HL-LHC WP2 meeting

11.10.2016

Effect of the crossing angle on coherent stability

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

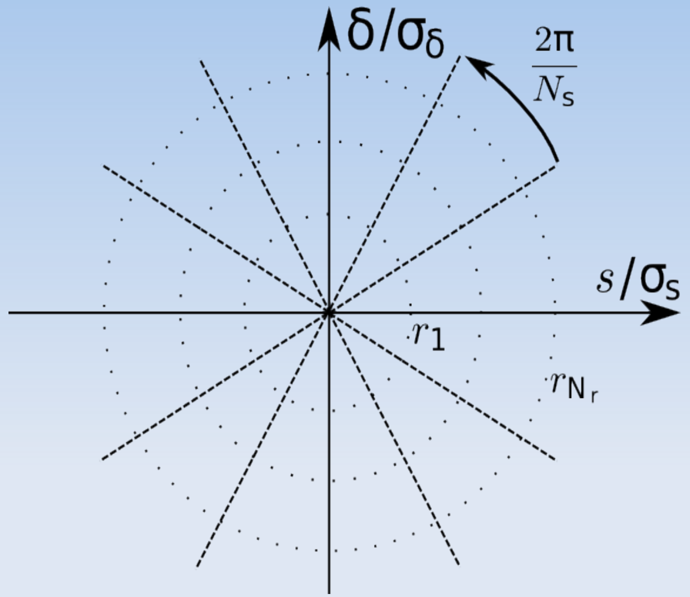
Acknowledgements : N. Biancacci, W. Herr, S. White

Content

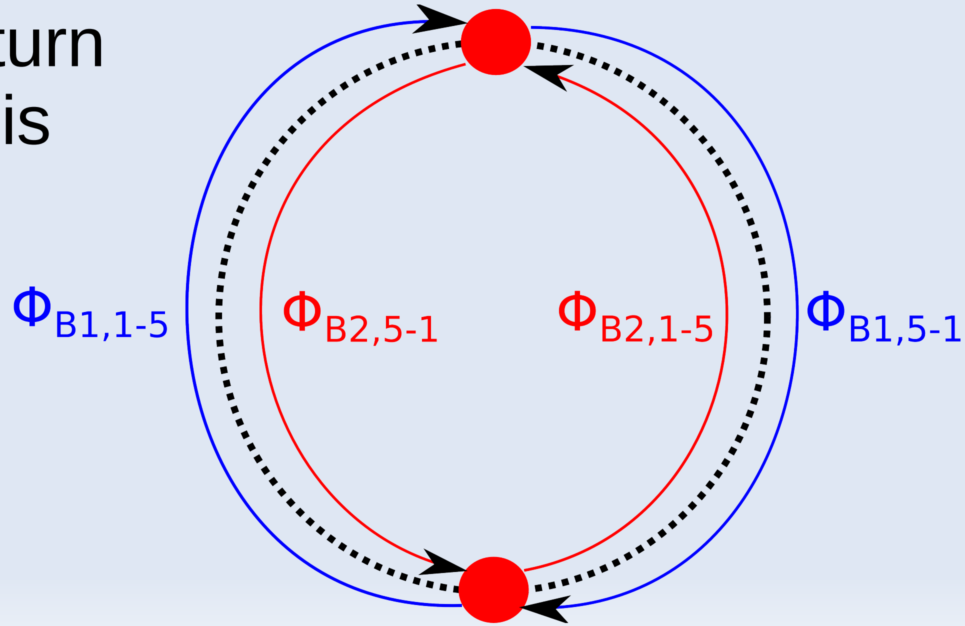
- Mode coupling instabilities
  - Head-on effects
  - Long-range coherent beam-beam modes
- Stability diagrams
  - Squeeze
  - Distortion of the distribution
  - Head-on effect
- Conclusion

The circulant matrix model (BimBim)

- Derive the transverse linearised equation of motion for a discretised longitudinal distribution, including :
  - Chromaticity
  - Beam coupling impedance
  - Linearised coherent beam-beam forces (6D, in arbitrarily complex configurations)
  - Transverse feedback
- Analyse the stability of the one turn matrix with normal mode analysis
- Neglects Landau damping



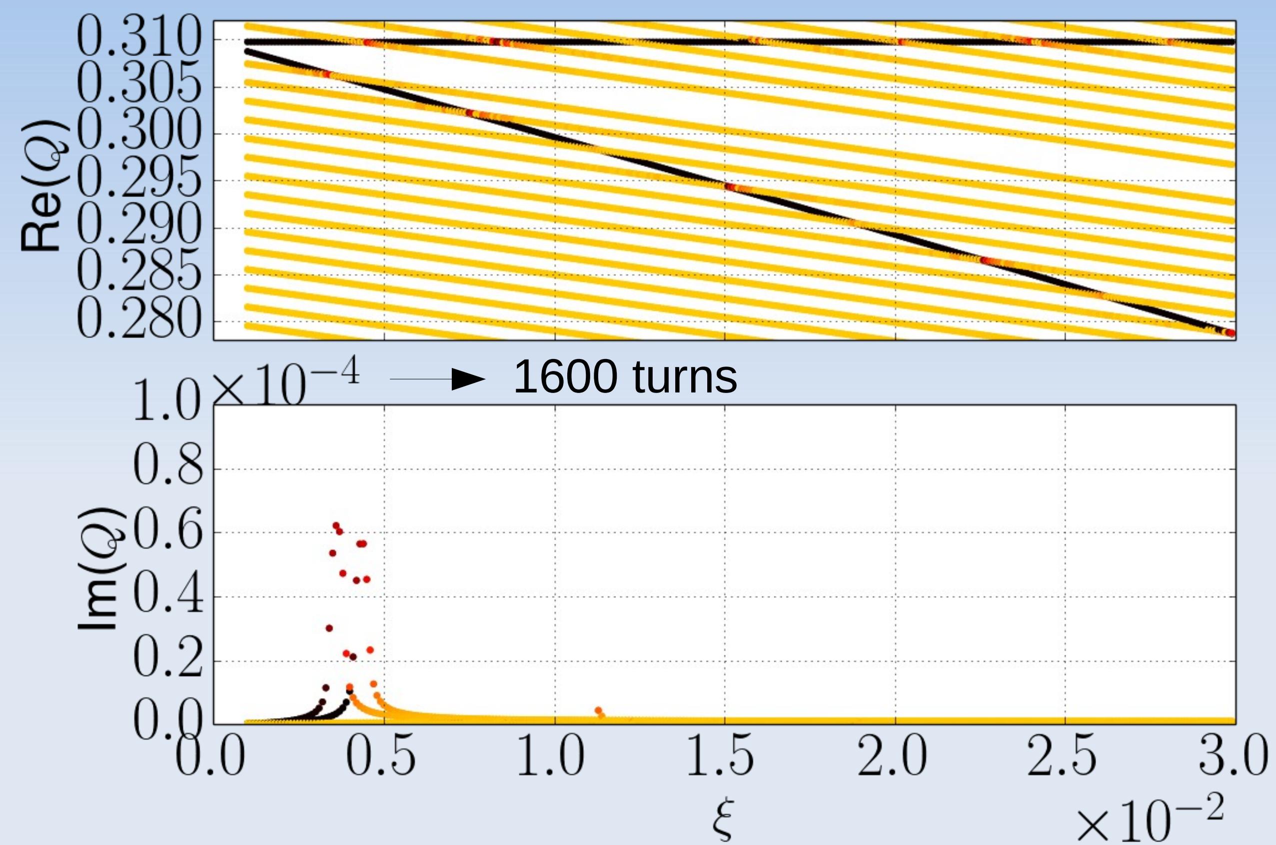
$$\underline{x}(t) = M^t_{One\,turn}\,\underline{x}(0) = \sum_j e^{-2\pi i Q_j t}\,\underline{v}_j$$



Mode coupling instability of colliding beams

- 2 head-on interactions (6D) with symmetric phase advances
  - HL-LHC baseline parameters but :

    β* = 11m, Q' = 0, G = 0



- Coupling instabilities are observed when coherent beam-beam mode frequencies overlap with head-tail modes
  - Observe in dedicated MDs at the LHC
  - Landau damping can be modeled in multiparticle tracking simluations

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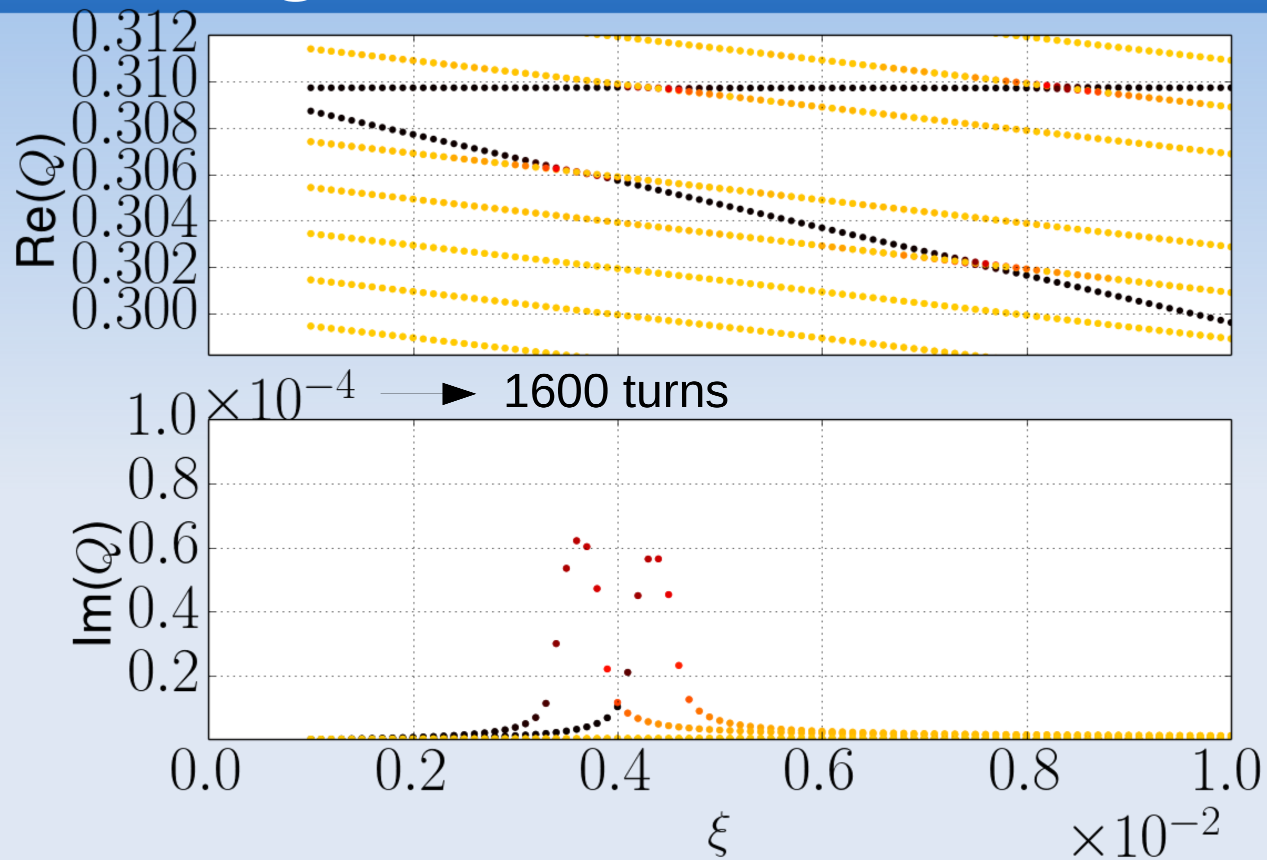

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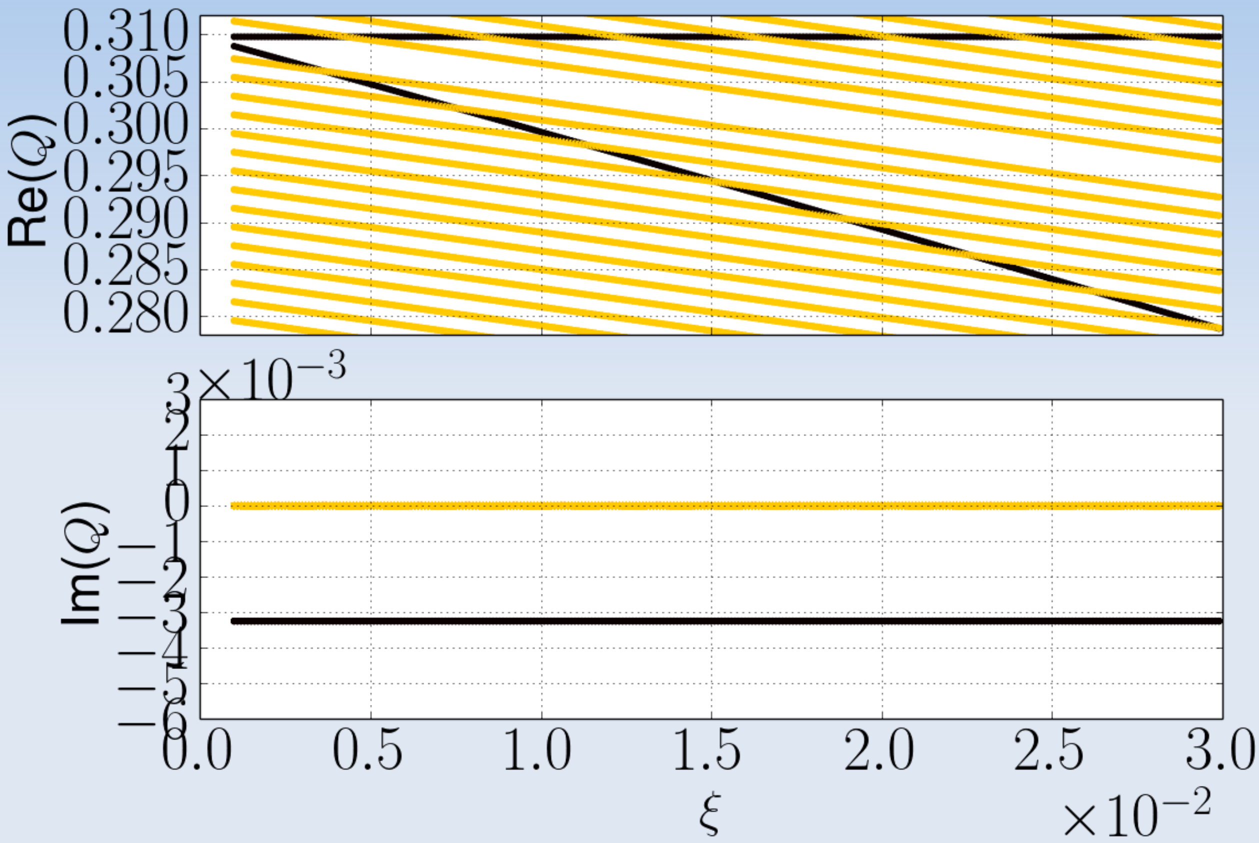
Effect of the transverse feedback

