# Maximum tolerable a4 and b5 errors on the triplets based on the available corrector strengths

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# Outline

- Expanded DA study of large IT a4, b5 errors including different ratios of a4 to b5 for a complete 2D scan
- More accurate estimate of the maximum strength of the IT a4, b5 correctors with increased number of random seeds from 60 to 600
- Estimate of the effect of a4, b5 in D1 on the IT corrector's strengths
- Evaluation of maximum allowed a4 and b5 uncertainty/random errors for the present corrector specifications
- Comparison with the measured a4, b5 data
- Conclusions

# DA simulations set-up

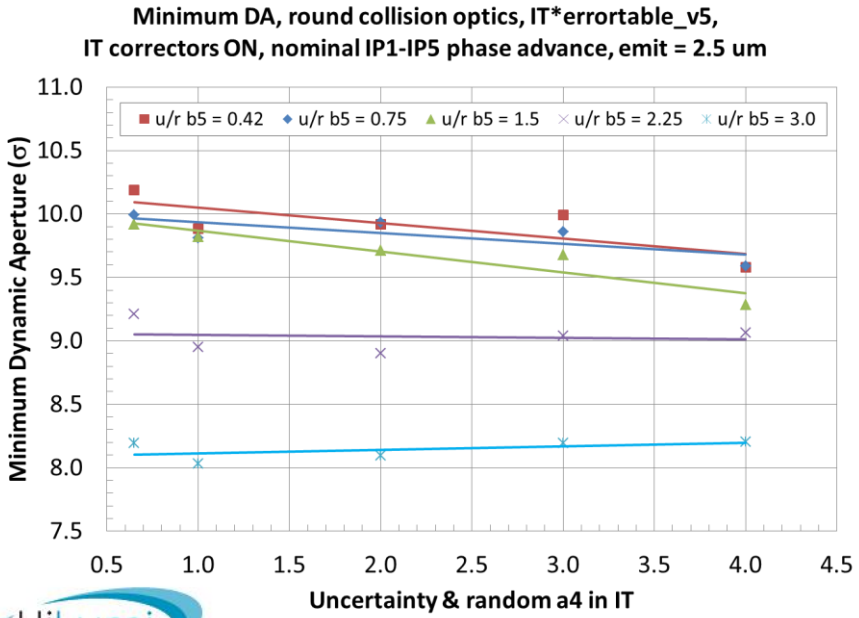
- Lattice configuration
  - HLLHCV1.0 lattice at collision (7 TeV)
  - Tune: 62.31, 60.32
  - Chromaticity: +3
  - Normalized emittance: 2.5 μm
  - Arc errors and standard corrections
  - IT non-linear correctors in IR1, IR5
  - 60 error seeds for calculation of DA
  - 600 seeds for calculation of the IT corrector strengths

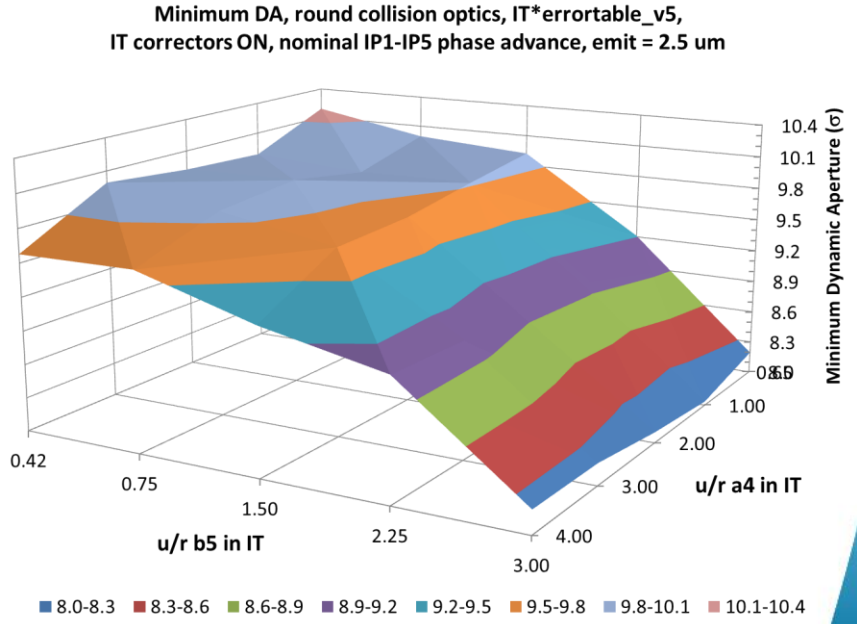
- FQ tables of IT, D1, D2, Q4, Q5 magnets
  - "ITbody_errortable_5", "ITcs_errortable_v5", "ITnc_errortable_v5" (with end effects)
  - "D1_errortable_v1_spec", "D2_errortable_v5_spec"
  - "Q4_errortable_v2_spec", "Q5_errortable_v0_spec"
  - a2 and b2 terms are set to zero to simulate linear correction

