Impact of coherent and incoherent beam-beam on the beams stability

X. Buffat

Acknowledgments : L. Barraud, S. Fartoukh, W. Herr, N. Mounet, E. Métral, T. Persson, T. Pieloni*, A. Ribes Metidieri, B. Salvant, C. Tambasco*, R. Tomas, S.M. White**

* EPFL ** ESRF The European Synchrotron

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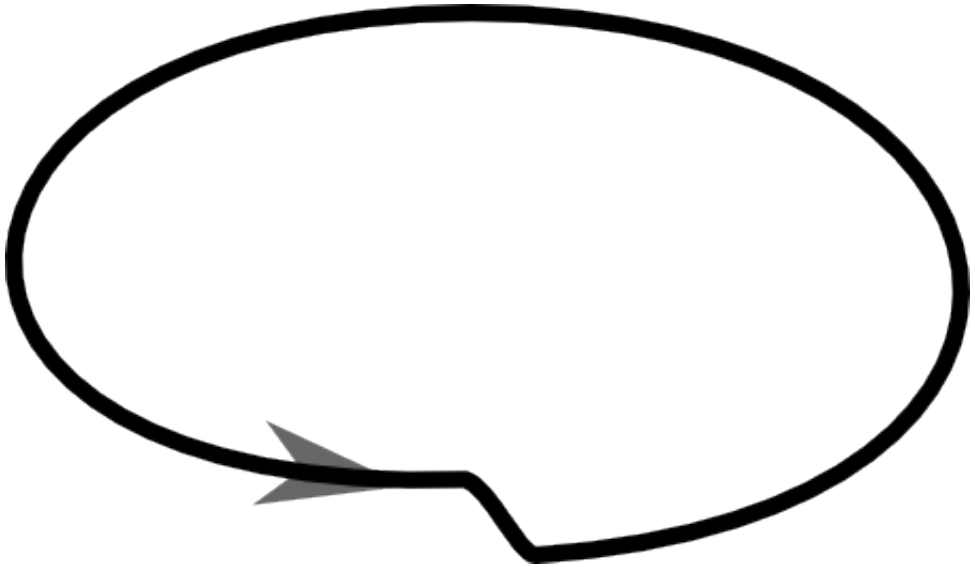
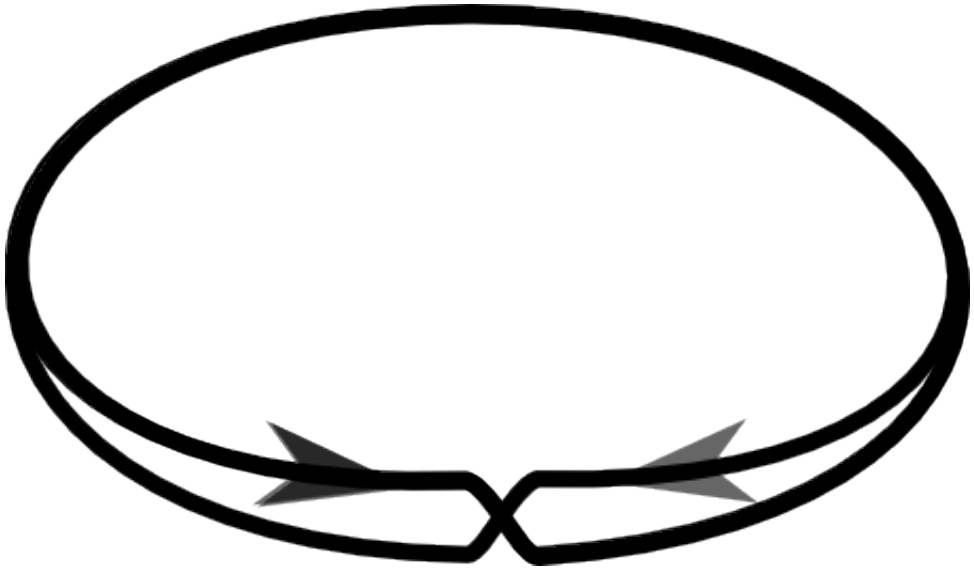
- Coherent beam-beam modes
  - Coherent resonance : The issue with asymmetric machines
  - The mode coupling instability of colliding beams
  - Longitudinal beam-beam mode : The Las Ketchup instability
- Amplitude detuning and Landau damping
  - Long-range
  - Offset and crossing angle : The Shakiri effect
  - Head-on interaction
- PACMAN linear coupling

Coherent beam-beam mode



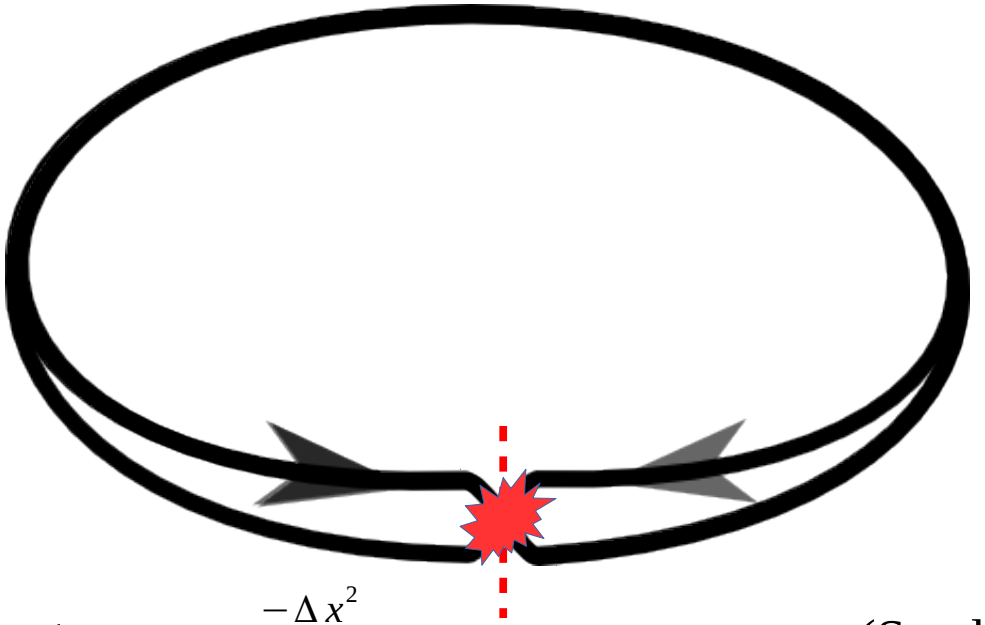
$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_{t+1} = \begin{pmatrix} \cos(2\pi Q) & \sin(2\pi Q) \\ -\sin(2\pi Q) & \cos(2\pi Q) \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_t$$

Coherent beam-beam mode



$$\begin{pmatrix} x_{B1} \\ x_{B1}' \\ x_{B2} \\ x_{B2}' \end{pmatrix}_{t+1} = \begin{pmatrix} \cos(2\pi Q) & \sin(2\pi Q) & 0 & 0 \\ -\sin(2\pi Q) & \cos(2\pi Q) & 0 & 0 \\ 0 & 0 & \cos(2\pi Q) & \sin(2\pi Q) \\ 0 & 0 & -\sin(2\pi Q) & \cos(2\pi Q) \end{pmatrix} \begin{pmatrix} x_{B1} \\ x_{B1}' \\ x_{B2} \\ x_{B2}' \end{pmatrix}_{t}$$

Coherent beam-beam mode

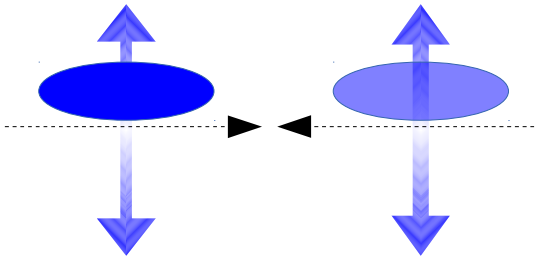


$$\Delta x'_{B1} = \frac{-2 r_0 N}{\gamma_r} \frac{1}{\Delta x} \left(1 - e^{\frac{-\Delta x^2}{4\sigma^2}}\right) \approx k \left(x_{B1} - x_{B2}\right)$$

(Small amplitude approximation)

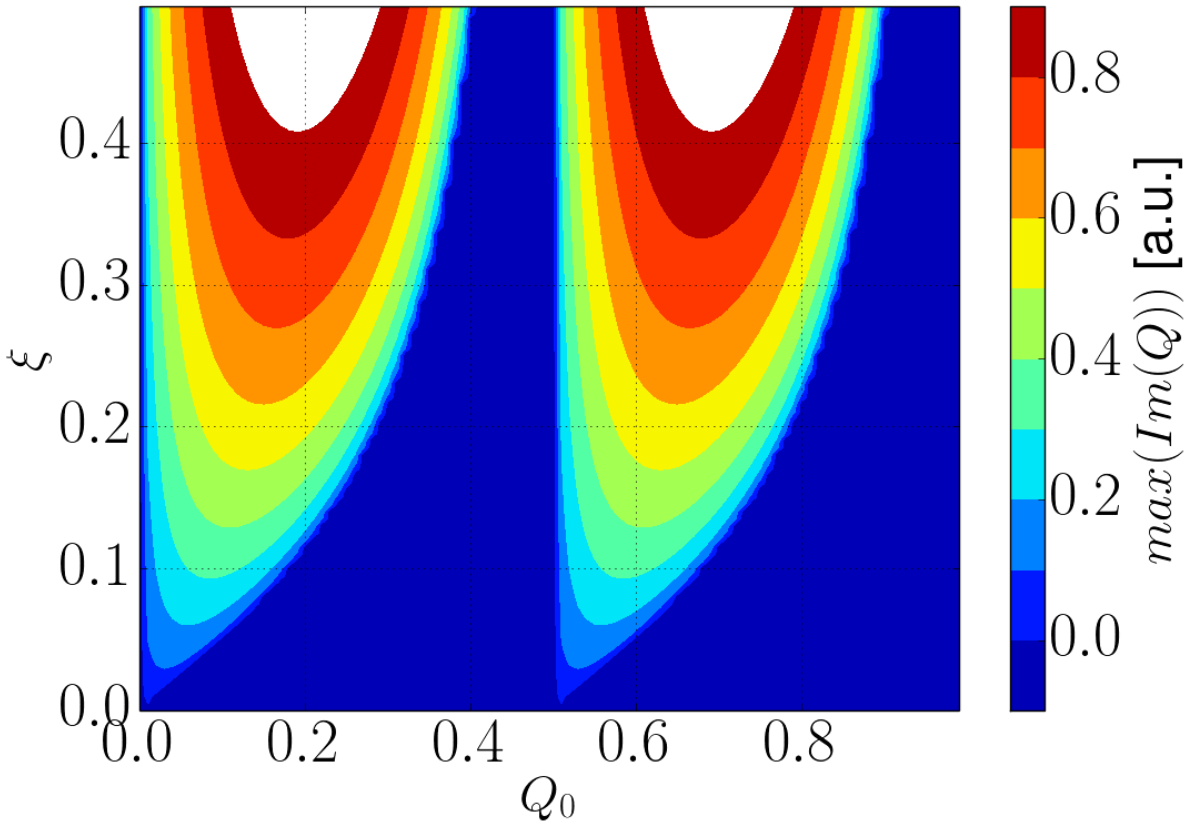
$$\begin{pmatrix} x_{B1} \\ x_{B1}' \\ x_{B2} \\ x_{B2}' \end{pmatrix}_{t+1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ +k & 1 & -k & 0 \\ 0 & 0 & 1 & 0 \\ -k & 0 & +k & 1 \end{pmatrix} \cdot M_{lattice} \begin{pmatrix} x_{B1} \\ x_{B1}' \\ x_{B2} \\ x_{B2}' \end{pmatrix}_{t}$$

Coherent beam-beam modes



$Q_\sigma = n/2$

$$\begin{pmatrix} x_i \\ x_i' \end{pmatrix}_{t+1} = M_{lattice} \cdot M_{BB} \begin{pmatrix} x_i \\ x_i' \end{pmatrix}_t$$



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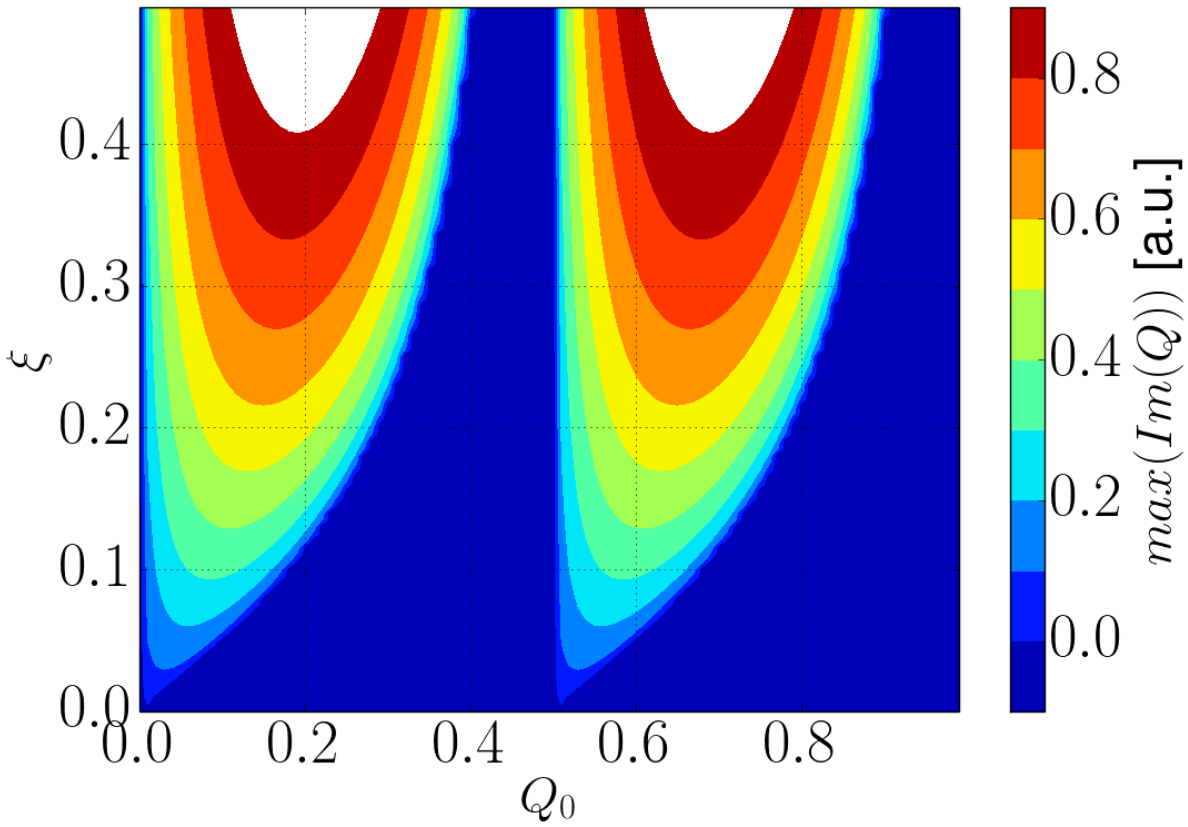

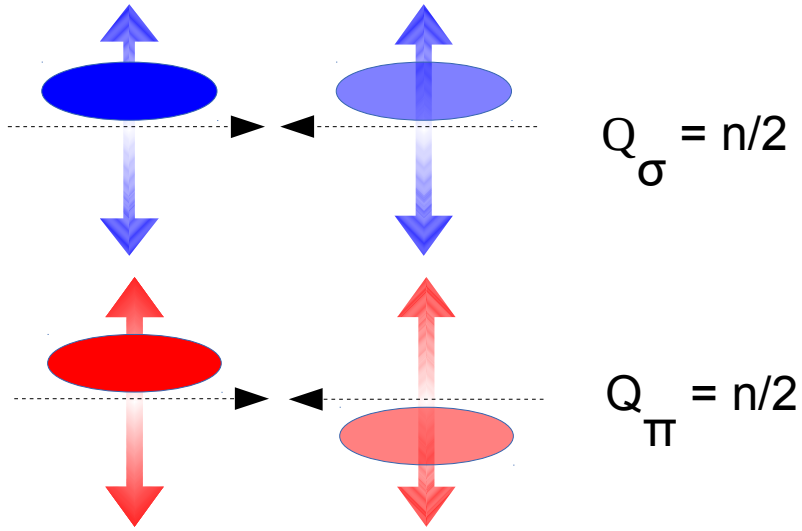

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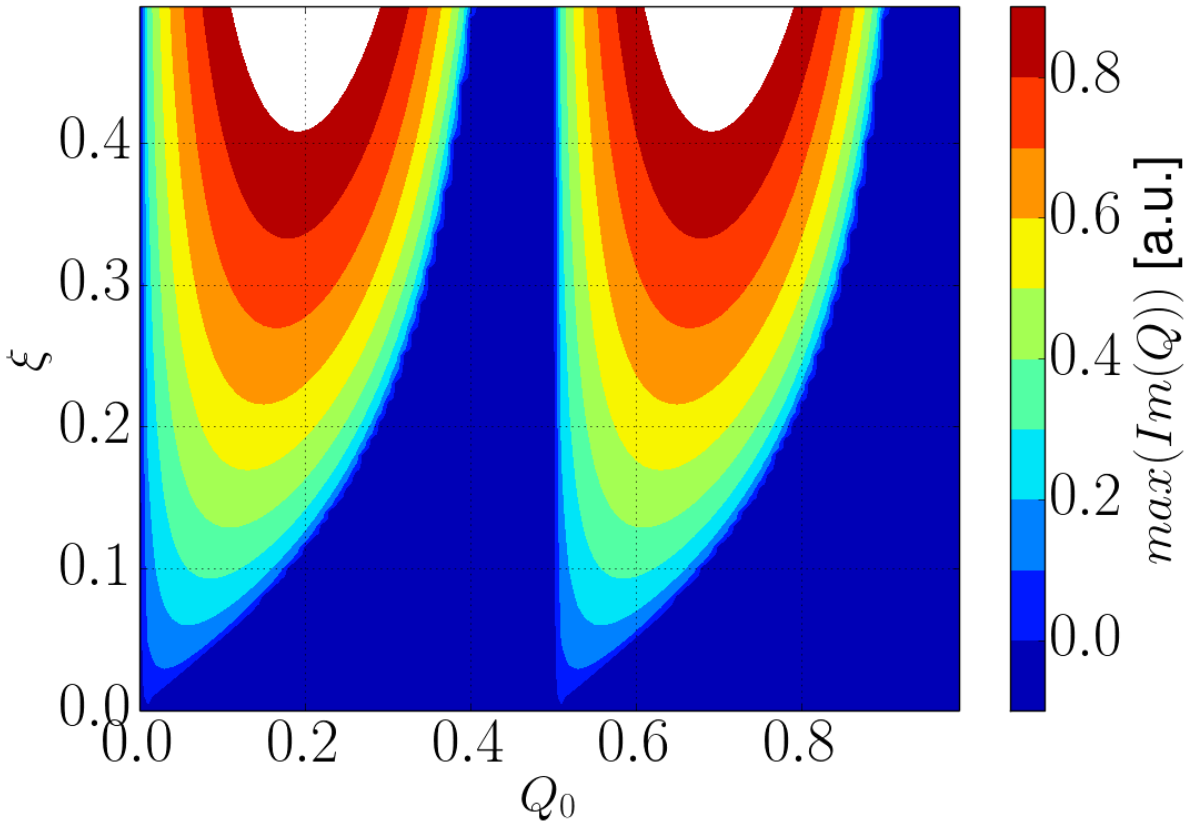

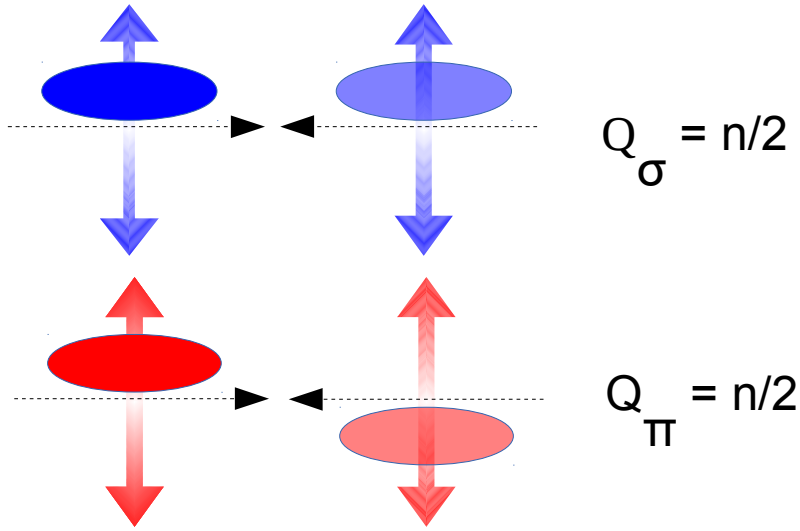

- Under resonant conditions coherent beam-beam modes may be driven unstable
  - Higher orders as well as synchrobetatron resonances can also lead to such instabilities
    e.g. *A. Chao, SSCL-346, 1991*

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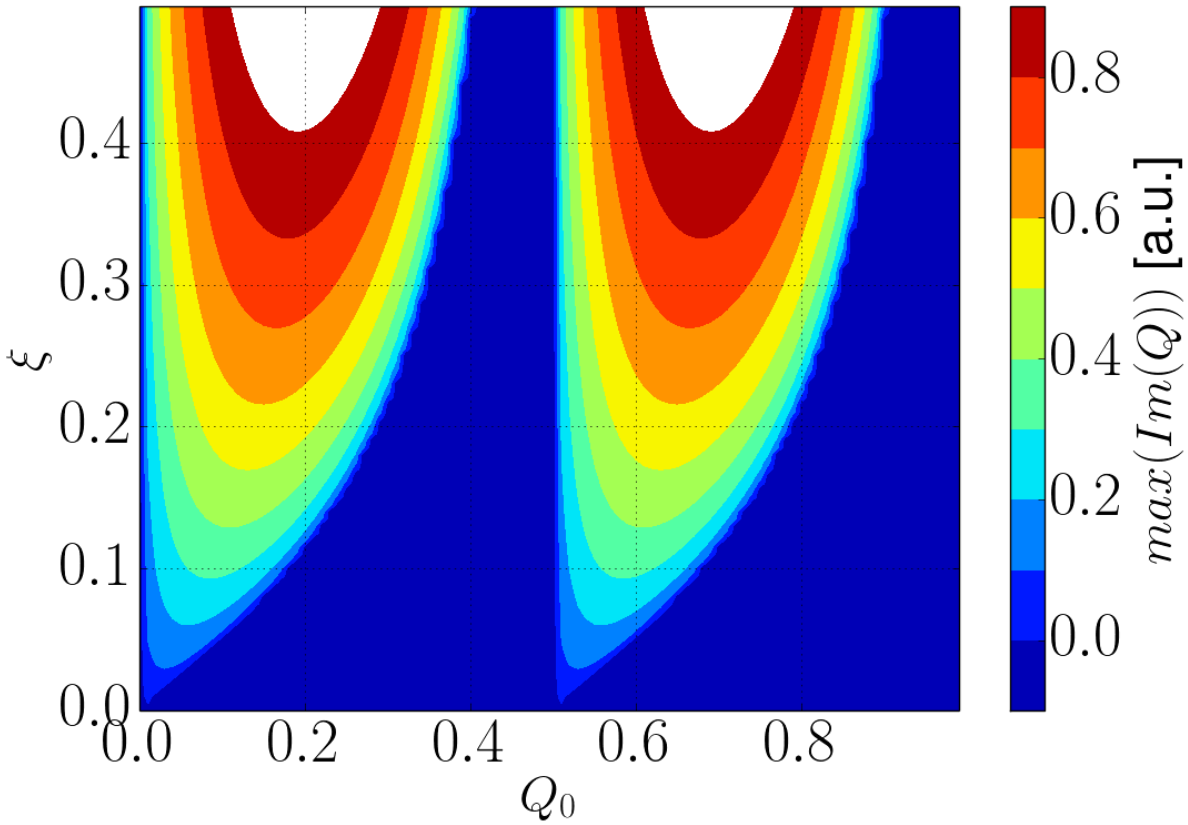
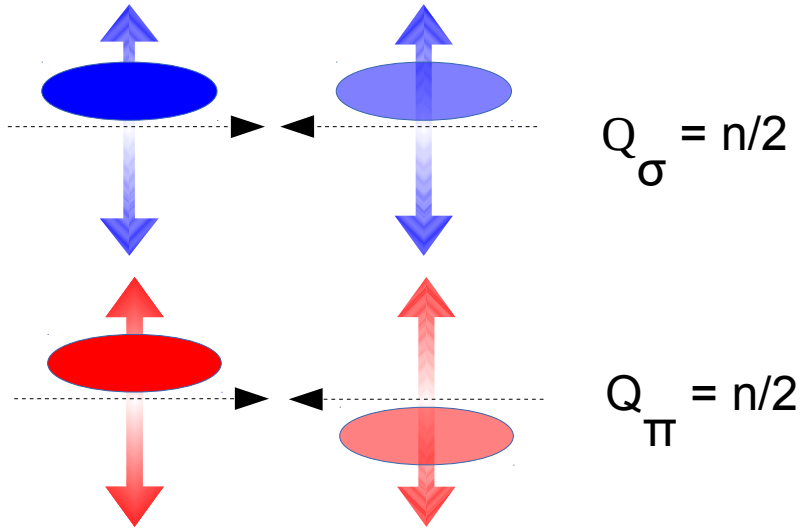
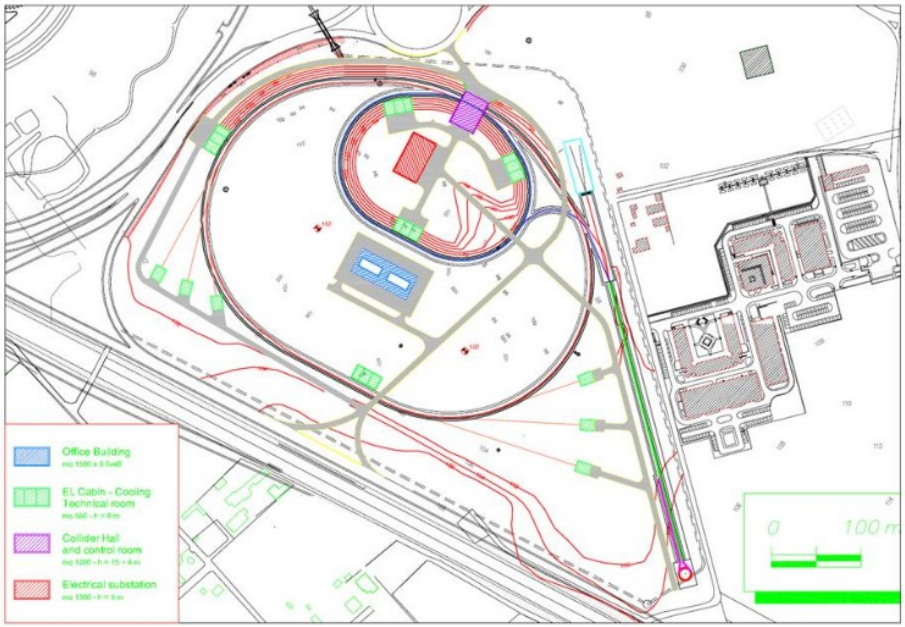




- Under resonant conditions coherent beam-beam modes may be driven unstable
  - Higher orders as well as synchrobetatron resonances can also lead to such instabilities
    e.g. *A. Chao, SSCL-346, 1991*
- The choice of a favourable working point usually matches the constraints also imposed by single particle stability

Coherent beam-beam mode : Asymmetric machines

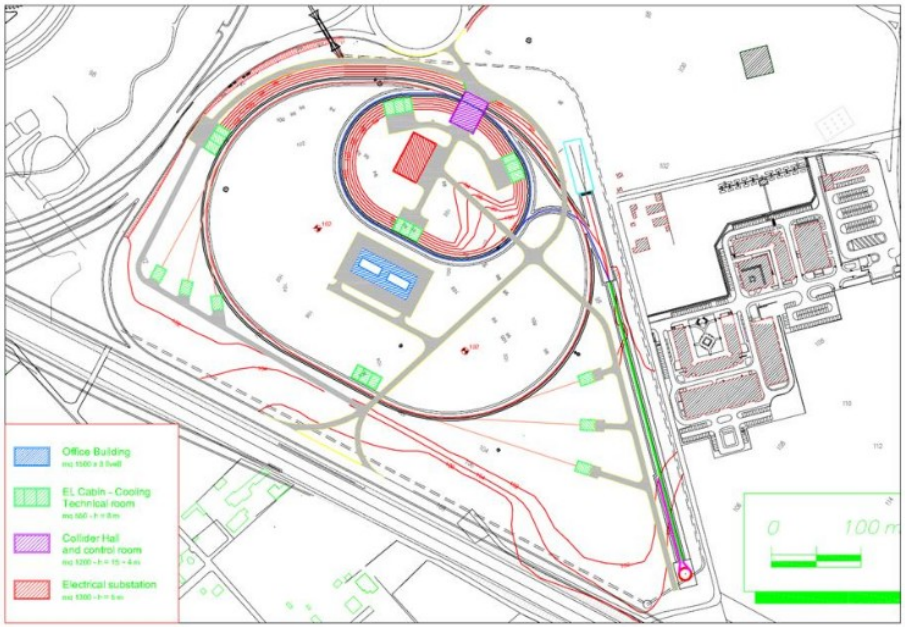
- At the design stage of B factories, colliders with asymmetric ring circumferences were considered



