Beam-beam studies for FCC-hh

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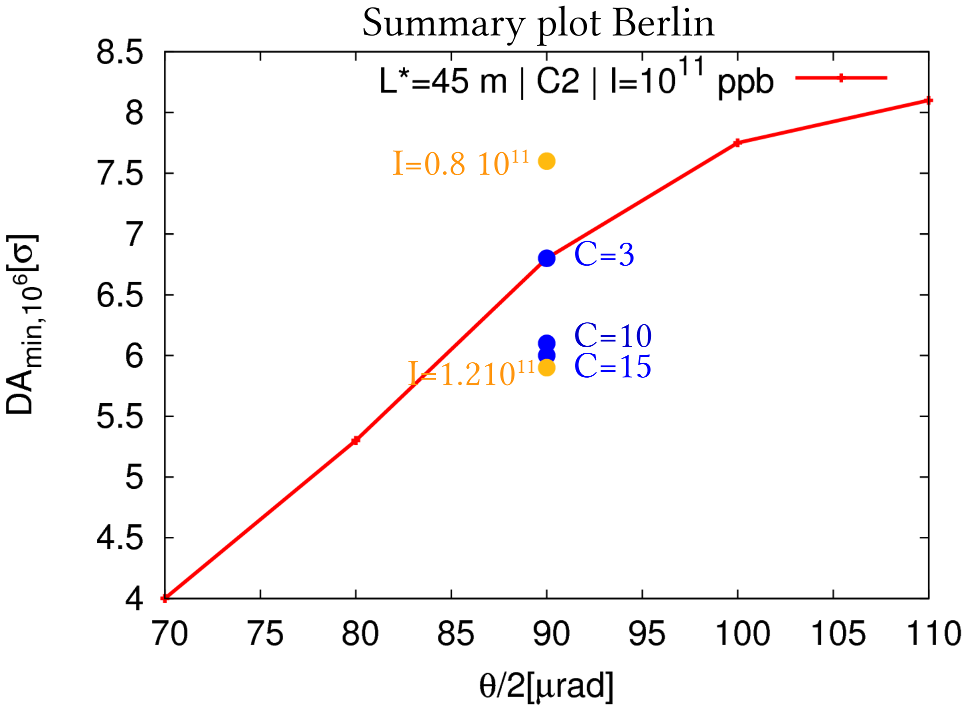
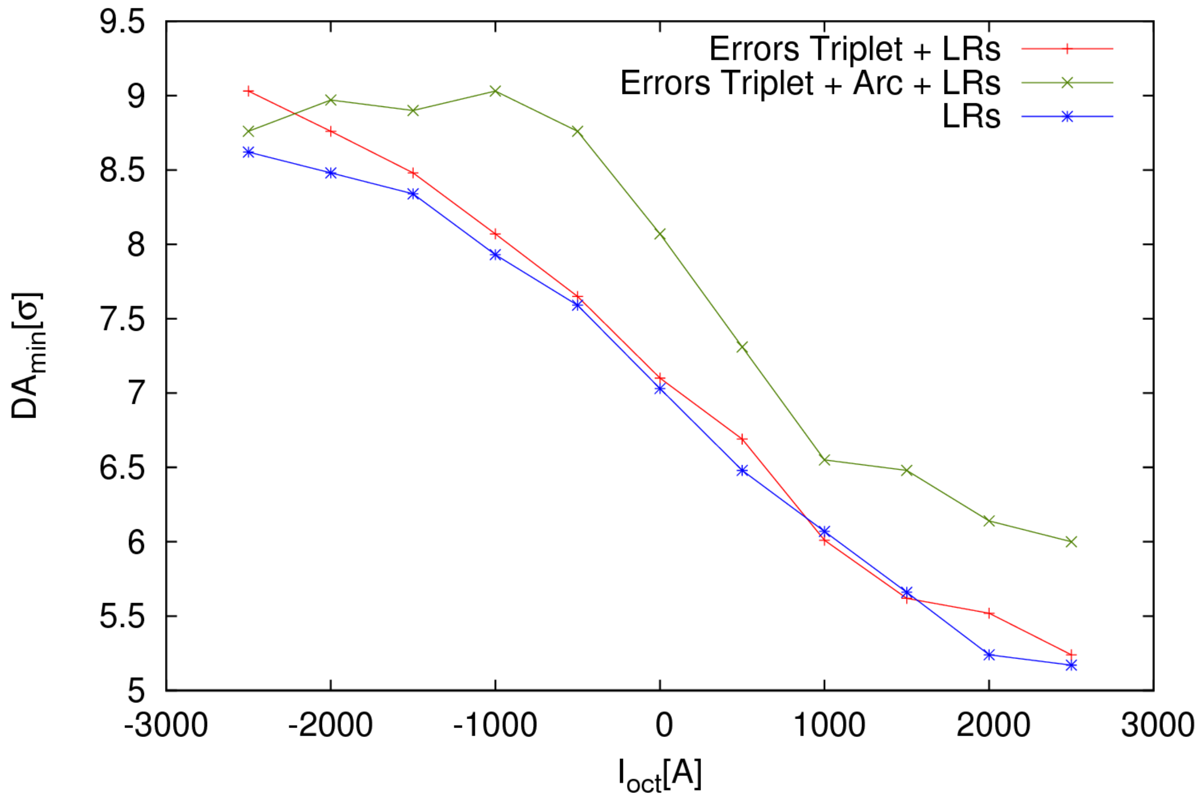
Reminder from Berlin

- During the FCC week in Berlin DA simulations with the latest available lattice (L^*=45 m) were presented.
- A 7.2 σ DA was ensured with **θ/2~90-100 μrad** at the beginning of the fill.
- No magnetic errors included
- Intensity fluctuation (10-20%) amounts for 10-20 μrad total.
- Different crossing schemes explored (HV, HH, VV)
- High chromaticity (3-15) operation requires additional crossing angle margin 10-20 μrad total.