2/G = 50 turns

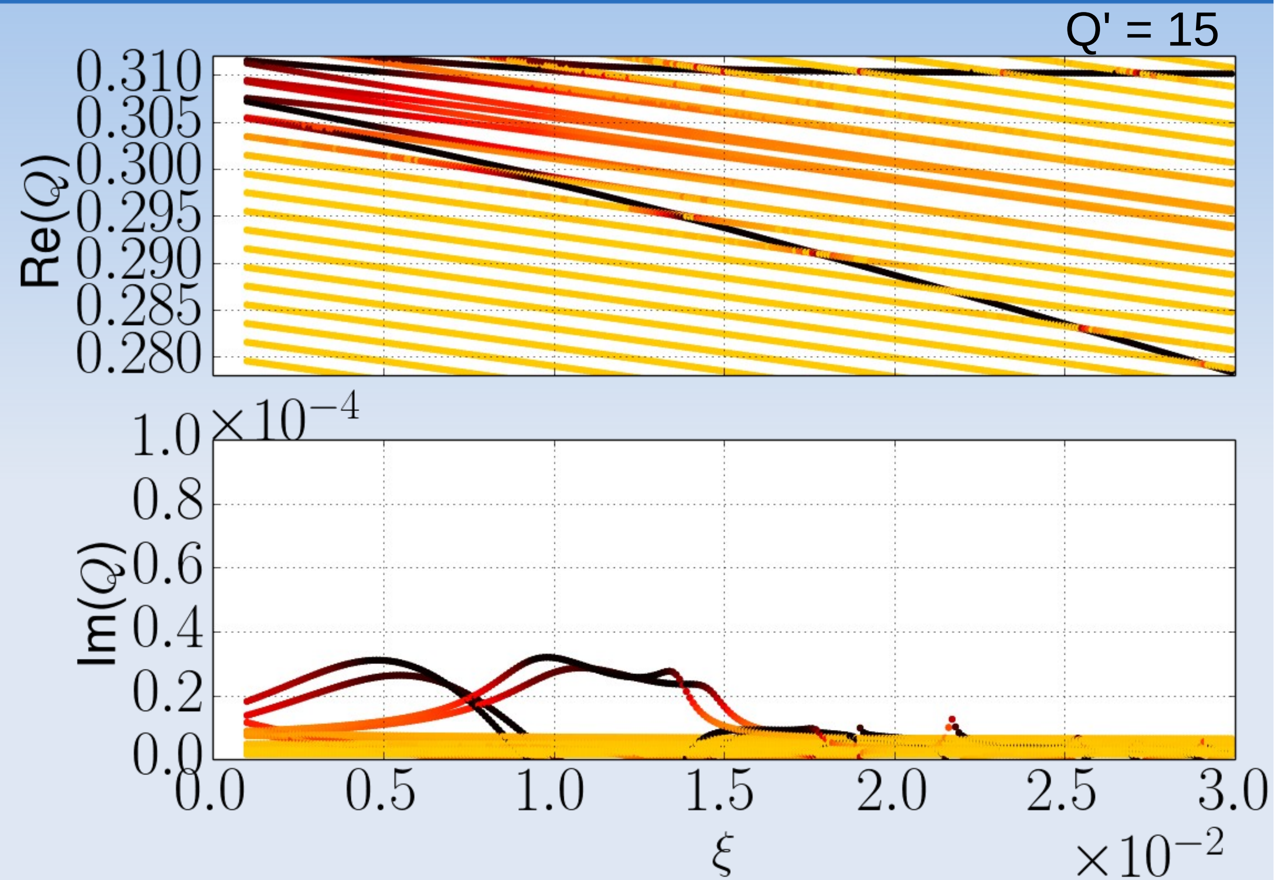


- The transverse feedback based on the dipolar moment (e.g. ADT) acts efficiently on modes with a dipolar component

Effect of chromaticity

- Chromaticity changes the nature of the nature of the head-tail modes

  → modifying their coupling through beam-beam interactions



- In absence of synchrobetatron coupling due to the beam-beam interaction, the modes couple through their dipolar component

  → coupled instabilities are still efficiently mitigated by a transverse feedback based on the dipolar moment (e.g. ADT)

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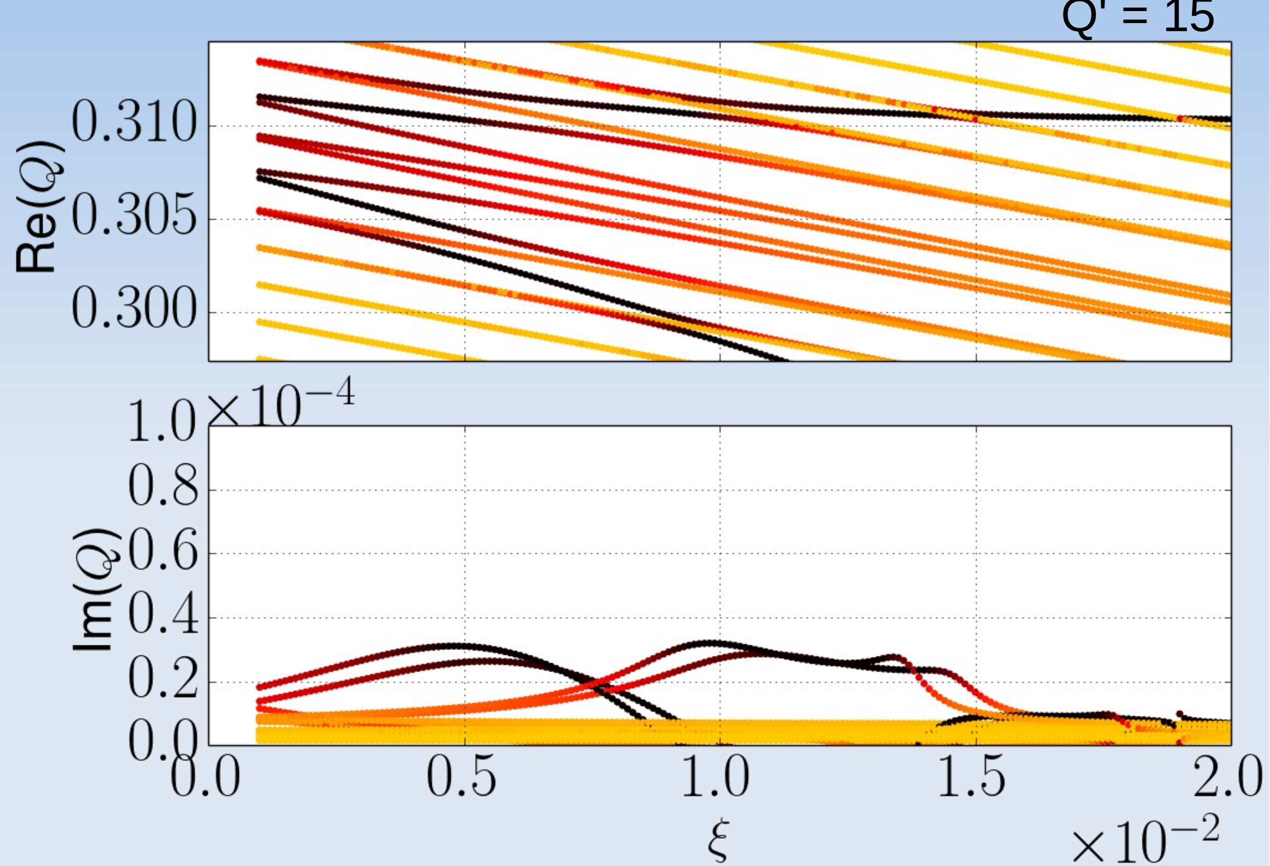

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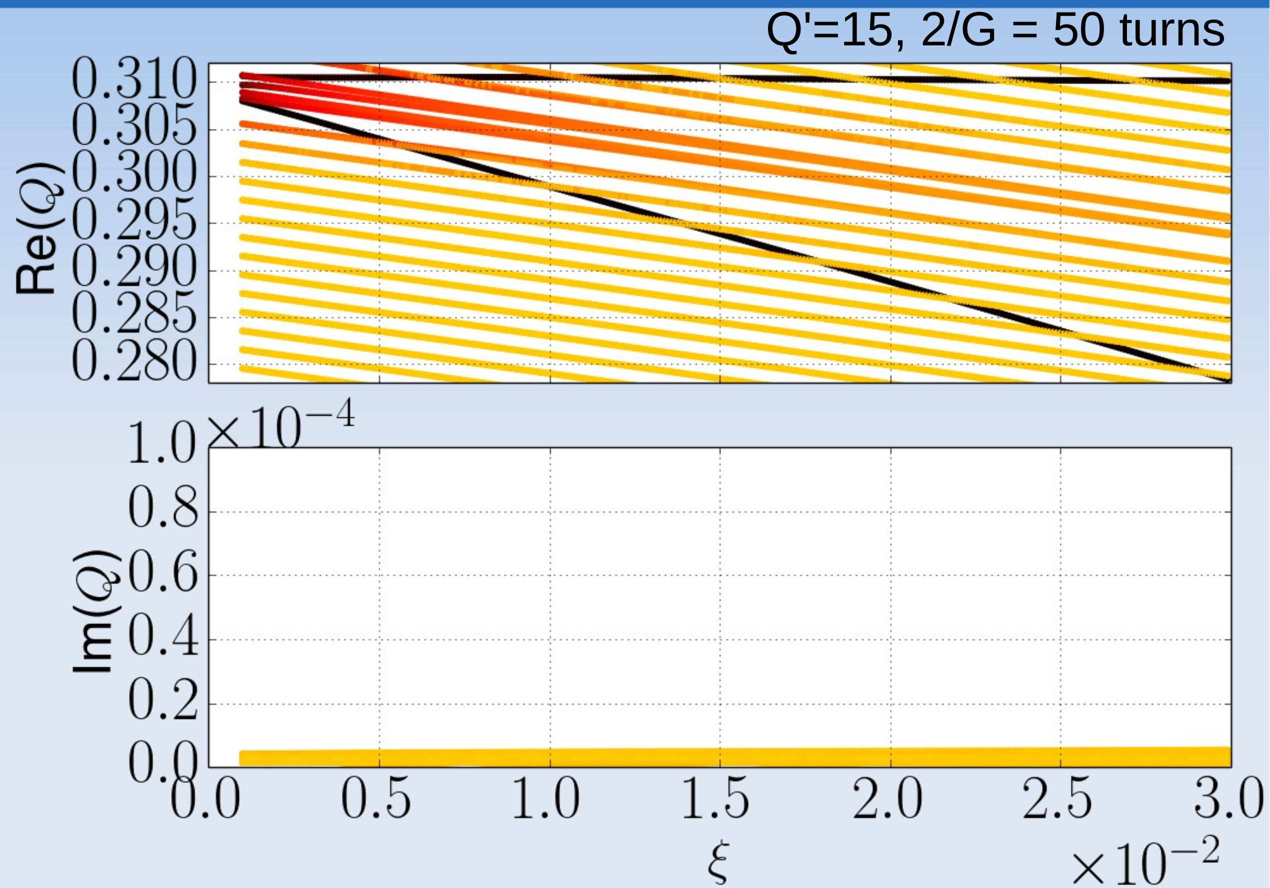

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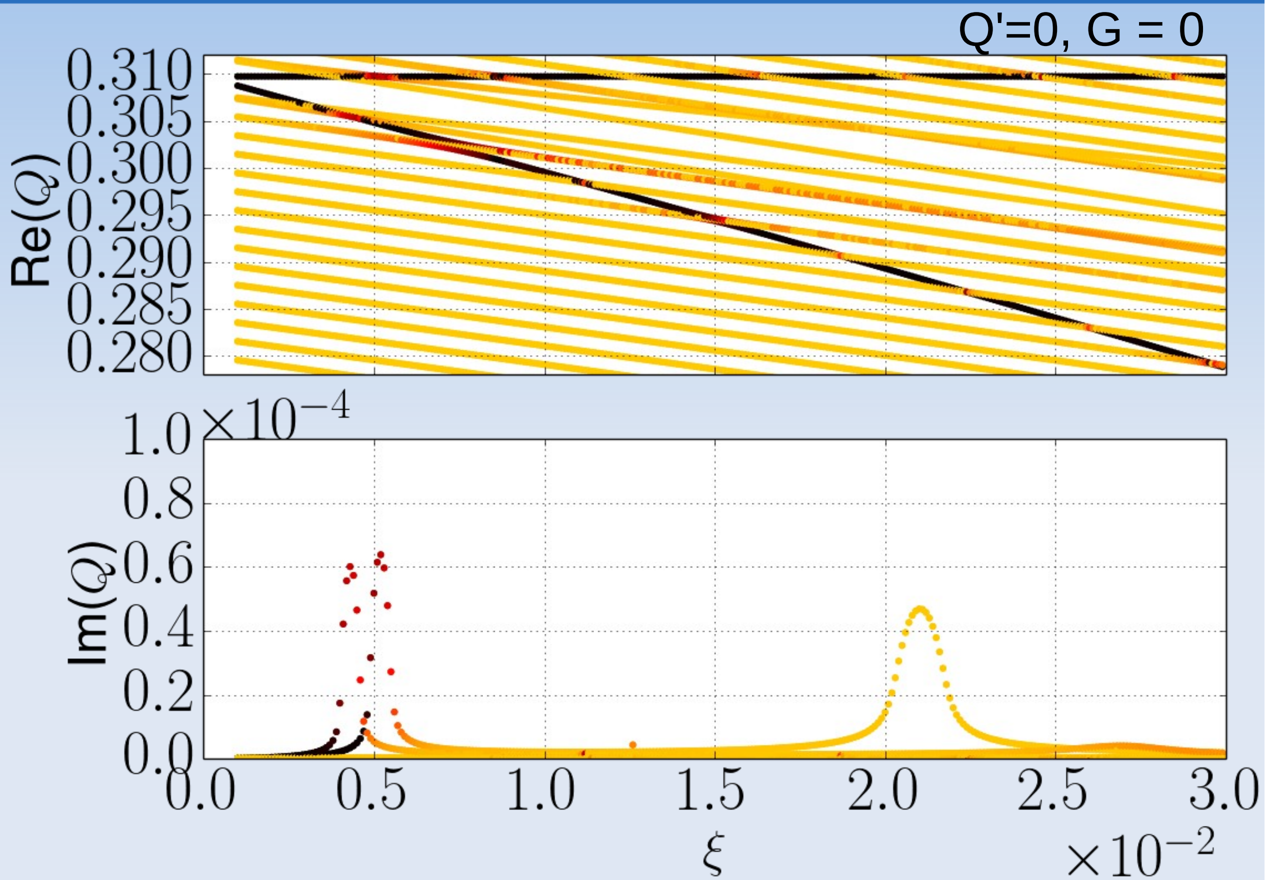
Effect of synchrobetatron coupling

