Update of the stability limits including the effect of electron cloud, implications for machine and HW parameters (e.g. ramp rates)

Elias Métral for the instability team (and BE-ABP-HSC section)

Joint LARP CM26/Hi-Lumi Meeting, SLAC, 19/05/2016

Contents

- Introduction
- Beam stability from impedance model
- Effect of beam-beam and ramp rates
- Effect of noise
- Effect of e-cloud
- Effect of linear coupling
- Conclusion

Introduction

- Transverse instabilities are a concern based on the experience of the LHC Run 1 (2012 with 50 ns) and beginning of Run 2 (2015 with 25 ns)

- 2 questions since 2012 => Why do we need (at high energy) to use
  - High chromaticities (~ +15 units)? *A known/predicted mechanism is e-cloud at injection...*
  - ~ Max current in the Landau octupoles (max = 550 A), i.e. much more (factor ~ 5) than predicted from impedance only?

- We have identified 3 possible mechanisms (so far) which could explain a factor ~ 5 increase in the required current of the Landau octupoles
  - Noise *=> Already predicted by simulations but not measured yet. 1st BTF measurements and related Stability Diagram (SD) at injection made in 2015*
  - E-cloud *=> Already measured in MD but simulations still to come*
  - Linear coupling between the transverse planes *=> Already predicted from simulations and measured in MD*

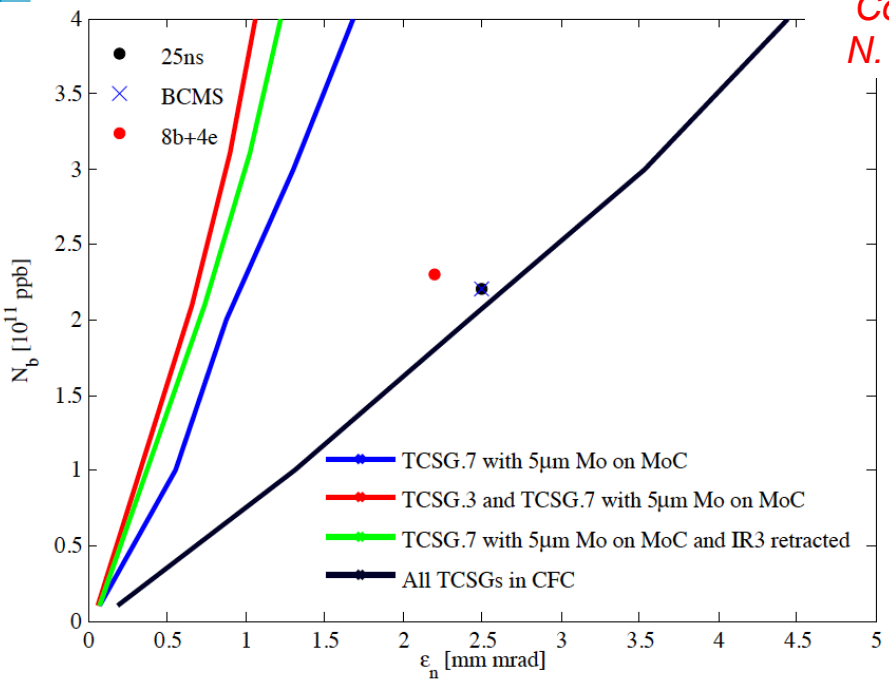
Introduction

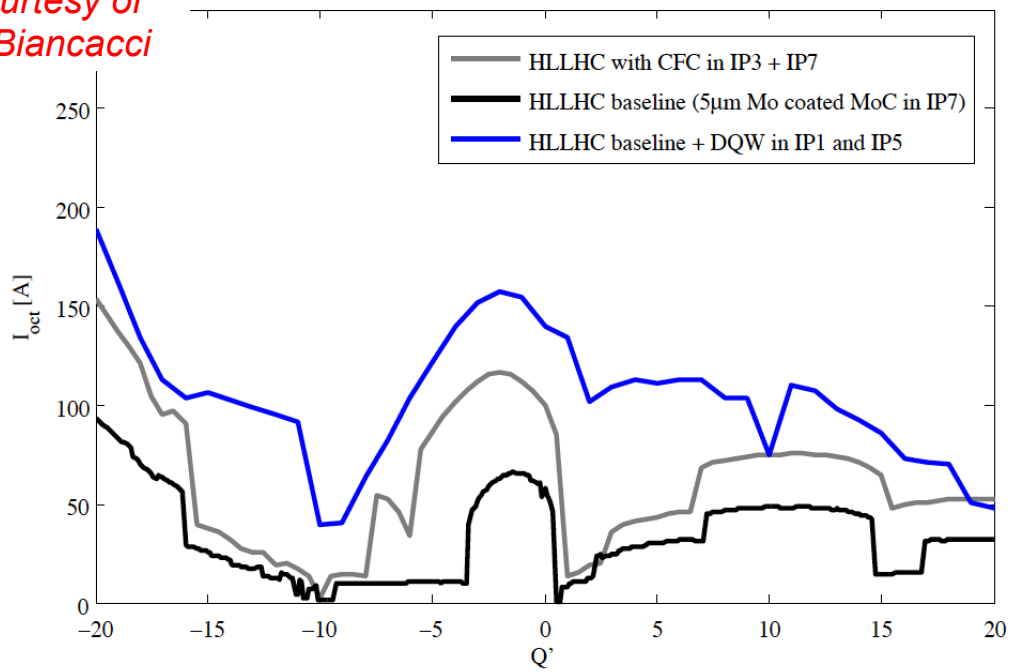
- In a machine like the LHC (and HL-LHC), not only all the mechanisms have to be understood separately, but (ALL) the possible interplays between the different phenomena need to be analyzed in detail, including the
  - Beam-coupling impedance (with in particular all the necessary collimators to protect the machine but also new equipment such as crab cavities at large β-function)
  - Linear and nonlinear chromaticity
  - Landau octupoles (and other intrinsic nonlinearities)
  - Transverse damper
  - Space charge
  - Beam-beam: BBLR (Long-Range) and BBHO (Head-On)
  - Electron cloud
  - Linear coupling strength
  - Tune separation between the transverse planes (bunch by bunch)
  - Tune split between the two beams (bunch by bunch)
  - Transverse beam separation between the two beams
  - Noise
  - Etc.

Beam stability from impedance model

- Curves scaled w.r.t. 2012 instabilities (assumed impedance-induced) w/o CC
- Curves NOT scaled w.r.t. 2012 instabilities, w/o & w CC, (2.2E11 p/b, 2.5 μm and 8.1 cm)

Courtesy of N. Biancacci



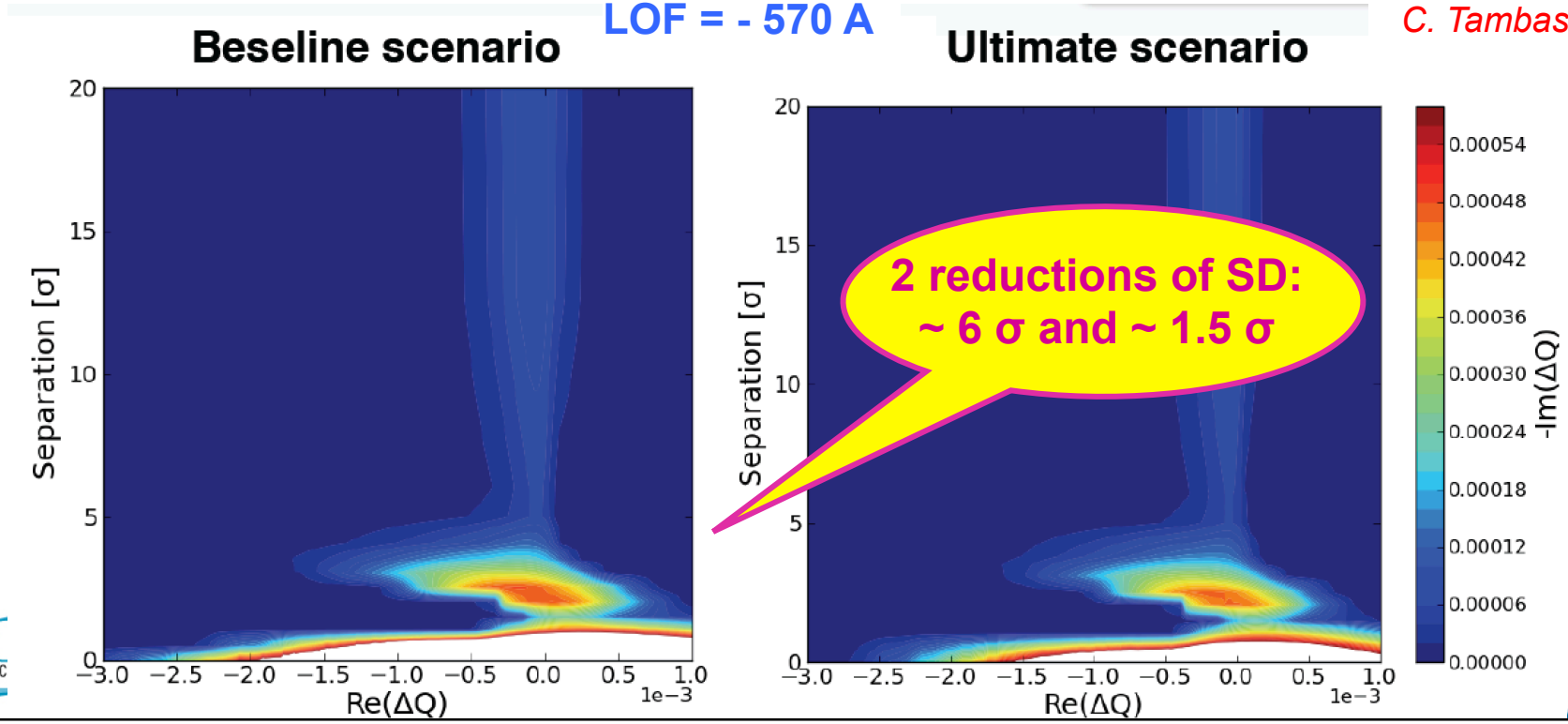


Effect of beam-beam and ramp rates

- Evolution of the SD during collapse of separation (crab crossing OFF), from BBLR + BBHO in IP1&5

Courtesy of C. Tambasco

LOF = - 570 A



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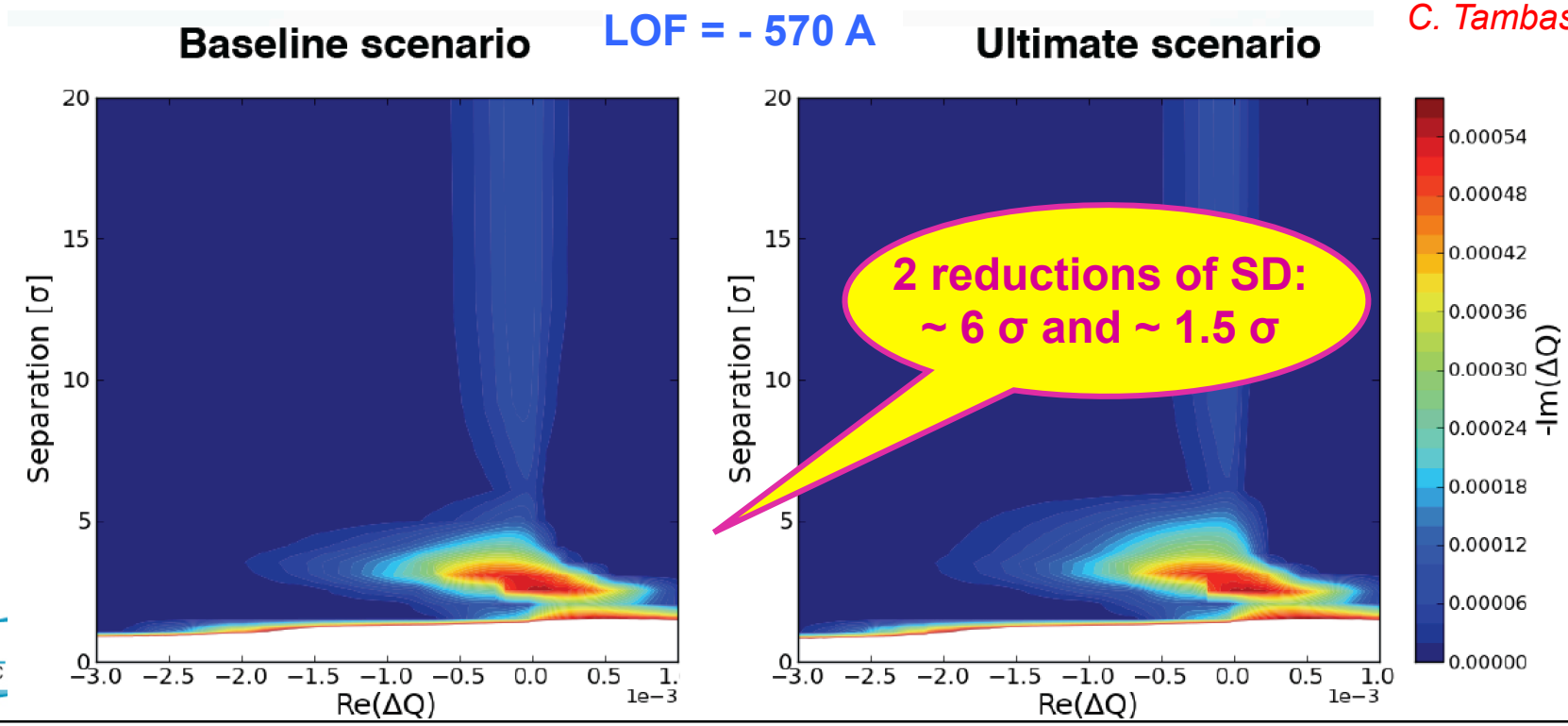


Effect of beam-beam and ramp rates

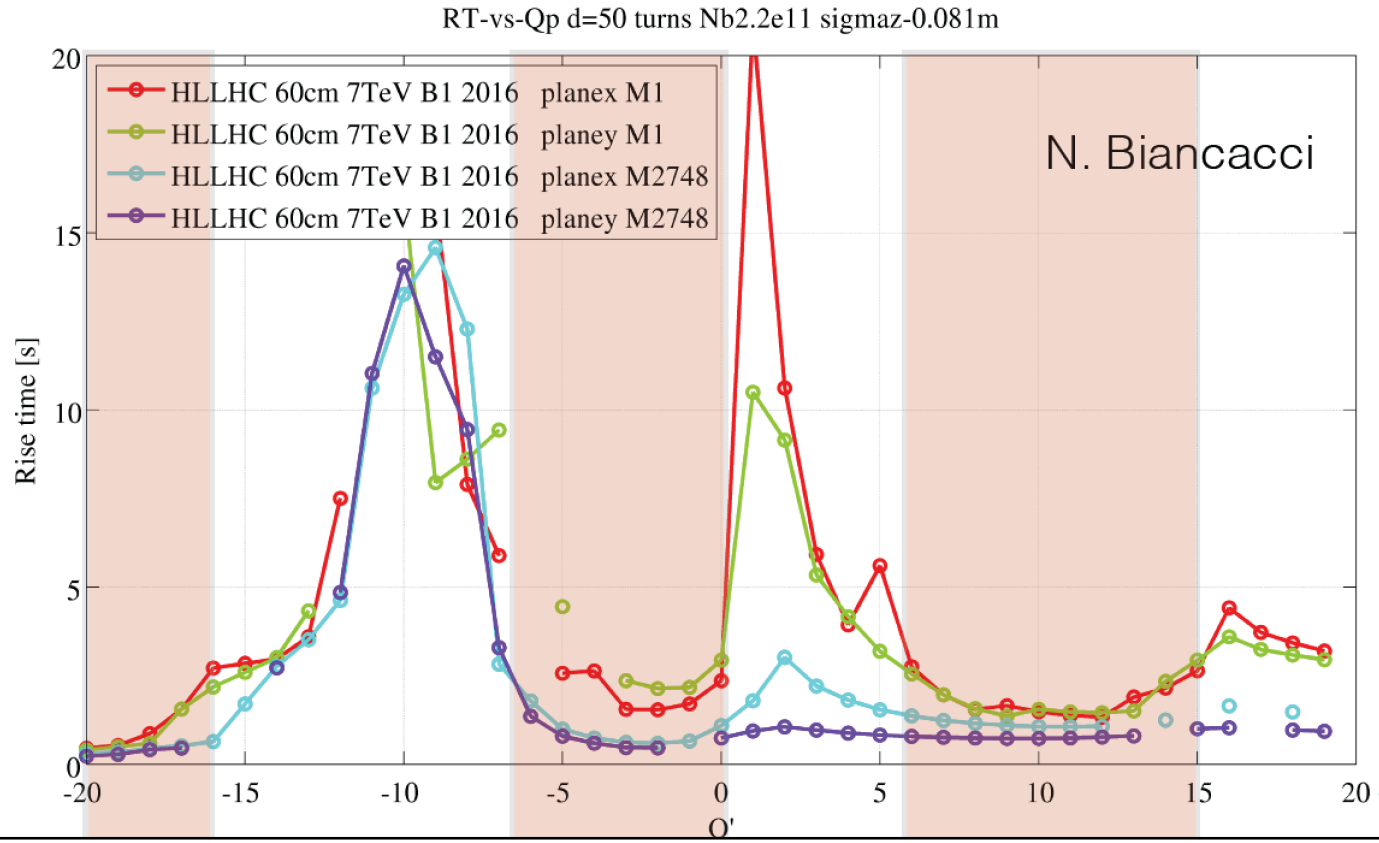
- LHC 2015 separation bump speed from 2σ to 1σ

