SLAC NATIONAL ACCELERATOR LABORATORY

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

Yuri Nosochkov

Y. Cai, Y. Jiao, M-H. Wang (SLAC)

S. Fartoukh, M. Giovannozzi, R. de Maria, E. McIntosh (CERN)

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# Outline

• Perform scaling of the measured field of the nominal LHC inner triplet (IT) quadrupoles to large aperture IT quadrupoles in the HL-LHC lattice.

• Determine dynamic aperture (DA) sensitivity to the IT field errors in the HL-LHC lattice using long term tracking.

• Specify field error tolerances for large aperture IT quadrupoles based on the DA sensitivities.

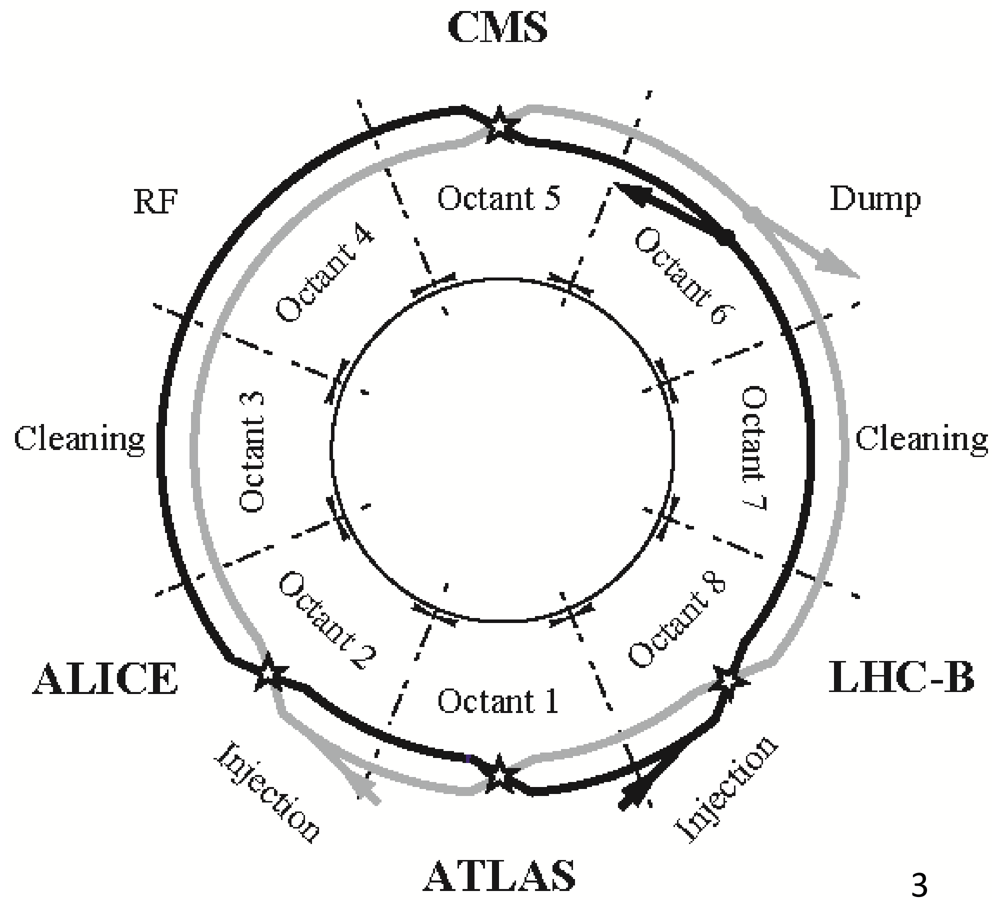
**Lattice:** HL-LHC V3.01, collision option “4444” with $\beta^*$=15/15 cm at IP1 and IP5, Nb-Ti superconducting IT quadrupoles with 120 mm coil diameter and 120 T/m gradient, 7 TeV beam energy.

**Code:** SixTrack.

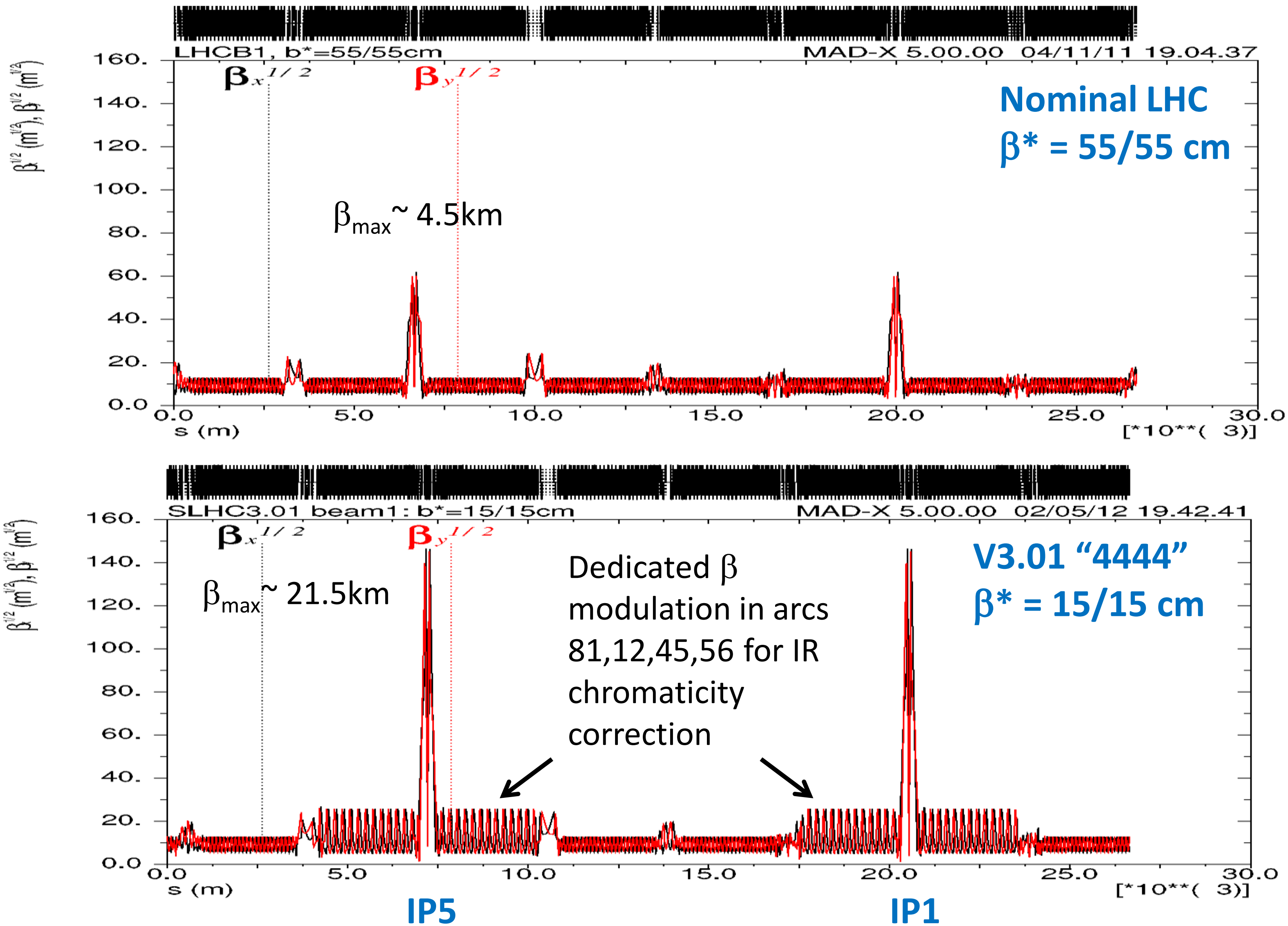
# Impact of low-β*

The HL-LHC V3.01 collision lattice has lower than nominal β* at IP1 (ATLAS) and IP5 (CMS) crossing points resulting in higher β-functions (~1/β*) in the IT quadrupoles. Large aperture IT quadrupoles with coil diameter of 120-150 mm are proposed to accommodate a larger beam size. A dedicated large β-modulation in the adjacent arcs is used for local cancelation of the IT non-linear chromaticity.