- Beam-beam effects are not included
- **Field errors are randomly generated according to** $b = b_s + (\xi_u / 1.5) b_u + \xi_r b_r$ **, where random** $\xi_u < 1.5$ **and** $\xi_r < 3$ **(with** $\sigma_\xi = 1$**); and similarly for the a-terms**

# Minimum DA vs a4 & b5

- Relatively mild impact at u/r a4 < 3 and b5 < 1.5
- Strong impact at u/r b5 > 1.5 (1.7σ reduction of minimum DA at b5 = 3)
- Optimization of IP1-5 phase advance may improve the DA; the result may depend on the a4, b5 values

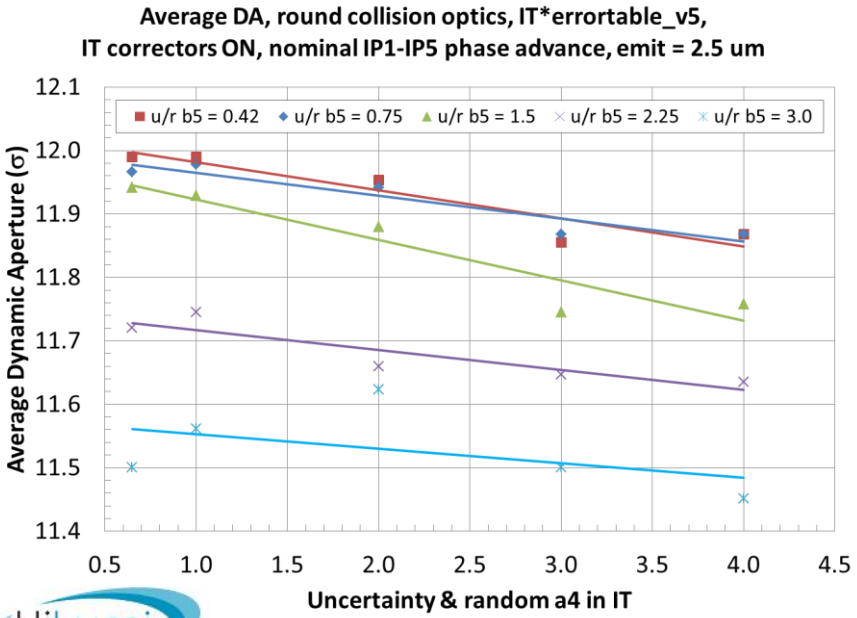


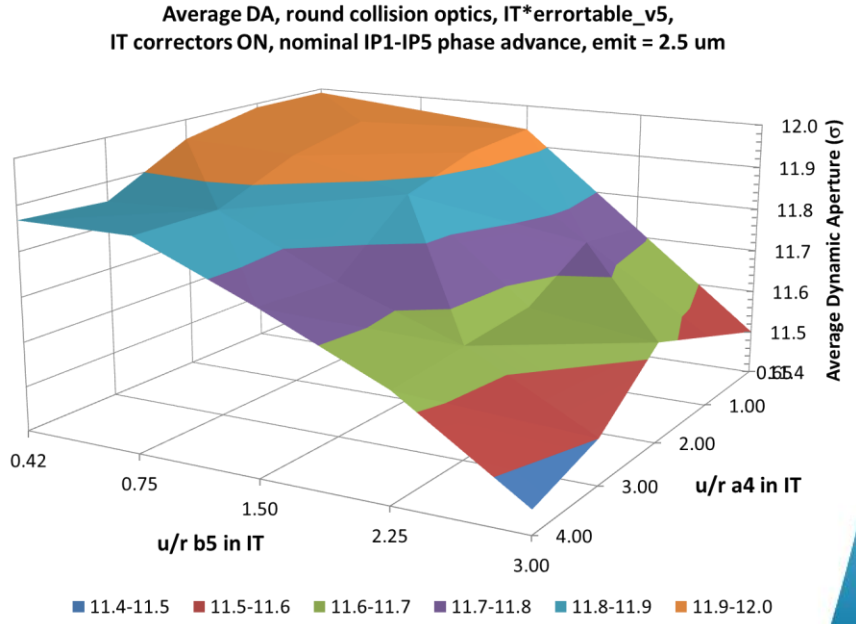




Present IT FQ expected at 7 TeV: u/r a4 = 0.65, b5 = 0.42

# Average DA vs a4 and b5

- Impact on the average DA is much less than on the minimum DA (0.5σ vs 2σ reduction at b5 = 3)
  - ➢ This indicates that the effect is mostly due to a large spread of the DA among different seeds at large uncertainty/random a4, b5
- A “desirable” a4, b5 range for a small impact on DA appears to be within a4u, a4r < 2 and b5u, b5r < 1