Fill #	ATLAS [s/σ]	CMS [s/σ]
4332	1.428	3.822
4337	1.368	4.152
4363	1.248	2.280
4364	1.86	1.962
4384	2.016	1.836
4391	1.774	1.670
4398	1.417	1.787
4555	1.458	2.226
AVERAGE	1.571	2.467

Courtesy of C. Tambasco

Effect of beam-beam and ramp rates

- HL-LHC instability rise-times for the baseline scenario

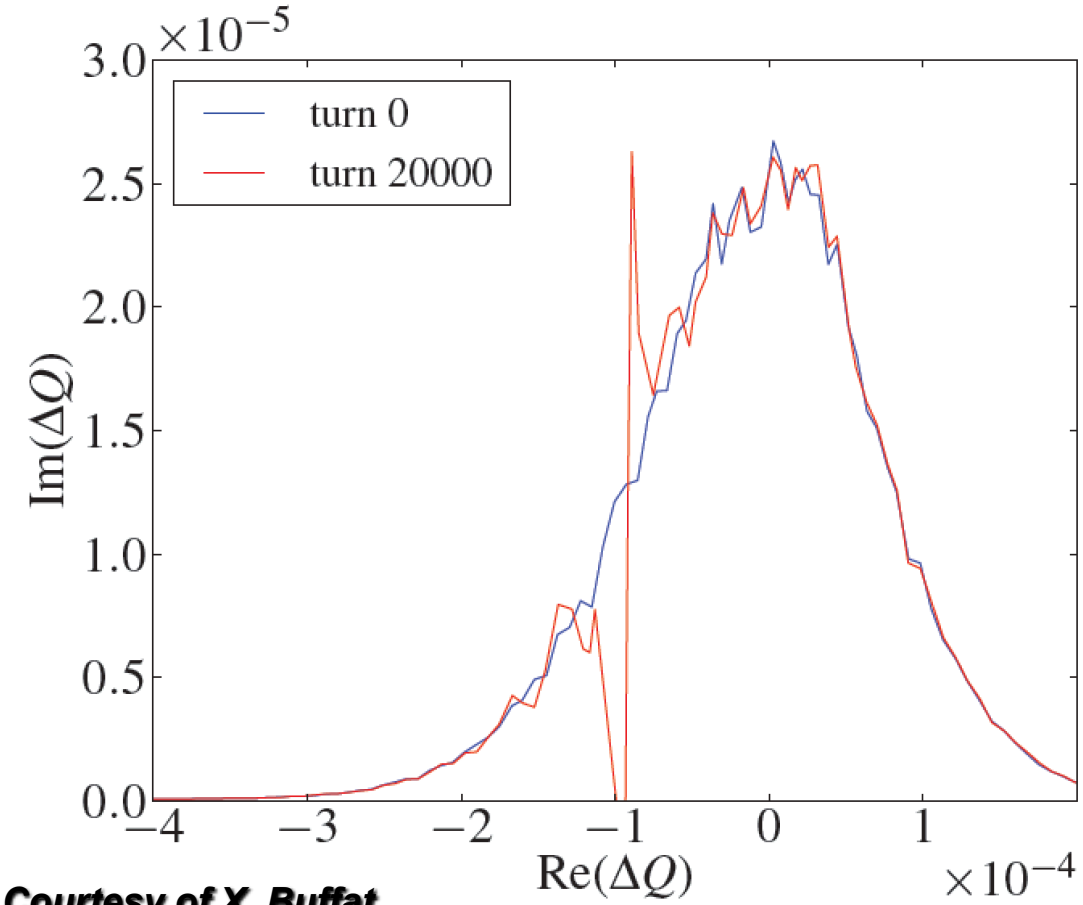


Effect of beam-beam and ramp rates

- Summary
  - 2 reductions of SD: ~ 6 σ and ~ 1.5 σ
  - No observations of instabilities at the minimum of SD during the regular operational fills
  - The minimum of SD at 1.5 σ occurs at the deceleration part of the correctors: increasing the ramp rate will not help
  - Going faster will have also bad impact on beam loss lifetimes
  - The LHC speed (from 2 σ to 1 σ) is ~ 1.6 s (ATLAS) and ~ 2.5 s (CMS) comparable with the HL-LHC rise times
    => Recommendation to go from 2 σ to 1 σ in less than 1 s
  - MDs are planned to explore fast instability at the minimum of SD

Effect of noise

- Possible mechanism which can lead to a loss of Landau damping (deforming / drilling holes in the SD)



Courtesy of X. Buffat

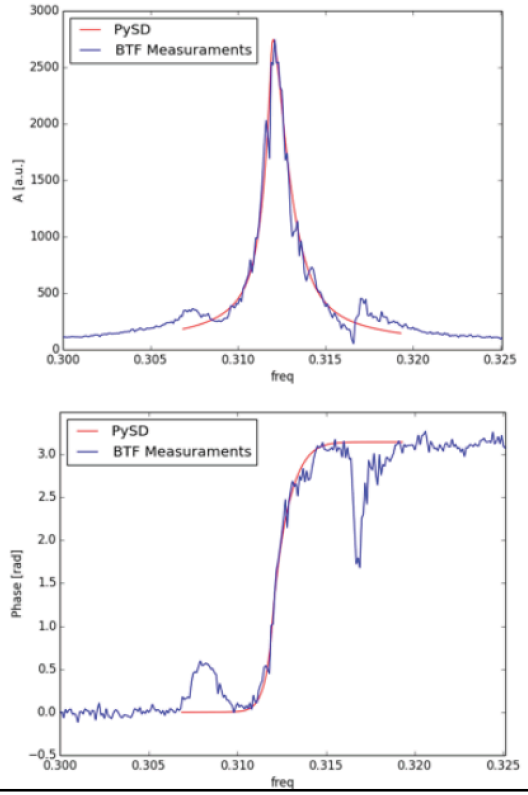
HiLumi HL-LHC PROJECT

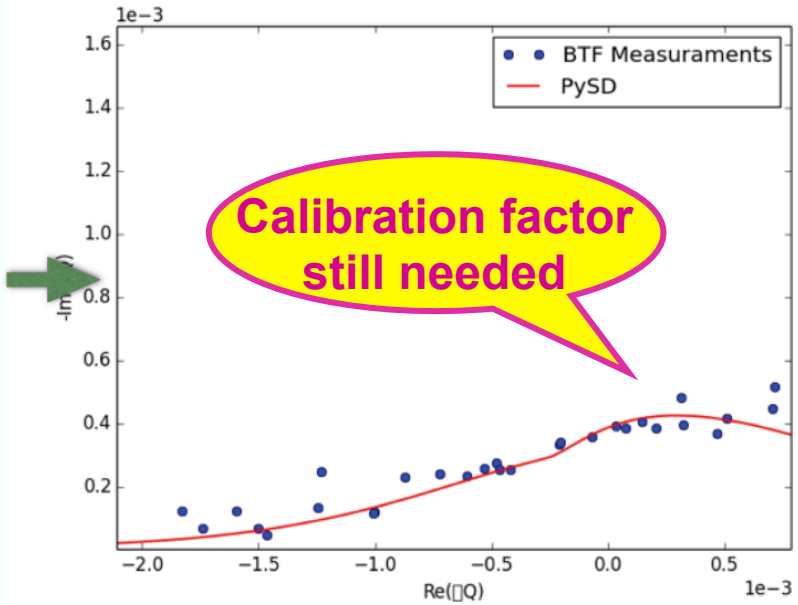
LARP

Effect of noise

- 1st (preliminary) results from BTF measurements in the LHC in 2015 and 1st measured SD at injection => To be continued…

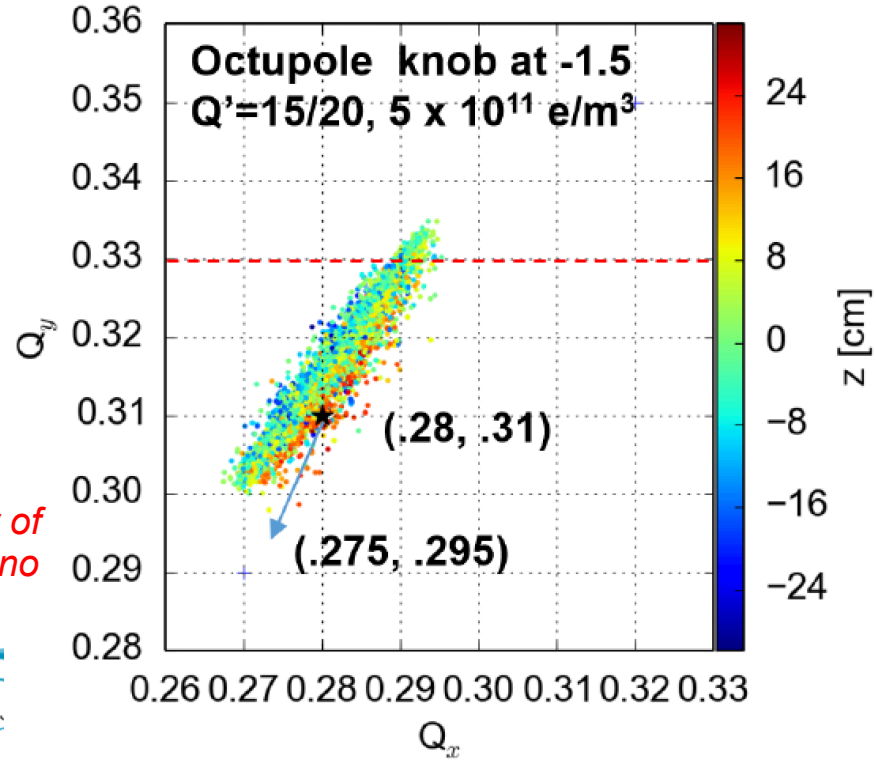
Courtesy of C. Tambasco



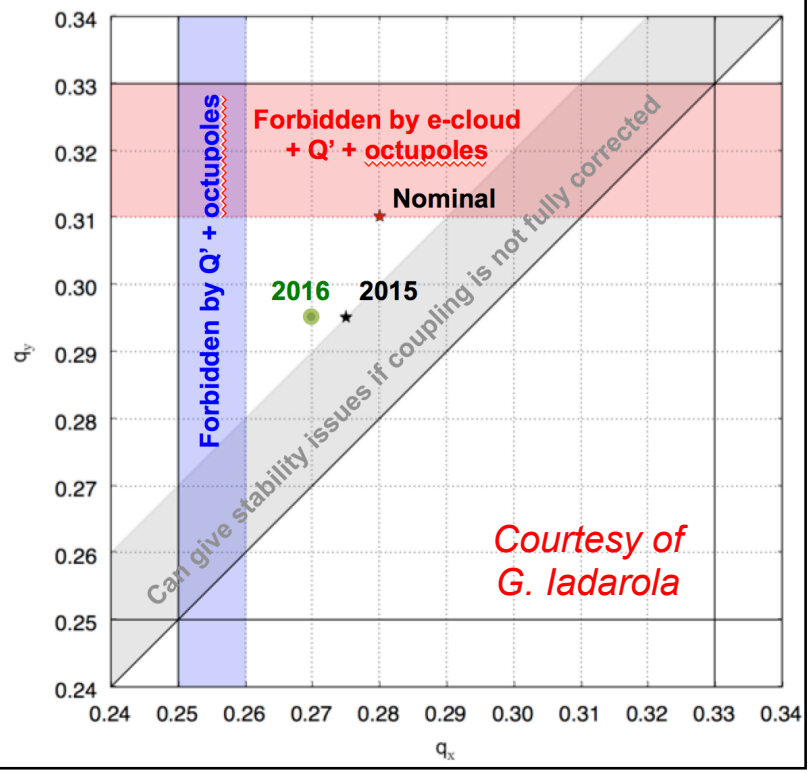


Effect of e-cloud

- Optimization of working point at injection



Courtesy of A. Romano

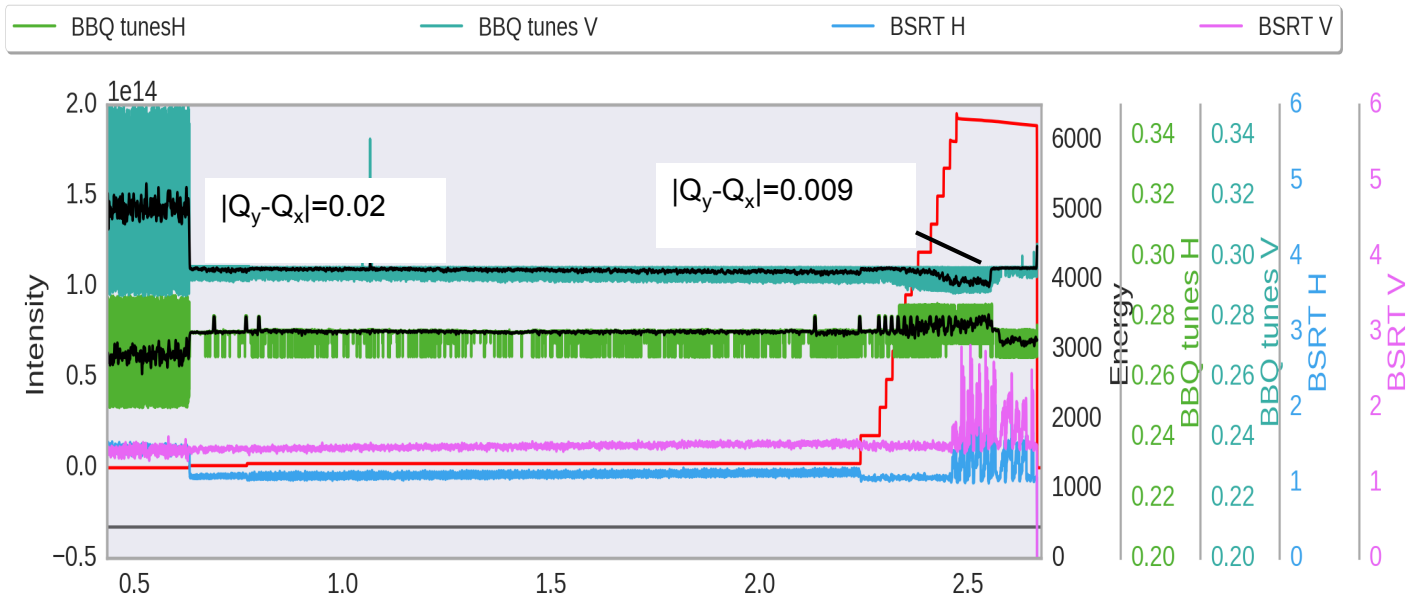


Courtesy of G. Iadarola

Effect of e-cloud

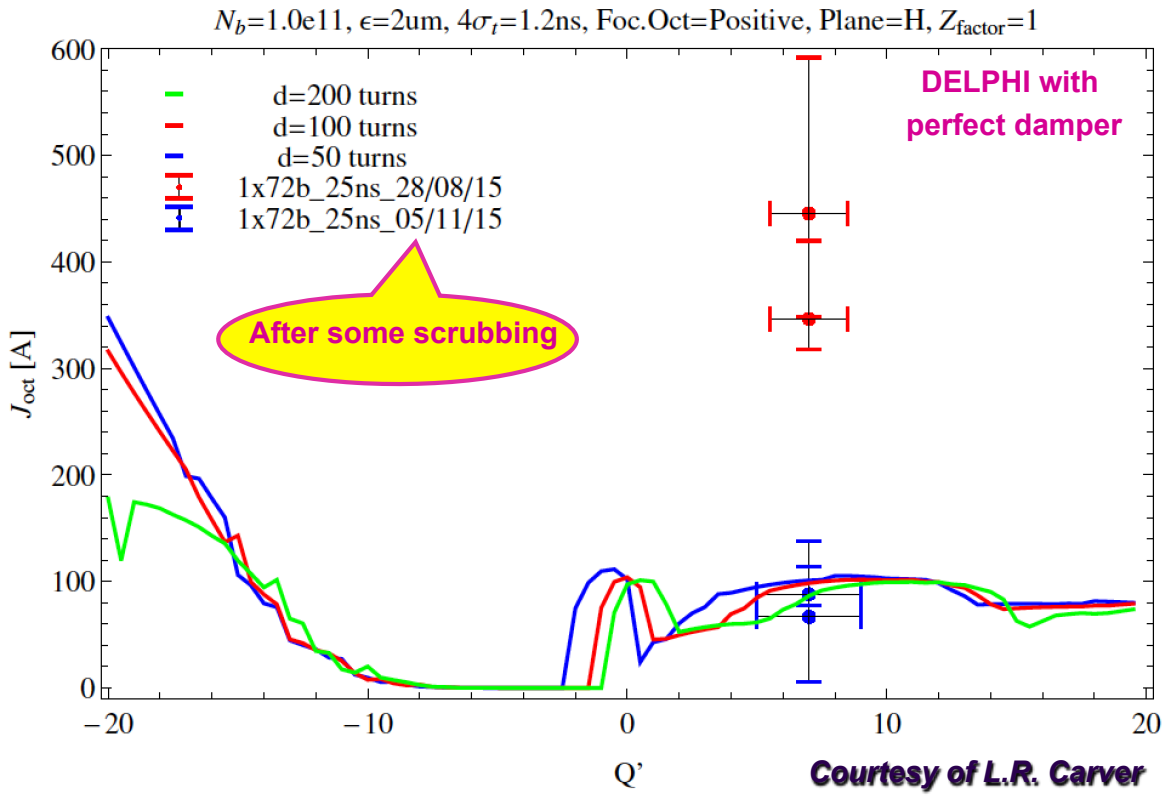
- Instabilities observed at injection when Laslett tune shifts not corrected => Believed to be due to linear coupling (see later)

