Beam-Beam Effects in the HE-LHC

J. Barranco, X. Buffat, **T. Pieloni**, C. Tambasco

Acknowledgements: B. Salvant, D. Amorim, S. Antipov, M. Crouch, R. Tomas, F. Zimmermann, J. Abellaira Fernandez, S. Arsenyev, D. Schulte, L. Van Riesen-Haupt, M. Hofer

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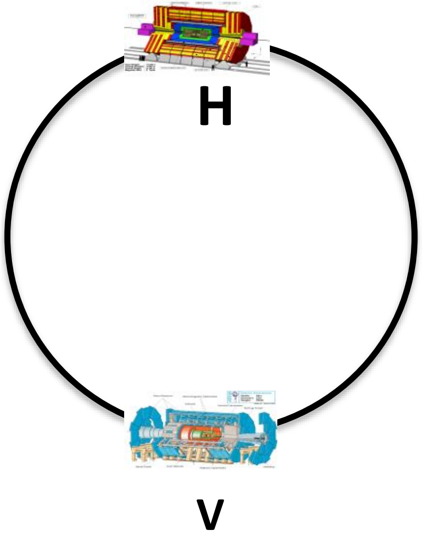
Contents

- Beam-beam effects
    - Head-On and Long-range crossing schemes
    - Alternative crossing schemes
    - Beta-beating
    - Orbit effects and noise
    - Flat versus round optics
    - Compensation schemes
- Conclusions

High Energy Colliders: Present/Future

PARAMETERS	LHC HL-LHC	High Energy LHC	FCC-hh Baseline - Ultimate	
Center of Mass Energy [TeV]	14	27	100	
Dipole Fields [T]	8.33	16	16	
Circumference [Km]	27	27	100	
Beam-Beam Interactions	120 LR + 4 HO	72(360)LR + 2 HO	352 LR + 4 HO (1764)	
Lattice Elements	23000	30000	100000	
Beam Current [A]	0.58 - 1.12	1.12	0.5	
Bunch Intensity [10^{11}]	1.15 - 2.2	2.2 (0.44)	1	1 (0.2)
Bunch spacing [ns]	25	25 (5)	25	25 (5)
RMS bunch length [cm]	7.55 – 8.1	7.55	7.55	
Luminosity [10^{34} $cm^{-2}s^{-1}$]	1 - 5	25	5	30
Events/bunch crossing	27 - 135	800 (160)	170	1k (200)
Stored Energy [GJ]	0.36 – 0.7	1.3	8.4	
β* [m]	0.55 – 0.2	0.25	1.1- 0.3	
Transverse beam size [μm]	3.75-2.5	2.5 (0.5)	2.2 (0.4)	

Beam-beam studies approach



Preliminary assumptions

- 2 Interaction Points
- 25 ns bunch spacing
- Fractional tune same as LHC (0.31,0.32)
- Alternating crossing to reduce Pacman (H crossing angle in IPA and V crossing angle in IPB)
- β^* 25 cm (most difficult scenario with maximum peak lumi)
- 72 LR total before D1
- Crab Cavities to compensate geometric reduction of 60-70%

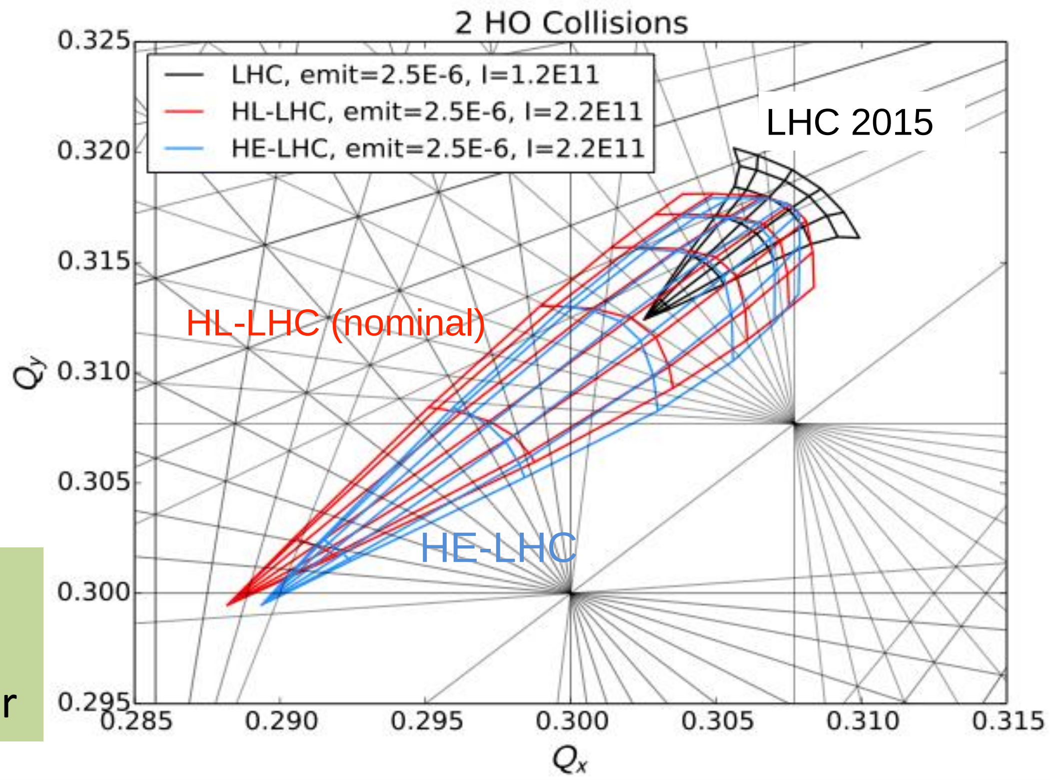
- First studies performed on Footprints and lattice checks (set-up of tools + optics available) + using all available studies from LHC and HL-LHC (similar BB effects) and FCC-hh
- Room for further optimization of Beam-Beam effects and optics → could only make things better

Head-on Footprints

Beam-beam parameter per interaction point:

$\xi \sim 5 \cdot 10^{-3}$
(LHC 2015 25ns, d_{sep}=12.3-9 σ)

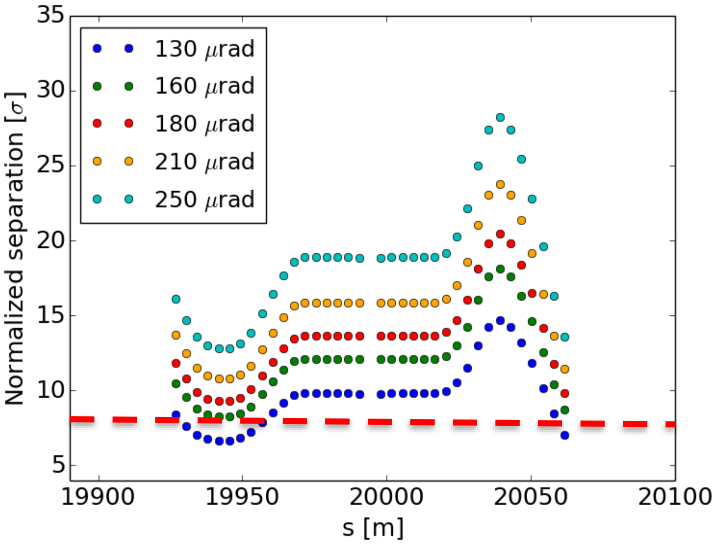
$\xi_{2.2E11} \sim 1 \cdot 10^{-2}$ (HE-LHC/HL-LHC)

