Collective Effects & its Diagnostics

part 2

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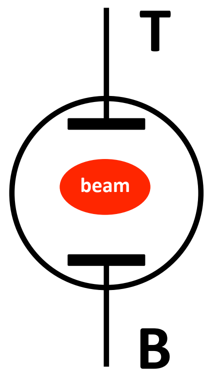
Schottky signals with collective effects

Schottky Signals

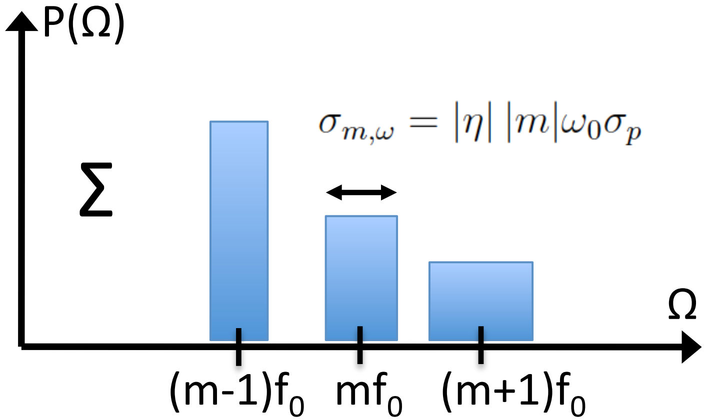
W.Schottky 1918: random fluctuations due to uncorrelated arrival of charges.
For beams in accelerator: signal due to discrete particles.

Longitudinal (Sum) Schottky signal: Σ=T+B
Transverse (Delta) Schottky signal: Δ=T−B
Without collective effects:

$$P_{||}(\Omega) \propto Z^2 f_0 N_p \sum_{\substack{m=-\infty \\ \neq 0}}^{\infty} \frac{1}{|m|} \Psi\left(\frac{\Omega - m\omega_0}{\sigma_{m,\omega}}\right)$$



Gives f_0, momentum spread



$\Delta\omega_0/\omega_0 = -\eta\ \Delta p/p$
rms $\sigma_p = \delta p/p$
Ψ is the lattice-related tune distribution; here the momentum distribution

S.Chattopadhyay, CERN 84-11 (1984)
F.Caspers, CAS Dourdan 2008, p.407

Schottky Signals

Longitudinal (Sum) Schottky signal: Σ=T+B

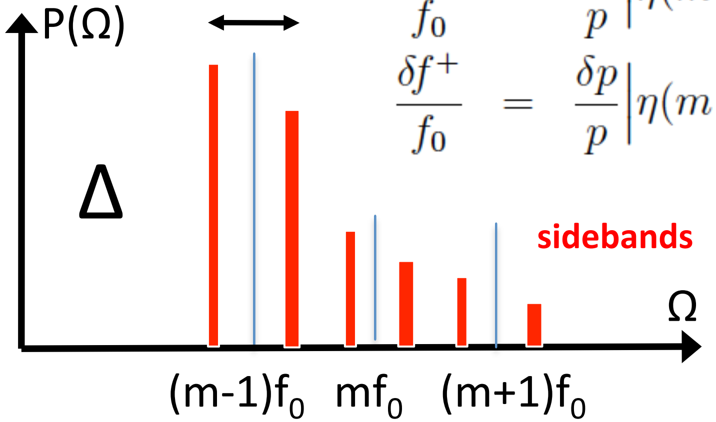
<u>Transverse (Delta) Schottky signal: Δ=T−B</u>

Without collective effects:

$$P_0(\Omega) = \mathcal{D}\,\Psi\left(\frac{\Omega}{n - Q_0}\right)$$

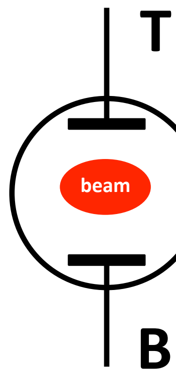
Ψ is the lattice-related tune distribution.

Gives the tune , chromaticity, tune shifts



$$\frac{\delta f^-}{f_0} = \frac{\delta p}{p}\left|\eta\left(m - Q_f + Q\frac{\xi}{\eta}\right)\right|$$

$$\frac{\delta f^+}{f_0} = \frac{\delta p}{p}\left|\eta\left(m + Q_f - Q\frac{\xi}{\eta}\right)\right|$$



Q_f is the fractional part of the tune;
(Q=4.3, Q_f=0.3)
$\Delta Q = \xi Q\, \Delta p/p$

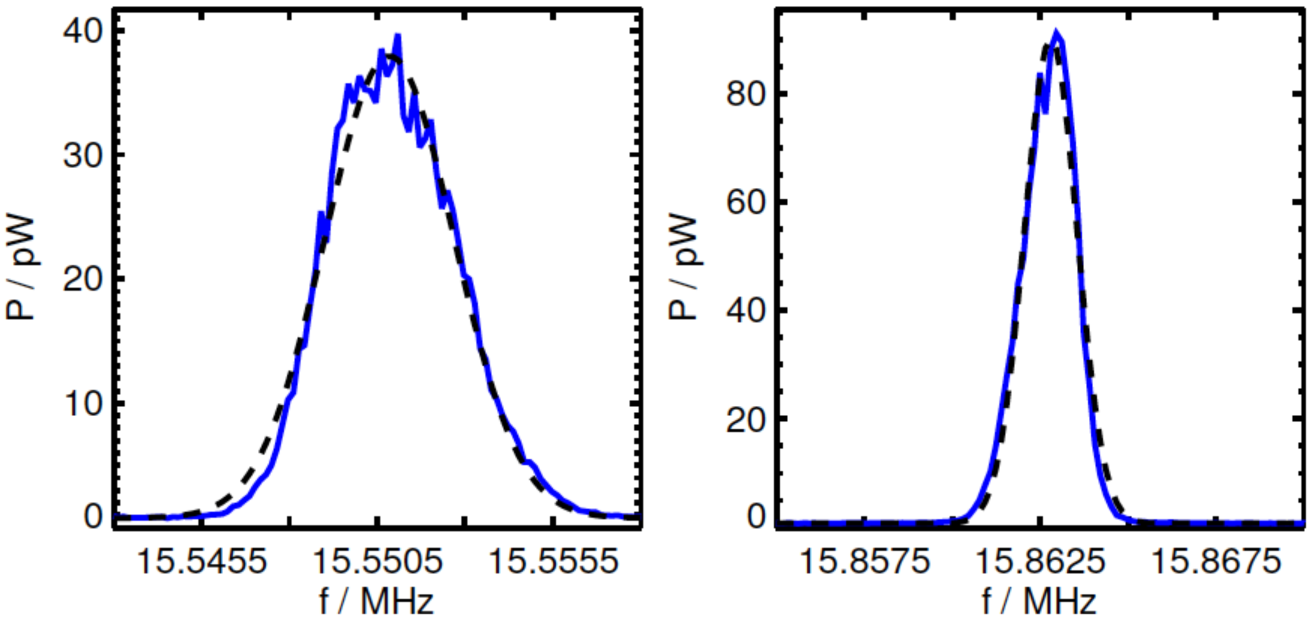
S.Chattopadhyay, CERN 84-11 (1984)
F.Caspers, CAS Dourdan 2008, p.407

Schottky Signals

Example:

Xe^{48+} ions in SIS18 at GSI:

m=20, Q_h=4.3, measured ξ_h=−1.3

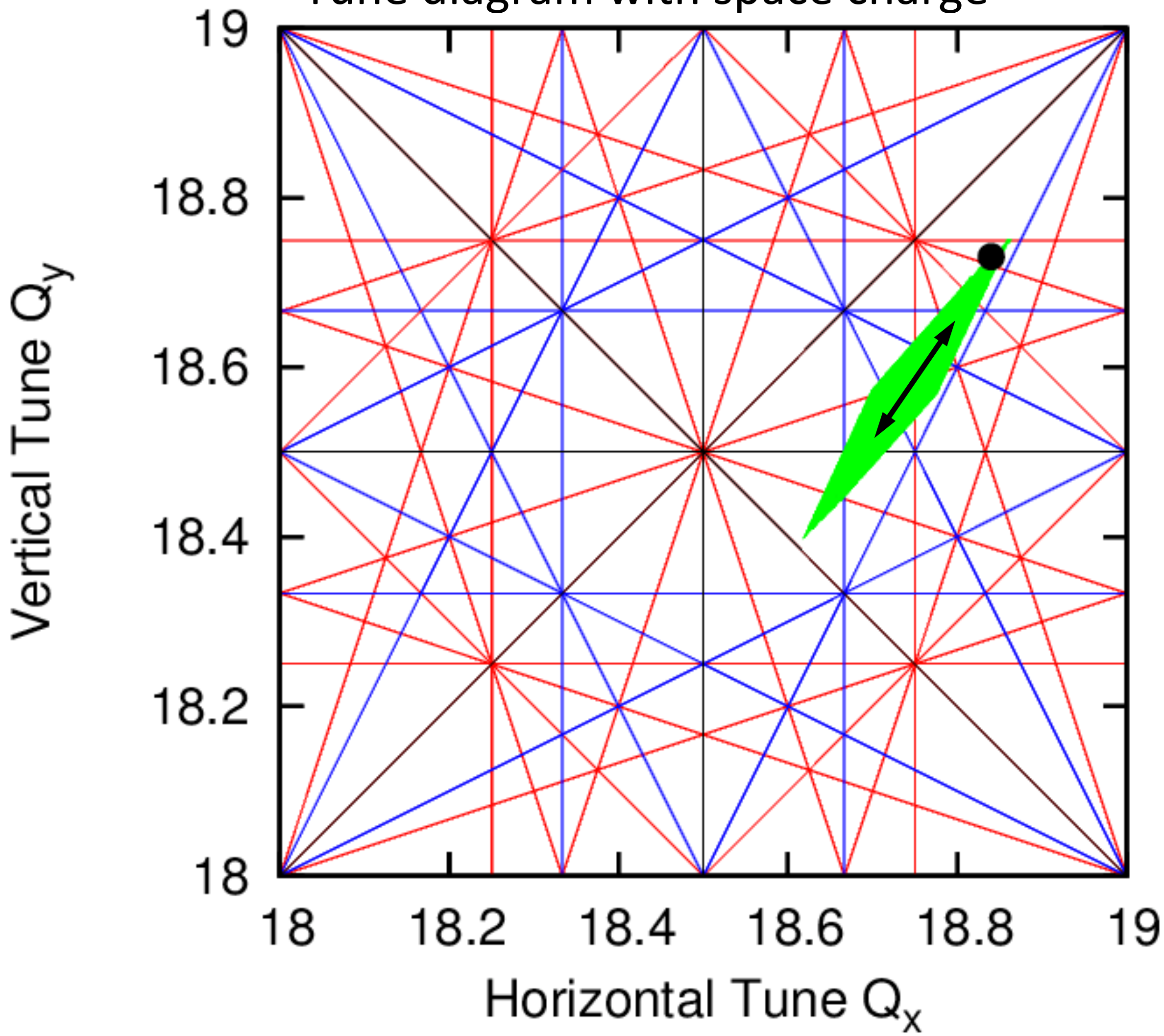


lower sideband

upper sideband

Schottky Signals

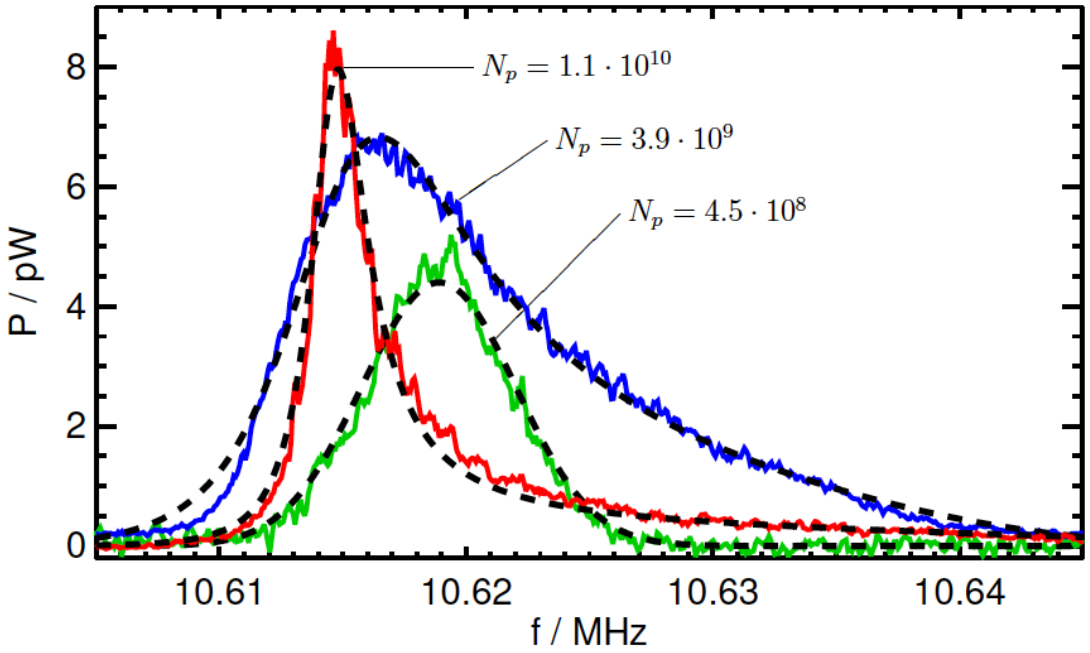
Tune diagram with space charge



The case with space charge: how the tune spread affects the Schottky side bands?

Schottky Signals

The Schottky sidebands transform at high intensities



Lower sidebands for m=50, Ar^{18+} beams in SIS18 at GSI, f_0=214 kHz
S.Paret, V.Kornilov, O.Boine-Frankenheim, PRSTAB 13, 022802 (2010)

In order to understand and to use these transformations, we need the Beam Transfer Function R(Ω)

Schottky Signals at High Intensity

Transverse unbunched Schottky noise without collective interactions (incoherent frequencies of uncorrelated particles)

$$P_0(\Omega) = \mathcal{D}\,\Psi\left(\frac{\Omega}{n - Q_0}\right)$$

With an impedance:

$$P = \frac{P_0}{|\varepsilon|^2}\,, \quad \varepsilon(\Omega) = 1 + iZ^{\perp}R_0(\Omega)$$

S.Chattopadhyay, CERN 84-11 (1984)
N.Dikansky, D.Pestrikov, Physics of Intense Beams and Storage Rings (1994)

what about space charge?
just include space-charge as an impedance?

