Control of linear coupling to avoid loss of Landau damping

L.R. Carver, X. Buffat, K. Li, E. Métral, and M. Schenk

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Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider

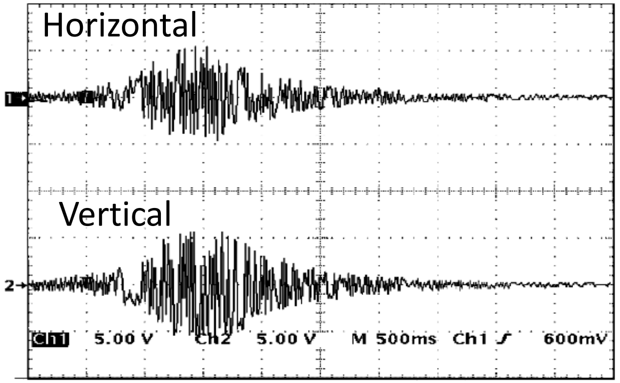
L. R. Carver,[1,*] X. Buffat,[1] K. Li,[1] E. Métral,[1] and M. Schenk[1,2]
CERN, CH-1211 Geneva, Switzerland
EPFL, CH-1015 Lausanne, Switzerland

Overview

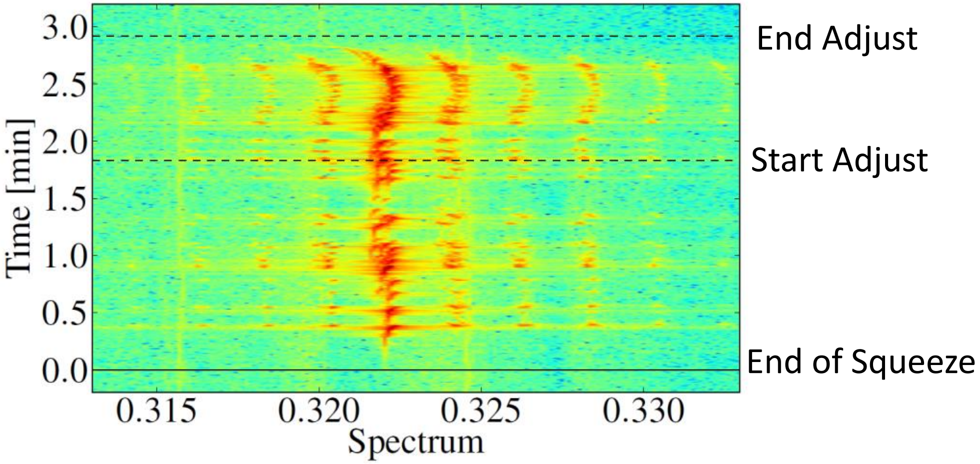
- Linear coupling is known to have an impact on transverse stability
  - At HERA, instabilities were observed when linear coupling was strong during the energy ramp [2] → **destabilising**.
  - In the PS, linear coupling was used to stabilize against strong horizontal instabilities by coupling to the vertical plane → **stabilising**.
  - In run I of the LHC, unexpected and unexplained instabilities were observed at the end of the betatron squeeze.
  - Persistent instabilities were identified at 450 GeV in the LHC during run II which occurred when the **tunes were moving closer together**.
  - Many other cases observed in many different machines [3]. Cases of both destabilising and stabilising effects.

- Stabilising effect has been studied for some machines.
- The mechanism for the destabilising effect is not as well studied.
- **Motivated a campaign of simulations and measurements to better understand this mechanism for the LHC**

HERA – Start of Ramp



LHC Run I – End of Squeeze (2012)



Effect of Linear Coupling on Transverse Stability

Coupling

- $Q_u - Q_x = -\frac{1}{2}\left(-Q_{sep} + \sqrt{Q_{sep}^2 + |C^-|^2}\right)$
- $Q_v - Q_y = +\frac{1}{2}\left(-Q_{sep} + \sqrt{Q_{sep}^2 + |C^-|^2}\right)$
- $Q_{sep} = |Q_x - Q_y|$
- $Q_{sep,coupled} = |Q_u - Q_v|$

- $|C^-|$ is the closest tune approach and is a global property.
- In the case where a single skew quadrupole is powered the local variations are minimized and $|C^-|$is a **good indicator for strength of coupling in the machine**.

