Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI

Transverse beam stability and Landau damping in hadron colliders

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J. Barranco, X. Buffat, T. Pieloni

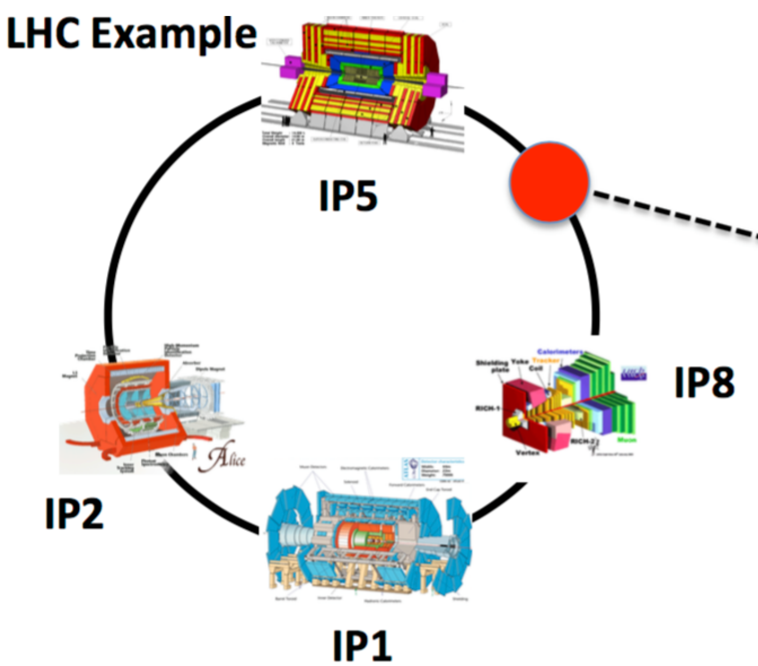
Acknowledgements: L. Barraud, E. Metral, B. Salvant, G. Rumolo, L. Mether, S. Antipov, D. Amorim, N. Biancacci, G. Iadarola, L. Carver

IHEP: The first international workshop on the Circular Electron Positron Collider 6-8 Nov 2017, Beijing, China

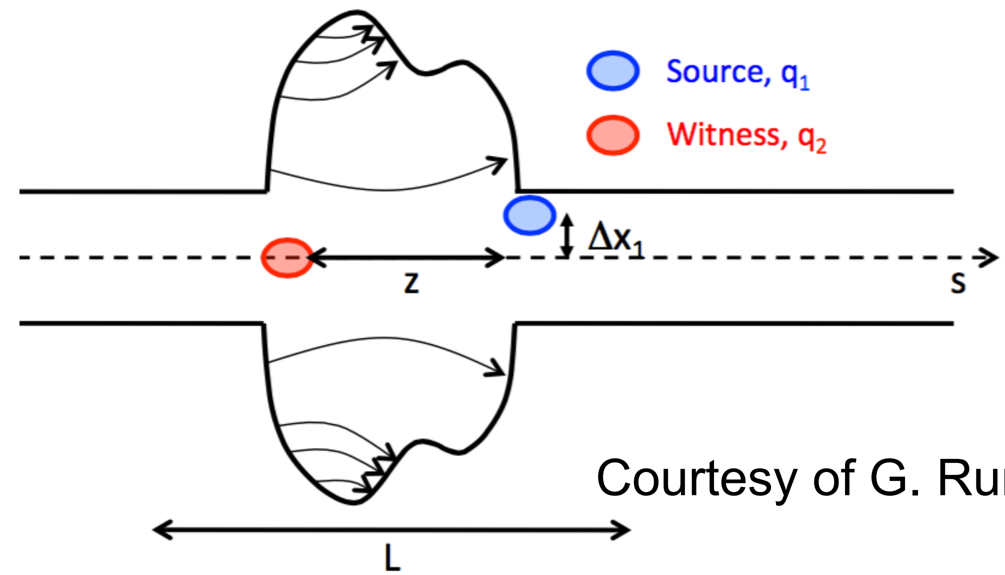
Contents

- Beam coupling impedance and coherent instabilities
- Mitigation techniques:
  - Landau damping from octupole magnets
  - Impact of dynamic aperture on Landau damping
  - Landau damping in presence of beam-beam interactions
- Beam-beam modes coupled with impedance
- Summary

Beam Coupling Impedance



Accelerator surroundings:
- Beam pipe
- Collimators (5.5 RMS beam size)



Courtesy of G. Rumolo

The source particle induces electromagnetic wake fields (**impedance**) that act back on the following particles modifying the electromagnetic fields provide by the lattice and RF

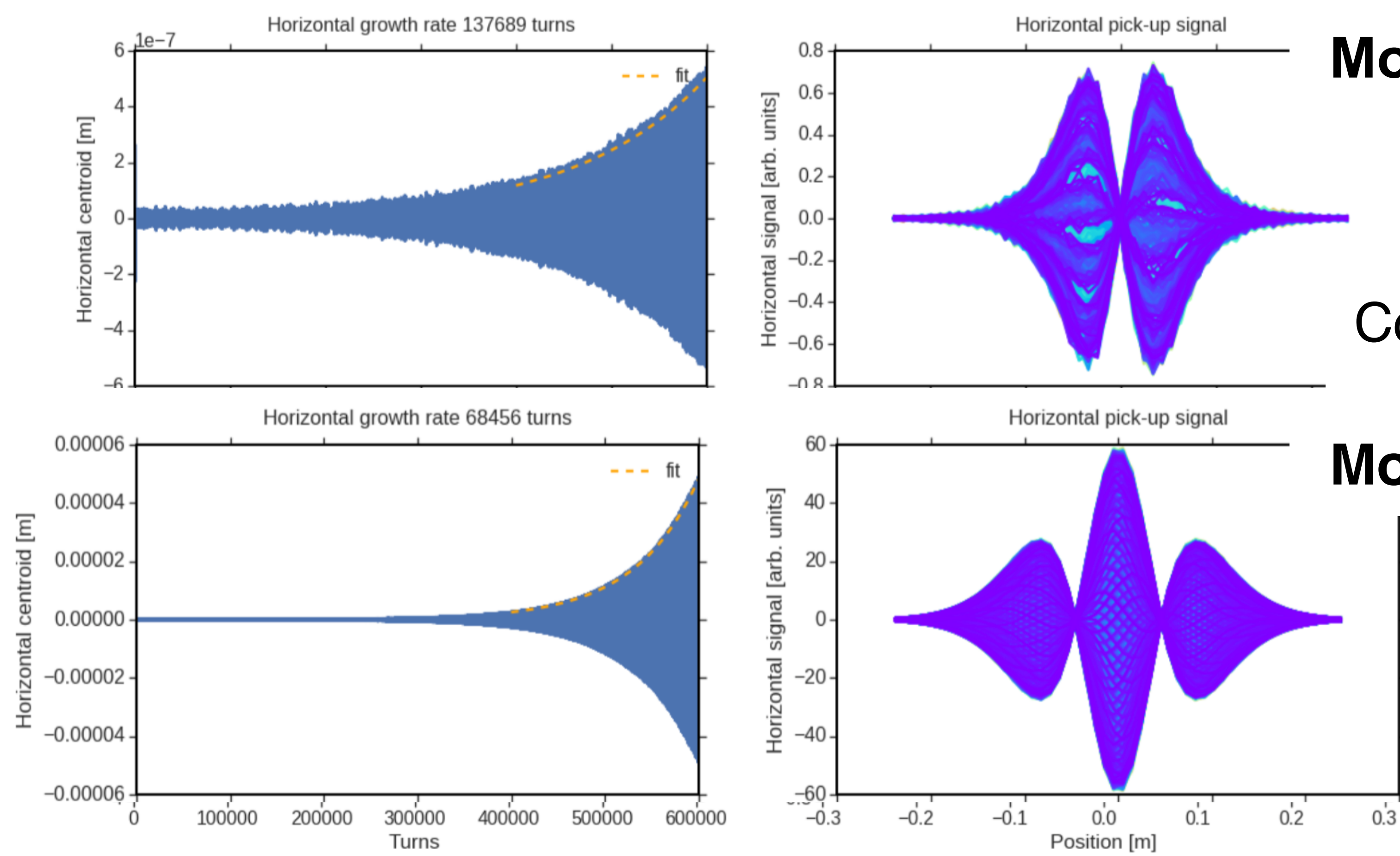
Stronger for high luminosity:

- High brightness beams (N/σ)

- Small aperture elements (collimator 5.5σ)

Head-tail instability

Impedance drives the so-called head-tail coherent instability



Mode 1

Courtesy of A. Oeftiger

Mode 2

Particles start moving with an organized motion ➔ **coherent instability** (center of mass effect)

Complex Tune shifts:

- Im(ΔQ): growth rate
- Re(ΔQ): coherent real tune shift

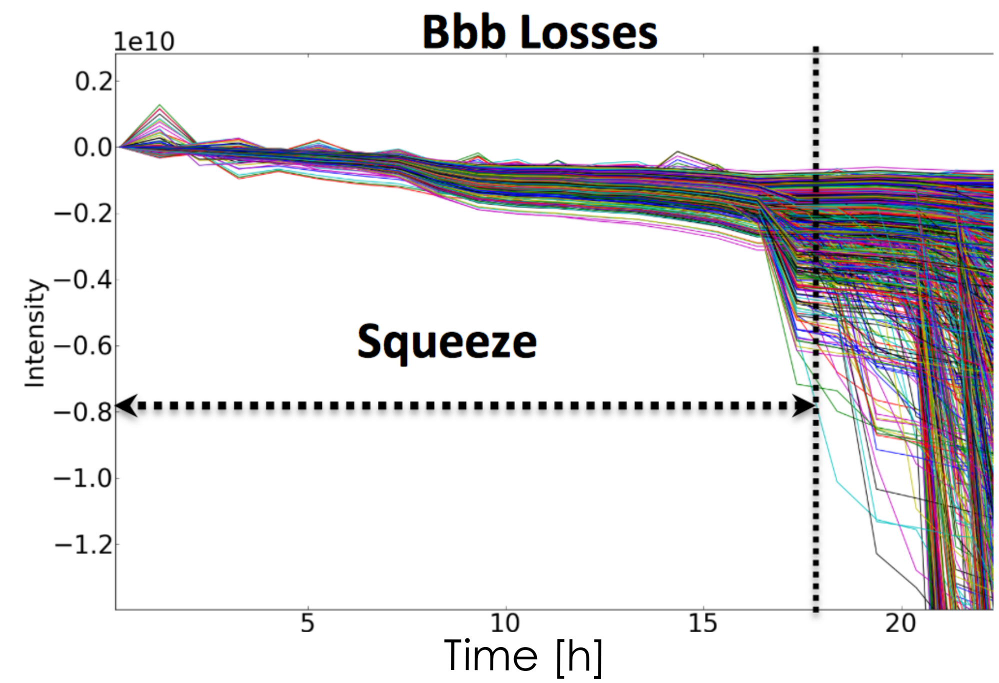
Coherent instabilities

In the LHC several coherent instabilities since the first run:

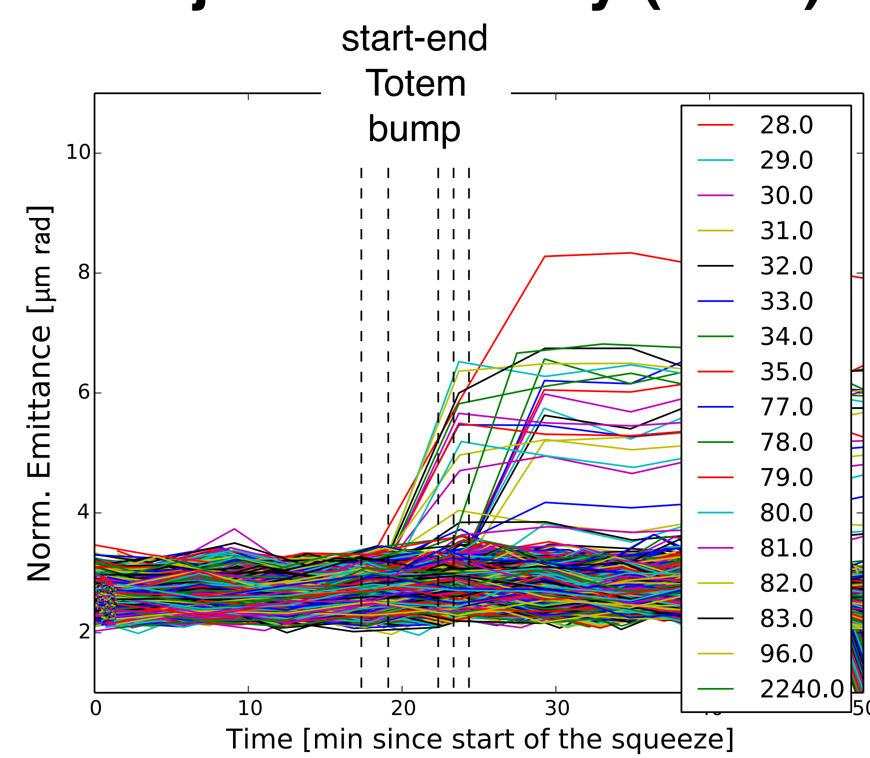
- Coherent oscillations of single bunches
- Emittance blow up
- Loss of intensity

