Beam-beam effects

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Acknowledgements: R. Martin, M. Hofer, R. Tomas, R. Bruce, L. Rivkin, A. Seryi, B. Dalena, M. Giovannozzi, A. Mereghetti, E. Métral, O. Boine-Frankenheim, F. Zimmermann

Contents

FCC-hh beam-beam effects:

- Nominal crossing scheme
- Dynamic aperture studies (Round Optics)
- Low Luminosity experiments
- Beam-beam Long range global compensation and phase advance optimization
- Head-on limit studies
- Alternative solutions (flat optics)

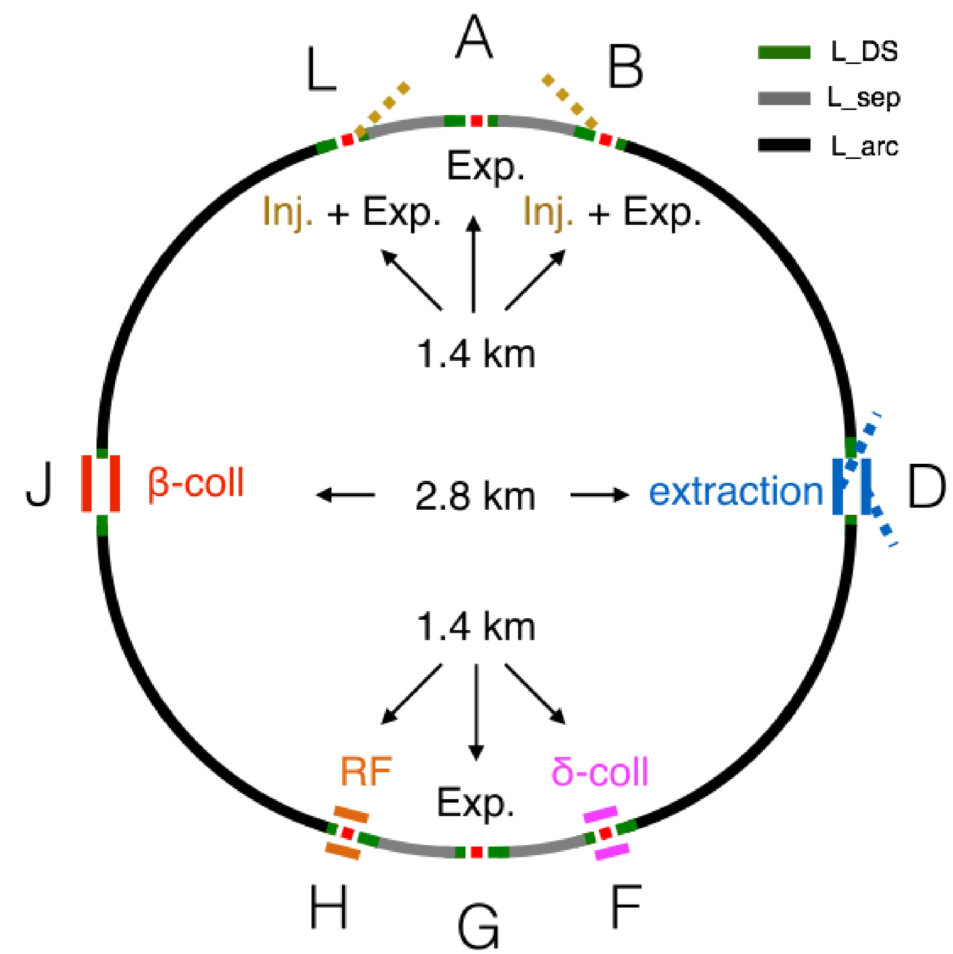
FCC-hh two beam stability:

- Stability at the end of the betatron squeeze
- “Collide & squeeze”
- Stability during the collapse of the separation bumps
- Alternative solutions for Landau damping and compensation

Collider Parameters

FCC CDR

Parameter	FCC-hh Baseline	FCC-hh Ultimate
Peak Luminosity [10^{34} cm $^{-2}$ s^{-1}]	5.0	< 30
Bunch distance [ns]	25	
Number of bunches	10400	
Bunch population [10^{11} p/bunch]	1.0	
Transverse Norm. Emittance [μm]	2.2	
RMS bunch length [cm]	8	
RMS IP beam size [μm]	6.8	3.5
IP beta functions [m]	1.1	0.3
Maximum Total BB tune shift	0.011	0.03
Full crossing angle [μrad]	104	200

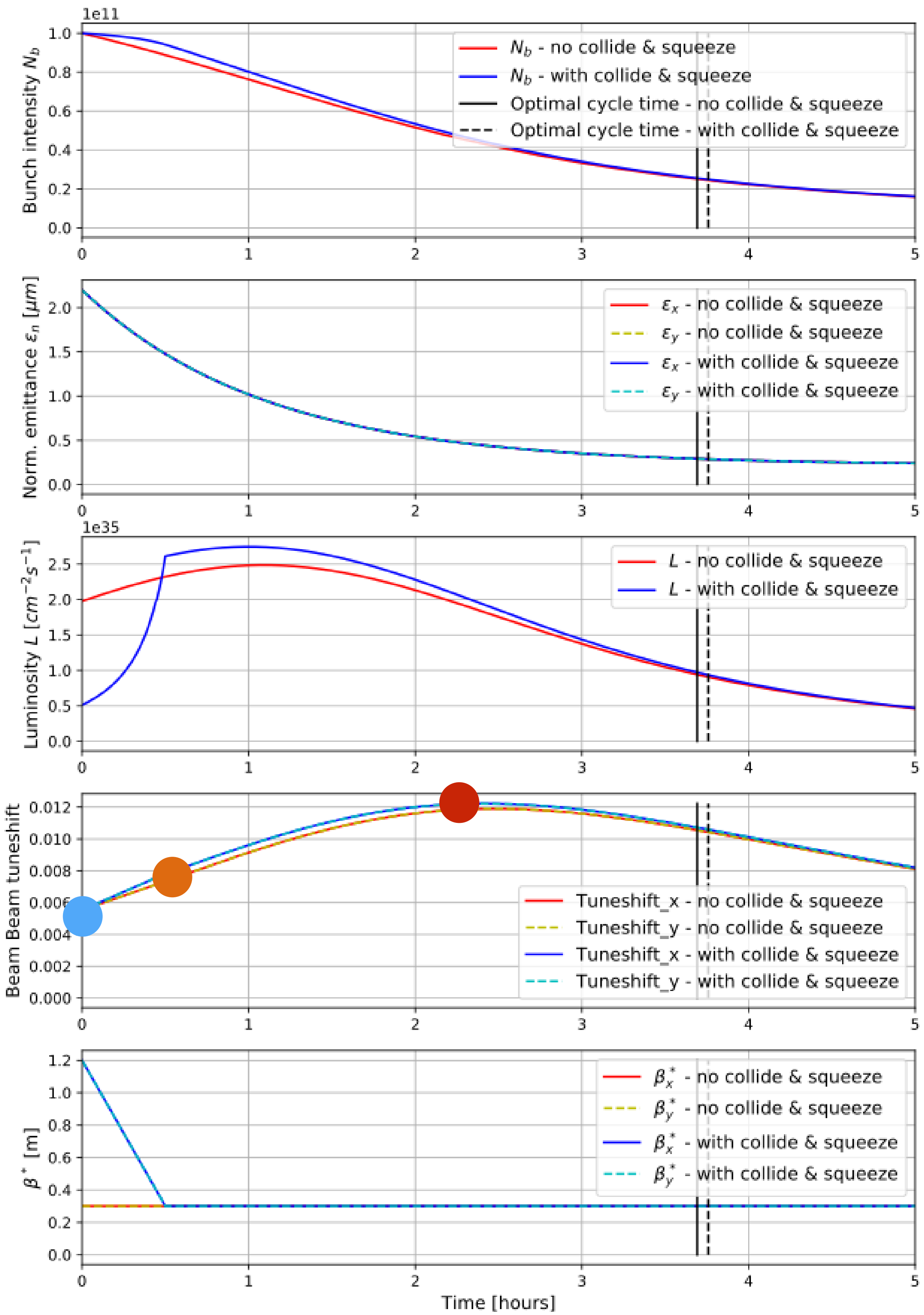


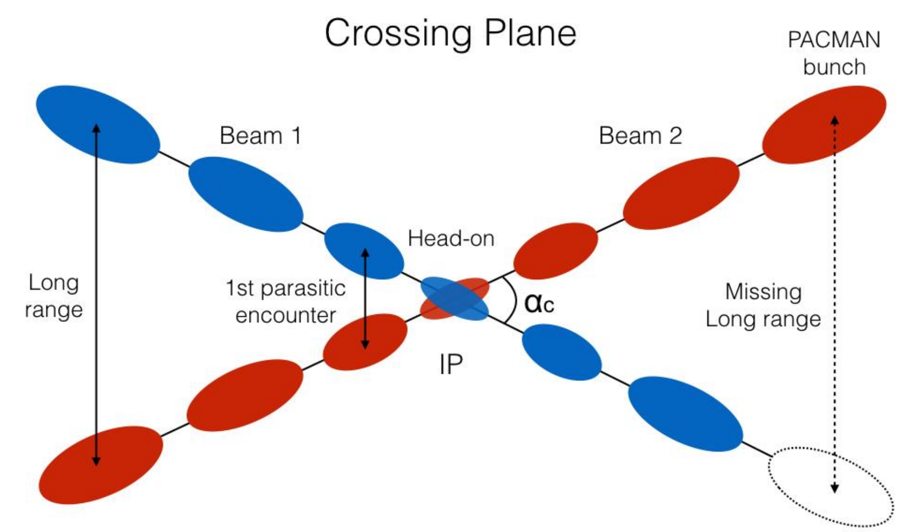
352 Long-Range interactions
For 4 Experiments

High luminosity experiments hosted in Interaction Point A and G → **provide maximum luminosity together with good lifetimes**

Low luminosity experiments hosted in Interaction Point L and B → **keep beam-beam effects in the shadow of the high luminosity IPs**

Evolution of beam parameters: beam-beam effects





An alternating (Horizontal and Vertical) crossing scheme is chosen for IPA & G in order to passively compensate for tune and chromaticity shifts for the PACMAN bunches

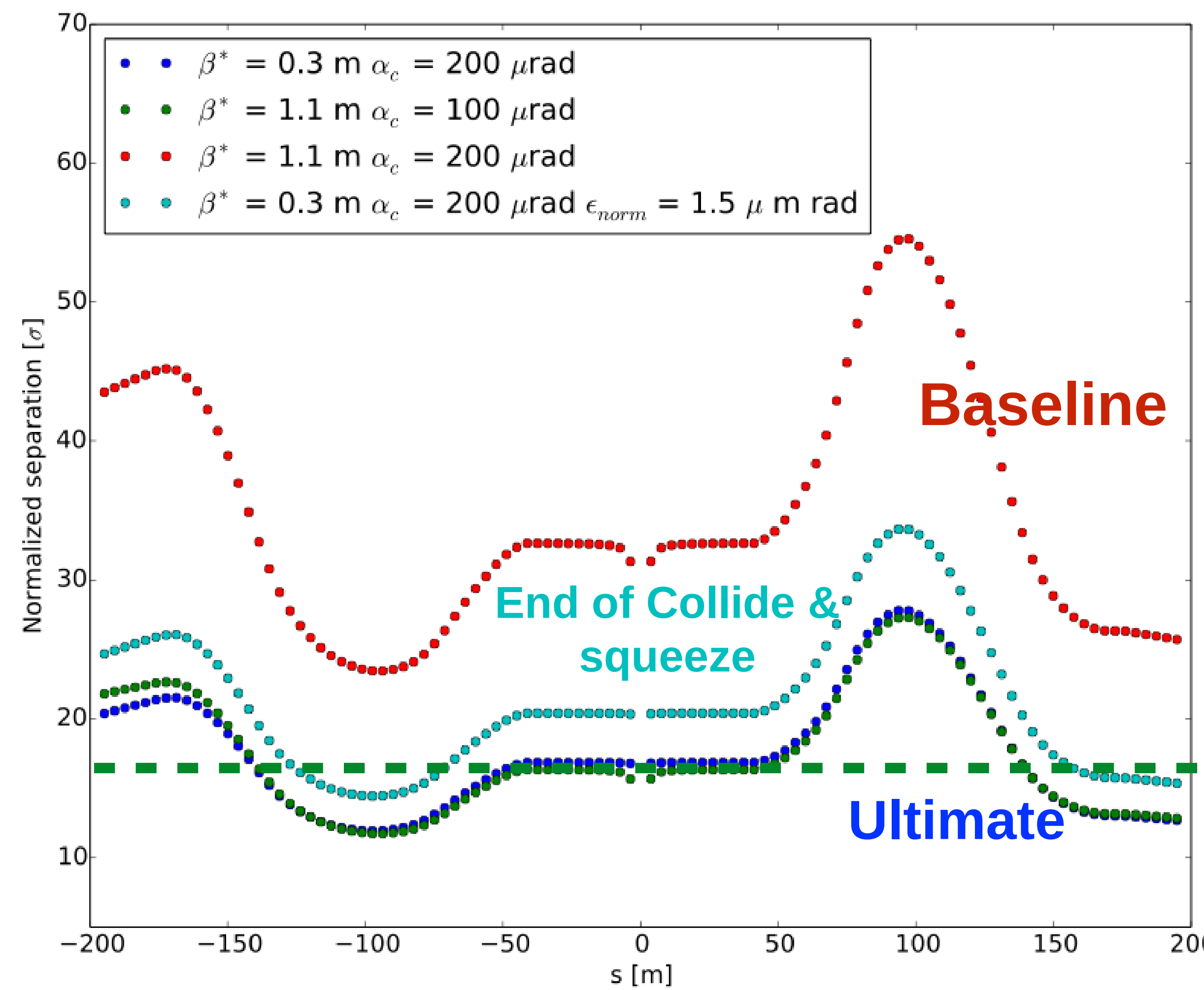
Due to strong radiation damping (emittance reduction) the **beam-beam tune changes over the fill:**

- $\Delta Q_{TOT} = 0.011$ at the beginning of the fill
- $\Delta Q_{TOT} = 0.016$ at the END of the Collide&Squeeze
- $\Delta Q_{TOT} = 0.03$ after two hours (maximum value)

Explore limitations for the different beam-beam cases
Propose a robust baseline and explore limits of ultimate

IR design : Crossing schemes and long term particle stability

See talk R. Martin



Tot. crossing angle of 200 μrad

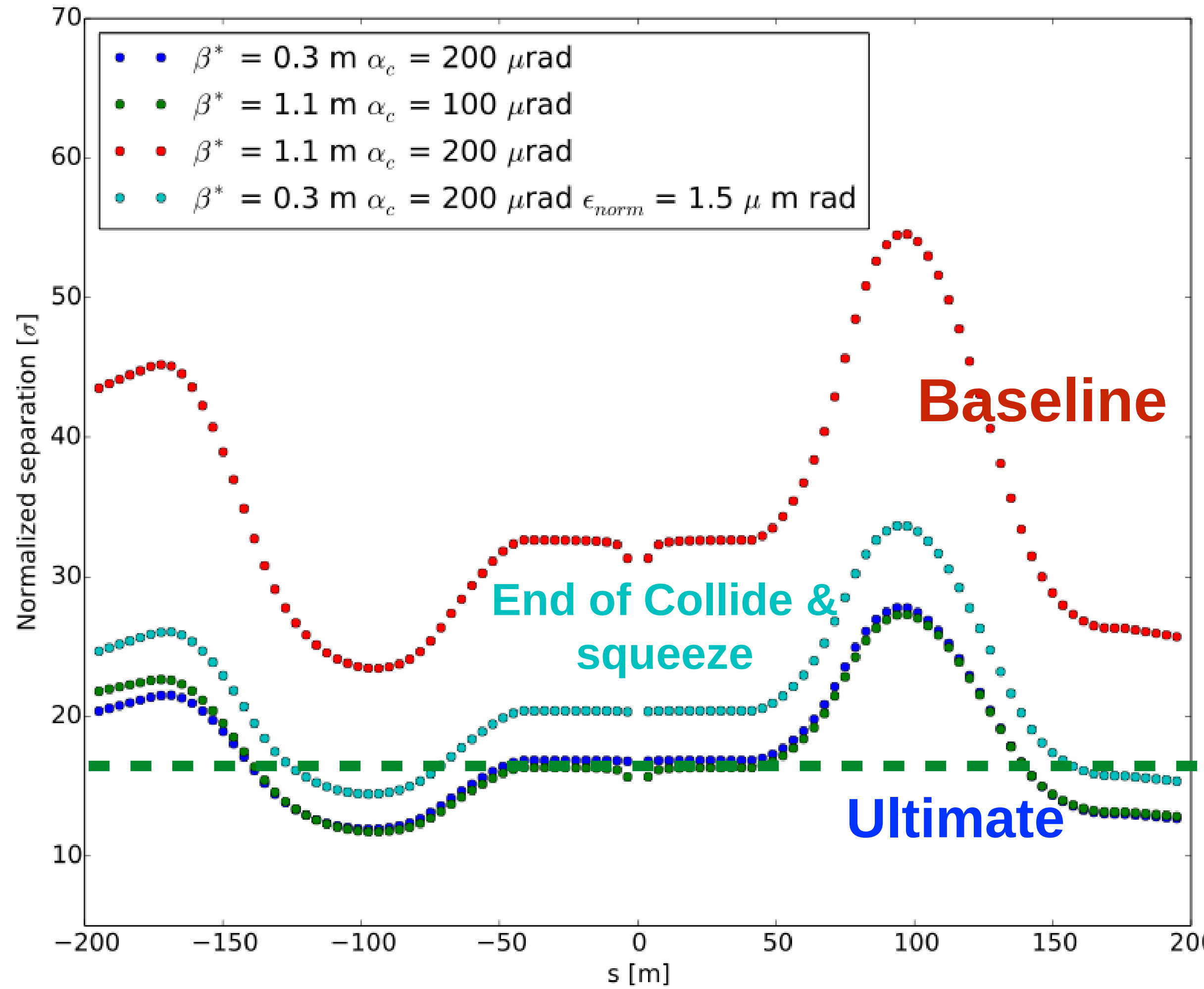
Baseline: LR$_{sep}$ = 30 σ → **DA > 13 σ** **b***

Ultimate: LR$_{sep}$ = 17 σ → **DA = 7.2 σ = baseline with reduced crossing angle ~ 104 μrad** (green points)