Courtesy of L.R. Carver



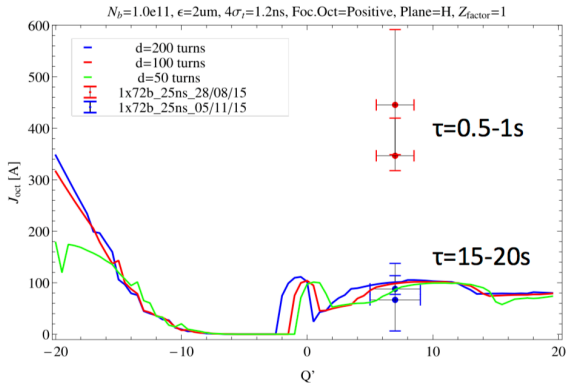
Effect of e-cloud

- Instabilities observed at high energy with a train of 72 b



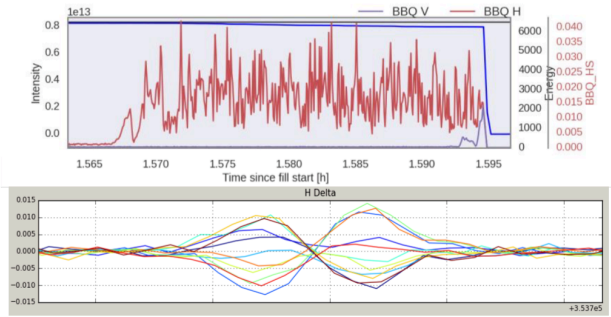
Courtesy of L.R. Carver

Effect of e-cloud

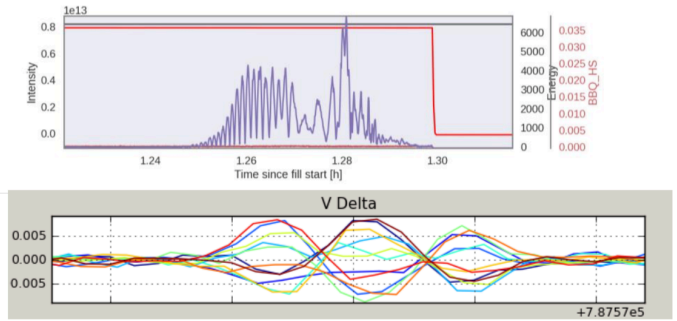


- 72b w/25ns became unstable at 350A (unscaled) with presence of e-cloud (≈0.8deg sync. phase shift) on 28/08.
- 72b w/25ns became unstable at currents consistent with single bunch measurements on 05/11. Sync. phase shift observed of ≈0.3deg.
- Difference due to effect of scrubbing at FT.
- Different kind of instability observed between two cases. 2 nodes expected from simulation for H or V single bunch instabilities.

B1, 1x72b, 28/08



B2, 1x72b, 05/11



Courtesy of L.R. Carver

Effect of e-cloud

- To be further studied (from both simulations and measurements)
  - What will happen with many batches / full beam?
  - Will we succeed to remove all the e^- from dipoles? Effect on beam stability?
  - What about the remaining e^- in the quads (effect on tune footprint, beam stability, etc.)?

Effect of linear coupling

- Linear coupling can be beneficial or detrimental
- Why could linear coupling be a problem for beam stability?

=> Because the coherent tunes are shifted by linear coupling differently compared to the incoherent tunes (providing the Landau damping) due to the nonlinear fields (from octupoles to create the tune spread). Therefore in some cases a too strong coupling can be detrimental, leading to instabilities due to a loss of transverse Landau damping

Effect of linear coupling

Proceedings of EPAC 2002, Paris, France

DESTABILISING EFFECT OF LINEAR COUPLING IN THE HERA PROTON RING

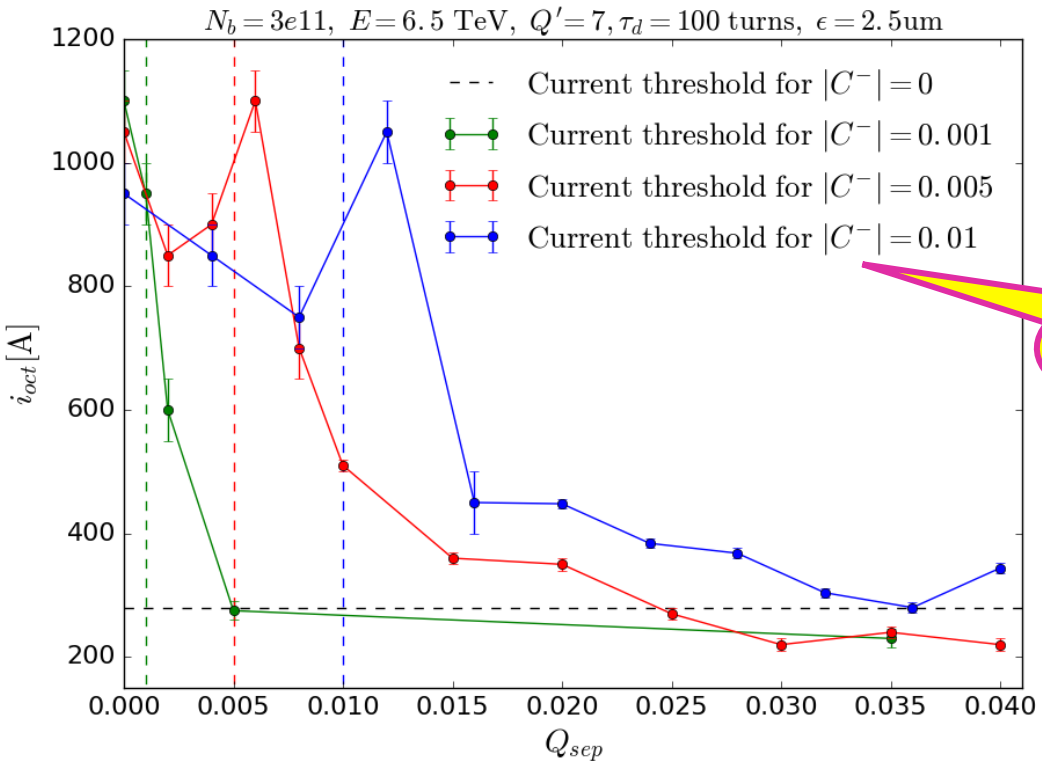
E. Métral, CERN, Geneva, Switzerland
G. Hoffstaetter, F. Willeke, DESY, Hamburg, Germany

Abstract

Since the first start-up of HERA in 1992, a transverse coherent instability has appeared from time to time at the beginning of the acceleration ramp. In this process, the emittance is blown up and the beam is partially or completely lost. Although the instability was found to be of the head-tail type, and the chromaticity and linear coupling between the transverse planes was recognized as essential for the instability to occur, the driving mechanism was never clarified. An explanation of the phenomenon is presented in this paper using the coupled Landau damping theory. It is predicted that a too strong coupling can be detrimental since it may shift the coherent tune outside the incoherent spectrum and thus prevent Landau damping. Due to these features, the name "coupled head-tail instability" is suggested for this instability in the HERA proton ring.

Simple model used (externally given elliptical spectrum…) => Detailed simulation study currently being performed for the LHC by L.R. Carver (see after)

Effect of linear coupling

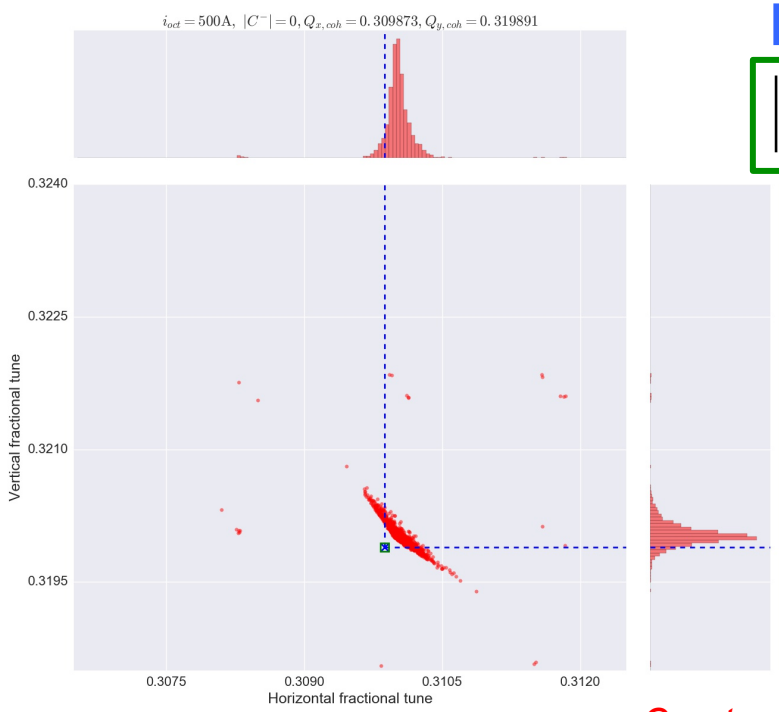


Closest tune approach

Courtesy of L.R. Carver

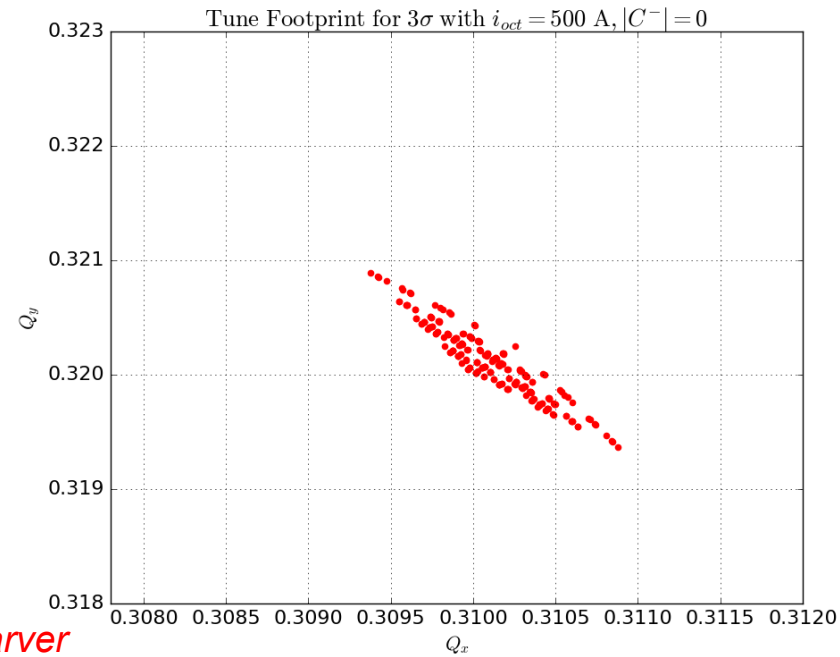
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles



LOF > 0

$$\boxed{|C^-| = 0}$$



Courtesy of L.R. Carver

Effect of linear coupling

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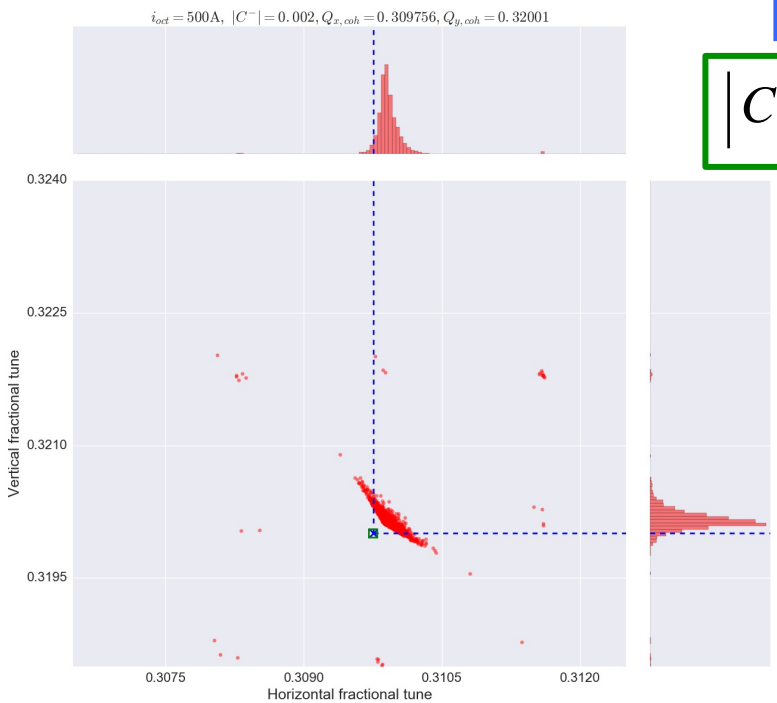
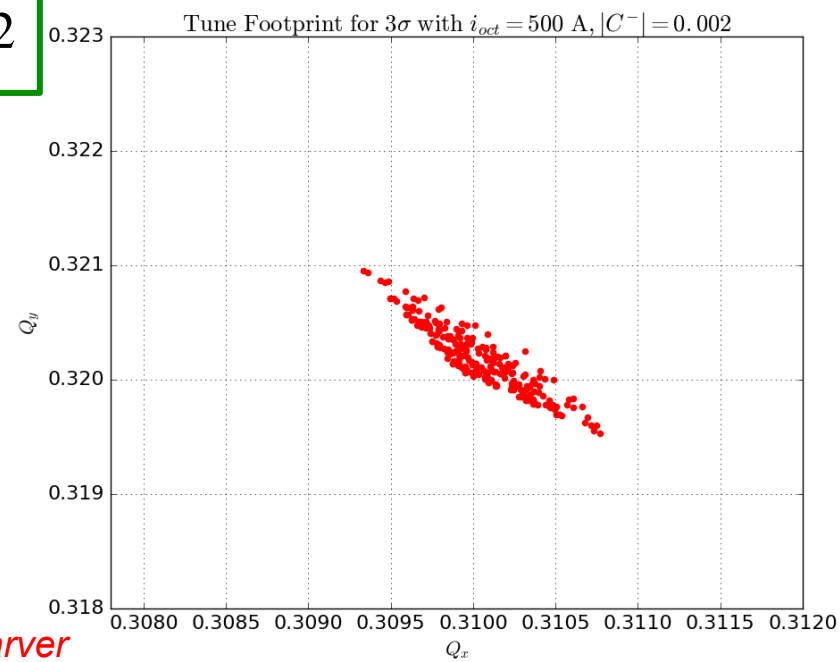