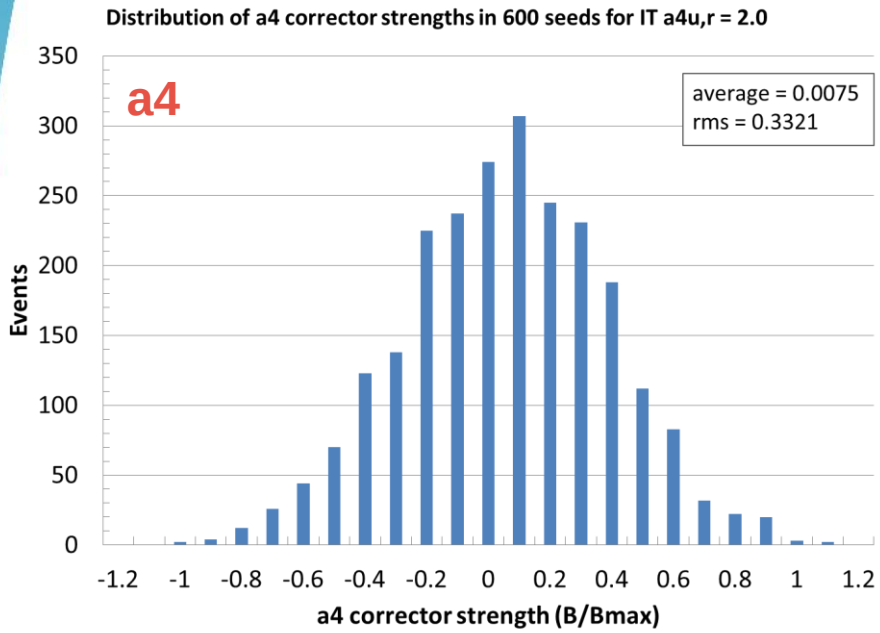

Present IT FQ expected at 7 TeV: u/r a4 = 0.65, b5 = 0.42

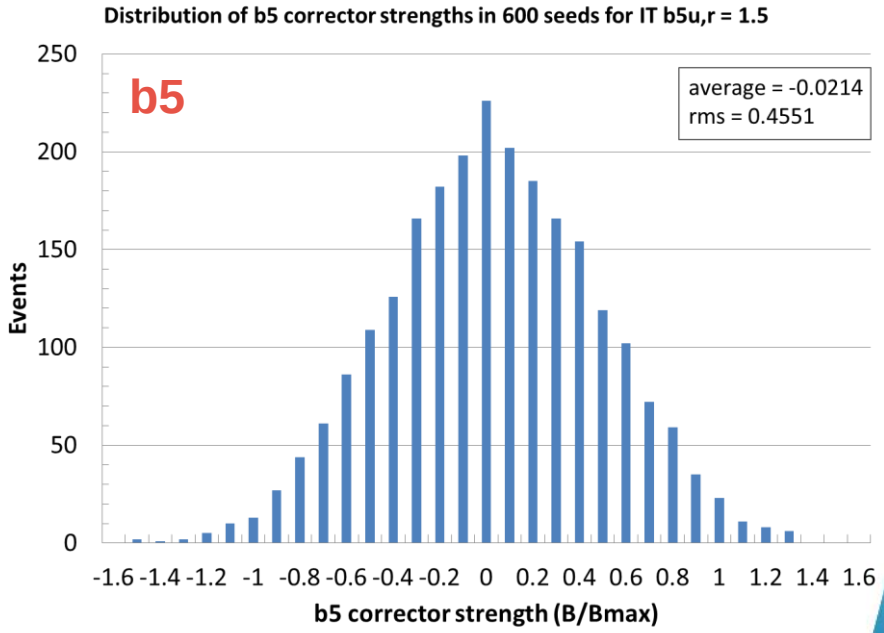
# Evaluation of maximum a4, b5 corrector strengths vs a4, b5

- Field errors are randomly generated according to $b = b_s + (\xi_u / 1.5) b_u + \xi_r b_r$ , where random $\xi_u < 1.5$ and $\xi_r < 3$ (with $\sigma_\xi = 1$); and similarly for the a-terms
- According to the above formula, the theoretically maximum generated error value is $b_{max} = b_u + 3*b_r$ (for $b_s = 0$) → high statistics is needed to approach this value
- We use large number of seeds (600) to determine maximum a4 & b5 corrector strengths as a function of theoretically maximum error values a4max & b5max