End of Collide&Squeeze: LR$_{sep}$ = 20 σ → **DA ~ 8.5 σ**

The choice of the crossing angle is **based on the Dynamic Aperture studies**

IR design : Crossing schemes and long term particle stability



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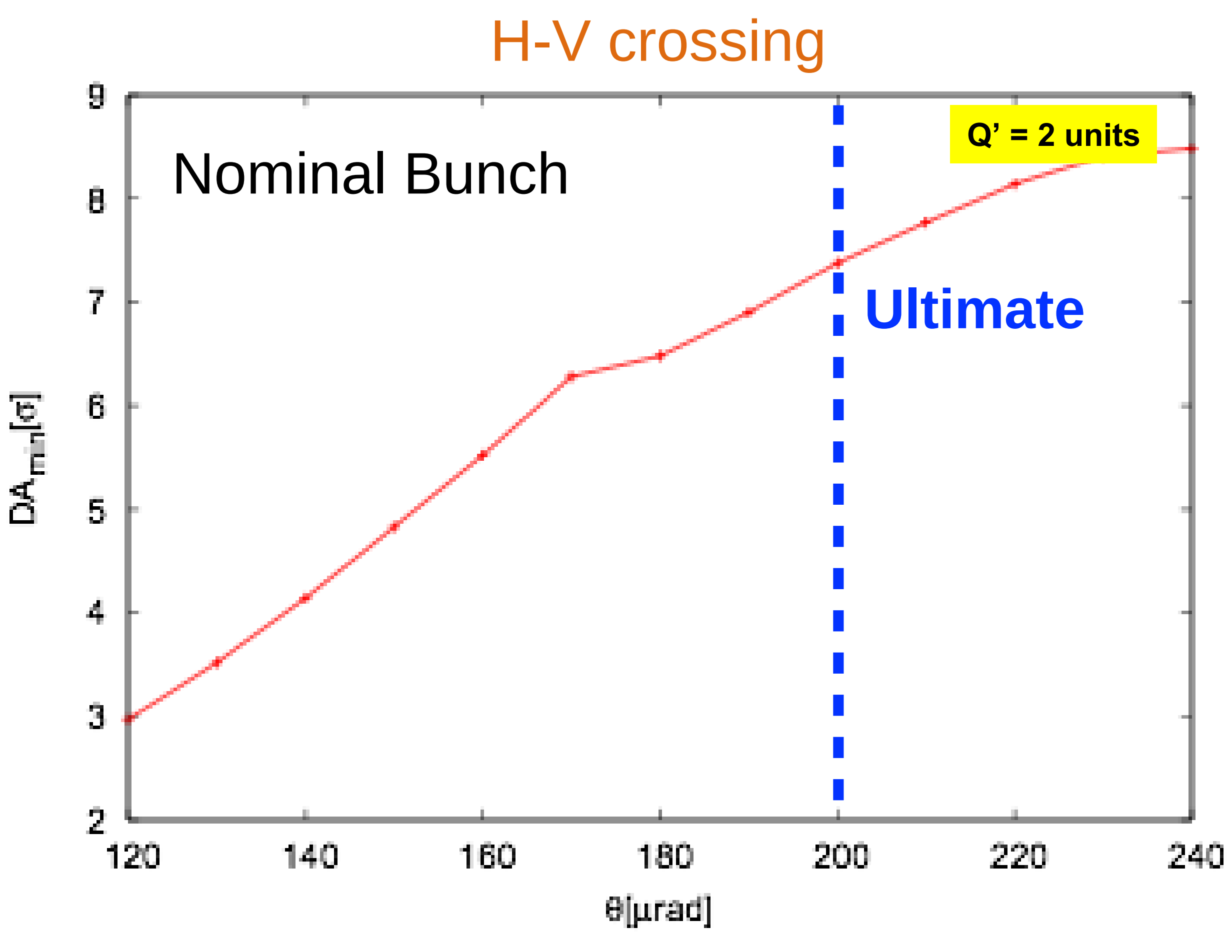
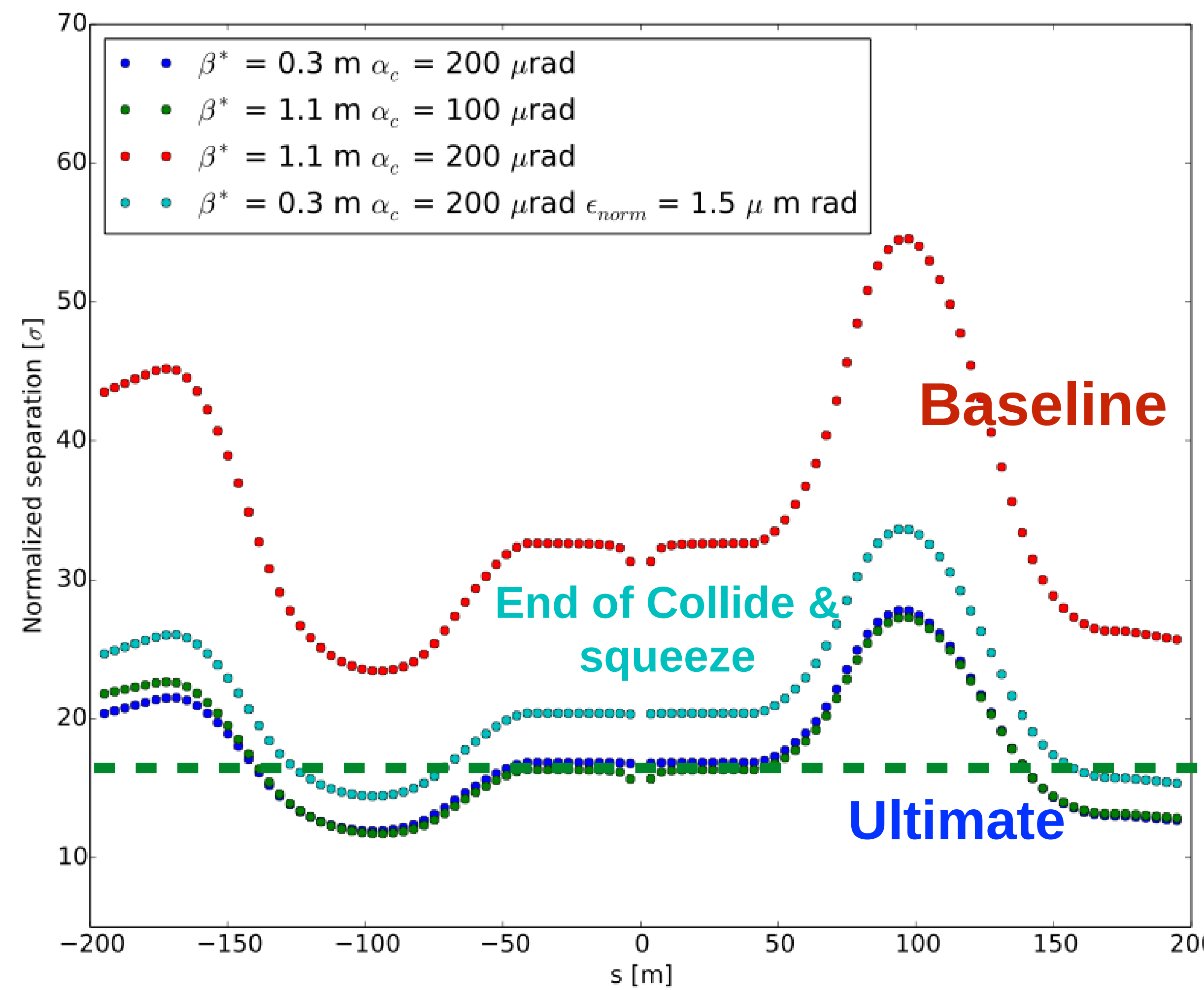
Margins available and several crossing schemes possible (HH,VV, HV or mixed status) to "spread" energy deposited at the interaction region → ROBUST Baseline!

IR design : Crossing schemes and long term particle stability





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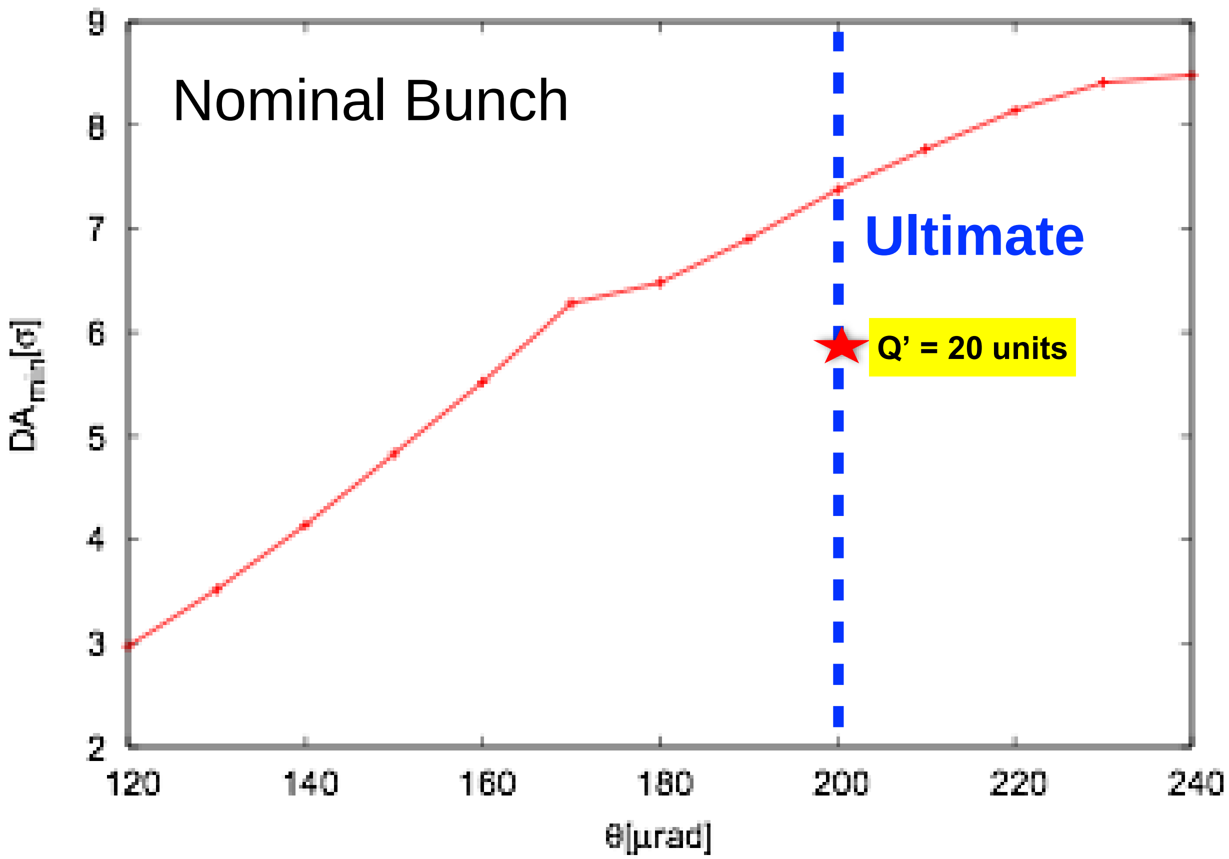
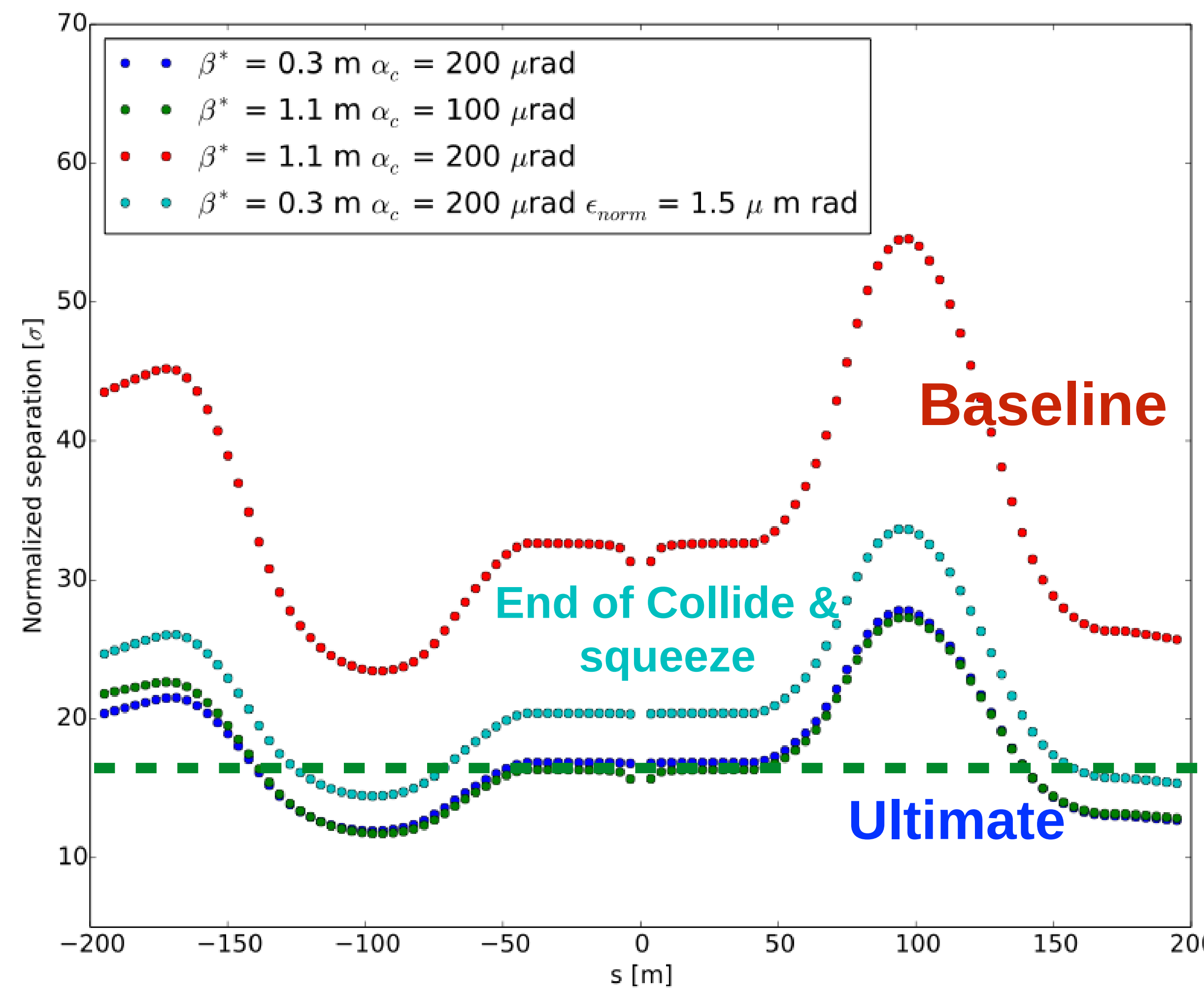
Challenging case where limits have to be explored and understood to study the physics reach and potentials of such collider

IR design : Crossing schemes and long term particle stability

H-V crossing





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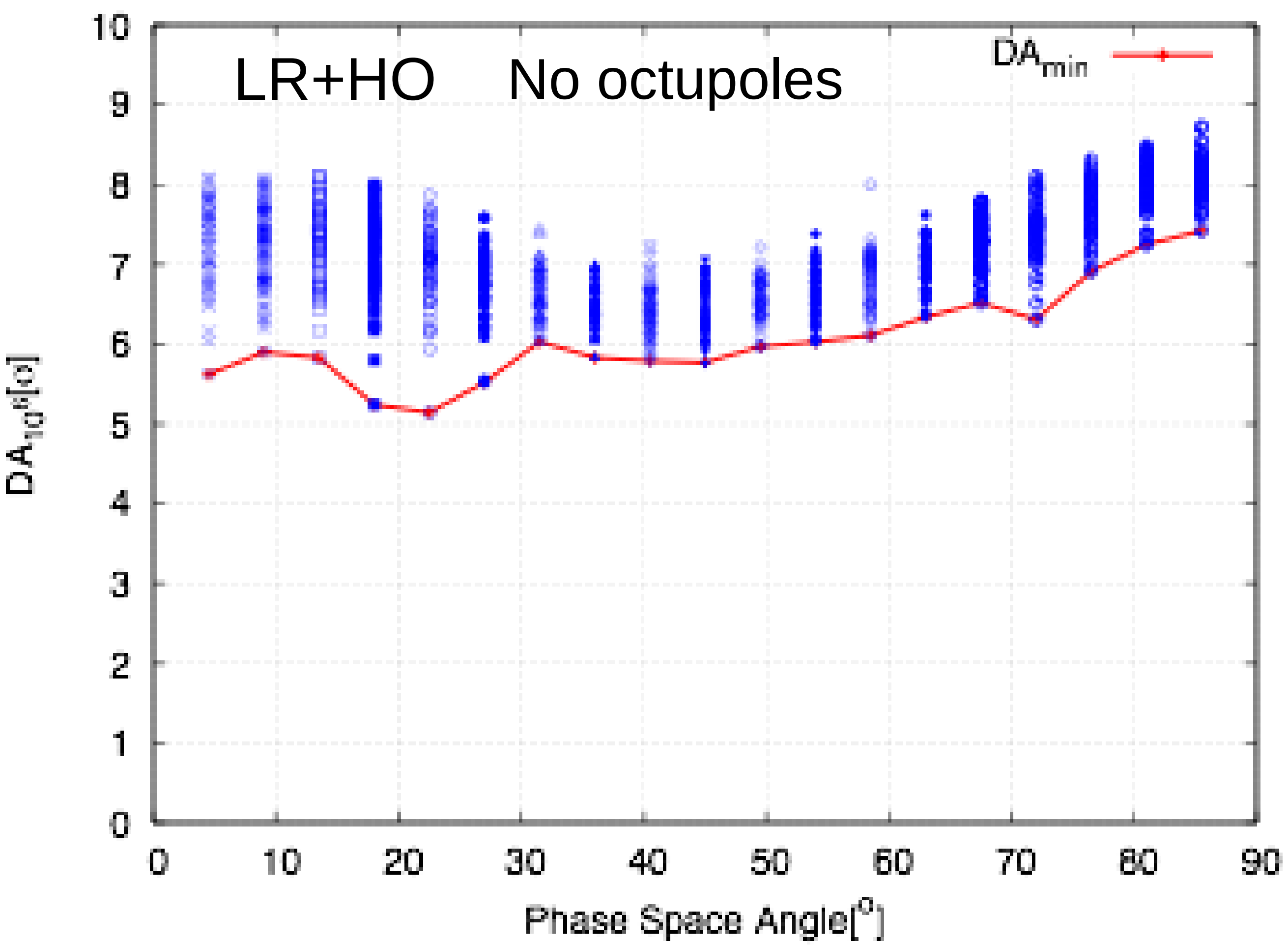
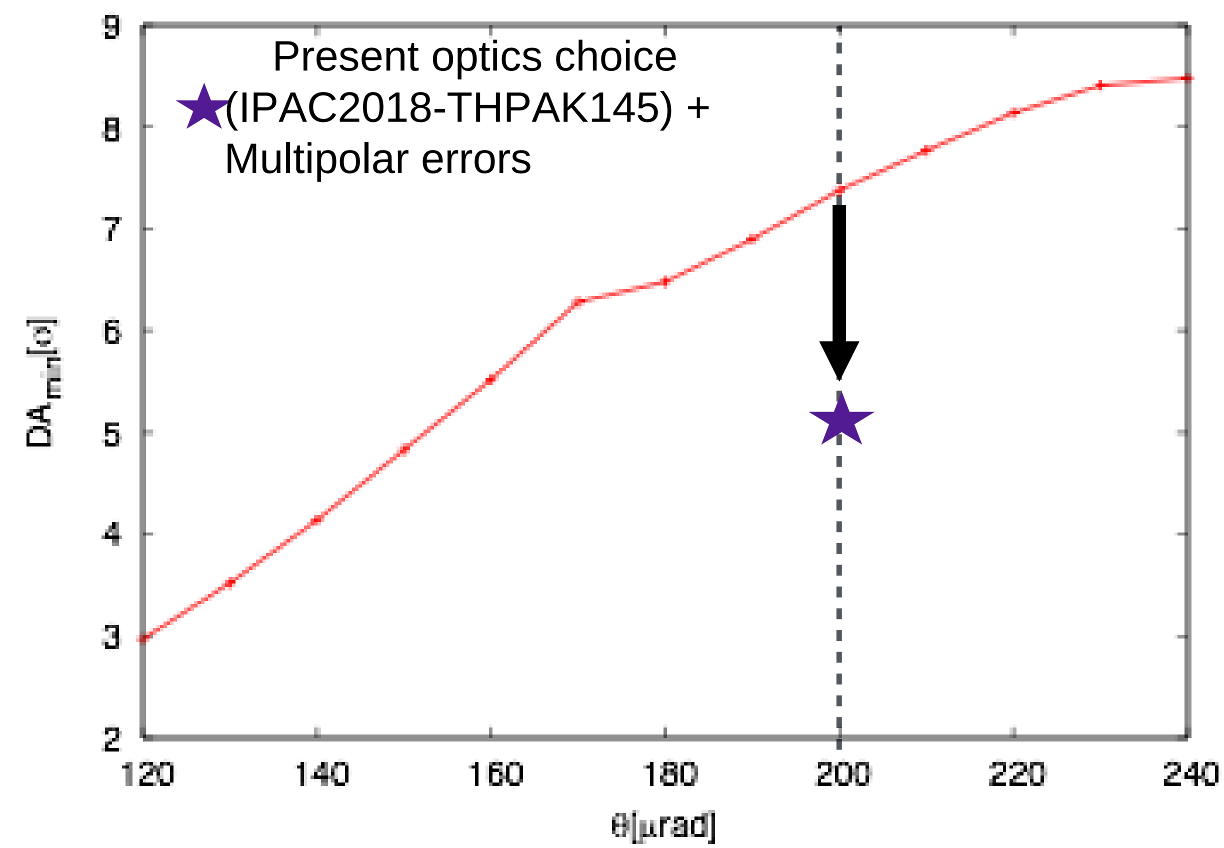
DA with multipolar errors

