Landau Damping of Transverse Oscillations in Bunches

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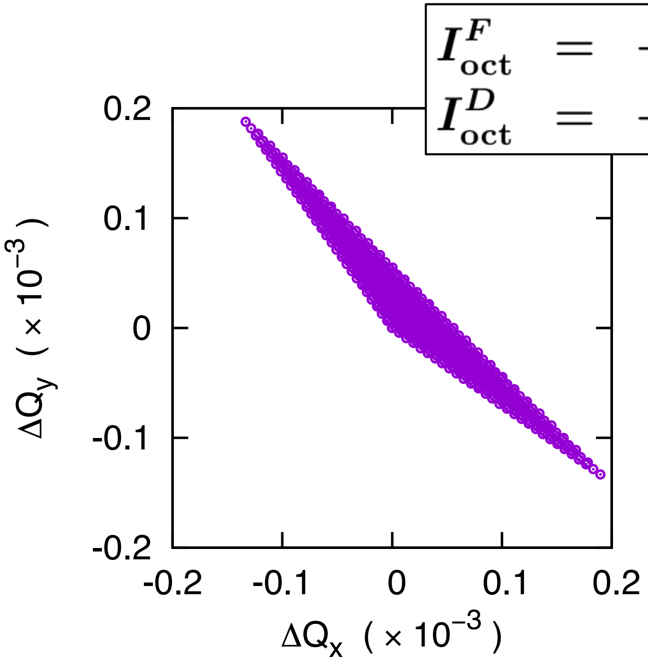
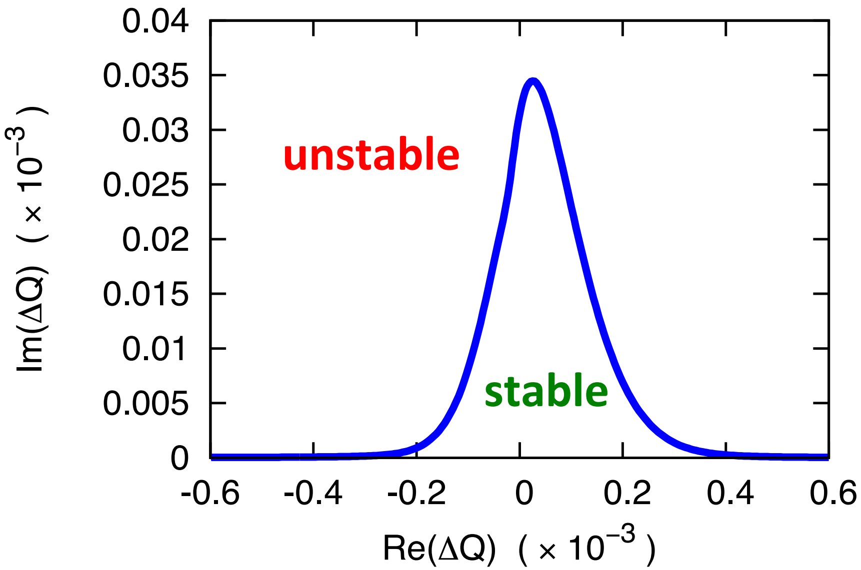
OUTLINE

1. Landau Damping of higher-order modes (intra-bunch oscillations)

2. Landau Damping, Instability Drive & Decoherence: octupoles, RF Quadrupole

Transverse Stability





FCC-hh

For the ΔQ_{coh}–Damping as in LHC:

3554 LHC-octupoles.

508 Advanced-technology octupoles.

V.Kornilov,
FCC Week 2017, Berlin

Tune spread provides Landau damping

Dispersion Relation

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

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

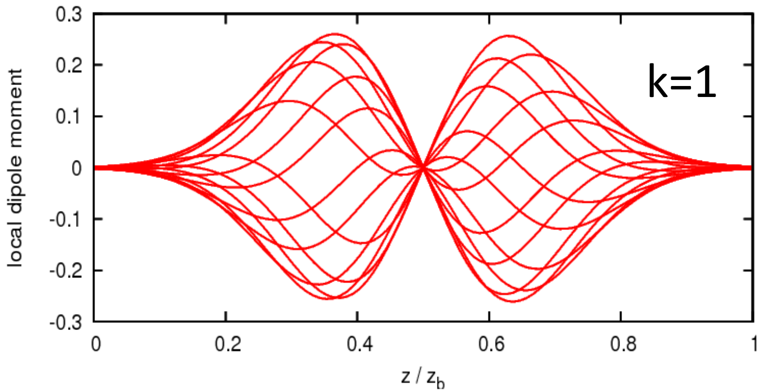
complex coherent tune shift for the beam without damping

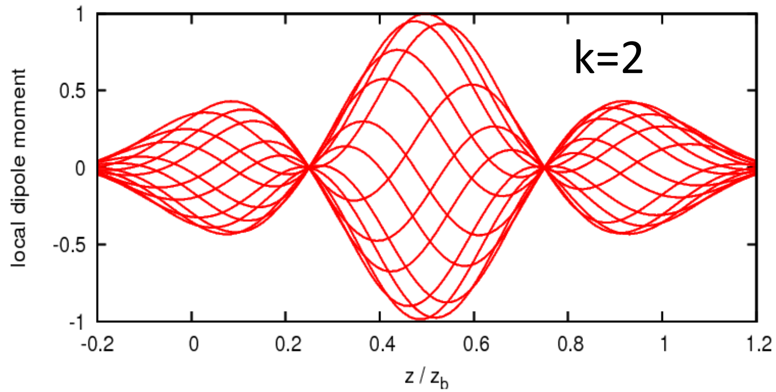
The solution: collective mode frequency Ω for the given impedance and beam

This dispersion relation has been used for the planning of the LHC octupole scheme.

