Optimization of Field Error Tolerances for Triplet Quadrupoles of the HL-LHC Lattice V3.01 Option 4444

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Goals

• Previously performed study of dynamic aperture (DA) sensitivity to multipole field errors in the inner triplet (IT) quadrupoles with 120 mm coil aperture resulted in a self-consistent set of field tolerances producing minimum DA of 12.3σ. These tolerances, however, are too tight relative to the expected achievable field quality in real magnets.

• Therefore, the goal for this study is to try to relax the tolerances towards the achievable field quality.

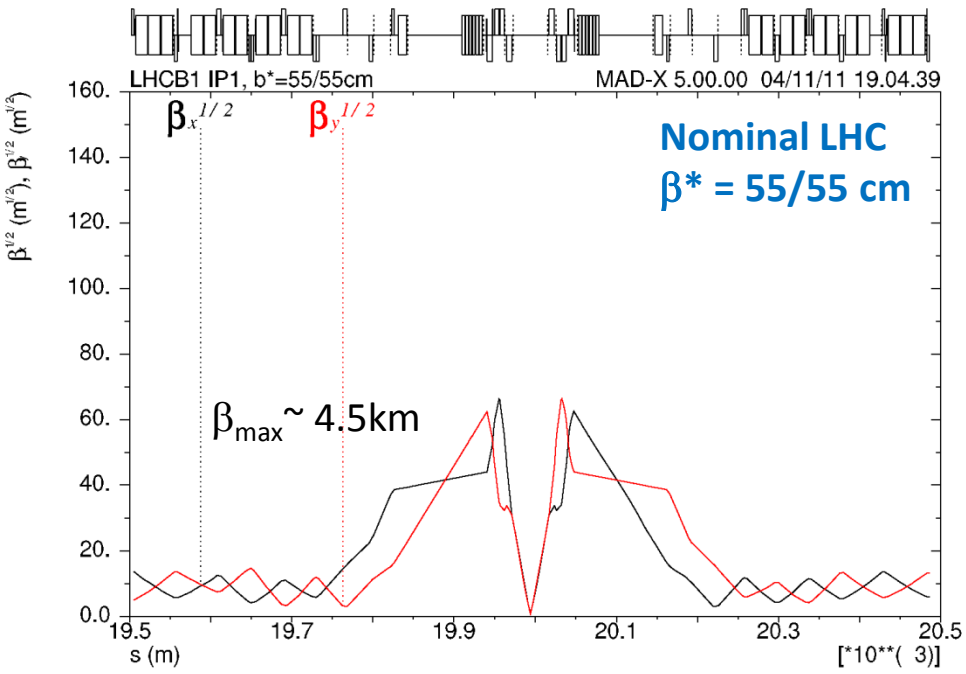
• This study is performed for the proposed IT quadrupoles with 150 mm coil aperture.

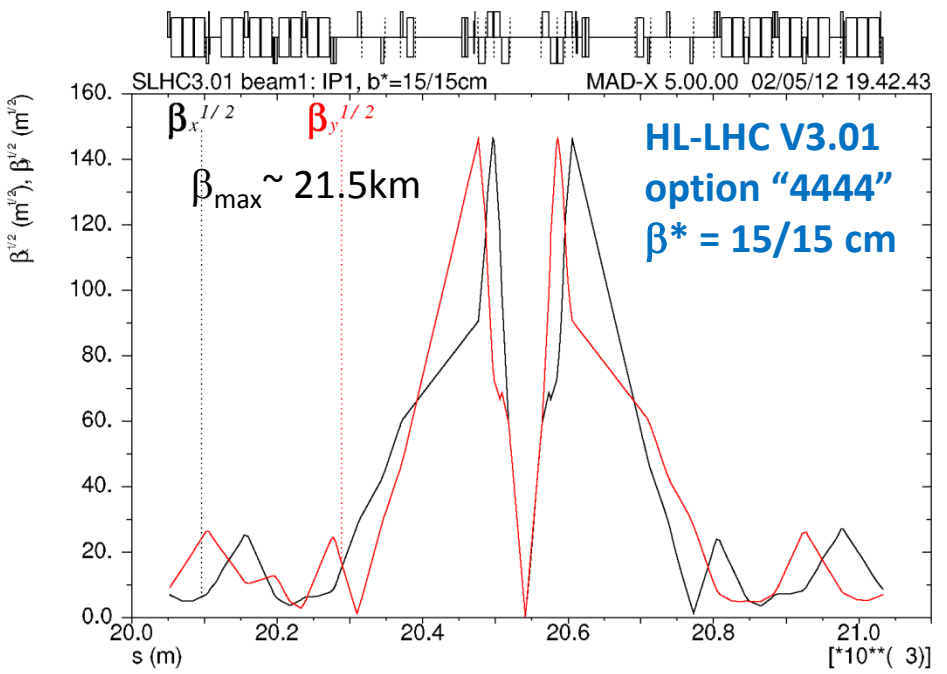
• The strategy to relax the tolerances includes setting a lower level for minimum DA (~11σ), a requirement for additional IT multipole field correctors ,and fine tuning and balancing of multipole coefficients.

Lattice: HL-LHC V3.01, collision option “4444” with β*=15/15 cm at IP1 and IP5, Nb-Ti superconducting IT quadrupoles with 150 mm coil diameter and 120 T/m gradient, 7 TeV beam energy.

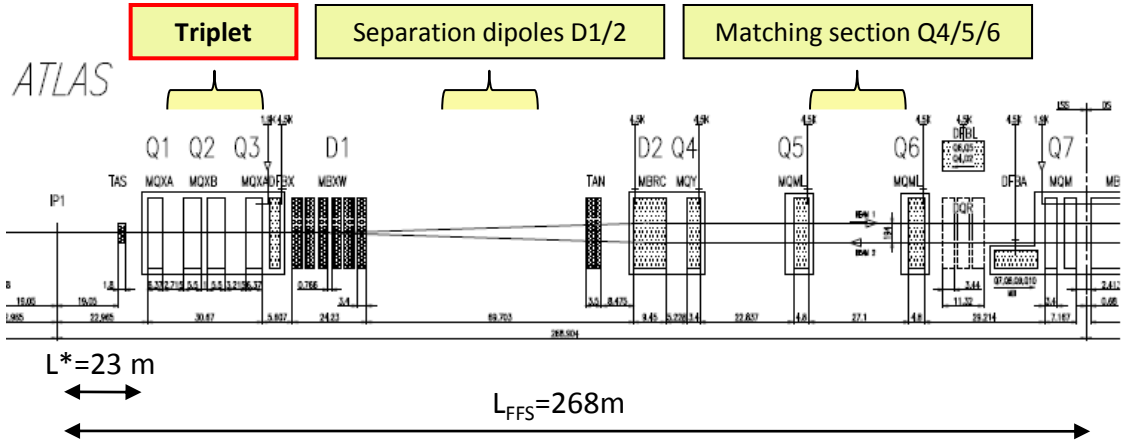
Code: SixTrack.