Limitation of machine performances
(luminosity reach)

End of squeeze instability (2012)



Adjust instability (2016)



LHC instabilities

Transverse loss of Landau damping (rise times of 1 to 10 s)
- End of squeeze instability (2012)
- Snowflakes (2012, beam-beam with offset)
- Linear coupling with collision tunes (2015)
- CB^2 (coupled bunch coupled beam instability, 2016)
- Weird B1V instability (2016), weird B1H instability (2017)
- Hunchback instability (2015, 2017)
- Popcorn instability

Mode coupling instability with colliding beams (2012 ~1 s)

Electron cloud instabilities (~1 s)

16L2 instability (~20 turns)

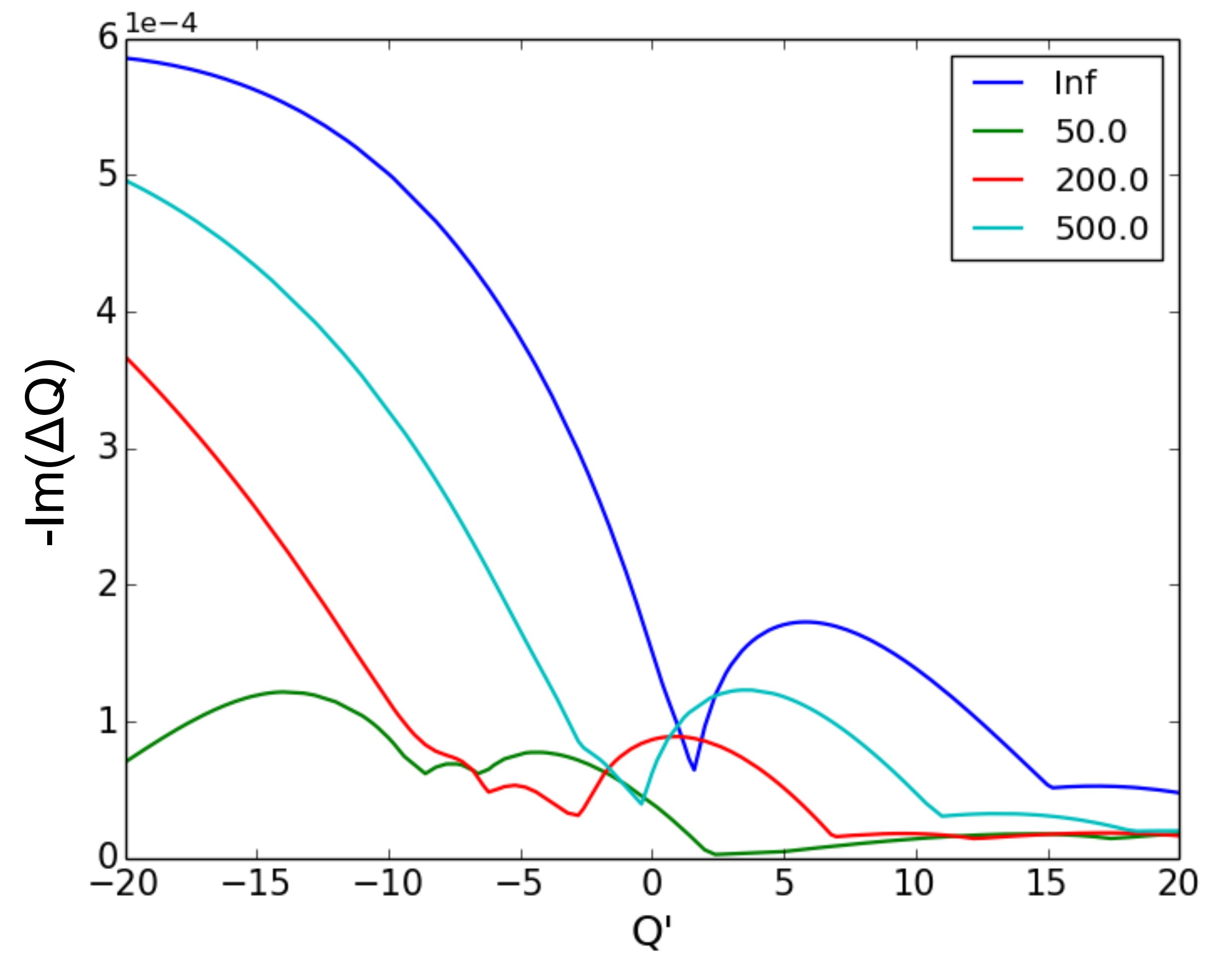
Courtesy of B. Salvant

In view of future colliders (HL-LHC, HE-LHC, FCC, SPPS) with high beam intensity and/or high beam energy → understand instabilities and limitation of models

E. Metral et al.
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016

Mitigation techniques

- **High chromaticity ➔** in the 2012 LHC run from Q'=+2 units to Q'=15-20 units (margins for DA, see T. Pieloni's talk)
- **Transverse Feedback ➔** easily damp m=0, intra-bunch modes more complicated (studies foreseen to define tolerances)
- **Landau damping ➔** passive mitigation
  wave↔particles interaction (coherent instability Landau damped when the energy of the wake is not absorbed)



Instability players

Collective Forces:

- Impedance
- Beam-beam interactions
- E-cloud
- Space charge
- Feedback System

Incoherent Effects:

- Lattice
- Q', Q''
- RFQ
- Linear Coupling
- Non-linearities (lattice, octupoles, e-cloud, beam-beam, space charge)

Perturbation

↓

Stability Diagram (Vlasov equation)

High beam intensity
Self-consistent

↓

Tracking (Vlasov solvers)

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Dispersion Integral

Analytical computation of the **Dispersion Integral [1]**

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y}\frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x,J_y) - i\epsilon} dJ_x dJ_y$$

[1] J. Berg and F. Ruggiero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

Dispersion Integral

Analytical computation of the **Dispersion Integral [1]**

Particle distribution (Dynamic Aperture)

$$SD^{-1} = \frac{-1}{\Delta Q_{x,y}} = \int_0^\infty \int_0^\infty \frac{J_{x,y} \frac{d\Psi_{x,y}(J_x,J_y)}{dJ_{x,y}}}{Q_0 - q_{x,y}(J_x, J_y) - i\epsilon} dJ_x dJ_y$$

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Detuning with amplitude
(non-linearities produce tune spread)

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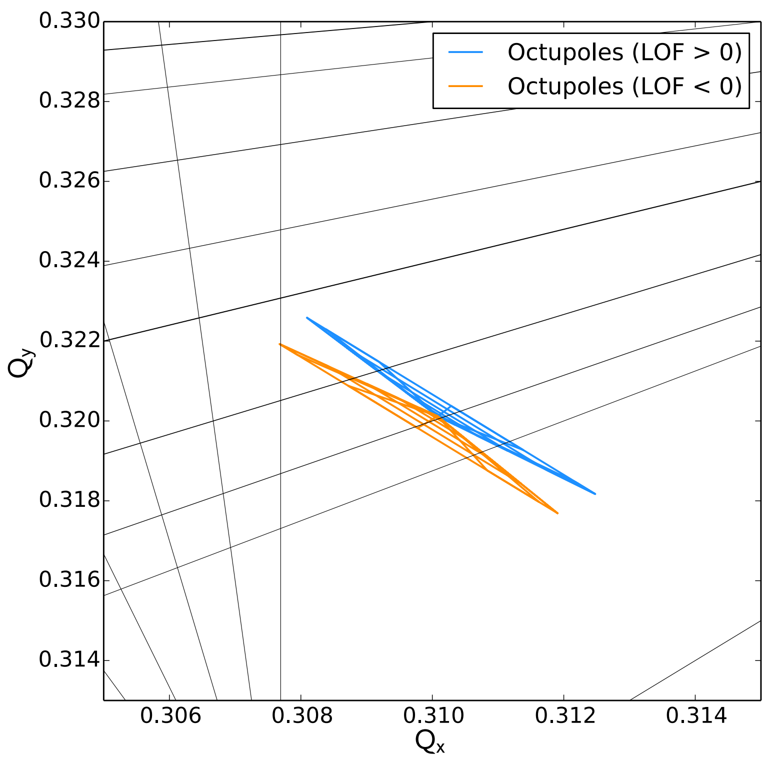
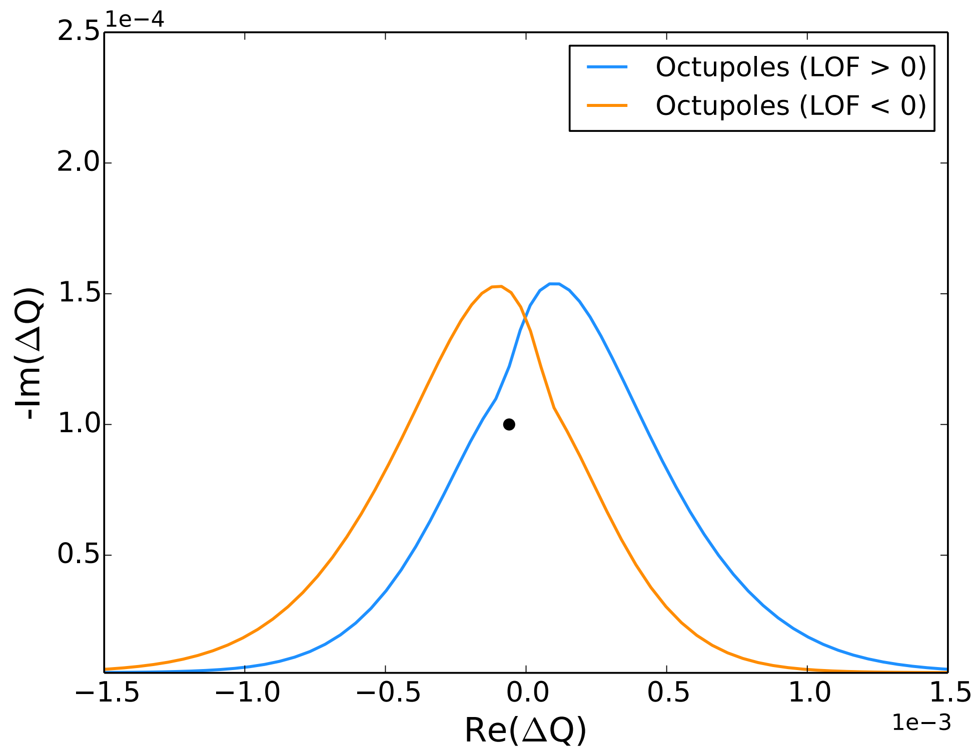
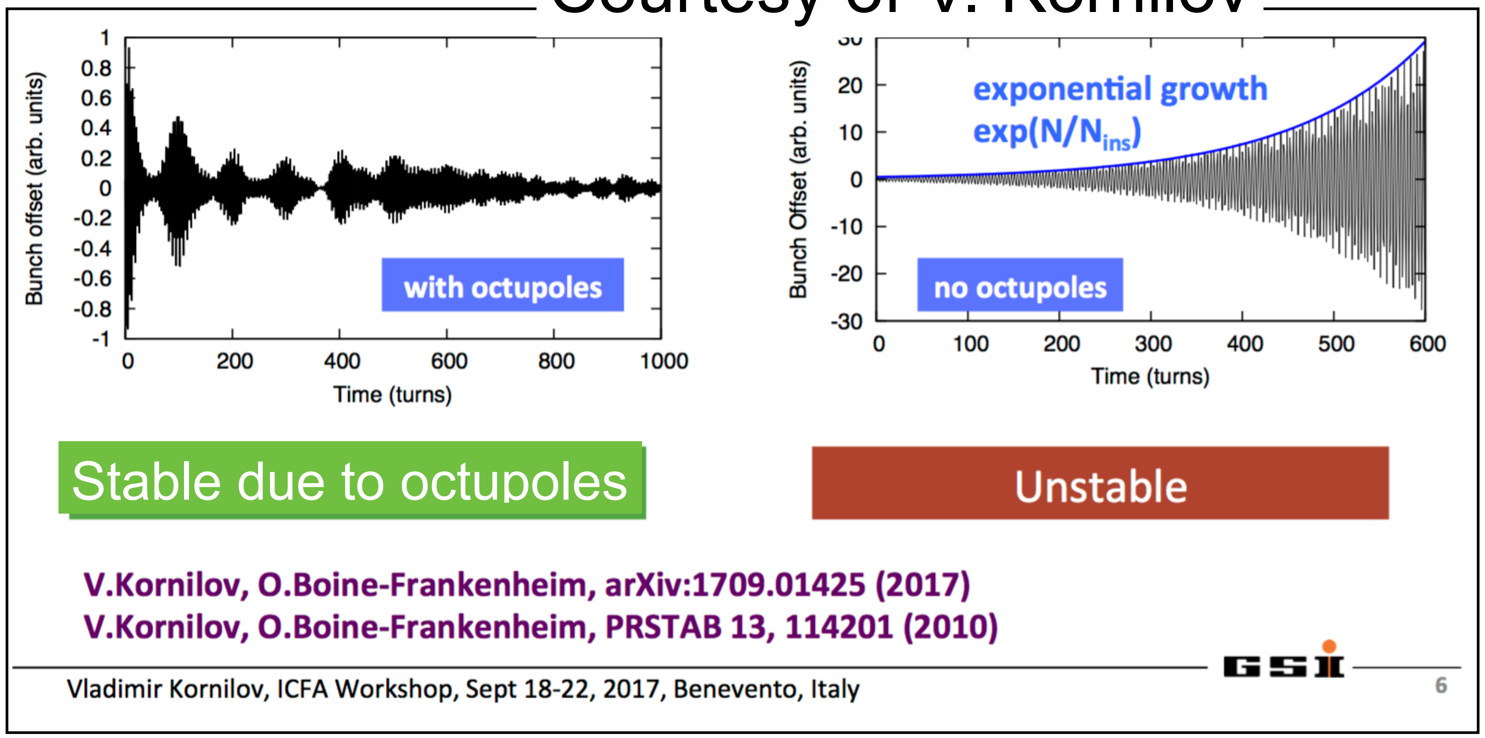