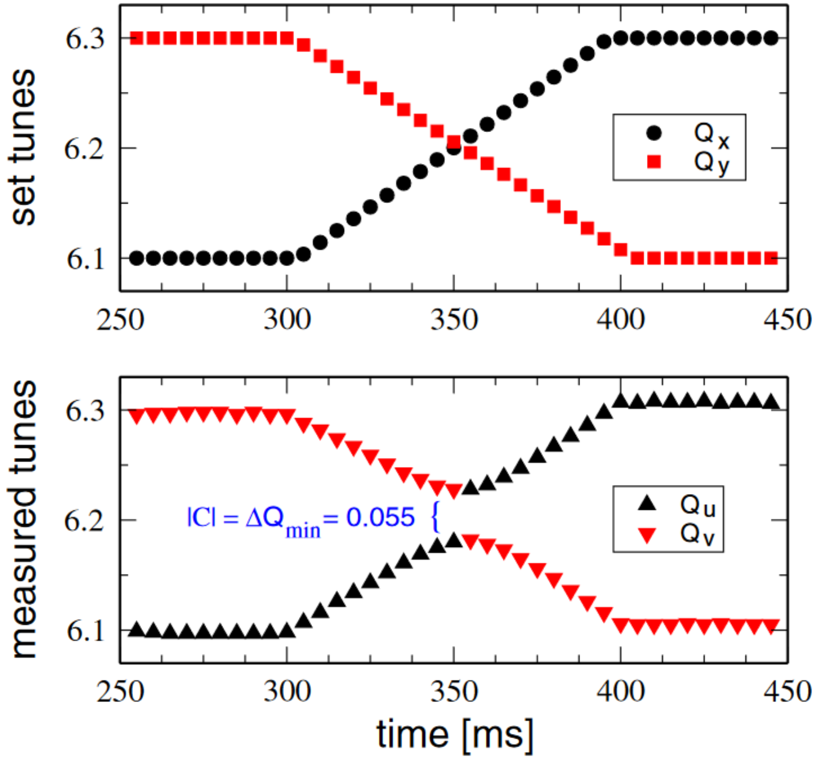


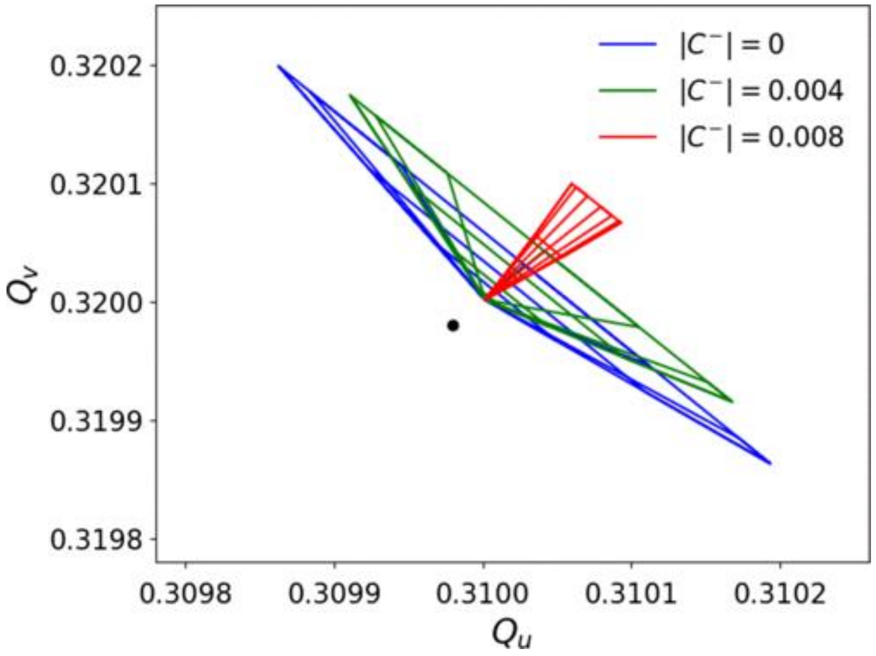
Figure reproduced courtesy of A. Franchi [4].

Effect of Linear Coupling on Transverse Stability

Coupling and Tune Spread

- In the LHC, Landau damping is achieved through a combination of tune spread, chromaticity and transverse feedback.
- The tune spread is controlled by the **amplitude detuning from the octupoles**.
- It is known that the presence of linear coupling can alter the normal and skew components of the octupoles [5].