Interaction Region β-functions





- Large IT β-functions in the HL-LHC.
- Large 150 mm coil diameter in the new proposed superconducting IT quadrupoles Q1,Q2,Q3 will provide the necessary aperture and help relaxing the IT field tolerances.



Multipole field scaling in a SC quadrupole

$$B_y + iB_x = 10^{-4} B_2 \times \sum_{n=2}^{\infty} (b_n + ia_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

where n=2 is for a quadrupole, etc.
B_2 is the main quadrupole field at r_0

Note: the a_n,b_n coefficients are defined in 10^{-4} units.
The a_n and b_n values are split in two components: the "uncertainty" term (deviation from systematic) and the "random" term. Their values in the presented field error tables correspond to sigma of a Gaussian distribution.

- **Scaling with reference radius r_0** does not affect dynamic aperture. Nominal r_0 = 17 mm → new IT quad **r_0 = 50 mm**.

$$b_n, a_n \propto r_0^{n-2} \rightarrow (50/17)^{n-2}$$

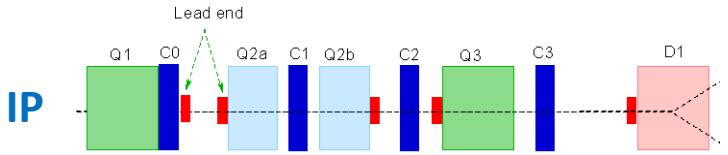
- **Scaling with coil diameter d_c** in a SC quad (B. Bellesia, et al., Phys. Rev. ST-AB 10, 062401 (2007)). Nominal d_c = 70 mm → new IT quad **d_c = 150 mm**.

$$b_n, a_n \propto 1/d_c^{n-1} \rightarrow (70/150)^{n-1}$$

- **Scaling with peak IT beta function β_{max}** to keep the IT non-linear resonance driving terms constant (S. Fartoukh, SLHC Project Report 0038). Nominal β_{max} = 4.5 km → new **β_{max} = 21.5 km**.

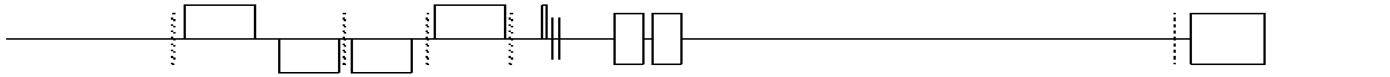
$$b_n, a_n \propto 1/\beta_{\max}^{n/2} \rightarrow (4.5/21.5)^{n/2}$$

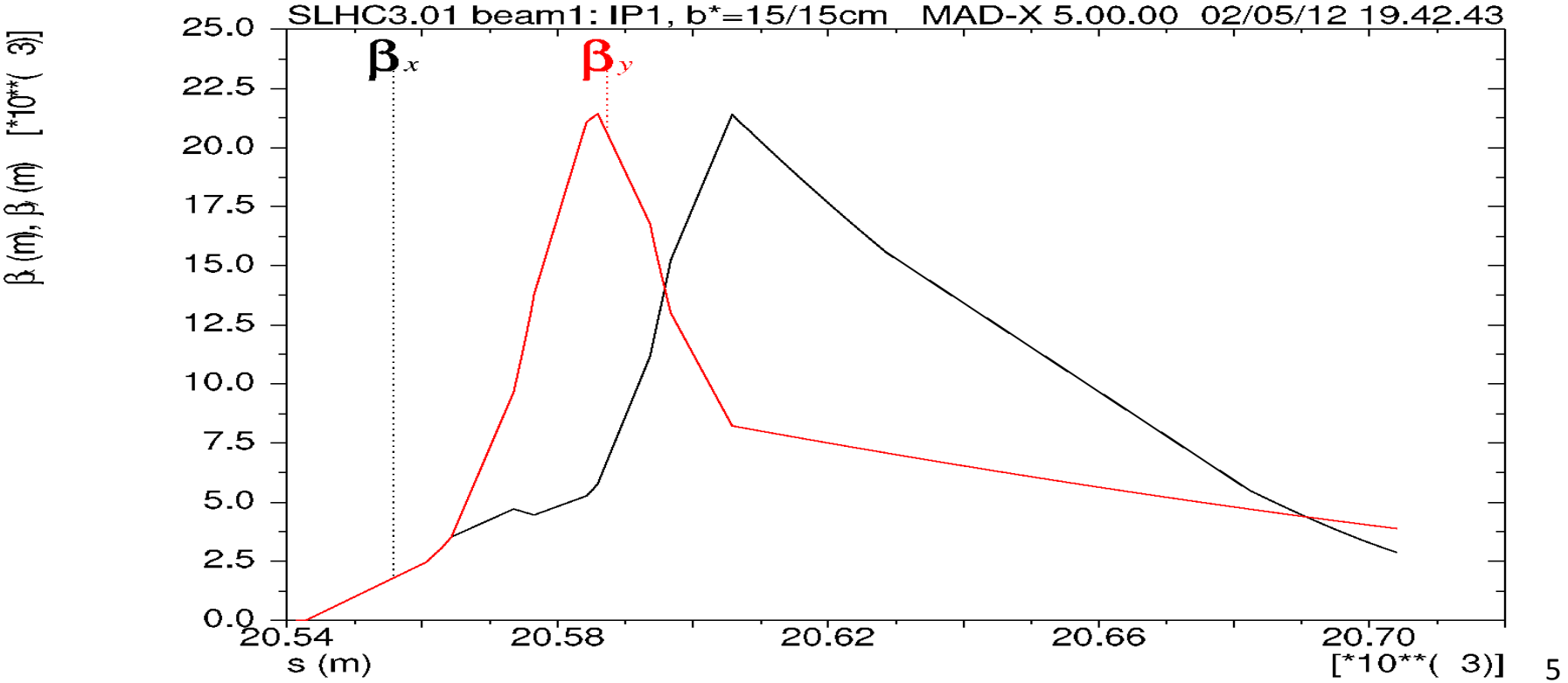
Multipole field correctors in the triplet



a3, b3, a4, b4, b6 correctors

The a3, b3, a4, b4, b6 correctors compensate the corresponding errors of the IT field thus relaxing the tolerances. The a5, b5, a6 correctors are planned to be included, however they were not explicitly included in this study.