[1] J. Berg and F. Ruggiero, *Landau damping with two dimensional betatron tune spread*, CERN SL-AP-96-71 (1996)

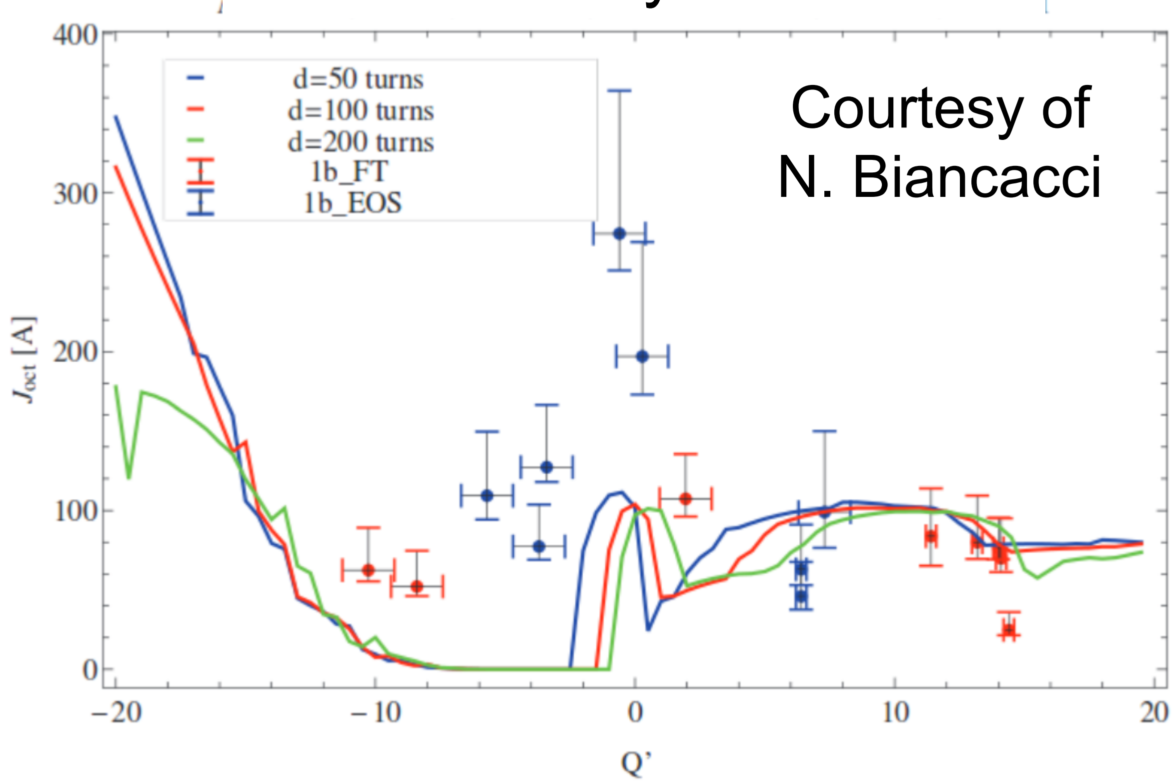
Landau Damping from octupoles

Courtesy of V. Kornilov



- Coherent instability damped by the tune spread distribution provided by Landau Octupoles
- The energy of the wake is not absorbed
- No emittance blow up (no decoherence effect)

LHC Instability Thresholds



LHC instability thresholds are evaluated by computation of dispersion integral

LHC is equipped with 168 Octupoles

➔ LHC octupole current ~ 470 A (4 times higher than predictions)

Landau damping and Dynamic Aperture

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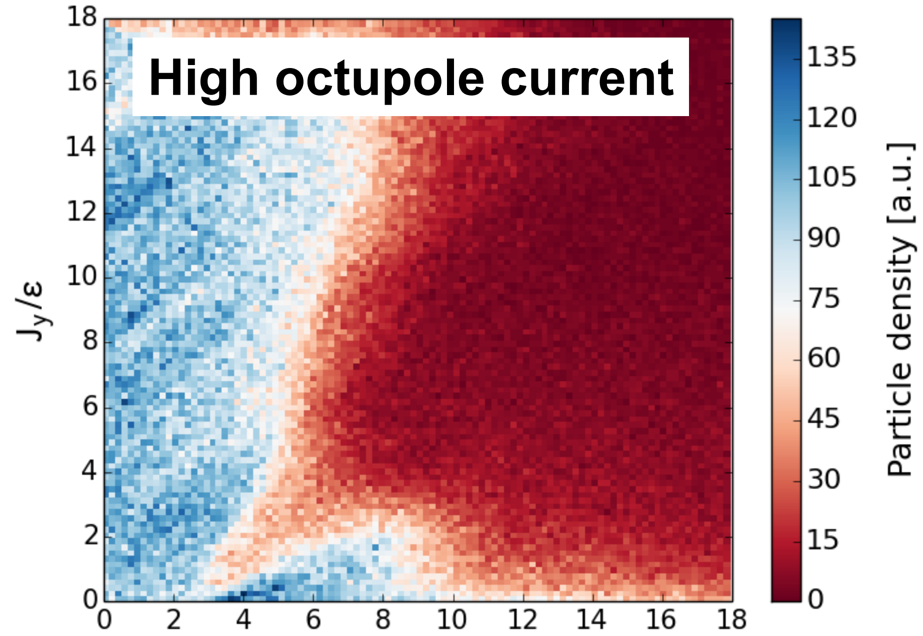
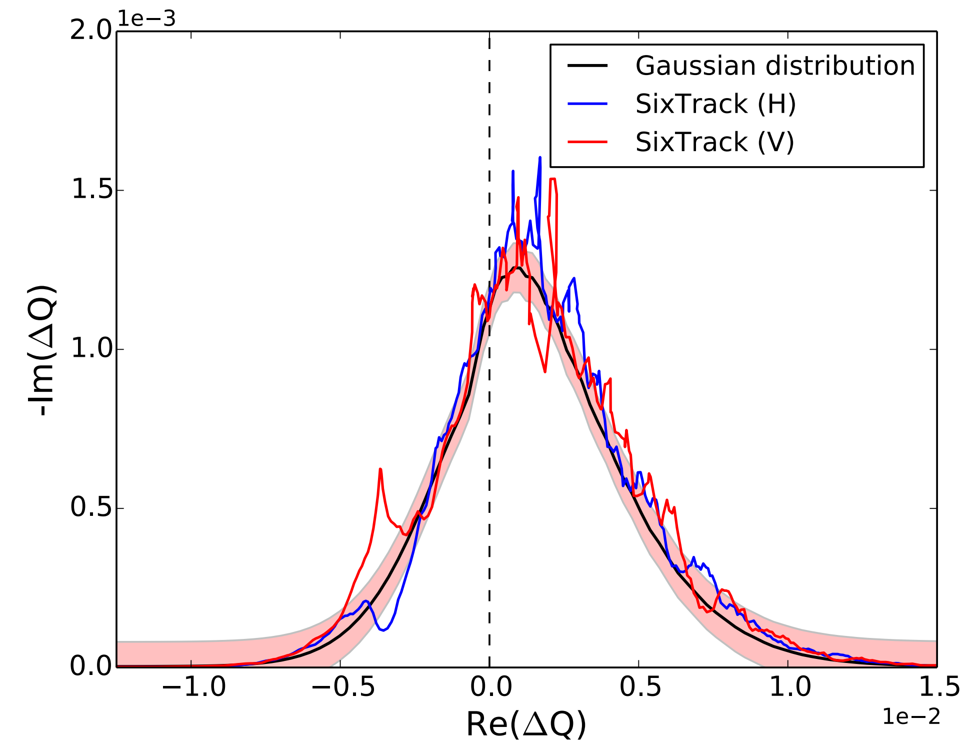
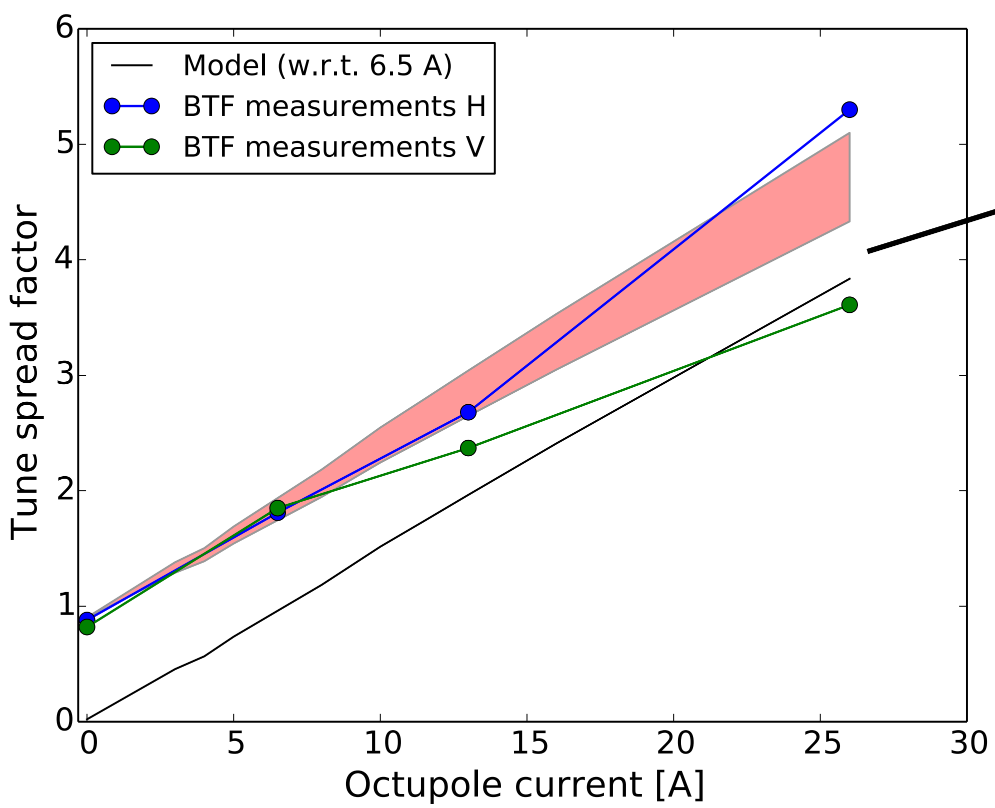
Tracked distribution