LOF > 0

$$\left|C^-\right| = 0.002$$



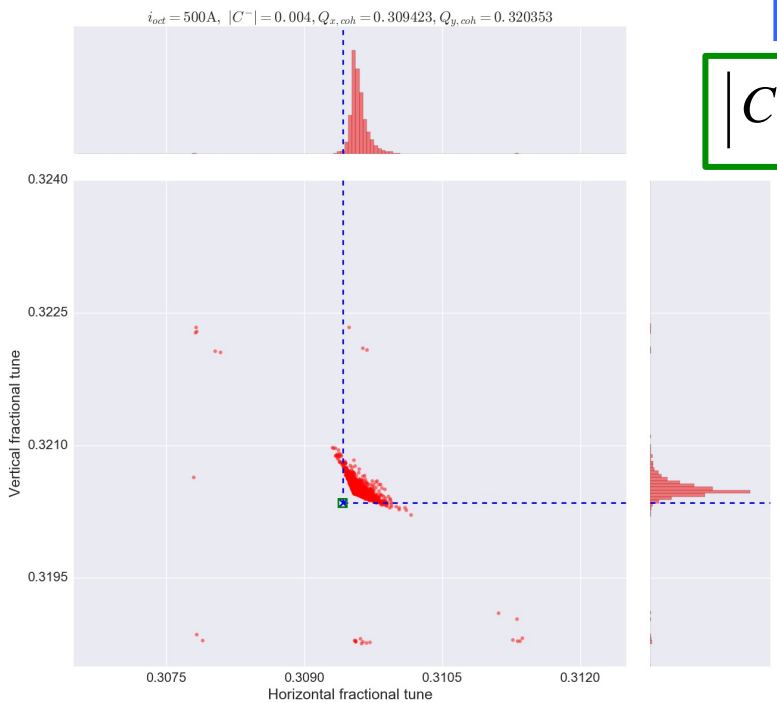
Courtesy of L.R. Carver

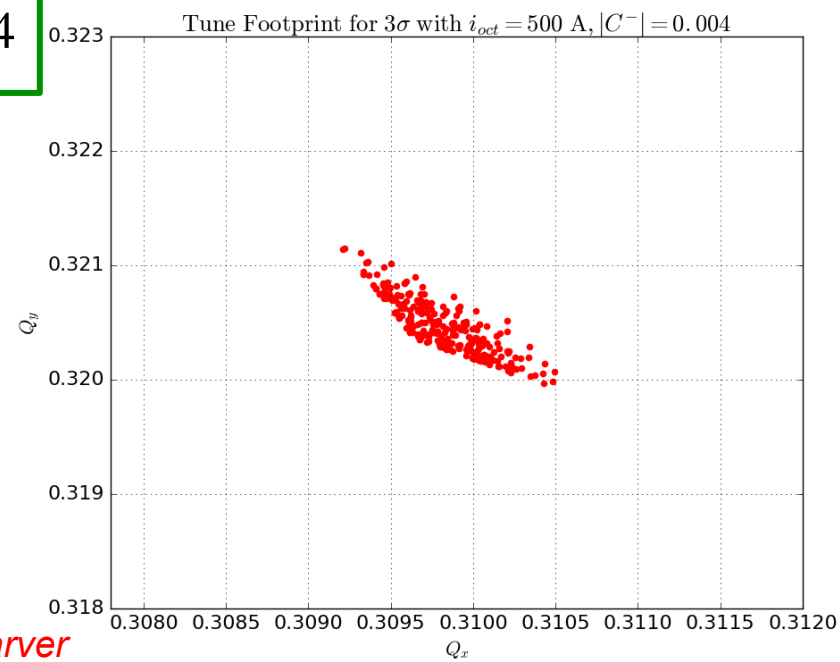
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

$$\left|C^{-}\right| = 0.004$$





Courtesy of L.R. Carver

Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner
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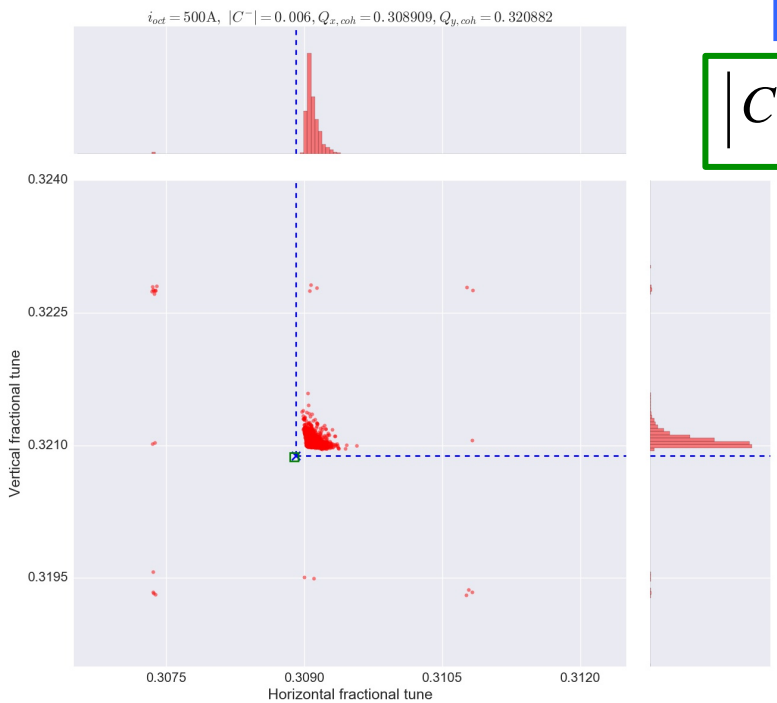
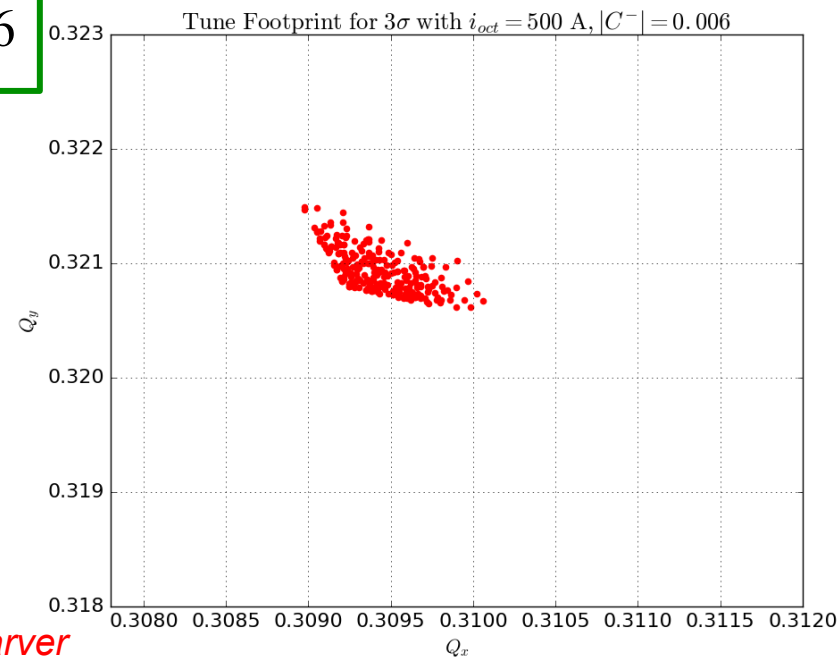


LOF > 0

$$\left|C^-\right| = 0.006$$



Courtesy of L.R. Carver

Effect of linear coupling

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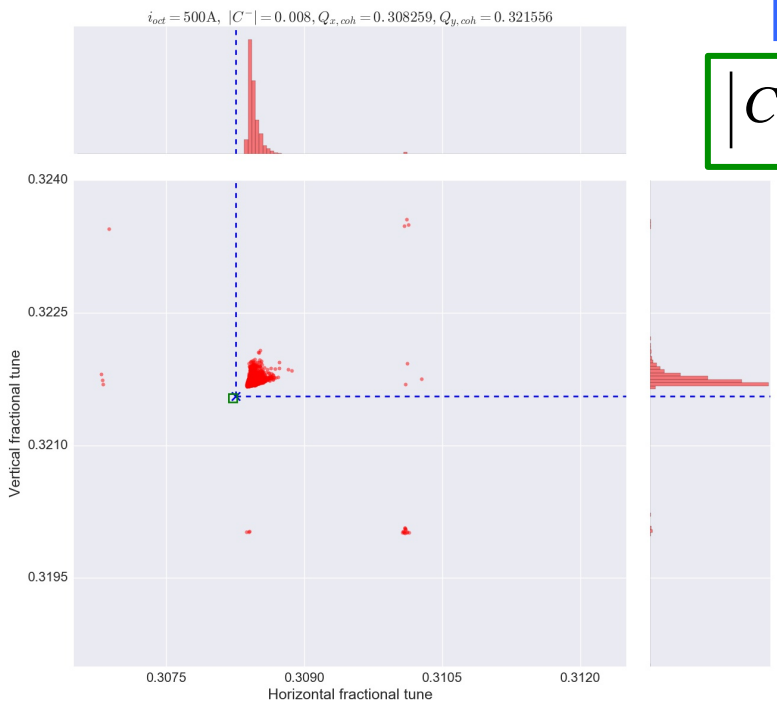
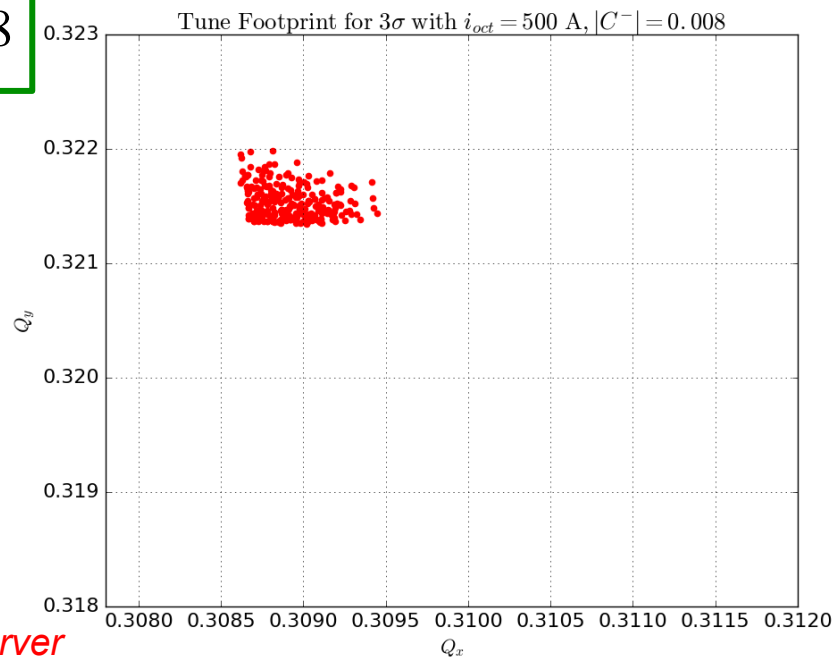


LOF > 0

$$\left|C^-\right| = 0.008$$



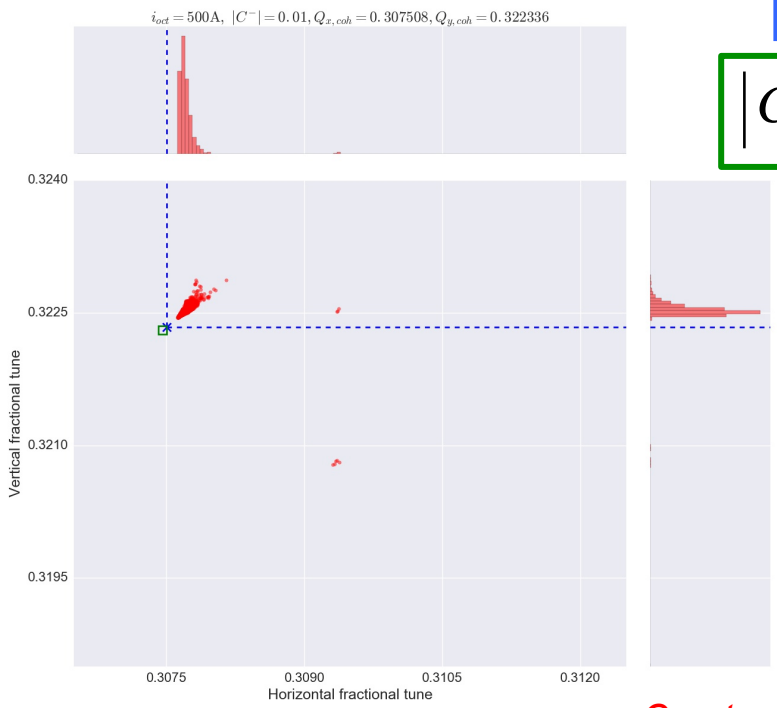
Courtesy of L.R. Carver

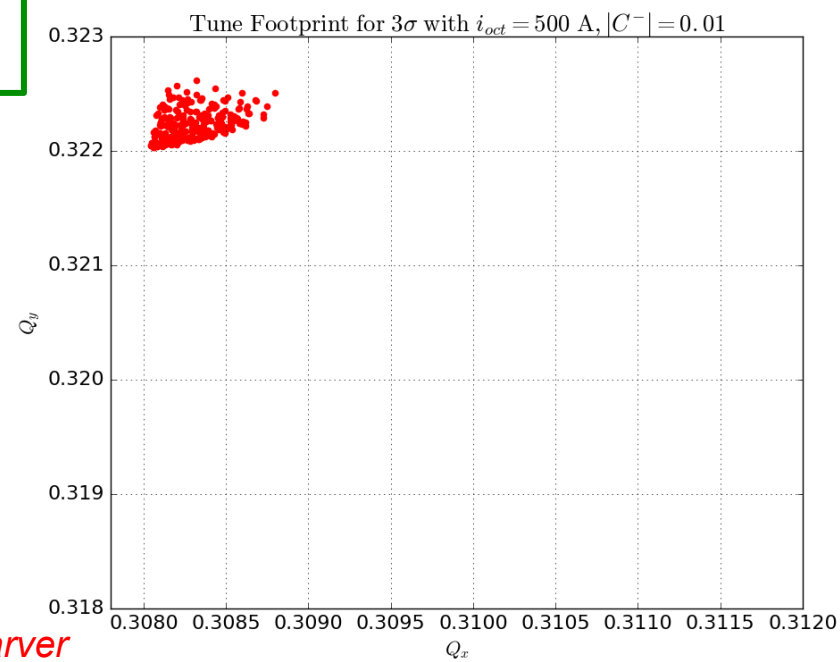
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner
- MADX with the real octupoles

LOF > 0

$$\left|C^{-}\right| = 0.01$$

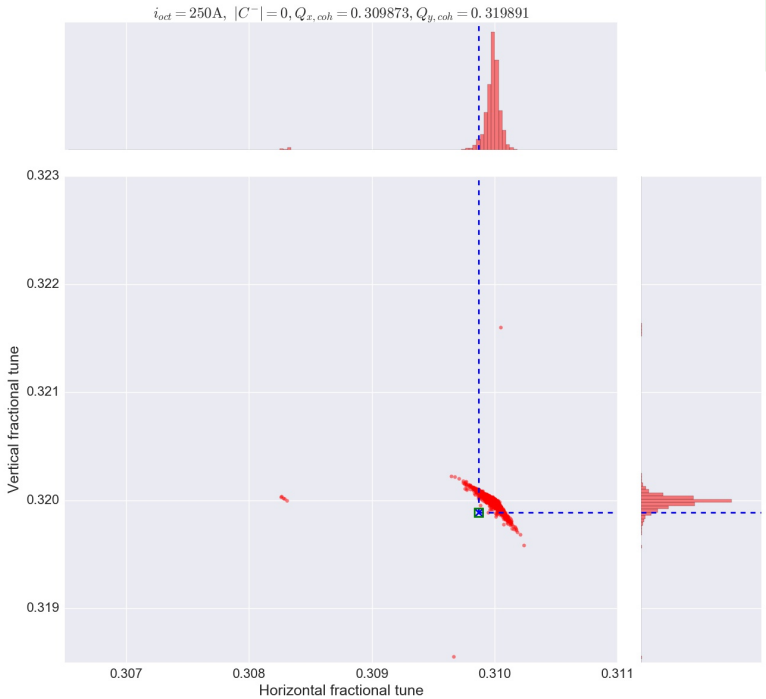




Courtesy of L.R. Carver

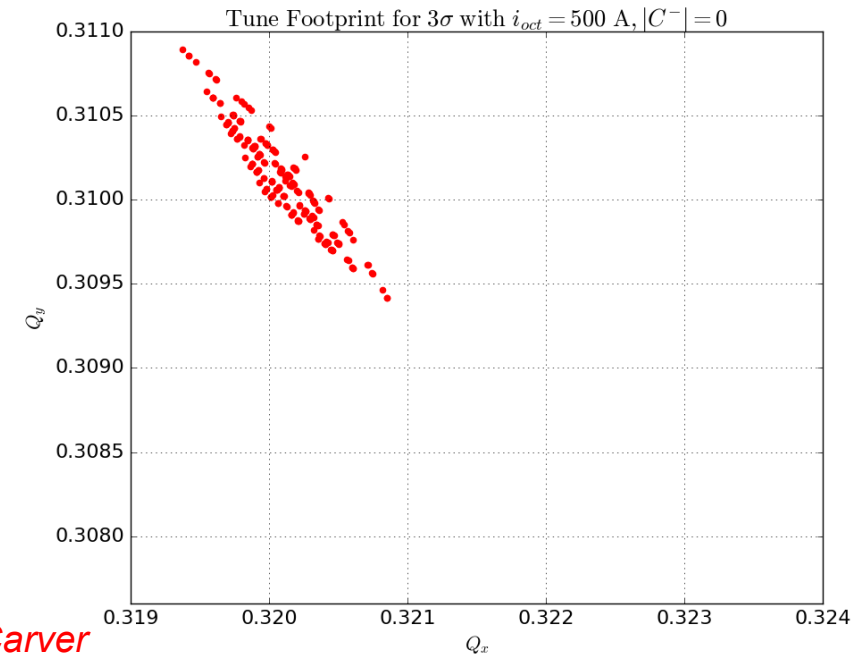
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner (**LOF < 0**)



$$\left|C^-\right| = 0$$

- MADX with the real octupoles (**LOF > 0, swapped tunes**)