SuperB asymmetric ring layout

Coherent beam-beam mode : Asymmetric machines

- At the design stage of B factories, colliders with asymmetric ring circumferences were considered
  - The tunes and the super-period are constrained by resonant conditions for the coherent beam-beam modes
    K. Hirata and E. Keil, Phy. Lett. B 232 ***3*** *(1989) / M. Zobov and Y. Zhang, IPAC'11*



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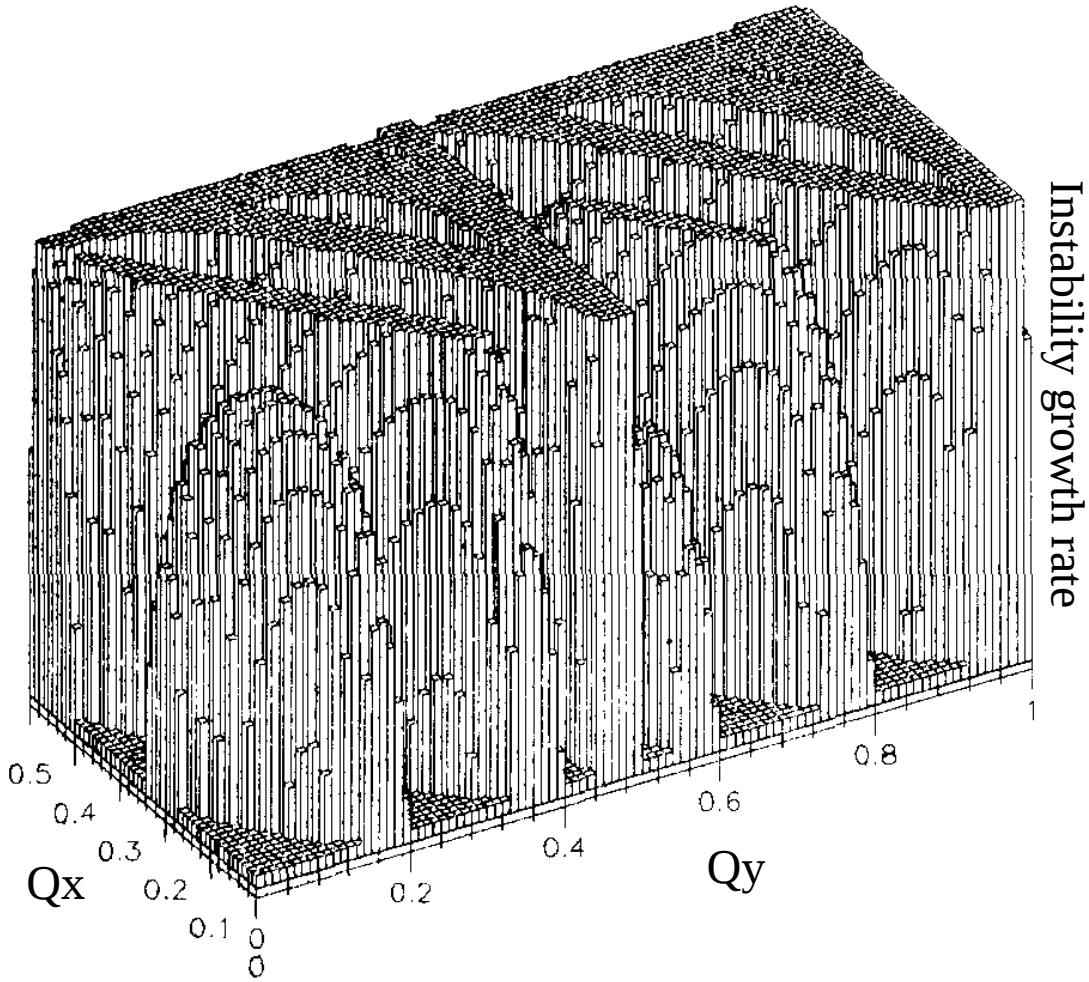
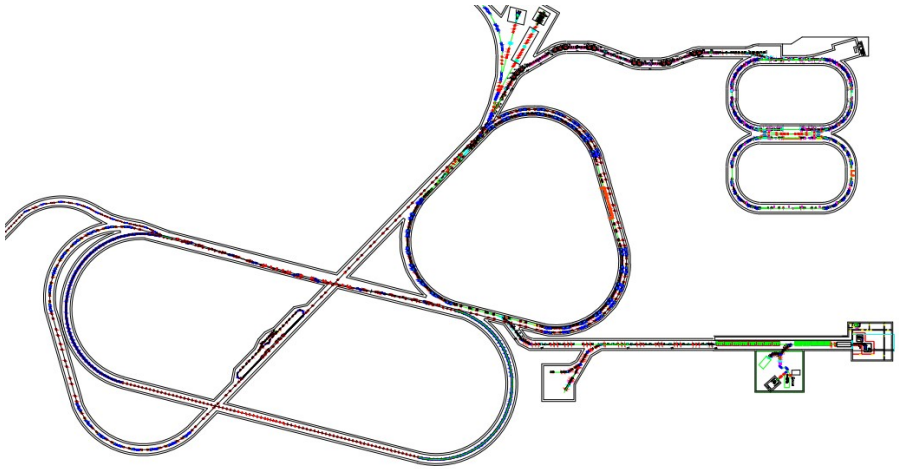


Coherent beam-beam mode : Asymmetric machines

- New 8-shape designs of electron-ion colliders features both asymmetric revolution frequencies and IP locations (→ JLEIC, EicC)

EicC-I layout* :



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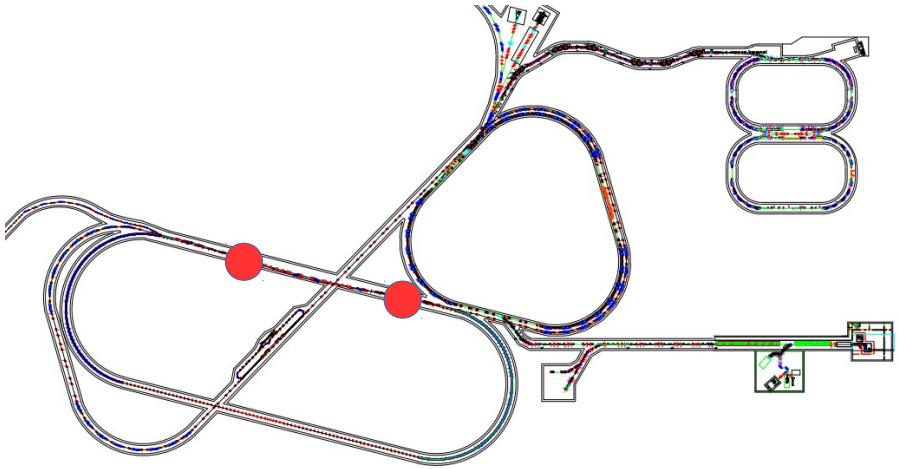

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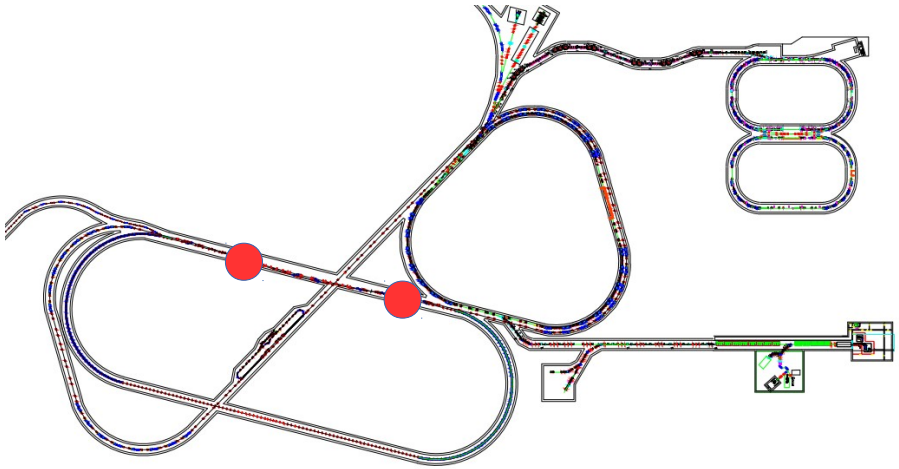
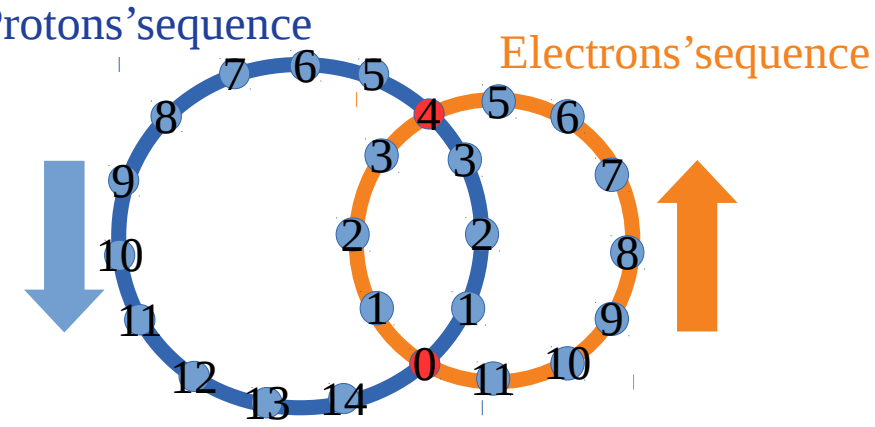


Model in the BimBim code:



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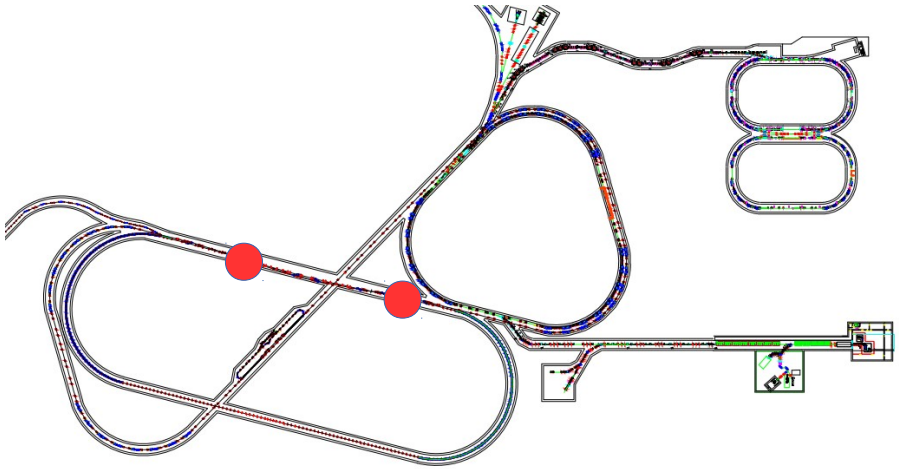

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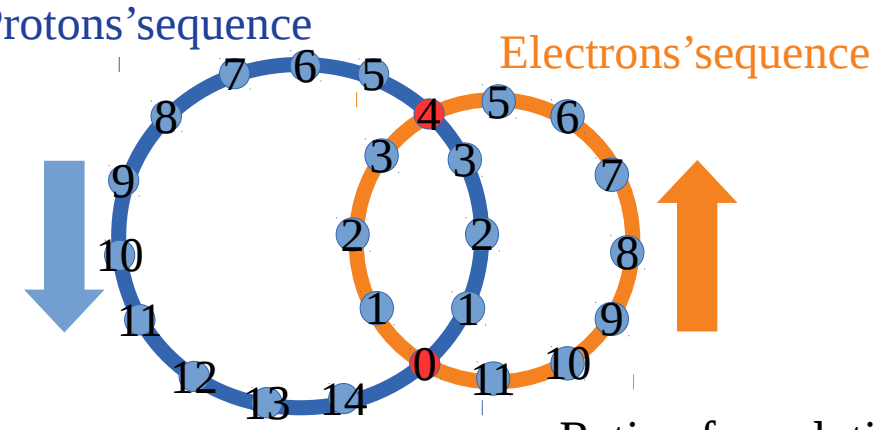
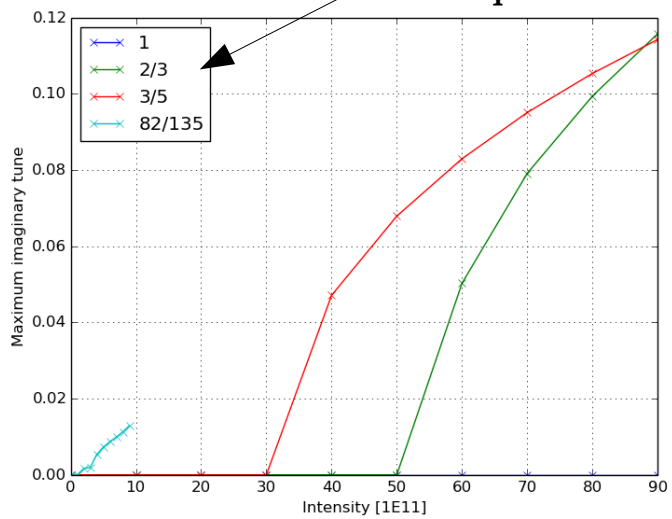


- The results obtained semi-analytically are in agreement with the guidelines of Hirata and Keil :
  - Short super-periods offer a large stable space in the terms of tunes and beam-beam tune shift
  - Long super-periods lead to weak instabilities even with low beam-beam tune shifts

Ratio of revolution frequencies



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Mode coupling instability of colliding beams

- The interaction of coherent beam-beam mode with the machine impedance can result in strong mode coupling instabilities *S. White, et al., Phys. Rev. ST Accel. Beams 17 041002 (2014)*
  - This instability is not driven by a resonant condition, it can therefore not be fully mitigated with choices of tunes
  - In some cases, the layout of IPs and phase advance between them can be used to control the beam-beam mode frequencies

→ Act on intrinsic Landau damping
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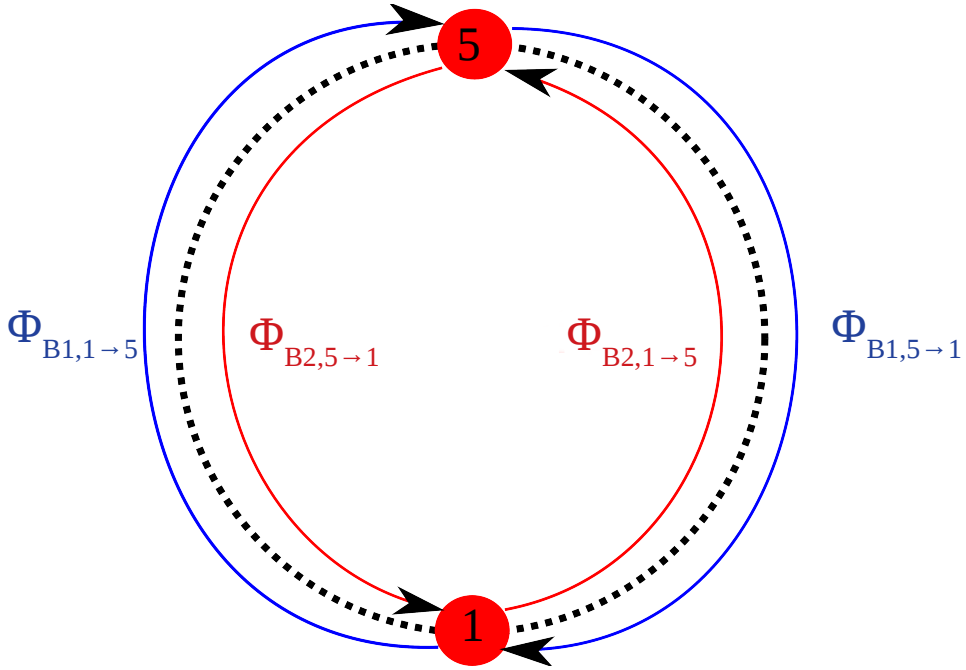

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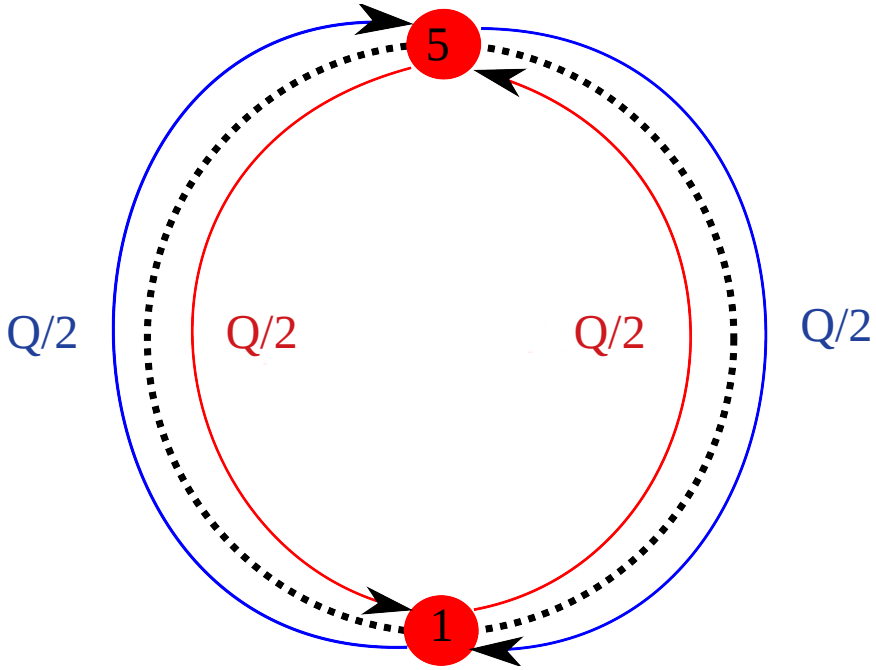

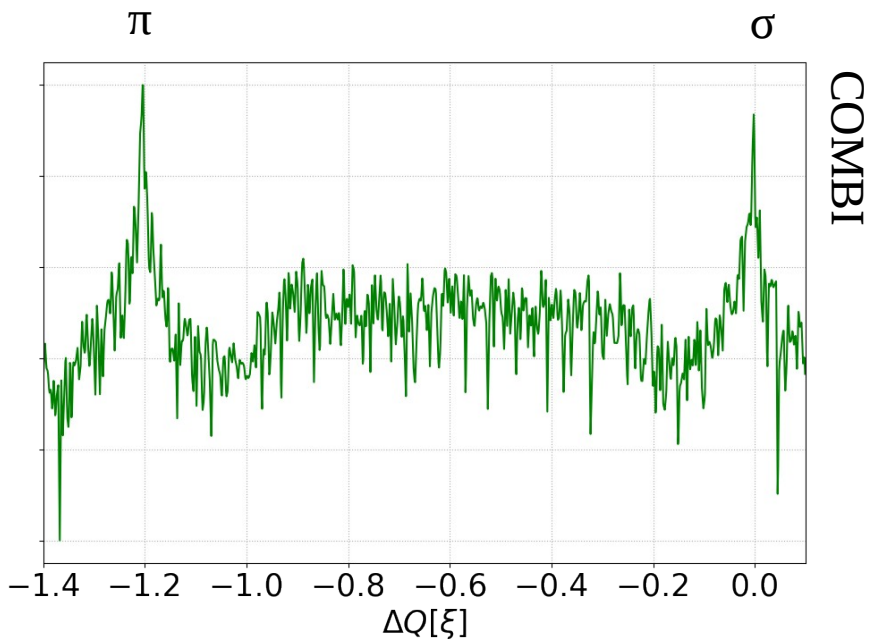

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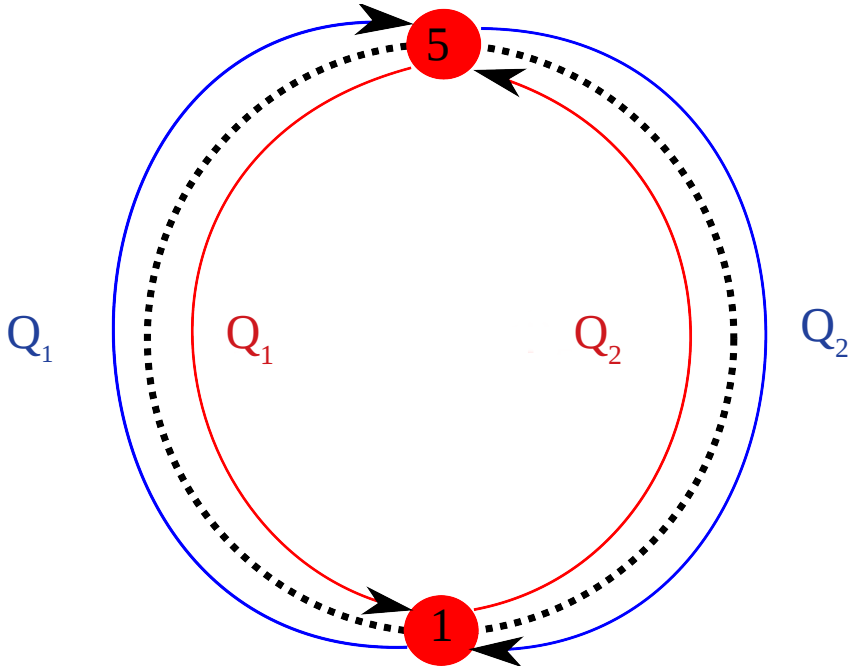
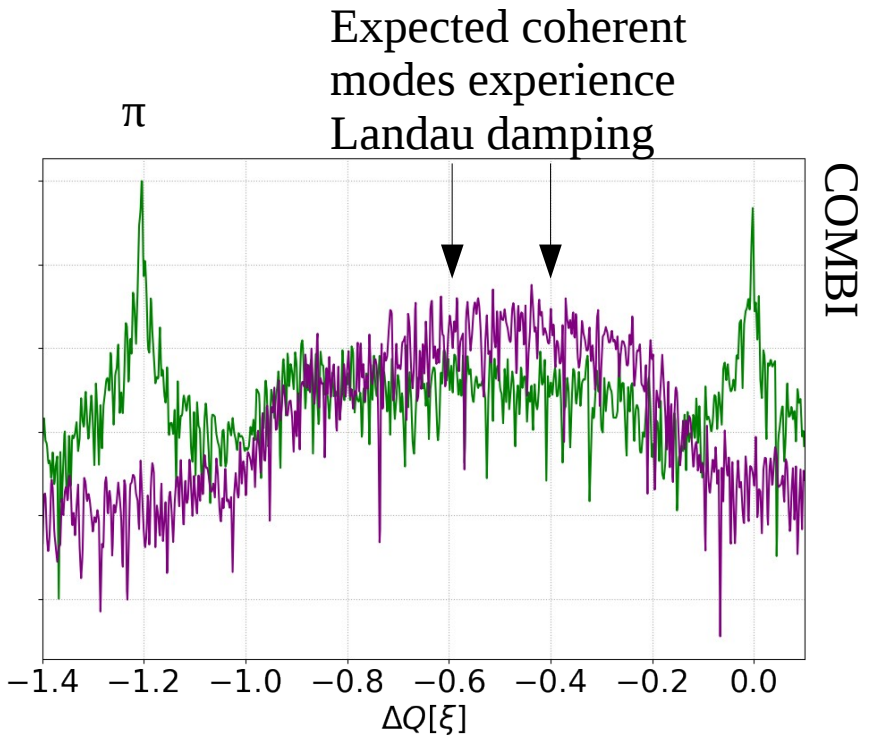


$Q_1 = 0.405$, $Q_2 = 0.905$
$Q_1+Q_2 = Q$



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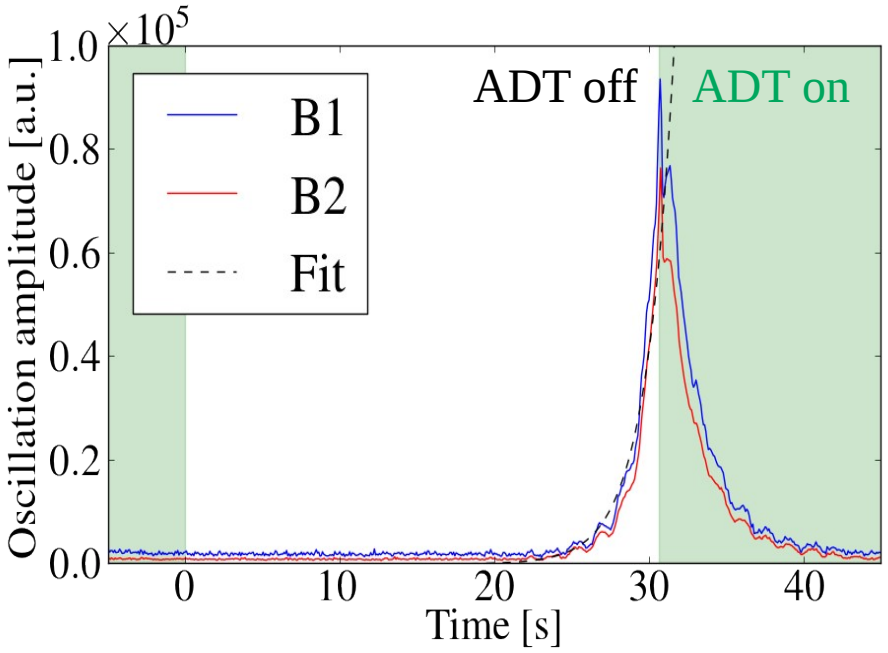

- The complexity of the layout of beam-beam interactions in the LHC prevents effective mitigation with phase advances
  - The transverse feedback is effective against this instability

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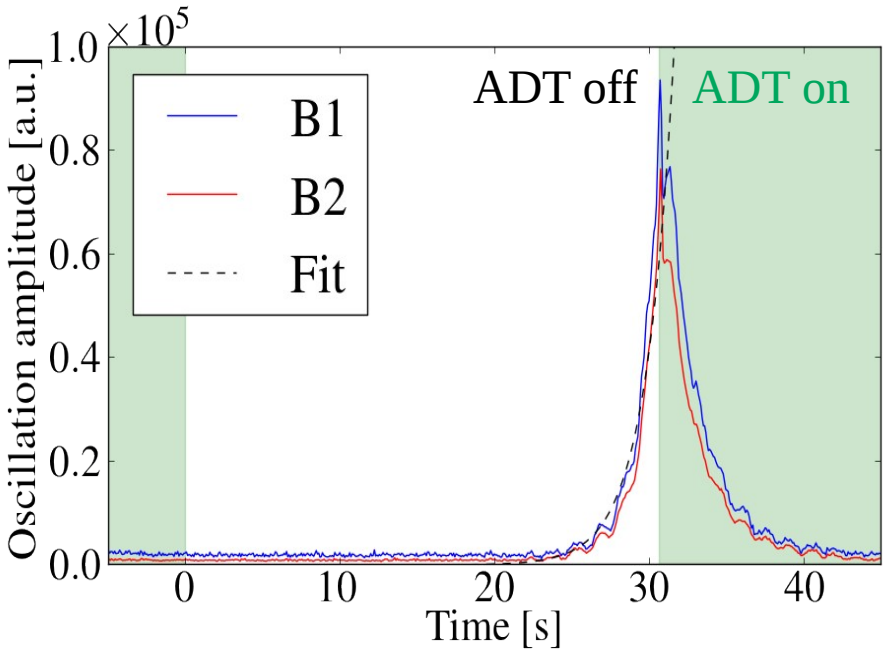

