
# Tracking Study of Triplet Field Quality in HL-LHC at Collision Energy

**Min-Huey Wang (SLAC)**

**Y. Cai, Y. Nosochkov (SLAC)**
**S. Fartoukh, M. Giovannozzi, R. de Maria, E. McIntosh (CERN)**

**Joint LARP CM20 / HiLumi Meeting 8—10 April 2013, Napa Valley, USA**

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 US Department of Energy contracts DE-AC02-07CH11359, DE-AC02-98CH10886, DE-AC02-05CH11231, and DE-AC02-76SF00515.

LARP

# Introduction

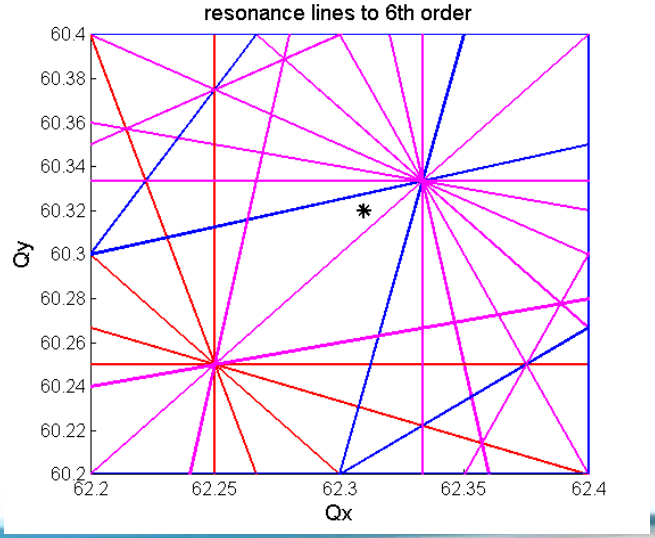
- Field error specifications for the inner triplet (IT) quadrupoles in the HL-LHC lattice at collision energy must be re-evaluated due to two major changes:
  - ✓ Beta functions in the IT quadrupoles at collision energy are significantly increased due to much lower $\beta^*$ functions at the IP1 and IP5.
  - ✓ New IT quadrupoles with 150 mm coil aperture will be installed.
- There are two major requirements for the IT field error specifications: 1) they must result in sufficient dynamic aperture (DA), and 2) they should be compatible with realistically achievable field quality.
- At the previous LHC-LARP meeting (Nov'12, Frascati), we presented the first optimized set of the IT field tolerances. This result corresponded to the earlier (June'12) prediction for the realistically achievable field quality in the IT.
- A new version of the achievable IT field quality was presented (by E. Todesco) at the Frascati meeting. This required re-optimization of our earlier result.
- Here, we present a re-optimized set of the IT field error tolerances based on the results of additional DA sensitivity study and taking into account the results of the earlier study.
- Lattice: SLHCV3.01, collision option "4444" with $\beta^*$=15/15 cm at IP1 and IP5, SC IT quadrupoles with 150 mm coil diameter and 120 T/m gradient, 7 TeV beam energy.
- Tracking code SixTrack.

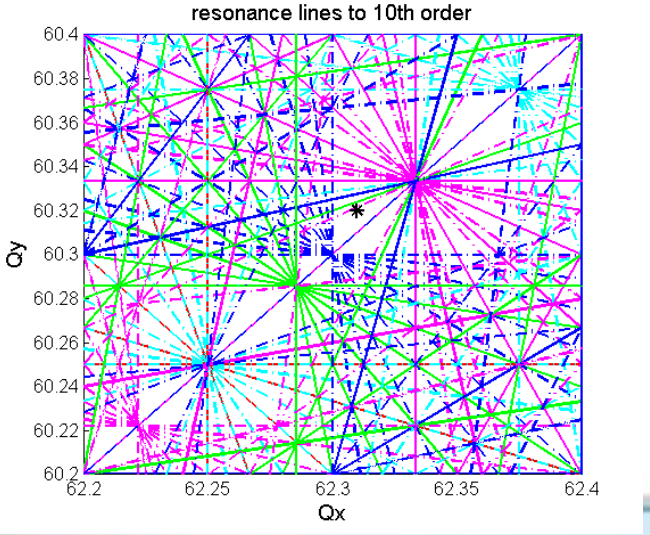
# Field errors

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

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

- The bn, an represent the n-th order "normal" and "skew" field components normalized to the main quad field at a given reference radius $r_0$ (in $10^{-4}$ units).
- In LHC, the an, bn are split in 3 terms: the "mean", the "uncertainty" (deviation from systematic), and the "random" terms. The uncertainty and random values in the specifications correspond to sigma of a cut Gaussian distribution.
- The an, bn values scale with reference radius as $b_n, a_n \propto r_0^{(n-2)}$
- The non-linear field errors excite high-order resonance effects limiting DA.
- The DA is very sensitive to the IT errors because of the very high IT beta functions.
- The DA is more sensitive to the low order IT errors. Therefore, the low-order resonance effects up to 6th order will be compensated using special IT correctors.



# Expected to achieve field quality in IT quadrupoles with 150 mm aperture at $r_0$ = 50 mm

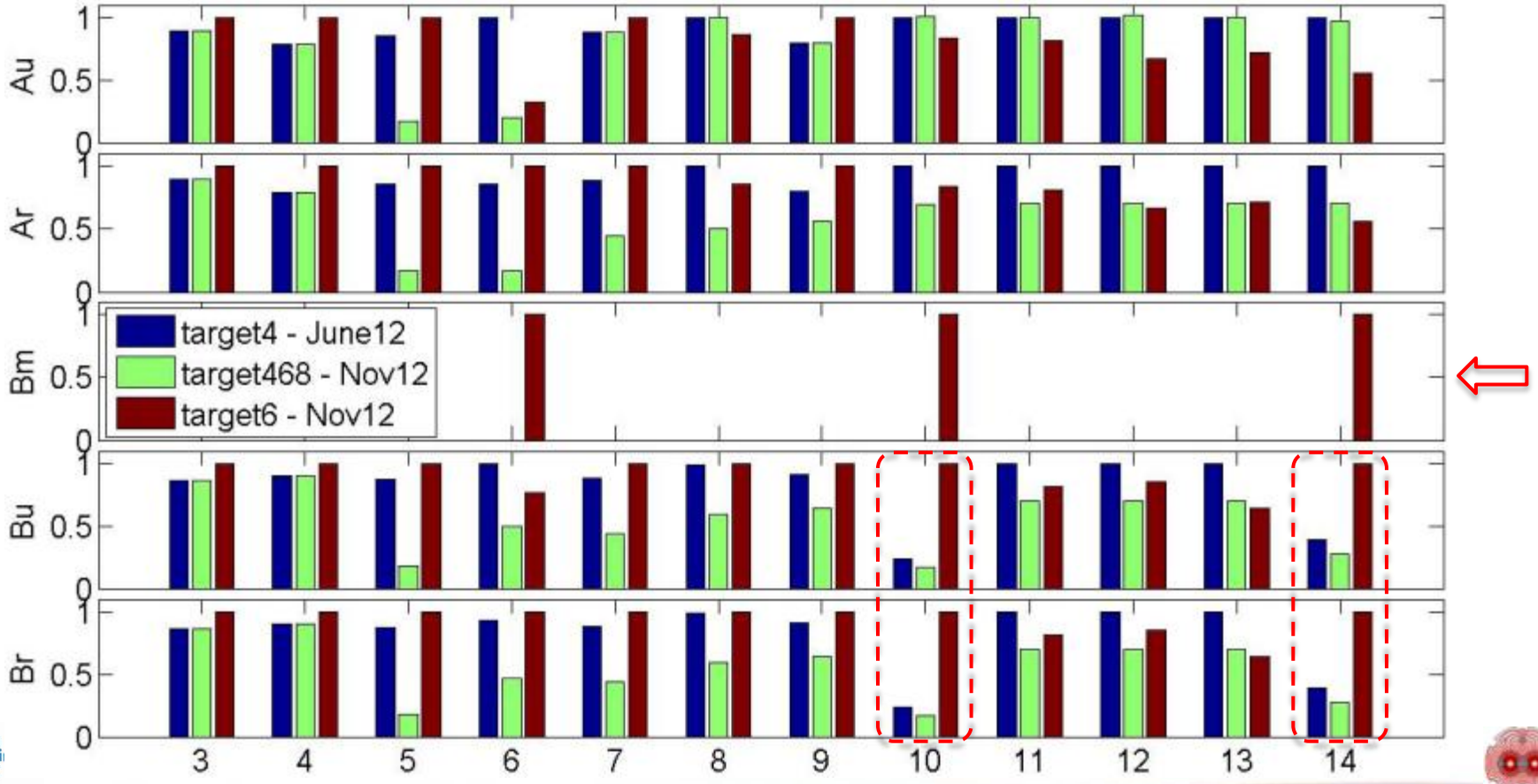
Presented by E. Todesco at the 2nd Joint HiLumi LHC-LARP Meeting, November 2012, Frascati
``FIELD QUALITY IN THE INNER TRIPLET AND IN THE SEPARATION DIPOLE''

