Impact of Measured Out-of-Spec IT FQ Terms on Dynamic Aperture

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Outline

- Introduction
  - Out-of-spec IT FQ terms from measurements
  - New IT FQ model for tracking simulations
- Impact of out-of-spec FQ terms on DA at collision energy
  - Round and flat optics
- Impact of out-of-spec FQ terms on DA at injection energy
- Conclusions

IT FQ measurements

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

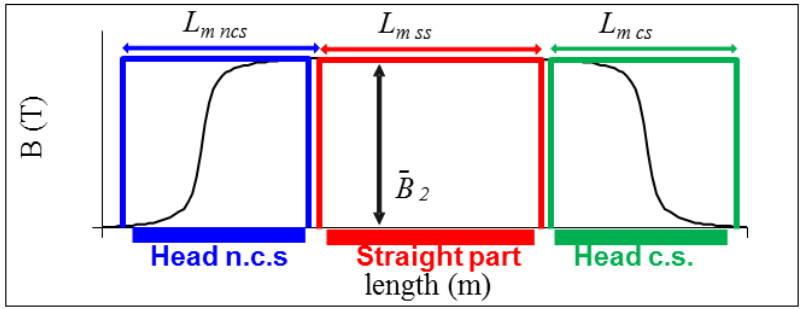
- Caveat: early phase of short models, different coils, field quality shold improve
  - But we have no understanding of the origin
  - And we also saw similar values for HQ (large a_4 and b_5)
  - These multipoles go above the possibility of correction with the magnetic shimming (max 0.8 of a_4, b_5 cannot be corrected since magnetic shimming acts on order 3 and order 4)
  - Today we have a random and uncertainty a4 and b5 of 0.57 and 0.42 units respectively (one sigma)
  - I would suggest to see the impact of increasing these values by a factor 2, 3 and 4

- Measured uncertainty and random a4 and b5 are larger than specified, and potentially may not be reduced
- (u/r) a4, b5 values:
  - Nominal: a4 = 0.65, b5 = 0.42
  - Actual: may be 2-4 times larger
- Study the impact on DA if the (u/r) a4, b5 are increased to:
  - a4 = 2.0. b5 = 1.5 (or more)

IT FQ model with quad end field

(S.I. Bermudez, E. Todesco, “MQXF Fringe Field Expectations”
HiLumi LHC-LARP meeting, May 2015)

- In previous studies the IT model did not explicitly include the effect of quad fringe FQ
- The new model splits each IT quadrupole into 3 parts: the long “body” (constant B) and two soft fringe ends (connection and non-connection sides), each having its own FQ table (the end FQ is based on field integral)



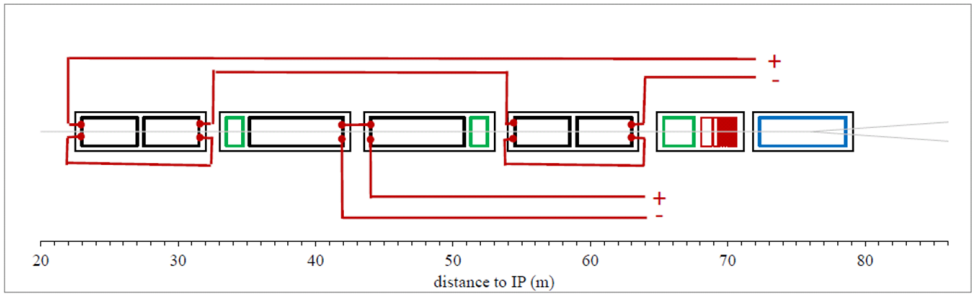


Figure 3-14: **Sketch of baseline for triplet powering (trims not shown)**

Evolution of IT FQ spec (collision energy)

Colored cells show changes since “IT_errortable_v3”

Values within red line border in “IT_errortable_v66_5” are reduced for larger DA

“ITcs*v5” and “ITnc*v5” are for the connection and non-connection sides

The new FQ is similar to “IT_errortable_v4”

New larger b14m

The larger (u/r) a4 and b5 will be applied to the “ITbody_errortable_v5”