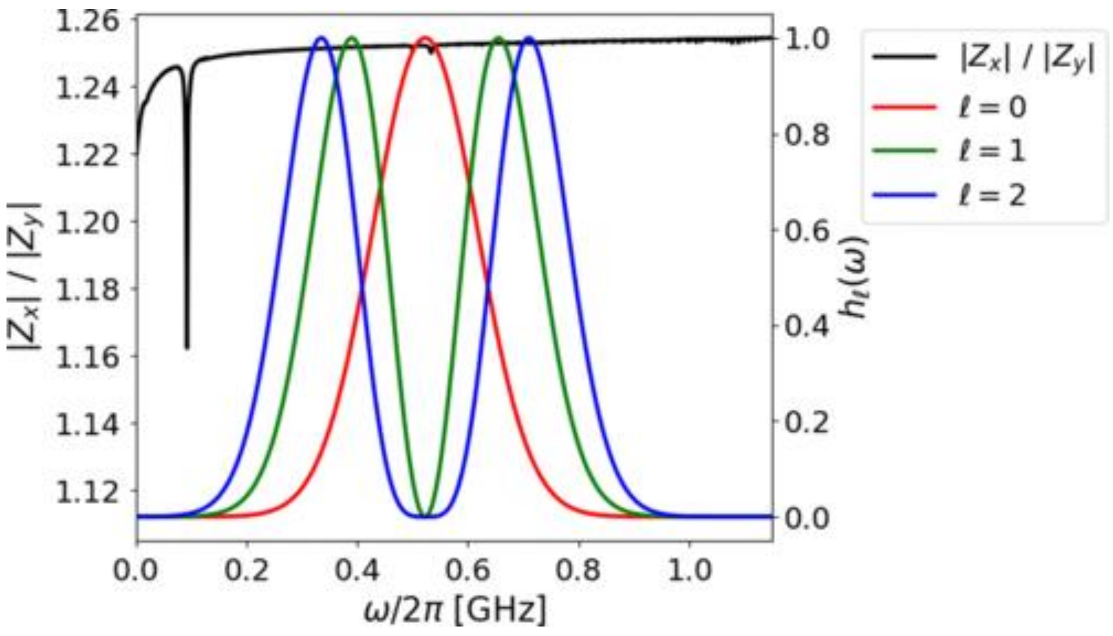
- For fixed tunes of $Q_u = 0.31, Q_v = 0.32$ the tune footprint up to $J_{u,v} = 5\sigma$ is plotted as a function of $|C^-|$.
- **Clear reduction in tune spread** as the $|C^-|$ approaches the $Q_{sep,coupled}$.



Effect of Linear Coupling on Transverse Stability

Impedance Assumptions

- In the PS (w/o tune spread) it has been shown that when one plane has much larger coherent modes compared to the other, **linear coupling can provide a stabilizing effect**.
- This occurs through a sharing of the instability growth rate* between the planes [6].
- In the case of the LHC, the impedance models are **approximately the same strength** in the frequency ranges of the first 3 modes for Q'=15,15 [7].
- If we assume that both planes are identical in all the relevant parameters (Chromaticity, Transverse Feedback and Impedance), then we can give an **uncoupled stability treatment to the coupled case**.

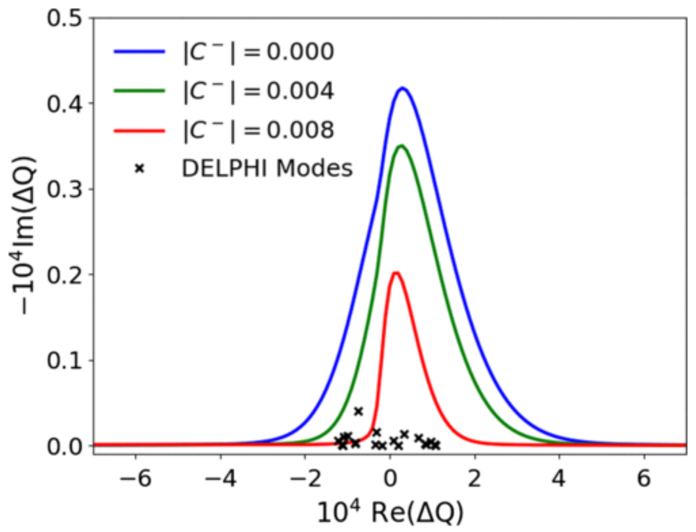


*does not include potential contributions from space charge or detuning impedance