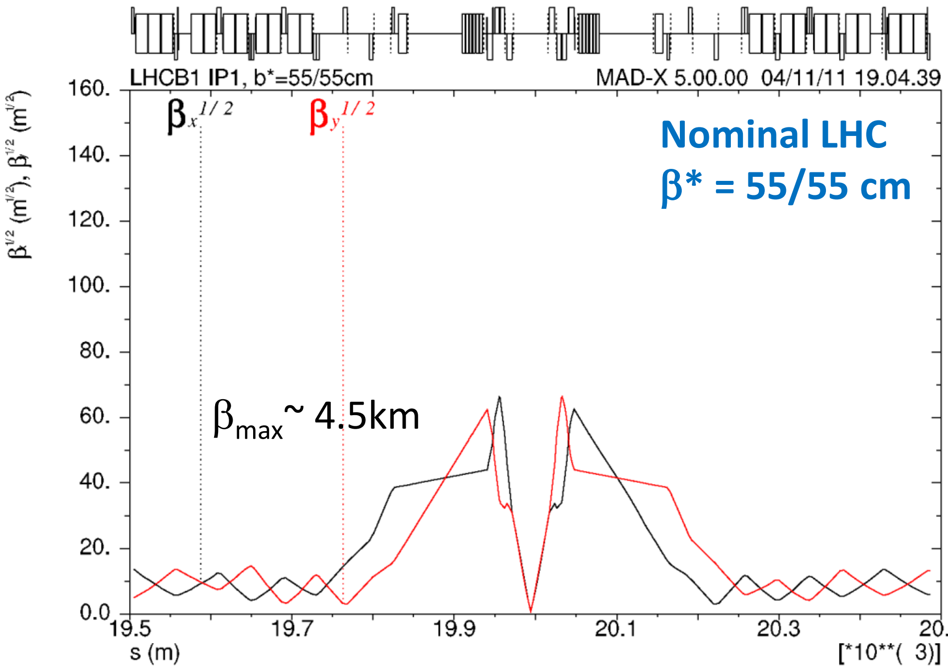
**Impact:** High β-functions in the triplet and adjacent arcs amplify the effects of IT errors and sextupole aberrations causing reduction of dynamic aperture. Crossing angle orbit in the IT quadrupoles further amplifies the field errors. **New tolerances on the triplet field errors need to be specified for an acceptable DA in collision.**

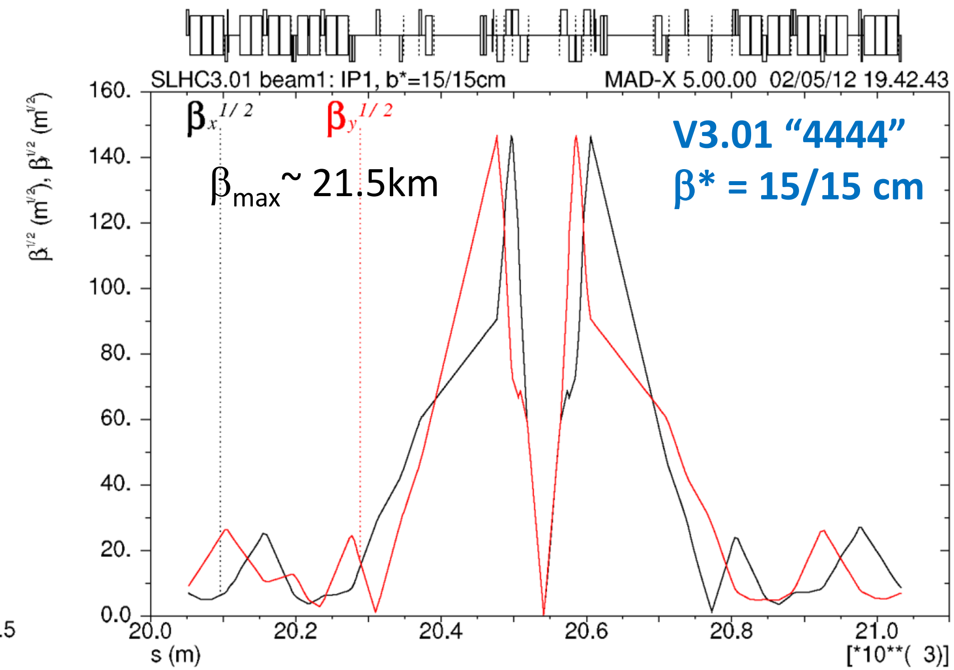


# Beta functions: Nominal LHC versus V3.01 “4444”

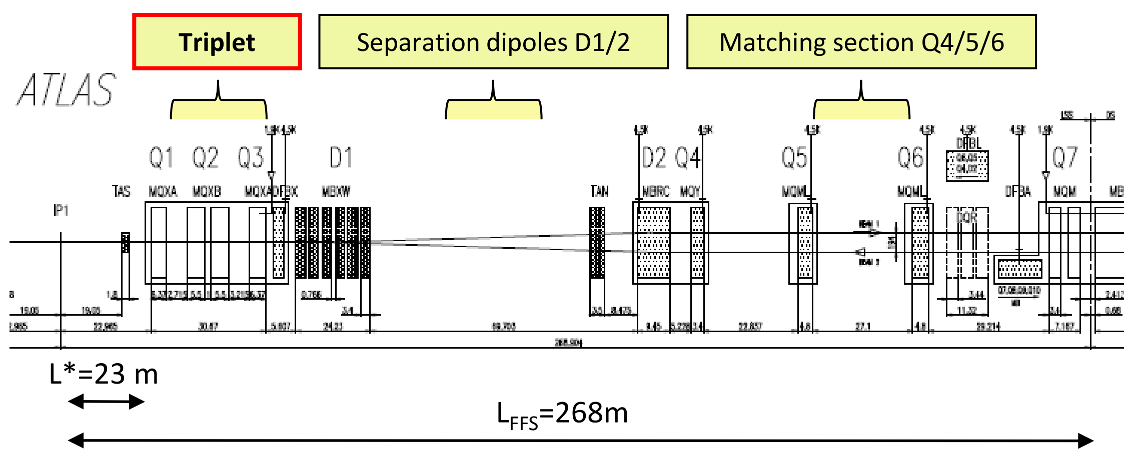


# Interaction Region: Nominal LHC versus V3.01 “4444”



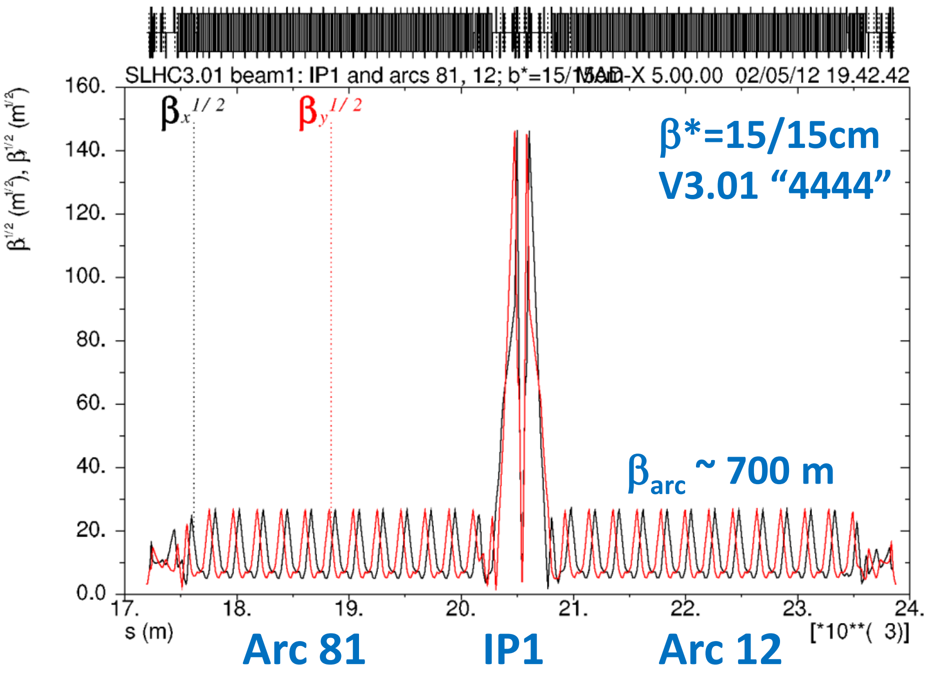



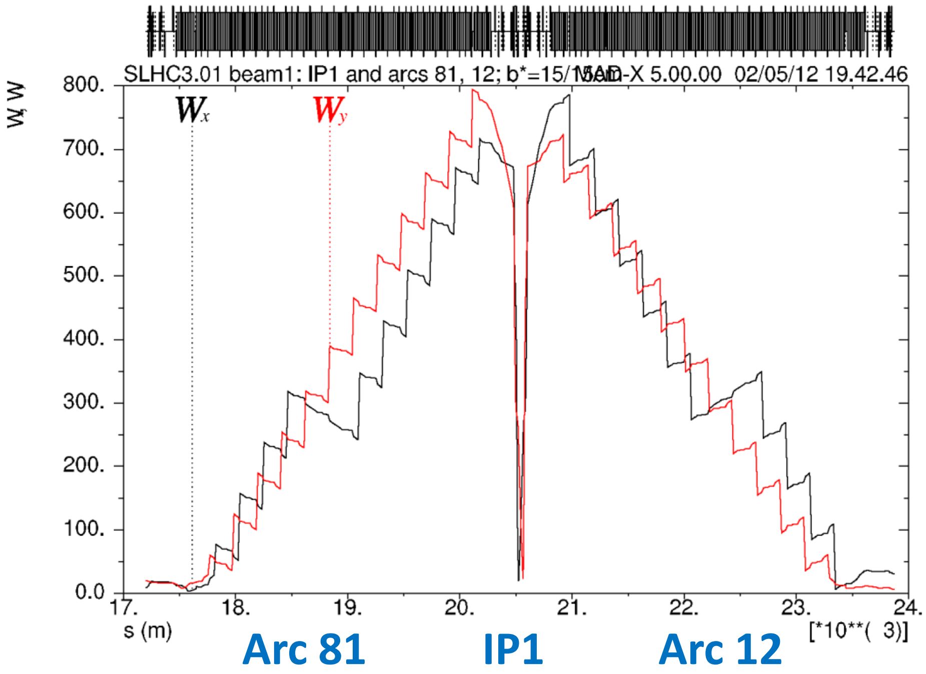

Proposed large aperture superconducting triplet quadrupoles Q1,Q2,Q3.
<u>This study:</u> coil diameter **$d_c$ = 120 mm**.



