Head-Tail Instability and Beam Break-Up Instability with Strong Space Charge

Vladimir Kornilov, GSI Darmstadt

Head-Tail Instability

PSB at CERN

U^{28+} operation in SIS100 at GSI

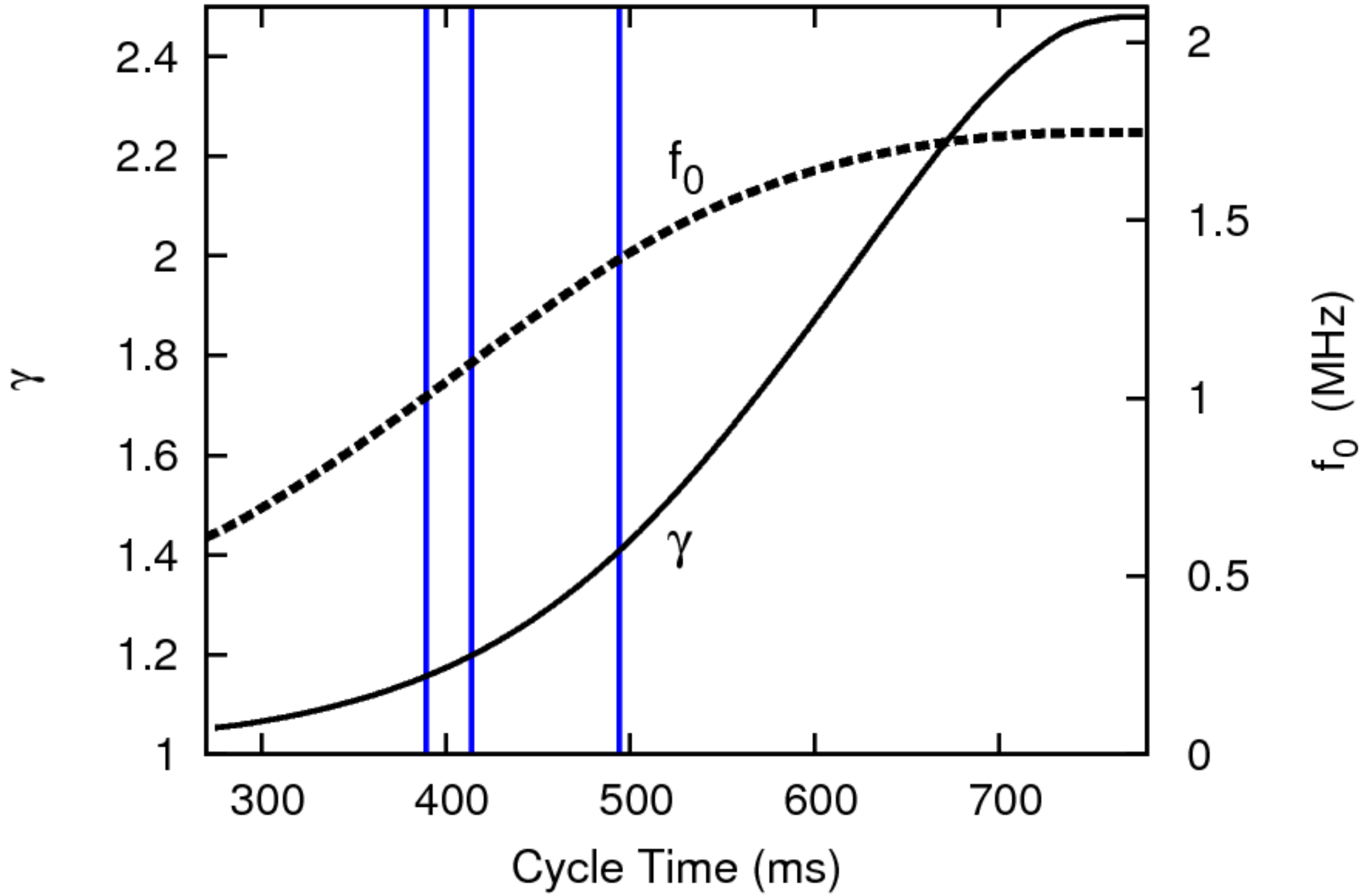
HEAD-TAIL IN THE PS BOOSTER

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

R=25m

Kin. energy
50 MeV-1.4 GeV

Q_h=4.27-4.17
Q_v=4.65-4.20
ξ_h=-0.95 ξ_v=-2.1



Measurement campaign at the PS Booster in June 2012.
Help of A.Findley, S.Aumon, B.Mikulec, G.Rumolo

HEAD-TAIL IN THE PS BOOSTER

The classical head-tail instability:

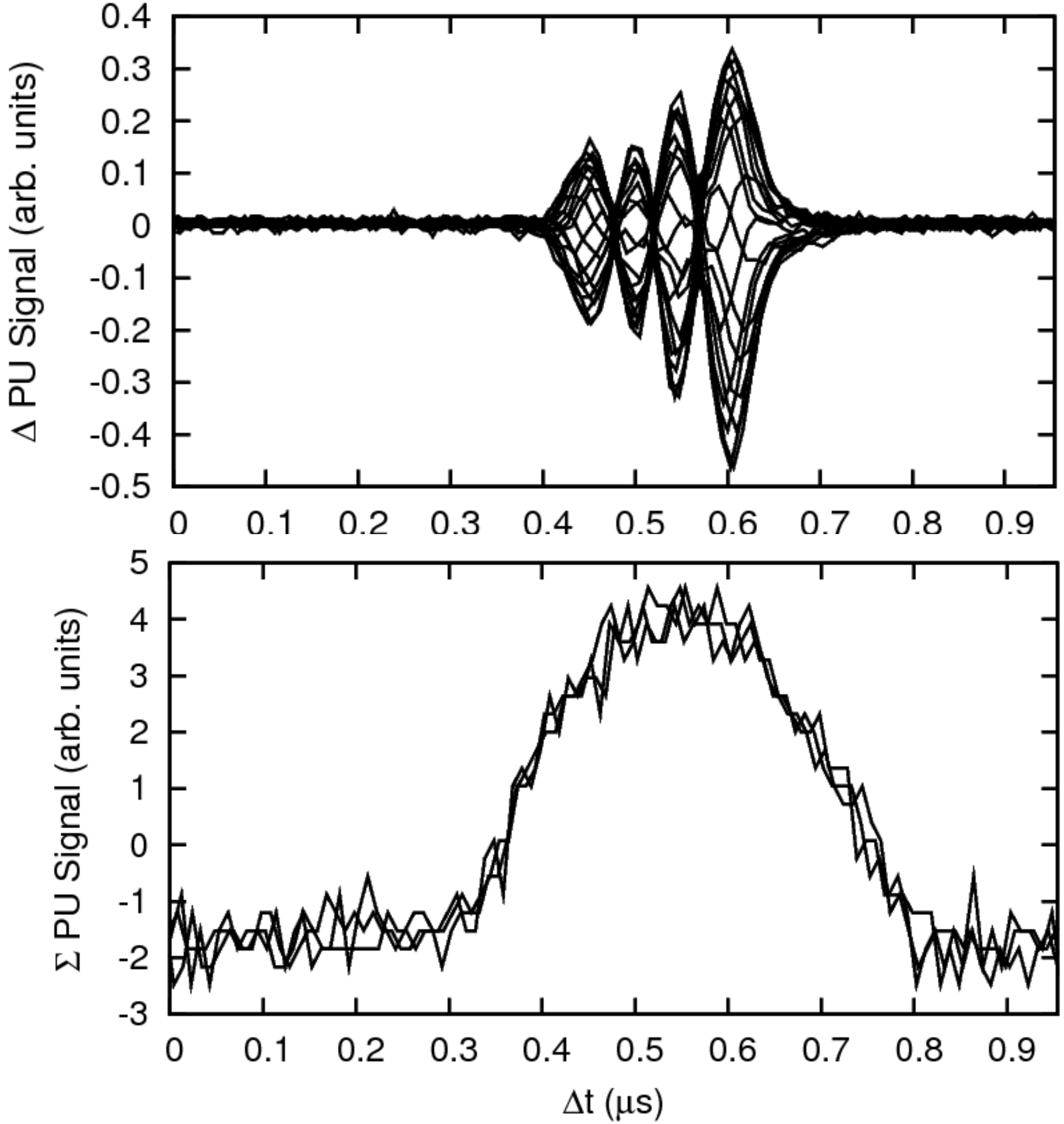
a standing-wave structure with the ξ-wiggles within; here 3 knots, the k=3 mode

nice exponential growth

$\Delta Q/Q_s<0.3$

Puzzling:

- **horizontal plane only**
- **fixed Ctimes, regardless the bunch distribution**