WRONG

D.Pestrikov, NIM 578, 65 (2007)
O.Boine-Frankenheim, V.Kornilov, S.Paret, PRSTAB 11, 074202 (2008)

Schottky Signals at High Intensity

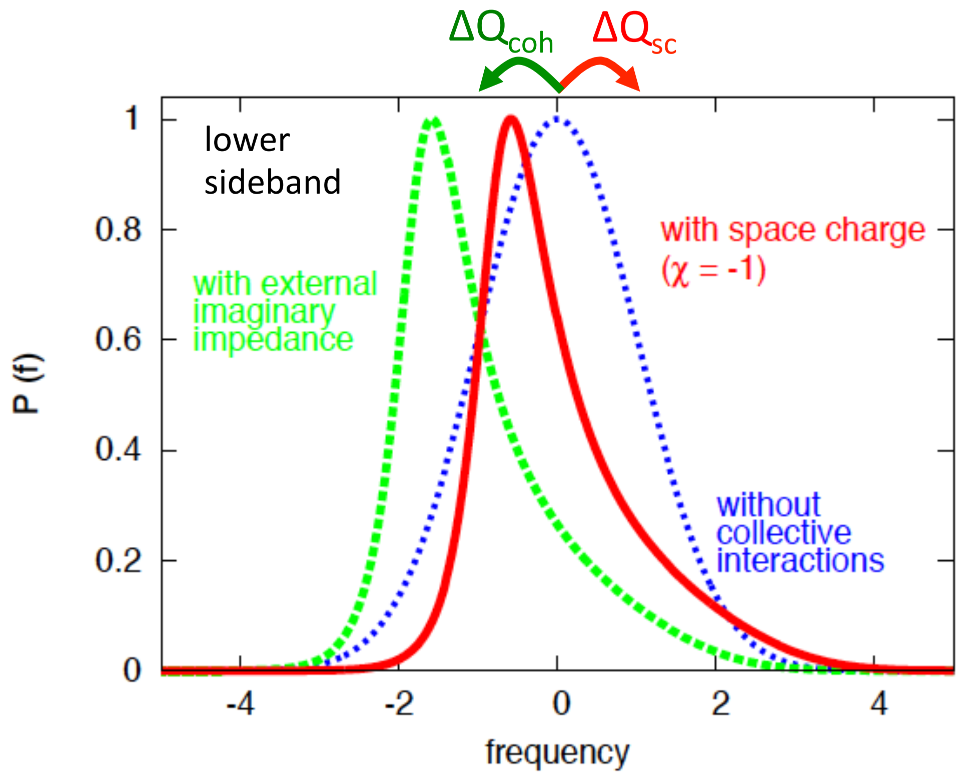
$$P(\Omega) = \frac{P_0^{\Delta}(\Omega)}{|\varepsilon(\Omega)|^2}$$

for an impedance

$$P_0^{\Delta}(\Omega) = P_0(\Omega)$$
$$\varepsilon = 1 + iZ^{\perp}R_0(\Omega)$$

for space charge

$$P_0^{\Delta}(\Omega) = P_0(\Omega - \Delta\omega_{sc})$$
$$\varepsilon = 1 + \chi R_0(\Omega - \Delta\omega_{sc})$$



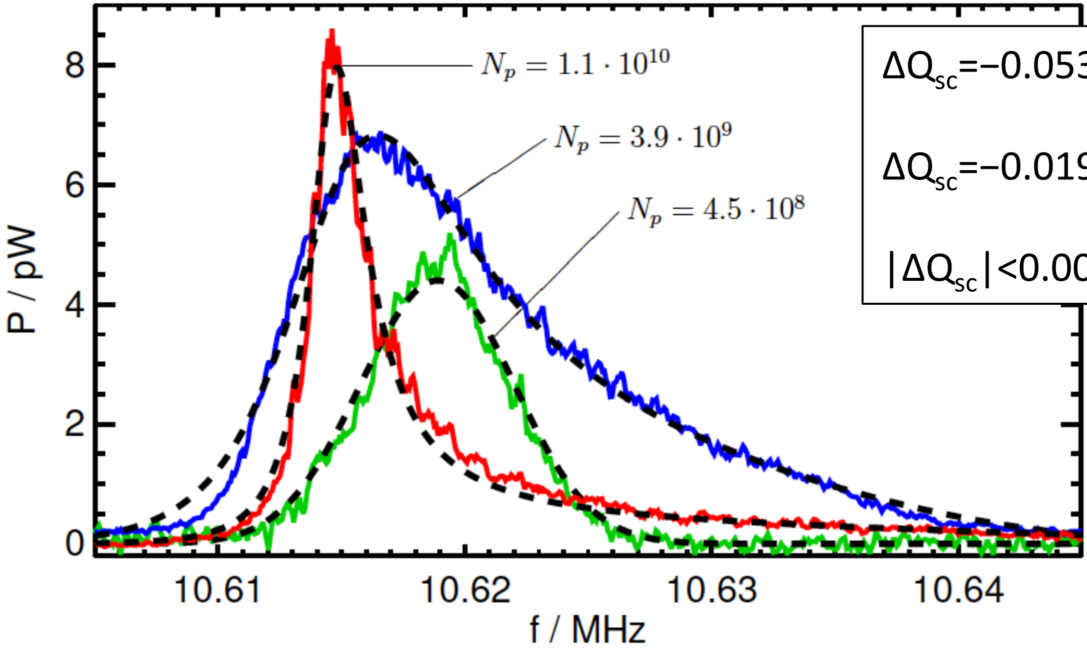
$$\chi = \frac{\Delta Q_{sc}}{\delta Q_{\xi}}$$ $\Delta Q=(\Omega-(m-Q_f)f_0)/f_0$

$\delta Q_{\xi}=|m\eta-(Q_f\eta-Q_0\xi)|\delta p/p$

Space-Charge: no total shift + deformation to the opposite side

Again: fundamental differences between impedance (ext coh) and space-charge (int incoh)

Schottky Signals at High Intensity



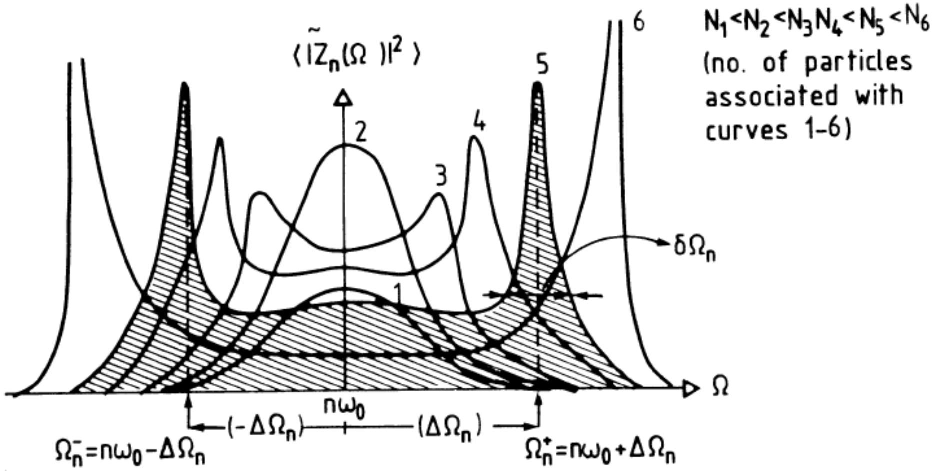
ΔQ_{sc}=−0.053	δ_p=0.78×10^{-3}
ΔQ_{sc}=−0.019	δ_p=0.67×10^{-3}
$\|\Delta Q_{sc}\|$<0.002	δ_p=0.28×10^{-3}

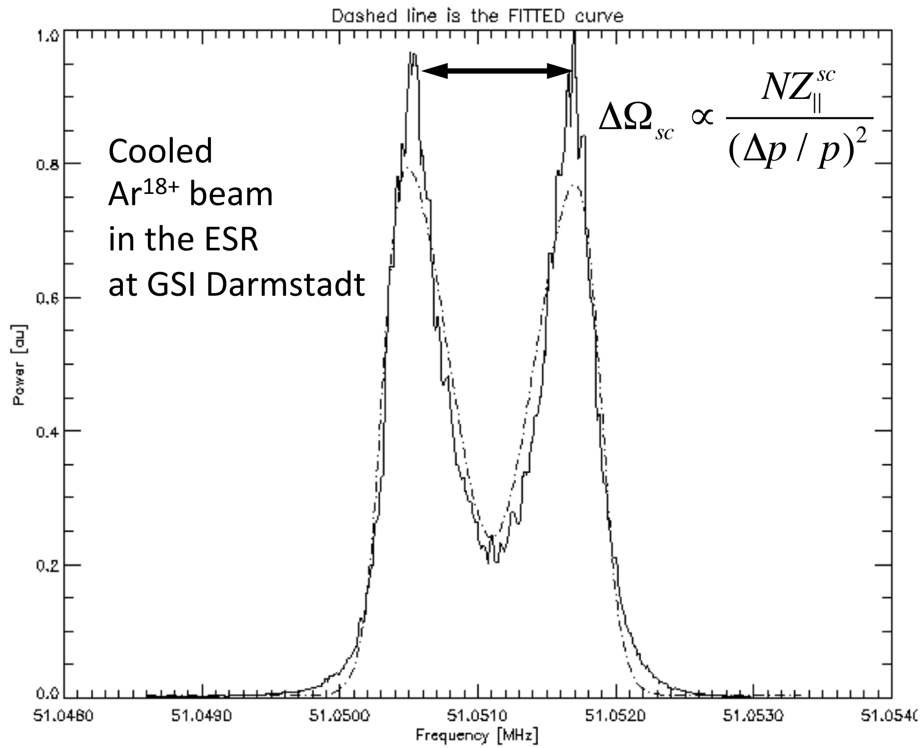
Lower sidebands for m=50, Ar^{18+} beams in SIS18 at GSI, f_0=214 kHz
S.Paret, V.Kornilov, O.Boine-Frankenheim, PRSTAB 13, 022802 (2010)

From the sideband deformation and shift,
the space-charge tune shift and/or the impedance can be determined

Schottky Signals at High Intensity

Also the longitudinal (the sum) Schottky spectrum is distorted by collective interactions.
Here: examples for space charge .





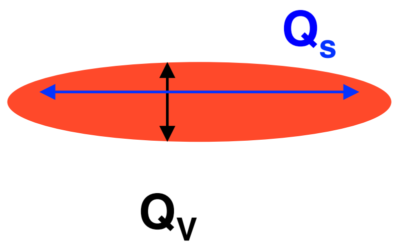
S.Chattopadhyay, CERN 84-11 (1984)

U. Schaaf, PhD thesis, Uni. Frankfurt (1991)

Transverse spectra
in bunches

Transverse Spectrum in Bunches

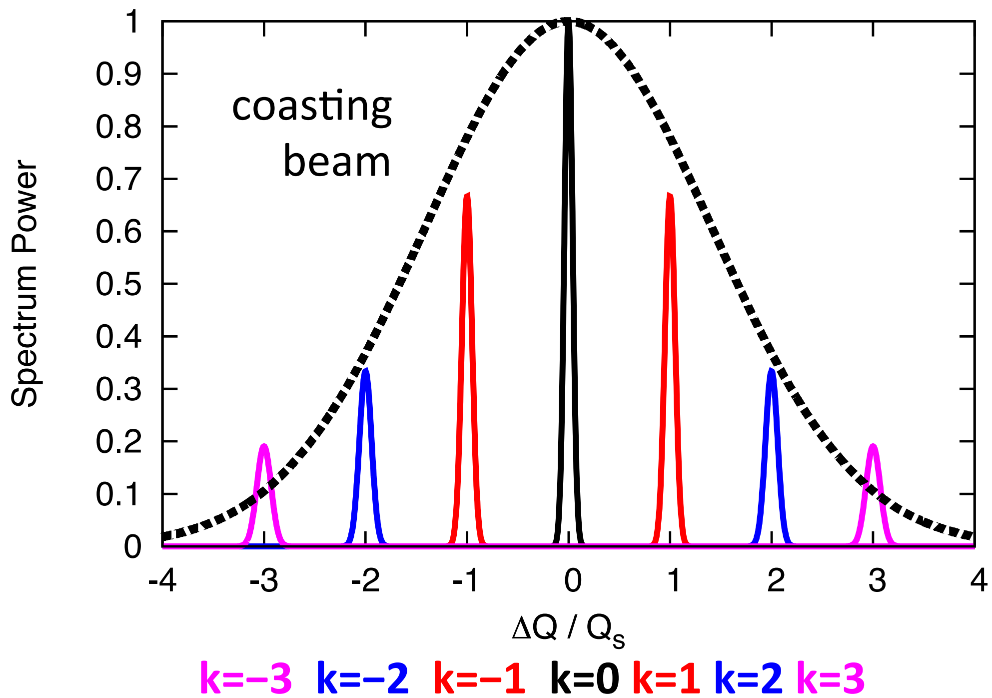
Transverse and longitudinal oscillations in a bunch



Q_s is the synchrotron tune
$Q_s = f_s/f_0$
for example:
f_0=200kHz, f_s=1kHz, Q_s=0.005

$\Delta Q = \Delta f/f_0$, $\Delta f = f - (m \pm Q_f)\, f_0$

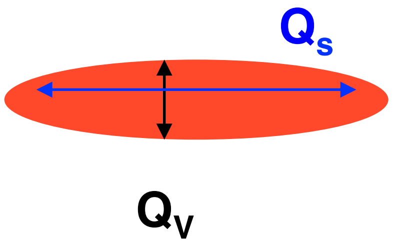
Sideband $((m \pm Q_f)\, f_0)$
in the transverse spectrum



The k=0 line normally dominates, but the |k|>0 lines can also be measured.
Gives the tune, chromaticity, coherent (Z) tune shifts, Q_s

Transverse Spectrum in Bunches

Transverse and longitudinal oscillations in a bunch



Q_s is the synchrotron tune

$Q_s = f_s/f_0$

for example:

f_0=200kHz, f_s=1kHz, Q_s=0.005

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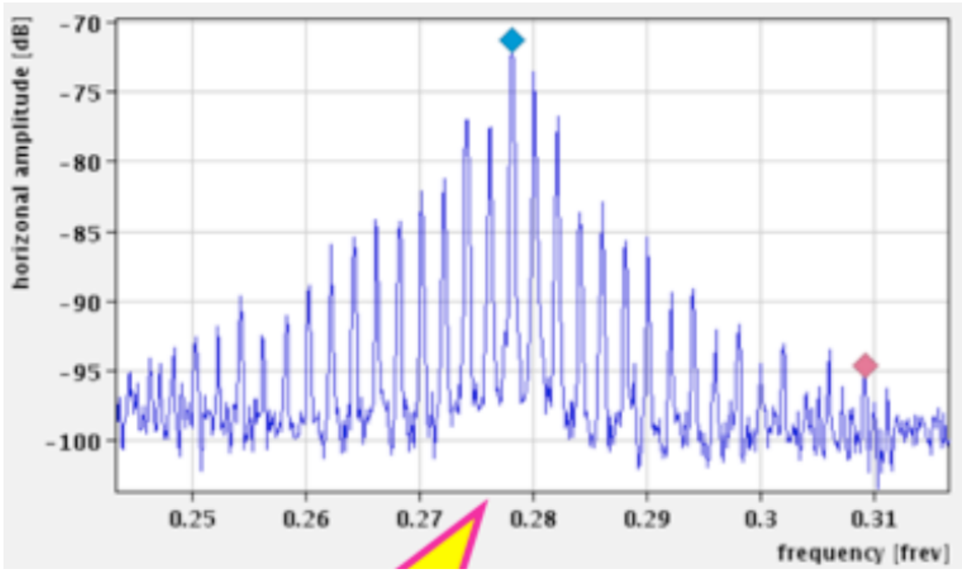