Collision	IT_errortable_v4			IT_errortable_v66_5 (optimized)			ITbody_errortable_v5			ITcs_errortable_v5		ITnc_errortable_v5	
	m	u	r	m	u	r	m	u	r	m	u/r	m	u/r
b2	0.0000	0.0000	0.0000	0.0000	0.0000	10.0000	0.0000	0.0000	10.0000	0.0000	0.0000	0.0000	0.0000
b3	0.0000	0.8200	0.8200	0.0000	0.8200	0.8200	0.0000	0.8200	0.8200	0.0000	0.0000	0.0000	0.0000
b4	0.0000	0.5700	0.5700	0.0000	0.5700	0.5700	0.0000	0.5700	0.5700	0.0000	0.0000	0.0000	0.0000
b5	0.0000	0.4200	0.4200	0.0000	0.4200	0.4200	0.0000	0.4200	0.4200	0.0000	0.0000	0.0000	0.0000
b6	0.4000	1.1000	1.1000	0.4000	0.5500	0.5500	-0.6400	1.1000	1.1000	8.9430	0.0000	-0.0250	0.0000
b7	0.0000	0.1900	0.1900	0.0000	0.0950	0.0950	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
b8	0.0000	0.1300	0.1300	0.0000	0.0650	0.0650	0.0000	0.1300	0.1300	0.0000	0.0000	0.0000	0.0000
b9	0.0000	0.0700	0.0700	0.0000	0.0350	0.0350	0.0000	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000
b10	-0.3900	0.2000	0.2000	-0.1560	0.1000	0.1000	-0.1100	0.2000	0.2000	-0.1890	0.0000	-0.8210	0.0000
b11	0.0000	0.0260	0.0260	0.0000	0.0208	0.0208	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
b12	0.0000	0.0180	0.0180	0.0000	0.0144	0.0144	0.0000	0.0180	0.0180	0.0000	0.0000	0.0000	0.0000
b13	0.0000	0.0090	0.0090	0.0000	0.0072	0.0072	0.0000	0.0090	0.0090	0.0000	0.0000	0.0000	0.0000
b14	-0.6700	0.0230	0.0230	-0.1675	0.0115	0.0115	-0.8700	0.0230	0.0230	-0.5450	0.0000	-1.0830	0.0000
a2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	10.0000	-31.3420	0.0000	0.0000	0.0000
a3	0.0000	0.8000	0.8000	0.0000	0.8000	0.8000	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a4	0.0000	0.6500	0.6500	0.0000	0.6500	0.6500	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a5	0.0000	0.4300	0.4300	0.0000	0.4300	0.4300	0.0000	0.4300	0.4300	0.0000	0.0000	0.0000	0.0000
a6	0.0000	0.3100	0.3100	0.0000	0.3100	0.3100	0.0000	0.3100	0.3100	2.2090	0.0000	0.0000	0.0000
a7	0.0000	0.1900	0.1900	0.0000	0.1520	0.0950	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
a8	0.0000	0.1100	0.1100	0.0000	0.0880	0.0550	0.0000	0.1100	0.1100	0.0000	0.0000	0.0000	0.0000
a9	0.0000	0.0800	0.0800	0.0000	0.0640	0.0400	0.0000	0.0800	0.0800	0.0000	0.0000	0.0000	0.0000
a10	0.0000	0.0400	0.0400	0.0000	0.0400	0.0320	0.0000	0.0400	0.0400	0.0650	0.0000	0.0000	0.0000
a11	0.0000	0.0260	0.0260	0.0000	0.0260	0.0208	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
a12	0.0000	0.0140	0.0140	0.0000	0.0140	0.0140	0.0000	0.0140	0.0140	0.0000	0.0000	0.0000	0.0000
a13	0.0000	0.0100	0.0100	0.0000	0.0100	0.0100	0.0000	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000
a14	0.0000	0.0050	0.0050	0.0000	0.0050	0.0050	0.0000	0.0050	0.0050	-0.2220	0.0000	0.0000	0.0000

w/o end field → ← with end field →

Tracking simulations set-up

- SixTrack
  - HLLHCV1.0 round and flat optics at 7 TeV, and injection optics at 450 GeV
  - 10^5 turns, 60 error seeds, 30 particle pairs per amplitude step (2σ), 11 x-y angles
  - Tune: 62.31, 60.32 (collision) and 62.28, 60.31 (injection)
  - Normalized emittance: 3.75 μm-rad
  - Arc errors and corrections included
  - IT correctors are ON in IR1 & IR5 and OFF in IR2 & IR8

- FQ error tables for IT, D1, D2, Q4, Q5 magnets
  - “ITbody_errortable_5”, “ITcs_errortable_v5”, “ITnc_errortable_v5”, “D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q4_errortable_v2_spec”, “Q5_errortable_v0_spec”
  - a2 and b2 are set to zero to simulate linear correction

- Beam-beam is not included

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DA evolution with IT FQ

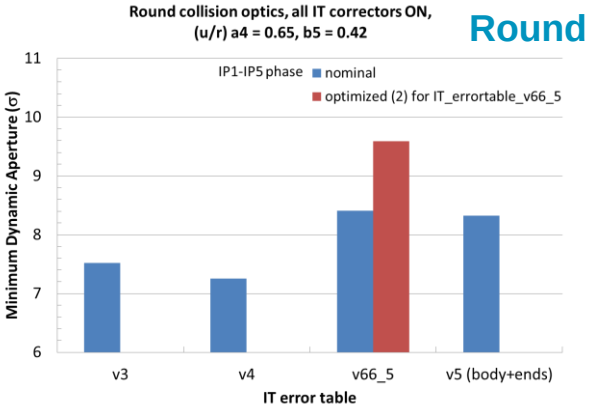
DAmin

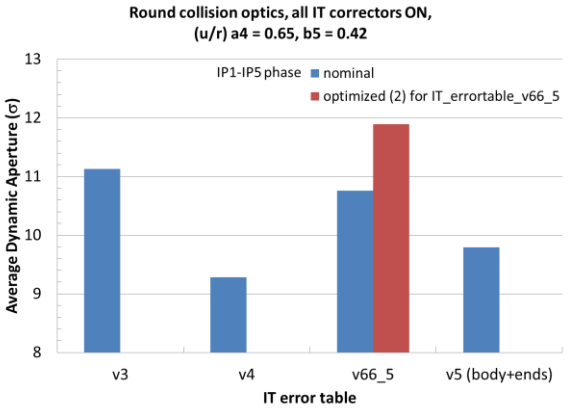
Nominal (u/r) a4 = 0.65, b5 = 0.42

> 1σ DA reduction with new FQ compared to the previous spec "IT_errortable_v66_5" (where some high order terms are reduced) and optimized IP1-IP5 phase advance