This table will be further referred as error table "target6". The goal of the tracking study is to obtain sufficient DA with IT field errors close to this table values (or larger).

| skew | uncertainty | random | | normal | mean | uncertainty | random |
|---|---|---|---|---|---|---|---|
| a3 | 0.800 | 0.800 | | b3 | 0 | 0.820 | 0.820 |
| a4 | 0.650 | 0.650 | | b4 | 0 | 0.570 | 0.570 |
| a5 | 0.430 | 0.430 | | b5 | 0 | 0.420 | 0.420 |
| a6 | 0.310 | 0.310 | | b6 | 0.800 | 1.100 | 1.100 |
| a7 | 0.190 | 0.190 | | b7 | 0 | 0.190 | 0.190 |
| a8 | 0.110 | 0.110 | | b8 | 0 | 0.130 | 0.130 |
| a9 | 0.080 | 0.080 | | b9 | 0 | 0.070 | 0.070 |
| a10 | 0.040 | 0.040 | | b10 | 0.150 | 0.200 | 0.200 |
| a11 | 0.026 | 0.026 | | b11 | 0 | 0.026 | 0.026 |
| a12 | 0.014 | 0.014 | | b12 | 0 | 0.018 | 0.018 |
| a13 | 0.010 | 0.010 | | b13 | 0 | 0.009 | 0.009 |
| a14 | 0.005 | 0.005 | | b14 | -0.040 | 0.023 | 0.023 |

# Comparison with error tables from the previous study

"target4" – previous version of expected to achieve field error table (June'12).
"target468" – previous optimized field error tolerance table satisfying DA (before Nov'12).
Main features of the "target6" table: 1) non-zero b6m, b10m, b14m (mean values); 2) significantly increased b10, b14 ("allowed" multipoles); 3) mostly higher low order terms (for which IT correction exists); 4) mostly lower high order terms (uncorrected).



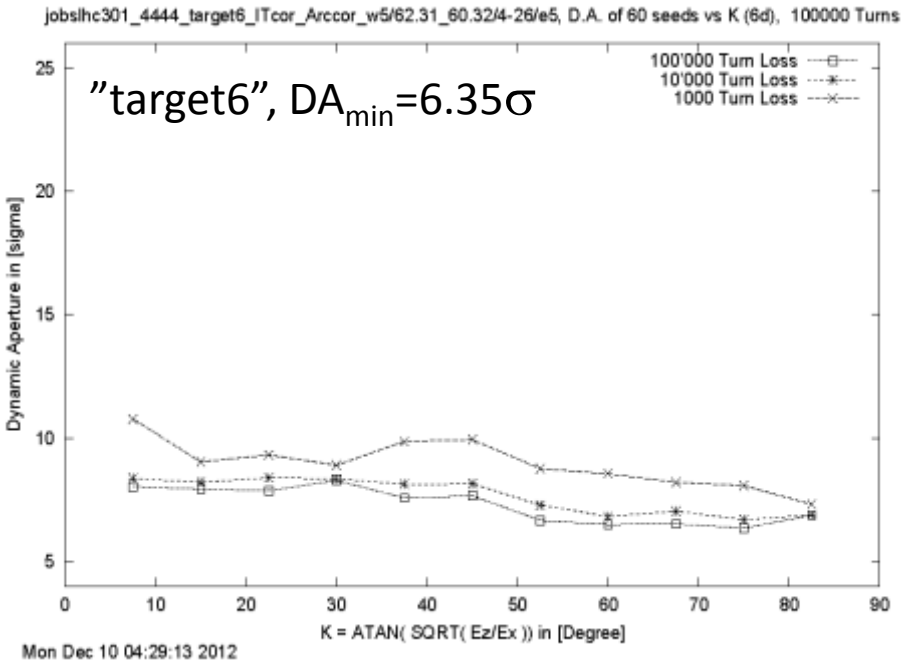
# Optimization strategy

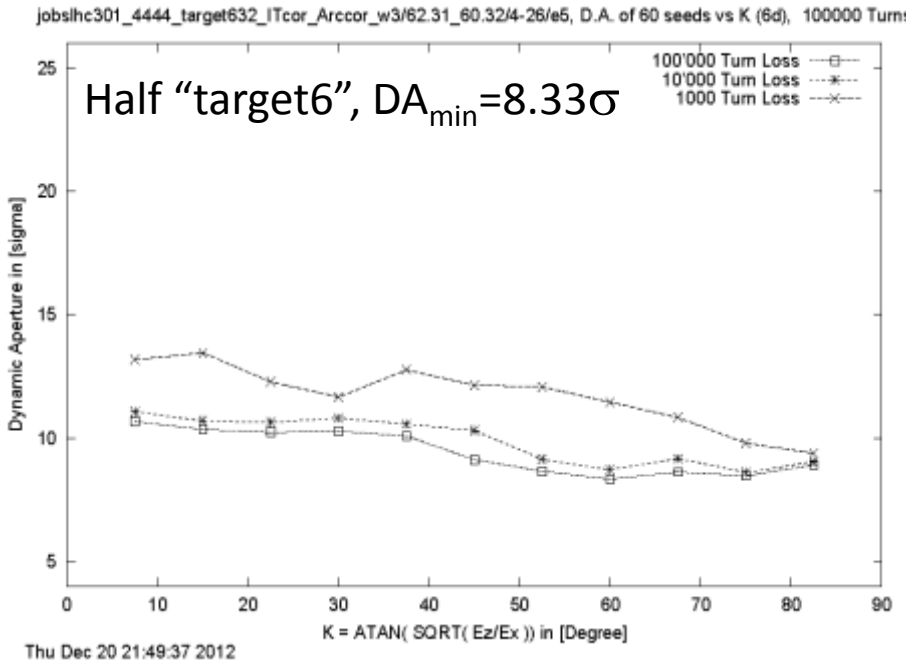
- The desired goal is to maximize field error tolerances towards the values in the error table “target6” while providing sufficient DA.
- Based on the earlier study, we realize that it may not be possible to reach the “target6” level for all an, bn coefficients. Therefore we set the minimum allowed level of an, bn tolerances to 50% of the “target6” values. However, we will maximize the tolerances where possible.
- Similar to the previous study, we set the acceptable minimum DA over 60 seeds of random errors to about 10.5$\sigma$ for the design 3.75 $\mu$m-rad emittance. Note that this corresponds to about 13$\sigma$ if the HL-LHC emittance will be 2.5 $\mu$m-rad as predicted.
- The table “target6” is used as the new basis for optimization. Therefore, we redo some of the DA sensitivity scans around the values in this table, especially for the new larger coefficients.
- Results of the previous optimization study are used for faster convergence to optimal solution. The final optimized set of the field error tolerances combines the results of the new study and the earlier study.

# Standard set-up for SixTrack tracking

- 100,000 turns
- 60 random error seeds
- 30 particle pairs per amplitude step ($2\sigma$)
- 11 angles
- 7 TeV beam energy
- Initial $\Delta p/p$ = 2.7e-4
- Tune = 62.31, 60.32
- Normalized emittance = 3.75 $\mu$m-rad
- Arc errors and correction are included
- IT correctors to compensate a3, b3, a4, b4, b6 errors are included
- IT correctors for a5, b5, a6 errors are not included in this lattice SLHCV3.01. To simulate this correction, we assume that a5, b5, a6 errors are residual (smaller) errors after correction. Note: the a5, b5, a6 correctors are currently being studied in detail for a different lattice layout SLHCV3.1b (M. Giovannozzi, et al).
- No field errors in D1, D2 separation dipoles and Q4 quadrupoles