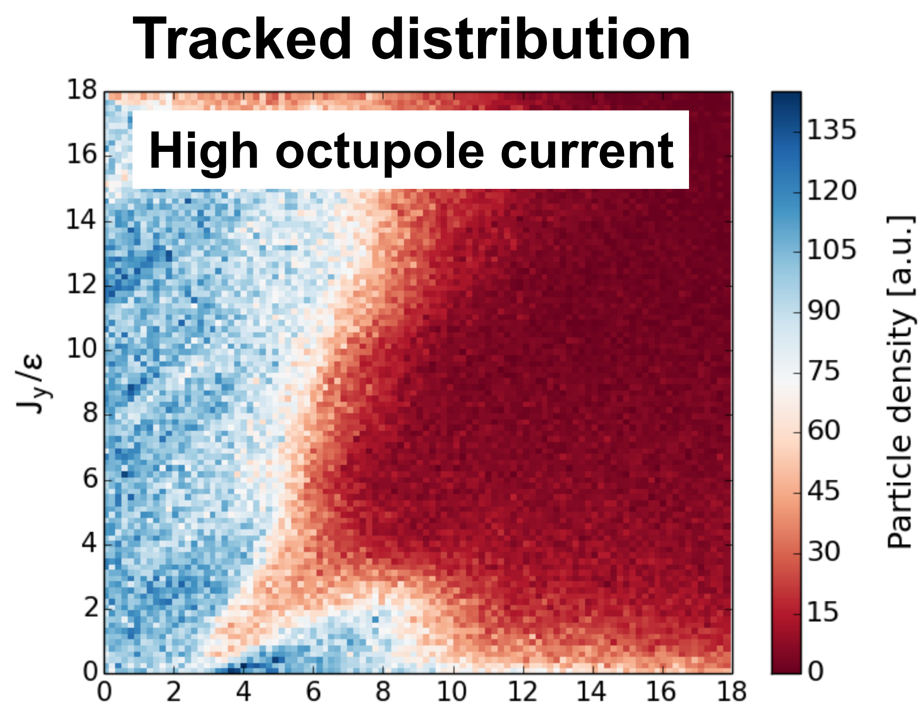


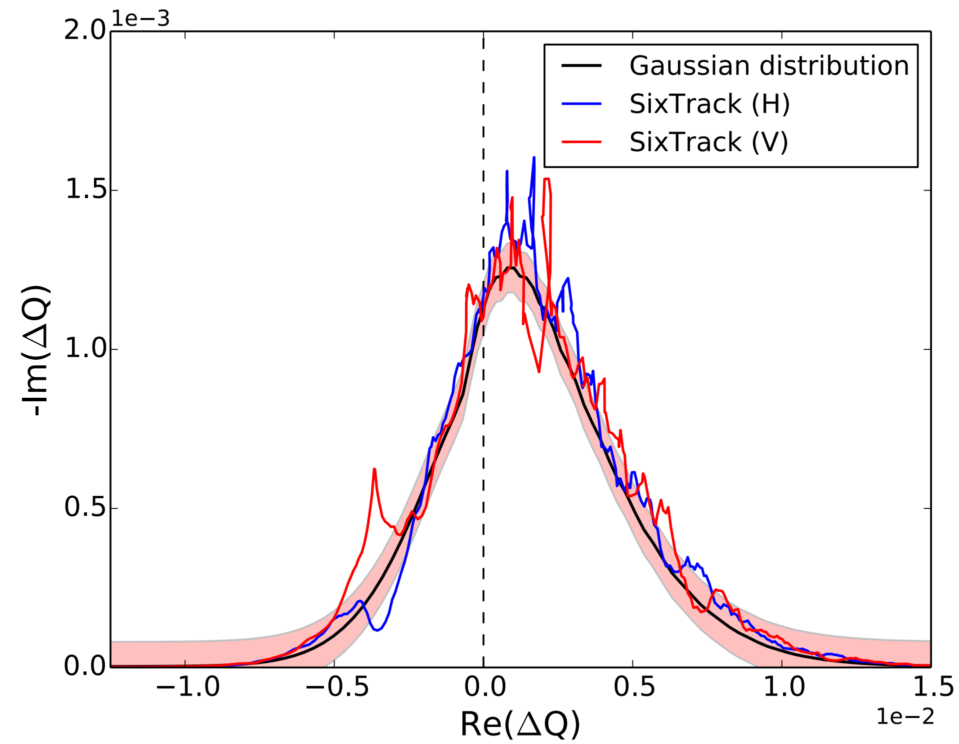


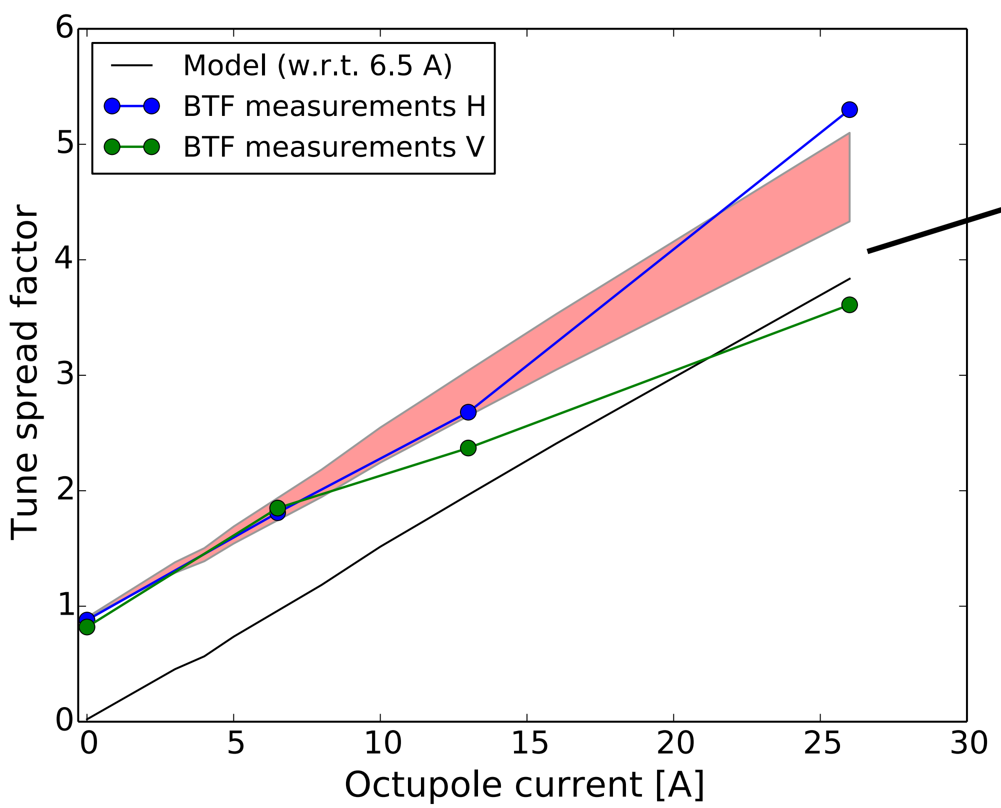
Vertical losses observed during the experiment + linear coupling (reduction of DA)

[2] C. Tambasco, EPFL Thesis 7867 (2017)

Landau damping and Dynamic Aperture





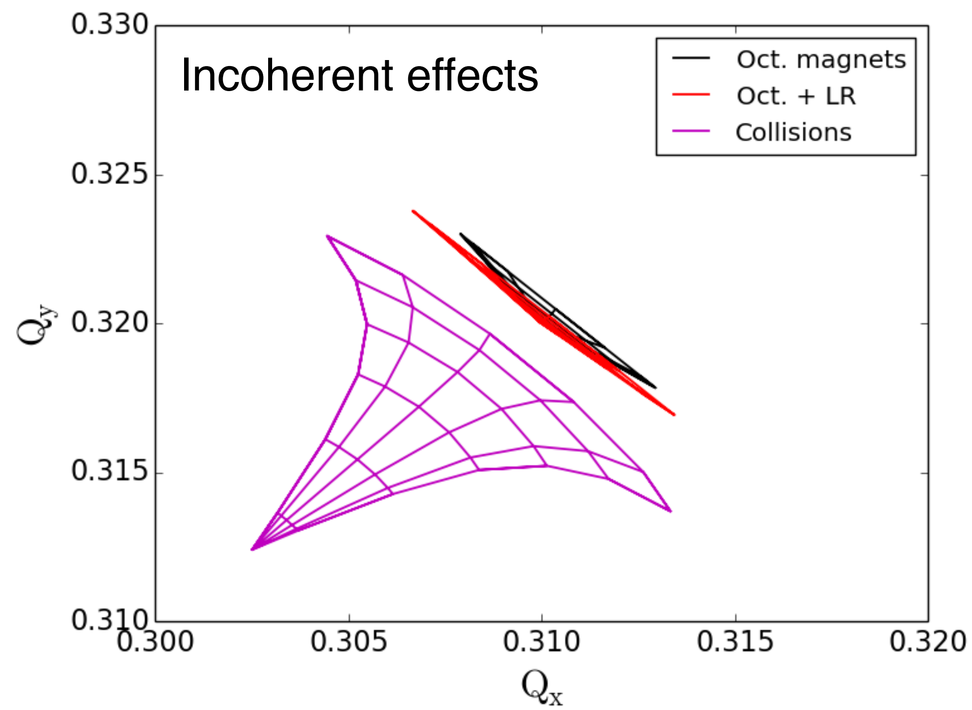


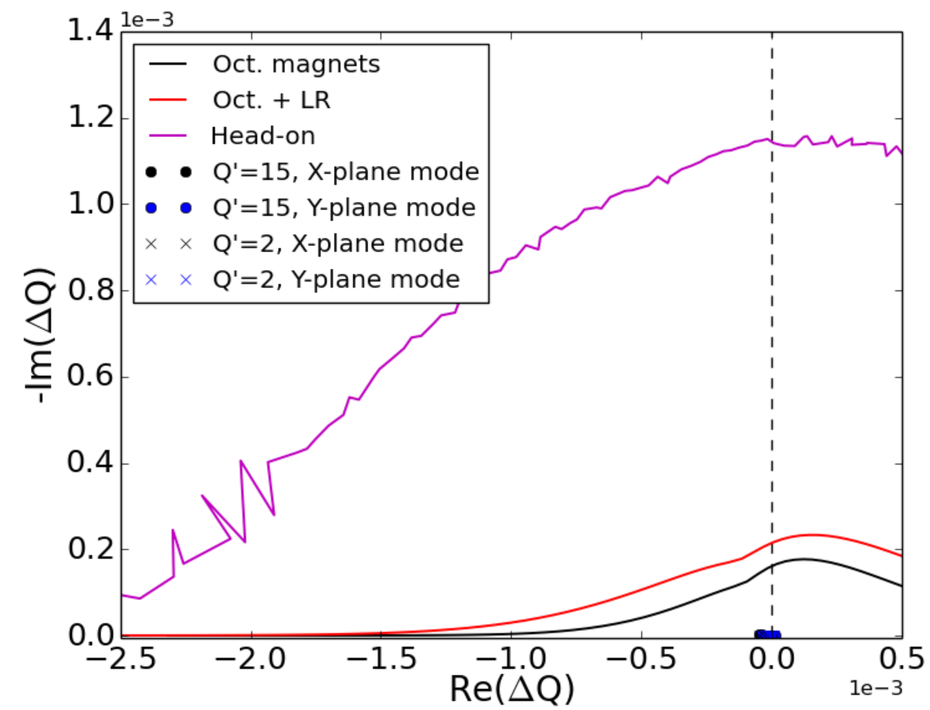
Vertical losses observed during the experiment + linear coupling (reduction of DA)

In presence of diffusive mechanisms and/or reduced dynamic aperture expected Landau damping may be reduced → evaluate impact of Dynamic Aperture [2]

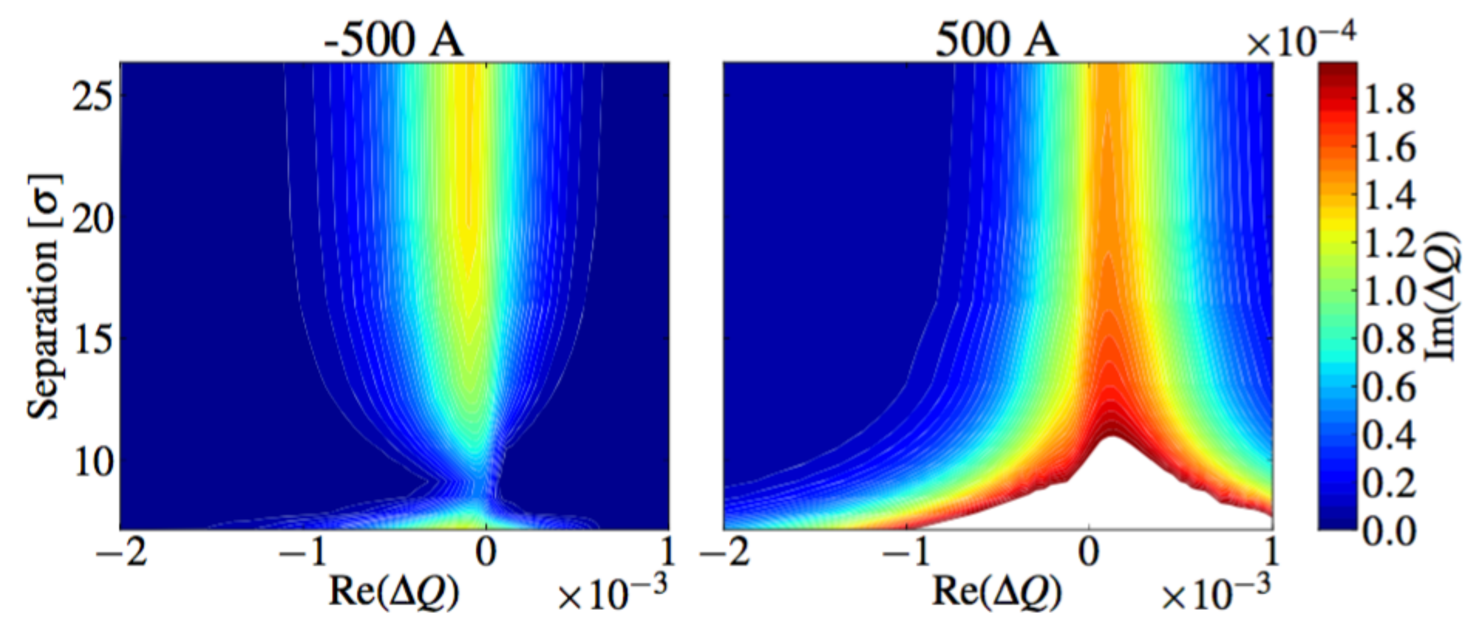
[2] C. Tambasco, EPFL Thesis 7867 (2017)