Dispersion Relation

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

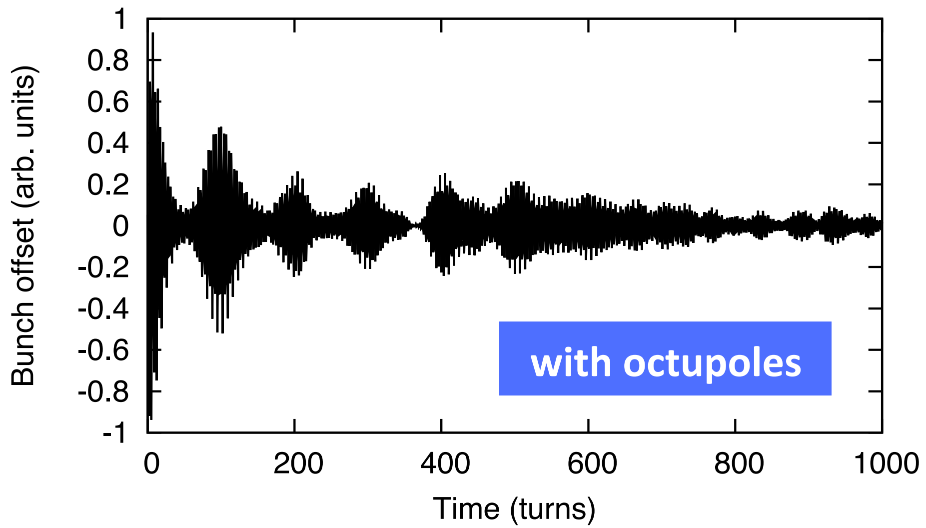


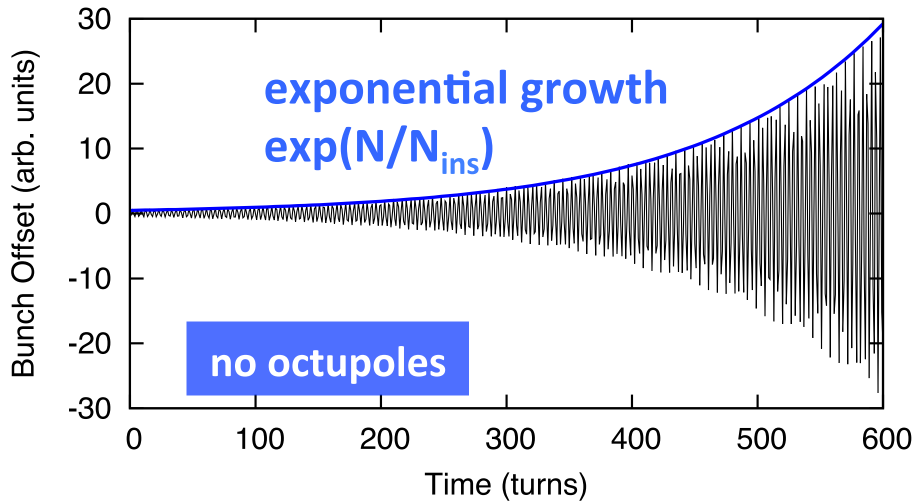


How many octupoles for the higher-order modes?
The k=0 mode is easier to damp by a feedback system.

Simulations

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



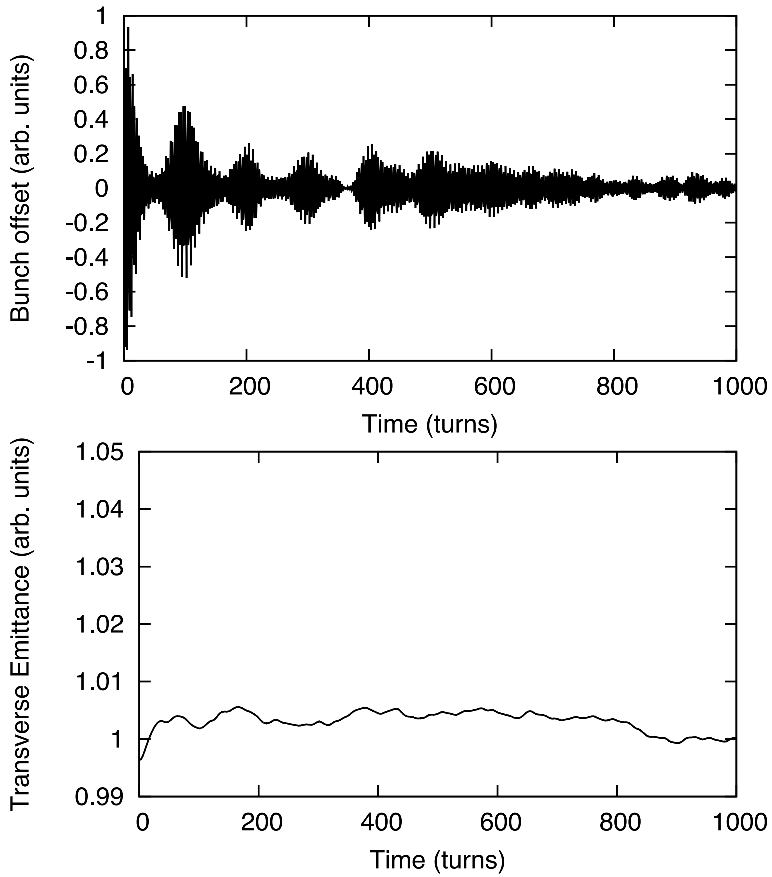


Stabile due to octupoles

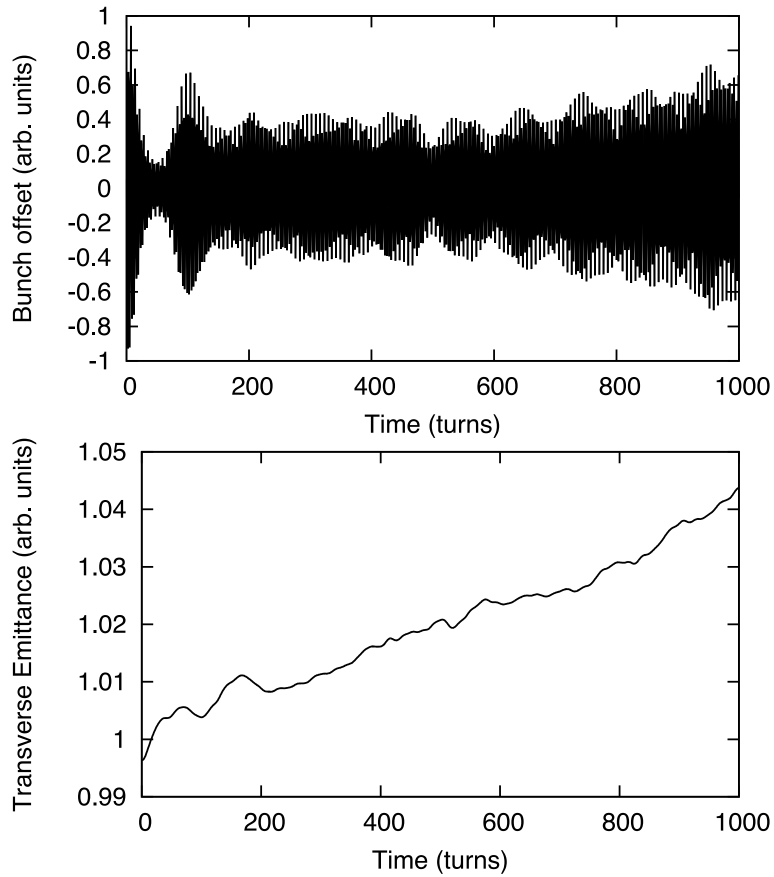
Unstable

V.Kornilov, O.Boine-Frankenheim, arXiv:1709.01425 (2017)
V.Kornilov, O.Boine-Frankenheim, PRSTAB 13, 114201 (2010)

Simulations



Stabile due to octupoles



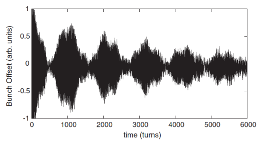
Above the threshold

Landau Damping in Beams

Reminder

Two channels of damping in beams

decoherence (phase-mixing)