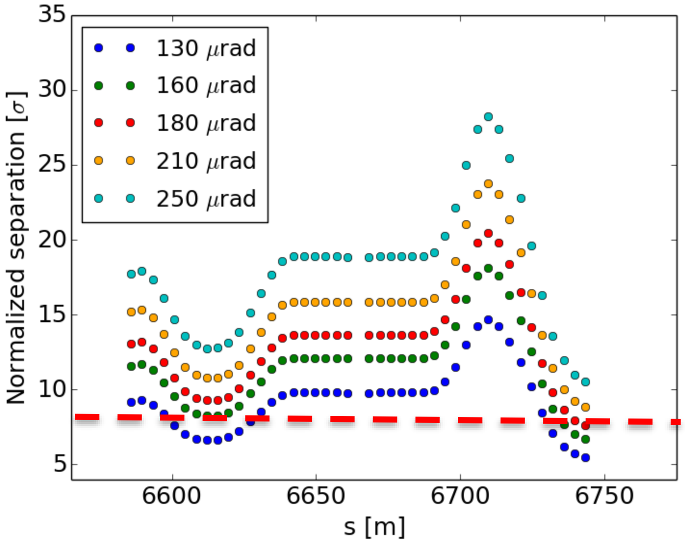


Beam-Beam parameter equivalent to HL-LHC
Head-on Beam-Beam very similar

Beam-Beam Long Range separations

Separations at the 36 Long range encounters





Beam-Beam Long Range separations

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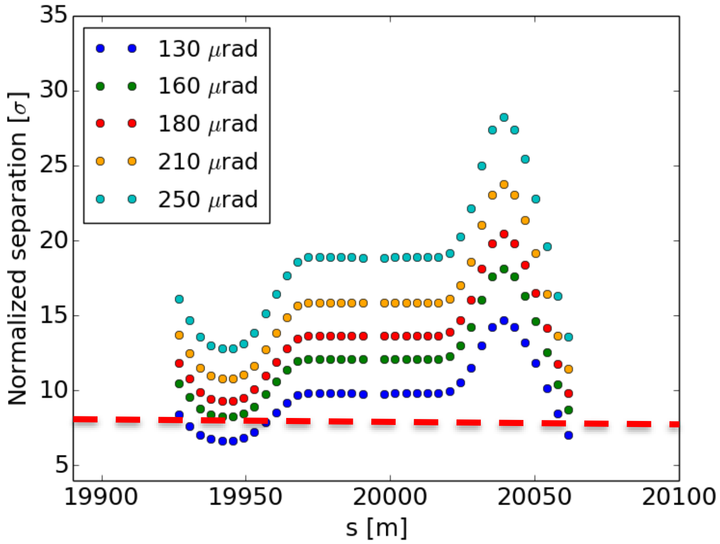
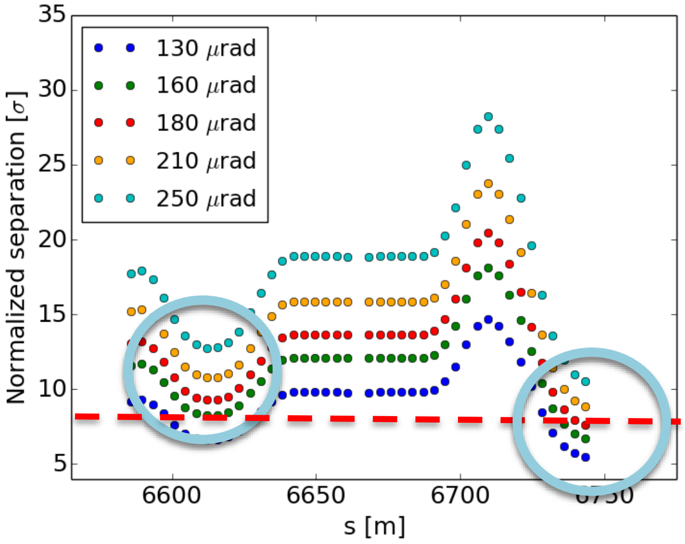
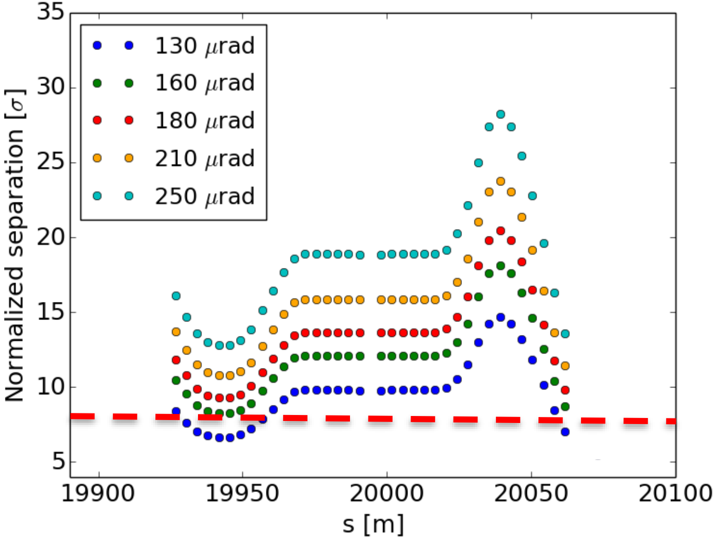




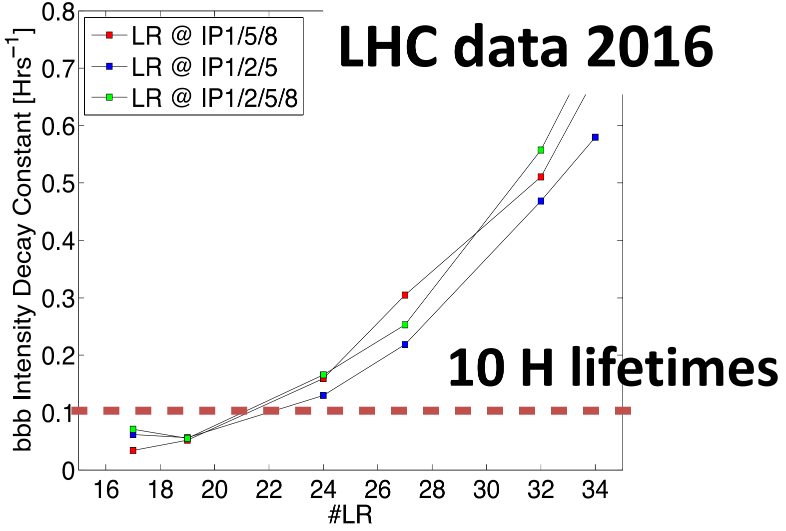
Need to optimization of IR optics to increase BB LR separations at minima

Room for improvement!

Beam-Beam Long Range separations



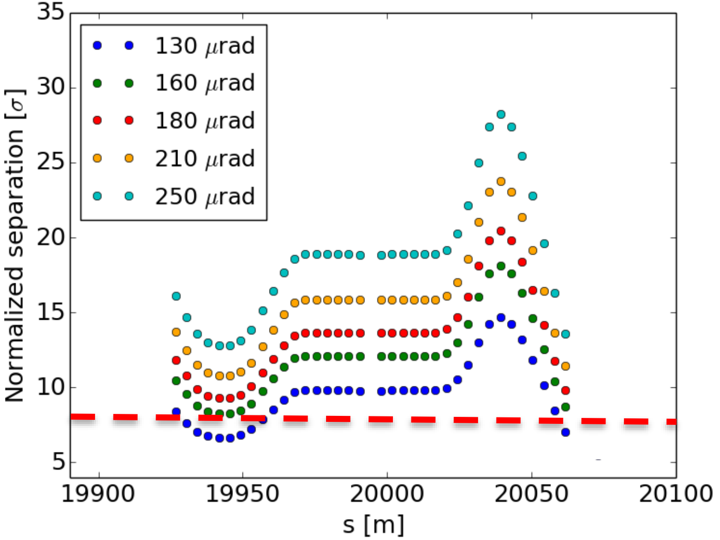
Bunch by bunch losses at small crossing angle 8 sigma first encounter

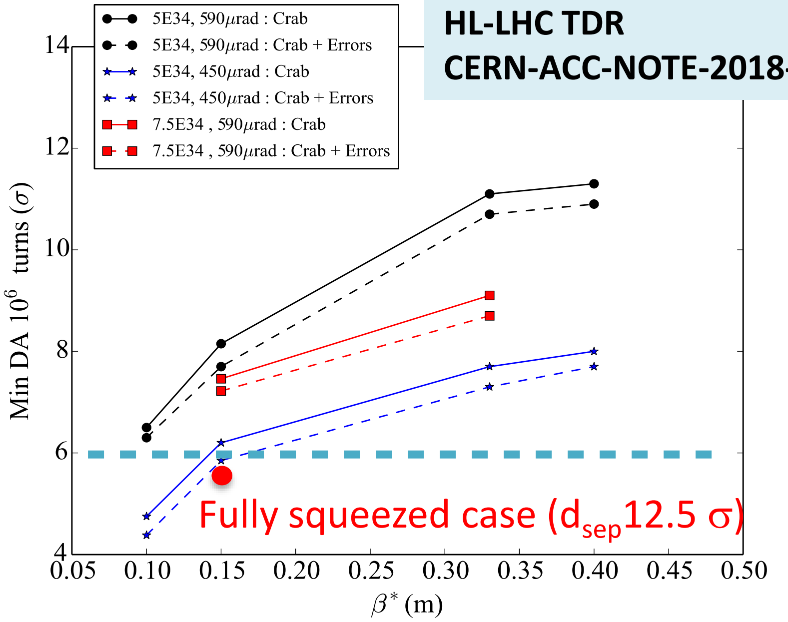


Effects of Long Range beam-beam are not linear with number of LRs for small separations.
Few closest encounters dominates losses if angles too small

$d_{sep} > 8\ \sigma$ → x-angle/2 > 160 μrad SAFE ASSUMPTION → optimization possible!