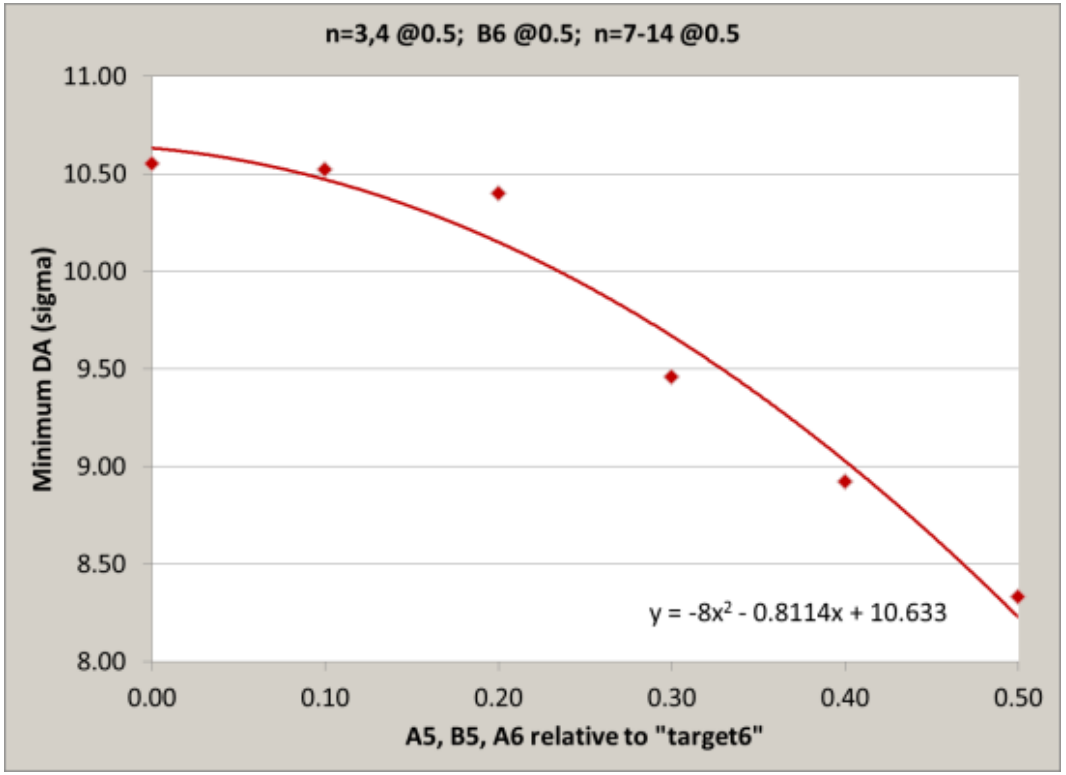
# Dynamic aperture at full and half values of “target6” coefficients



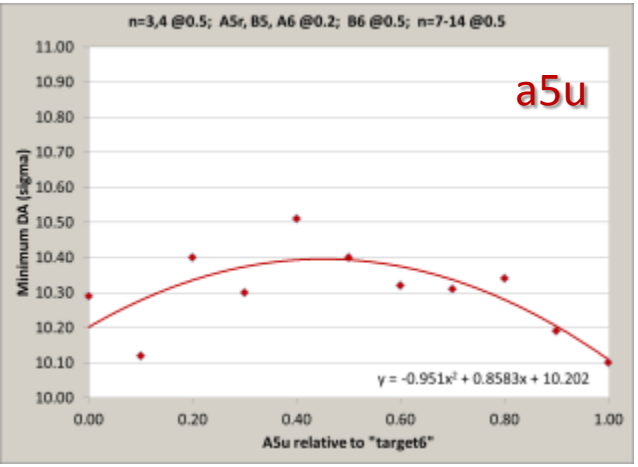

- We first test DA at full and half-values of table “target6”. These plots show minimum DA as a function of angle.
- The DA is well below the desired 10.5σ even at half values of “target6”.
- As a first step, we need to study correction of a5, b5, a6 terms. These IT correctors are not implemented in this lattice SLHCV3.01. To simulate the correction, we allow smaller a5, b5, a6 terms assuming they are residual values after correction. Then we scan them to determine the required values.

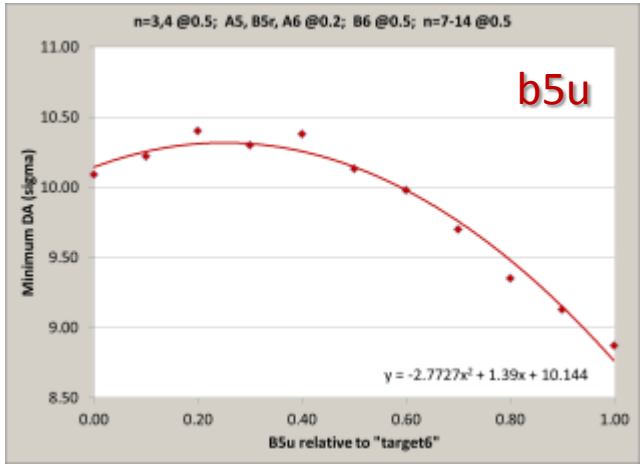
# DA sensitivity to combined scan of a5, b5, a6

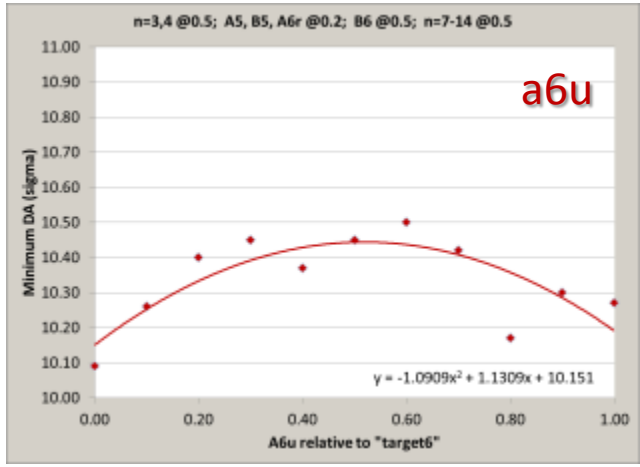


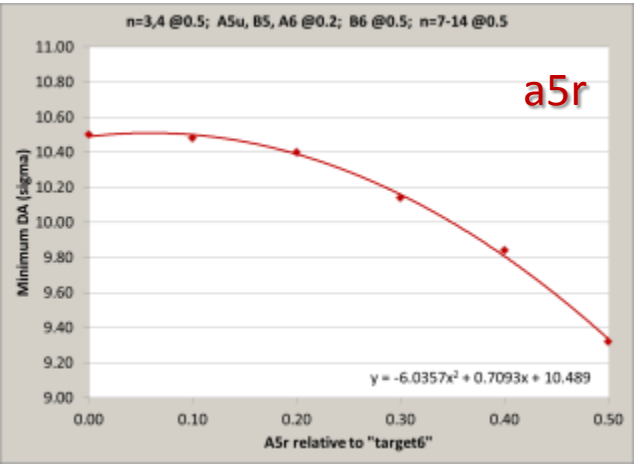

- In this scan, all other an, bn coefficients are set to half-values of “target6” table.
- Conclusion: the effective residual a5, b5, a6 values (after correction) should be near 0.2 level relative to “target6” values. The actual a5, b5, a6 magnet error tolerances (before correction) will be higher.
- In all the following scans we set the a5, b5, a6 terms to 0.2 relative to “target6” and the other an, bn terms to 0.5.

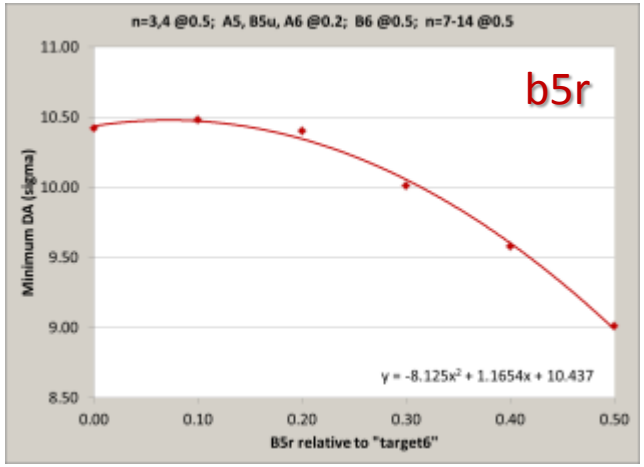
# Scan of “uncertainty” and “random” parts of a5, b5, a6

