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Landau Damping of Intra-Bunch Oscillations

Vladimir Kornilov
GSI Helmholtzzentrum, Darmstadt, Germany

Oliver Boine-Frankenheim
TU Darmstadt, GSI Helmholtzzentrum, Darmstadt

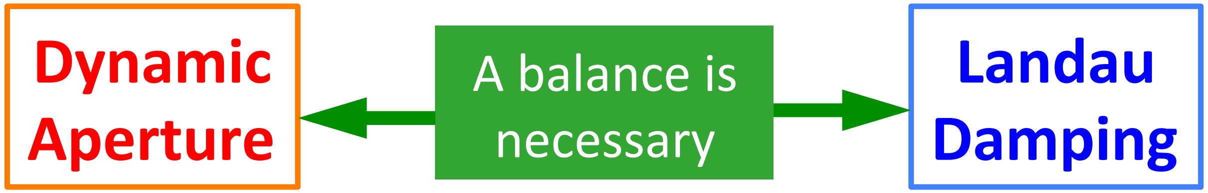
EuroCirCol FCC-hh Task 2.4

Octupoles for Landau Damping

Octupole magnets → tune spread → Landau damping

$$B_{\mathrm{oct}} \propto x^3$$

$$\Delta Q_{\mathrm{oct}} \propto a^2$$



$$\Delta Q_{\mathrm{coh}}^{\mathrm{FCC}} \approx \Delta Q_{\mathrm{coh}}^{\mathrm{LHC}}$$

168 Octupoles are the essential part of the beam stability in LHC,
FCC would need much more.

V.Kornilov, FCC Week 2016, Rom

Overview FCC Landau Octupoles

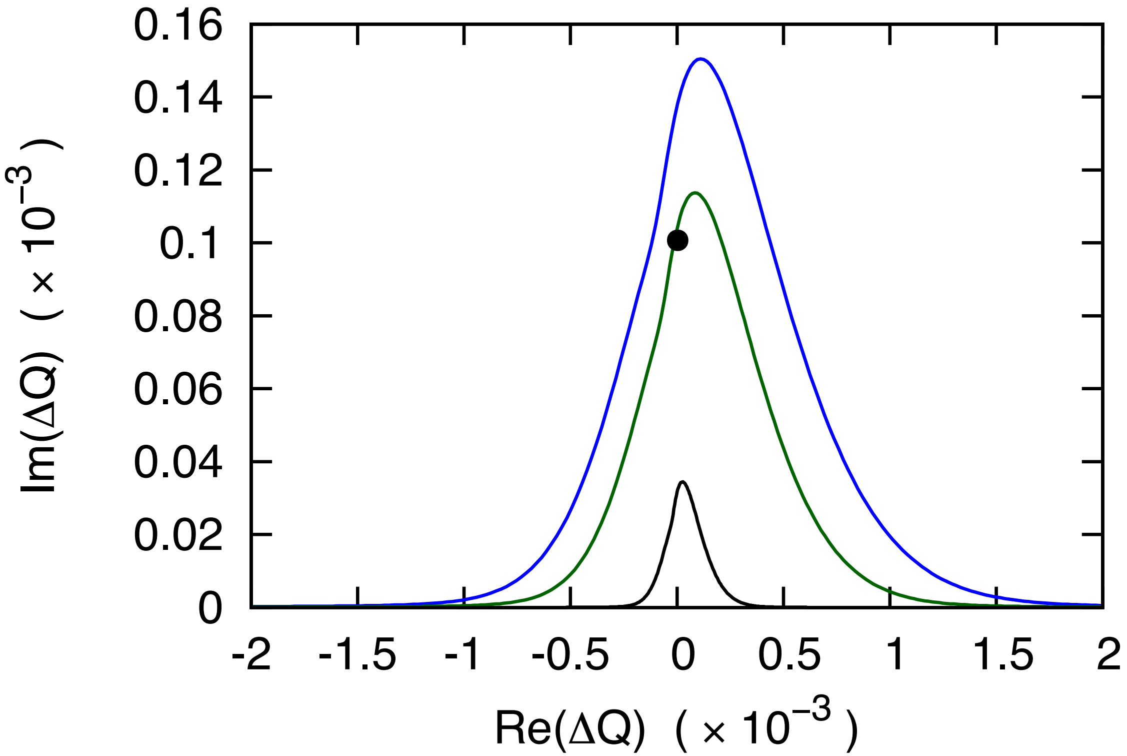
Blue: ΔQ_{coh}–Damping as in LHC.
3554 Octupoles.

Green: enough damping for the (•) impedances.
2686 octupoles.

Black: $N_{MO} = N_{MQ} =$ **814**

LHC: 168 octupoles.
LHC octupole magnets are assumed here.

Update to V.Kornilov, FCC Week 2016, Rom



Stability Diagram:
stable below the line,
unstable above the line.

