



## Field quality to achieve the required lifetime goals (single beam)

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# Outline

- Update on IT corrector strengths with large  $a_4$ ,  $b_5$  in the IT quads at collision energy
- Dynamic aperture vs tune at collision and injection energies
- Dynamic aperture and choice of tune during energy ramp and pre-squeeze
- Impact of strong octupoles and large chromaticity at injection energy
- Summary and Conclusions

# DA vs large a4, b5 in IT (7 TeV): summary of previous study

- **Measured:** IT a4 up to 6.5 and b5 up to 3.2 (*S.I. Bermudez, E. Todesco, et al*) → May remain large in final magnets
- **FQ spec:** a4<sub>u,r</sub> = 0.65, b5<sub>u,r</sub> = 0.42, a4<sub>s</sub> = 0, b5<sub>s</sub> = 0
- **Studied:** a4<sub>u</sub> = a4<sub>r</sub> ≥ 2, b5<sub>u</sub> = b5<sub>r</sub> ≥ 1.5 (and higher)

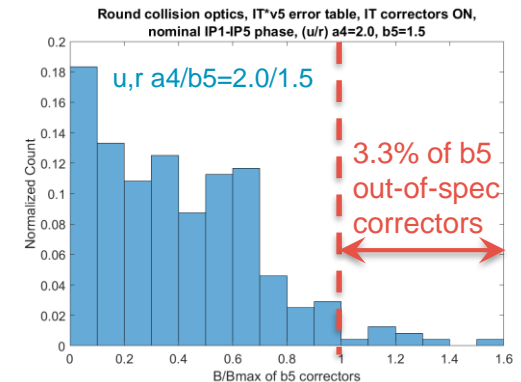
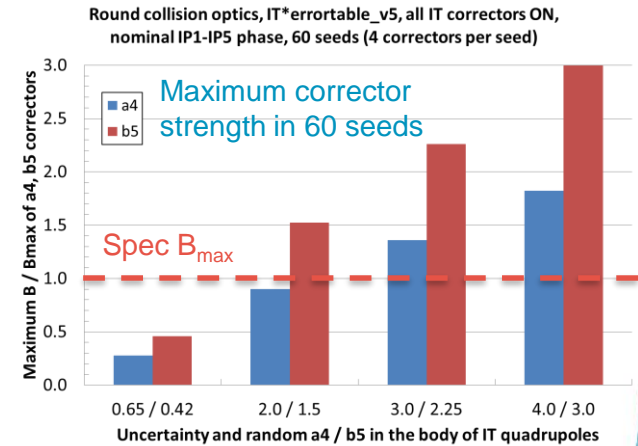
## Findings:

- At a4<sub>u,r</sub> = 2, b5<sub>u,r</sub> = 1.5 → DA at collision is reduced by ~0.5σ
- Strongest a4, b5 IT correctors exceed their maximum spec field at a4<sub>u,r</sub> > 2.2 and b5<sub>u,r</sub> > 1.0
- Suggested remedies: a) longer a4, b5 IT correctors, b) additional b5 correctors for D2

## Question:

- What is the relationship between the IT a4, b5 errors and the a4, b5 maximum corrector strengths?

Note that based on  $b = b_s + (\xi_u / 1.5)b_u + \xi_r b_r$ , where random values  $\xi_u < 1.5$ ,  $\xi_r < 3$ , the maximum possible: a4 = a4<sub>u</sub> + 3\*a4<sub>r</sub> and b5 = b5<sub>u</sub> + 3\*b5<sub>r</sub> (e.g. a4<sub>u,r</sub> = 2 → a4<sub>max</sub> = 8; b5<sub>u,r</sub> = 1.5 → b5<sub>max</sub> = 6)



# DA vs large a4, b5 in IT (7 TeV): new study

- Each of the IR1 & IR5 has two a4 and two b5 IT correctors compensating the randomly generated a4 and b5 in each IR's 12 IT quads
- Correlation between the two corrector strengths and the corresponding errors in the IT is not straightforward → it depends on a4, b5 random distribution in the 12 IT quads
- **A different approach → assume that the IT a4 and b5 are systematic only**
  - $a4s = a4u + a4r$ ,  $b5s = b5u + b5r$ , and set  $a4u = a4r = b5u = b5r = 0$
  - → easy to determine maximum corrector strength vs systematic error
- In this case, it is also easy to determine the contribution to the a4, b5 corrector strengths from u/r a4, b5 in D1 by comparing two cases
  - D1 with the spec  $a4u = a4r = 0.444$ ,  $b5u = b5r = 0.365$
  - D1 with  $a4 = 0$ ,  $b5 = 0$
- Tracking for round ( $\beta^* = 15$  cm) and flat (7.5/30 cm) collision optics at 7 TeV

# Tracking simulations set-up

- SixTrack
  - HLLHCV1.0 optics at collision (7 TeV) and injection (450 GeV) energies
  - $10^5$  turns, 60 error seeds, 30 particle pairs per amplitude step ( $2\sigma$ ), 11 x-y angles
  - Tune: 62.31, 60.32 (collision) and 62.28, 60.31 (injection)
  - Normalized emittance: **3.75  $\mu\text{m-rad}$**  (for  $\sigma$  calculation)
  - Chromaticity: +3
  - Arc errors and standard corrections
  - IT non-linear correctors are ON in IR1/IR5 (collision only), and OFF in IR2/IR8
- Latest FQ 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 terms are set to zero to simulate linear correction
- Beam-beam effects are not included

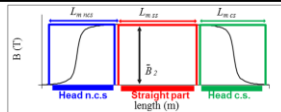
# IT FQ spec at injection and collision energies