Beam-Beam Long Range separations



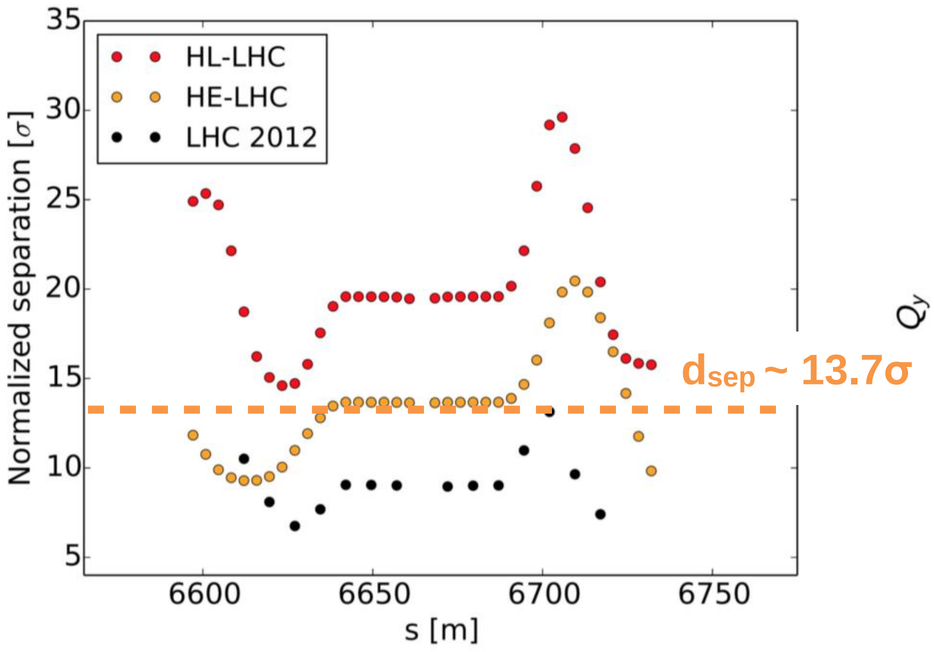


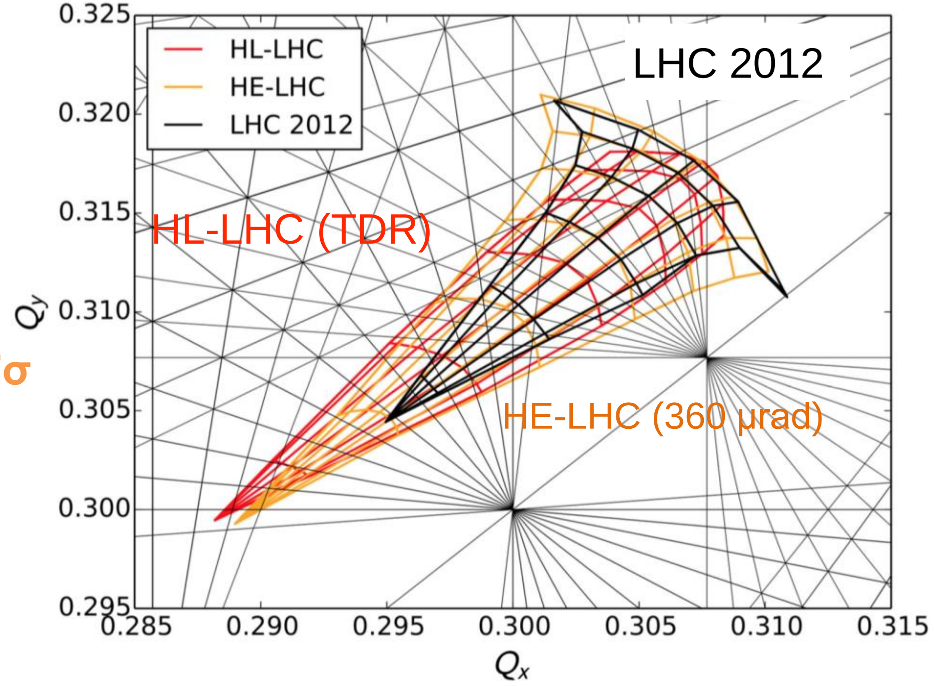
HL-LHC TDR
CERN-ACC-NOTE-2018-035

$d_{sep} > 8\ \sigma$ ➞ x-angle/2 > 160 μrad SAFE ASSUMPTION → need optimize!

$d_{sep} > 9\ \sigma$ ➞ x-angle/2 > 180 μrad (13.5 σ)
Need DA studies but having radiation damping of emittances helps in keeping margins

Head-on and long range interactions





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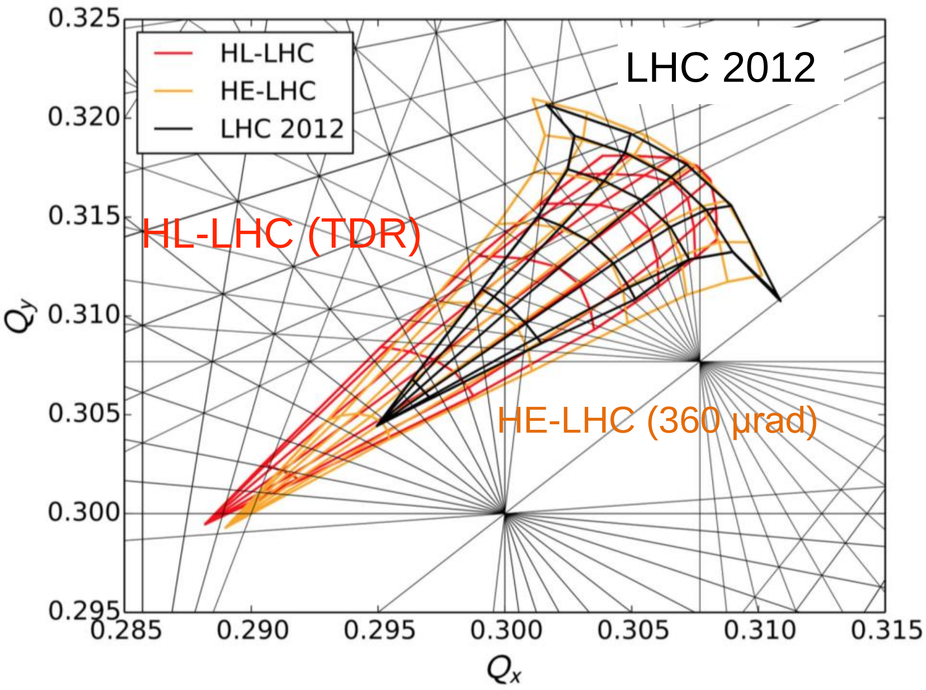
Options to mitigate long range interactions

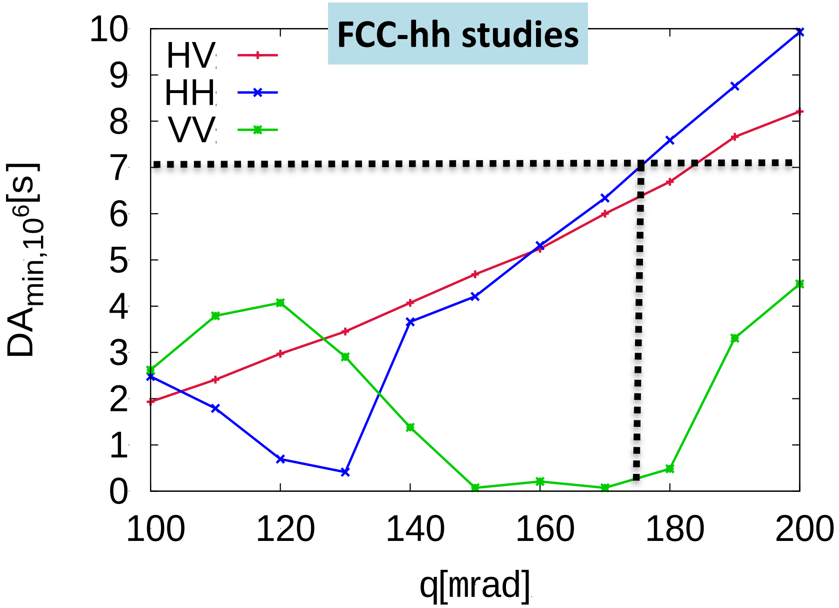
X-angle/2 > 210 μrad at the limit of the aperture

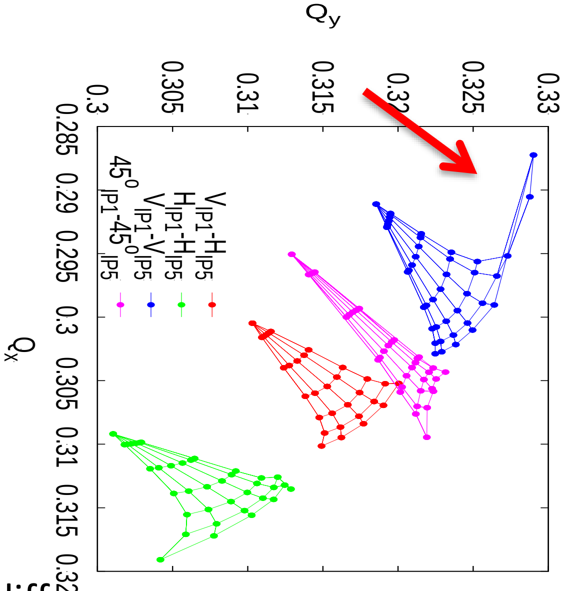
→ Option is to increase β* → little loss in performances β* = 40 cm
→ 15.8 σ separations for x-angle = 165 μrad



β* 25 cm → x-angle/2=180-210 μrad → 8.7-10 MV cavities
β* 40 cm → x-angle/2=165 μrad → 8 MV

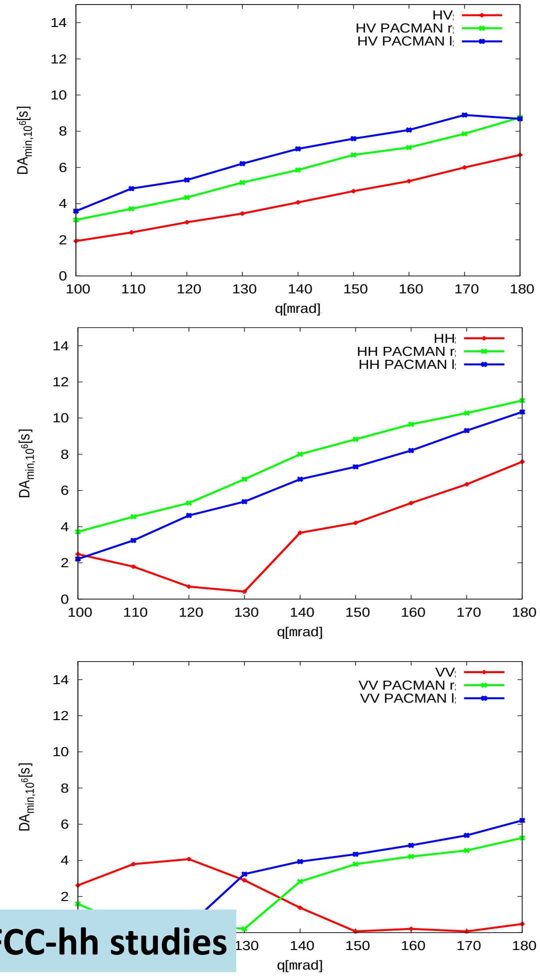
Alternatives crossing schemes are possible