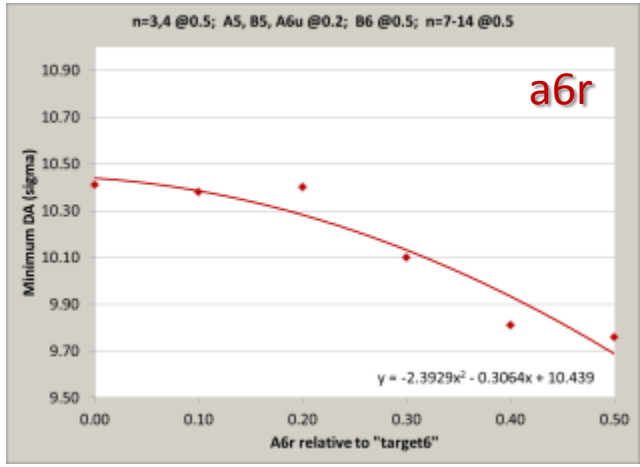


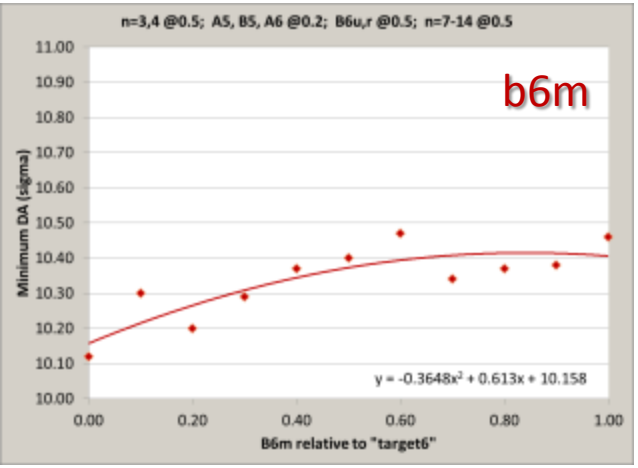



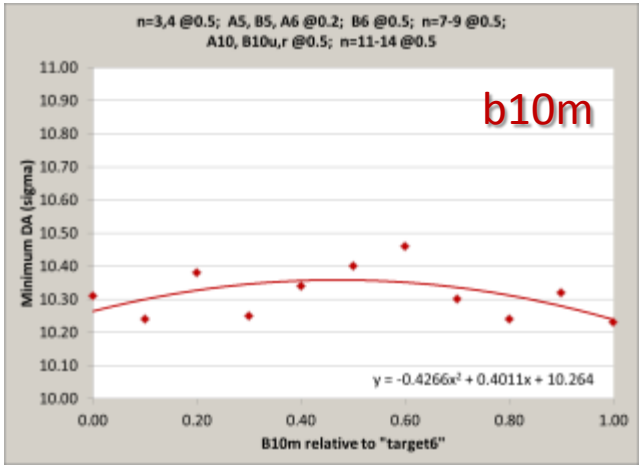



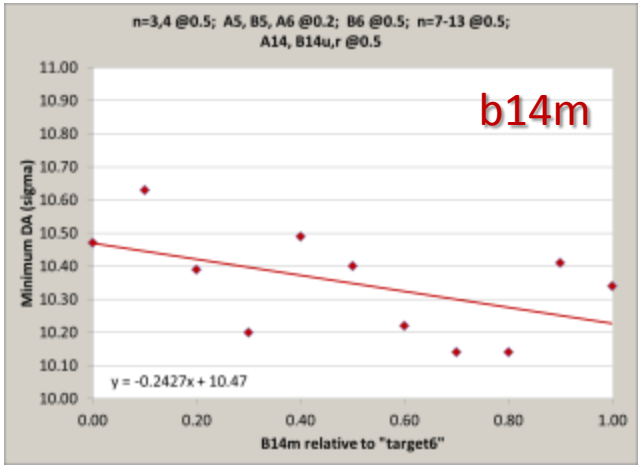



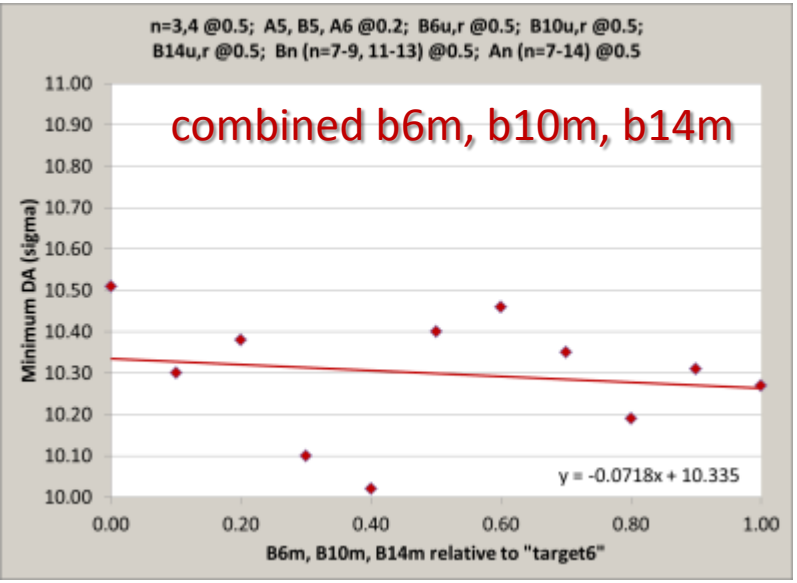

- DA is more sensitive to the random components and b5u.
- Conclusion: the residual a5r, b5u, b5r, a6r should stay at 0.2 level (relative to “target6”), and a5u, a6u may be somewhat relaxed.

# Sensitivity to b6m, b10m, b14m



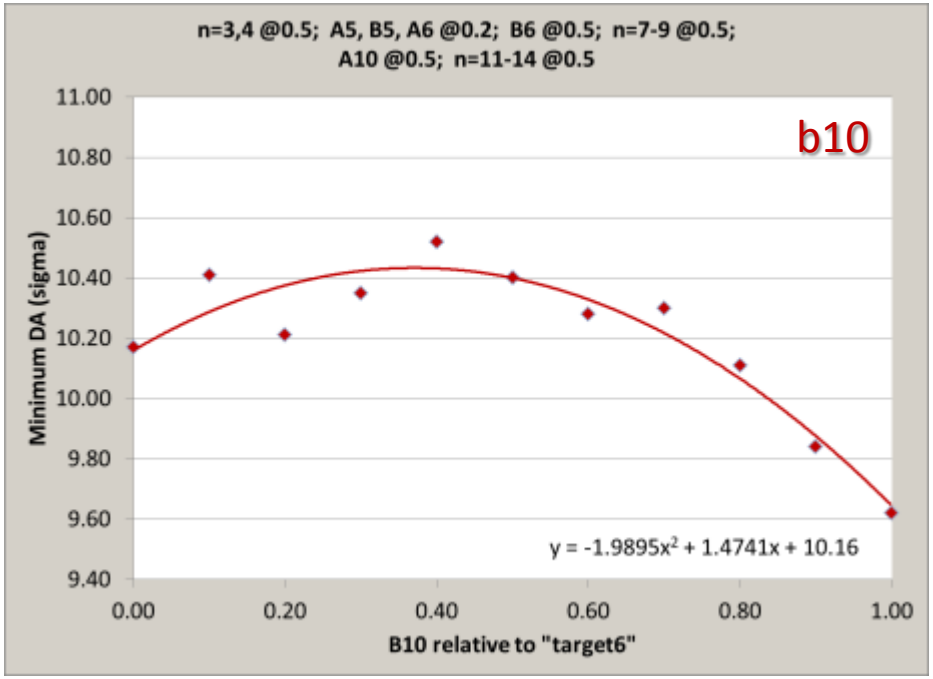



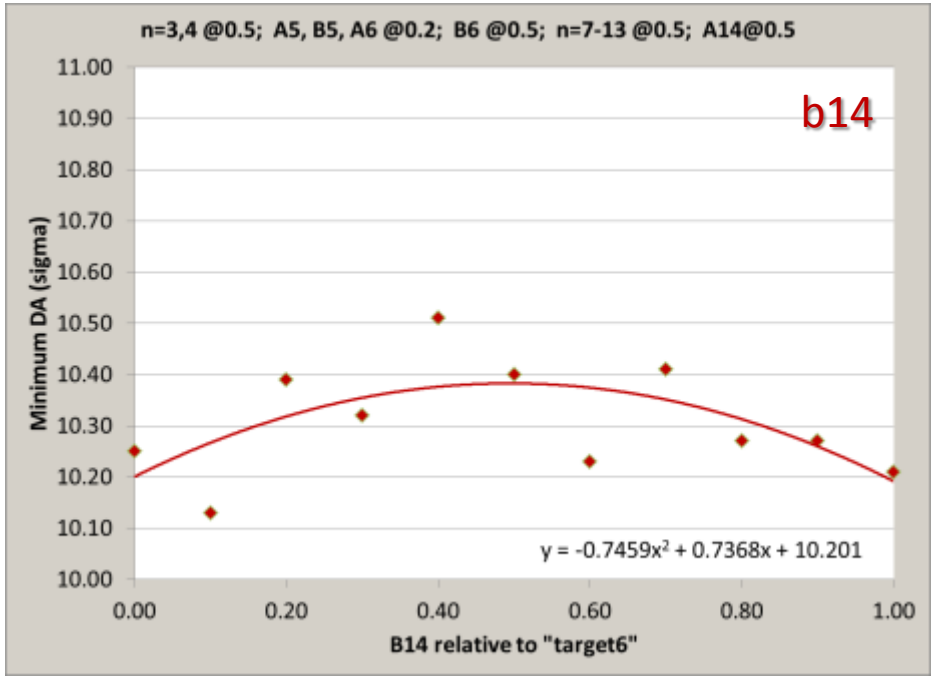




- Table "target6" introduces non-zero "mean" components for the "allowed" multipoles b6, b10, b14.
- DA is not very sensitive to b6m in this range due to the IT correction.
- DA starts decreasing when b10m, b14m > 0.5 level.
- Conclusion: b6m tolerance may be relaxed to up to 1.0 level (relative to "target6"); the b10m, b14m should be at 0.5 level or slightly above.