## 7 TeV

## 450 GeV

Collision	ITbody_errortable_v5			ITcs_errortable_v5		ITnc_errortable_v5	
	s	u	r	s	u/r	s	u/r
b2	0.0000	0.0000	10.0000	0.0000	0.0000	0.0000	0.0000
b3	0.0000	0.8200	0.8200	0.0000	0.0000	0.0000	0.0000
b4	0.0000	0.5700	0.5700	0.0000	0.0000	0.0000	0.0000
b5	0.0000	0.4200	0.4200	0.0000	0.0000	0.0000	0.0000
b6	-0.6400	1.1000	1.1000	8.9430	0.0000	-0.0250	0.0000
b7	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
b8	0.0000	0.1300	0.1300	0.0000	0.0000	0.0000	0.0000
b9	0.0000	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000
b10	-0.1100	0.2000	0.2000	-0.1890	0.0000	-0.8210	0.0000
b11	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
b12	0.0000	0.0180	0.0180	0.0000	0.0000	0.0000	0.0000
b13	0.0000	0.0090	0.0090	0.0000	0.0000	0.0000	0.0000
b14	-0.8700	0.0230	0.0230	-0.5450	0.0000	-1.0830	0.0000
a2	0.0000	0.0000	10.0000	-31.3420	0.0000	0.0000	0.0000
a3	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a4	0.0000	0.6500	0.6500	0.0000	0.0000	0.0000	0.0000
a5	0.0000	0.4300	0.4300	0.0000	0.0000	0.0000	0.0000
a6	0.0000	0.3100	0.3100	2.2090	0.0000	0.0000	0.0000
a7	0.0000	0.1900	0.1900	0.0000	0.0000	0.0000	0.0000
a8	0.0000	0.1100	0.1100	0.0000	0.0000	0.0000	0.0000
a9	0.0000	0.0800	0.0800	0.0000	0.0000	0.0000	0.0000
a10	0.0000	0.0400	0.0400	0.0650	0.0000	0.0000	0.0000
a11	0.0000	0.0260	0.0260	0.0000	0.0000	0.0000	0.0000
a12	0.0000	0.0140	0.0140	0.0000	0.0000	0.0000	0.0000
a13	0.0000	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000
a14	0.0000	0.0050	0.0050	-0.2220	0.0000	0.0000	0.0000

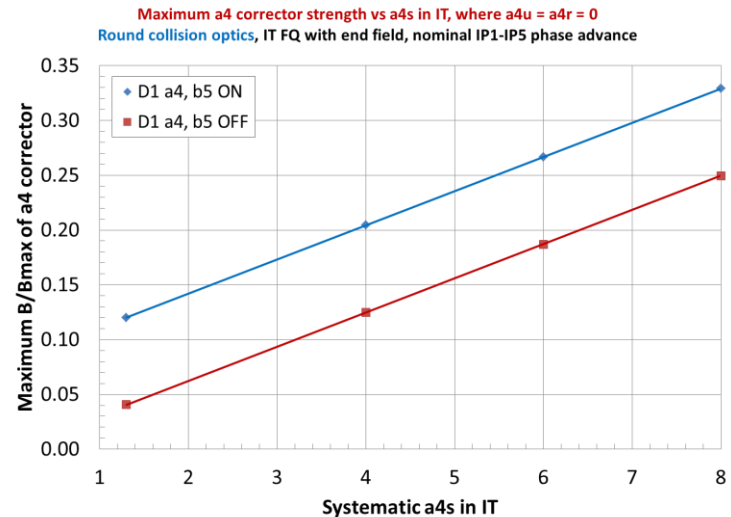
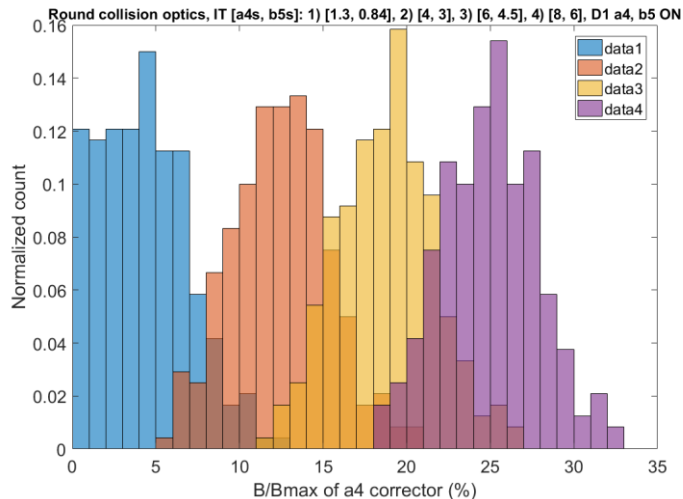
Injection	ITbody_errortable_v5			ITcs_errortable_v5		ITnc_errortable_v5	
	s	u	r	s	u/r	s	u/r
b2	0.0000	0.0000	10.0000	0.0000	0.0000	0.0000	0.0000
b3	0.0000	0.8200	0.8200	0.0000	0.0000	0.0000	0.0000
b4	0.0000	0.5700	0.5700	0.0000	0.0000	0.0000	0.0000
b5	0.0000	0.4200	0.4200	0.0000	0.0000	0.0000	0.0000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



End field included

# a4 corrector strength vs IT a4s (7 TeV)

- Four settings of IT a4s,b5s: [1.3,0.84], [4,3], [6,4.5], [8,6]
- Two settings of D1 a4, b5: on and off
- Linear dependence of maximum a4 corrector strength vs a4s
- **Weak a4 correctors compared to case with uncertainty/random a4** → corrector will reach the spec limit at a4s ≈ 29 → a4u,r = 14.5 → **too optimistic**
- Contribution of D1 to the a4 corrector strength is about 8% of the corrector  $B_{\max}$



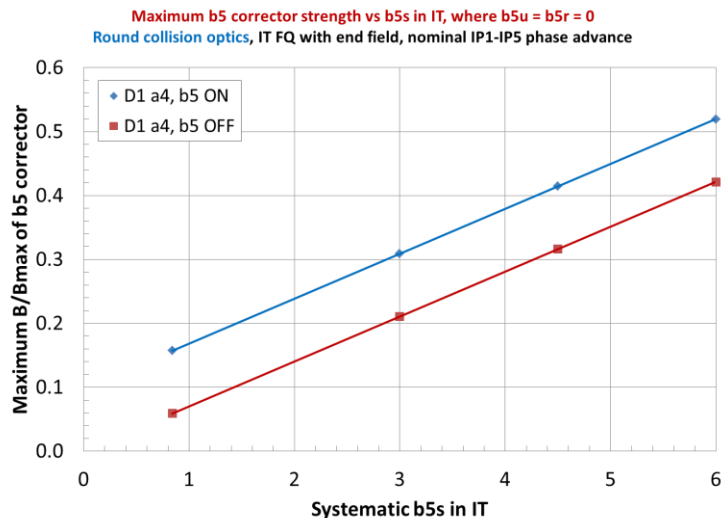
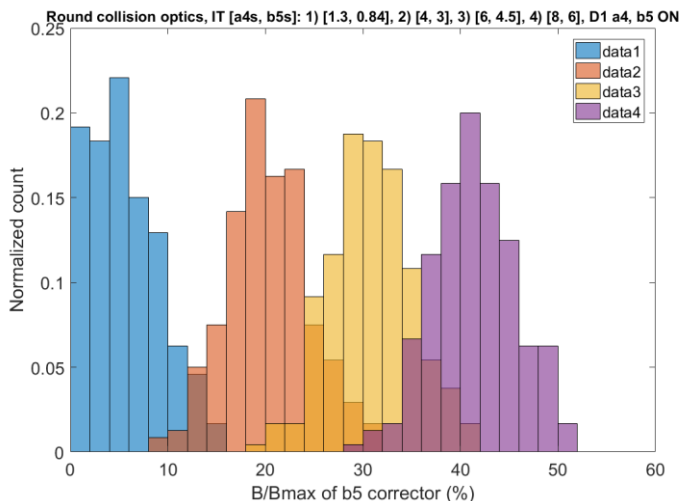
Same result for collision and flat optics