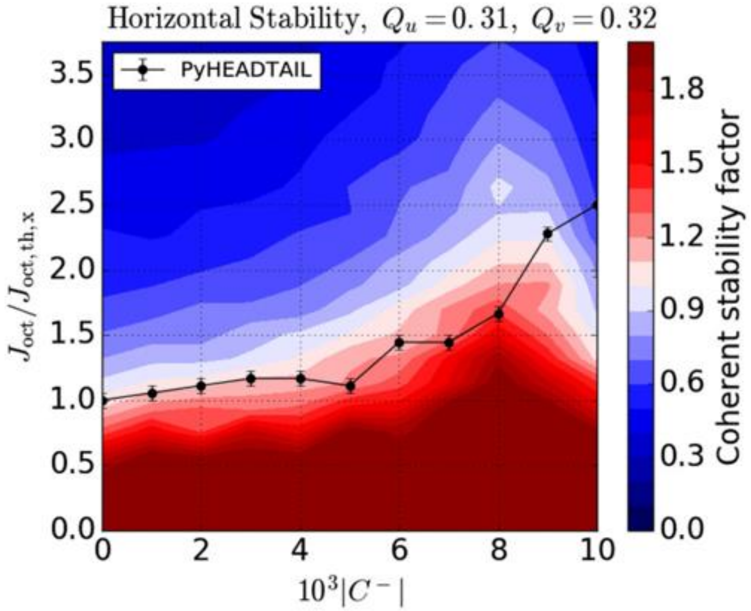
Effect of Linear Coupling on Transverse Stability

Simulations

- For fixed coupled tunes of $Q_u = 0.31, Q_v = 0.32$ and $J_{oct} = 500\text{A}$ (close to maximum) the $|C^-|$ is varied and footprint is computed.
- This is then taken in conjunction with the coherent modes computed in DELPHI, and the stability factor is calculated.



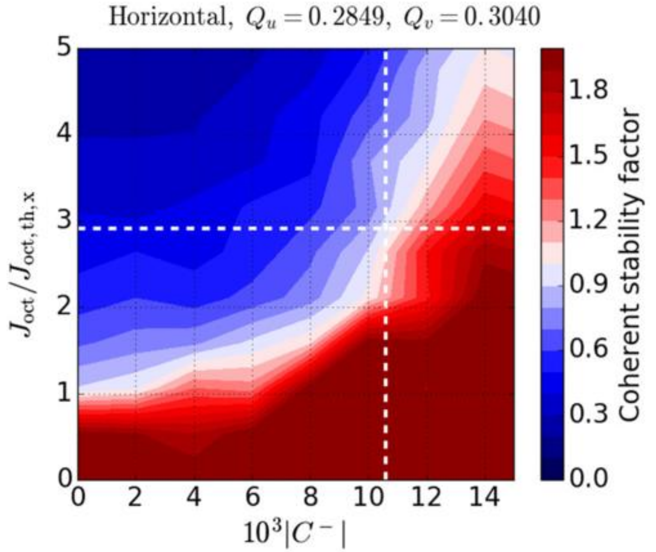
- Comparing this analytical approach with stability simulations in PyHEADTAIL.
- **Good agreement is seen between the two approaches.**

