Dynamic Aperture for the Operational Scenario Before Collision

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Outline

- Dynamic aperture (DA) with updated crossing bump scheme
- Optics sensitivity to crossing bump adjustment at IP1, IP5
- DA versus β^* during beta squeeze
- DA for operational range of chromaticity
- Impact of Landau damping octupoles at maximum strength
- Sensitivity to IT correctors during the pre-squeeze

Note: Some of these results are very recent and should be considered as work in progress which may require further study and analysis

Simulations set-up (1)

- HLLHCV1.0 lattice:
  - Nominal "round" optics in the range from β*= 6 m to 15 cm at IP1, IP5
  - Other collision lattices with the following β* at IP1, IP5: "flat" (7.5/30 cm, 30/7.5 cm), "flathv" (30/7.5 cm, 7.5/30 cm), "sround" (10 cm, 10 cm), "sflat" (5/20 cm, 20/5 cm), "sflathv" (20/5 cm, 5/20 cm)
  - Half beam separation at IP1, IP5 at collision is increased from ±0.75 mm to ±2 mm; the half crossing angle remains at ±295 μrad (these are exchanged between x and y planes in IP1 and IP5)
- SixTrack tracking set-up:
  - 10^5 turns, 60 random error seeds, 30 particle pairs per amplitude step (2σ), 11 x-y angles
  - Beam energy: 7 TeV
  - Initial Δp/p: 2.7e-4
  - Tune: 62.31, 60.32 (beta squeeze and collision), 62.28, 60.31 (injection lattice)
  - Normalized emittance = 3.75 μm-rad
  - Nominal chromaticity = +3
  - Arc errors and corrections included
  - IT correctors are on in IR1, IR5 and off in IR2, IR8
  - Landau damping octupoles

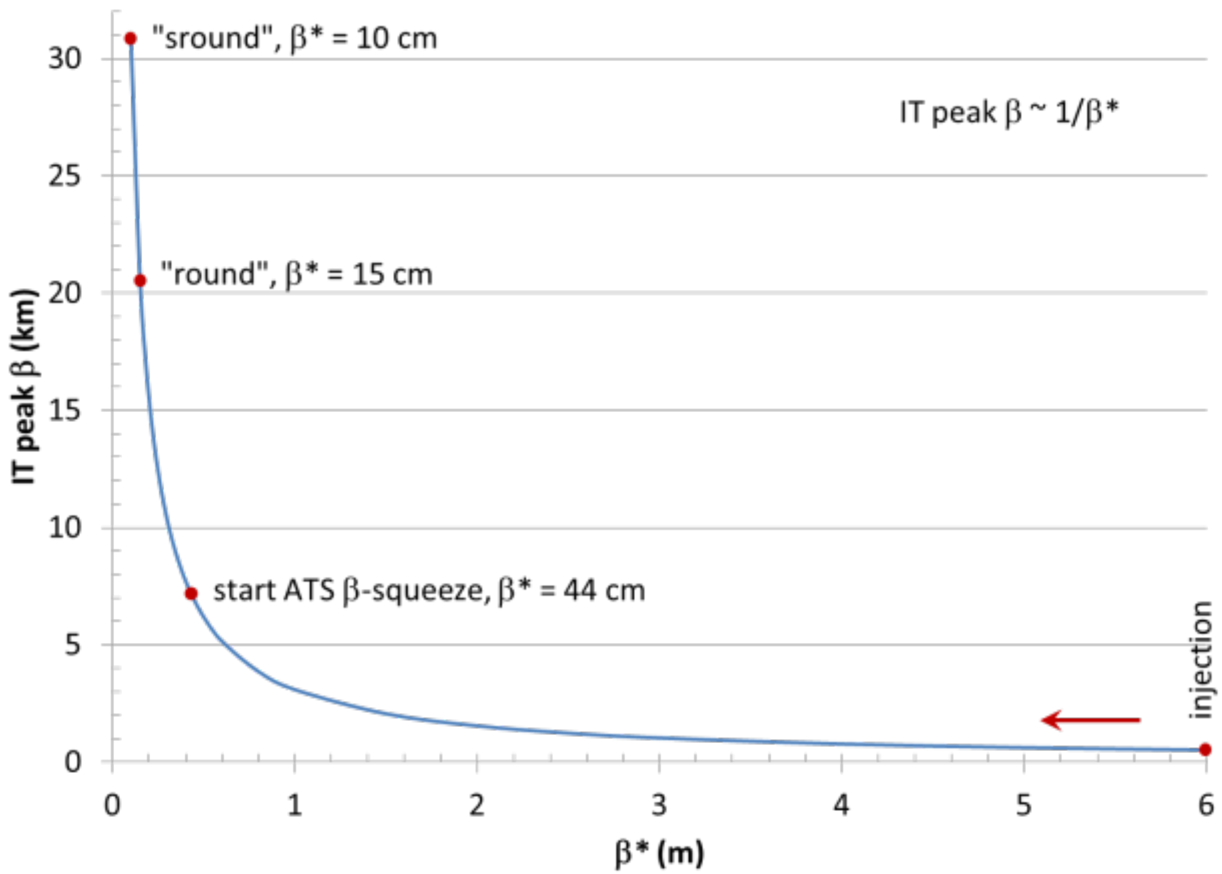
Thanks to S. Fartoukh for providing the SixTrack mask files and related tools

Simulations set-up (2)

- Field Quality tables for IT, D1, D2, Q4, Q5 magnets:
  - "IT_errortable_v66_5"
  - "D1_errortable_v1_spec"
  - "D2_errortable_v5_spec"
  - "Q4_errortable_v2"
  - "Q5_errortable_v0_spec"
- Chromaticity:
  - A positive chromaticity is required to mitigate beam instabilities
  - Tracking was performed for a chromaticity range from +2 to +18 to cover the expected range of operational chromaticity
- Damping octupoles (MO):
  - 168 octupoles per each beam (21 per arc) can be used to mitigate collective beam instabilities
  - The maximum range of the operational MO current is set at ±570 A
  - The tracking was performed for two strength values: 0 and -570 A

Beta squeeze

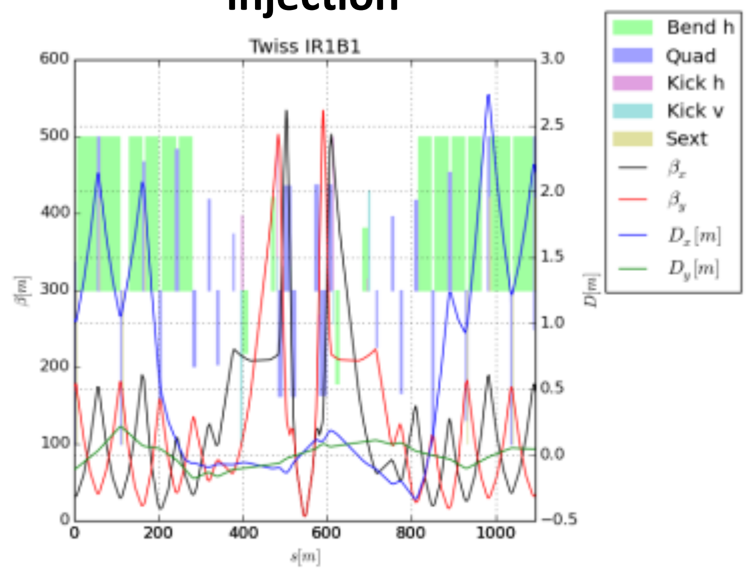
After the energy ramp, the IP1, IP5 beta functions will be reduced from the injection values of 6 m to collision values. The ATS scheme will be implemented starting from β^* = 0.44 m. The IT peak beta is increased 40 times in the round optics.