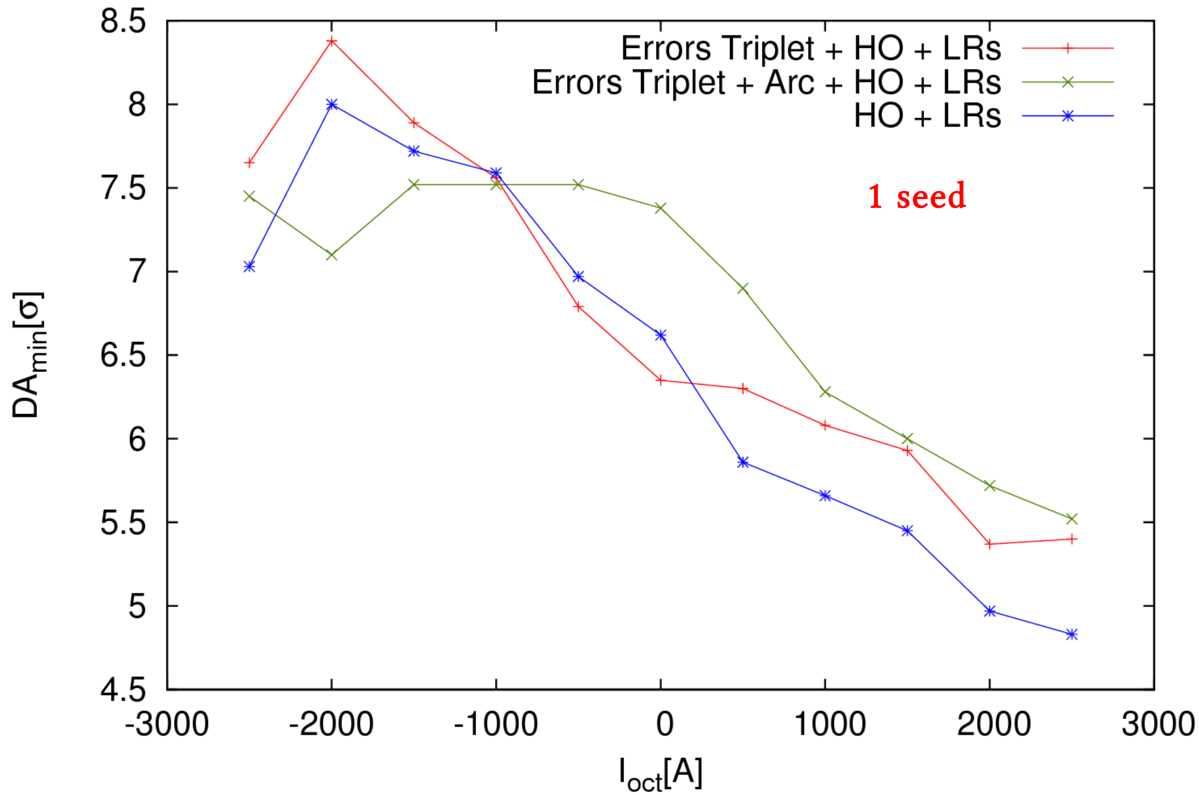
Angle rough estimates: 90 (nominal) + 5 (15 Units Chroma) + 5 (10% intensity) + 5 (0.5 s effect of Multipolar errors) +/- Octupoles (difficult to judge) = 100 μrad + Landau spread, imperfections…

Magnetic Errors impact L*=45 m



- Effect of magnetic errors (1 seed) and octupoles for L*=45 m and LRs on DA evaluated.
- Beam-beam is the main driver of DA.
- Magnetic errors can improve DA. In the L*=45 m case the arc errors contribute to increase DA.
- Effect of 60 seeds to be studied.
- Negative octupoles compensate for LRs effects. DA improves and starts saturating around Ioct=-2500 A.

Magnetic Errors impact L*=45 m

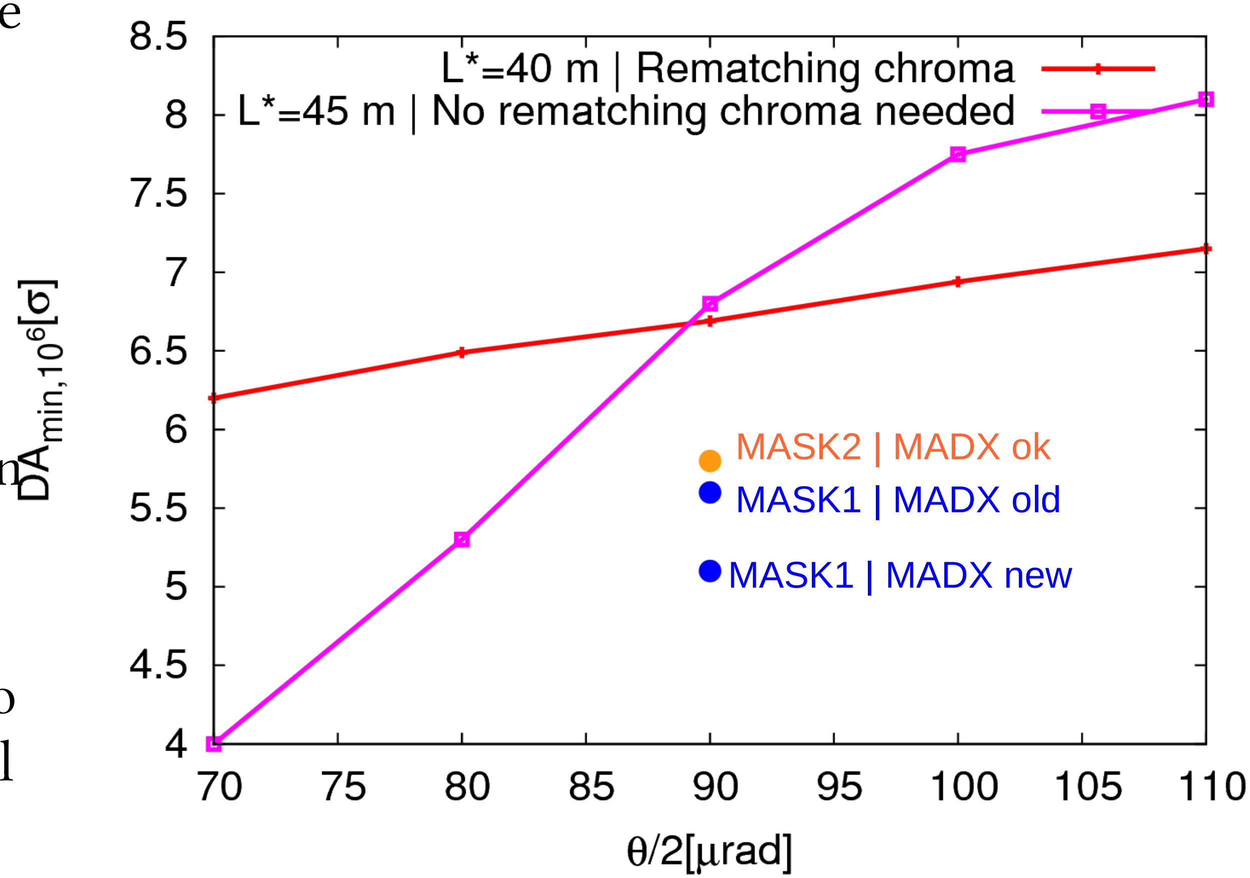


- Effect of magnetic errors (1 seed) and octupoles for L*=45 m and HO+LRs on DA evaluated.
- HO reduces an additional 0.4 σ for I_{oct}=0 A.
- Magnetic errors can improve DA. In the L*=45 m case the arc errors contribute to increase DA for positive polarity. For negative saturates DA faster.
- Effect of 60 seeds to be studied.
- Negative octupoles compensate for LRs effects. DA improves and starts saturating before wrt LRs case.