- This method avoids ambiguity related to the dependence of four a4 (or b5) corrector strengths on the 24 random values of a4 (b5) errors in the 24 IT quadrupoles in IR1 & IR5
- From this dependence we can determine the maximum allowed a4max & b5max values satisfying the a4 & b5 corrector specifications, namely
  - a4 -> $BL_{max}$ = 0.046 Tm @ 50 mm
  - b5 -> $BL_{max}$ = 0.025 Tm @ 50 mm
- Finally, we can determine the corresponding maximum allowed uncertainty & random a4 & b5 for the present corrector spec
  - a4u = a4r = a4max / 4
  - b5u = b5r = b5max / 4

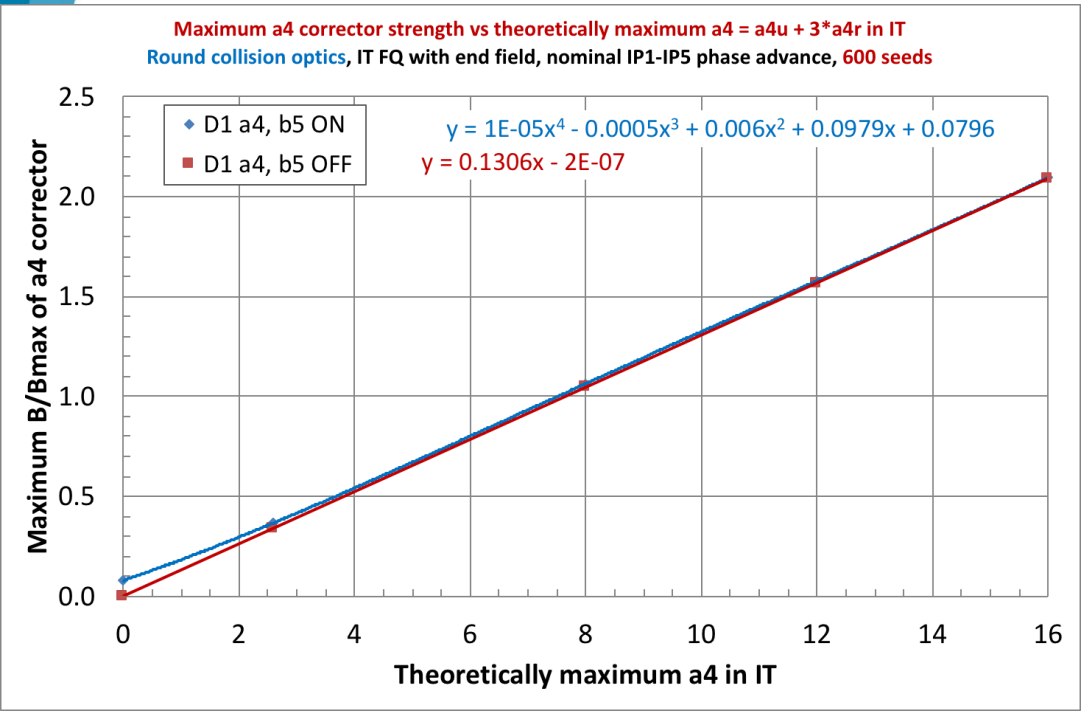
# Example of distribution of a4 and b5 corrector strengths