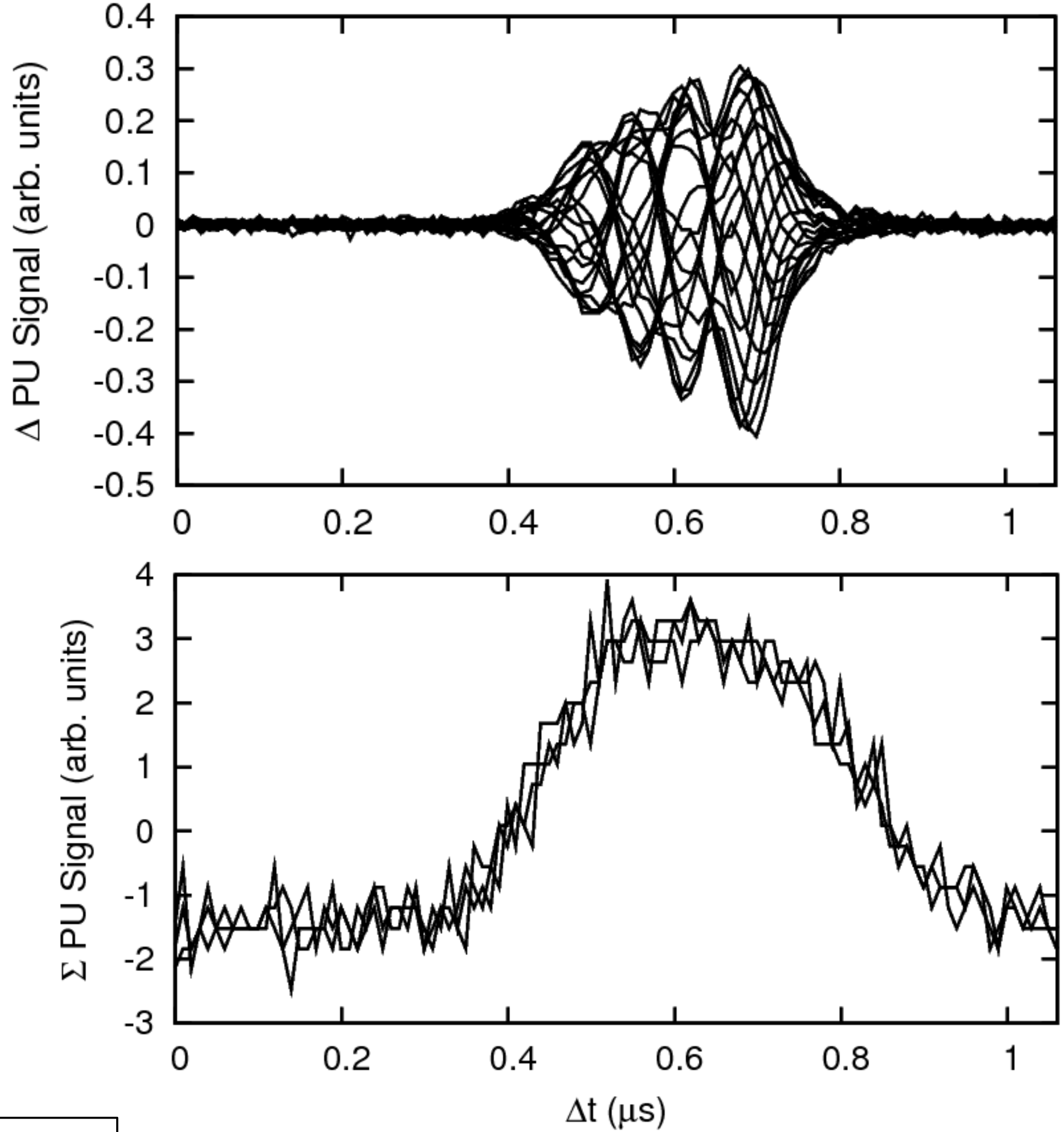


HEAD-TAIL IN THE PS BOOSTER

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: modified by the impedance



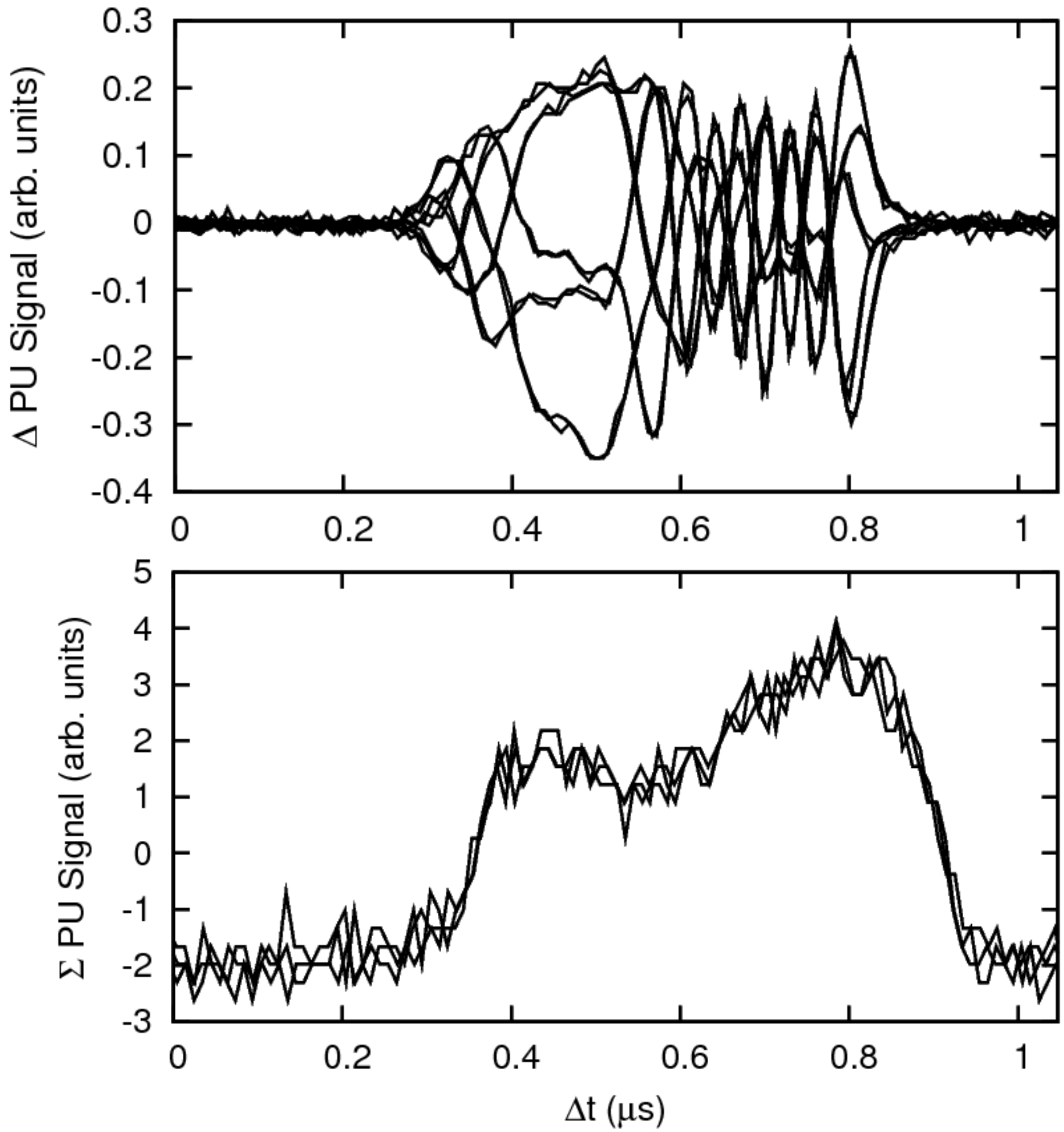
more details in the upcoming CERN Report