Dispersion Relation

L.Laslett, V.Neil, A.Sessler, 1965
D.Möhl, H.Schönauer, 1974
J.Berg, F.Ruggiero, CERN SL-96-71 AP 1996

$$\Delta Q_{\mathrm{coh}} \int \frac{1}{\Delta Q_{\mathrm{oct}} - \Omega/\omega_0} J_x \frac{\partial \psi_\perp}{\partial J_x} dJ_x dJ_y = 1$$

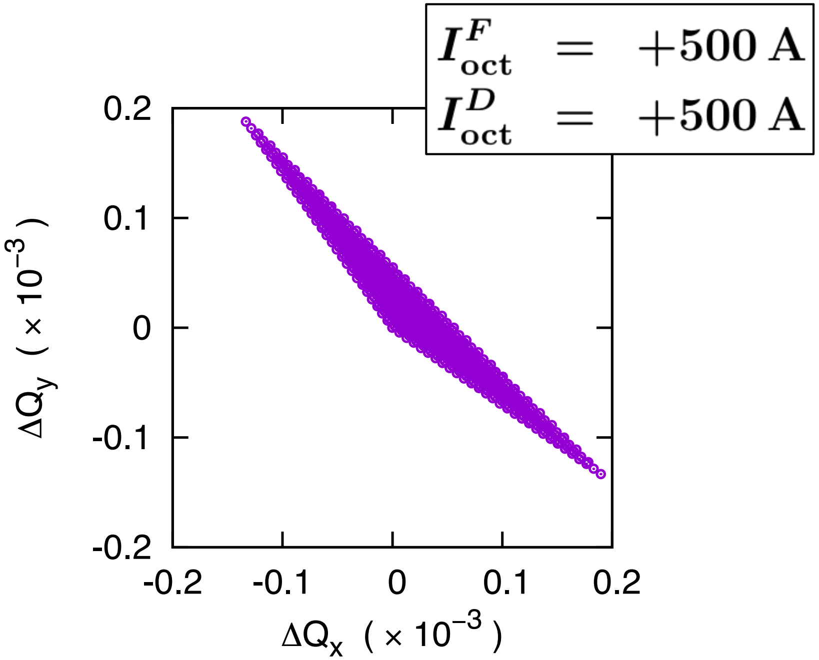
complex coherent tune shift for the beam without damping

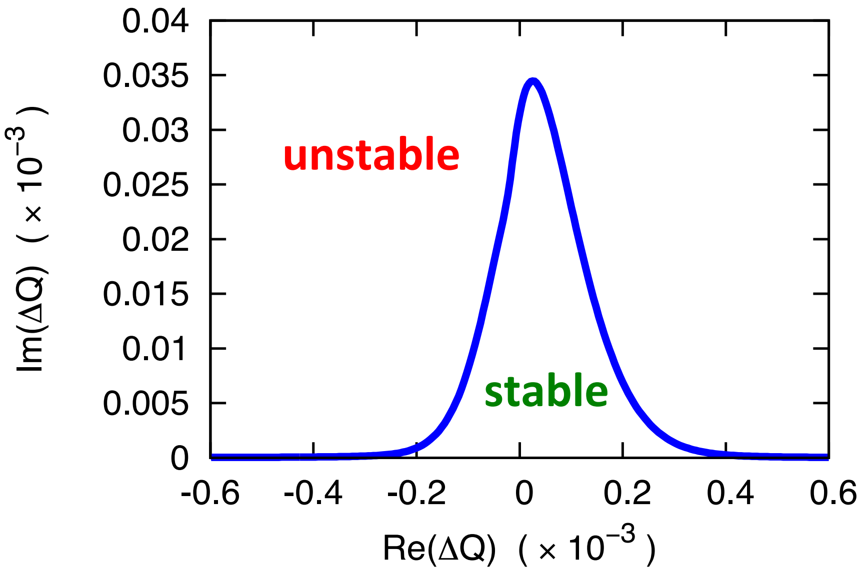
The solution: collective mode frequency Ω for the given impedance and beam

This dispersion relation has been used for the LHC planning, and confirmed in specific measurements.

V.Kornilov, FCC Week 2016, Rom

Stability Diagram





footprint

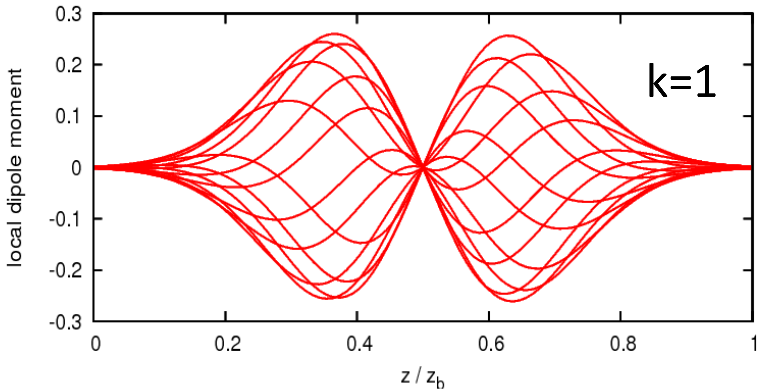
$$J_x + J_y < 6\varepsilon_x$$

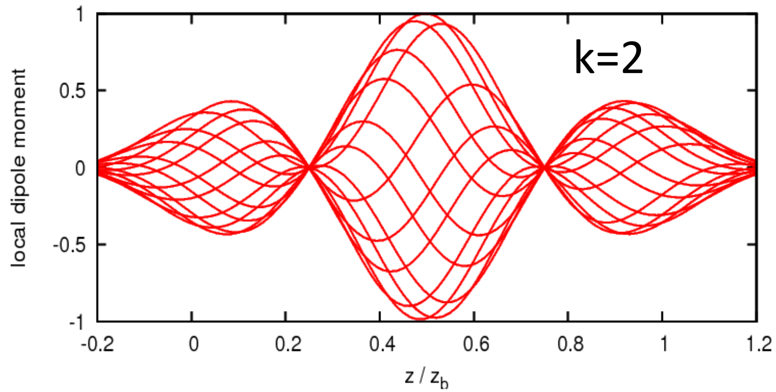
$6\varepsilon_x$ in action ($3.5\sigma_x$ in ampl) gives ≈ the damping extent

Tune spread provides Landau damping

Intra-Bunch Oscillations

But this is a 2D dispersion relation.
What about Gaussian bunches and intra-bunch oscillations?
Not known so far.





