BEAM STUDIES IN THE PS BOOSTER: HEAD-TAIL INSTABILITY

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Machine operation:

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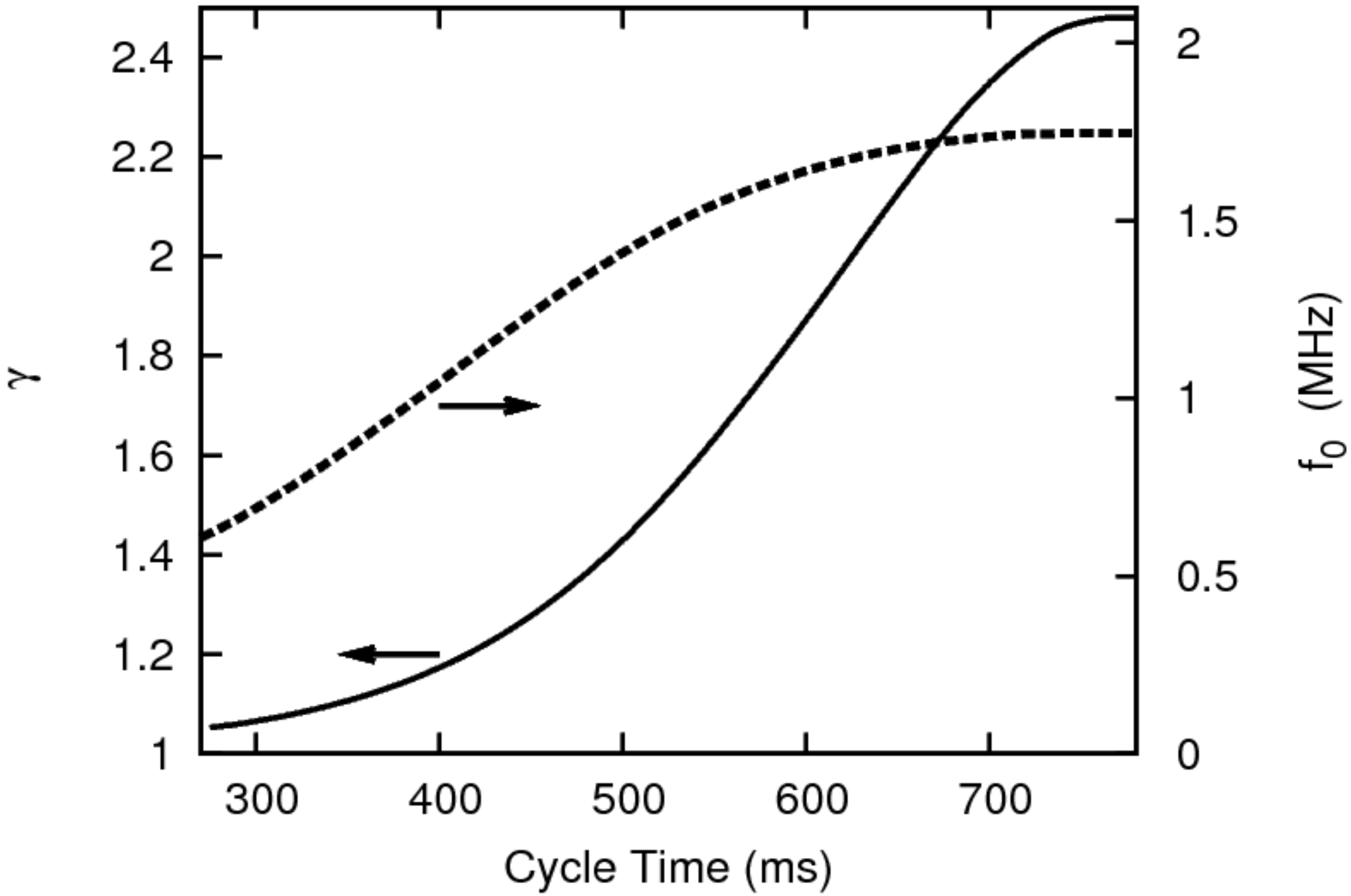
PS BOOSTER CYCLE

R=25m

Kin. energy
50 MeV
1.4 GeV

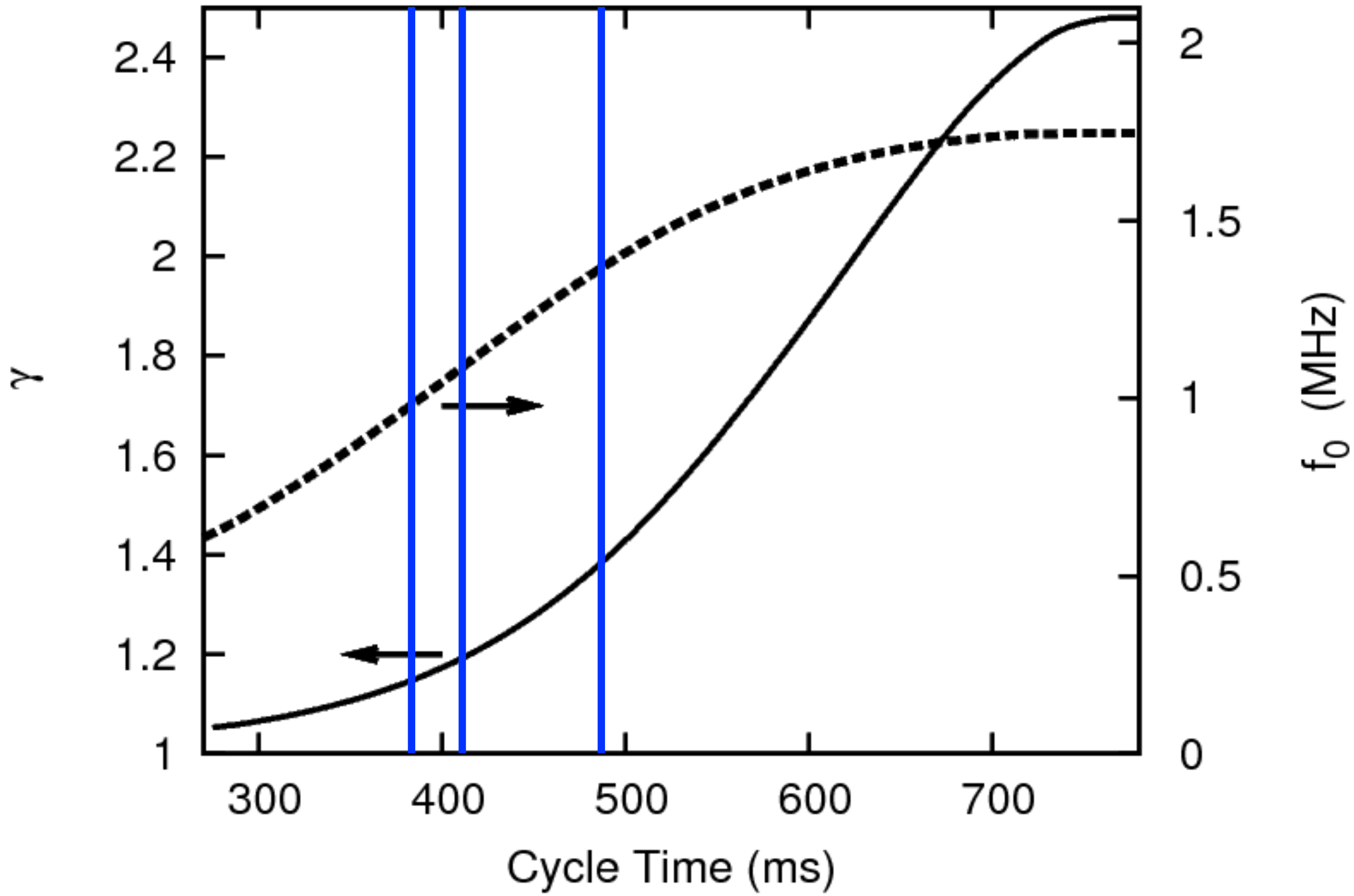
Betatron tunes
Q_h=4.27-4.17
Q_v=4.65-4.20

ξ_h=-0.95 ξ_v=-2.1



PS BOOSTER CYCLE

once the transverse feedback system is switched off: strong transverse oscillations and losses (within ms)



INSTABILITY: AN EXAMPLE

The instability:

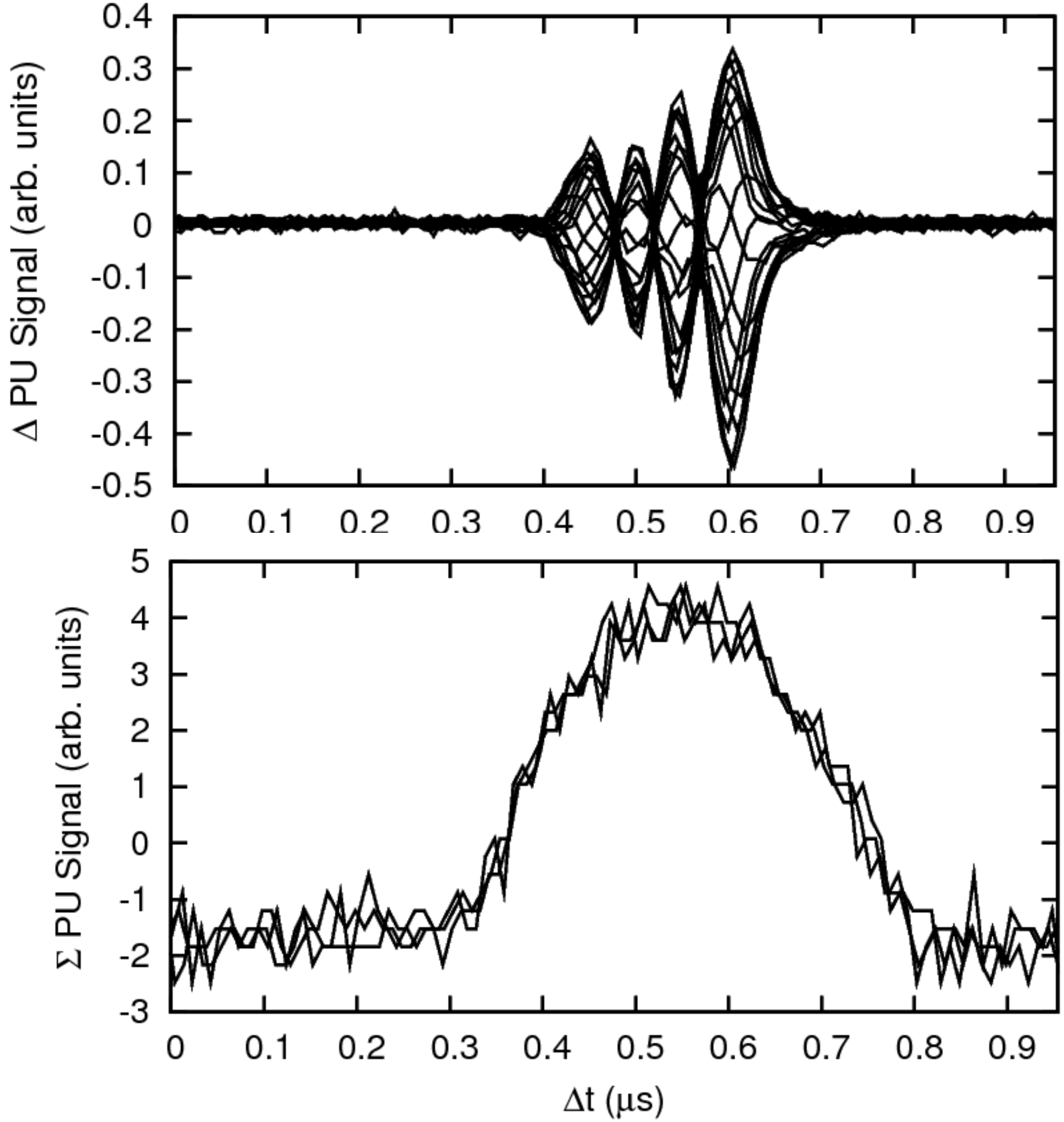
a standing-wave structure with the ξ-wiggles within; here 3 knots, i.e. k=3 mode (rarely that nice)

nice exponential growth

slower then the synchrotron motion, $\Delta Q/Q_s<0.3$

↓

an unstable head-tail mode

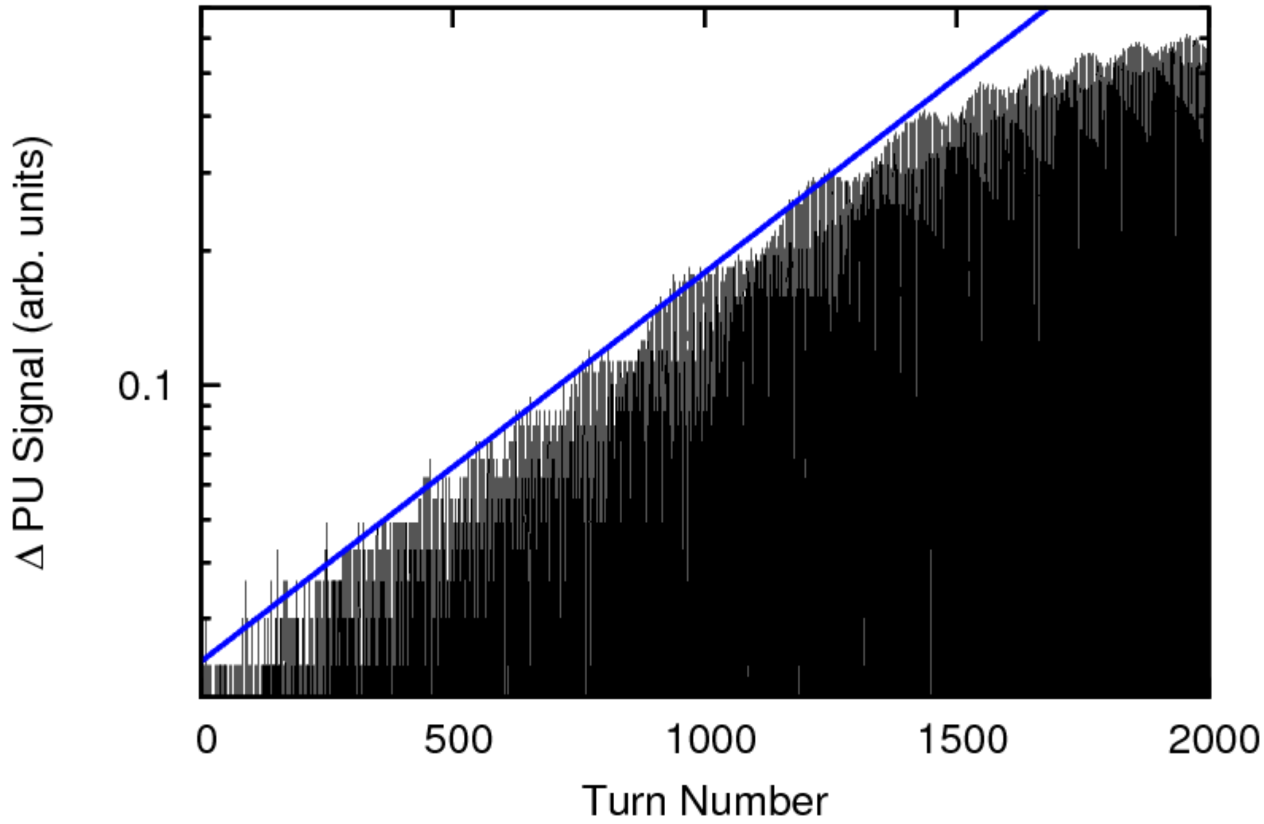


INSTABILITY: AN EXAMPLE

an example for the exponential growth

The instability at C392ms:
ΔQ=3.1e-4,
τ=0.53ms,
$\Delta Q/Q_s$=0.16

a general assumption so far has been:
driven by the Resistive-Wall Impedance

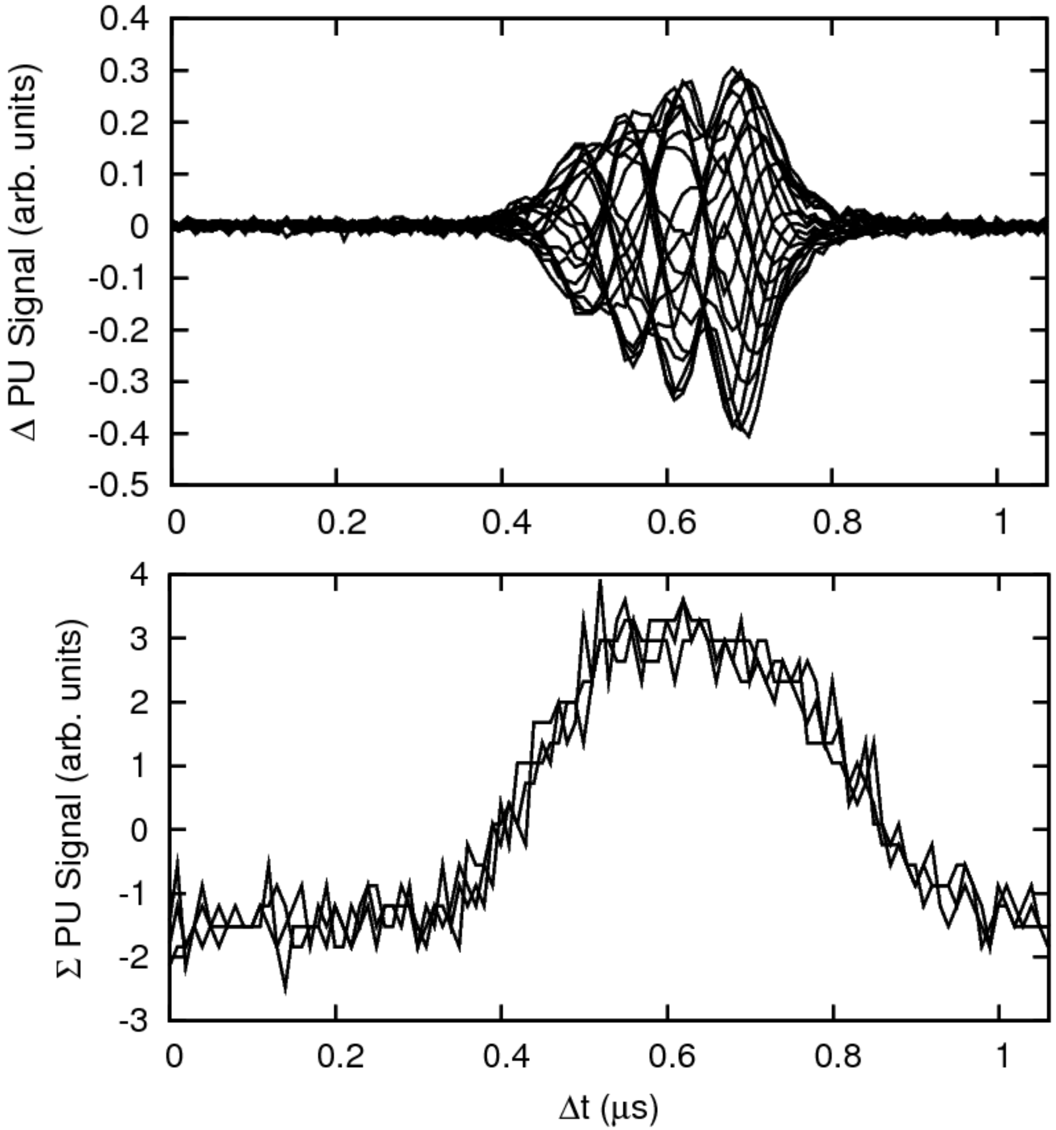


EXAMPLE OF THE INSTABILITY

Instability at C386ms
single rf

N_p=370e10
ΔQ=2.3e-4,
$\Delta Q/Q_s$=0.13

the mode k=3
the mode structure is not an ideal head-tail, it is modified by the impedance