Landau damping and beam-beam interactions



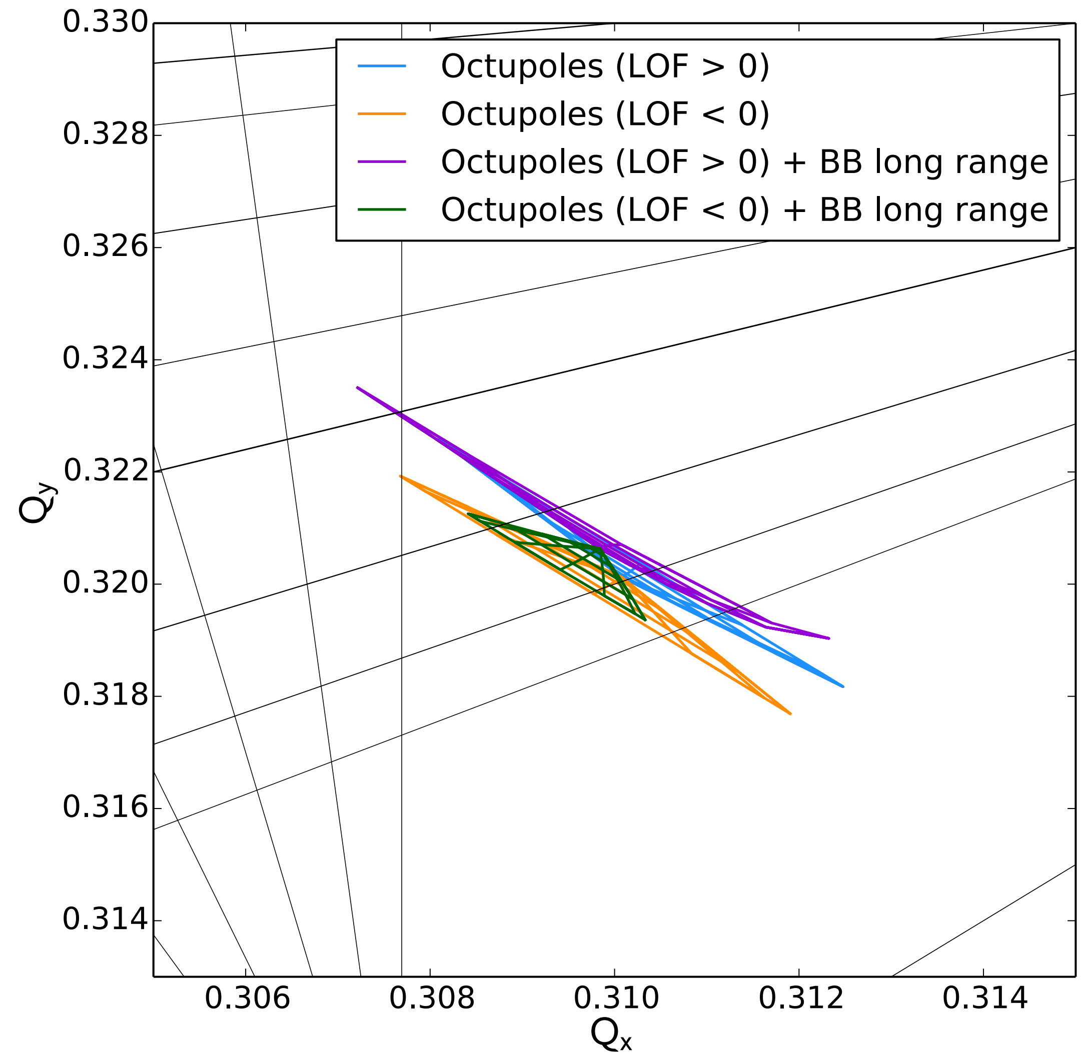


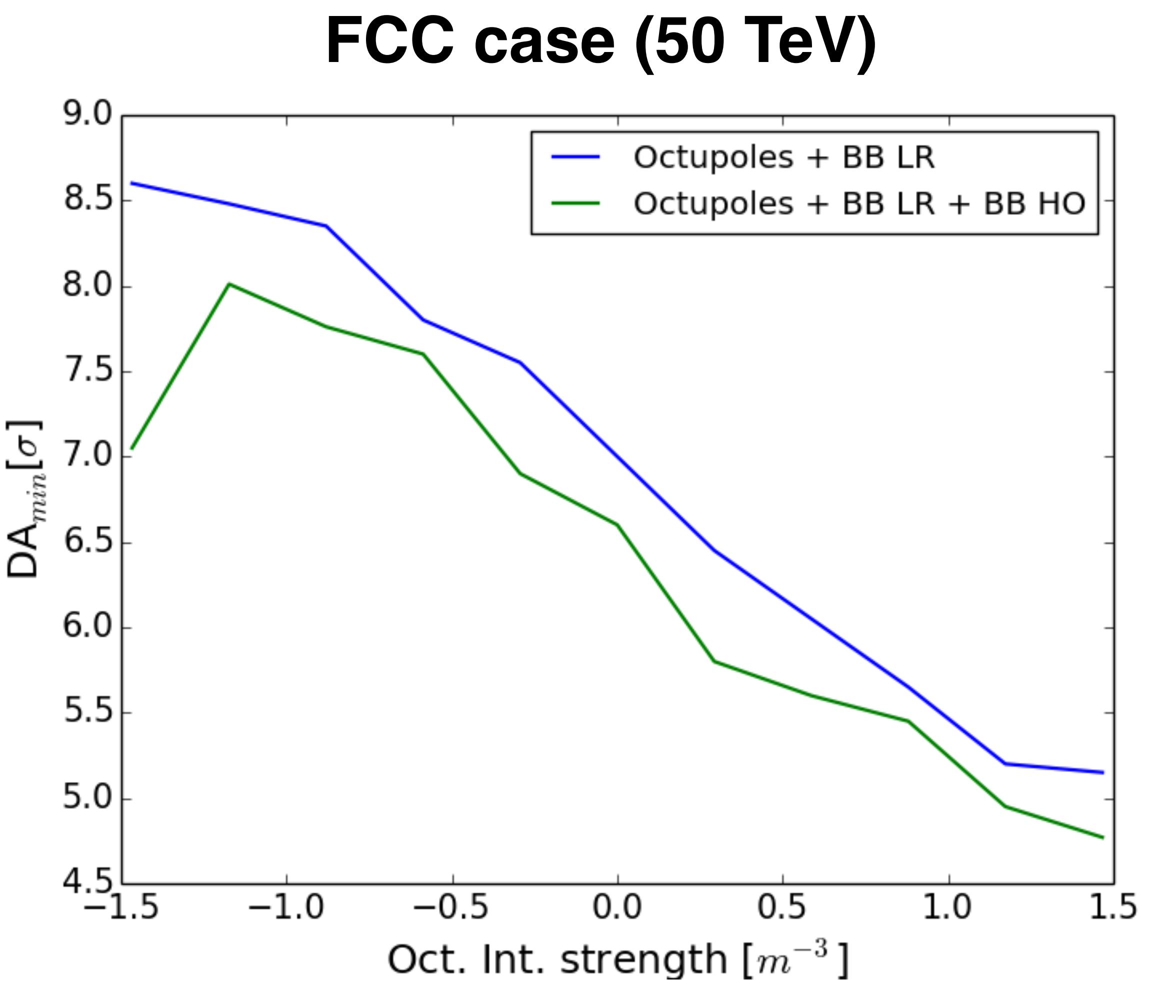
- Different detuning with amplitude according to beam-beam interaction type (head on, offset, long range)
- The detuning with amplitude generated by beam-beam modifies Landau damping from octupoles only [3, 4]



[3] X. Buffat et *al*., *Stability diagrams of colliding beams in the Large Hadron Collider*, PRSTAB 111002 (2014)
[4] X. Buffat et *al*.,EPFL TH6321 (2015)