FCC New Lattice L* 40 m 200 μrad at IPA and IPG

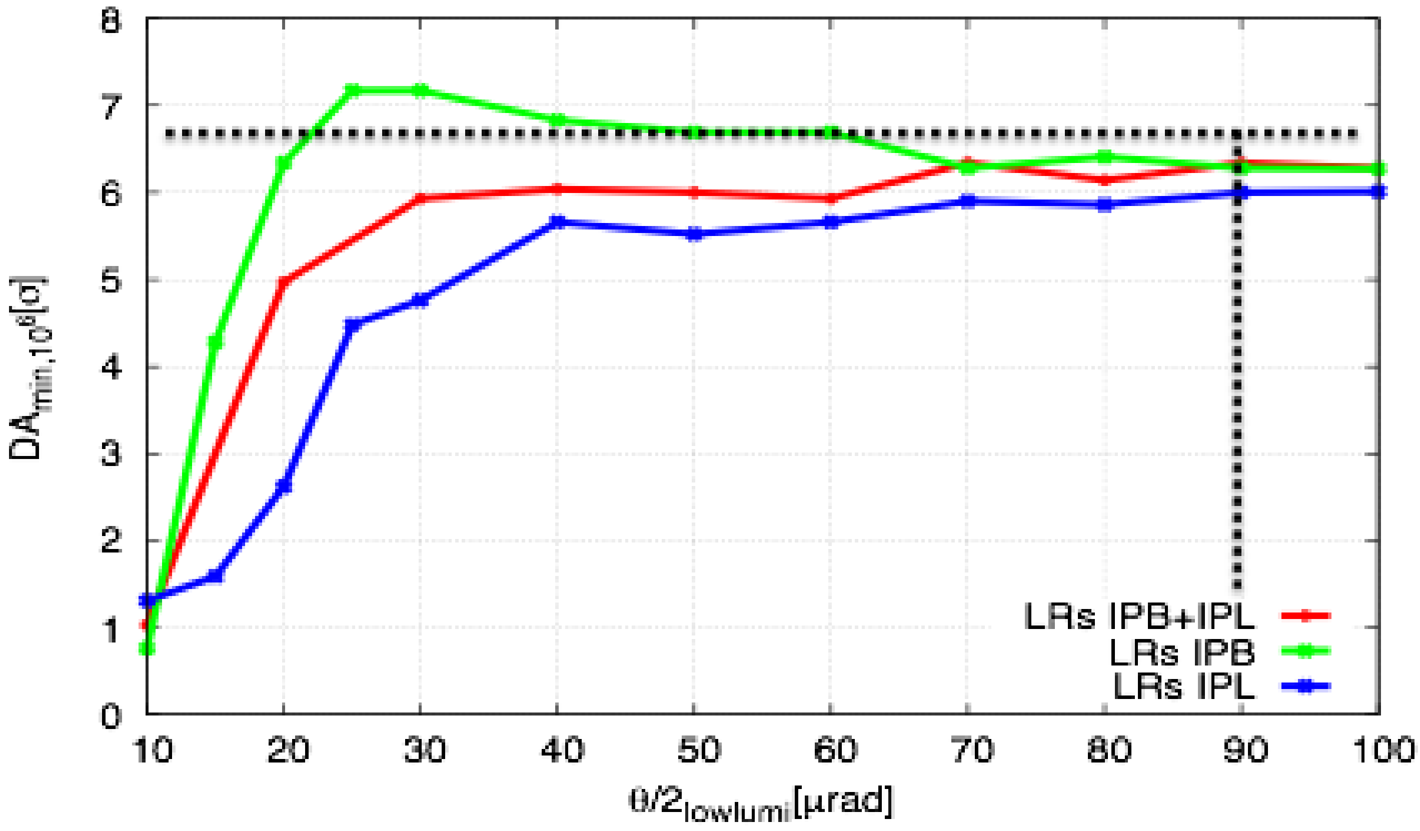




- 60 seeds simulation → 60 different machines
- Minimum of DA 5 σ reached ➞ Reduction of 2 σ w.r.t. the case without errors
- **Challenging set-up that needs further studies and newer ways to look at DA because of the very large parameter space → Machine Learning project on-going to automatize the optimization of DA-lifetimes and feedback to design**

Low Luminosity experiments: IPL & IPB

See talk M. Hofer



The long-range effects of IPL and B will impact bunches differently **(no passive compensation)**

To have them not perturbing the high luminosity experiments should have **angles (tot) > 180 μrad (3 m optics)**

Head-on collisions: level by separation to avoid strong tune shifts

Same strategy as for in LHC and HL-LHC

Long range: crossing angles larger than **180 μrad for the 3 m optics**
Head-on: apply separation leveling of luminosity ➞ limit on integrated luminosity per year of run!
Need to be defined together with tune optimization

Global compensation of long range interactions

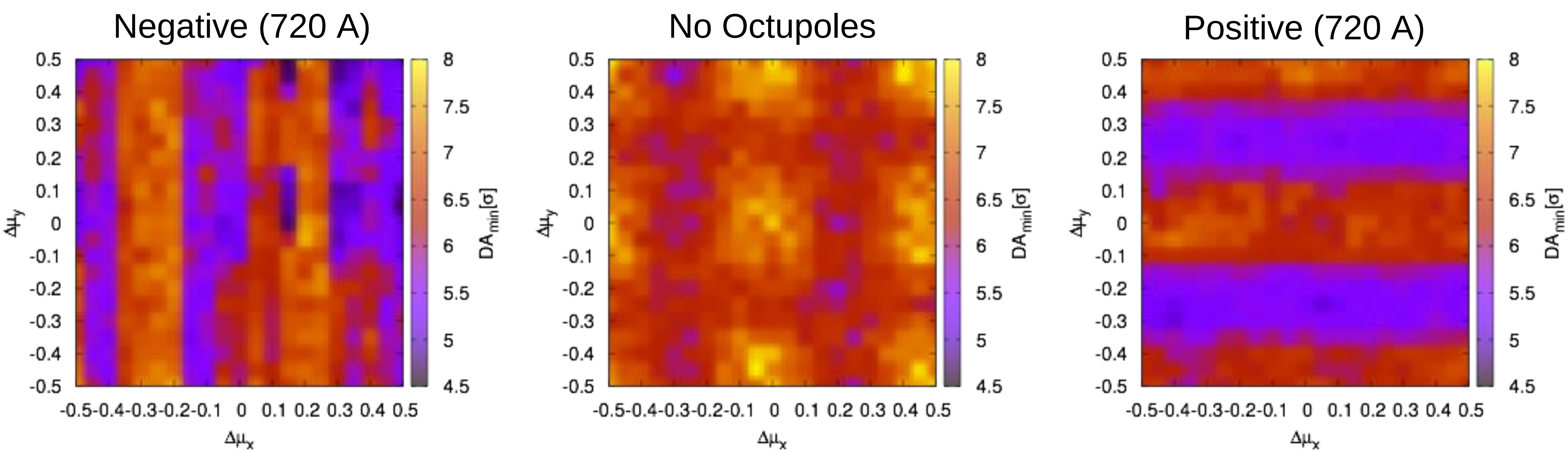
See talks A. Chance, E. Cruz

We choose to have Landau Octupoles powered such that they compensate the BB long-range effects:

- provides larger stability for single beam (see beam stability studies)
- **allows for larger Dynamic aperture → beam lifetimes**

Full integration in the lattice design **(J. Shi et al., CERN-ACC-NOTE-2017-036)**

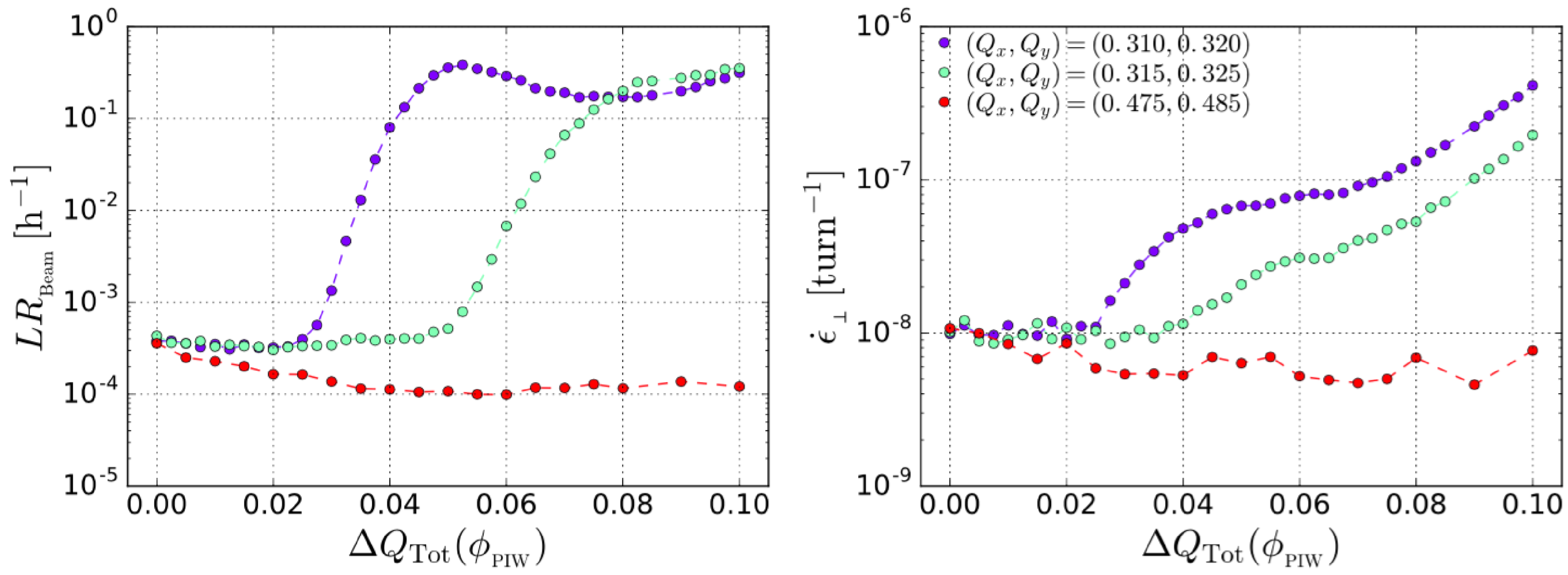
Dynamic Aperture with head-on + Long range interactions



Lattice and Beam-Beam optimized together to enhance at a design stage the natural compensation between effects and allow these flexibility.

Head-on limit: losses and emittance growth

Full crab crossing

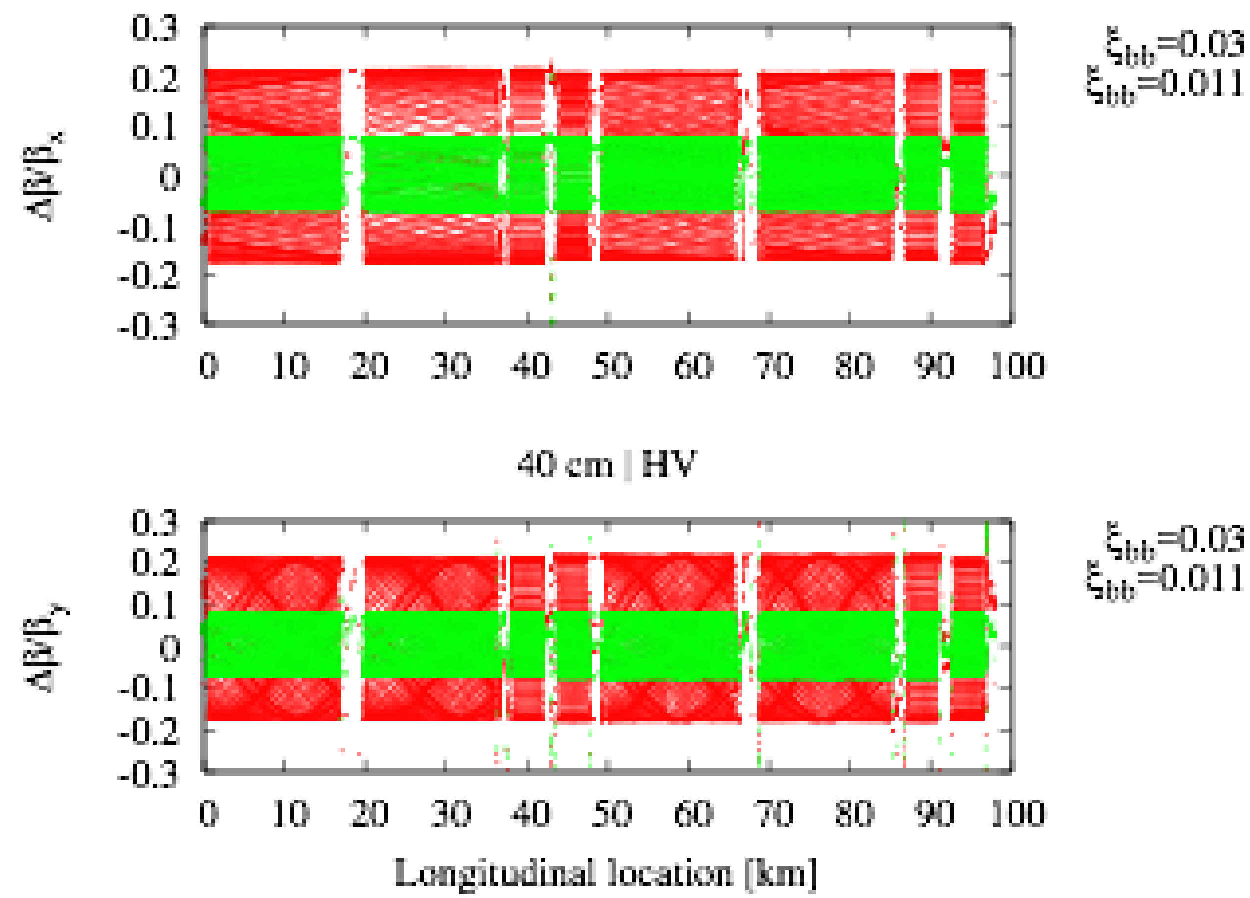


- **Baseline scenario (total beam-beam tune shift 0.02) shows no limitations** (confirmed also by LHC measurements of lifetimes)
- Ultimate (total beam-beam tune shift 0.03) is challenging ➞ **optimization of the working point** improves beam quality
- The ultimate beam-beam tune shift of **0.03 considered for the FCC-hh baseline with crab cavities seems within reach** while the limit for non-zero crossing angle is significantly smaller

Further studies needed to explore possible limitations linked to a larger head-on beam-beam tune shift: LHC data benchmark fundamental!