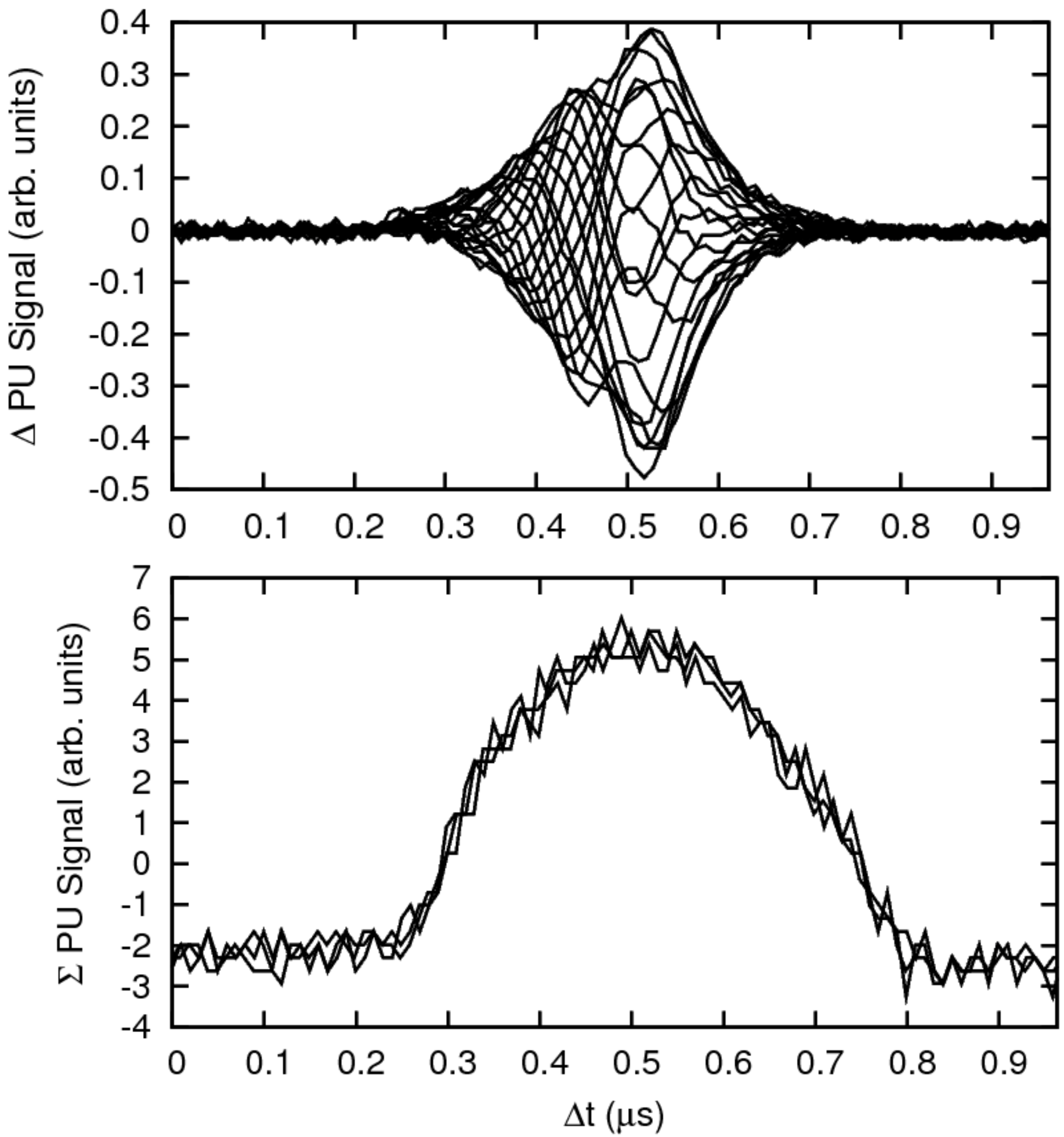


EXAMPLE OF THE INSTABILITY

Instability at C386ms
single rf,
higher intensity

N_p=600e10
ΔQ=4.4e-4,
$\Delta Q/Q_s$=0.24

the mode structure
is stronger deformed
by the driving impedance

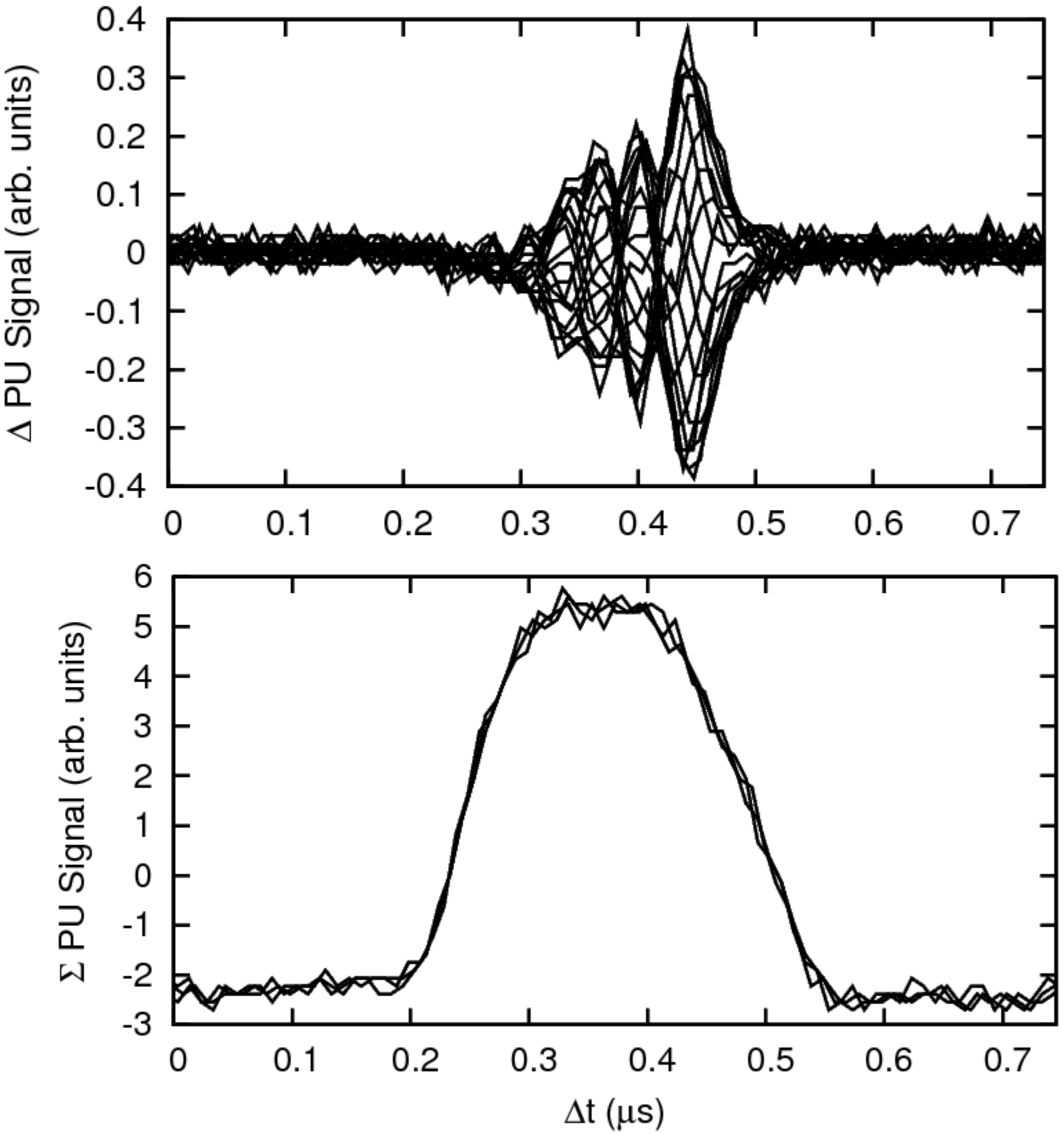


EXAMPLE OF THE INSTABILITY

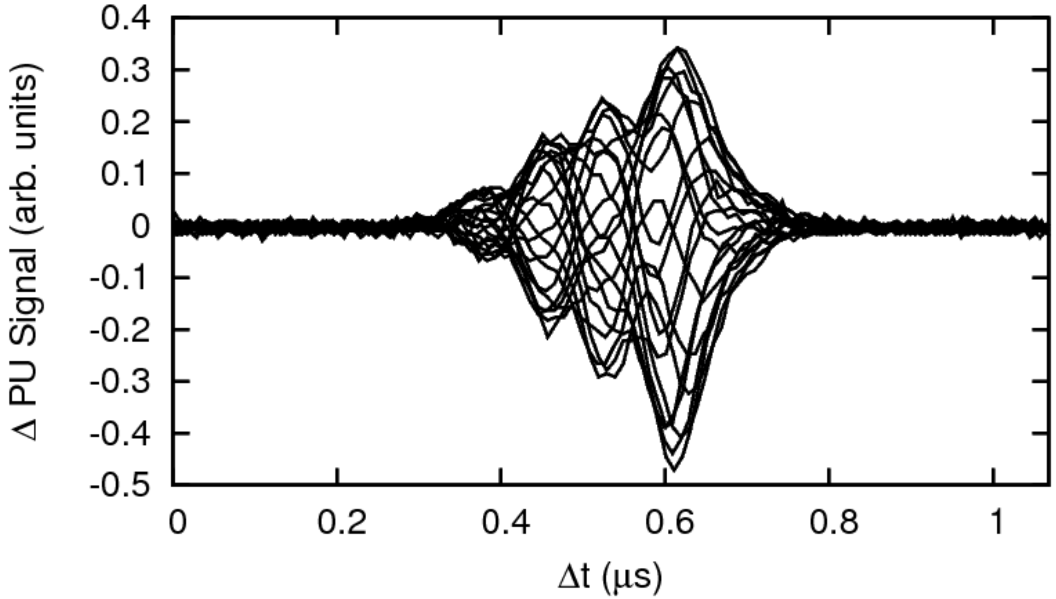
Instability at C491ms
single rf

N_p=380e10
ΔQ=0.6e-4,
$\Delta Q/Q_s$=0.064

the mode k=4?
higher mode index
for later CTimes



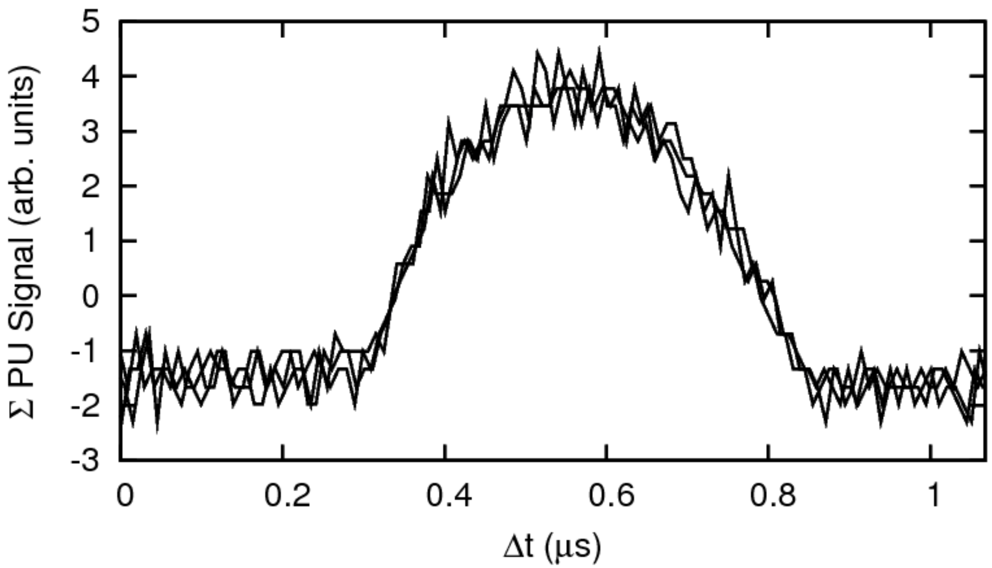
EXAMPLE OF THE INSTABILITY



Instability at C383ms
single rf,
large transverse emittance

N_p=400e10

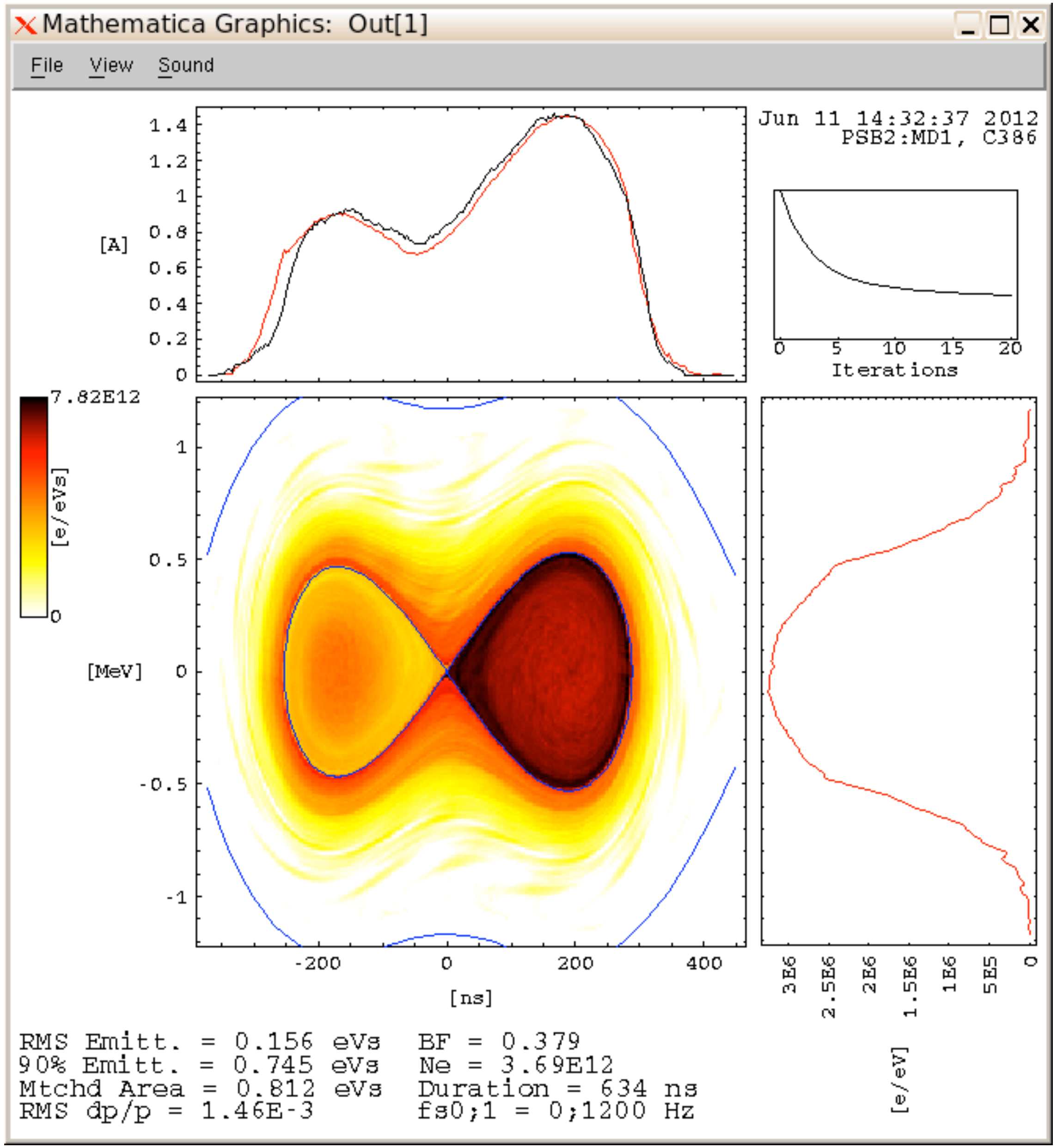
the mode k=3
no clear effect of weaker space charge



RF BUCKET: DOUBLE RF

double rf, standard at PSB

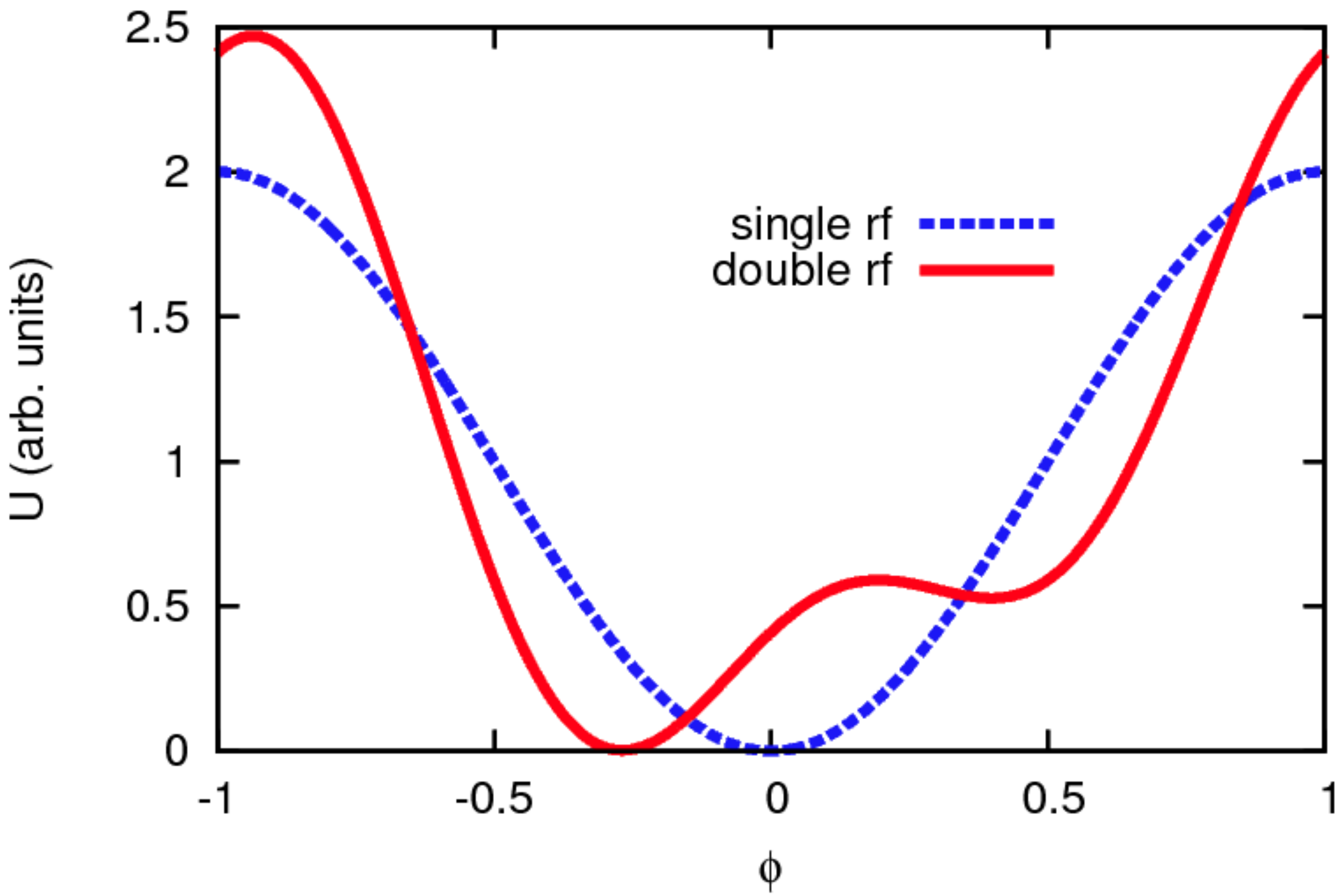
the h=2 cavity is shifted,
the voltage of the h=2 cavity
is the same (8kV).



RF BUCKET: DOUBLE RF

<u>an example</u>

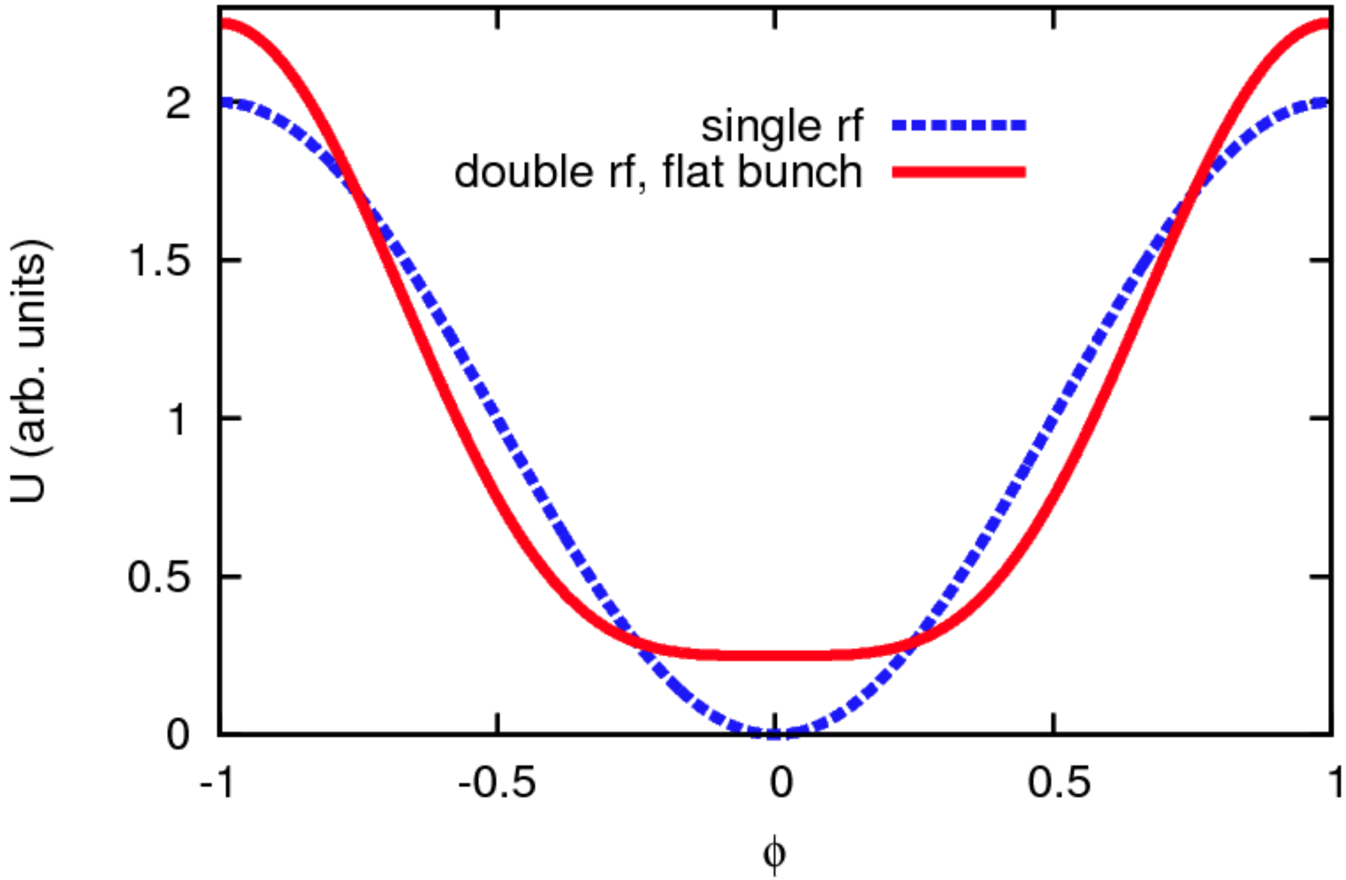
related to the h=1 cavity:
the h=2 cavity is shifted by 0.8π,
the voltage of the h=2 cavity is the same.