HEAD-TAIL IN THE PS BOOSTER

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

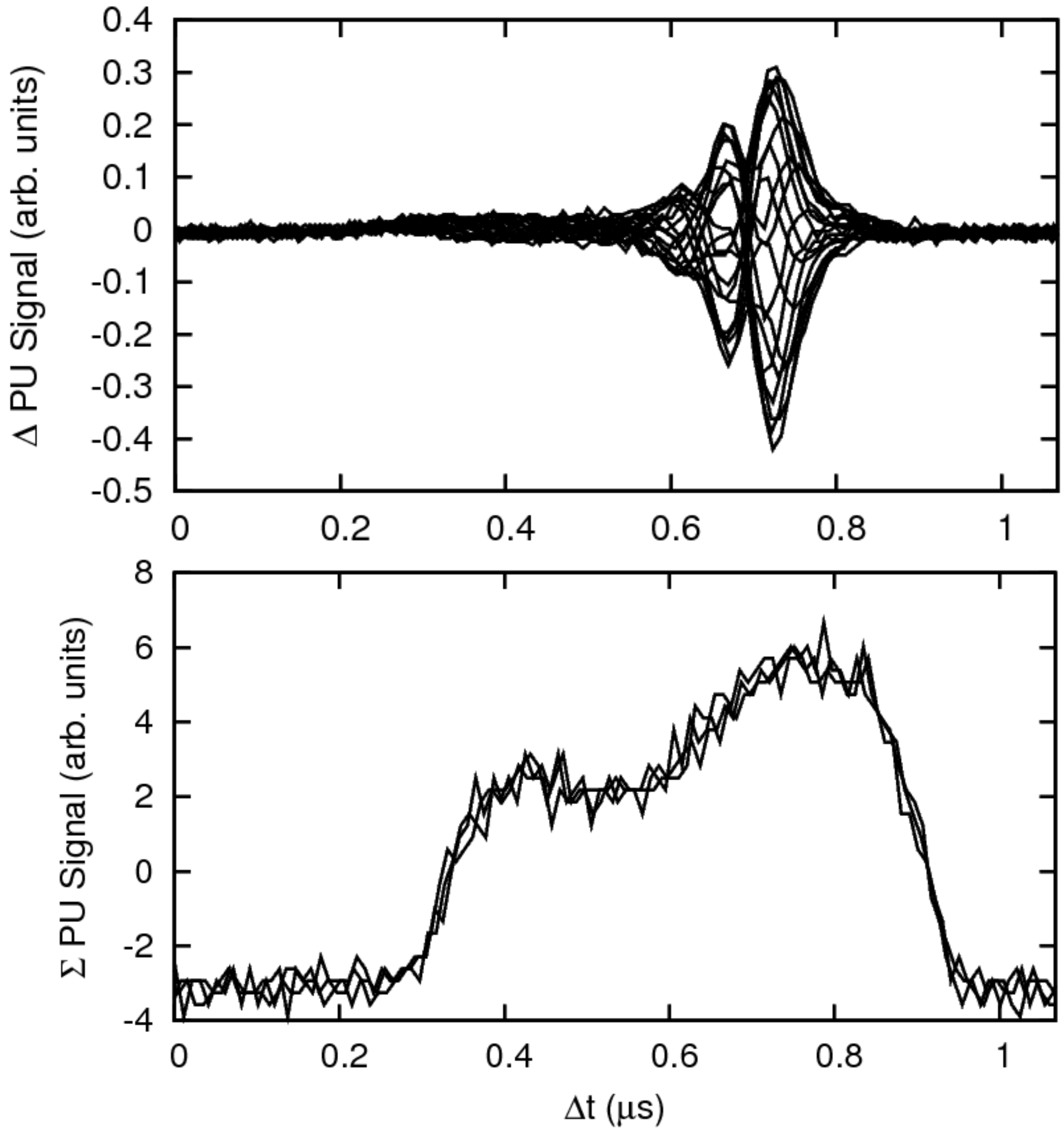


HEAD-TAIL IN THE PS BOOSTER

Instability at C394ms
double rf, PSB standard
higher intensity

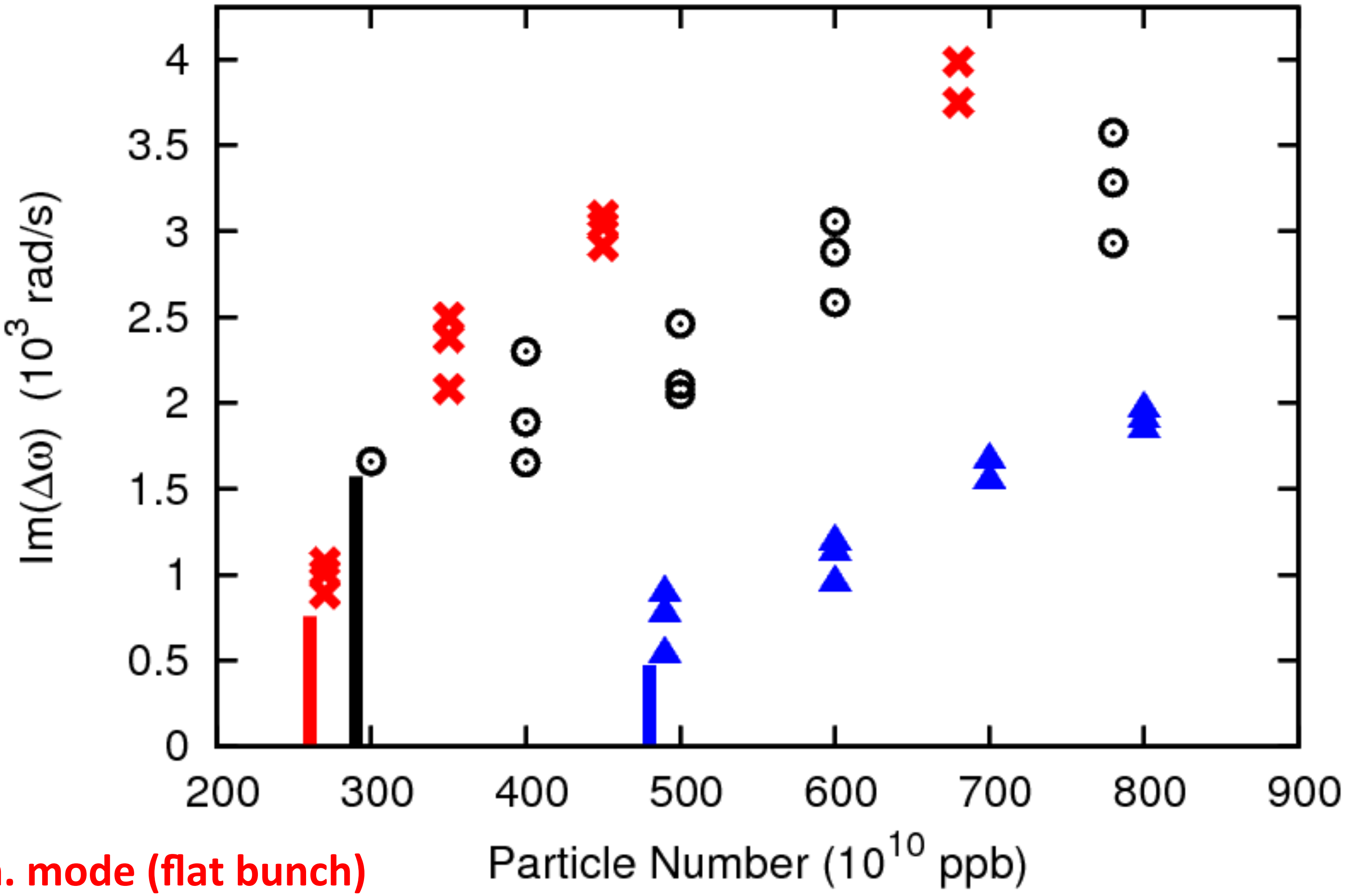
N_p=950e10

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



HEAD-TAIL IN THE PS BOOSTER

Summary of the instability growth rates and thresholds

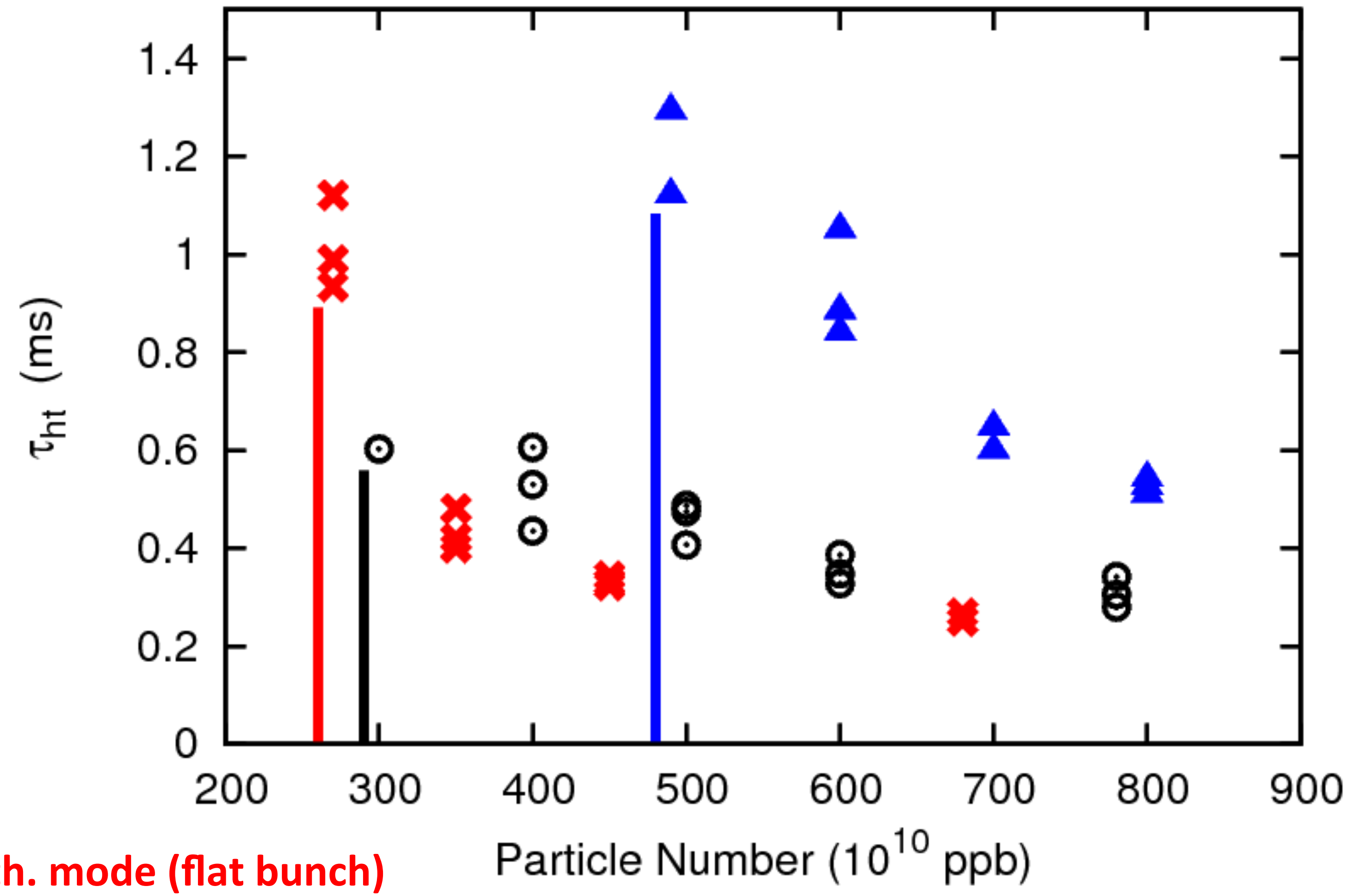


- ○ **single rf**
- ✖ **double rf length. mode (flat bunch)**
- ▲ **double rf - PSB standard**

more details in the upcoming CERN Report

HEAD-TAIL IN THE PS BOOSTER

Summary of the instability growth times and thresholds



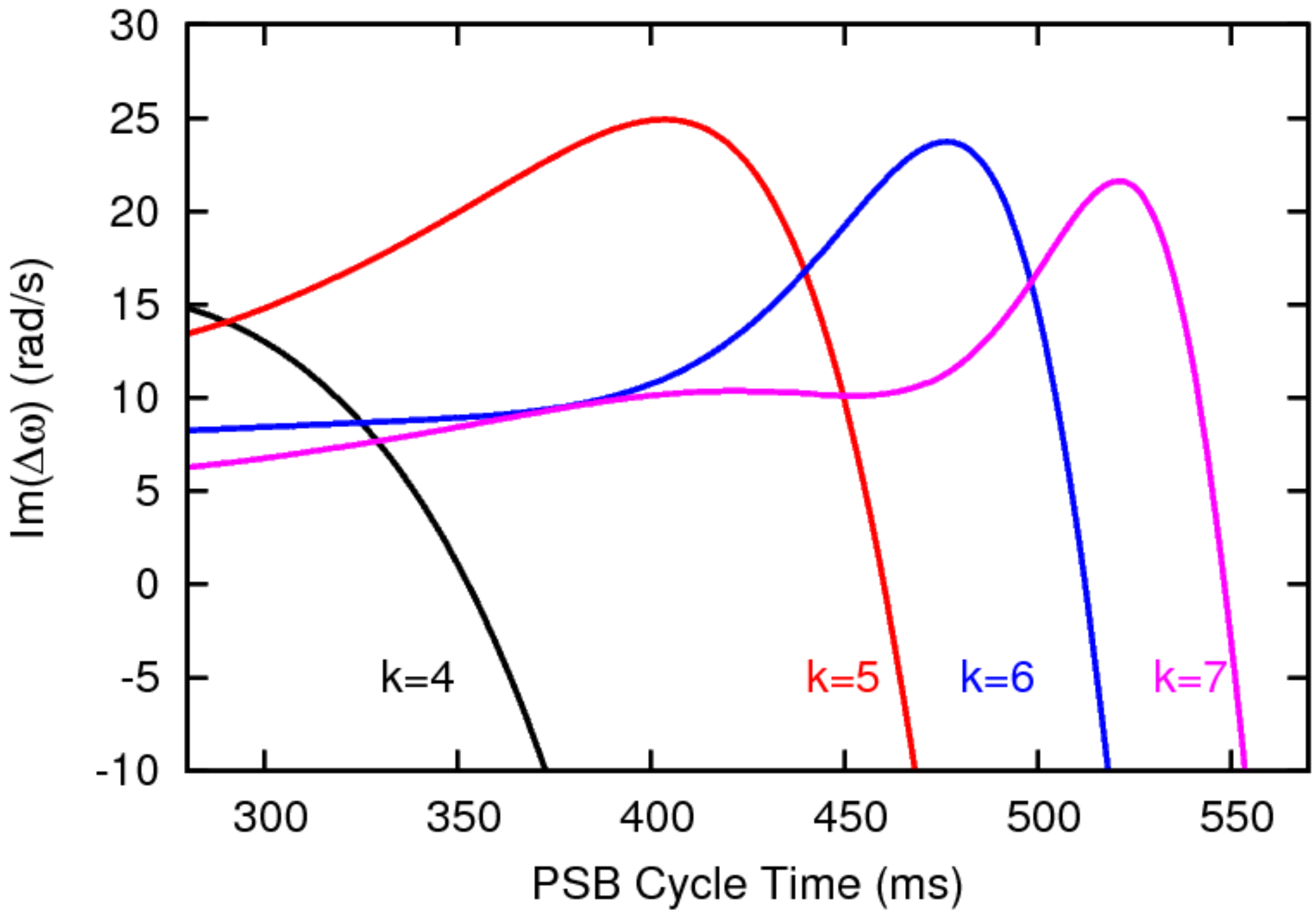
- o **single rf**
- ✖ **double rf length. mode (flat bunch)**
- ▲ **double rf - PSB standard**

more details in the upcoming CERN Report

HEAD-TAIL IN THE PS BOOSTER

The head-tail growth rate given by the Sacherer theory for each single ms along the PSB ramp.