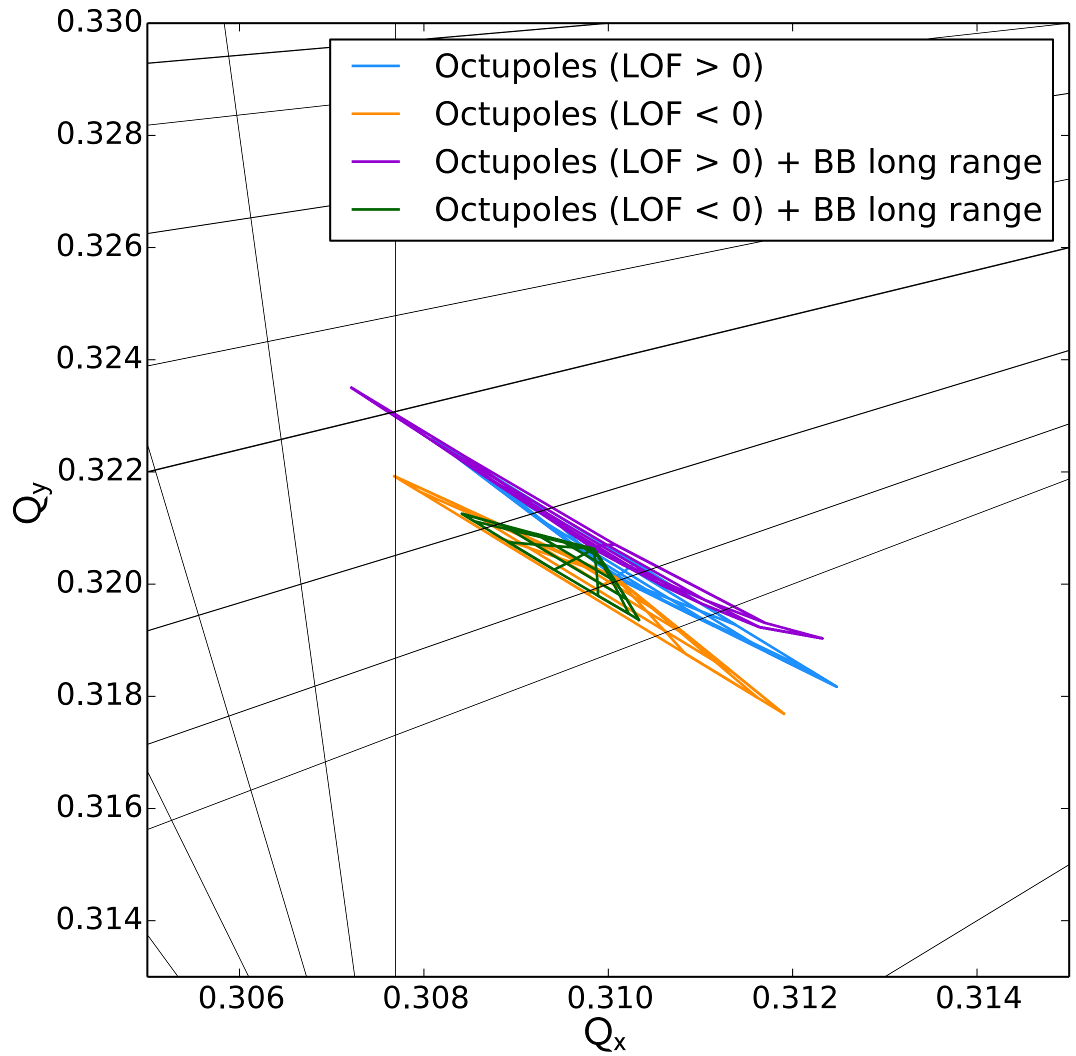
FCC - hh beam stability

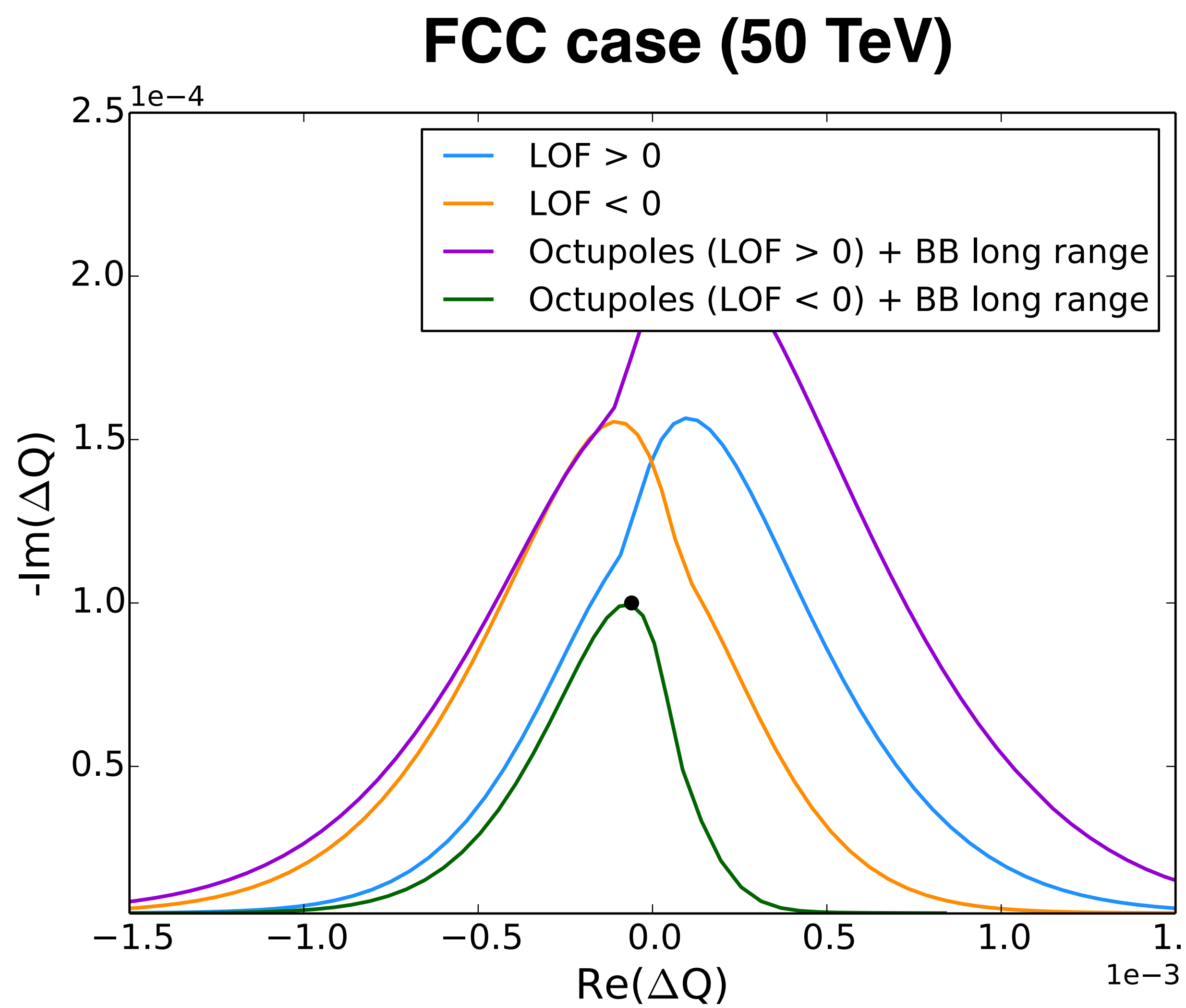




- 1100 Octupole at maximum power are required for FCC to damp single coherent instabilities
- Beam-beam long range interactions excite resonances with different impact on DA
- **Compensation of LR BB observed for negative octupoles → DA above 6.5 σ**
- **DA is reduced in case of positive octupole polarity and beam-beam long range interactions (5.5 σ)**

FCC - hh beam stability





DA > 5 σ stability diagram, Gaussian distribution is a good approximation

Other sources of Landau damping

Octupoles magnets [J. Berg and F. Ruggero]	Electron lenses [V. Shiltsev et al.]	RFQ [M. Schenk, A. Grudiev] et al.]
☑ Tune spread from octupoles ☑ Tune spread from Beam-beam interactions	☑ Evaluate tune spread from e-lens (injection, flat top)	☑ Preliminary studies for FCC by M. Schenk et al. that show stabilizing effects

Impact on Dynamic Aperture

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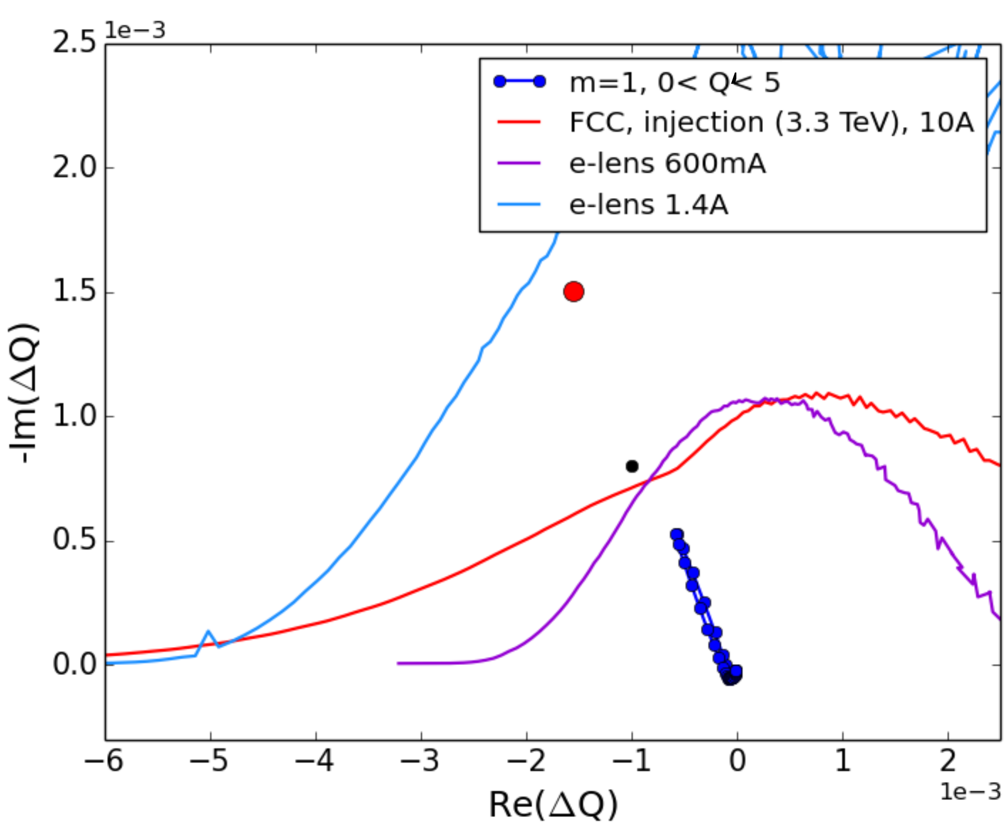

Electron lenses provide tune spread for small amplitude particles
➔ similar spread as HO collision (very effective Landau damping)

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Instability players

Collective Forces:

- Impedance
- Beam-beam interactions
- E-cloud
- Space charge
- Feedback System

Incoherent Effects:

- Lattice
- Q', Q''
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- Linear Coupling
- Non-linearities (lattice, octupoles, e-cloud, beam-beam, space charge)

Not always possible to treat these effects separately!

Perturbation

↓

Stability Diagram (SD Vlasov equation)

High beam intensity
Self-consistent

↓

Tracking (Vlasov solvers)

Many important assumptions made:

- Small Perturbation
- Uncoupled motion
- Weak head-tail
- No coupled modes (beam-beam, TMCI)

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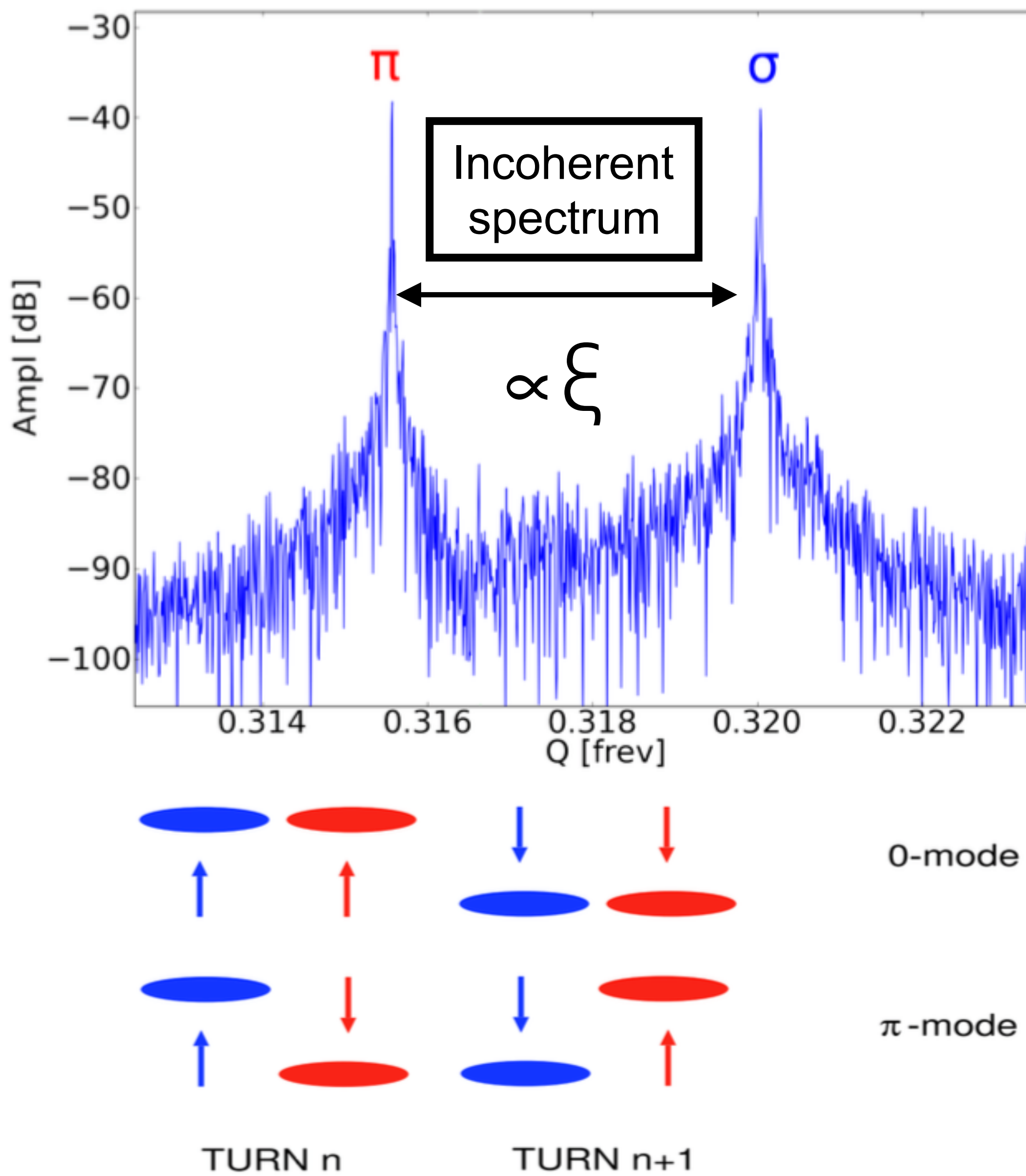
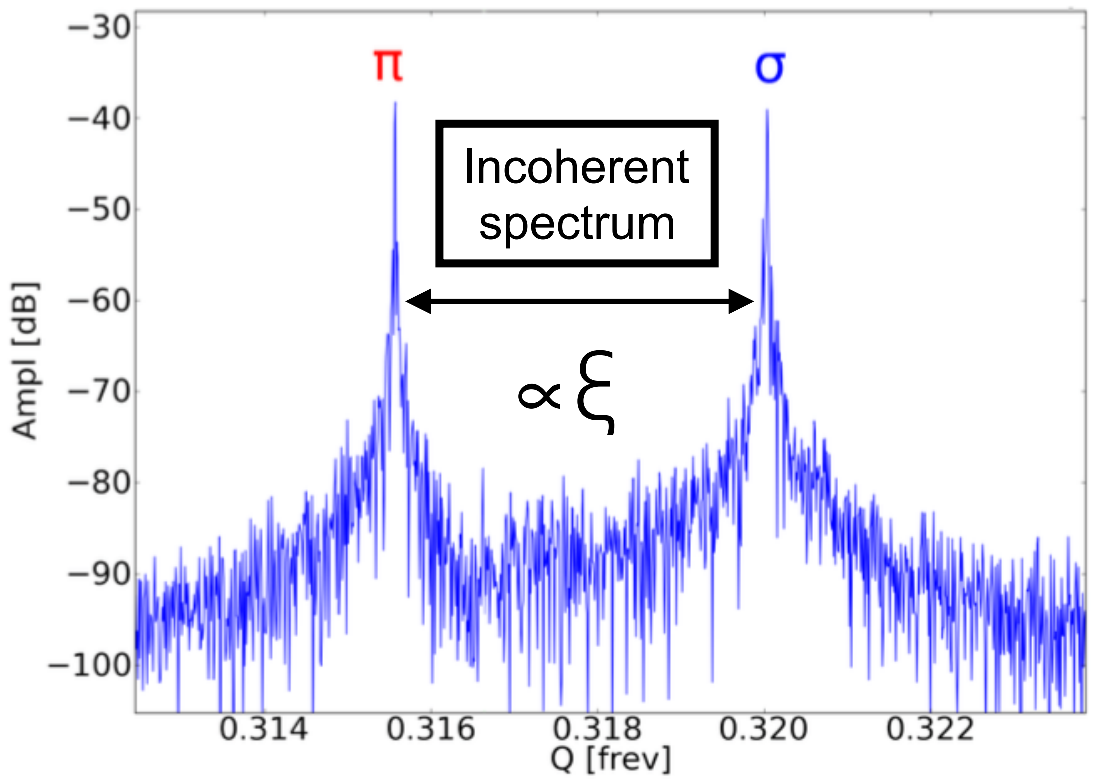
Head-tail and beam-beam mode coupling instability