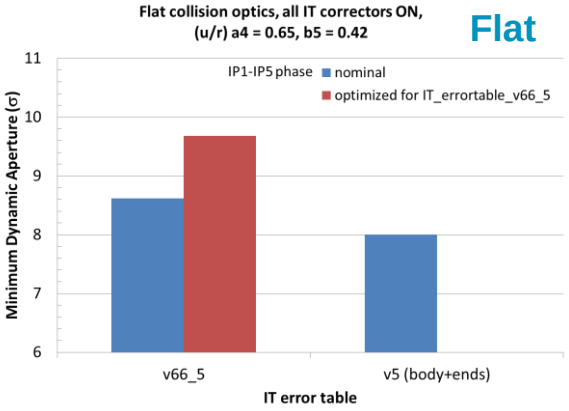
DAave

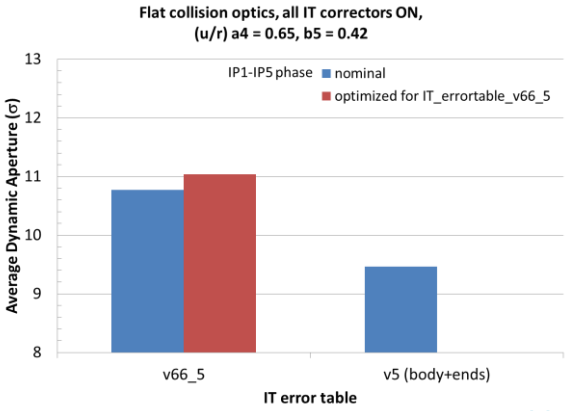
Round





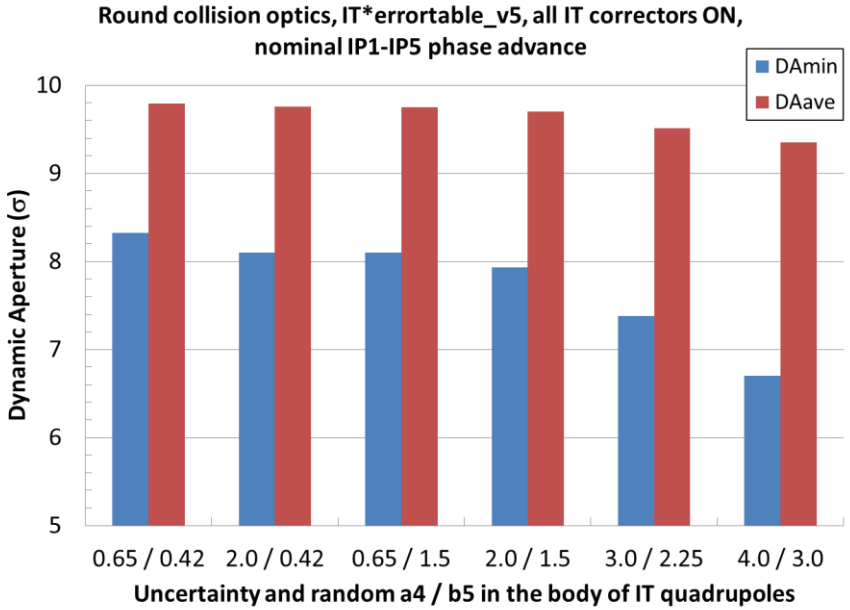
Flat



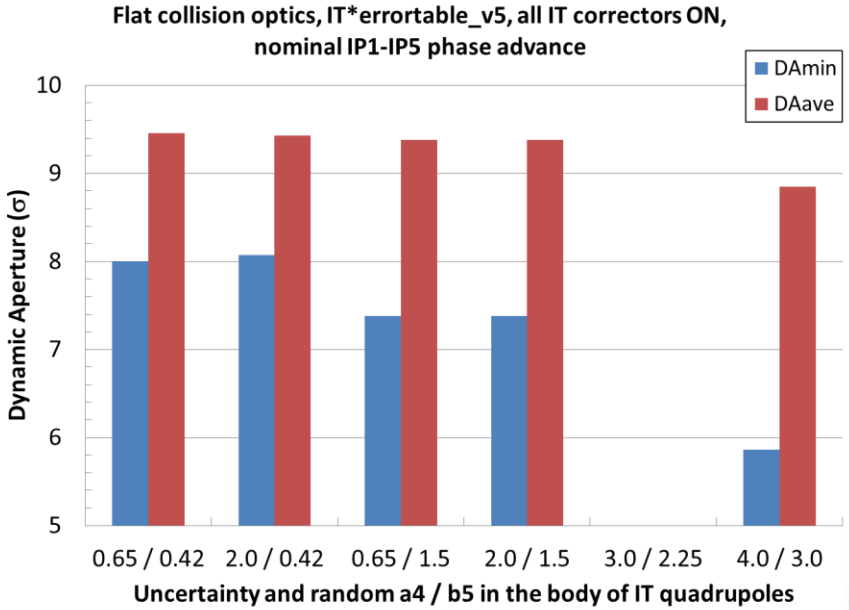


Impact of large a4 and b5 in the new FQ

- With (u/r) a4 = 2.0, b5 =1.5 and IT correctors ON, the DAmin is reduced by 0.4σ-0.6σ, and DAave by ~0.1σ
- Much stronger impact at larger a4, b5