Distribution of a4 and b5 corrector strengths in 600 seeds for a4u = a4r = 2 and b5u = b5r = 1.5



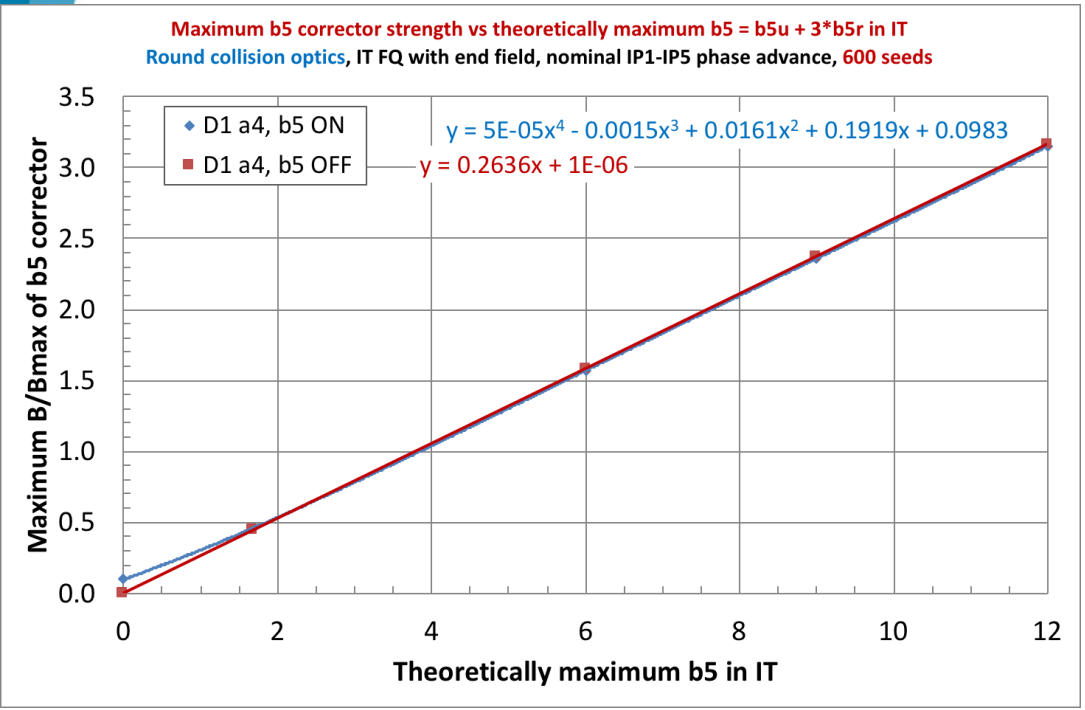



# Maximum a4 corrector strength vs theoretically maximum a4 error




- Corrector strength is normalized to the corrector spec ($BL_{max}$ = 0.046 Tm @ 50 mm)
- The effect of D1 a4 error on the maximum a4 corrector strength is small (about 8%)
- According to the linear fit, the corrector spec strength is reached at the theoretically maximum error of a4max = 7.508
- This corresponds to the maximum uncertainty & random values: a4u = a4r = a4max / 4 = 1.877
- This maximum value is within the estimated “desirable” range of u/r a4 < 2
- To provide margin on the a4 FQ spec, the latter should be improved compared to this estimate, or the a4 corrector strength increased