$\delta\omega_\beta$

Landau damping wave ↔ particles interaction

$$\partial f / \partial J_x \Big|_{\omega=\Omega_{\mathrm{coh}}}$$

tune spread, other effects

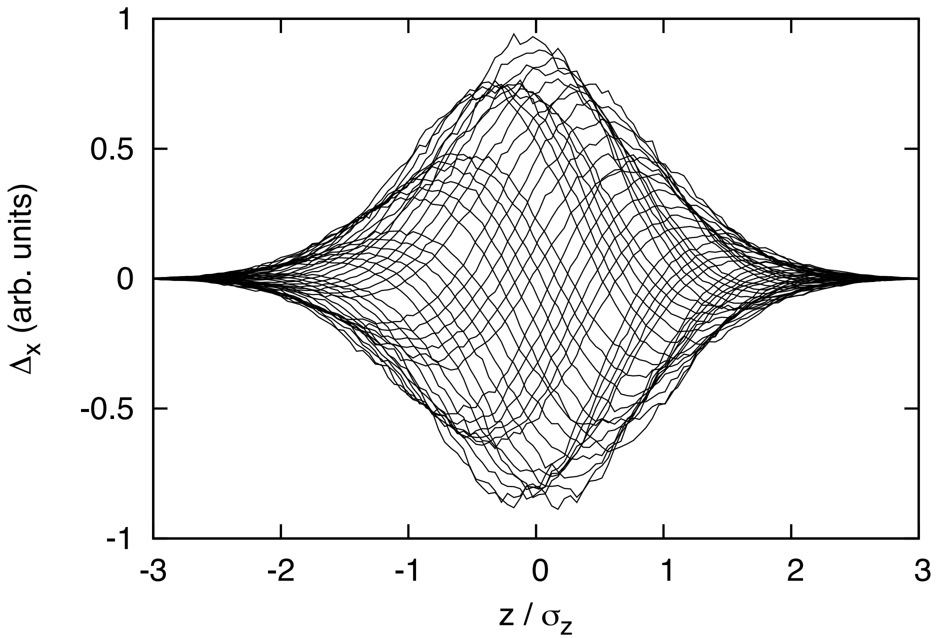
affects the beam bulk → emittance blow-up

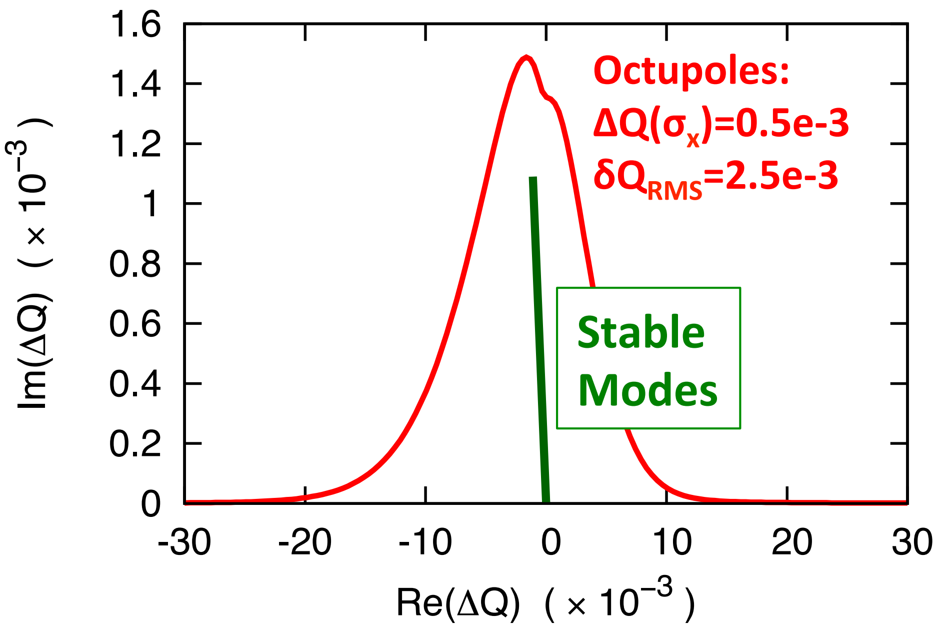
distribution function, tune shifts $\Delta Q(J_x, J_y)$