Head-on Limit: beta-beating

MAD-X (no lattice errors) L*=40 m and β*=30 cm (full crab x-ing)



- The BB interaction causes non-linear amplitude detuning
- For small amplitude particles (< 1 σ) the kick is linear
- The change of the β-function assuming a series of small quadrupole errors is given by:

$$\frac{\Delta\beta(s)}{\beta_0(s)} = \frac{2\pi\xi}{\sin(2\pi Q_0)} \sum_{i=0}^{N} \cos(2\,|\mu_0(s) - \mu_0(s_i)| - 2\pi Q_0)$$

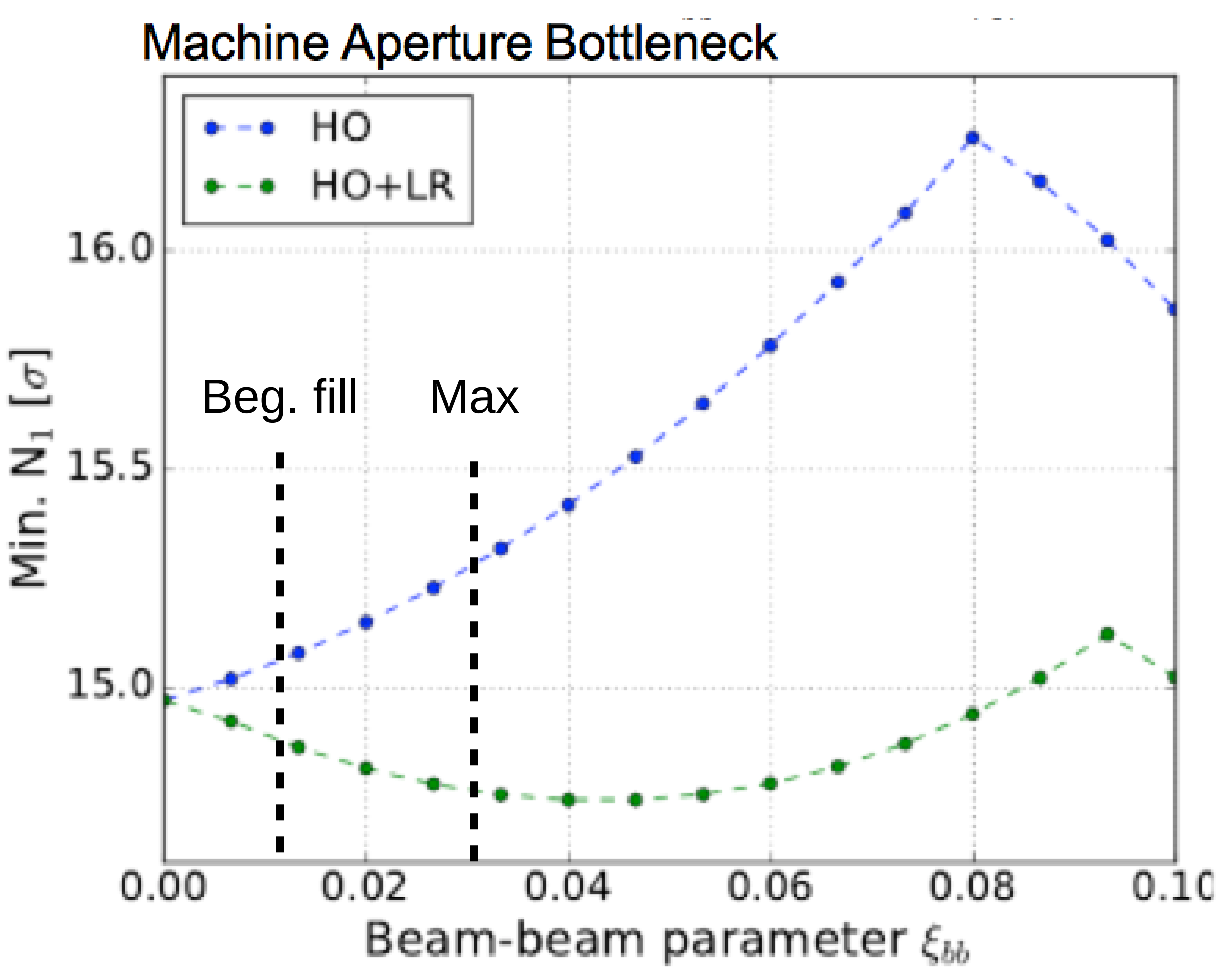
- The beating is directly proportional to the BB parameter

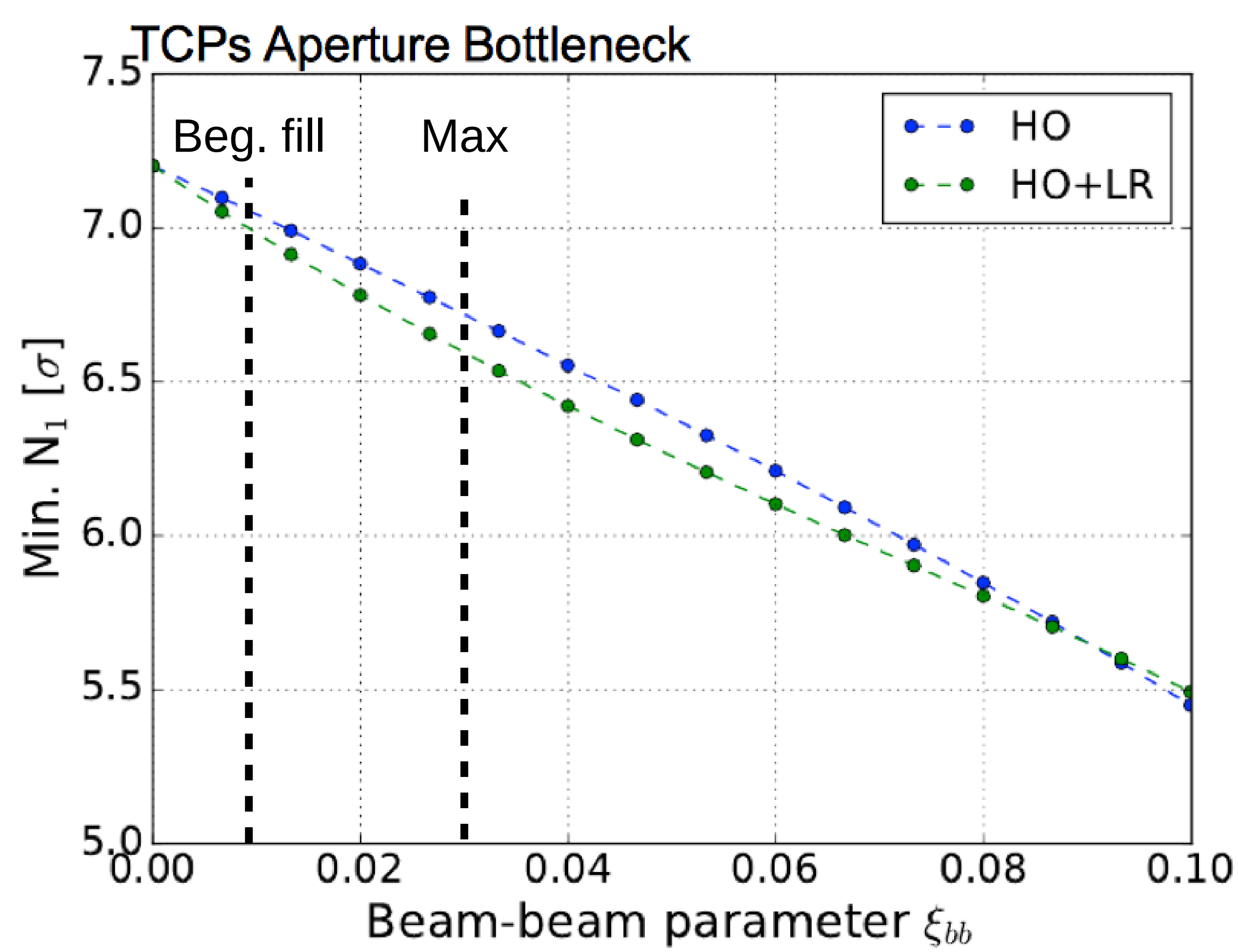
- $\xi_{bb,tot}$=0.011 (beg. Fill) → Δβ/β = 8 %
- $\xi_{bb,tot}$=0.03 (max) → Δβ/β = 22 %
- This optics distortion becomes another parameter on optimization (HO, octupoles)
- Collimation tollerance is fixed at Δβ/β < 10 % as in the LHC

Beta-beating: impact on aperture

With Collimation team

- We explored the impact on machine and collimator apertures for various ξ_{bb}. Only linear beating is considered (worst case).
- Machine aperture bottleneck in separation dipole MBRD.B4RA.H1.
- For HO only no aperture decrease for expected ξ_{bb} FCC range (0.01-0.03).
- For HO+LRs there is a decrease of -0.25 σ for max ξ_{bb}=0.03
- Collimation hierarchy is not changed
- Non-gaussian beams to Luminosity impact is minimal in the range of interest ξ_{bb} FCC range (0.01-0.03).





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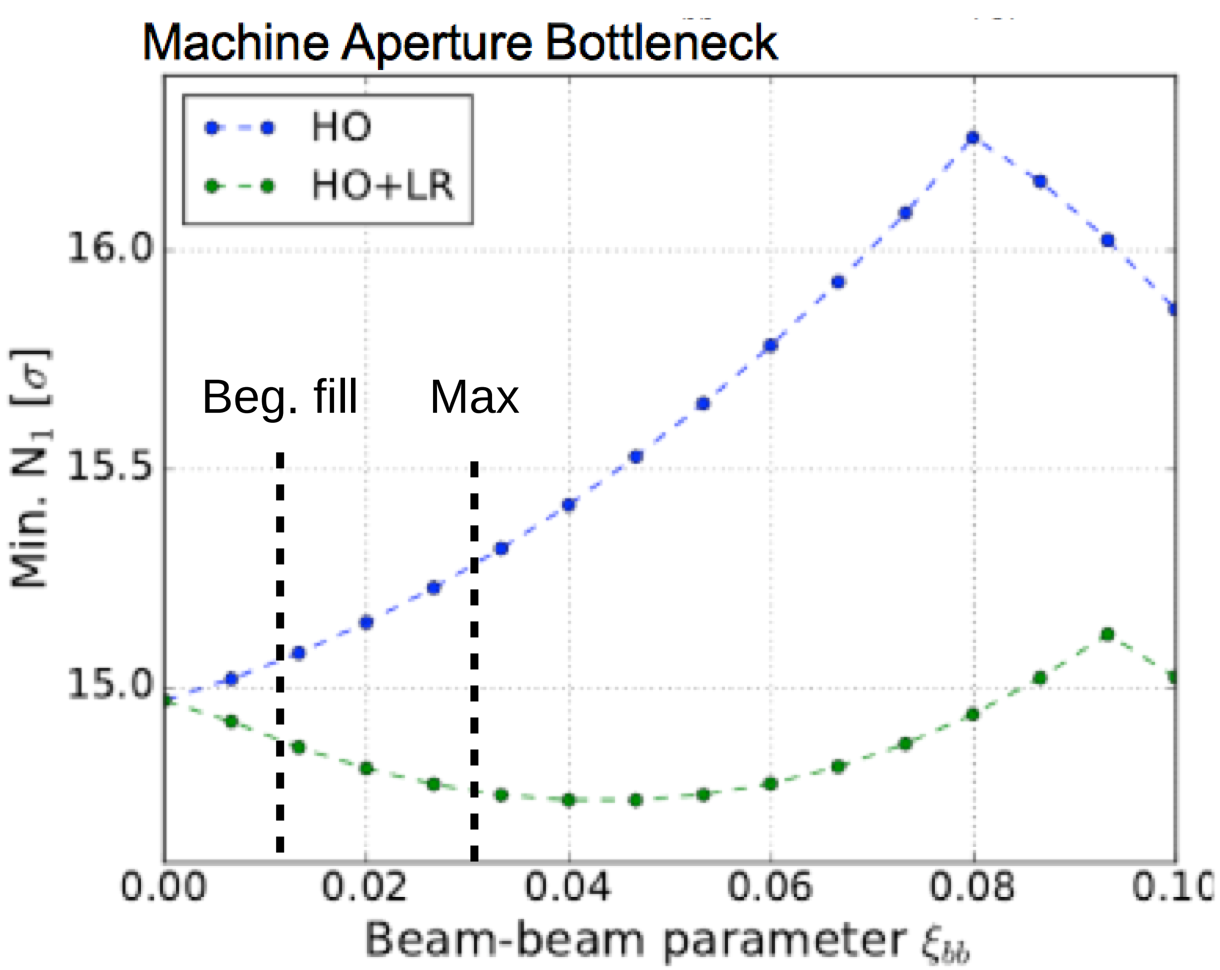
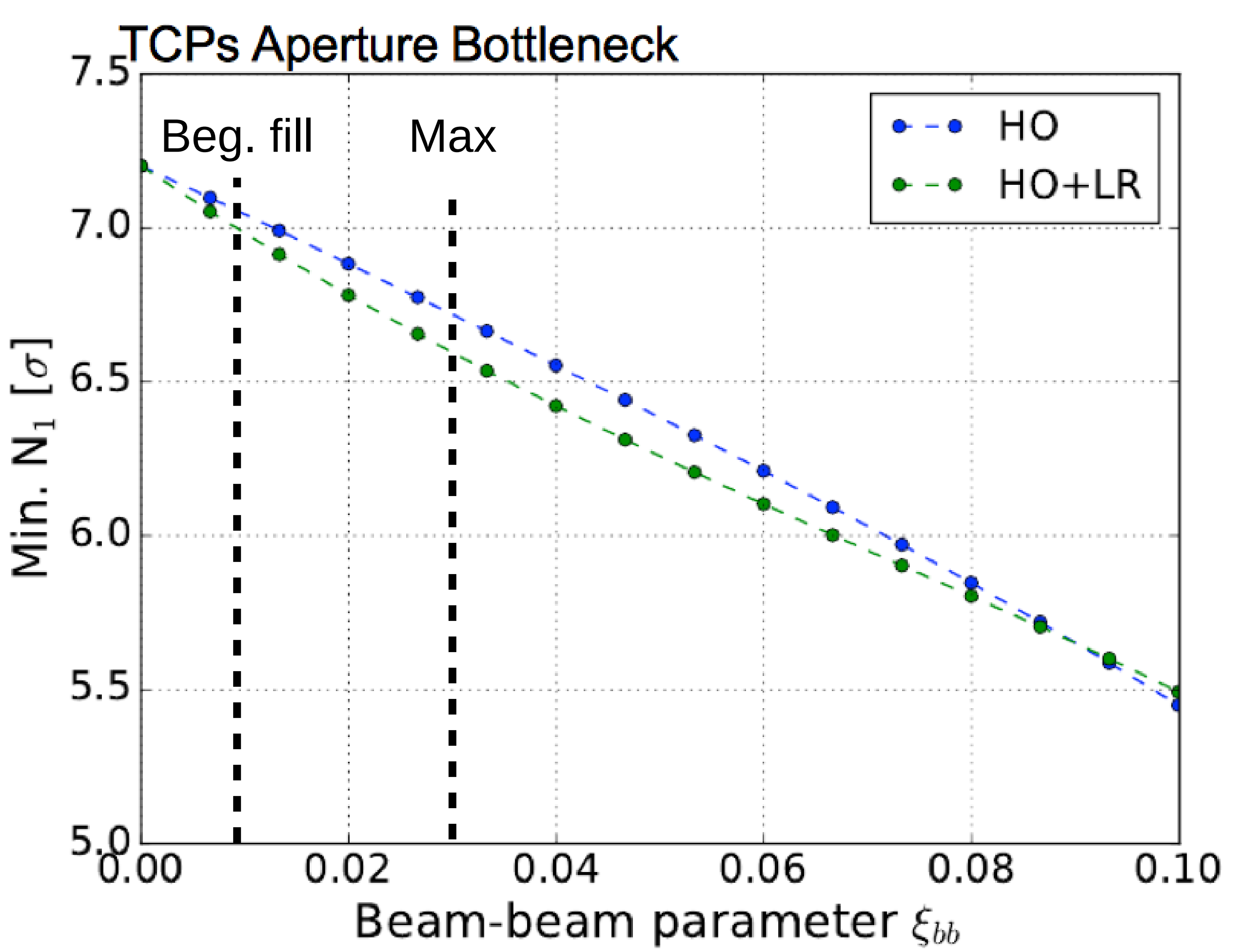
In the range of study ξ_{bb} FCC range (0.01-0.03)small impact observed → further studies needed.





Alternative solutions: flat optics

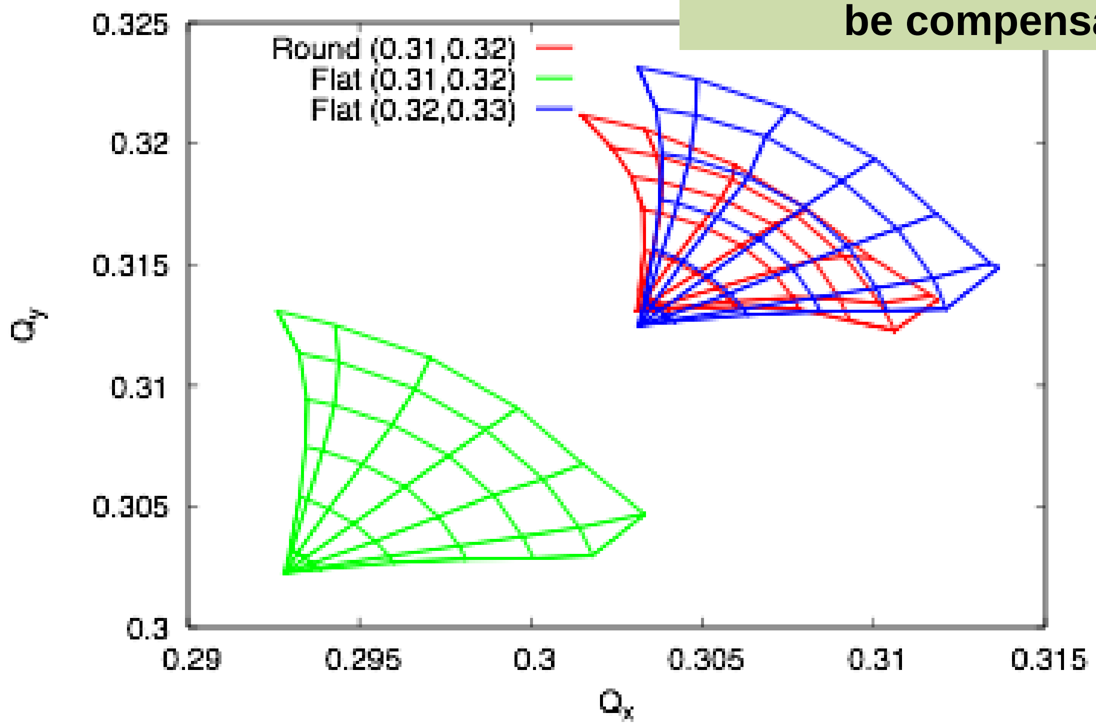
See talk L. Van Riesen-Haupt

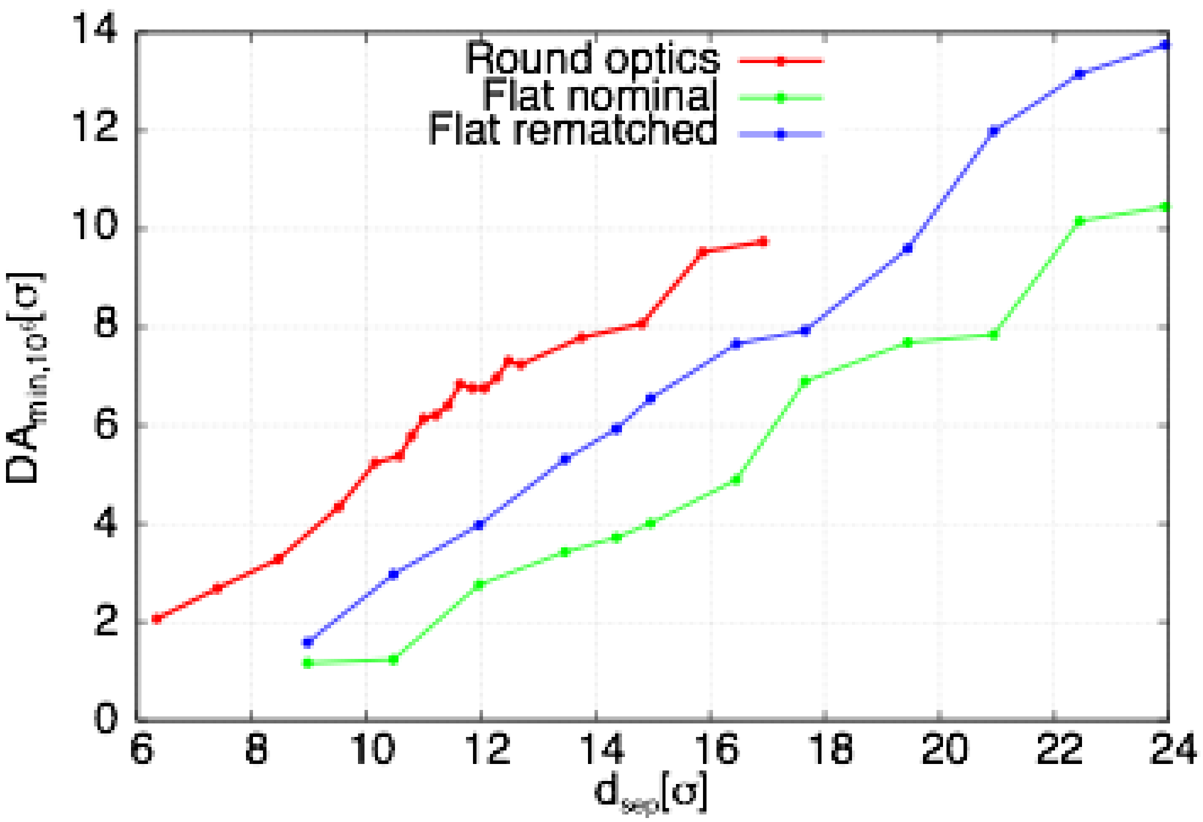
Flat optics is the natural back up solution in case crab cavities do not perform as expected