Courtesy of L.R. Carver

Effect of linear coupling

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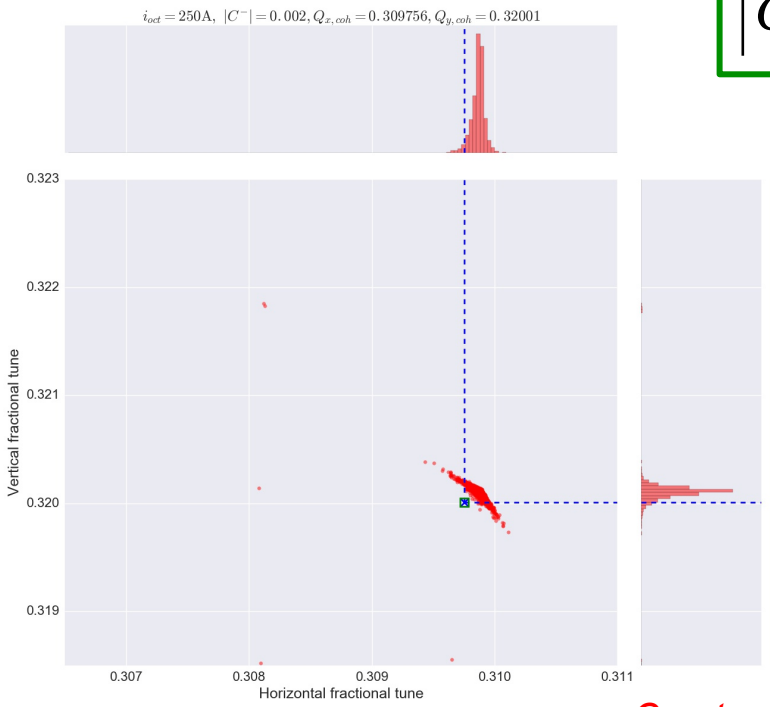
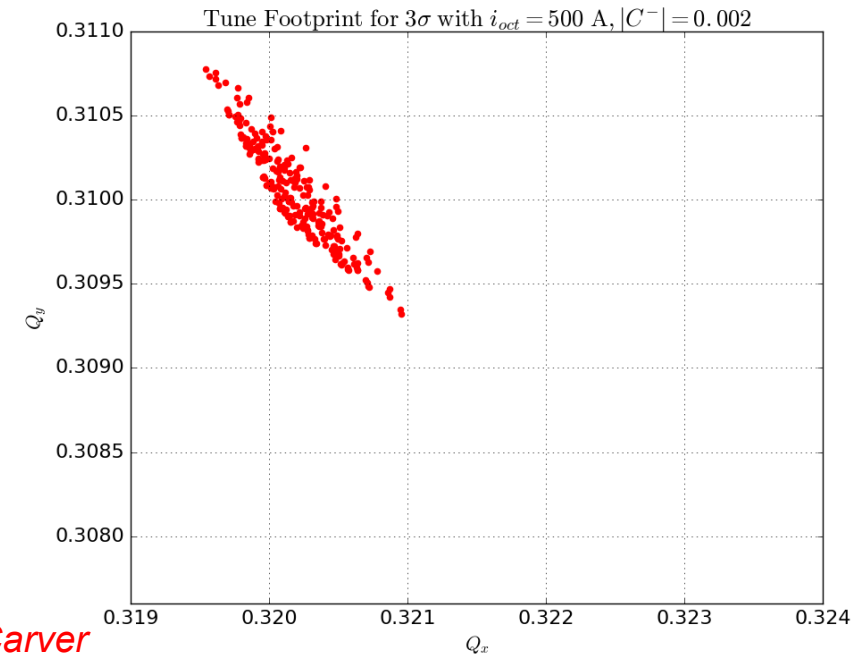


$$\left|C^-\right| = 0.002$$

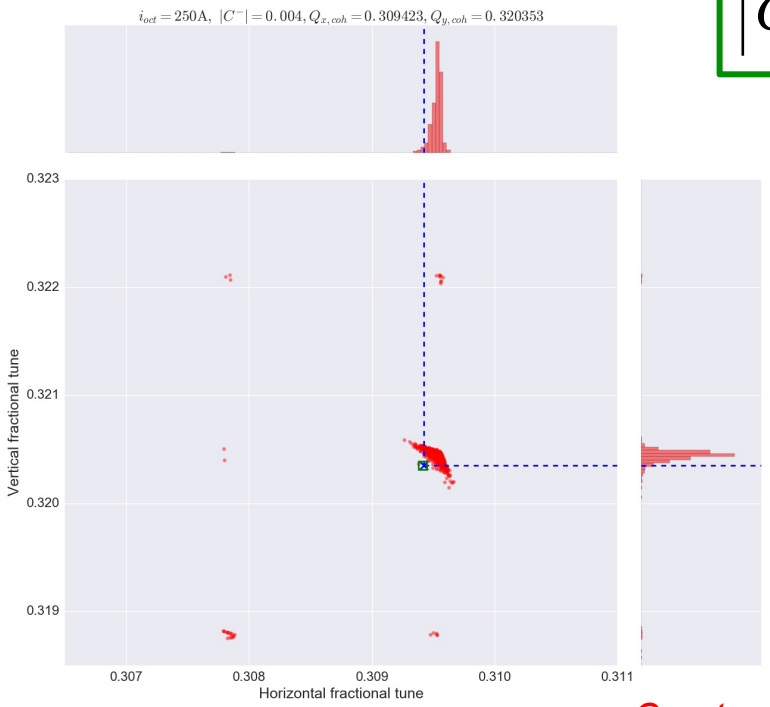
- MADX with the real octupoles (**LOF > 0, swapped tunes**)



Courtesy of L.R. Carver

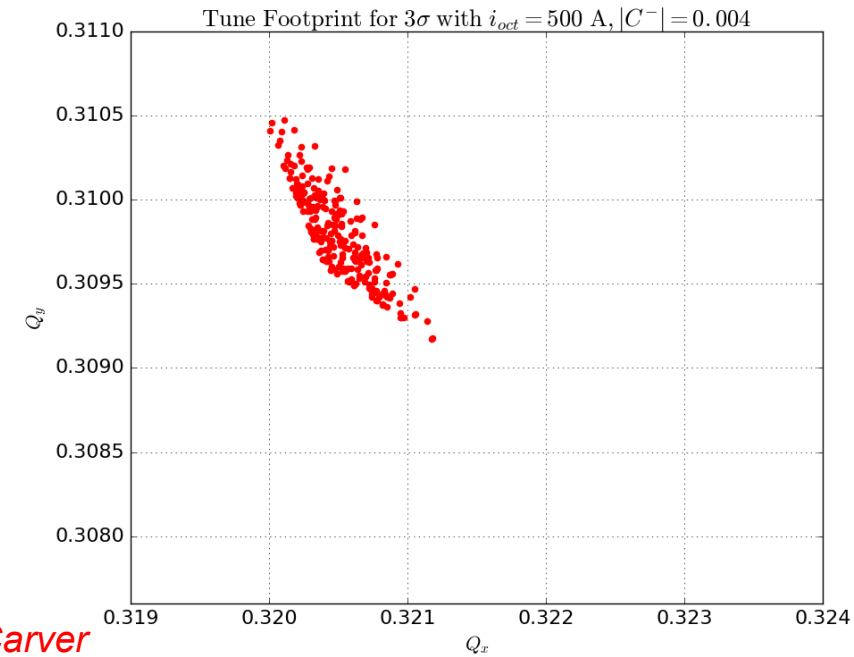
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner (**LOF < 0**)



$$\left|C^-\right| = 0.004$$

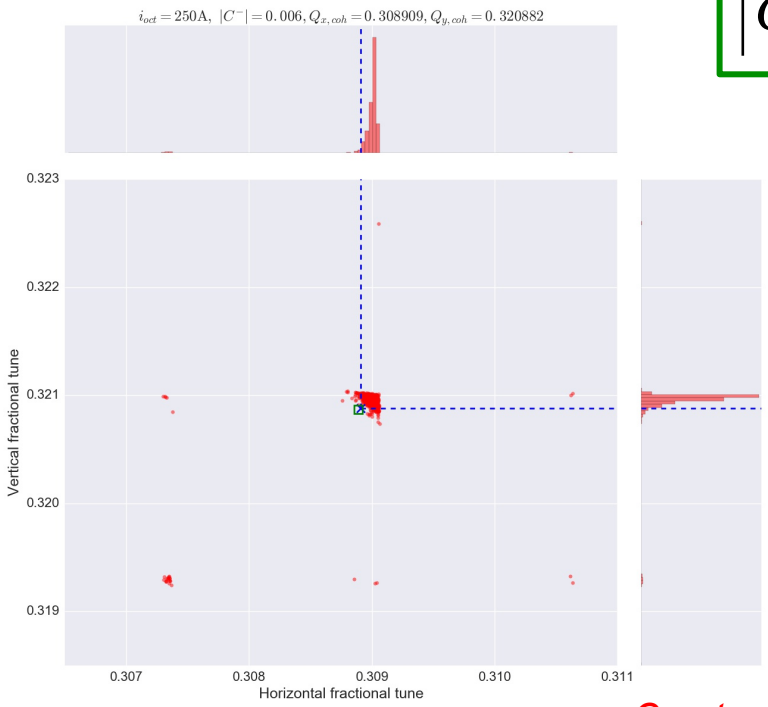
- MADX with the real octupoles (**LOF > 0, swapped tunes**)



Courtesy of L.R. Carver

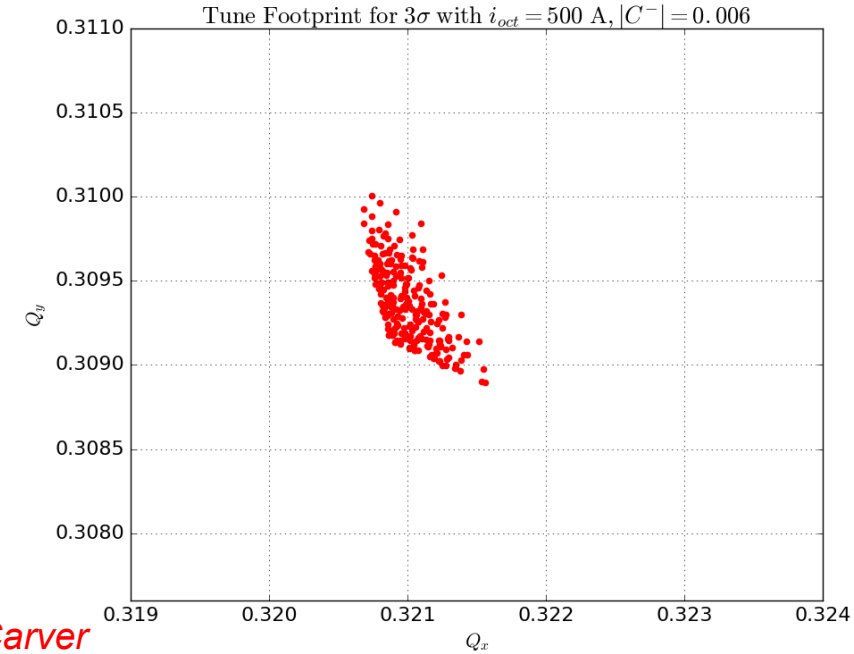
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner (**LOF < 0**)



$$\left|C^-\right| = 0.006$$

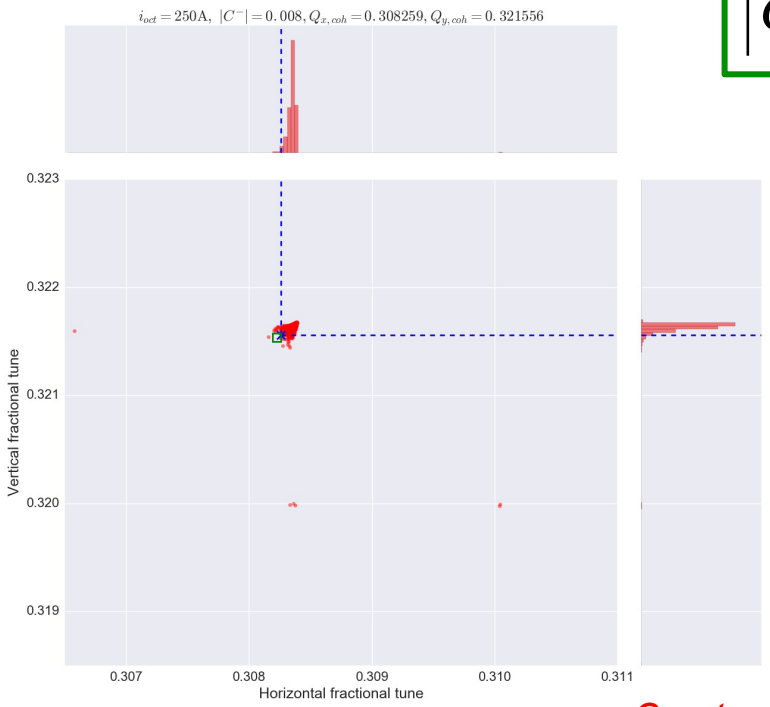
- MADX with the real octupoles (**LOF > 0, swapped tunes**)



Courtesy of L.R. Carver

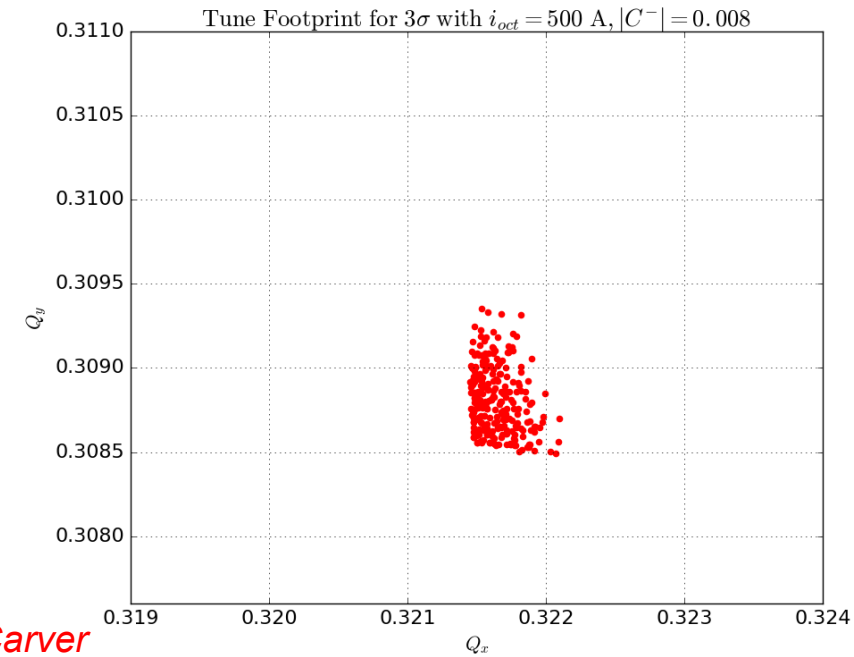
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner (**LOF < 0**)



$$\left|C^-\right| = 0.008$$

- MADX with the real octupoles (**LOF > 0, swapped tunes**)



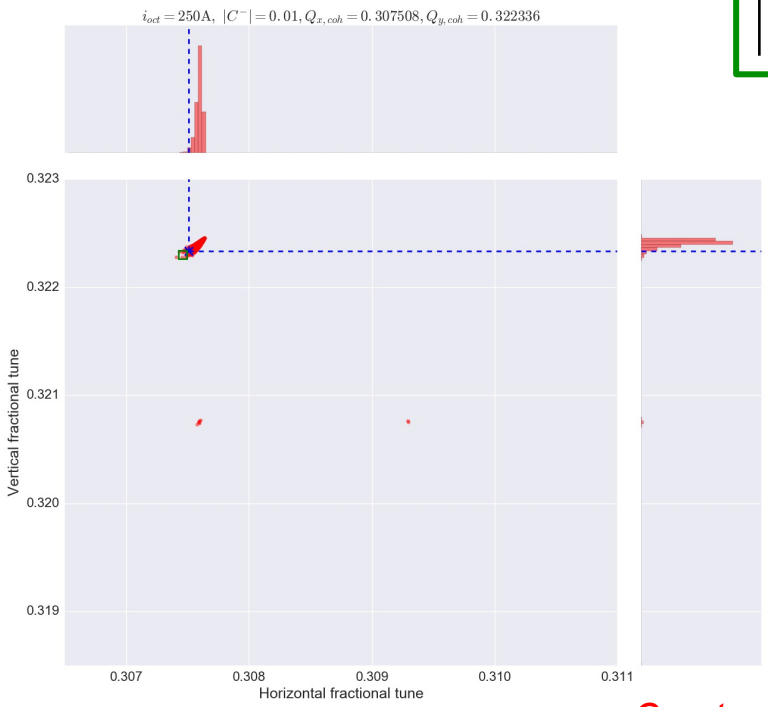
Courtesy of L.R. Carver

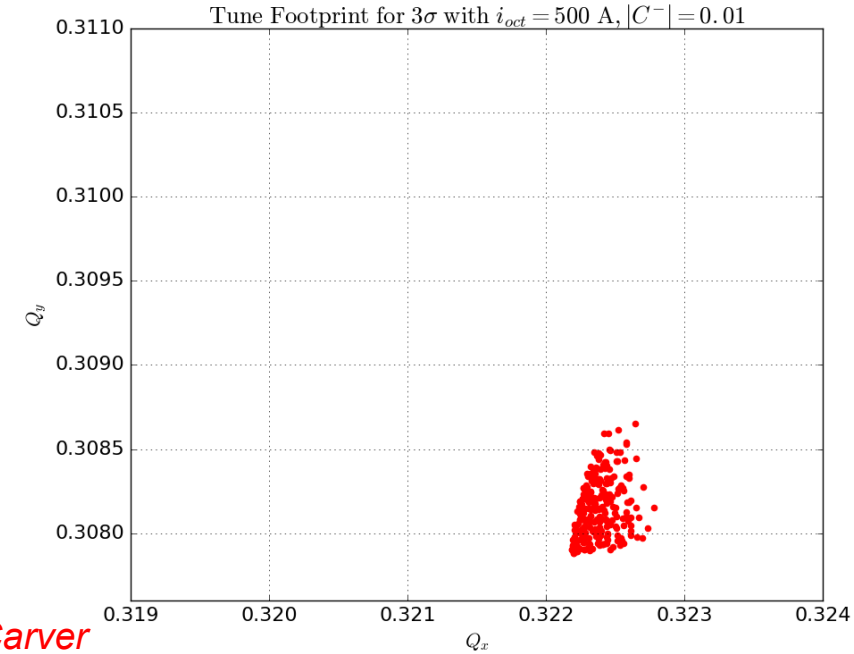
Effect of linear coupling

- pyHEADTAIL simulations with an octupole as detuner (**LOF < 0**)

$$\left|C^{-}\right| = 0.01$$

- MADX with the real octupoles (**LOF > 0, swapped tunes**)

