic measurements).
- Different optics configurations will be considered: [round/flat](#), [sround/sflat](#), as well as during the squeeze.
- Next on the list of topics
 - The analysis of the impact on DA of stray fields of large aperture magnets, [IT and D1](#), (with [A. Wolsky & co-workers](#)).
- In parallel
 - Work on efficient [post processing of tracking data](#) in view of extracting useful information on DA is progressing ([M. Fitterer and R. de Maria](#)).
 - Reflection on [statistical approach for small-series magnets](#).

Thank you for your attention



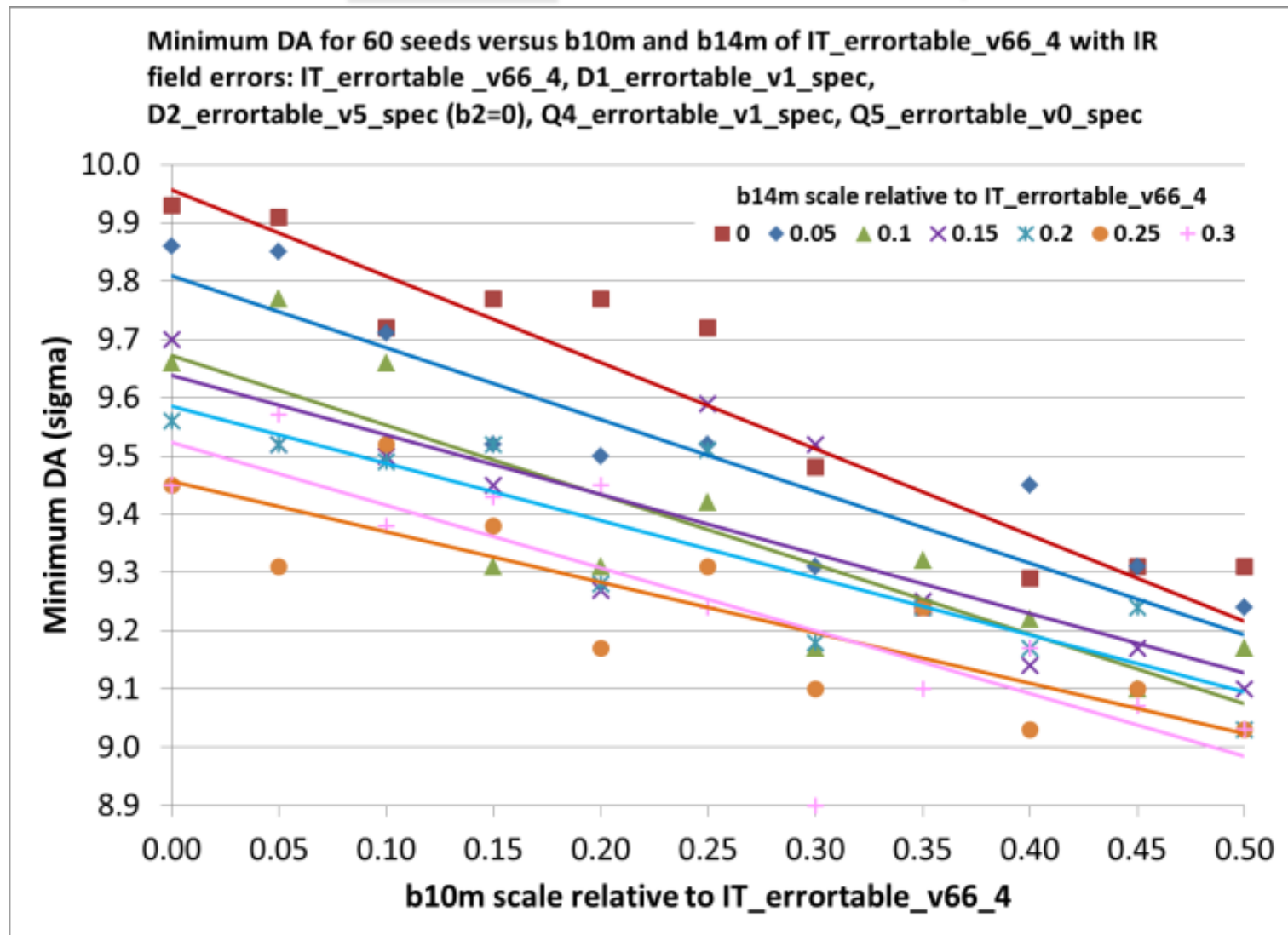
cern.ch

2D scan of average DA at collision versus IT b10m, b14m - 2



Smooth dependence of average DA on b10m and b14m.