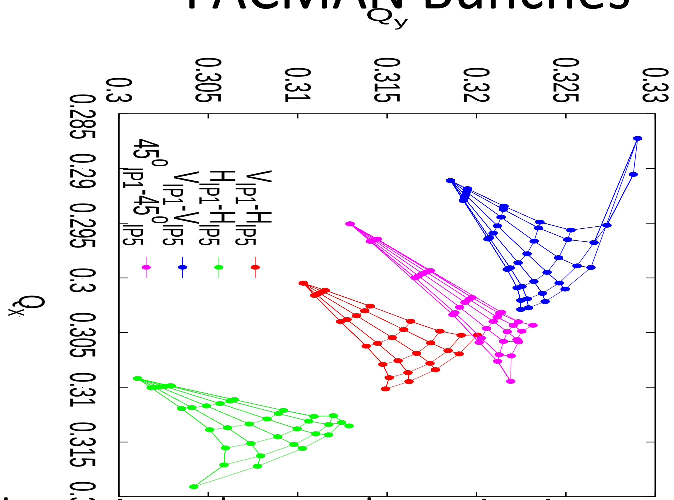


- HV crossing is preferred to reduced bunch to bunch differences
- To give flexibility for energy deposition constrains (F. Cerutti et al.) alternative crossing schemes are possible! Tilted angles are under study.
- **Need detailed studies: dynamic aperture simulations and different working point (mirrored tune as for FCC-hh studies)**

PACMAN Bunches



FCC-hh studies



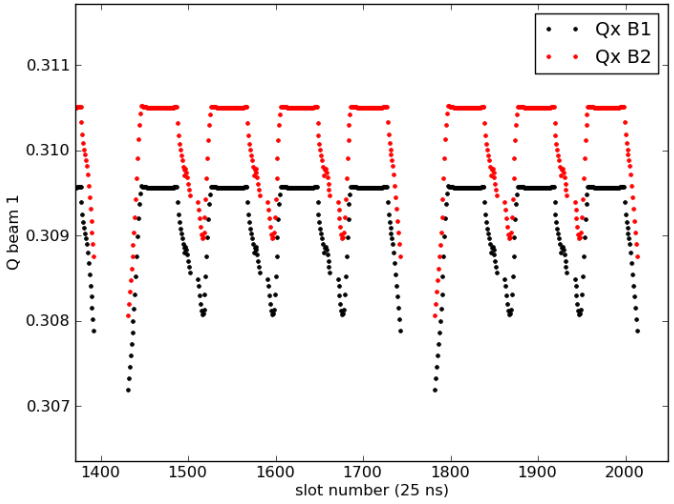
- For all crossing schemes the major impact of long-range effects are on the **nominal bunches**
- **PACMAN bunches (bunches with reduced BB interactions)** always show a better dynamic aperture, DA is defined by nominal bunches

Could be possible to use rotatable crossing angles to dilute radiation dose if needed
→ Expected similar behavior as for the FCC-hh studies

Alternating crossing versus alternatives

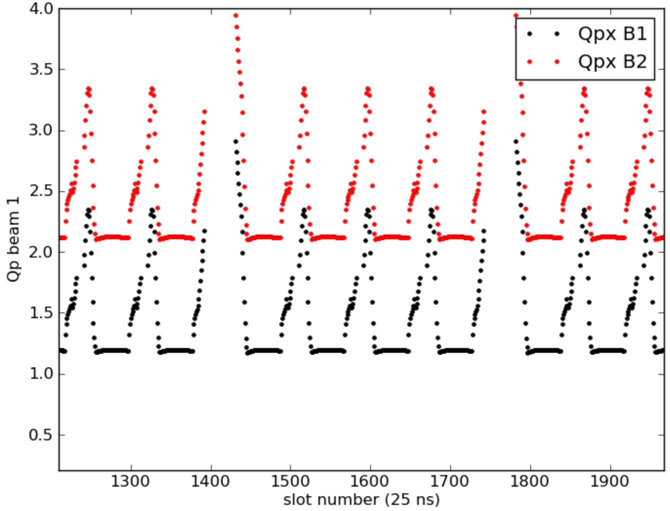
Estimates from HL-LHC fully squeezed
(β^* 15 cm, Int 2.2e11, emittance 2.5 μm)
→ Beam-Beam total tune shift of 0.02 total + LR at **12.5 σ**

PACMAN Tune shifts



ΔQ_{spread} = 0.003
(reduced **0.002 for 15.8** σ sep scaling with the $1/d^2$)

PACMAN Chroma changes



$\Delta Q'_{spread}$ = 2-3 units

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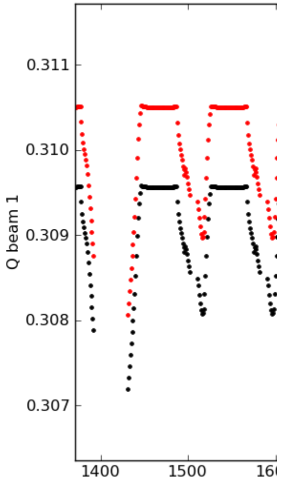
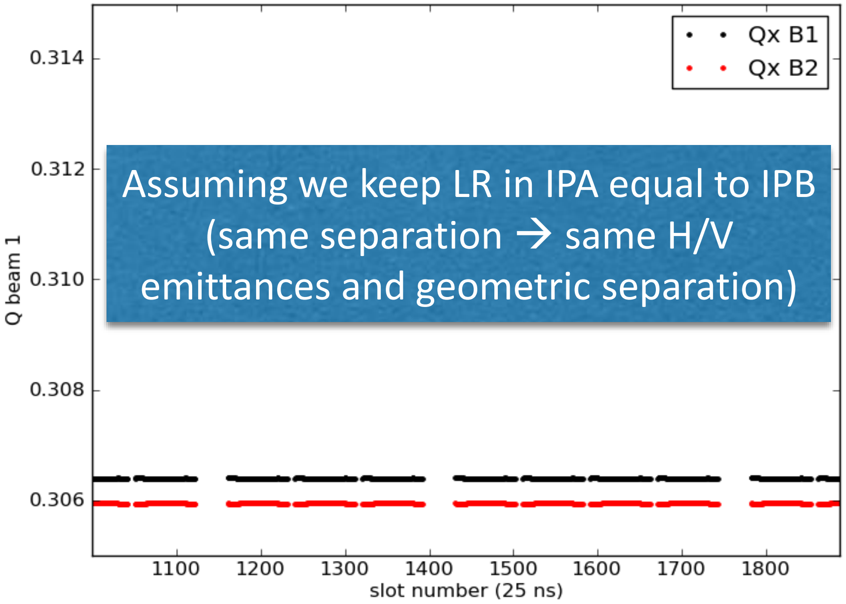
Alternating crossing versus alternatives

Estimates from HL-LHC fully squeezed
(β^* 15 cm, Int 2.2e11, emittance 2.5 μm)

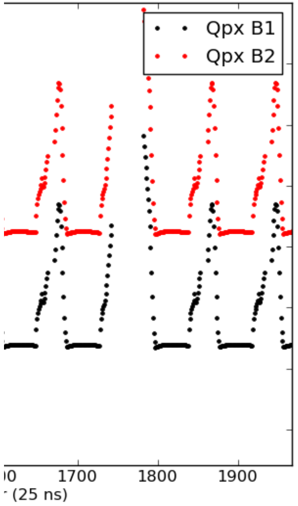
PACM





Assuming we keep LR in IPA equal to IPB
(same separation → same H/V
emittances and geometric separation)

ma changes

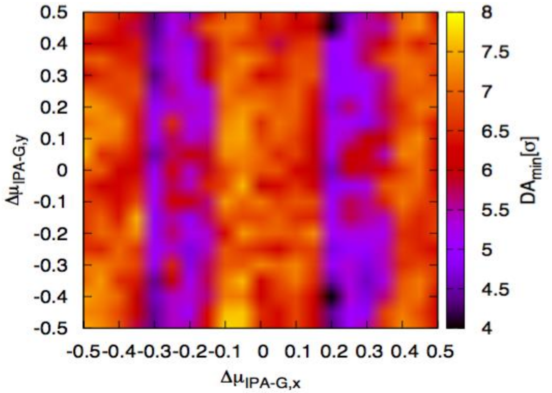


ΔQ_{spread} = 0.003
(reduced **0.002 for 15.8** σ sep scaling with the 1/d^2)