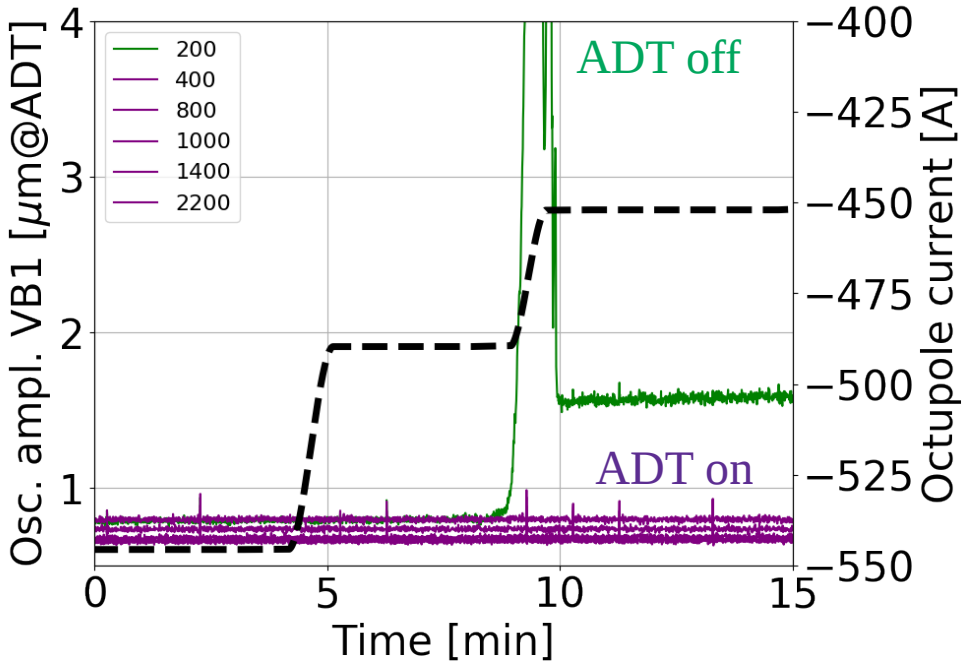

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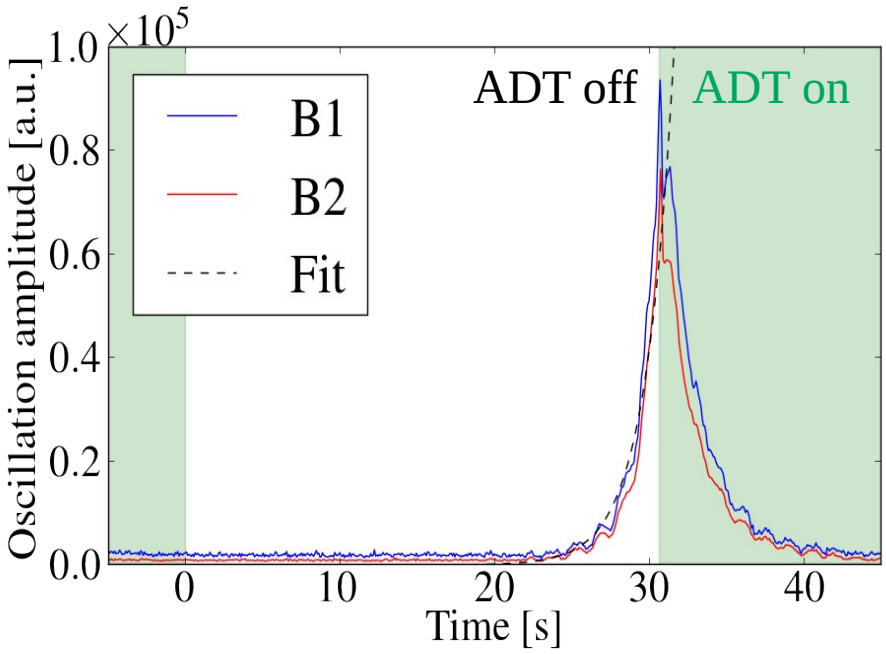

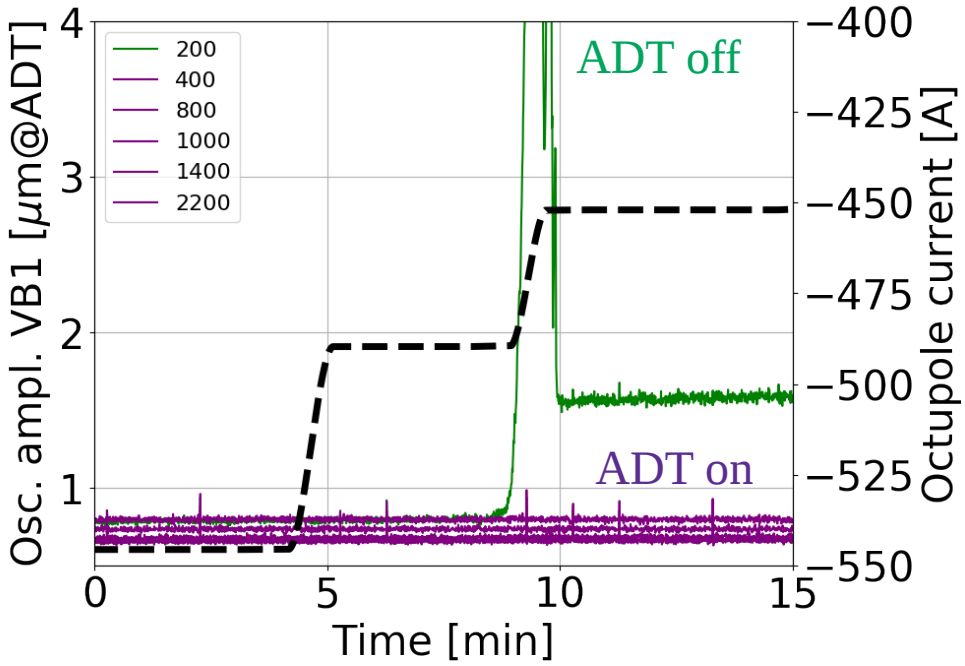

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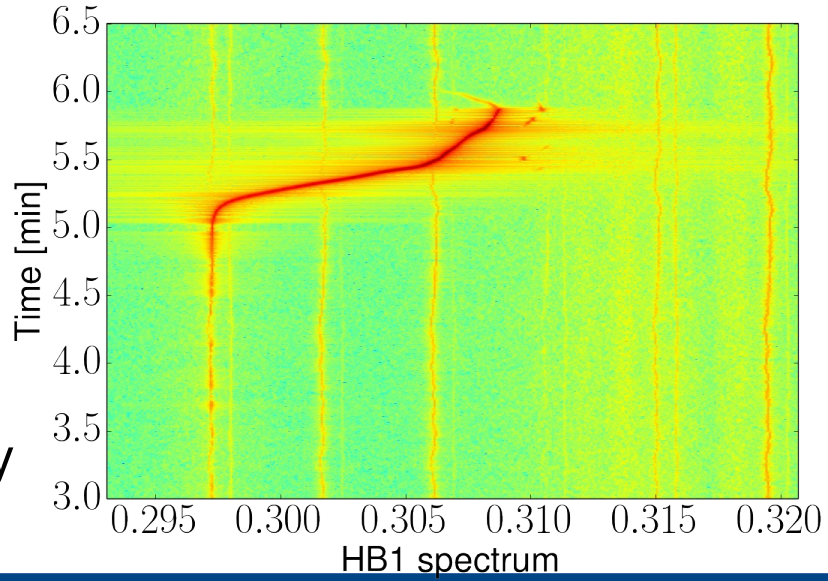

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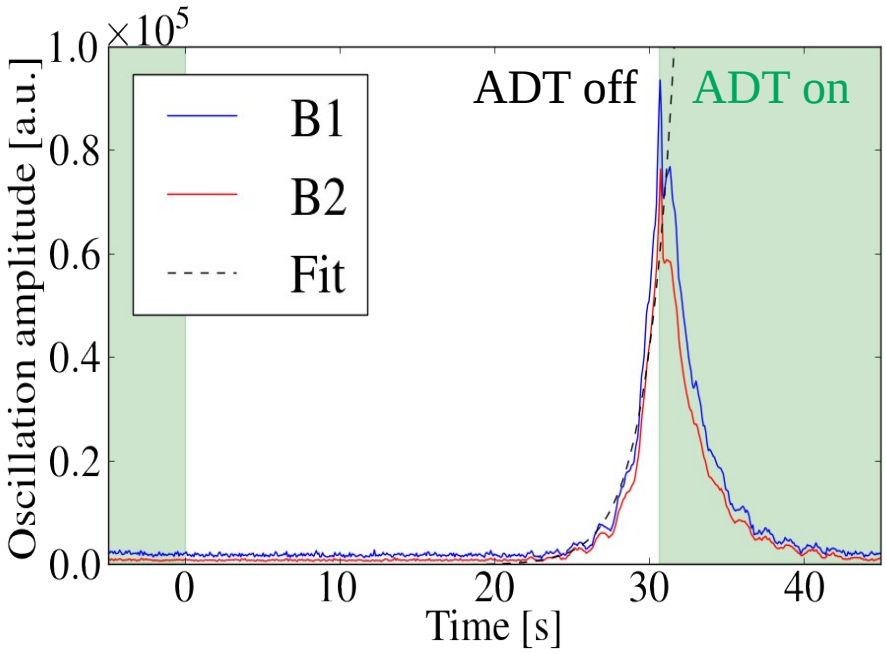

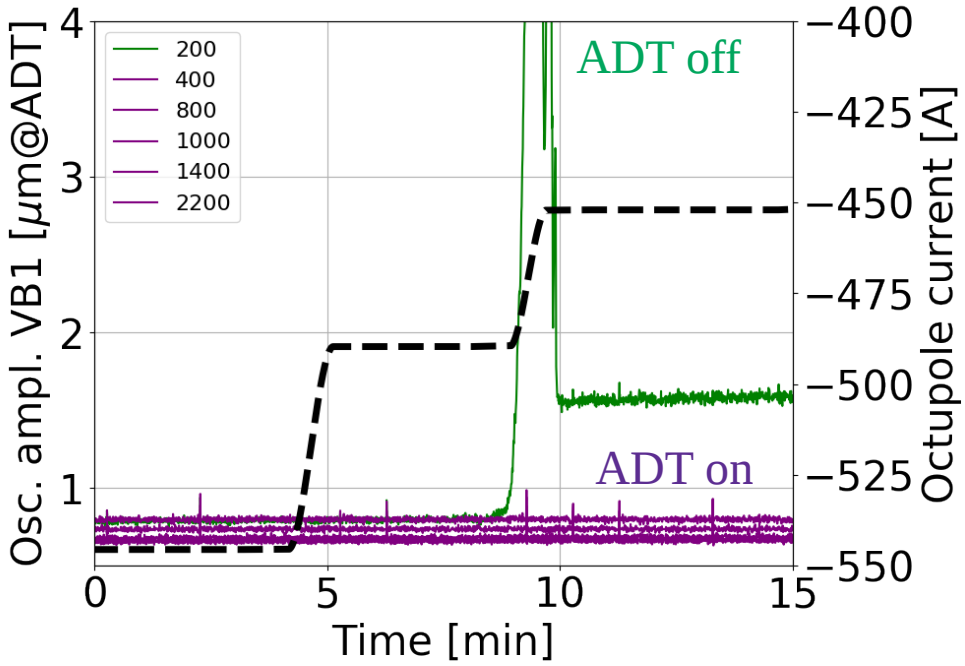

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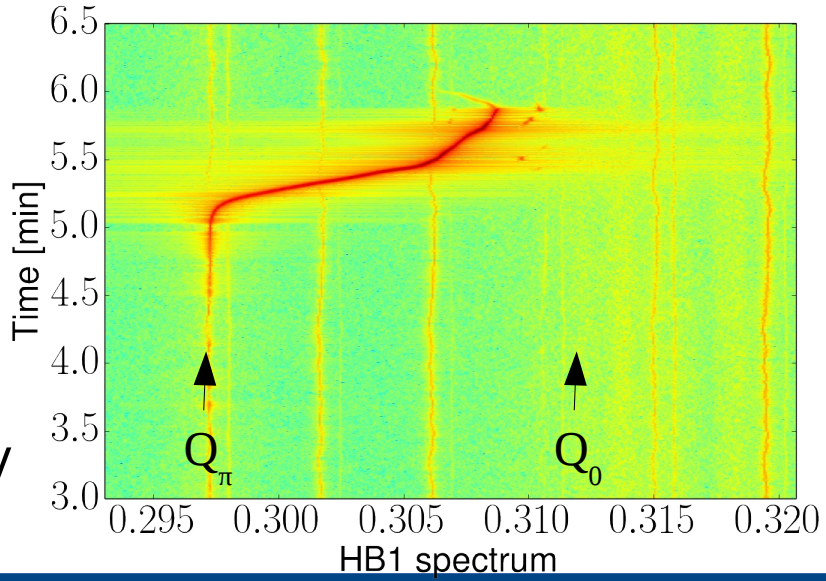
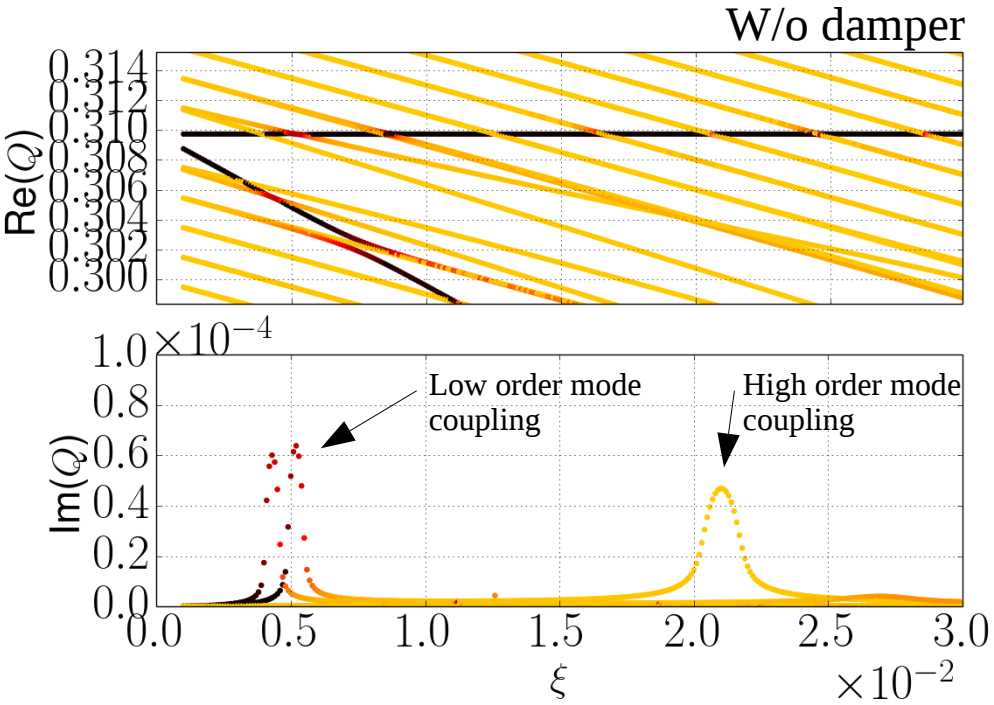


Mode coupling instability at the HL-LHC



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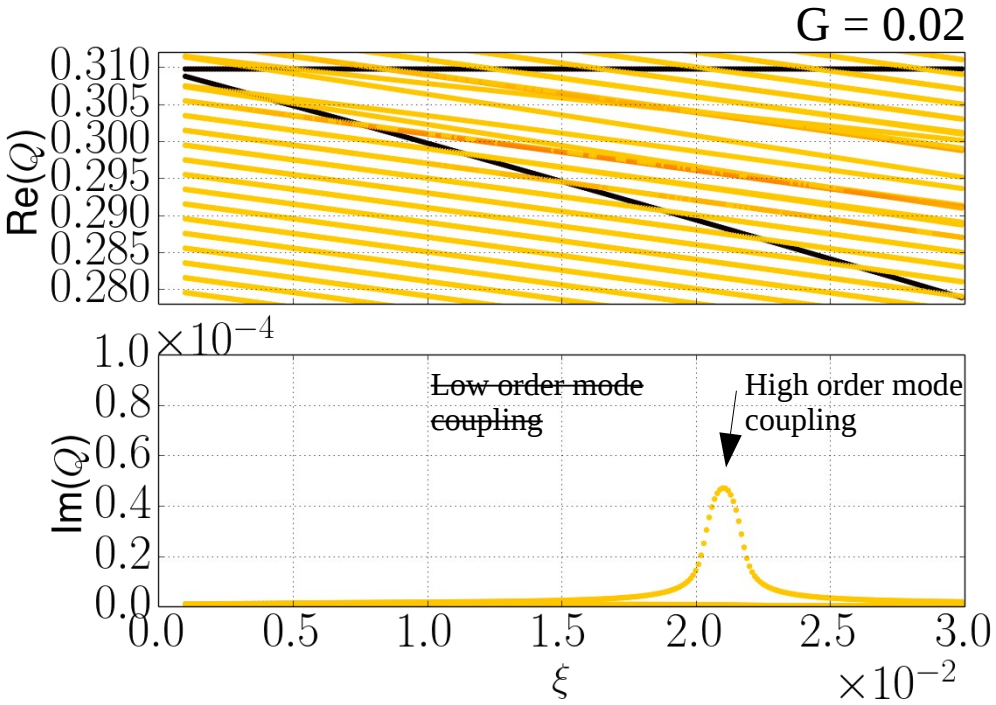

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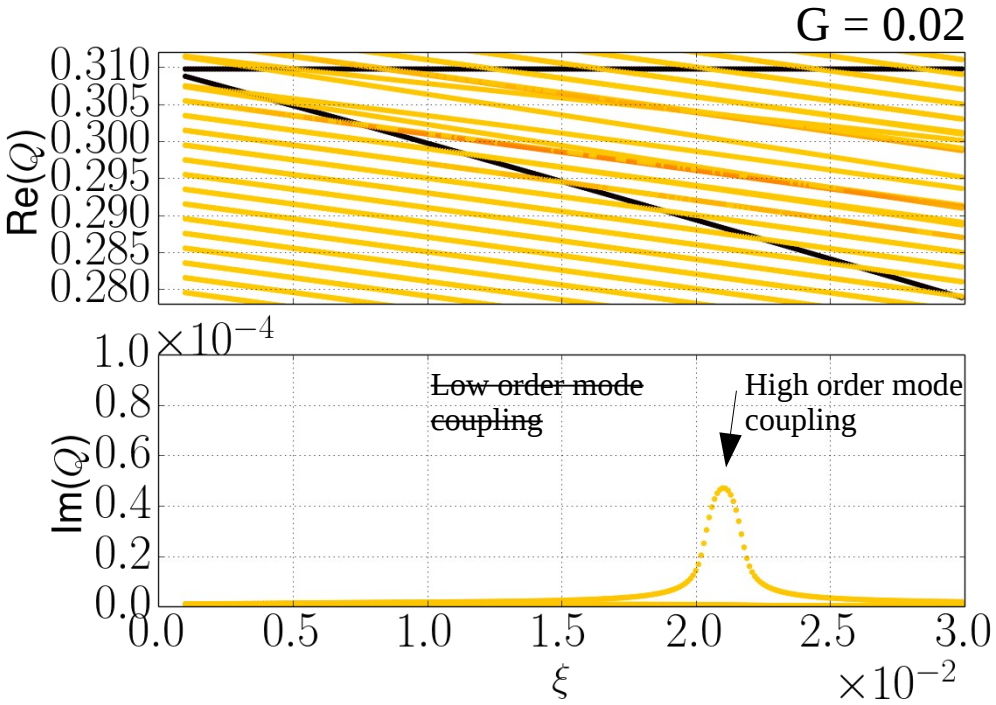

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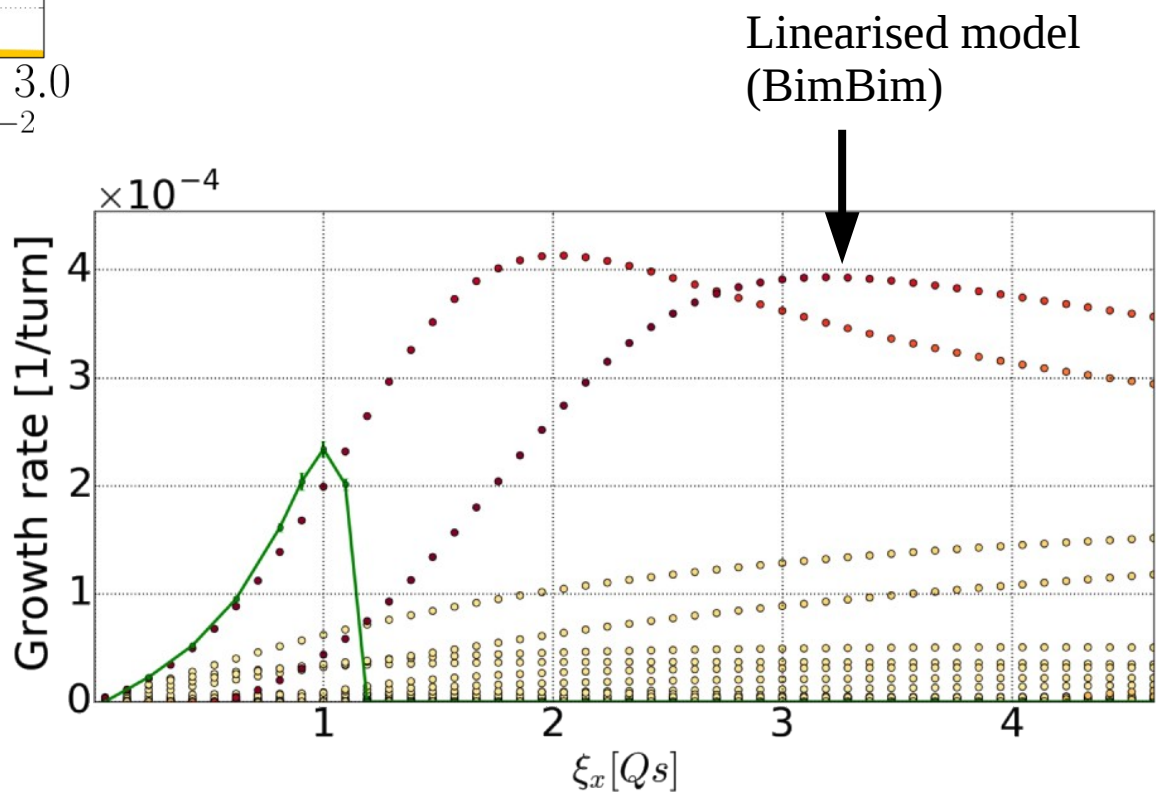

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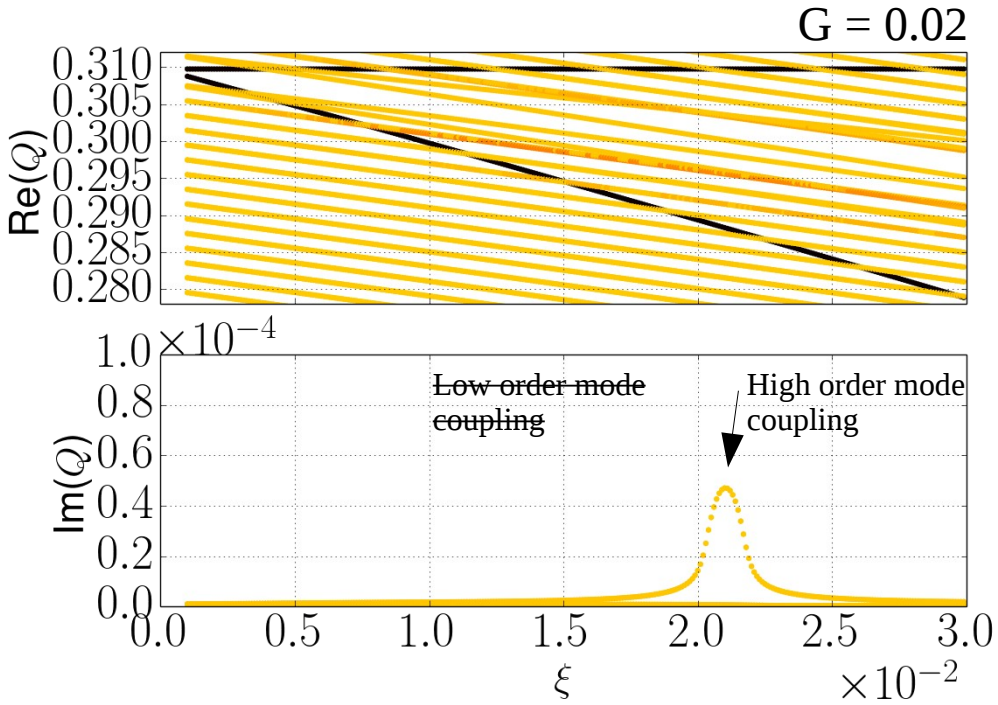

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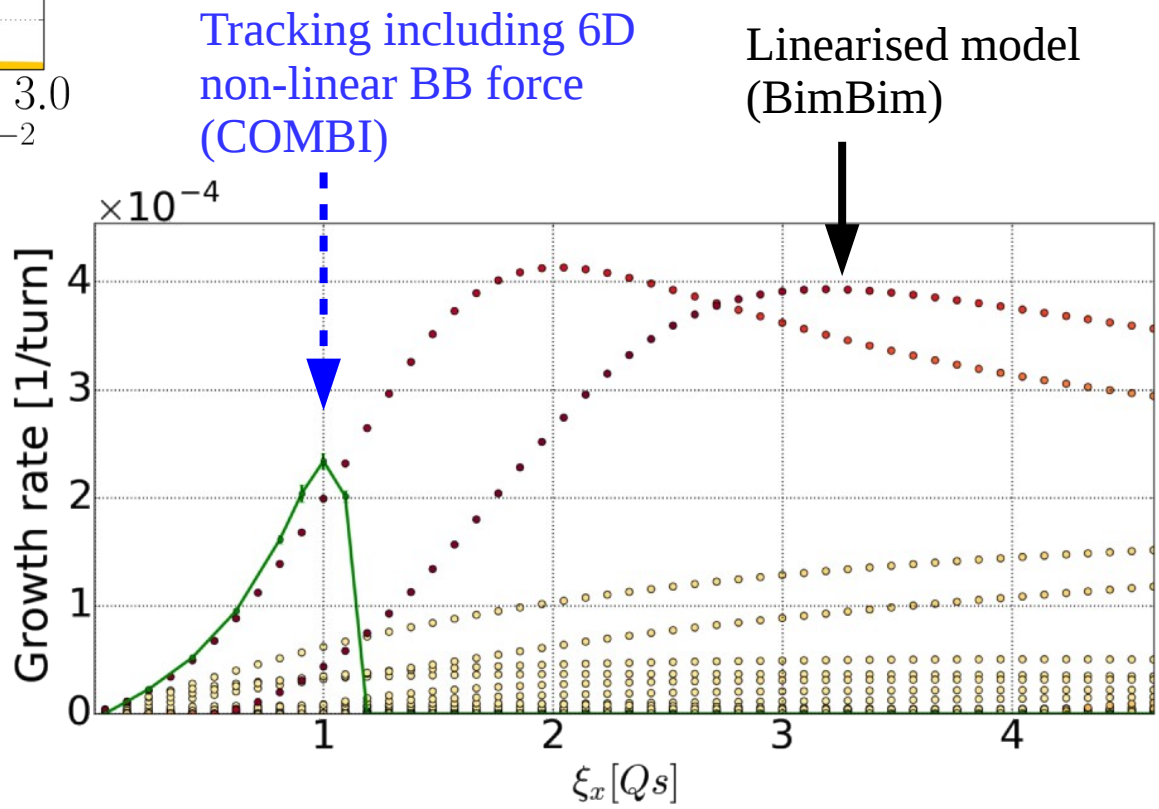
- Landau damping by synchrotron side-bands (enabled by the large Piwinski angle or hourglass effect) is sufficient to ensure stability for beam-beam parameter larger than Q_s in the HL-LHC

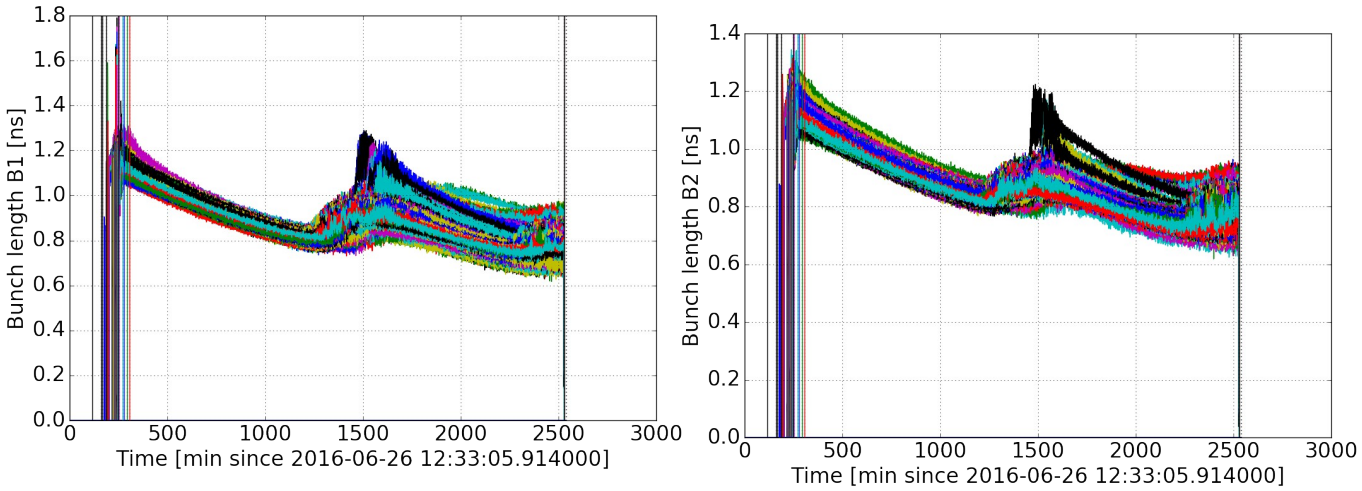
L. Barraud, et al., CERN-ACC-NOTE-2019-0032



Las Ketchup instability

- In the presence of a crossing angle or hourglass effect, beam-beam interaction leads to an energy change

  → Longitudinal coherent beam-beam modes



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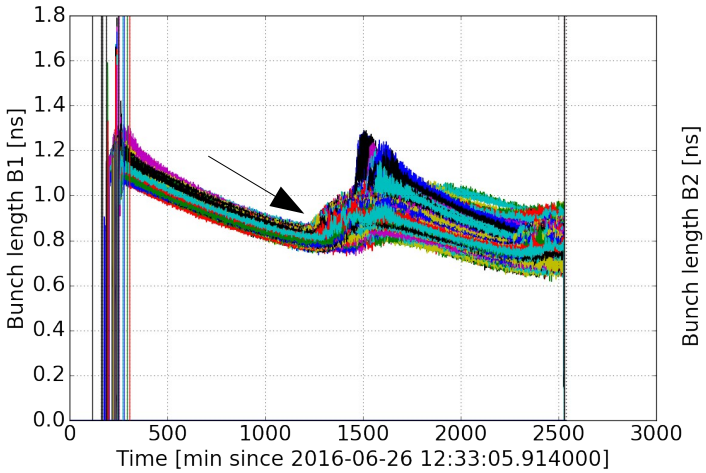