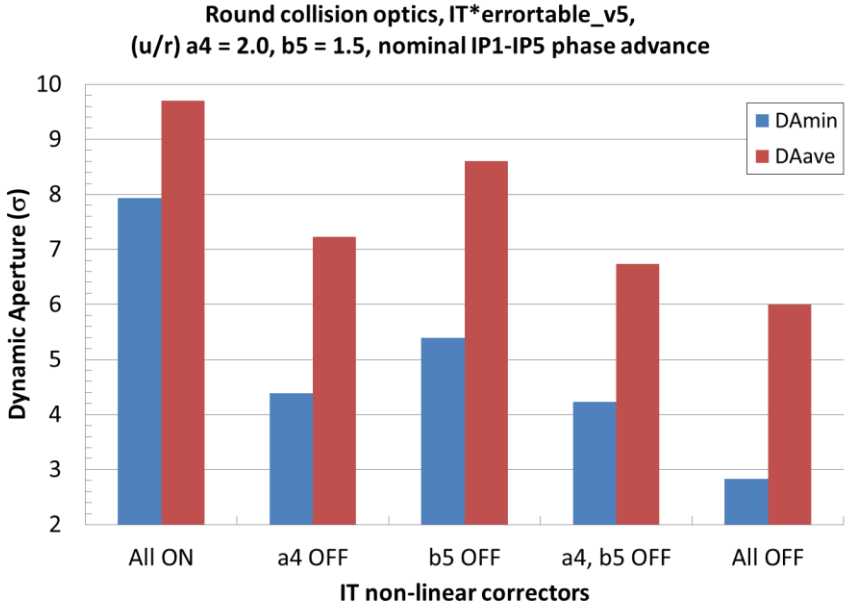
Round



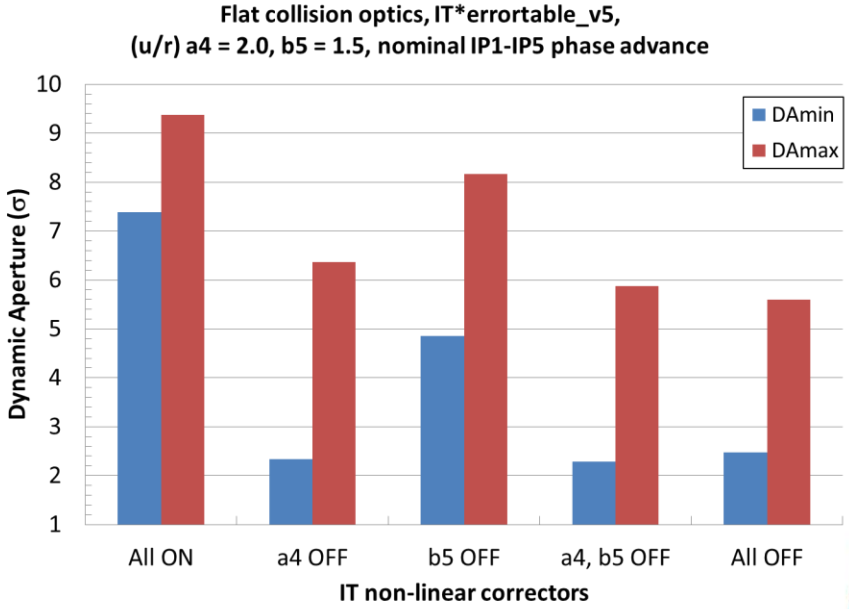
Flat

Impact of IT correctors at larger a4, b5

- With (u/r) a4 = 2.0, b5 =1.5 and the corresponding IT correctors OFF, the DAmin / DAave are ~4σ / 7σ (round) and ~2σ / 6σ (flat)
- The DA is more sensitive to a4 corrector than to b5 corrector