Set-up for long term SixTrack tracking

- 100,000 turns
- 60 random error seeds
- 30 particle pairs per amplitude step (2σ)
- 11 angles
- 7 TeV beam energy
- initial $\Delta p/p$ = 2.7e-4
- tune = 62.31, 60.32
- normalized emittance = 3.75 μm-rad
- IT multipole field correctors to compensate a3, b3, a4, b4, b6 terms are included (IT correctors for a5, b5, a6 terms have been added to the latest HL-LHC version, but not included in this study)
- Arc errors and correction are included
- No field errors in D1, D2 separation dipoles and Q4 quadrupoles (future study)

Expected to achieve field quality for 150 mm aperture IT quadrupole at R_{ref} = 50 mm based on magnet design estimates

	Uncertainty	Random		Uncertainty	Random
b3	0.712	0.712	a3	0.712	0.712
b4	0.512	0.512	a4	0.512	0.512
b5	0.368	0.368	a5	0.368	0.368
b6	1.440	1.024	a6	0.960	0.264
b7	0.168	0.168	a7	0.168	0.168
b8	0.128	0.128	a8	0.128	0.128
b9	0.064	0.064	a9	0.064	0.064
b10	0.048	0.048	a10	0.048	0.048
b11	0.032	0.032	a11	0.032	0.032
b12	0.021	0.021	a12	0.021	0.021
b13	0.014	0.014	a13	0.014	0.014
b14	0.009	0.009	a14	0.009	0.009
150 mm aperture, Rref=50 mm					

``REVIEW OF ESTIMATES OF RANDOM COMPONENTS IN THE INNER TRIPLET''
E. Todesco, Hi-Lumi and LARP Collaboration Meeting, CERN, June 7, 2012

Expected to achieve error table (by E. Todesco) scaled to R_{ref} = 40 mm (table "target4")

For SixTrack simulations, we scale the expected to achieve field error table by E. Todesco for 150 mm IT quadrupole to R_{ref} = 40 mm as this is hard wired in the code.

skew	uncertainty	rms		normal	uncertainty	rms
a3	0.5696	0.5696		B3	0.5696	0.5696
a4	0.3277	0.3277		b4	0.3277	0.3277
a5	0.1884	0.1884		b5	0.1884	0.1884
a6	0.3932	0.1081		b6	0.5898	0.4194
a7	0.0551	0.0551		b7	0.0551	0.0551
a8	0.0336	0.0336		b8	0.0336	0.0336
a9	0.0134	0.0134		b9	0.0134	0.0134
a10	0.0081	0.0081		b10	0.0081	0.0081
a11	0.0043	0.0043		b11	0.0043	0.0043
a12	0.0023	0.0023		b12	0.0023	0.0023
a13	0.0012	0.0012		b13	0.0012	0.0012
a14	0.0006	0.0006		b14	0.0006	0.0006

Previous study: Tolerance table "target39" normalized to "target4" (in %), providing $DA_{min} = 12.3\sigma$

skew	uncertainty	rms		normal	uncertainty	rms
a3	40.3	48.9		b3	31.8	60.6
a4	77.6	68.0		b4	27.2	27.3
a5	35.7	8.0		b5	24.5	19.3
a6	43.2	10.2		b6	37.2	38.0
a7	65.8	15.2		b7	6.1	7.2
a8	81.5	6.4		b8	21.6	4.3
a9	247.5	16.3		b9	14.3	13.2
a10	195.4	19.1		b10	38.8	14.0
a11	242.1	21.9		b11	25.6	31.2
a12	258.7	16.5		b12	21.3	17.0
a13	263.3	31.7		b13	28.3	19.2
a14	216.7	41.7		b14	70.0	41.7

- These tolerances are based on approximately equal impact of each coefficient on DA while providing $DA_{min} > 12\sigma$.
- This study showed that DA is not very sensitive to high order Anu coefficients.

Optimization strategy

• The desired goal is to achieve field quality specified in the error table “target4”. There is also a possibility that with some effort the achievable field quality could be improved by as much as 50%. Therefore, the goal of this study is to obtain the most relaxed tolerances, ideally in the range of 50-100% values of the table “target4”.

• This requires a compromise on the level of acceptable DA and improvement of the IT field compensation.

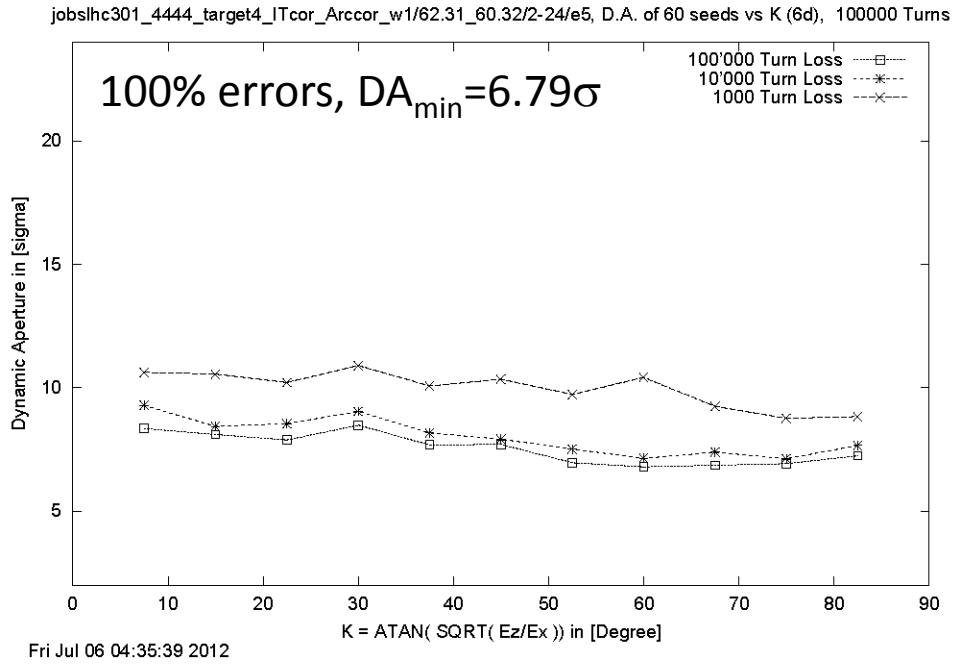
• It was decided for this study to lower the level of DA_{min} with the IT errors to about $10.5\sigma - 11\sigma$.