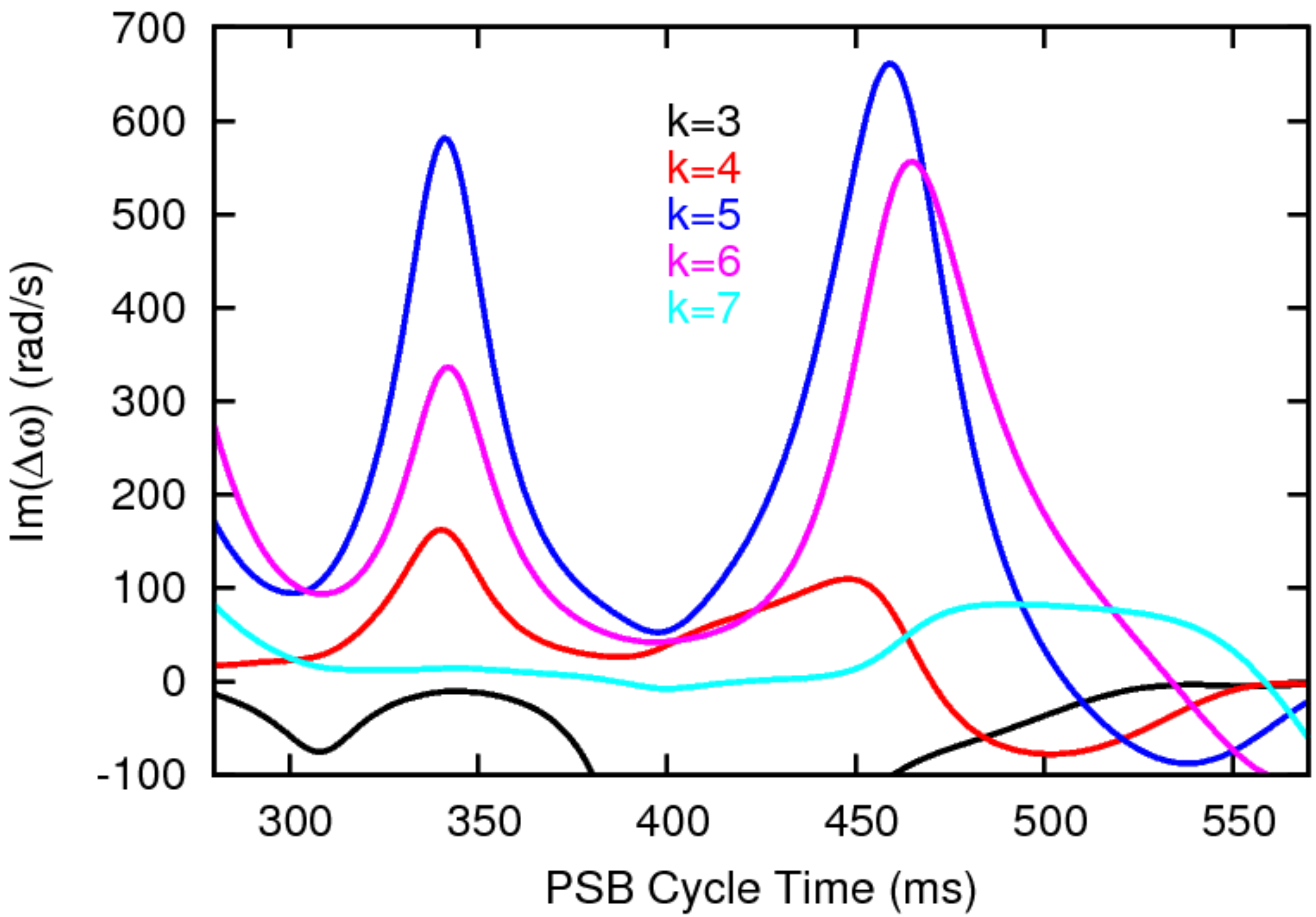
The Resistive Wall Impedance: PSB overestimated



Growth rates orders of magnitude smaller than observed

HEAD-TAIL IN THE PS BOOSTER

The head-tail growth rate given by the Sacherer theory for each single ms along the PSB ramp.



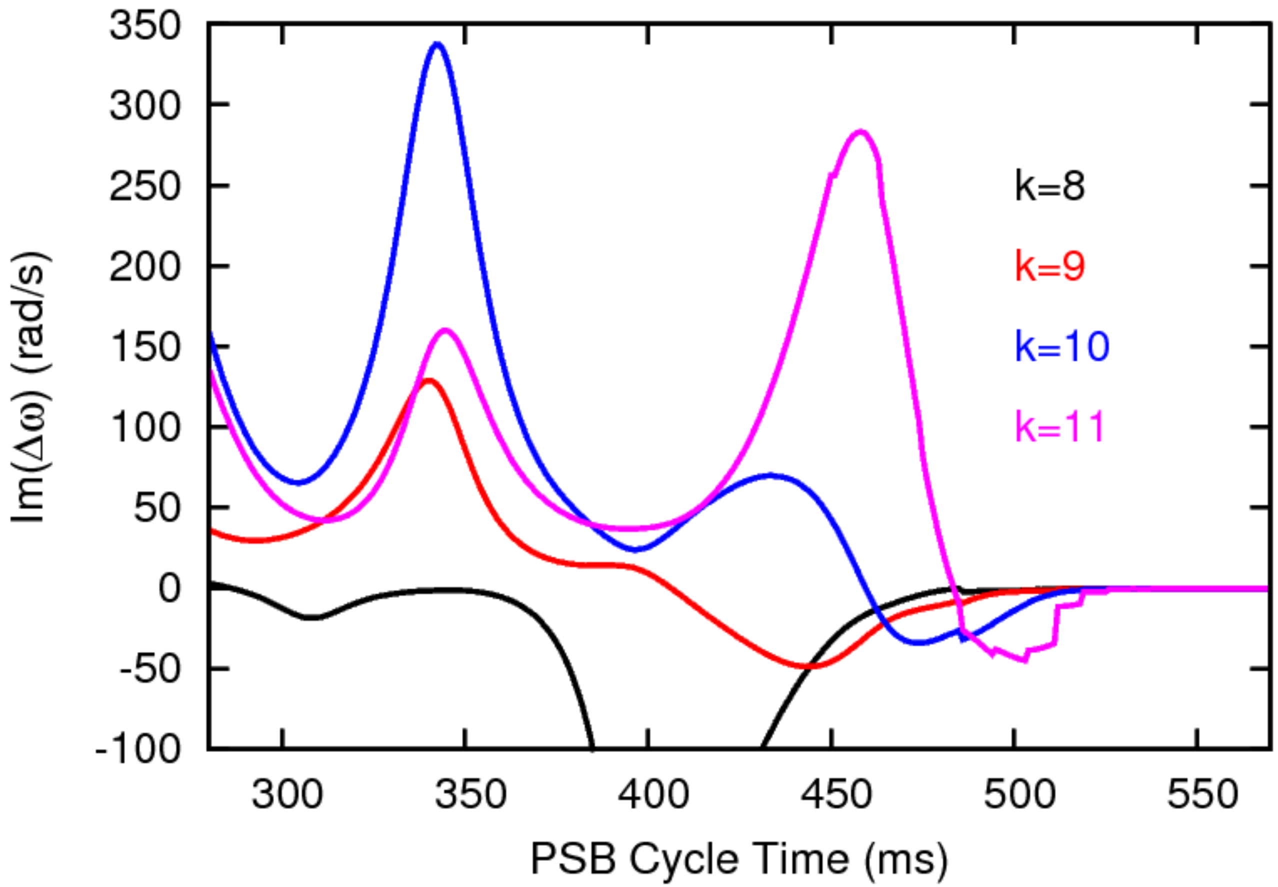
an example:
A Narrow-Band Impedance
f_r=2.2MHz, Q_T=8,
R_T=3MΩ/m

horizontal
ξ_h=-0.95

Corresponds to the observations:
- a "resonant" behavior as the bunch frequencies hit the impedance
- independent from the distribution details

HEAD-TAIL IN THE PS BOOSTER

The head-tail growth rate given by the Sacherer theory for each single ms along the PSB ramp.



an example:
A Narrow-Band Impedance
f_r=2.2MHz, Q_T=8,
R_T=3MΩ/m

vertical
ξ_v=-2.1

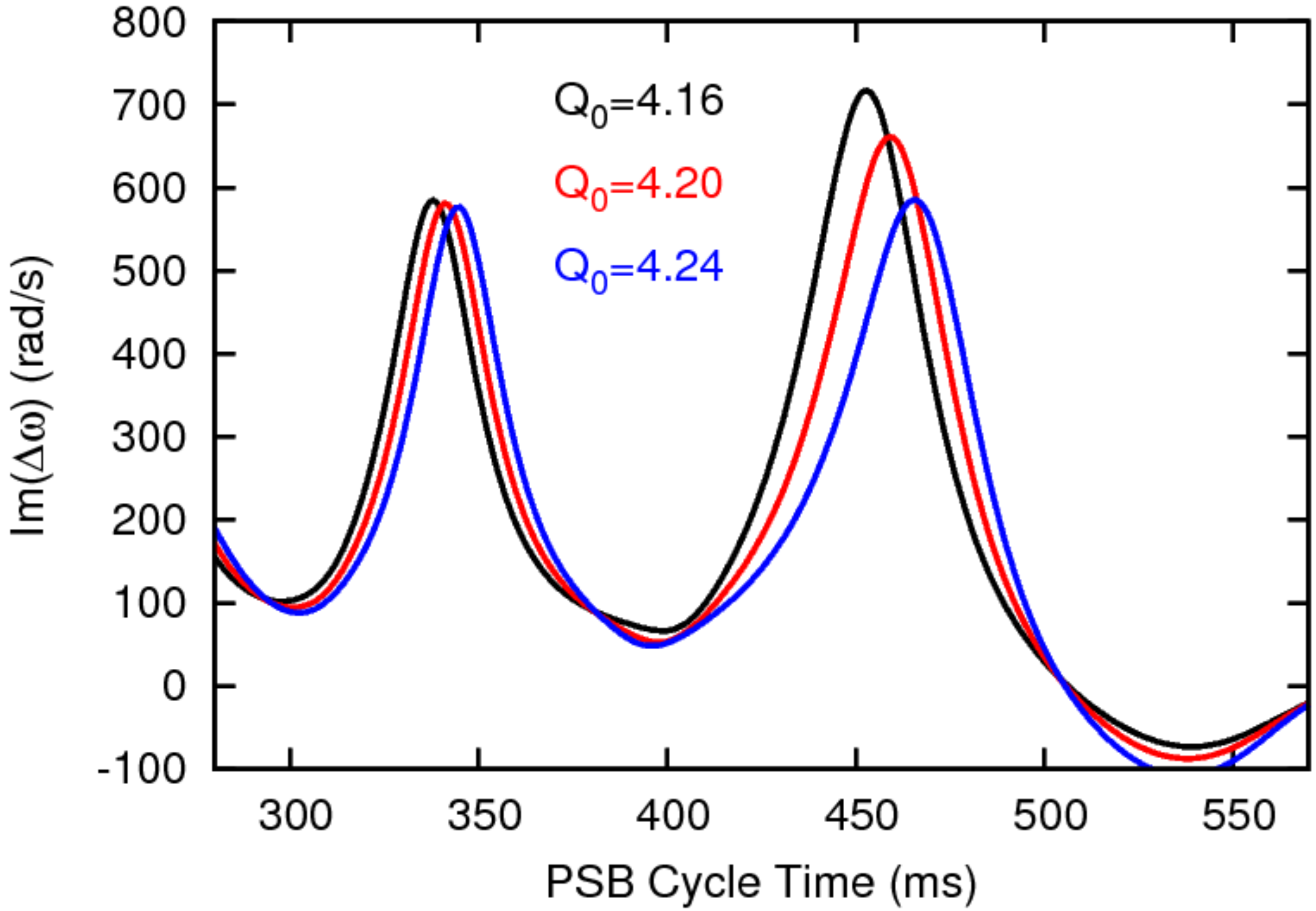
Corresponds to the observations:
Vertical plane instabilities are weaker due to higher-order modes provided by higher chromaticity