New lattice version (L^*=40 m)

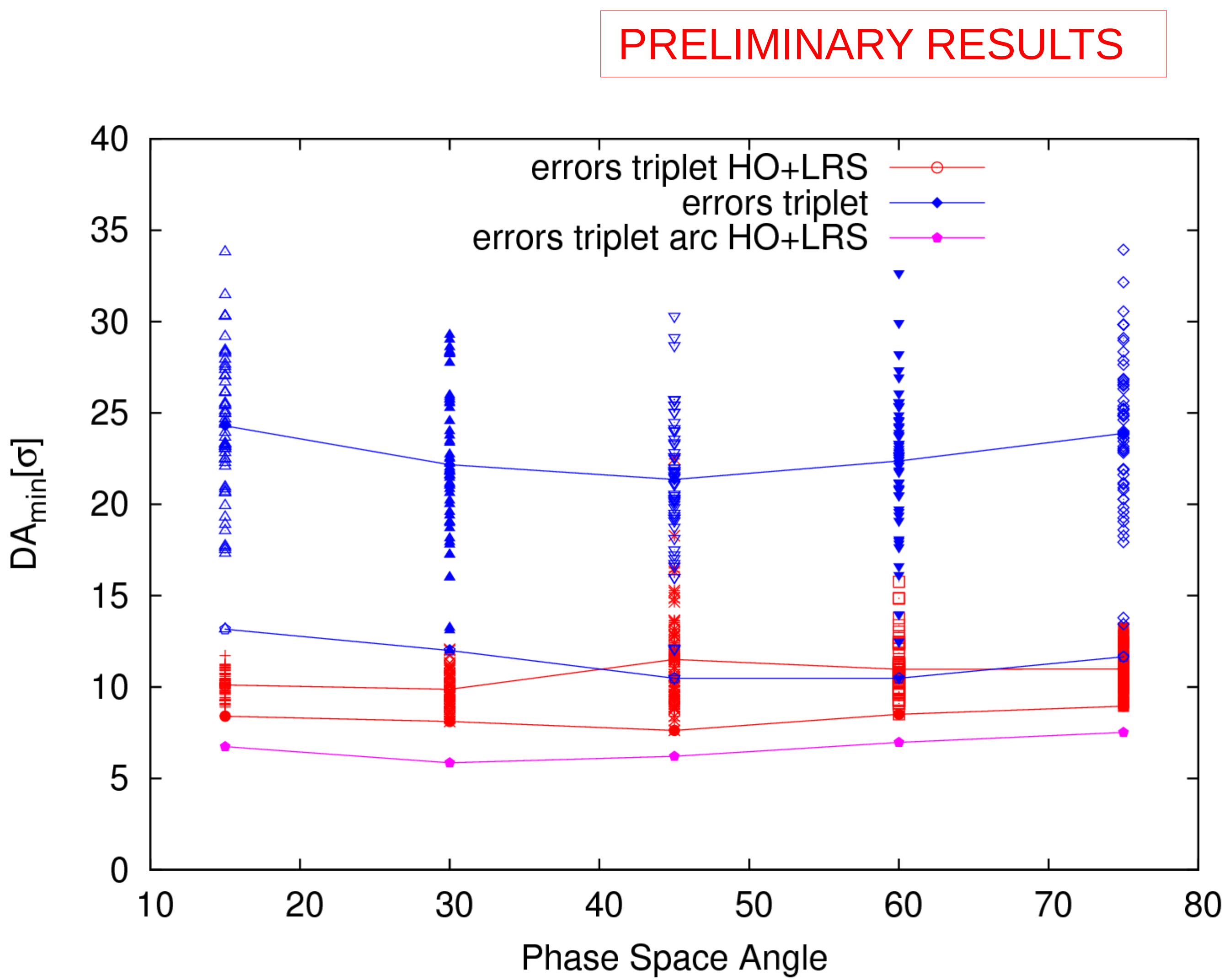
- After Berlin L^*=40 m became the new baseline.
- Shorter L^* implies 6 LRs per side per IP.
- Bug fixed in MADX recently found in the separation sign during the MADX-SixTrack conversion.
- Chromaticity difference between MADX-SixTrack (bug reported for small separations)
- Several masks available. Need to converge to a single one with all macros working (supporting Antoine's proposal for a contributed optics repository).
- Further checks on-going.

- I=10^{11} ppb | ε=2.2 μrad



DA with errors + BB (L*=40 m)

- Preliminary results for L*=40 m DA w/o rematching chroma after BB.
- 60 seeds showing individual seeds, minimum and average.
- Case errors triplet+ar with HO+LRs on going.
- Only errors has some very bad seeds that bring down DA significantly. Average~22 σ – Min~10 σ.
- Errors triplet + HO +LRs. Average~10 σ – Min~7 σ.
- Errors triplet arc + HO +LRs. Average~5.5 σ – Min~5.5 σ.