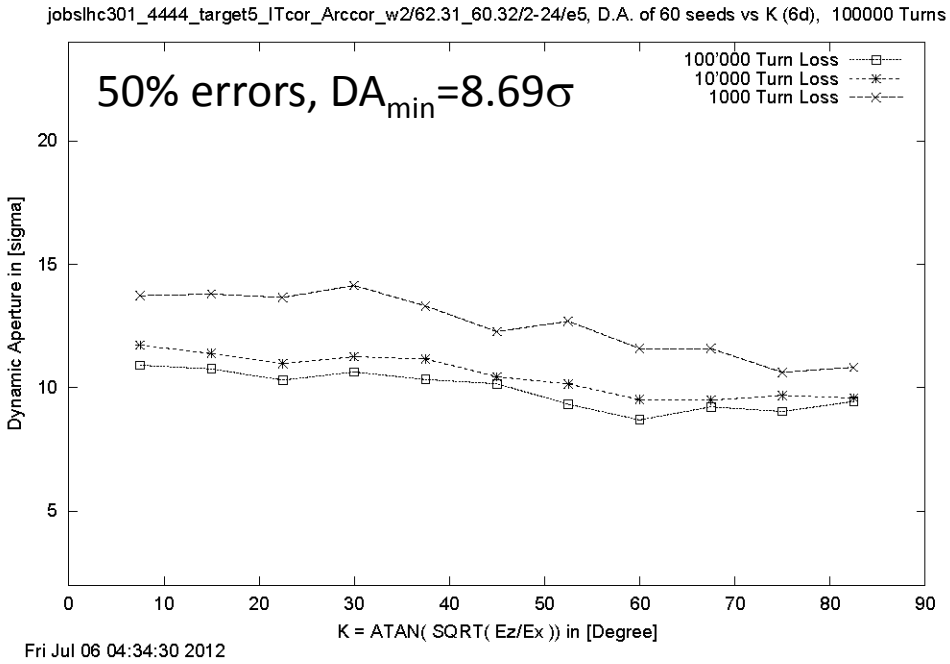
• Secondly, it was assumed that the IT correctors for A5, B5, A6 errors will be installed. Since these correctors are not yet implemented for this lattice, we artificially reduced the A5, B5, A6 errors assuming that these represent residual errors after correction.

• The individual multipole coefficients have to be optimized in order to relax and better balance the tolerances. This can be obtained by using various scans.

• The highest order coefficients may need to be better relaxed since their tolerances are likely more difficult to control.

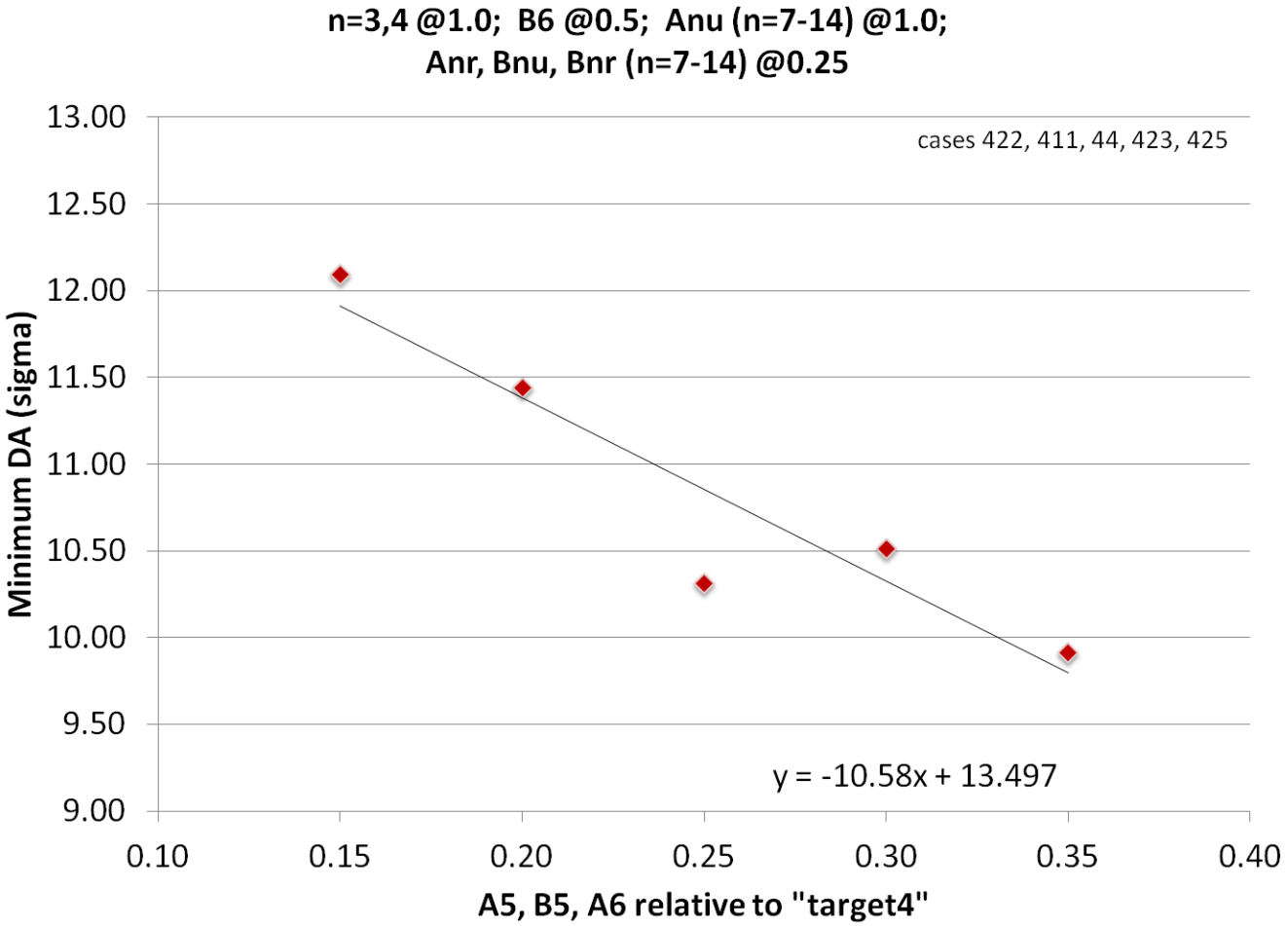
Dynamic aperture at 100% and 50% of the “target4” values