a4  $B_{\max} L = 0.046 Tm @ 50 mm$

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# b5 corrector strength vs IT b5s (7 TeV)

- Four settings of IT a4s,b5s: [1.3,0.84], [4,3], [6,4.5], [8,6]
- Two settings of D1 a4, b5: on and off
- Linear dependence of maximum b5 corrector strength vs b5s
- **Weak b5 correctors compared to case with uncertainty/random b5 → corrector will reach the spec limit at b5s ≈ 13 → b5<sub>u,r</sub> = 6.5 → too optimistic**
- Contribution of D1 to the b5 corrector strength is about 10% of the corrector B<sub>max</sub>



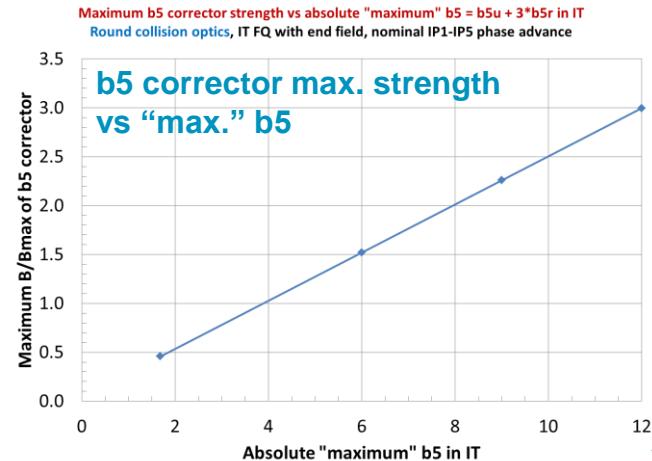
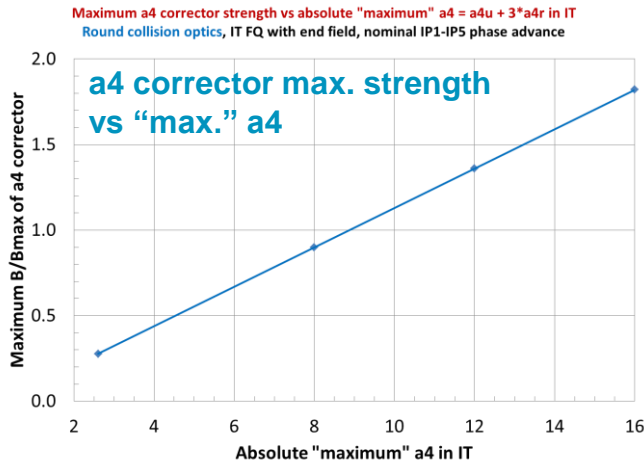
Same result for collision and flat optics

b5 B<sub>max</sub>L = 0.025 Tm @ 50 mm

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# Maximum a4, b5 corrector strengths vs “maximum” a4, b5

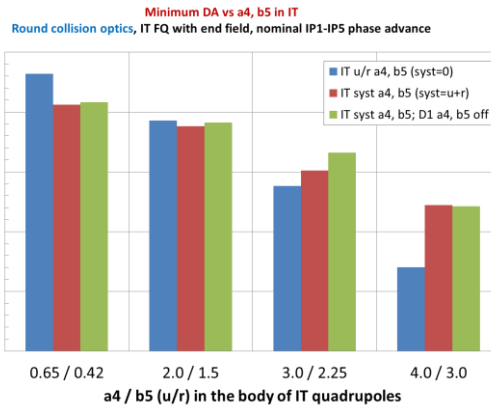
- IT corrector strengths with systematic a4s, b5s are low → too optimistic
- The reason → systematic field errors change sign in focusing and defocusing IT quads → sum of all errors is reduced → weaker corrector
- Random & uncertainty errors may add up → stronger correctors needed
- Revisit the study with u/r a4, b5 and plot maximum corrector strength vs absolute maximum of  $a4 = a4u + 3 \cdot a4r$  and  $b5 = b5u + 3 \cdot b5r$  (may not be reached due to limited statistics with 60 seeds)
- In this case, **a4 corrector reaches the limit at max a4 ≈ 8.8, and b5 corrector at max b5 ≈ 4** → optimistic limit on measured errors (based on correction only) → more random seeds are needed for better accuracy



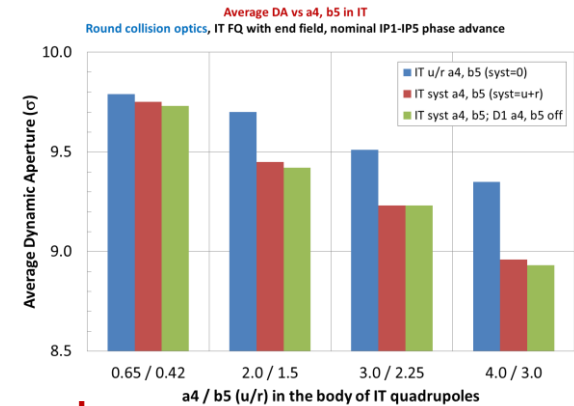
# DA with a4, b5 (u/r vs systematic)

- Round and flat collision optics
- Minimum and average DA vs IT a4, b5
- **3 cases:**
  1. u/r a4, b5 with syst = 0
  2. syst = u+r, with u/r reset to 0
  3. as in (2), but D1 a4, b5 are off
- Comparable minimum DA in all cases at  $a4u,r = 2, b5u,r = 1.5$  ( $a4s = 4, b5s = 3$ )
- At larger a4, b5 the minimum DA is reduced more with u/r errors than with systematic errors, but the average DA with u/r errors is larger due to a larger DA spread
- Impact of D1 a4, b5 is  $\approx 0.1-0.2\sigma$