# Achromatic Telescopic System (ATS) for the HL-LHC

High peak beta functions in the IT quadrupoles ($\beta_{max} \sim 1/\beta^*$) result in high IT chromaticity which requires strong correcting sextupoles. A dedicated $\beta$-modulation is created in the arcs adjacent to IP1 and IP5 in order to raise beta functions at the sextupoles ($\beta_{sext} \sim 1/\beta^*$) and increase their effect without exceeding their field limit. These sextupoles are arranged in -I pairs to cancel their geometric aberrations, and have a proper phase advance relative to the triplets for a localized correction of non-linear IT chromaticity.



# Path to the new IT field error tolerances

- Follow the method described in the "Phase-1" upgrade lattice study ("LHC Project Report 40" by B. Holzer).

- The target minimum DA is **12-13 $\sigma$** when the IT multipole field correction , arc errors and correction are included. In this case, field errors are not included in the D1, D2 separation dipoles and Q4 quadrupoles (future study).

- Start with the measured multipole field coefficients for the nominal IT quadrupoles.

- Scale the measured field coefficients to the new reference radius (**$r_0$ = 50 mm**) and new IT quadrupole coil diameter (**$d_c$ = 120 mm**). Name this table "**target3**". Verify dynamic aperture (expected to be small due to high IT beta in the HL-LHC V3.01).

- Scale the "target3" coefficients with the peak IT beta function in the HL-LHC V3.01 (**$\beta_{max}$ ~ 21.5 km**). This will reduce the coefficients. Name this table "**target31**".

- If the "target31" minimum DA > 13 $\sigma$, then relax the coefficients by scanning them between "target31" and "target3" values.

- Scan the field coefficients individually to determine DA sensitivities.

- Obtain tolerances by scaling all the coefficients according to their individual sensitivities until the target minimum DA is reached.

# 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 field error tables represent Gaussian sigmas for generating random errors.

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

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

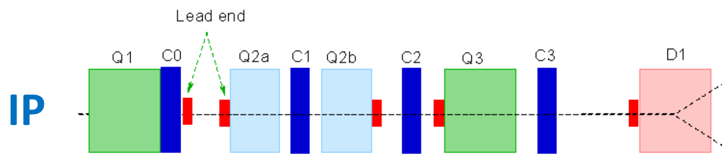
- **Scaling with coil diameter $d_c$** in a SC quad (B. Bellesia, et al., Phys. Rev. ST-AB 10, 062401 (2007)). Nominal $d_c$ = 70 mm → new IT quad **$d_c$ = 120 mm**.

$$b_n, a_n \propto 1/d_c^{n-1} \rightarrow (70/120)^{n-1}$$

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

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

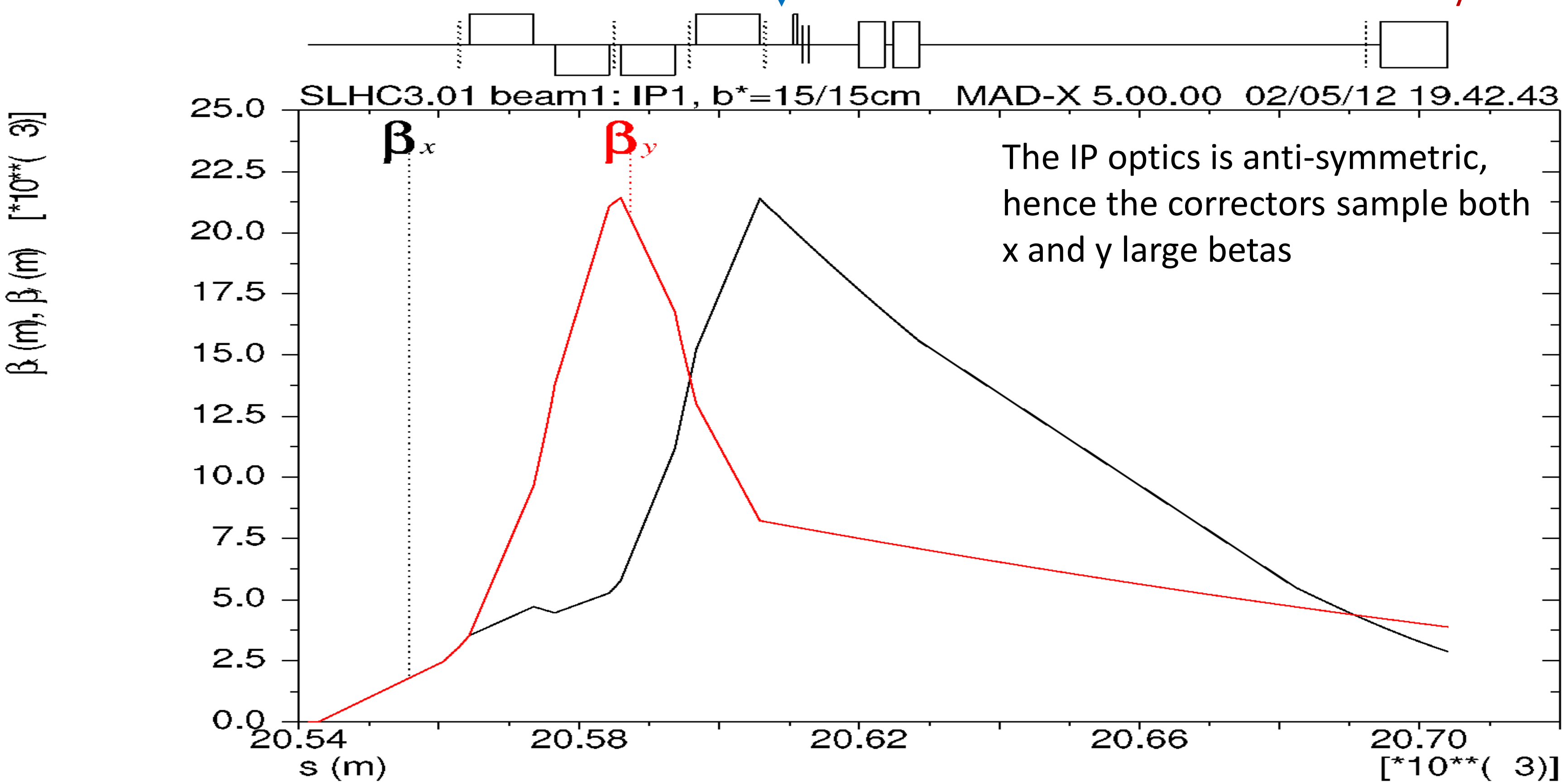
# Multipole field correctors in the triplet




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

The a3, b3, a4, b4, b6 correctors compensate non-linear effects from the corresponding terms of the IT field. Tolerances on these terms are expected to be relaxed.

The newest a5, b5, a6 correctors are not included in this study.