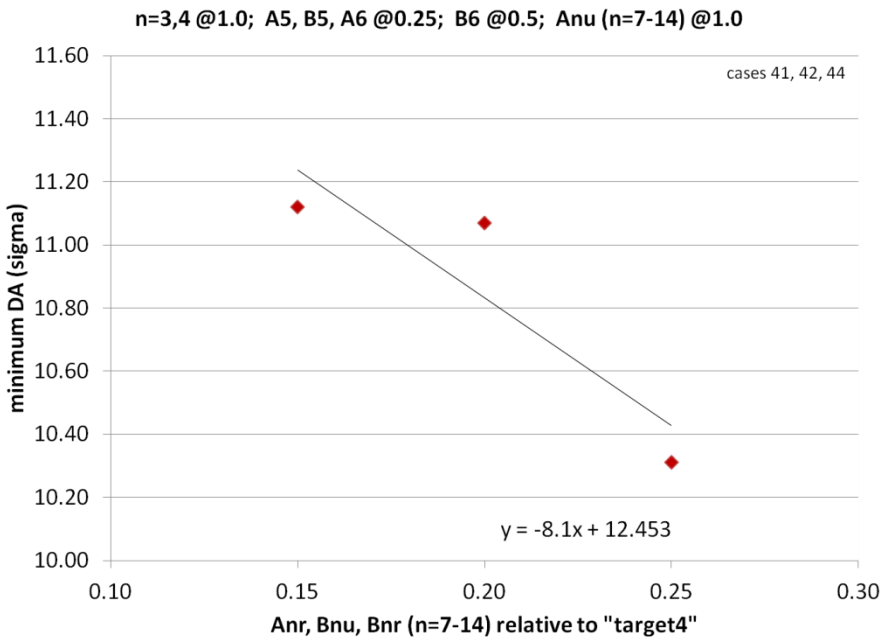
The DA at 50% scale is not sufficient. Detailed optimization of various multipole coefficients is required.

Scan of A5, B5, A6 assuming their IT correction is included

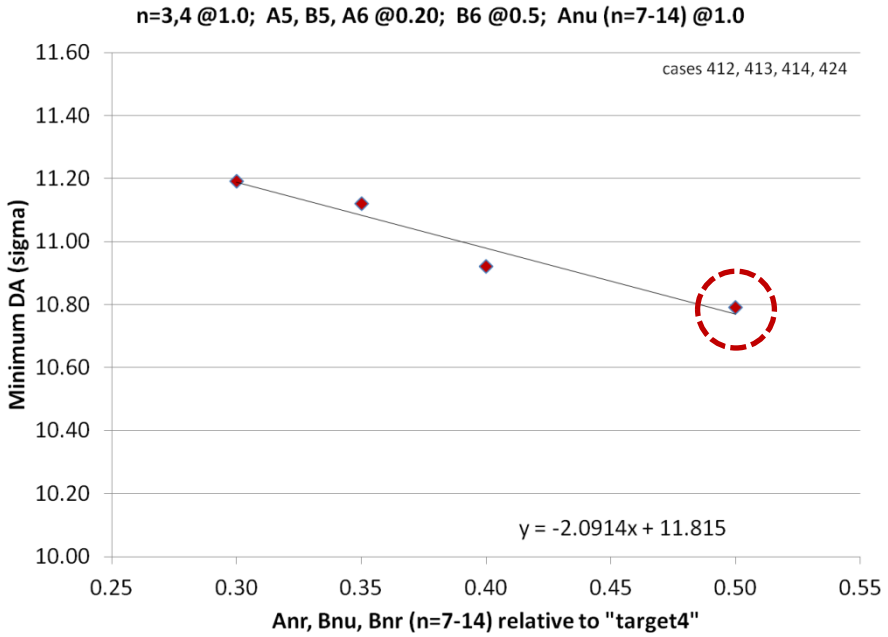


- This indicates that for ~11σ DA, one needs to have the residual A5, B5, A6 coefficients within 20-25% of “target4” or smaller.
- Note that in this scan the high order multipoles are not yet within the desired range.

Scan of high order Anr, Bnu, Bnr (n=7-14) for two settings of A5, B5, A6 (20% and 25%)