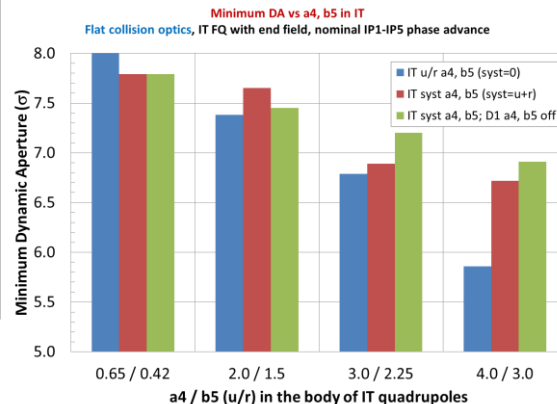
## Minimum DA



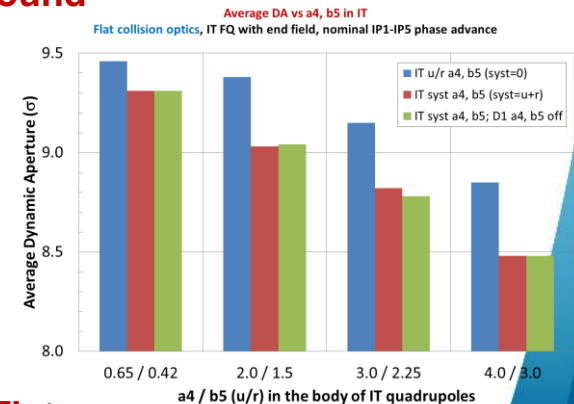
## Average DA



Round



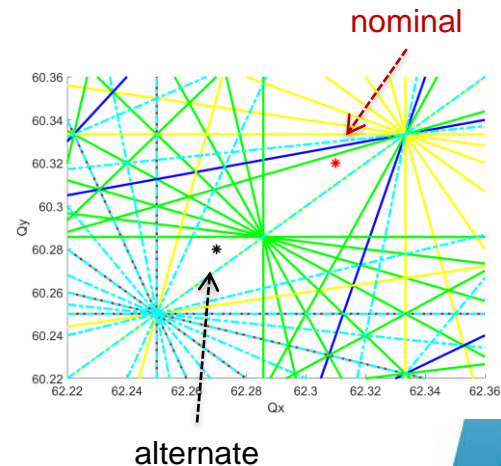
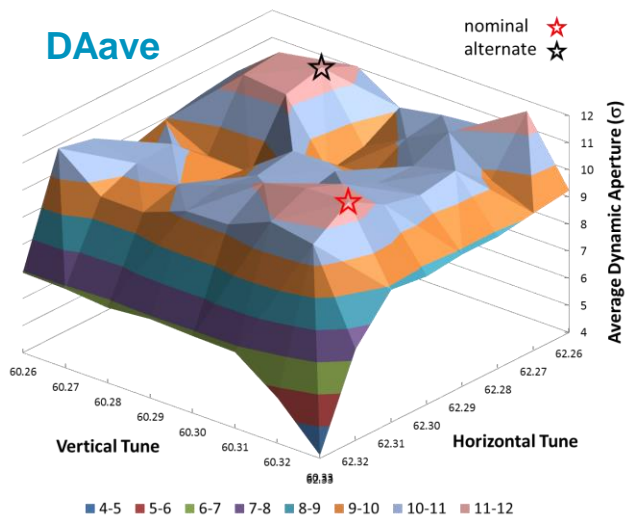
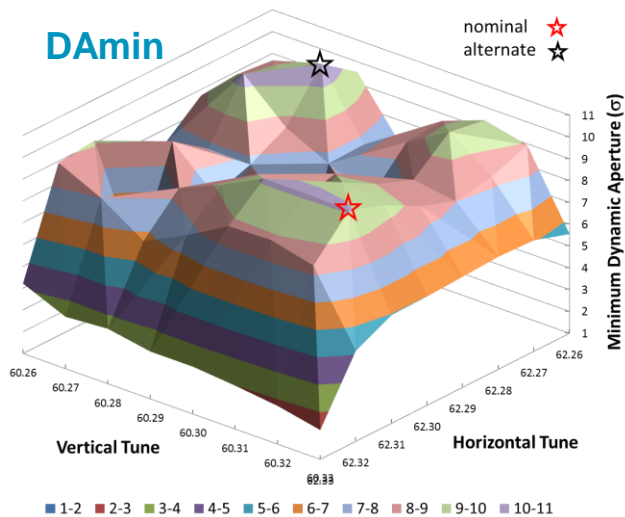
Flat