- Head-on collision with a finite β* (hourglass) or a crossing angle introduces synchrobetatron coupling
  - Allows for coupling of higher order head-tail modes (possibly without dipolar component)
  - Observed at VEPP-2000



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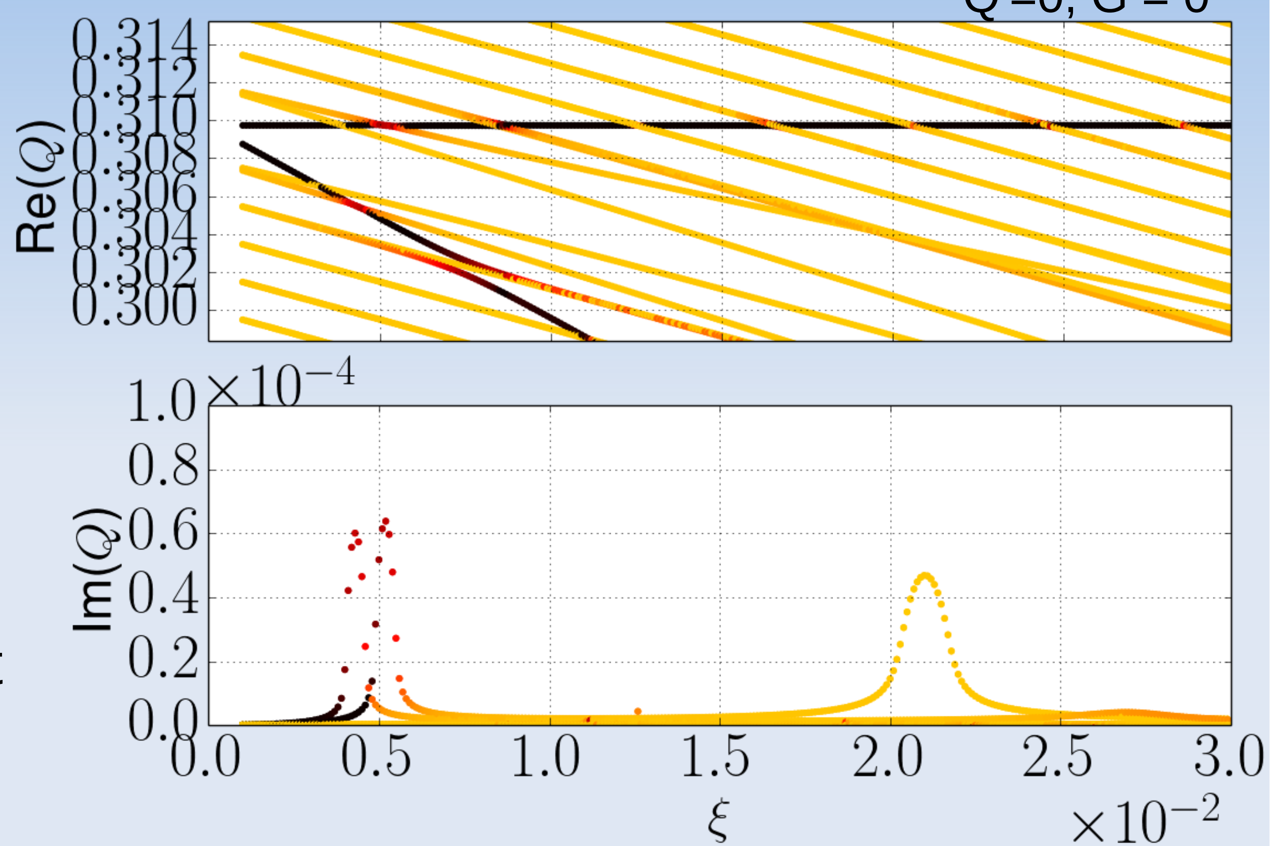

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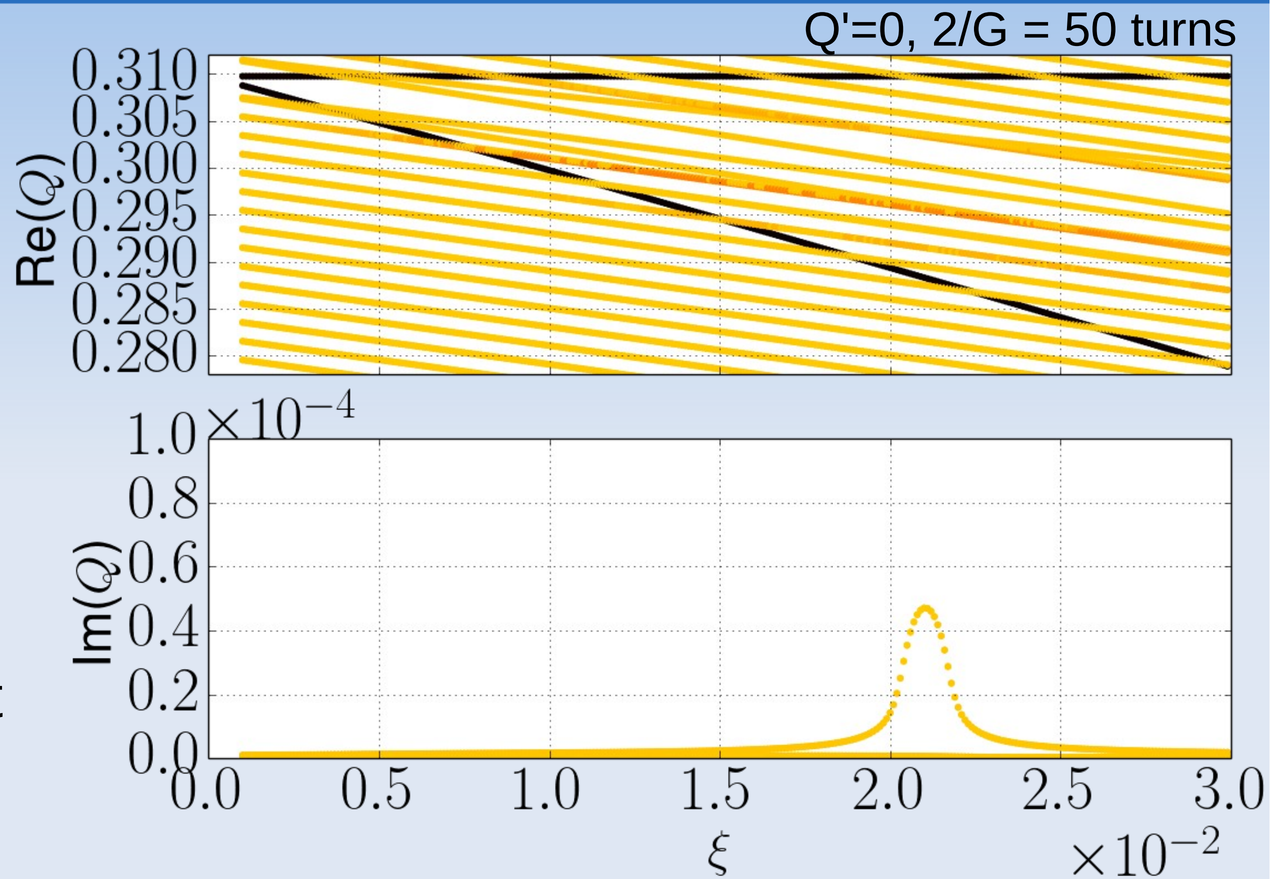

- A feedback based on the dipolar moment is no longer effective

→ Effect of Landau damping needs to be quantified

Baseline

- Thanks to the crab cavities, the crossing angle has no impact on the head-on interaction
  → Synchrobetatron coupling due to the low β* (20 cm) is fairly weak

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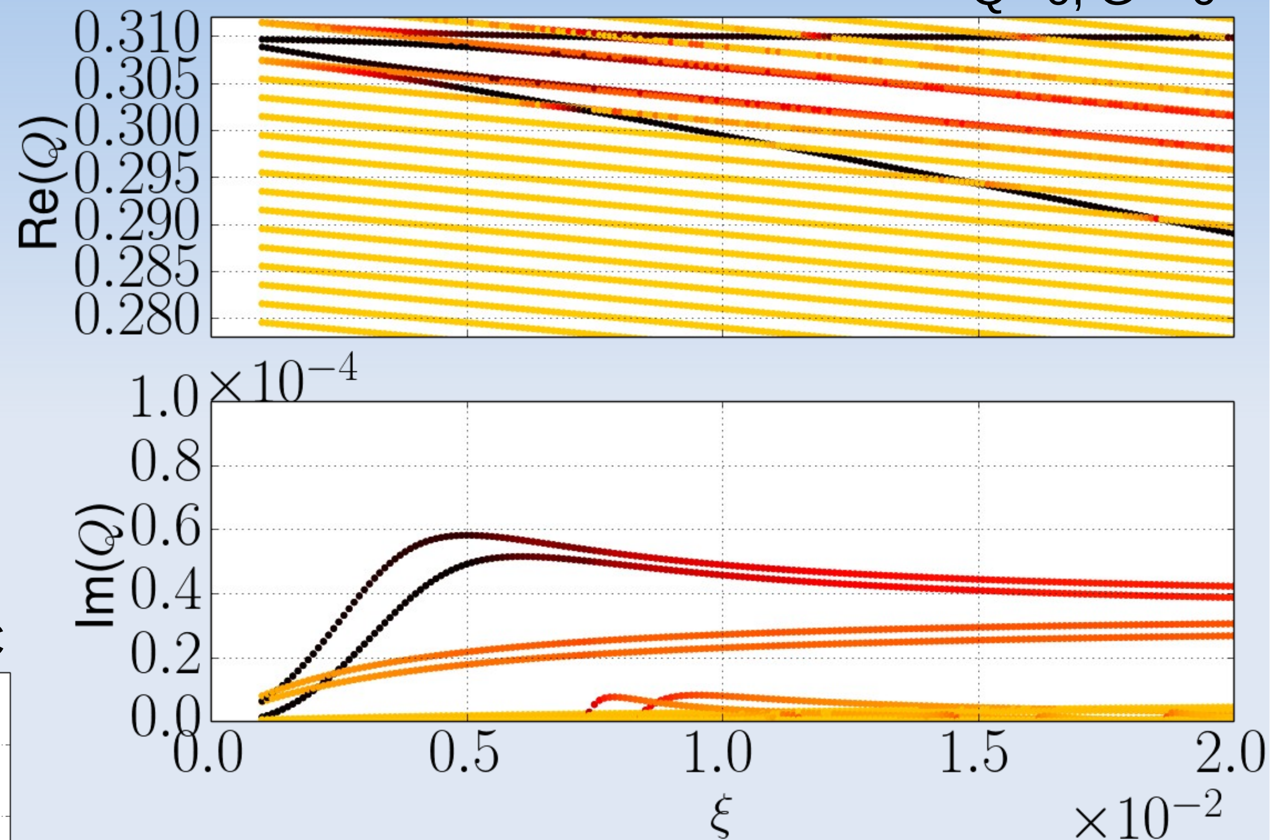
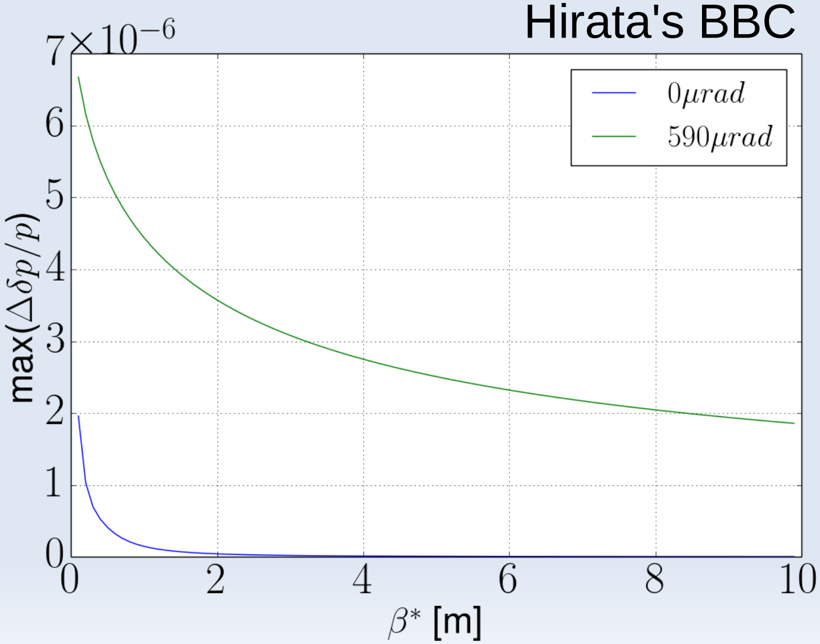