RF BUCKET: DOUBLE RF

double rf, flat bunch

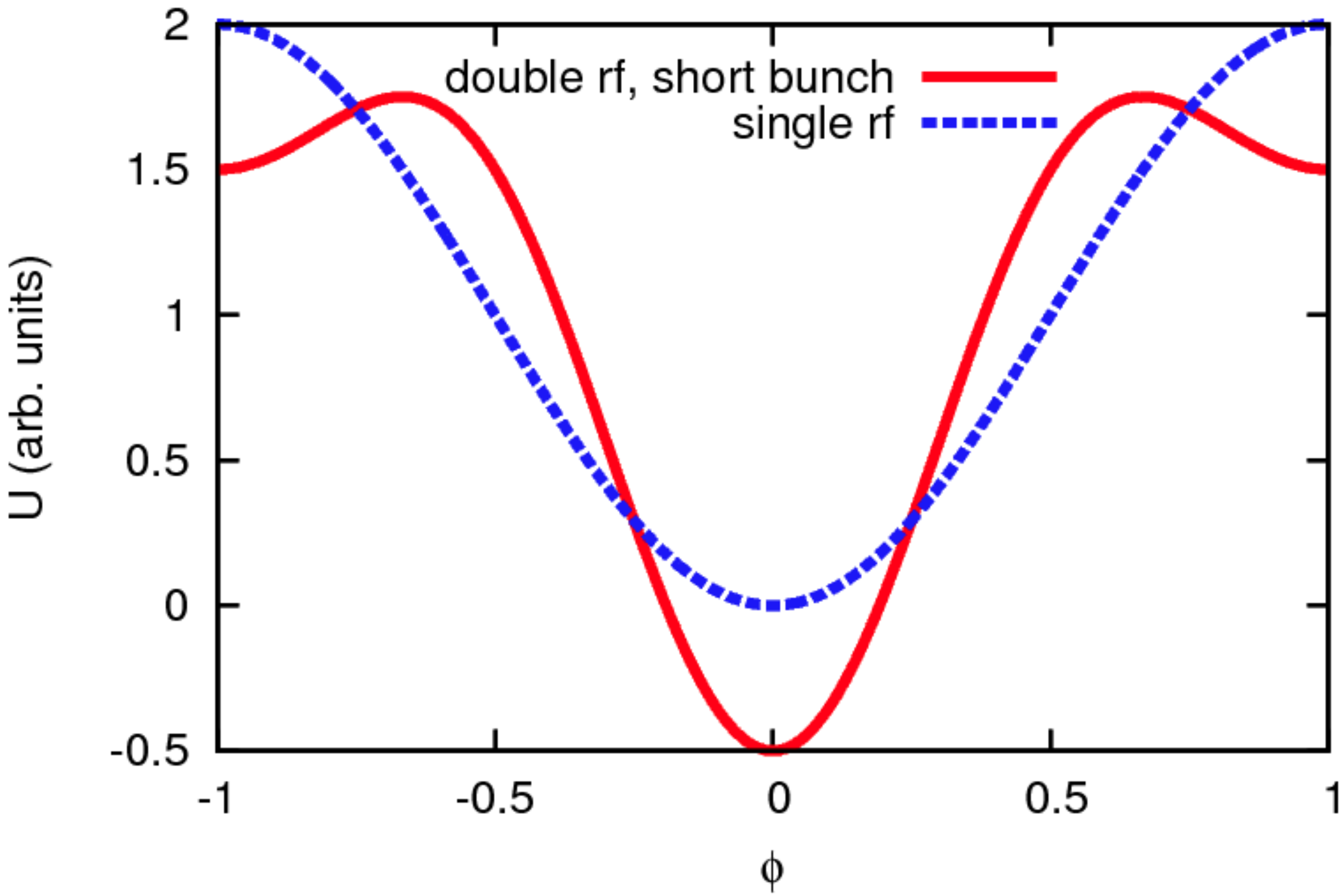
related to the h=1 cavity:
the h=2 cavity is shifted by π,
the voltage of the h=2 cavity is a half (4kV).



RF BUCKET: DOUBLE RF

double rf, short bunch

related to the h=1 cavity:
the h=2 cavity shift is equal zero,
the voltage of the h=2 cavity is the same.