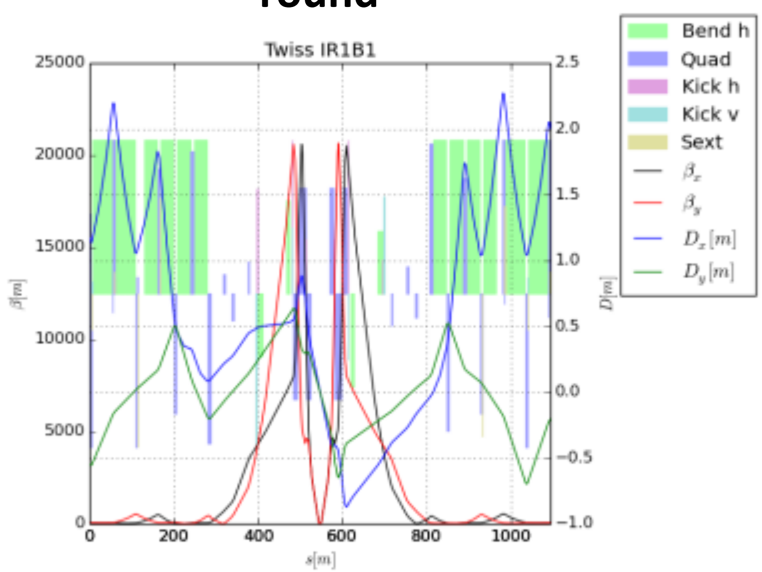
IR beta

IT peak beta functions vary from ~500 m in the injection lattice to ~20 km in the round optics and to ~40 km in the flat optics. These large beta functions lead to strong impact of the IT field errors on dynamic aperture.

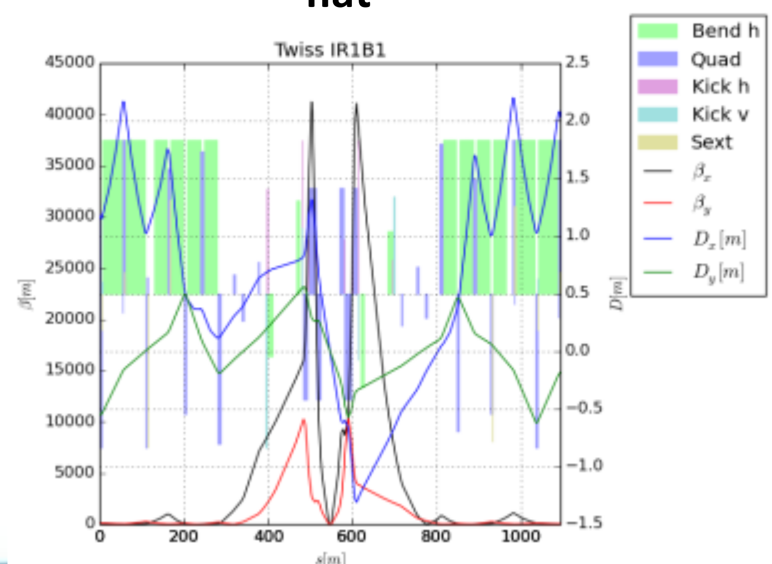
injection



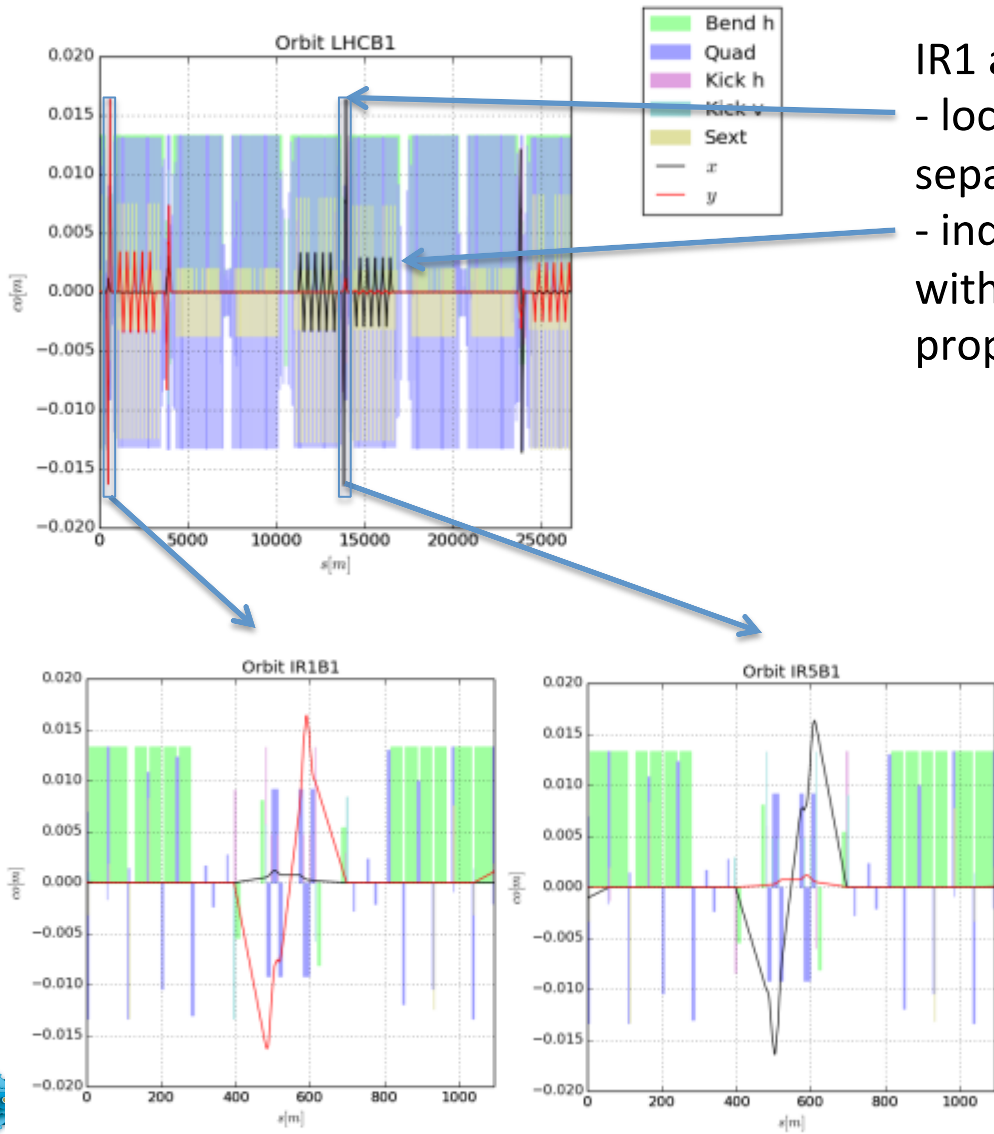
round



flat



Crossing scheme in IR1, IR5



IR1 and IR5 have:
- local alternated plane crossing and separation schemes (±295 μrad, ±2 mm)
- induced dispersion compensation in the arc with orbit bumps, e.g orbit amplitude proportional to crossing and separation

Orbit induced feed-down effects depend on crossing angle and separation due to:

- IT and arcs field imperfections and
- non-linear correctors: MS, MO, MSS

The effects are enhanced by higher β functions during the ATS β-squeeze, but some compensation exists due to π/2 cells.