The IP optics is anti-symmetric, hence the correctors sample both x and y large betas

# SixTrack tracking set-up

- 100,000 turns
- 60 random error seeds for final tracking, 20 seeds for multipole coefficient scans
- 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
- 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)

# Measured field error table for the nominal IT quadrupole MQXB with $d_c$=70 mm at $r_0$=17 mm

| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.5235 | 0.6354 | | b3 | 0.4135 | 0.7873 |
| a4 | 0.4432 | 0.3883 | | b4 | 0.1552 | 0.1563 |
| a5 | 0.0874 | 0.1423 | | b5 | 0.1142 | 0.2171 |
| a6 | 0.2306 | 0.2637 | | b6 | 0.2098 | 0.3088 |
| a7 | 0.0254 | 0.0411 | | b7 | 0.0311 | 0.0374 |
| a8 | 0.0140 | 0.0280 | | b8 | 0.0060 | 0.0096 |
| a9 | 0.0127 | 0.0078 | | b9 | 0.0085 | 0.0116 |
| a10 | 0.0094 | 0.0179 | | b10 | 0.0303 | 0.0086 |
| a11 | 0.0046 | 0.0028 | | b11 | 0.0084 | 0.0106 |

(G.V. Velev *et al., IEEE Trans. Appl. Supercond.,* ***17***, 1109-1112 (2007))

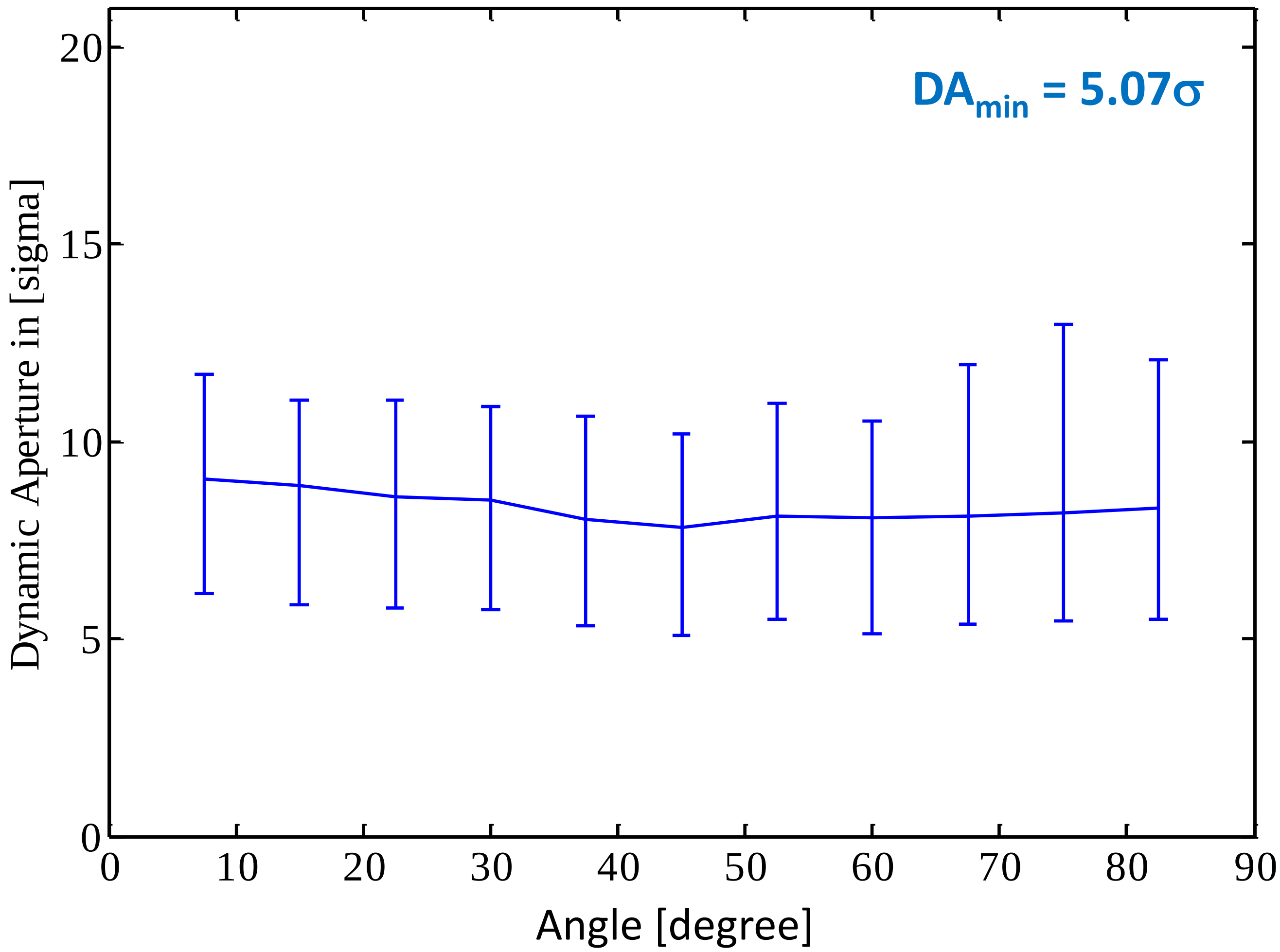
# Field error table "target3" scaled from the measured table to $r_0$=50 mm and $d_c$=120 mm

| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.5239 | 0.6359 | | b3 | 0.4139 | 0.7879 |
| a4 | 0.7611 | 0.6667 | | b4 | 0.2664 | 0.2683 |
| a5 | 0.2574 | 0.4191 | | b5 | 0.3365 | 0.6396 |
| a6 | 1.1655 | 1.3328 | | b6 | 1.0603 | 1.5608 |
| a7 | 0.2203 | 0.3564 | | b7 | 0.2701 | 0.3244 |
| a8 | 0.2087 | 0.4162 | | b8 | 0.0889 | 0.1423 |
| a9 | 0.3238 | 0.2003 | | b9 | 0.2165 | 0.2971 |
| a10 | 0.4137 | 0.7838 | | b10 | 1.3256 | 0.3755 |
| a11 | 0.3457 | 0.2116 | | b11 | 0.6340 | 0.7965 |
| a12 | 0.1863 | 0.1863 | | b12 | 0.1863 | 0.1863 |
| a13 | 0.1164 | 0.1164 | | b13 | 0.2328 | 0.1164 |
| a14 | 0.4366 | 0.1455 | | b14 | 0.5821 | 0.1455 |

- These values should be achievable in the magnet design.
- Values for n = 12,13,14 are added from table "ITD1_errortable_v2" (SLHC Project Report 0040).

# Dynamic aperture for the field error table “target3”

The line represents the average aperture for 60 seeds and the error bars show the spread between the minimum and maximum aperture for 11 x-y angles