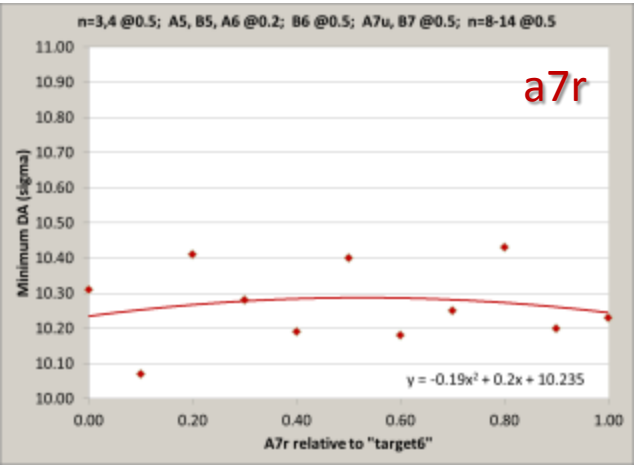
# Scan of b10 and b14 (combined mean, uncertainty and random terms)

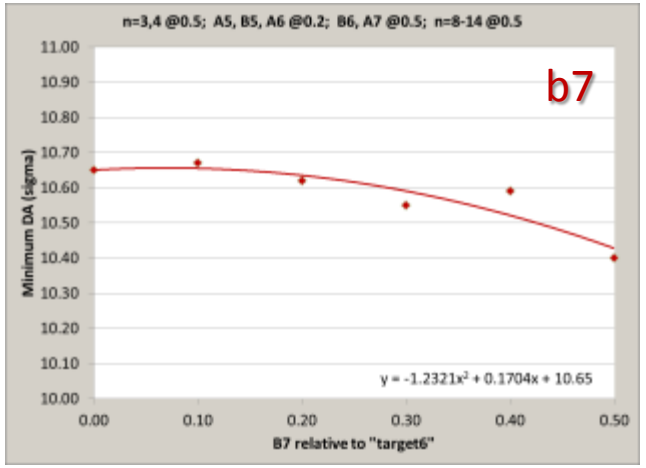


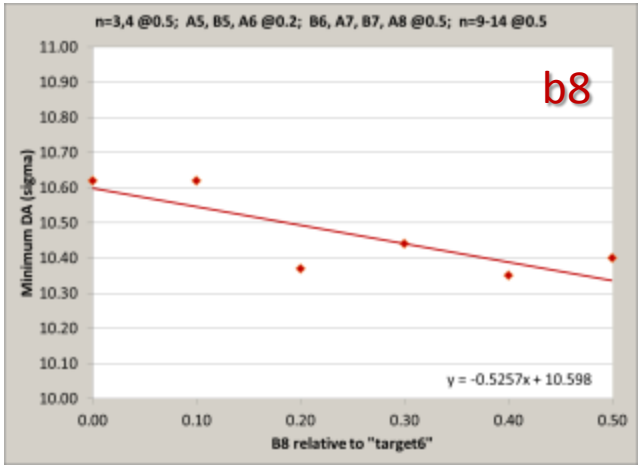



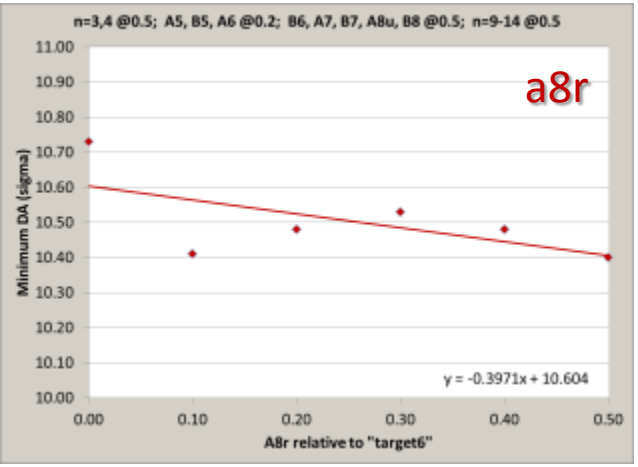

- The predicted b10, b14 uncertainty and random components in the table "target6" are several times higher relative to the previous prediction.
- DA decreases for b10 and b14 above 0.5 level.
- Conclusion: b10, b14 tolerances should be near 0.5 level relative to "target6".

# Sensitivity to anr, bn for n=7,8



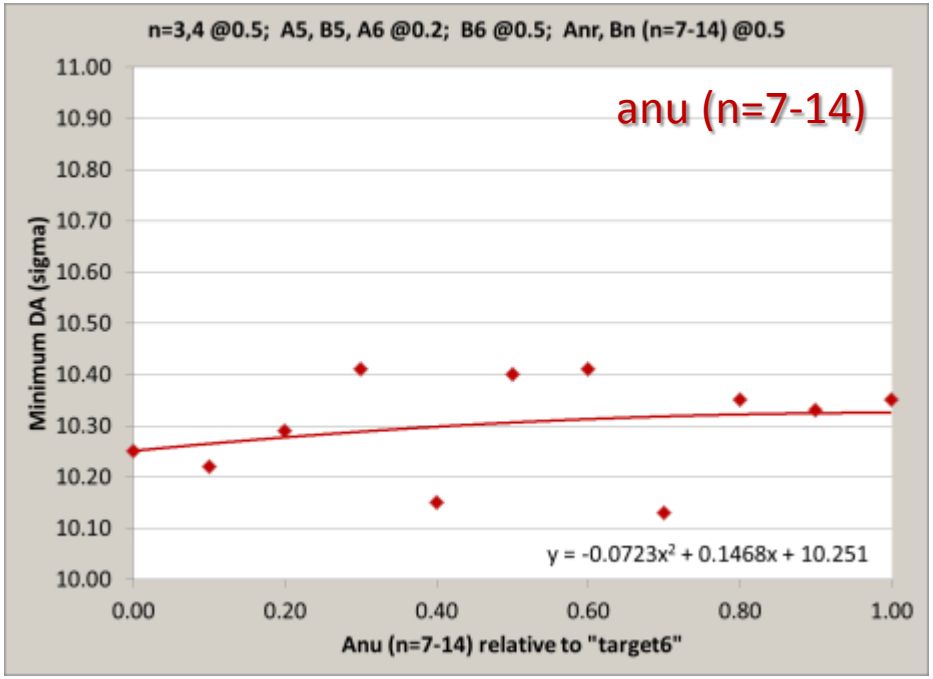



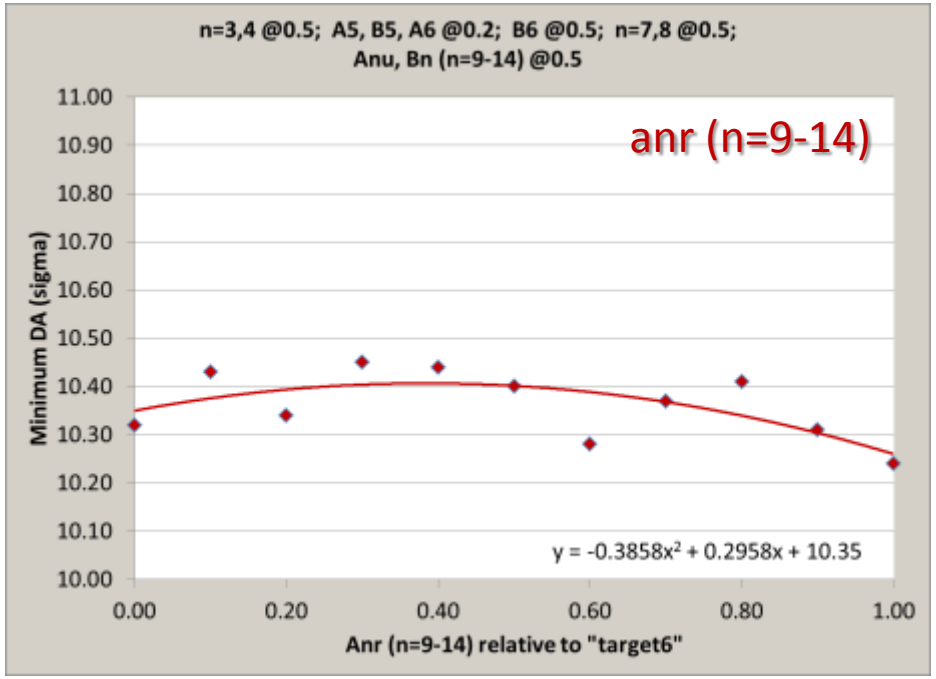




- DA is decreasing with a8r, b7 and b8.
- Conclusion: a8r, b7, b8 tolerances should stay at the minimum allowed level of 0.5; a7r may be somewhat relaxed depending on final DA.