Beam-Beam long-range and head-on behave differently:

- Due to trains and broken passive compensation tune shifts (for H-V crossing schemes)
- Head-on beam-beam creates larger detuning with amplitude

Flat optics introduces some unwanted effects that have to be compensated





Study case beta ratio of 4 and H-V crossing scheme

- Flat optics will need the **43 %** more separation for round
- **Correcting for tune shift reduces the needs but still need 26%** larger separation
- **Larger aspect ratios of betas make things worse**
- **Need a special operation mode and further studies**

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- “Collide & squeeze”
- Stability during the collapse of the separation bumps
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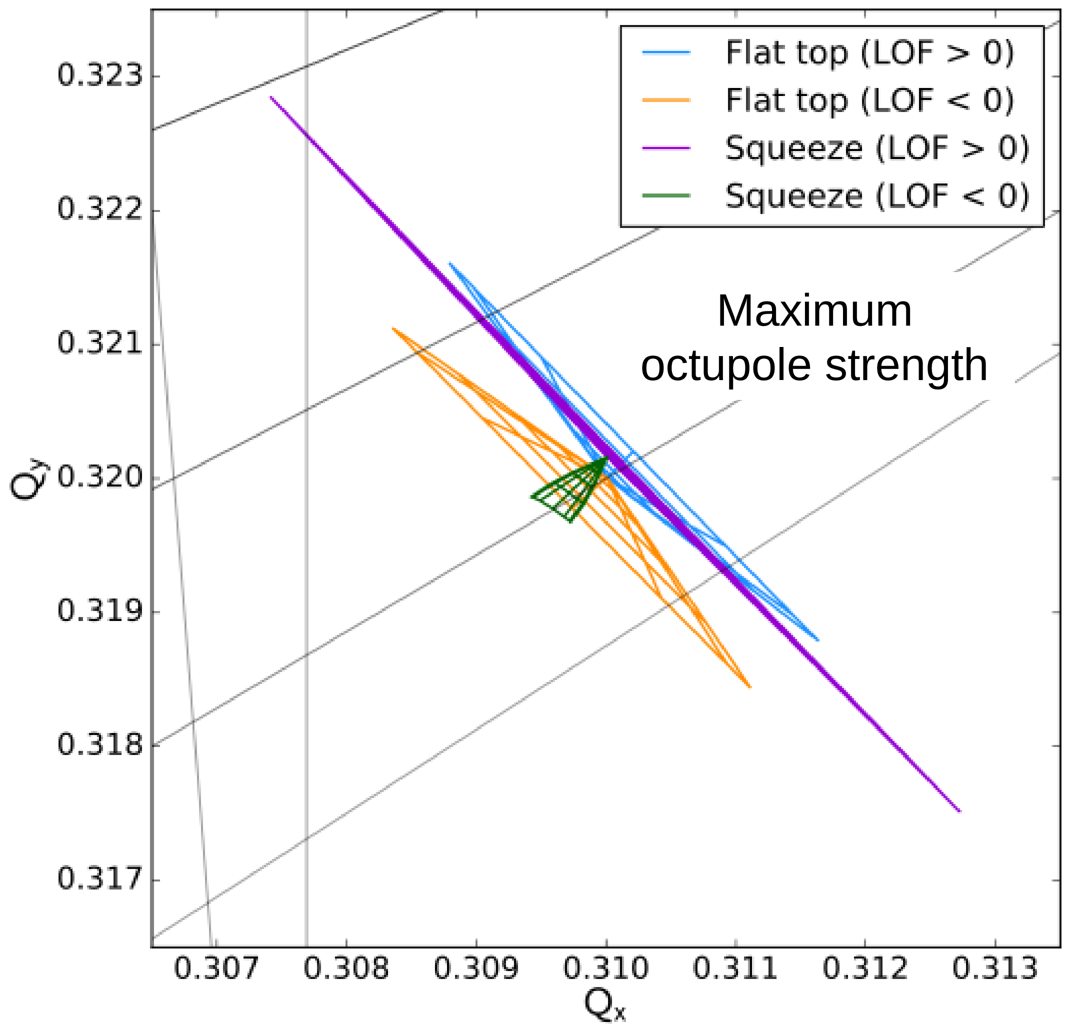
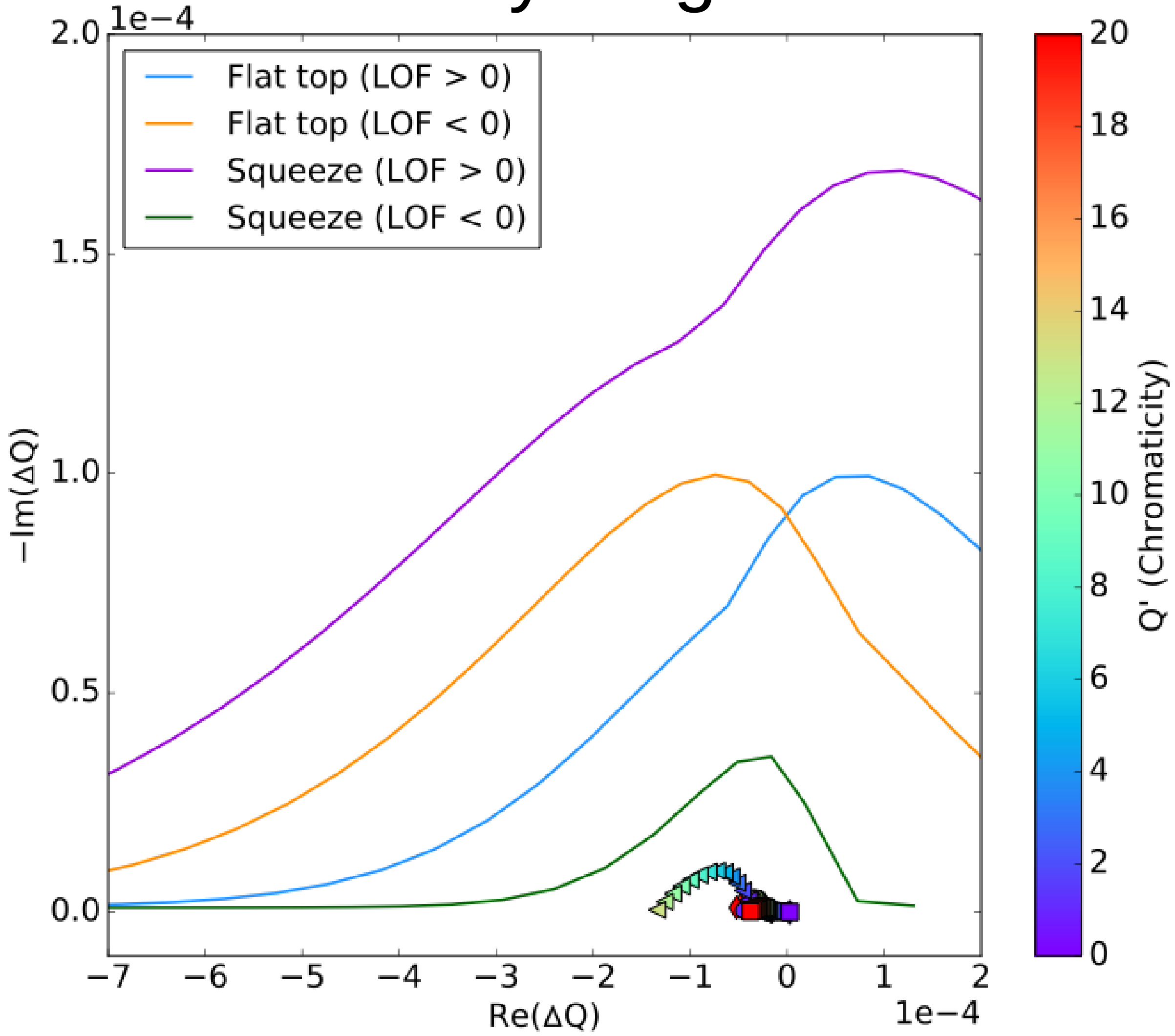
Two beam stability: fully squeezed optics

See talk of O. Boine-Frankenheim

50 TeV β*=0.30 m



Stability diagram

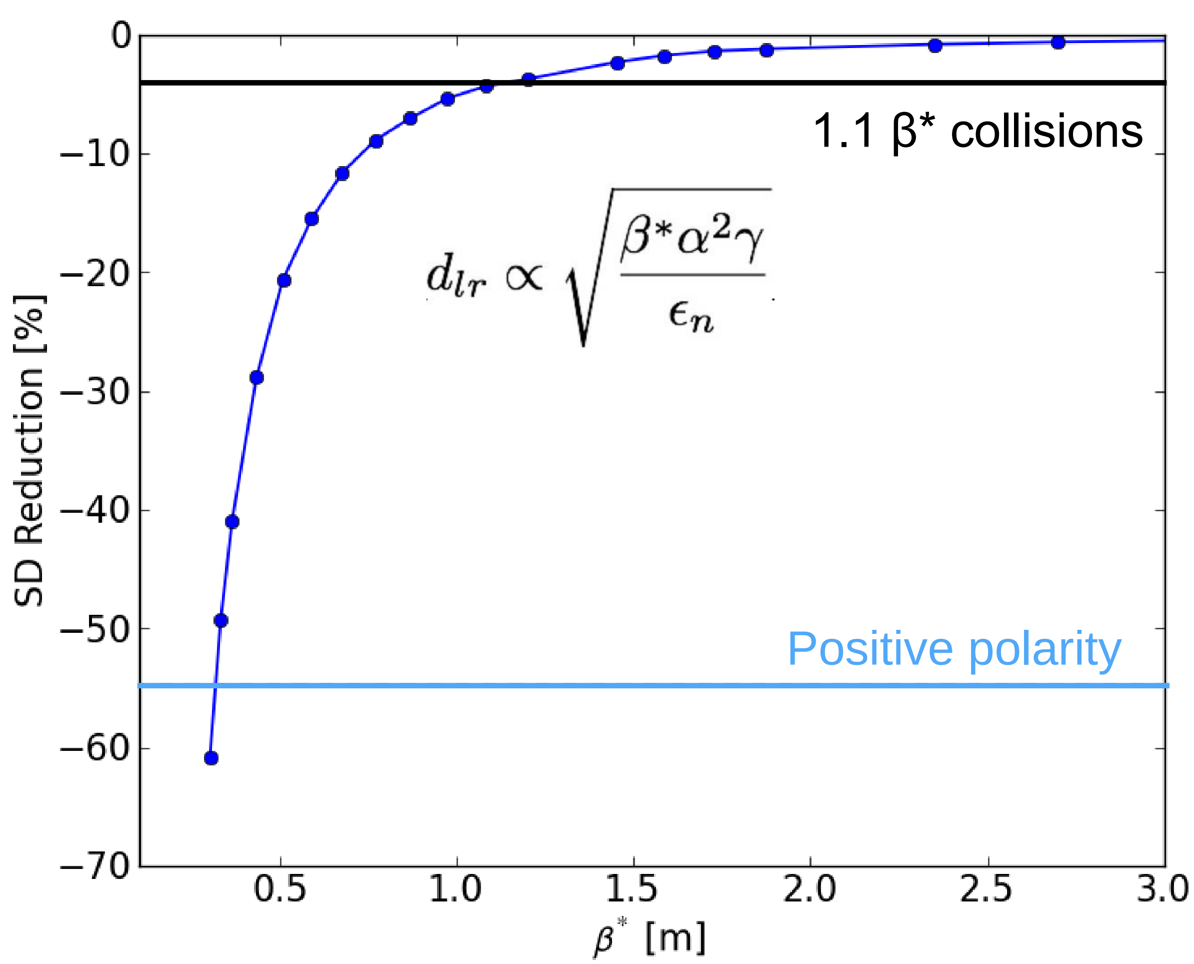


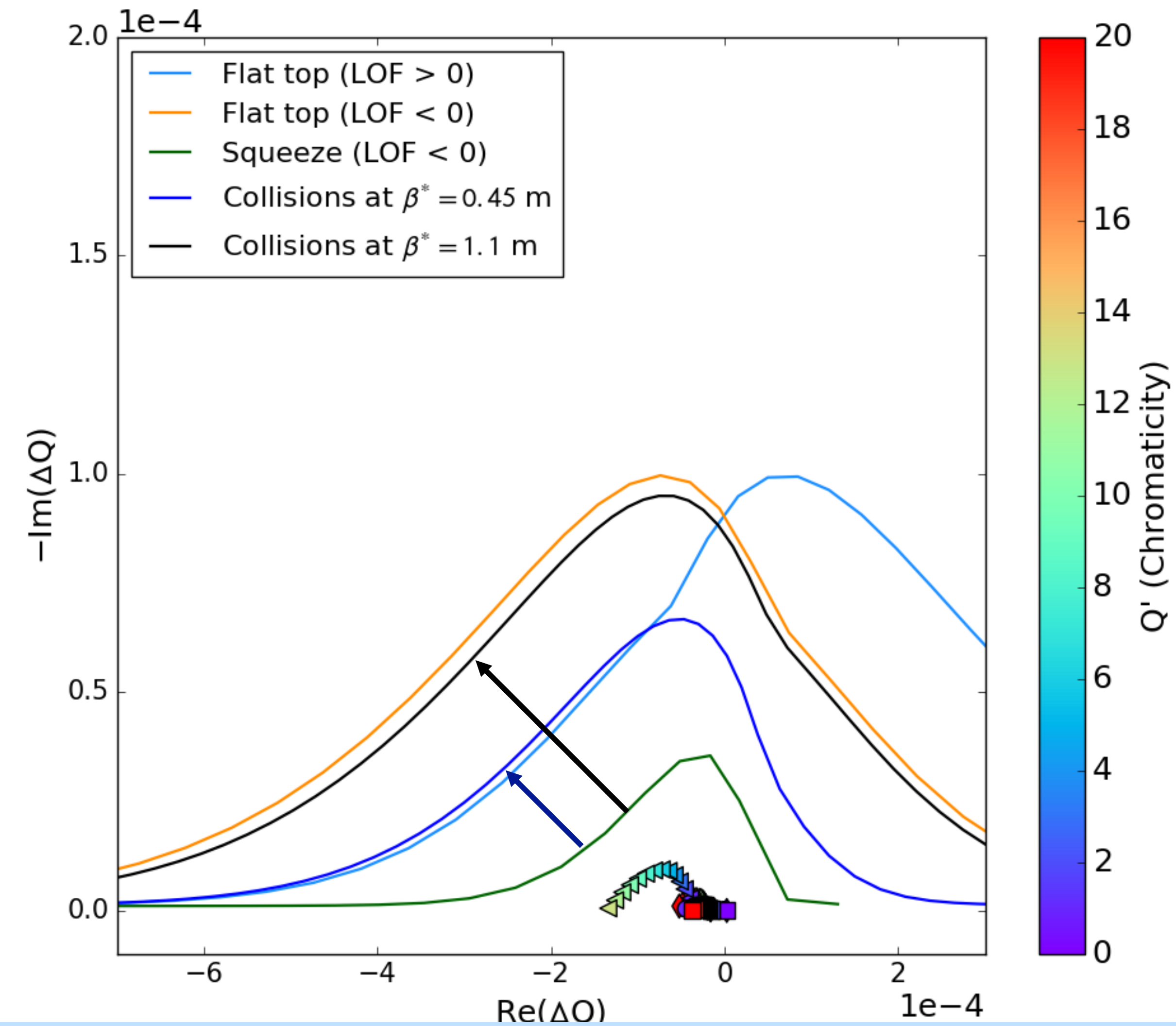
- **Better dynamic aperture expected for negative oct. and optimized lattice** (DA <5 σ for positive polarity **to be added: multipolar errors + high chromaticity operations**)
- **Negative polarity provides more margins in terms of DA thanks to LR global compensation**
- The **stability is reduced** at the end of the betatron squeeze ➔ additional margins are required: **collide at larger β***

Two beam stability: Collide & Squeeze

In order to avoid stability reduction during the squeeze, collisions at larger β* are foreseen (as for the HL-LHC)

Beam-beam wise we cancel long-range beam-beam effects and have only head-on → go to reduced separations when beams transverse emittances have been reduced due to damping