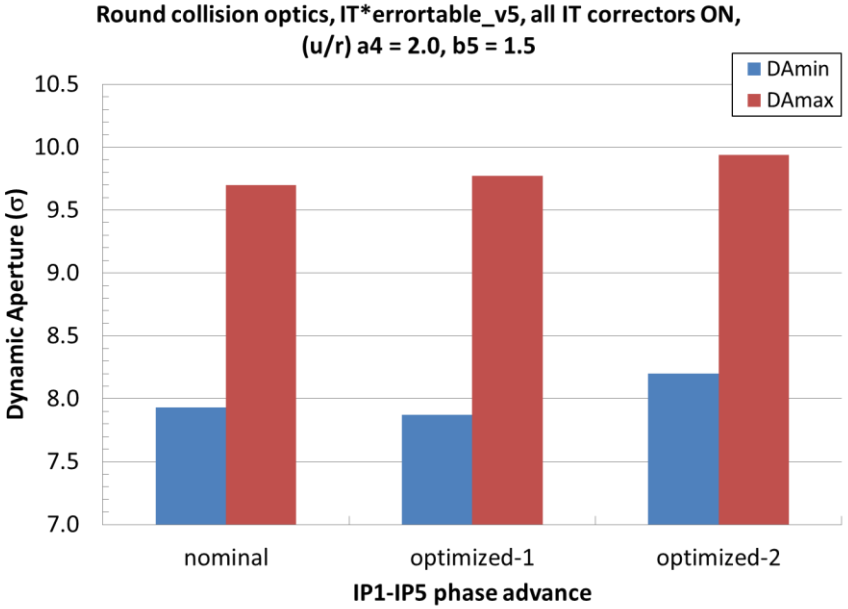
Round



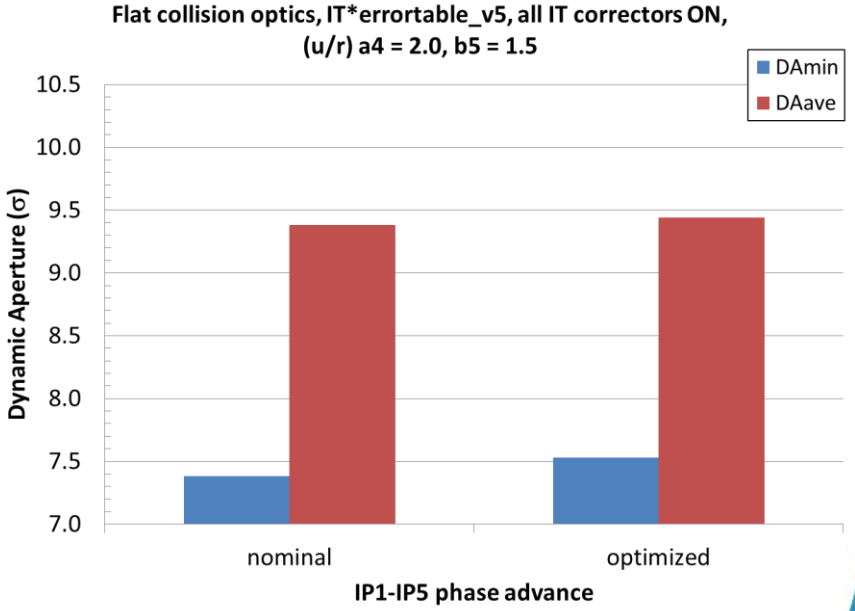
Flat

DA with previously optimized IP1-IP5 phase advance

- Little improvement with the previously optimized IP1-IP5 phase advance (for IT_errortable_v66_5) and the new IT FQ, where (u/r) a4 = 2.0, b5 = 1.5
- Optimal IP1-IP5 phase is sensitive to the IT FQ → optimization may need to be redone



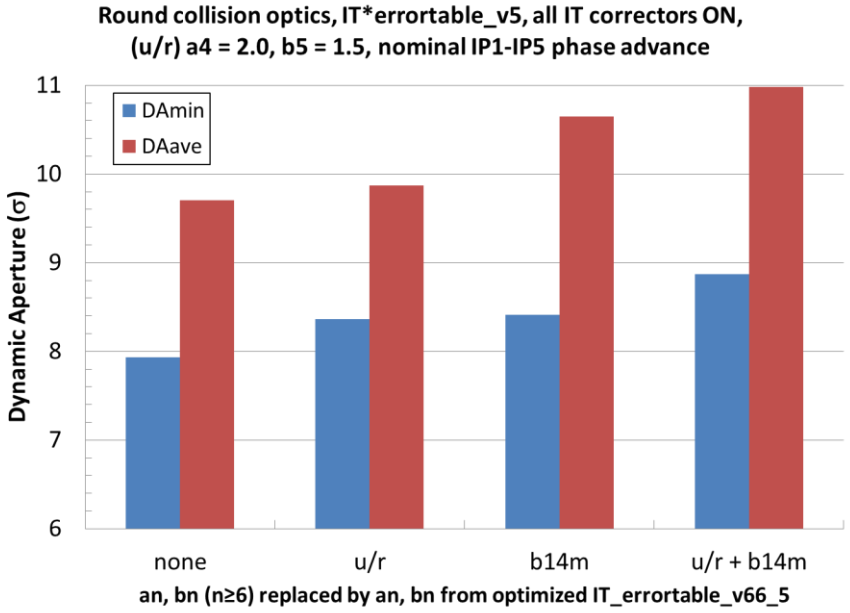
Round



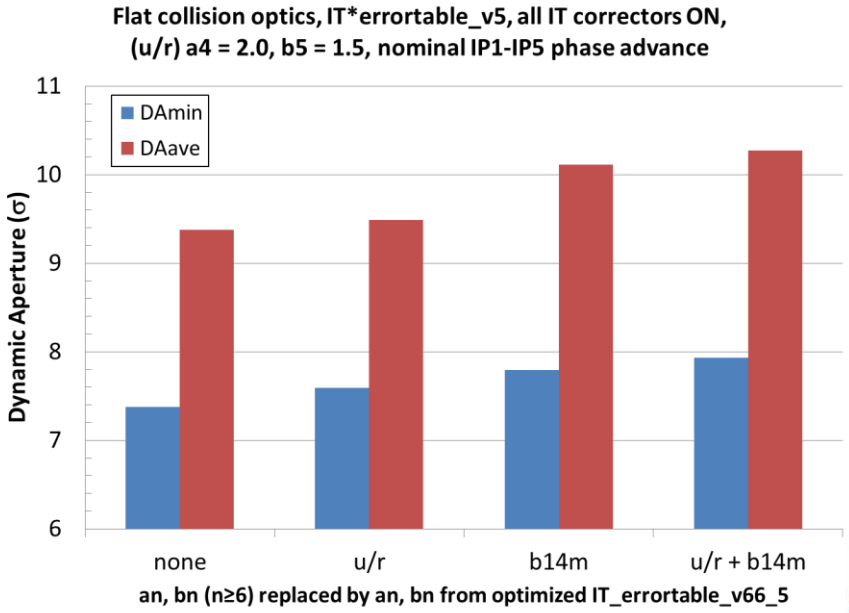
Flat

DA with previously optimized high order an, bn terms

- DA is increased up to ~1σ when b14m and high order u/r terms are reduced to values in “IT_errortable_v66_5” (b14m is reduced from -0.87 to -0.1675, and some n≥6 u/r terms are reduced by 20-50%), where (u/r) a4 = 2.0, b5 = 1.5