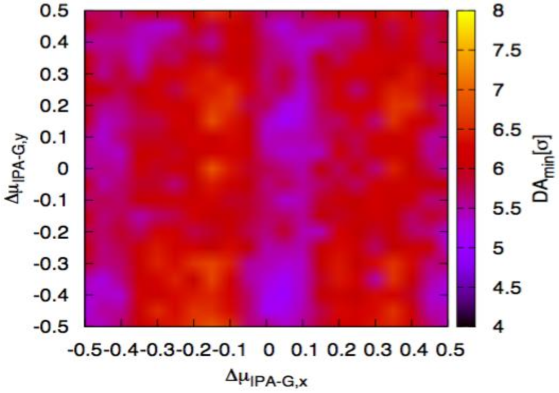
$\Delta Q'_{spread}$ = 2-3 units

Dynamic Aperture

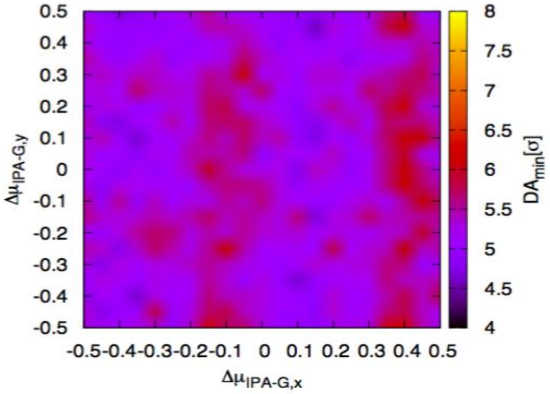
- Landau Octupoles



Beam-Beam Effects



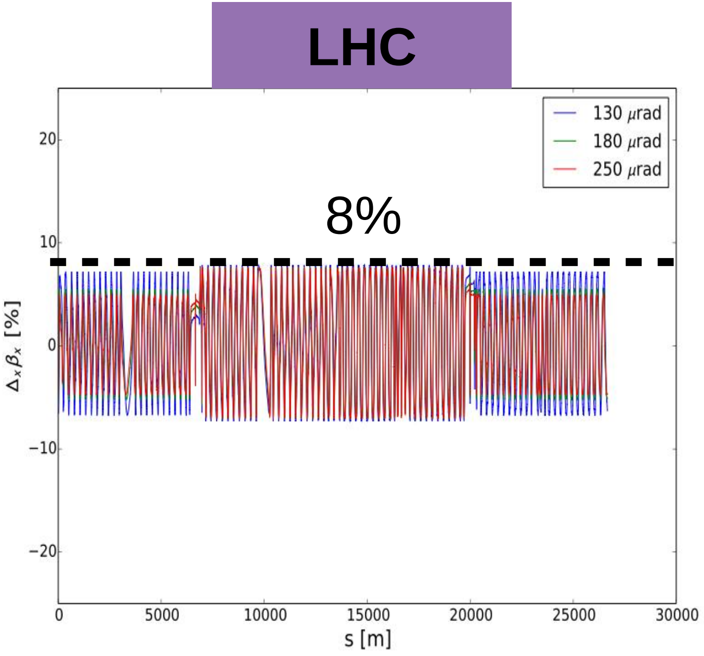
+ Landau Octupoles

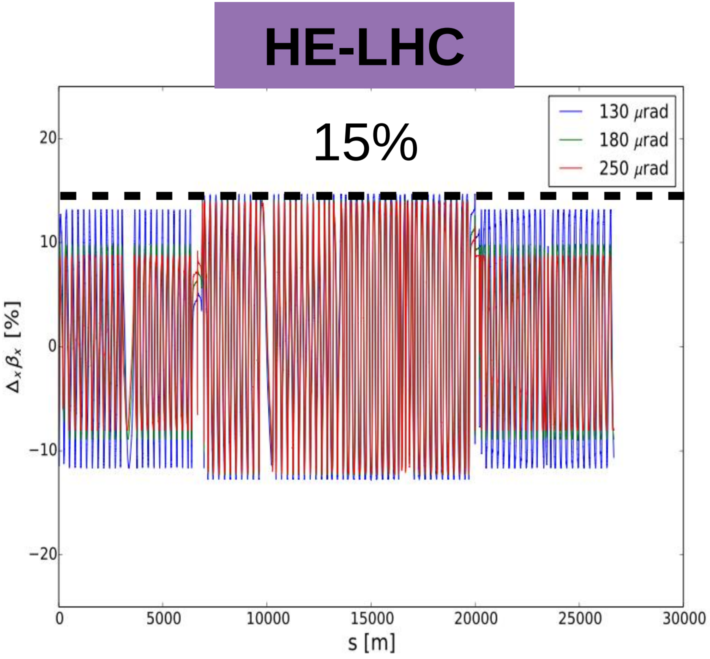


- Studies set-up on-going after single lattice implementation (**see talks Thursday M. Hofer, L. Van Riesen-Haupt and R. Tomas**)
- Room for optimization with DA studies using IPA/IPB phase advance (**as in FCC-hh studies E. Cruz**)
- Optics optimization with BB to allow for compensation techniques:
  - Global compensation with Landau octupole magnets (**J. Shi and CERN-ACC-NOTE-2017-036**)
  - Local use of e-lens for long-range compensation (**V. Schiltsev et al.**)

Ongoing work: dynamic aperture simulation studies and optimization

BB β-beating (2 ho collisions)



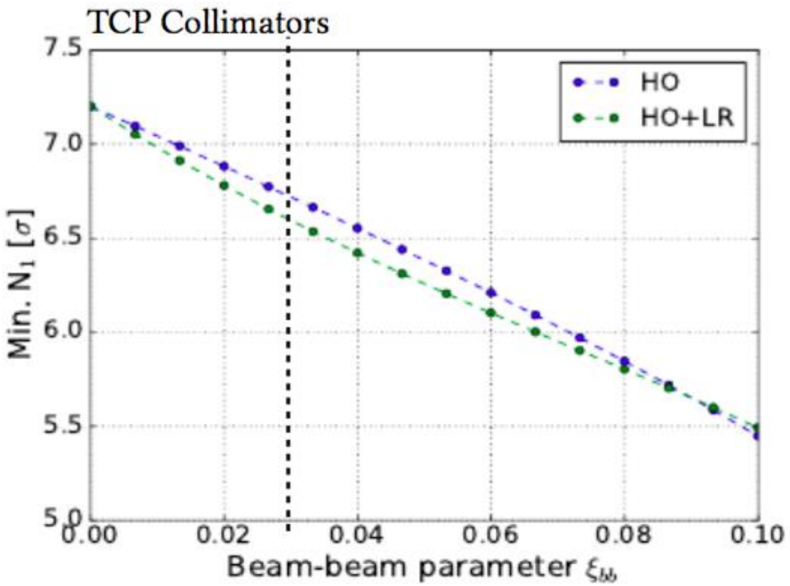


2 IPs β-beating increase of 15% → out of tolerances

Need to adjust phase advance to profit in luminosity performances

β* → reduced by 9-6 % due to BB β-beating, try to use the effect for luminosity enhancement

Beam-Beam β-beating



FCC-hh studies
Show small effect

P. Goncalves EPFL Master thesis
Eurocircle Meeting Oct2017

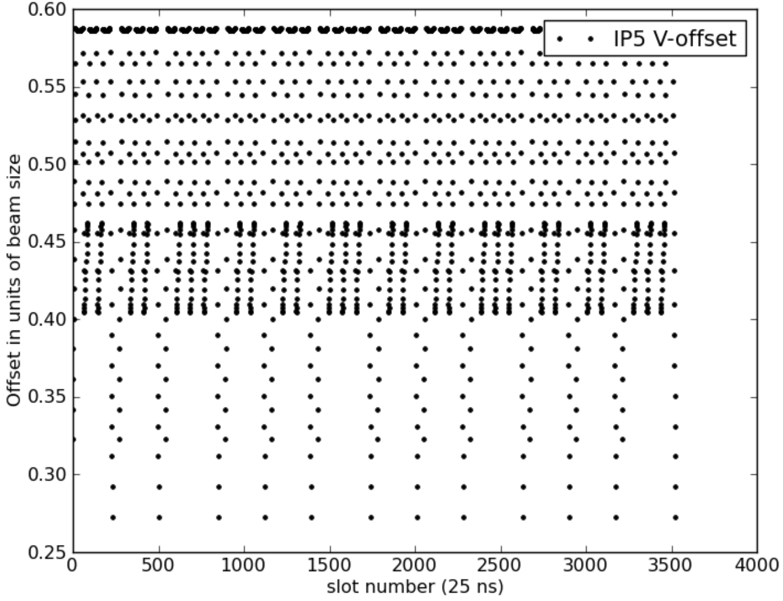
Maximum Beam-beam beta-beating expected of 15% (2 HO)

- Impact on β* luminosity
- Impact on mechanical aperture (→ impact on impedance etc…) to be evaluated

Further studies needed to address impact on loss maps and collimation system

Orbit Effects

HL-LHC: Int 2.2 e11 BB sep 12.5

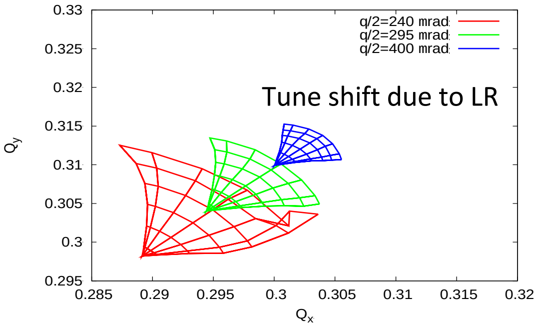


From HL-LHC studies → expected BB orbit spread of 0.4 σ → lumi reduction 1-2%

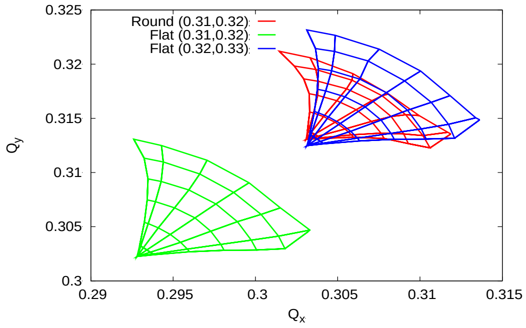
Larger BB separations will allow for a reduced orbit spread 0.4 σ (12.5 σ sep)→ 0.3 σ (15.8 σ sep) → Lumi impact less than 1%

Alternative solutions: Flat optics versus round

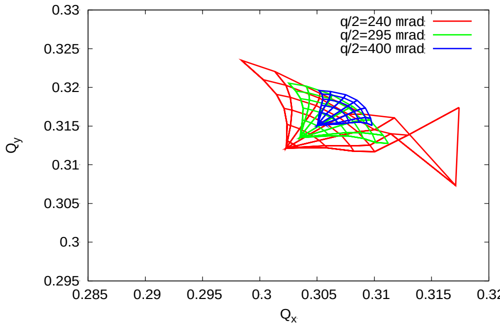
Flat optics x-angle scan



Flat optics x-angle scan
Tune shift compensation



Round optics x-angle scan



Flat optics is the natural alternative-back up solution in case of crab cavities do not work, because for same normalized separation one has smaller geometric loss factor in the luminosity