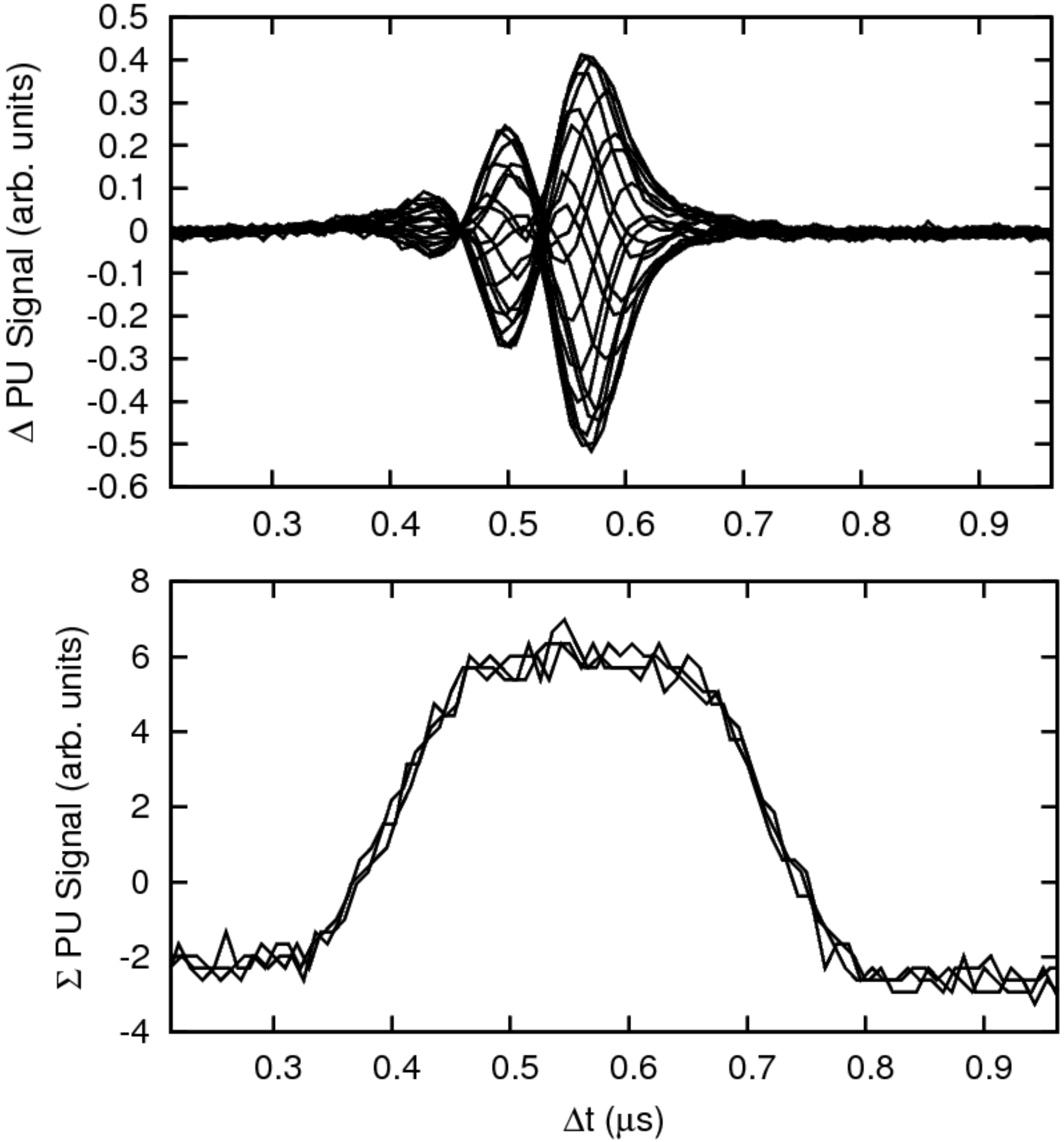


EXAMPLE OF THE INSTABILITY

Instability at C384ms
double rf, short bunch

N_p=610e10
ΔQ=3.8e-4,
Q_s=3.17e-3
$\Delta Q/Q_s$=0.12

the mode k=2,
result of a shorter bunch

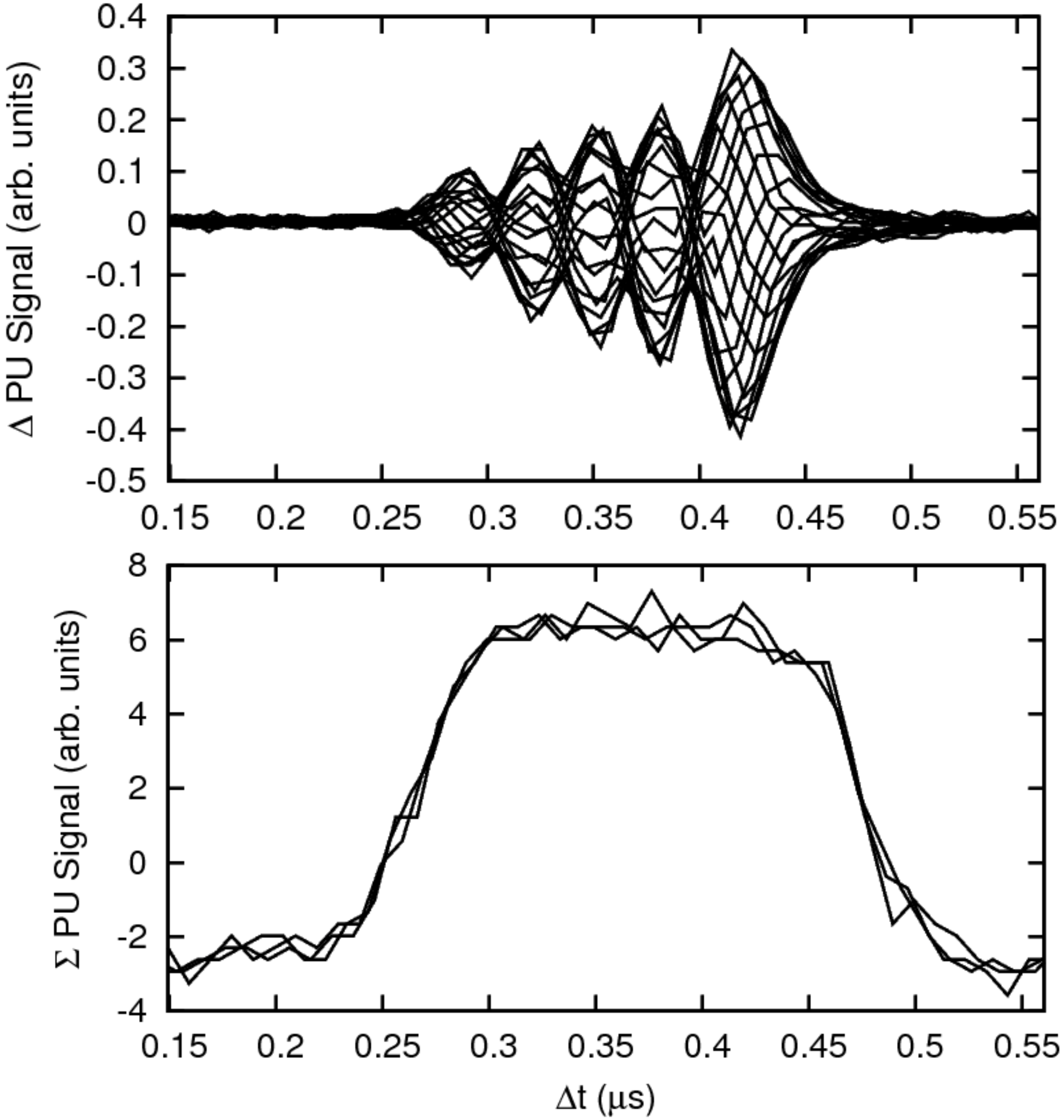


EXAMPLE OF THE INSTABILITY

Instability at C493ms
double rf, short bunch

N_p=500e10
Q_s=1.62e-3

the mode k=4
higher mode index
for later CTimes

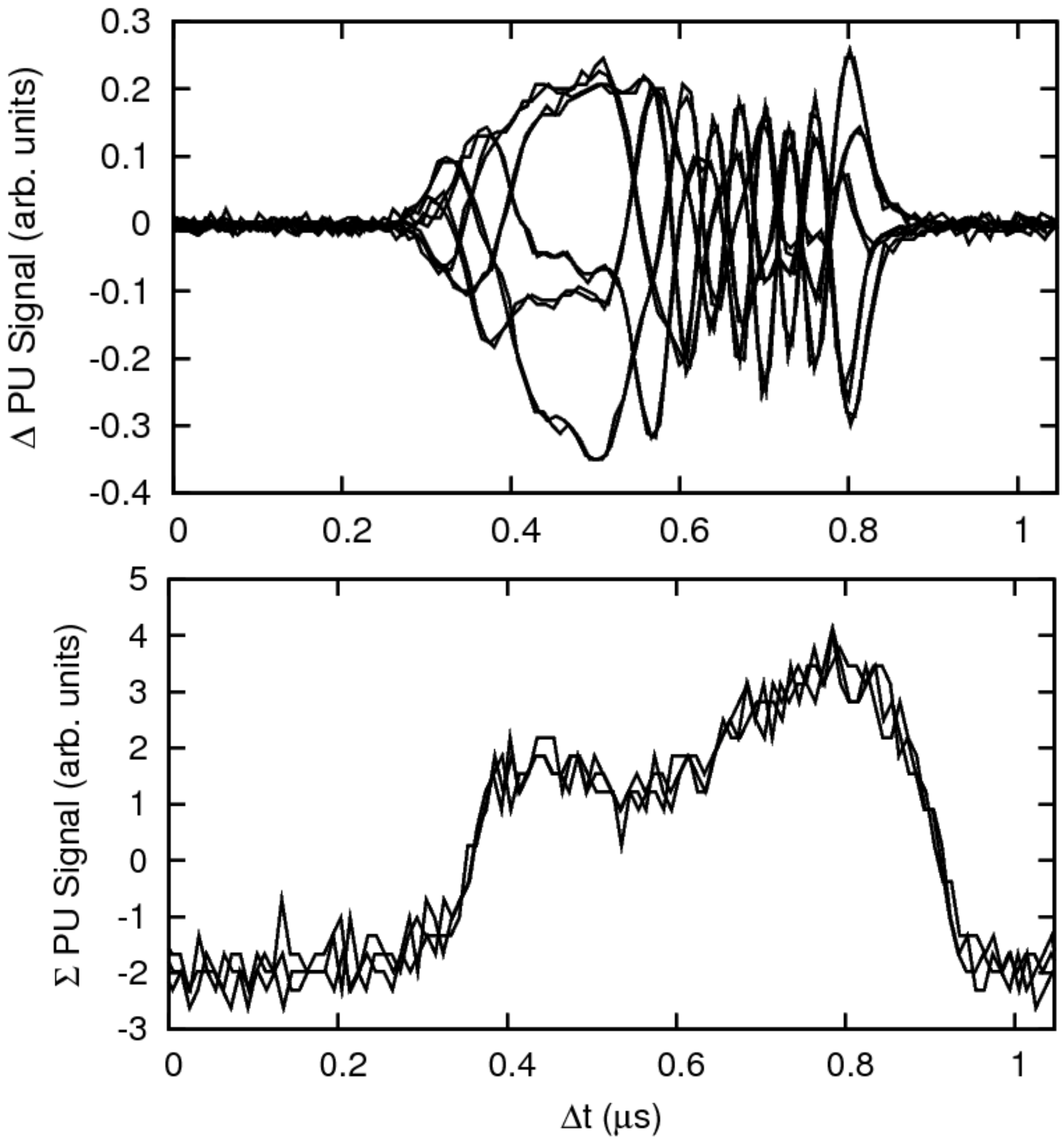


EXAMPLE OF THE INSTABILITY

Instability at C394ms
double rf, PSB standard

N_p=500e10
ΔQ=1.3e-4
$\Delta Q/Q_s$=0.071

a complex mode structure in double rf

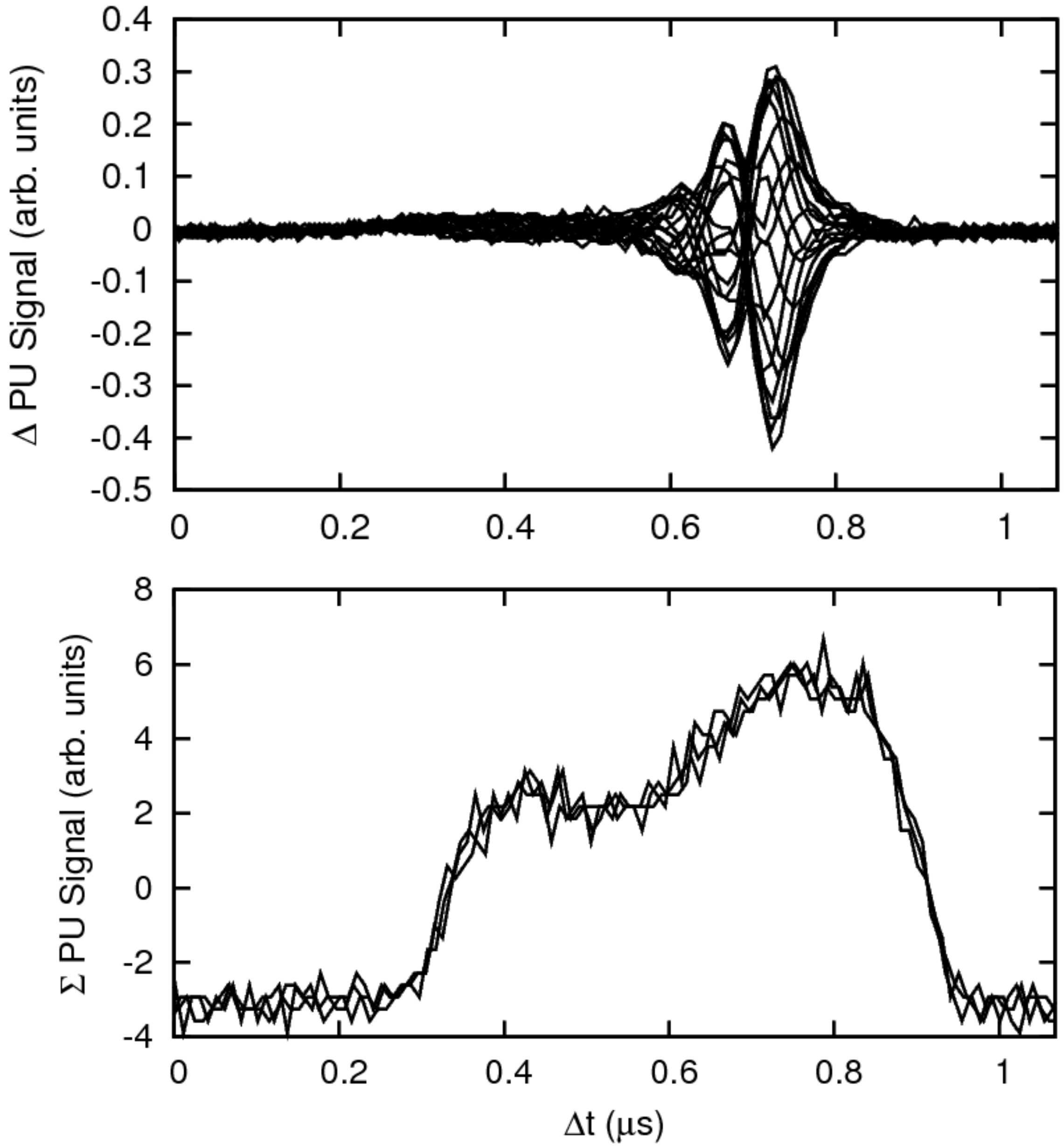


EXAMPLE OF THE INSTABILITY

Instability at C394ms
double rf, PSB standard
higher intensity

N_p=950e10

looks like the k=2 mode in the more dense, tail half of the bunch

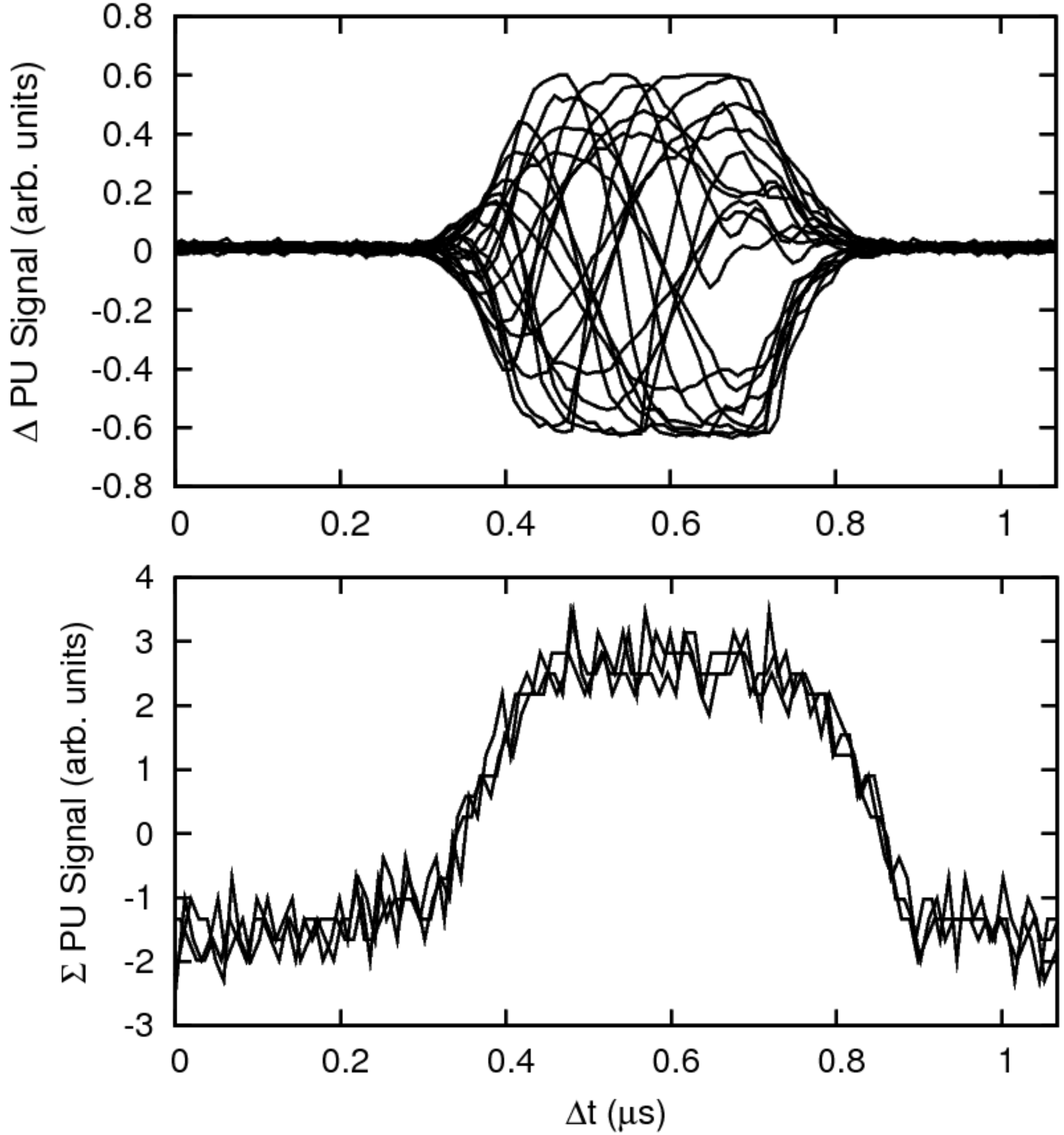


EXAMPLE OF THE INSTABILITY

Instability at C385ms
double rf, flat bunch

N_p=450e10
ΔQ=5.1e-4
$\Delta Q/Q_s$=0.28

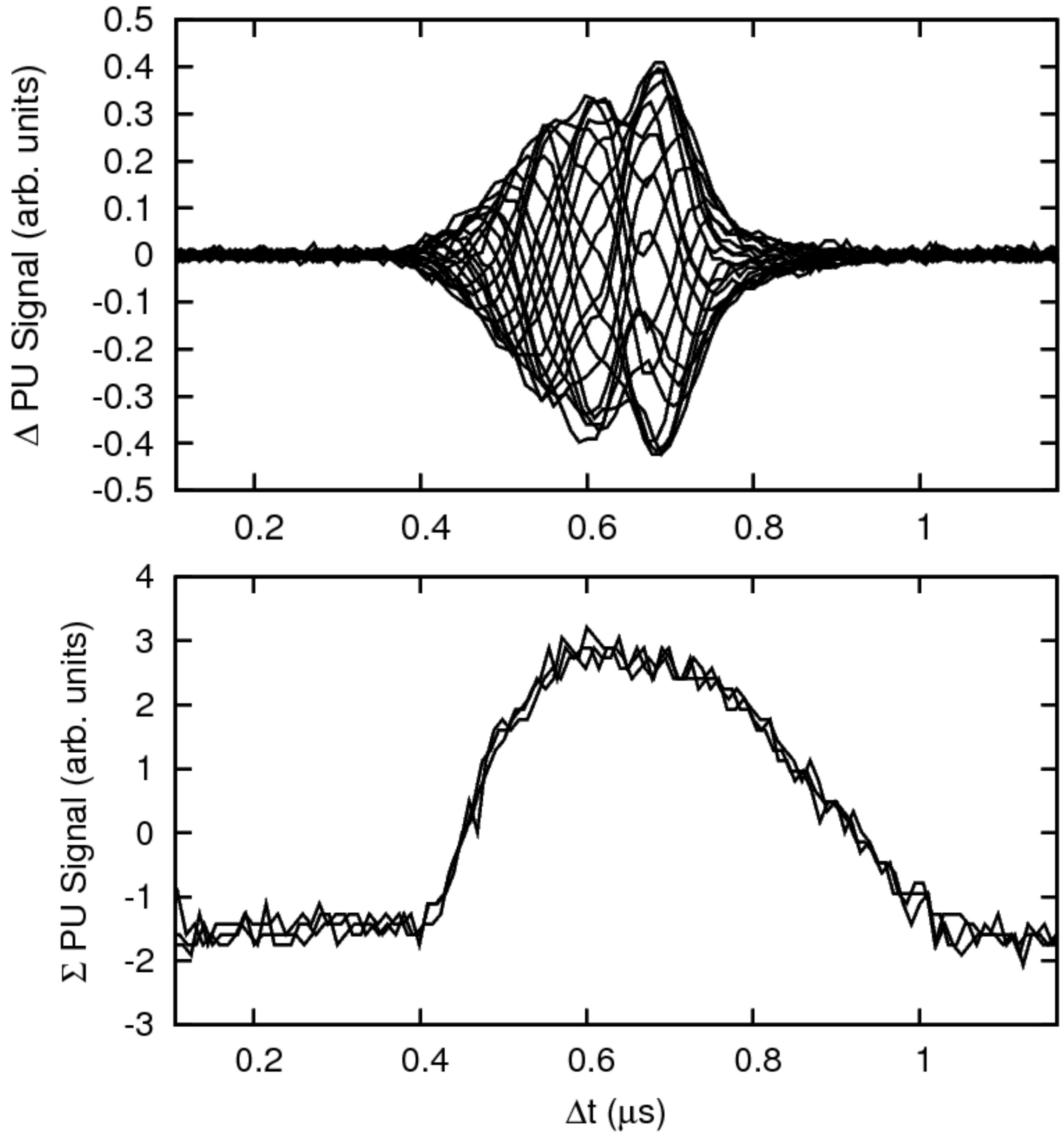
a complex mode structure in double rf



EXAMPLE OF THE INSTABILITY

Instability at C385ms
single rf, V_0=4kV
(until now 8kV)

N_p=400e10 (near the threshold)
ΔQ=2.2e-4
Q_s=0.66e-3
$\Delta Q/Q_s$=0.33



OBSERVATIONS AT PSB

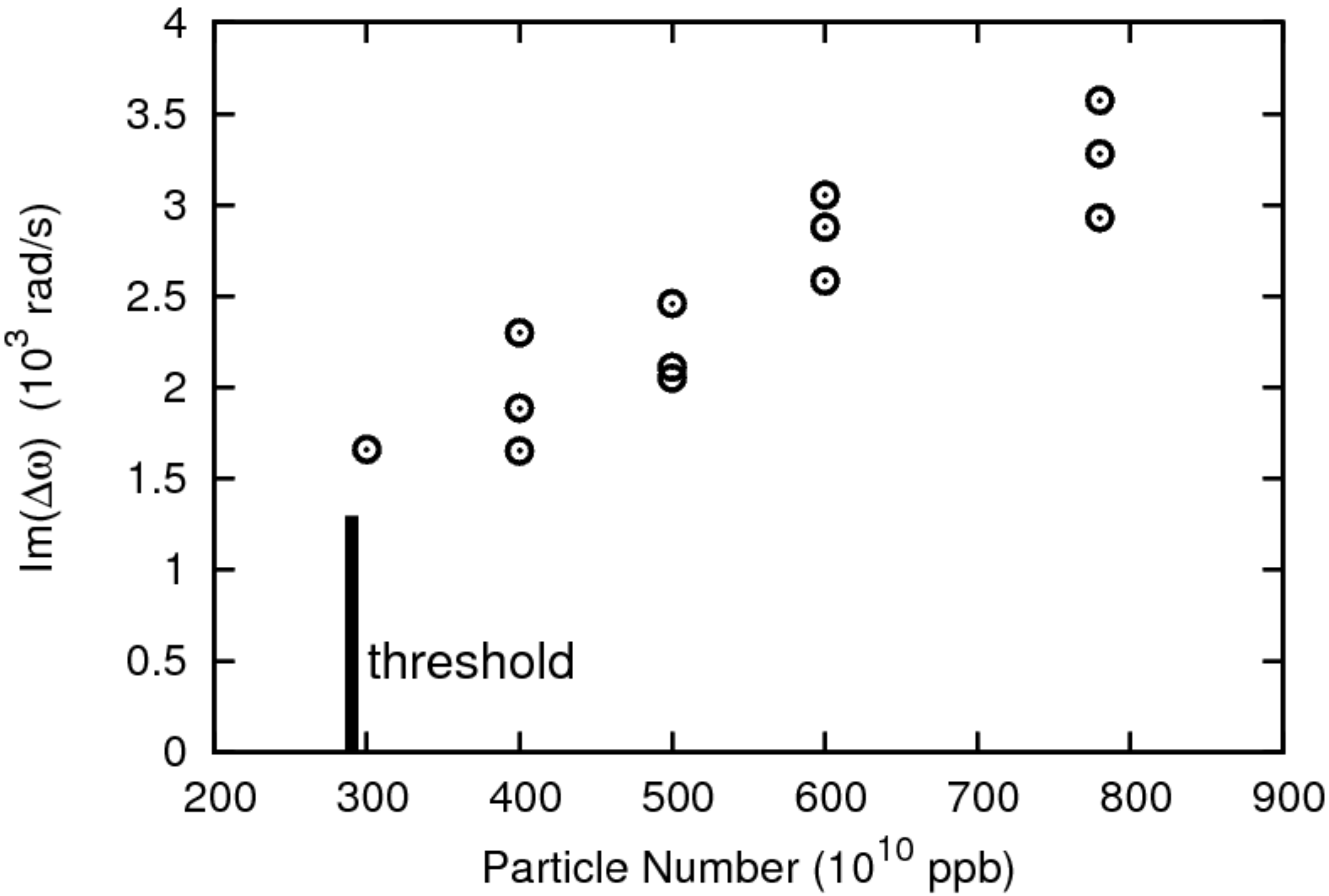
questions appear

At PSB we observe	Generally we know
the instability occurs at reproducible cycle times	triggering of a collective instability is irregular (example: at PS flat-bottom)
the instability is always and only in the horizontal plane	the vertical Resistive-Wall impedance at PSB is larger then the horizontal
the instability has a clear intensity threshold, depending on settings	the head-tail instability has no intensity threshold
higher mode index *k* at later Ctimes; lower mode index *k* for shorter bunches; mode structure deformed by the $Z_\perp$; no clear effect of weaker space-charge	