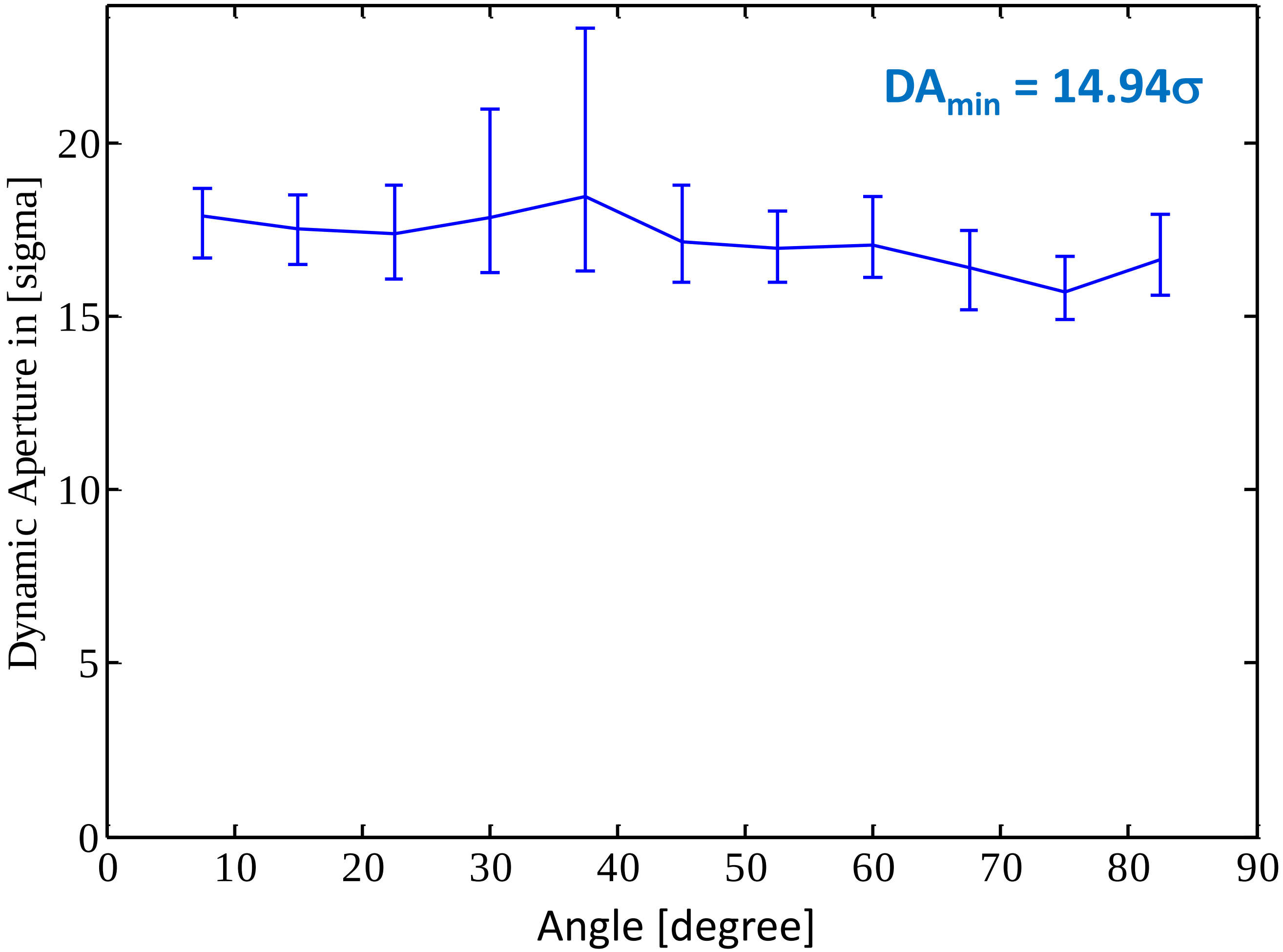

**Aperture is too small**

# Field error table “target31” scaled from table “target3” to $\beta_{max}$ = 21.5 km

| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.05016 | 0.06089 | | b3 | 0.03963 | 0.07545 |
| a4 | 0.03334 | 0.02920 | | b4 | 0.01167 | 0.01175 |
| a5 | 0.00516 | 0.00840 | | b5 | 0.00674 | 0.01281 |
| a6 | 0.01069 | 0.01223 | | b6 | 0.00972 | 0.01431 |
| a7 | 0.00092 | 0.00150 | | b7 | 0.00113 | 0.00137 |
| a8 | 0.00042 | 0.00080 | | b8 | 0.00015 | 0.00027 |
| a9 | 0.00029 | 0.00019 | | b9 | 0.00019 | 0.00024 |
| a10 | 0.00018 | 0.00030 | | b10 | 0.00054 | 0.00018 |
| a11 | 0.00007 | 0.00007 | | b11 | 0.00015 | 0.00015 |
| a12 | 0.000016 | 0.000016 | | b12 | 0.000016 | 0.000016 |
| a13 | 0.000004 | 0.000004 | | b13 | 0.000009 | 0.000004 |
| a14 | 0.000008 | 0.000003 | | b14 | 0.000010 | 0.000003 |

**Coefficients are significantly reduced (too small for realistic magnet design)**

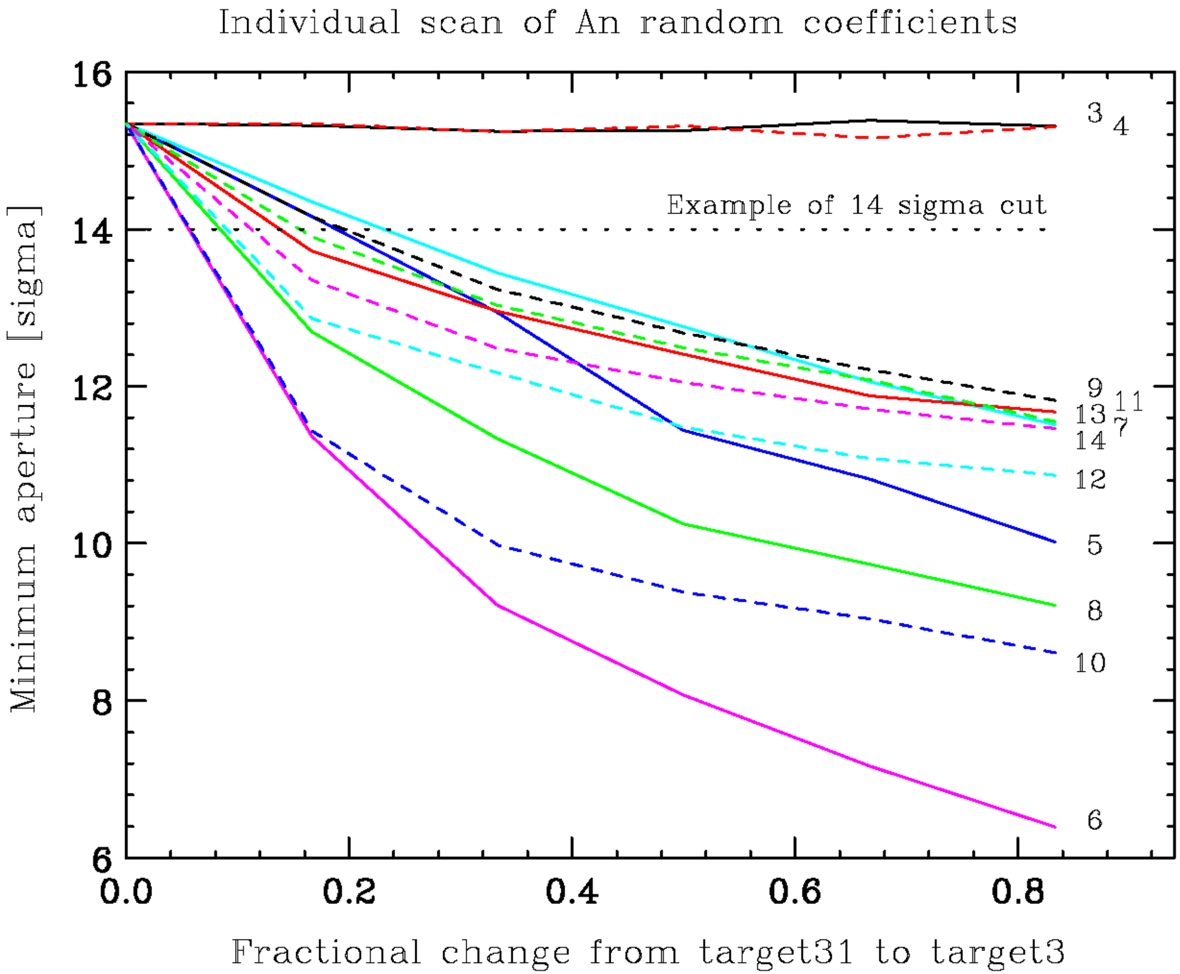
# Dynamic aperture for the field error table "target31"




**The minimum DA is large (close to DA without IT errors).**
**The coefficients can be relaxed to reduce DA$_{min}$ to 12-13σ.**

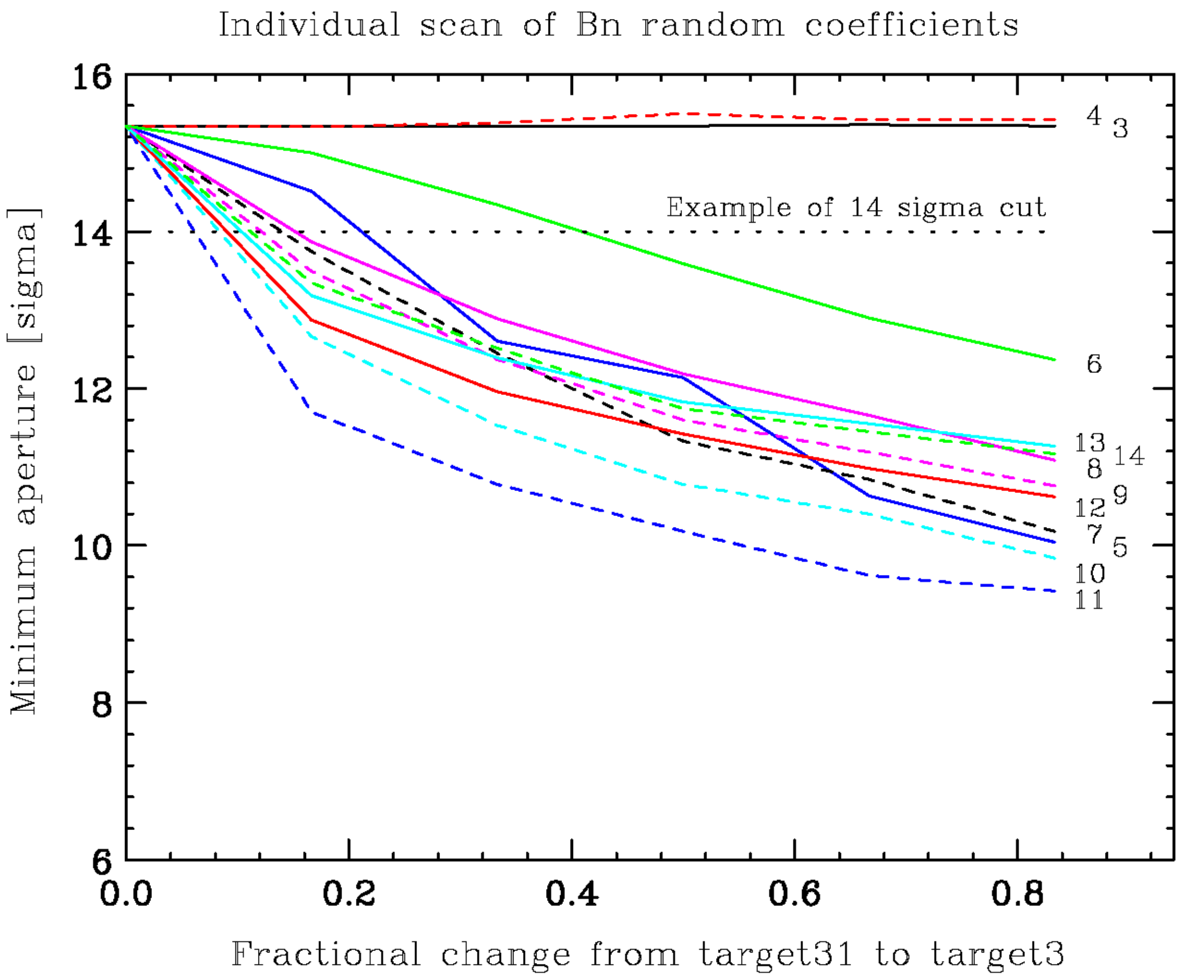
# Individual scan of $a_n$ "random" coefficients

Each coefficient is scanned between "target31" and "target3" values while all other coefficients are fixed at "target31" values.