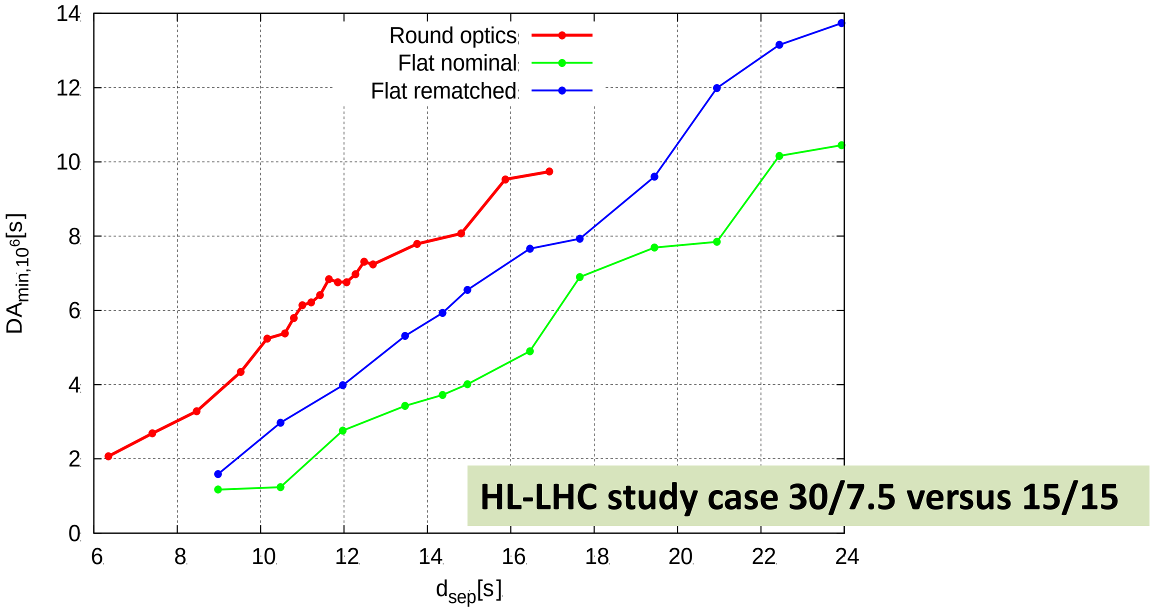
However Beam-Beam long-range and head-on behave differently:

- Due to trains and brake of passive compensation → bunch to bunch tune shifts (need to correct for)
- Head-on beam-beam creates asymmetric detuning with amplitude

Flat optics introduces some unwanted effects, one cannot assume same as round normalized separations

See talk J. Abelleira Fernandez

Flat versus round optics: beam-beam effects



- Flat optics will need **43%** more separation respect to round (larger aspect ratio makes things worse)
  - Correcting for the tune shift reduces the needs (28%)
    - Larger β* ratios make things worse

Flat optics becomes competitive if BB separation can be reduced further
→ Compensation schemes needed (global with oct, local with wires…)! Need detailed studies!

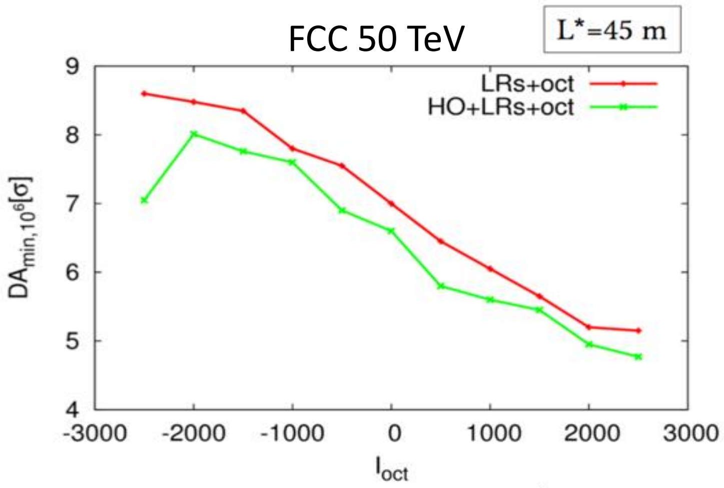
Beam-beam compensation schemes

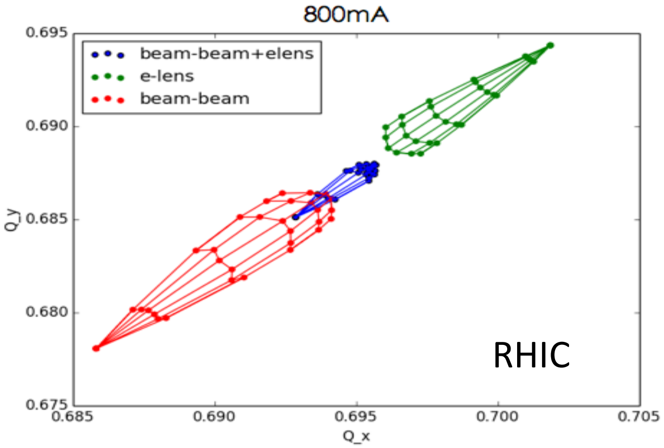
- Compensations schemes should be explored and can relax angles and DA constrains → evident from HL-LHC and FCC-hh studies → IPs phase advance important

- Global compensation with octupoles magnets should be putted in place from very early optics design (similar behavior as HL-LHC and FCC-hh CERN-ACC-2017-0065), e-lenses to compensate long-range at a bunch to bunch level for alternative crossing schemes

- E-lenses to reduce head-on in case of noise issue and to counter act the emittance shrinking (large BB parameter) and possible use for Landau damping

- Room to improve performances!





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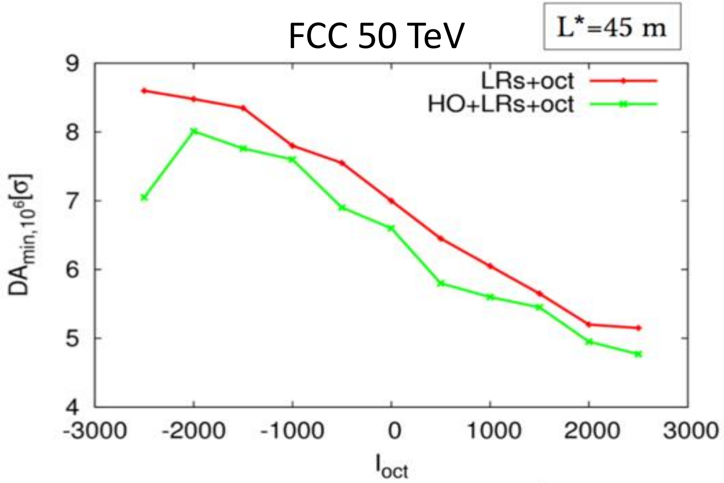
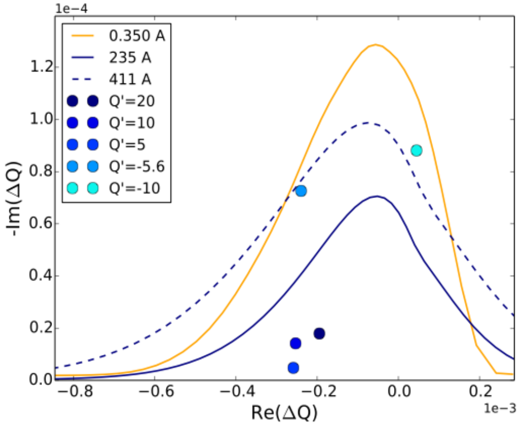




Summary

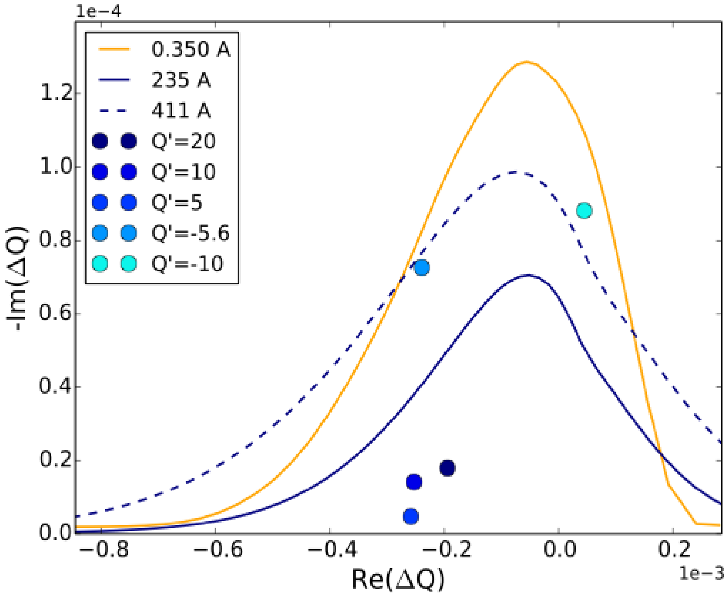
- **Scenario with H-V crossing and beam-beam separation of 13,5 σ (angle 360 μrad) is proposed rescaling from LHC, HL-LHC and FCC studies**
  - **Detailed DA** studies needed to address non-linearities impact (high Q' operations and magnets errors)
  - **Lattice optimization** in presence of beam-beam could improve further performances (reduced crossing angles)
- Relaxed scenario with β* from 25 cm to 40 cm (some loss in performances 15%)
- Separation can be reduced using **compensation schemes** → needed detailed study!
  - **Global compensation** with octupole magnets → seems robust from simulations for FCC and HL-LHC but needs optimized optics over the cycle to be kept in the presence of errors and optics changes.
  - **Local compensation** by using e-lenses (bunch to bunch differences for alternative crossing schemes)
- Two beam stability studies on-going
- **Alternative or rotatable x-angles are possible to dilute doses in IRs as for FCC-hh if needed.**
- Flat optics: work on-going to evaluate the effective gain vs round optics by DA simulations

Thank You!