The practical relevance:
The higher-order modes would probably need less than 3600 octupoles.
The damping of the k=0 mode can be provided by a feedback system.

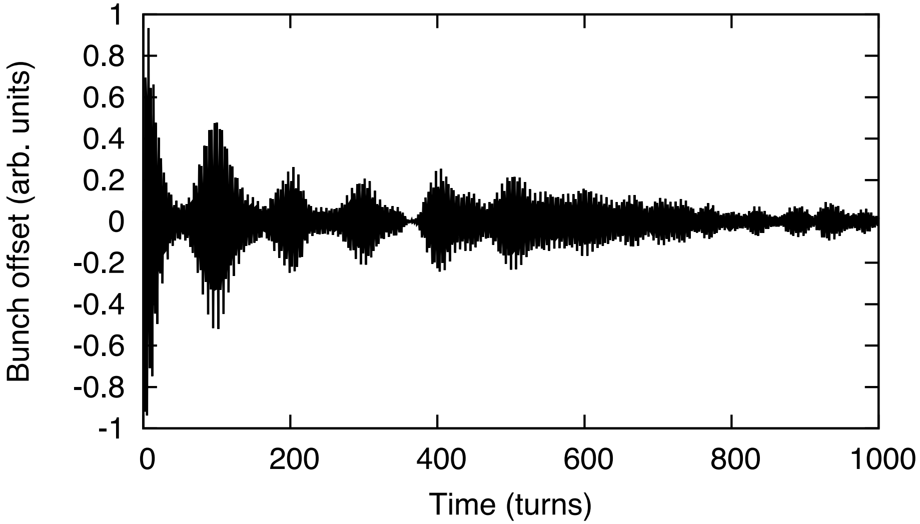
Particle Tracking Simulations

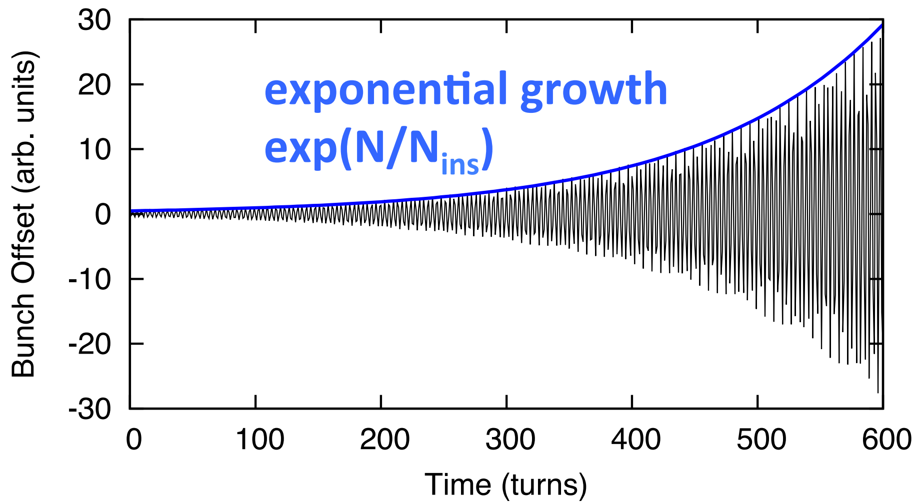
The PIC code PATRIC

- 2.5D sliced bunches
- Self-consistent space-charge, frozen space-charge
- Impedances, Wakes
- Snapshot domain (space), fixed-location domain (time)
- Tune shifts, spectra, instabilities verified with analytical theories:
  V. Kornilov and O. Boine-Frankenheim, Proc. of ICAP2009, San Francisco (2009)
  O.Boine-Frankenheim, V.Kornilov, Proc. of ICAP2006 (2006)
- Verified vs. HEADTAIL (CERN)
- Landau damping simulations, head-tail modes with space-charge:
  V.Kornilov, O.Boine-Frankenheim, PRSTAB **13**, 114201 (2010)

Particle Tracking Simulations

- Start with a small eigenmode perturbation
- Apply an impedance (resistive-wall here)
- Apply octupoles