Flat

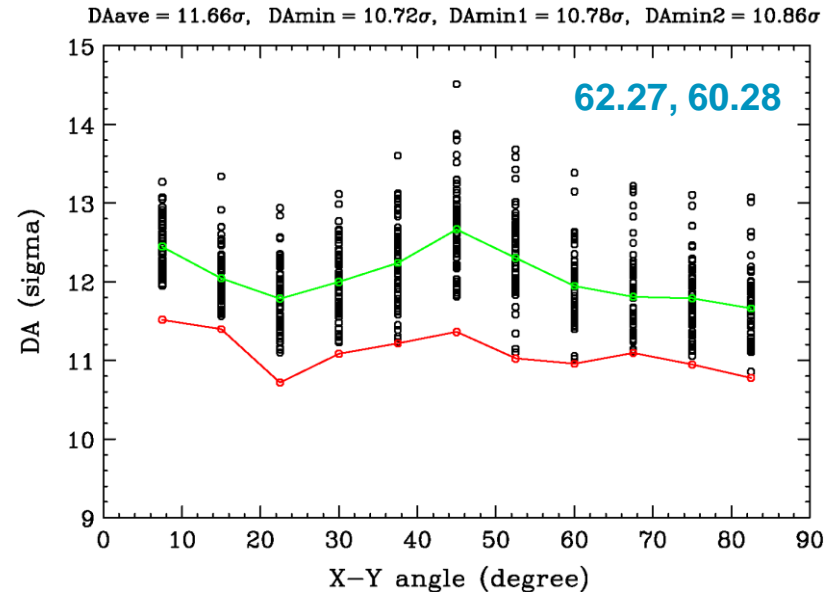
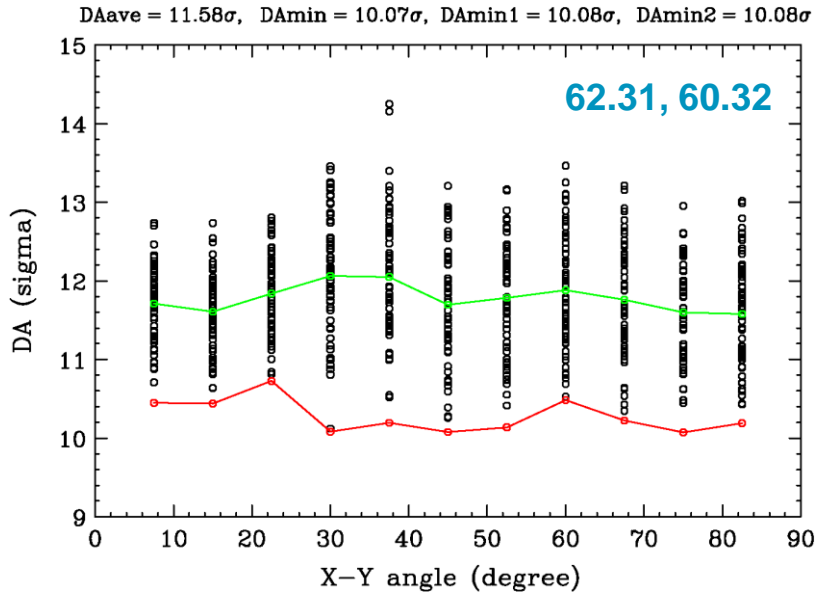
# DA vs tune at collision energy

- Is the LHC collision tune 62.31, 60.32 still optimal?
- Perform dynamic aperture tune scan with nominal settings and octupoles off
- Round collision optics, earlier version of IT FQ without end field
- Still good DA at the nominal tune of 62.31, 60.32
- Comparable DA at “alternate” tune of 62.27, 60.28



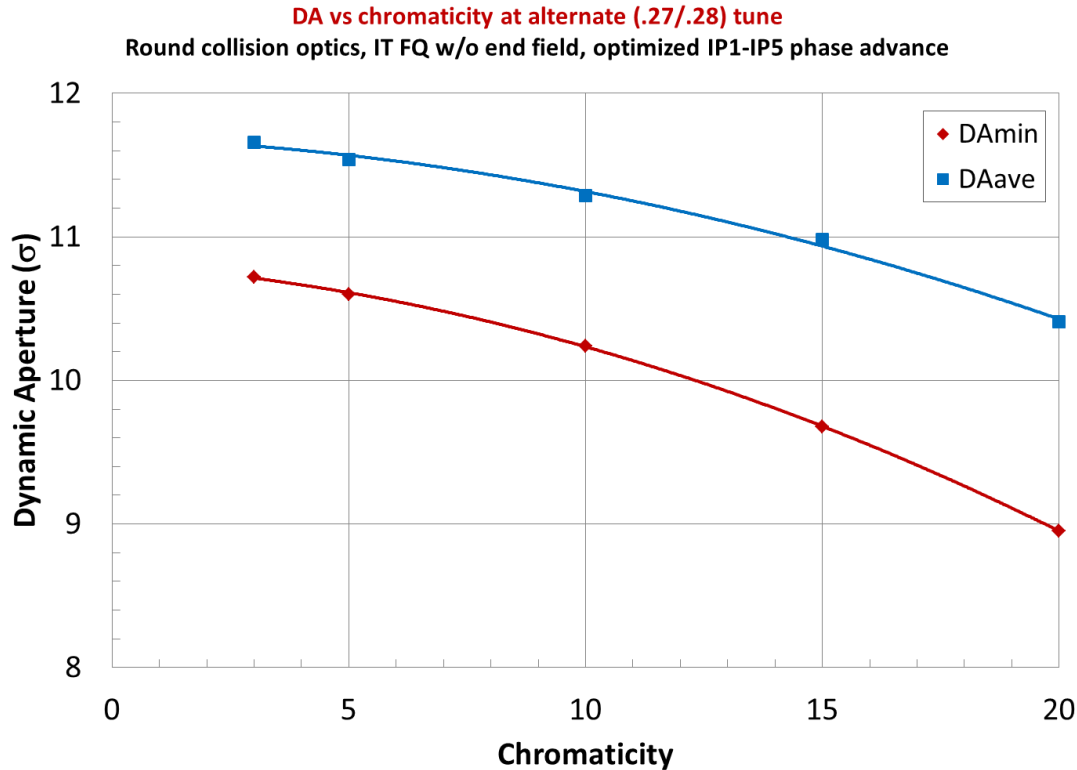
# DA: Nominal vs alternate tune at collision energy

- Round optics, octupoles off
- Nominal tune 62.31, 60.32 →  $DA_{min} = 10.07\sigma$ ,  $DA_{ave} = 11.58\sigma$
- Alternate tune 62.27, 60.28 →  $DA_{min} = 10.72\sigma$ ,  $DA_{ave} = 11.66\sigma$