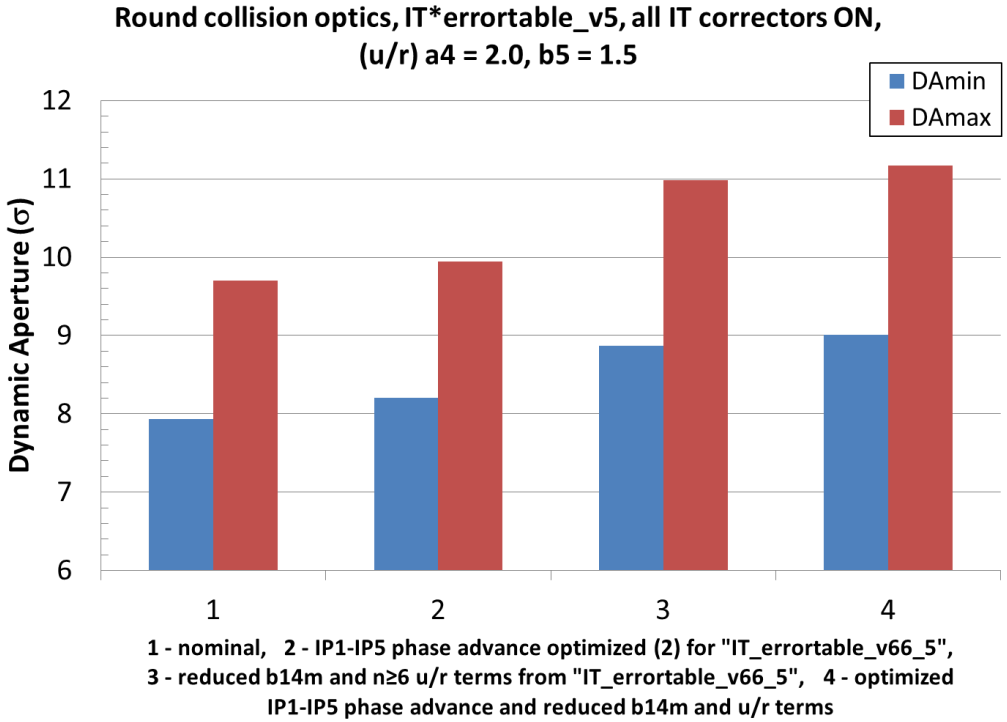
Round



Flat

Summary of possible DA improvements at collision

- The DA with the larger a4, b5 could be improved by
  - Re-optimizing the IP1-IP5 phase advance
  - Reducing some of the high order terms of the new IT FQ



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- Conclusions

Evolution of IT FQ spec (injection energy)

Colored cells show changes since “IT_errortable_v3”

Uncertainty / random terms have not changed (except a3)

“ITcs*v5” and “ITnc*v5” are for the connection and non-connection sides

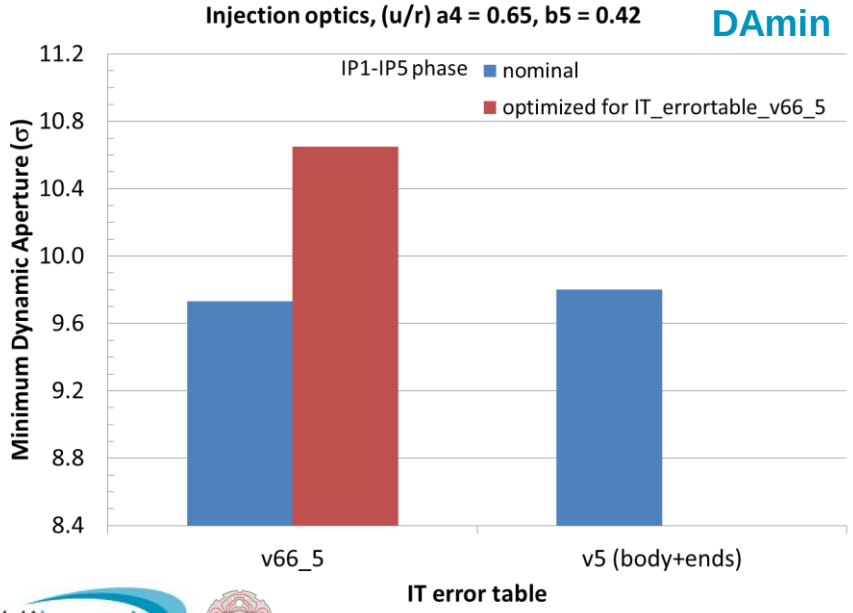
New larger b6m

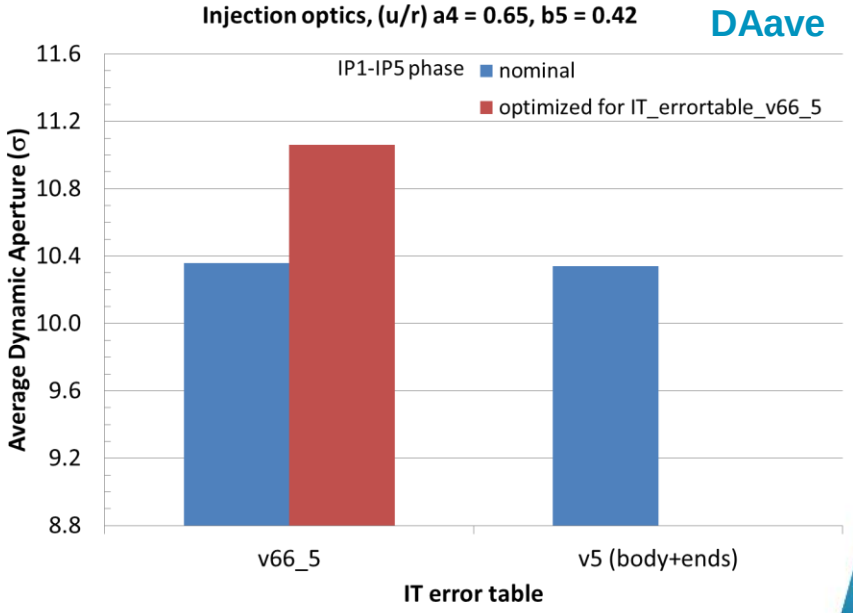
The larger a4 and b5 will be applied to the “ITbody_errortable_v5”