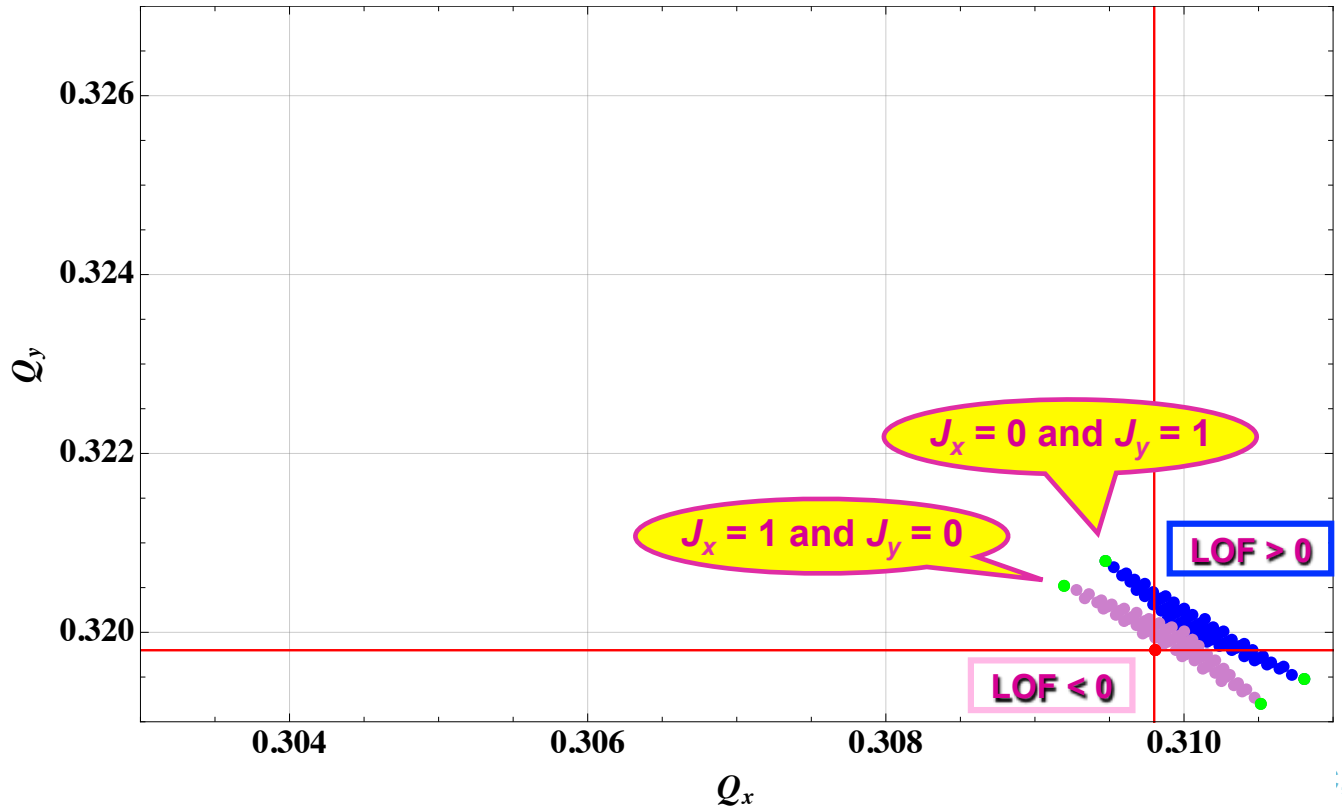




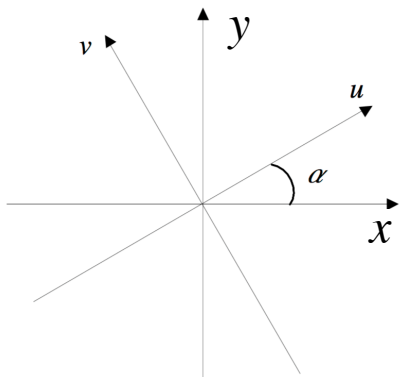
Courtesy of L.R. Carver

Effect of linear coupling

- Physical mechanism => Simple model?



Effect of linear coupling

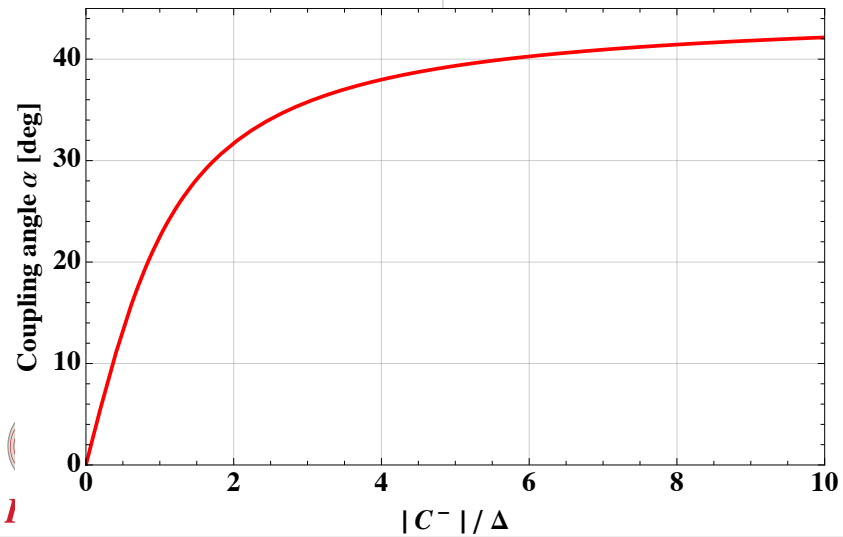


$$Q_u = Q_x - \frac{|C^-|}{2}\tan\alpha$$

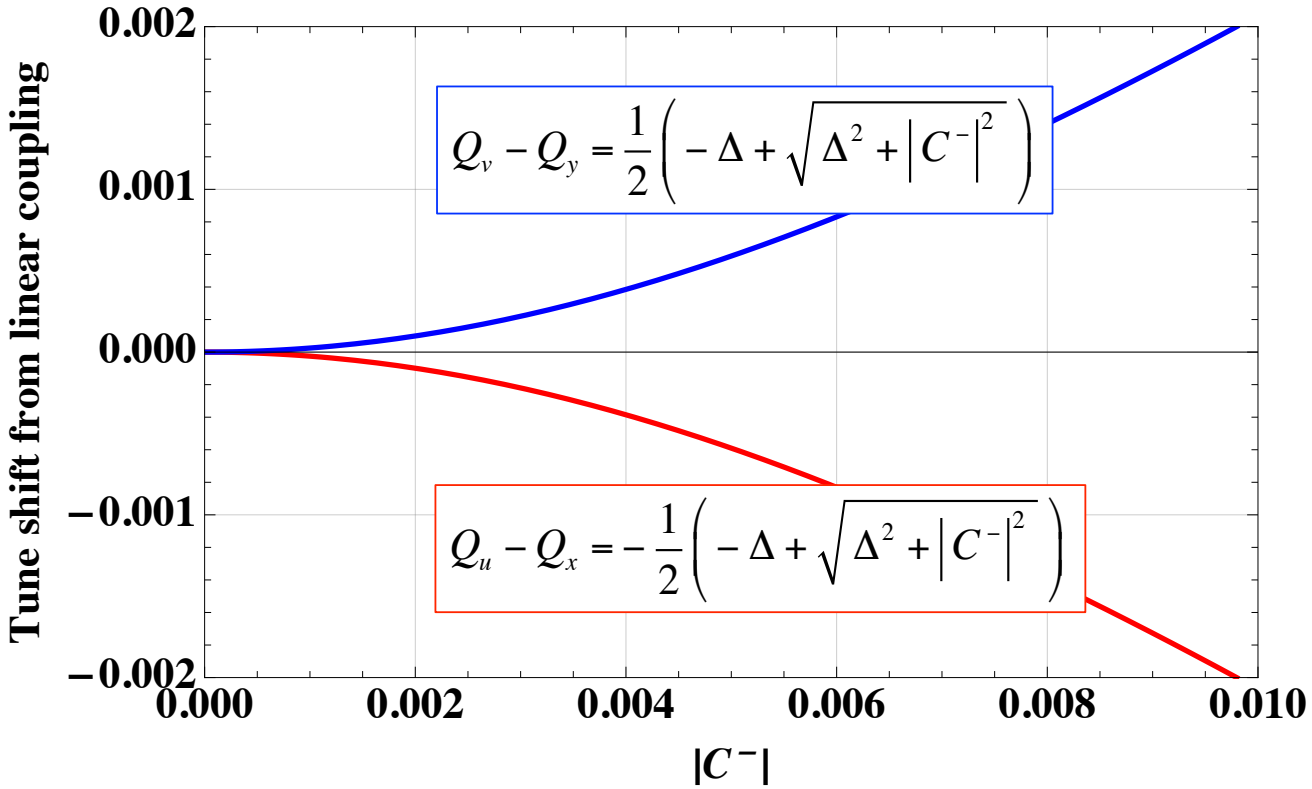
$$Q_v = Q_y + \frac{|C^-|}{2}\tan\alpha$$

$$\Delta = Q_y + l - Q_x = q_y - q_x$$
$$= Q_{sep}$$

$$\tan(2\alpha) = \frac{|C^-|}{\Delta}$$



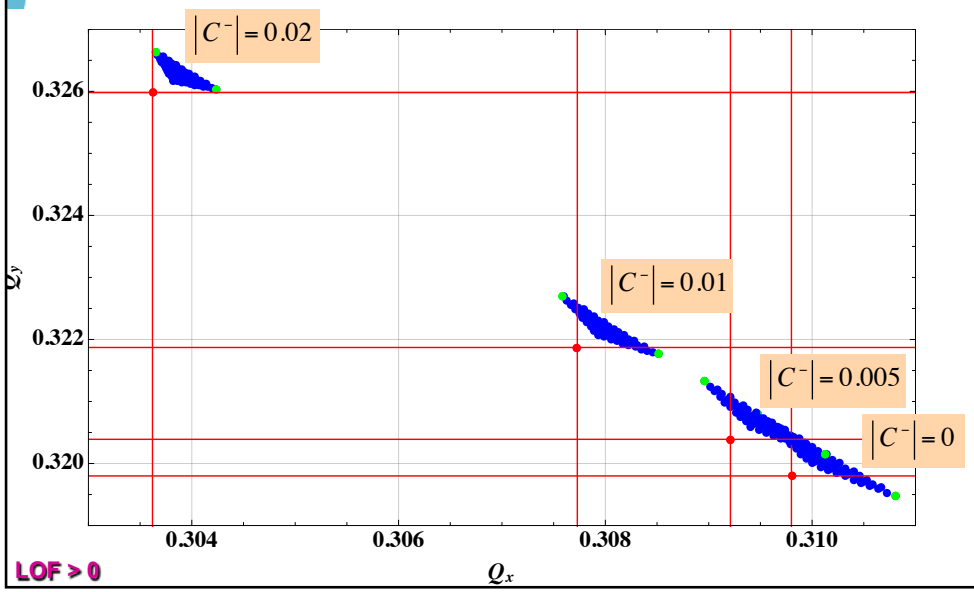
Effect of linear coupling

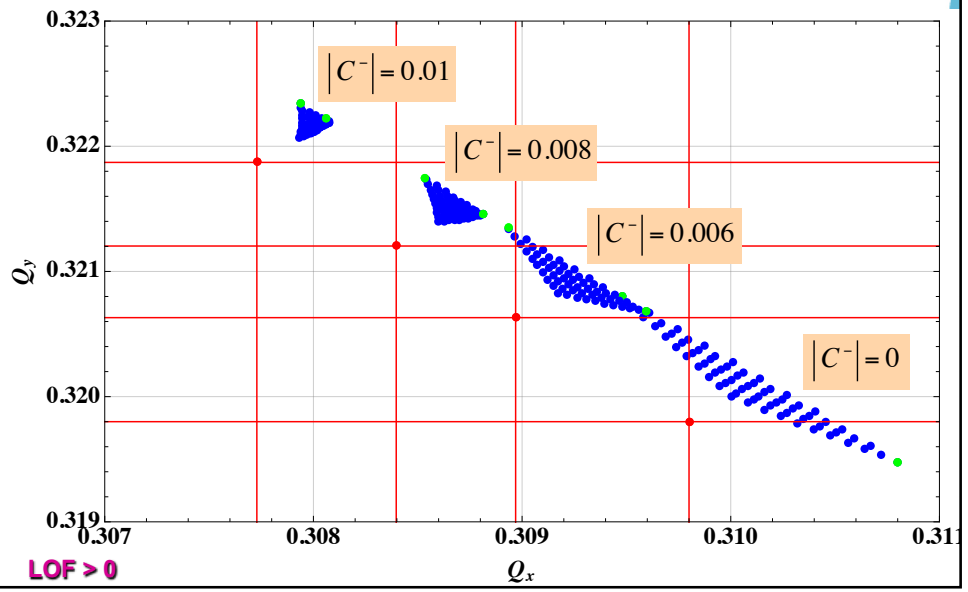


Effect of linear coupling

- Similar (but much smaller) behaviour seen
- Another ingredient is needed => Amplitude-dependent C^-
  - Example found empirically:

$$\left|C^-\right| \times \left[1 + 0.15\left(J_x - J_y\right)\right]$$





Effect of linear coupling

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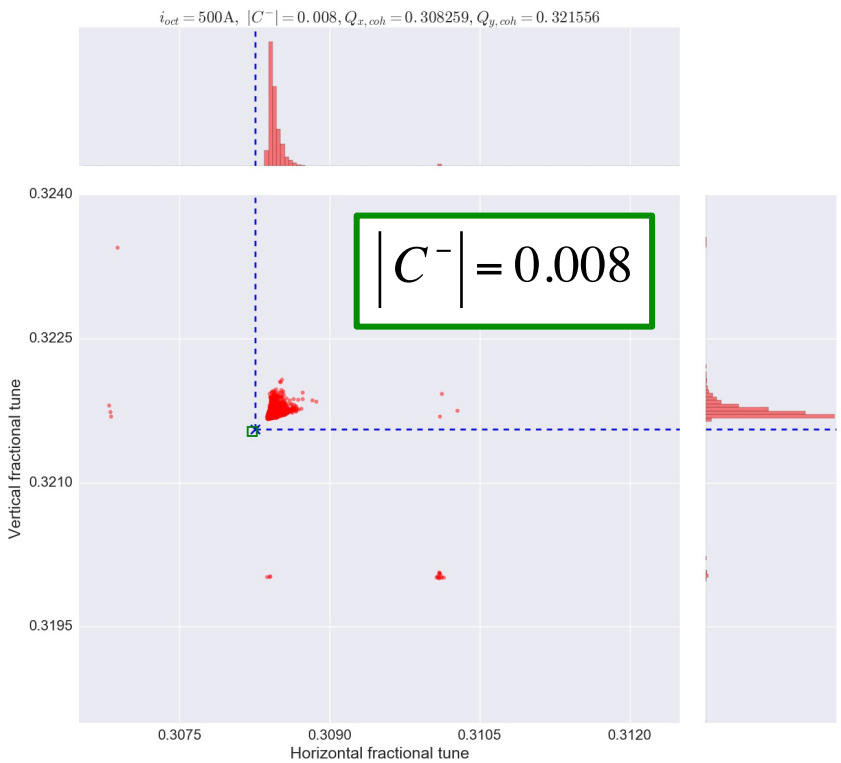
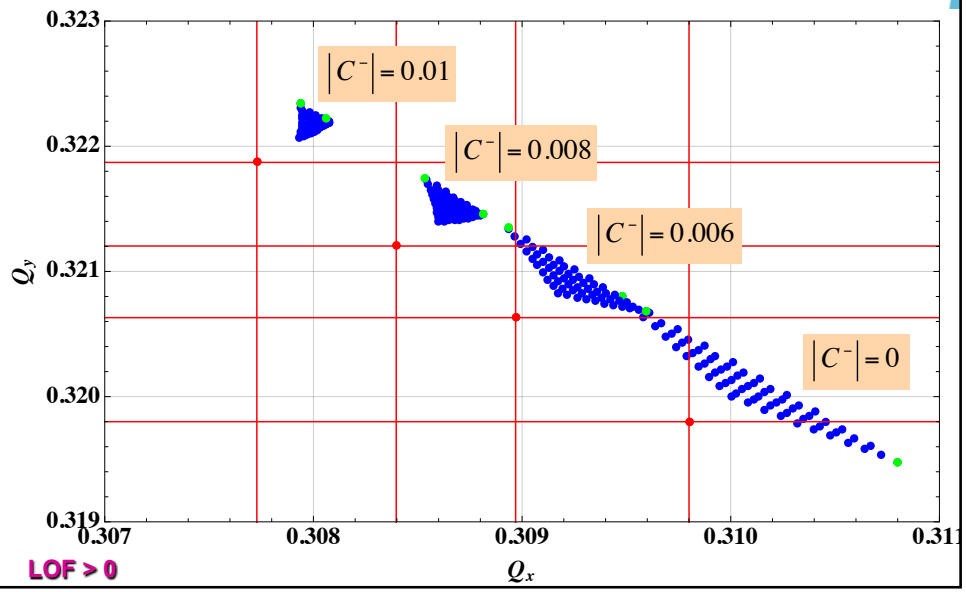
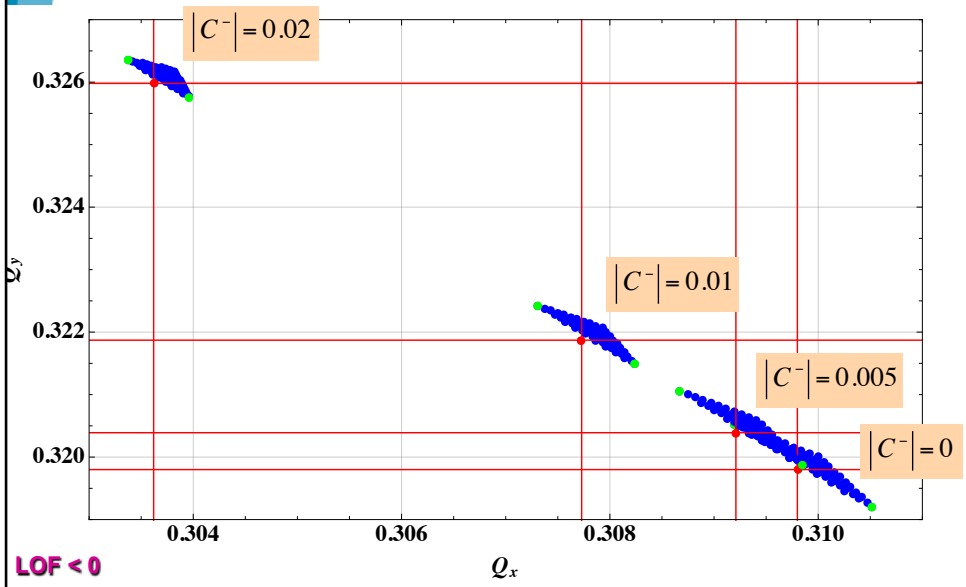
$$\left|C^-\right| \times \left[1 + 0.15\left(J_x - J_y\right)\right]$$