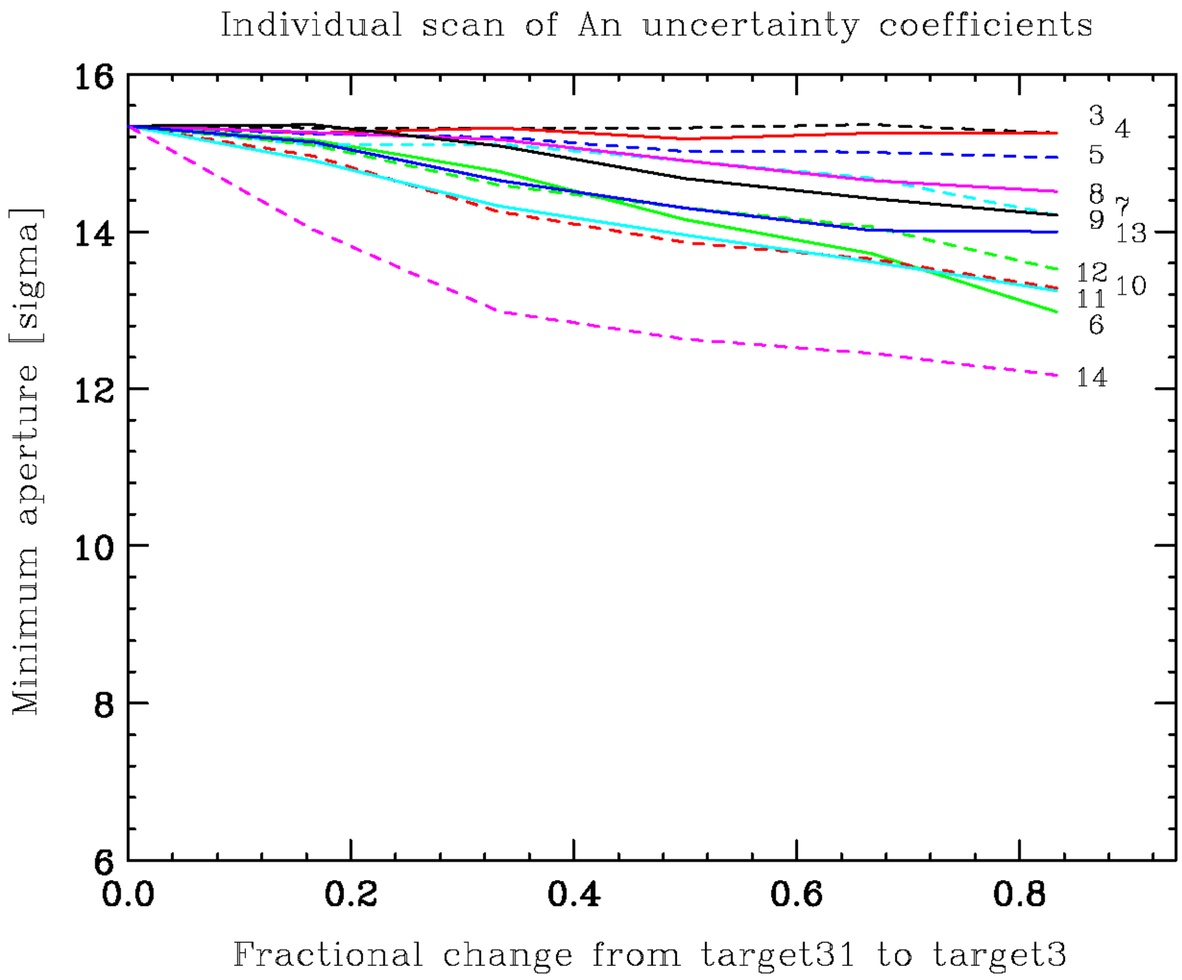

The DA is not sensitive to the corrected a3, a4 terms.
The strongest effects are from a6, a10 terms.

# Individual scan of $b_n$ "random" coefficients



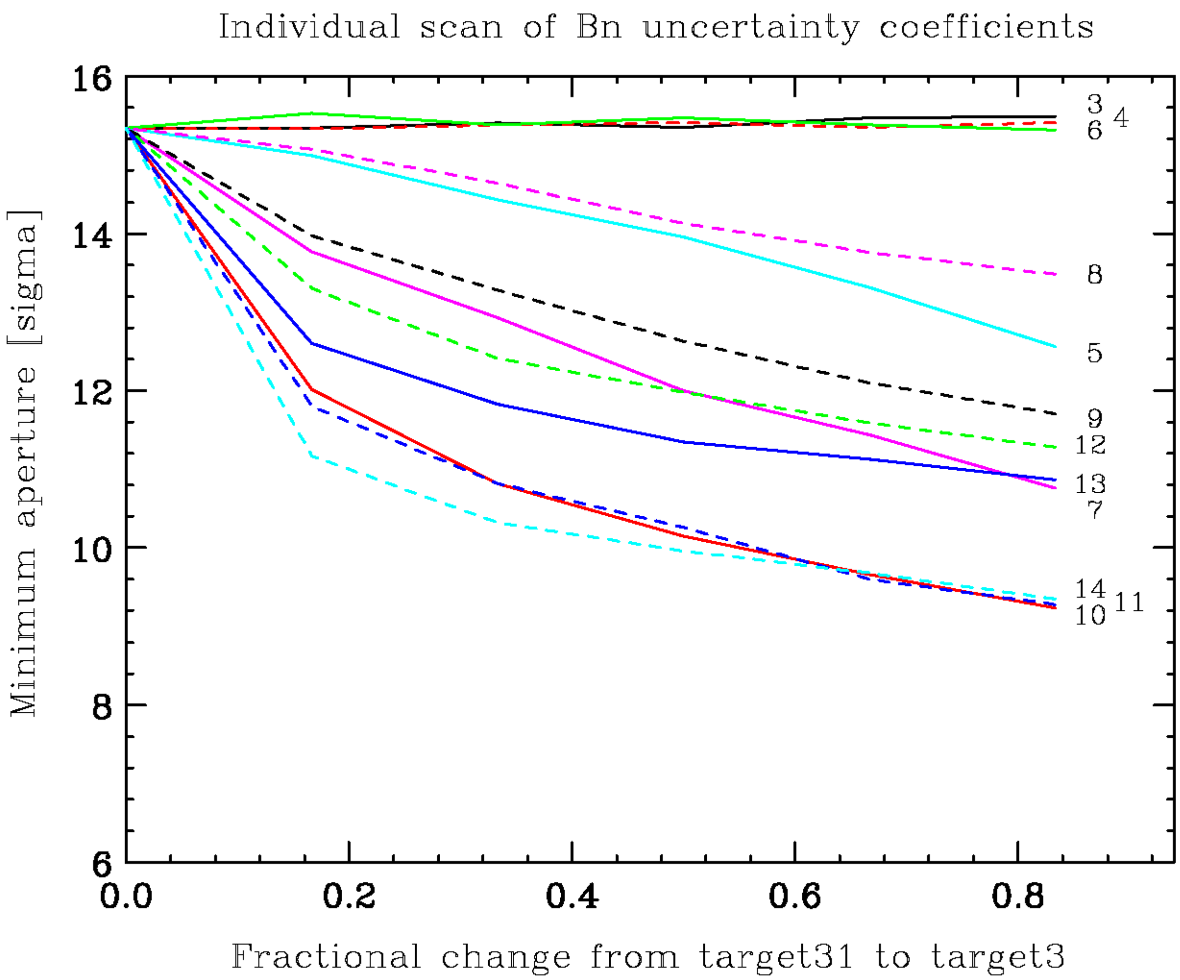

The b3, b4 terms are well corrected, but the b6 still affects the DA.
"DA cut" will be used later to set the coefficients for about equal impact on DA.

# Individual scan of $a_n$ "uncertainty" coefficients




The a3, a4 terms are well corrected.
Overall, a smaller impact on DA compared to effect of "random" $a_n$.