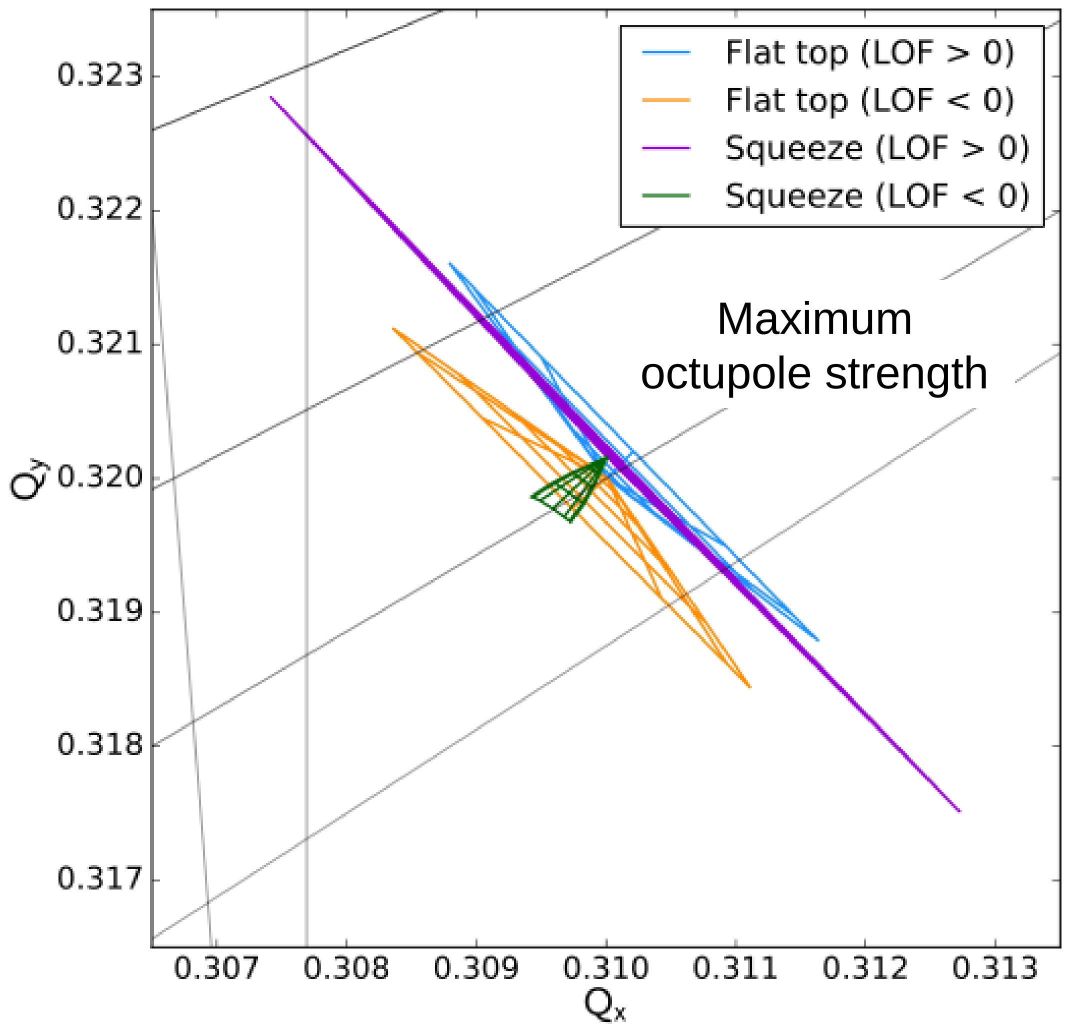




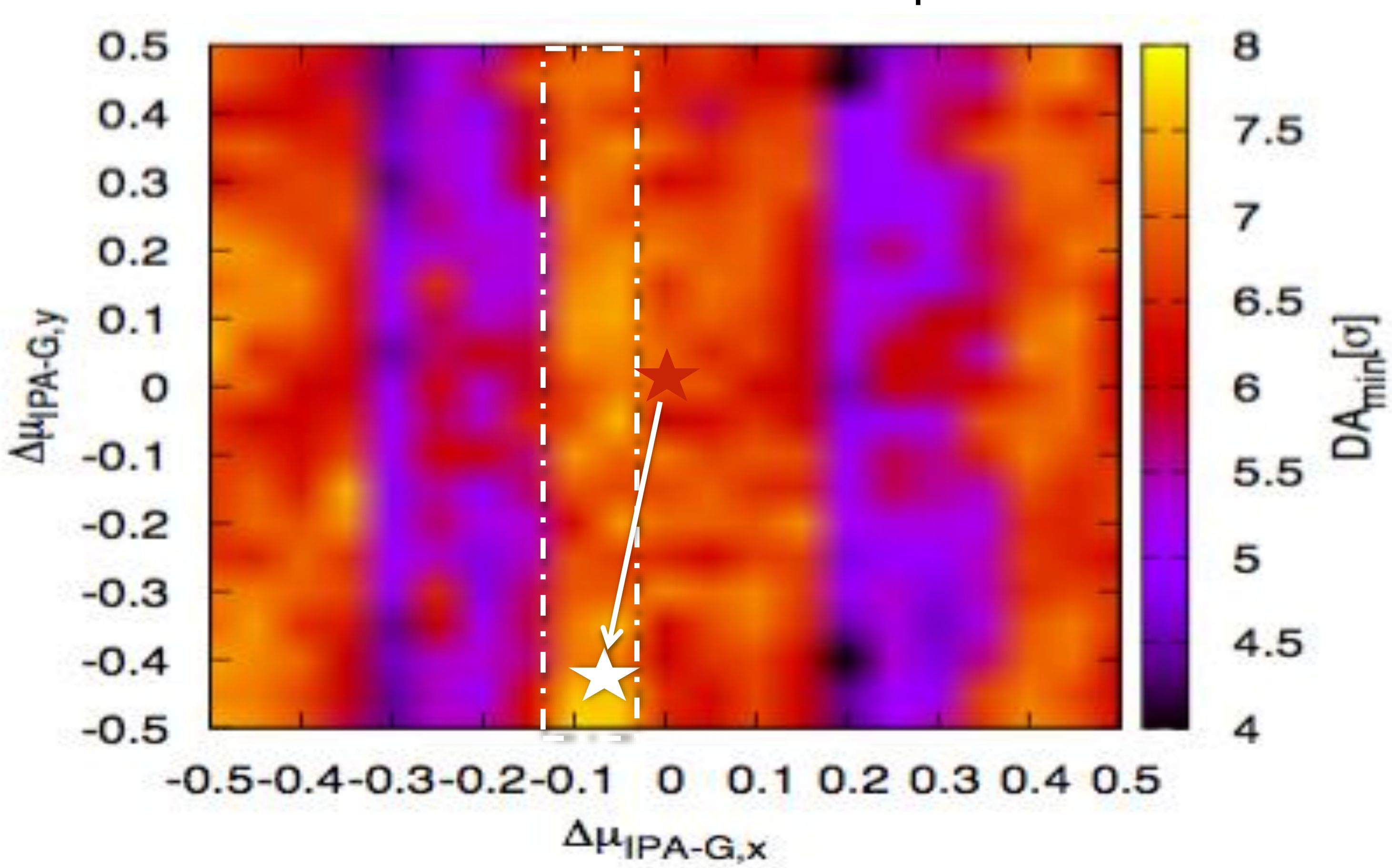
- Stability reduction evaluated w.r.t. the flat top SD with negative octupole polarity (relative difference of the negative real part at the half-height)
- **β*= 1.1 m:** reduction of stability of few percent → **negligible effect**

Two beam stability: fully squeezed optics

50 TeV β*=0.30 m



Beam-Beam Effects + Octupoles



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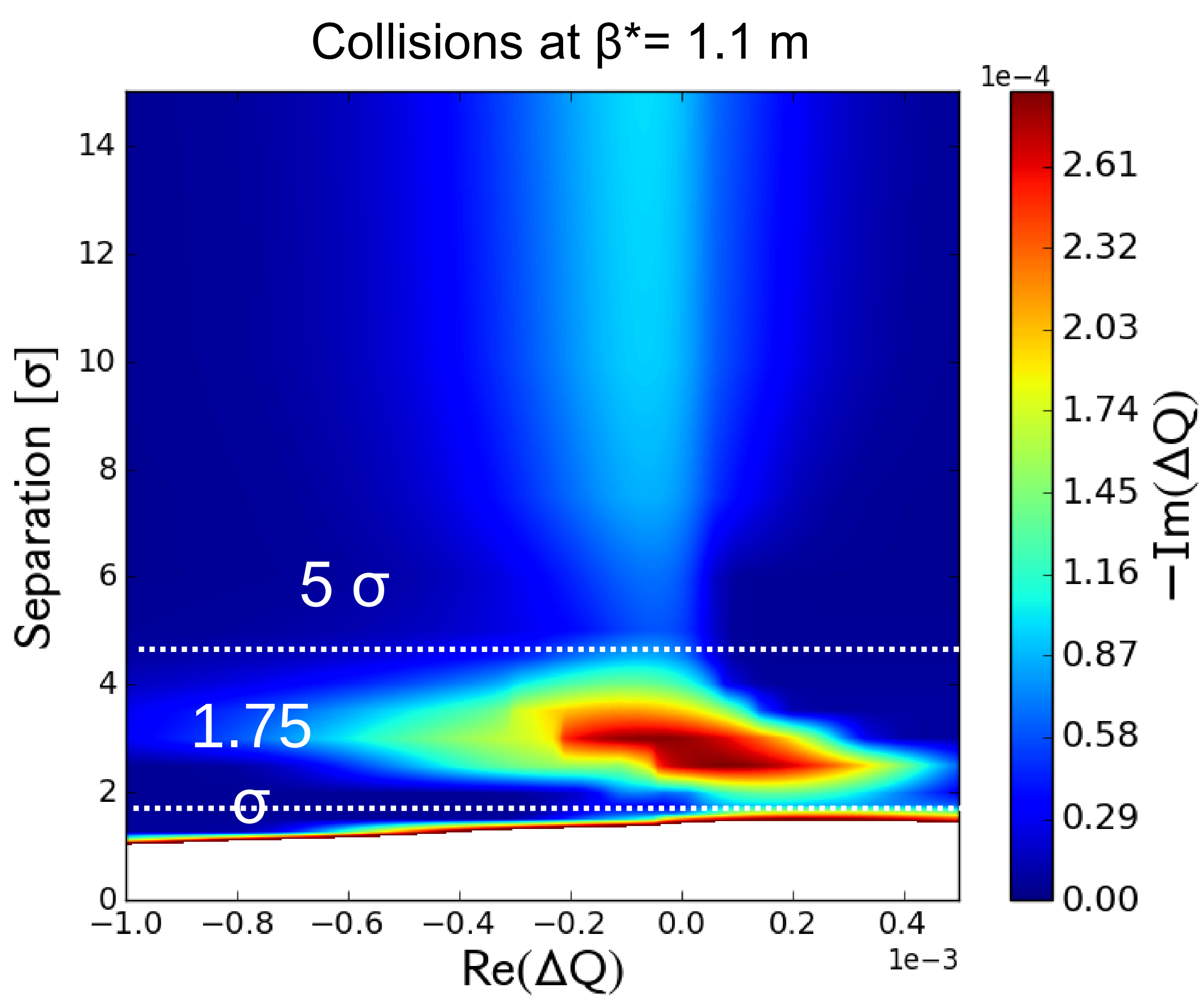
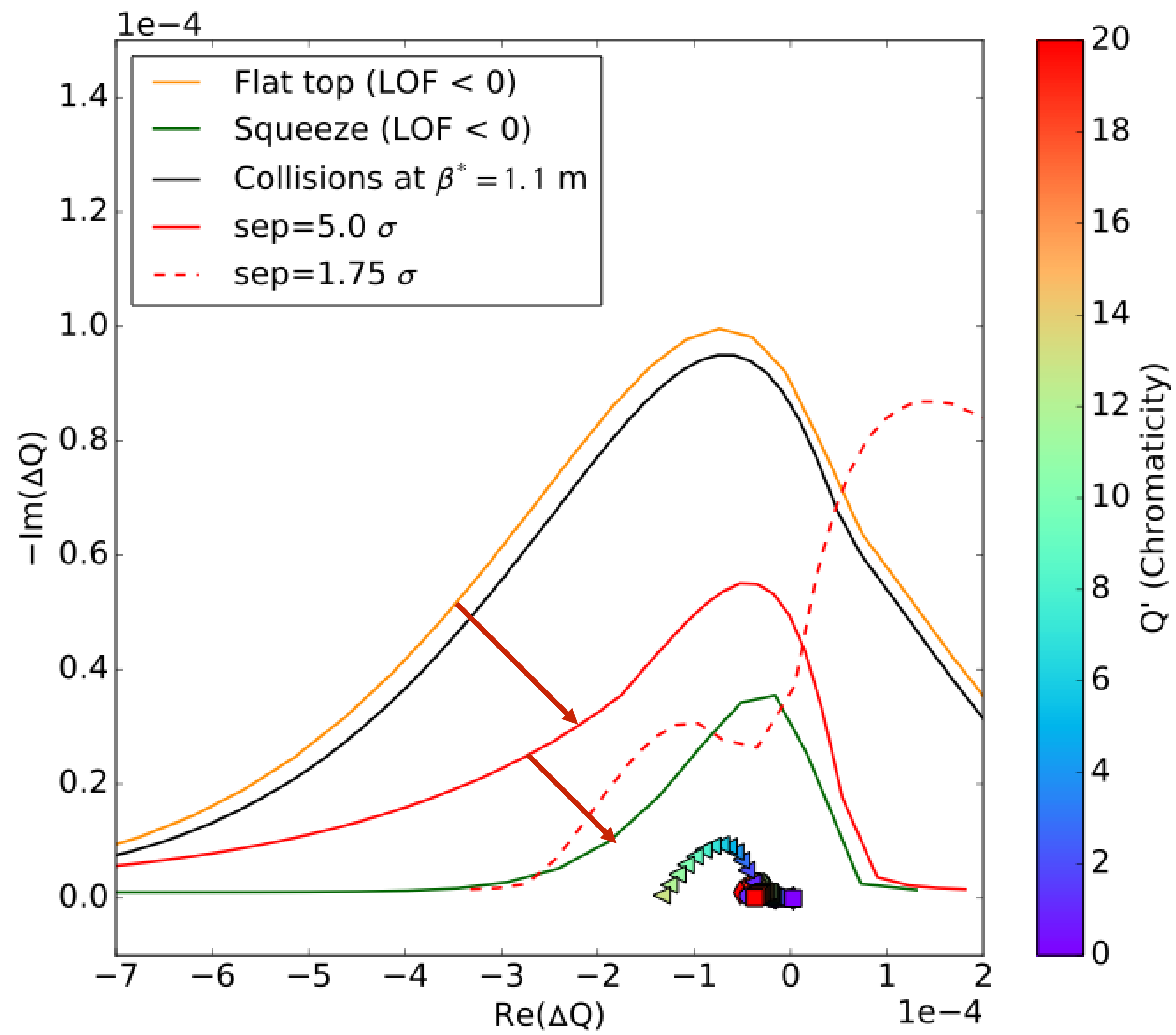
- **Negative polarity provides more margins in terms of DA thanks to Long Range global compensation→ need for a global optimization with lattice**

Stability during the collapse of the separation bumps

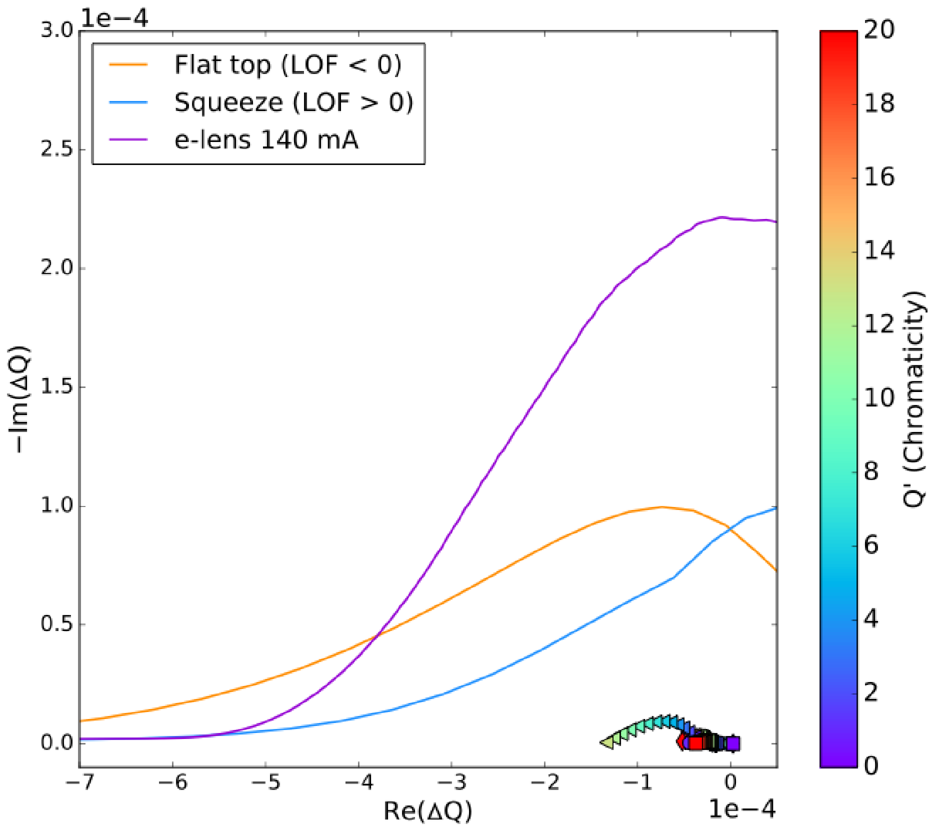
Octupoles powered with negative polarity at their maximum strength





- **Maximum stability when in head-on collisions**
- **Two minima** identified: at 5 σ and 1.75 σ separation (**larger than EOS with β*= 0.30 m**)
- **Go faster than instability rise time** < 5 s (m=-1 Q'~ 8-6 units) as done for LHC and HL-LHC

Alternatives for Landau damping: Electron Lens and RF quadrupoles



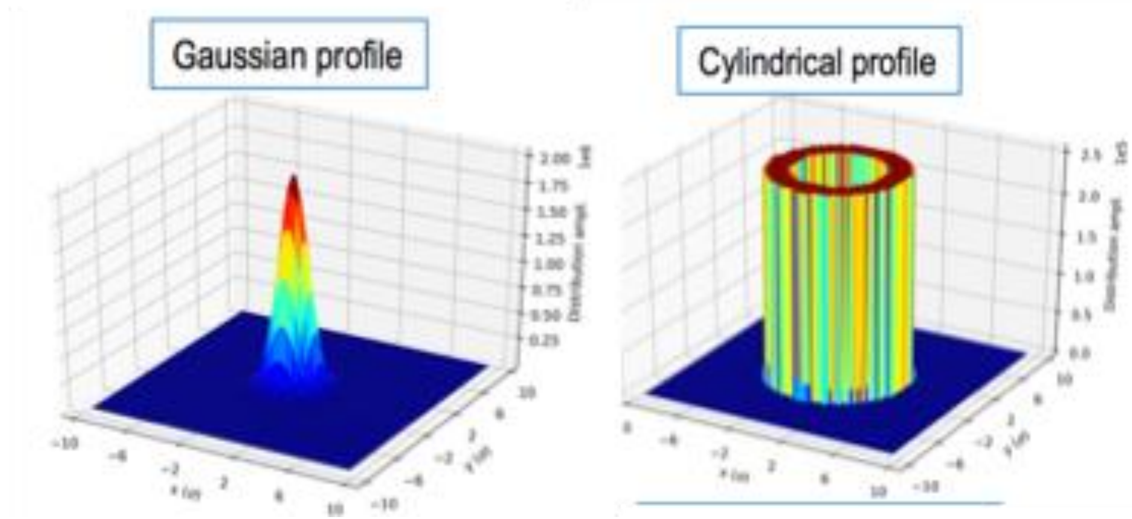
Electron lens [V. Shiltsev et al., 10.1103/PhysRevLett.119.134802]

- 140 mA will be sufficient to provide enough Landau damping for m=1 up tp Q'=20 units (no feedback)
- 400 mA are required to damp m=0 at Q'=0

→ **very efficient since it acts on the core particles**

→ **Can help in compensating beam-beam head-on if needed**

→ **Collimation can also profit of studies**



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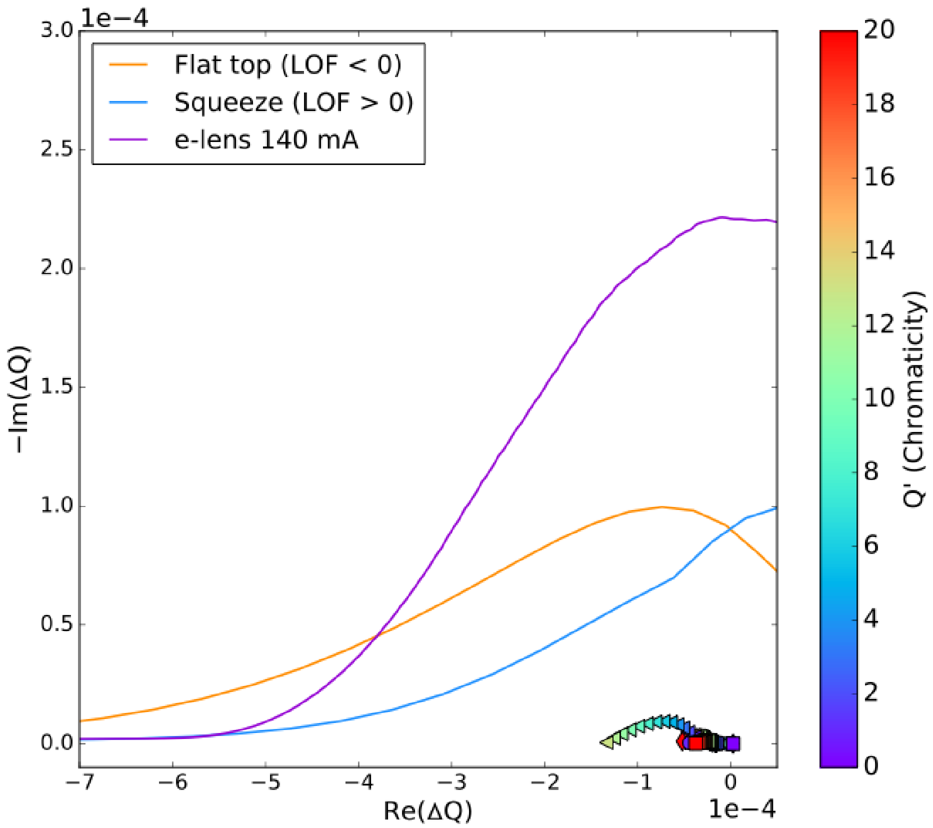