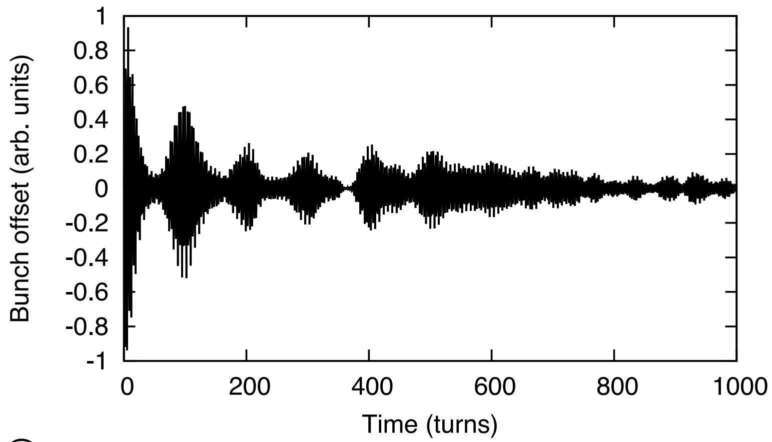


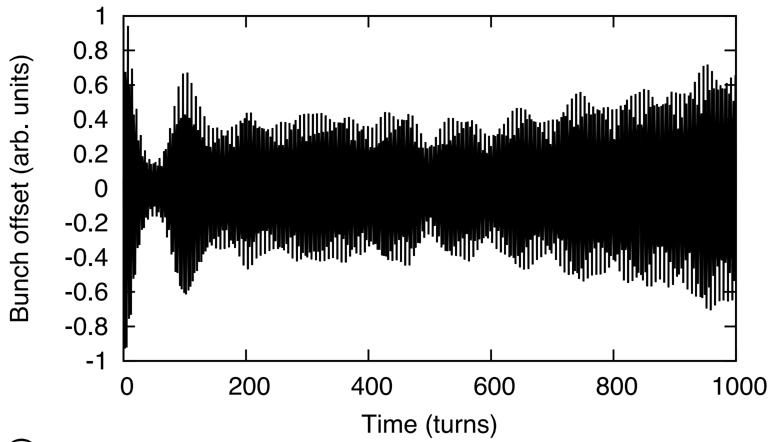
Stabile due to octupoles

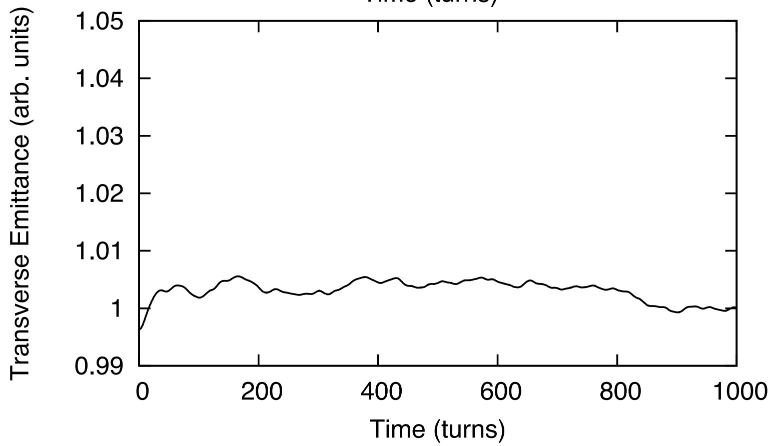
Unstable

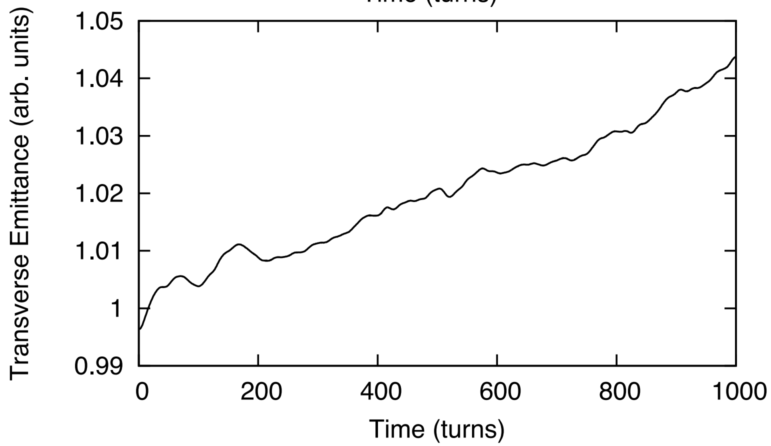
Particle Tracking Simulations

Accurately determining the stability thresholds







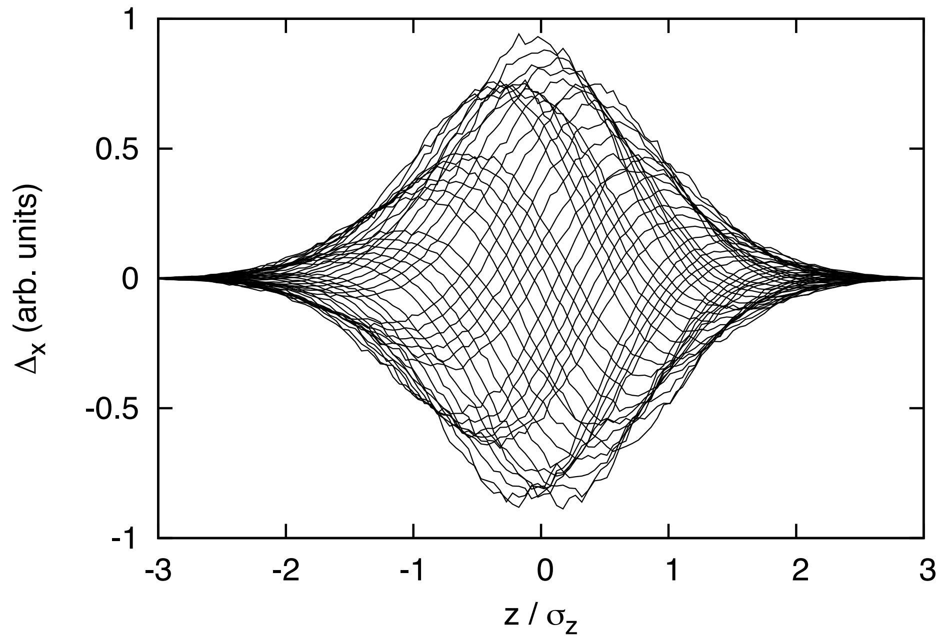


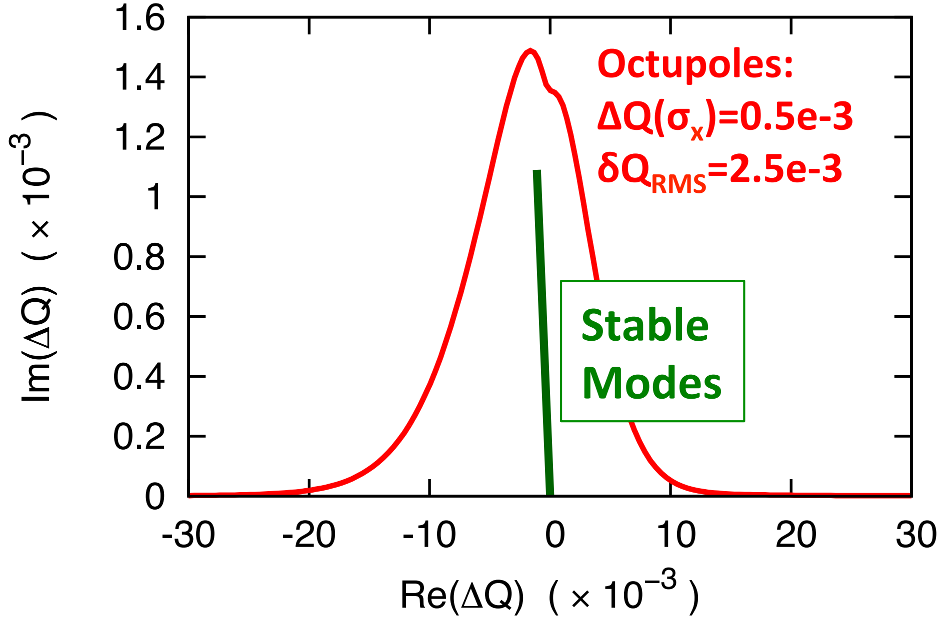
Stabile due to octupoles

Above the threshold