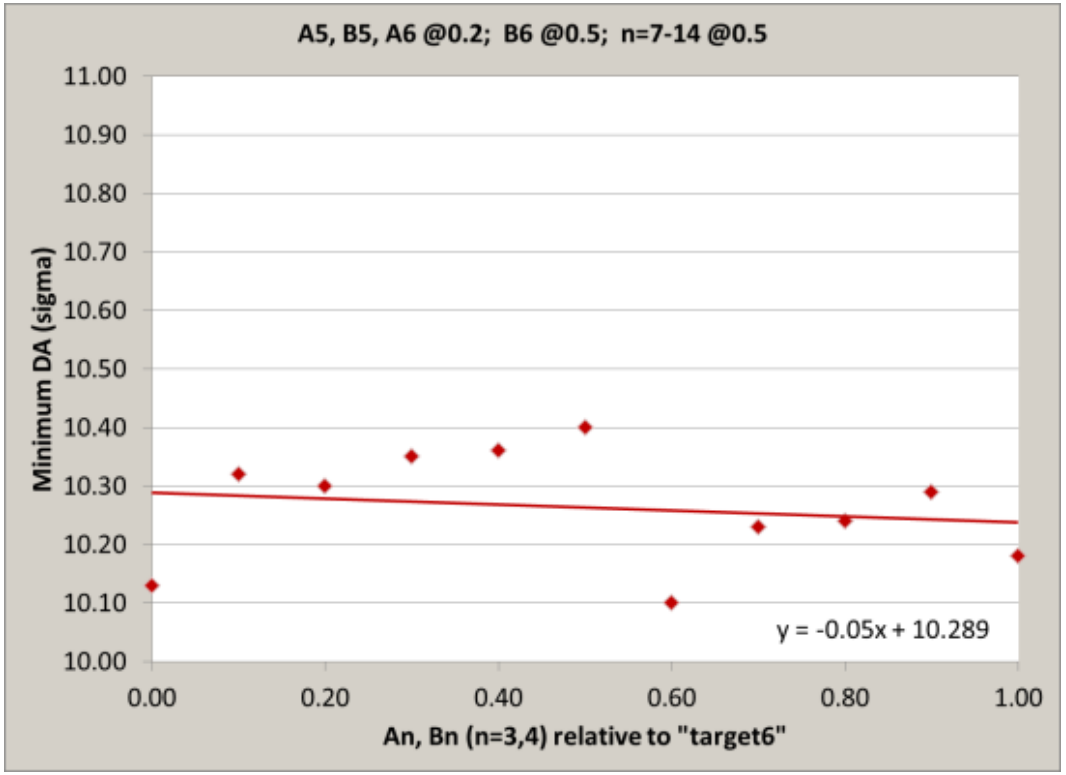
# Sensitivity to high order anu and anr




- This scan confirms the results of earlier studies that DA is not very sensitive to high order an terms.
- Conclusion: tolerances for high order an may be set to the level of 0.8-1.0 relative to “target6”.

# Sensitivity to the lowest order an, bn (n=3,4)




- The n=3,4 errors are compensated with the IT correctors. As a result, the DA is not very sensitive to these terms in agreement with the previous study.
- Conclusion: n=3,4 error tolerances may be set to the level of up to 1.0 relative to “target6”.

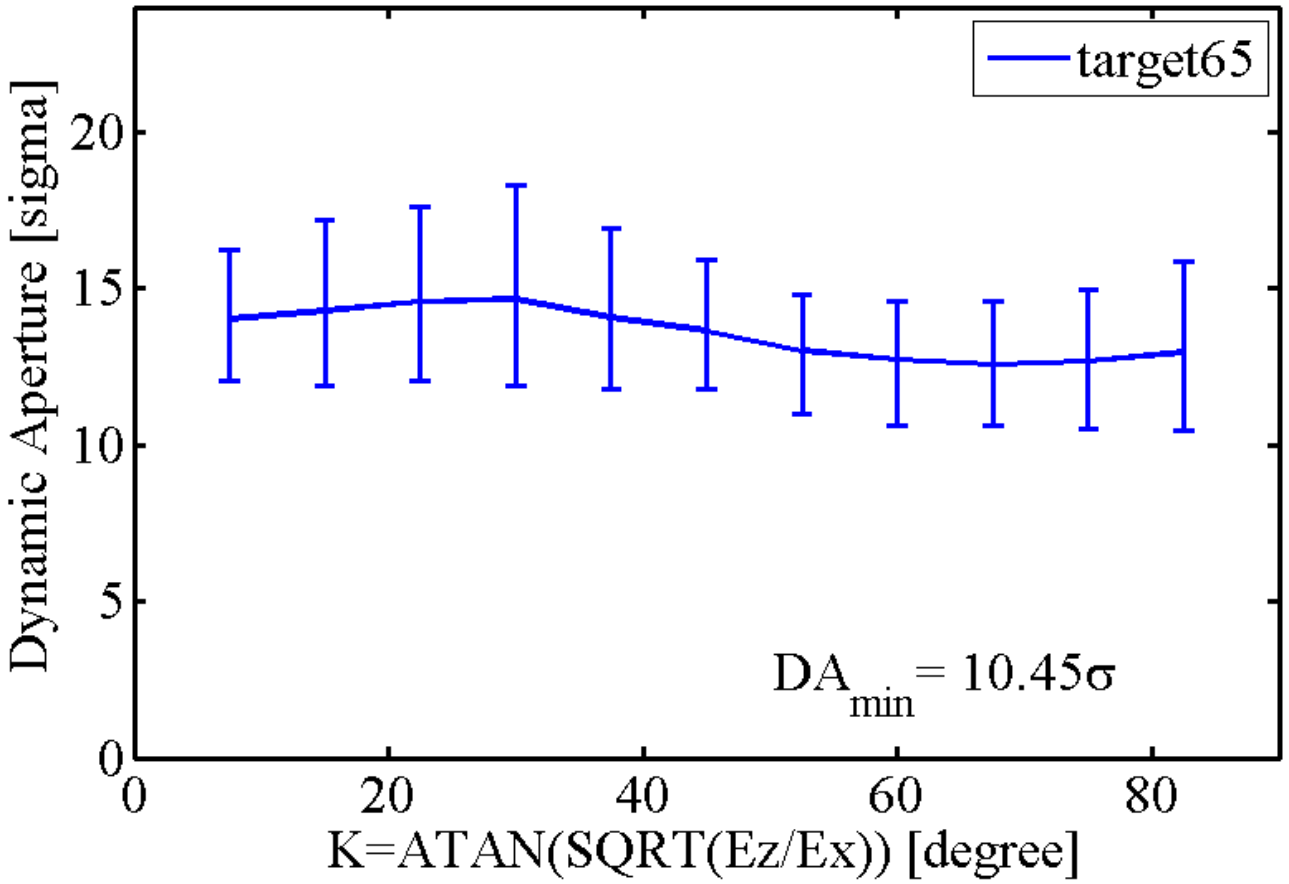
# Presently best IT error tolerance table "target65" (normalized to "target6" values) with $DA_{min} \approx 10.5\sigma$

| skew | uncertainty | random | | normal | mean | uncertainty | random |
|---|---|---|---|---|---|---|---|
| a3 | 1.0 | 1.0 | | b3 | -- | 1.0 | 1.0 |
| a4 | 1.0 | 1.0 | | b4 | -- | 1.0 | 1.0 |
| a5* | 0.2 | 0.2 | | b5* | -- | 0.2 | 0.2 |
| a6* | 0.5 | 0.2 | | b6 | 1.0 | 0.5 | 0.5 |
| a7 | 0.8 | 0.5 | | b7 | -- | 0.5 | 0.5 |
| a8 | 0.8 | 0.5 | | b8 | -- | 0.5 | 0.5 |
| a9 | 0.8 | 0.5 | | b9 | -- | 0.5 | 0.5 |
| a10 | 1.0 | 0.8 | | b10 | 0.5 | 0.5 | 0.5 |
| a11 | 1.0 | 0.8 | | b11 | -- | 0.8 | 0.8 |
| a12 | 1.0 | 1.0 | | b12 | -- | 0.8 | 0.8 |
| a13 | 1.0 | 1.0 | | b13 | -- | 0.8 | 0.8 |
| a14 | 1.0 | 1.0 | | b14 | 0.5 | 0.5 | 0.5 |

These settings combine the results of the latest sensitivity study and the optimized values in table "target468" from the previous study.