Sources of Landau damping*

Octupoles magnets [J. Berg and F. Ruggero]	Electron lenses [V. Shiltsev et al.]	RFQ [M. Schenk, A. Grudiev et al.]
☑ Evaluate tune spread from octupoles ☑ Single beam (injection, flat top) ☑ Beam-beam	☑ Evaluate tune spread from e-lens (injection, flat top)	☑ Preliminary studies for FCC by M. Schenk et al. that show stabilizing effects
DA impact	DA impact	DA impact

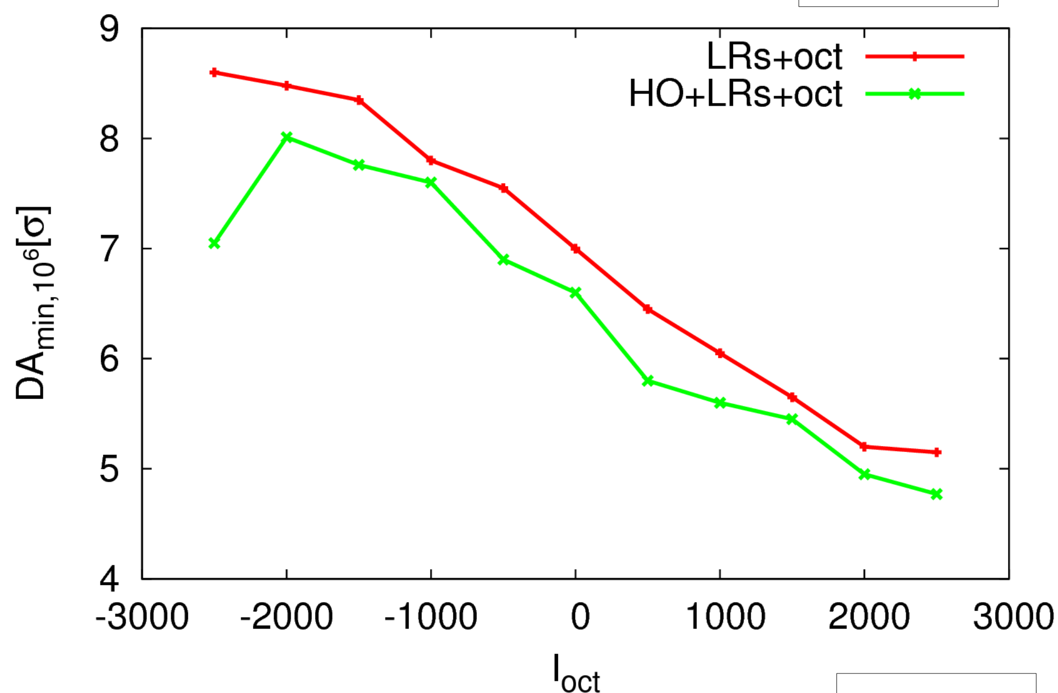
* More info in C. Tambasco, « Beam-Beam Effects, octupoles and Landau damping », this workshop.

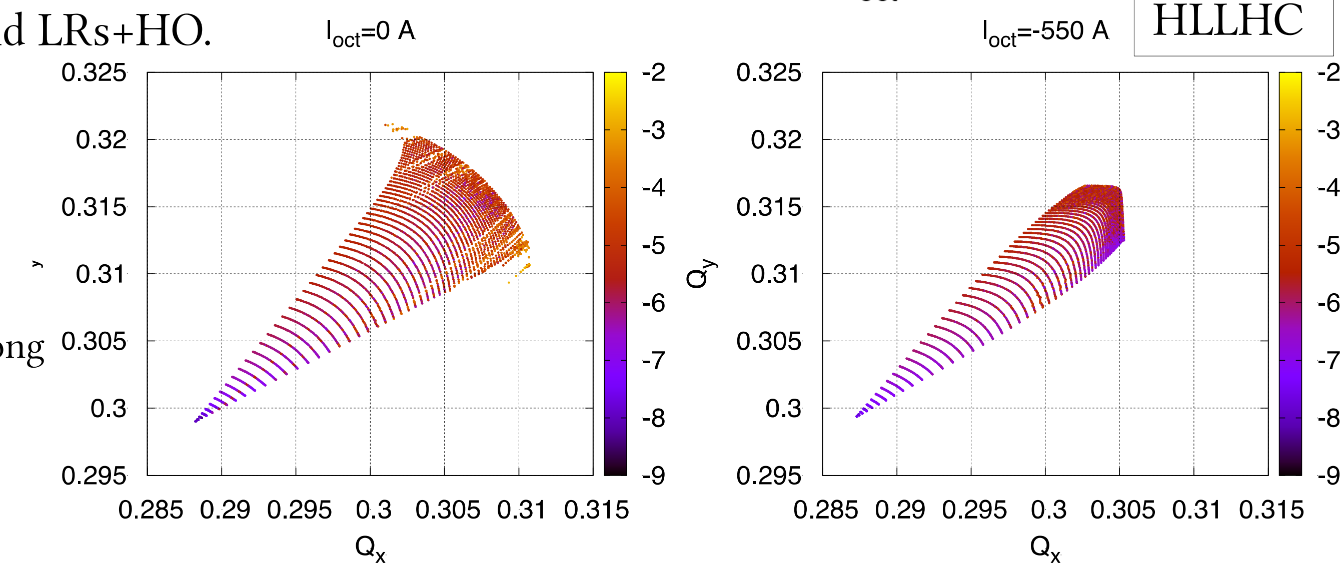
What's their impact on the dynamic aperture ?

Landau Octupoles and BBLR compensation

- Lattice with 460 octupoles already available (inj & coll).
- Stability studies by Claudia using a L*=45 m (see next talk).
- Octupoles are **not only** beneficial for Landau damping but they **compensate for the LR encounters.**
- First simulations for FCC show **similar** behaviour as for HLLHC*.
- **Negative polarity** improves the DA in more than 1 σ for both LRs and LRs+HO.