Particle Tracking Simulations

1. Case: the mode k=0



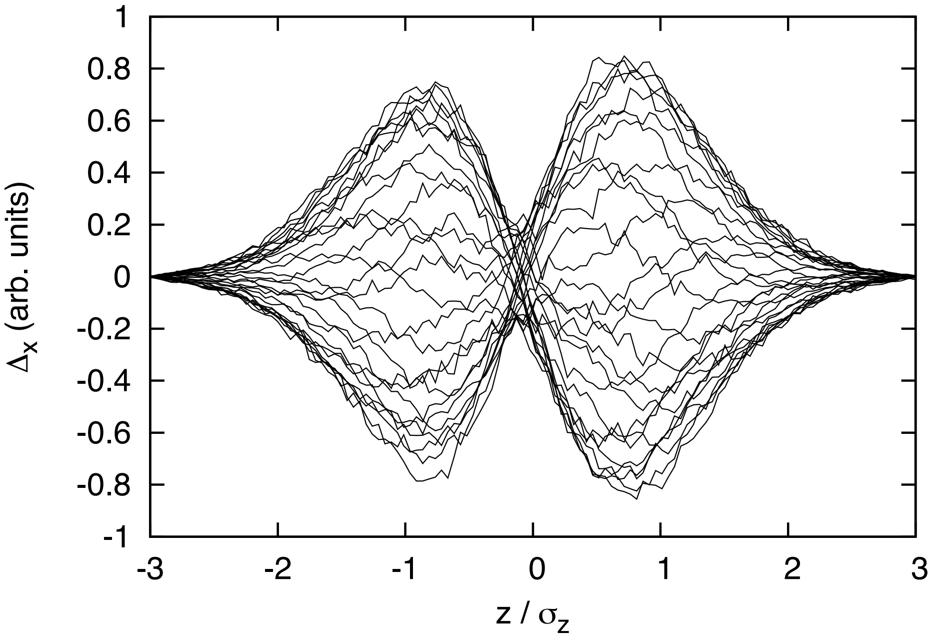


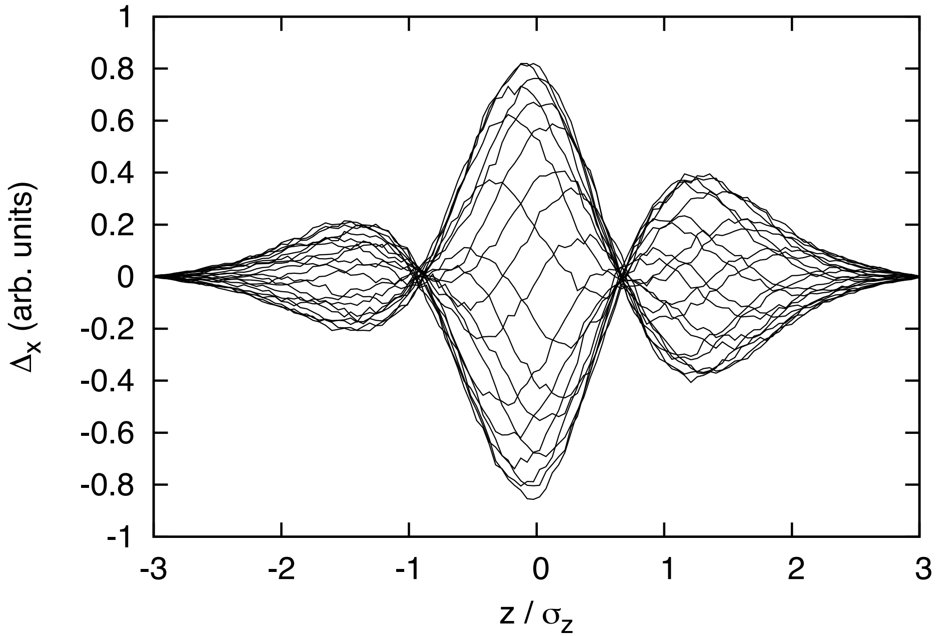
Surprising agreement

- 2D dispersion relation vs. 3D Gaussian bunches
- Stability due to phase-mixing and not purely Landau damping (involved discussion)

Particle Tracking Simulations

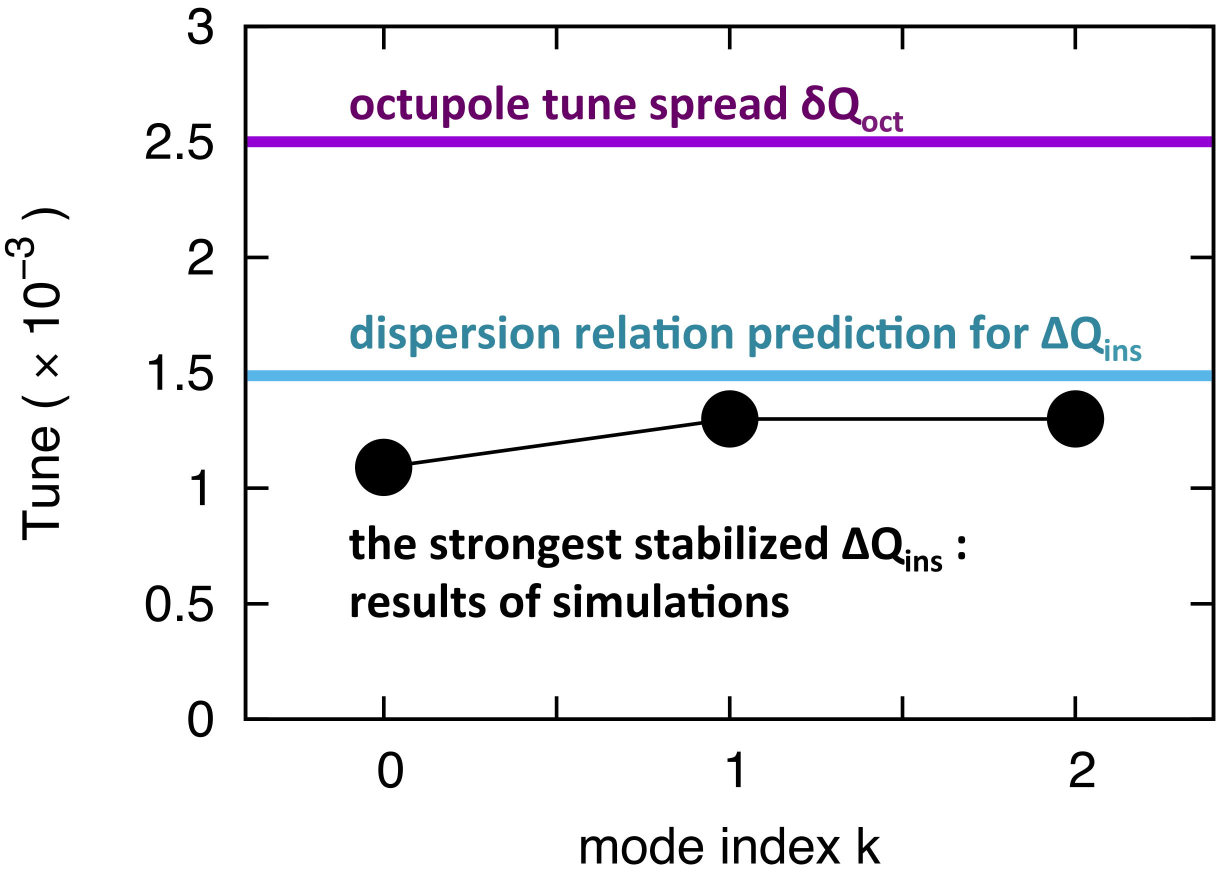
Similar simulation scans for the k=1 and k=2 modes





- Intra-Bunch oscillation produce a small global offset
- The growth rates are smaller than for the k=0 mode.
  Here: factor 4 for k=1, factor 6 for k=2

Summary of Simulation Results



- The octupoles provide a similar stability to the high-order modes
- The instability growth rate and the tune spread are related (DR!)
- Basically, a 2D mode↔particles interaction all along the bunch