Hirata's BBC



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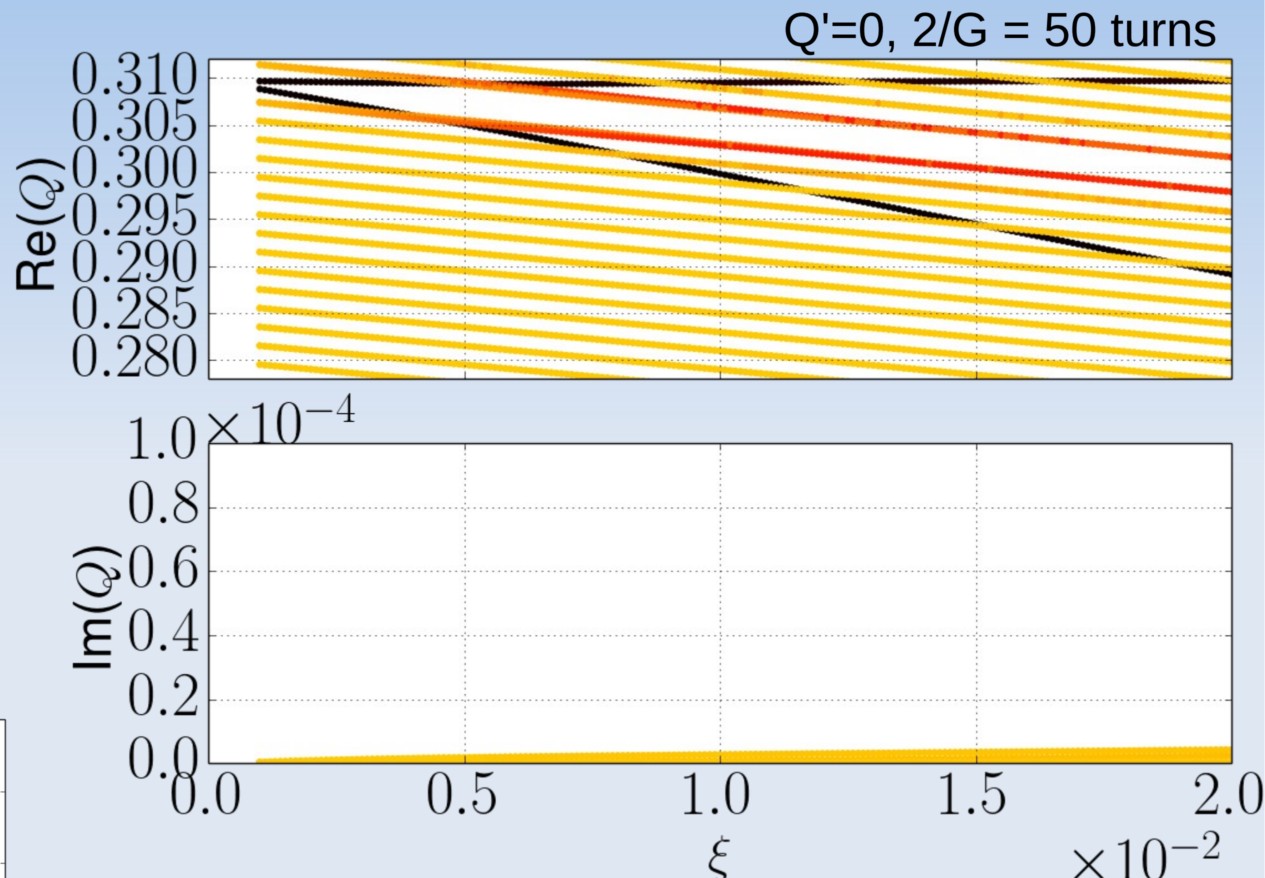
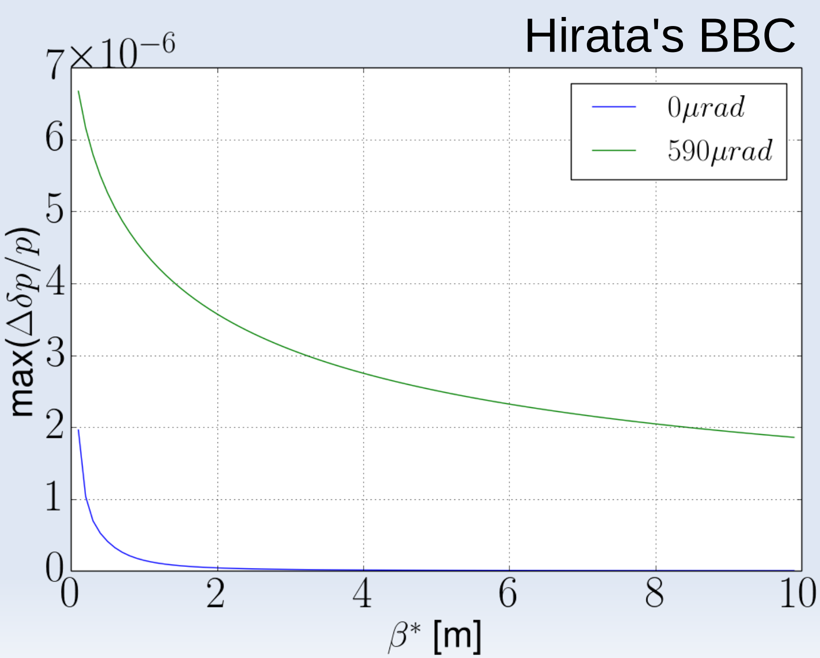
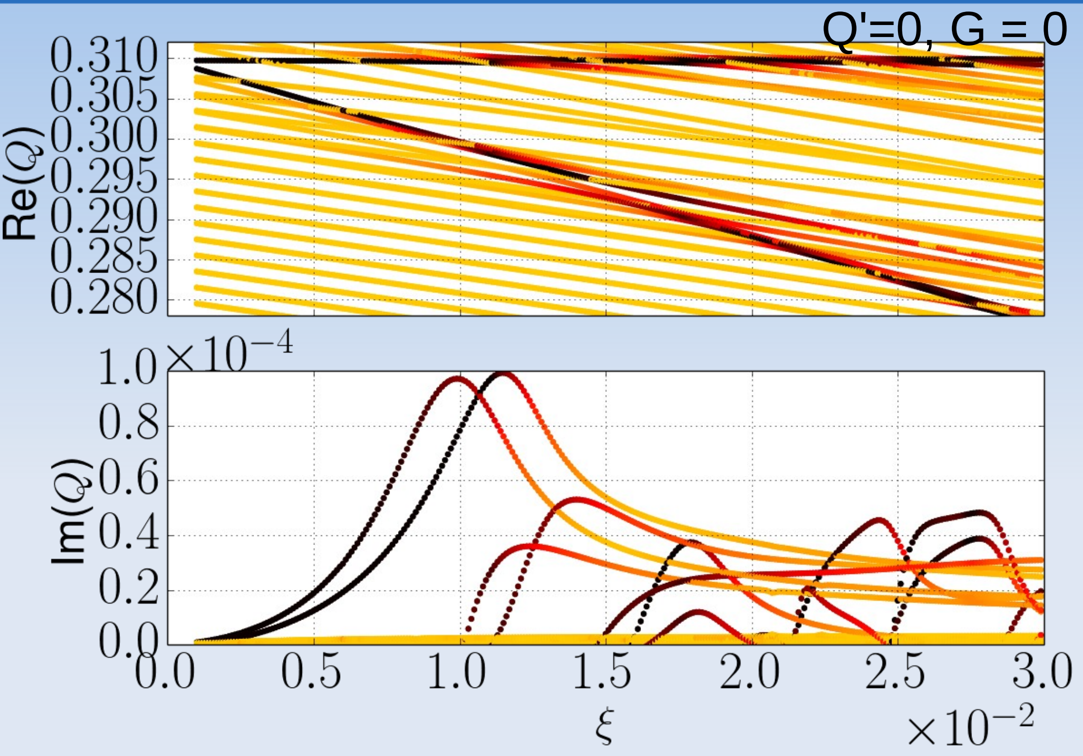




→ The transverse feedback is effective against the mode coupling instabilities (for any positive chromaticity)

HL-LHC without crab-cavity



- β*=0.2 m, full Xing angle 510μrad → 12.5 σ normalised beam-beam separation
- Without full crabbing scheme, large crossing angles lead to strong synchrobetatron coupling

  → Potential issue with coupled high order head-tail modes has to be addressed with tracking simulations

  - Small crossing angles are favorable for this type of instabilities

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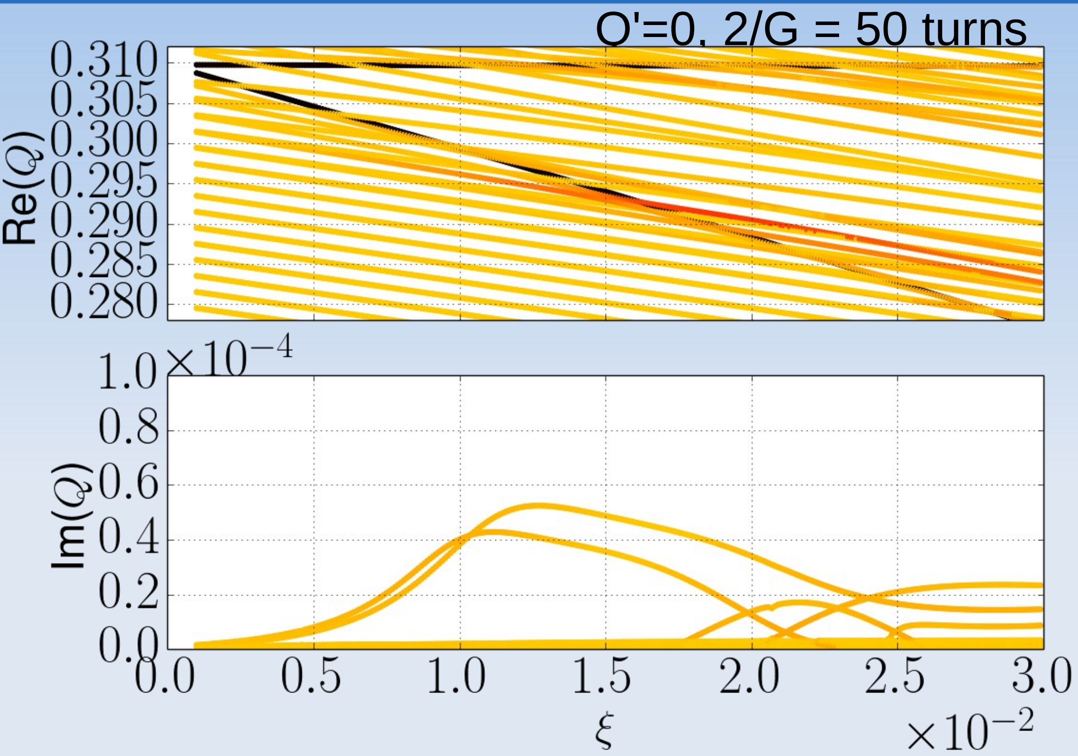

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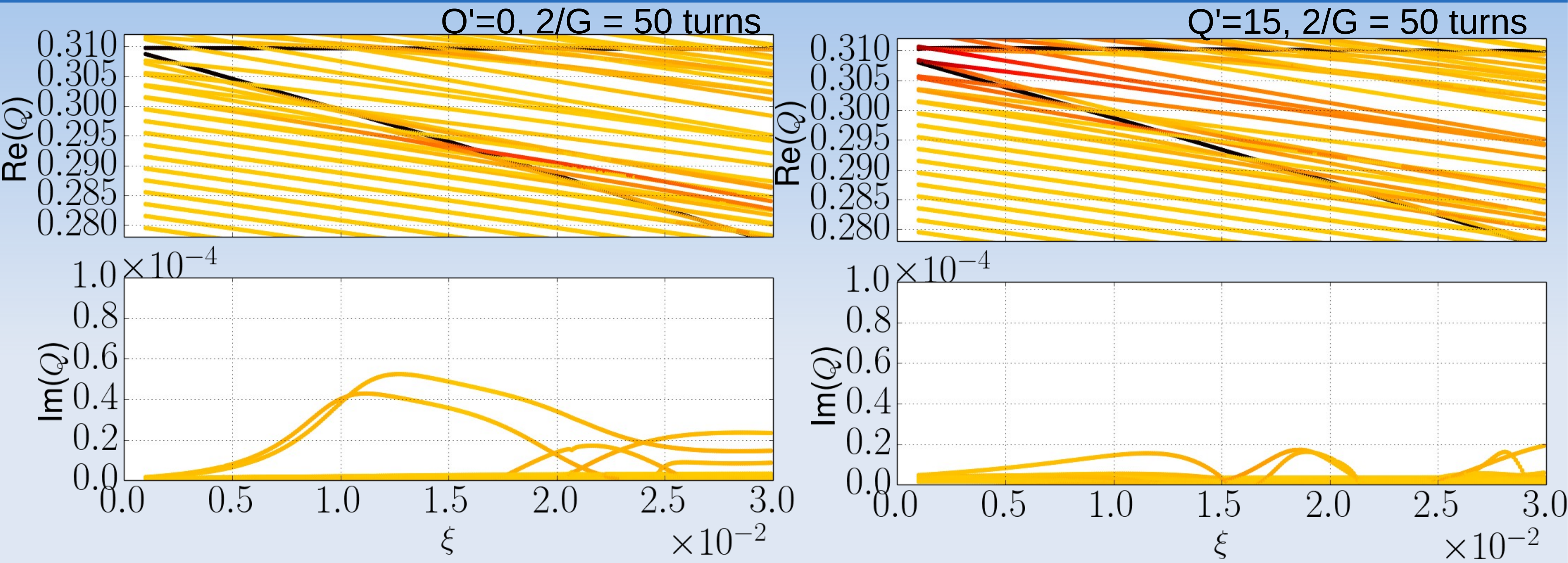