Transverse spectrum in LHC, 3.5TeV, Q_s=0.002
E.Metral, B.Salvant, N.Monet, IPAC2011

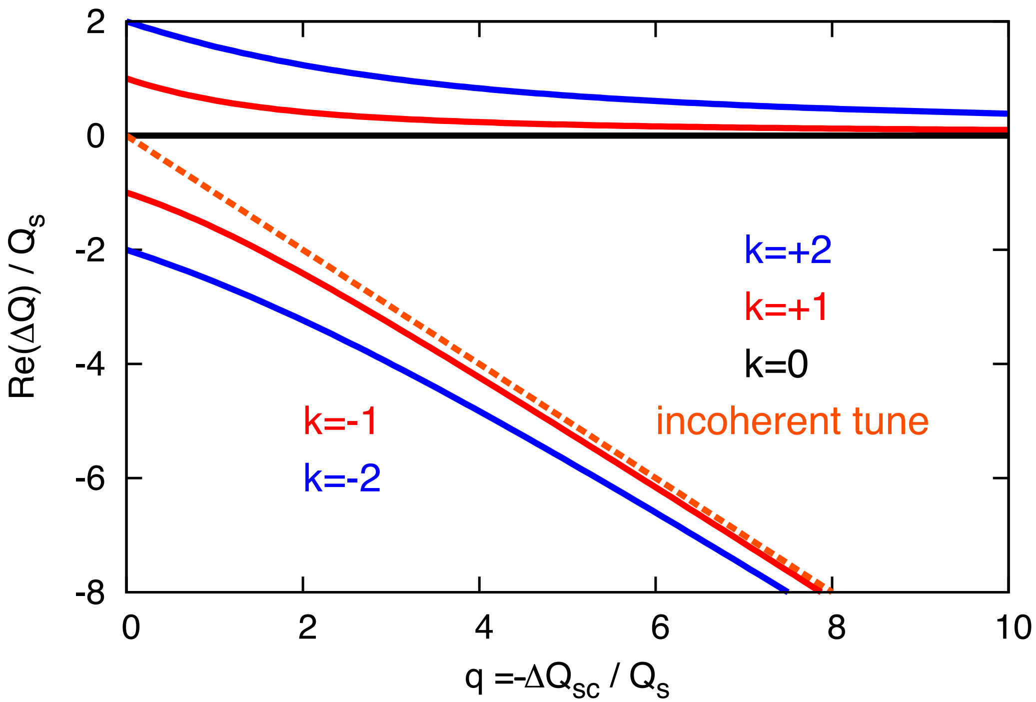
The k=0 line normally dominates, but the |k|>0 lines can also be measured. Gives the tune, chromaticity, coherent (Z) tune shifts, Q_s

Bunch spectrum is distorted by collective interaction

Space Charge in Bunches

The airbag model for arbitrary space-charge
M.Blaskiewicz, PRSTAB **1**, 044201 (1998)

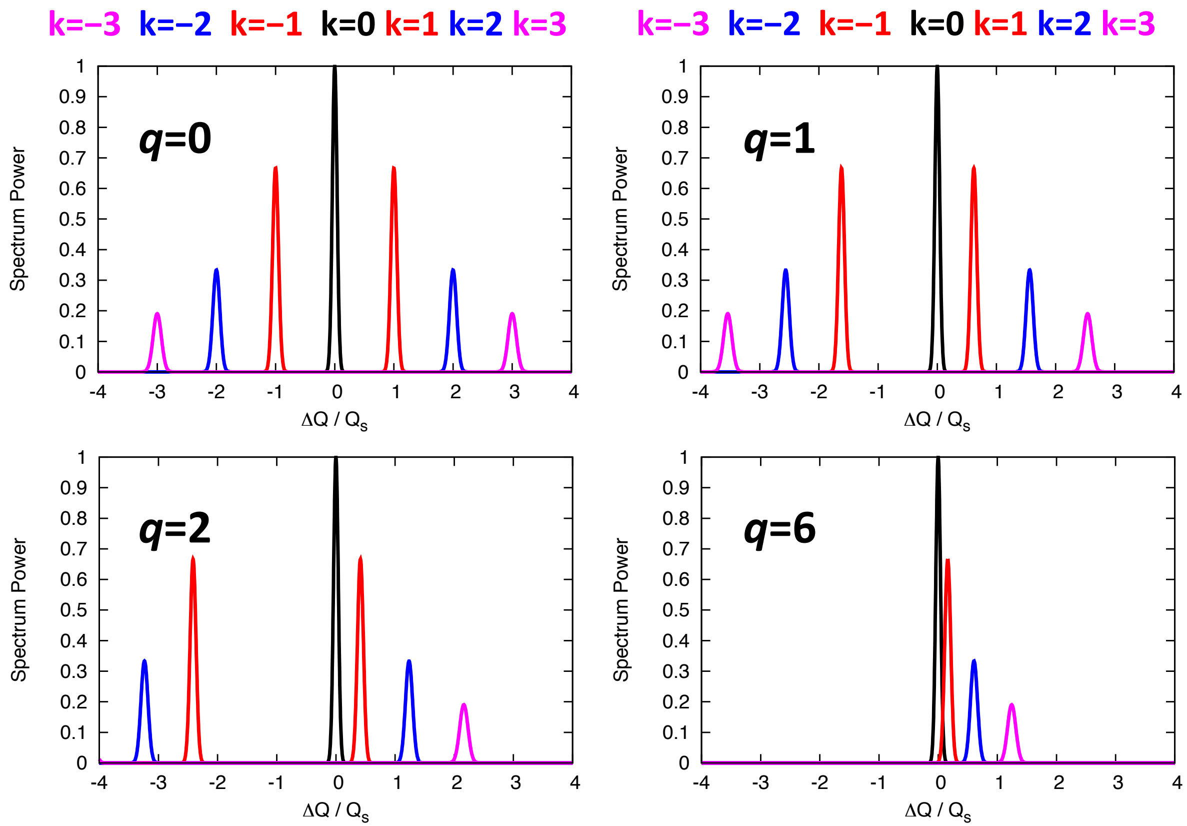
$$\Delta Q_k = \frac{\Delta Q_{\rm sc}}{2} \pm \sqrt{\frac{\Delta Q_{\rm sc}^2}{4} + k^2 Q_s^2}$$



The space charge parameter for bunches

$$q = -\frac{\Delta Q_{\rm sc}}{Q_s}$$

Space Charge in Bunches



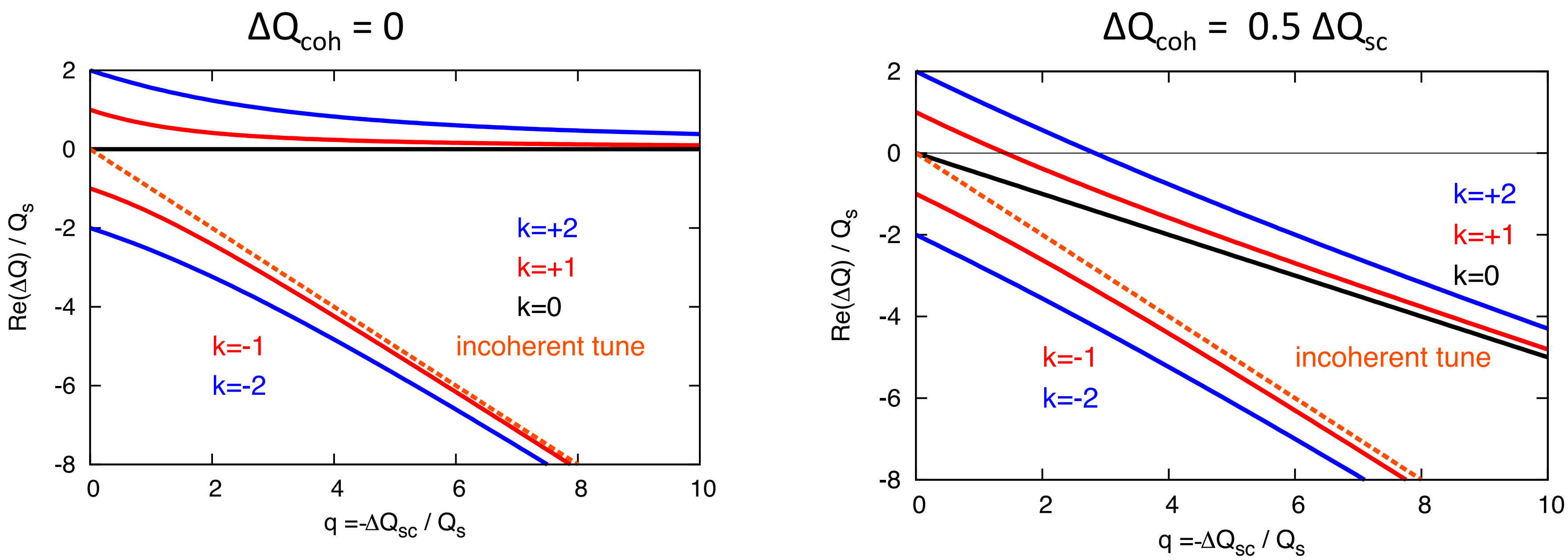
$$q = -\frac{\Delta Q_{sc}}{Q_s}$$

- The k=0 line is not affected by space charge
- The line distance is not Q_s , more difficult to resolve
- The incoherent tune is at $(-q)$

Space Charge + Impedance in Bunches

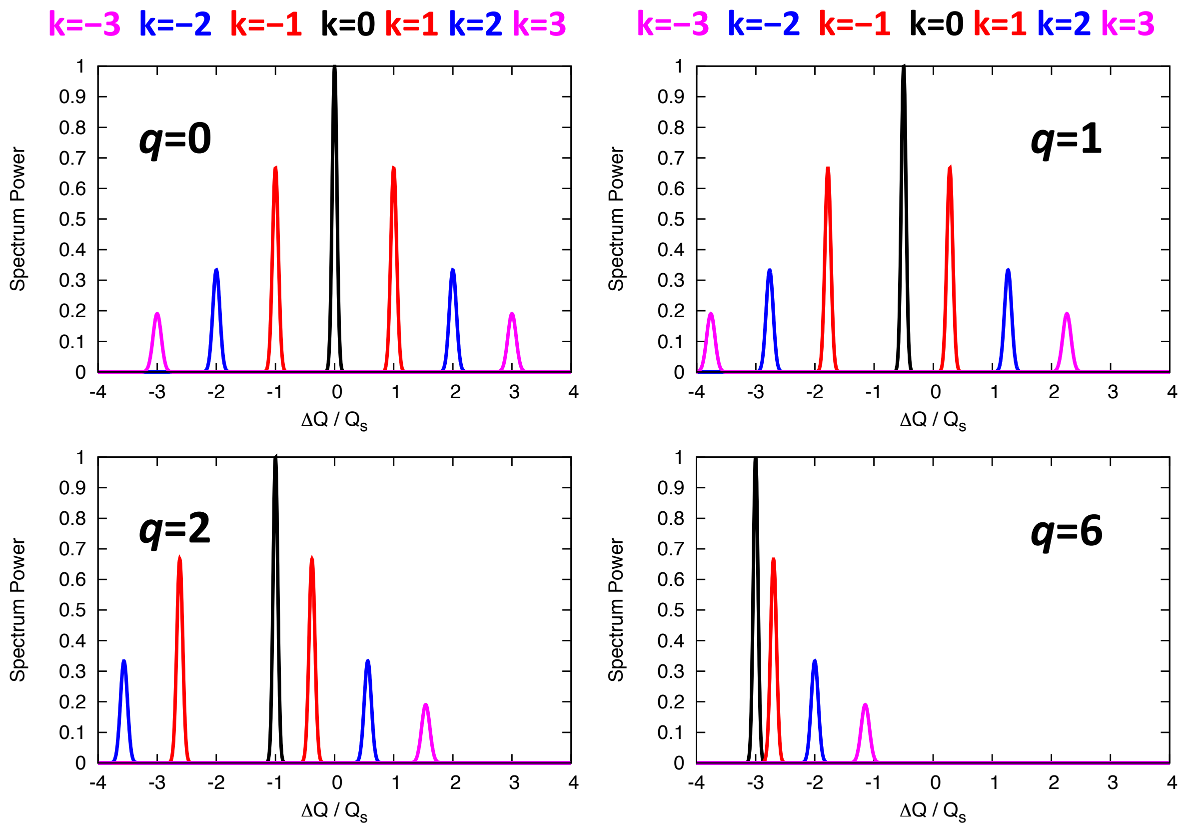
The effect of a coherent tune shift (imaginary impedance) in the airbag theory

$$\Delta Q_k = \frac{\Delta Q_{\rm sc} + \Delta Q_{\rm coh}}{2} \pm \sqrt{\frac{(\Delta Q_{\rm coh} - \Delta Q_{\rm sc})^2}{4} + k^2 Q_s^2}$$



O.Boine-Frankenheim, V.Kornilov, PRSTAB **12**, 114201 (2009)

Space Charge + Impedance in Bunches



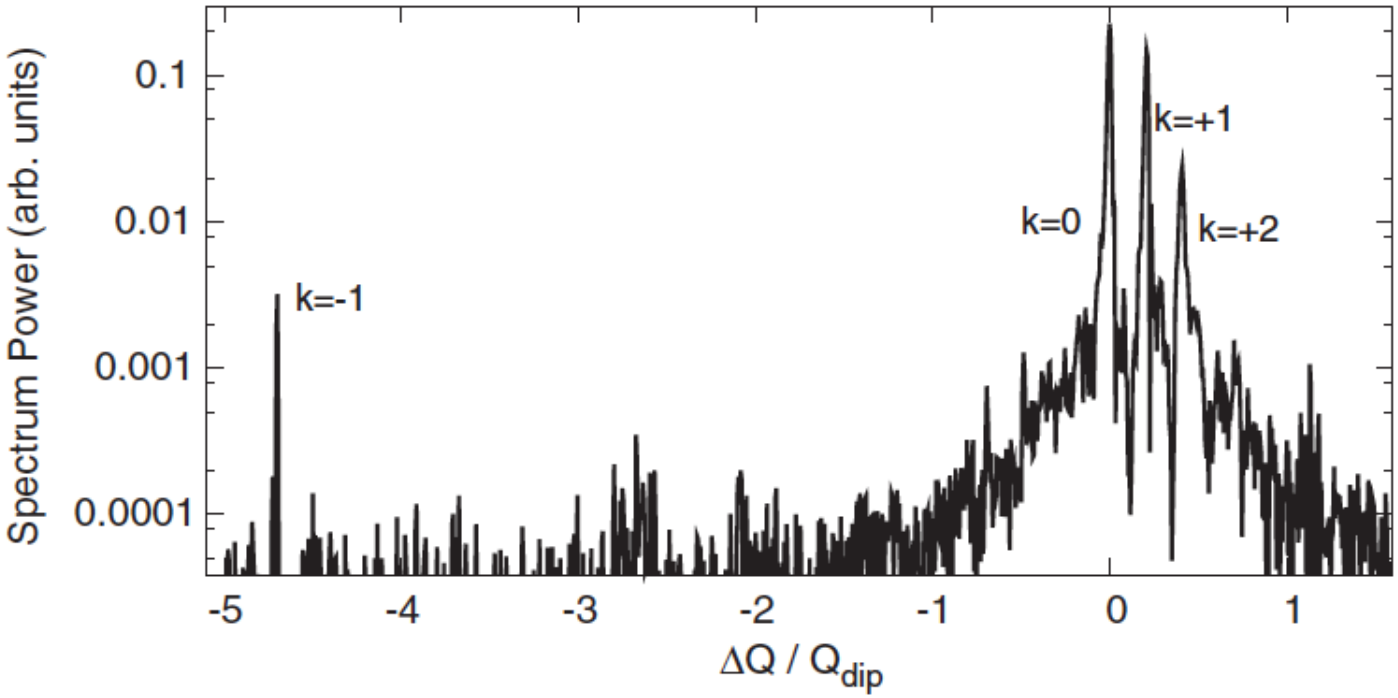
$$q = -\frac{\Delta Q_{sc}}{Q_s}$$

example here:
ΔQ_{coh} = 0.5 ΔQ_{sc}

- The k=0 line is shifted by ΔQ_{coh}
- The |k|>0 lines are shifted by both space charge and impedance
- The |k|>0 lines: it is not just everything shifted by ΔQ_{coh}