L*=45 m

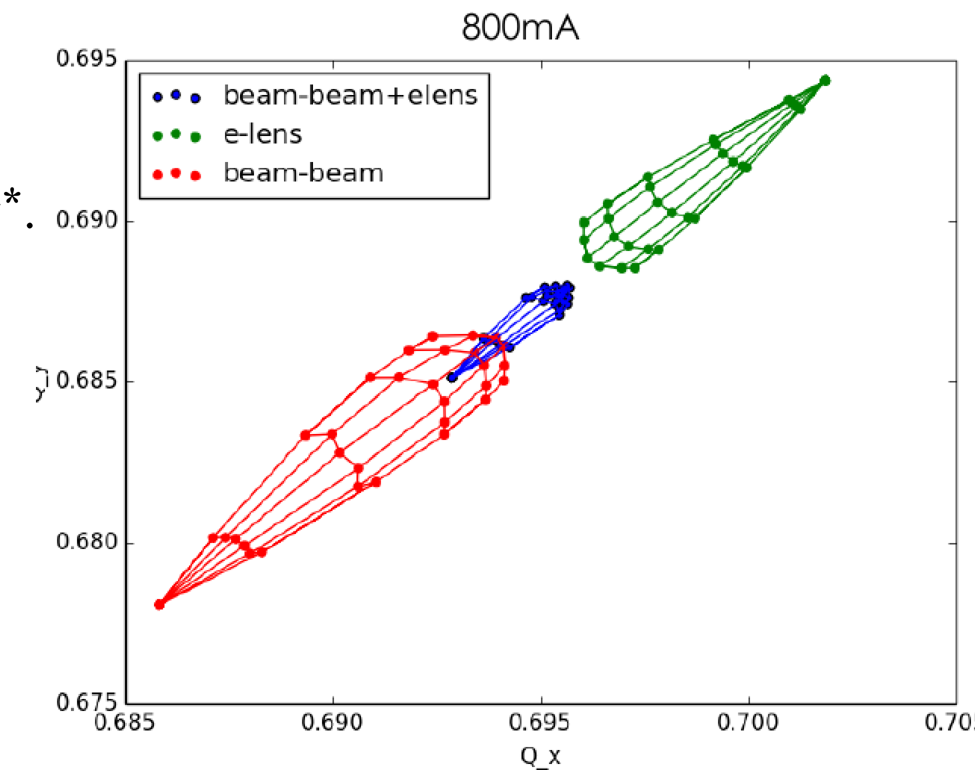




*J. Barranco et al., Study of beam-beam long range compensation with octupoles, CERN-ACC-2017-0065

E-lens and BBHO compensation

- The use of e-lens to provide Landau damping has been proposed by V. Shiltsev*.
- However when in collision, stability is ensured by the BB spread.
- @ Collision the e-lens can be used to compensate for the head-on interaction.
- Exisiting operational experience @ RHIC**.
- SixTrack **beam-beam element** has been **adapted** to simulate e-lens.
- Ready to start simulations to evaluate e-lens impact on DA and BBHO compensation.



E-lens simulations with COMBI

*V. Shiltsev *et al.*, Landau Damping of Beam Instabilities by Electron Lenses, PRL.

**X. Gu, Electron lenses for head-on beam-beam compensation in RHIC, PRAB.

RFQ impact on DA

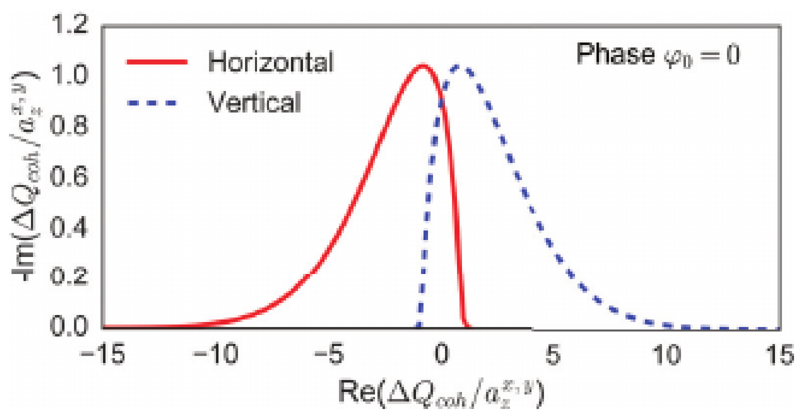
- RF quadrupole was proposed for Landau damping by A. Grudiev*.
- PyHEADTAIL simulations demonstrated the suitability of RFQ to provide stability and schemes together with octupoles are proposed**.
- It is necessary to evaluate the impact on DA studies of such a device.
- Simulations will be performed using the high order RF multipoles implemented in SixTrack[1] for HLLHC crab cavities studies.
- M. Schenk is already working on first input parameters to perform first RFQ simulations in presence of BB @ FCC.

Normal quadrupole

$$\Delta x' = -\frac{b_2}{B\rho} x \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)$$

$$\Delta y' = \frac{b_2}{B\rho} y \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)$$

$$\Delta\delta = \frac{1}{2}\frac{b_2}{B\rho}(x^2 - y^2) \sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)\frac{\omega}{c}$$



RFQ stability diagram. Courtesy M. Schenk

* A. Grudiev ,Radio frequency quadrupole for Landau damping in accelerators, PRAB.

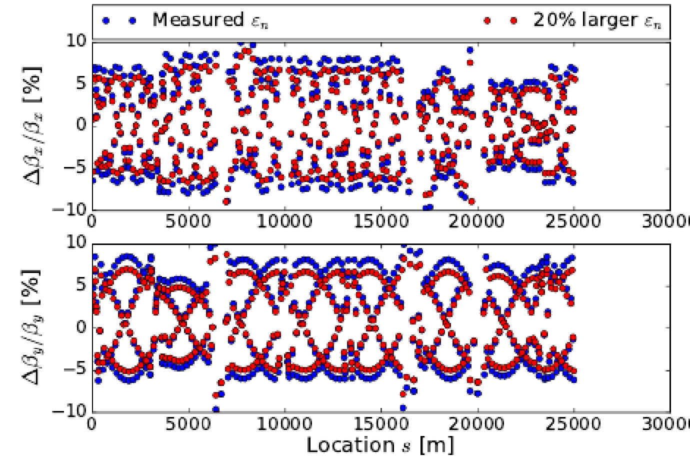
** M. Schenk *et al.*, Analysis of transverse beam stabilization with radio frequency quadrupoles, PRAB.