HEAD-TAIL IN THE PS BOOSTER

In the PSB experiment, by changing the lattice tunes a 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

The head-tail growth rate given by the Sacherer theory for the narrow-band imp.



Another nice agreement with the observations at the PS Booster

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)

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

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

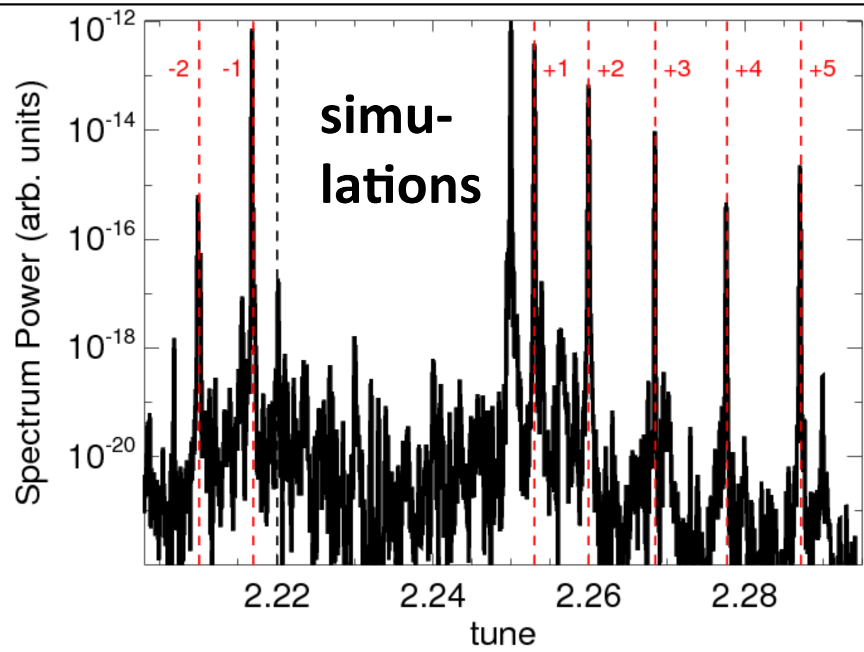
SPACE CHARGE

Space Charge in bunches:

- shifts the head-tail line, for an airbag bunch:

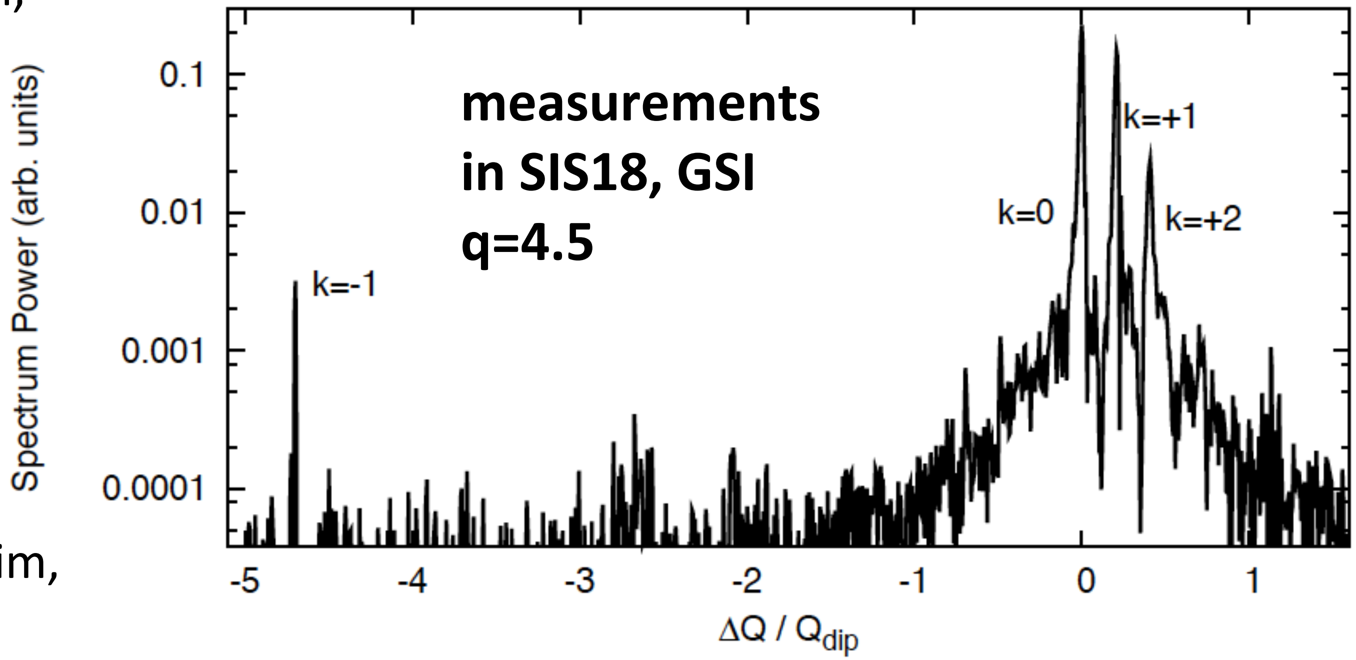
$$\Delta Q_k = -\frac{\Delta Q_{sc}}{2} \pm \sqrt{\frac{\Delta Q_{sc}^2}{4} + k^2 Q_s^2}$$