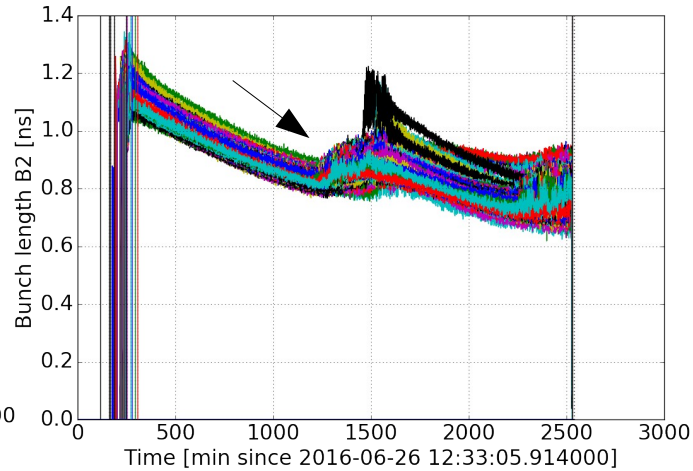

- In the first part of 2016, loss of Landau damping in the longitudinal plane was observed due to radiation damping

  H. Timko, Evian 2016

Las Ketchup instability

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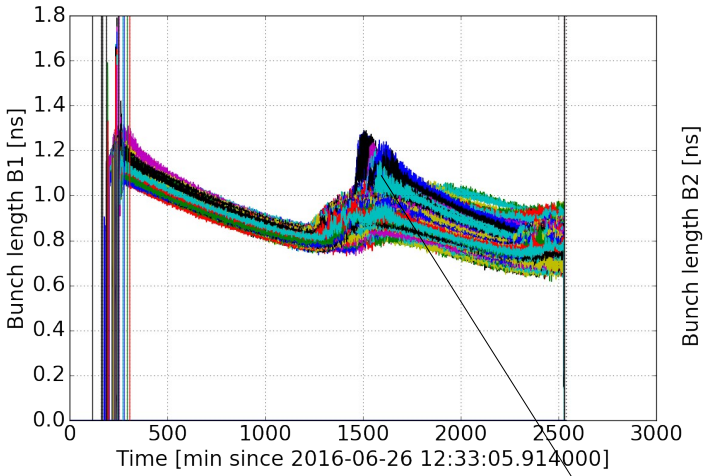

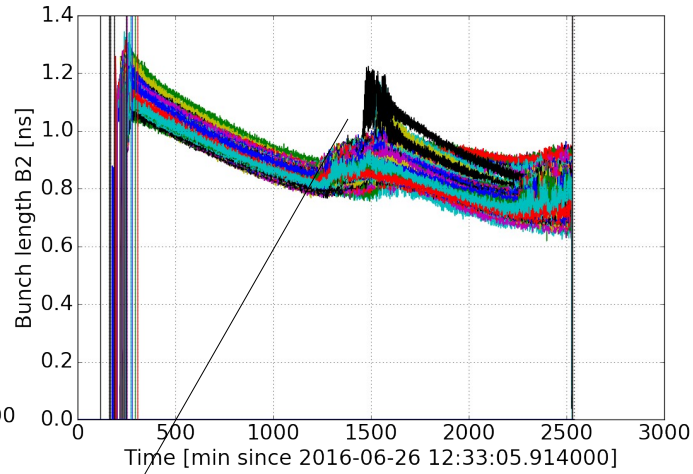

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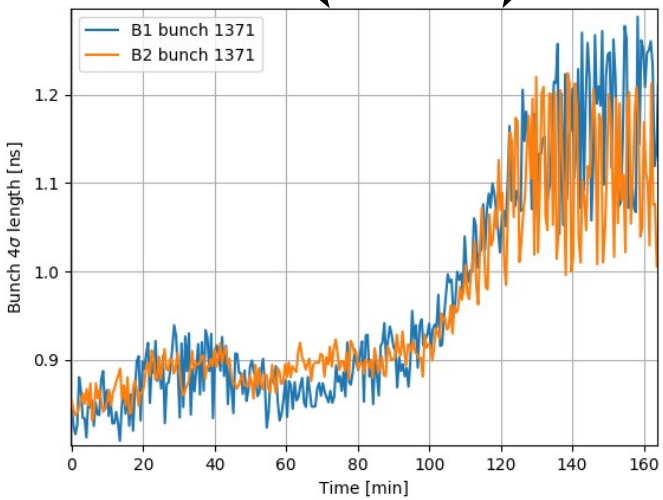
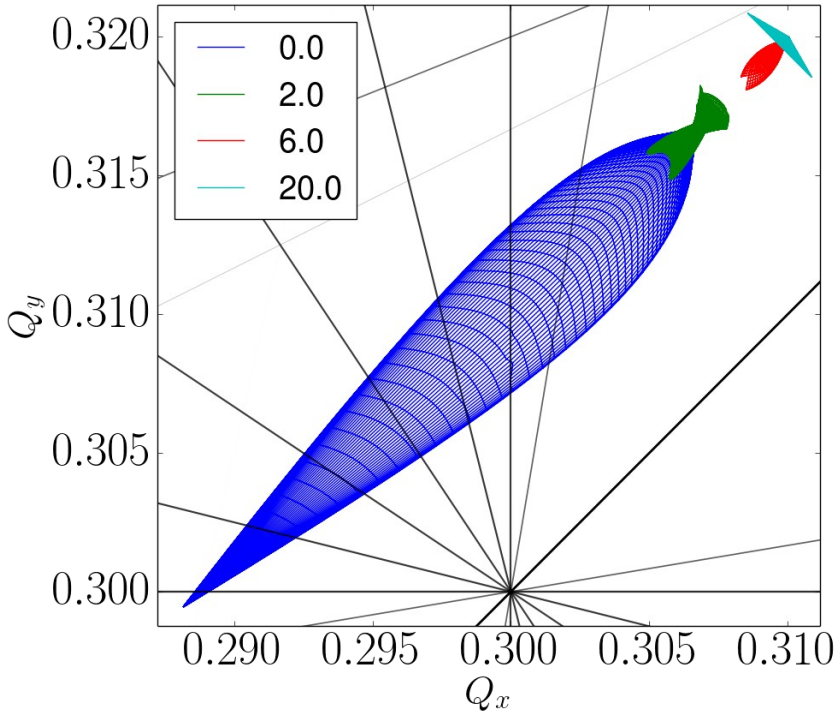
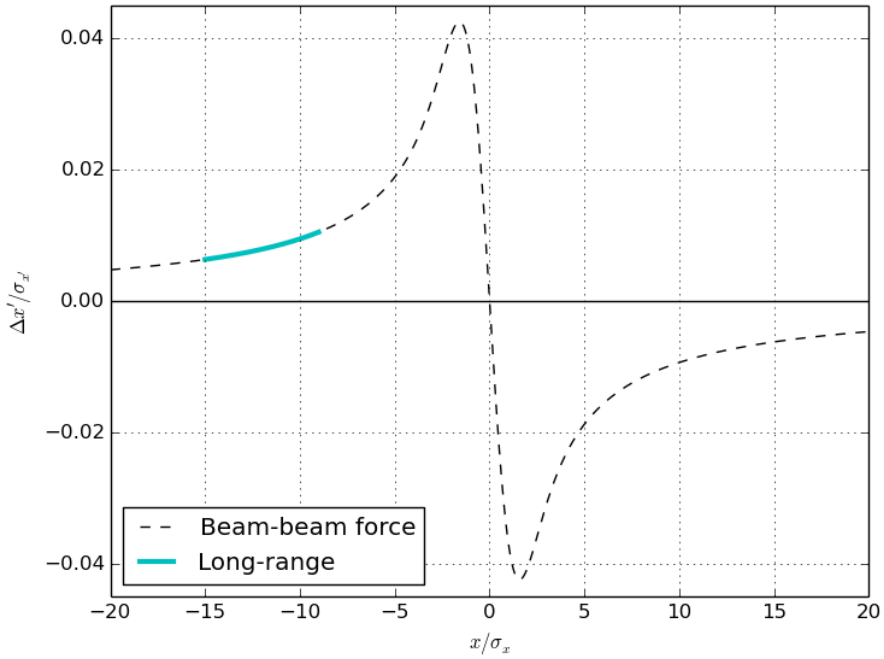


- Some signals are correlated in the two beams

  → Potential candidate for coherent longitudinal beam-beam mode, but not studied thoroughly

Landau damping of head-tail modes





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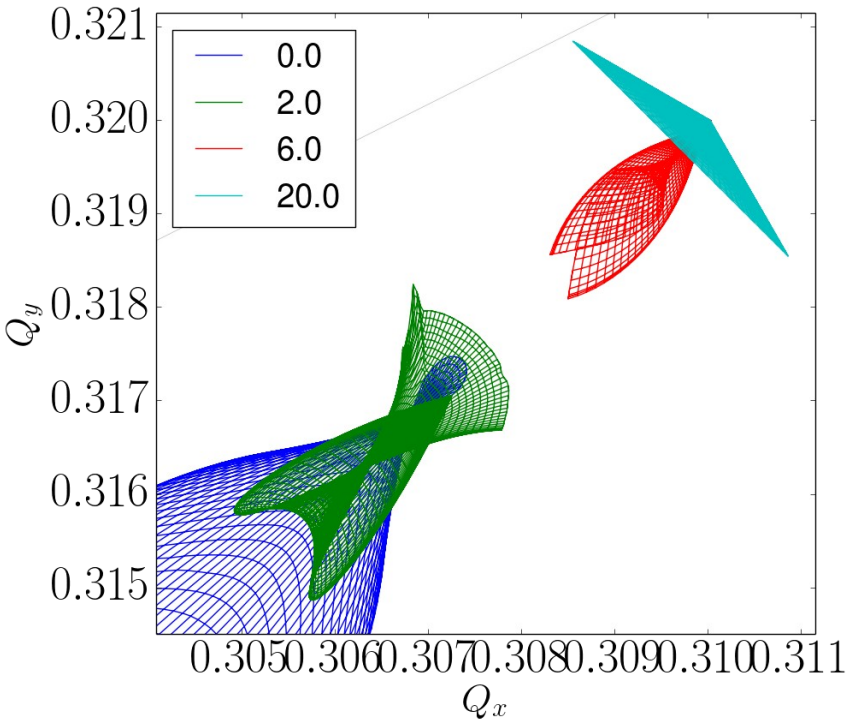
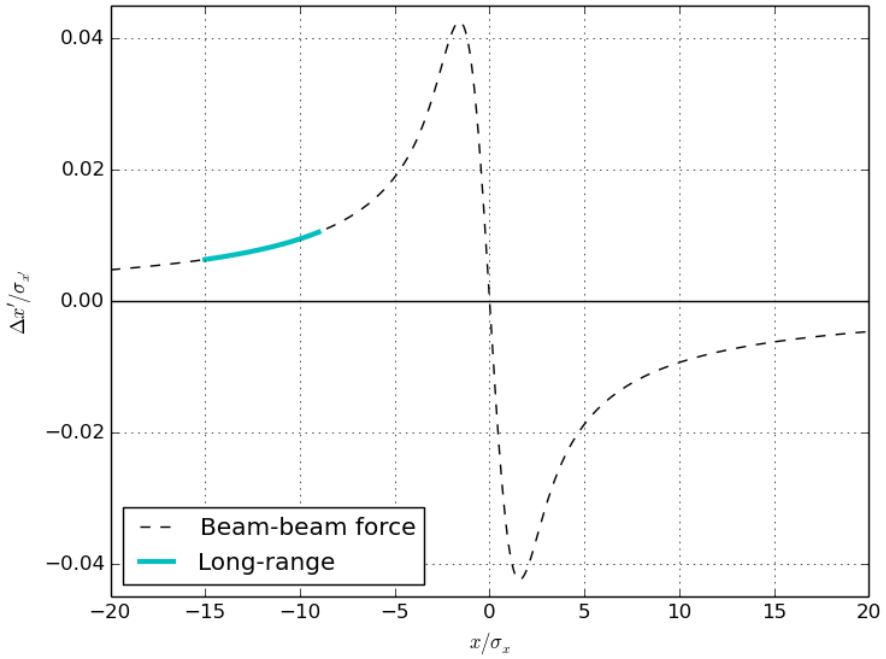
Landau damping of head-tail modes





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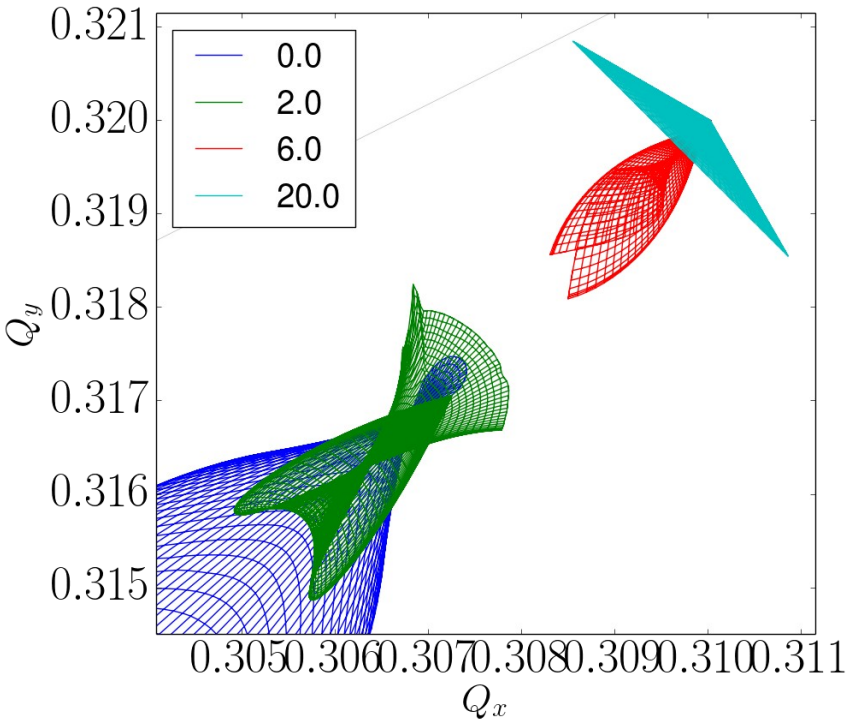

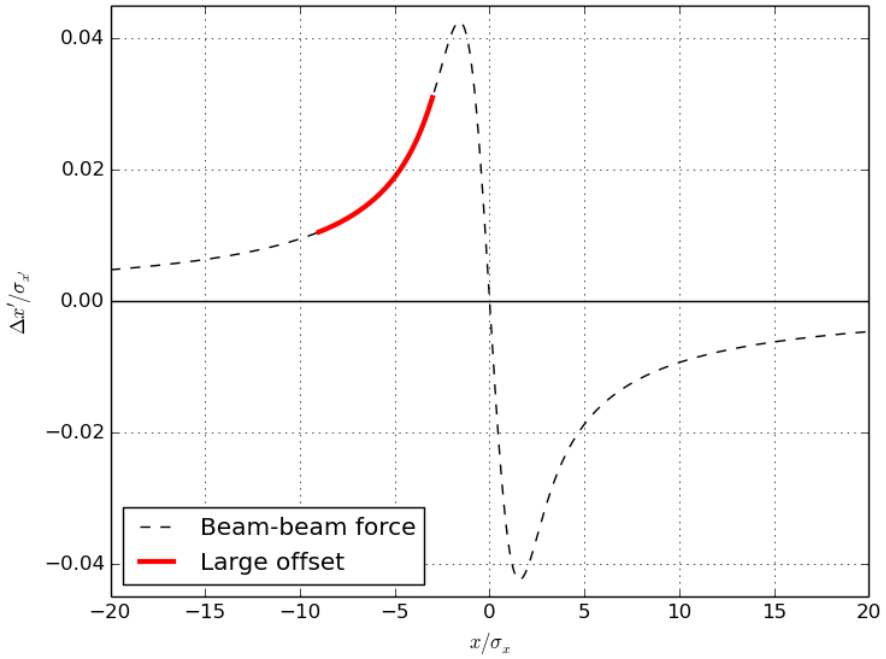

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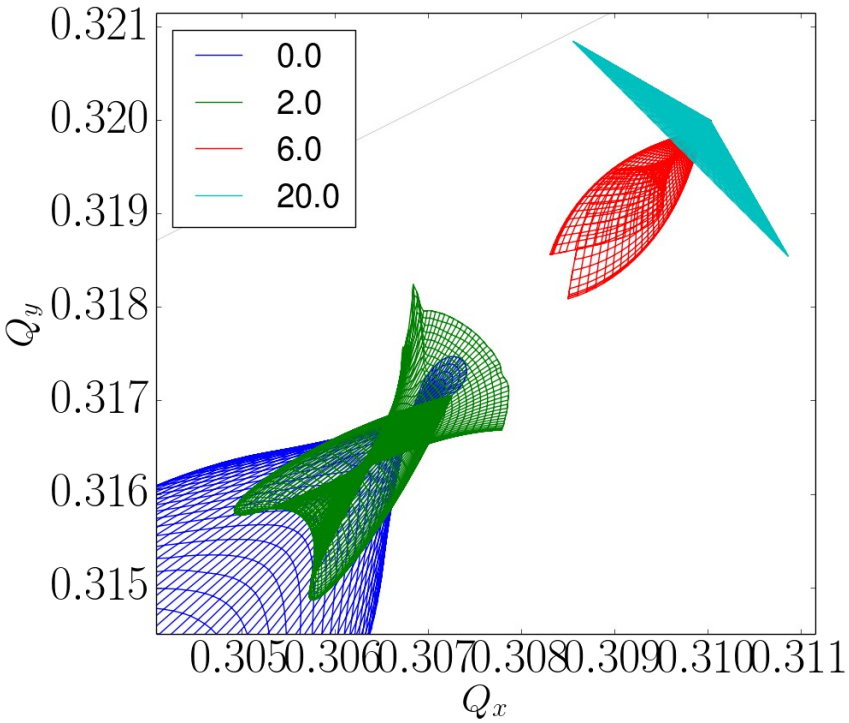

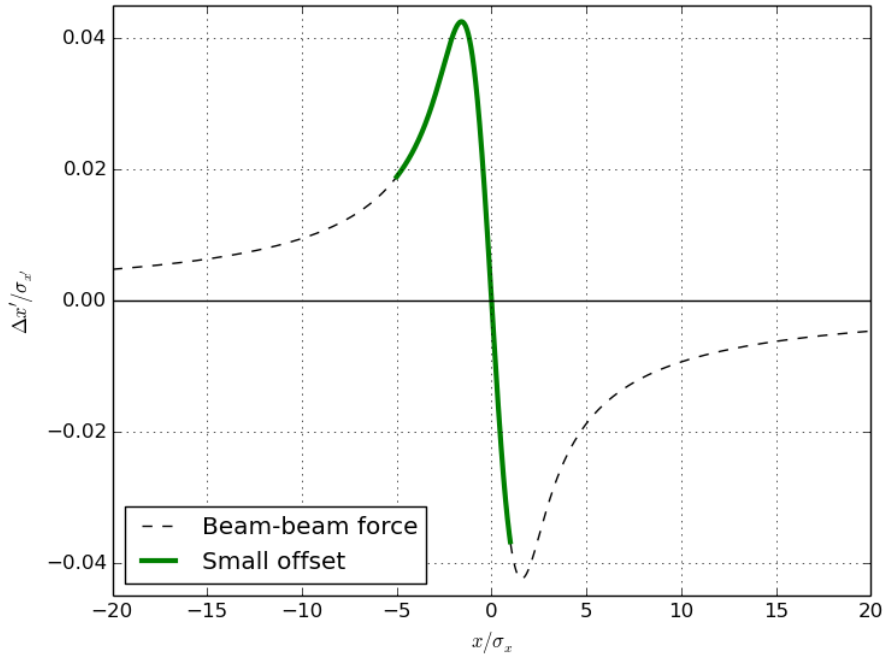

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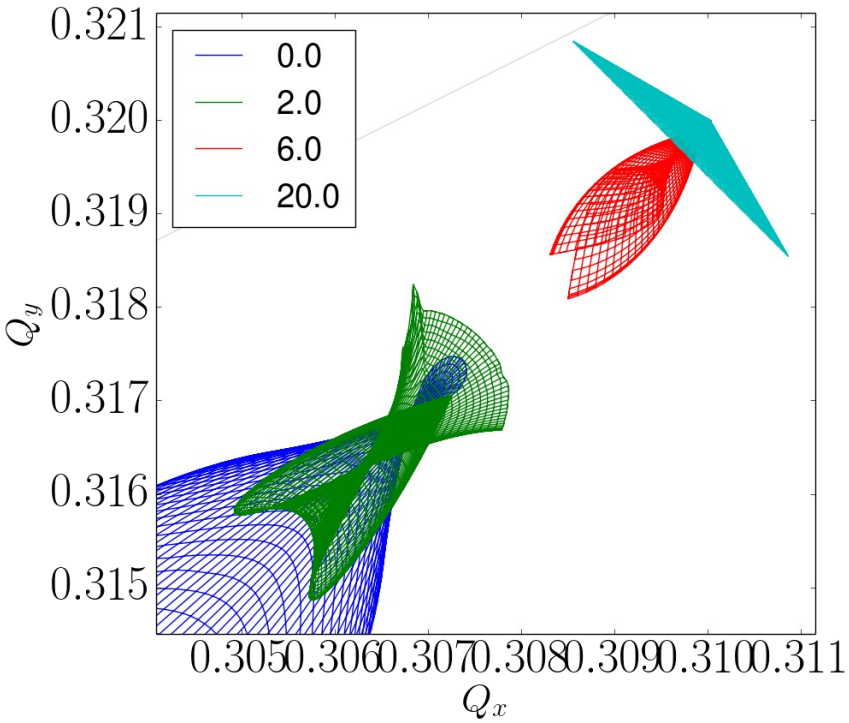

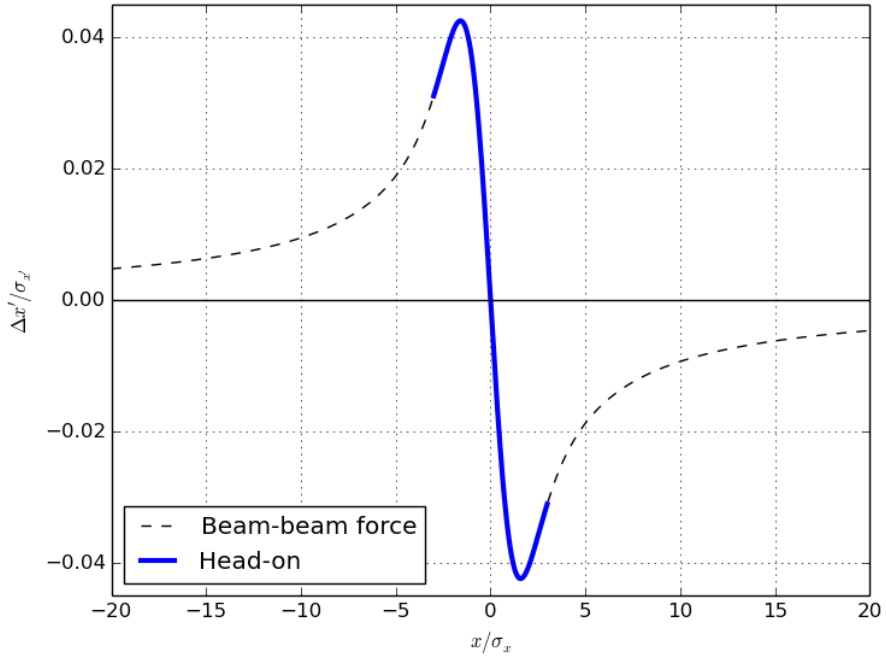

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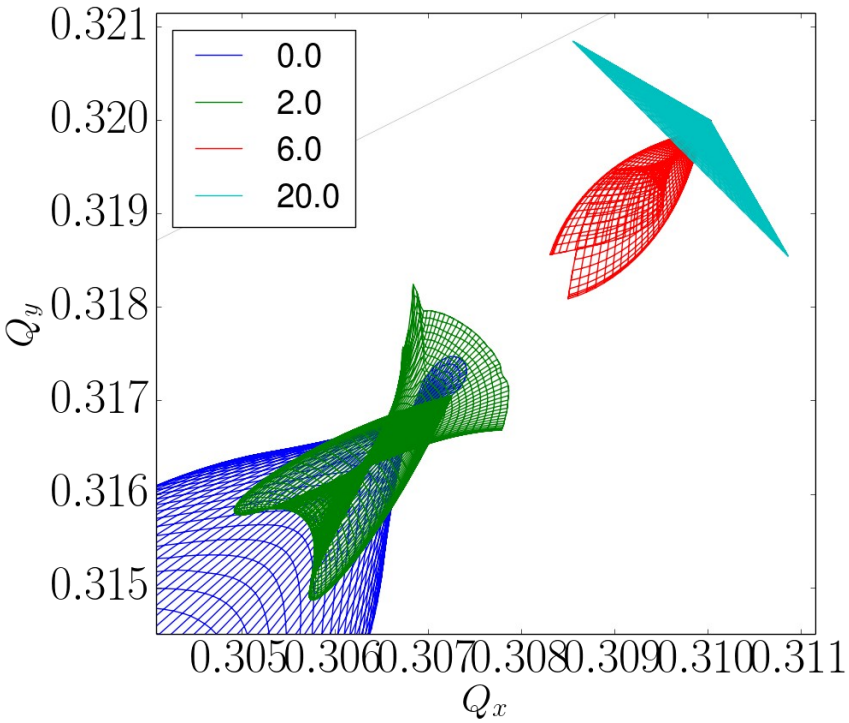
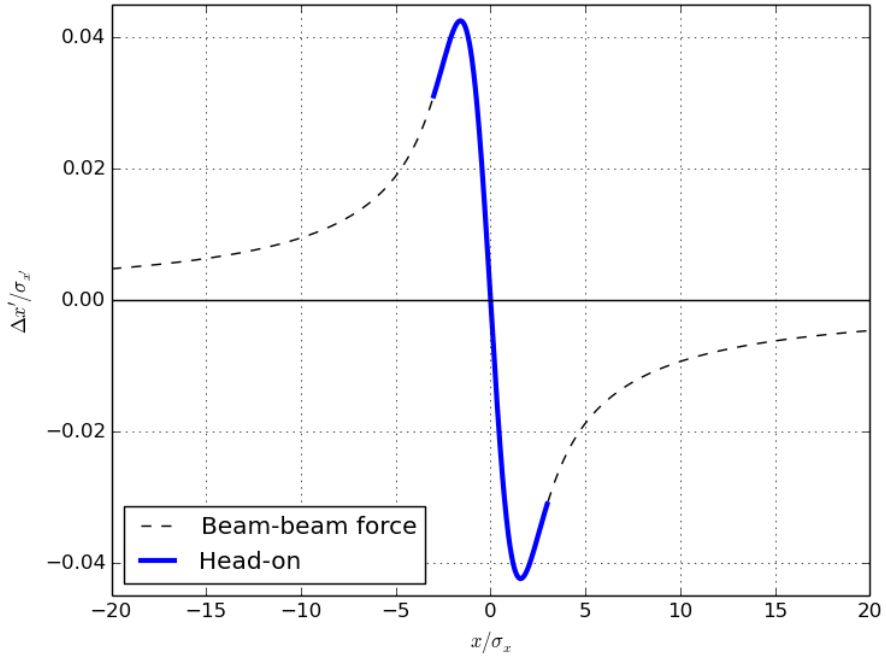
Landau damping of head-tail modes