***J. Barranco *et al.*, Long term dynamics of the high luminosity Large Hadron Collider with crab cavities, PRAB.

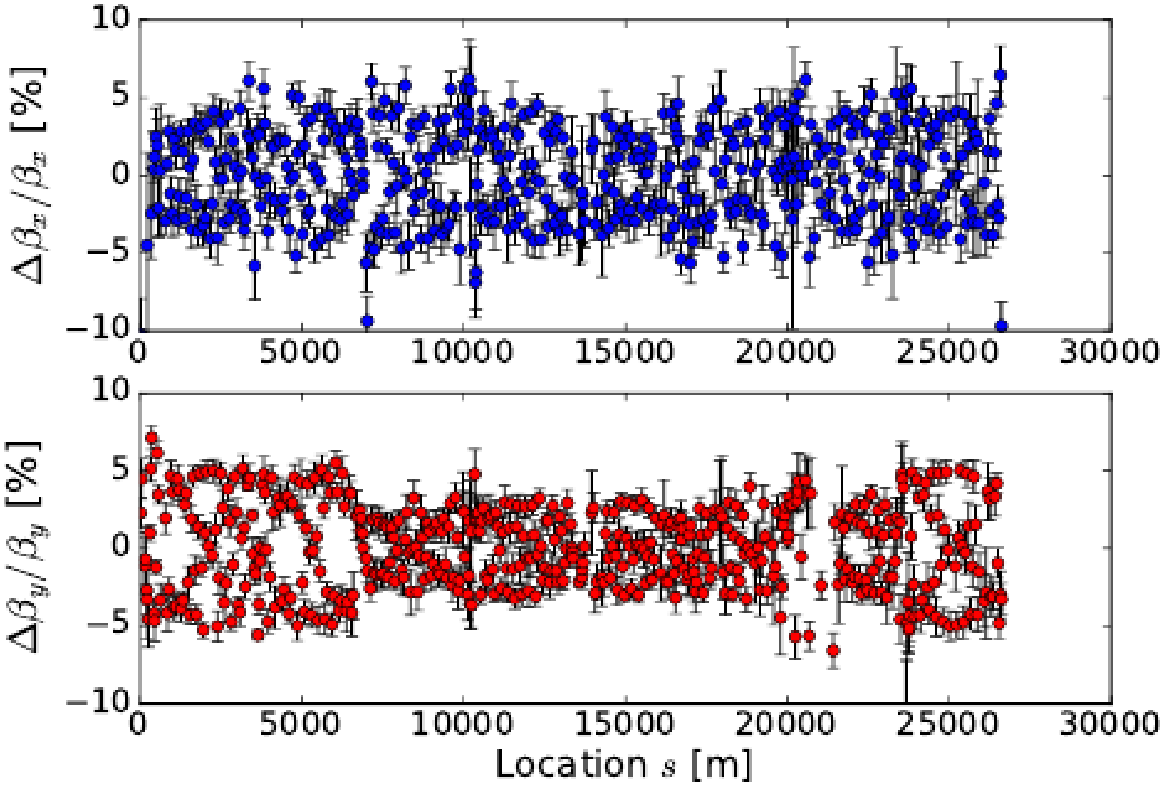
β-beating beam-beam induced

- The beam-beam interaction will introduce an optics distortion with amplitude depedence.
- For small amplitudes acts like defocusing quad.
- **Measurements and MADX simulations agreed qualitatively.**

MADX simulations



LHC measurements

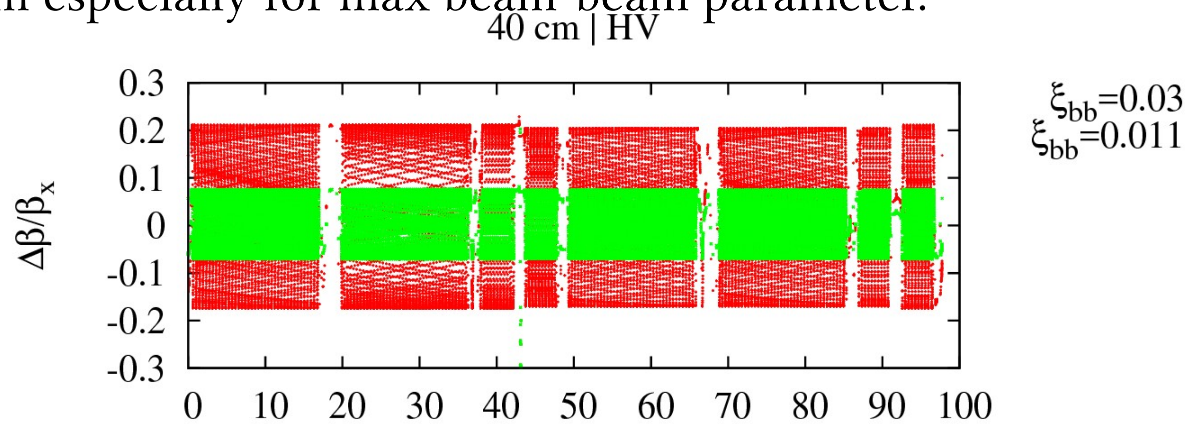


First β-beating due to BB in a collider*.

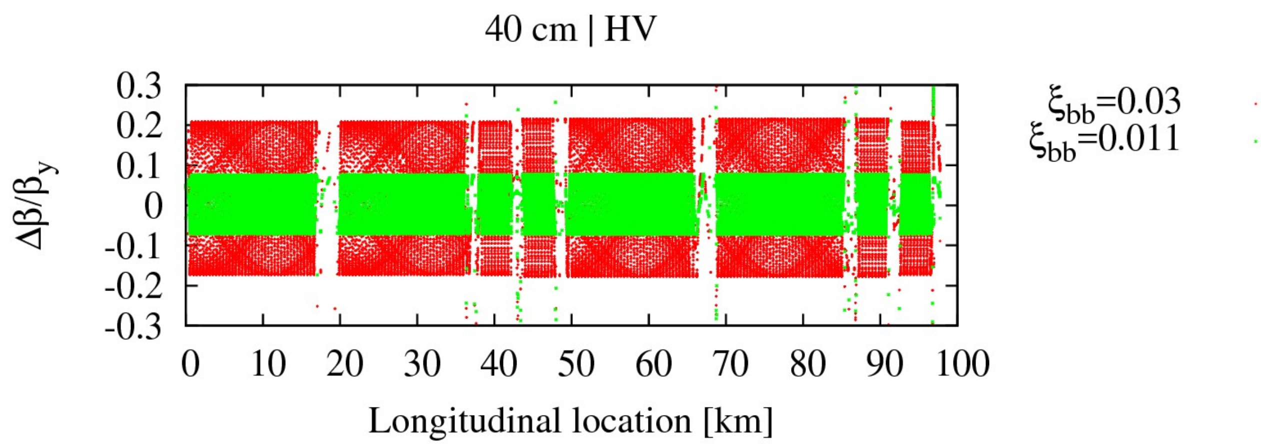
*P.J. Gonçalves, EPFL Master thesis, 2017

β-beating beam-beam induced

- Linear beating (twiss table) for the latest version of the lattice (L *= 40 m) evaluated.
- Two ξ_{bb}=0.011 (beg. Fill) - $\Delta\beta/\beta_{max}$=8 % and **ξ_{bb}=0.03 (max) -$\Delta\beta/\beta_{max}$=22 %**.
- Collimators experts request $\Delta\beta/\beta_{max}$<10 % as in the LHC.
- Algorithms for correction developed and working in simulations by Luis Medina*. Need to test them especially for max beam-beam parameter.