Minimum DA at collision versus IT b10m, b14m



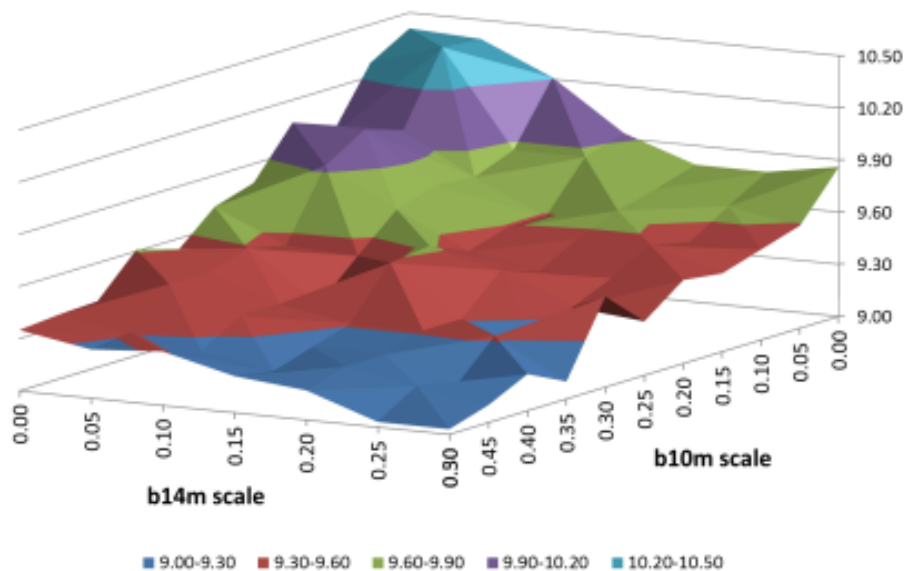
Finding the optimal setting of the IT b10m, b14m based on the minimum DA is not straightforward due to the DA fluctuation.

Impact of the worst seeds on minimum DA versus b10m, b14m of the “IT_errortable_v66_4” at collision energy - 1

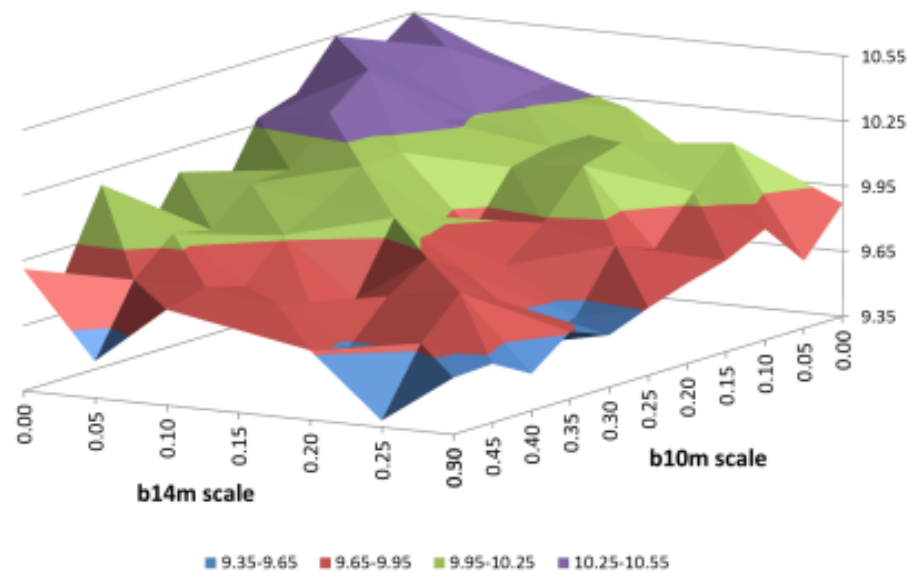
DA_{min1} (the worst seed removed)

DA_{min2} (two worst seeds removed)

Minimum DA [σ] excluding the worst seed with IR field errors:
IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0),
Q4_errortable_v1_spec, Q5_errortable_v0_spec



Minimum DA [σ] excluding two worst seeds with IR field errors:
IT_errortable_v66_4, D1_errortable_v1_spec, D2_errortable_v5_spec (b2=0),
Q4_errortable_v1_spec, Q5_errortable_v0_spec



It was determined that two bad seeds in this scan consistently produce the lowest DA values.