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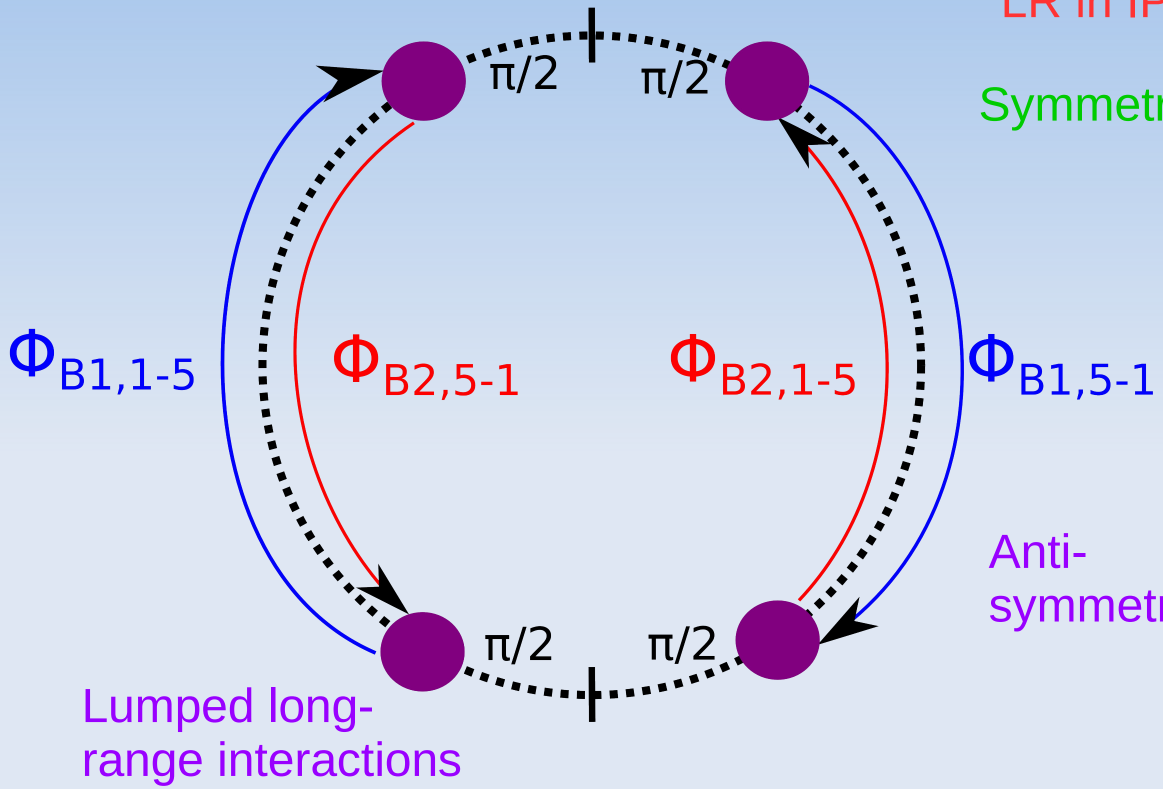
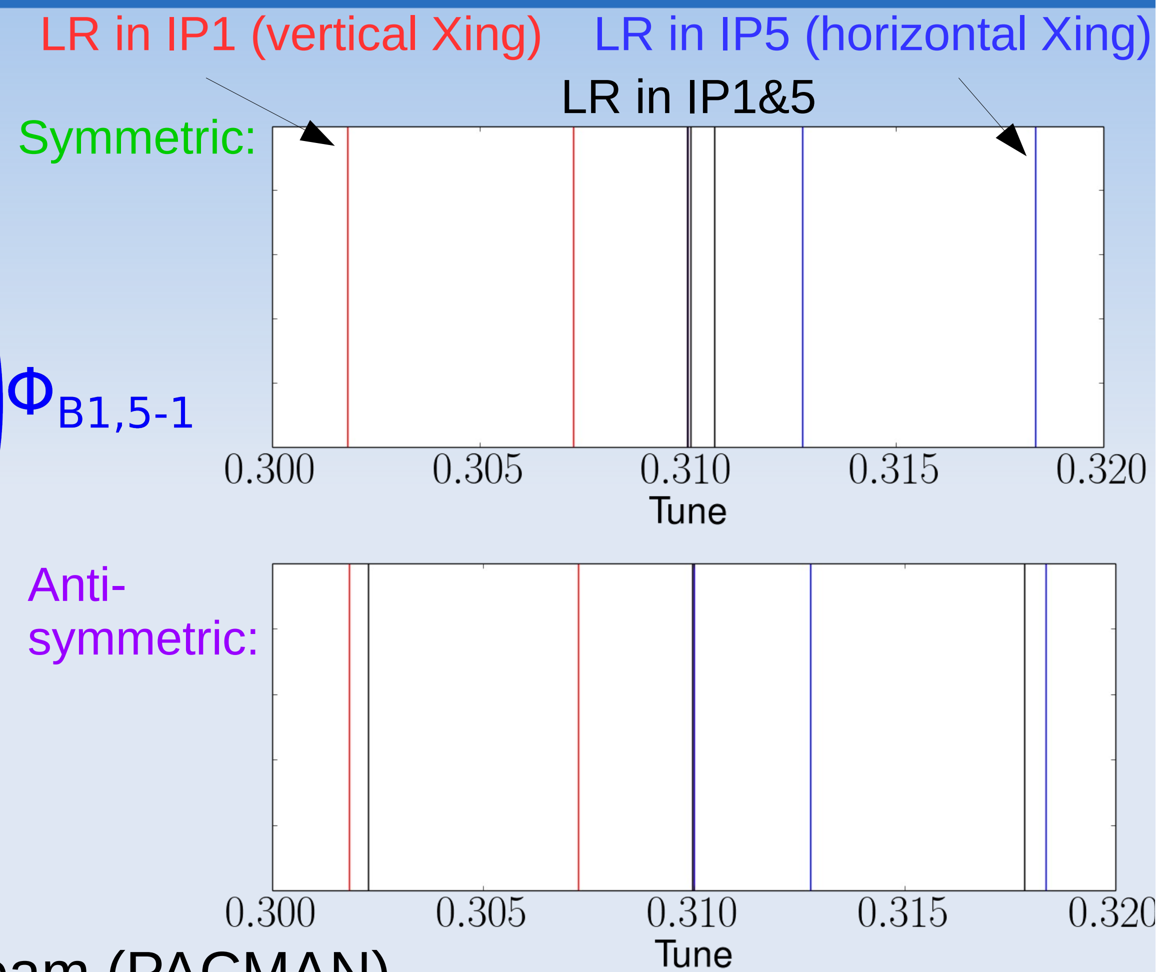
Long-range coherent beam-beam modes



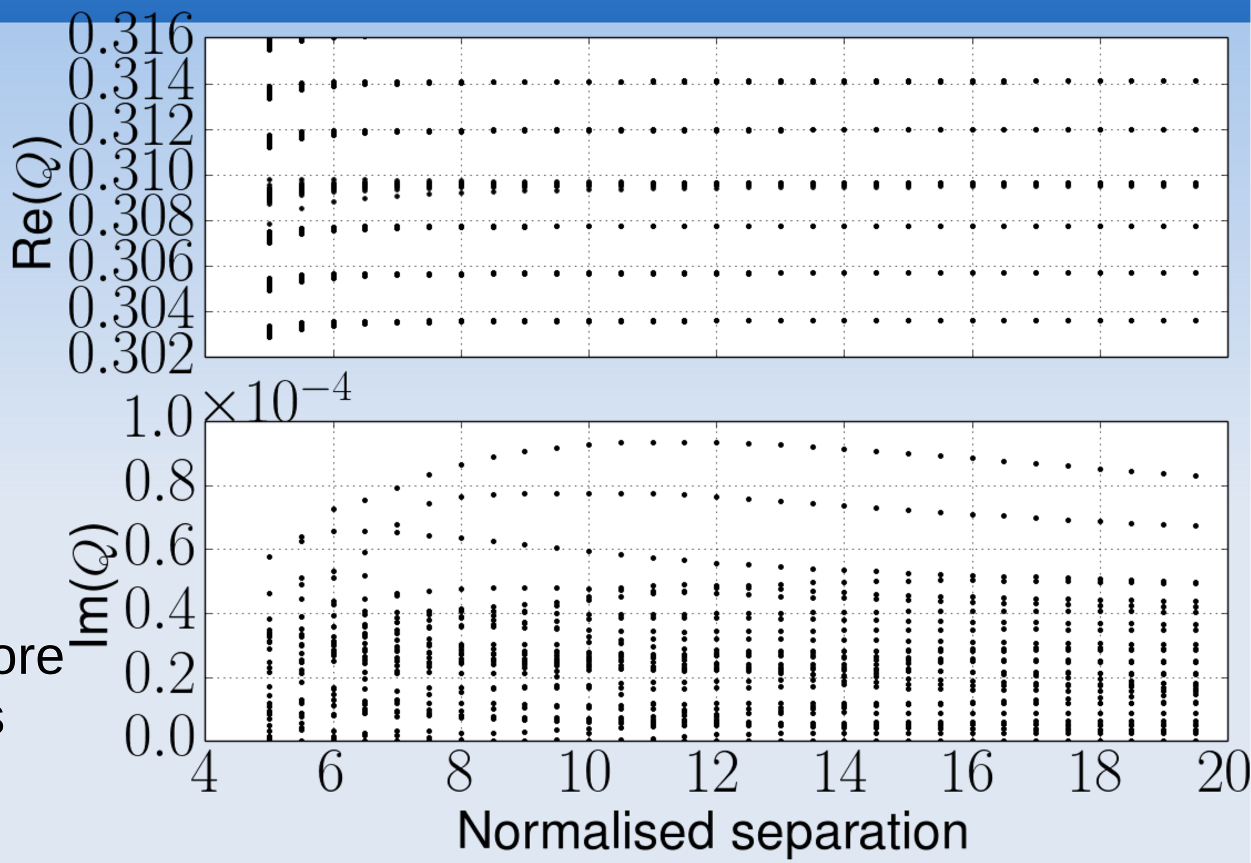


- 1 bunch train of 3 bunches per beam (PACMAN)
- Passive compensation of the tune shift due to long-range interactions for symmetric configuration

  → Broken for the coherent modes in anti-symmetric configurations, but not for the single particles (i.e. the coherent modes are outside of the incoherent spectrum)

Long-range coherent beam-beam modes

- 36b model (long-range interactions are not lumped → proper modelling of PACMAN effect)
- In the baseline HL-LHC optics, the horizontal phase advances are close to a symmetric configurations
  - → weak shift of the coherent mode frequencies and therefore no mode coupling instabilities



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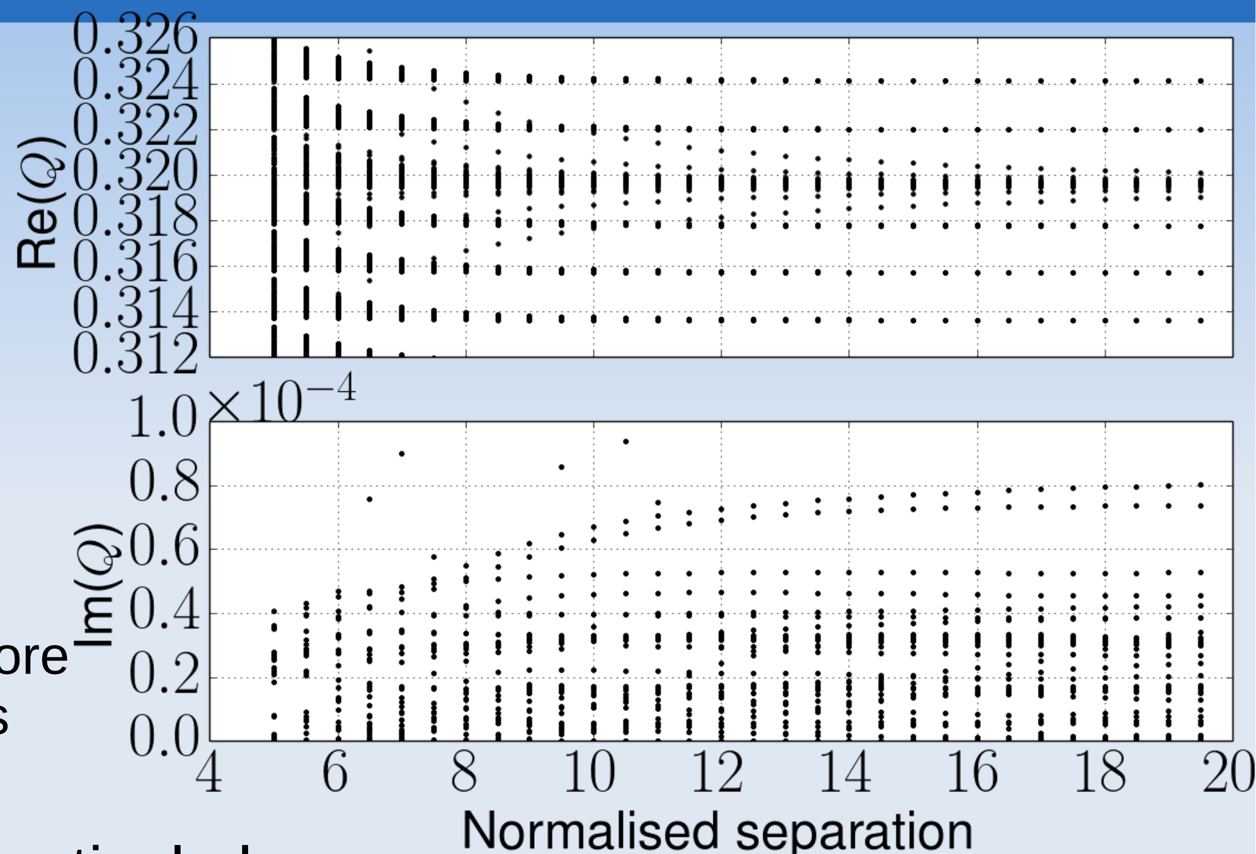


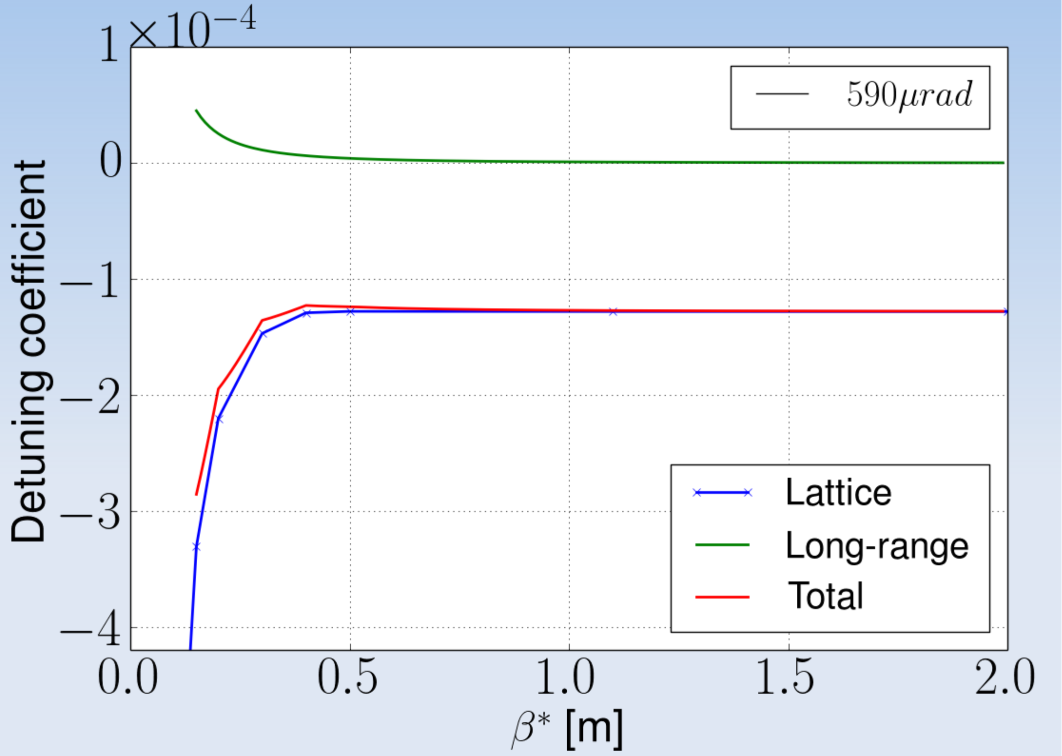
- The opposite is true in the vertical plane
- Long-range interactions do not induce synchrobetatron coupling
  - → the feedback is always effective
- Note : The coupled bunch instability is naturally damped at low separation, since PACMAN bunches are detuned with respect to the other bunches