RF Quadrupole

A.Grudiev, PRSTAB 17, 011001 (2014)
A.Grudiev, et.al., HB2014, East Lansing, USA, (2014)
M.Schenk, et.al., HB2016, Malmö, Sweden (2016)

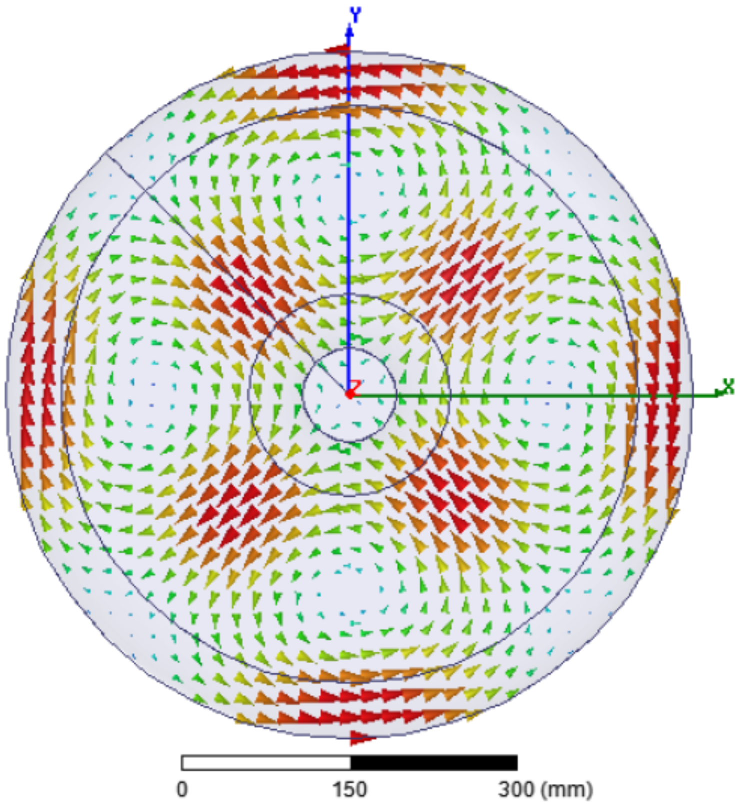


Figure 1: Magnetic field distribution in the transverse plane of the TM quadrupolar mode cavity of the RFQ.

For LHC:

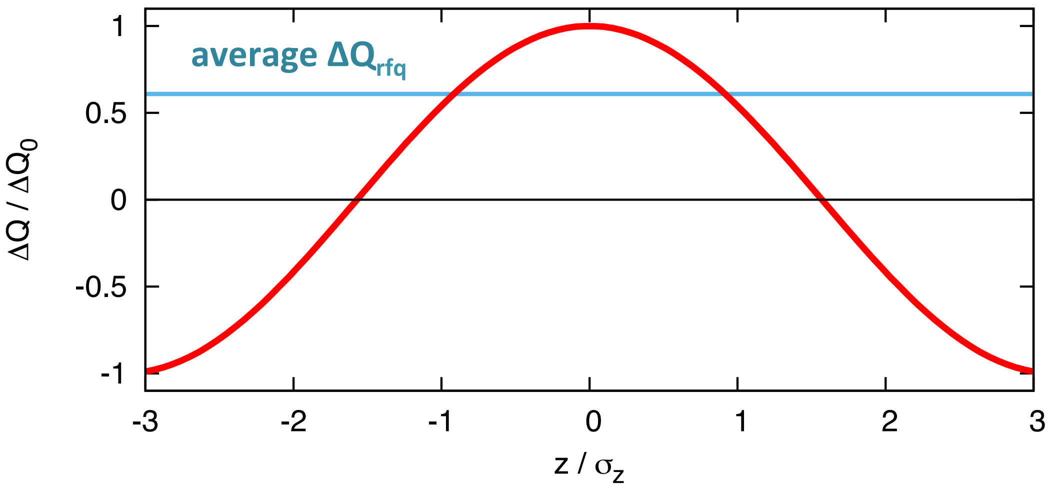
L = 0.15 m, 6 cavities
E = 46 MV/m
ω = 800 MHz, λ = 0.375 m

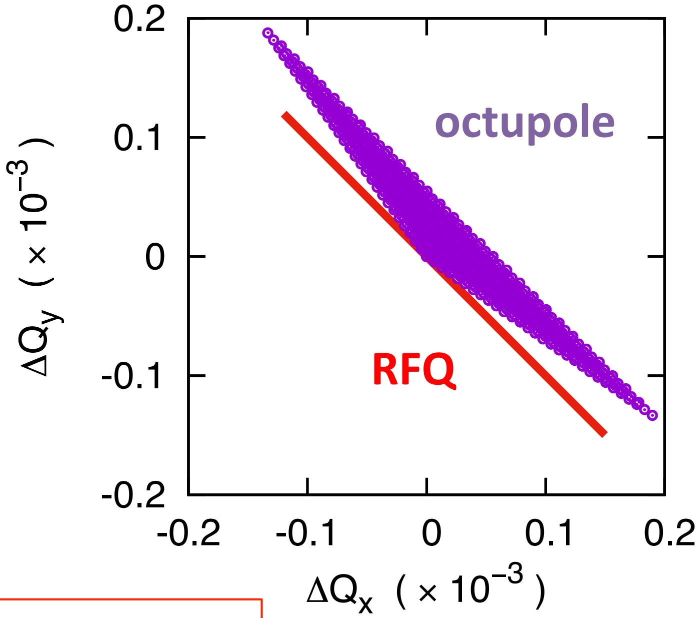
The incoherent tune shift:

$$\Delta Q_{\mathrm{RFQ}}(z) = \pm \frac{\beta k_2}{4\pi} \cos(\omega z / c)$$

The related tune spread should provide Landau damping

RF Quadrupole

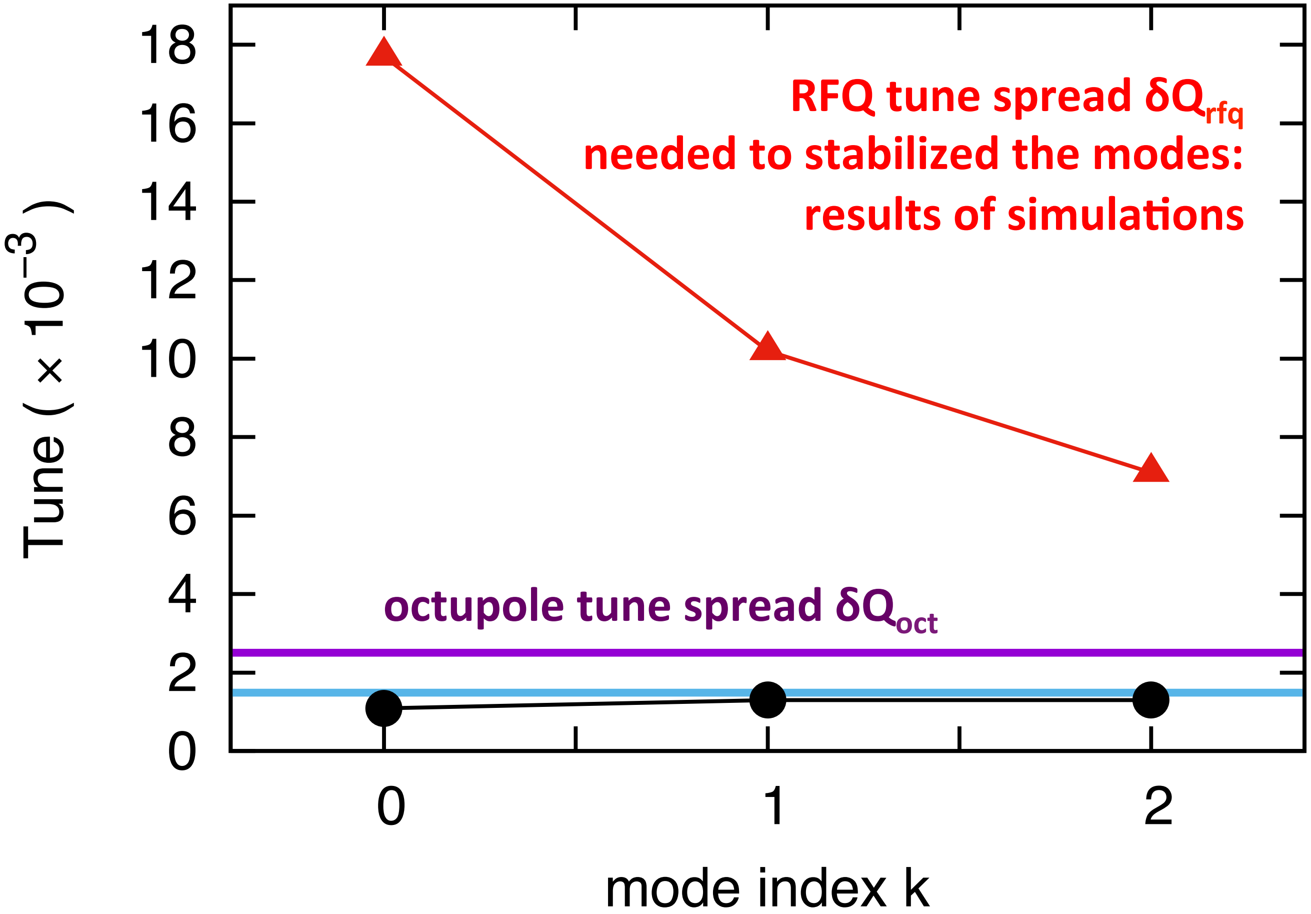




$$\Delta Q_{\mathrm{RFQ}}(z) = \Delta Q_{0\mathrm{RF}} \cos(\omega z / c)$$

- Tune spread (rms δQ_{rfq}=0.4 ΔQ_{0RF})
- Global tune shift (average ΔQ_{rfq} = 0.6 ΔQ_{0RF})
- Modification of the chromaticity effect
- → Affects the instability drive
- Tune spread is longitudinal: in every slice zero spread

Summary of Simulation Results



The needed RFQ tune spread is much bigger (factor ≈5−10)

RFQ can provide stability (like ξ). Does it provide Landau damping?

Conclusions

- Nearly 3600 LHC-octupoles are needed at FCC to ensure the transverse stability
- Stability of intra-bunch oscillations ($k \geq 1$ modes) due to octupoles corresponds to the 2D Landau damping DR.
  → the true Landau damping and
  higher tolerable impedances, or less octupoles
- RF Quadrupole provides stability only by factors ≈5−10 larger tune spreads
  → existence of Landau damping is not clear,
  it can be the instability drive modification (like ξ)