- induces strong Landau damping



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

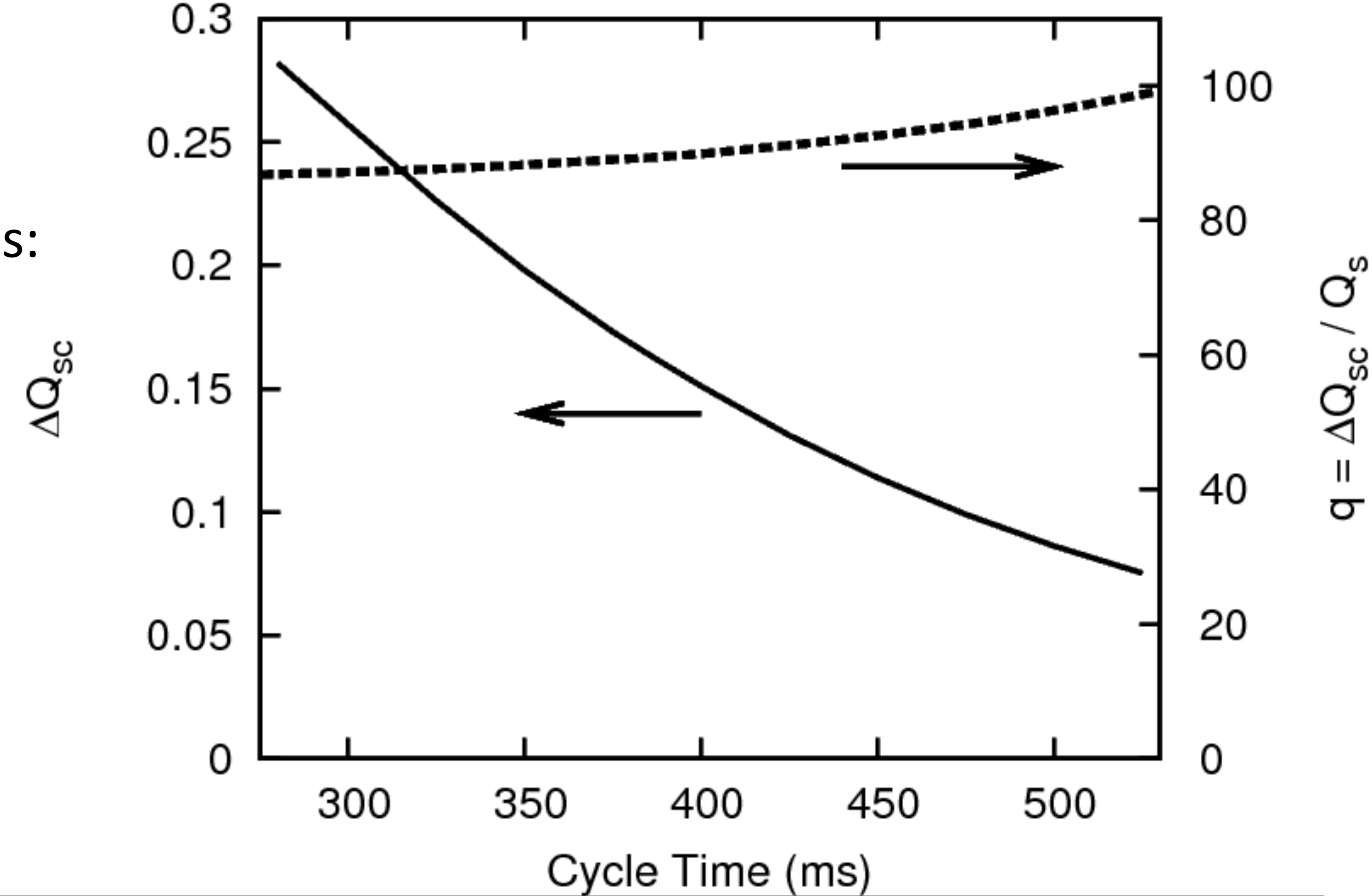
Confirmed by simulations and experiment



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

HEAD-TAIL IN THE PS BOOSTER

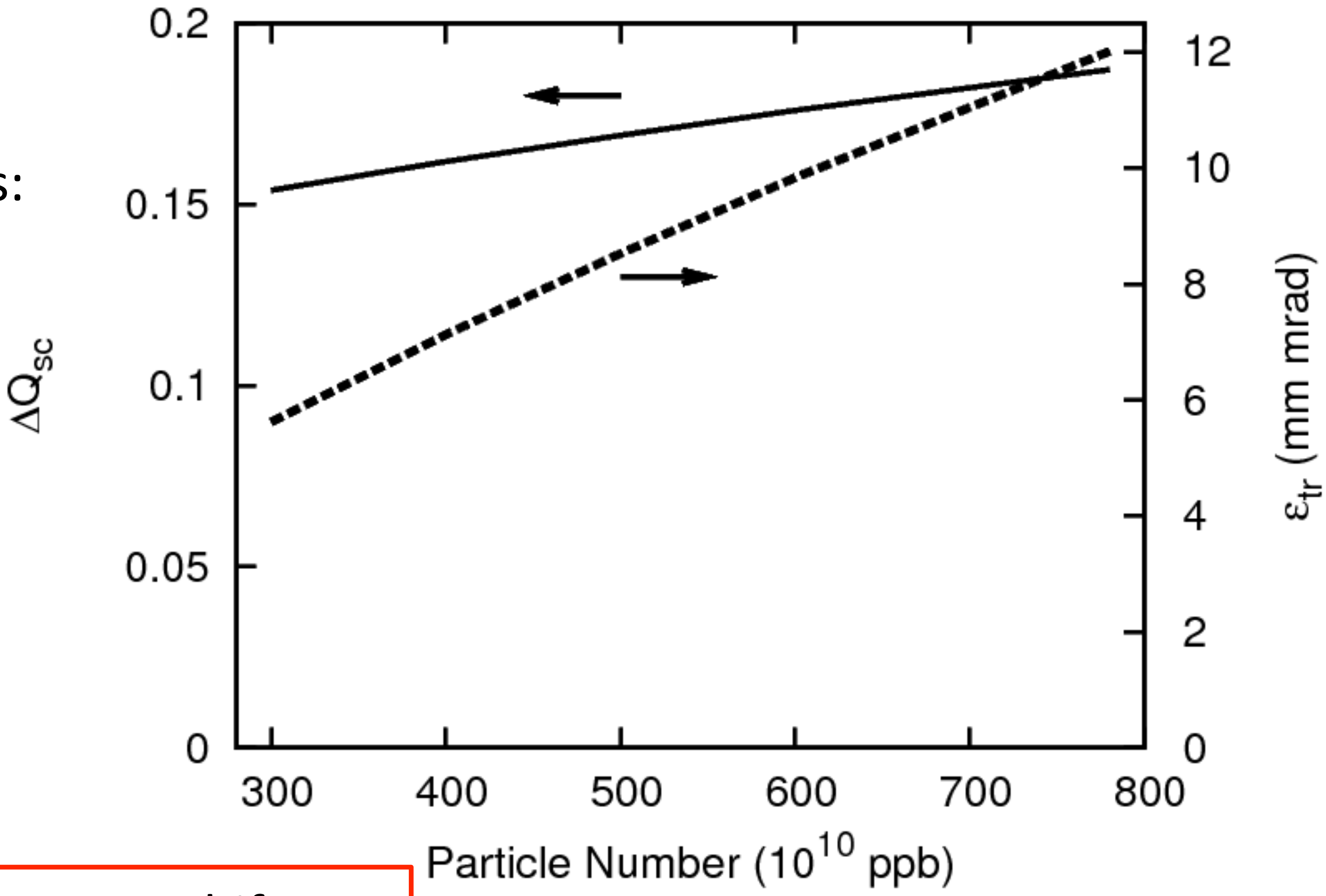
from the measurements: space-charge tune shift for single rf, V_0=8kV, 300e10 ppb, horizontal



the space-charge parameter *q* stays const. during the ramp;
very strong space charge regime;
no direct-SC Landau damping for the relevant (k<6) head-tail modes

HEAD-TAIL IN THE PS BOOSTER

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 of the intensity

HEAD-TAIL IN THE PS BOOSTER

another aspect of Space Charge: The Pipe Image Charges

the eigenfrequencies of the bunch head-tail modes
with arbitrary space-charge and coherent shift:

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

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

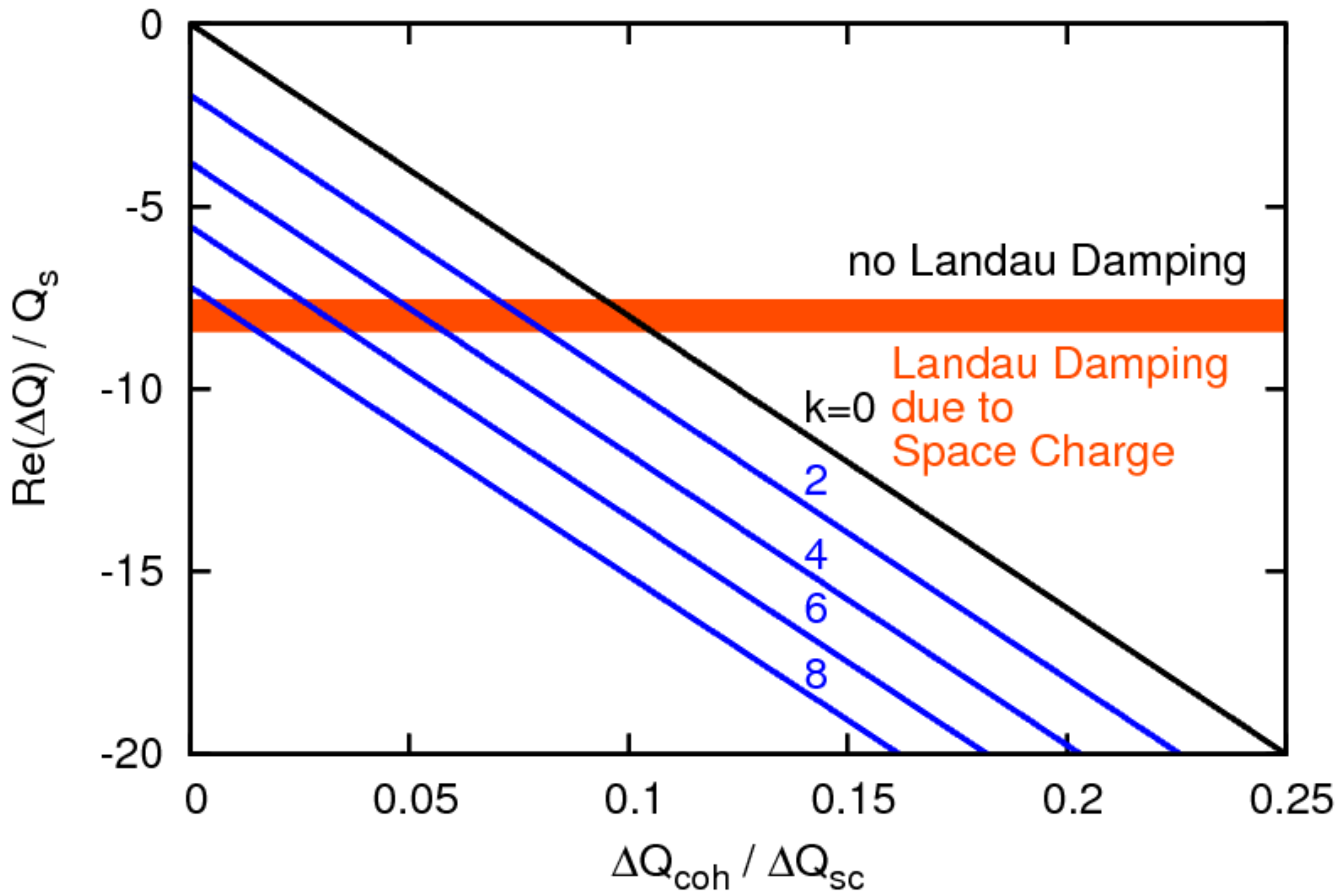
O.Boine-Frankenheim, V.Kornilov, PRSTAB **12**, 114201 (2009)
V.Kornilov, O.Boine-Frankenheim, PRSTAB **13**, 114201 (2010)
M.Blaskiewicz, PRSTAB **1**, 044202 (1998)

HEAD-TAIL IN THE PS BOOSTER

consider
Space Charge typical
for PSB:
q=80

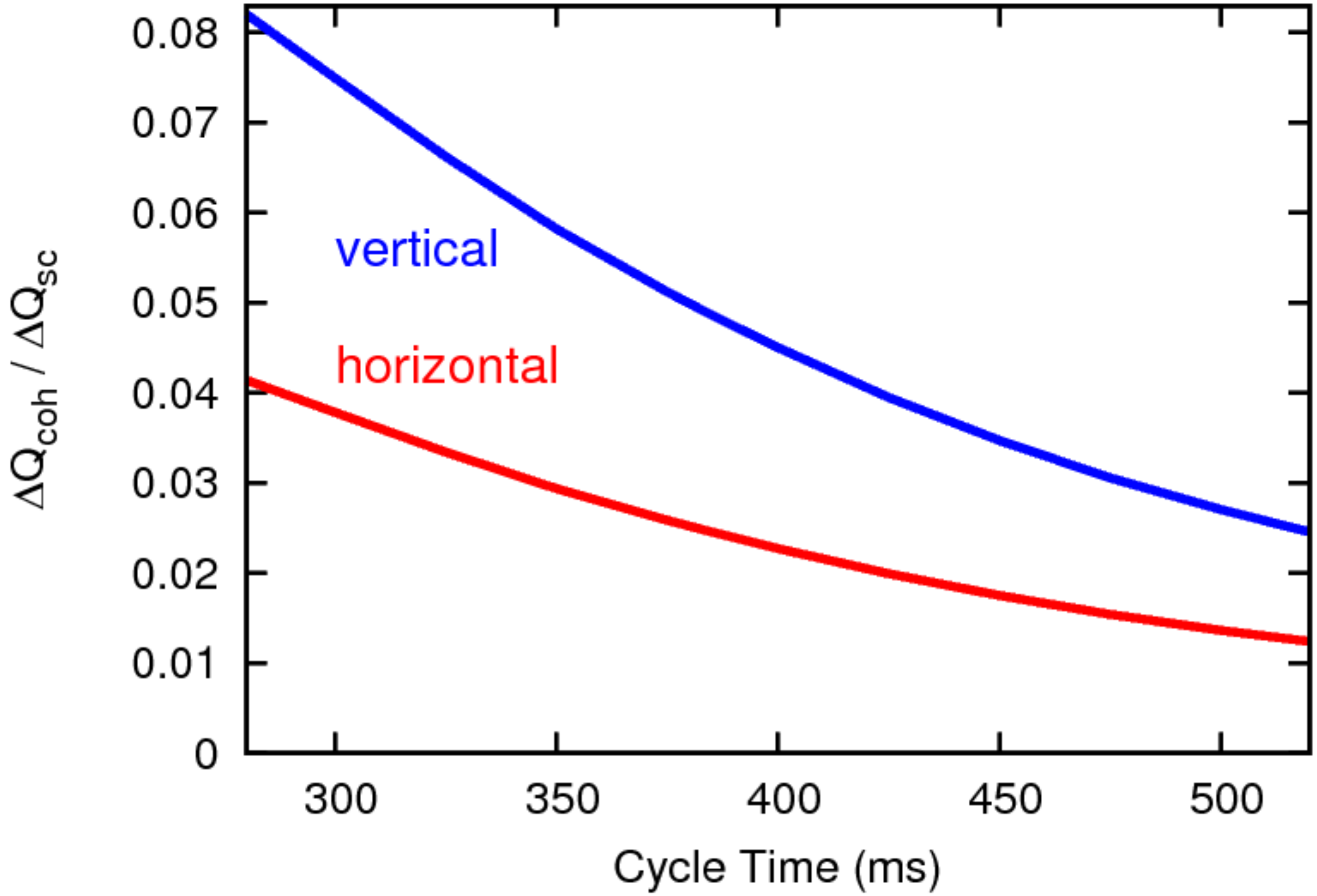
Landau damping
effective boundary
($-0.1q_{sc}$)