Single beam stability

- Installed Landau octupoles provide enough Landau damping (impact on DA to be evaluated)

- Electron implemented in the COMBI code: maximum flexibility and different distributions for e-lens profile (EPFL Project by Master student F. Barantani)



D. Amorim et al. « Single-beam transverse collective effects for HE-LHC » (ICFA paper)

Single beam stability

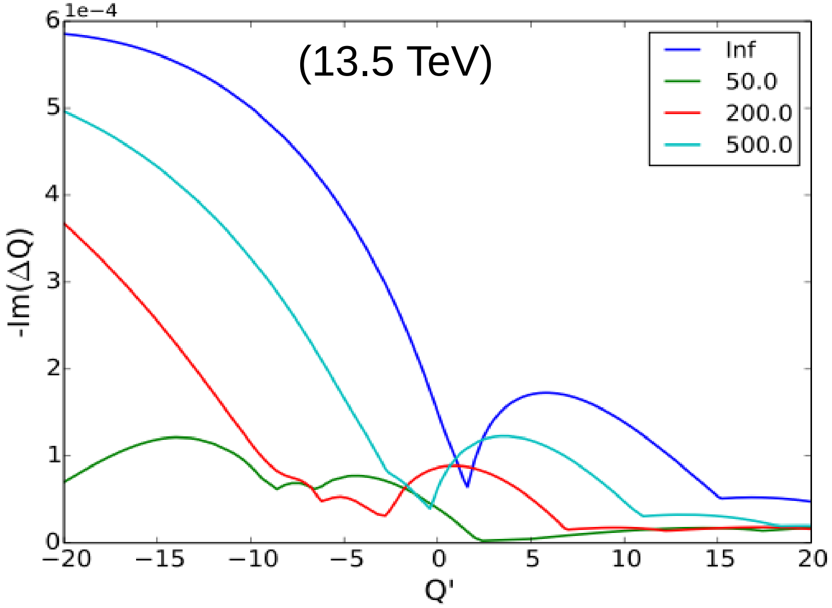
BIM-BIM code ➞

Beam-Beam and Impedance → Coherent mode analysis
Study single/multibunch instability mechanisms involving the impedance and beam-beam interactions

- Transverse Feedback
- Chromaticity

- Modes computed for HE-LHC at flat top and ingection energy Benchmarked with DELPHI

➞ Extend these studies including beam-beam coupled with impedance

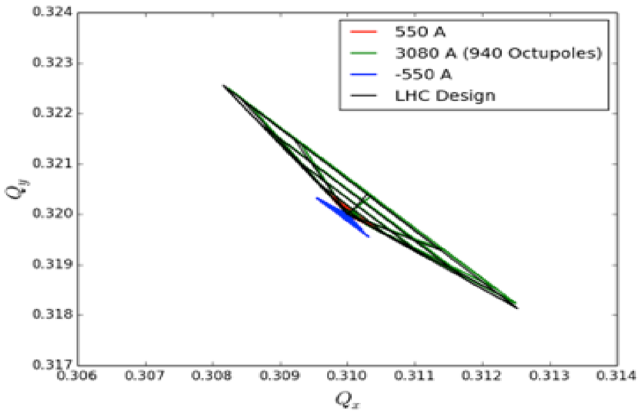


Landau damping

Octupoles magnets [J. Berg and F. Ruggero]	Electron lenses [V. Shiltsev et al.]	RFQ [M. Schenk, A. Grudiev et al.]
Installed octupoles in the optics to add beam-beam contribution to Landau damping	Evaluation of tune spread and Landau damping from e-lens	Preliminary studies for FCC by M. Schenk et al. show stabilizing effects

Impact on Dynamic Aperture

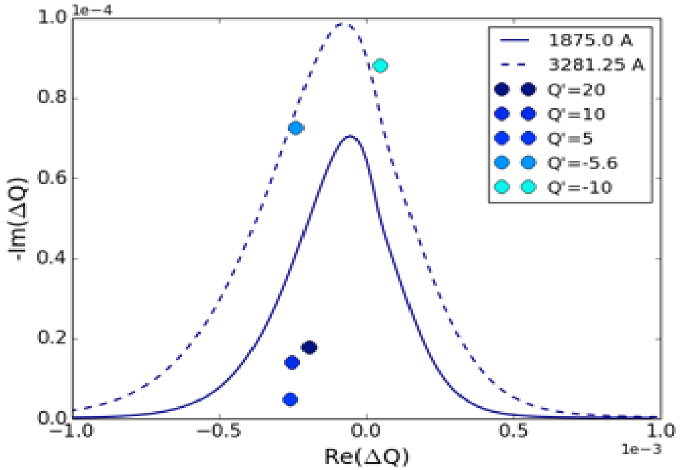
Landau damping from octupole magnets



- Preliminary analysis, footprint computed by COMBI
- Linear detuning from octupole magnets (LHC type)
- To reproduce LHC tune spread with 500 A, 940 Octupoles are needed

- Stability diagrams computed by PySSD code with linear detuning from octupole magnets (LHC type)

➞ Installation of octupoles magnets in the available optics

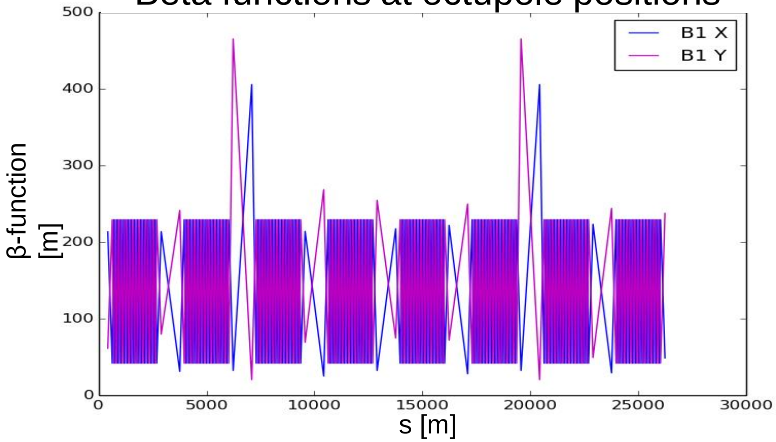


Installation of octupole magnets for Landau damping studies

Octupoles installed at location of focusing and defocusing quadrupoles (defined as QFH and QDH in the lattice):

- 264 Octupoles installed
- FCC octupole type:
  - Length=0.32 m
  - G_{max}=220000 T/m^3
  - Maximum current= 720 A

Beta functions at octupole positions



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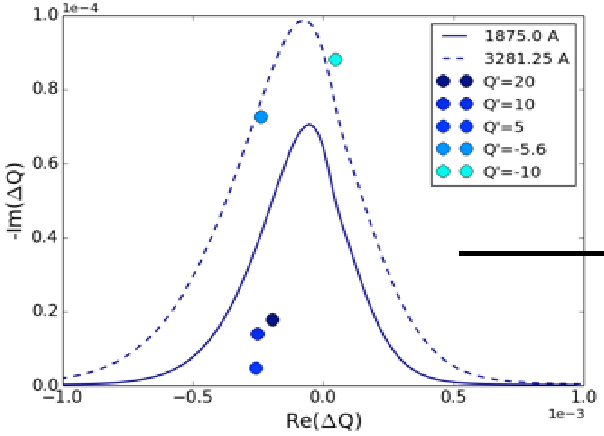
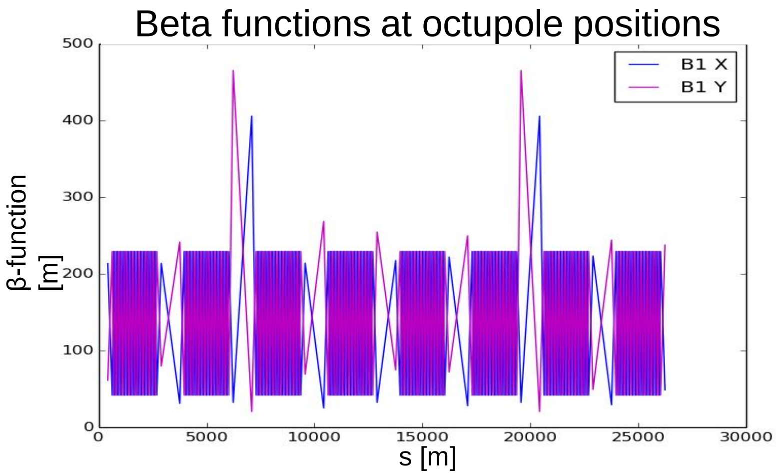
  - Maximum current= 720 A





188 A sufficient to riproduce same SD:

1875 A (LHC) ~ 188 A (HE LHC) · 264/168 · 220000/53000 · 230/188 · 2.5/2

Number of octupoles

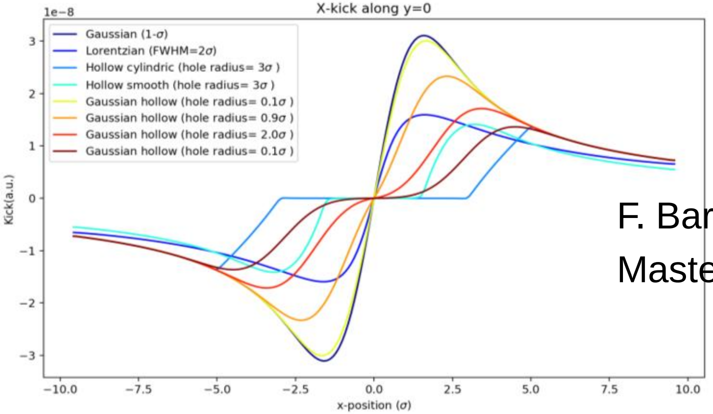
Octupole gradient

Max β-function

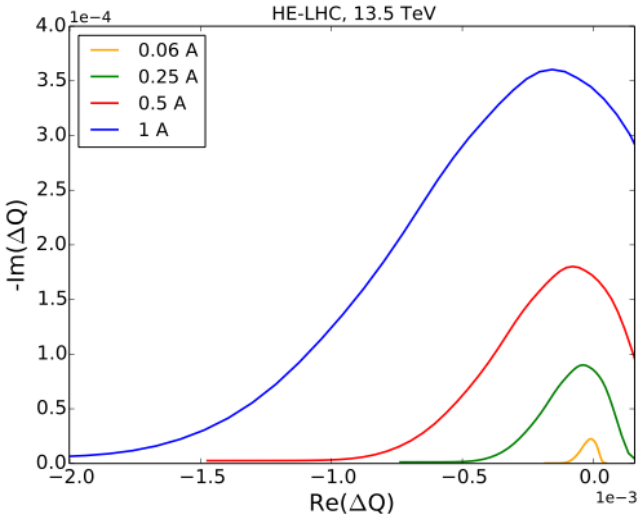
Emittance

Landau damping from e-lens

- Implemented e-lens in COMBI code (thanks for inputs by G. Stancari, V. Shiltzev, A. Valishev):
  - Maximum flexibility (different machine configurations)
  - Possibility to chose different distribution for e-lens profile (F. Barantani)