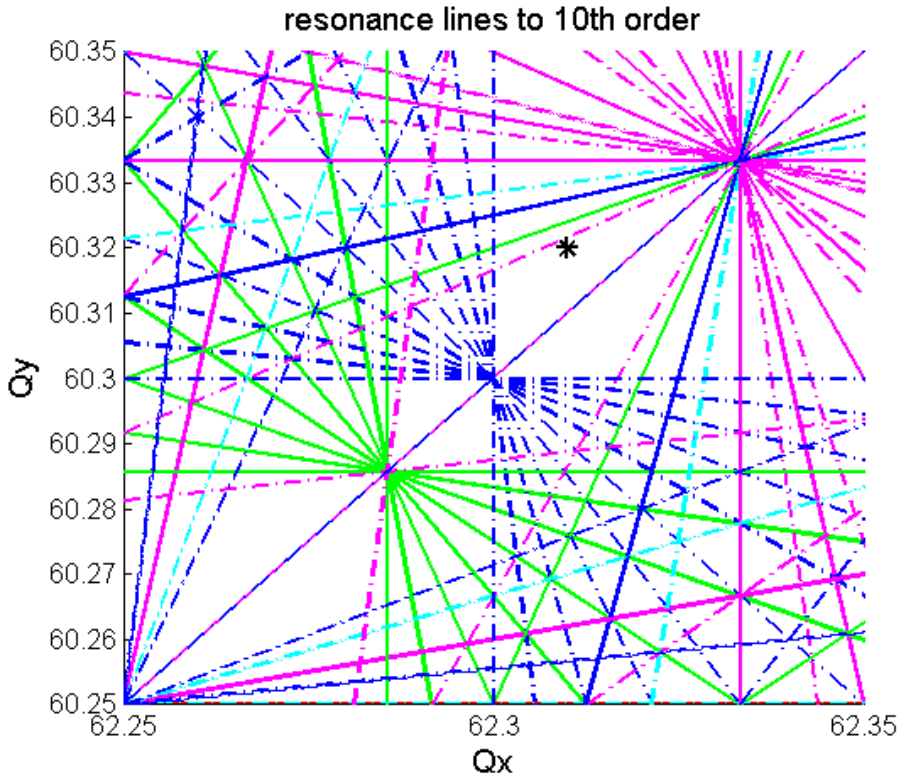
* a5, b5, a6 terms in the table are effective residual errors after correction. The actual a5, b5, a6 in the IT quadrupoles will be higher.

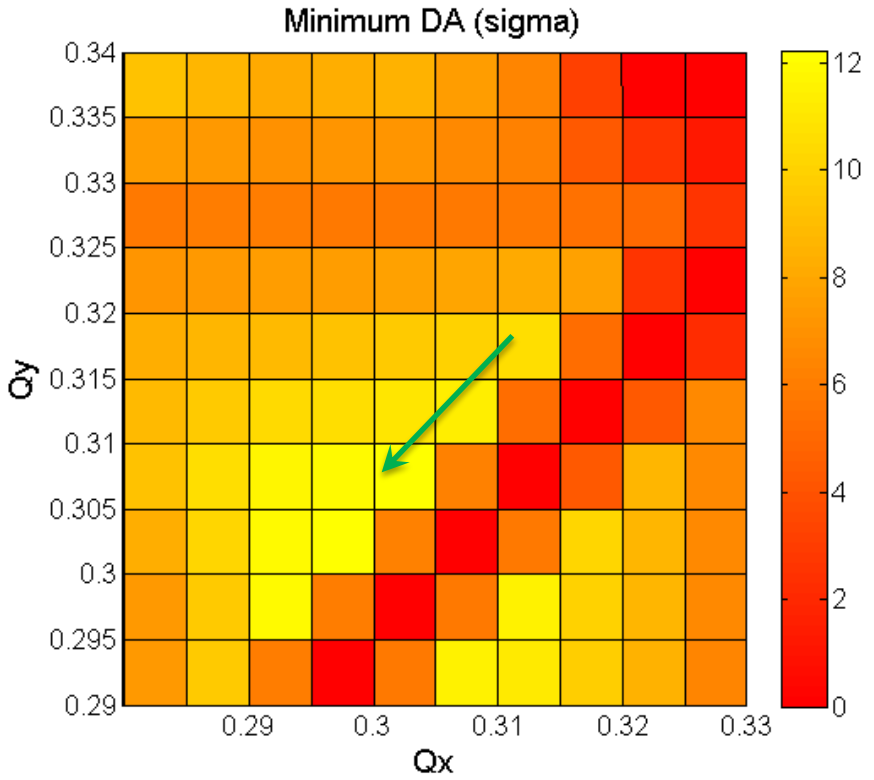
# Dynamic aperture for IT error table “target65”




The line shows an average DA as a function of angle.
Vertical bars show range of DA for 60 seeds at each angle.

# Test of DA sensitivity to working tune (w/o beam-beam effects)




- This is a preliminary test. The simulation does not include beam-beam effects, and the SixTrack may not maintain optimal phase conditions at ATS sextupoles when the tune is scanned.
- It indicates an operational flexibility for improving the DA by optimizing the tune. In this case, the DA is improved by moving the tune farther from the 3rd order resonance crossing point.
- However, to verify this conclusion, a more accurate scan needs to be done including beam-beam effects and proper conditions at the ATS sextupoles.

# Summary

- Field error tolerances for 150 mm aperture IT quadrupoles in the SLHCV3.01 lattice have been re-optimized with respect to the latest “expected to achieve” error table “target6”.
- The resultant optimized error table “target65” provides minimum DA of ≈10.5σ at 3.75 μm-rad normalized emittance.
- The lowest and highest order error tolerances are set to near the desired values of the “target6” table due to the IT correction and lower DA sensitivity, respectively.
- The most sensitive terms are set to half-value of the “target6” table.
- The required level of a5, b5, a6 correction has been determined. These correctors are currently being studied in detail for a different lattice layout SLHCV3.1b.
- A preliminary tune scan without beam-beam effects indicates that DA may be improved by optimizing the working point. This would add operational flexibility for improving the DA. However, to make a final conclusion, the beam-beam effects must be included in the simulation.

# Back-up slides

# Optimized IT field error table "target65" at $r_0$ = 50 mm

| skew | uncertainty | random | | normal | mean | uncertainty | random |
|---|---|---|---|---|---|---|---|
| a3 | 0.800 | 0.800 | | b3 | 0 | 0.820 | 0.820 |
| a4 | 0.650 | 0.650 | | b4 | 0 | 0.570 | 0.570 |
| a5* | 0.086 | 0.086 | | b5* | 0 | 0.084 | 0.084 |
| a6* | 0.155 | 0.062 | | b6 | 0.800 | 0.550 | 0.550 |
| a7 | 0.152 | 0.095 | | b7 | 0 | 0.095 | 0.095 |
| a8 | 0.088 | 0.055 | | b8 | 0 | 0.065 | 0.065 |
| a9 | 0.064 | 0.040 | | b9 | 0 | 0.035 | 0.035 |
| a10 | 0.040 | 0.032 | | b10 | 0.075 | 0.100 | 0.100 |
| a11 | 0.026 | 0.021 | | b11 | 0 | 0.021 | 0.021 |
| a12 | 0.014 | 0.014 | | b12 | 0 | 0.0144 | 0.0144 |
| a13 | 0.010 | 0.010 | | b13 | 0 | 0.0072 | 0.0072 |
| a14 | 0.005 | 0.005 | | b14 | -0.020 | 0.0115 | 0.0115 |

* a5, b5, a6 terms in the table are effective residual errors after correction. The actual a5, b5, a6 in the IT quadrupoles will be higher.