affects a few resonant particles

Simulations

Summary of the simulation scans



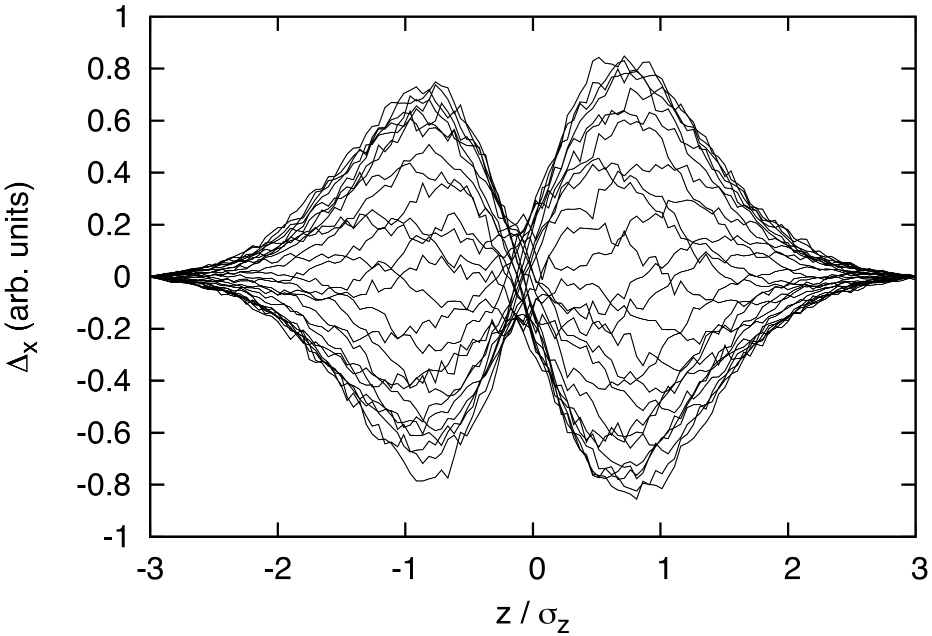


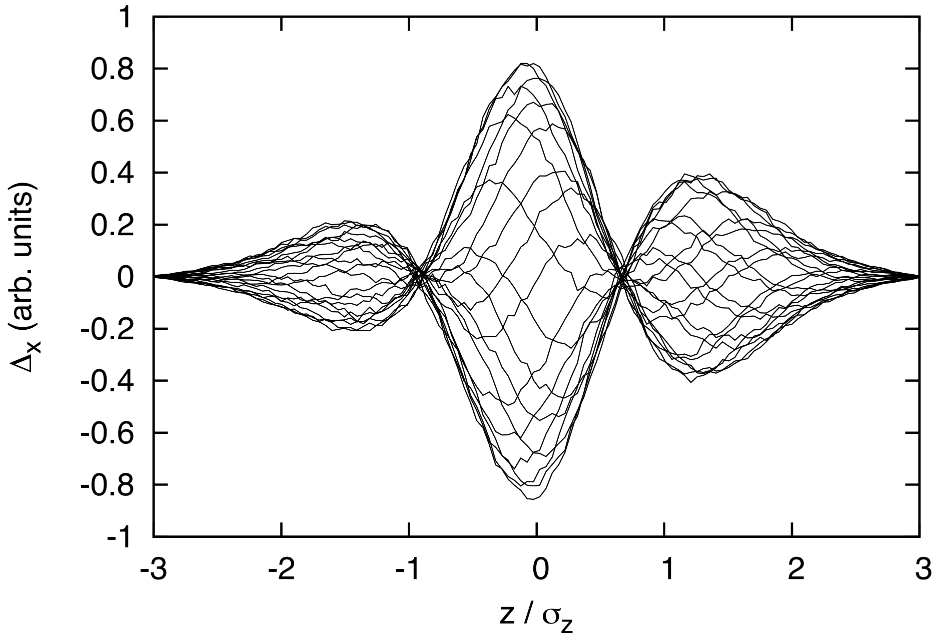
<u>Surprising agreement</u>

- 2D dispersion relation vs. 3D Gaussian bunches
- Stability due to Landau damping and phase-mixing

Simulations

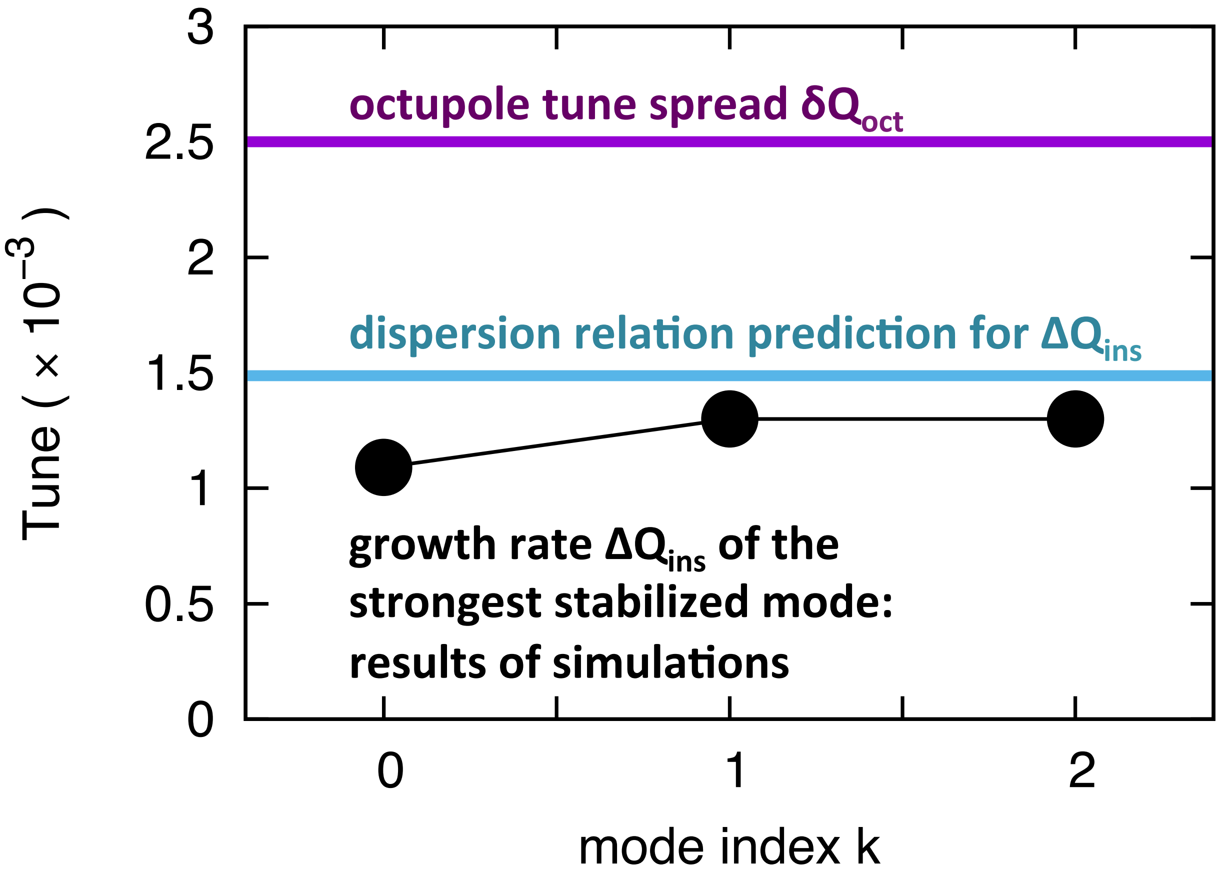
<u>Similar simulation scans for the k=1 and k=2 modes</u>





- 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

Simulations



- 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

part 2

Landau Damping,
Instability Drive,
Decoherence:

octupoles, RF Quadrupole

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)

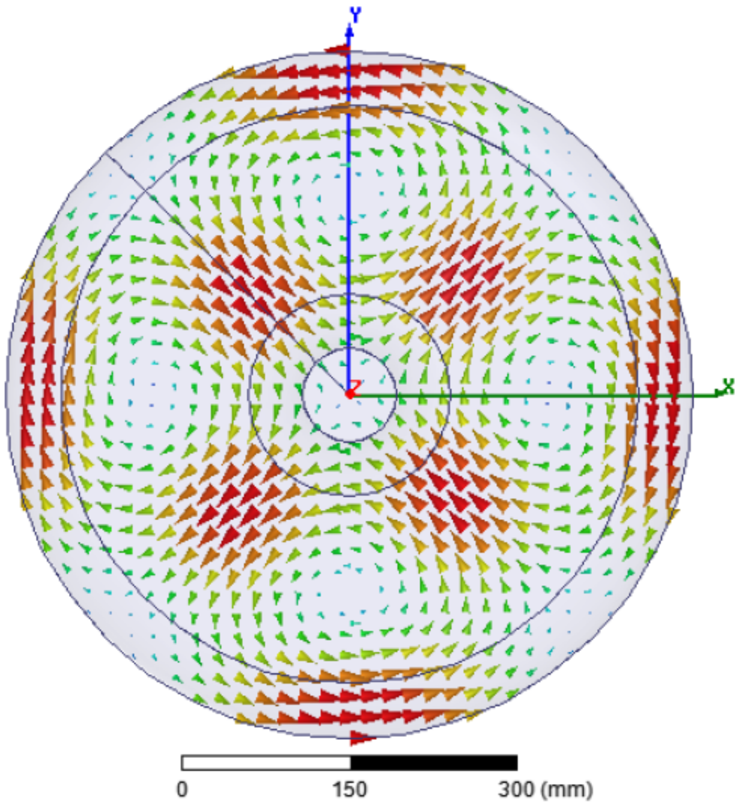


Figure 1: Magnetic field distribution in the transverse plane of the TM quadrupolar mode cavity of the RFQ.