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



might be important for machines like PSB, SIS100. Further simulation studies under progress

HEAD-TAIL IN THE PS BOOSTER



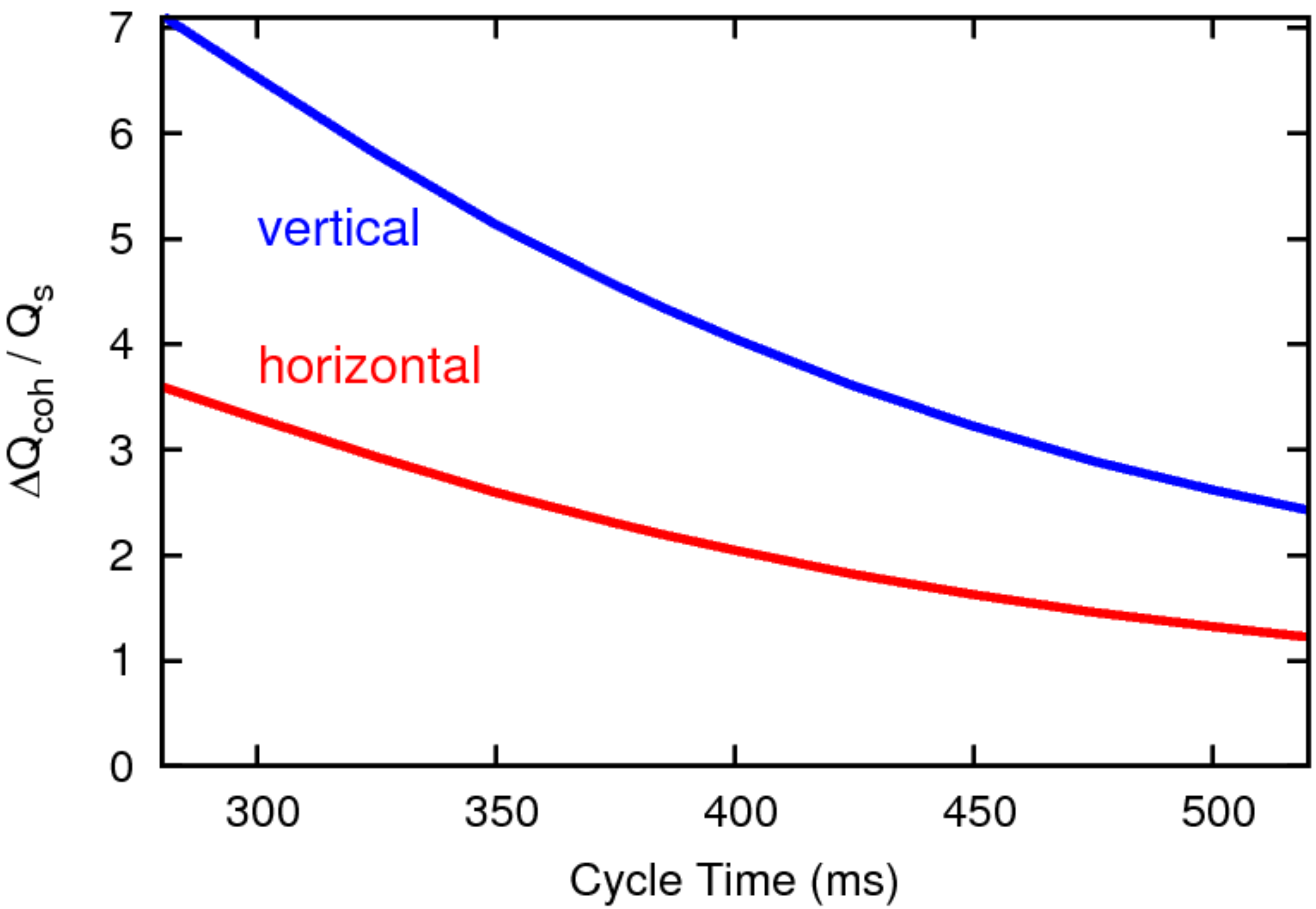
Landau damping is stronger in the vertical plane;
the damping contribution decreases along the cycle.
This may contribute to the horizontal exclusiveness and to the later occurrence in CTime

HEAD-TAIL IN THE PS BOOSTER

good news:

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

During the cycle, the head-tail modes cross a wide frequency range



Still, no fast Transverse Mode Coupling Instability (TMCI) observed. Suppressed by space charge?

Theory predictions: Blaskiewicz prstab 1998; Burov prstab 2009

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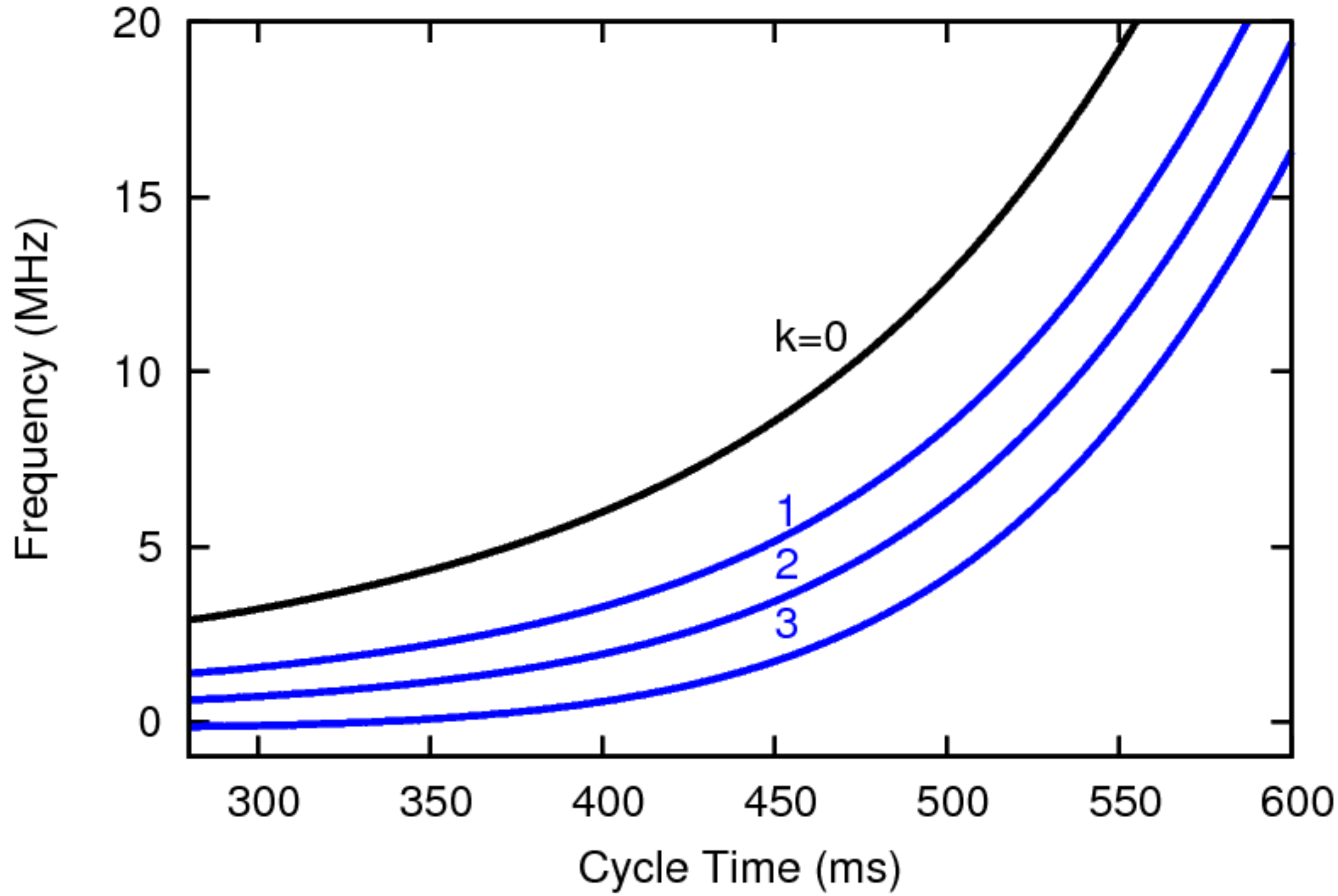


Still, no fast Transverse Mode Coupling Instability (TMCI) observed. Suppressed by space charge?