GROWTH RATES SUMMARY

As the imaginary part of the frequency, or the instability increment

single rf
V_0=8kV

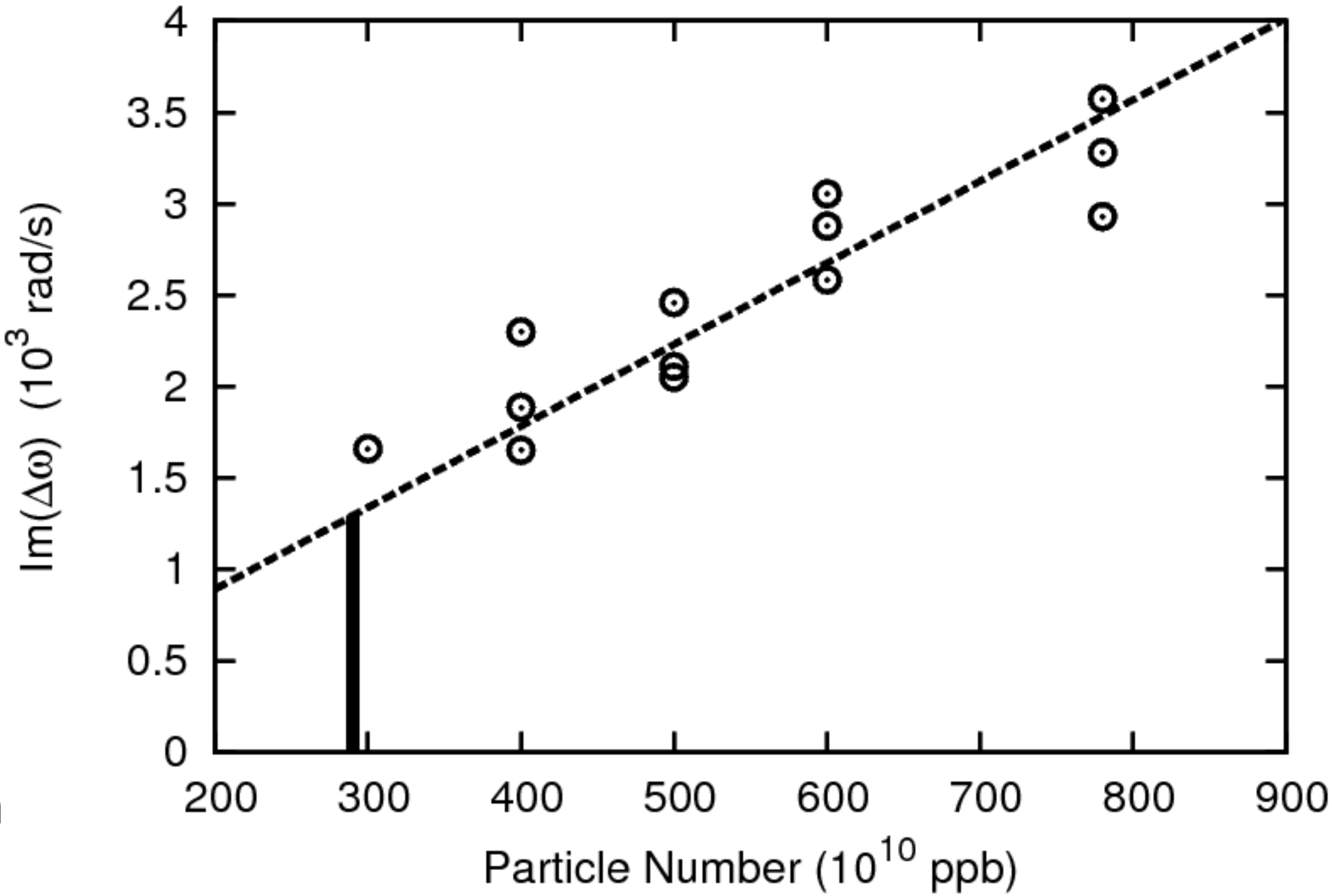


GROWTH RATES SUMMARY

As the imaginary part of the frequency, or the instability increment

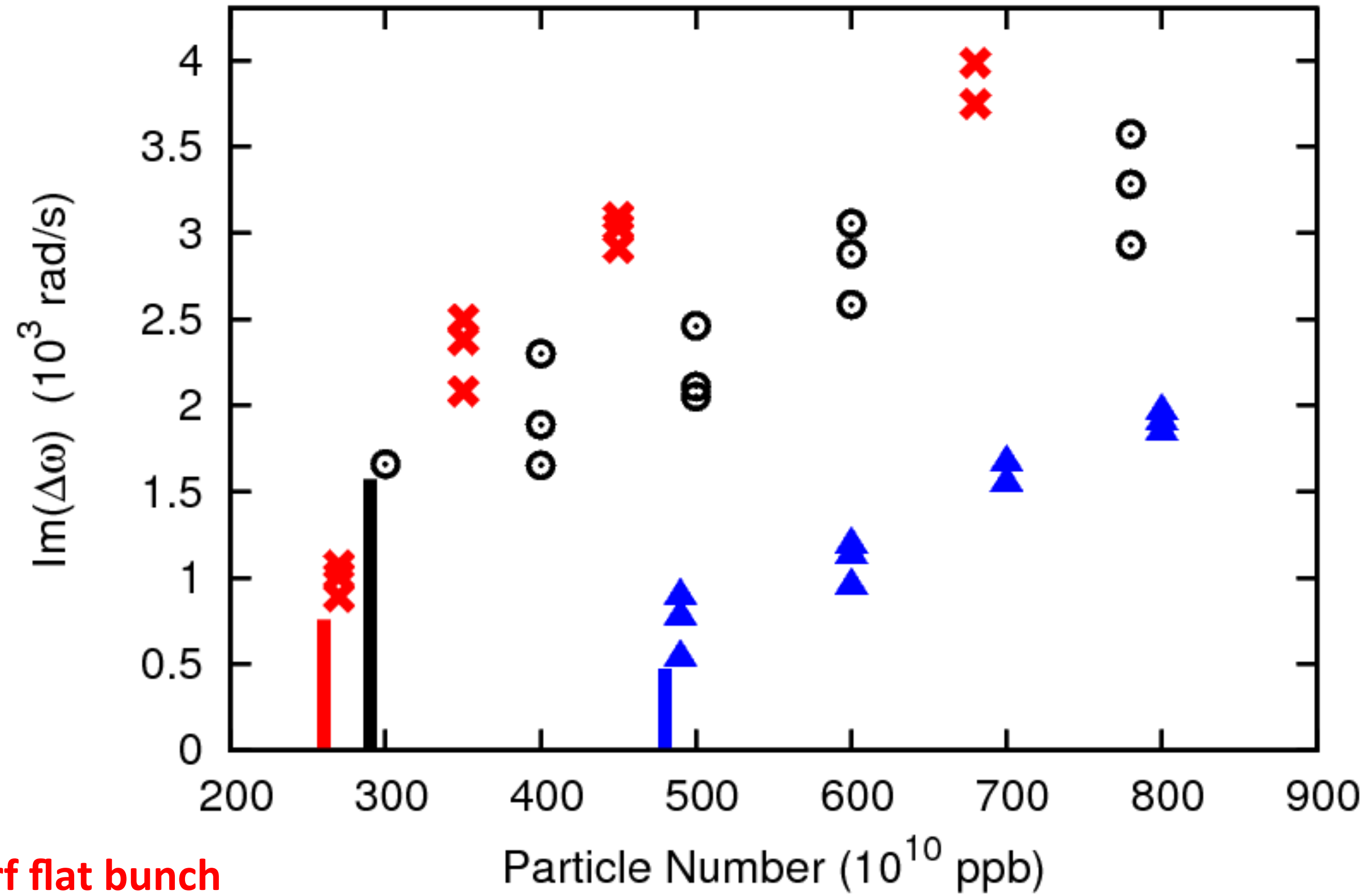
single rf
V_0=8kV

the dashed line crosses the origin



GROWTH RATES SUMMARY

As the imaginary part of the frequency, or the instability increment

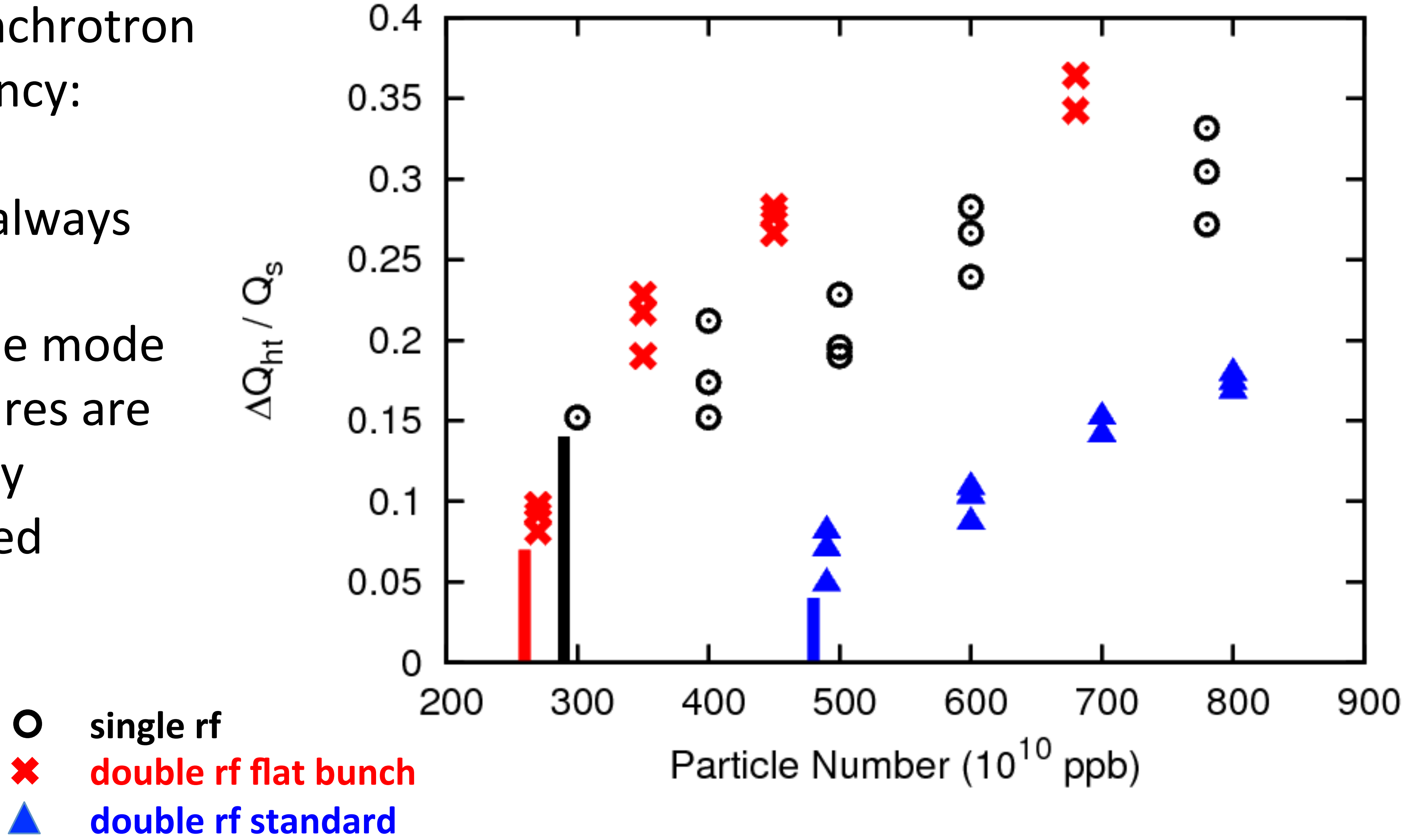


- single rf
- double rf flat bunch
- double rf standard

GROWTH RATES SUMMARY

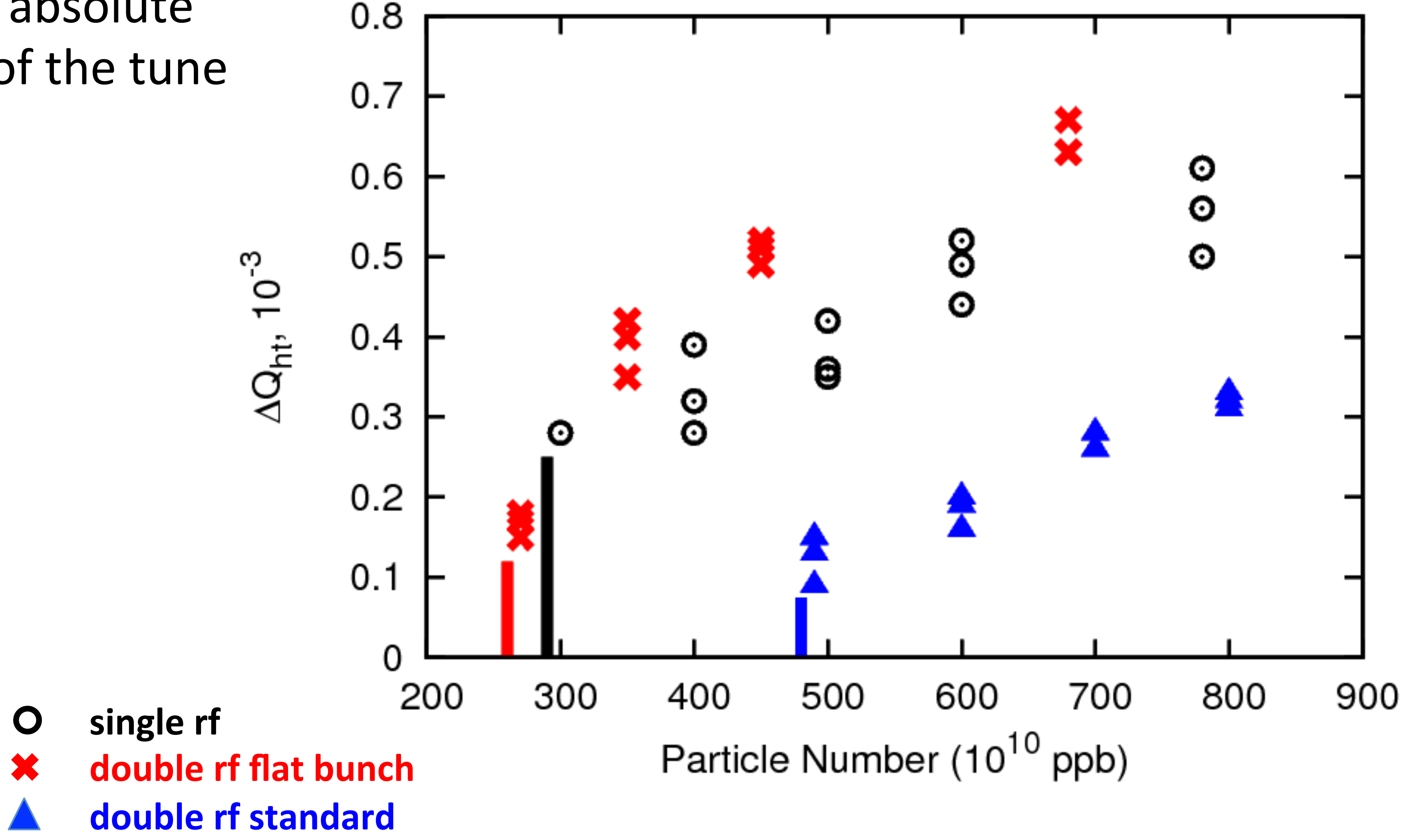
Normalized by the synchrotron frequency:

this is always large,
thus the mode structures are strongly modified



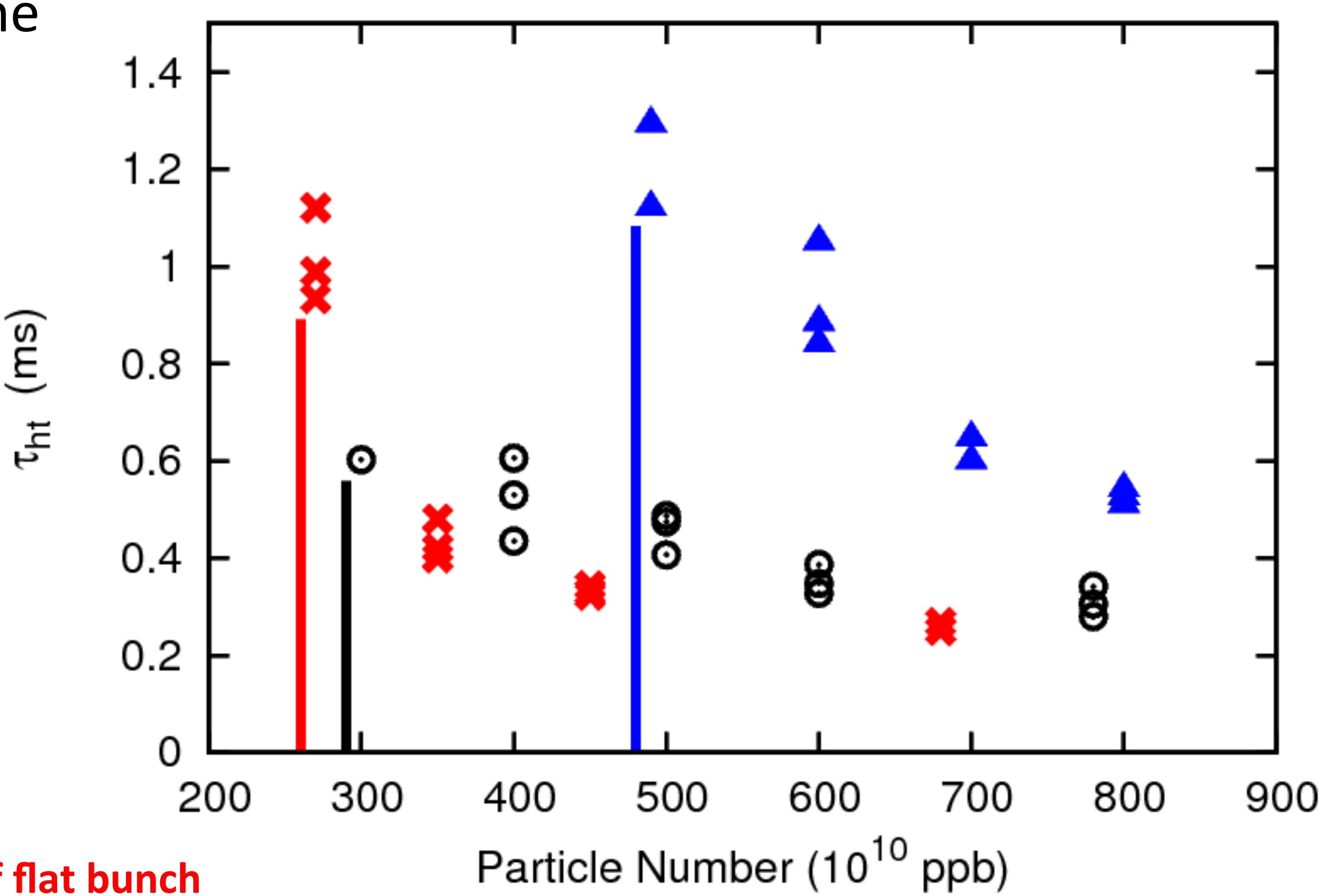
GROWTH RATES SUMMARY

As the absolute value of the tune shift



GROWTH RATES SUMMARY

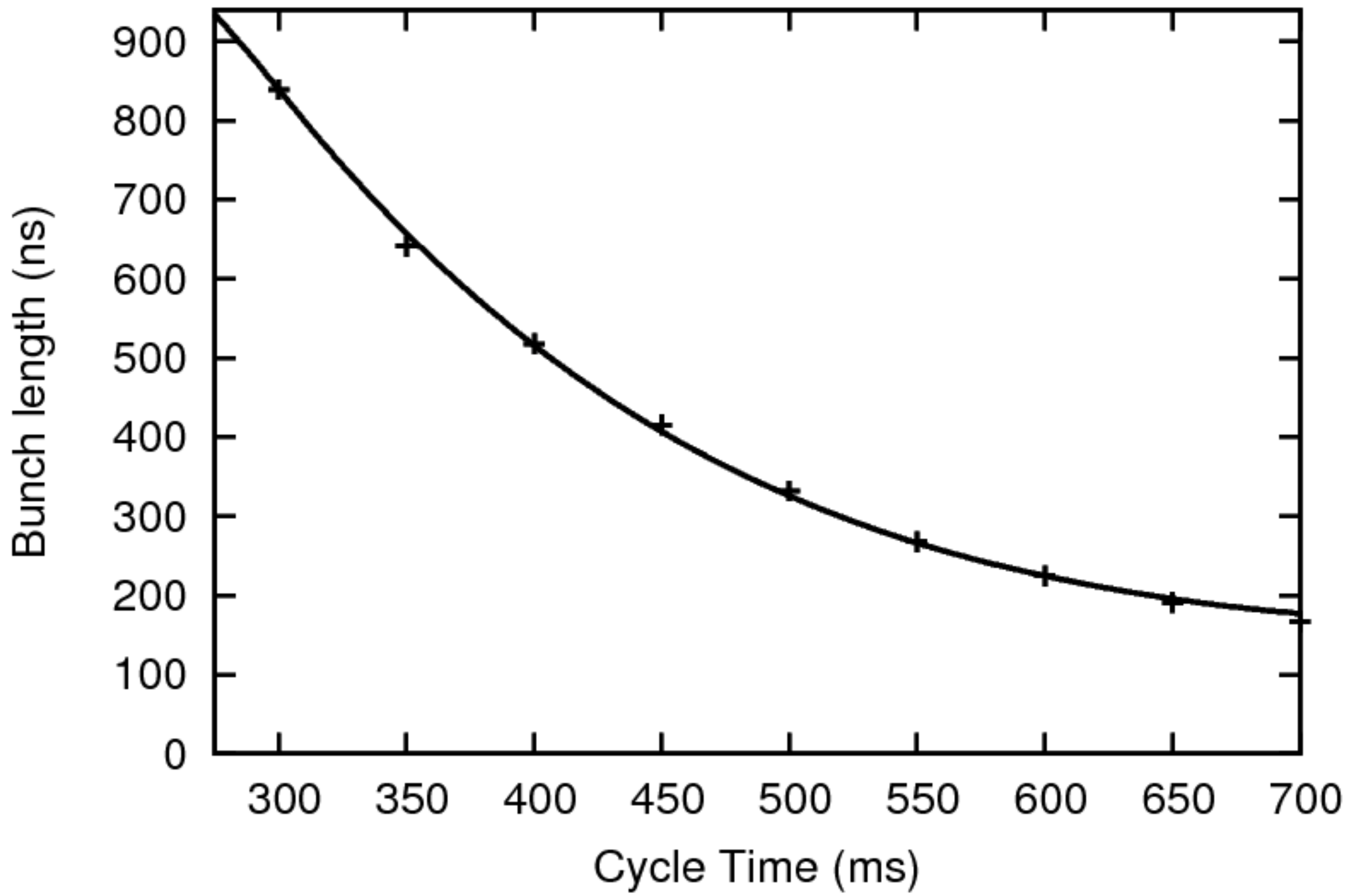
As the growth time



single rf
double rf flat bunch
double rf standard

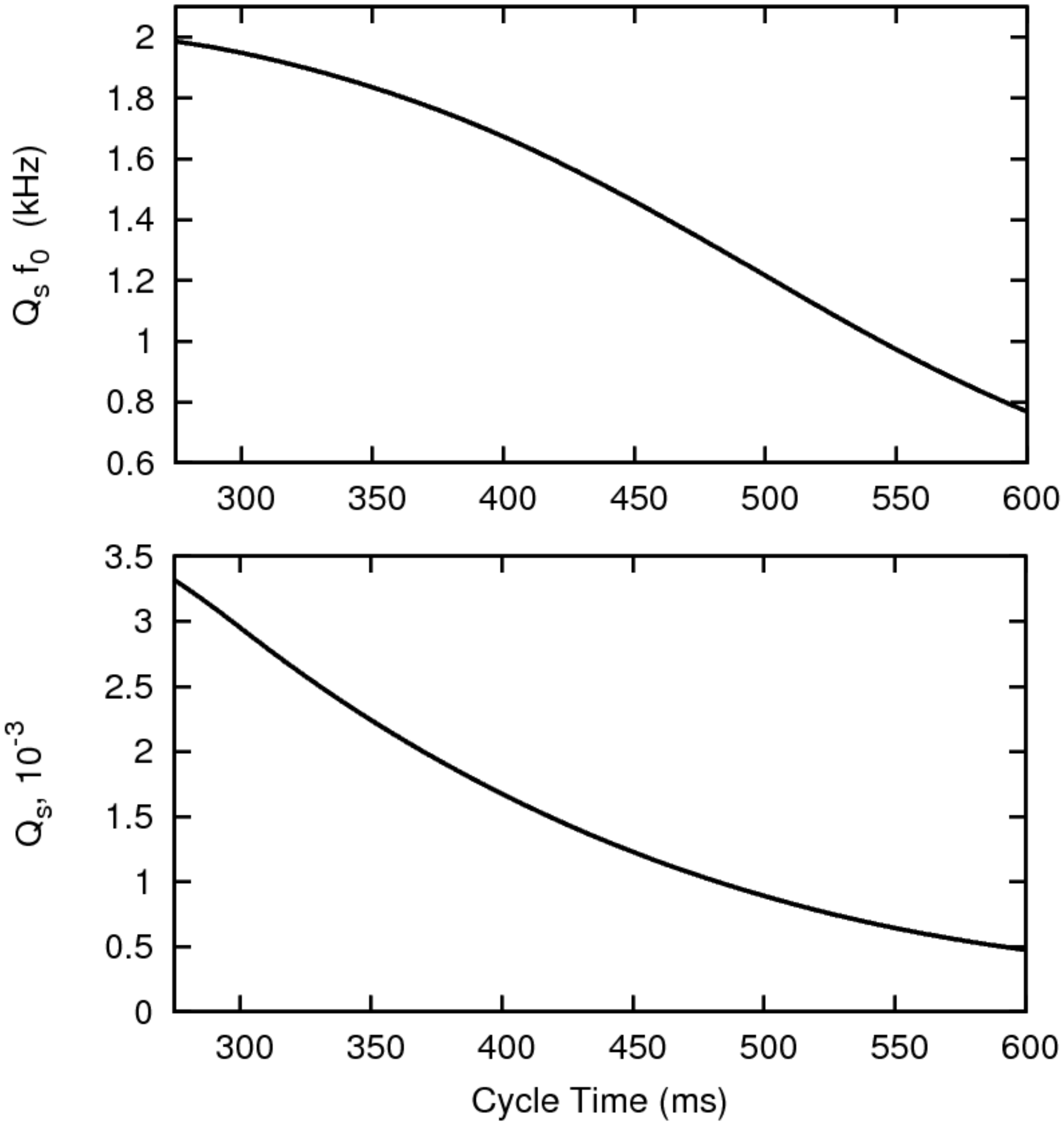
BUNCH DURING THE RAMP

bunch length for the ε_z=const,
and measurements for single rf, V_0=8kV



BUNCH DURING THE RAMP

synchrotron frequency
and
the synchrotron tune
for single rf, V_0=8kV



SPACE CHARGE

the space-charge tune shift (rms-equiv. K-V beam)

$$\Delta Q_{\rm sc} = \frac{\lambda_0 r_p R}{\gamma^3 \beta^2 \varepsilon_\perp}$$

the space-charge parameter

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

Elliptic cross-section:
(ε_x, ε_y rms emittances,
$\varepsilon_\perp$ total for the rms-equivalent K-V)

$$\varepsilon_\perp = 2\Big(\varepsilon_x + \sqrt{\varepsilon_x \varepsilon_y \frac{Q_{0x}}{Q_{0y}}}\Big)$$

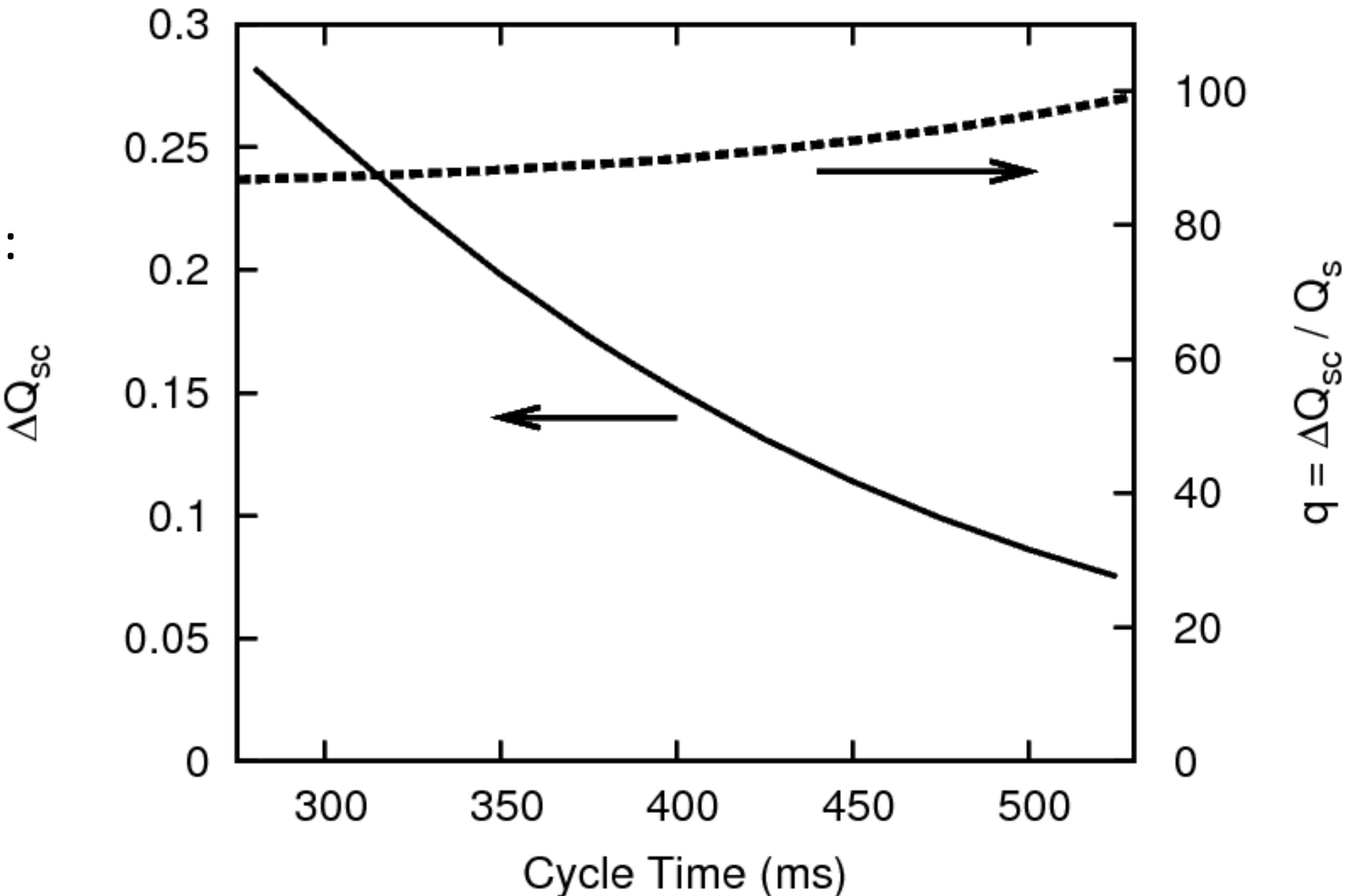
Gaussian profile: $\Delta Q_{\rm sc}^{\rm max} = 2\Delta Q_{\rm sc}$

Space-charge tune spread:

- different transverse amplitudes
- density variation along the bunch

SPACE CHARGE AT PSB

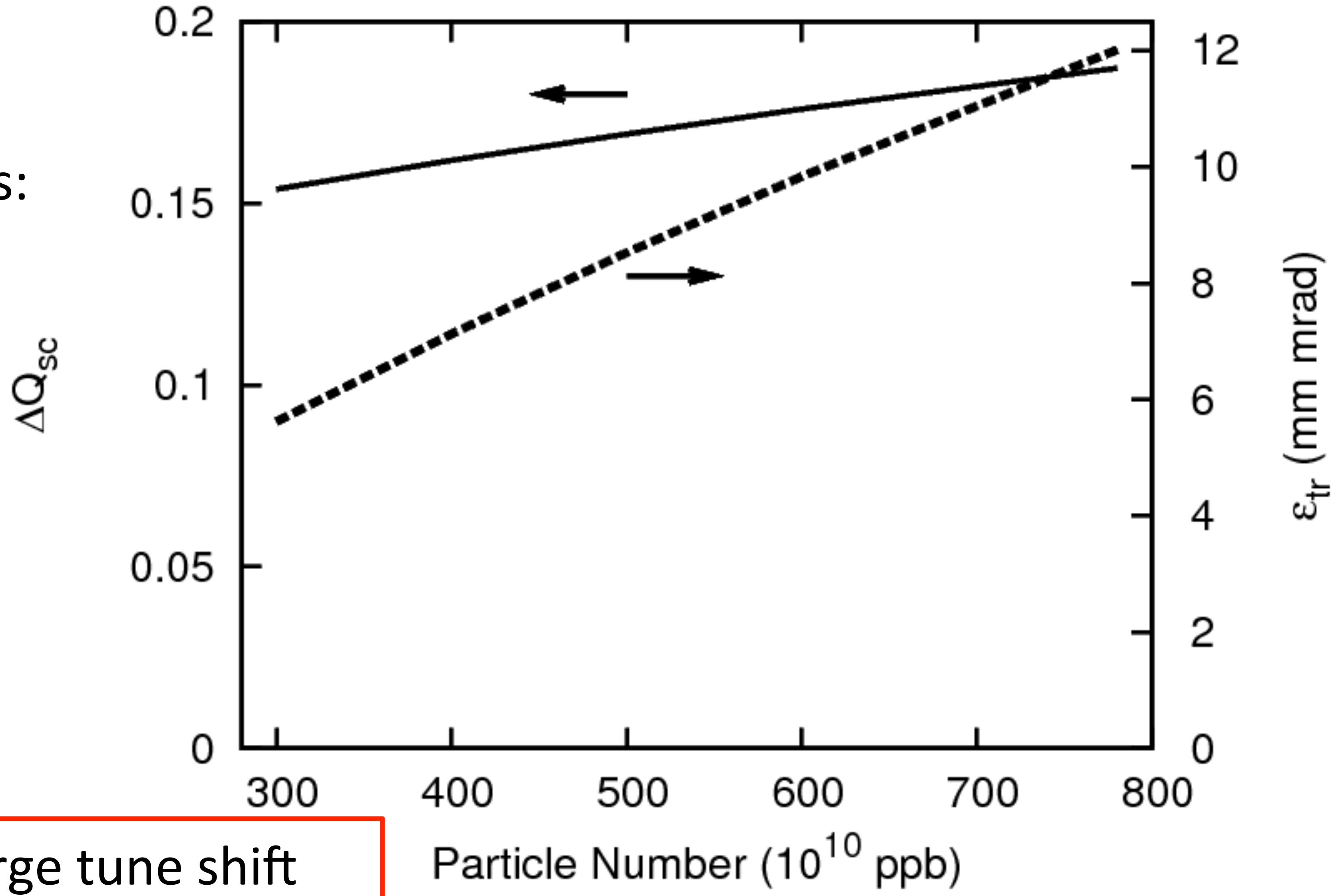
from the measurements: space-charge tune shift for single rf, V_0=8kV, 300e10 ppb, horizontal



the space-charge parameter *q* is a flat function along the intensity; very strong space charge regime => a minor change not crucial; no Landau damping for the relevant (k<6) head-tail modes

SPACE CHARGE AT PSB

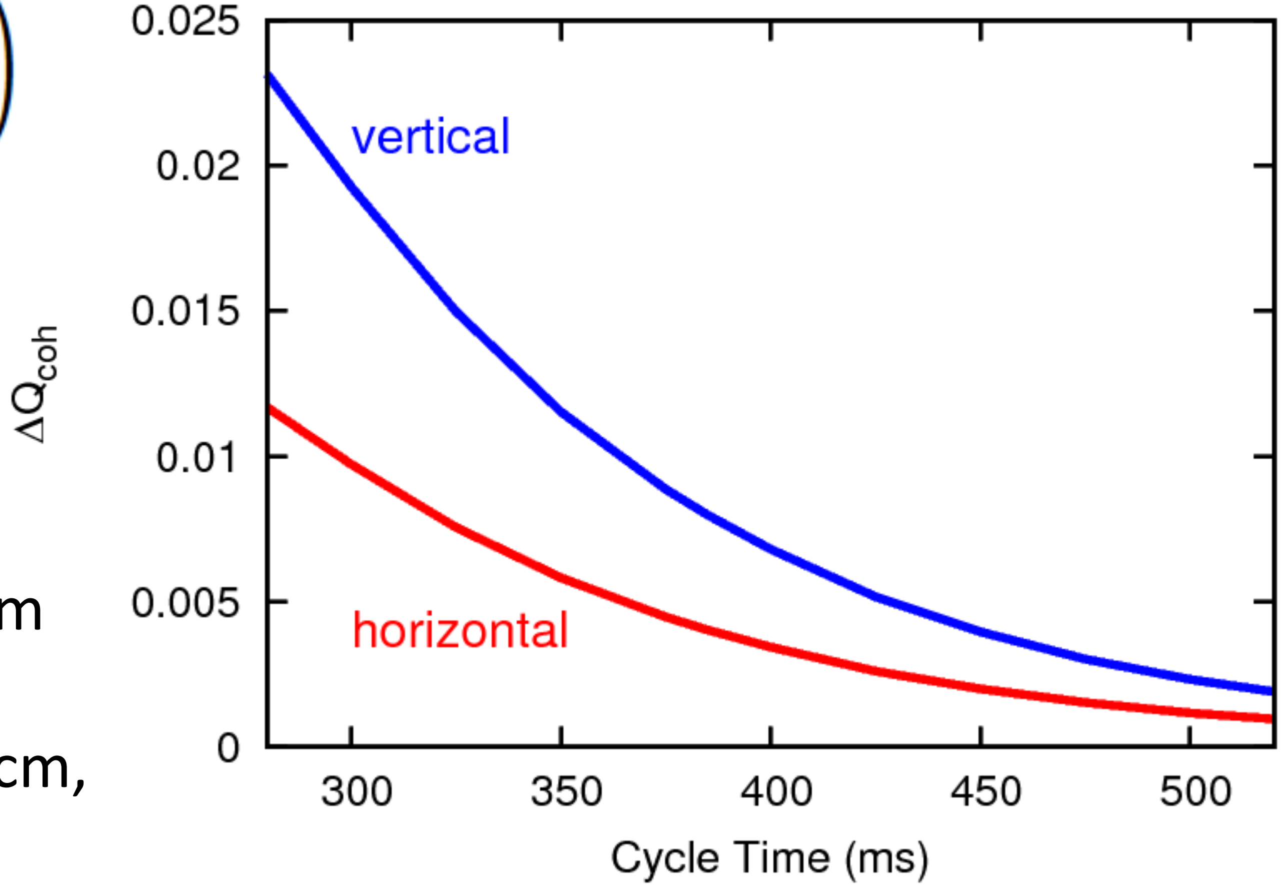
from the measurements: space-charge tune shift at C385, for single rf, V_0=8kV, horizontal



the space-charge tune shift is a flat function along the intensity

THE PIPE: IMAGE CHARGES

$$\frac{\Delta Q_{\mathrm{coh}}}{\Delta Q_{\mathrm{sc}}} = \left(\frac{a_{\mathrm{beam}}}{b_{\mathrm{pipe}}}\right)^2$$



here for the PSB vacuum pipe assumed:
two-thirds circular b=8cm,
one-third elliptic,
horizontal h=8cm,
vertical w=3.5cm

SPACE CHARGE & IMAGE CHARGES

the eigenfrequencies of the bunch head-tail modes
for the airbag bunch model
with arbitrary space-charge and coherent force:

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

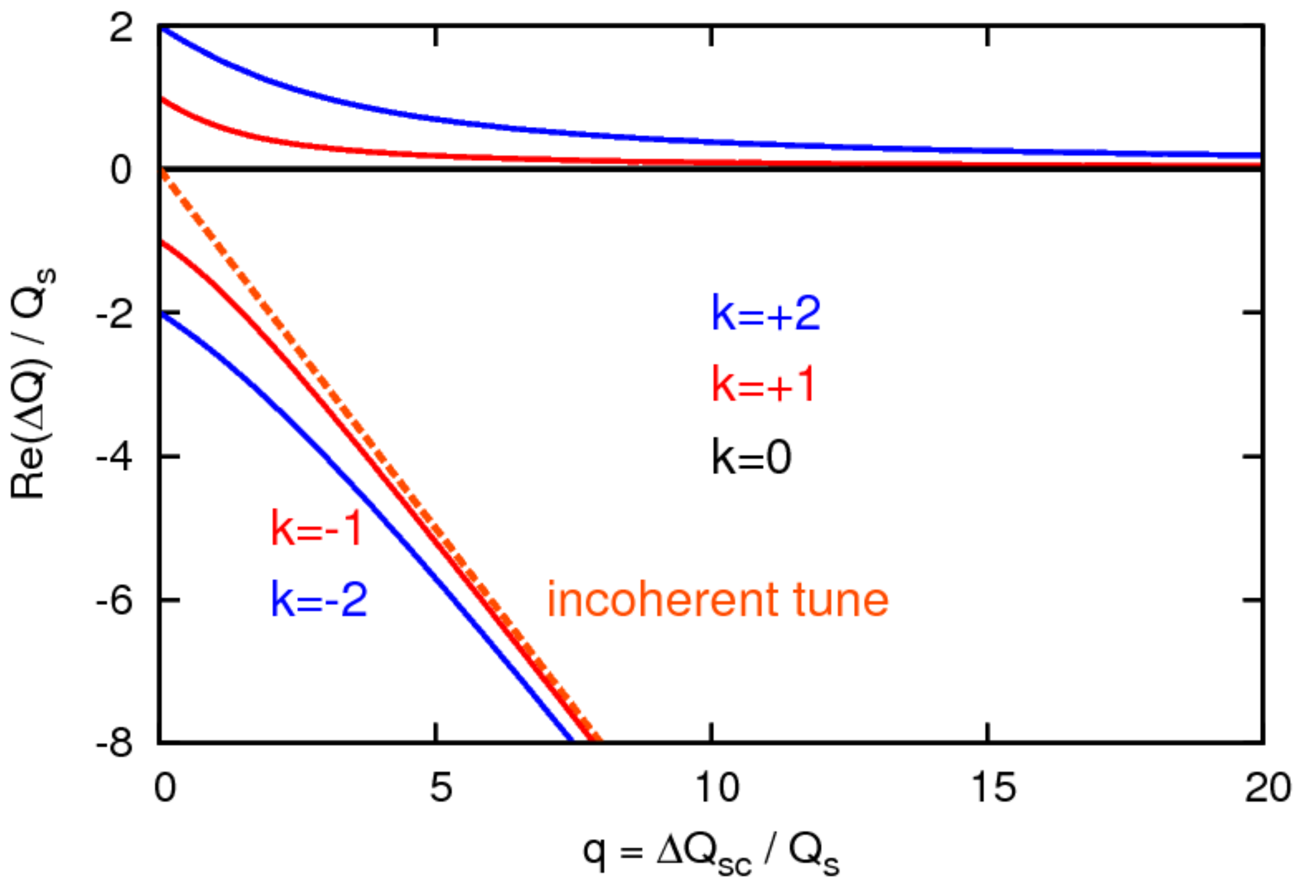
$$\frac{\Delta Q_k}{Q_s} = -\frac{q}{2}\left(1 + \frac{\Delta Q_{\rm coh}}{\Delta Q_{\rm sc}}\right) \pm \sqrt{\frac{q^2}{4}\left(1 - \frac{\Delta Q_{\rm coh}}{\Delta Q_{\rm sc}}\right)^2 + k^2}$$

O.Boine-Frankenheim, V.Kornilov, PRSTAB **12**, 114201 (2009)
V.Kornilov, O.Boine-Frankenheim, PRSTAB **13**, 114201 (2010)
M.Blaskiewicz, PRSTAB **1**, 044202 (1998)

SPACE CHARGE

with space charge only, ΔQ_{coh}=0

the k=0 mode is not affected;
the positive modes close to Q_0;
the negative modes close to the incoherent tune and are strongly damped



SPACE CHARGE & IMAGE CHARGES

with a coherent tune shift,
$\Delta Q_{coh}/\Delta Q_{sc} = 0.1$

the k=0 mode:
$\Delta Q = -\Delta Q_{coh}$
the k>0 modes enter the incoherent spectrum
$-2\Delta Q_{sc} < \Delta Q < 0$
=> Landau damping

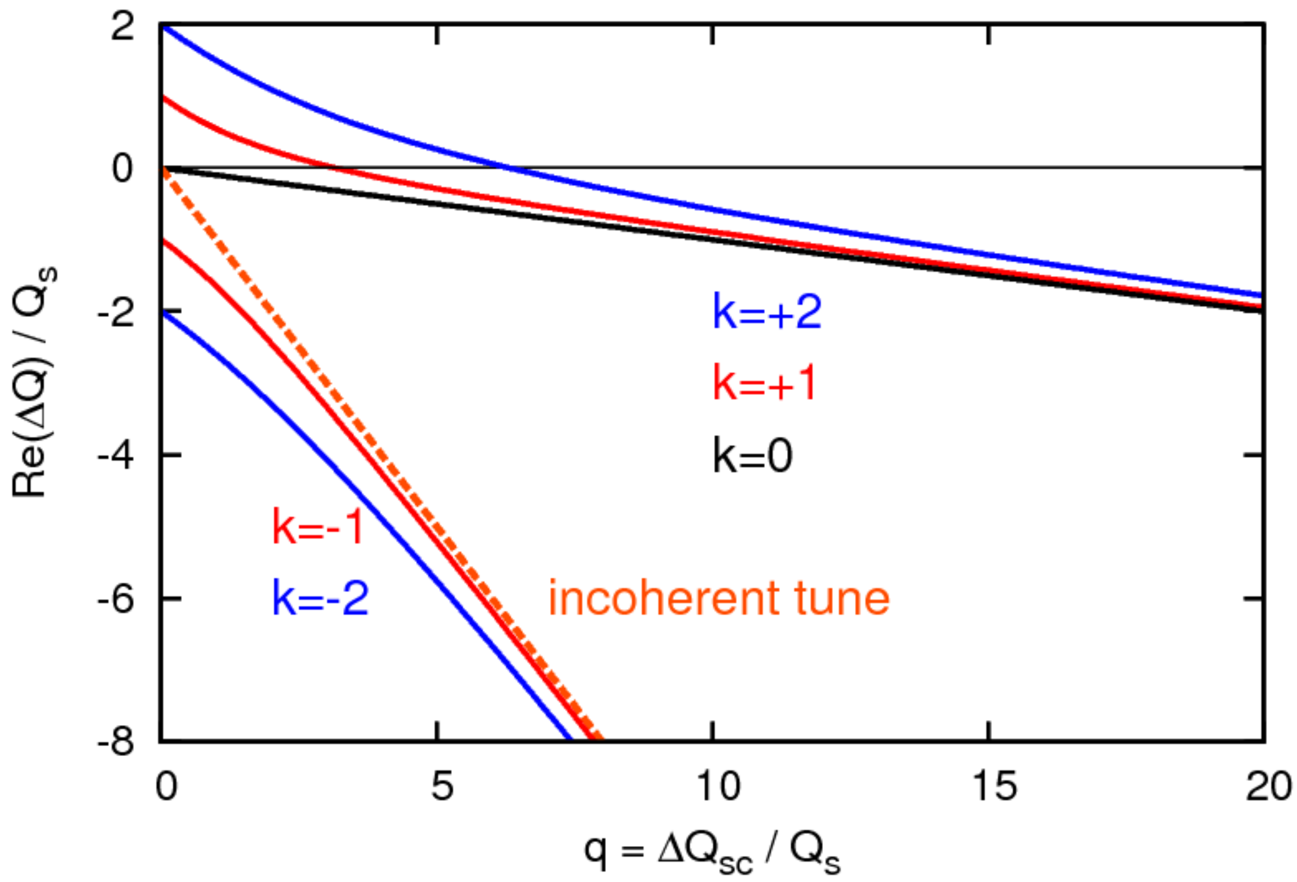
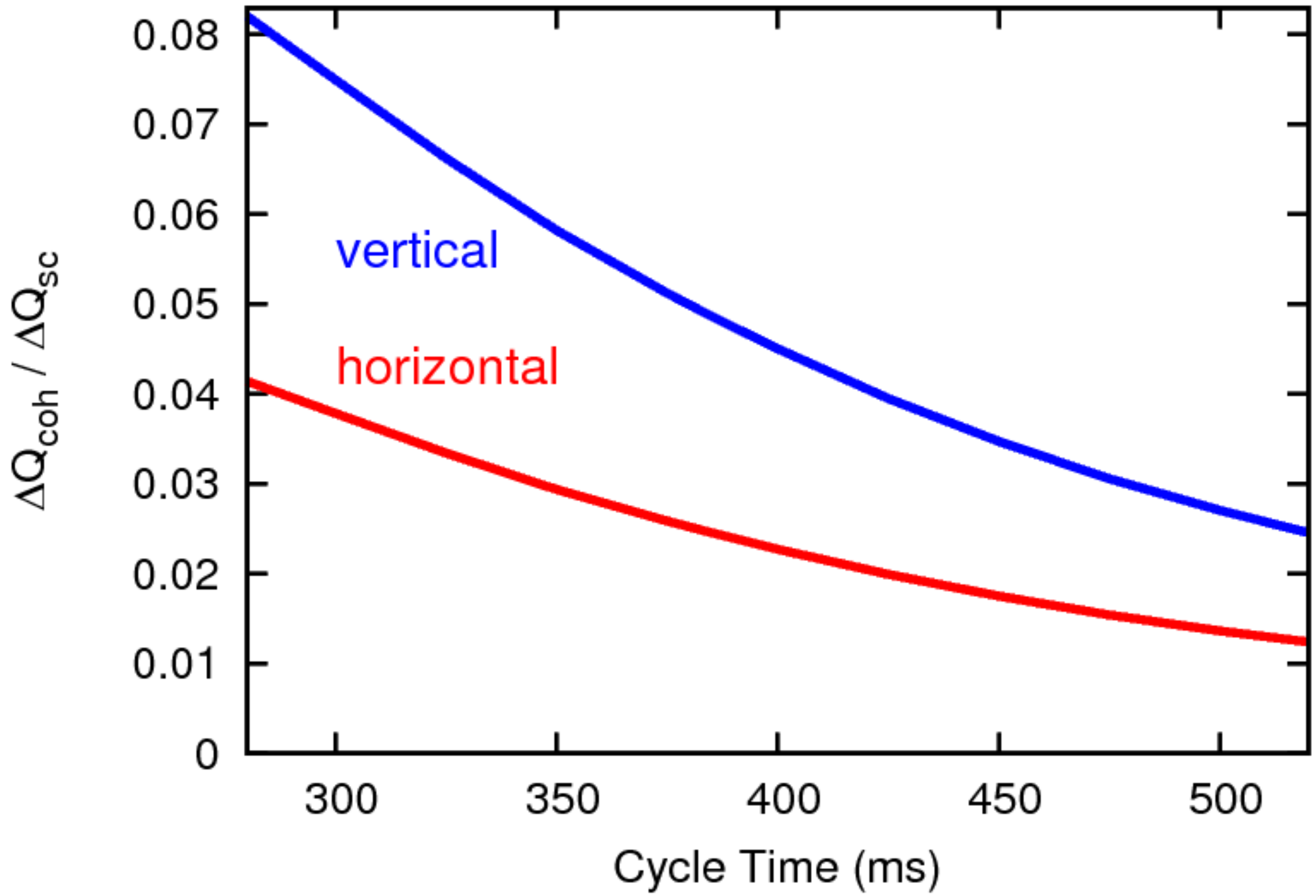


IMAGE CHARGES AT PSB

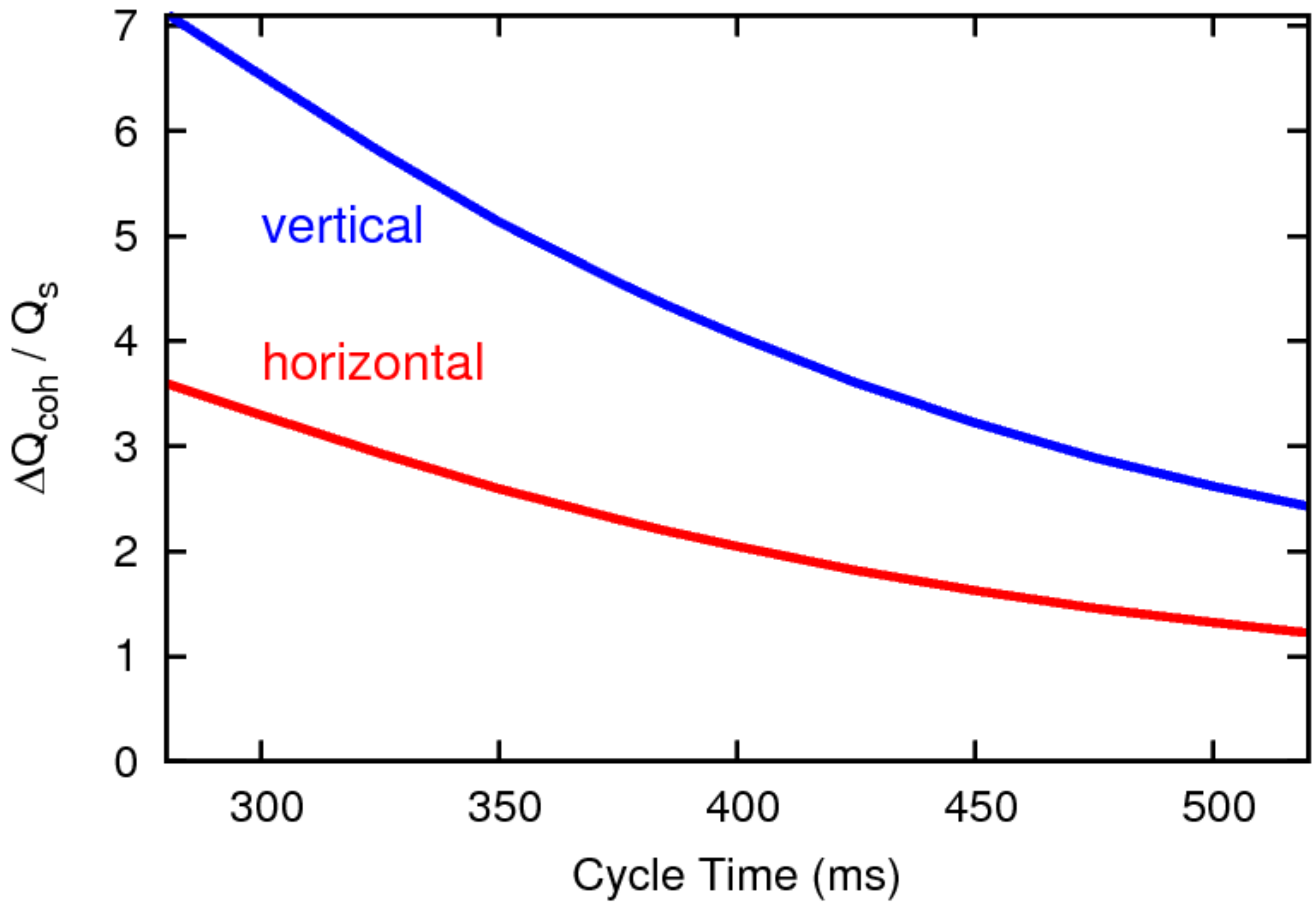


Landau damping is stronger in the vertical plane;
the damping contribution decreases along the cycle.
This may contribute to the horizontal exclusiveness and to the later occurrence in CTime

IMAGE CHARGES AT PSB

The real ΔQ_{coh} is larger then the synchrotron tune.