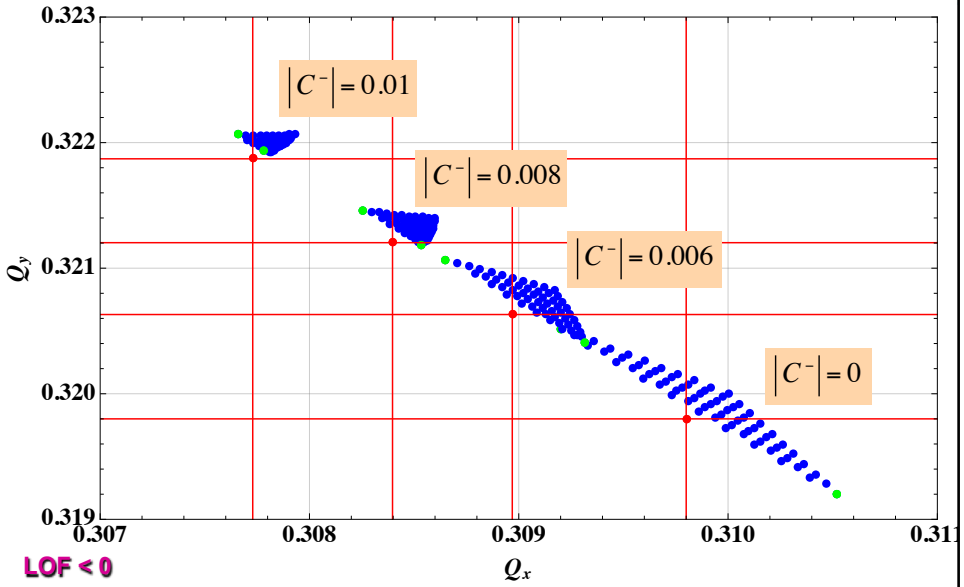




Effect of linear coupling

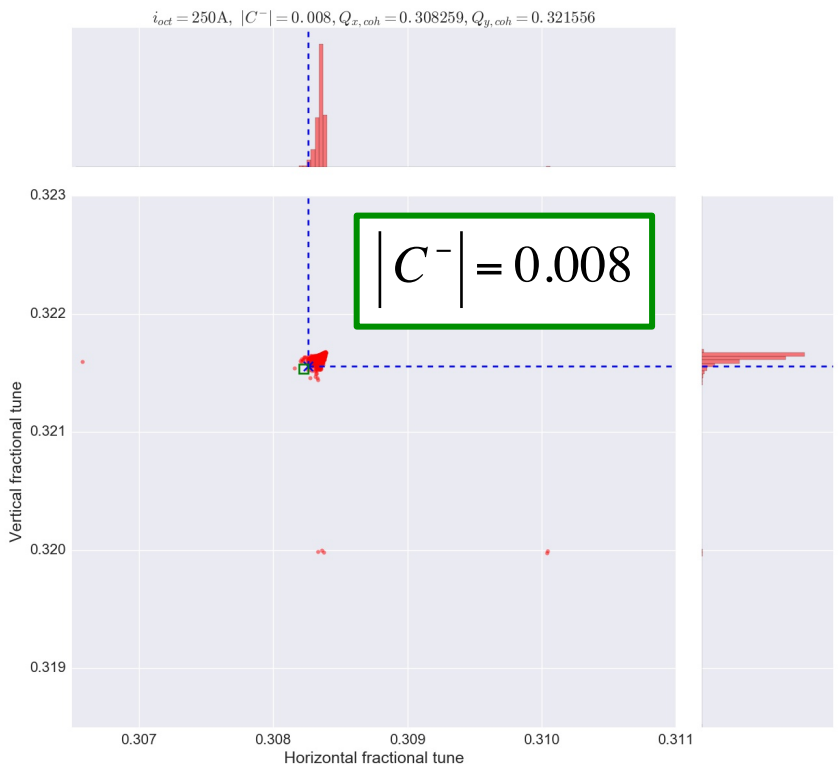
$$\left|C^-\right| \times \left[1 - 0.15\left(J_x - J_y\right)\right]$$

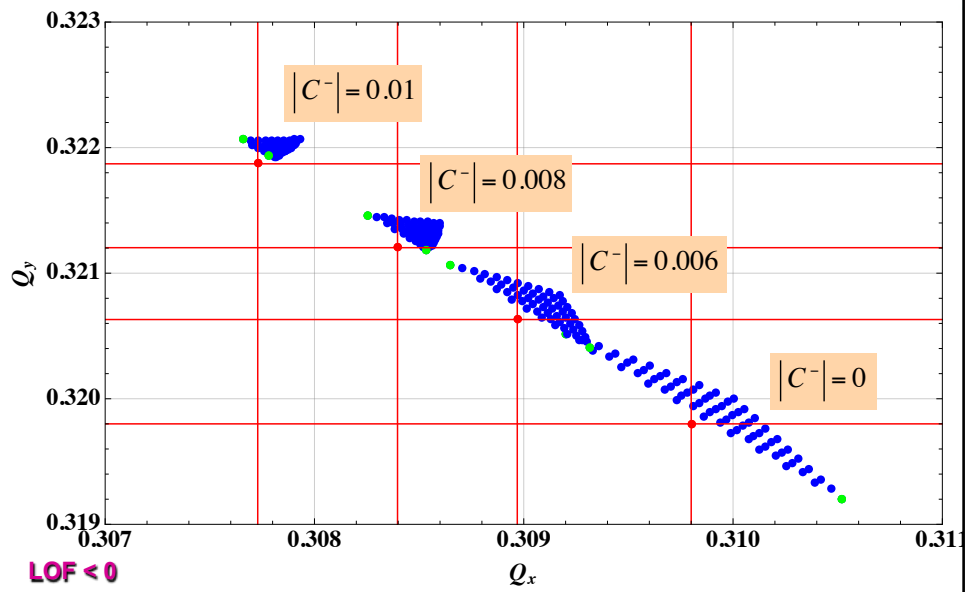




Effect of linear coupling

$$\left|C^-\right| \times \left[1 - 0.15\left(J_x - J_y\right)\right]$$





Effect of linear coupling

- See also R. Tomas et al., “Amplitude dependent closest tune approach” (submitted to PRAB) => However, the amplitude-dependent C^- discussed before is not the same as the one in the paper and has been deduced empirically => To be continued…

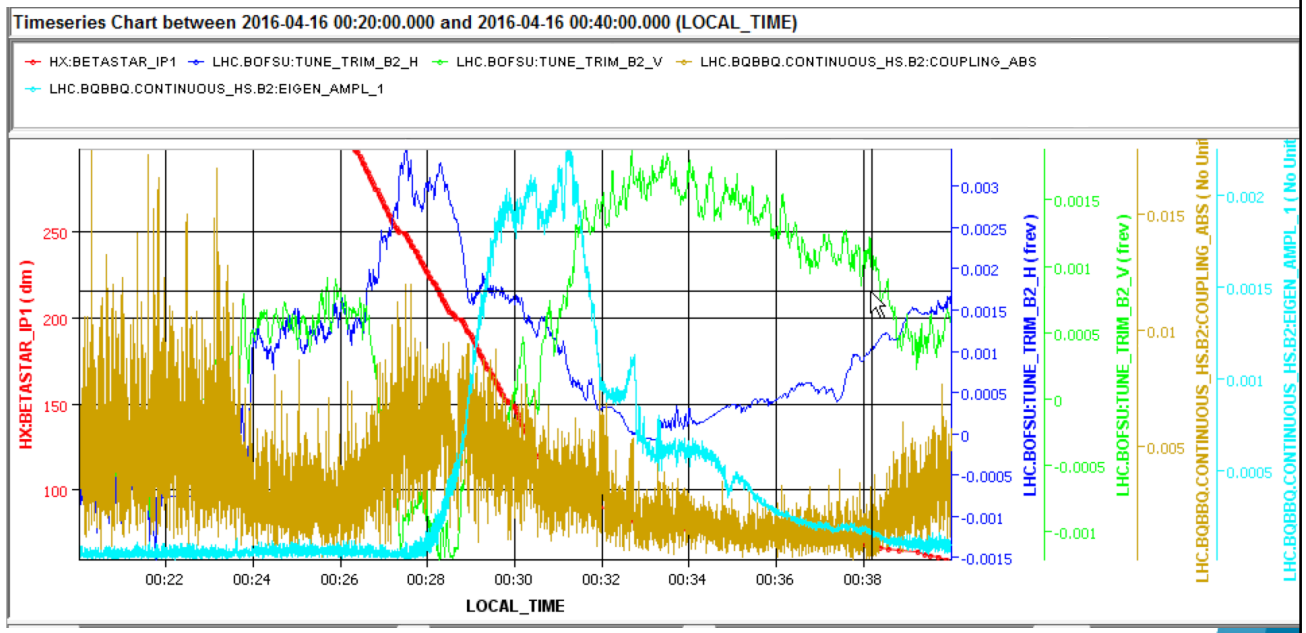
Effect of linear coupling

- Dedicated instability measurements in the LHC on 16/04/2016
  - 1) During the betatron squeeze
  - 2) At top energy (before the betatron squeeze)

Effect of linear coupling

- 1) During the betatron squeeze: ADT on, Q' ~ 9 and LOF = + 285 A

- $|C^-|$ ~ 0.008
- Q_1/Q_2 kept at 0.31/0.32 (tune feedback) => Q_x ~ 0.312 and Q_y ~ 0.318 => $Q_y - Q_x$ ~ 0.006 (i.e. tune feedback is amplifying the coupling effect!)
- Instability observed with LOF = + 285 A, i.e. ~ 4 times higher octupole current than uncoupled threshold



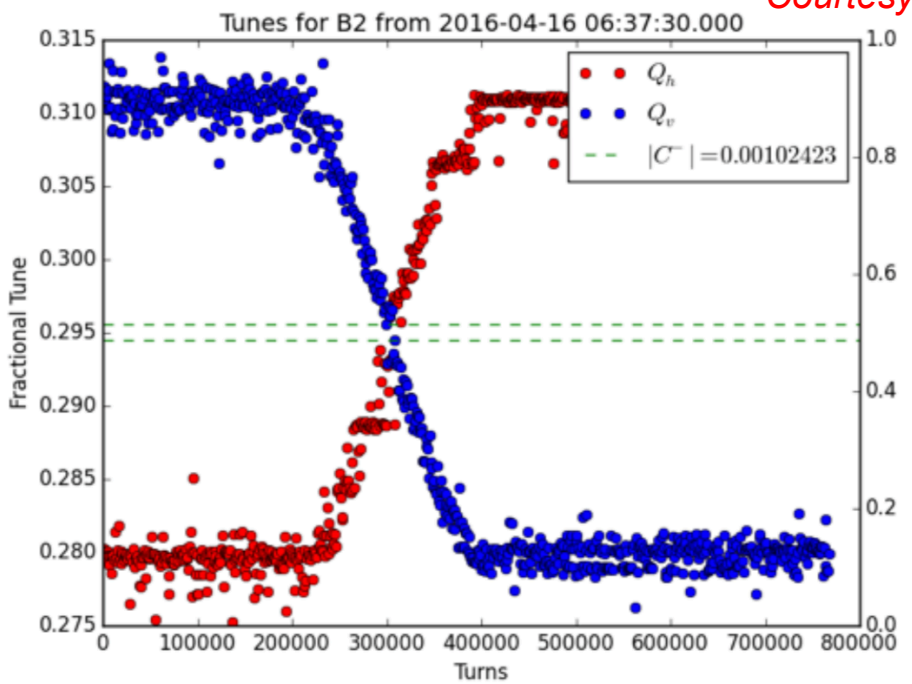
Effect of linear coupling

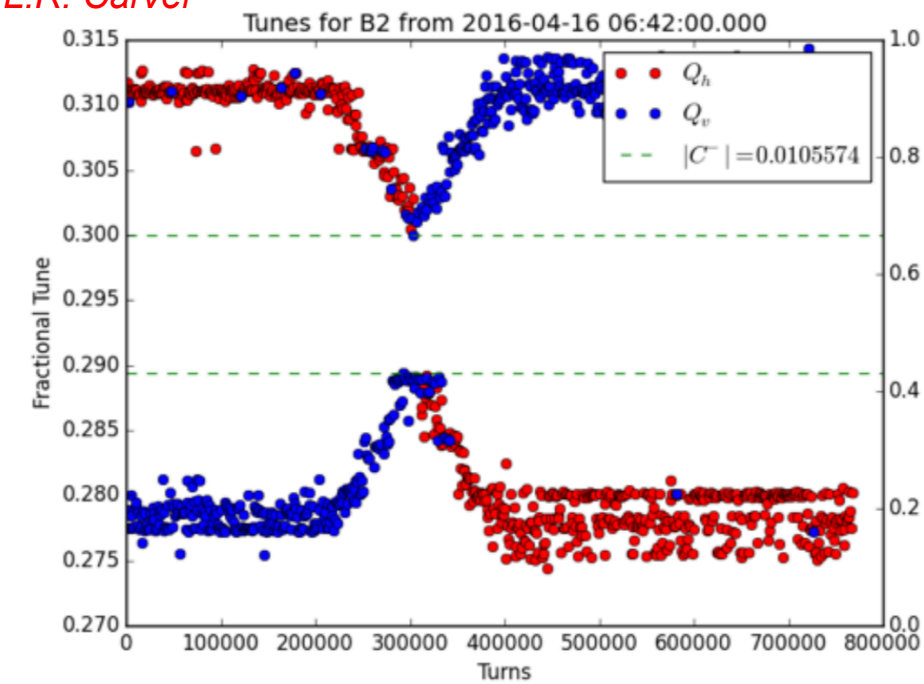
- 2) At top energy (before the betatron squeeze)