For LHC:

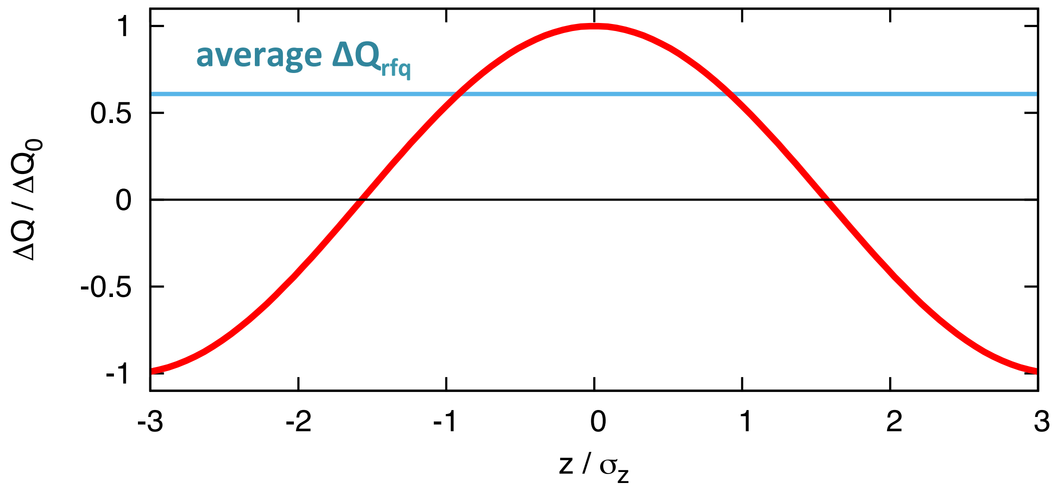
L = 0.15 m, 6 cavities
E = 46 MV/m
ω = 800 MHz, λ = 0.375 m

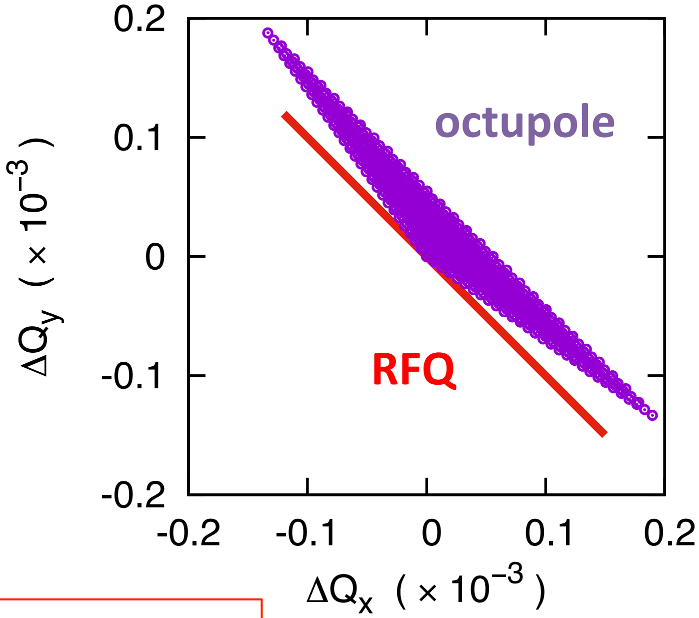
The incoherent tune shift:

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

The related tune spread should provide Landau damping

RF Quadrupole



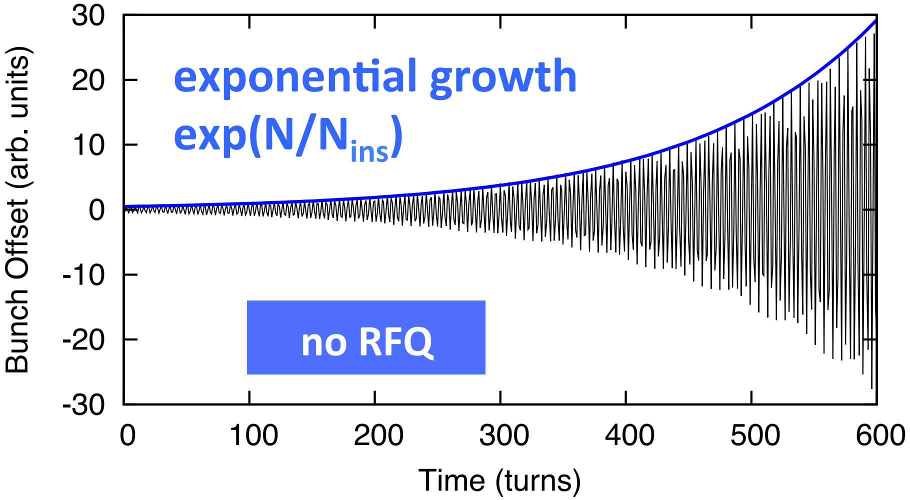


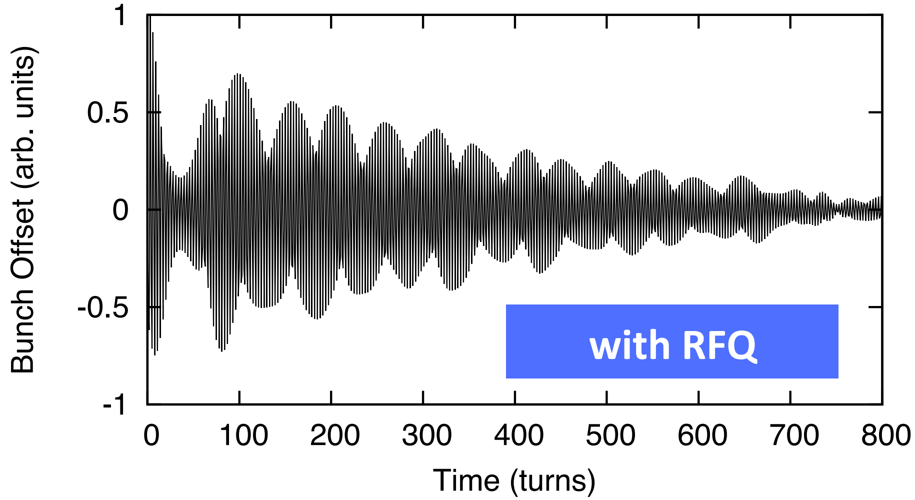
$$\Delta Q_{\mathrm{RFQ}}(z) = \Delta Q_{0\mathrm{RF}} \cos(\omega z/c)$$