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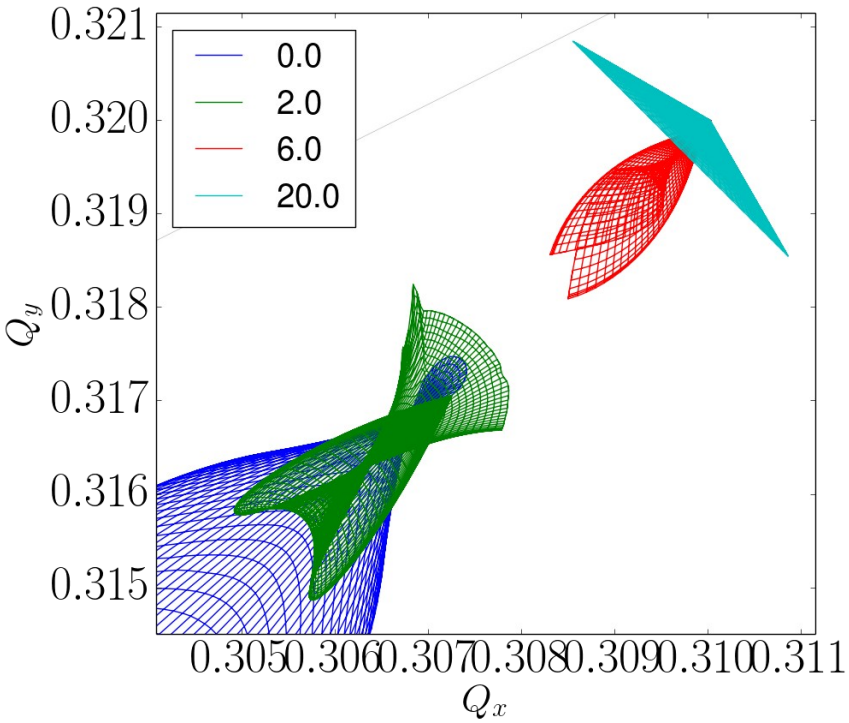
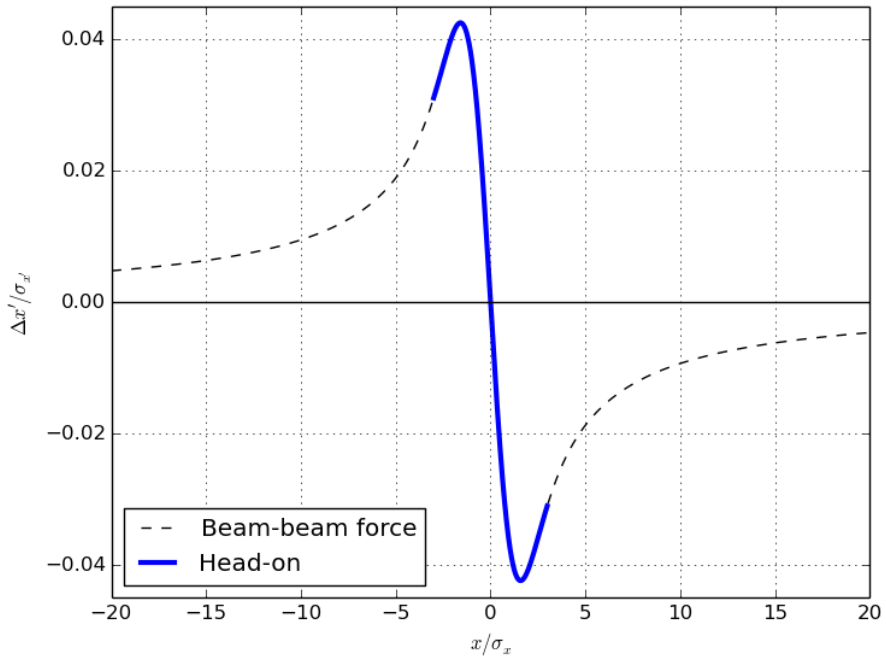
Landau damping of head-tail modes





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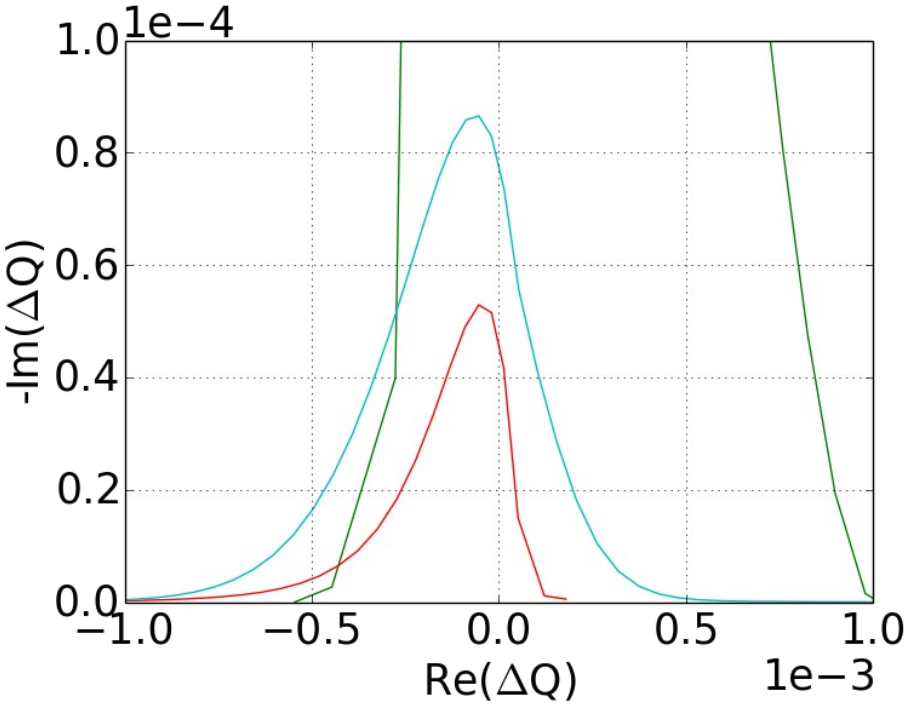
- The stability diagram can be obtained by numerical integration of the dispersion integral based on tracking data → PySSD *X. Buffat, et al., Phys. Rev. ST Accel. Beams 17, 111002 (2014)*

Landau damping of head-tail modes



- The coherent stability factor indicates the criticality of Landau damping
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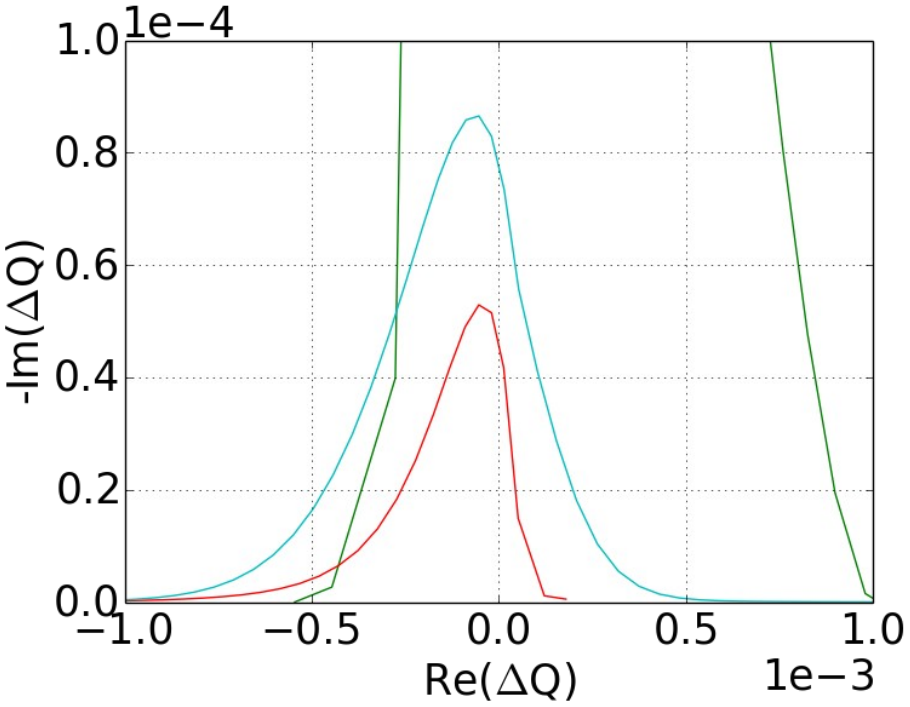
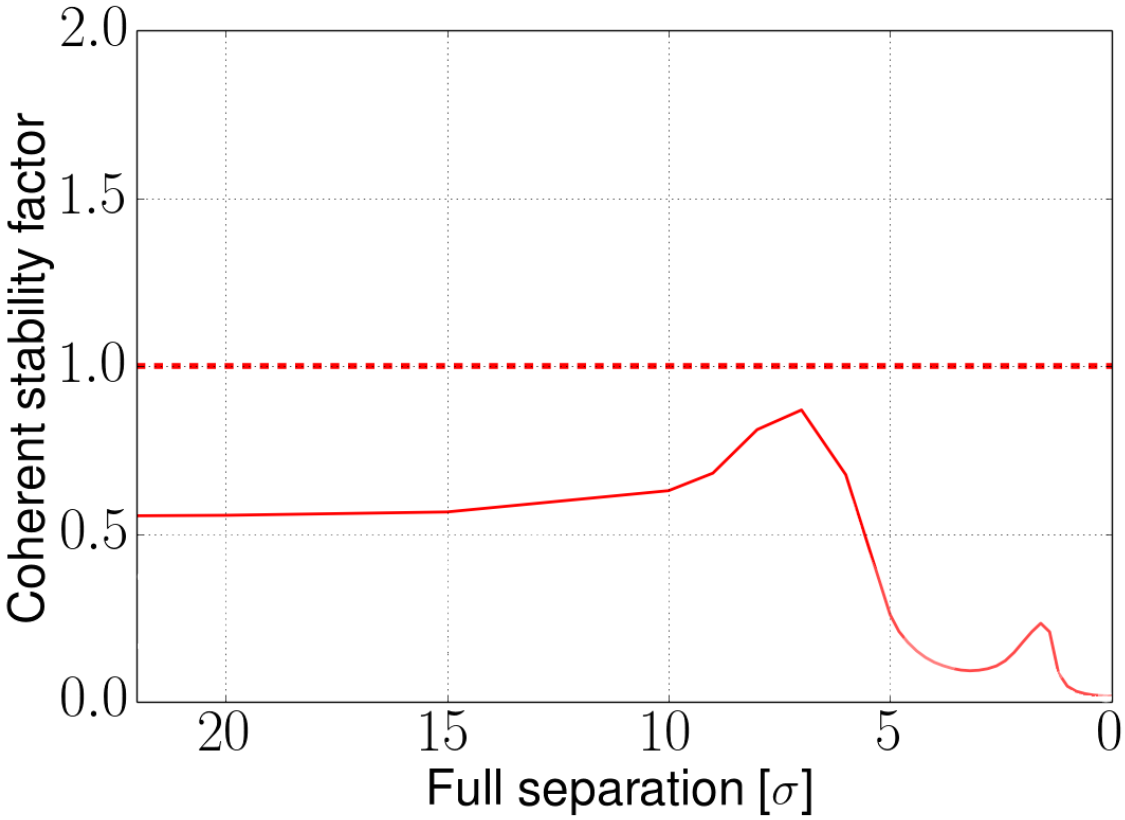
Landau damping of head-tail modes





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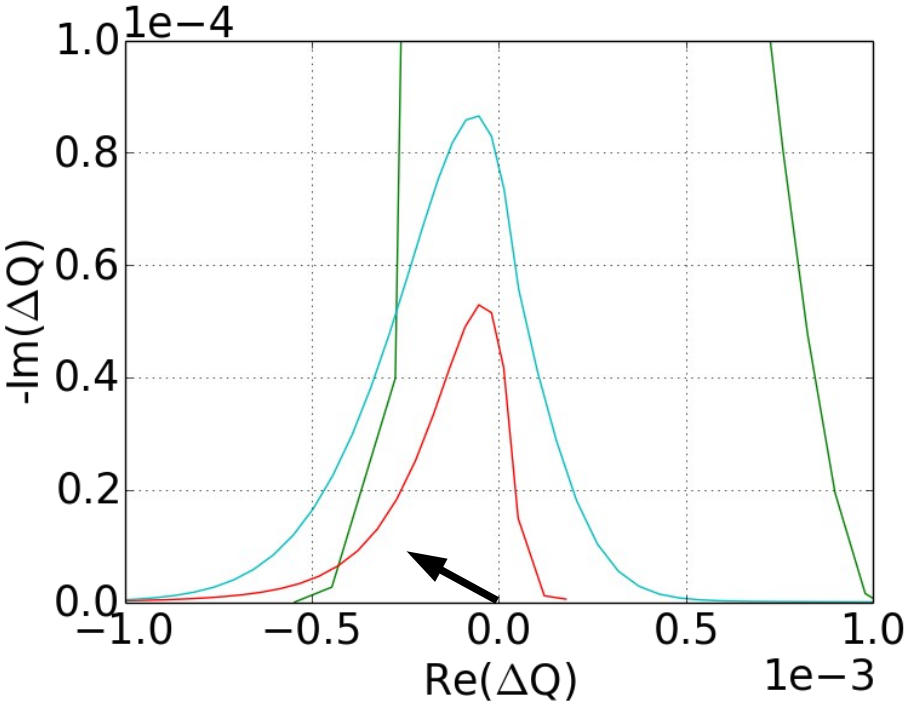

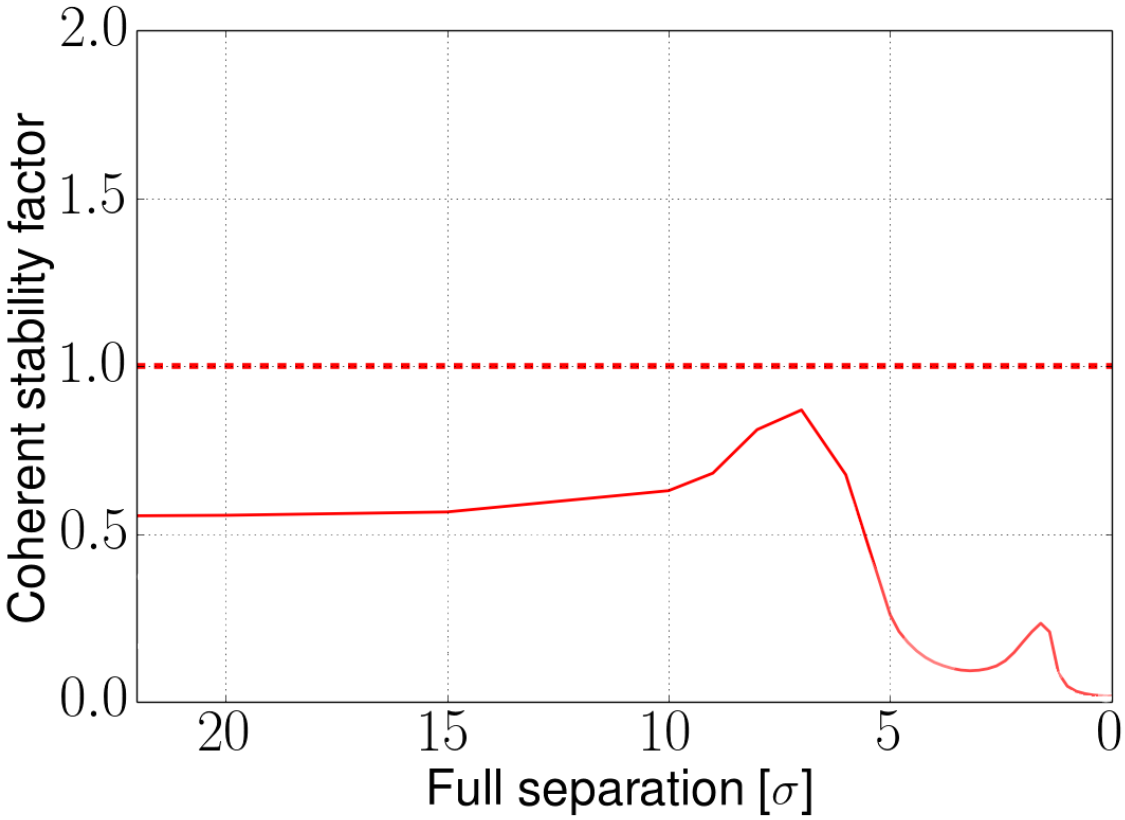

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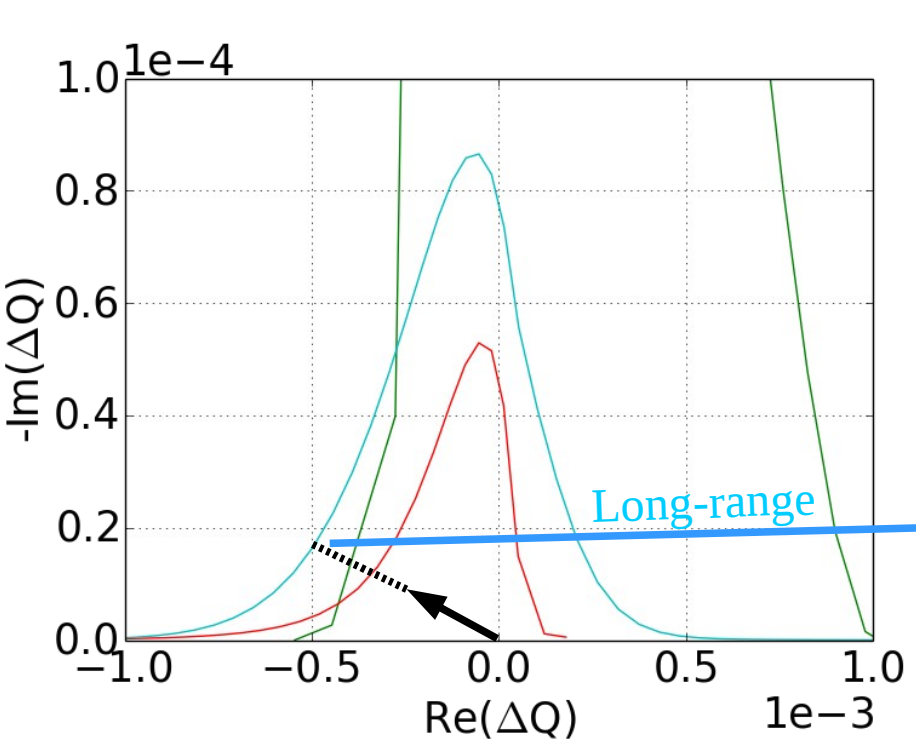

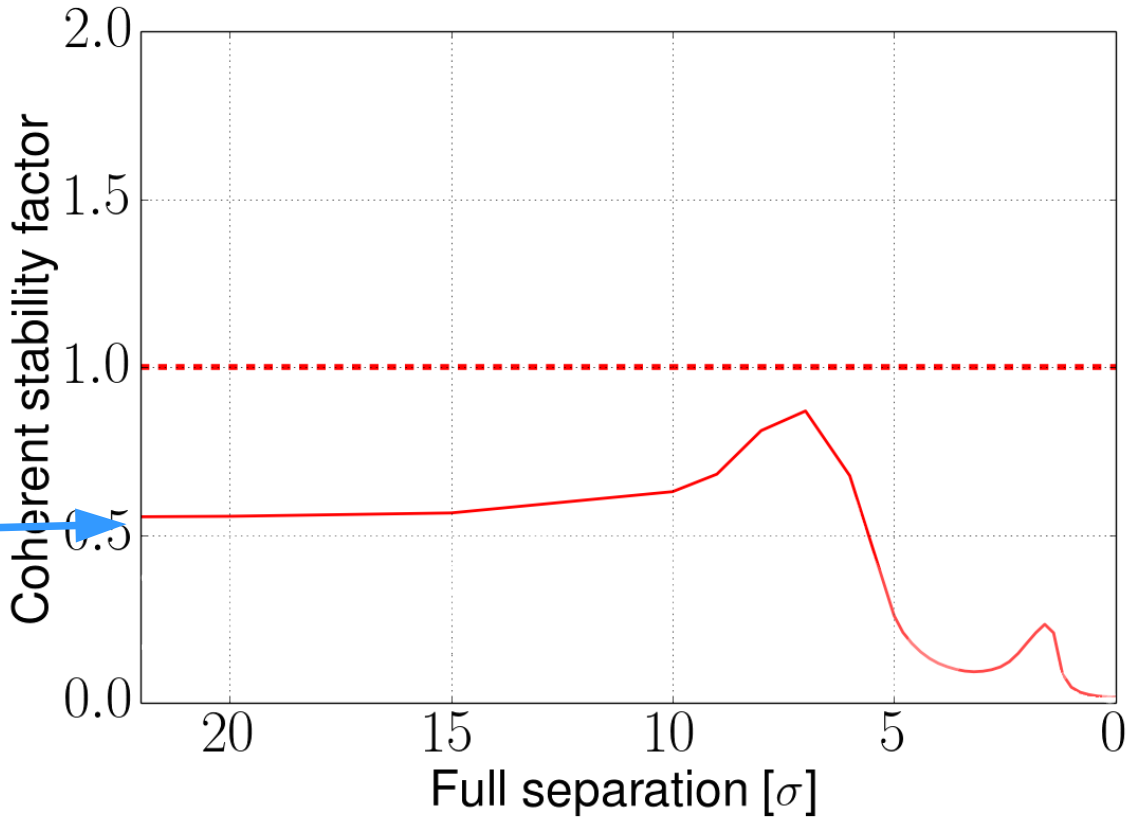

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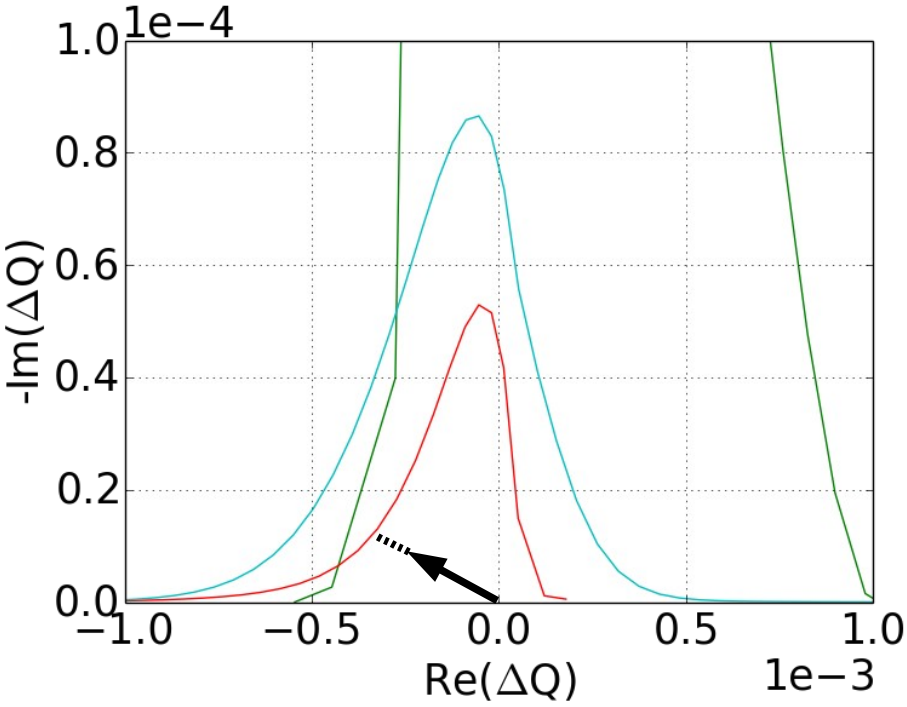

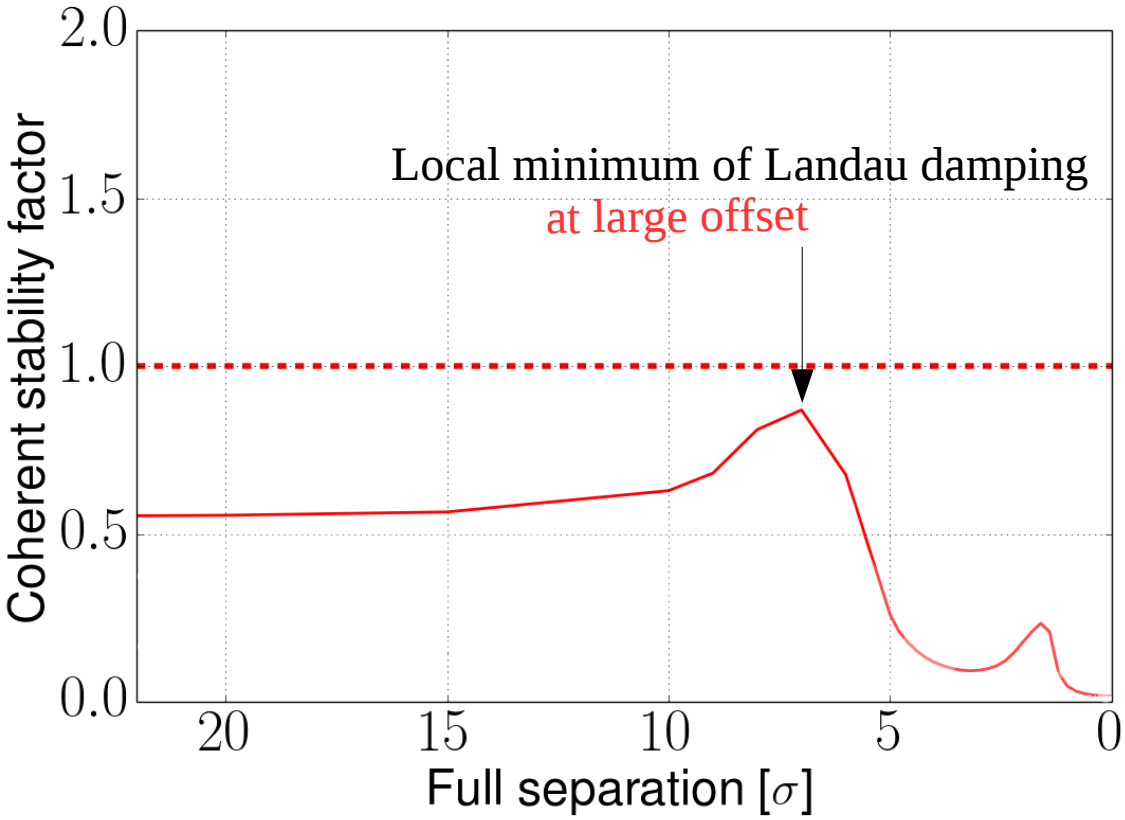

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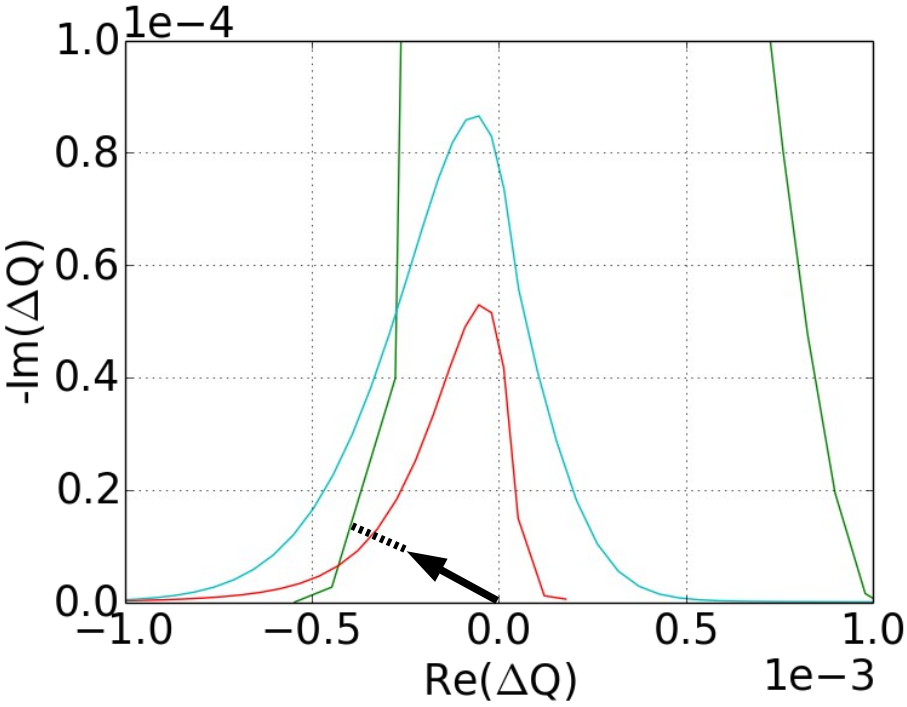