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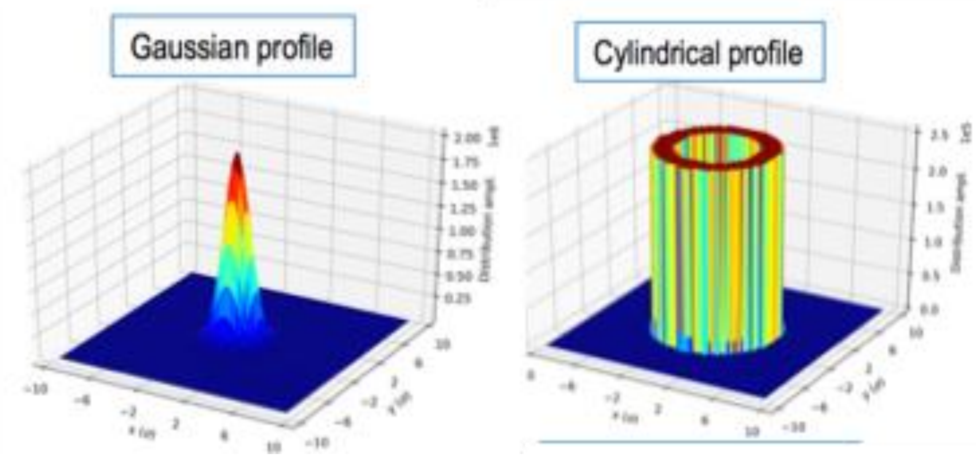
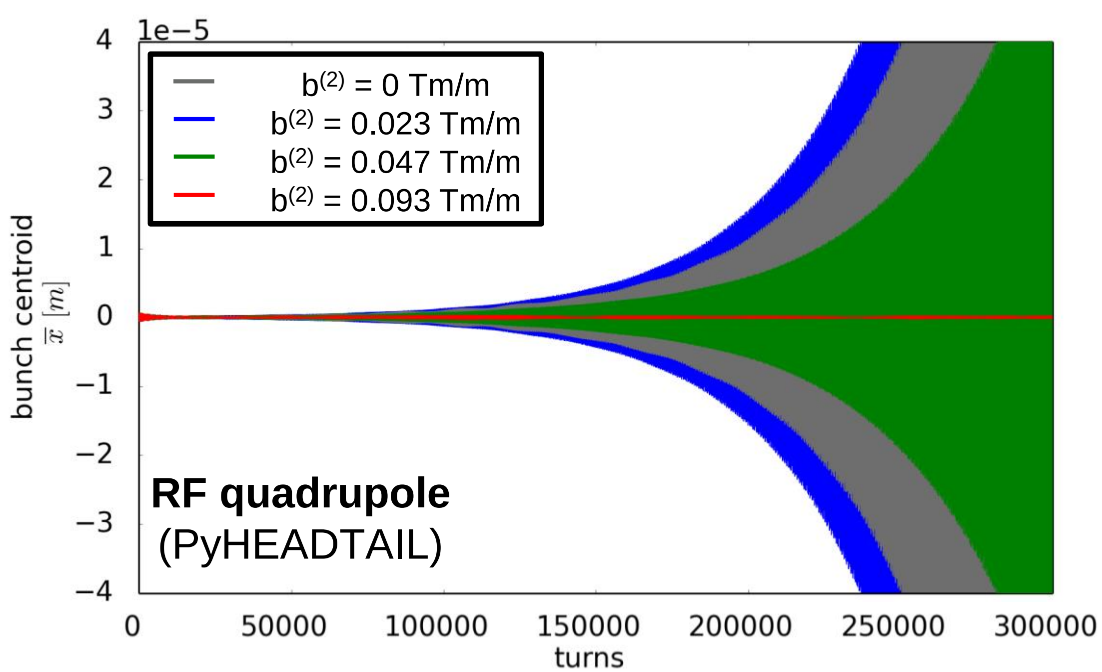
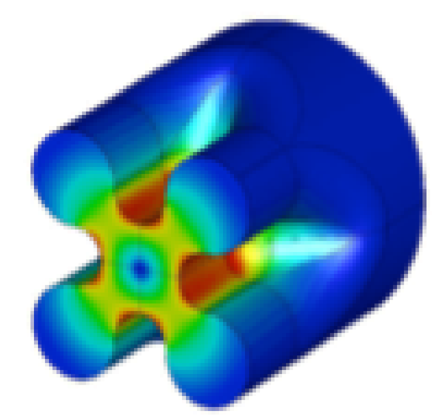




- An RF quadrupole is equally able to cure the instability by introducing a large enough betatron tune spread.

- RFQuad$(\Delta Q_x)_{RMS}$ ≈ $(3.5 \pm 0.5)\cdot 10^{-5}$ ≈ 0.017 Q_s
- LO$(\Delta Q_x)_{RMS}$ ≈ $(2.4 \pm 0.3)\cdot 10^{-5}$ ≈ 0.012 Q_s



→ Study the impact on dynamic aperture

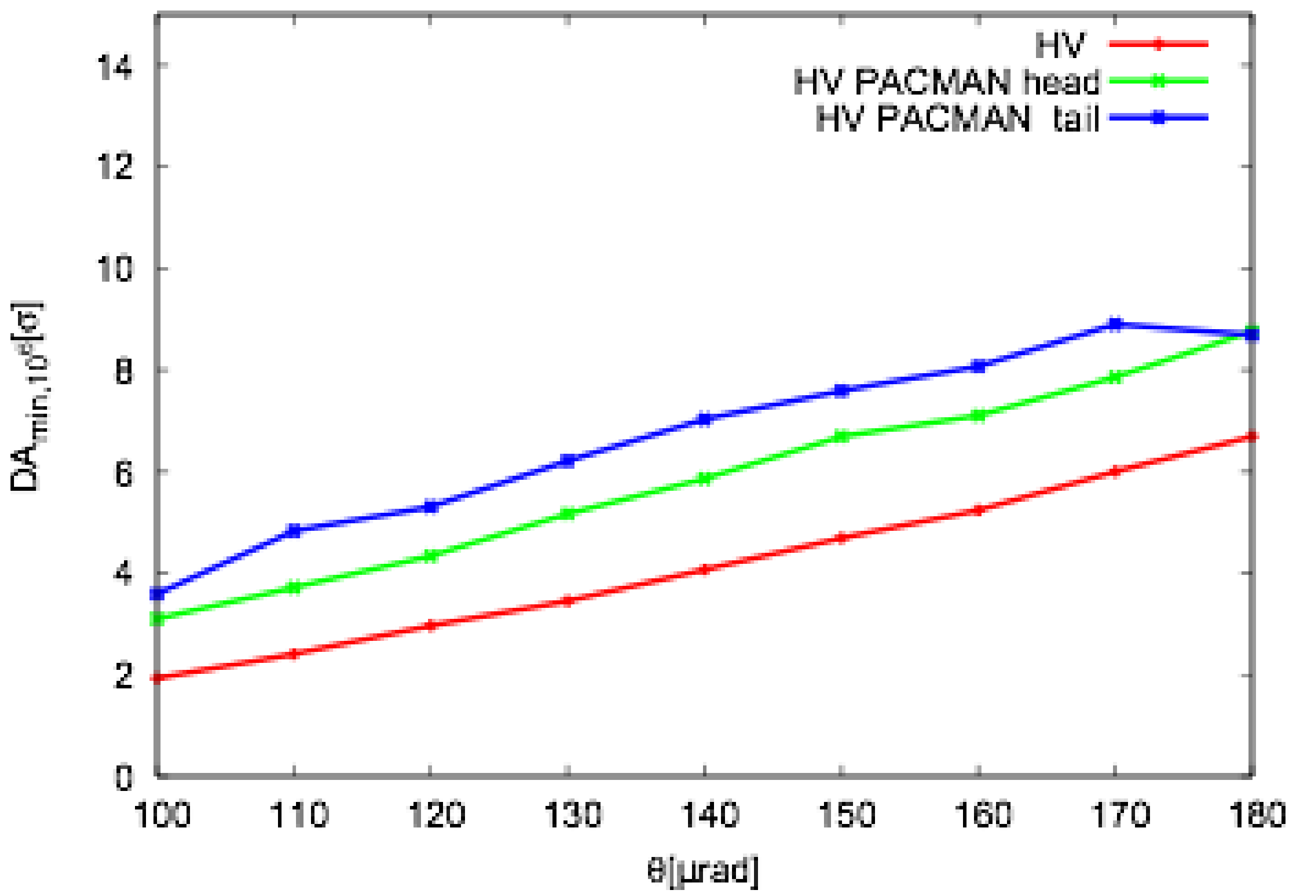
→ Extend the studies

M. Schenk, K. Li, A. Grudiev

Summary

- A robust baseline scenario has been studied and beam-beam separation proposed based on dynamic aperture **(from 30 σ to 17 σ Long Range separation for β= 1.1 - 30 cm)**
- **Optimized optics parameters allow highest dynamic aperture** together with a global compensation scheme using Landau octupoles → **Scenario with negative oct. polarity included in the CDR**
- **Head-on beam-beam limit seems far away from chosen parameters with full crab crossing** (optimized working points improve beam quality)
- **Large beta-beating should be expected (22 %) and needs further understand of implications** (collimation system, luminosity, multiple IP effects)
- **Alternative scenarios** have been explored to allow for flexibility in the presence of other constrains
- **Fully squeezed optics does not allow margins at end of squeeze** (limitation on the SD theory i.e. noise, diffusions mechanisms**)** → **collisions at larger β* (1.1 m) are foreseen→ Collide and Squeeze**
- **Alternative solutions for Landau damping: RF quads and electron lenses** are explored
- **Continuous benchmark to LHC data is fundamental** to understand predictive power of simulations

PACMAN Bunches



Dynamic Aperture for PACMAN bunches as a function of the total crossing angle in IPA&G

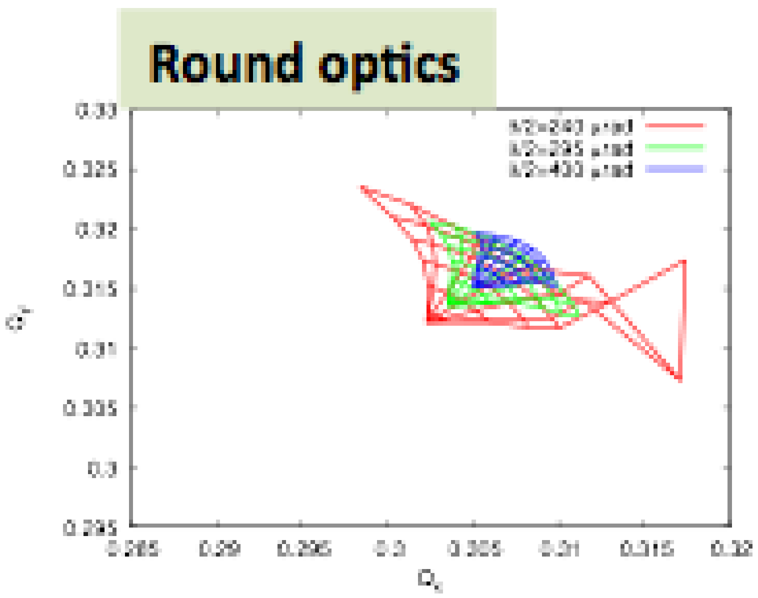
H-V alternating crossing scheme

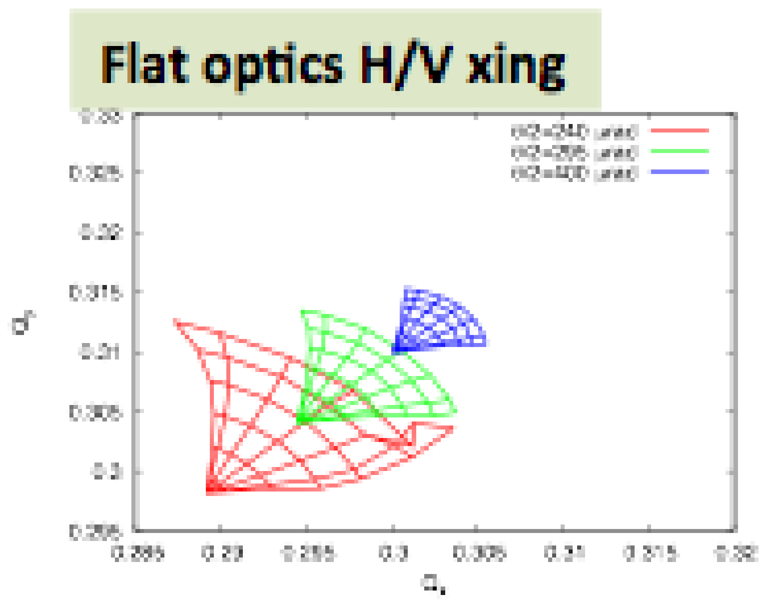
DA for PACMAN bunches always above the DA for Nominal Bunches

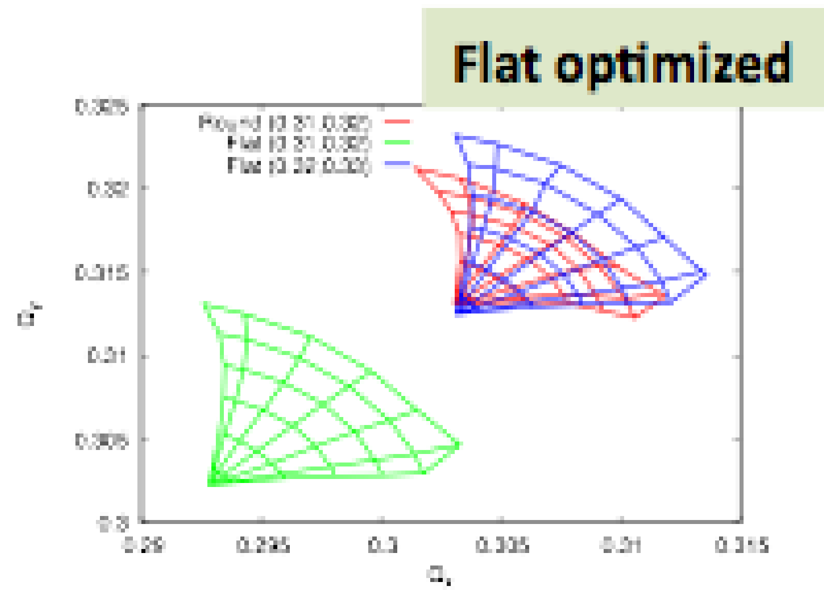
The PACMAN effects of tune and chromaticity shifts are negligible assuming the passive compensation with alternating crossing planes in IPA and IPG

Alternative Solutions: flat optics

Flat optics is the natural back up solution in case crab cavities do not perform as expected