Injection	IT_errortable_v4			IT_errortable_v66_5 (optimized)			ITbody_errortable_v5			ITcs_errortable_v5		ITnc_errortable_v5	
	m	u	r	m	u	r	m	u	r	m	u/r	m	u/r
b2	0.0000	0.0000	0.0000	0.0000	0.0000	10.0000	0.0000	0.0000	10.0000	0.0000	0.0000	0.0000	0.0000
b3	0.0000	0.8200	0.8200	0.0000	0.8200	0.8200	0.0000	0.8200	0.8200	0.0000	0.0000	0.0000	0.0000
b4	0.0000	0.5700	0.5700	0.0000	0.5700	0.5700	0.0000	0.5700	0.5700	0.0000	0.0000	0.0000	0.0000
b5	0.0000	0.4200	0.4200	0.0000	0.4200	0.4200	0.0000	0.4200	0.4200	0.0000	0.0000	0.0000	0.0000
b6	-15.8000	1.1000	1.1000	-15.8000	1.1000	1.1000	-21.3000	1.1000	1.1000	8.9430	0.0000	-0.0250	0.0000
b7	0.0000	0.1900	0.1900	0.0000	0.1900	0.1900	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
b8	0.0000	0.1300	0.1300	0.0000	0.1300	0.1300	0.0000	0.1300	0.1300	0.0000	0.0000	0.0000	0.0000
b9	0.0000	0.0700	0.0700	0.0000	0.0700	0.0700	0.0000	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000
b10	3.6300	0.2000	0.2000	3.6300	0.2000	0.2000	3.8900	0.2000	0.2000	-0.1890	0.0000	-0.8210	0.0000
b11	0.0000	0.0260	0.0260	0.0000	0.0260	0.0260	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
b12	0.0000	0.0180	0.0180	0.0000	0.0180	0.0180	0.0000	0.0180	0.0180	0.0000	0.0000	0.0000	0.0000
b13	0.0000	0.0090	0.0090	0.0000	0.0090	0.0090	0.0000	0.0090	0.0090	0.0000	0.0000	0.0000	0.0000
b14	-0.6000	0.0230	0.0230	-0.6000	0.0230	0.0230	0.2100	0.0230	0.0230	-0.5450	0.0000	-1.0830	0.0000
a2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	10.0000	-31.3420	0.0000	0.0000	0.0000
a3	0.0000	0.8000	0.8000	0.0000	0.8000	0.8000	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a4	0.0000	0.6500	0.6500	0.0000	0.6500	0.6500	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a5	0.0000	0.4300	0.4300	0.0000	0.4300	0.4300	0.0000	0.4300	0.4300	0.0000	0.0000	0.0000	0.0000
a6	0.0000	0.3100	0.3100	0.0000	0.3100	0.3100	0.0000	0.3100	0.3100	2.2090	0.0000	0.0000	0.0000
a7	0.0000	0.1900	0.1900	0.0000	0.1900	0.1900	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
a8	0.0000	0.1100	0.1100	0.0000	0.1100	0.1100	0.0000	0.1100	0.1100	0.0000	0.0000	0.0000	0.0000
a9	0.0000	0.0800	0.0800	0.0000	0.0800	0.0800	0.0000	0.0800	0.0800	0.0000	0.0000	0.0000	0.0000
a10	0.0000	0.0400	0.0400	0.0000	0.0400	0.0400	0.0000	0.0400	0.0400	0.0650	0.0000	0.0000	0.0000
a11	0.0000	0.0260	0.0260	0.0000	0.0260	0.0260	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
a12	0.0000	0.0140	0.0140	0.0000	0.0140	0.0140	0.0000	0.0140	0.0140	0.0000	0.0000	0.0000	0.0000
a13	0.0000	0.0100	0.0100	0.0000	0.0100	0.0100	0.0000	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000
a14	0.0000	0.0050	0.0050	0.0000	0.0050	0.0050	0.0000	0.0050	0.0050	-0.2220	0.0000	0.0000	0.0000

DA evolution with IT FQ at injection

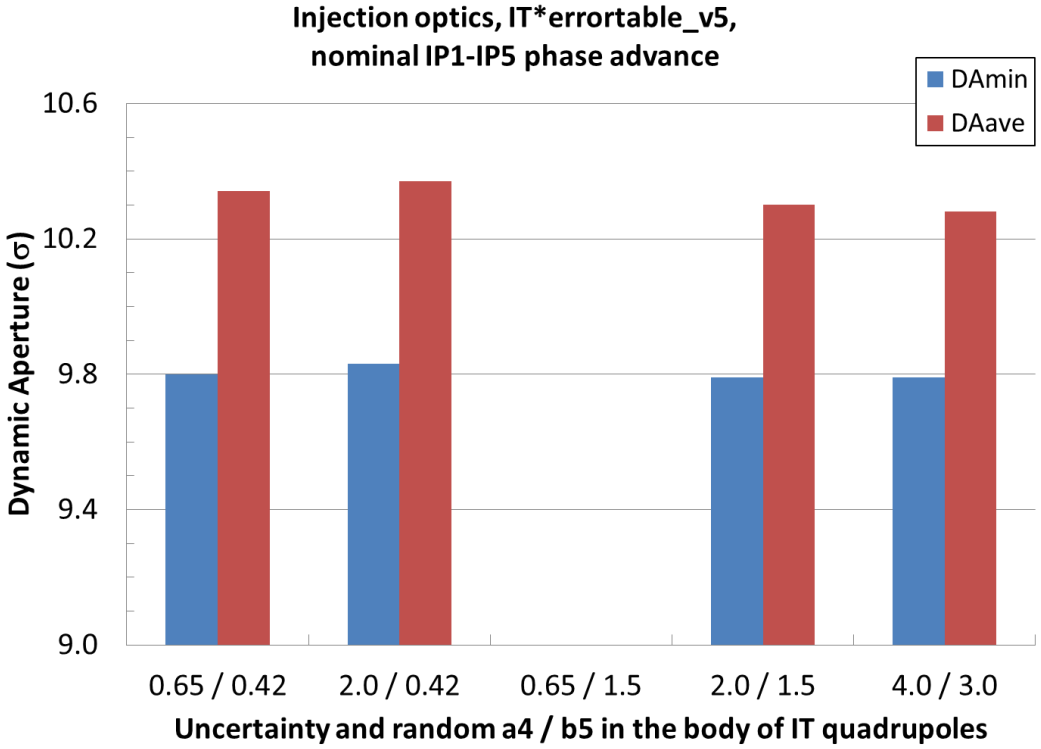
- Nominal (u/r) a4 = 0.65, b5 = 0.42
- No DA reduction at the nominal IP1-IP5 phase advance, but almost 1σ lower DA if compared to the DA with previous FQ and optimized phase advance