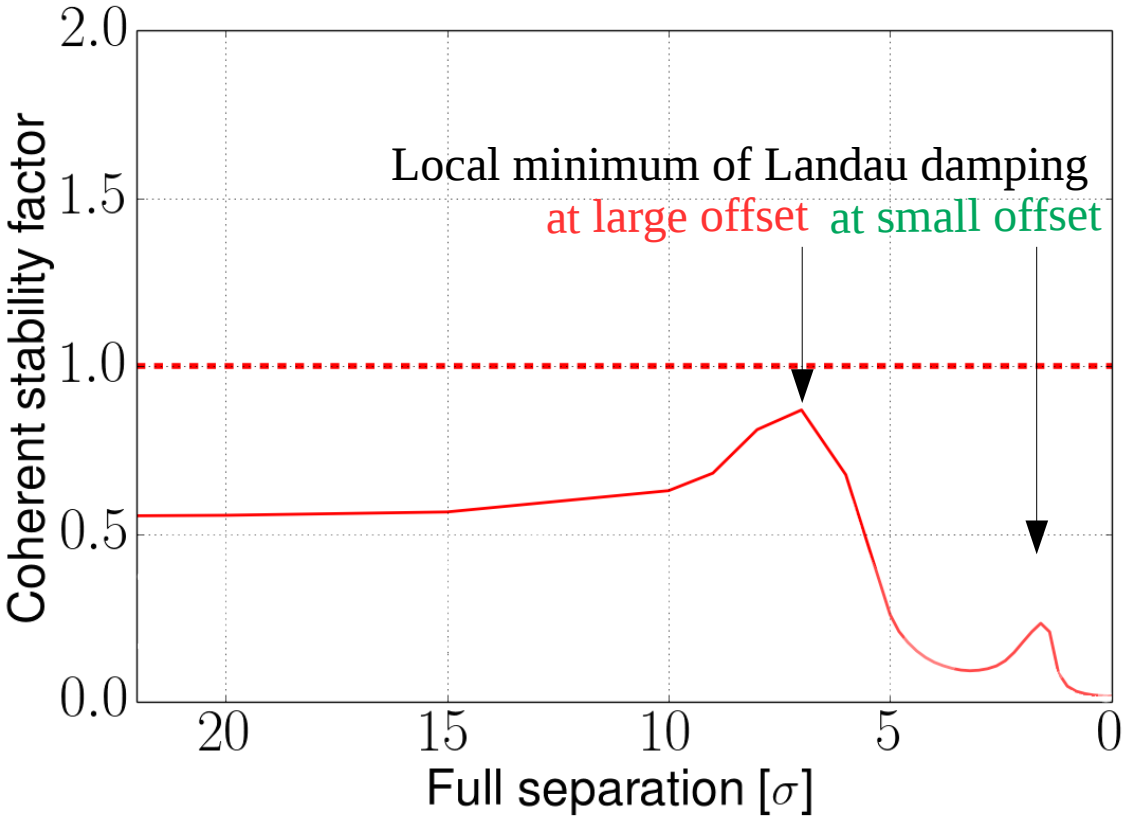

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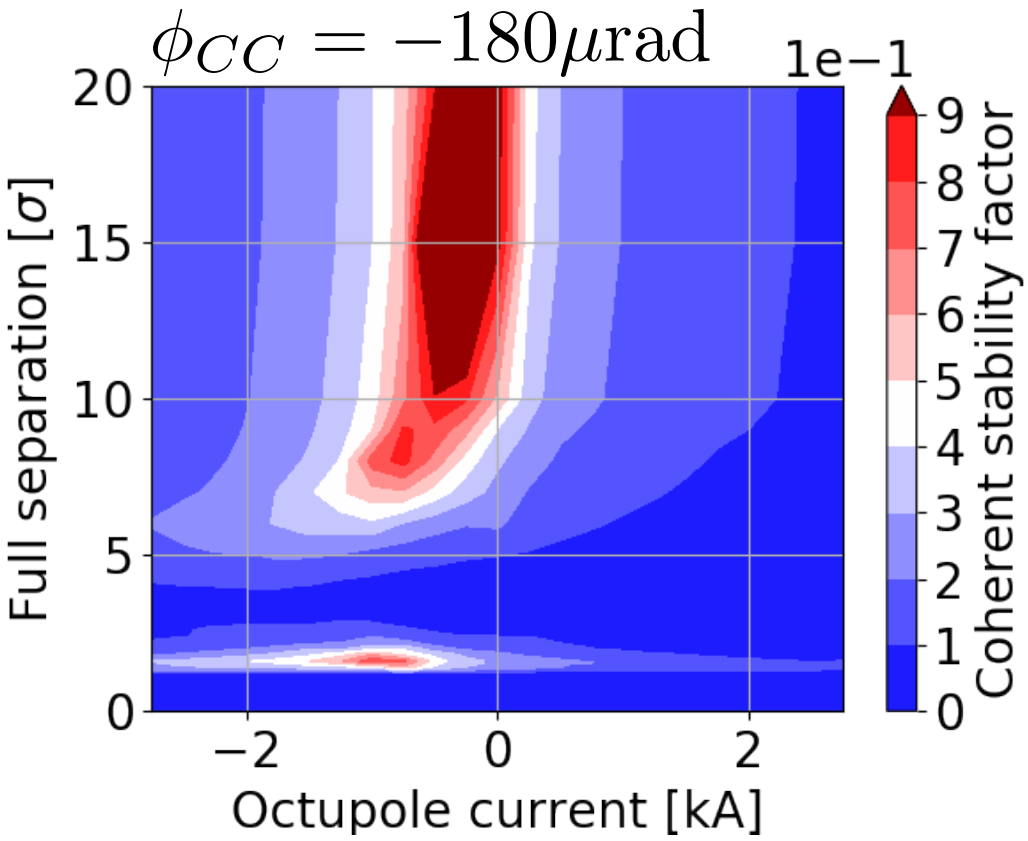
Offset collisions



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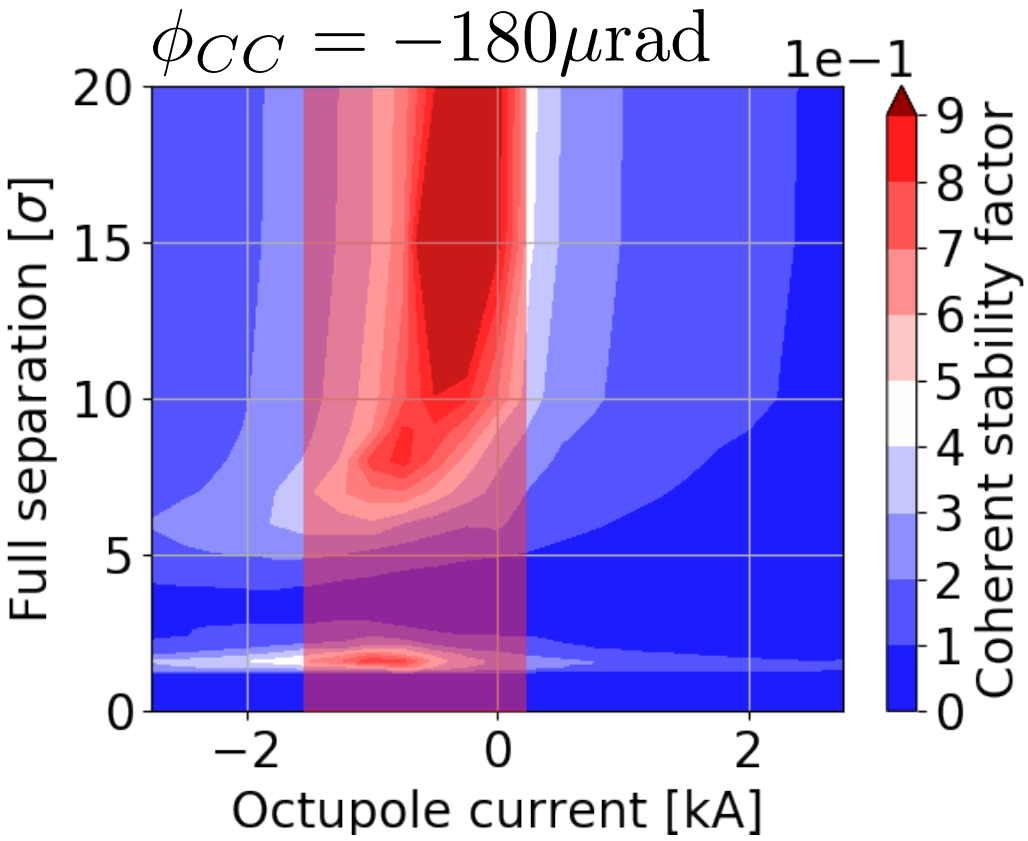

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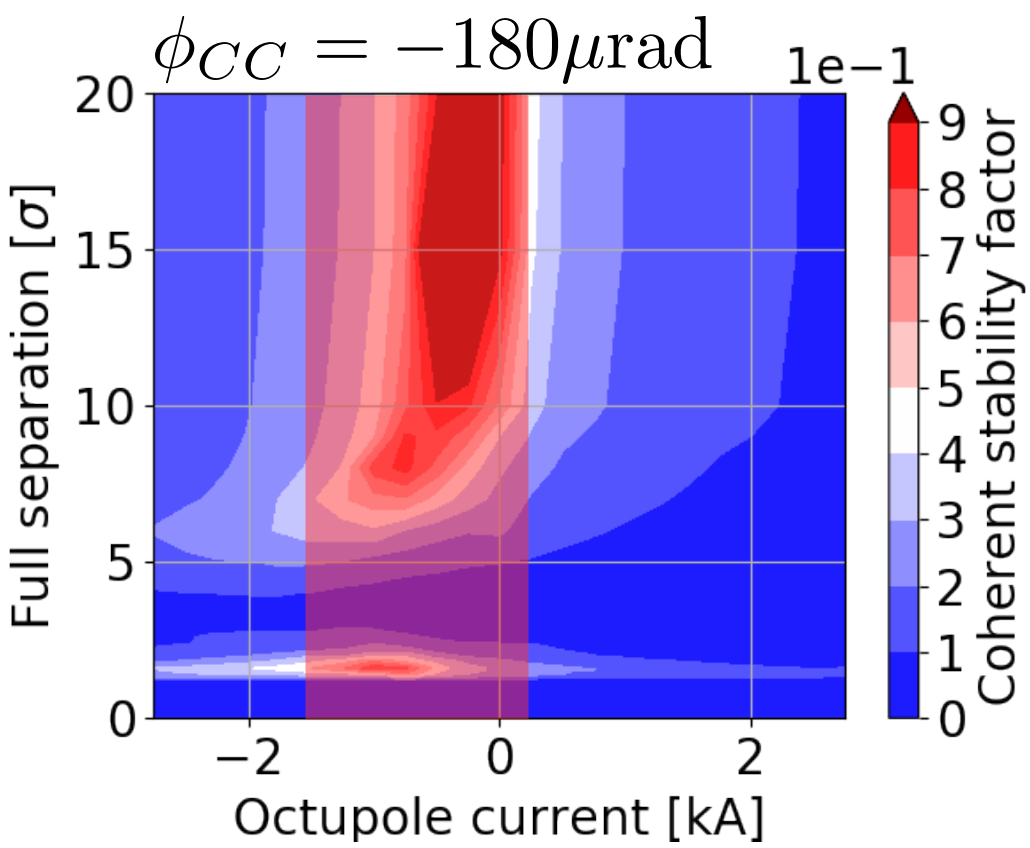

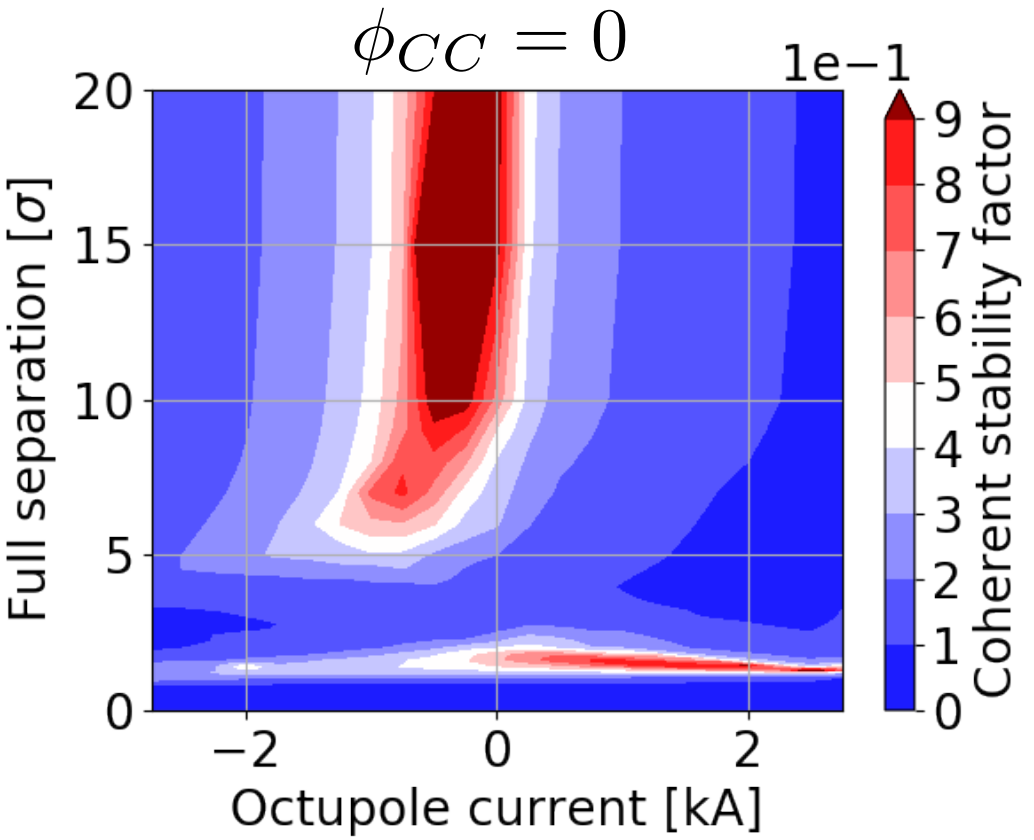

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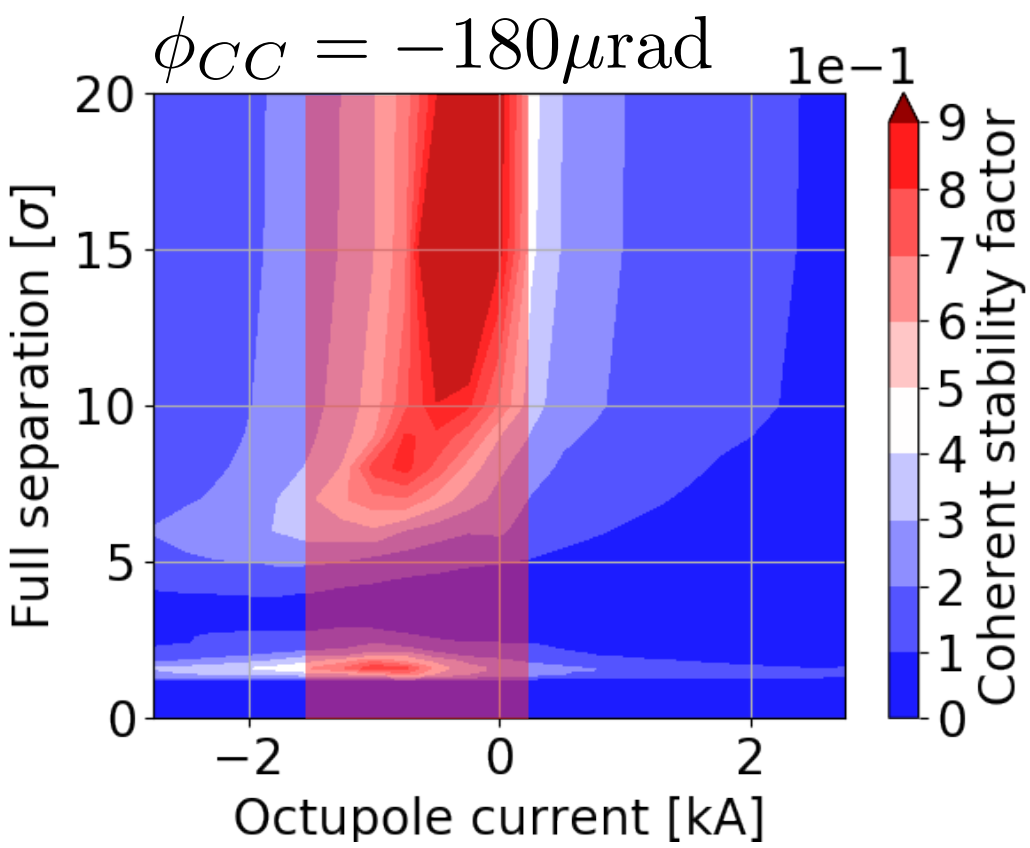

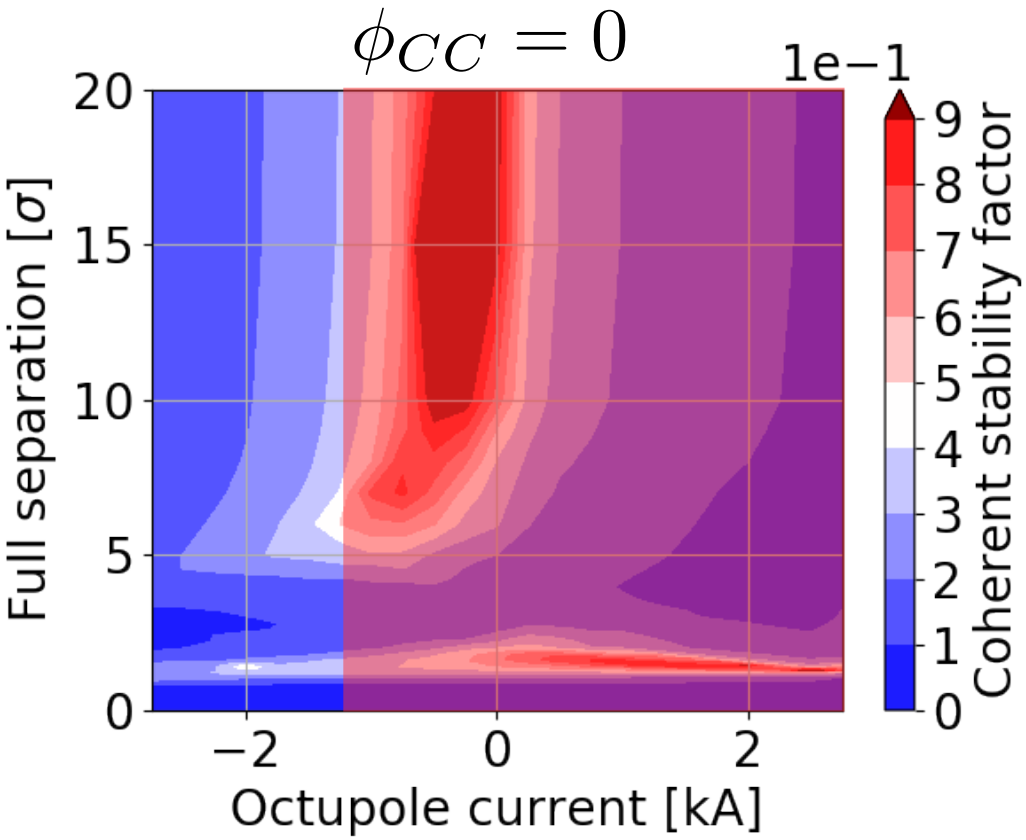

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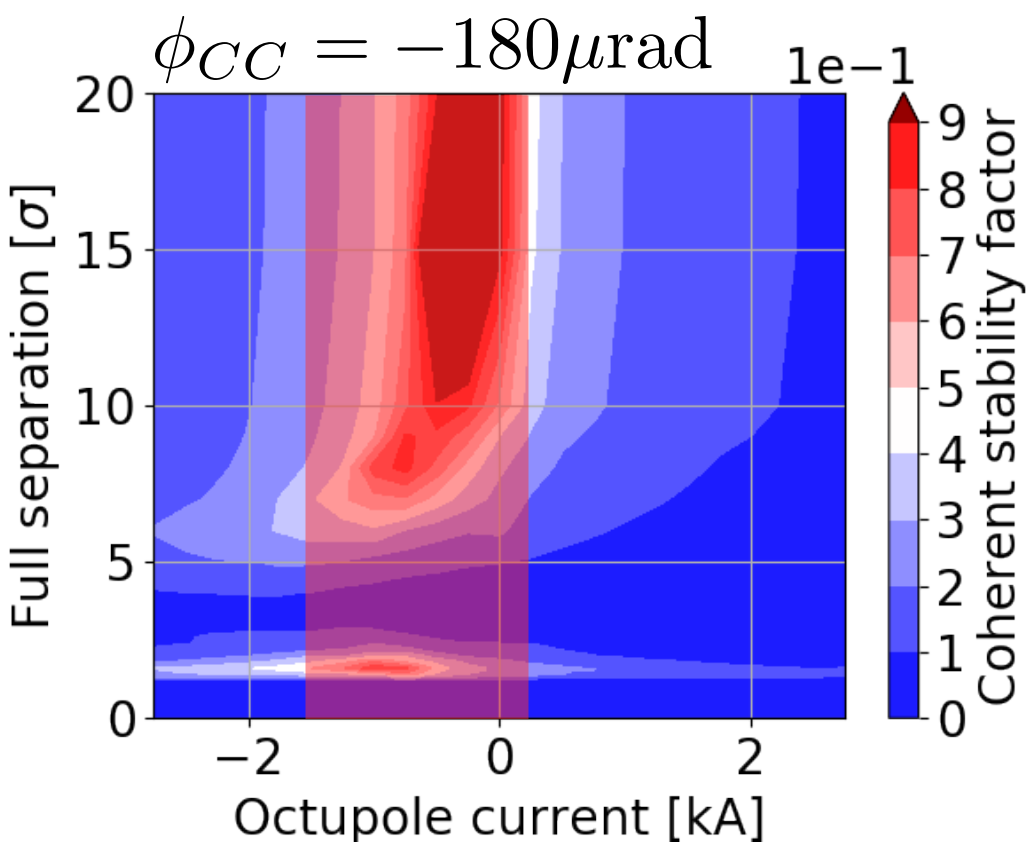
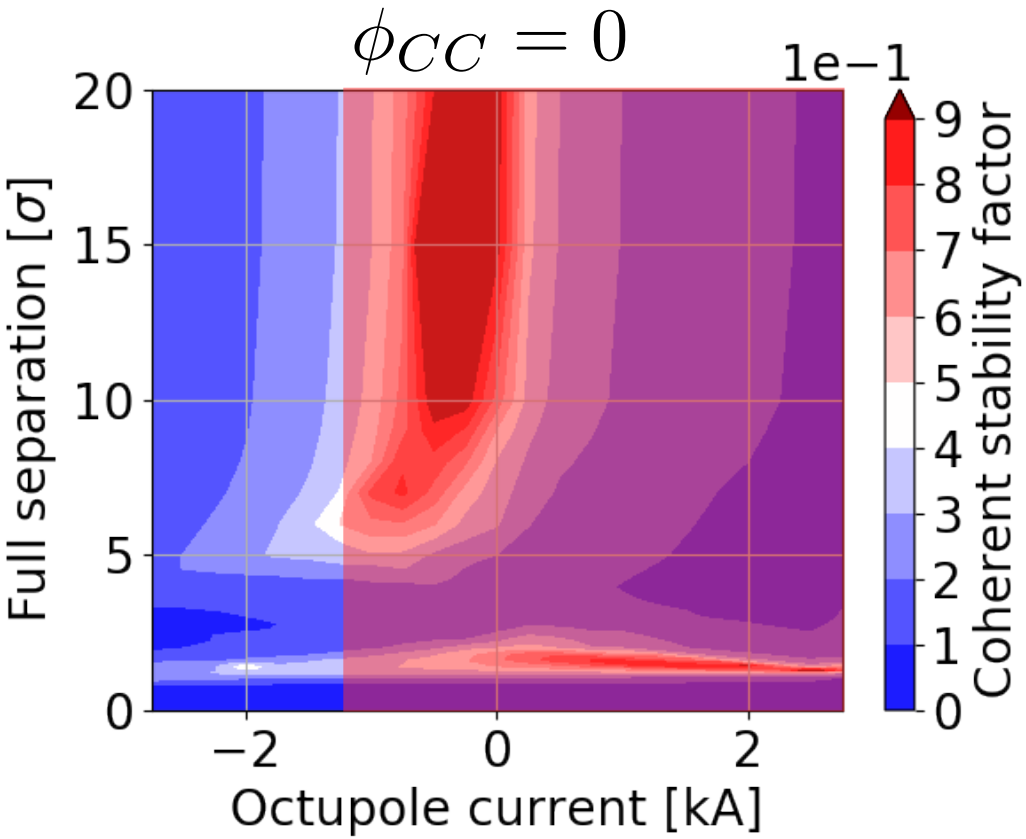
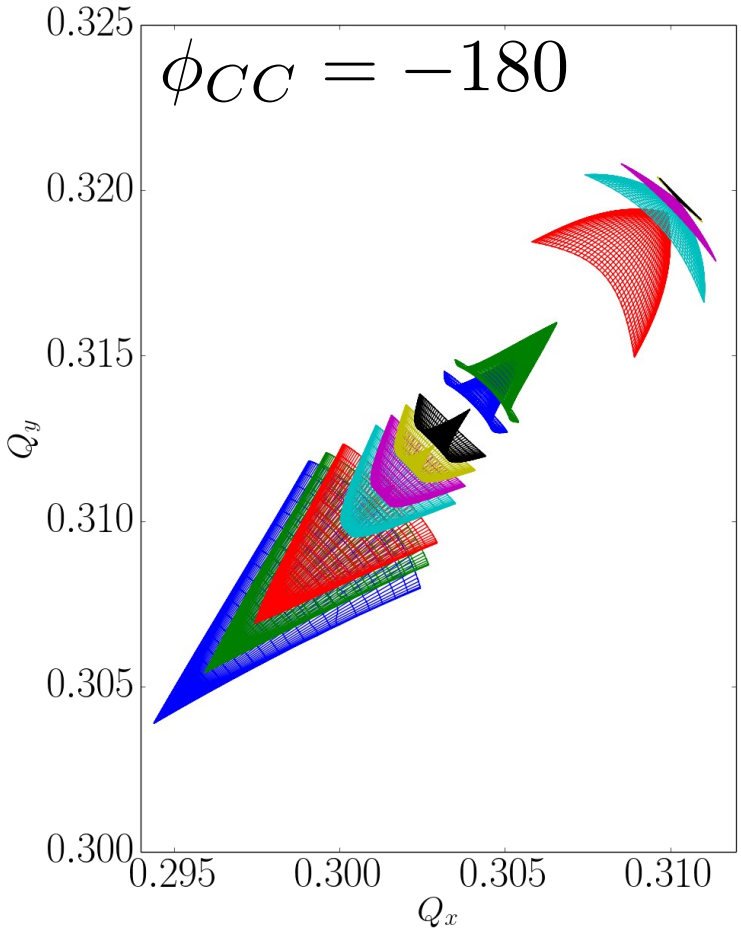




- The operation of the crab cavities with offset beams affects the beam stability as well as the interplay with the amplitude detuning driven by the octupoles
- So does:
  - The β*
  - The crossing / crab angle
  - The plane and synchronisation of the separation bumps in the different IPs

The Shakiri effect



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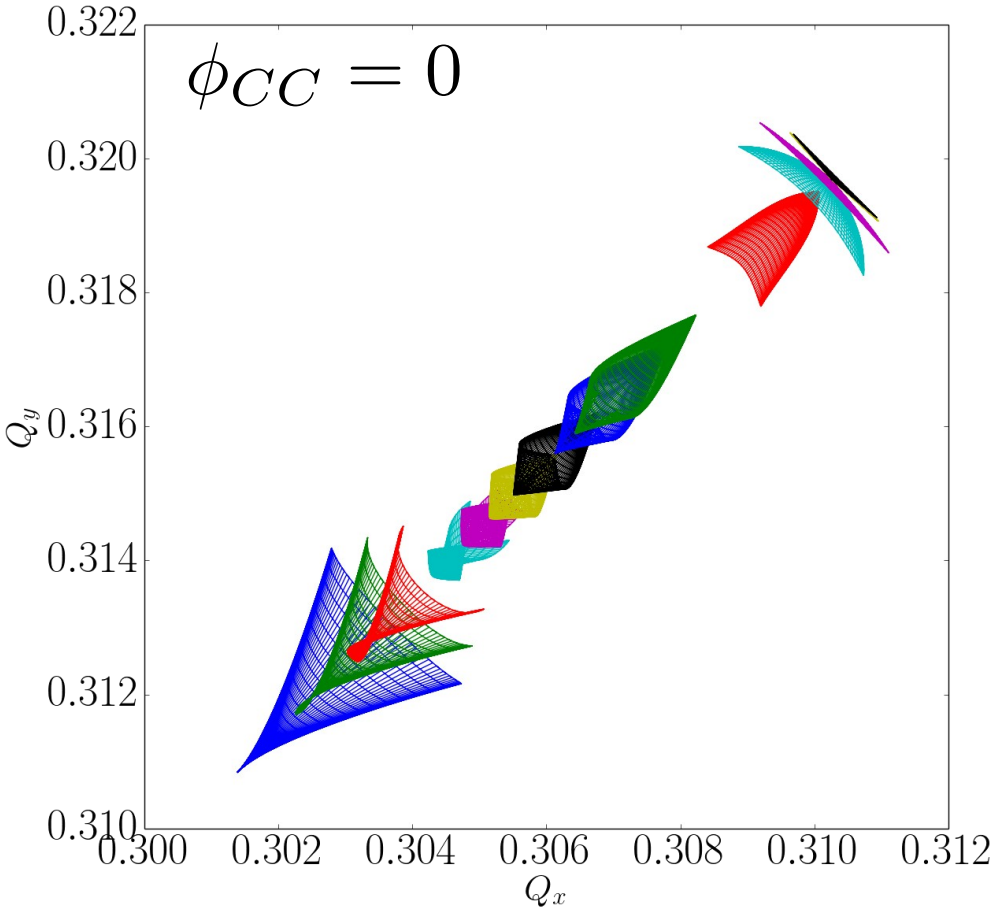