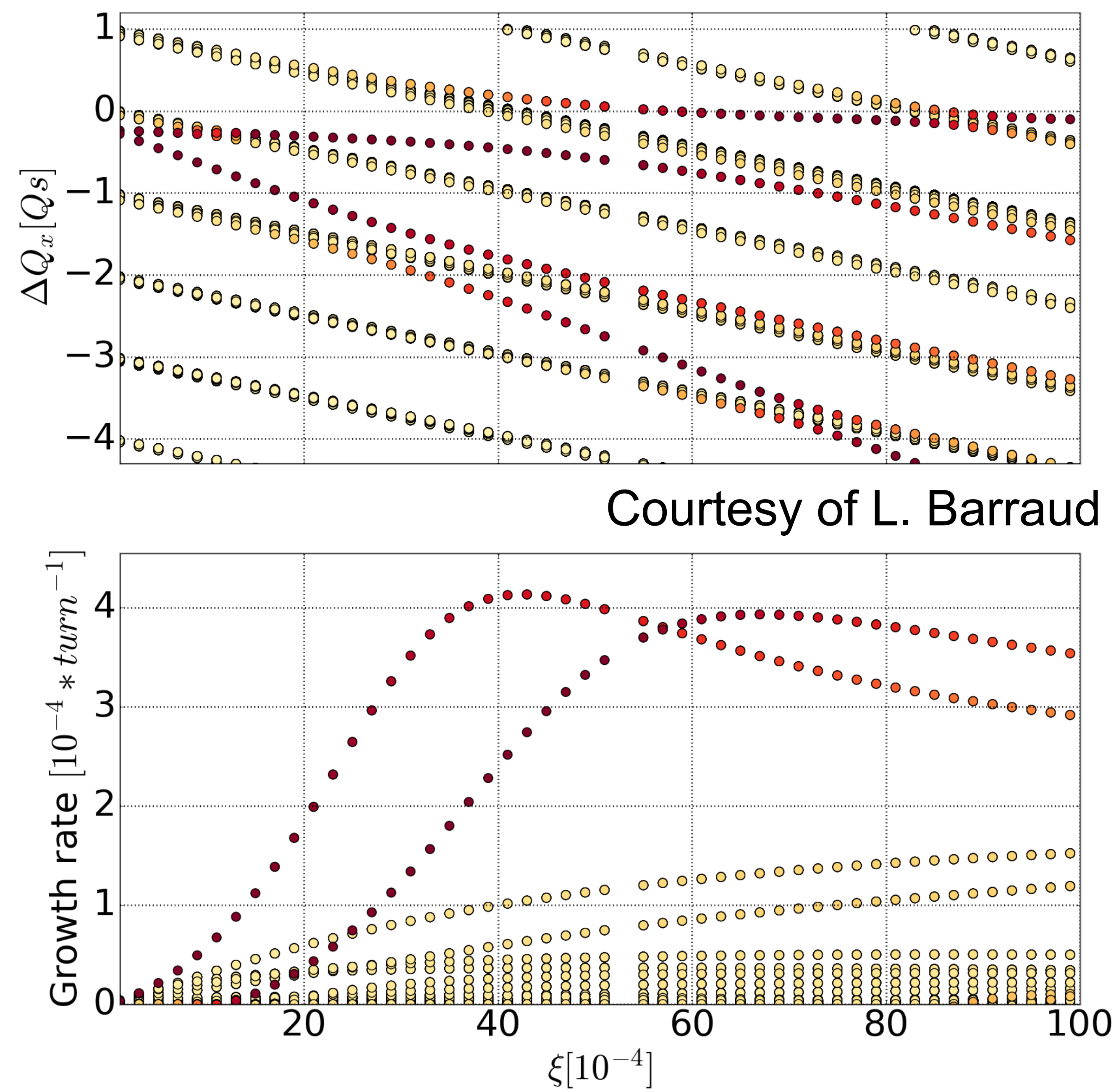
Strength of the beam-beam interaction
$\propto \xi$ (beam-beam parameter)



Two coherent modes when in collisions

Head-tail and beam-beam mode coupling instability

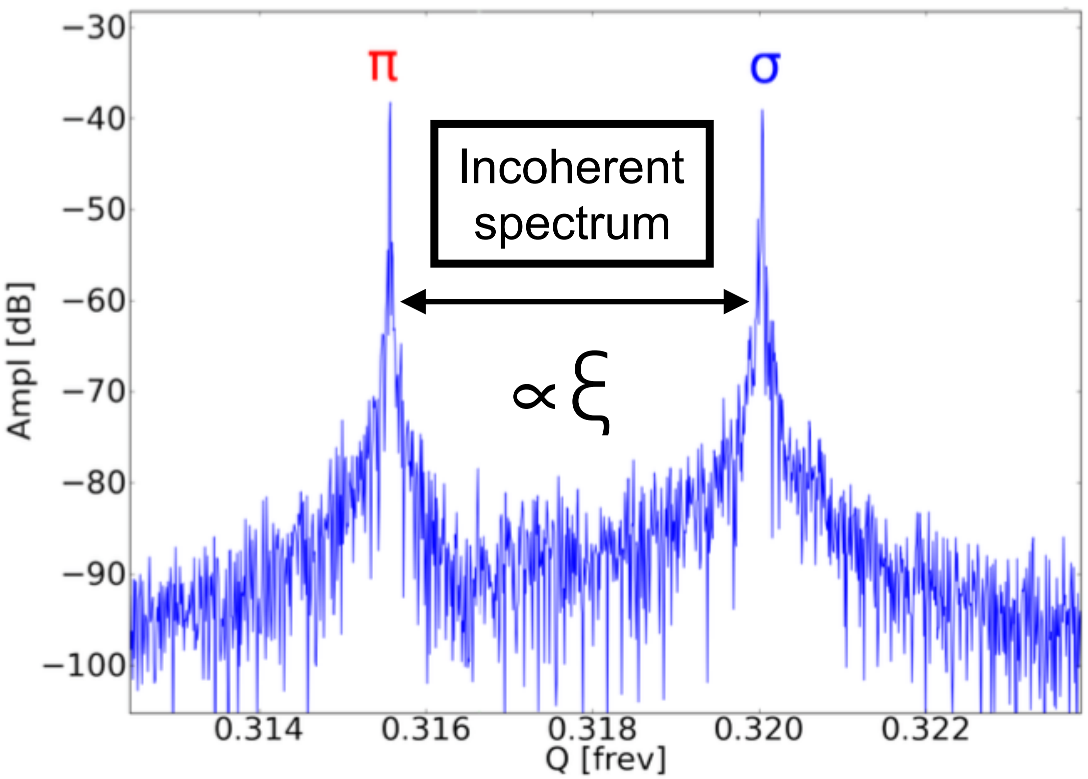


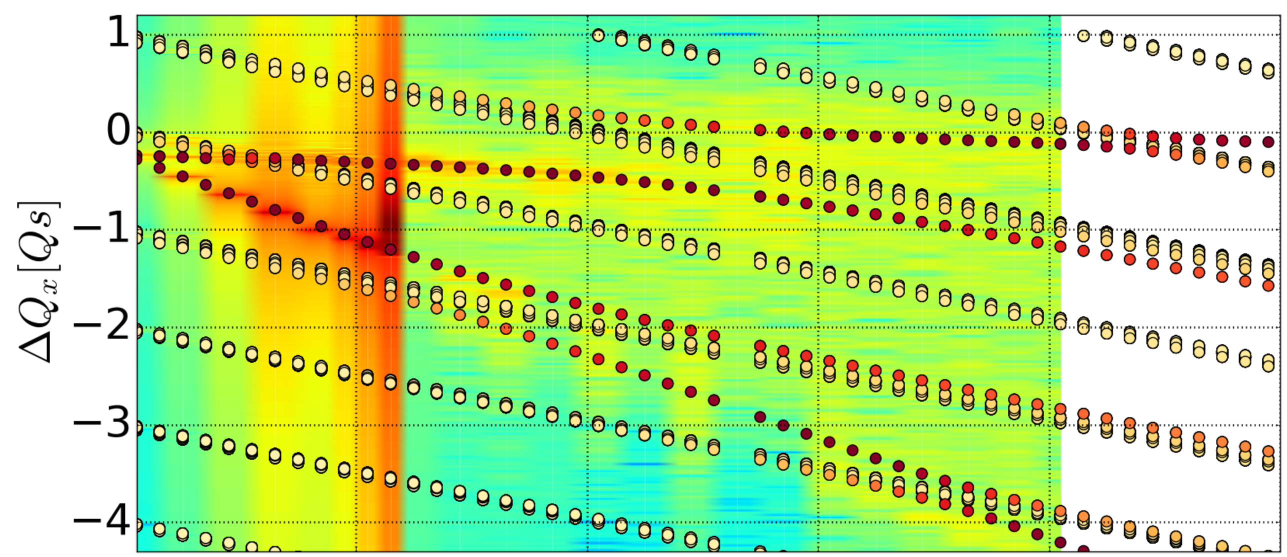


Courtesy of L. Barraud

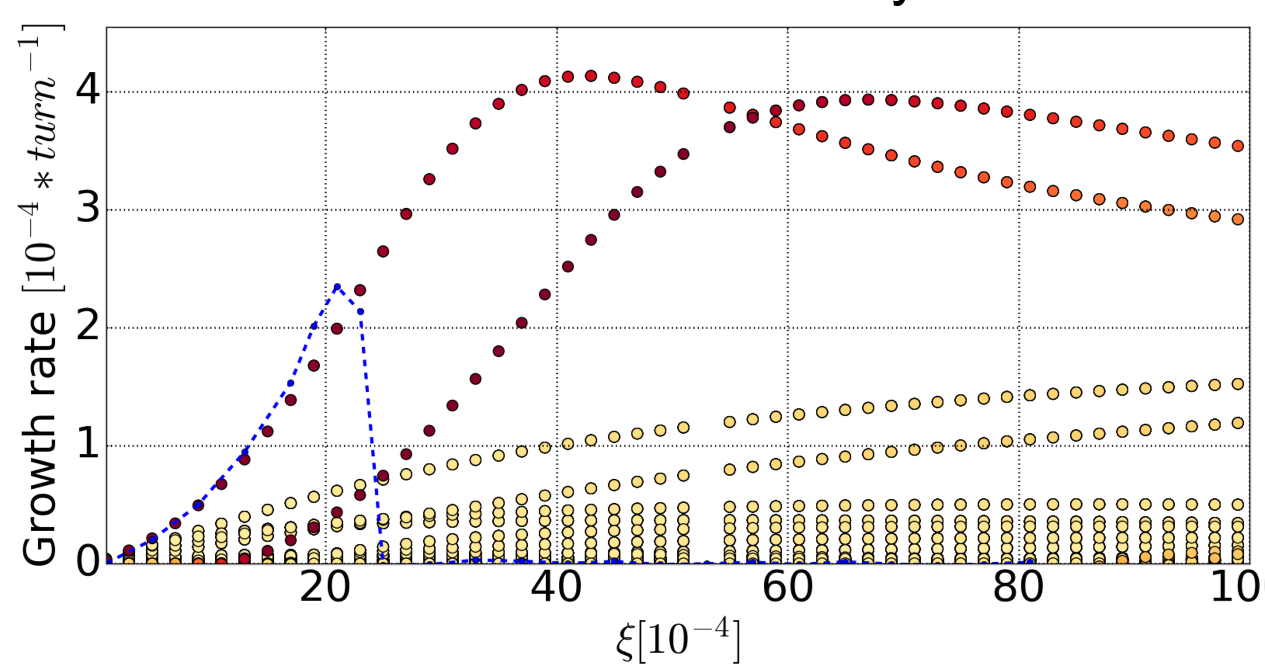
Mode coupling instability: collision modes coupled with oscillation mode driven by the wake field