A5, B5, A6 at 25%

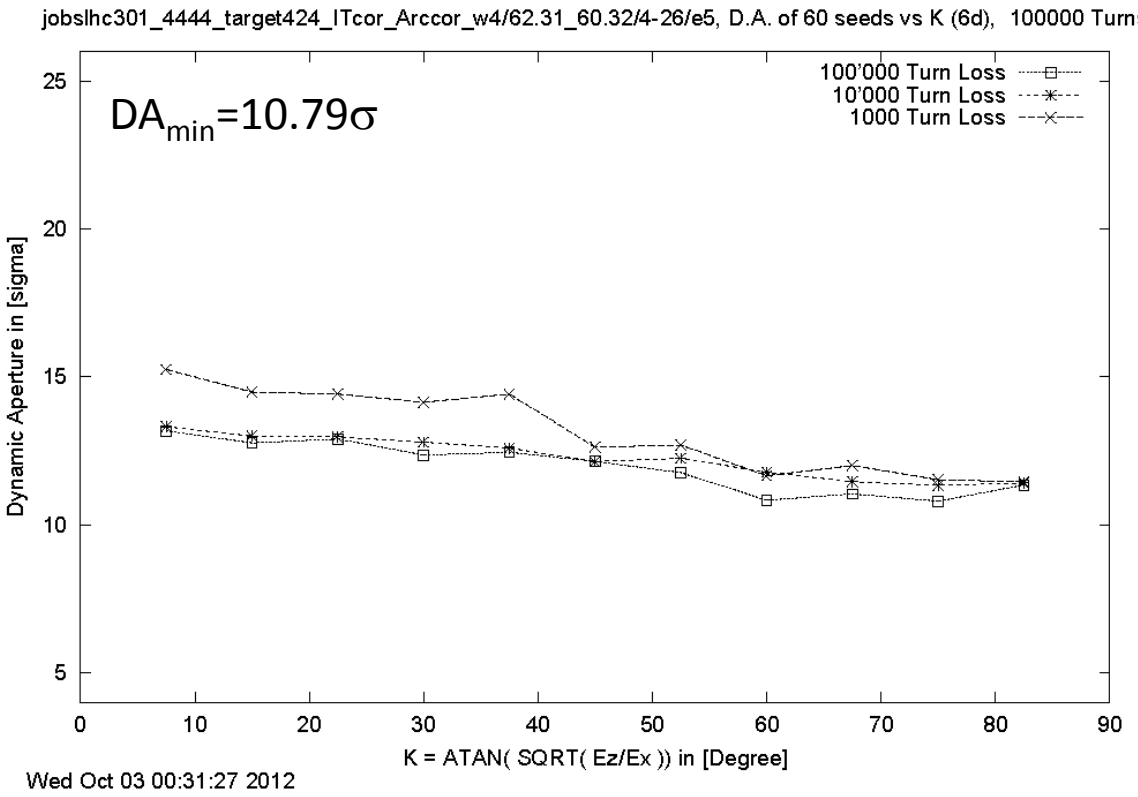


A5, B5, A6 at 20%

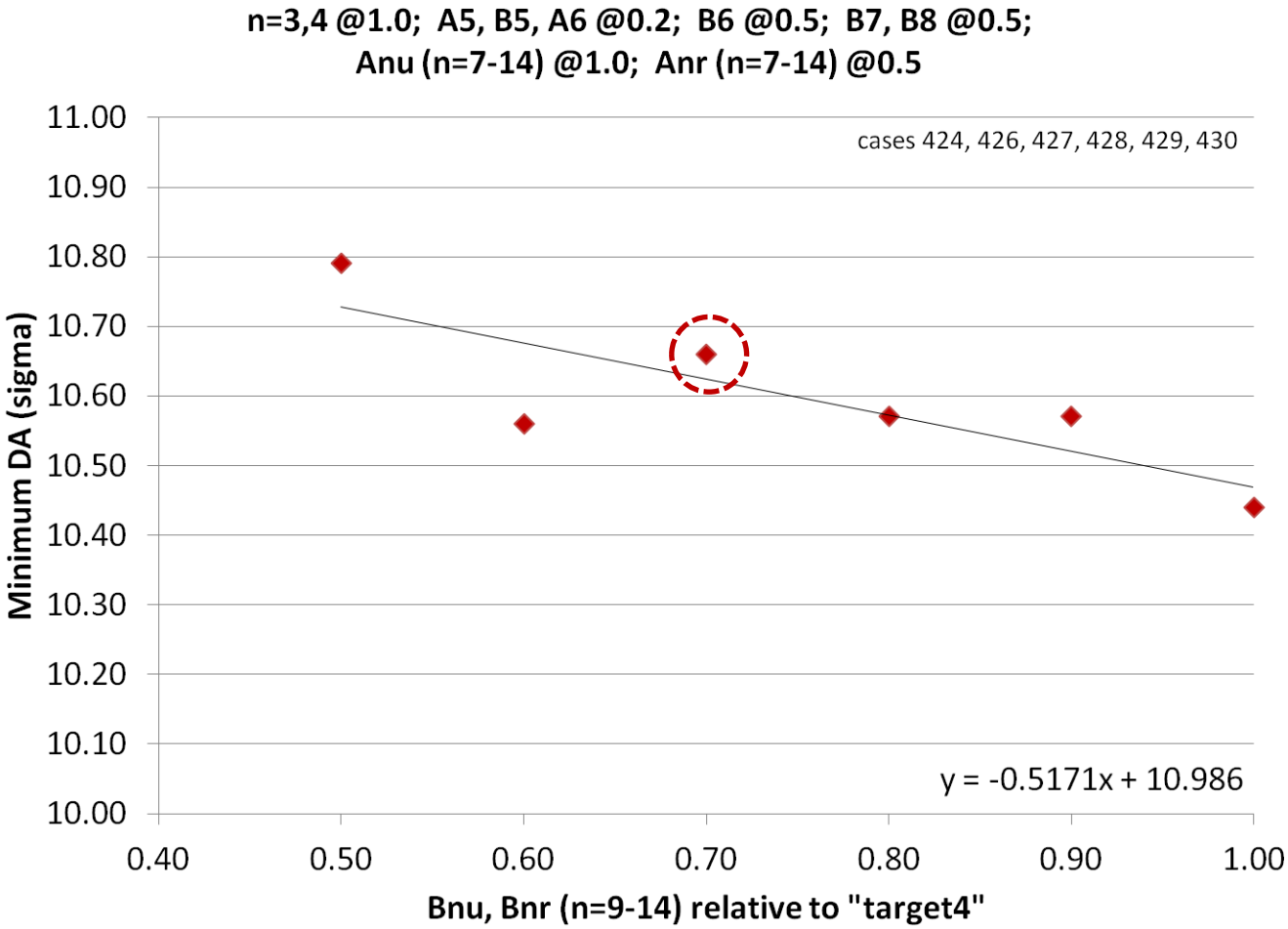
- The A5, B5, A6 values are assumed to be the residual values after IT correction.
- This indicates that in order to reach 50% tolerances for high order multipoles, the A5, B5, A6 residual errors after IT correction must be ~20% of “target4” values.
- The case shown by circle (“target424”) has all coefficients at ≥50% values except A5, B5, A6 (assumed to be corrected). This is the starting point for high order scans.

Dynamic aperture for error table “target424”

Settings relative to “target4”: n=3,4 at 100%; A5, B5, A6 at 20%; B6 at 50%;
Anu (n=7-14) at 100%; Anr, Bn (n=7-14) at 50%.
This satisfies the bare minimum requirement for the ≥50% tolerance values.
This is the starting point for more scans trying to relax high order multipoles.