Sensitivity to crossing bump adjustment

Study of the impact of:

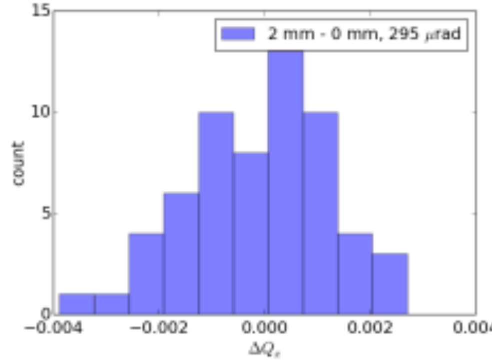
- collapsing the separation bump as foreseen in operation
- reducing the crossing angle by half to measure the sensitivity

on tune, coupling and chromaticity with machine errors and non-linear correctors.

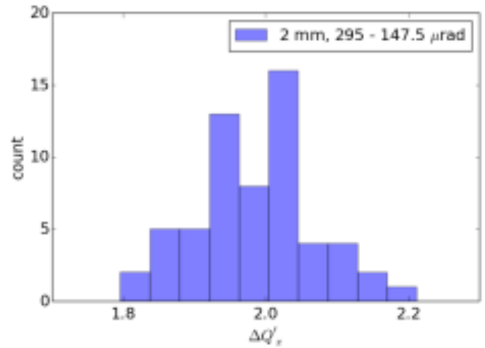
Bump adjustment	Impact due to	$\Delta Q_{x,y}$ $[10^{-3}]$	$\Delta Q'_{x,y}$	$\Delta\lvert C^-\rvert$ $[10^{-3}]$
Separation collapse	Triplet only	4, 4	0.3, 0.3	4
	Arcs and MO	4, 4	0.6, 0.3	5
Reducing angle	Triplet only	1.5, 1.5	0.2, 0.3	2
	Arcs and MO	9, 9	2.2, 0.3	3

- Relatively small effects in operational separation collapse.
- MOs have the largest impact through feed-down effects for crossing angle changes (not foreseen in normal operations).

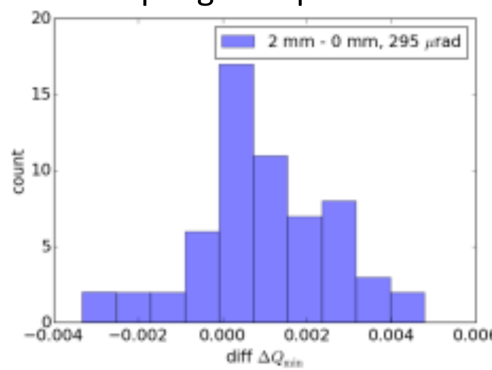
Tune vs separation



Chromaticity vs angle



Coupling vs separation



60 error seeds

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IT Field Quality

skew	mean	uncertainty	random	normal	mean	uncertainty	random
a3	0	0.800	0.800	b3	0	0.820	0.820
a4	0	0.650	0.650	b4	0	0.570	0.570
a5	0	0.430	0.430	b5	0	0.420	0.420
a6	0	0.310	0.310	b6	-15.8	1.100	1.100
a7	0	0.190	0.190	b7	0	0.190	0.190
a8	0	0.110	0.110	b8	0	0.130	0.130
a9	0	0.080	0.080	b9	0	0.070	0.070
a10	0	0.040	0.040	b10	3.63	0.200	0.200
a11	0	0.026	0.026	b11	0	0.026	0.026
a12	0	0.014	0.014	b12	0	0.018	0.018
a13	0	0.010	0.010	b13	0	0.009	0.009
a14	0	0.005	0.005	b14	-0.6	0.023	0.023

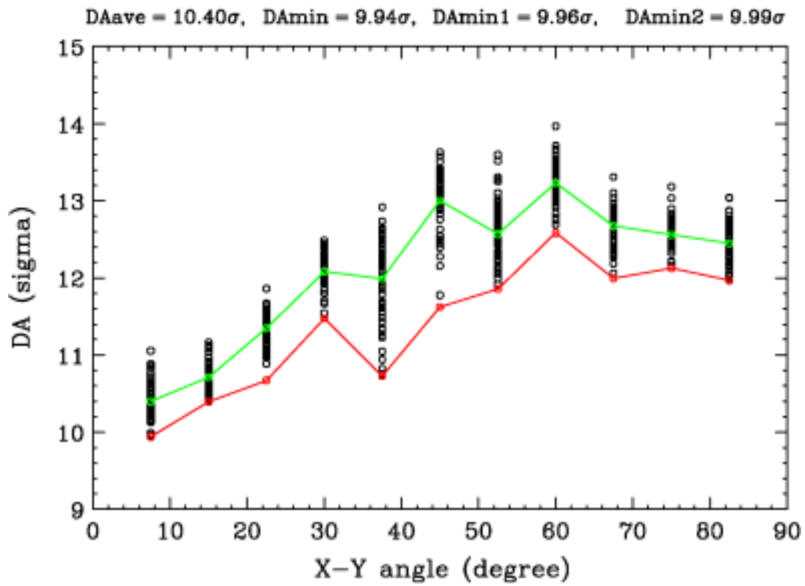
450 GeV

7 TeV

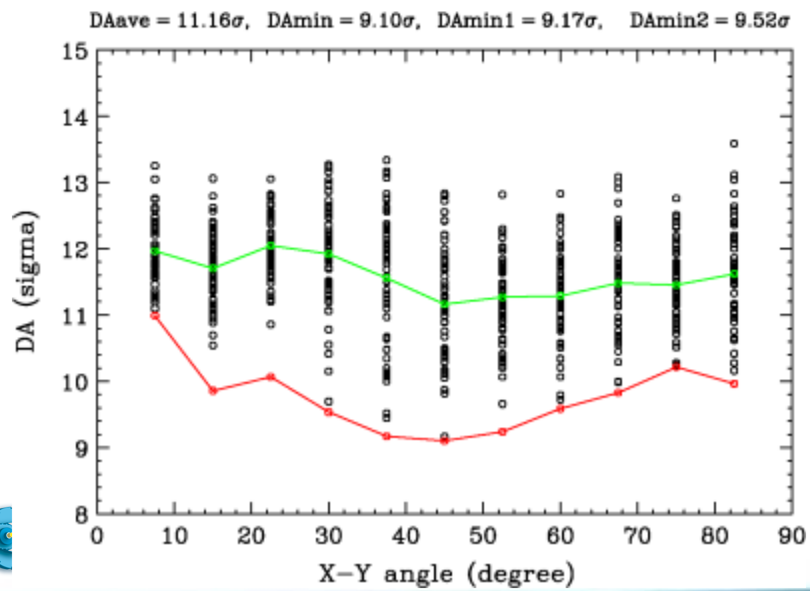
skew	mean	uncertainty	random	normal	mean	uncertainty	random
a3	0	0.800	0.800	b3	0	0.820	0.820
a4	0	0.650	0.650	b4	0	0.570	0.570
a5	0	0.430	0.430	b5	0	0.420	0.420
a6	0	0.310	0.310	b6	0.40	0.550	0.550
a7	0	0.152	0.095	b7	0	0.095	0.095
a8	0	0.088	0.055	b8	0	0.065	0.065
a9	0	0.064	0.040	b9	0	0.035	0.035
a10	0	0.040	0.032	b10	-0.156	0.100	0.100
a11	0	0.026	0.0208	b11	0	0.0208	0.0208
a12	0	0.014	0.014	b12	0	0.0144	0.0144
a13	0	0.010	0.010	b13	0	0.0072	0.0072
a14	0	0.005	0.005	b14	-0.1675	0.0115	0.0115