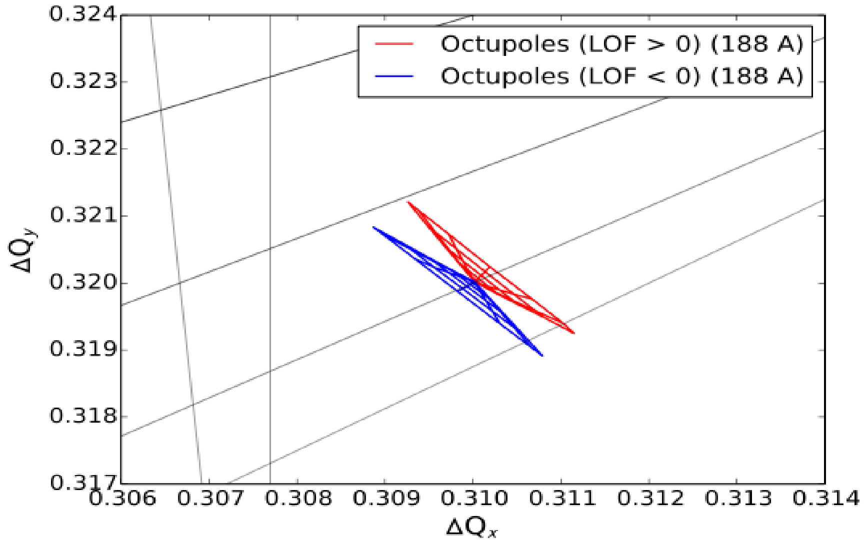


F. Barantani (EPFL Master student)



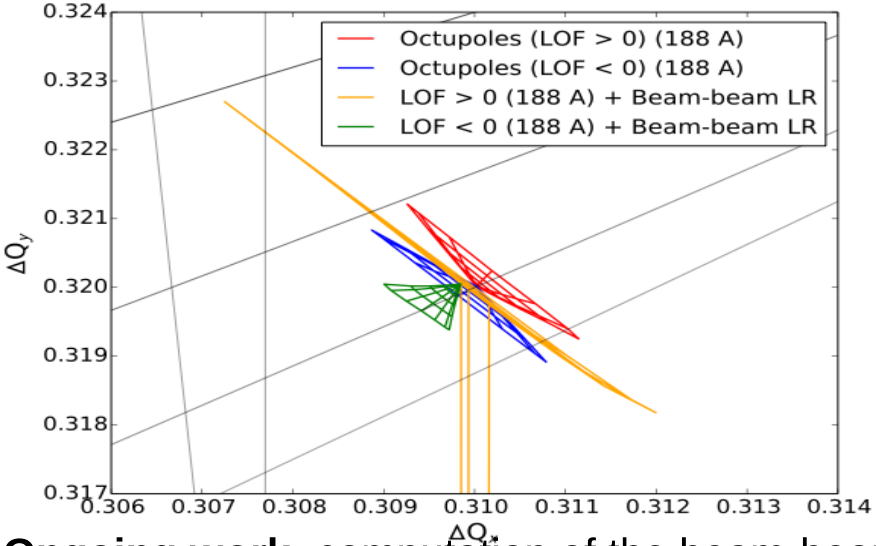
Landau damping in presence of beam-beam interactions

The installation of the octupoles in the optics allows to add beam-beam contribution (non linear) to linear detuning from octupoles magnets



Landau damping in presence of beam-beam interactions

The installation of the octupoles in the optics allows to add beam-beam contribution (non linear) to linear detuning from octupoles magnets

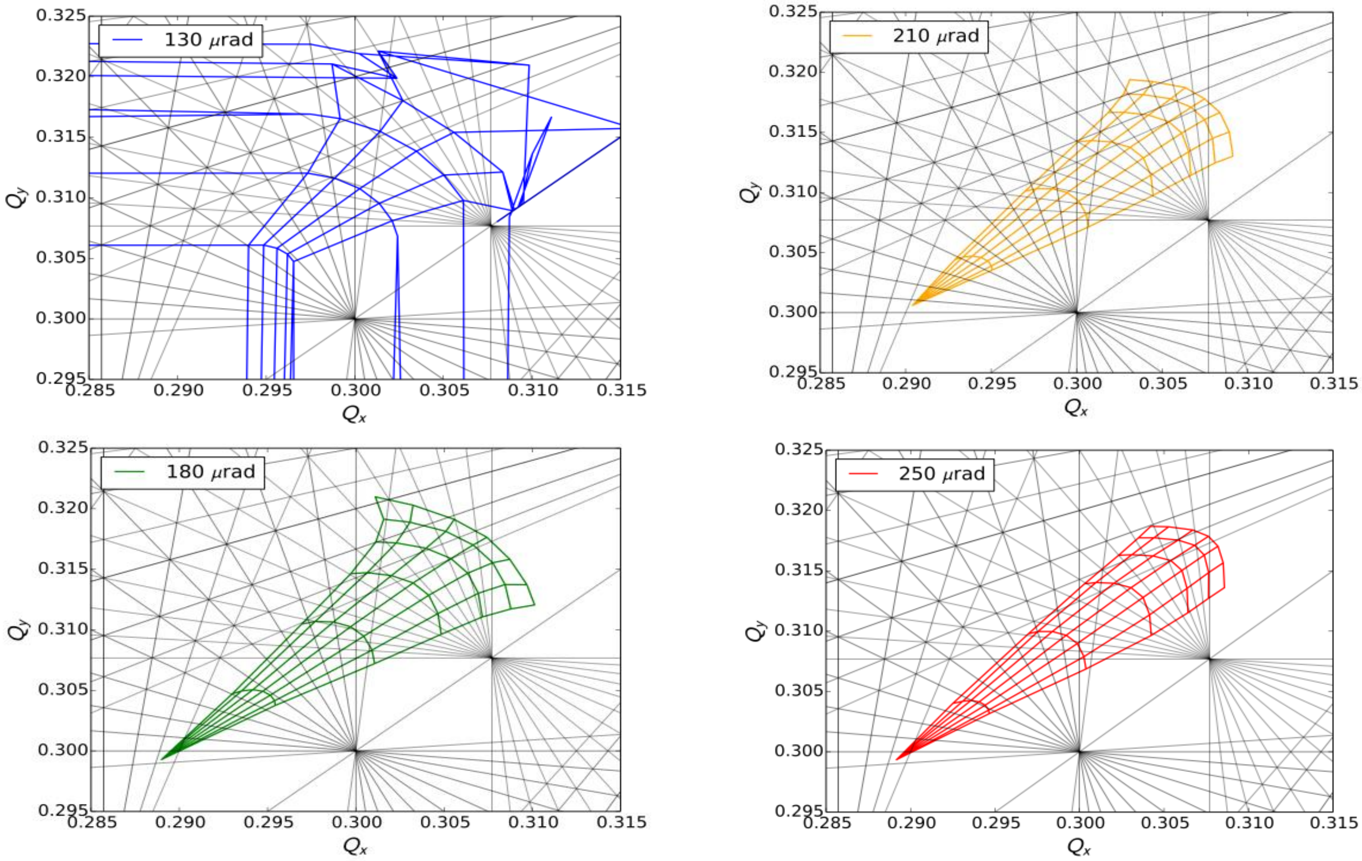


Beam-beam long range interactions modify the Landau damping from octupoles:

- Positive polarity: additional spread (beneficial for Landau damping but reduction of DA)
- Negative polarity: reduce Landau damping but compensate the LRs (better DA)

Ongoing work: computation of the beam-beam modes coupled with impedance (BIMBIM code)

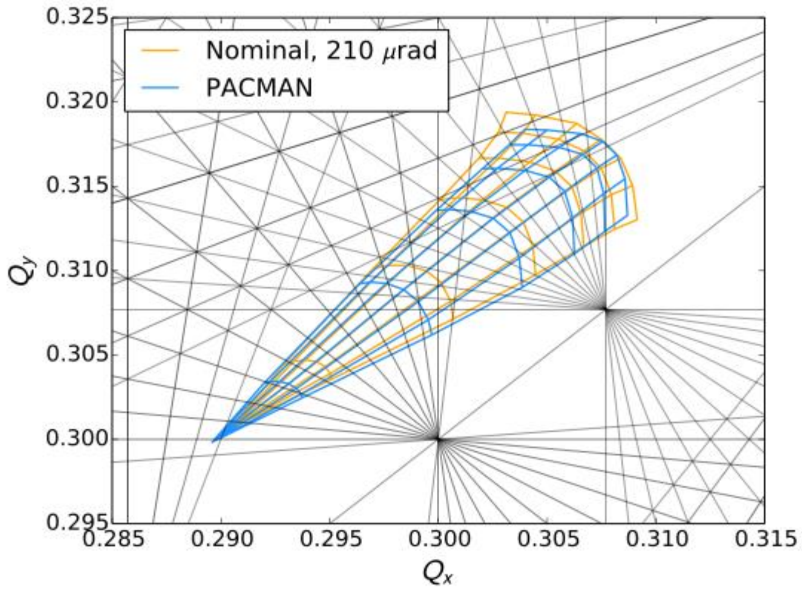
Footprints HO + LR crossing angle scan



PACMAN effects

As expected negligible effects for PACMAN bunches

→ DA will be driven by nominal bunches, PACMAN will be always better



Alternative crossing schemes are explored to overcome energy deposition constrains
→ changeable angles to dilute the particles losses in the IR.
(I. Besana and F. Ceruti)