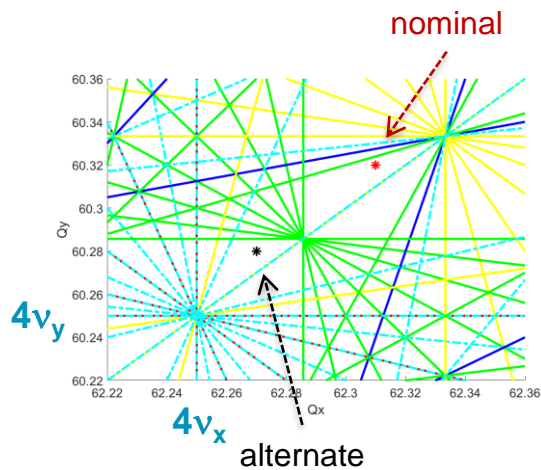
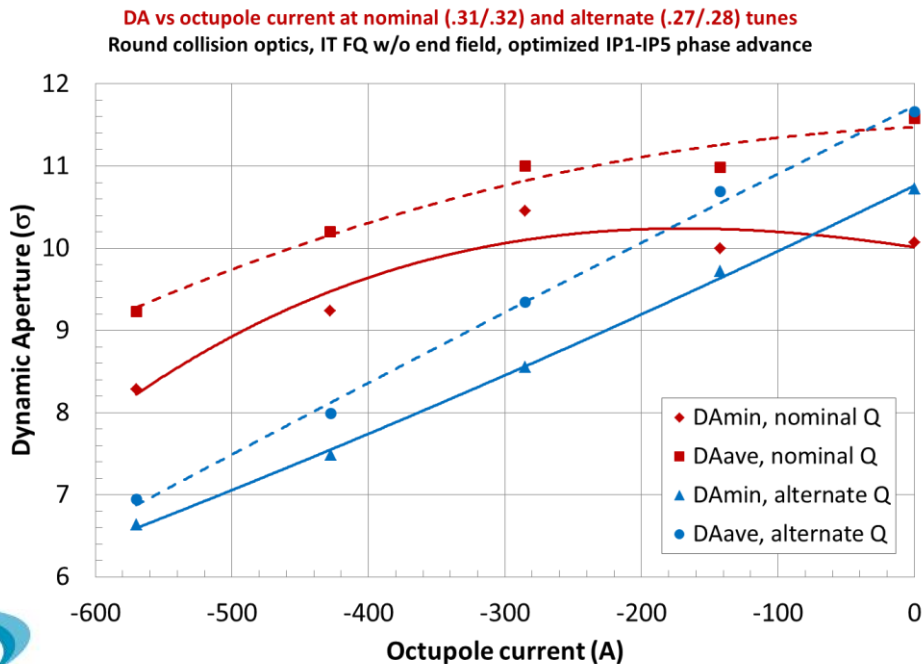
# DA at alternate tune vs chromaticity at collision energy

- DA chromatic dependence is comparable at the nominal and alternate tunes



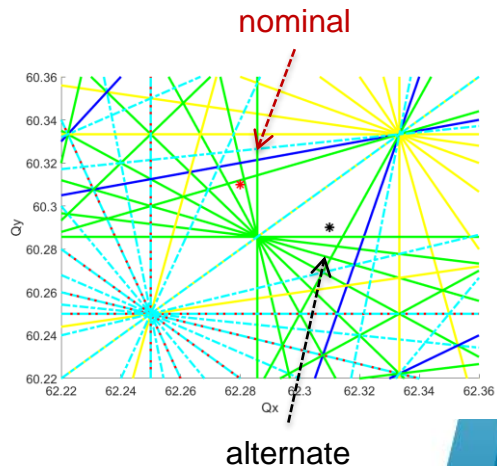
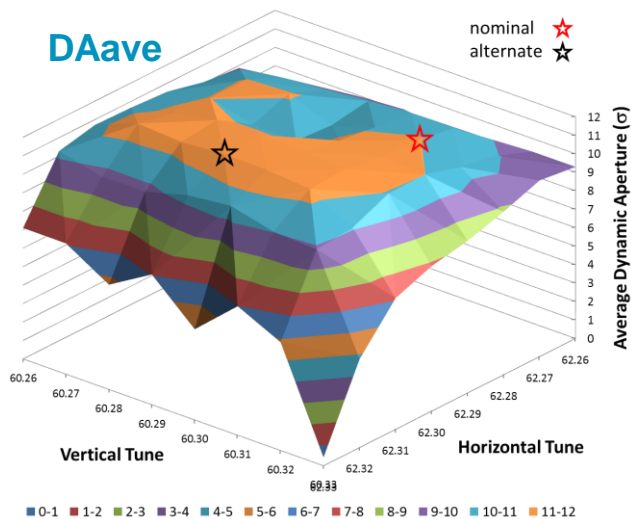
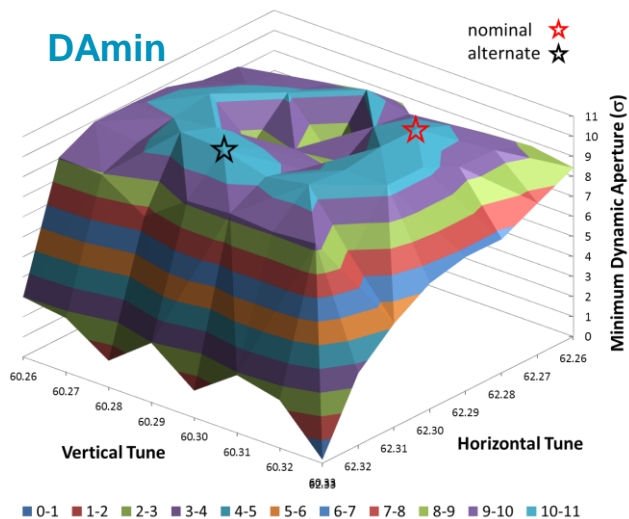
# DA with octupoles: Nominal vs alternate tune at collision energy

- Strong impact of octupoles at the alternate tune 62.27, 62.28
- The effect is due to the tune being close to the octupole driven 4<sup>th</sup> order resonances
- Better performance with the 62.31, 60.32 nominal tune



# DA vs tune at injection energy

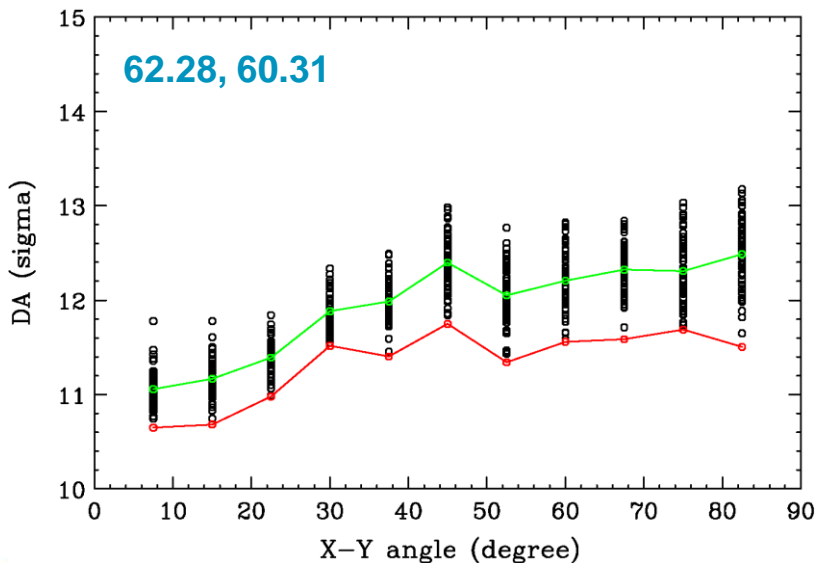
- Perform dynamic aperture tune scan with nominal settings and octupoles off
- Injection optics, IT FQ without end field
- Still good DA at the nominal tune of 62.28, 60.31
- Comparable DA at tune of 62.31, 60.29 (on the other side of  $\nu_x = \nu_y$  resonance line)