- 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

Simulations

Particle tracking simulations:
RF Quadrupole can provide stability





Resistive-Wall: unstable

Stable due to RFQ

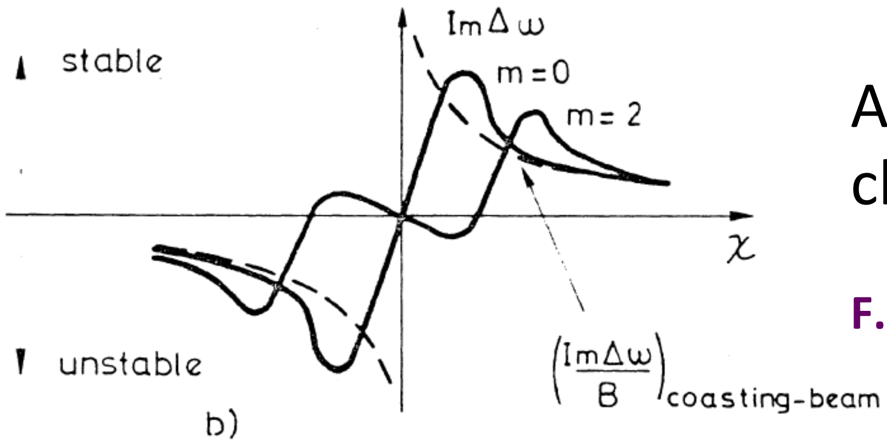
Instability Drive vs. Damping

Reminder

$$\Delta\Omega = \Delta\Omega_{\mathrm{Re}} + i\gamma_{\mathrm{drive}} + i\gamma_{\mathrm{damping}}$$

change the parameters of the driving mechanism

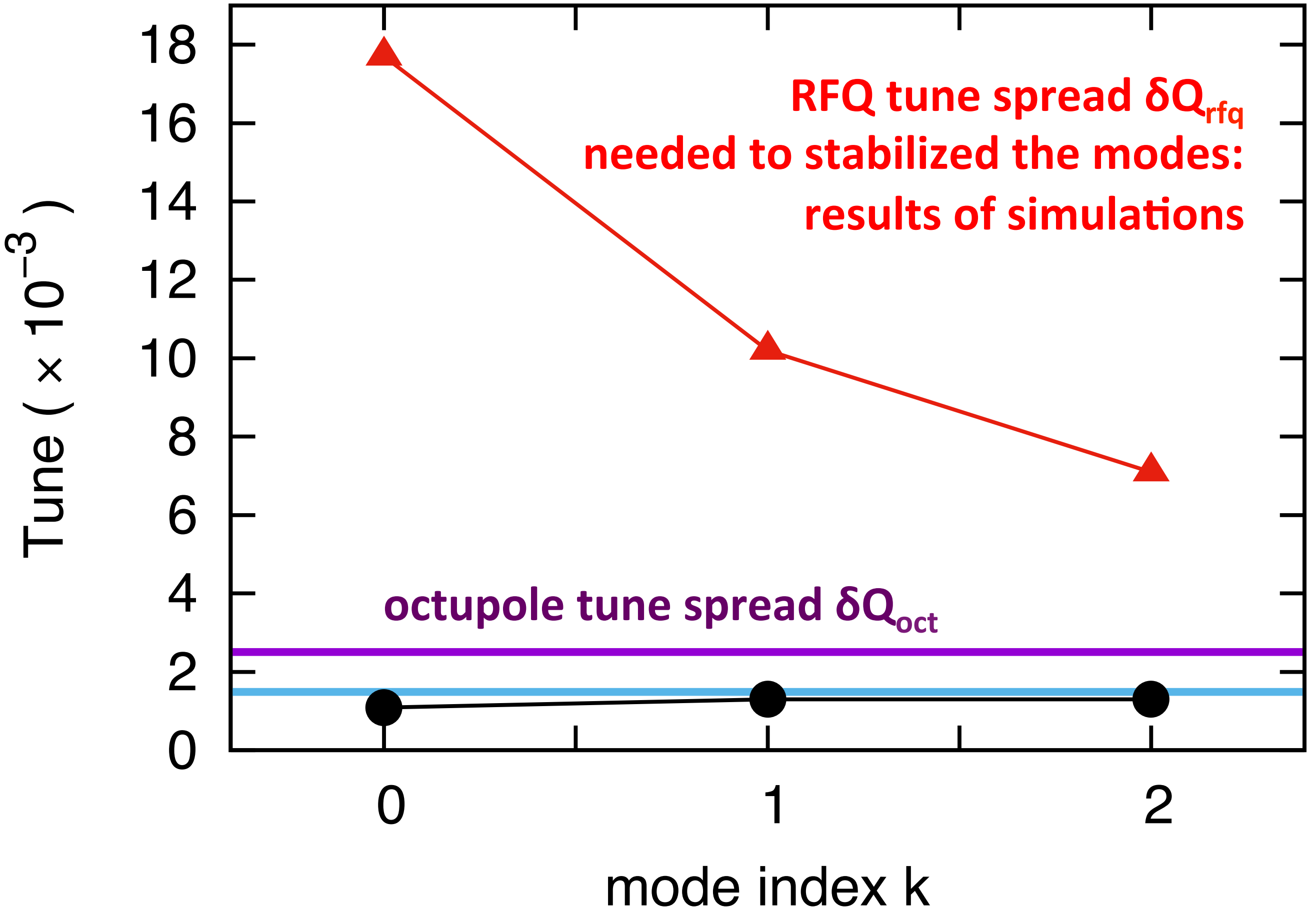
use and enhance the damping mechanisms



An example:
chromaticity for the head-tail modes

F.Sacherer, CERN/PS/BR 76-21 (1976)