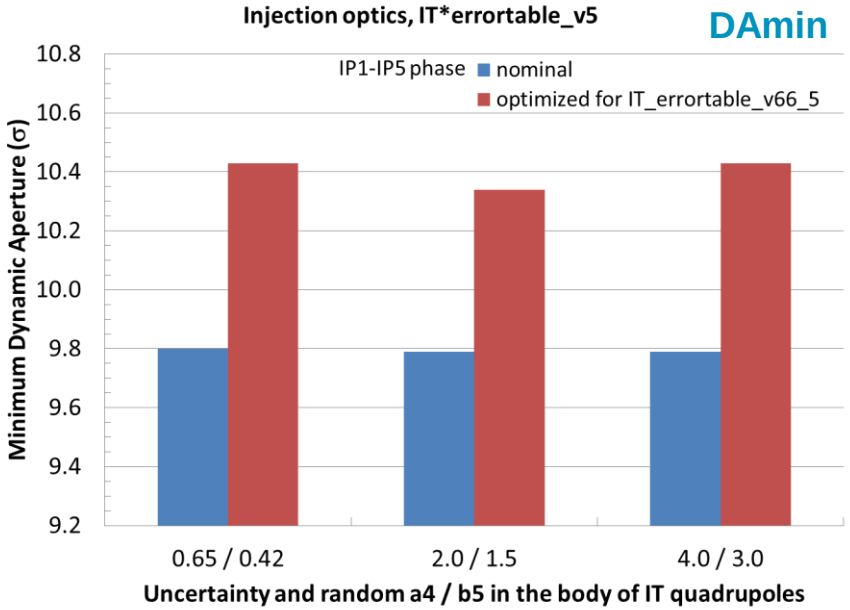
Impact of large a4 and b5 at injection

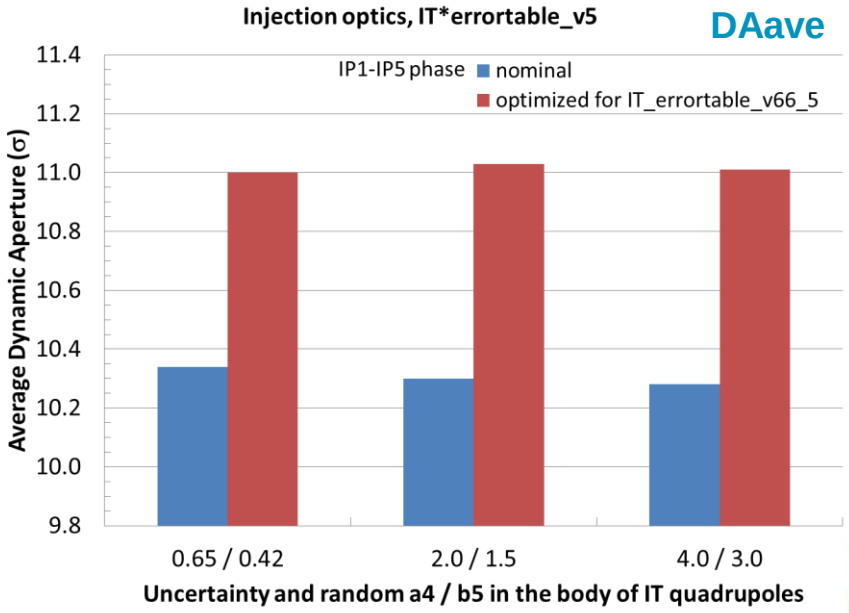
- Small impact on DA with the new IT FQ and (u/r) a4, b5 increased up to a4 = 4.0, b5 = 3.0



DA at injection with previously optimized IP1-IP5 phase advance

- Almost the same level of DA improvement with the new IT FQ when using the previously optimized IP1-IP5 phase advance (for IT_errortable_v66_5)
- Low sensitivity to a4 and b5





Conclusions

- Sixtrack simulations with the large (u/r) a4 and b5 terms of the IT FQ at collision energy show that
  - Reduction of minimum DA can be on the order of 0.5σ
  - The impact of the large a4, b5 is significantly increased if the corresponding IT correctors are OFF
  - The previously optimized IP1-IP5 phase advance does not significantly improve the DA with the new IT FQ (body + end field)
  - Impact on the flat optics DA is somewhat worse compared to the round optics
  - Options for improving the DA may include a re-optimization of the IP1-IP5 phase advance and a modest reduction of high order an, bn terms
- Simulations at injection energy show that
  - DA is not sensitive to the a4, b5 in the studied range
  - The previously optimized IP1-IP5 phase advance provides similar DA improvement with the new IT FQ and larger (u/r) a4, b5 as with the previous IT FQ

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