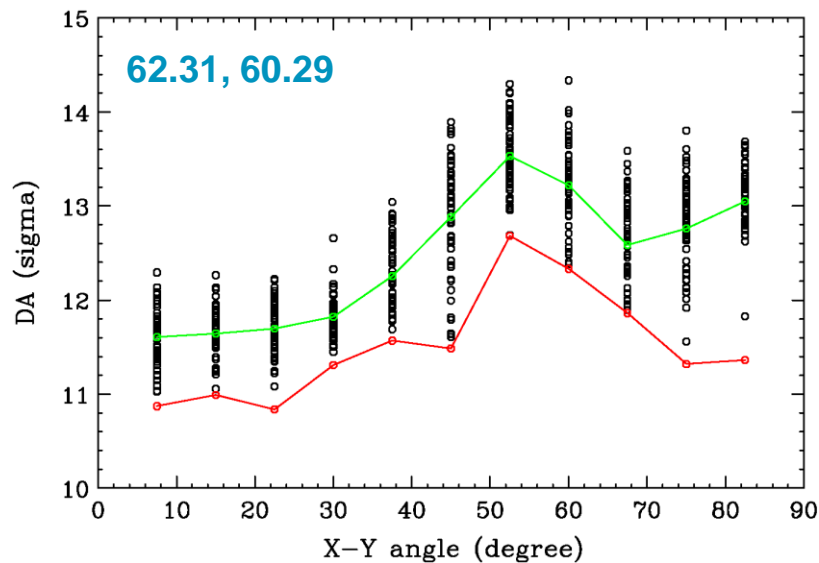
# DA: Nominal vs alternate tune at injection energy

- Injection optics, octupoles off
  - Nominal tune 62.28, 60.31  $\rightarrow$   $DA_{min} = 10.65\sigma$ ,  $DA_{ave} = 11.06\sigma$
  - Alternate tune 62.31, 60.29  $\rightarrow$   $DA_{min} = 10.84\sigma$ ,  $DA_{ave} = 11.61\sigma$
- But transition to collision tune requires crossing the  $\nu_x = \nu_y$  resonance line

$DA_{ave} = 11.06\sigma$ ,  $DA_{min} = 10.65\sigma$ ,  $DA_{min1} = 10.68\sigma$ ,  $DA_{min2} = 10.75\sigma$

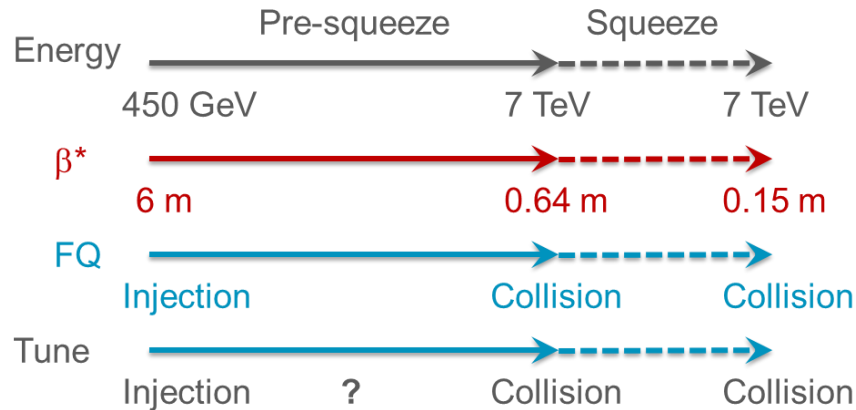


$DA_{ave} = 11.61\sigma$ ,  $DA_{min} = 10.84\sigma$ ,  $DA_{min1} = 10.87\sigma$ ,  $DA_{min2} = 10.99\sigma$



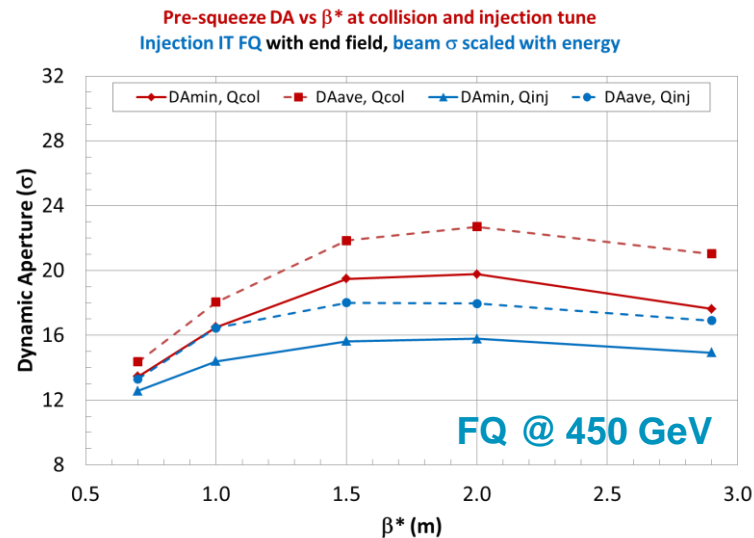
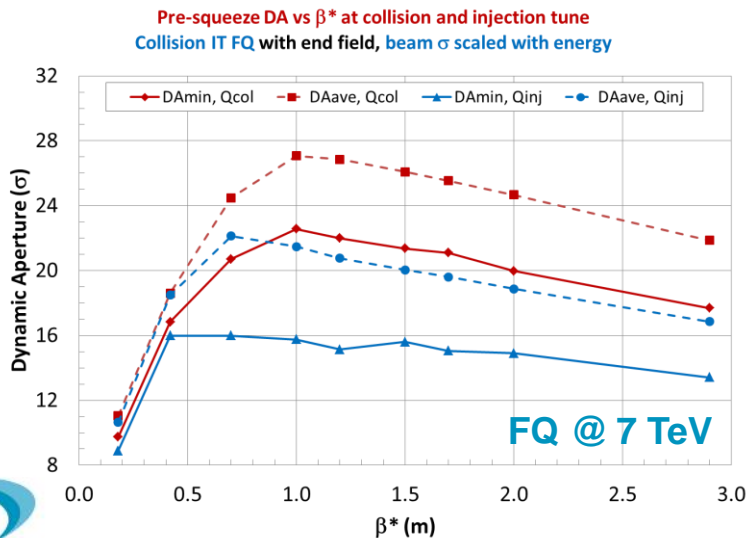
# DA vs tune during energy ramp and pre-squeeze