Space Charge in Bunches

The space-charge tune shifts of the lines in the bunch spectrum can also be measured



Ar^{18+} bunches in SIS18 at GSI Darmstadt, Q_s=0.0032, q=4.5
V.Kornilov, O.Boine-Frankenheim, PRSTAB 15, 114201 (2012)

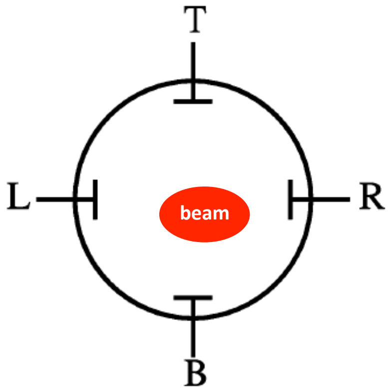
Quadrupole Pickup

Σ=L+T+R+B

Δ_h=R−L

Δ_v=T−B

κ=T+B−R−L

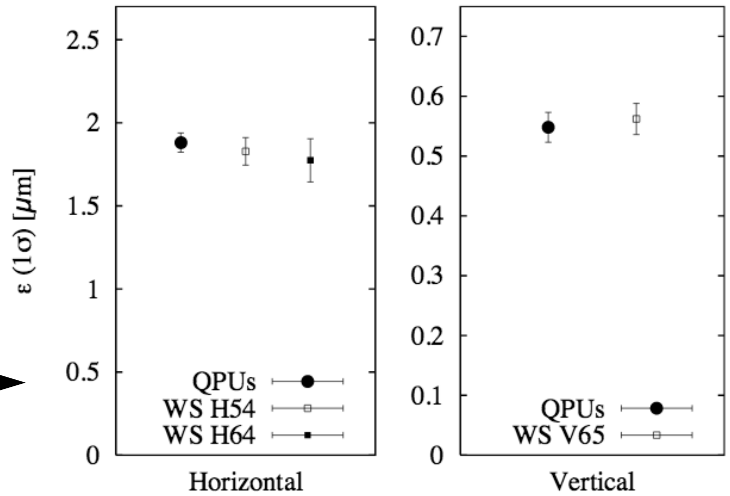


Beam Quadrupole moment:

$$\kappa = \sigma_x^2 - \sigma_y^2 + \langle x \rangle^2 - \langle y \rangle^2$$

Beam width oscillations, lines at ($m \pm 2Q_0$)

Also used to measure the transverse emittances (2 pickups needed)



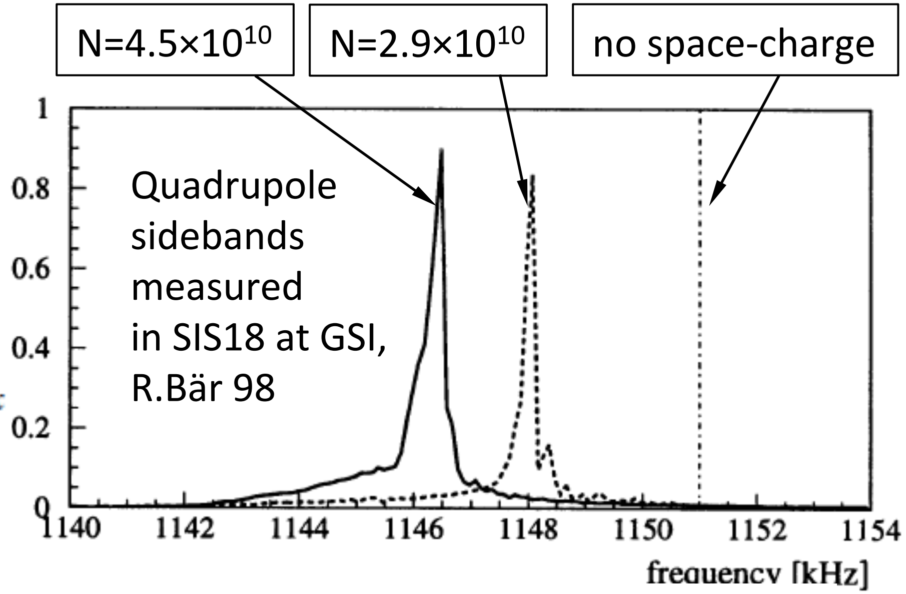
Comparison of the transverse emittance measurements using the quadrupole pickup and the wire scanner in CERN PS, A.Jansson, PRSTAB 5, 072803 (2002)

First measurements were at SLAC, R.Miller, et.al. PAC1983

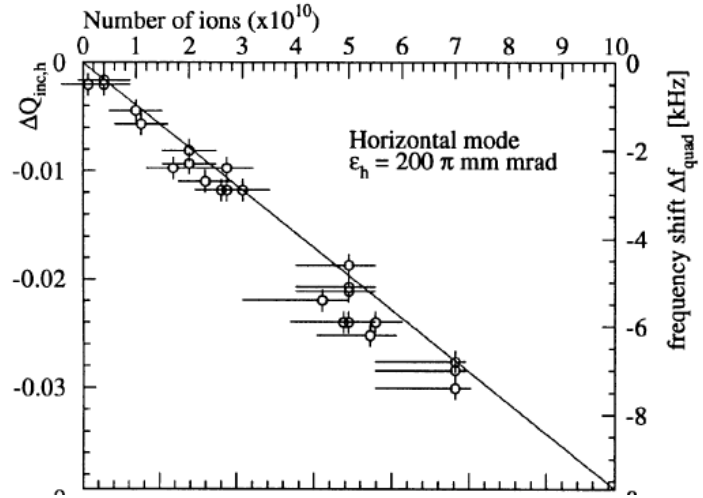
Quadrupole Pickup

Shift of the quadrupolar line due to space charge: a diagnostics which directly rely on a high-intensity effect

$$Q_{\mathrm{coh},1} - 2Q_{0,x} = -\frac{1}{2}\left(3 - \frac{a_x}{a_x + a_y}\right)\Delta Q_{\mathrm{inc},x}$$



The quadrupole sidebands are strongly Landau damped: a dedicated quadrupole exciter is needed



W.Hardt, CERN ISR/Int 300 GS/66.2 (1966)
R.Bär, et.al., NIMA 415, 460, (1998)
R.Singh, et.al., IBIC2014

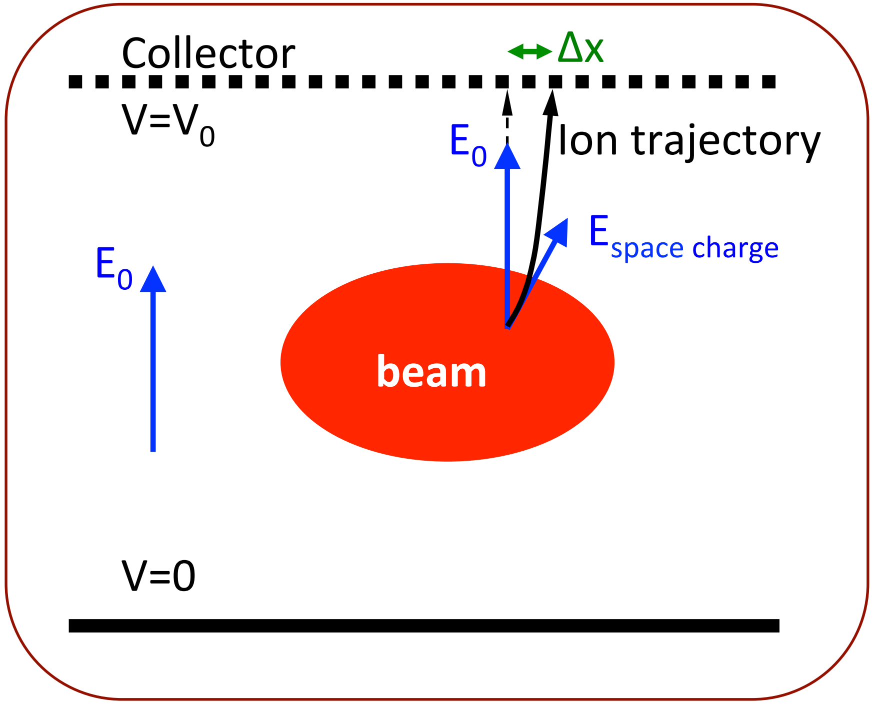
Profile Monitors

An example for a diagnostics with distorted signals due to space charge

Ionization Profile Monitor (IPM)

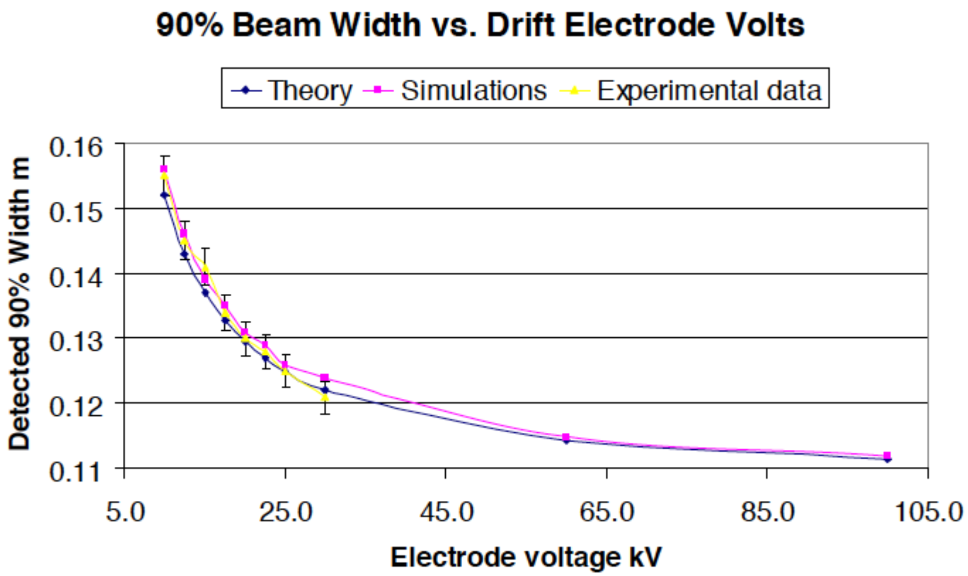
The beam ionizes the atoms of the rest gas → ions → detected on a collector.

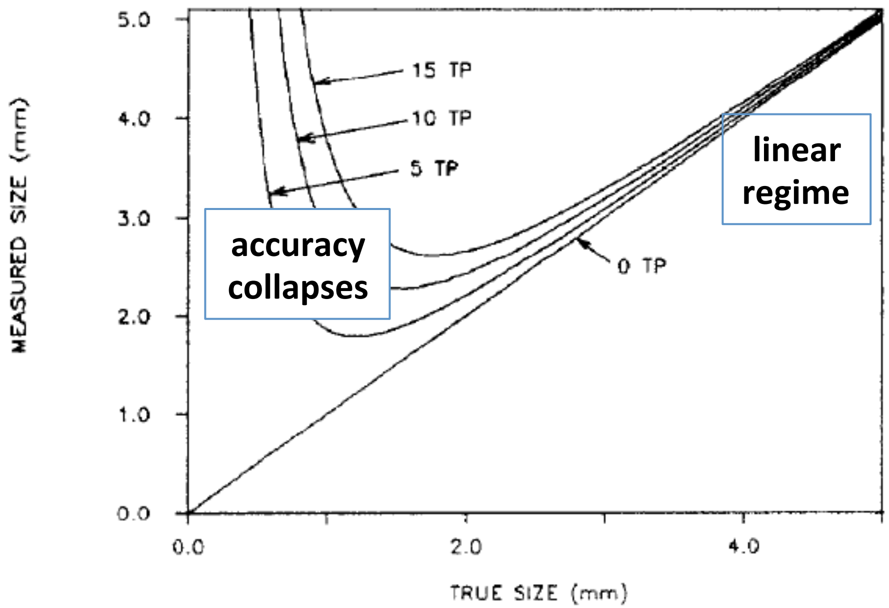
The field of beam space-charge deflects the ions and distort the resulting profiles.