During the cycle, other transverse impedance must cause mode coupling and a fast TMCI. Space-charge tune shifts prevent it.



This might be an experimental proof of the mode coupling suppression by space charge

Theory predictions: Blaskiewicz prstab 1998; Burov prstab 2009

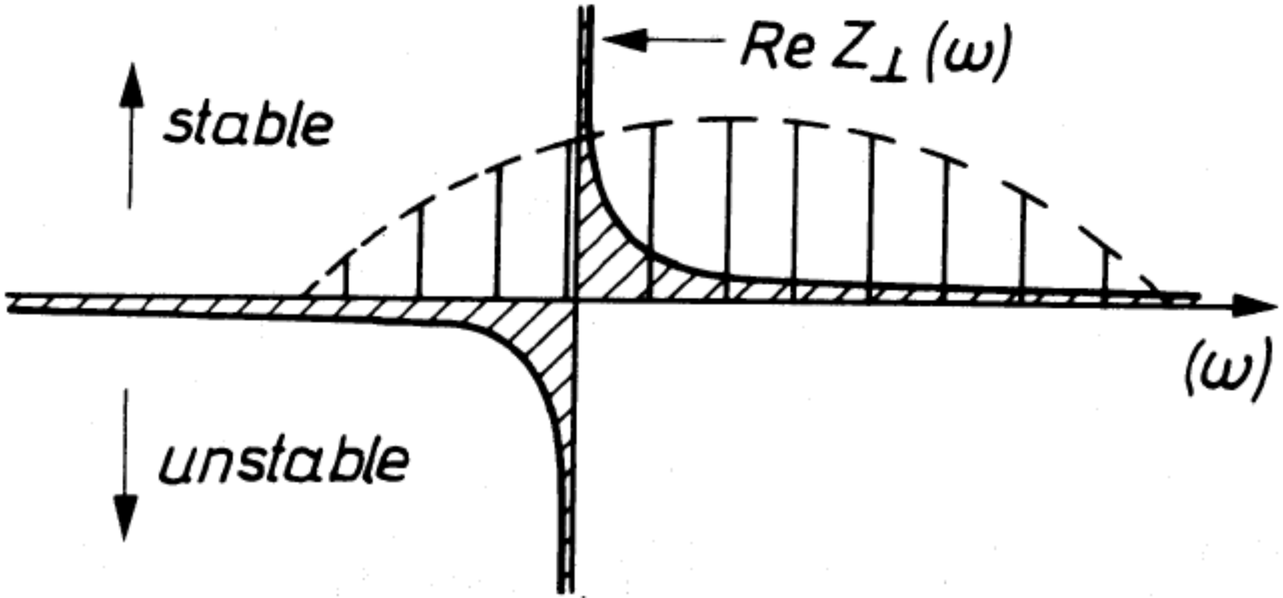
THE HEAD-TAIL INSTABILITY

F.Sacherer 1974

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

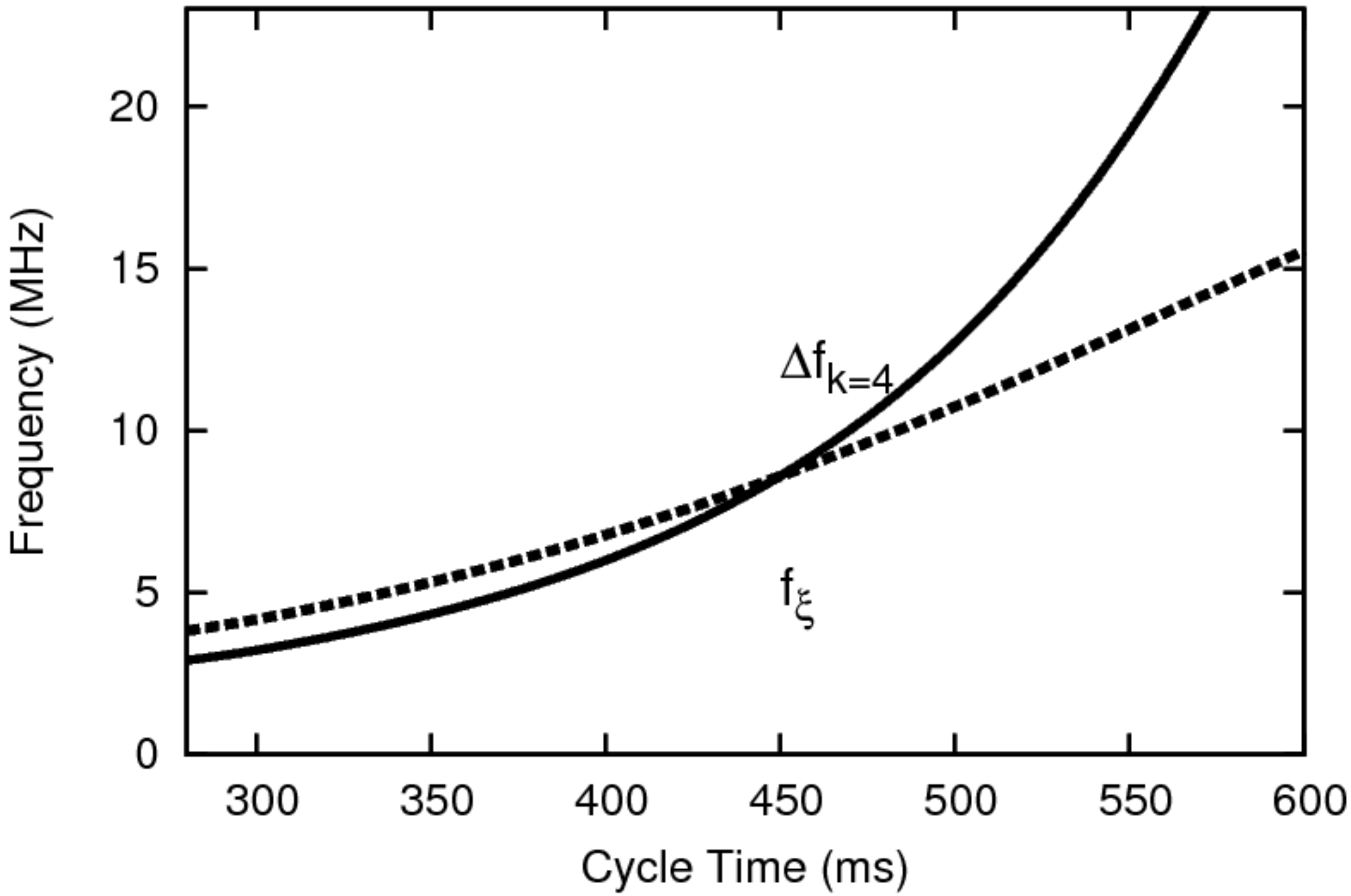
$$\omega_p = (p+Q_0)\omega_0 + k\omega_s$$

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



HEAD-TAIL SPECTRUM AT PSB

Evolution along the cycle of the chromaticity frequency shift (the k=0 mode) and the spectrum position of the *k*=4 mode.

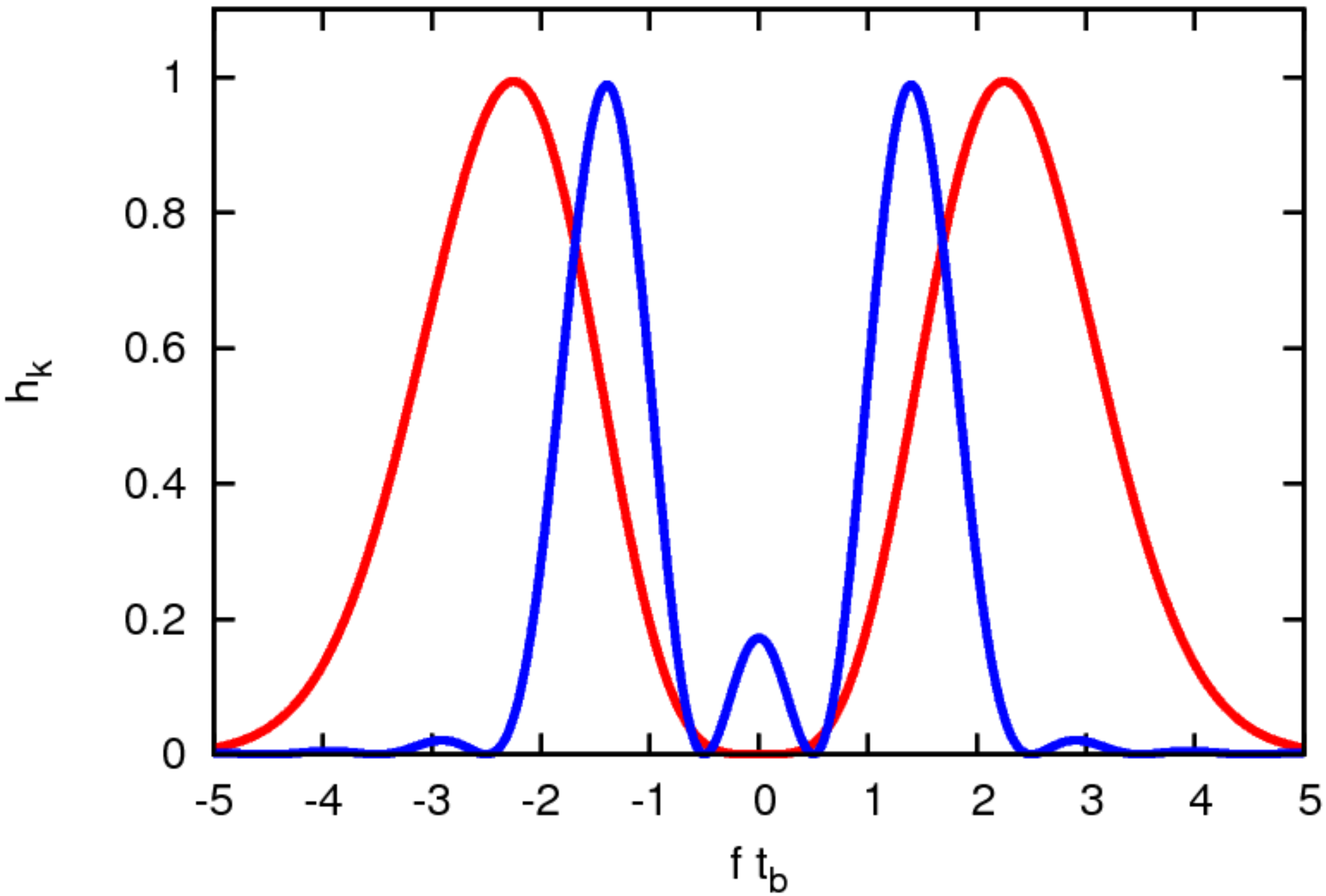


BUNCH SPECTRUM

Beam spectrum of the k=2 mode for different bunch profiles:
the sinusoidal bunch,
the Gaussian bunch.

A realistic bunch is more complicated

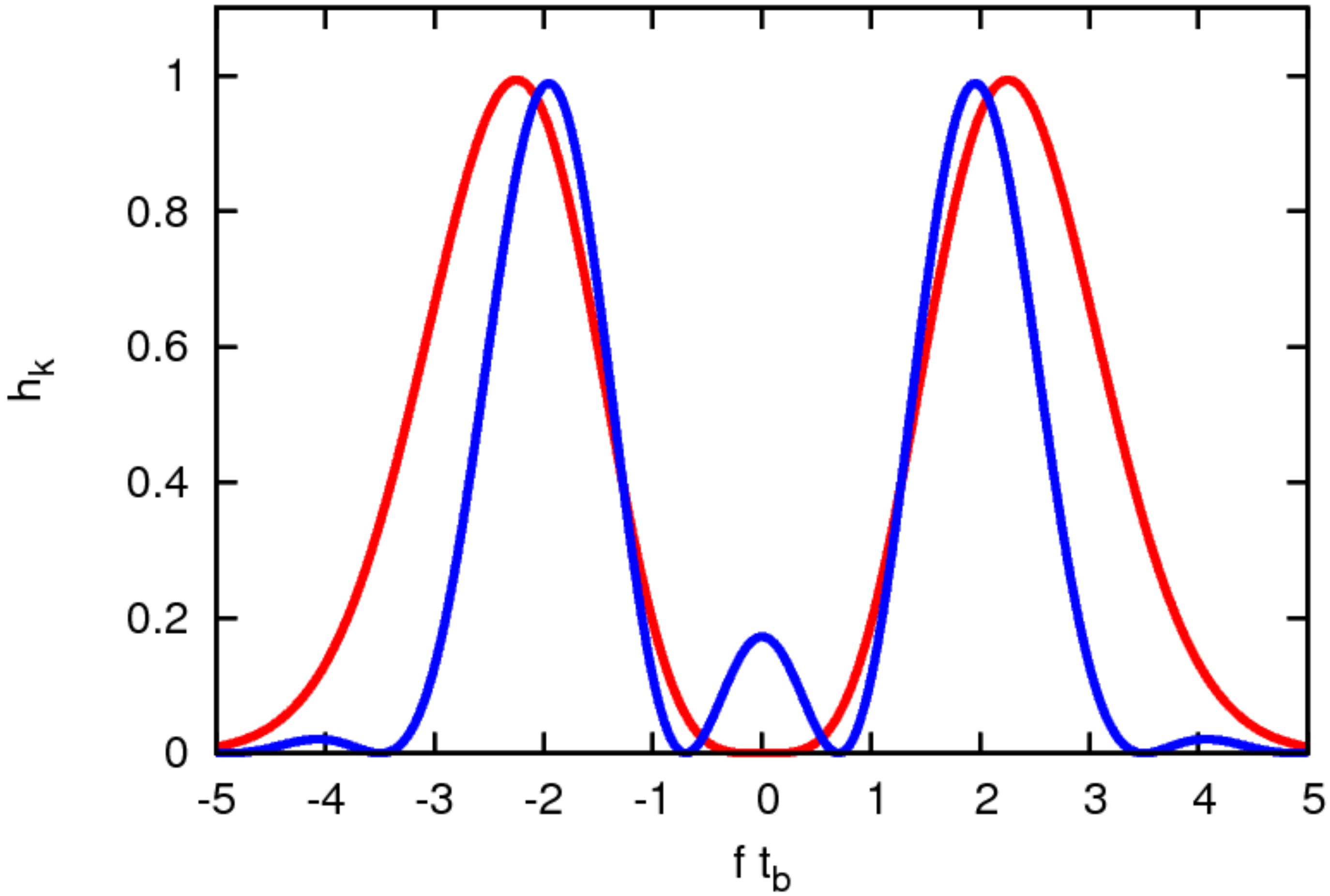
This causes some uncertainty for the impedance the bunch couples to.



BUNCH SPECTRUM

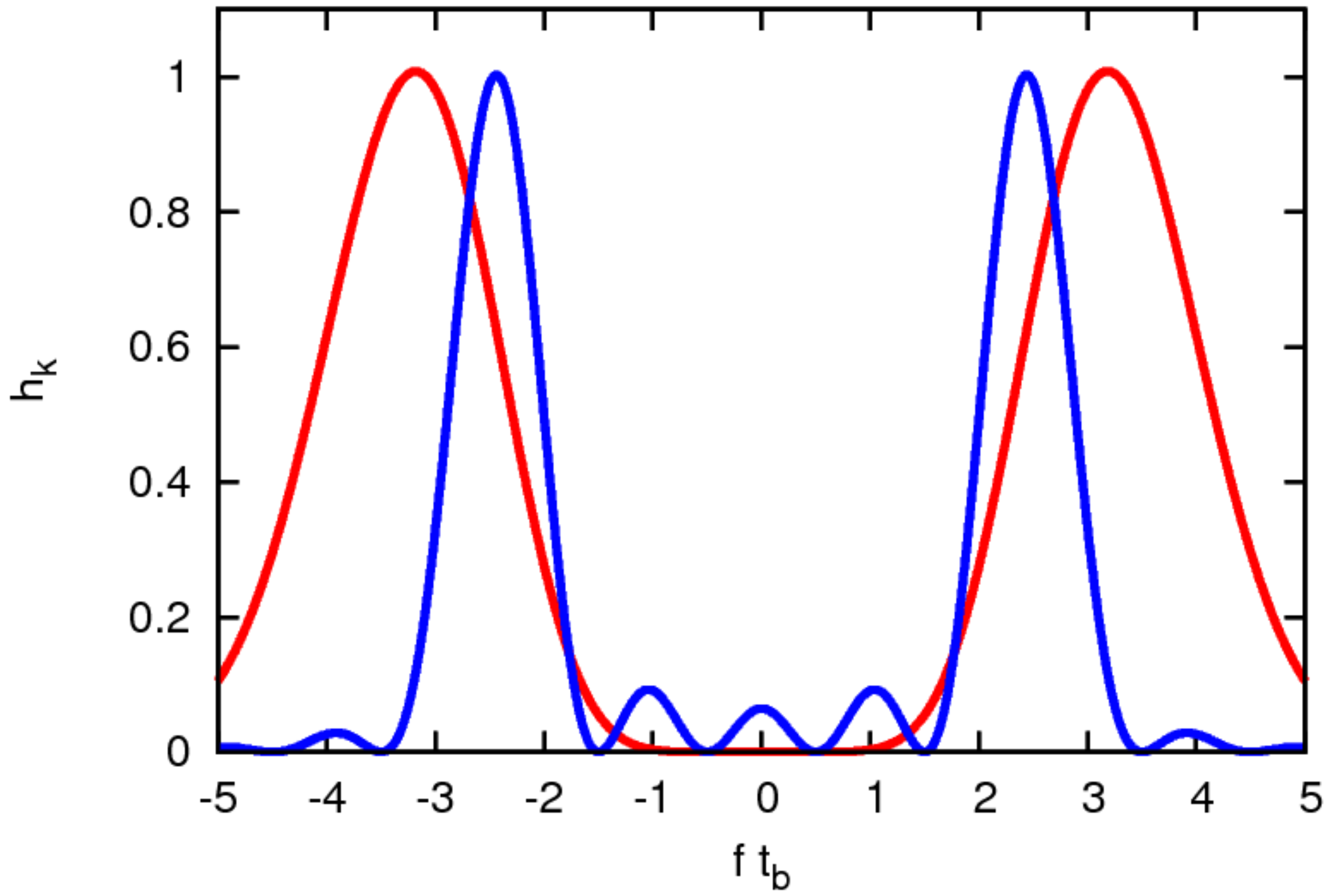
To cope with this difference,
the spectrum of a sinusoidal bunch can be stretched, here by a factor 1.4.

the sinusoidal bunch
the Gaussian bunch



BUNCH SPECTRUM

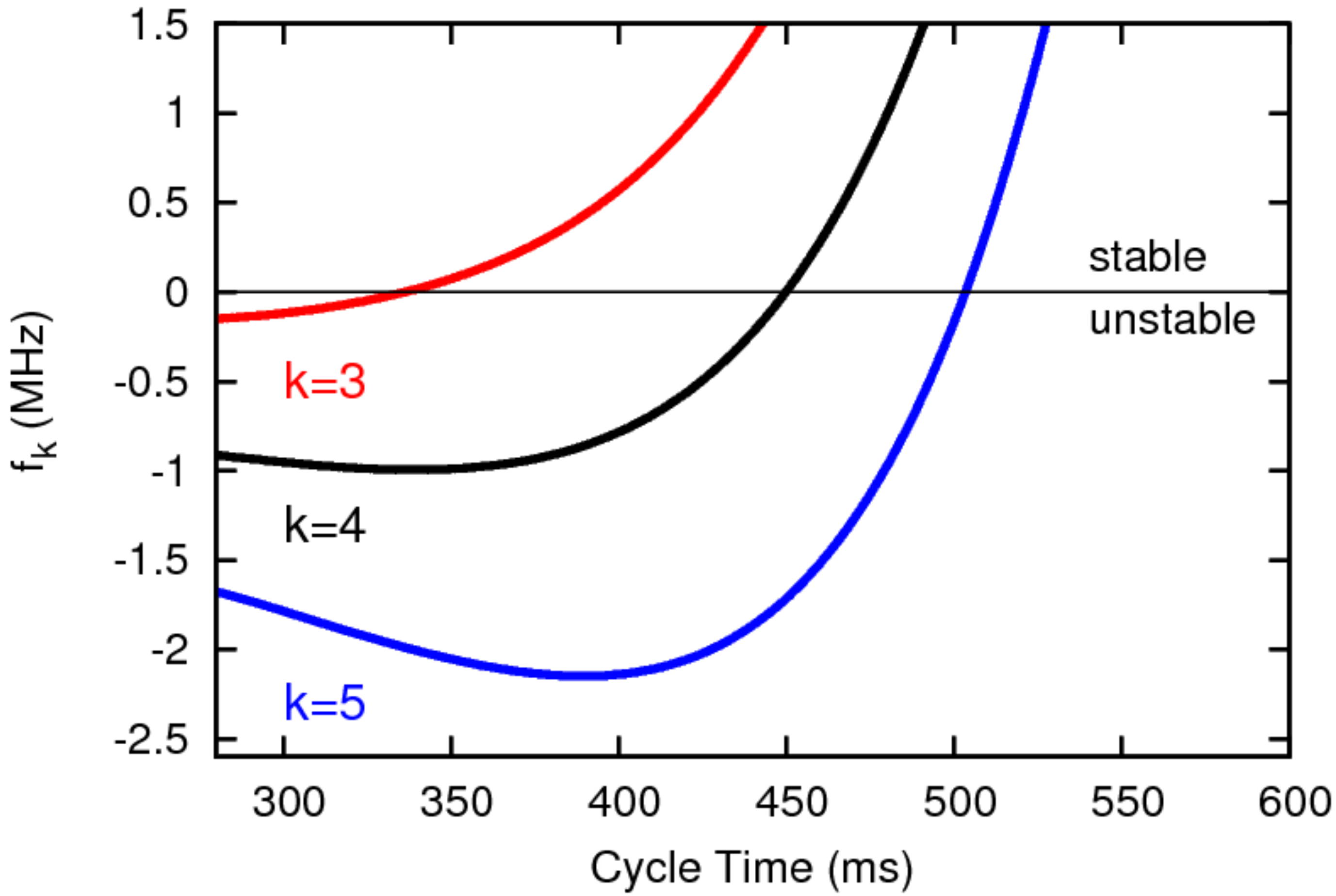
The spectrum width is also an uncertainty factor.
Here the bunch spectrum of the k=4 mode for
the sinusoidal bunch,
the Gaussian bunch.