- $|C^-|$ ~ 0.001 and Q_{sep} = 0.03:
=> Stability for LOF = + 71 A

- $|C^-|$ ~ 0.01 and LOF = + 310 A
=> Instability for Q_{sep} ~ 0.018

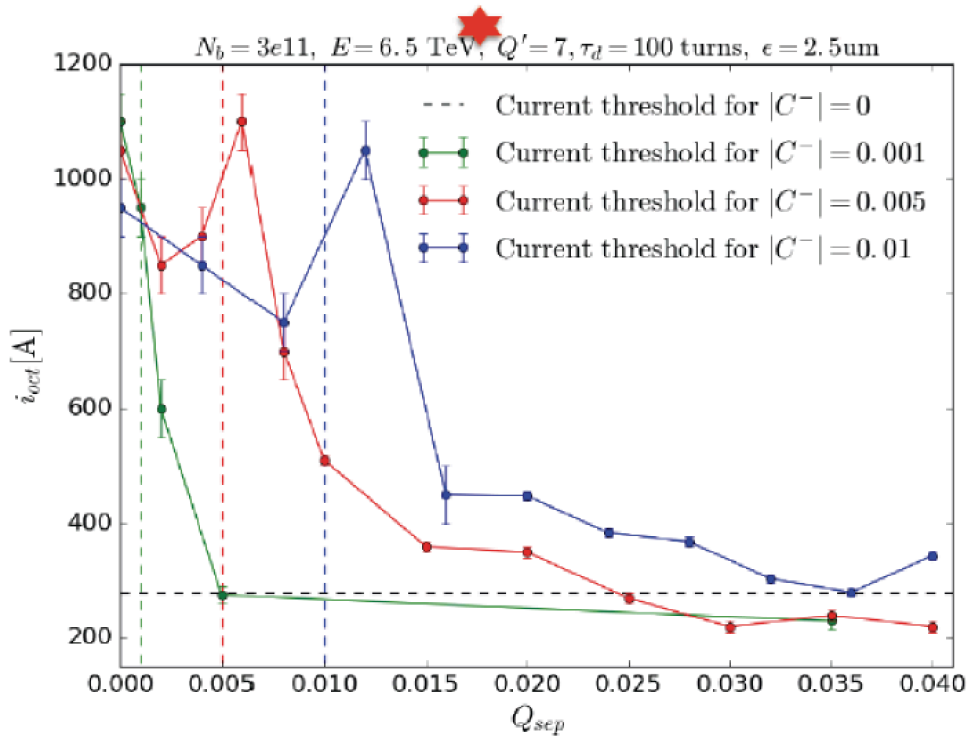
Courtesy of L.R. Carver





Effect of linear coupling

=>This gives a factor 310 / 71 = 4.4 increase in Landau octupoles current compared to the uncoupled case

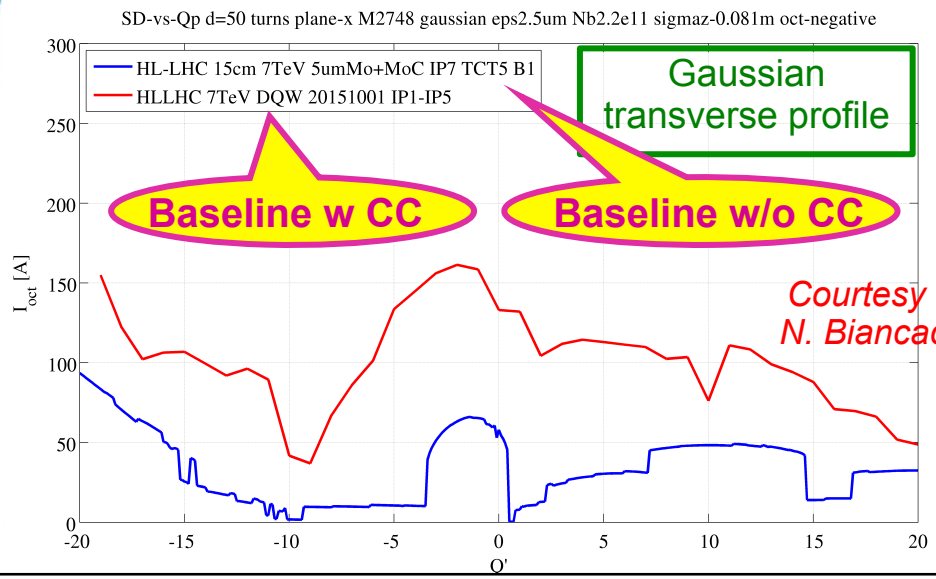


Courtesy of L.R. Carver

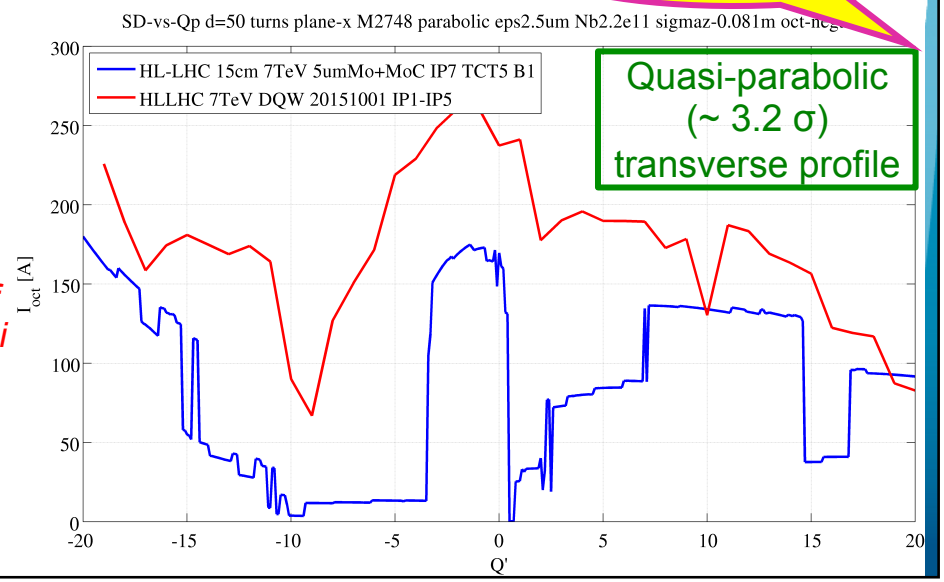
Conclusion

- Beam stability predictions were based so far on a scaling from instabilities observed in 2012
  - The limit from impedance only is believed to be (much) higher (at least for Q' > ~ 2, from meas. in LHC => See talk on impedance)

e.g. from e-lens



Courtesy of N. Biancacci

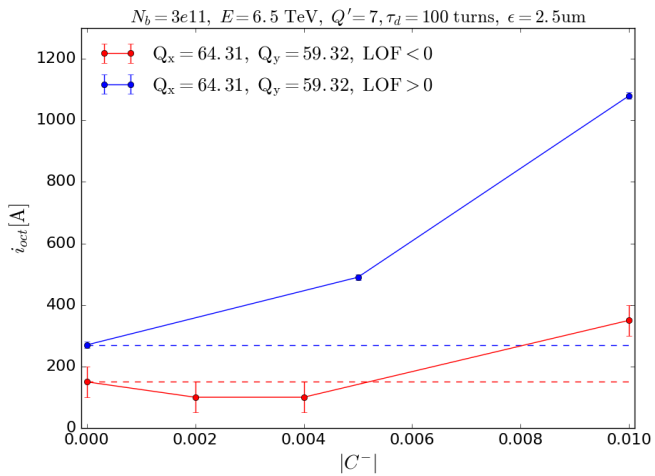


Conclusion

- Should work more now on the other mechanisms

Recommendations

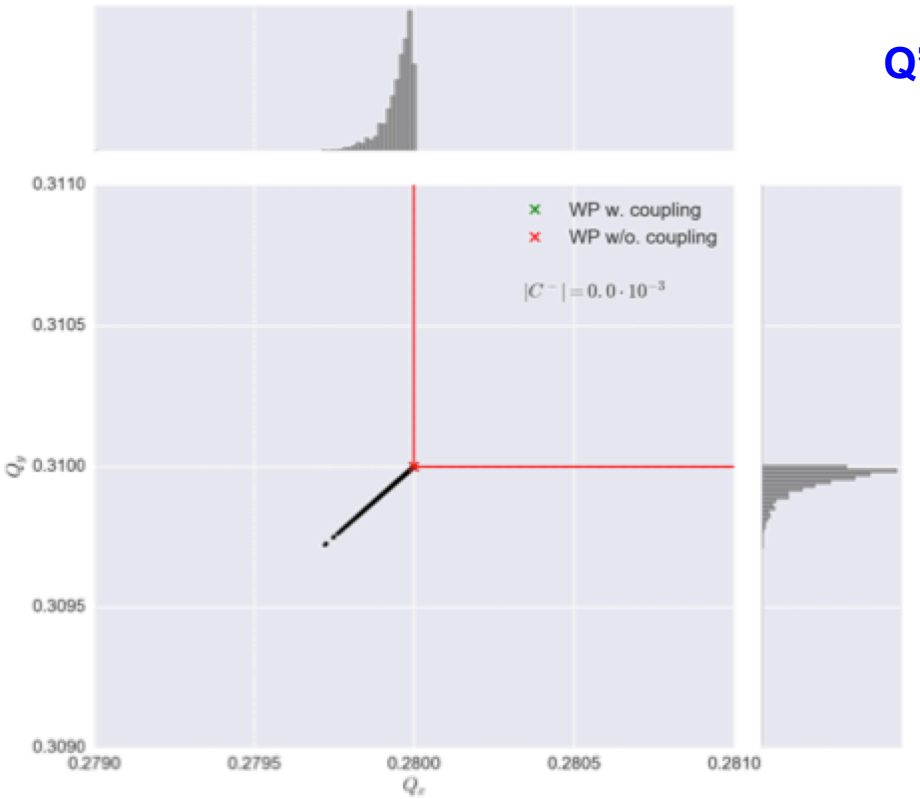
- Linear coupling
  - For LOF > 0 (as LHC in 2016) => For each bunch: $\frac{Q_y - Q_x}{|C^-|} > \sim 4$
  - For LOF < 0 (as for HL-LHC) => Bit less critical: $\frac{Q_y - Q_x}{|C^-|} > \sim 2$



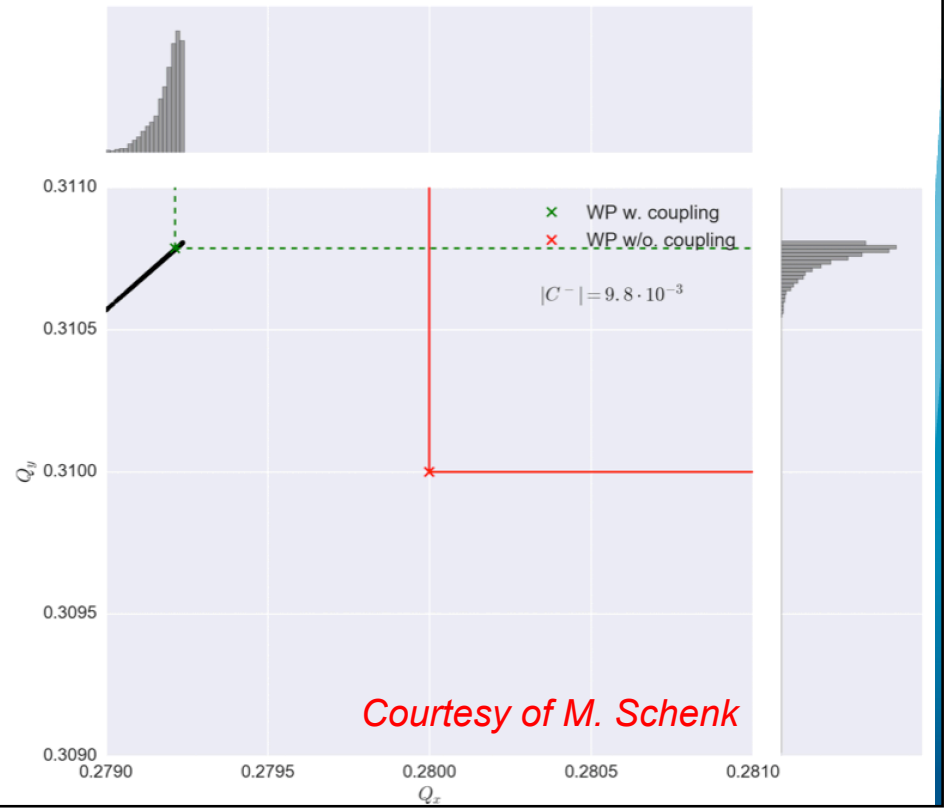
Courtesy of L.R. Carver

Conclusion

- Note that using Q” or an RFQ (for longitudinal-to-transverse Landau damping), linear coupling should not be detrimental for beam stability!



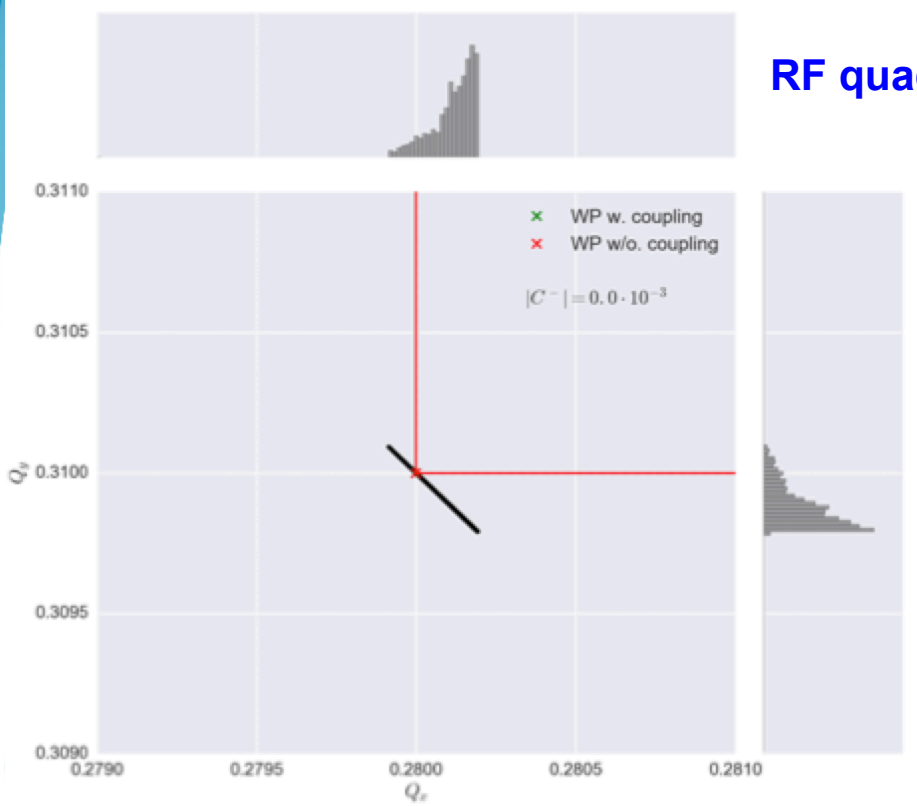
Q”

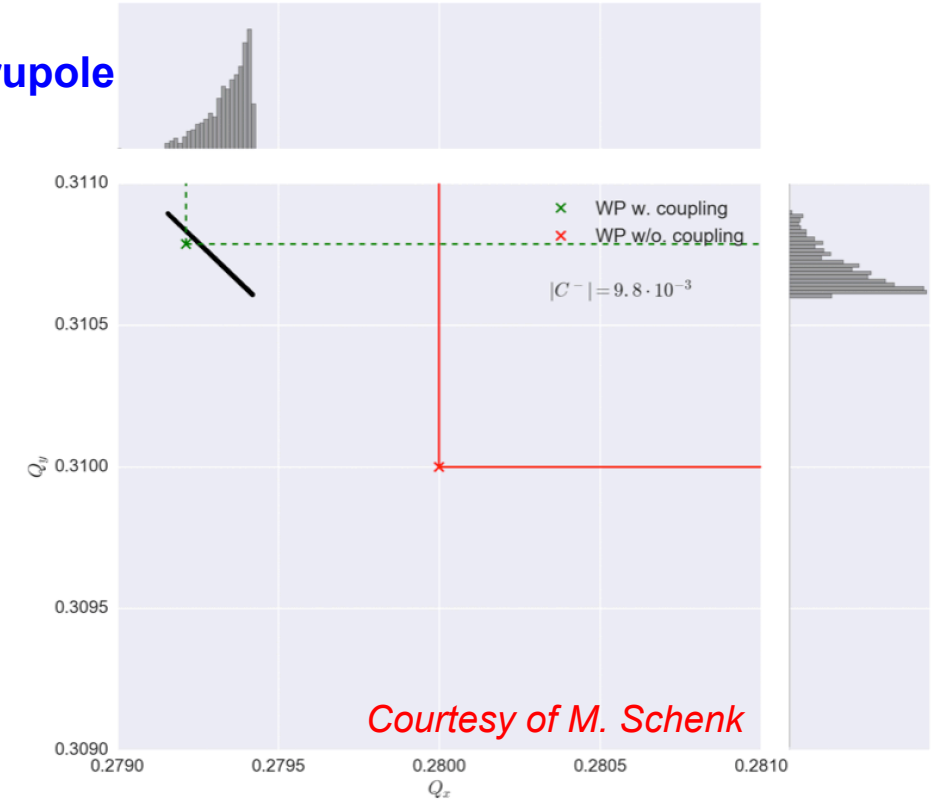


Courtesy of M. Schenk

Conclusion

RF quadrupole





Courtesy of M. Schenk

Conclusion

- E-cloud => Coating (low SEY) + scrubbing + further studies needed (ongoing)
- Noise
  - 1st SD measured at injection (BTF)
  - Evolution of SD still to be measured at high energy
  - The 12 non-colliding bunches (in the witness region and with ADT in bunch-by-bunch) unstable in stable beams on 13/05/2016 after few hours => Effect of noise? => To be continued…
- Working point at injection
  - Same as 2016? => 0.27/0.295 instead of nominal 0.28/0.31
  - Compensation of Laslett tune shifts (otherwise possible issues with linear coupling)

Conclusion

- Going into collision
  - Recommendation to go from 2 σ to 1 σ in less than 1 s
  - MDs are planned to explore fast instability at the minimum of SD

HiLumi
HL-LHC PROJECT

Thank you for your attention!

LARP