Profile Monitors

Two examples for the IPM usage with beam space-charge





Effect of space-charge on IPM in ISIS at RAL, UK
B.Pine, C.Warsop, S.Payne, EPAC2006

Model for IPM measurements in AGS bunched beams. R.Thern, PAC1987

The measured/true beam size model depends on IPM design, bunch parameters, and can give accurate results

Longitudinal Phase Space

Collective effects in the longitudinal plane:
space-charge, beam loading, impedances.
Need to be taken into account for operation

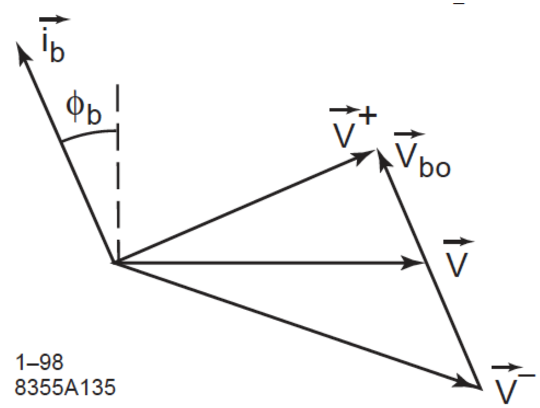
The space-charge voltage changes the bucket potential, the line density and the particle synchrotron frequency

$$V_{\mathrm{sc}}(z) \propto -N_p \frac{\partial \lambda}{\partial z}$$

Beam induced voltage adds to the generator voltage and changes the resulting cavity voltage

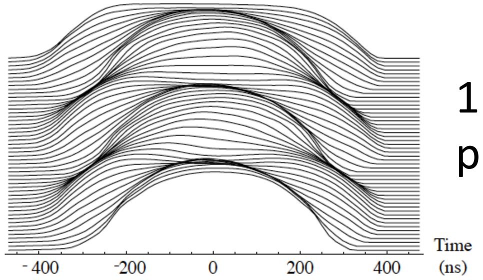
$$V_{\mathrm{b}} \propto -N_p R_s$$

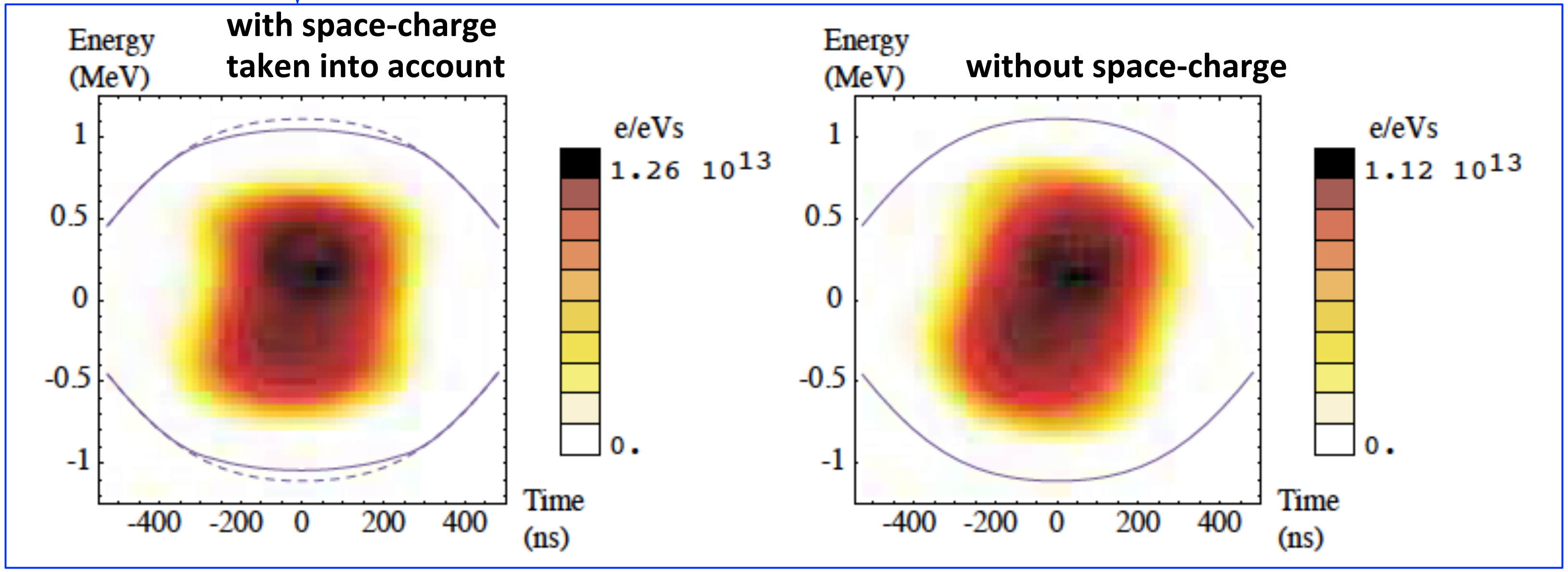
V_{b0}: Beam-induced rf voltage.
V: Net voltage seen by the bunch.
V^-: Voltage before the beam passage.
V^+: Voltage after the beam passage.



D. Boussard, Handbook of Acc. Physics and Eng., 2013, 2.4.3

Longitudinal Phase Space Tomography





Phase space reconstruction for a CERN PS Booster bunch, 6.5×10^{12} p, 100 MeV

S.Hancock, M.Lindroos, S.Koscielniak, PRSTAB 3, 124202 (2000)

Effect of space-charge must be taken into account for a correct reconstruction

Decoherence

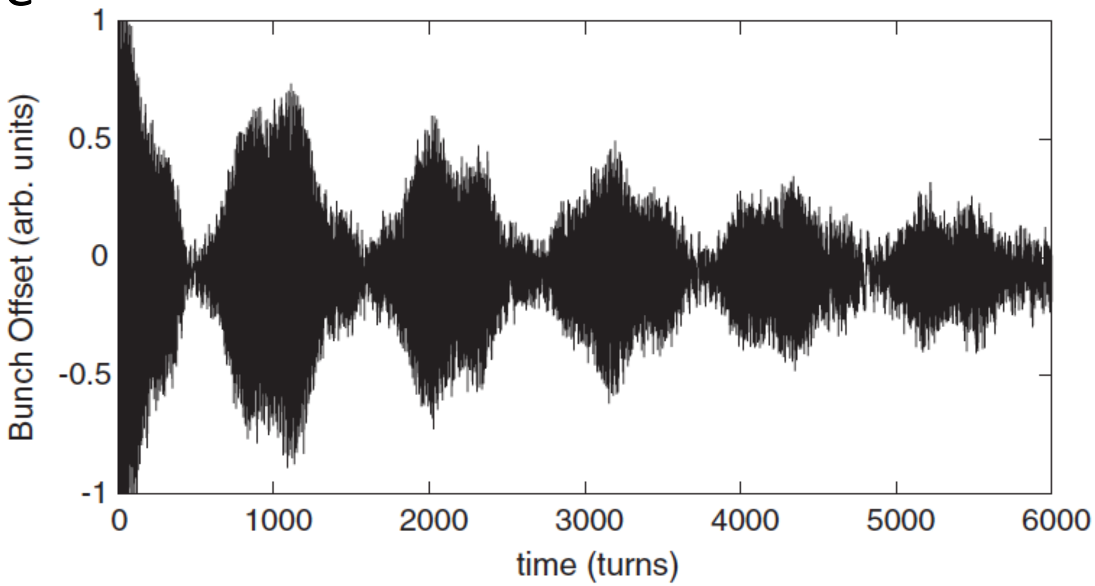
K.Y.Ng, Physics of Intensity Dependent Beam Instabilities, 2006
A.Hofmann, Proc. CAS 2003, CERN-2006-002
A.Chao, Phys. Coll. Beam Instab. in High Energy Acc. 1993
A.W. Chao, et al, SSC-N-360 (1987)

Decoherence

Collective beam oscillations after a short (one turn or shorter) kick

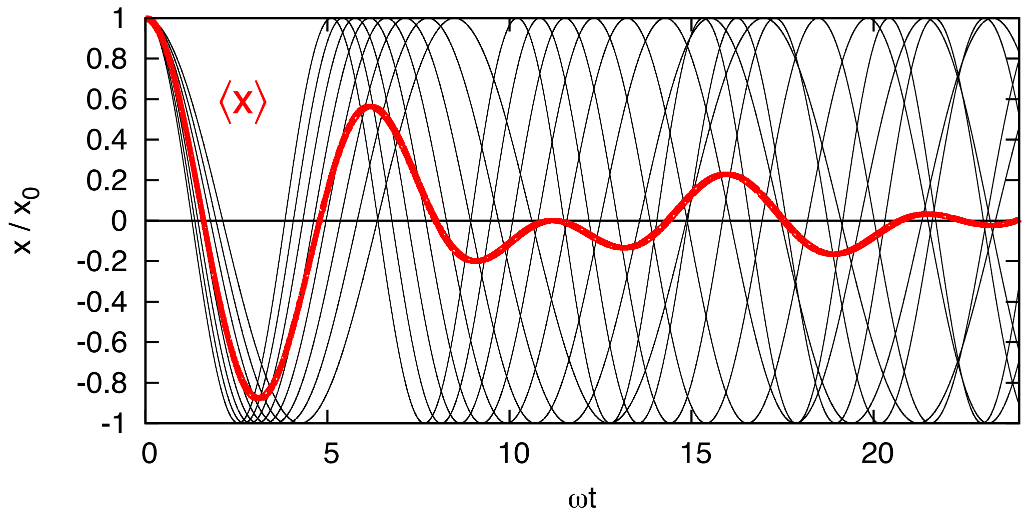
- Usually the beam displacement is comparable to the beam size
- In reality, signals can be very complicated
- A common diagnostics
- **Decoherence** is a **process** affected by many **effects**

A bunched beam Ar^{18+} in SIS18. Transverse signal after a kick



V.Kornilov, O.Boine-F., PRSTAB 15, 114201 (2012)

Pulse Response



8 particles with different frequencies

Betatron oscillations: frequency spread

$$\delta\omega = Q_0 \xi \omega_0 \delta_p$$

$$g(t) = \frac{\langle x(t) \rangle}{x_0}$$

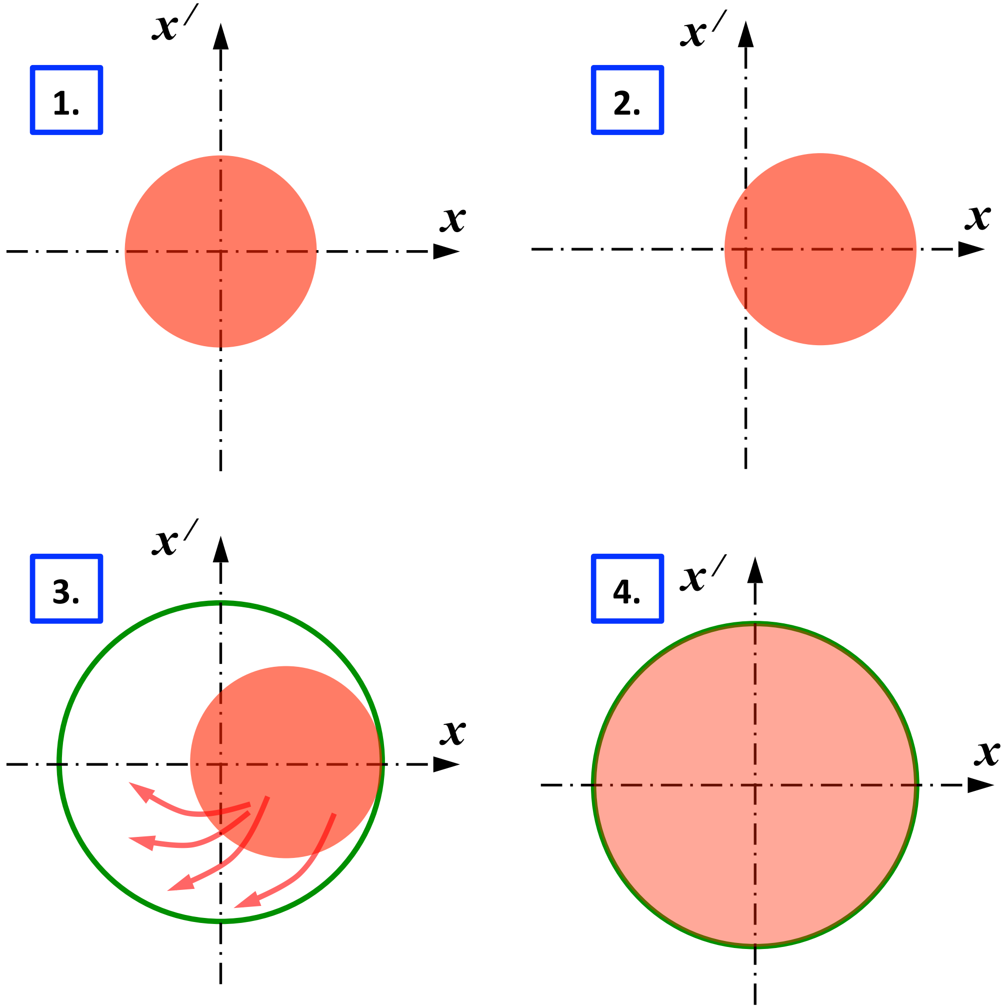
$$g(t) = \int f(\omega) \cos(\omega t) d\omega$$

$$g(t) = \text{Fourier}^{-1}\left\{R(\omega)\right\} = \frac{1}{2\pi} \int R(\omega) e^{-i\omega t} d\omega$$

The Pulse Response is the Fourier image of BTF

Phase-Mixing (Filamentation)

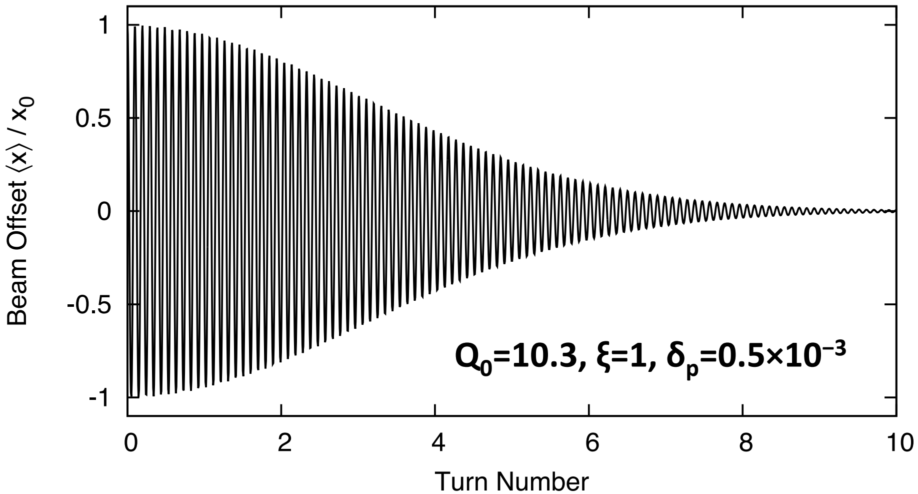
Phase-mixing of non-correlated particles with a tune spread



- Beam offset oscillations decay
- Beam size increases (blow-up)

Phase-Mixing, Coasting Beam

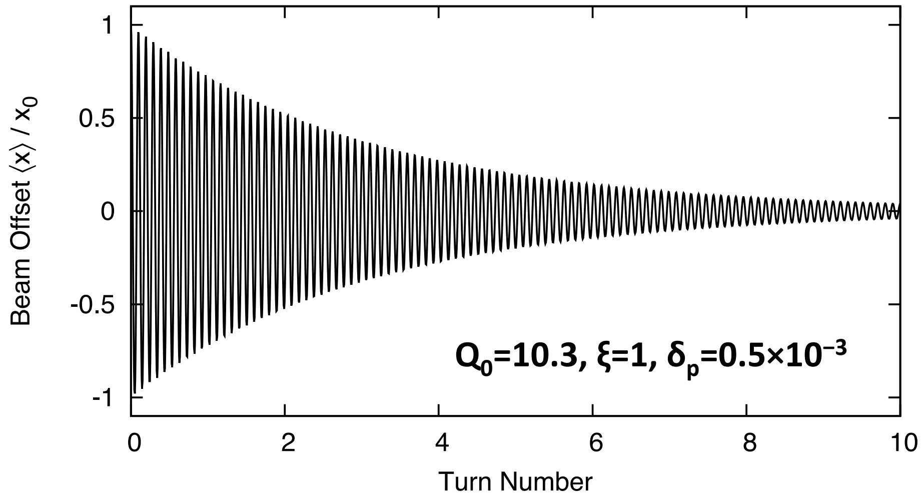
Gaussian Distribution



$$f(\omega_\beta) = \frac{1}{\sqrt{2\pi}\delta\omega^2} e^{-\omega_\beta^2/2\delta\omega^2}$$

$$g(t) = e^{-\delta\omega^2 t^2/2}\cos(\omega_\beta t)$$

Lorentz Distribution



$$f(\omega_\beta) = \frac{1}{\pi\ \delta\omega} \frac{1}{1+\omega_\beta^2/\delta\omega^2}$$

$$g(t) = e^{-\delta\omega\ t}\cos(\omega_\beta t)$$

This is the case without any collective interactions: phase-mixing of non-correlated particles