DA of injection lattice should improve at top energy due to better IT FQ and smaller beam size

Collision and injection DA from previous study

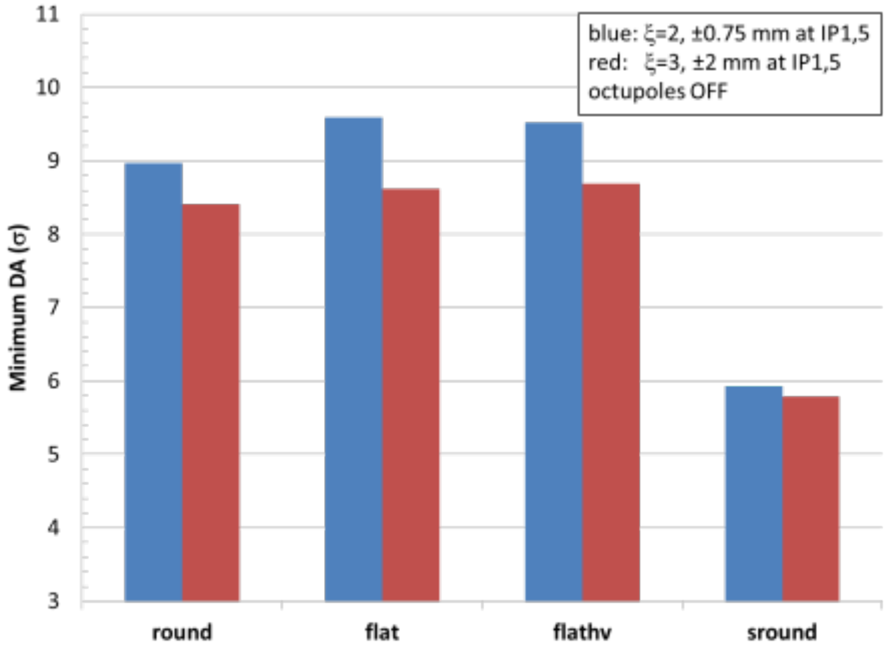


- Injection DA at 450 GeV and chromaticity of +2 is about 10σ.
- Expected to be improved at 7 TeV.

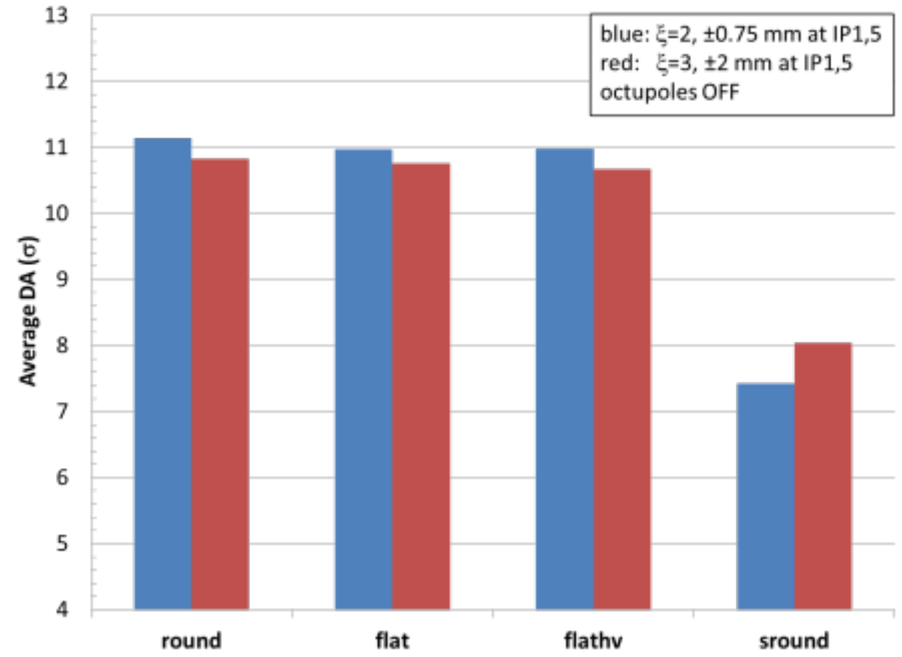


- DA at 7 TeV for round optics with β^*=15 cm, chromaticity of +2, and IP separation of ±0.75 mm is above but close to 9σ.
- Minimum DA is influenced by two bad seeds.
- Expected to be reduced due to the effects of octupoles and larger chromaticity of +3.

New versus old DA for collision lattices (octupoles off)