Head-tail and beam-beam mode coupling instability



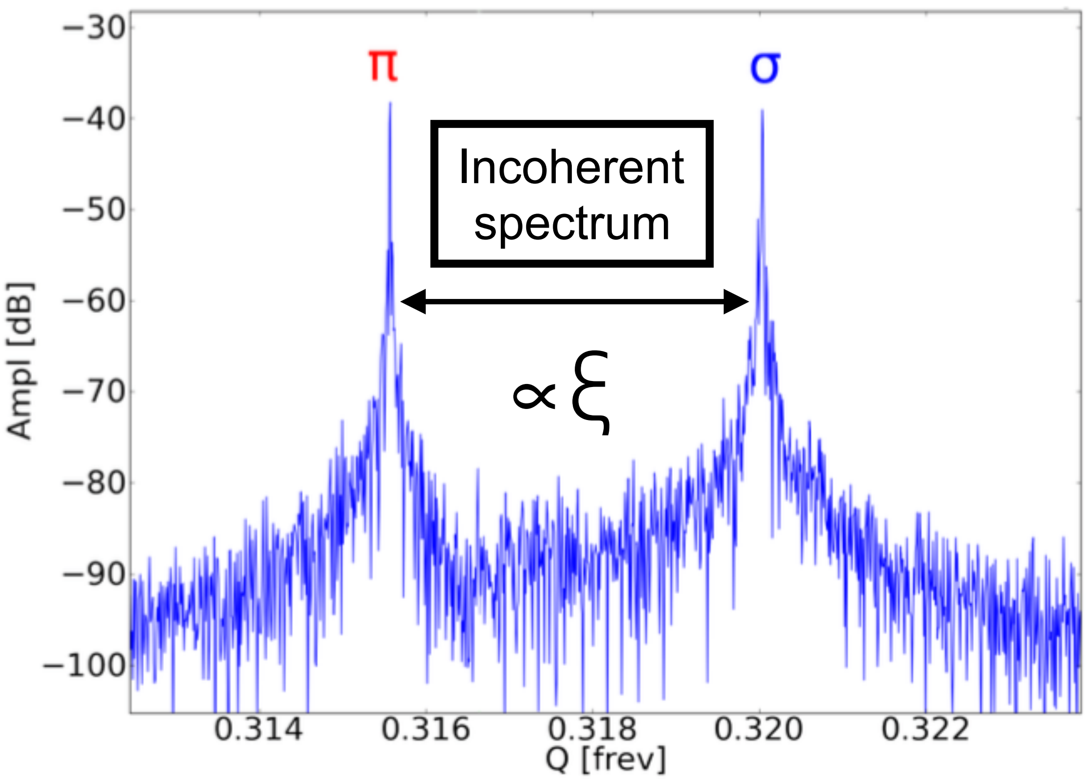


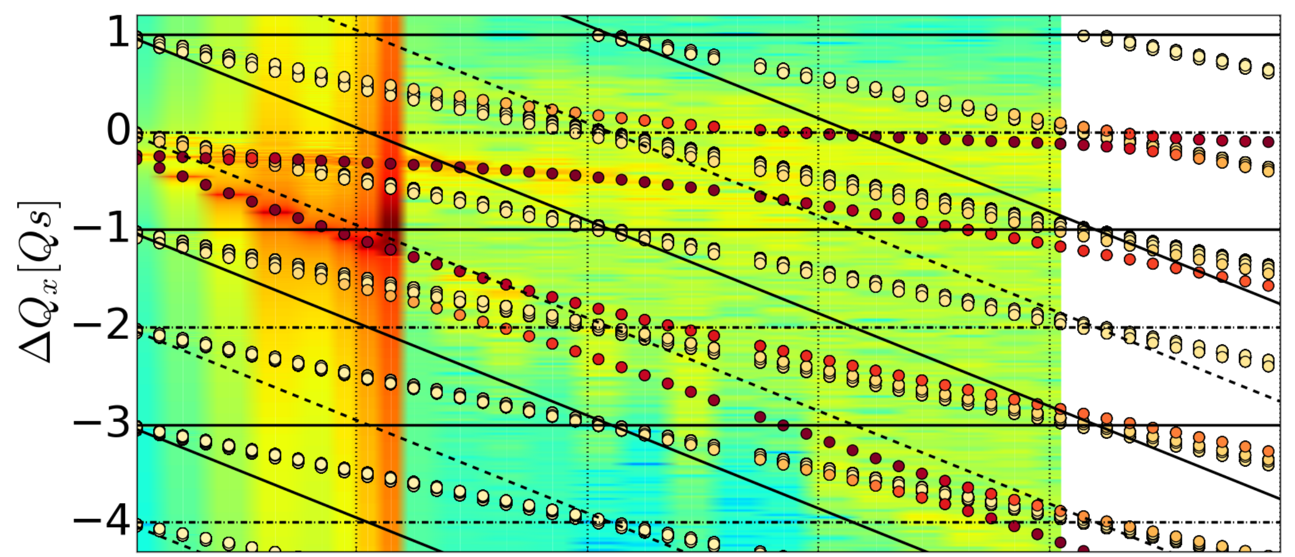
Courtesy of L. Barraud



Particle tracking simulations well reproduce growth rate of unstable modes

Head-tail and beam-beam mode coupling instability





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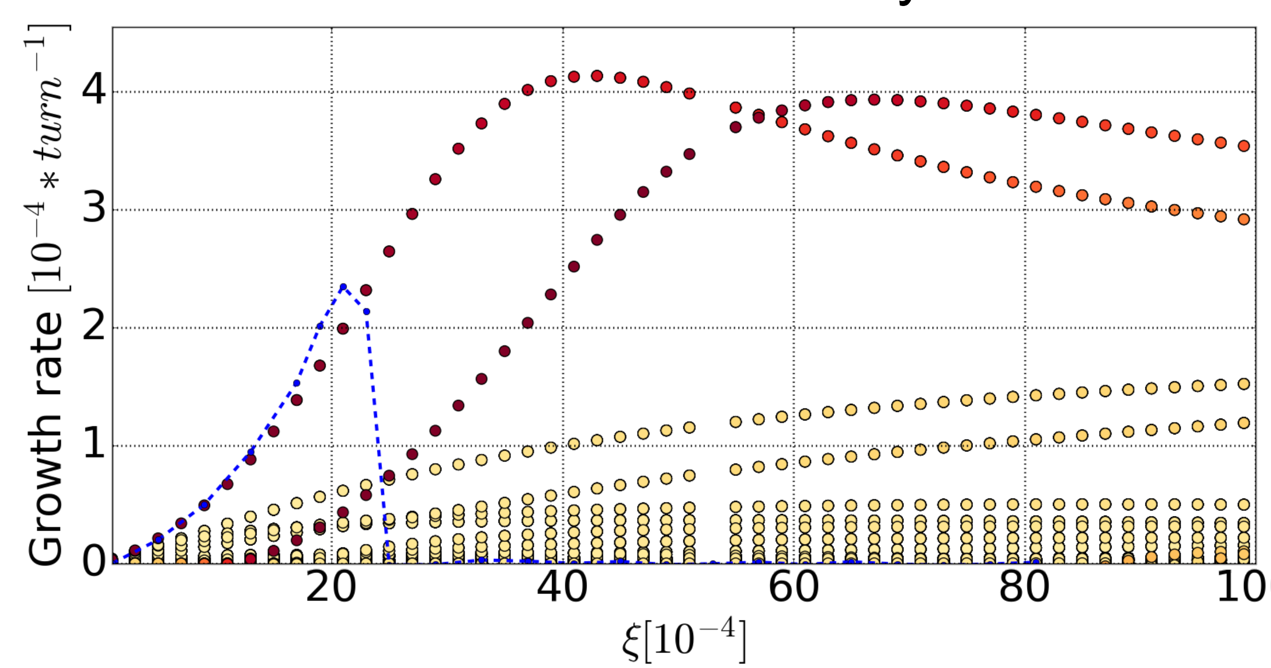


When the synchrotron sideband enters in the incoherent spectrum the Landau damping is efficient to damp unstable motion (for ξ > 0.0021 ≈ Qs)

Summary

- Collective effects (beam coupling impedance, space charge, beam-beam, e-cloud) may drive coherent instabilities (more important for high brightness beams)
- Coherent instability due to beam coupling impedance can be mitigated by chromaticity, transverse feedback, Landau damping
- Landau damping of weak head-tail modes can be quantified by Stability Diagram (perturbed Vlasov equation) for any non-linearities in the accelerator (beam-beam, octupoles, e-lens) ➔ impact on DA has to be always taken into account
- Impedance modes can be coupled with other effects (for instance beam-beam modes) ➔ particle tracking codes (Vlasov solvers) are needed to evaluate Landau damping in such cases
- Challenging studies to understand the interplay of different effects ➔ extensions of theory and simulation codes together with experimental activities
- Higher energies bring hadrons closer and closer to leptons ➔ in which way synchrotron radiation modifies coherent stability?

Thanks for your attention!

Back-up slides

Hadron Machines

- Heavy particles (**m_p=1836 m_e**)

  ➔ Much more force to accelerate and bend hadrons than leptons
  ➔ More difficult to focus: larger emittance and bunch length with similar focusing forces

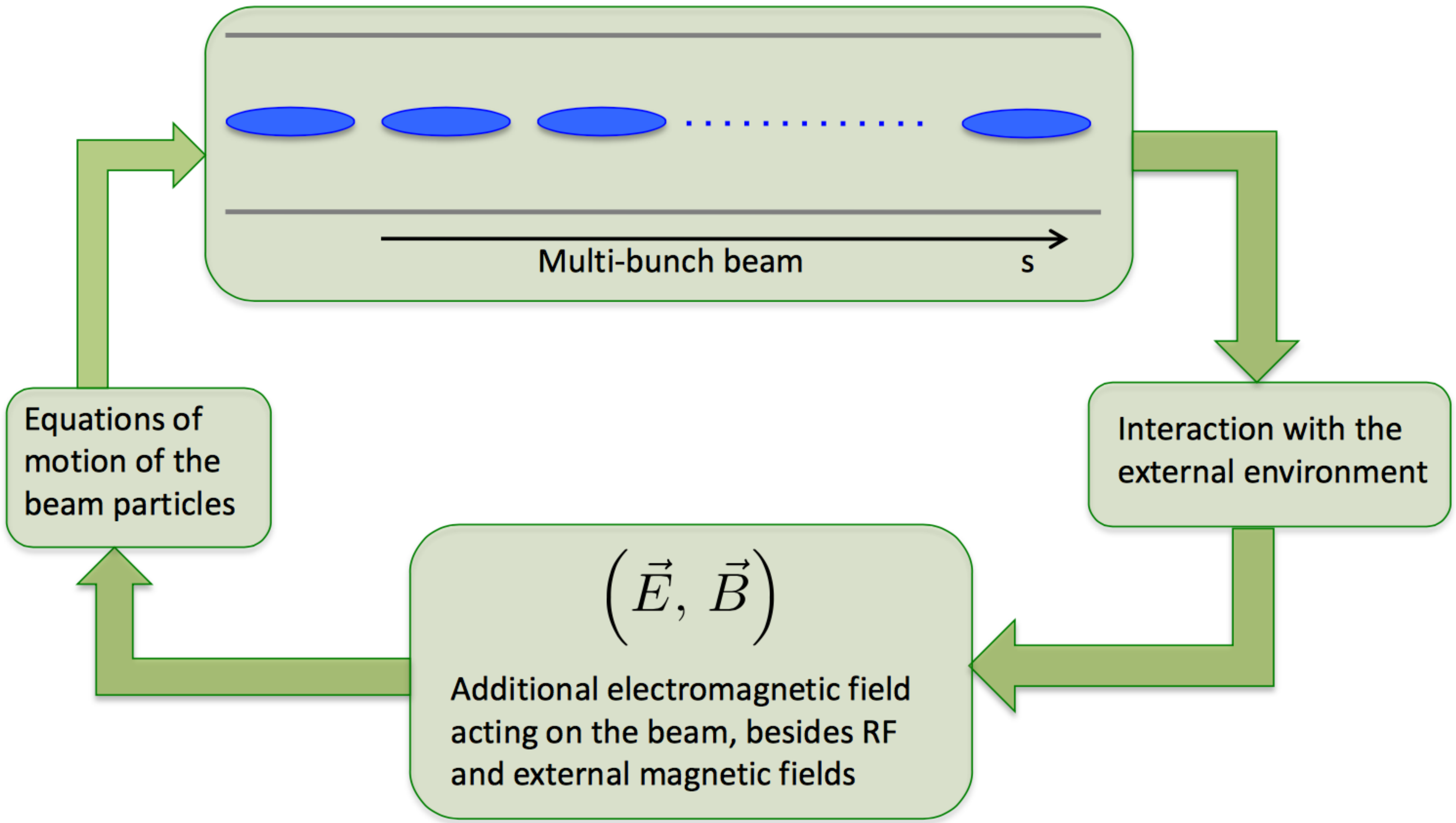
- Large beam power (LHC: 360 MJ per beam) ➔ collimation system is needed (stronger impedance)

- Lower relativistic gamma ➔ less synchrotron radiation damping but lager normalized emittance:

  ➔ more tune spread available for Landau damping
  ➔ octupoles more efficient to damp instabilities

But larger energies bring hadrons now closer and closer to leptons
(FCC 50000 GeV beam energy)

Instability Loop



For high intensity bunches a self-consistent treatment is needed to well describe beam dynamics