- $\beta^*$  pre-squeeze (6 m  $\rightarrow$  0.64 m) is planned to be done during energy ramp (450 GeV  $\rightarrow$  7 TeV)
- Injection tune (62.28, 60.31) must change to collision tune (62.31, 60.32) during the pre-squeeze
- $\rightarrow$  At what  $\beta^*$  should the tunes switch in view of maximum DA?
- During the ramp and pre-squeeze
  - $\beta^*$  is changed  $\rightarrow$  impact on DA
  - FQ is continuously changed with energy  $\rightarrow$  impact on DA
  - Beam size is changed as  $1/\sqrt{E}$   $\rightarrow$  impact on size of DA in number of  $\sigma$ 's



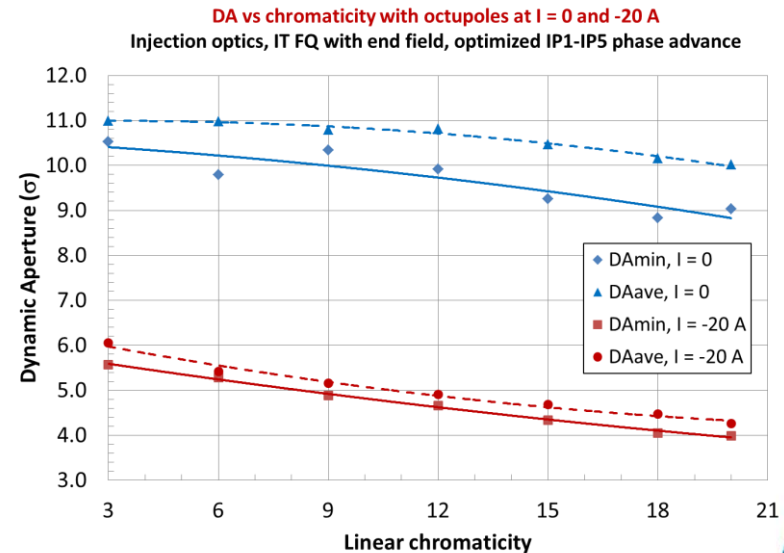
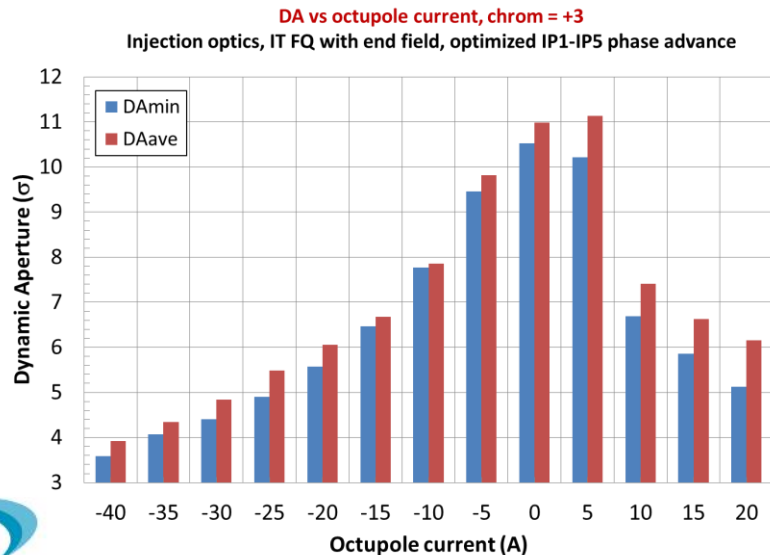
# DA in pre-squeeze: collision vs injection tune

- Second half of the pre-squeeze is checked  $\rightarrow \beta^*$  from 2.9 m to 0.7 m
- Using 7 TeV settings for tracking except
  - Two cases of FQ  $\rightarrow$  corresponding to 450 GeV and 7 TeV
  - For DA plots, beam  $\sigma$  is scaled as  $1/\sqrt{E}$ , assuming linear change of  $\beta^*$  with energy
- A larger DA at collision tune in this  $\beta^*$  range  $\rightarrow$  the tune switch may be done early in the pre-squeeze ( $\beta^* > 3$  m) to maximize the DA  $\rightarrow$  more points needed for accuracy



# Impact of strong octupoles and large chromaticity at injection energy

- Based on LHC operation, it may be required to extend the operational range of octupole current in the HL-LHC injection lattice well beyond the nominal -20 A
- Findings → strong impact of octupoles on the DA**
  - At -20 A of octupole current minimum DA is below  $6\sigma$ , and large chromaticity of +20 reduces DA by another  $\sim 1.5\sigma$
  - At -40 A and nominal +3 chromaticity minimum DA is below  $4\sigma$



# Summary and Conclusions

- Systematic a4, b5 in IT require weaker IT correctors than the random & uncertainty a4, b5
  - → **Compensation of systematic errors due to alternating polarities of IT quads, while random/uncertainty errors may add up**
- The previous study of u/r a4, b5, assuming maximum generated a4, b5 values and a4, b5 correctors are within spec, estimates an **optimistic limit on measured  $a4 \leq 8.8$  and  $b5 \leq 4$**  → **more random seeds are needed for better accuracy**
- Contribution of D1 a4, b5 u/r errors to the IT corrector strengths is 8-10% of the corrector  $B_{\max}$
- Tune scan finds **alternate working points at collision (62.27, 60.28) and injection (62.31, 60.29) energies** where DA is comparable to the nominal DA, however
  - DA at the alternate collision tune is strongly reduced by **octupole effects**
  - Switch from alternate injection tune to collision tune requires **transition across main coupling resonance**
- → **The present nominal tunes are still optimal**
- **The switch from injection to collision tune can be done early in the pre-squeeze** since the DA in the second half of the pre-squeeze is larger at the collision tune
- **The injection DA is strongly reduced by octupoles** → may be unacceptable at very large octupole strengths ( $< 4\sigma$  at -40 A)



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