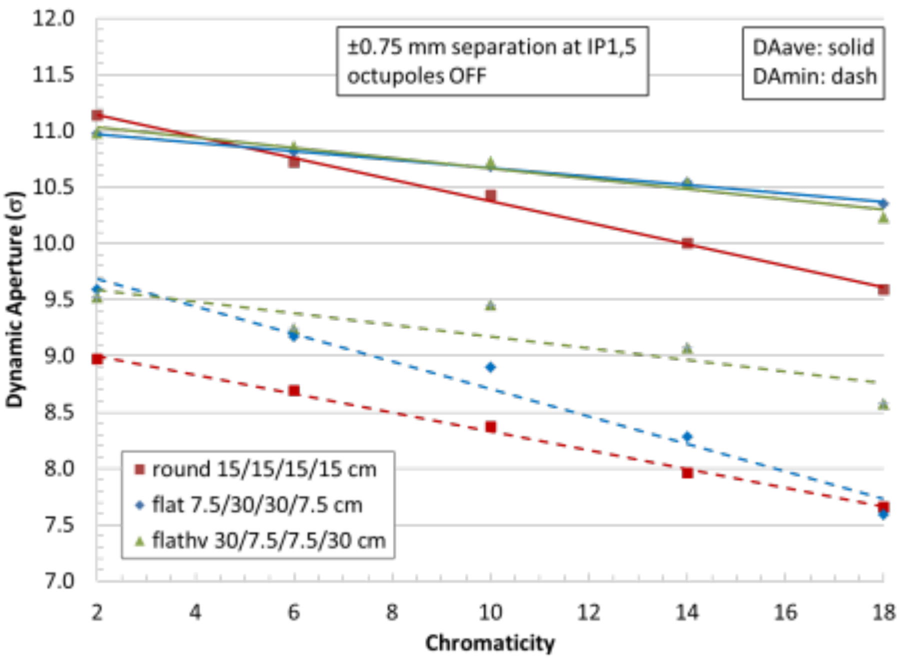
Low-β lattices



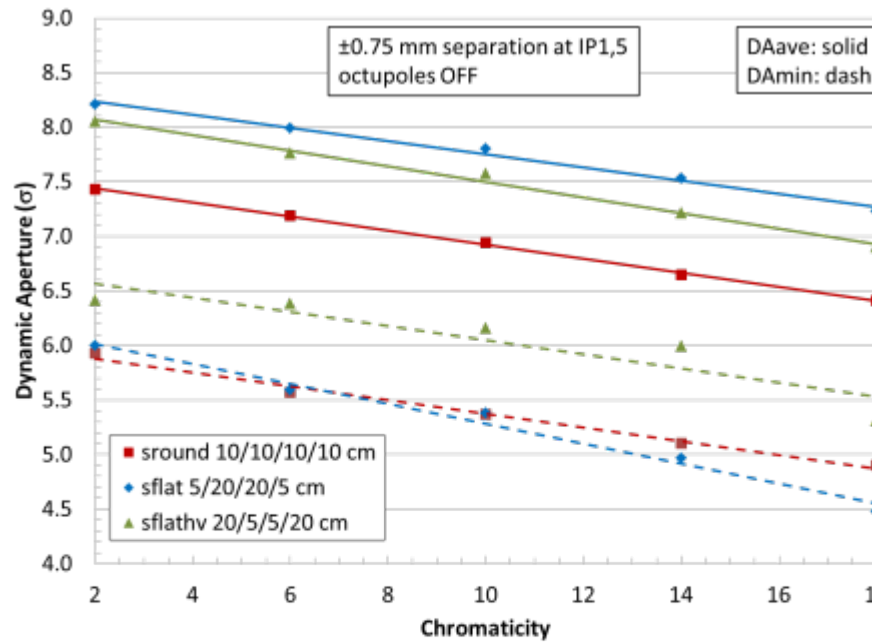
Super low-β lattices

Relatively small reduction of average DA (~0.3σ), but larger impact on minimum DA (0.6 - 0.9σ) due to the increased IP separation and chromaticity. Minimum DA for nominal collision optics is near 8.5σ.

DA versus chromaticity for round/flat/flathv lattices



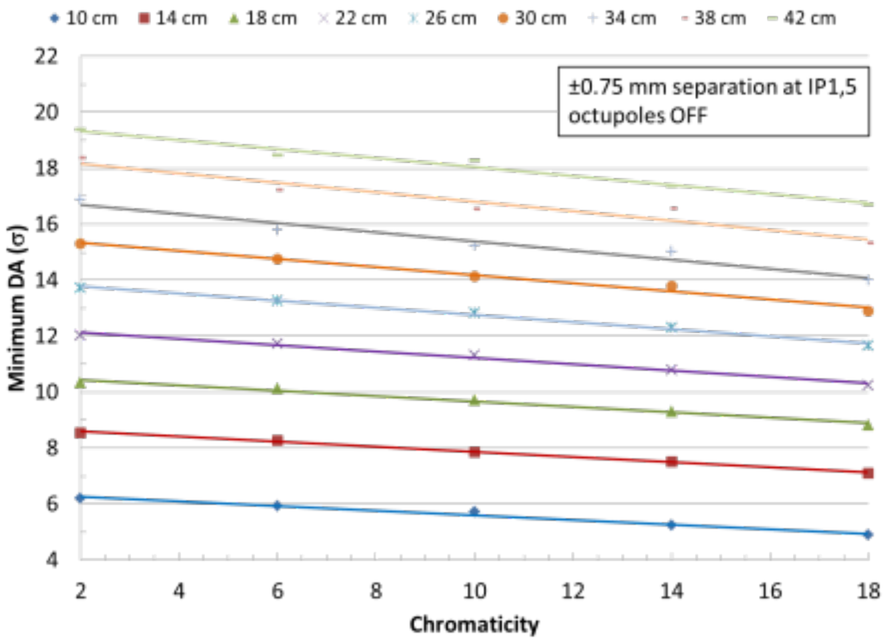
Low-β lattices

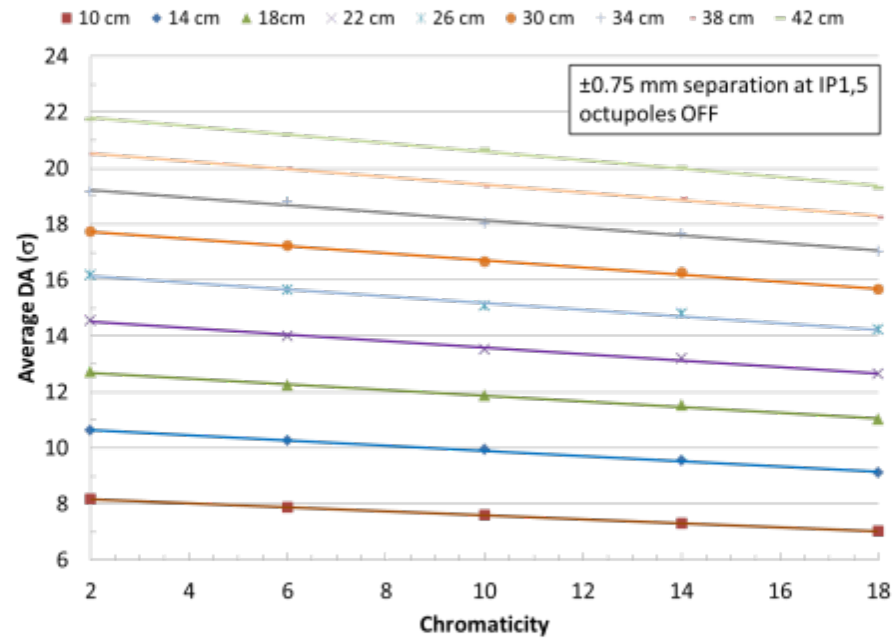


Super low-β lattices

- Lattice with ±0.75 mm IP separation and octupoles off.
- Linear DA reduction with chromaticity.
- Maximum DA loss for ξ from +2 to +18 is within 1-2σ.

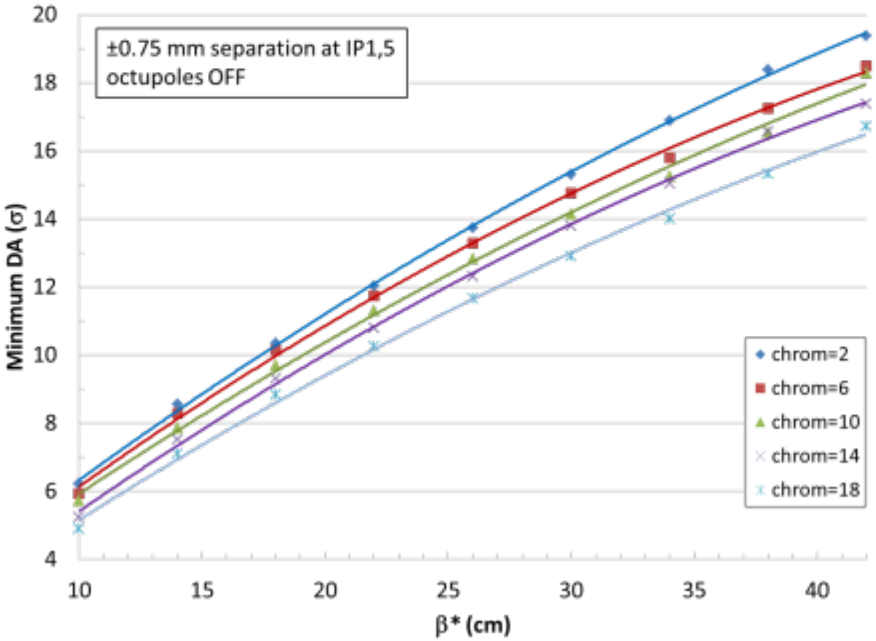
DA versus chromaticity in β-squeeze (1)