Simulations



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

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

Stability Diagram

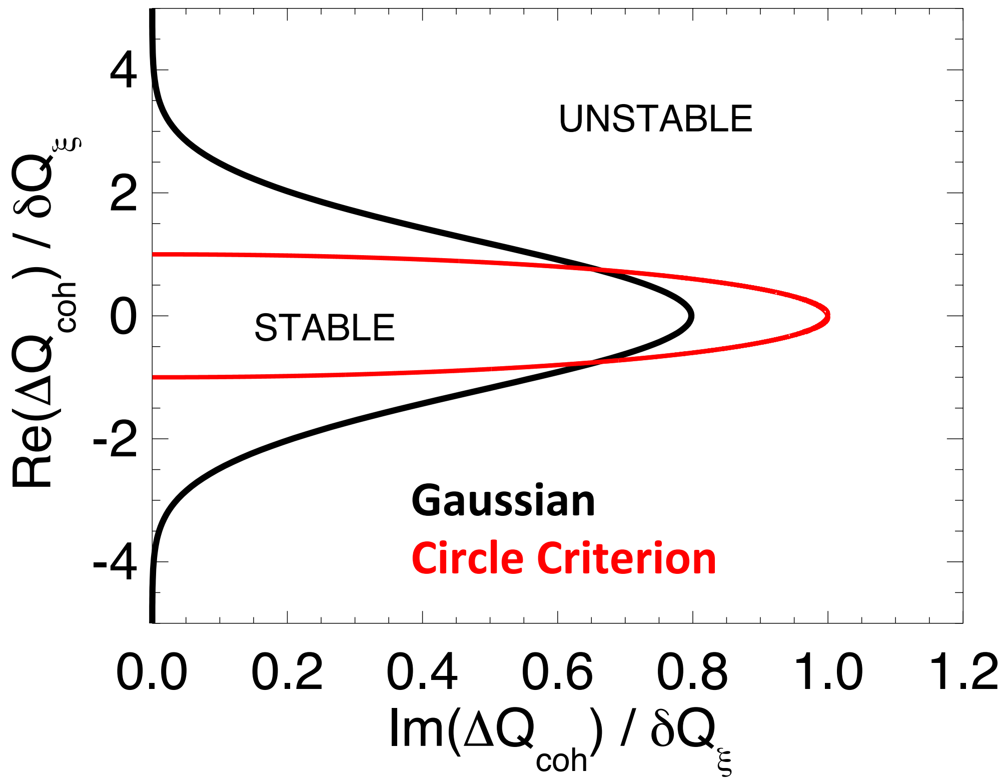
Reminder

Dispersion relation

$$\Delta Q_{\rm coh} R(\Omega) = 1$$

Circle Criterion

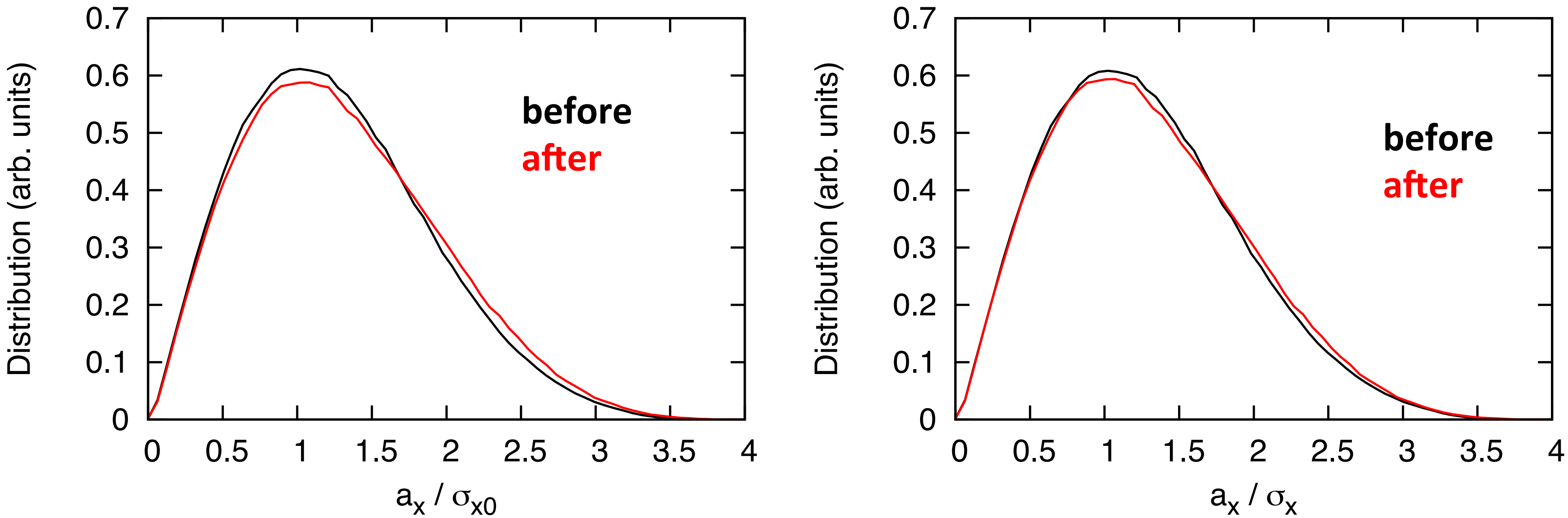
$$\frac{|\Delta Q_{\rm coh}|}{\delta Q_\xi} = 1$$



Strength of Landau Damping is proportional (or related) to the tune-spread

Simulations

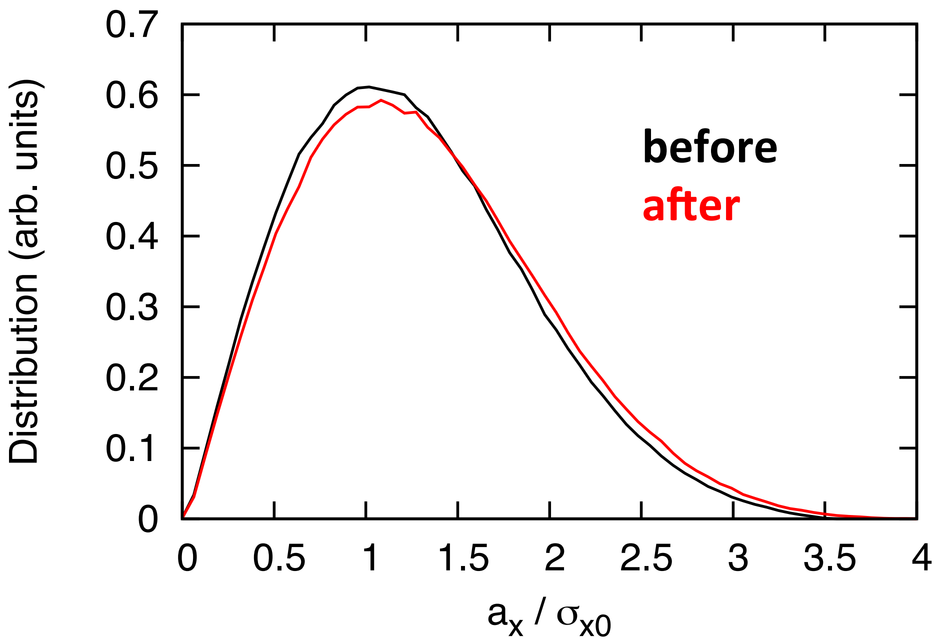
Amplitude distribution **before** an **after**
decay of a perturbation (with an impedance) due to OCTUPOLES

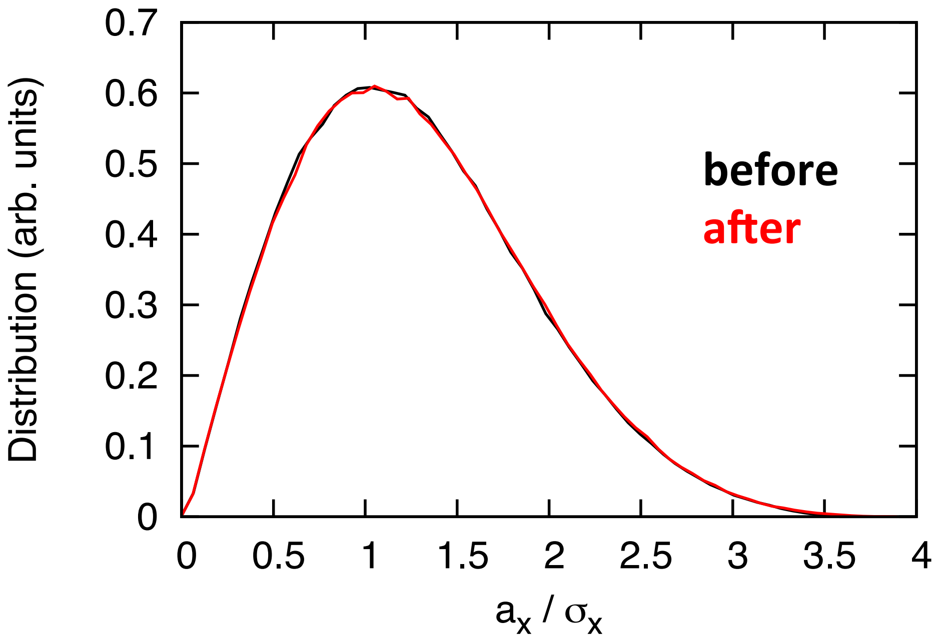


Modification of the amplitude distribution:
particles are driven to larger amplitudes