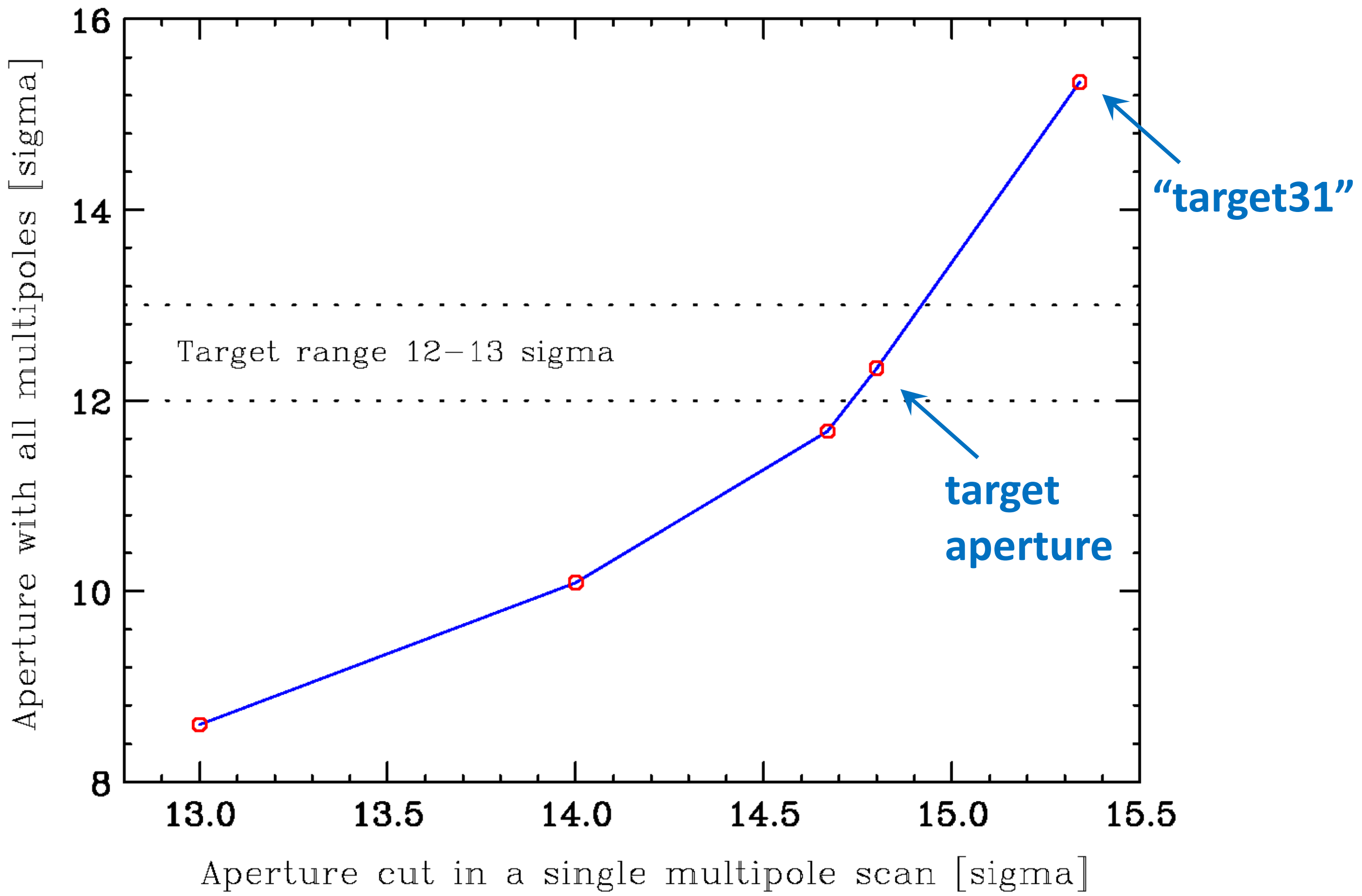
# Individual scan of $b_n$ "uncertainty" coefficients




The b3, b4, b6 terms are well corrected.
High order terms are still important.

# Final field scaling for the target DA

We construct the tolerances, where the effects of individual coefficients on DA are about equal. This is done by setting to the values corresponding to the same DA in the individual scans using "DA cut". The target DA is reached when the DA cut is 14.8$\sigma$.