Stability diagram during the squeeze

- Simple model :

$$Q_x = Q_{0,x} + a \cdot J_x + b \cdot J_y$$

$$a_{LR} \approx \frac{3}{2} \frac{N_{LR} \cdot \xi}{d^4} \quad \left(\xi = \frac{r_0 N}{4 \pi \epsilon}, d = \sqrt{\frac{\beta^* \gamma}{\epsilon}} \right)$$



- Lattice detuning coefficient from MAD-X (sextupoles + octupoles at LOF at -550A)
- The total detuning coefficient due to the effect of the octupoles and of the long-range beam-beam interactions only increases during the squeeze with the baseline parameters

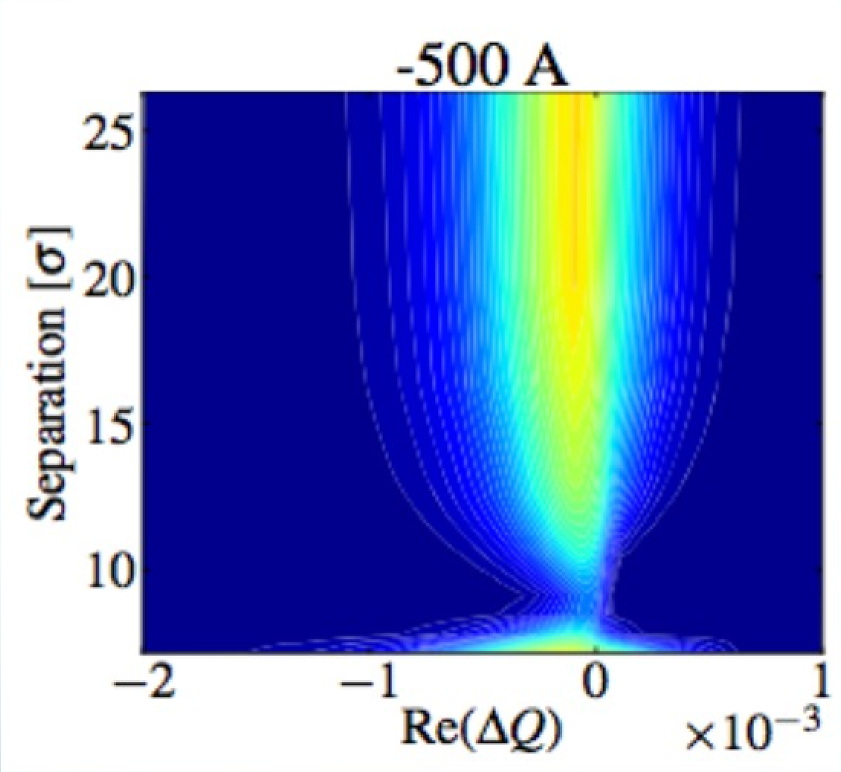
Stability diagram during the squeeze

HL-LHC vs LHC

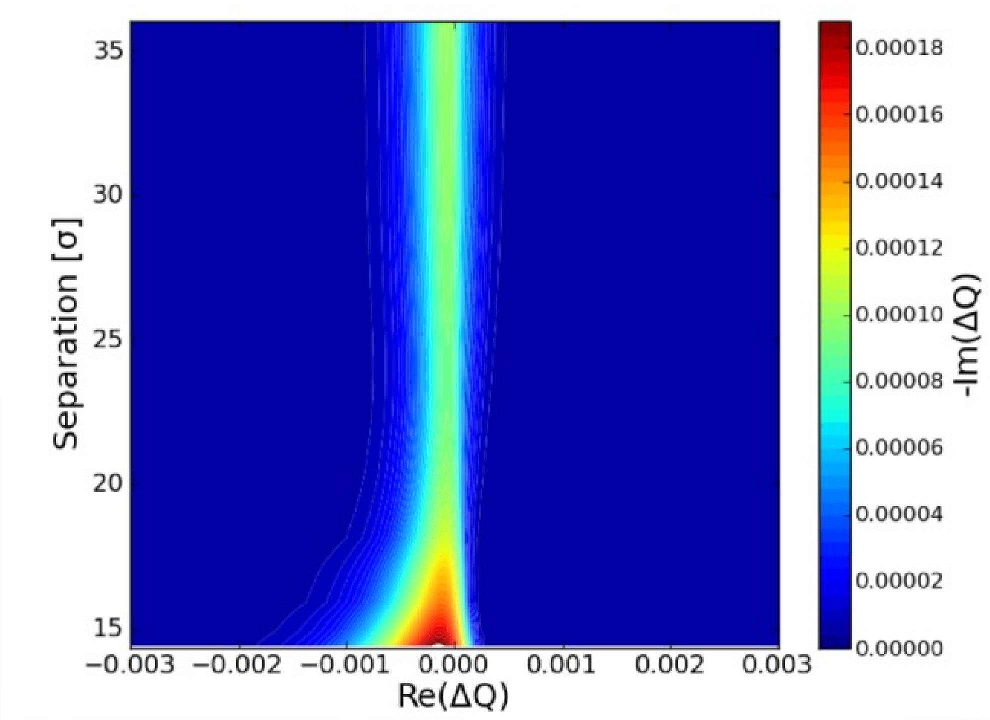
C. Tambasco, et al,
@ WP2 meeting
27.03.2015

Evolution of the betatron squeeze with LR beam beam

LR beam-beam in IP1 and IP5



Negative LOF



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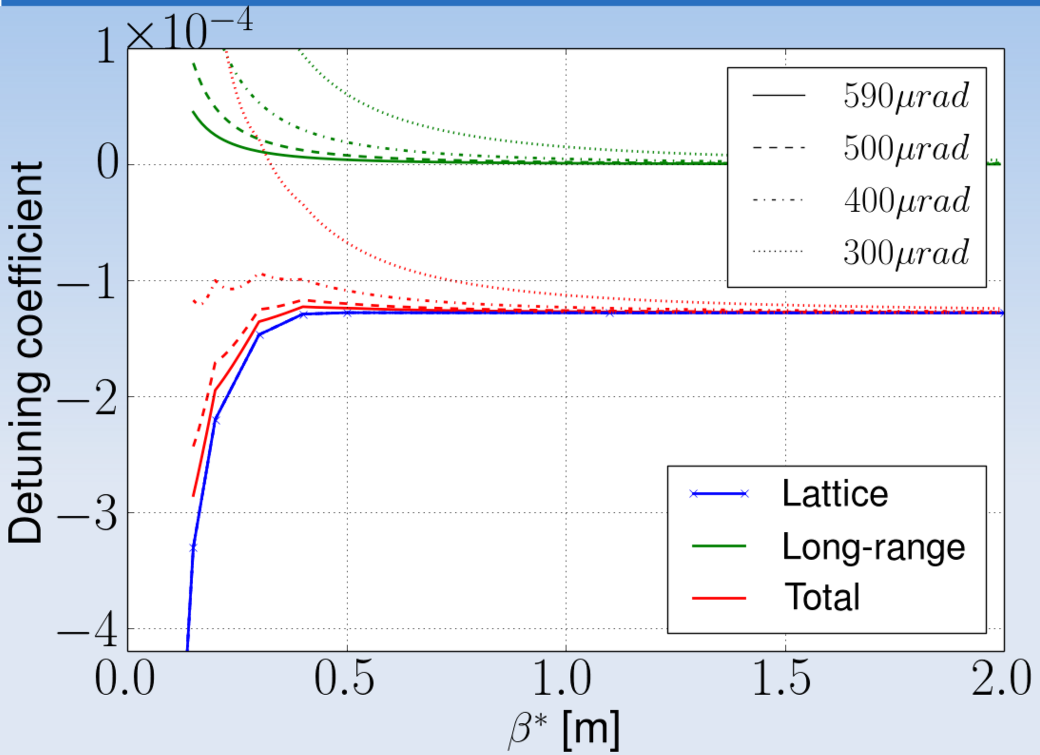

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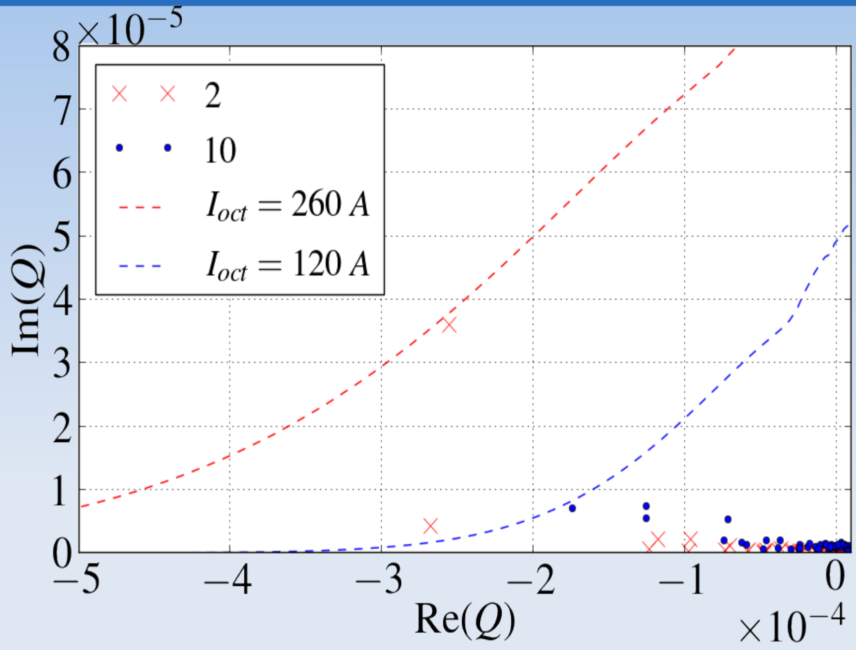
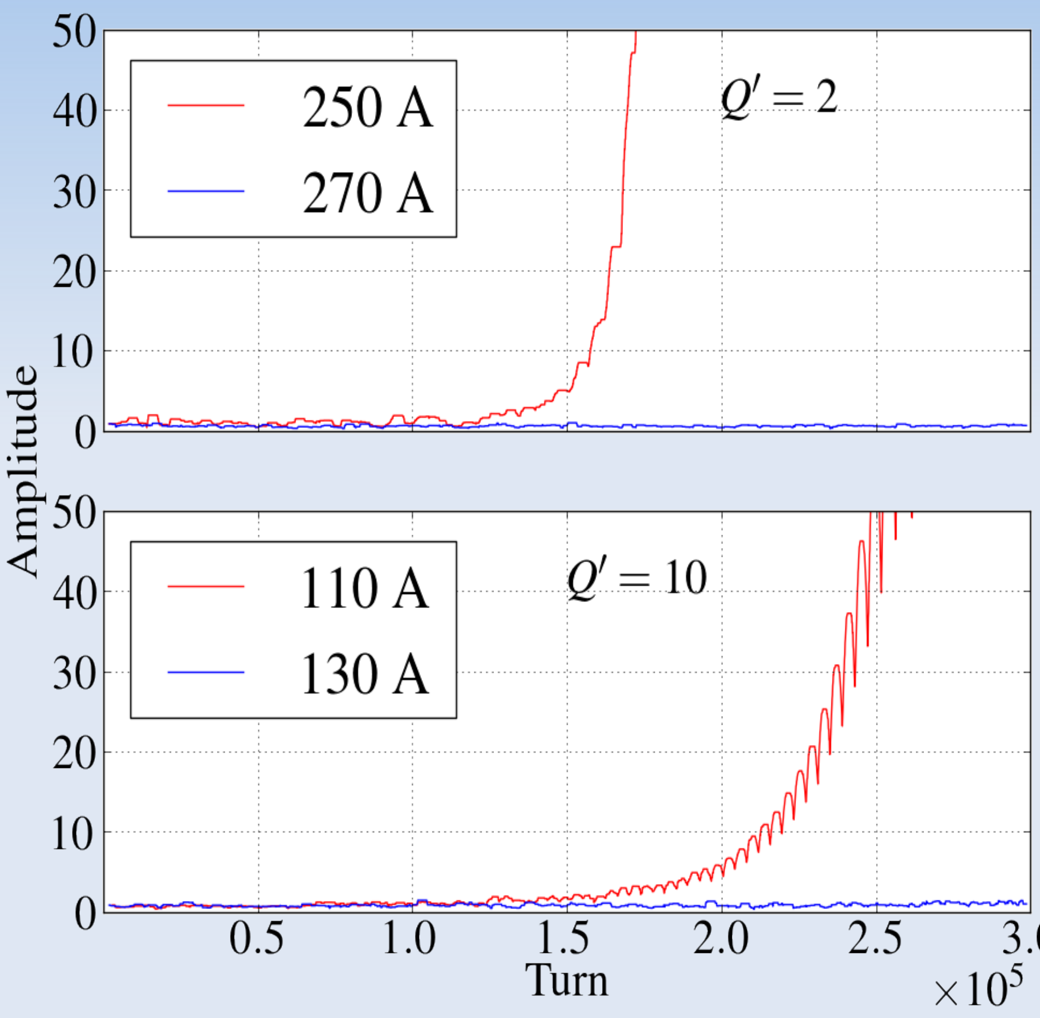
- The total detuning coefficient due to the effect of the octupoles and of the long-range beam-beam interactions only increases during the squeeze with the baseline parameters
  - Reducing the crossing angle can lead to a deterioration about the 50cm, where the squeeze starts