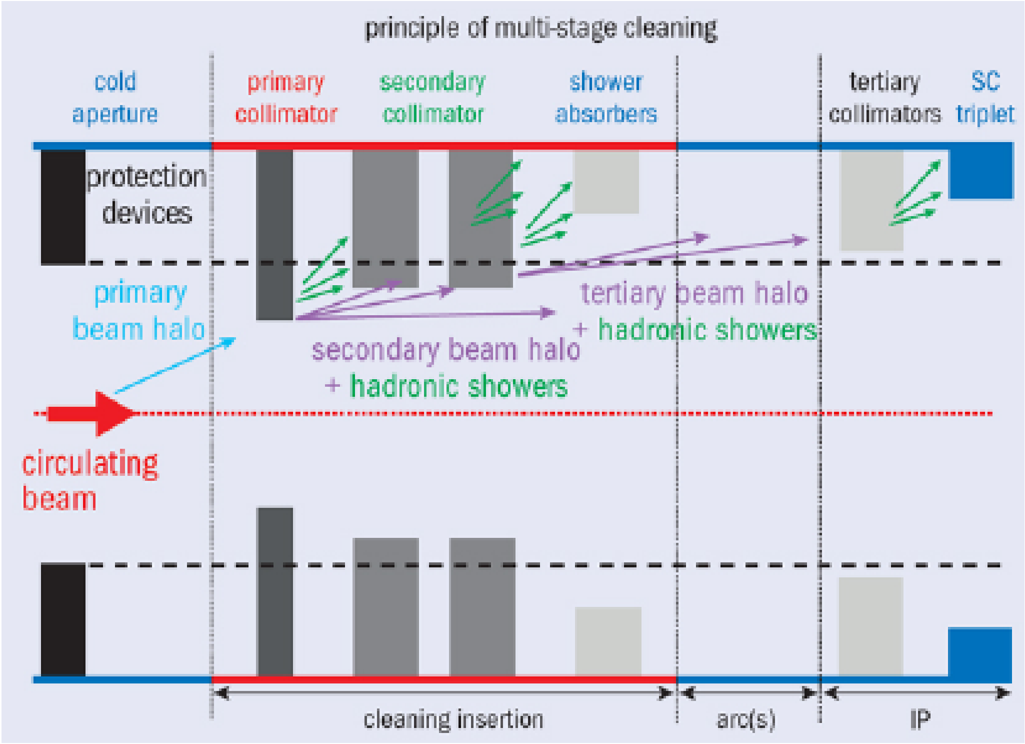
*L. Medina et al., Correction of beta-beating due to beam-beam for LHC and its impact on dynamic aperture. IPAC 2017



Impact of collimation system hierarchy

- Optics will be distorted along the machine due to BB interactions ($\Delta\beta/\beta_{max,FCC}$=22 %.)
- Apertures will be modified ⟶ **Cleaning efficiency affected ??**
- Aperture variation evaluated for L*=45 m lattice considering only the betatron collimation.
- Collimators aperture values from Andy's presentation @ Berlin.
  - TCP – 7.2 σ
  - TCS – 9.4 σ
- MADX aperture command used, set to calculate N1 as real aperture (halo={6,6,6,6} set up)

Multistage collimation system principle

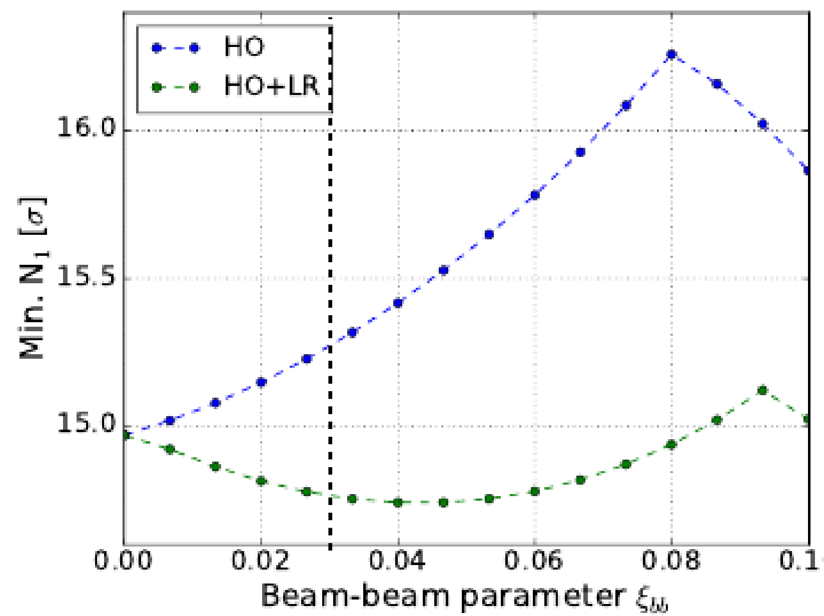


Impact of collimation system aperture

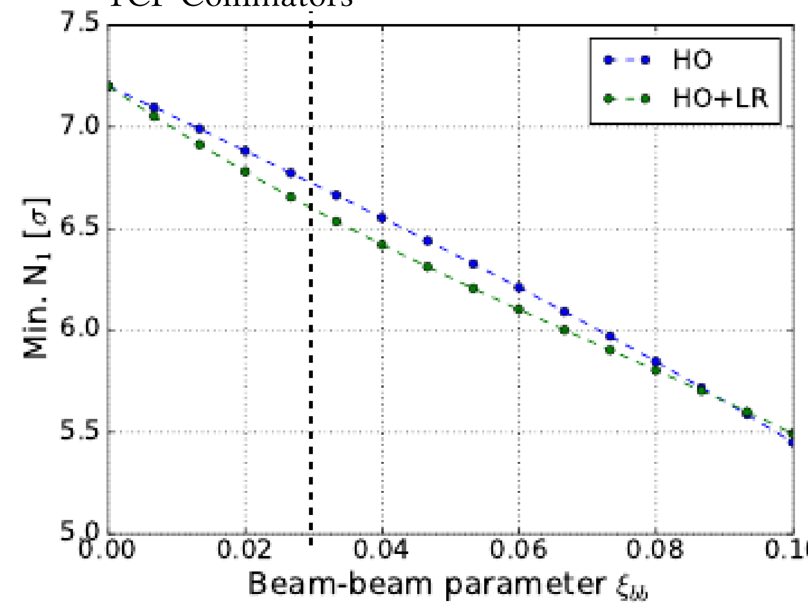
- Collimators are fully retracted in the lattice aperture definition.
- We close them « manually » to the nominal apertures.
- Machine aperture is @ 15 σ. HO+LRs decreases by ~0.25 σ @ ξ_{bb}=0.03 (MBRD.B4RA.H1)
- Considering the collimators as well the bottleneck is now @ TCP.B6L2.B1/ TCP.A6L2.B1.