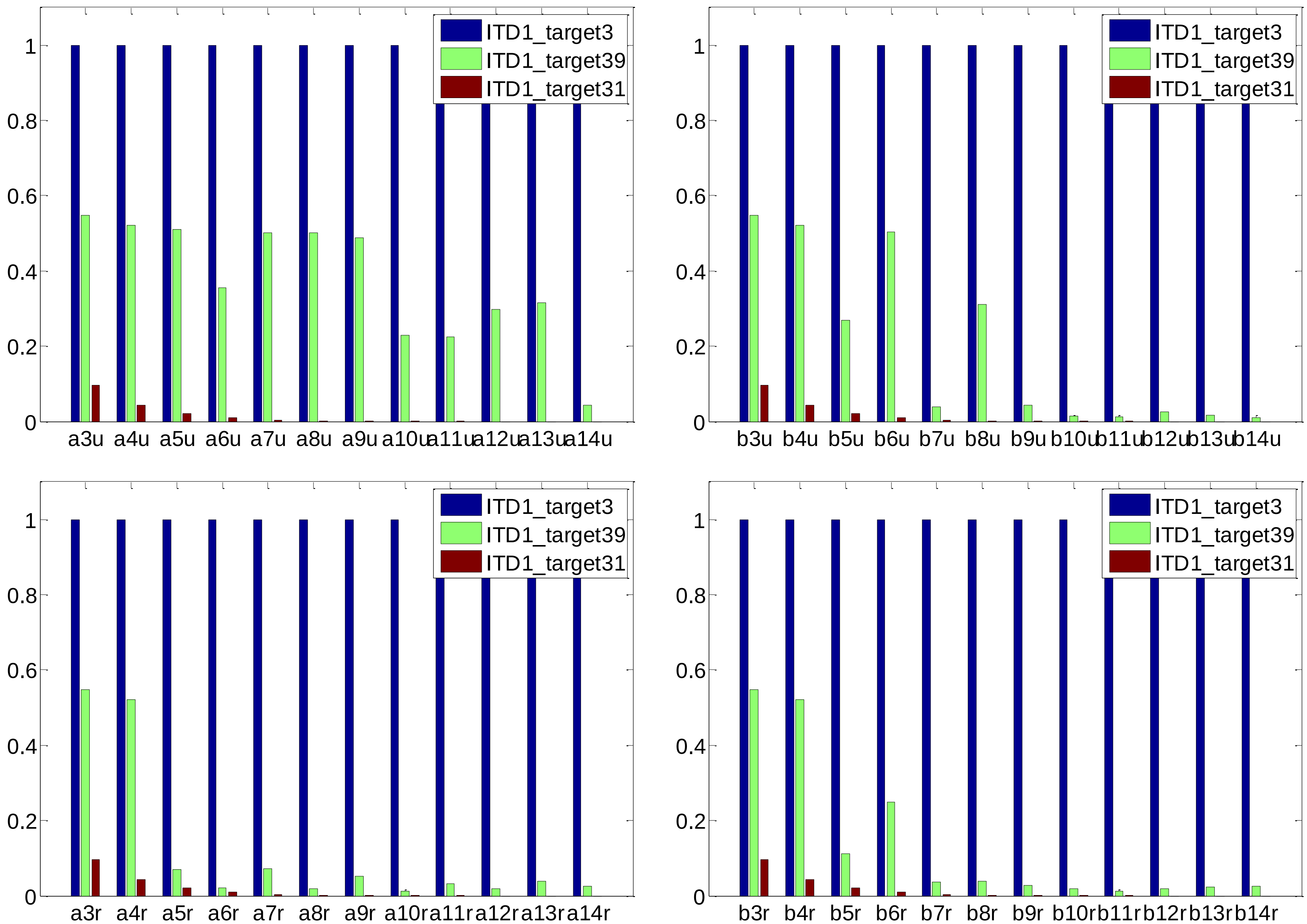


# Tolerance table "target39" at $r_0$=50 mm

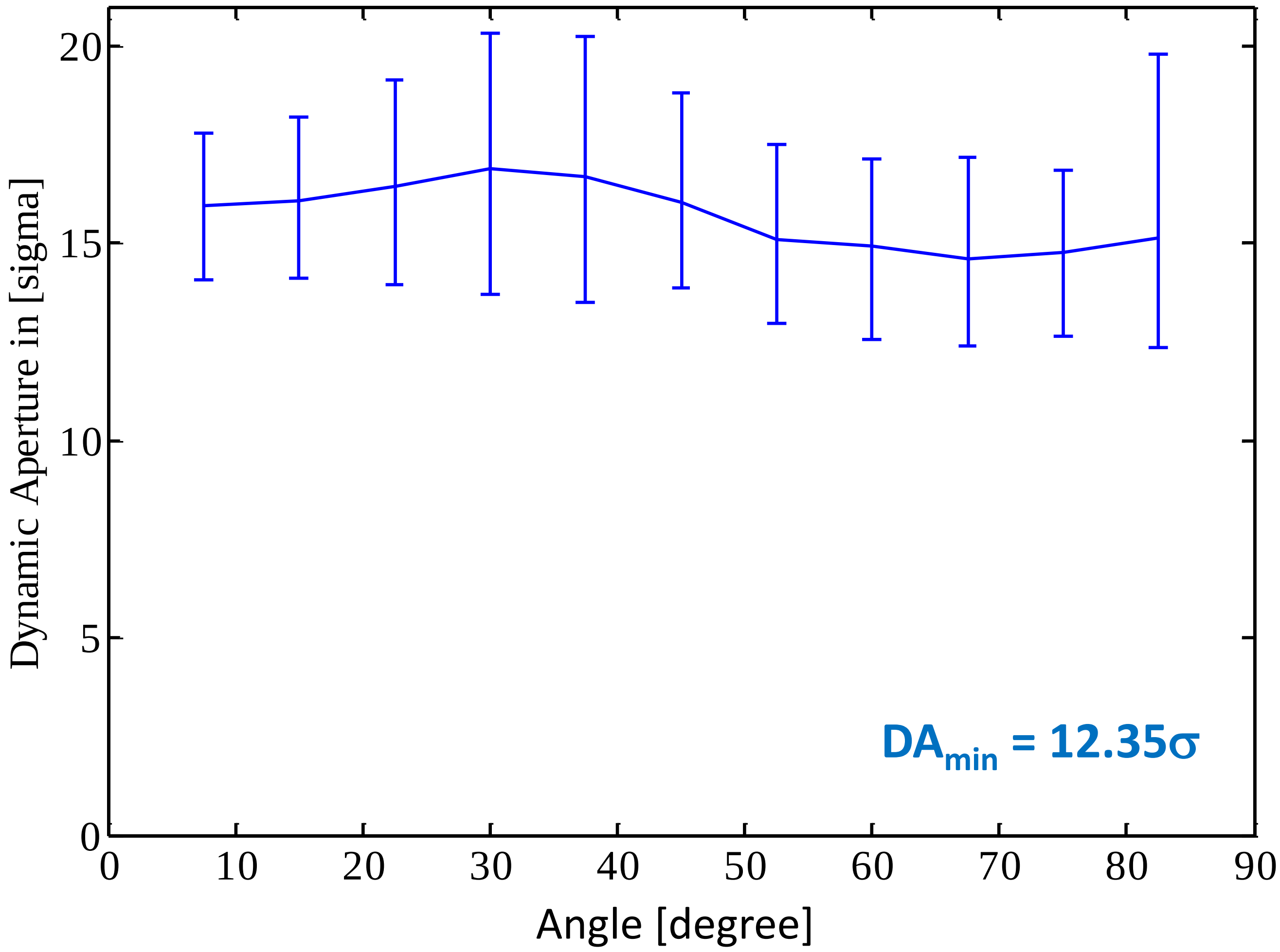
| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.28701 | 0.34839 | | b3 | 0.22675 | 0.43166 |
| a4 | 0.39722 | 0.34797 | | b4 | 0.13905 | 0.14002 |
| a5 | 0.13129 | 0.02945 | | b5 | 0.09018 | 0.07111 |
| a6 | 0.41458 | 0.02698 | | b6 | 0.53501 | 0.38921 |
| a7 | 0.11063 | 0.02557 | | b7 | 0.01031 | 0.01215 |
| a8 | 0.10452 | 0.00820 | | b8 | 0.02766 | 0.00557 |
| a9 | 0.15817 | 0.01044 | | b9 | 0.00911 | 0.00844 |
| a10 | 0.09435 | 0.00924 | | b10 | 0.01872 | 0.00674 |
| a11 | 0.07756 | 0.00700 | | b11 | 0.00820 | 0.00998 |
| a12 | 0.05541 | 0.00354 | | b12 | 0.00456 | 0.00363 |
| a13 | 0.03679 | 0.00442 | | b13 | 0.00396 | 0.00268 |
| a14 | 0.01892 | 0.00364 | | b14 | 0.00611 | 0.00364 |

The least sensitive terms could be set to large "target3" values. But in the above table "target39" we intentionally limited them to a mid-value between the "target3" and "target31" settings in order to help relaxing the other tighter terms. As an alternative, we also constructed the table "target36", where the non-sensitive terms are set to "target3" values at the expense of somewhat tighter other tolerances.

# Comparison of “target3”, “target31” and “target39” tables
## (normalized to “target3” values)



# Dynamic aperture for tolerance table “target39”



# Summary

• DA sensitivity to individual multipole field errors in the large aperture IT quadrupoles of the HL-LHC V3.01 lattice (option "4444") have been determined using long-term tracking in SixTrack.
• The setting for the IT field error tolerances have been obtained based on analytical scaling for the new IT coil diameter and peak beta functions, and taking into account the DA sensitivity to individual multipole coefficients.
• The obtained tolerances may be too tight – further optimization is needed.
• This work was presented at IPAC'12, paper MOPPC020.

# Next steps

Try to relax the tolerances towards the field error estimate presented by E. Todesco (E.T.) at the Hi-Lumi & LARP Collaboration Meeting, 7 June 2012:

- Set the least sensitive coefficients to the E.T. estimate – verify DA.
- Assume a5, b5, a6 terms are corrected – set to 20% of the E.T. estimate (to simulate the correction without actual correctors in tracking).
- Reduce the target minimum DA to 11$\sigma$ to loosen the tolerances.

# Back-up slides

# Field error table from presentation by E. Todesco

| | Uncertainty | Random | | Uncertainty | Random |
|---|---|---|---|---|---|
| b3 | 0.890 | 0.890 | a3 | 0.890 | 0.890 |
| b4 | 0.640 | 0.640 | a4 | 0.640 | 0.640 |
| b5 | 0.460 | 0.460 | a5 | 0.460 | 0.460 |
| b6 | 1.800 | 1.280 | a6 | 1.200 | 0.330 |
| b7 | 0.210 | 0.210 | a7 | 0.210 | 0.210 |
| b8 | 0.160 | 0.160 | a8 | 0.160 | 0.160 |
| b9 | 0.080 | 0.080 | a9 | 0.080 | 0.080 |
| b10 | 0.060 | 0.060 | a10 | 0.060 | 0.060 |
| b11 | 0.040 | 0.040 | a11 | 0.040 | 0.040 |
| b12 | 0.026 | 0.026 | a12 | 0.026 | 0.026 |
| b13 | 0.017 | 0.017 | a13 | 0.017 | 0.017 |
| b14 | 0.011 | 0.011 | a14 | 0.011 | 0.011 |

120 mm aperture, Rref=40 mm

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

# Tolerance table "target39" scaled to $r_0$=40 mm

| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.22961 | 0.27871 | | b3 | 0.18140 | 0.34533 |
| a4 | 0.25422 | 0.22270 | | b4 | 0.08899 | 0.08961 |
| a5 | 0.06722 | 0.01508 | | b5 | 0.04617 | 0.03641 |
| a6 | 0.16981 | 0.01105 | | b6 | 0.21914 | 0.15942 |
| a7 | 0.03625 | 0.00838 | | b7 | 0.00338 | 0.00398 |
| a8 | 0.02740 | 0.00215 | | b8 | 0.00725 | 0.00146 |
| a9 | 0.03317 | 0.00219 | | b9 | 0.00191 | 0.00177 |
| a10 | 0.01583 | 0.00155 | | b10 | 0.00314 | 0.00113 |
| a11 | 0.01041 | 0.00094 | | b11 | 0.00110 | 0.00134 |
| a12 | 0.00595 | 0.00038 | | b12 | 0.00049 | 0.00039 |
| a13 | 0.00316 | 0.00038 | | b13 | 0.00034 | 0.00023 |
| a14 | 0.00130 | 0.00025 | | b14 | 0.00042 | 0.00025 |

# Field error table “target3” scaled to $r_0$=40 mm

| skew | uncertainty | rms | | normal | uncertainty | rms |
|---|---|---|---|---|---|---|
| a3 | 0.4191 | 0.5087 | | b3 | 0.3311 | 0.6303 |
| a4 | 0.4871 | 0.4267 | | b4 | 0.1705 | 0.1717 |
| a5 | 0.1318 | 0.2146 | | b5 | 0.1723 | 0.3275 |
| a6 | 0.4774 | 0.5459 | | b6 | 0.4343 | 0.6393 |
| a7 | 0.0722 | 0.1168 | | b7 | 0.0885 | 0.1063 |
| a8 | 0.0547 | 0.1091 | | b8 | 0.0233 | 0.0373 |
| a9 | 0.0679 | 0.0420 | | b9 | 0.0454 | 0.0623 |
| a10 | 0.0694 | 0.1315 | | b10 | 0.2224 | 0.0630 |
| a11 | 0.0464 | 0.0284 | | b11 | 0.0851 | 0.1069 |
| a12 | 0.0200 | 0.0200 | | b12 | 0.0200 | 0.0200 |
| a13 | 0.0100 | 0.0100 | | b13 | 0.0200 | 0.0100 |
| a14 | 0.0300 | 0.0100 | | b14 | 0.0400 | 0.0100 |