    → Start the change of the arc β earlier in the presqueeze

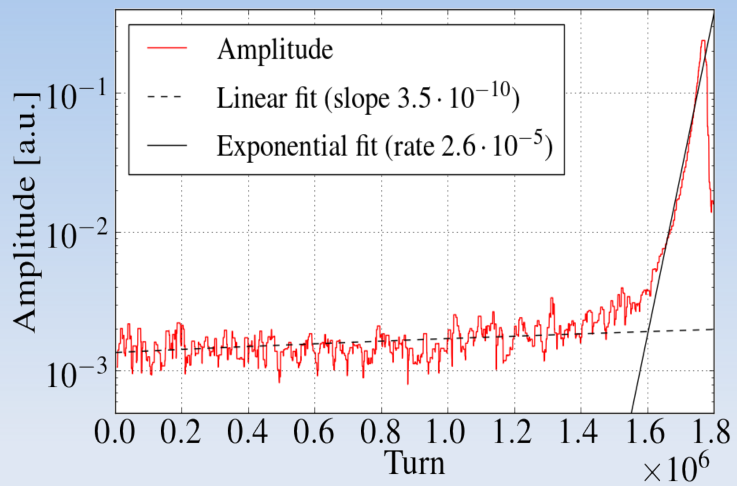
Distorted distributions
An example





- Single bunch (Intensity 1.5E11/ emittance 2E-6)
- Enhanced impedance (2x)
- Chromaticity : 10.0
- Damper gain : 2E-2 (i.e. 100 turns)
- Octupole : 120 A required for stability
- 2E6 macro particles, 100 slices

Distorted distributions
An example



- 300 A in the octupoles (2.5 time more than required)
- The beams becomes unstable after a latency
- During the latency, the diffusion is enhanced in parts of the action space

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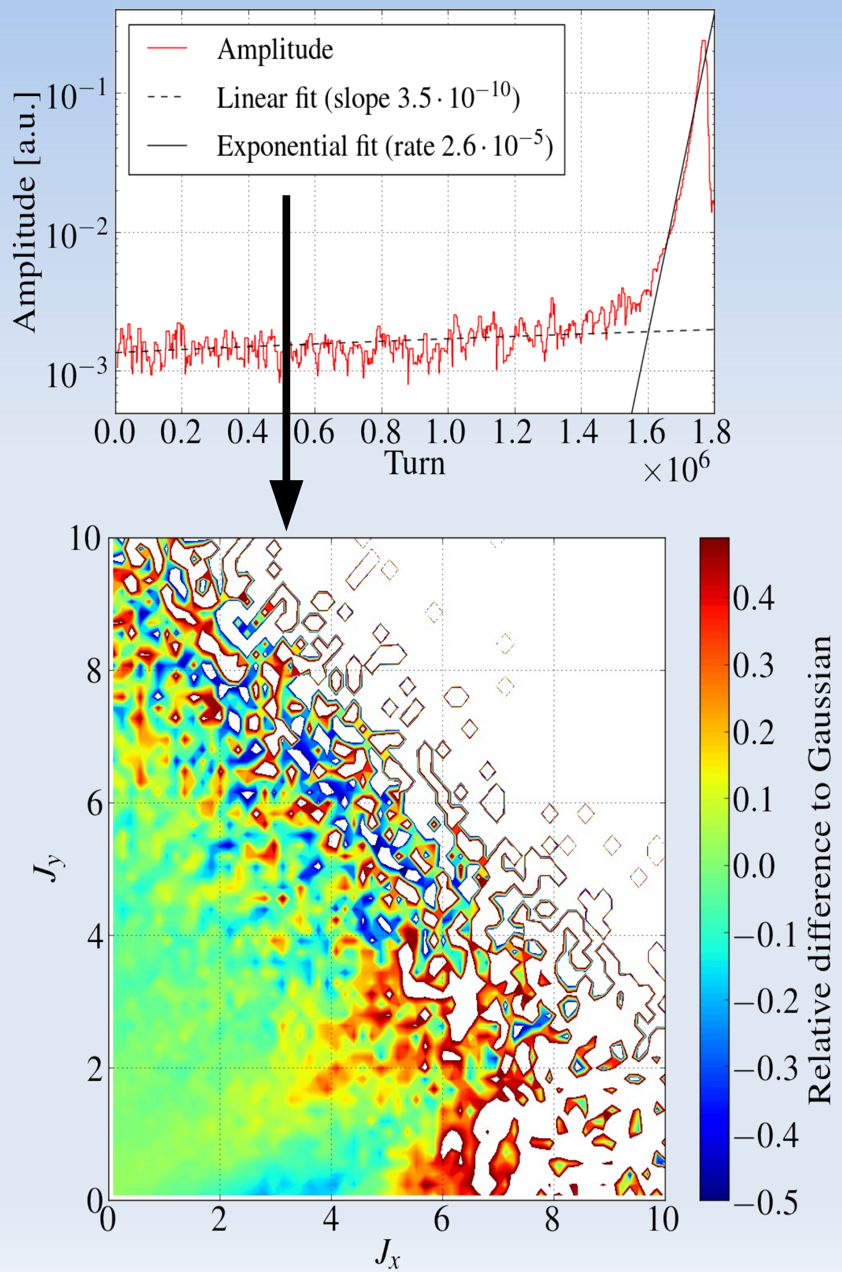

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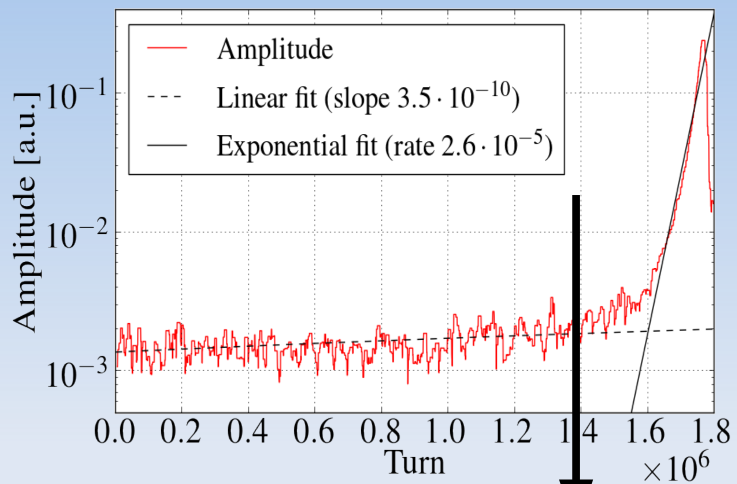
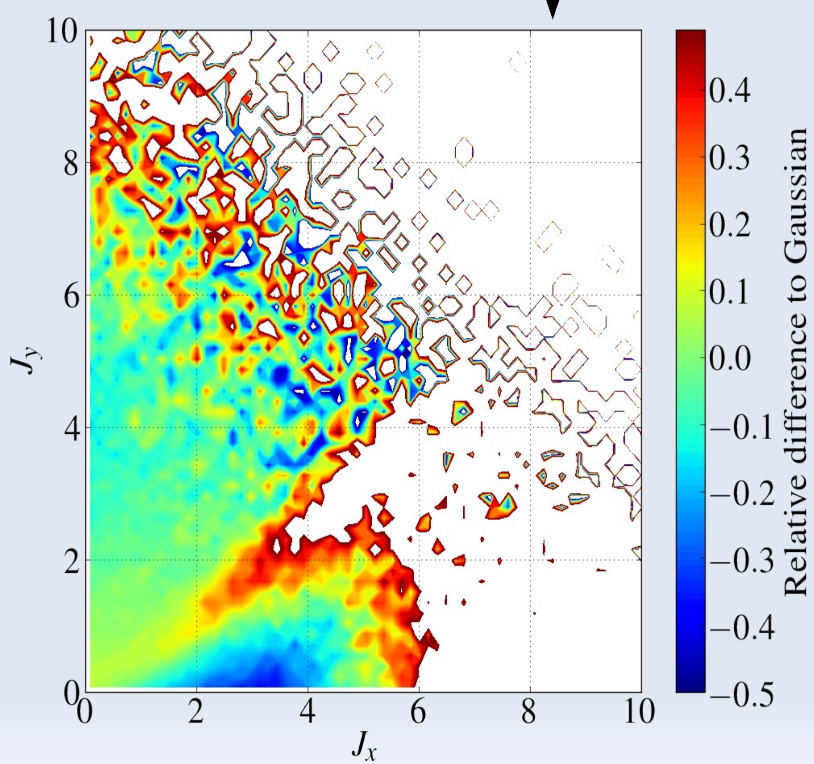
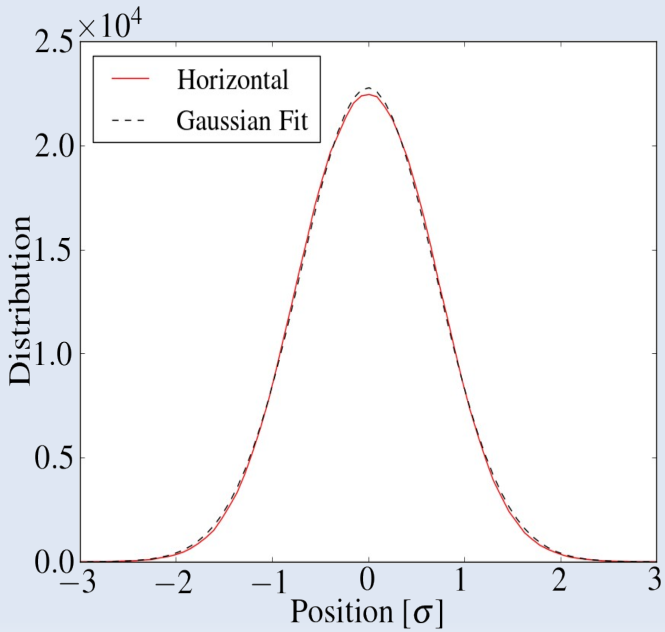
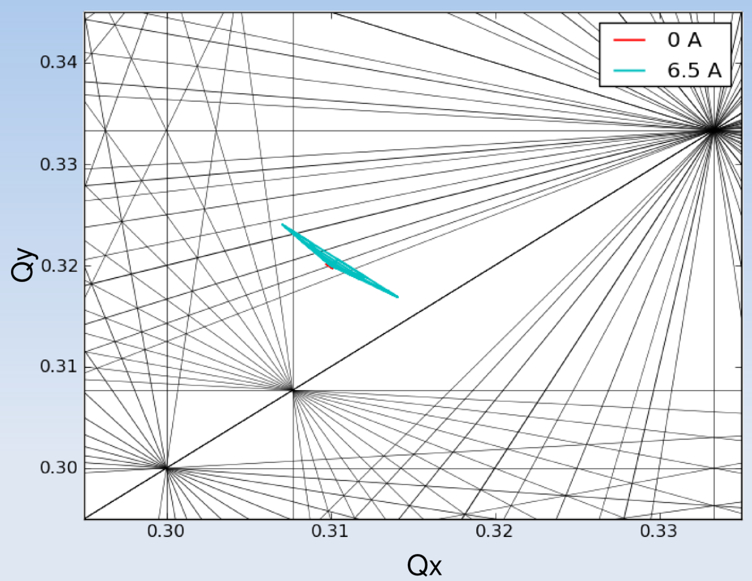


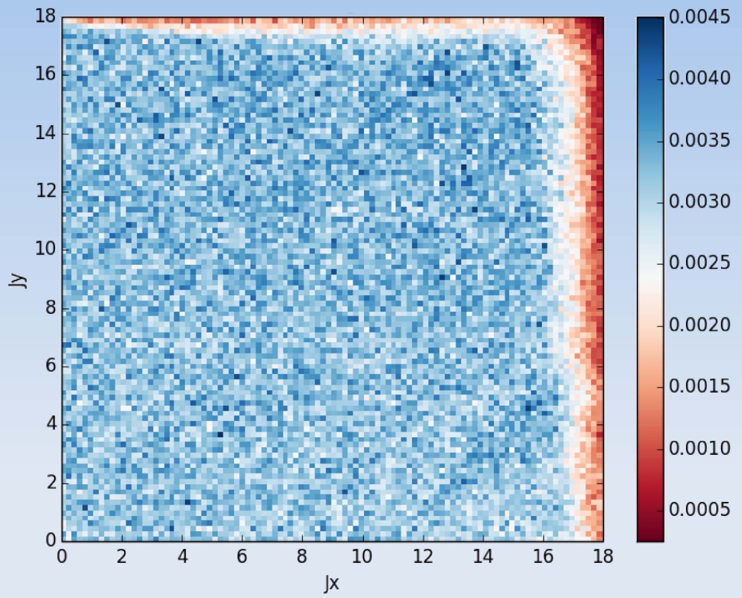
- Large effect in action space
- Small effect in real space → Difficult to measure in the transverse profiles





Distortion of the distribution due to a dynamic aperture restriction





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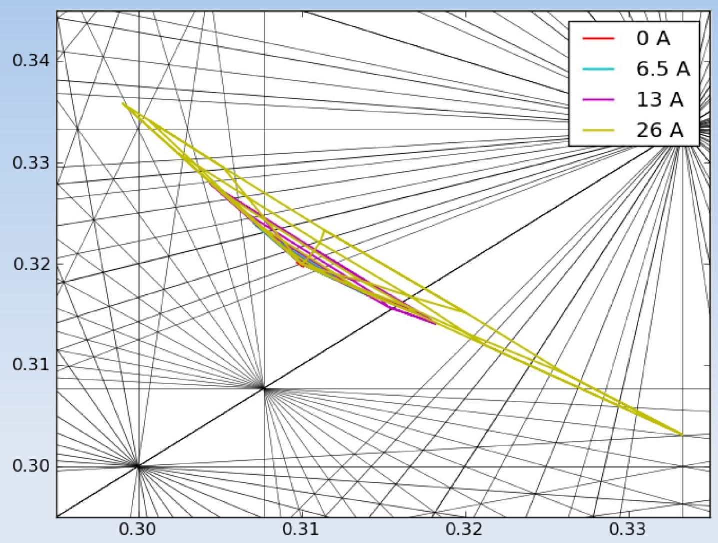