Simulations

Amplitude distribution **before** an **after**
decay of a perturbation (with an impedance) due to RFQ

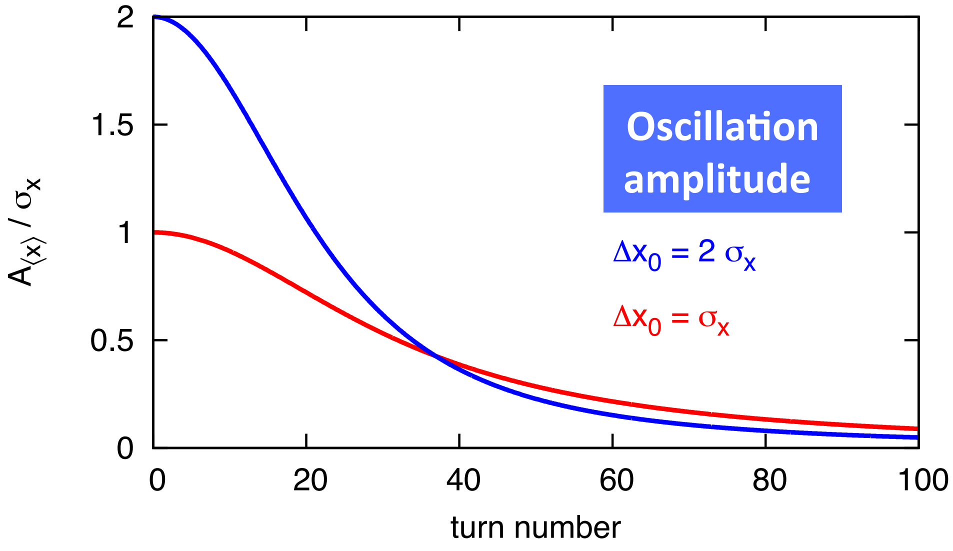


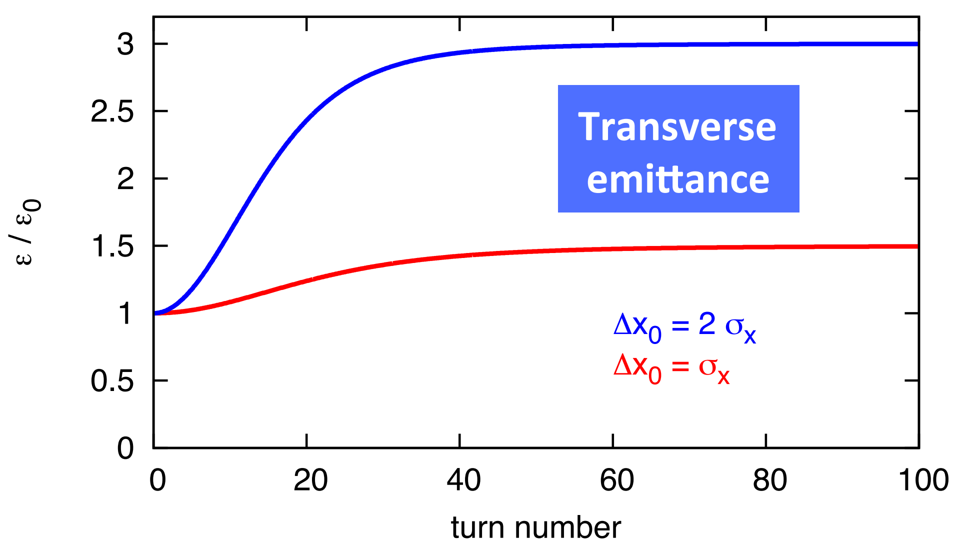


NO Modification of the amplitude distribution:
just an emittance blow-up

Reminder

Phase-Mixing generates emittance blow-up





Example: analytical nonlinearity in a bunch, A.W. Chao, et al, SSC-N-360 (1987)

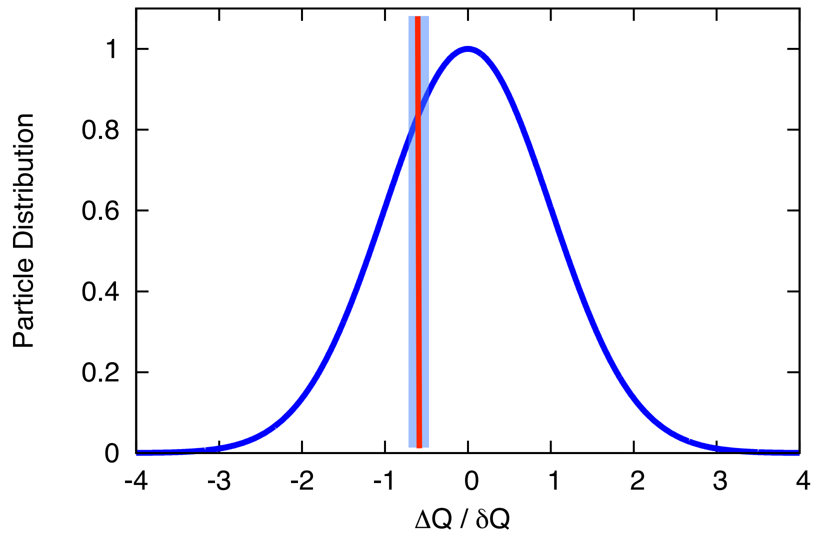
Landau Damping

Reminder

We know at least two examples where:

1. Head-tail modes and the chromaticity tune-spread
2. Nonlinear space-charge in coasting beams

- there is a **tune spread**
- the coherent frequency overlaps with the incoherent spectrum



still, there is **NO Landau Damping!**

a tune spread does not automatically means Landau Damping

Summary

- The classic 2D dispersion relation provides reasonable predictions for the k=0 modes (Landau damping, Phase-mixing), and for the higher-order modes.

- RF Quadrupole can provide stability.
  - the needed tune-spread is much larger than that for the Landau damping
  - emittance blow-up (phase-mixing) and no distribution modifications (phase-mixing LD channel?)
  - instability drive affected (only?)
  - tune-spread does not automatically means Landau Damping

- Comparisons and detailed studies are a great instrument to learn about Landau damping in beams