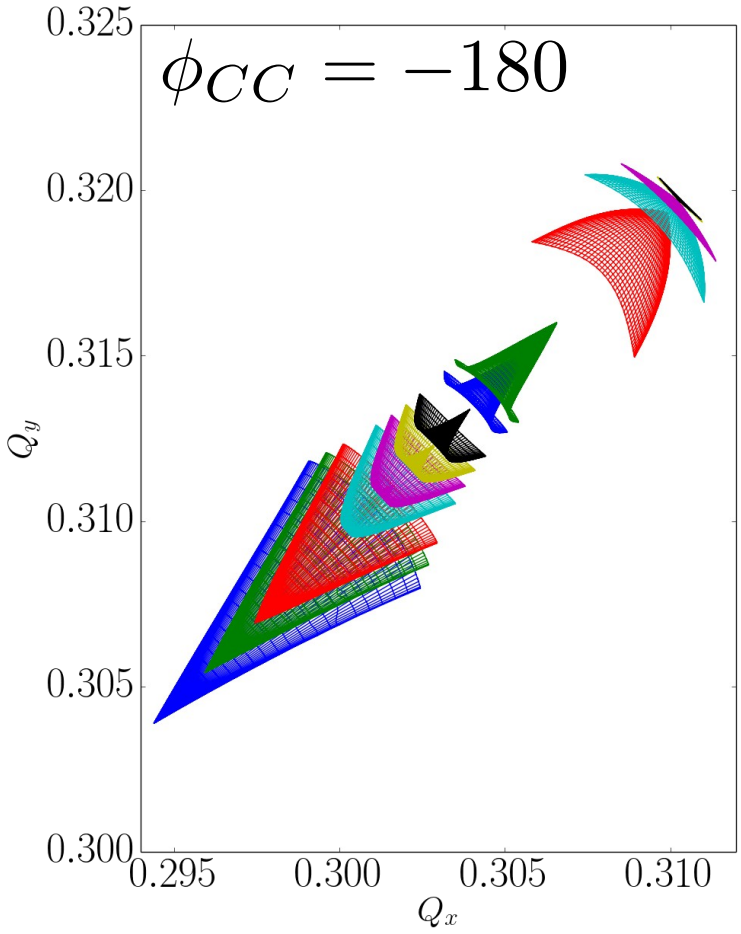

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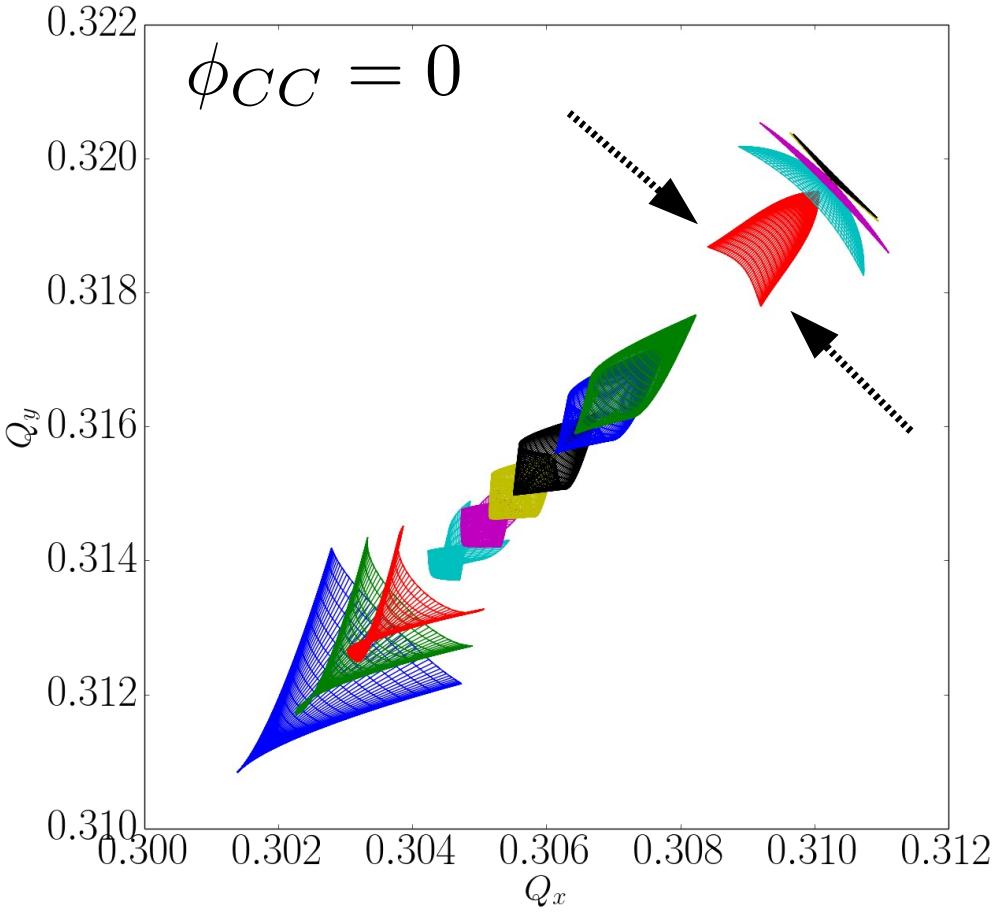

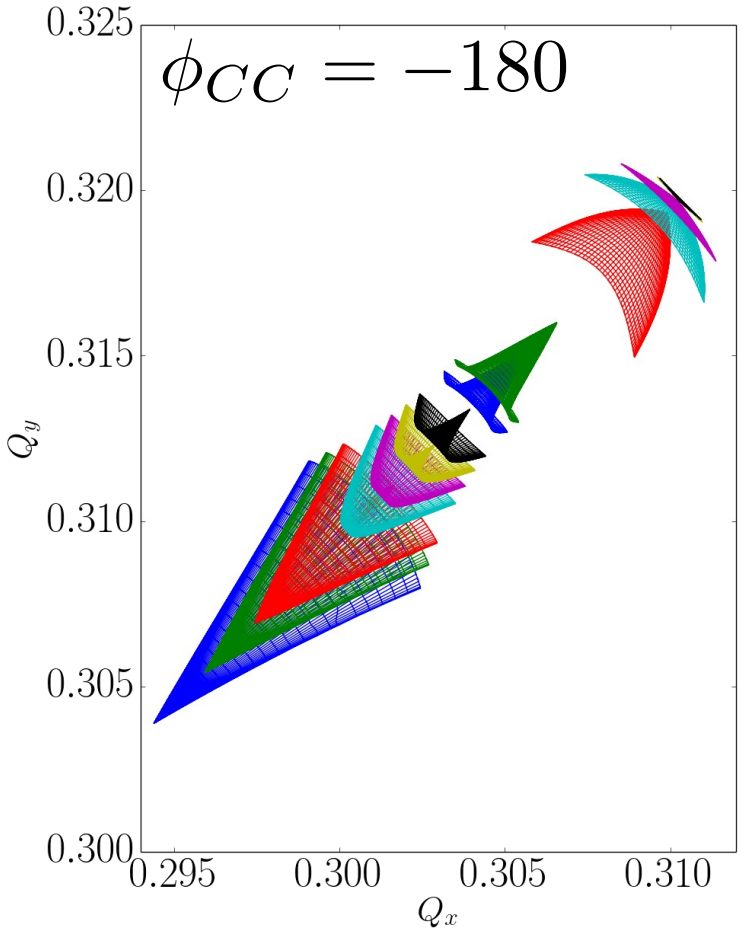

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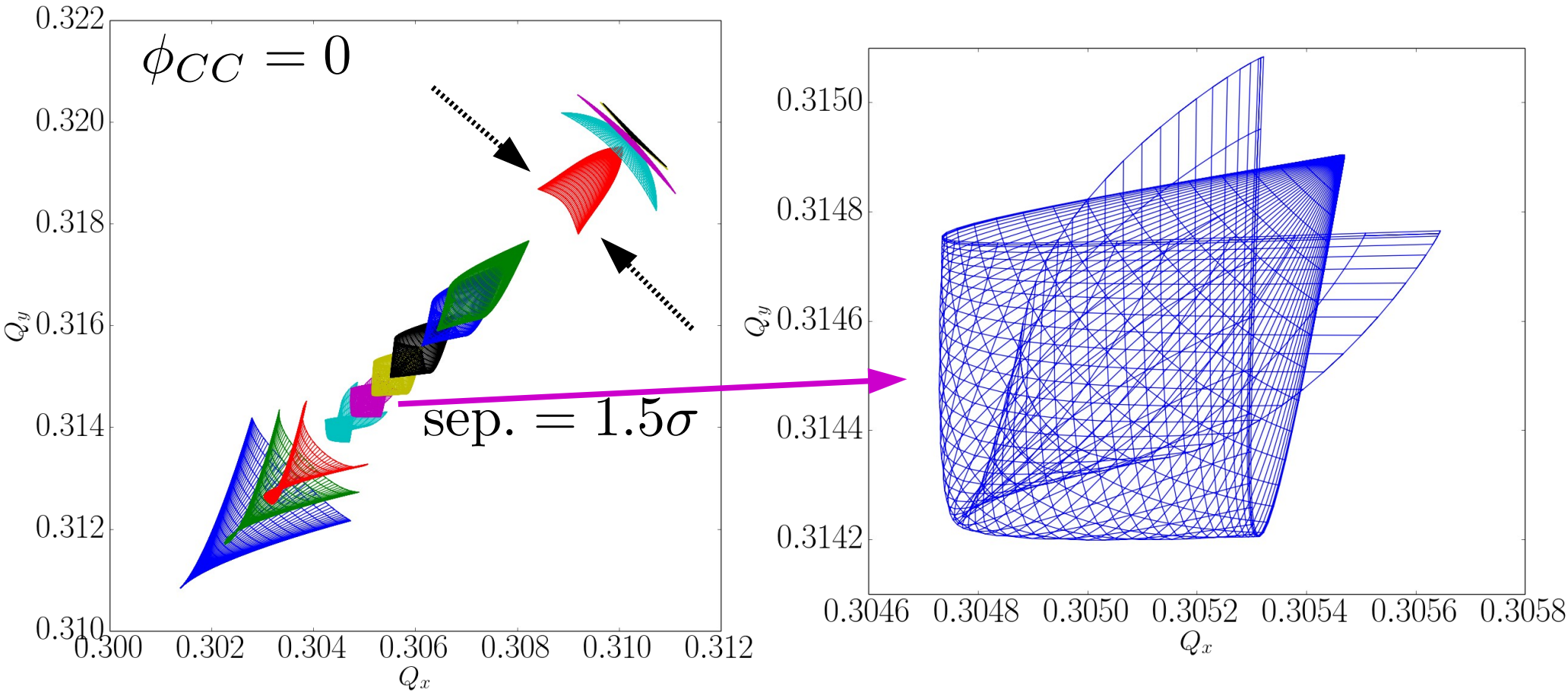

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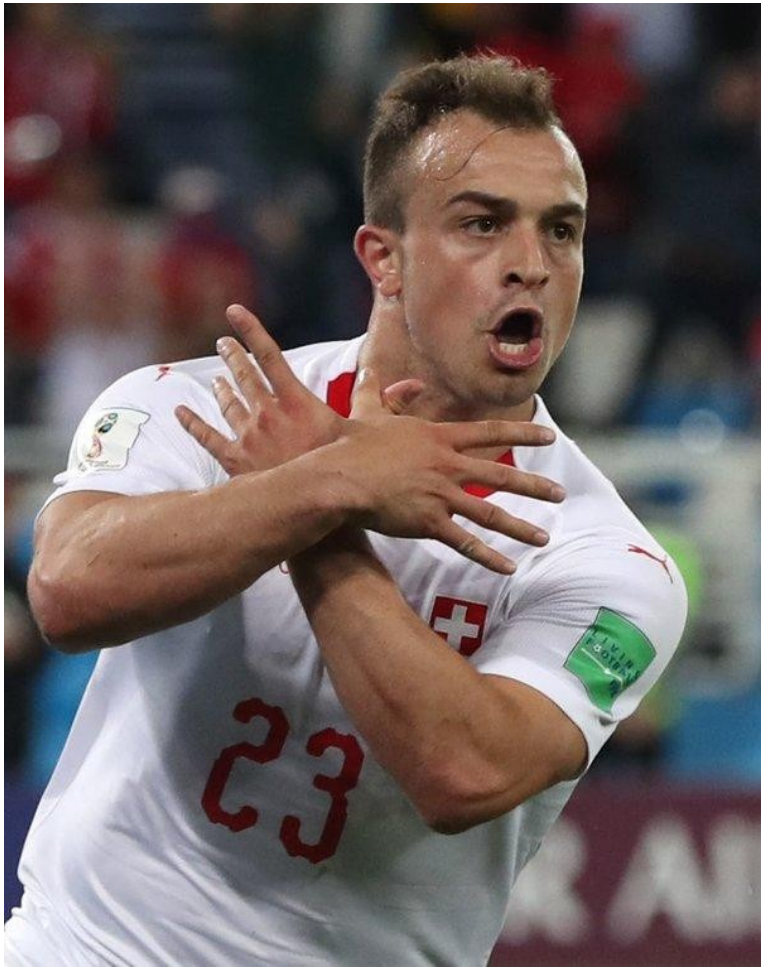
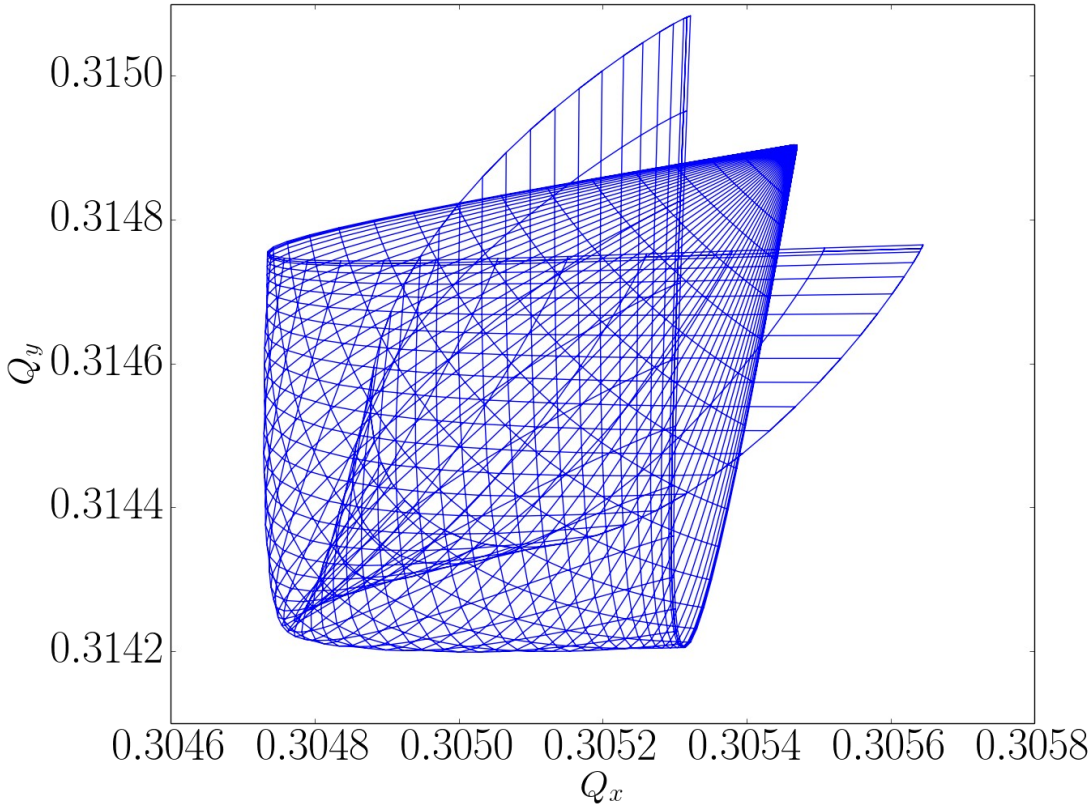


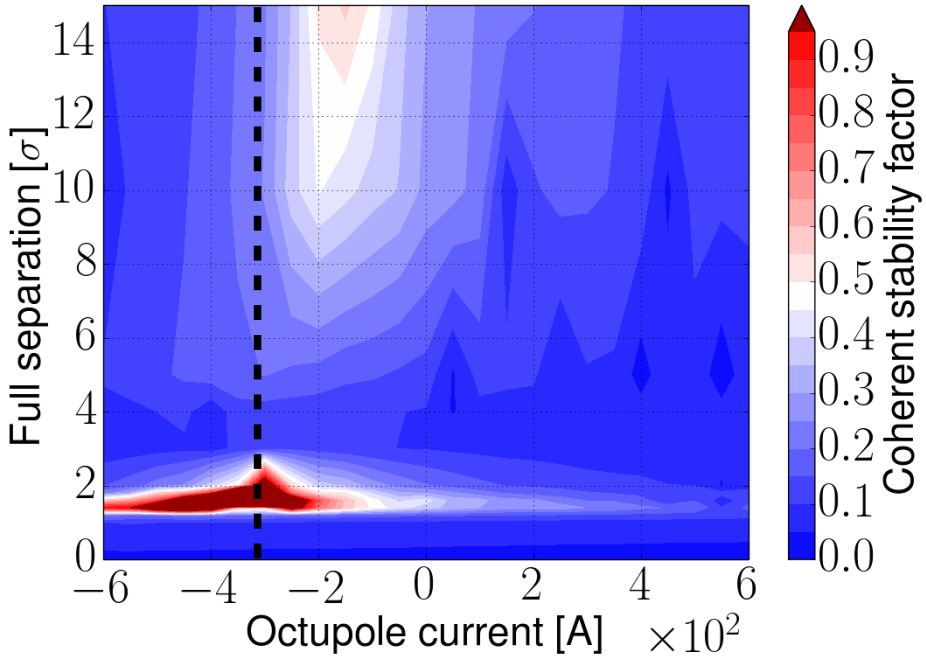


- Xherdan Shakiri was misunderstood: he was trying to tell us about a mitigation strategy for the loss of Landau damping with offset beams

Observations

- First observations in 2012, due to offset levelling in IP8
- Dedicated experiment in 2018, demonstrating mitigation by fast crossing of the unstable condition S. Fartoukh, et al., CERN-NOTE-2019, in prep.

  → This mitigation is not suitable for luminosity levelling



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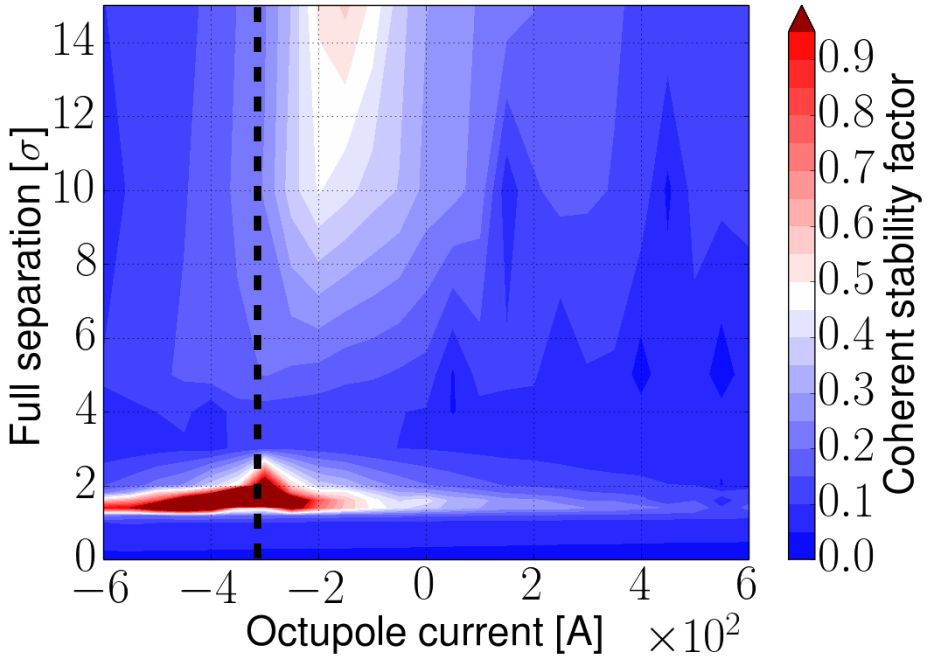

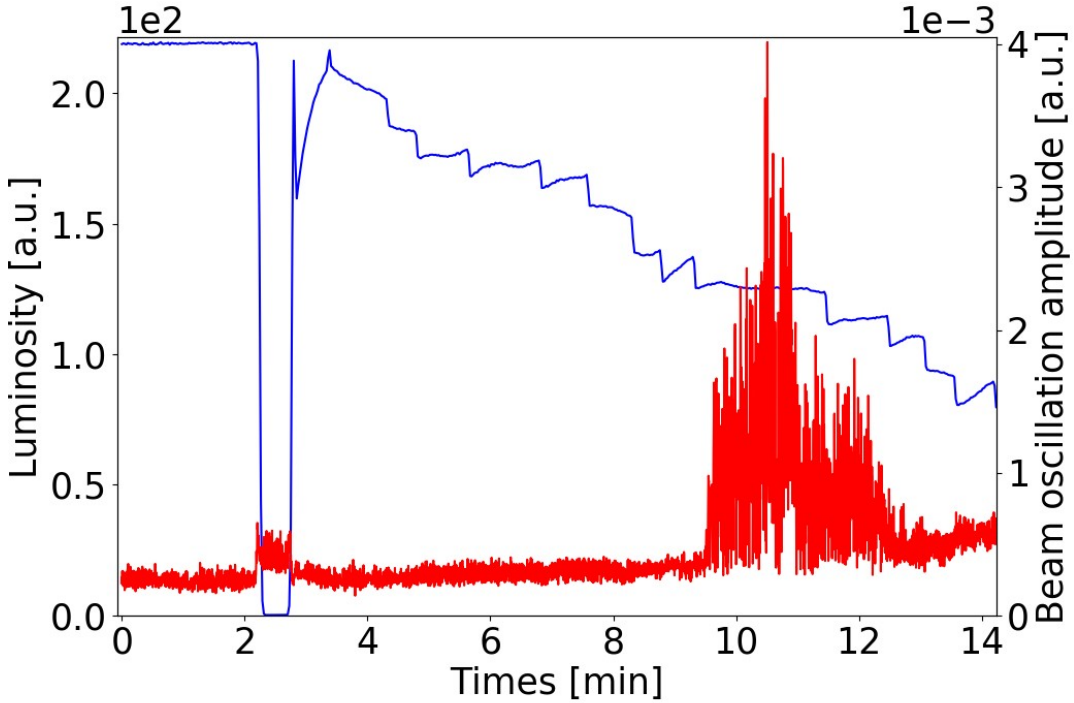

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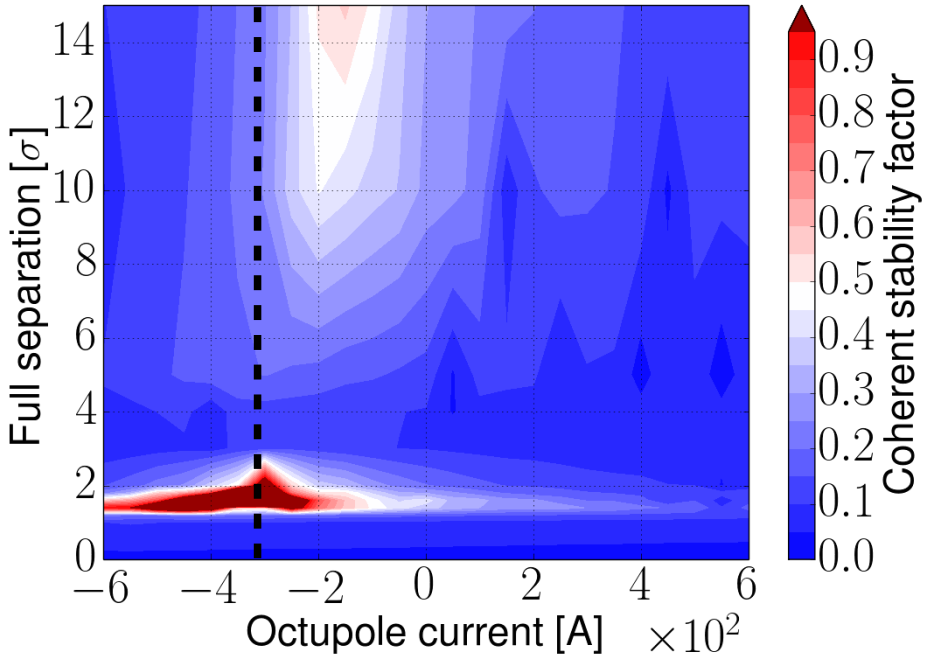

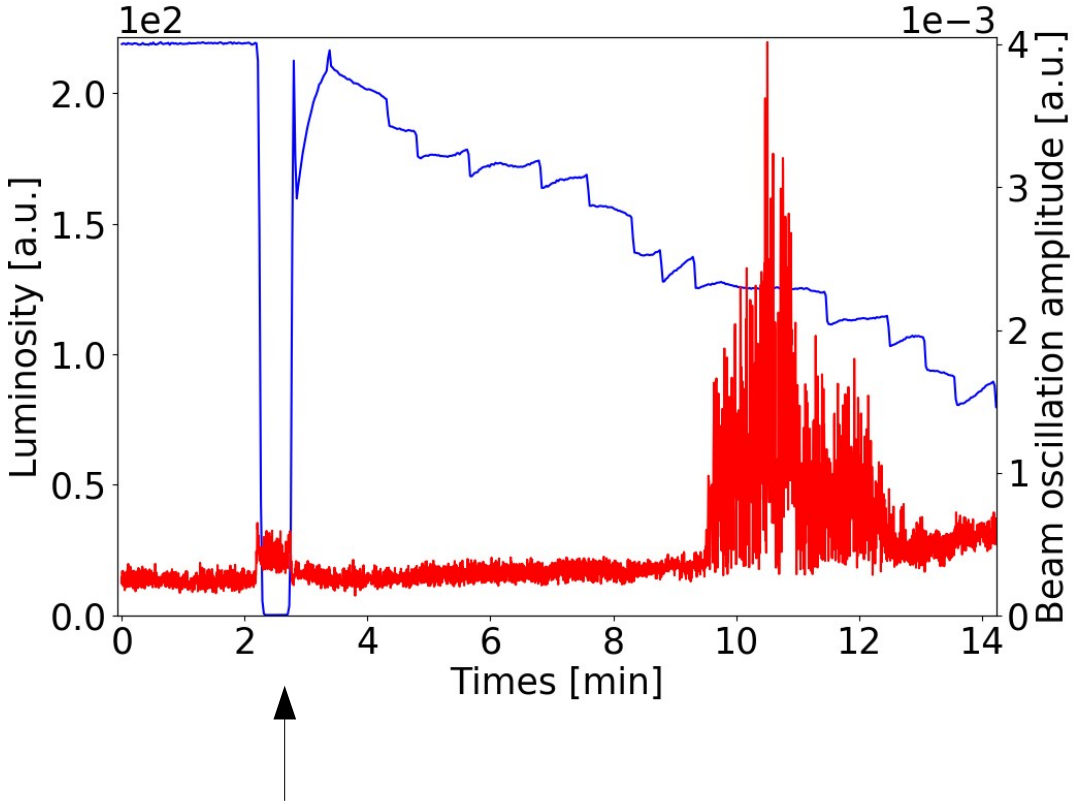

Fast crossing of transient unstable configuration

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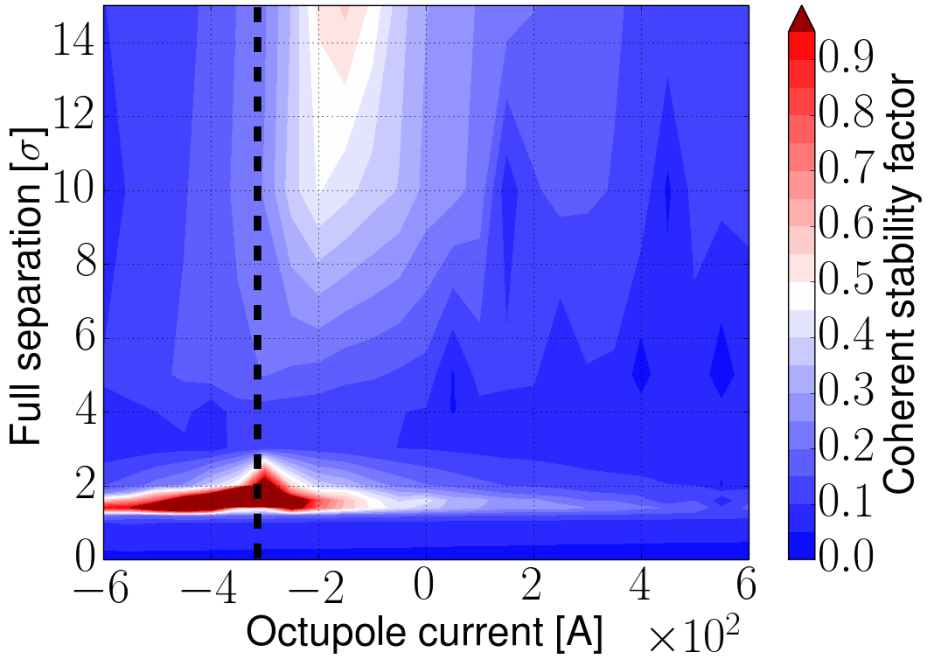
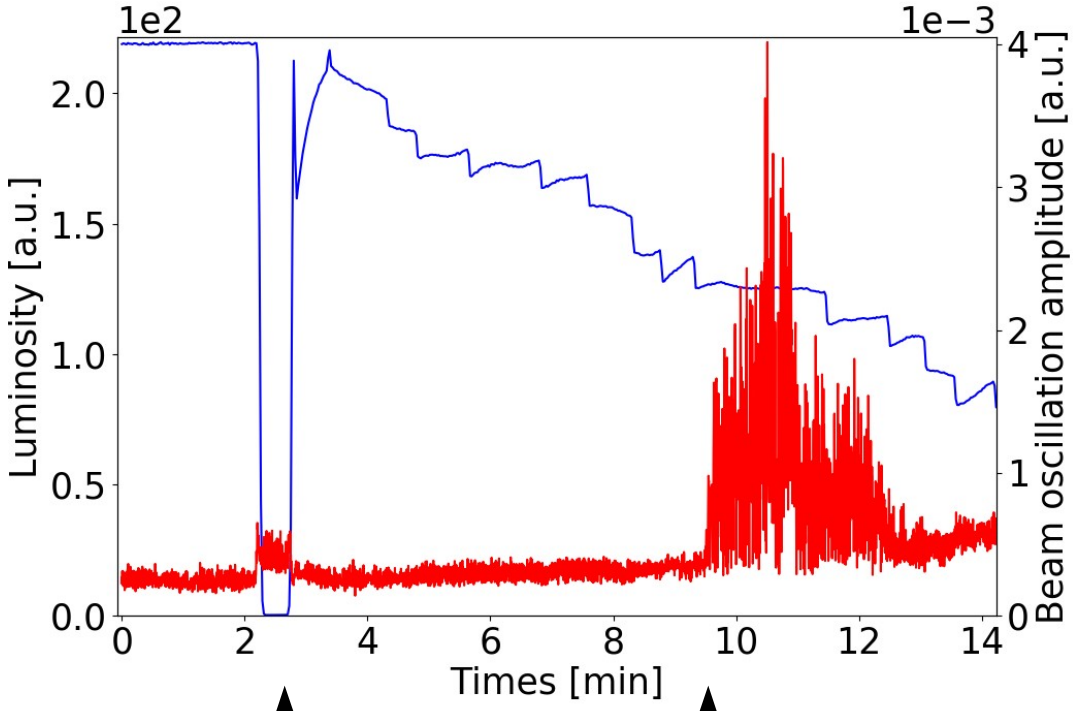
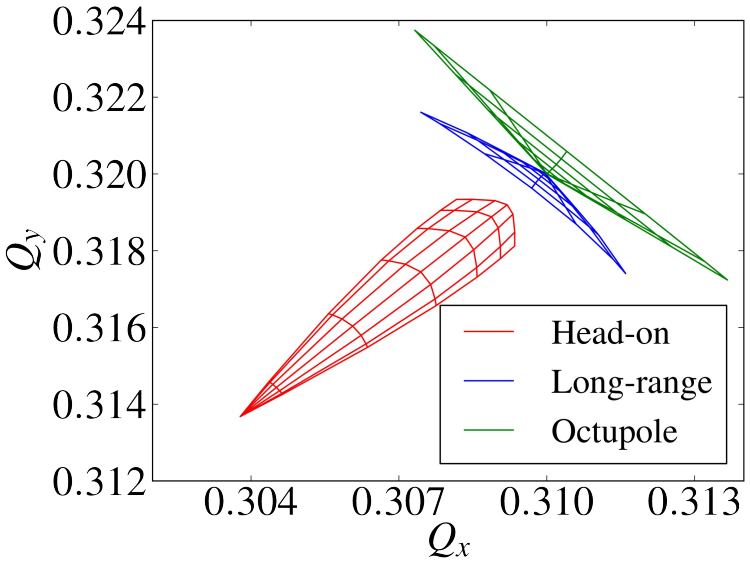