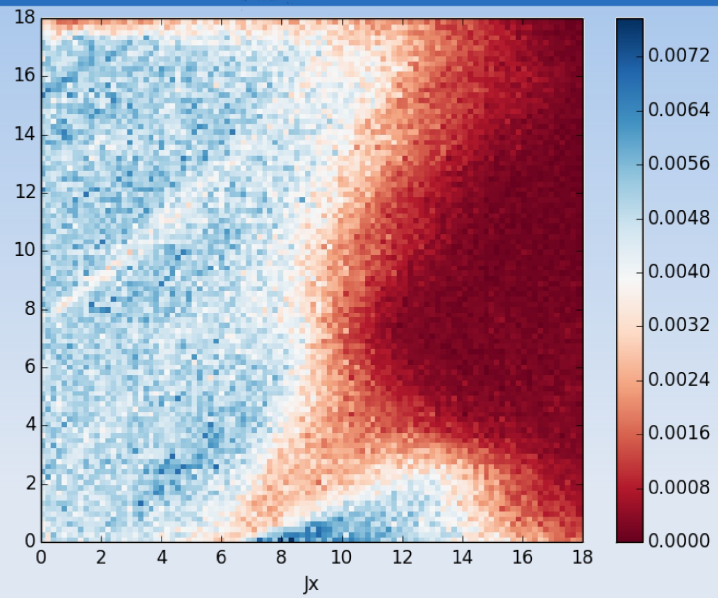

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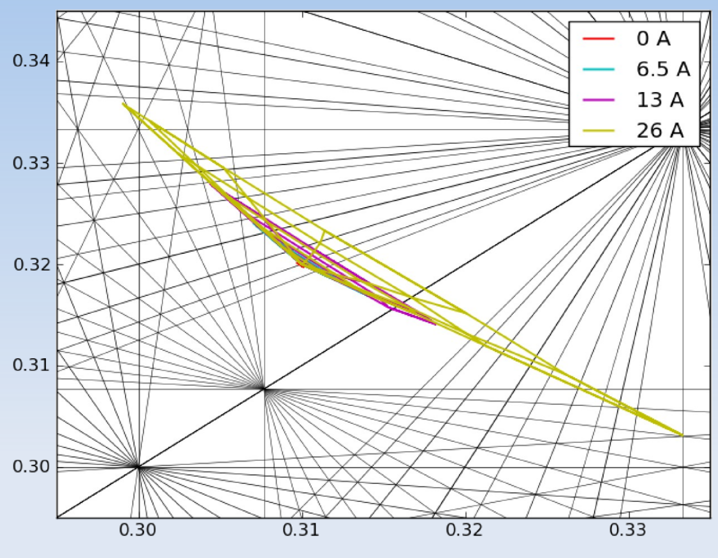

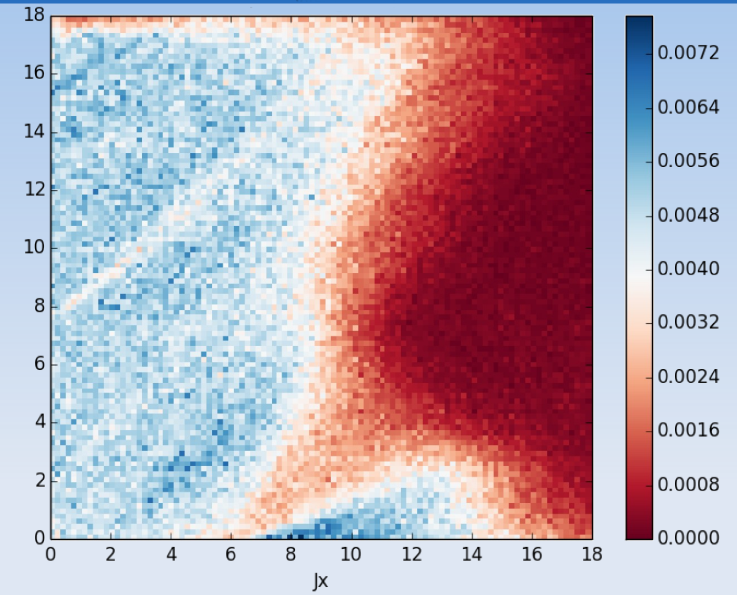

$$\frac{-1}{\Delta Q_x} = \iint_0^{\infty} \frac{J_x \frac{d\Psi_x(J_x, J_y)}{dJ_x}}{Q - q_x(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

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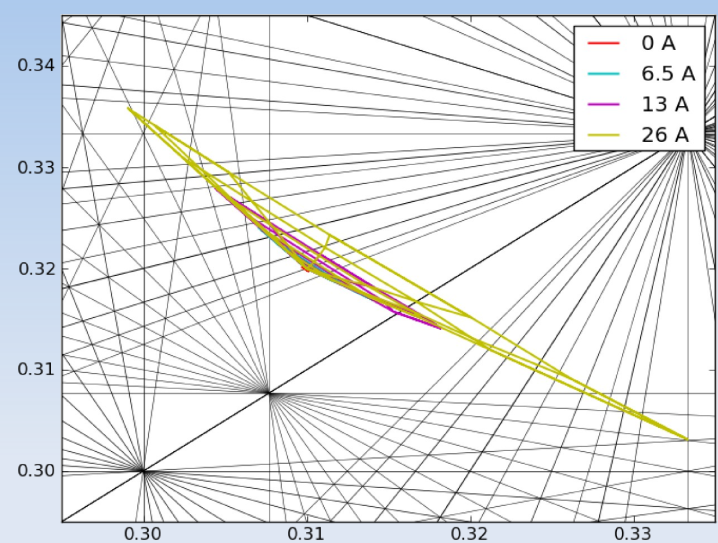
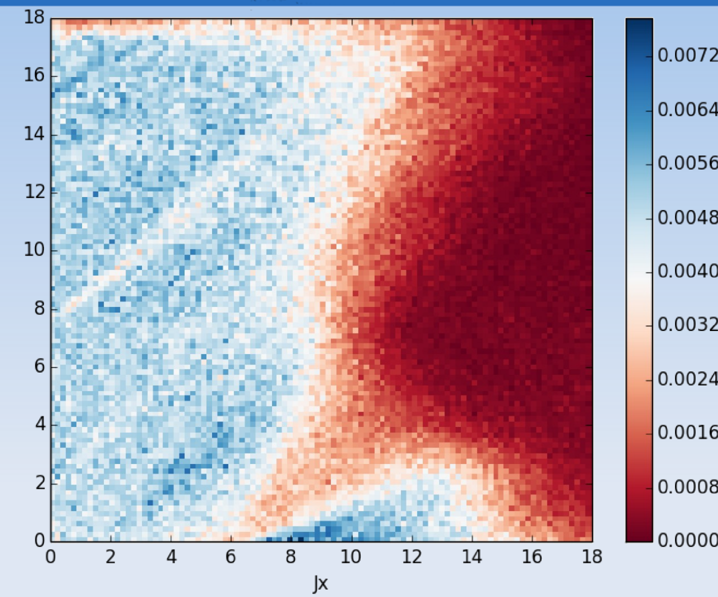
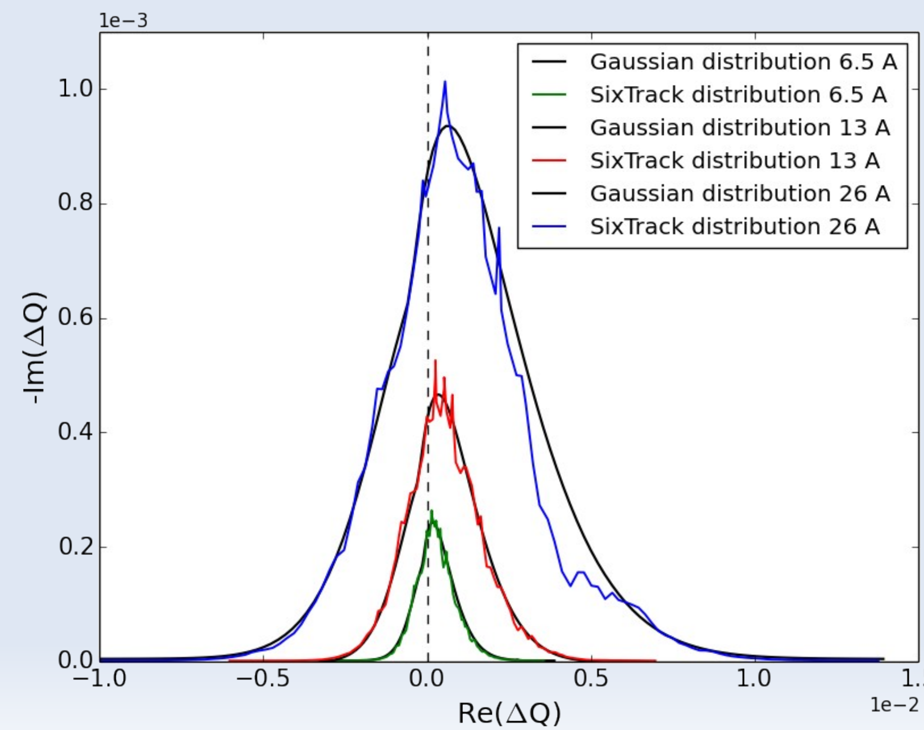


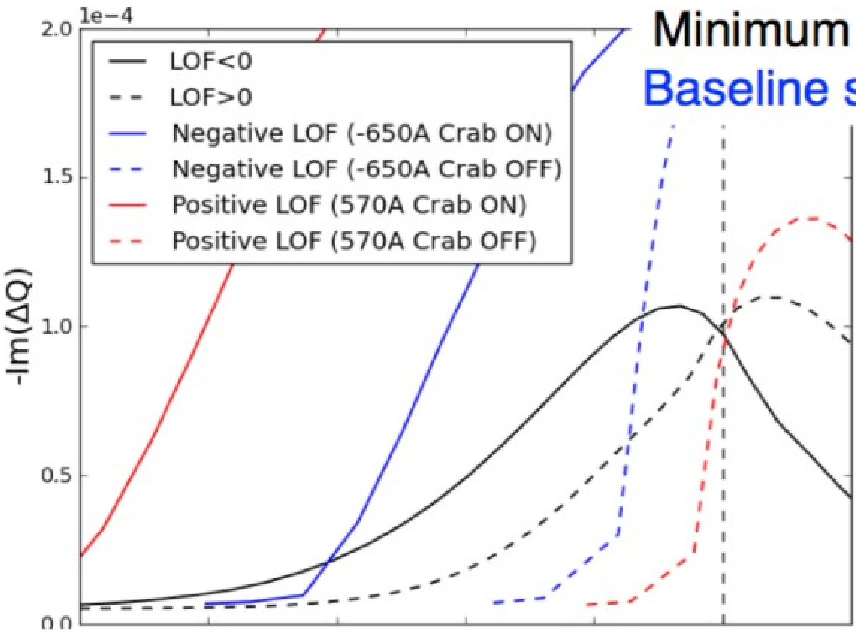


- The stability diagram is evaluated based on the distribution obtained after 10^6 turns with sixtrack → i.e. including diffusion due to non-linearities
- The hole in the distribution lead to a hole in the stability diagram, possibly leading to loss of Landau damping
  - Resonances affecting the core can have a stronger impact on the stability diagram

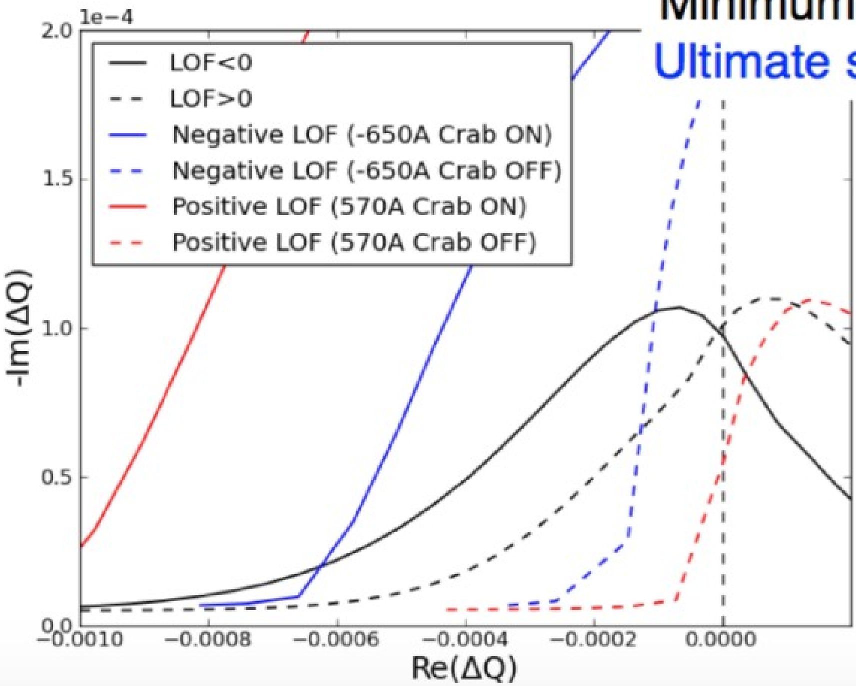


Reduction at 1.5σ during collapse

Minimum at 1.5σ
Baseline scenario



Minimum at 1.5σ
Ultimate scenario



SD strongly reduction for both polarities of the Landau Octupoles

Larger reduction of SD for positive Landau octupoles polarity

Positive worst than negative polarity

C. Tambasco, et al, @ WP2 meeting 19.04.2016

A minimum of stability diagram can not be avoided

- A reduced crossing angle increases the head-on tune spread

  → Improved stability in adjust and in collision

Conclusion

- Mode coupling instabilities are well mitigated by the feedback in absence of synchrobetatron coupling
  - Strong synchrobetatron coupling due to head-on collision with a large crossing angle may lead to coupling instabilities of high order head-tail modes which are not damped by the feedback → further studies required

    → Not an issue in the presence of a full crabbing scheme
  - Long-range interactions do not contribute to synchrobetatron coupling → no issues expected in the presence of the transverse feedback
- Stability diagrams of head-tail mode are not deteriorated during the squeeze, thanks to the increase of the β at the octupoles location
  - With a reduced crossing angle, the change of β could be shifted earlier in the presqueeze to compensate the increase of the long-range beam-beam forces
  - Sufficient DA is required to ensure that the distribution (and therefore the stability diagram) is not deteriorated
- Small crossing angles are favourable for Landau damping during adjust and while colliding due to the larger tune spread from head-on interactions