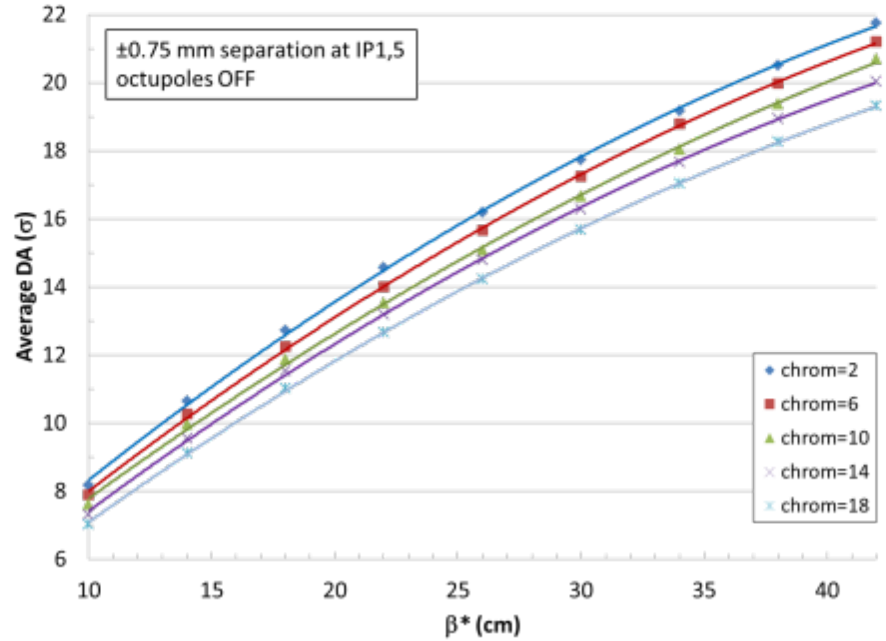




- Lattice with ±0.75 mm IP separation and octupoles off.
- Linear DA reduction with chromaticity.
- Maximum DA loss is near 1.5σ at low β*. It increases to ~3σ loss at higher β* within the β-squeeze, but the DA is larger there.

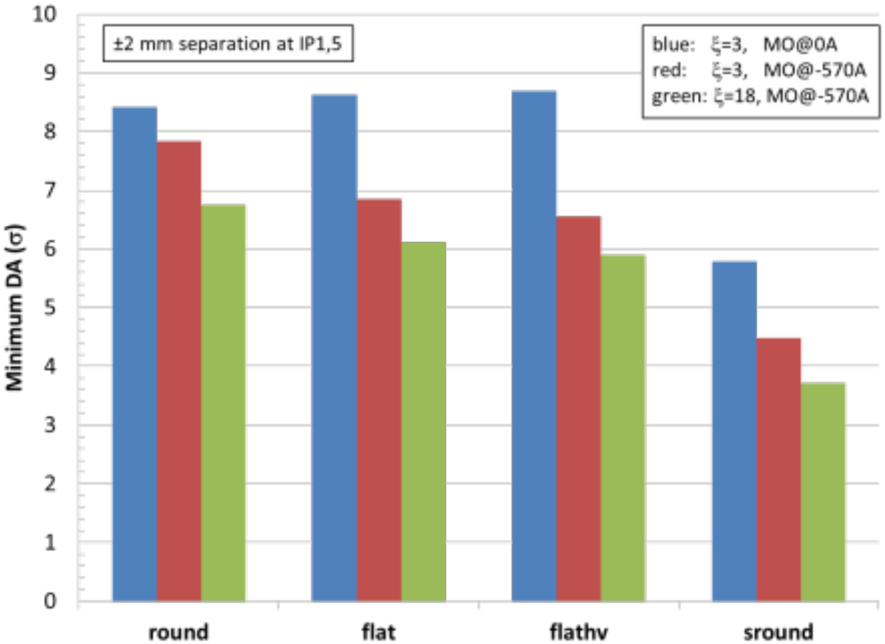
DA versus chromaticity in β-squeeze (2)



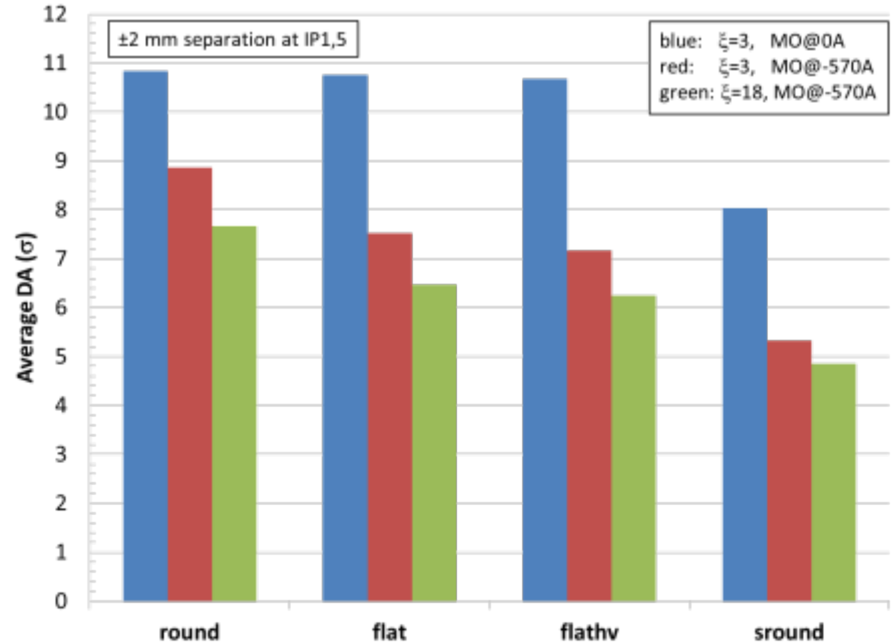


- Lattice with ±0.75 mm IP separation and octupoles off.
- Slightly quadratic DA dependence with β* due to increasing error fields at larger amplitudes.
- Considerable DA improvement even with small increase of β* (~0.9σ per 2 cm of β*).

DA with full strength octupoles at low-β



Low-β lattices



Super low-β lattices

- DA of the round optics is modestly reduced by the full strength octupoles – about 0.6σ, however, it falls below 8σ. The average DA (9σ) is reduced more (2σ) indicating a smaller DA spread among different seeds.
- Stronger effect on flat(hv) lattices: minimum and average DA are below 7σ and 8σ.
- Large chromaticity further reduces the DA (just below 7σ).