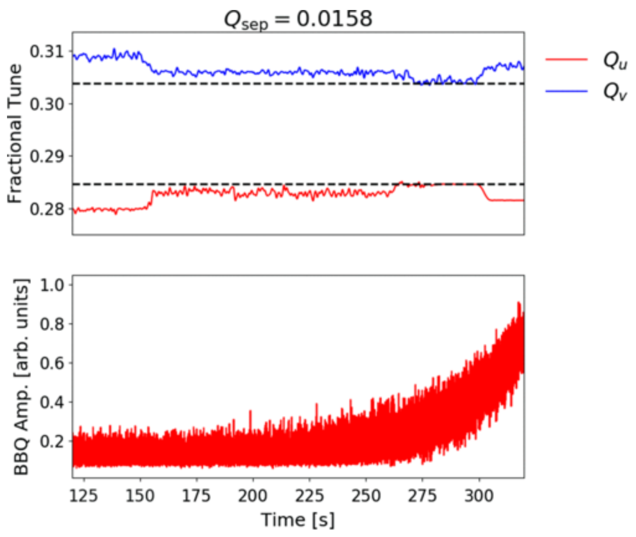


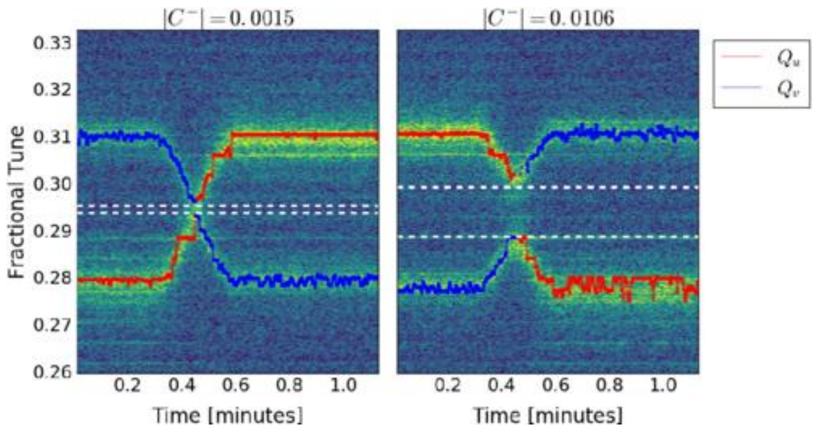
Effect of Linear Coupling on Transverse Stability

Measurement

- Single bunch measurement in the LHC at 6.5TeV.
- Introduced coupling and measured $|C^{-}|$ by a fast tune crossing.
- Slowly moved tunes closer together until instability develops.
- We can take the machine settings (octupole current, tune separation at instability, and $|C^{-}|$) and compute stability threshold.
- **Good agreement between simulation and measurement**.