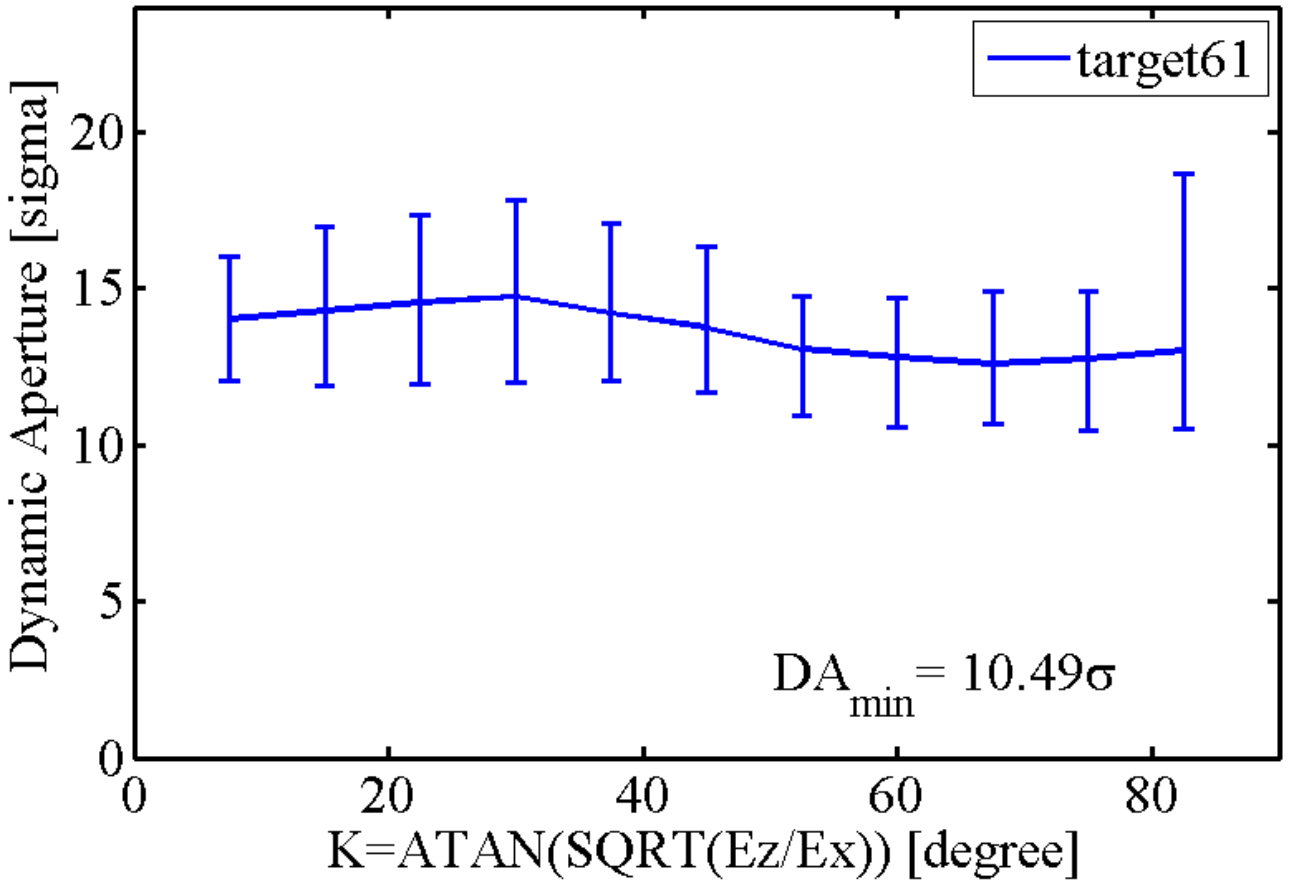
# Second option: IT field error table "target61" at $r_0$ = 50 mm

| skew | uncertainty | random | | normal | mean | uncertainty | random |
|---|---|---|---|---|---|---|---|
| a3 | 0.640 | 0.640 | | b3 | 0 | 0.656 | 0.656 |
| a4 | 0.520 | 0.520 | | b4 | 0 | 0.456 | 0.456 |
| a5* | 0.086 | 0.086 | | b5* | 0 | 0.084 | 0.084 |
| a6* | 0.155 | 0.062 | | b6 | 0.400 | 0.550 | 0.550 |
| a7 | 0.152 | 0.095 | | b7 | 0 | 0.095 | 0.095 |
| a8 | 0.088 | 0.055 | | b8 | 0 | 0.065 | 0.065 |
| a9 | 0.064 | 0.040 | | b9 | 0 | 0.035 | 0.035 |
| a10 | 0.040 | 0.032 | | b10 | 0.075 | 0.100 | 0.100 |
| a11 | 0.026 | 0.021 | | b11 | 0 | 0.021 | 0.021 |
| a12 | 0.014 | 0.014 | | b12 | 0 | 0.0144 | 0.0144 |
| a13 | 0.010 | 0.010 | | b13 | 0 | 0.0072 | 0.0072 |
| a14 | 0.005 | 0.005 | | b14 | -0.020 | 0.0115 | 0.0115 |

The n=3,4 and b6m terms are lower than in the table "target65".

* a5, b5, a6 terms in the table are effective residual errors after correction. The actual a5, b5, a6 in the IT quadrupoles will be higher.

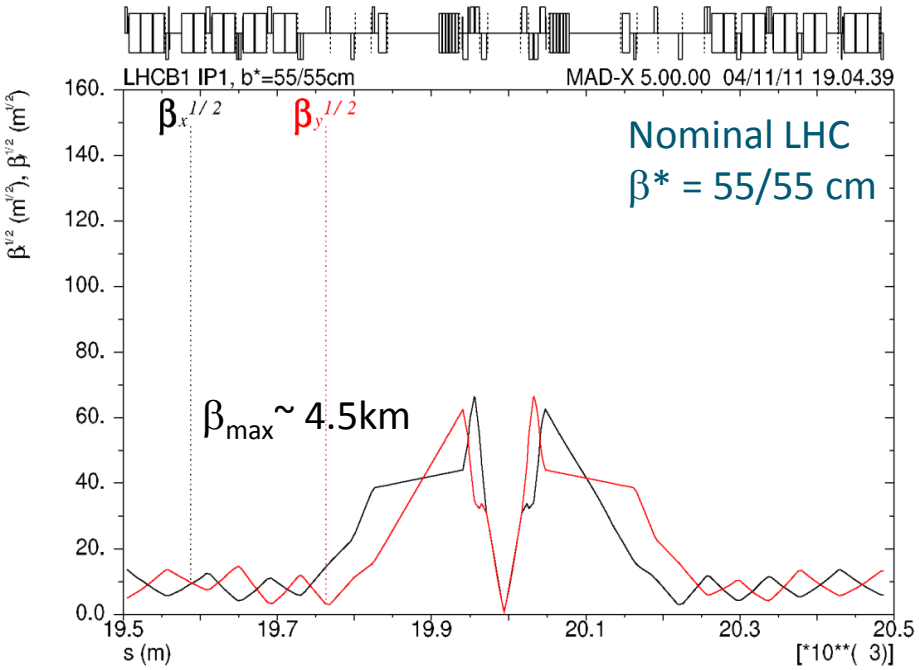
# Dynamic aperture for IT error table “target61”

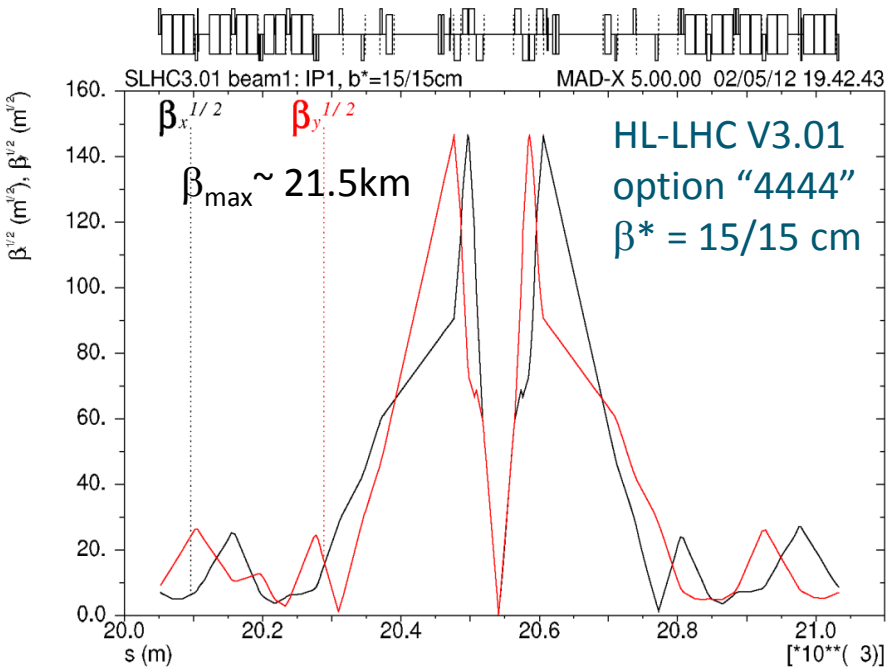



The line shows an average DA as a function of angle.
Vertical bars show range of DA for 60 seeds at each angle.

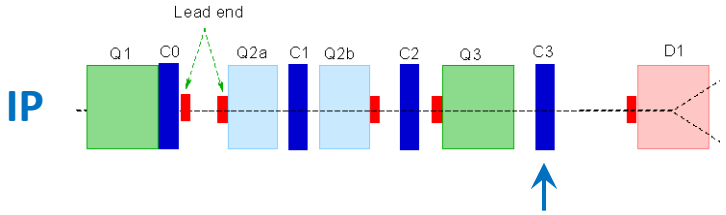
# Triplet β-functions in the HL-LHC

- High IT β-functions increase the non-linear effects of triplet field errors on DA.
- 150 mm IT quadrupoles will provide the necessary aperture for larger beam in the triplet and help relaxing the field tolerances.



# Triplet non-linear field correctors




**a3, b3, a4, b4, b6 correctors**

The a3, b3, a4, b4, b6 correctors compensate the corresponding IT field errors thus relaxing the tolerances. The a5, b5, a6 correctors are also planned to be implemented.