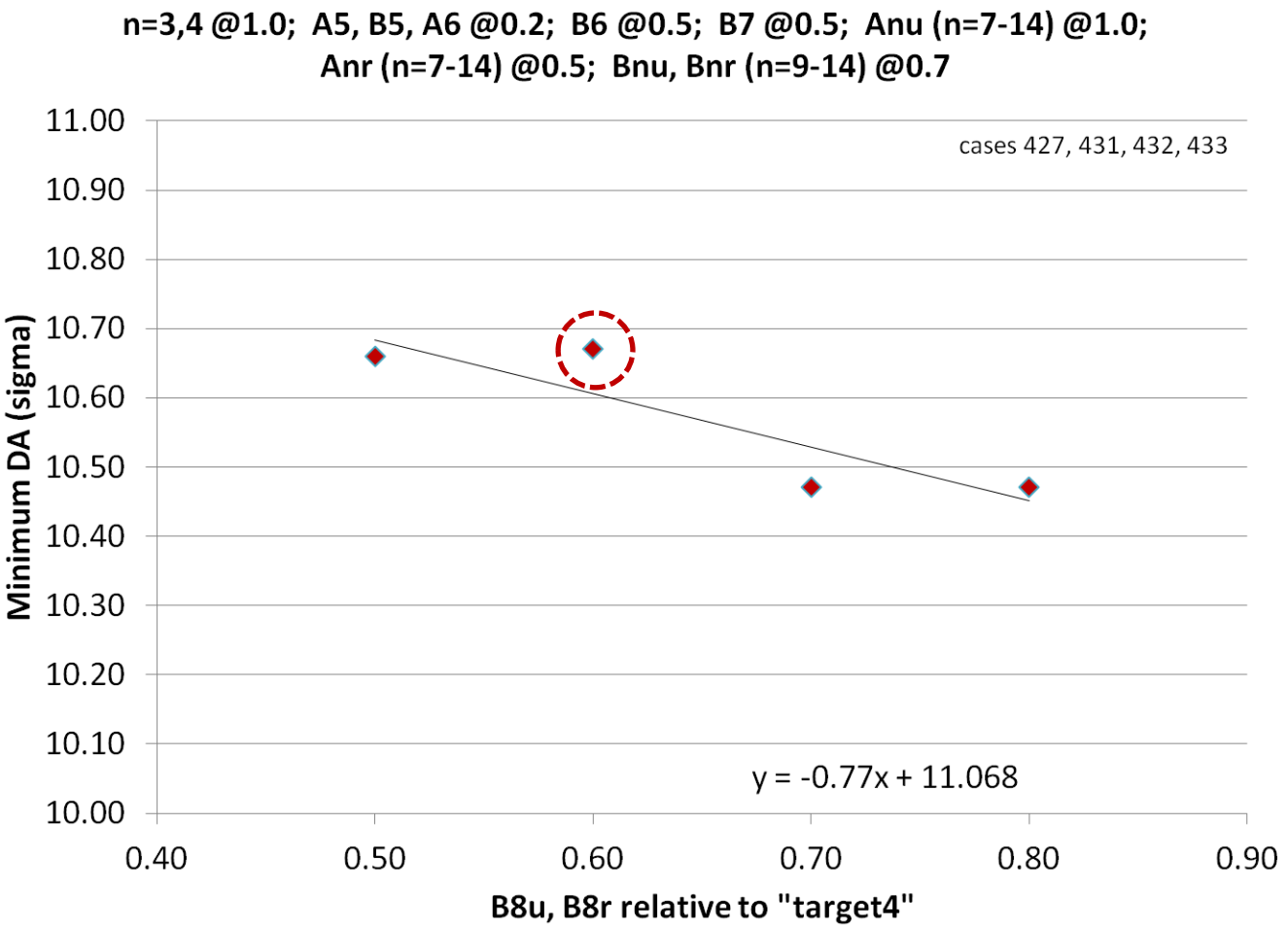


Scan of high order Bn (n=9-14)



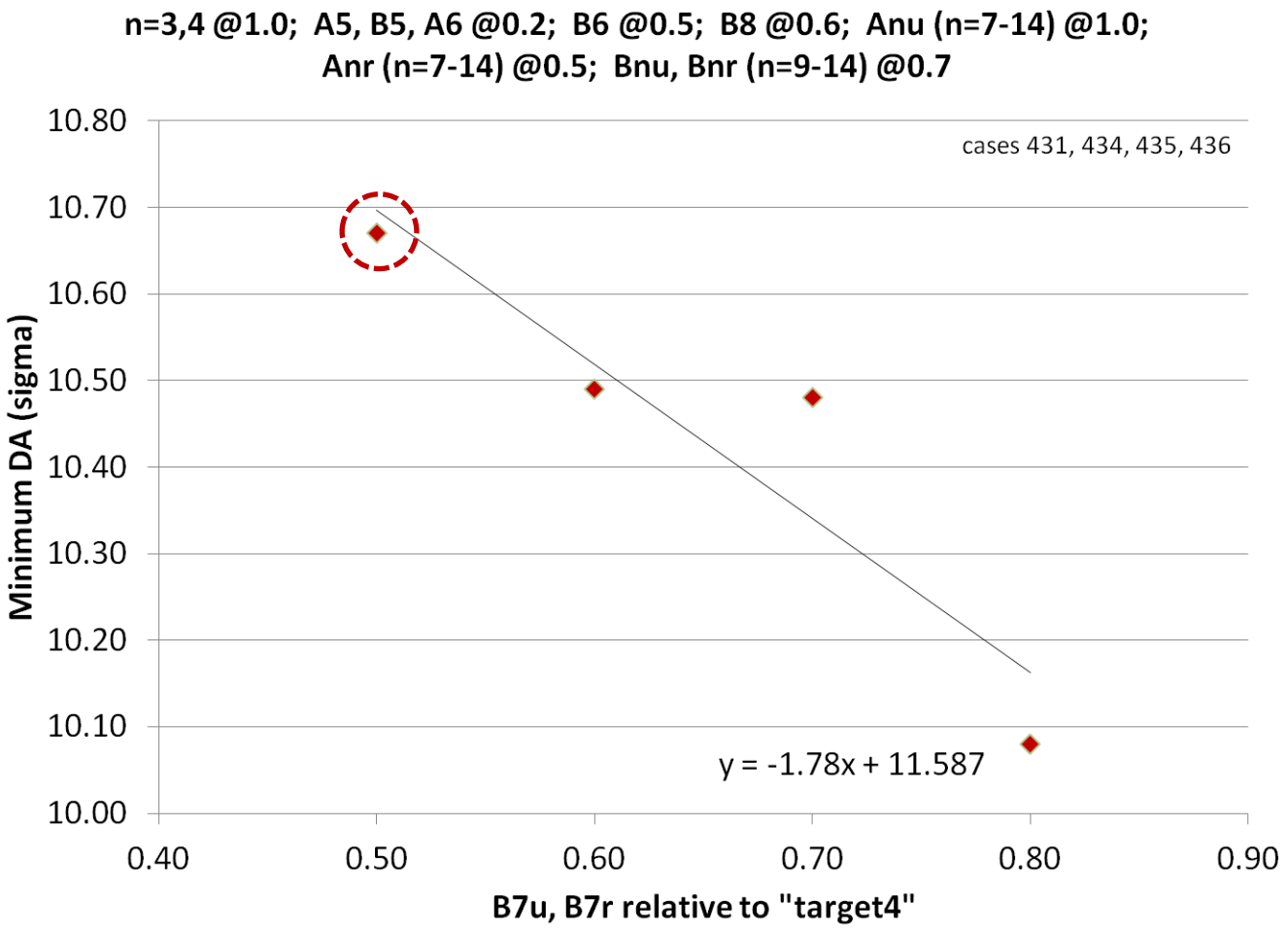
We require that DA >10.6σ. This indicates that Bn (n=9-14) should be set to 70%. This setting ("target427") then will be used to scan B8 while still trying to keep the DA >10.6σ.