$\xi_{bb}=0.03 \Rightarrow \Delta A_{TCP} = -0.6\ \sigma$

Machine aperture



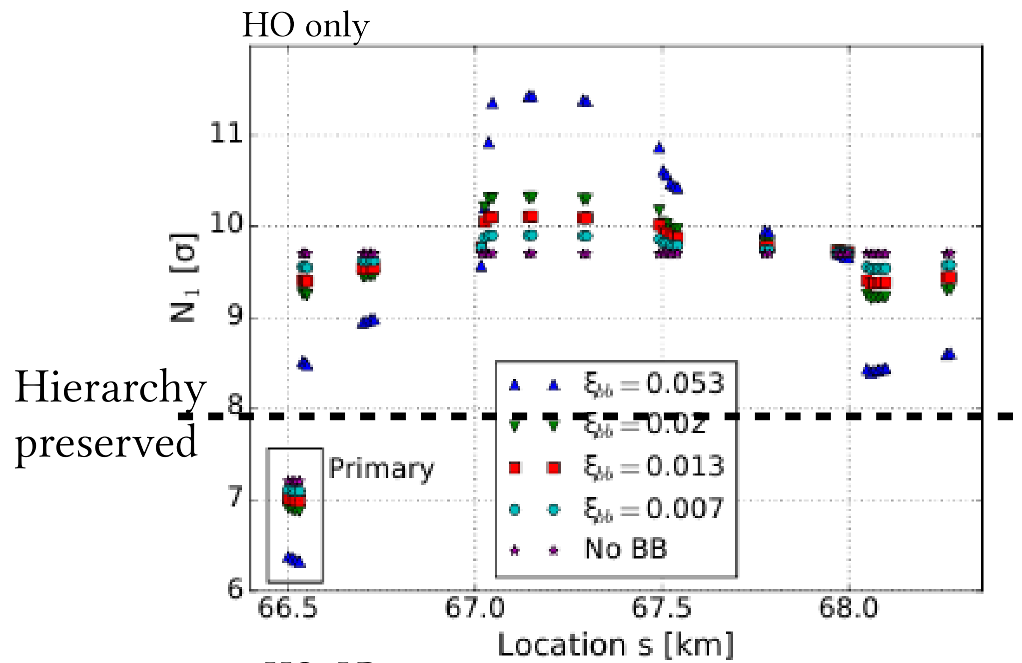
TCP Collimators

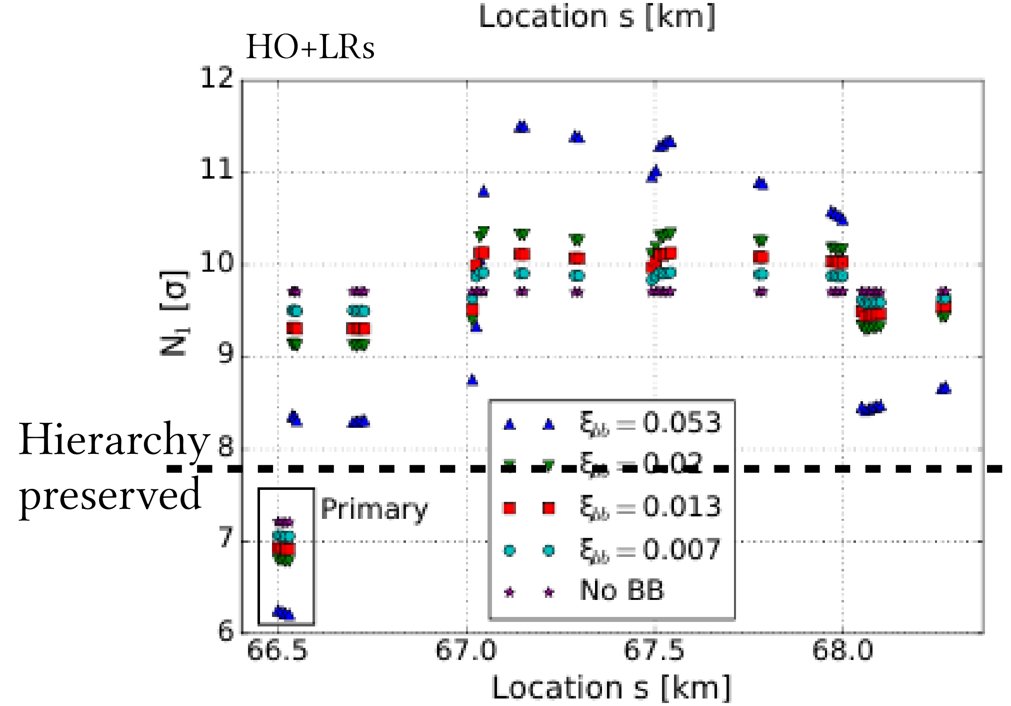


Impact on collimation system hierarchy

- Collimation hierarchy is evaluated for various ξ_{bb}.
- We consider HO only and HO+LRs.
- Only for very large ξ_{bb}=0.053 the aperture bottleneck is significantly reduced for TCP and TCS.
- In all cases the hierarchy is preserved. However this is not conclusive until complete collimations simulations are performed to evaluate the cleaning efficiency in each and loss maps.

$$\xi_{bb}=0.03 \Rightarrow A_{TCP} < A_{TCS}$$





Conclusions and outlook

- Simulations for L*=45 m from Berlin were extended by the inclusion of errors in the arcs and in the triplets.
- Errors table has been already changed so new simulations are needed. However BB seems to be the main driver of DA.
- The new version with L*=40 m shows a worst DA performance compared with L*=45 m. Need to identify the causes. Issues with chromaticity to be solved.
- Landau octupoles are shown to compensate for the LRs effects when powered with negative polarity.
- L*=40 m simulations should be extended consideration the evolution during the fill, low lumi exp, etc.
- SixTrack code ready to start Landau damping devices (e-lens and RFQ) impact on DA.
- Linear β-beating evaluated for HV configuration ($\Delta\beta/\beta_{max}$=22 % for ξ_{bb}=0.03). Correction algorithms are necessary for largest beam-beam parameter.
- Aperture distortion evaluated and the hierarchy preservation checked. However no conclusion can be drawn of cleaning efficiency until complete simulations are performed.