HEAD-TAIL SPECTRUM AT PSB

Evolution of the lower (unstable) bunch spectrum part along the PSB cycle .

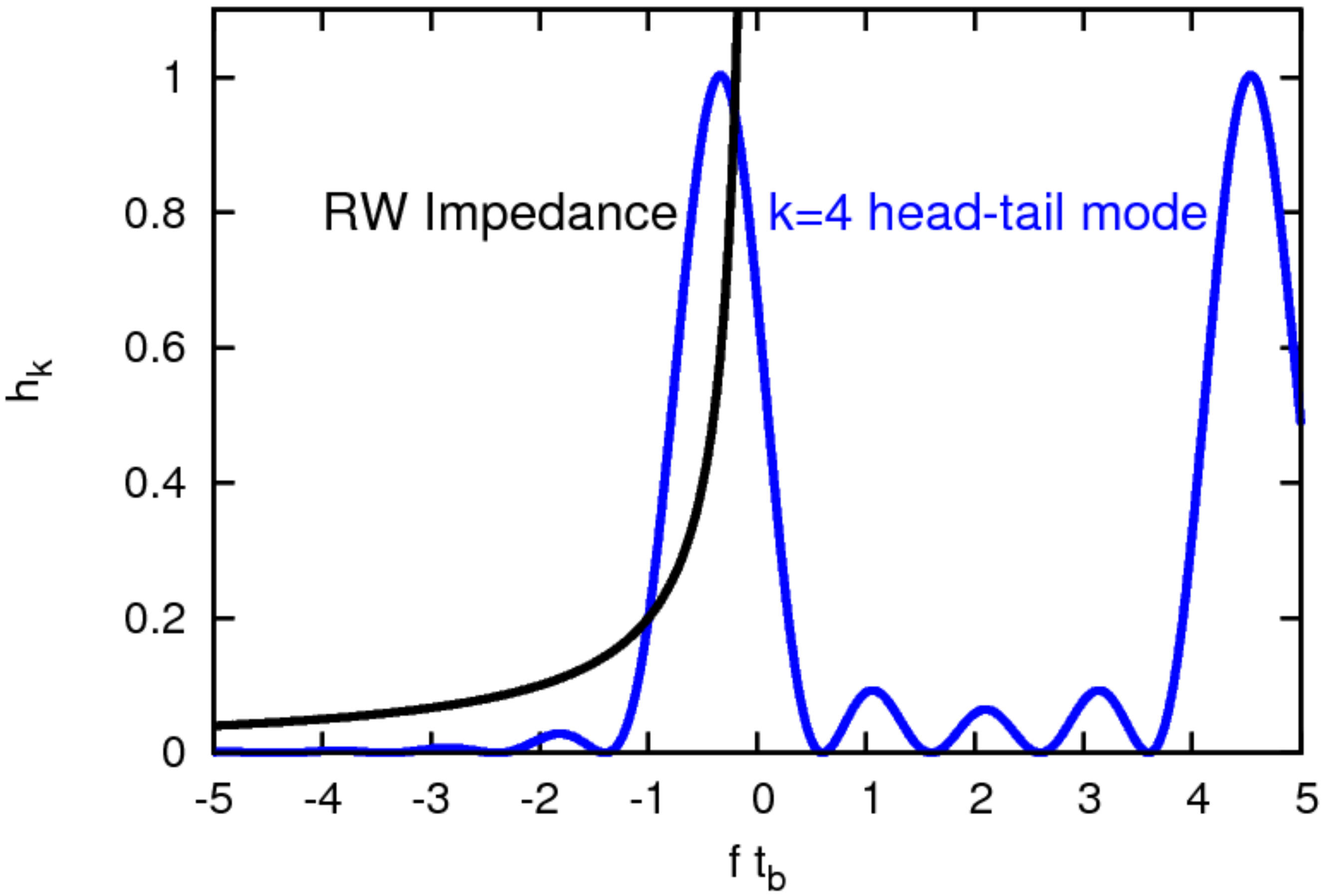
Higher-order modes cross the Resistive-Wall Impedance later in Ctime.



UNSTABLE HEAD-TAIL MODE AT PSB

As the bunch spectrum migrates during the cycle, it can become unstable due to coupling to the Resistive-Wall impedance, here a "narrowband" impedance.

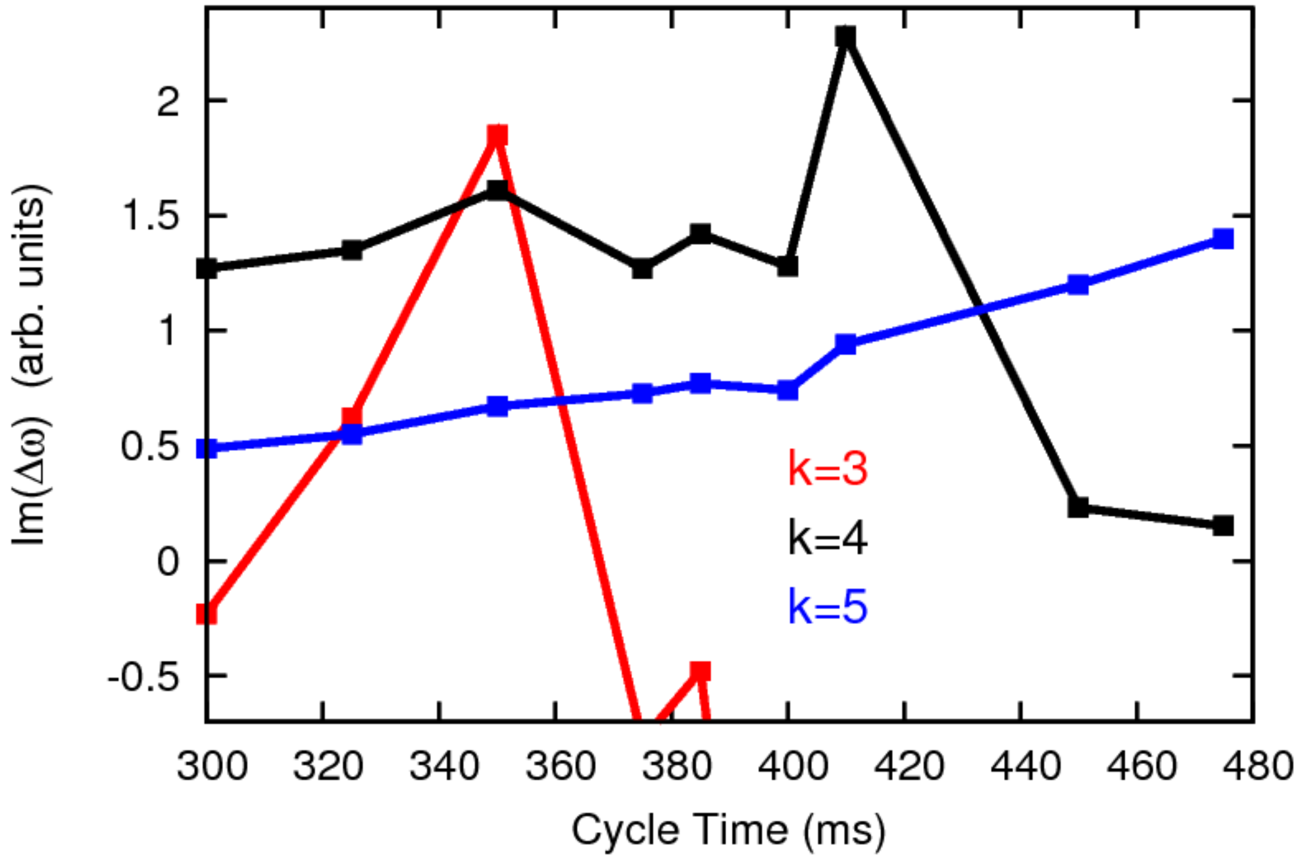
Another low-frequency (MHz) narrowband impedance can not be ruled out.



UNSTABLE HEAD-TAIL MODE AT PSB

Growth rates of the head-tail modes along the PSB cycle, as given by the Sacherer model, for the Resistive-Wall impedance

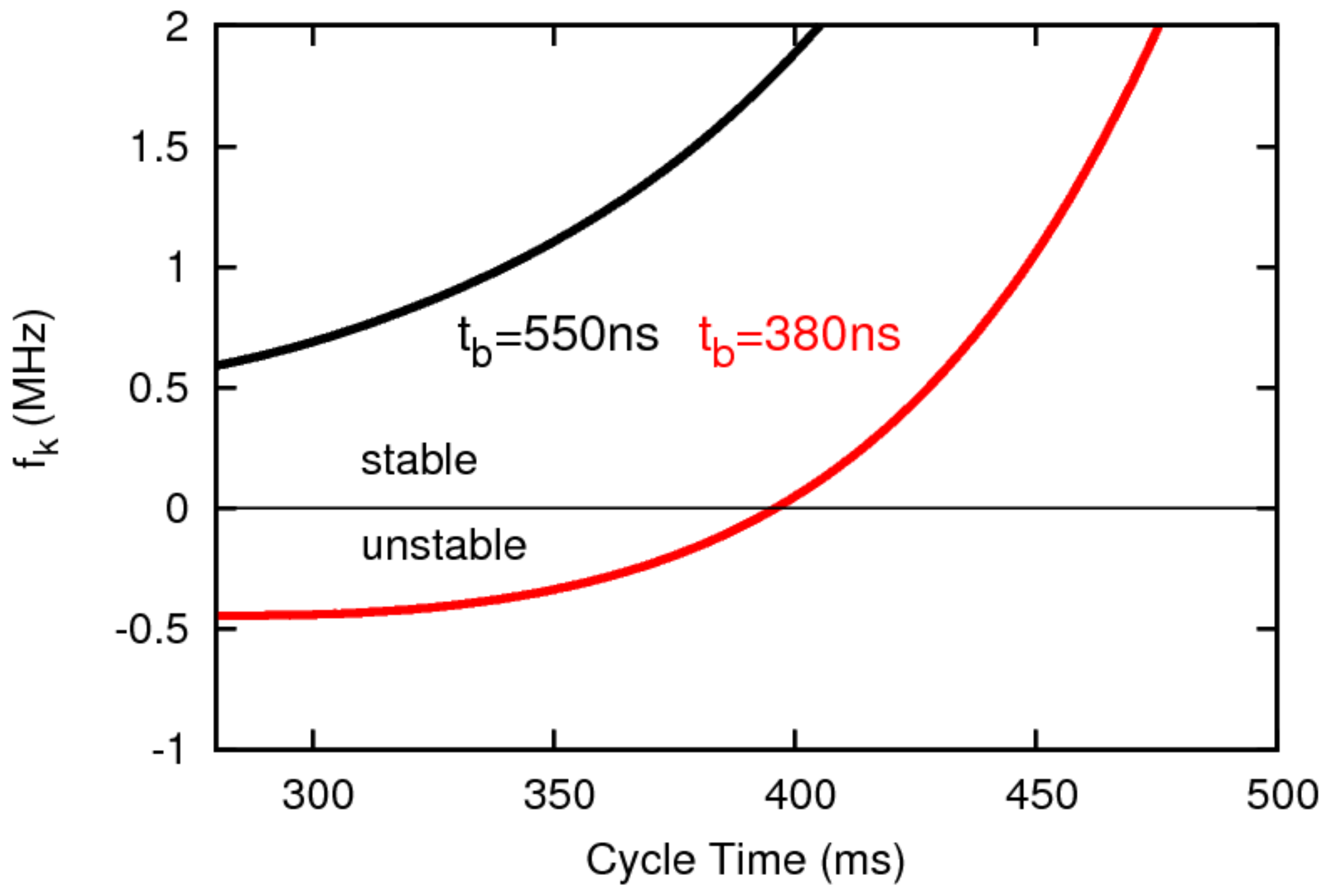
the main uncertainty for the quantitive estimations is due to the bunch spectrum (here a preliminary example for ξ=-0.8, detailed analysis in progress)



HEAD-TAIL SPECTRUM AT PSB

Lower-order head-tail modes for shorter bunches.

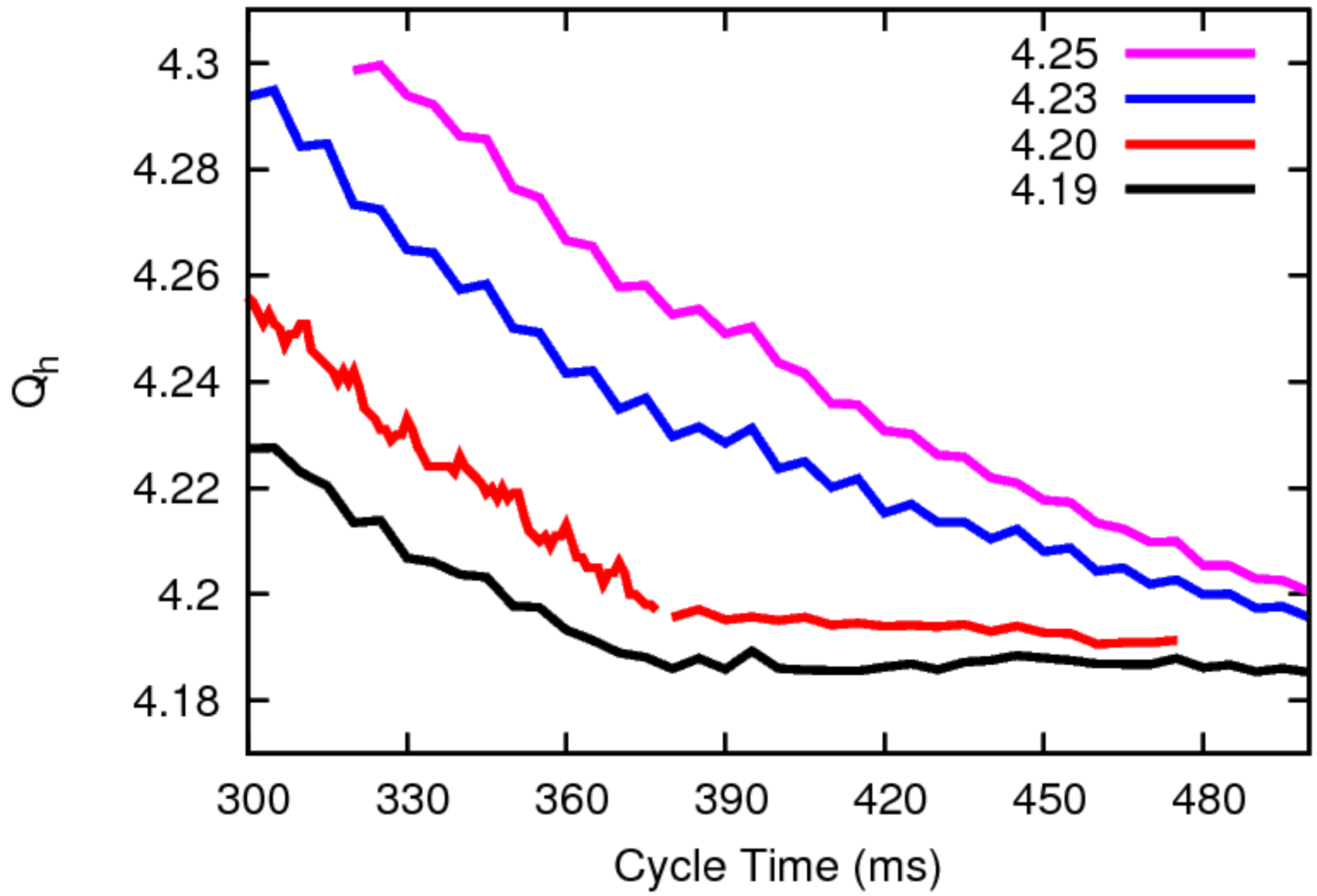
Evolution of the *k*=2 lower spectrum peak along the PSB cycle.



VARYING THE HORIZONTAL TUNE

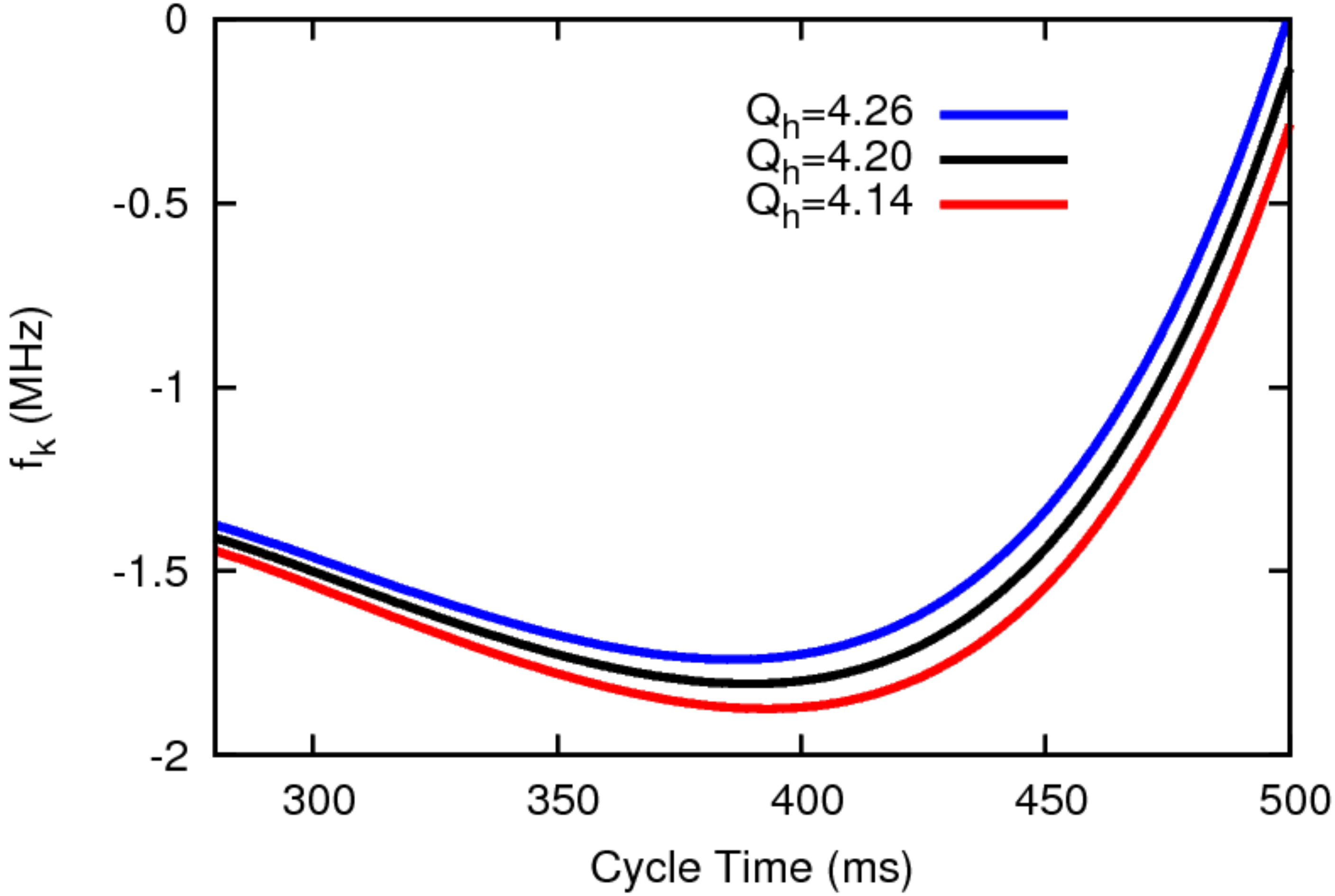
By changing the lattice tunes a (small) systematic shift of the instability Ctime has been observed.

Q_h=4.19: around C384
Q_h=4.20: around C386
Q_h=4.23: around C389
Q_h=4.25: around C392



HEAD-TAIL SPECTRUM AT PSB

Effect of the lattice betatron tune on the evolution of the frequency position for the k=4 mode.



CONCLUSIONS

The unstable head-tail modes observed during the PSB ramp are normally strongly deformed by the impedance

Intensity thresholds, growth rates and the mode structure are compared for single rf bucket and for double rf types: PSB standard, flat-bunch, short-bunch

The PSB bunches are in the strong space-charge regime

The Landau damping due to image charges with the direct space charge, if strong enough for PSB parameters, may contribute to the horizontal instability and to the later Ctimes of the instability

Analysis of the time evolution of the head-tail modes according to the Sacherer theory can explain higher-order modes for later Ctimes, lower-order modes for shorter bunches, and the Resistive-Wall impedance (or a low-frequency norrowband) as the driving force.