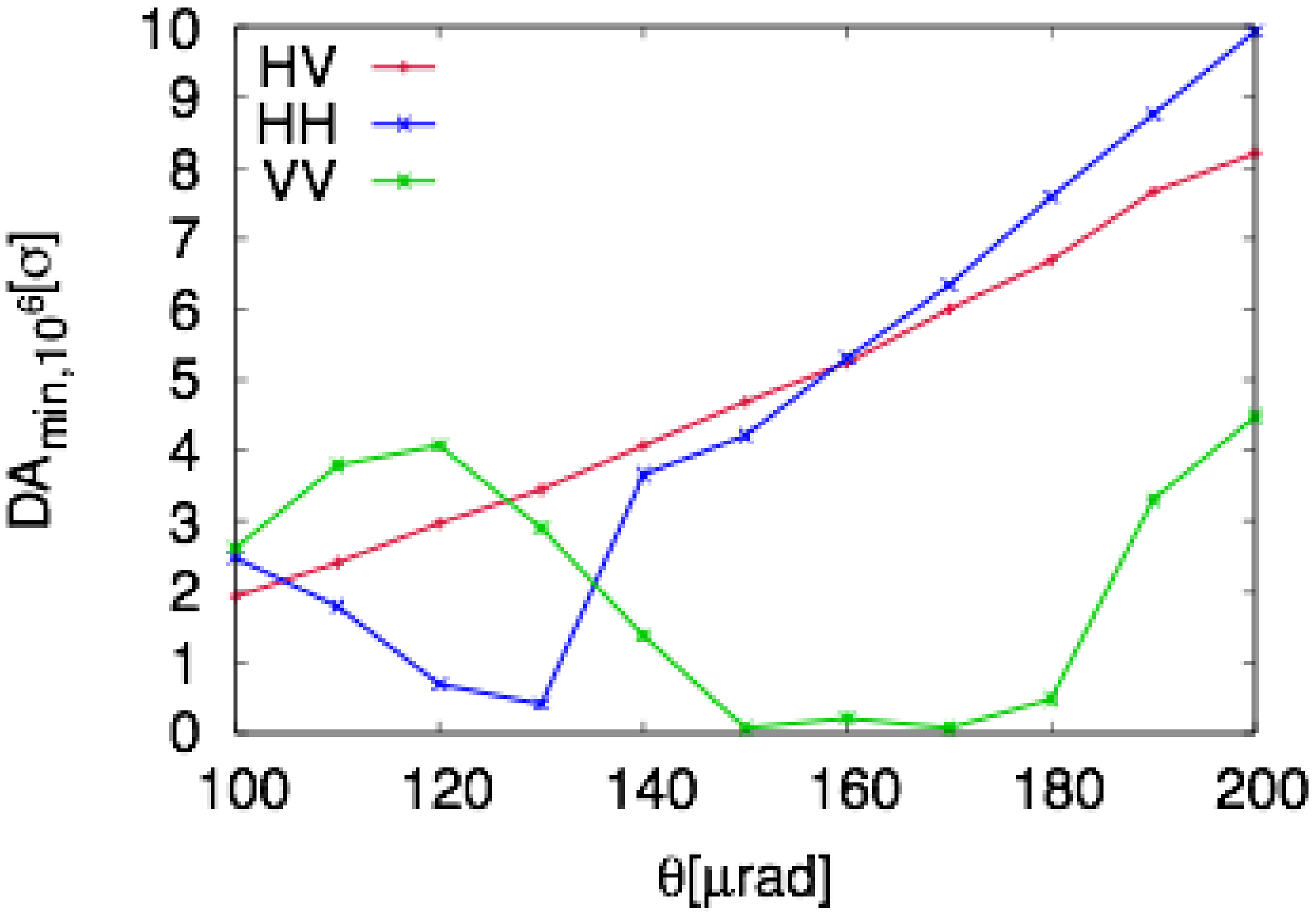


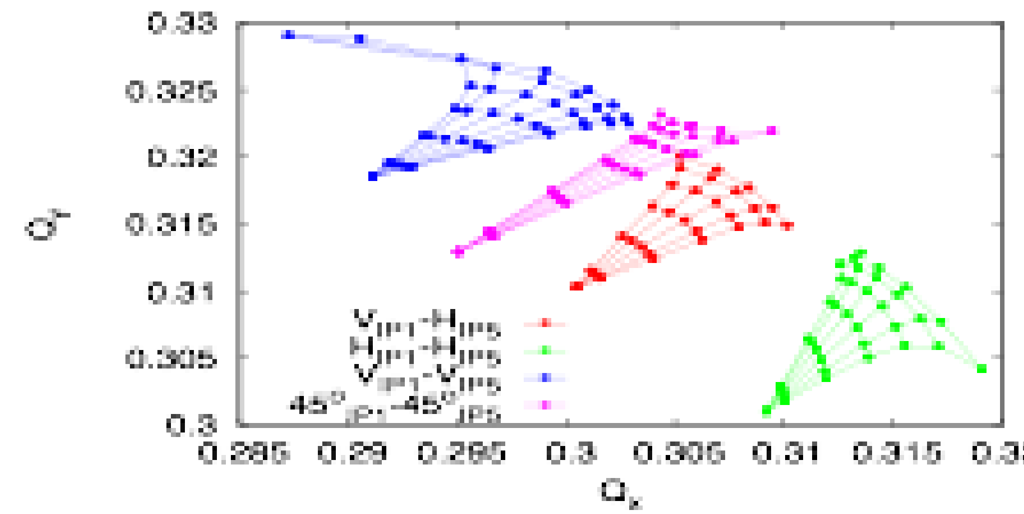


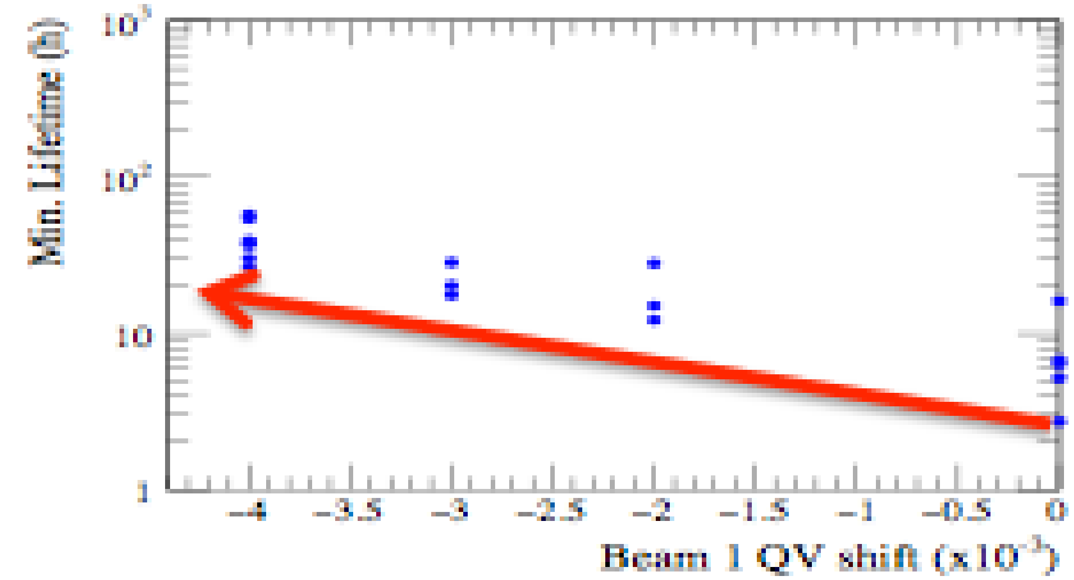


Flat optics introduces some unwanted effects that have to be compensated

Alternative crossing schemes: H-H and V-V crossing







Pacman Bunches?

Alternative crossing scheme have been explored and show larger flexibility in terms of dynamic aperture with optimized tunes:

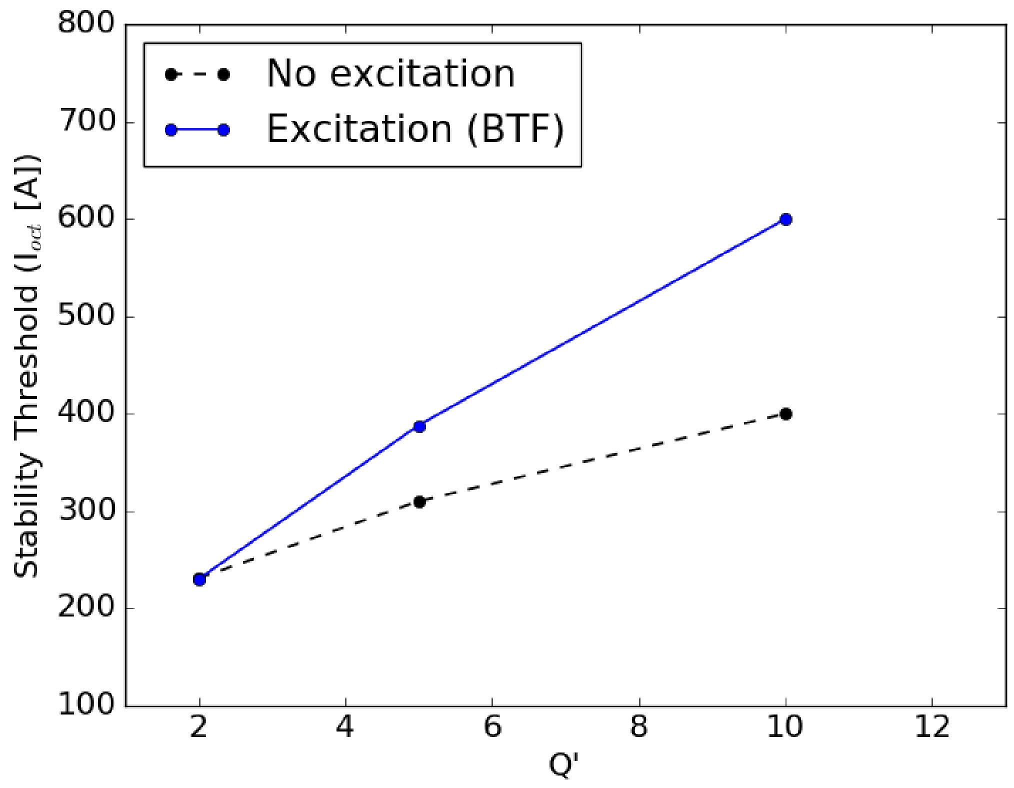
- **HH** or **VV** crossing is **equivalent to HV with optimization and easy for the baseline with collide and squeeze**
- **VV not acceptable at the (0.31-0.32) working point** due to strong impact of the 3rd order resonance effect ➞ mirrored tunes will solve the problem

Why maximize Landau damping?

Unwanted effects could reduce Landau damping:

- Linear coupling reduces detuning from Landau octupoles ➞ correct for it during operation
- Particle distribution deformation due to resonance excitation ➞ good Dynamic Aperture (no losses)
- Noise make the beam more sensitive to any external excitation ➞ not easy to control

BTF Exc. Amplitude = $2 \cdot 10^{-4}\,\sigma$



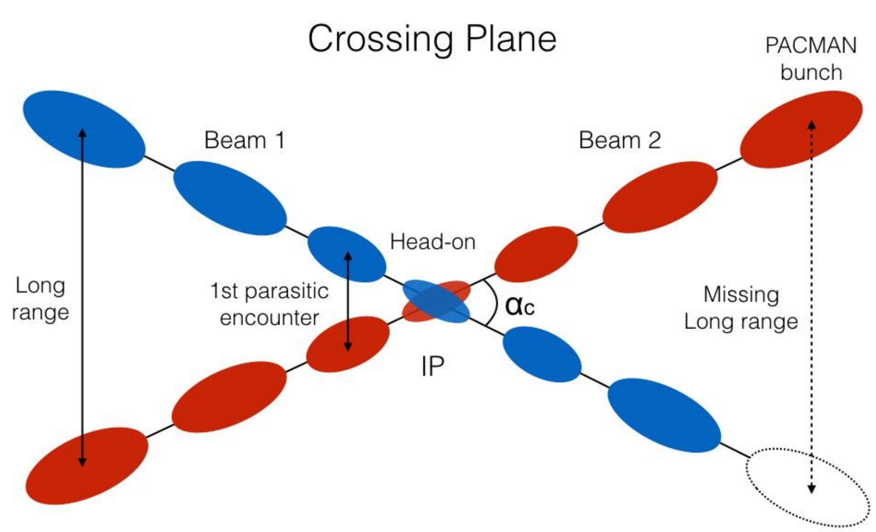
- For a chromaticity Q'=10 units the required increase is of ~50%
- Possible mechanism to explain the observed higher octupole threshold needed during LHC operation
- External sources of noise can compromise the beam stability, with latencies of several minutes as shown by recent experimental studies in the LHC by X. Buffat et *al*. [The impact of noise on beam stability, 8th HL-LHC collaboration meeting – CERN – 11.10.2018]

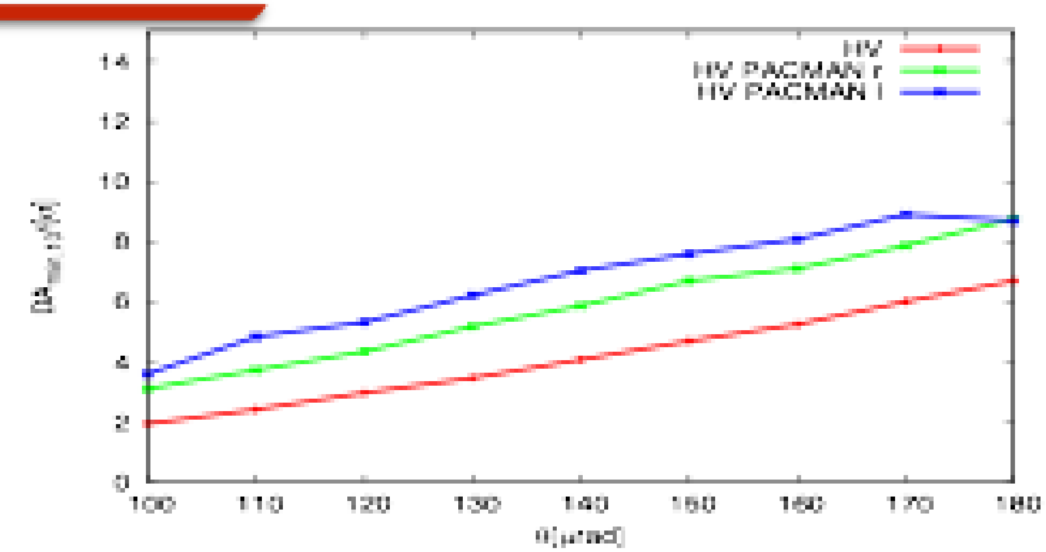
Maximize beam stability during the full operational cycle
Limitation in the strength of the FCC Landau octupoles might be a problem in the presence of noise
→ **collisions at 1.1 m β* ensure stability with margins**

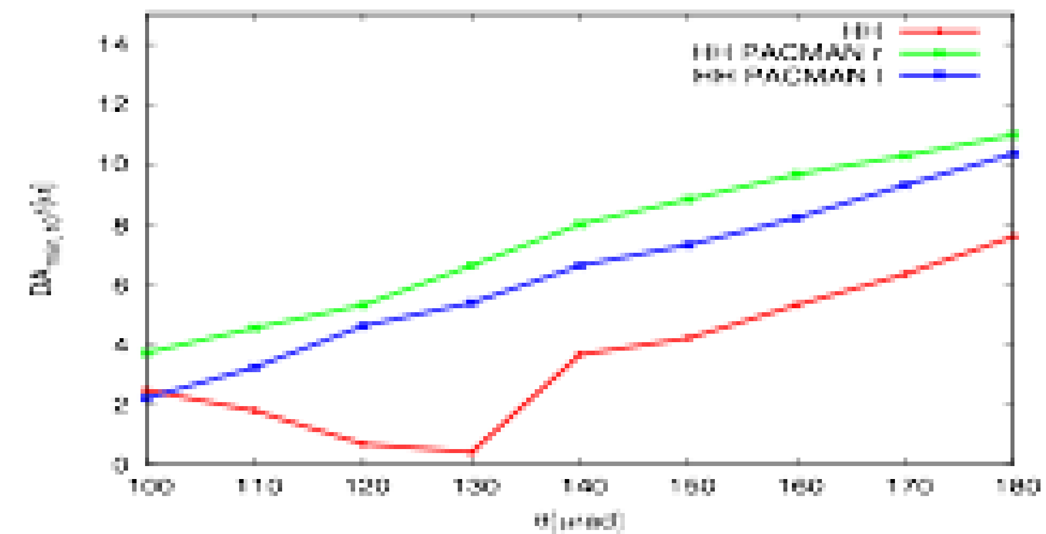
Nominal and PACMAN bunches

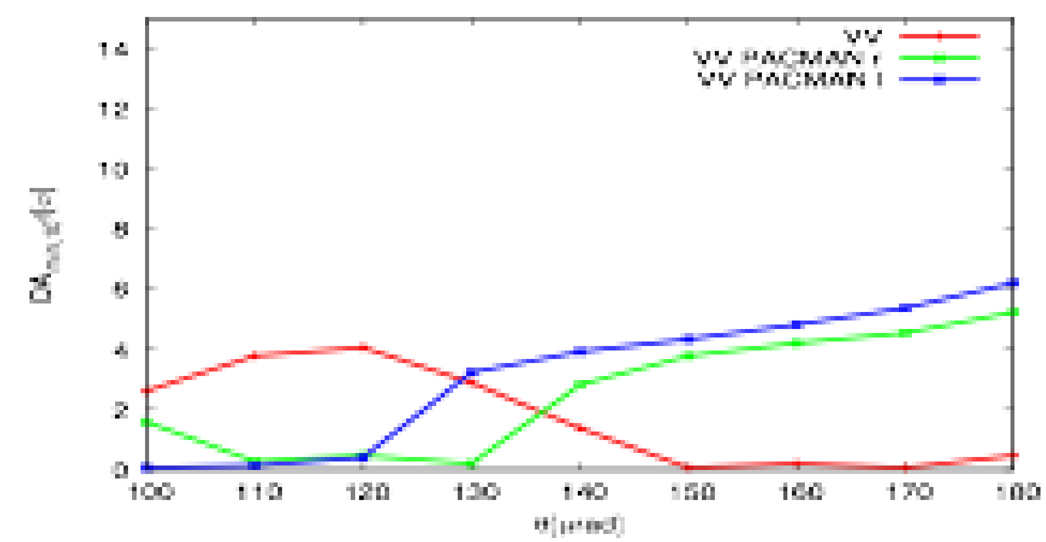
- **Nominal Bunches:** bunches in the middle of a train → see all LR interactions
- **PACMAN bunches**: located in the head or in the tails of the trains, see empty slots → see fewer long range interactions

Different beam-beam effects for the two families of bunches









Baseline no relevant PACMAN effects expected

Ultimate case differences in tune shift are expected

- dynamics is driven by Nominal bunches
- optimizations of working point needed also at bunch to bunch level

Alternative solutions: flat optics

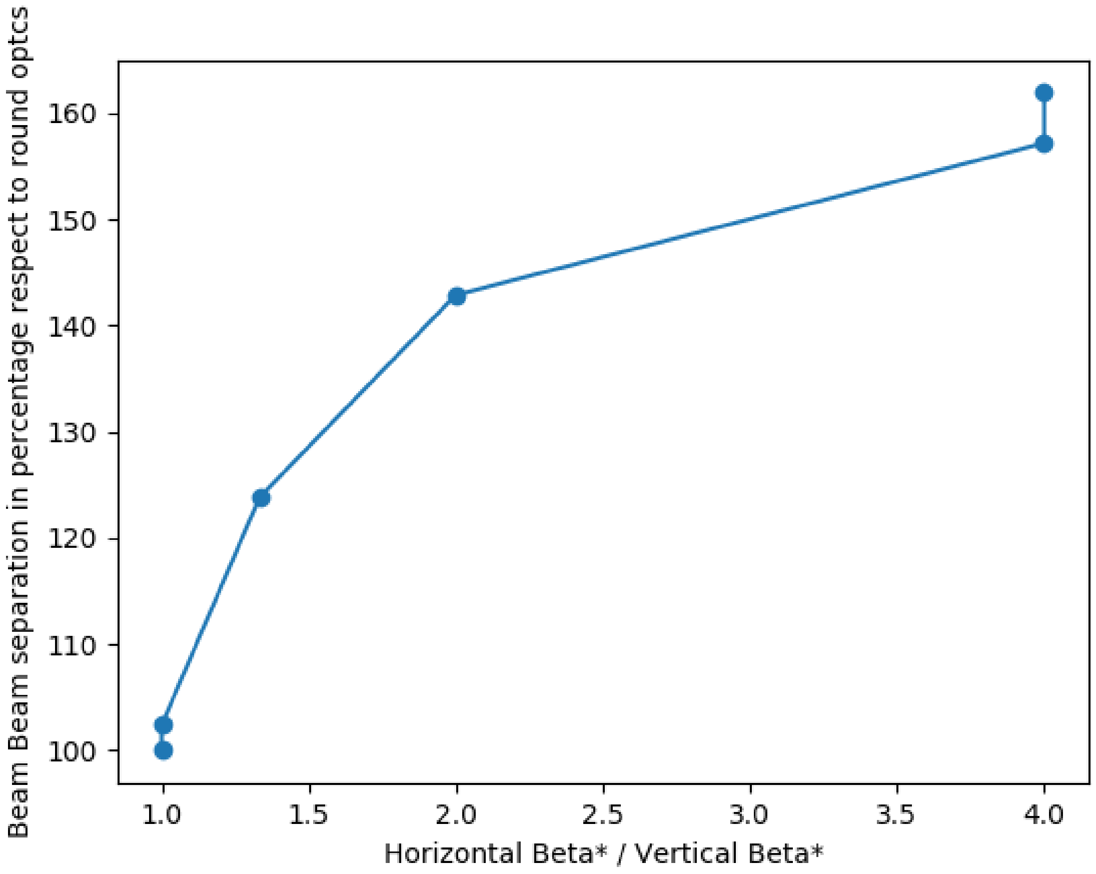
See talk L. Van Riesen-Haupt

Flat optics is the natural back up solution in case crab cavities do not perform as expected

Beam-Beam long-range and head-on behave differently:

- Due to trains and broken passive compensation tune shifts (for H-V crossing schemes)
- Head-on beam-beam creates larger detuning with amplitude

Extra beam-beam separation scaling with betas ratio for optics



Study case beta ratio of 4 and H-V crossing scheme

- Flat optics will need the **43 %** more separation for round
- **Correcting for tune shift reduces the needs but still need 26%** larger separation
- **Larger aspect ratios of betas make things worse**
- **Need a special operation mode**