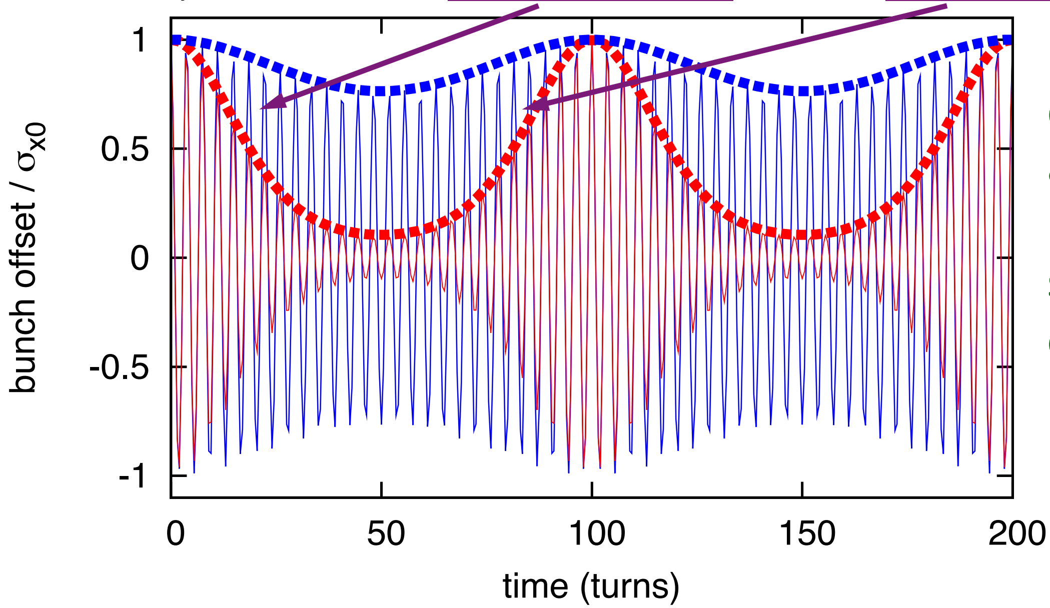
Phase-Mixing, Bunched Beam

Due to the particle synchrotron motion,
the initial positions return after a synchrotron period

$$A(N) = A_0 \exp\left\{-2\left(\frac{\xi Q_0 \delta_p}{Q_s}\sin(\pi Q_s N)\right)^2\right\}$$

In literature, named as "**decoherence**" and "**recoherence**"

ξ=0.5
ξ=1.4
N_s=100
Q_s=0.01



dashed lines: amplitude

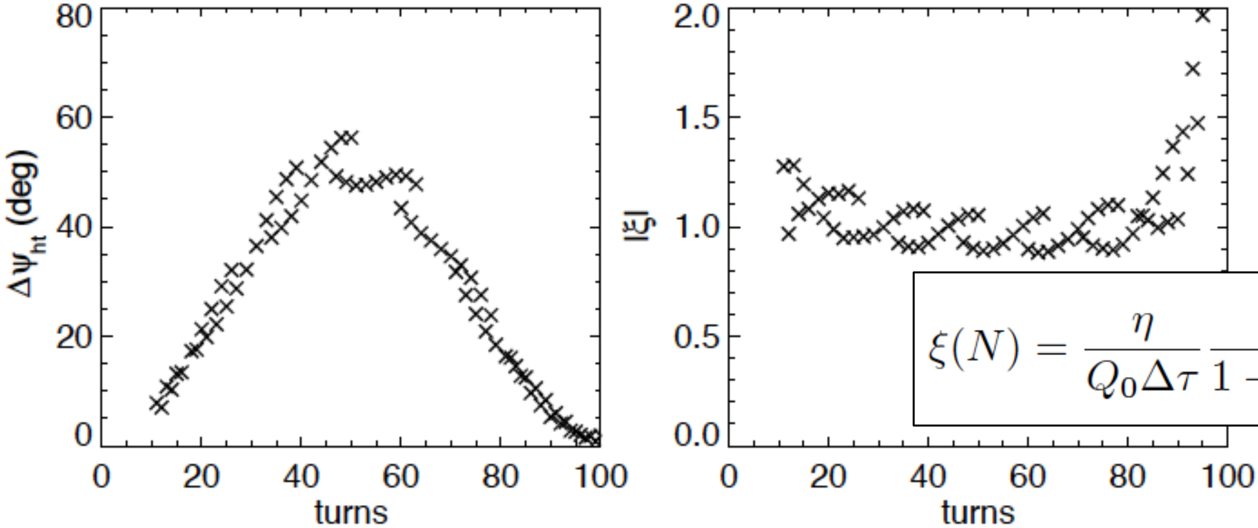
solid lines: offset

In reality, the decoherence is very different (other effects)

Phase-Mixing, Bunched Beam

From the decoherence signals can be extracted:
betatron tunes, synchrotron tune, momentum spread, chromaticity

D.Cocq, O.Jones, H.Schmickler, Proc. BIW98
V.Kornilov, O.Boine-Frankenheim, Proc. HB2010, paper MOPD21



$$\xi(N) = \frac{\eta}{Q_0 \Delta\tau} \frac{\Delta\psi_{\mathrm{ht}}(N)}{1 - \cos(2\pi N Q_{\mathrm{s}})}$$

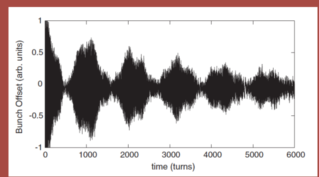
This is ideal case: in reality, the decoherence is often different (other effects), ξ determination is not possible

Decoherence

Landau Damping

Phase-mixing

Decoherence



Chromaticity

Octupoles

Space-charge

Image charges

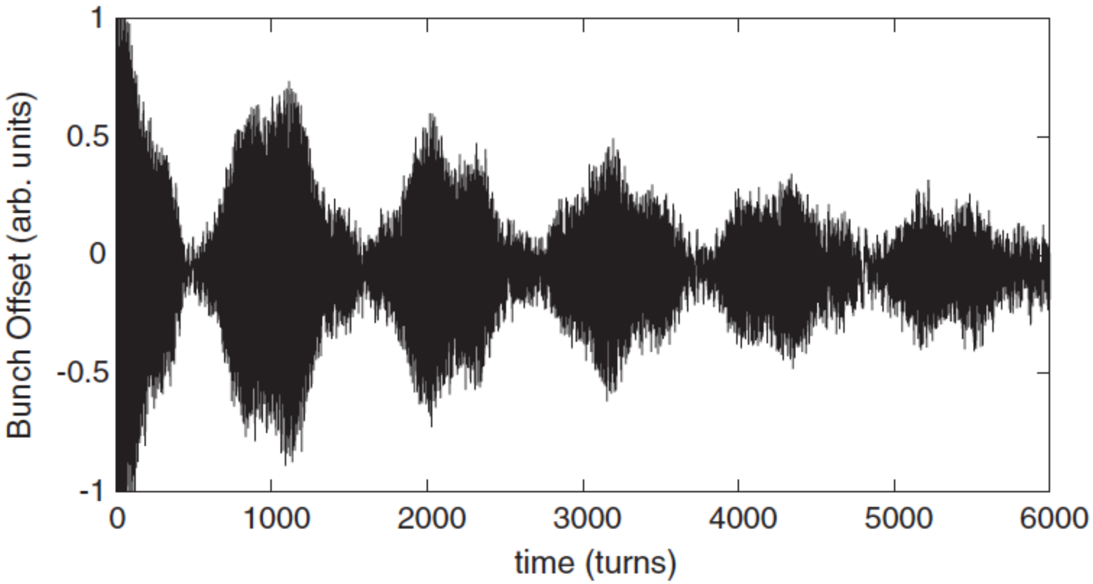
Impedances

Other nonlinearities

After a kick, we observe the decoherence, which is a mixture of effects.

Decoherence

Measurements and analysis of the decoherence provides knowledge about the machine and beam conditions



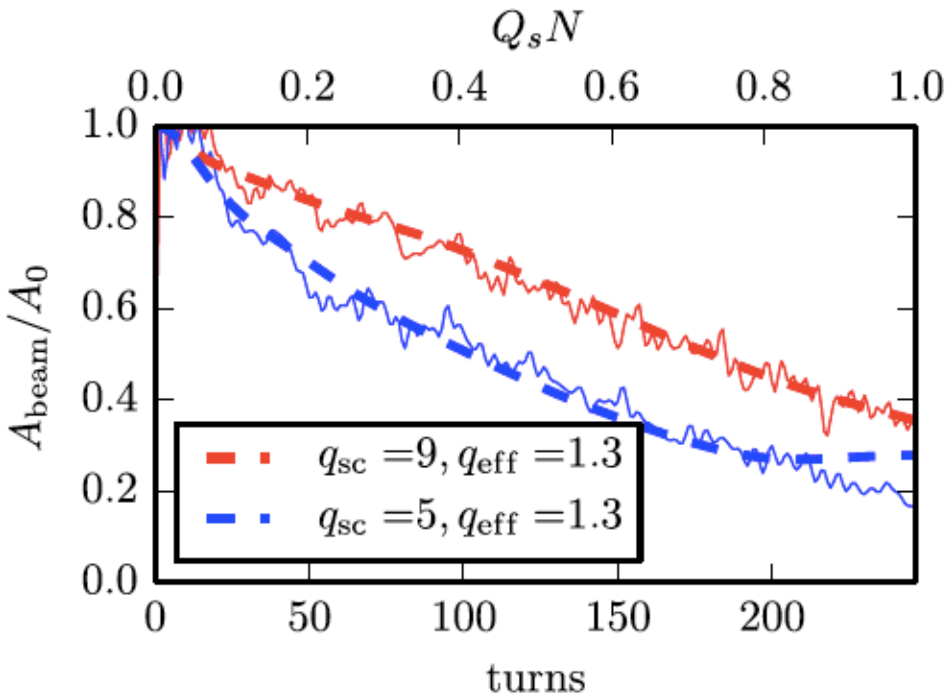
Measurements

V.Kornilov, O.Boine-F., PRSTAB 15, 114201 (2012)

SIS18, GSI, long-time decoherence:
mix of head-tail modes and Landau damping

Decoherence

Measurements and analysis of the decoherence provides knowledge about the machine and beam conditions



Measurements (fill lines)
Simulations (dashed line)

I.Karpov, et al, PRAB 19, 124201 (2016)

SIS18, GSI, short-time decoherence: dominated by space charge and ξ

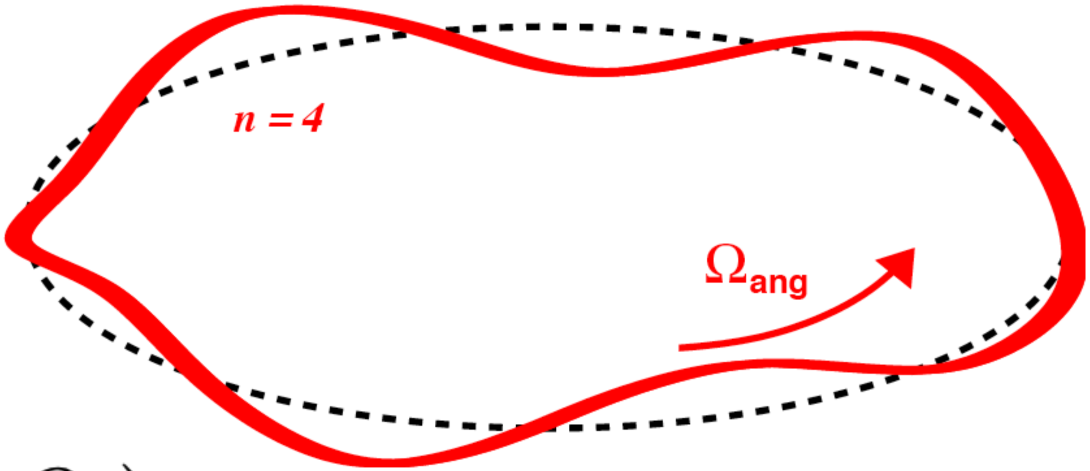
Instabilities

Handbook of Acc. Physics and Eng., 2013, Subject Index: Collective Instabilities
K.Y.Ng, Physics of Intensity Dependent Beam Instabilities, 2006
A.Chao, Phys. Coll. Beam Instab. in High Energy Acc. 1993
E. Metral, et.al., Beam Instabilities in Hadron Synchrotrons, IEEE Trans. Nucl. Sci., 63, 1001 (2016)

Coasting Beam Instability

Transverse oscillations in a coasting beam

$$x(s,t) = x_0 e^{ins/R - i\Omega t}$$



n is the mode index.