Scan of B8



To maintain DA >10.6σ the B8 should be set to 60% (“target431”).
The next step is to scan B7 while trying to keep the DA >10.6σ.

Scan of B7

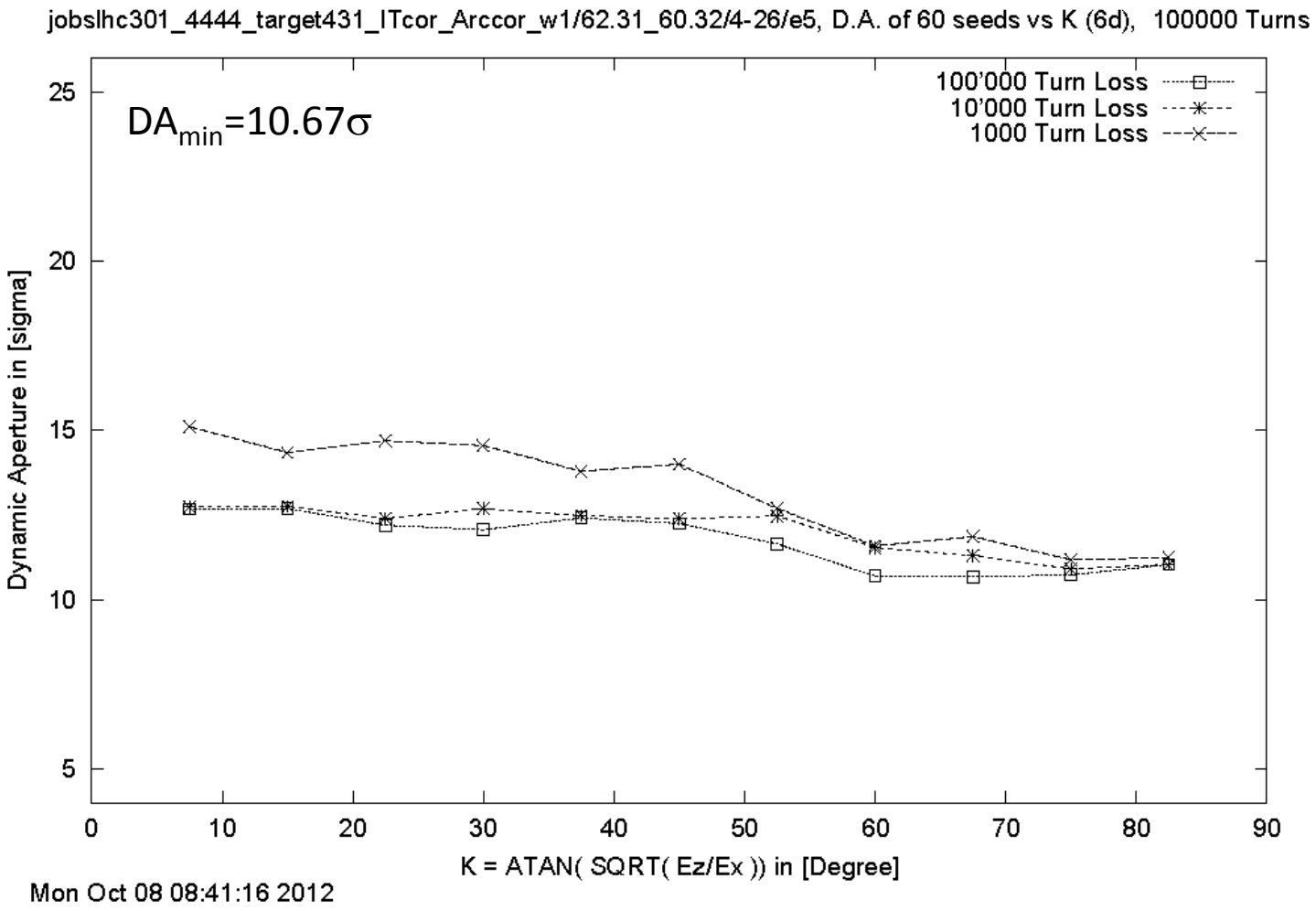


To maintain DA >10.6σ the B7 is set at 50%.
This is the currently the best obtained setting named “target431”.

Error table “target431” normalized to “target4” values (in %)

skew	uncertainty	rms		normal	uncertainty	rms
a3	100	100		b3	100	100
a4	100	100		b4	100	100
a5	20	20		b5	20	20
a6	20	20		b6	50	50
a7	100	50		b7	50	50
a8	100	50		b8	60	60
a9	100	50		b9	70	70
a10	100	50		b10	70	70
a11	100	50		b11	70	70
a12	100	50		b12	70	70
a13	100	50		b13	70	70
a14	100	50		b14	70	70

Dynamic aperture for error table “target431”



Summary

• Settings for the IT field error tolerances have been optimized using various scans of the field coefficients. It provides that all uncorrected coefficients are within 50-100% range of the desired field quality based on magnet design estimates. This setting assumes good quality correction of A5, B5, A6 terms.

• This work is in progress. More optimization scans will be done to further improve this solution.