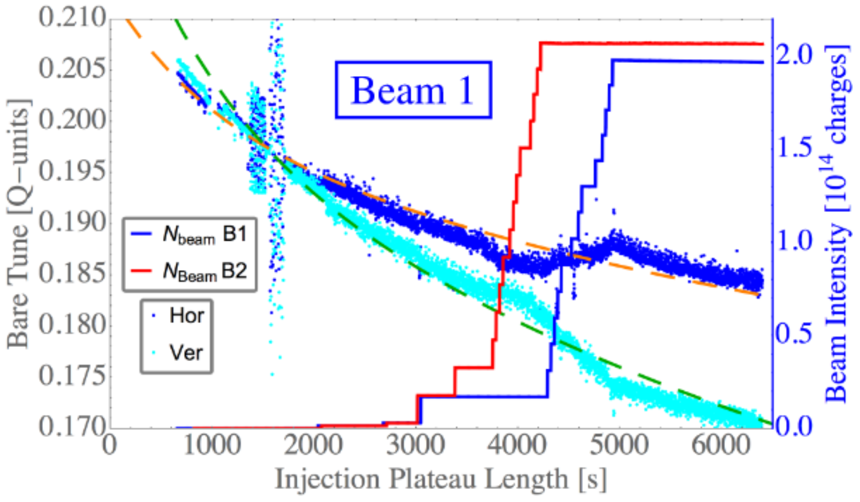


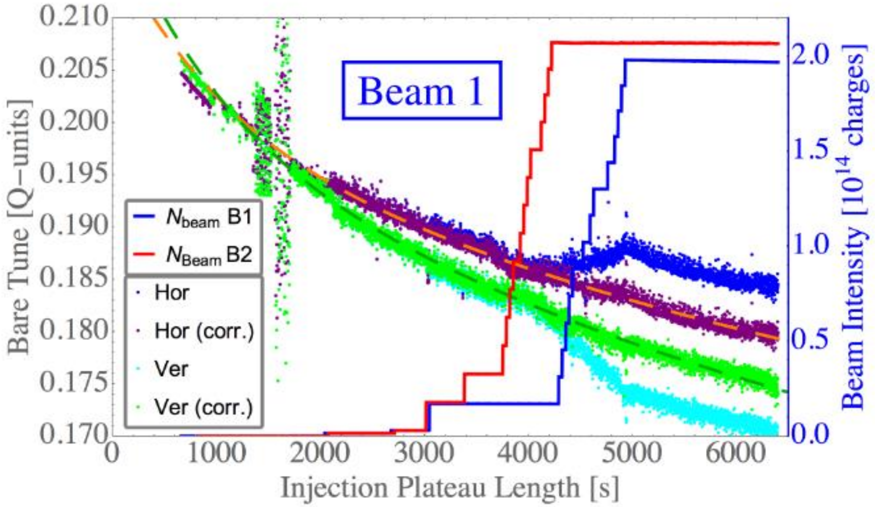


Control of Linear Coupling

Implementation

- Results of this study highlighted the **criticality of keeping the coupling and tunes well corrected in all stages of the machine cycle.**
- As the tune feedback cannot be kept on during injection, the Laslett tune shift is calculated and the **tunes are corrected while injecting** [8].
- Avoids loss of Landau damping at injection.

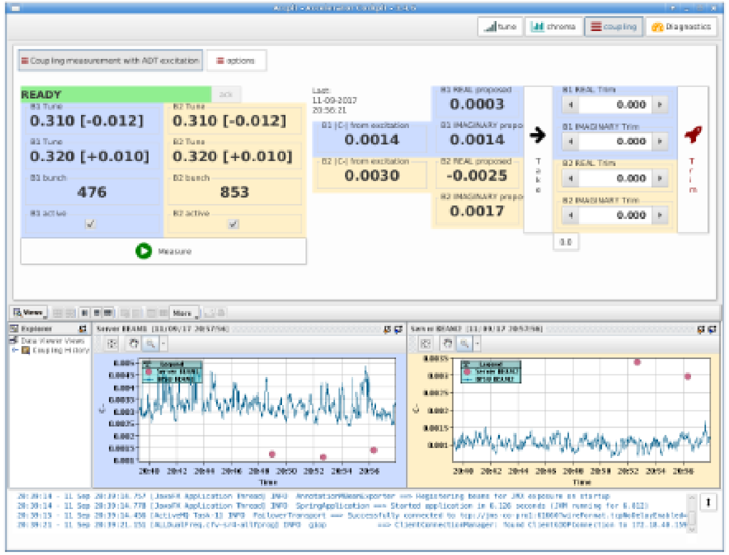


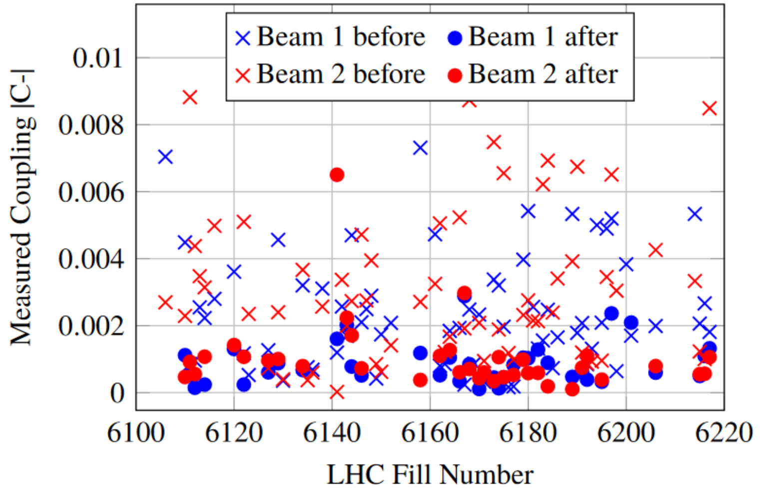


Control of Linear Coupling

ADT-AC Dipole

- At the time of the study, measurements of the linear coupling were made using the AC Dipole or from injection oscillations [9].
- AC dipole excites all bunches in the machine, cannot be used during regular operation.
- The transverse damper (ADT) was modified to provide an AC dipole like excitation only on a **few selected bunches** [10].
- **Linear coupling is now measured and corrected regularly during physics operation.**
- $|C^{-}|$ is now more closely monitored to understand the sources of linear coupling and better predict future running scenarios for the LHC.





Conclusions

- The work here is applicable to machines where **tune spreads are provided by octupoles** to give Landau damping.
- The model **is no longer accurate** when there is a **large difference between the horizontal and vertical modes**.
- When $\frac{|C^-|}{Q_{sep}} > 0.4$, the tune spread from octupoles becomes strongly distorted, loss of landau damping can occur leading to beam instabilities.
- This simulation model was verified with dedicated measurements in the LHC.
- Operational steps have now been taken to ensure that linear coupling is **well measured and corrected in all stages of the machine cycle.**

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