Wave length: *C/n*

Frequencies:

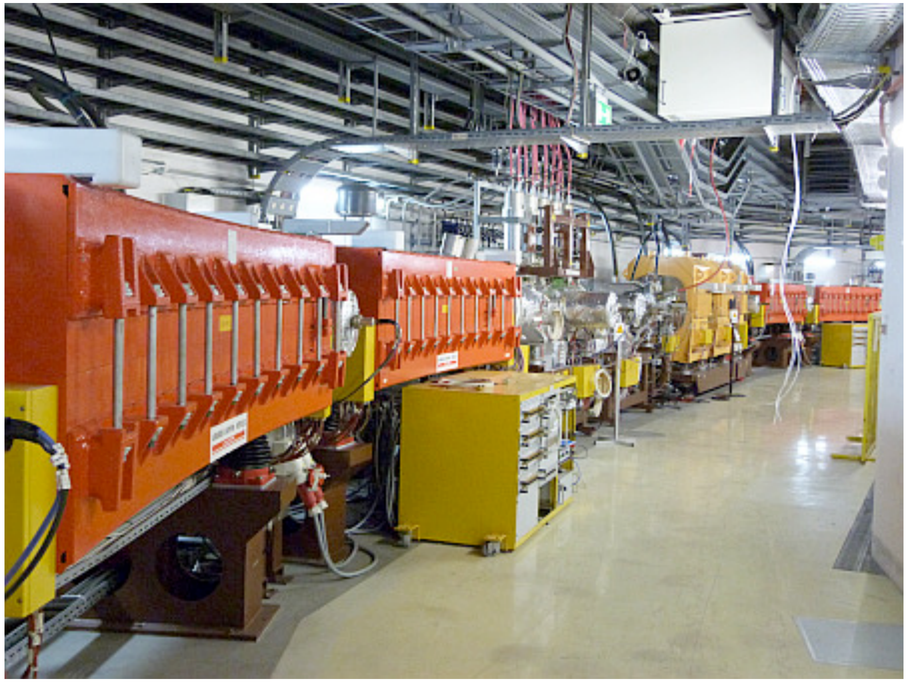
$$\begin{aligned} \text{slow wave} \quad \Omega_s &= (n - Q_\beta)\omega_0 \\ \text{fast wave} \quad \Omega_f &= (n + Q_\beta)\omega_0 \end{aligned}$$

Angular rotation (Ω_s):

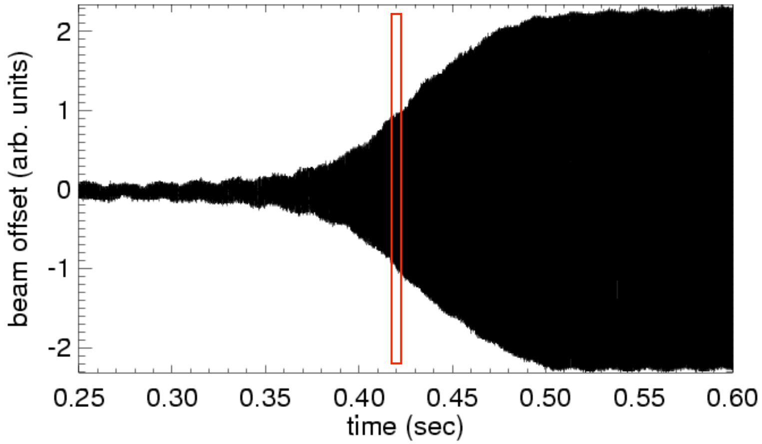
$$\Omega_{\text{ang}} = \left(1 - \frac{Q_\beta}{n}\right)\omega_0$$

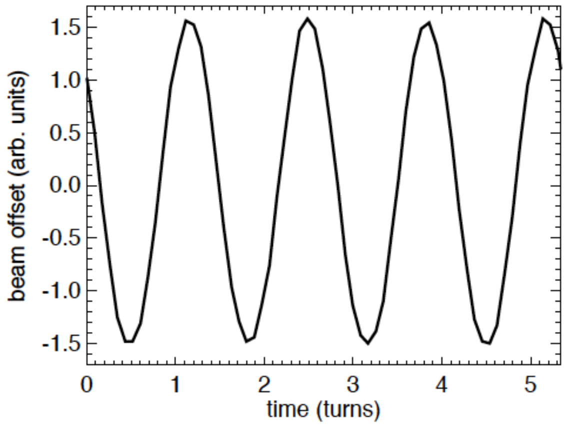
Coasting Beam Instability

Experimental observations of the coasting-beam waves



SIS18 synchrotron at GSI Darmstadt





V. Kornilov, O. Boine-Frankenheim,
GSI-Acc-Note-2009-008, GSI Darmstadt (2009)

n=4 unstable mode, Chromaticity control, measured the impedance

Head-Tail Modes

Bunch transverse eigenmodes:
head-tail modes

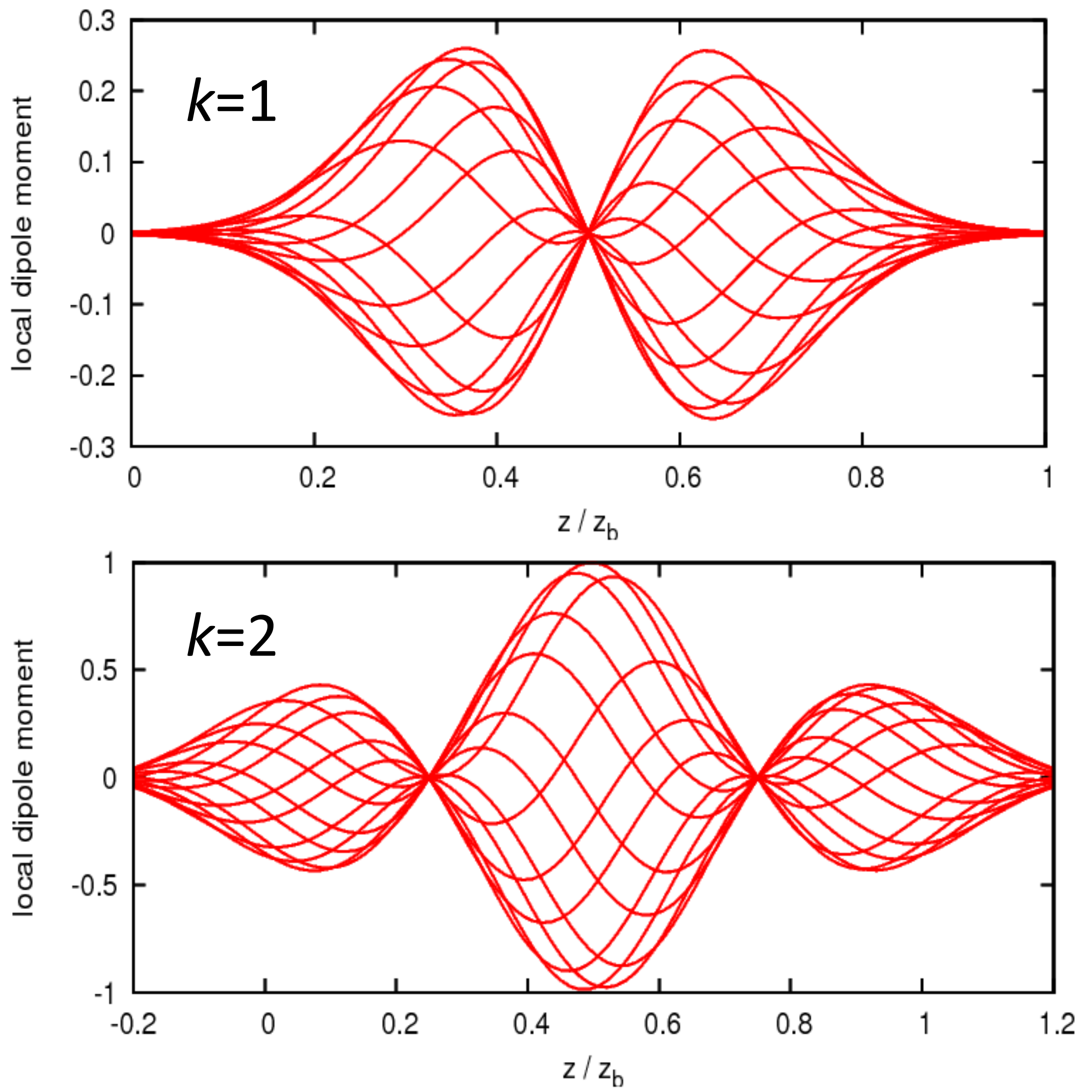
the mode index *k* = number of nodes;
wiggles inside: due to the chromaticity

if unstable:

- no threshold
- exponential growth $e^{t/\tau}$

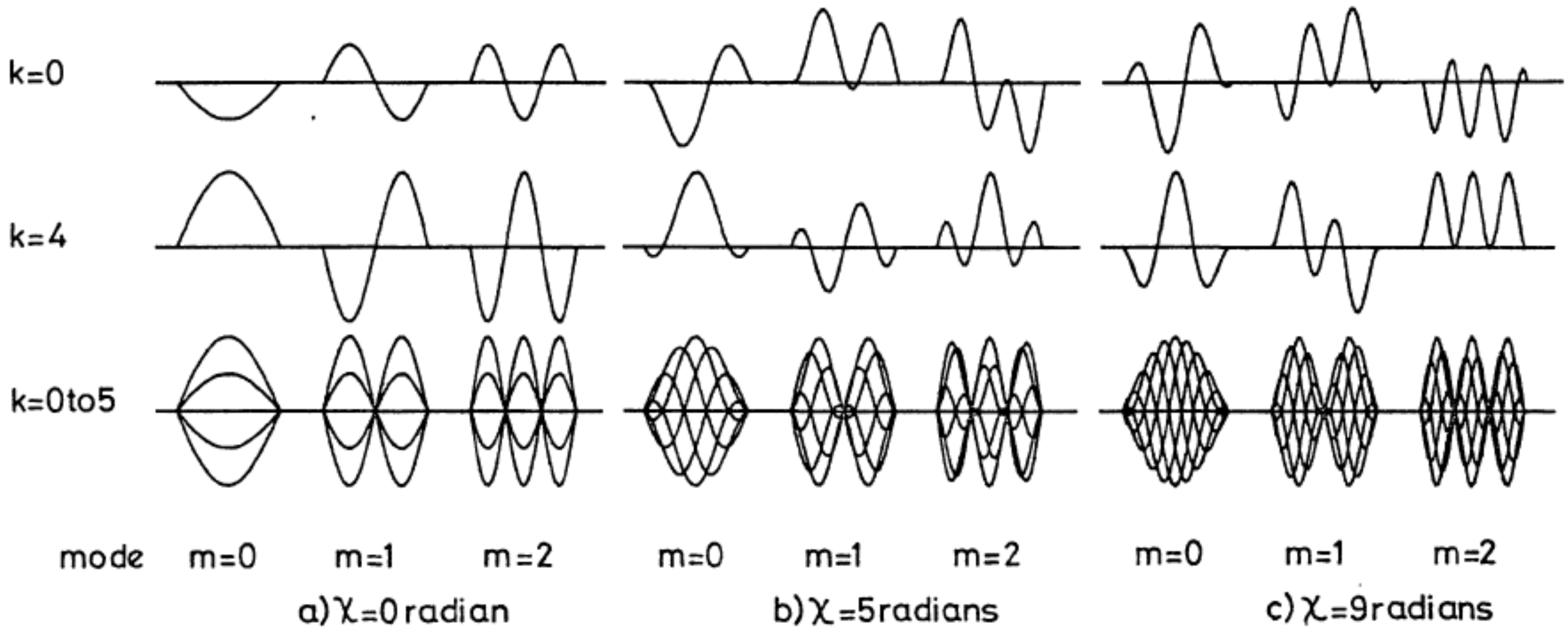
Useful as a tool:

- identify the ring impedances
- learn a lot about transverse dynamics in your machine



Head-Tail Modes

A theory: F. Sacherer 1974, CERN



$$\Delta\text{-signal} \propto p_m(t)e^{j\omega_\xi t + j2\pi kQ}$$

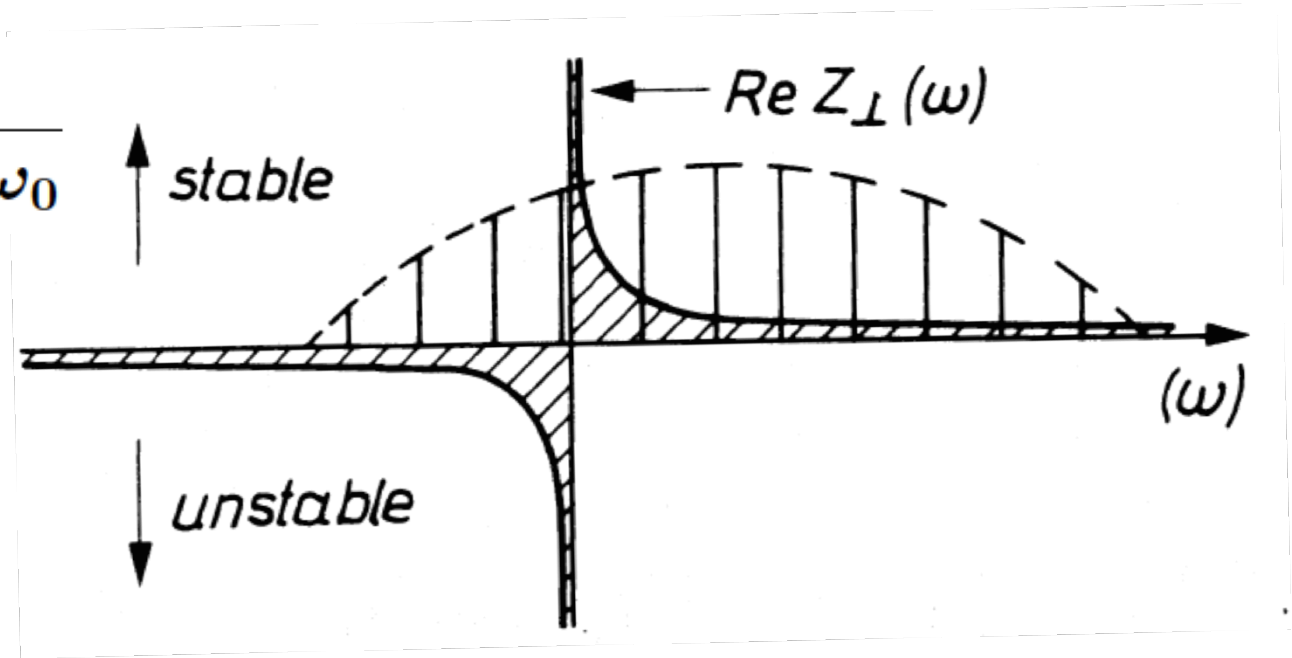
Head-Tail Modes

F. Sacherer 1974

$$\Delta Q_k = \frac{\Upsilon}{1+k} \frac{\sum(-i)Z_\perp(\omega_p)h_k(\omega_p - \omega_\xi)}{\sum h_k(\omega_p - \omega_\xi)}$$

$$\omega_p = (p + Q_0)\omega_0 + k\omega_s$$

$$\Upsilon = \frac{I_0 q_{\mathrm{ion}}}{4\pi\gamma m c Q_0 \omega_0}$$



Head-Tail Modes

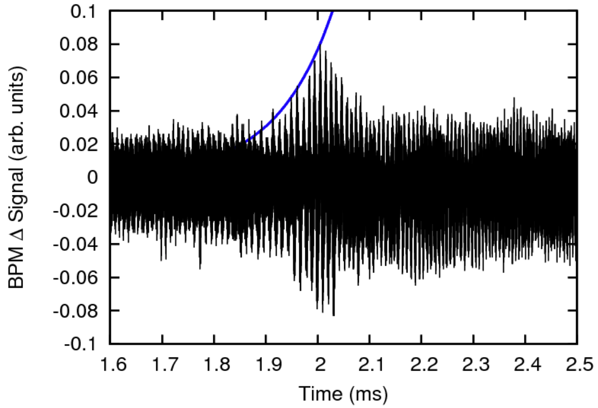
Instability observations in the ISIS synchrotron (RAL, UK)