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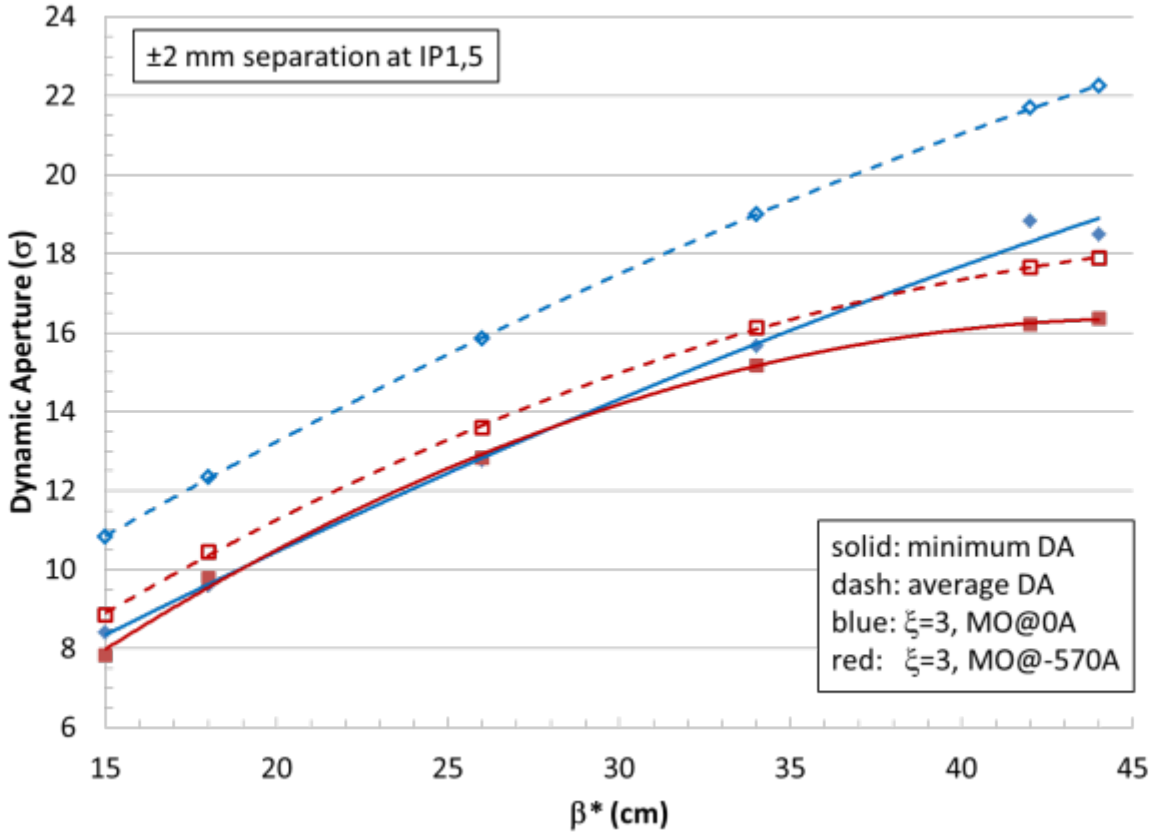
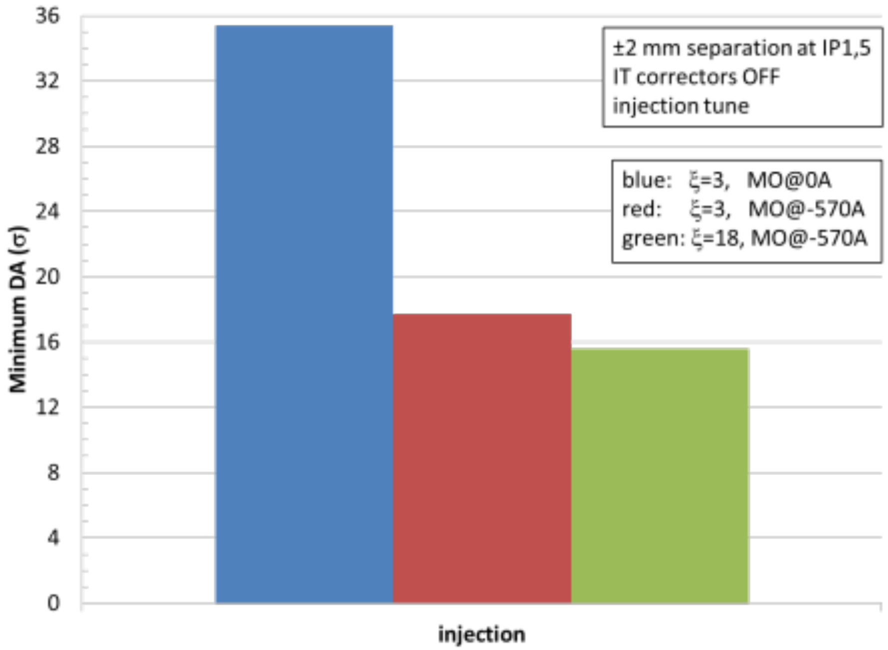
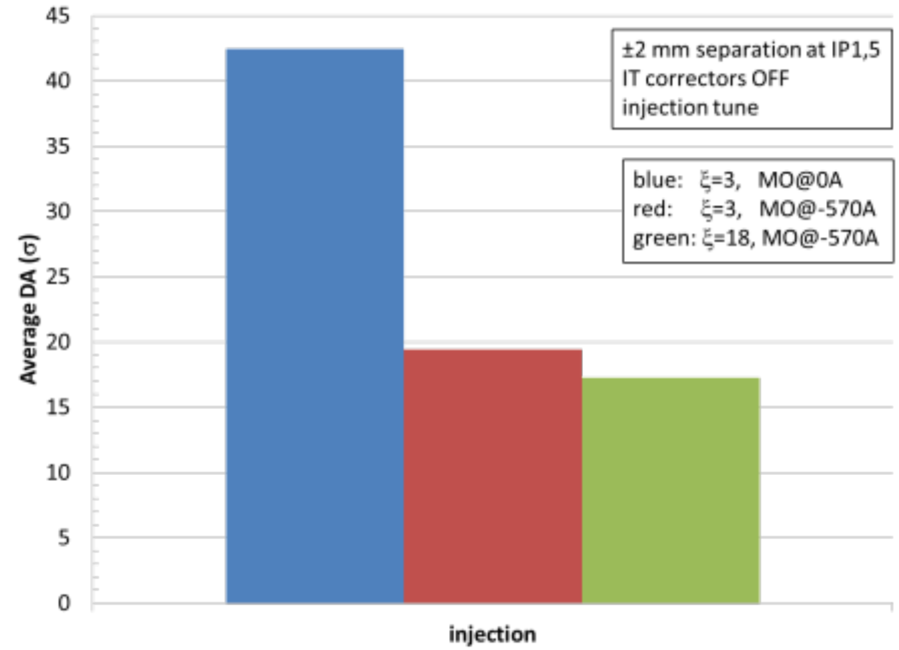
Octupole effects in β-squeeze



- Minimum DA of the round optics shows low dependence on octupoles for $\beta^* < 30$ cm. The DA loss is increased up to 1.5σ at $\beta^* = 44$ cm, but the DA is also larger.
- Stronger impact on average DA: from 2σ loss at $\beta^* = 15$ cm to 4σ at 44 cm.