# Maximum b5 corrector strength vs theoretically maximum b5 error



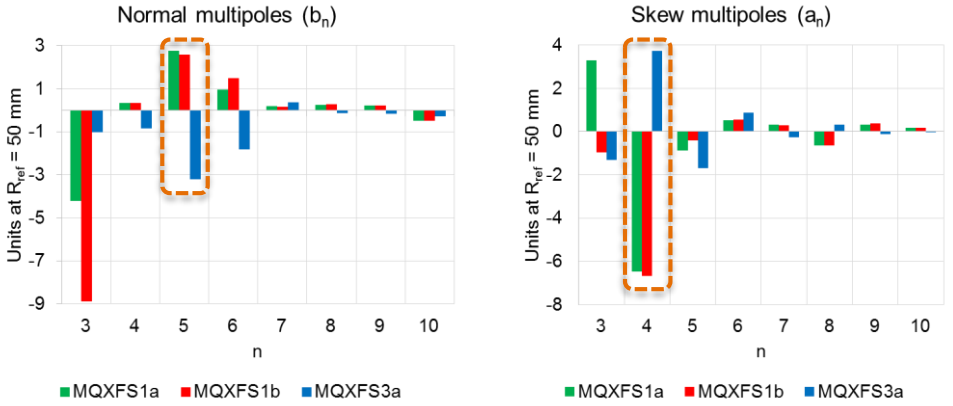

- Corrector strength is normalized to the corrector spec ($BL_{max}$ = 0.025 Tm @ 50 mm)
- The effect of D1 b5 error on the maximum b5 corrector strength is small (10%). To note that the D1 b5 currently features 0 systematic component.
- According to the linear fit, the corrector spec strength is reached at the theoretically maximum error of b5max = 3.778
- This corresponds to the maximum uncertainty & random values: b5u = b5r = b5max / 4 = 0.944
- This maximum value is within the estimated “desirable” range of u/r b5 < 1
- To provide margin on the b5 FQ spec, the latter should be improved compared to this estimate, or the b5 corrector strength increased

# Comparison with measured a4, b5 errors

(E. Todesco et al, 28-Feb-2017 WP2 meeting)

- We have observed in few model large values for the $a_4$ and $b_5$ due to geometric field errors
  - These components are present already in the room temperature measurements [see S. Izquierdo Bermudez at HL LHC meeting in Paris 2016]
  - MQXFS1: $a_4$ of -6.5 units, $b_5$ of 2.8 units
  - MQXFS3: $a_4$ of 3.7 units, $b_5$ of -3.2 units

(S.I. Bermudez et al, 6th HL-LHC collaboration meeting, Nov 2016)




- So far, the measured a4 & b5 are within the maximum values allowed by the corrector spec
  - measured a4 < 6.5 → less than a4max = 7.508 → a margin of 13%
  - measured b5 < 3.2 → less than b5max = 3.778 → a margin of 15%
- The measurements have limited statistics to determine the distribution
- The margin on the corrector strength can be increased by
  - making the correctors longer and/or
  - increasing the maximum corrector current

# Conclusions

- Impact of large a4, b5 IT errors on the collision DA is evaluated in the range of a4u, a4r < 4 and b5u, b5r < 3
- A “desirable” a4, b5 range, where the impact on the DA is relatively small, is estimated to be within a4u, a4r < 2 and b5u, b5r < 1
- A large number of seeds (600) is used to determine the maximum strengths of IT a4, b5 correctors vs the a4, b5 IT errors
- The present corrector spec is compatible with the errors up to
  - a4max = 7.508, corresponding to the maximum a4u = a4r = 1.877
  - b5max = 3.778, corresponding to the maximum b5u = b5r = 0.944
- These “acceptable” error values are within the estimated “desirable” range
- The impact of D1 a4, b5 spec errors on the maximum corrector strength is small
- So far, the measured a4, b5 errors are below the estimated maximum “acceptable” errors, with a margin of 13% (a4) and 15% (b5)
  - The margin can be increased by making the correctors longer and/or increasing the maximum corrector current