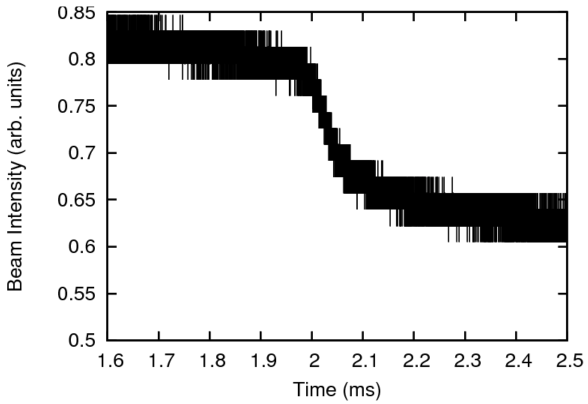
Q_v above 3.86:
Strong vertical oscillations and Losses

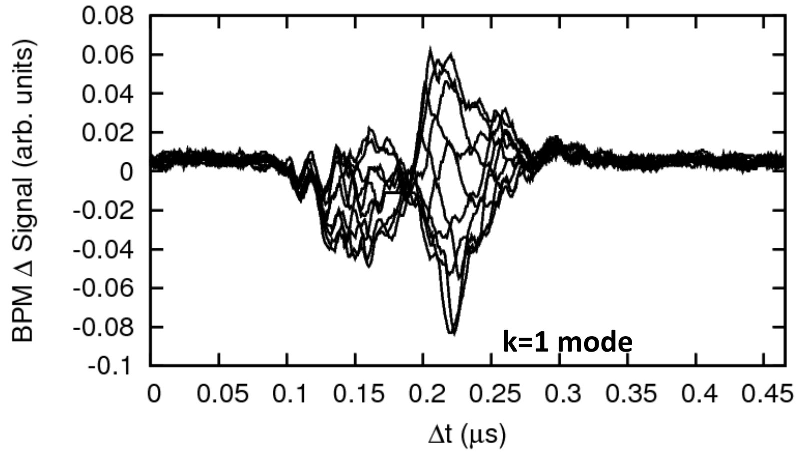
N_{beam}=8.2e12

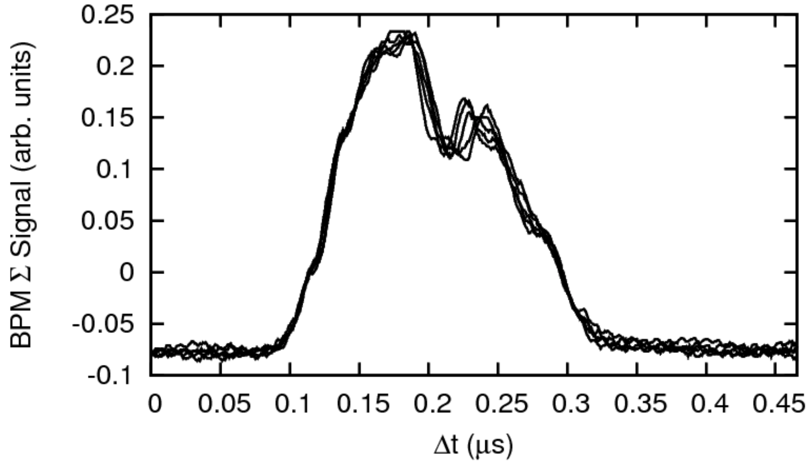
growth time τ=0.1ms

V.Kornilov, et al, HB2014









Head-Tail Modes

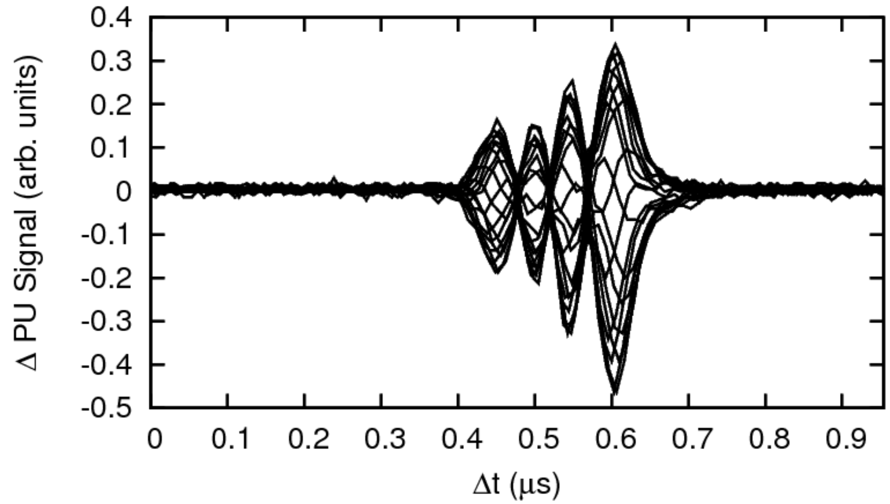
Instability observations in the PSB, CERN

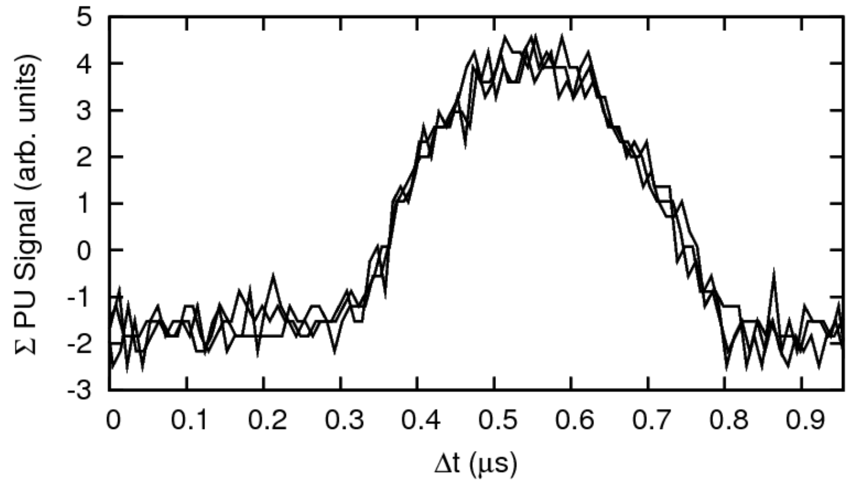
Once the transverse feedback system is switched off: strong transverse oscillations and losses.

Instability growth time τ=0.5 ms

Operation in 2rf−1rf modes, emittance issues.

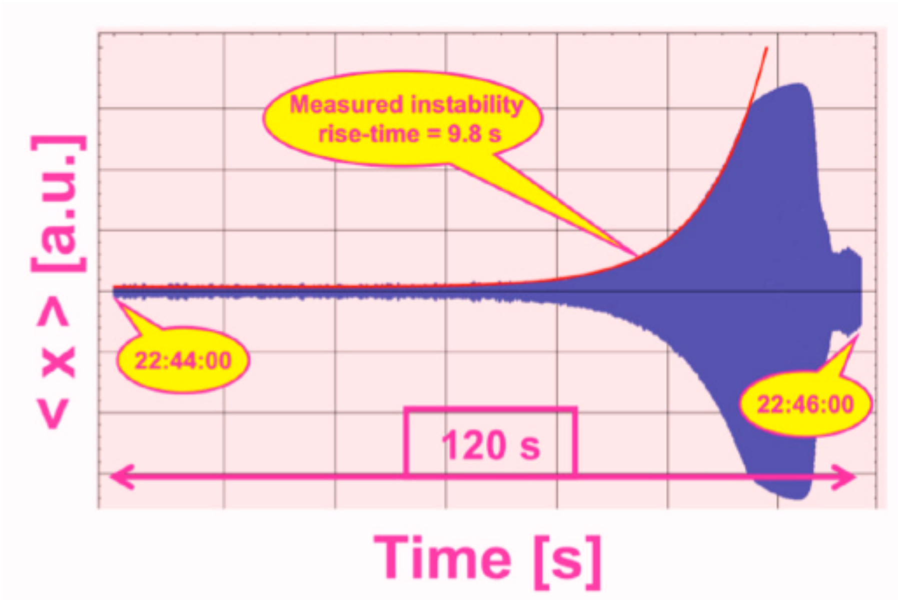
V. Kornilov, et al, CERN-ATS-Note-2013-038 MD, (2013)





Instabilities

Instability observations in the LHC, CERN



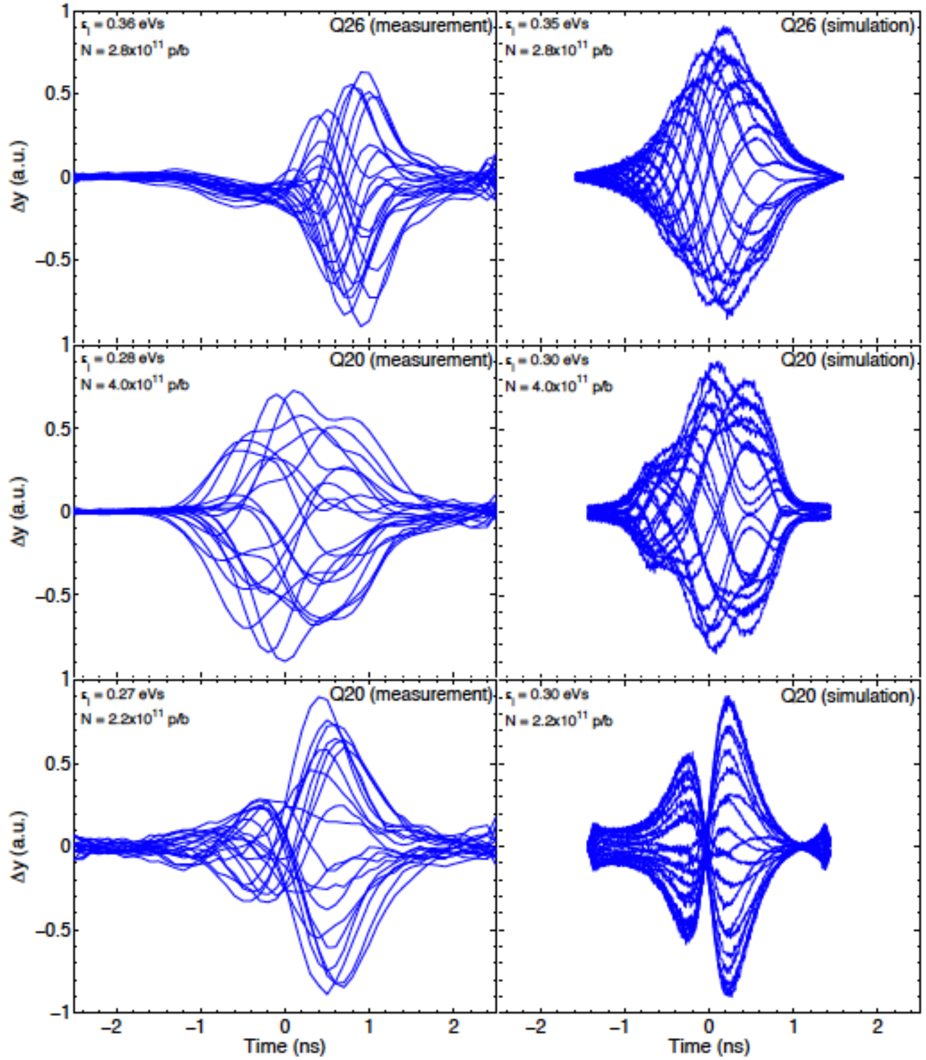
E.Metral, et. al., IPAC2011
E.Metral, et. al., HB2016

Operation improvements: octupole–damper–chromaticity configuration, the roles of coupling, e-cloud

Instabilities

Vertical signals from the SPS Head-Tail monitor (left) in comparison with the simulations (right): Transverse Mode Coupling Instability (TMCI)

→ Optimization of the SPS lattice: from Q26 to Q20. Advances for the LIU.

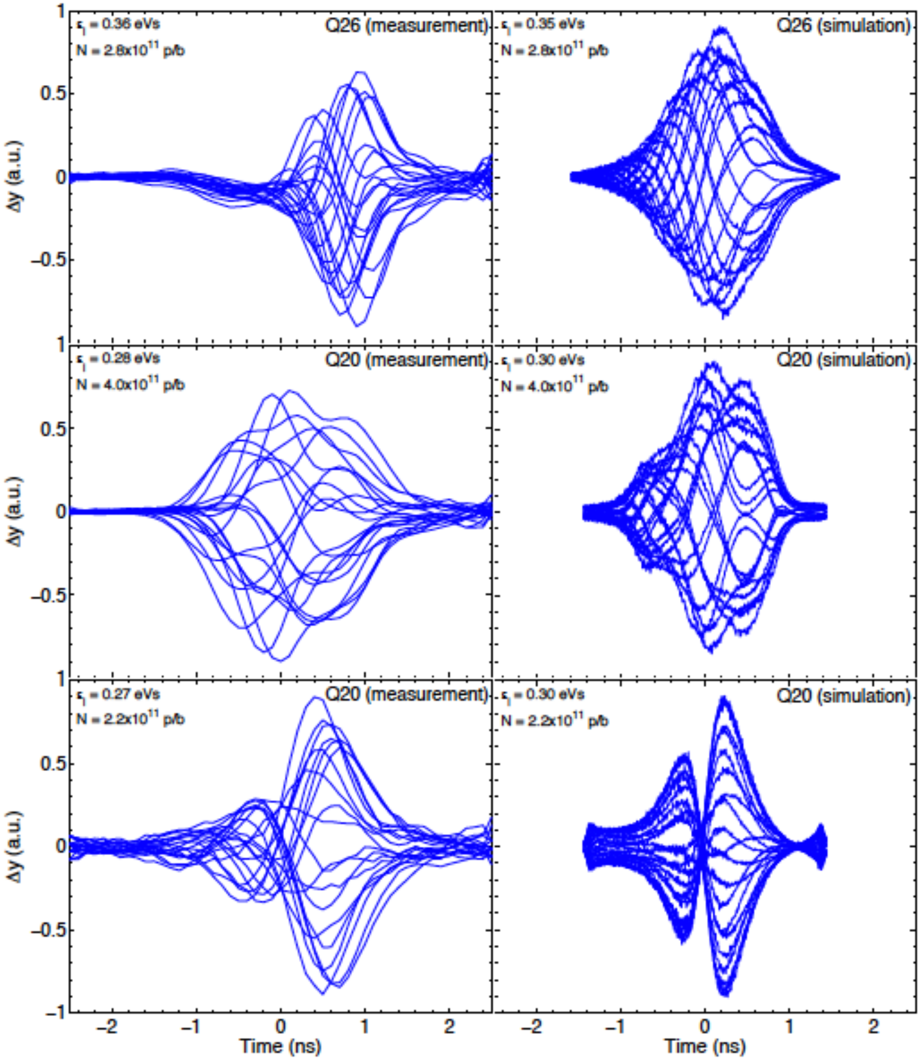


H. Bartosik et al, IPAC2014

Instabilities

Generally, observing & analyzing the instabilities is a powerful instrument for understanding and improving the accelerator operation.

(see proc. of every IPAC, HB, …)



H. Bartosik et al, IPAC2014