Removing one or both of these seeds does not significantly reduce fluctuation of the minimum DA dependence on b10m and b14m.

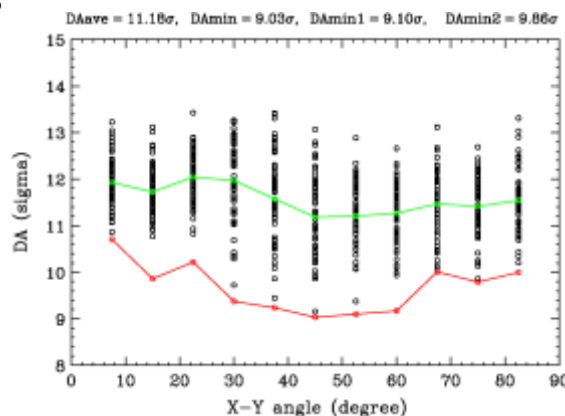
DA sensitivity to b6u (uncertainty) and b6r (random) terms of the “IT_errortable_v66_4” at collision energy

Since the b6m term in the updated IT field quality “IT_errortable_v66_4” at collision is reduced a factor of 2, one can investigate if the b6u, b6r terms can be relaxed. The shown results, where b6u, b6r are scaled a factor of 2, suggest that it may be possible to somewhat relax the b6u term.

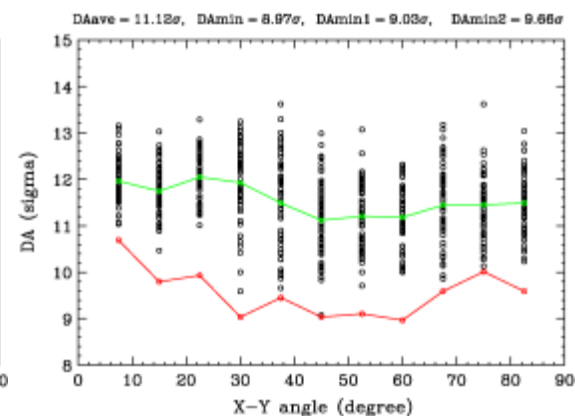
Field tables: “IT_errortable_v66_4” (with adjusted b10m*0.4, b14m*0.25),
 “D1_errortable_v1_spec”,
 “D2_errortable_v5_spec”,
 “Q4_errortable_v1_spec”,
 “Q5_errortable_v0_spec”.

b6u	× 1	× 2	× 1	× 2
b6r	× 1	× 1	× 2	× 2
DAave	11.18	11.12	11.11	11.09
DAmin	9.03	8.97	8.77	8.83
DAmin1	9.10	9.03	9.31	9.10
DAmin2	9.86	9.66	9.31	9.24

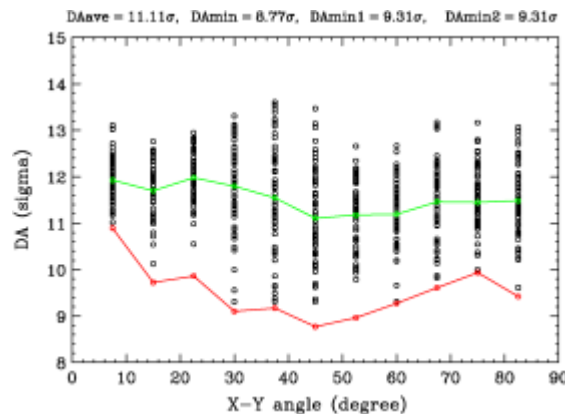
b6u × 1, b6r × 1



b6u × 2, b6r × 1



b6u × 1, b6r × 2



b6u × 2, b6r × 2