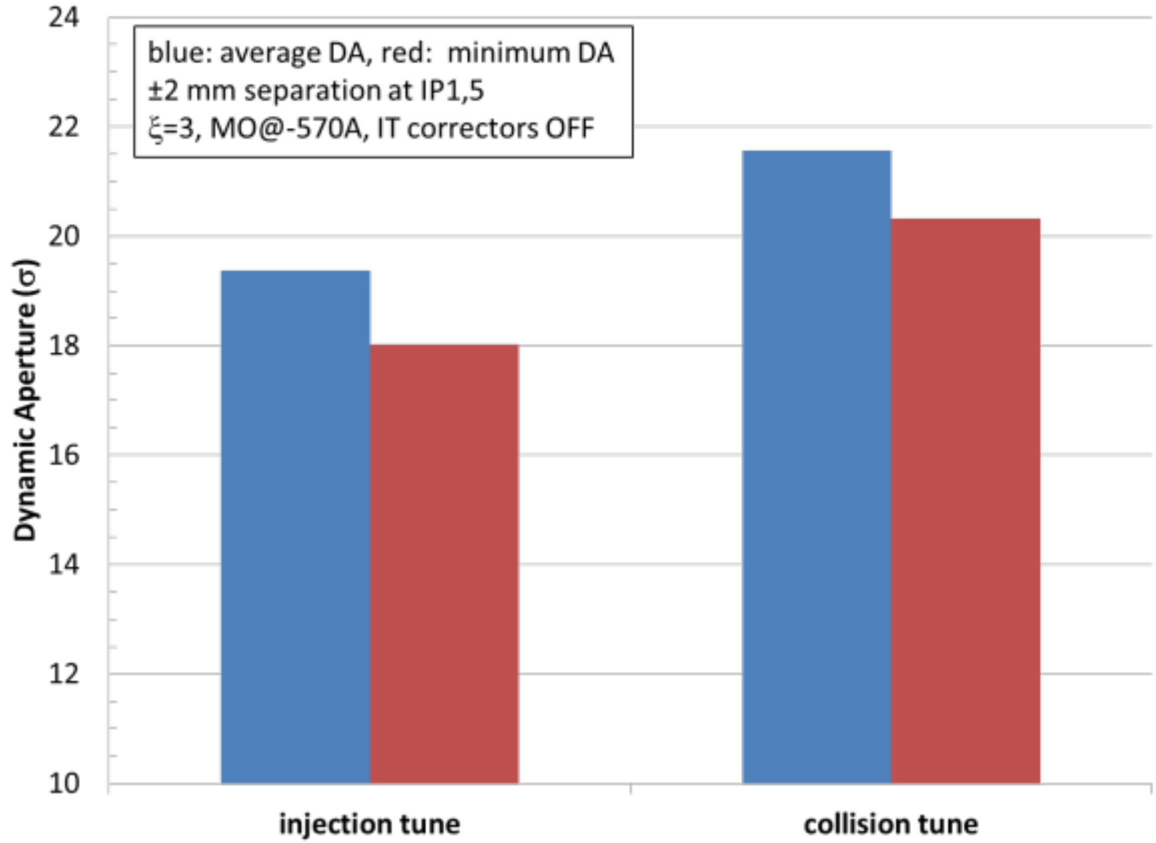
DA of injection lattice at 7 TeV with full strength octupoles





- Large DA of injection lattice at 7 TeV with octupoles off.
- A factor of 2 reduction due to octupoles at maximum strength, but the DA is still large – about 18σ.
- About 2σ loss due to +18 chromaticity.

DA of injection lattice versus tune at 7 TeV



- The tune of injection lattice will change at 7 TeV from [62.28, 60.31] to collision tune of [62.31, 60.32].
- The DA is increased about 2σ at collision tune (with full strength octupoles).

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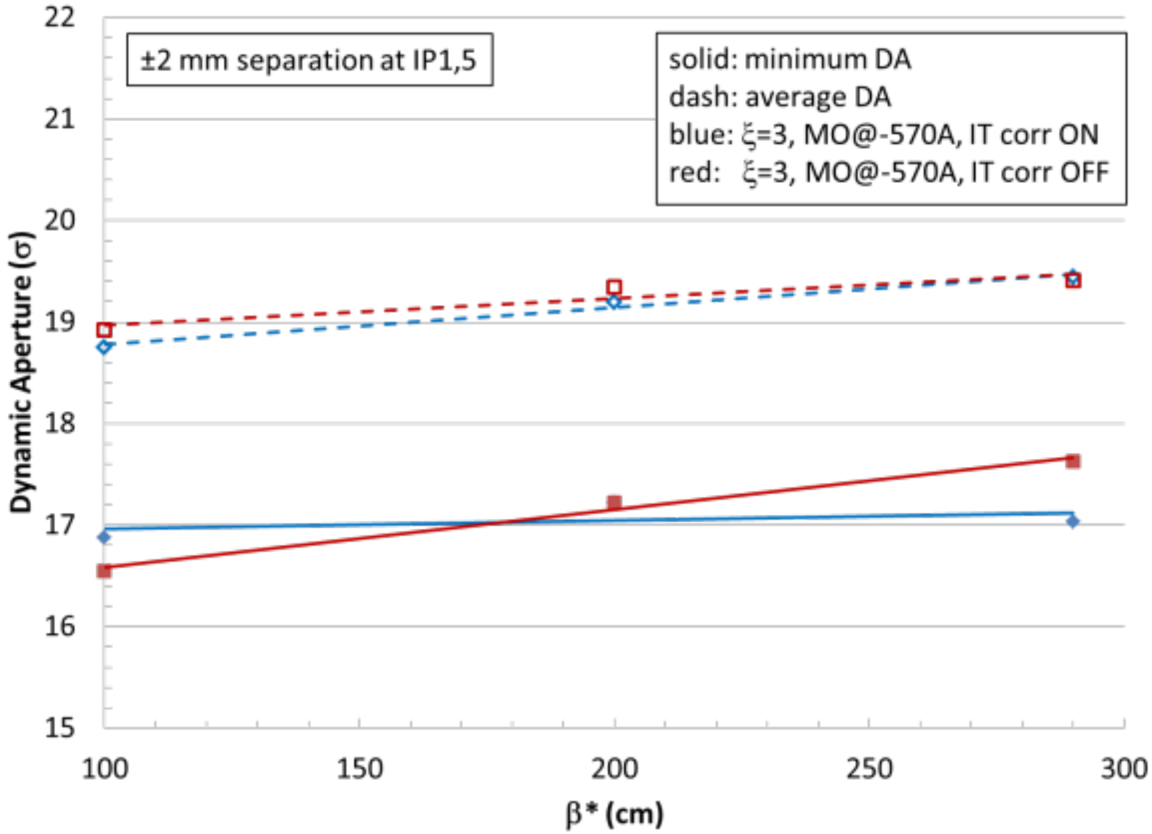
Impact of IT correctors in pre-squeeze



- The DA of round optics is not sensitive to the IT correction in IR1, IR5 for β^* above 100 cm and full strength octupoles.

Conclusions

- The larger beam separation at IP1, IP5 (±2 mm) and larger chromaticity (+3) reduce the minimum DA by 0.6 – 0.9σ to about 8.5σ.
- The maximum DA loss at low-β^* due to the +18 chromaticity is in the range of 1–2σ depending on the optics. The loss is higher (up to 3σ) at higher β^* in the β-squeeze where the DA is also larger.
- Full strength octupoles do not significantly affect the DA for β^* from 15 cm to 30 cm: the DA loss is within 0.6σ, however the DA falls just below 8σ. The loss increases at higher β^* — up to 2.5σ at 44 cm, where DA is larger. The loss of average DA is larger (2σ at 15 cm and 4σ at 44 cm).
- The octupole effect on DA of the flat(hv) optics is stronger — up to 2σ of minimum DA loss (and up to 3.5σ for average DA).
- With full strength octupoles and ξ = +18 the minimum DA falls to just below 7σ.
- The DA of injection lattice at 7 TeV is large (36σ). It is reduced by half with the full strength octupoles (18σ at injection tune and 20σ at collision tune). The +18 chromaticity reduces the DA by another 2σ.
- The DA is insensitive to the use of IT correctors in IR1, IR5 at β^* > 100 cm.
- The DA considerably improves even with minor increase of β^* (~0.9σ per 2 cm).
- Note that σ is defined at the larger 3.75 μm emittance as compared to nominal.
- These results should be considered as work in progress – further tracking and analysis may be needed.
- With the DA getting lower, it becomes important to verify these findings with beam-beam effects included.

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