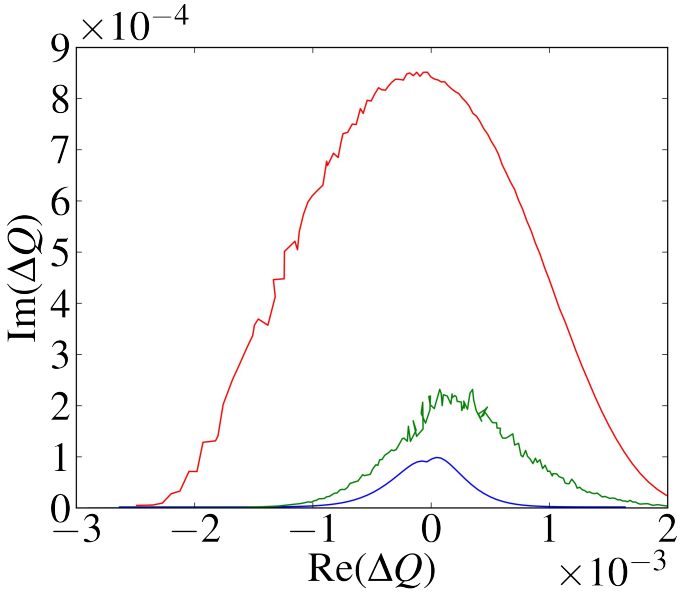


Fast crossing of transient unstable configuration

Instability when steady at 1.6σ full separation between the beams

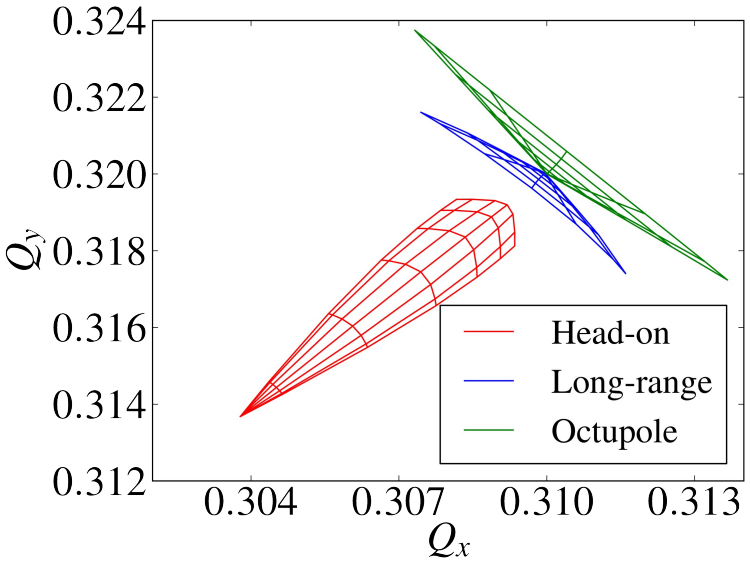
Head-on interaction

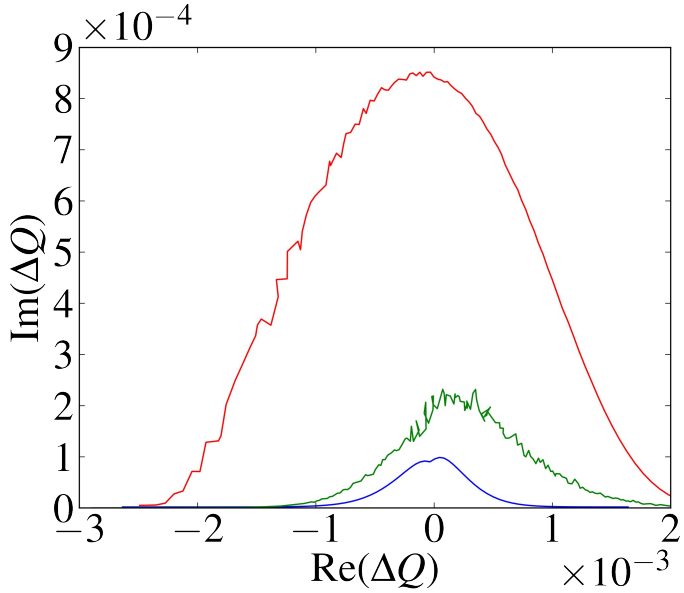




- By generating a large amplitude detuning for the core of the beam distribution, head-on interaction is very efficient at providing Landau damping

Head-on interaction





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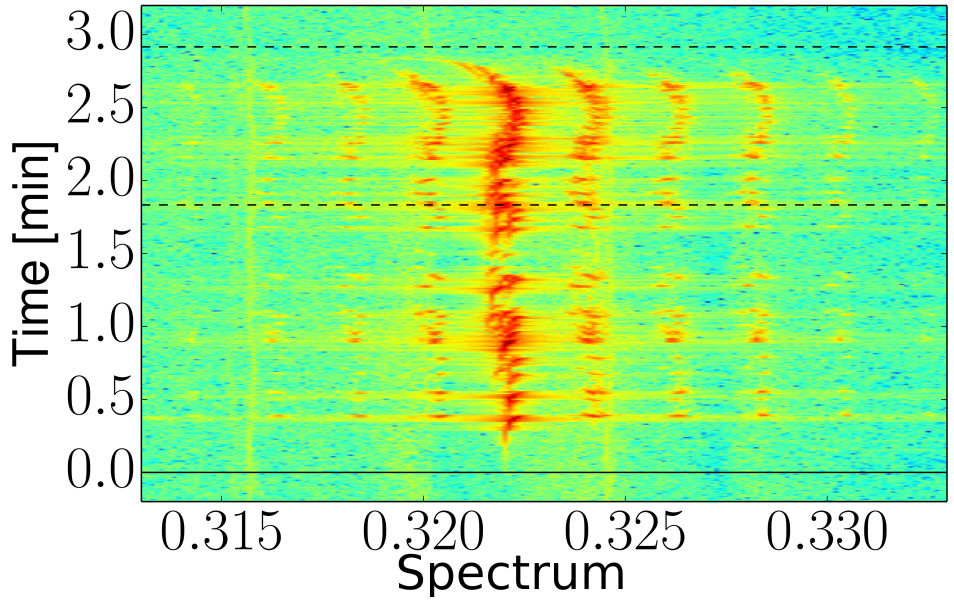
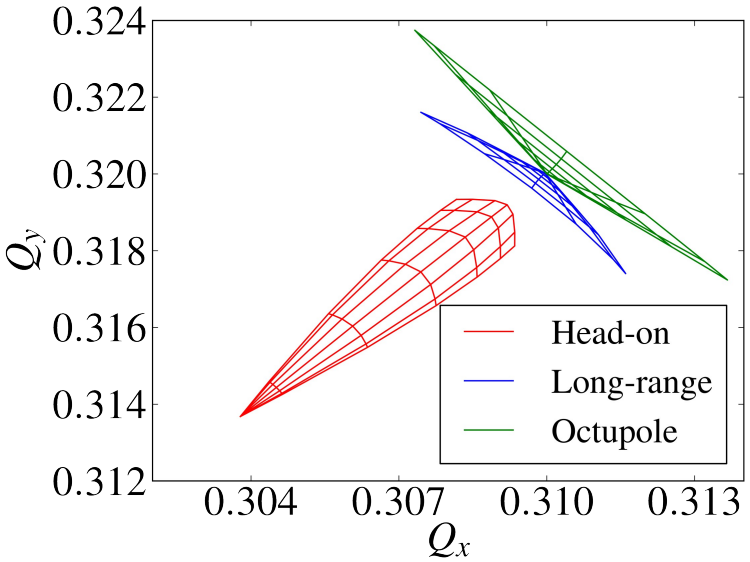
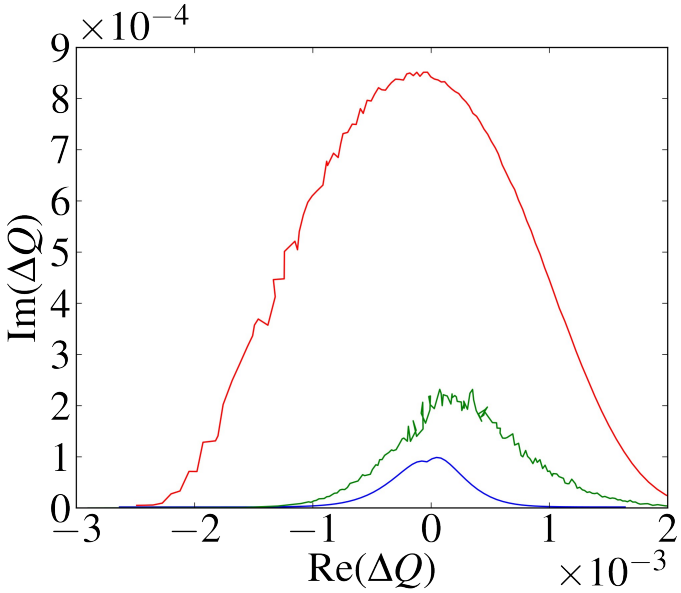


Head-on interaction





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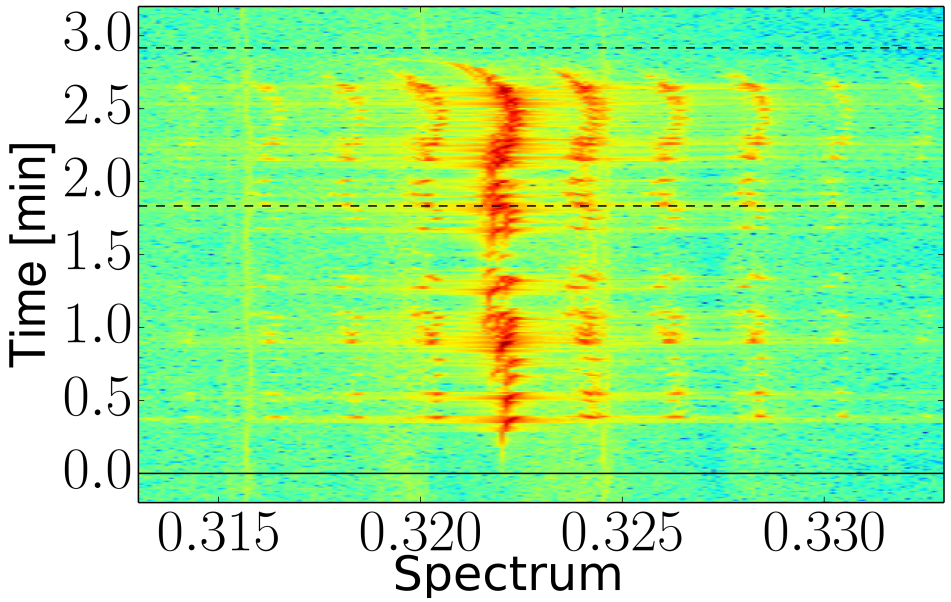
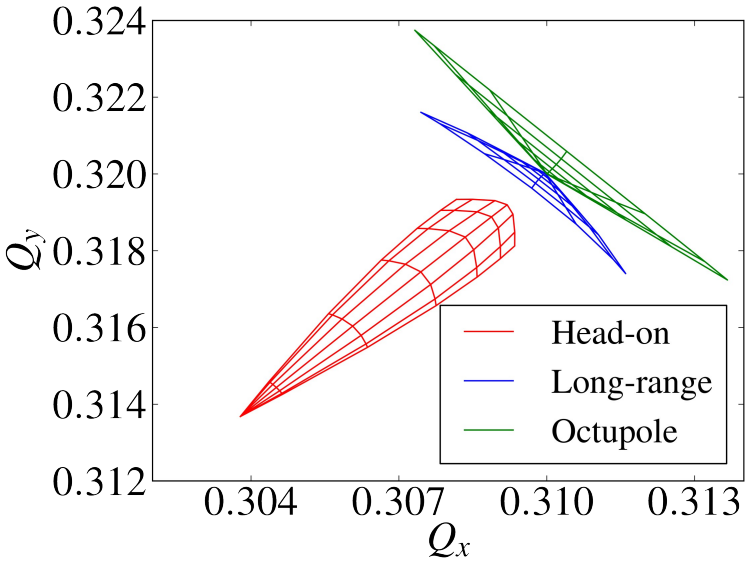
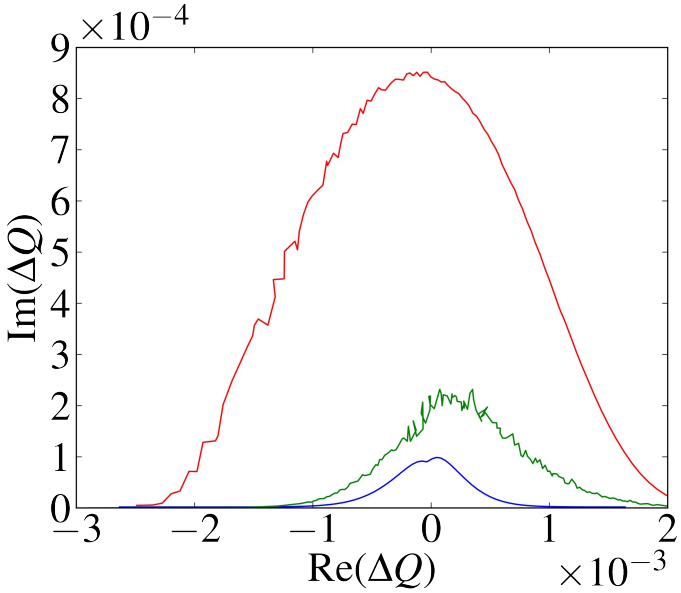
    A. Romano, et al., Phys. Rev. Accel. Beams 21, 061002 (2018)



Head-on interaction





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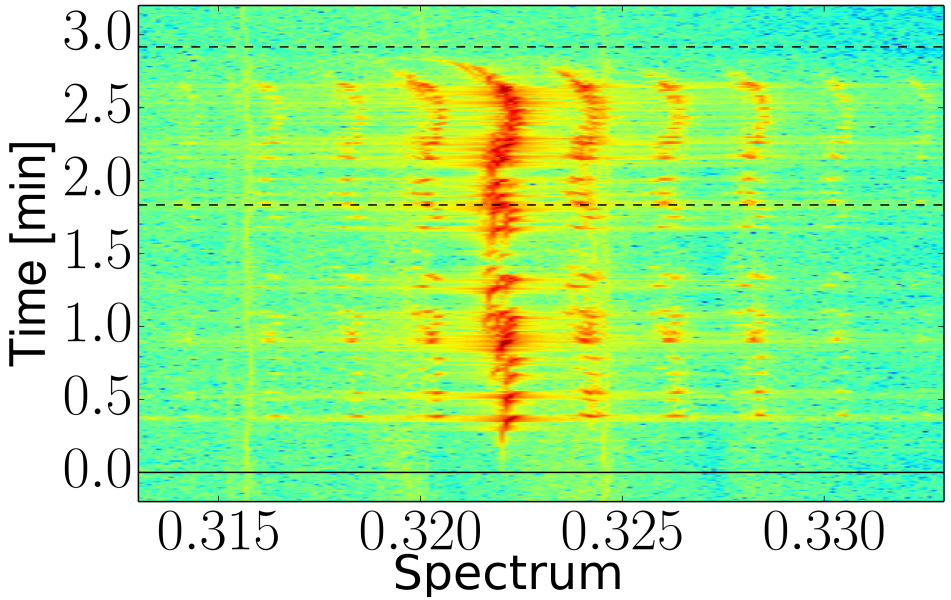
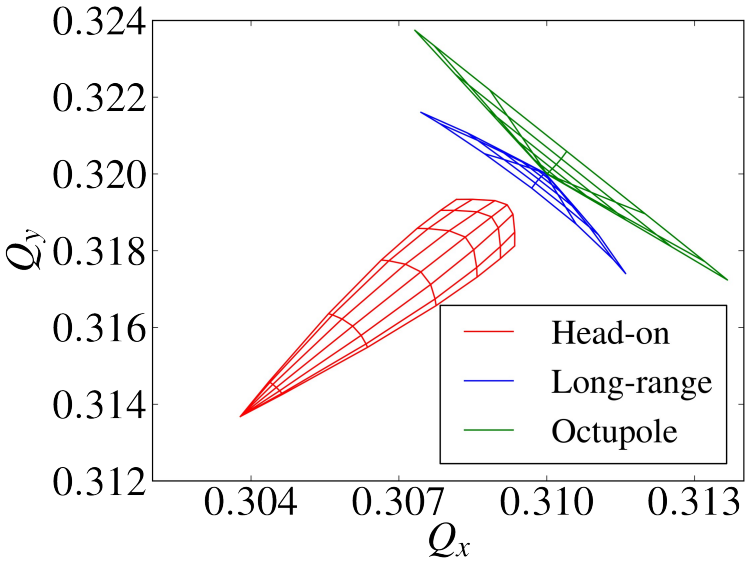
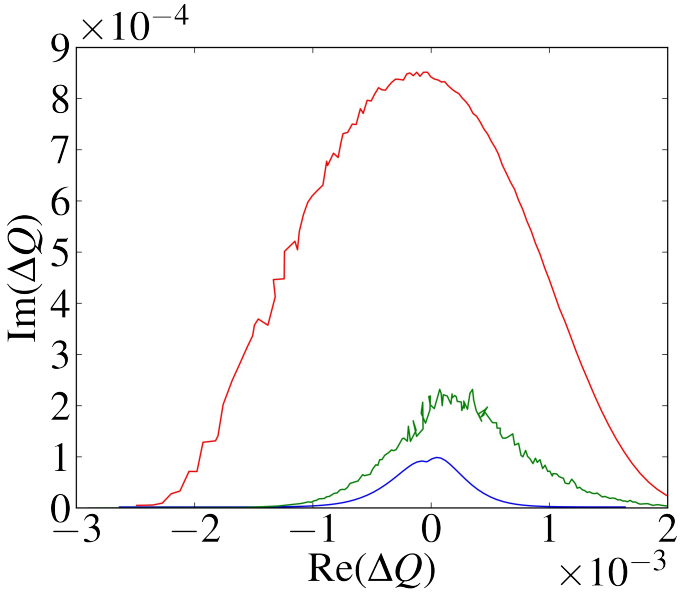


Head-on interaction





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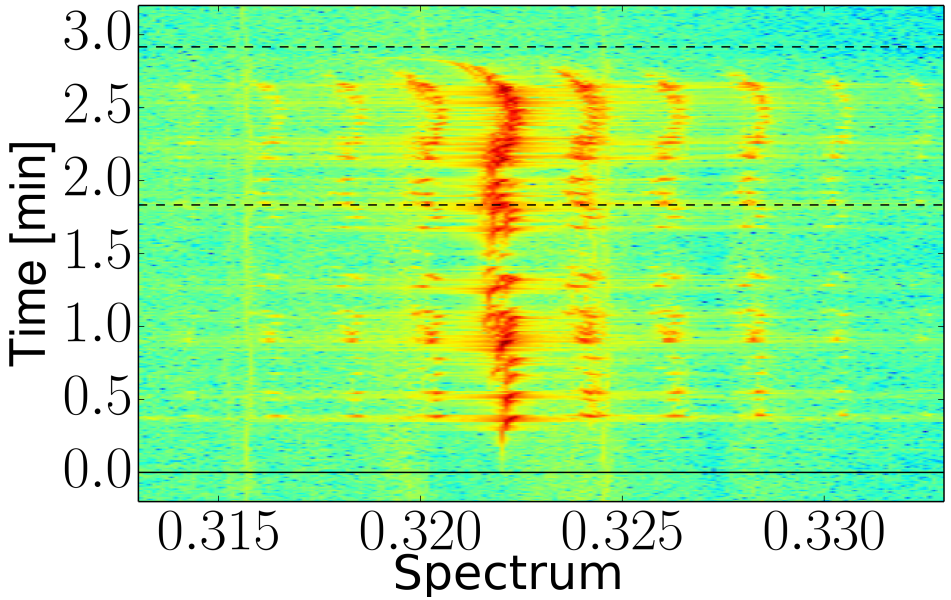
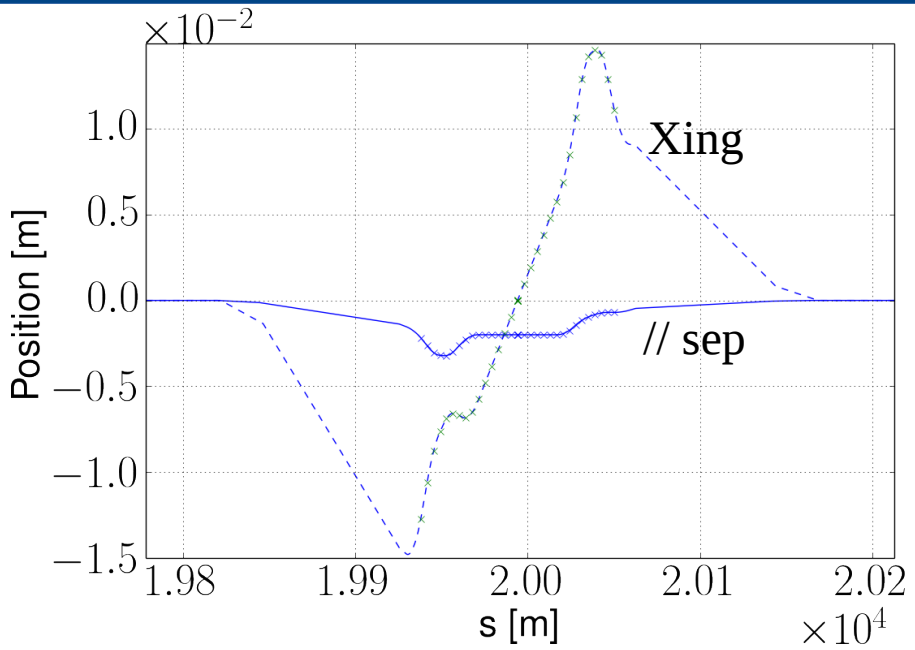
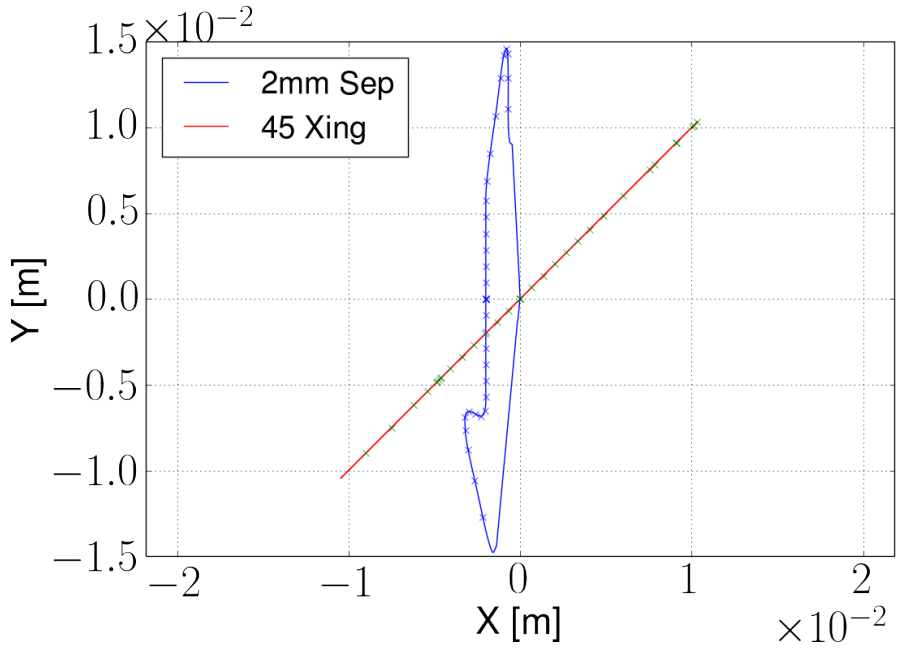
    V. Shiltsev, el al., Phys. Rev. Lett. 119, 134802 (2017)



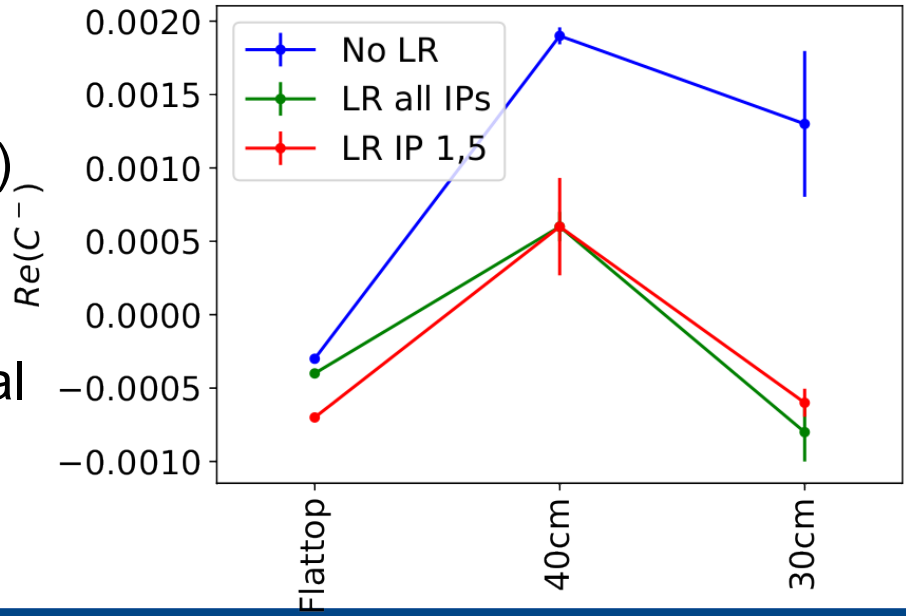
Linear coupling due to beam-beam interactions





- Long-range beam-beam interactions on a skew plane generate coupling and therefore can reduce Landau damping
- Missing long-range interaction (PACMAN effect) makes this contribution uncorrectable for all bunches A. Ribes Metidieri, et al., CERN-ACC-NOTE-2019-0037
- The control of the orbit in the IR becomes critical for the beam stability

J. Wenninger, et al., CERN-ACC-NOTE-2018-0026



Summary

- The mitigation of coherent beam-beam instabilities starts with the rings' layout mostly for asymmetric *periodic* colliders
- The interaction of coherent beam-beam modes with the machine impedance can lead to mode coupling instabilities
  - Depending on the impedance and the interaction type (long-range, head-on, crossing angle, crab angle, β^*/σ_s) a transverse feedback may constitute an effective mitigation
  - Intrinsic Landau damping from the non-linearity of the interaction may be controlled through phase advances between IP(s) in each beam
- The impact of beam-beam interactions on amplitude detuning can be
  - Beneficial for Landau damping mainly thanks to the strong impact of head-on beam-beam interaction on the core of the beam distributions
  - Detrimental for Landau damping mainly by compensating other sources of tune spread
    - The mitigation of the loss of Landau damping with offset beams require a detail understanding of the impact of the non-linearities on the tune spread and the stability diagram (crossing / crab angle, β^*, ε, σ_s)