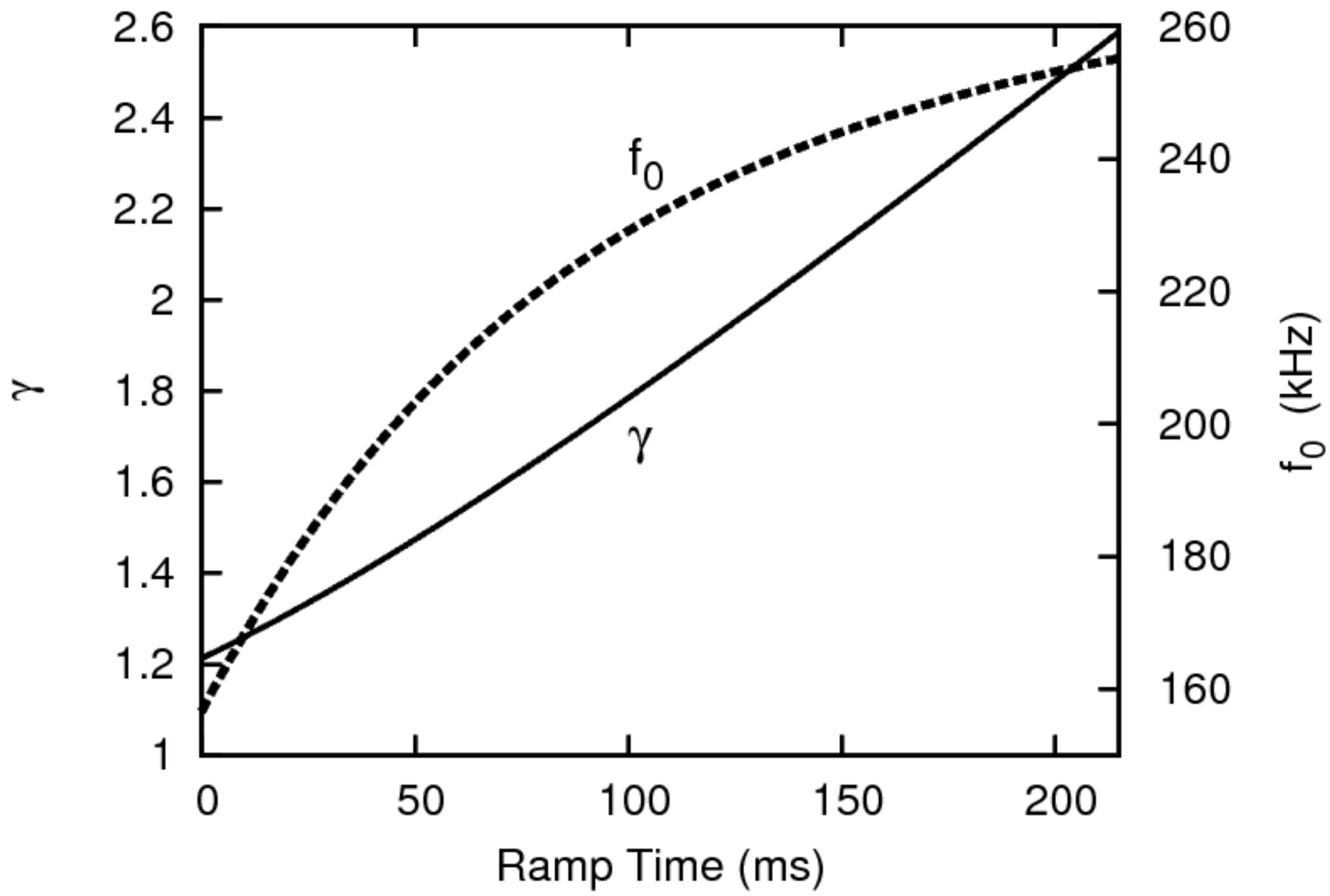
Theory predictions: Blaskiewicz prstab 1998; Burov prstab 2009

HEAD-TAIL IN SIS100

R=172.46m

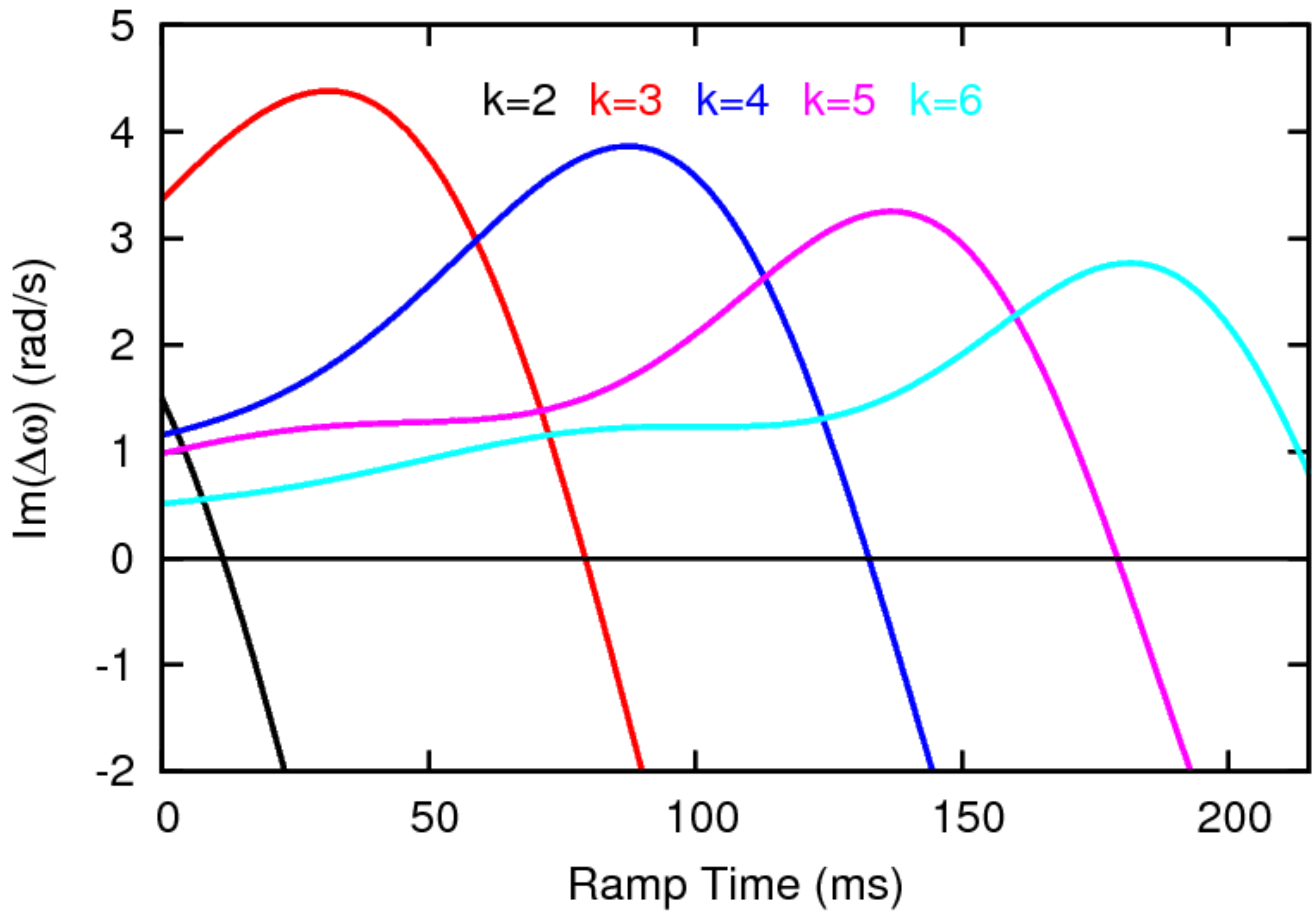
Heavy Ions:
Kin. energy
200MeV−1.5GeV

Q_h=18.84
Q_v=18.73
ξ_v=-1.2



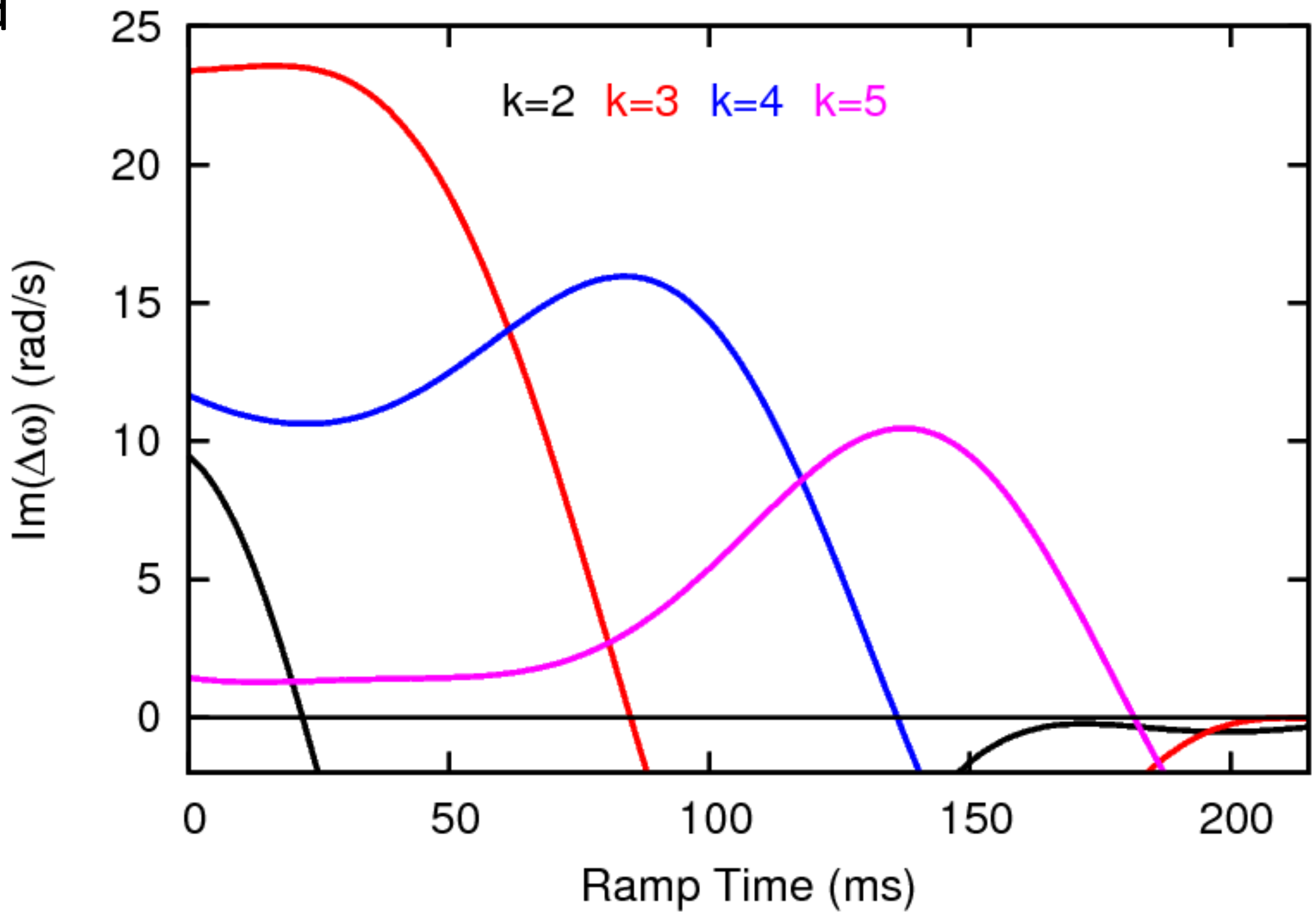
HEAD-TAIL IN SIS100

The head-tail growth rate given by the Sacherer theory for the Resistive-Wall Impedance



HEAD-TAIL IN SIS100

For a Narrow-Band Impedance
f_r=3MHz,
R_T=3MΩ/m,
Q_T=2

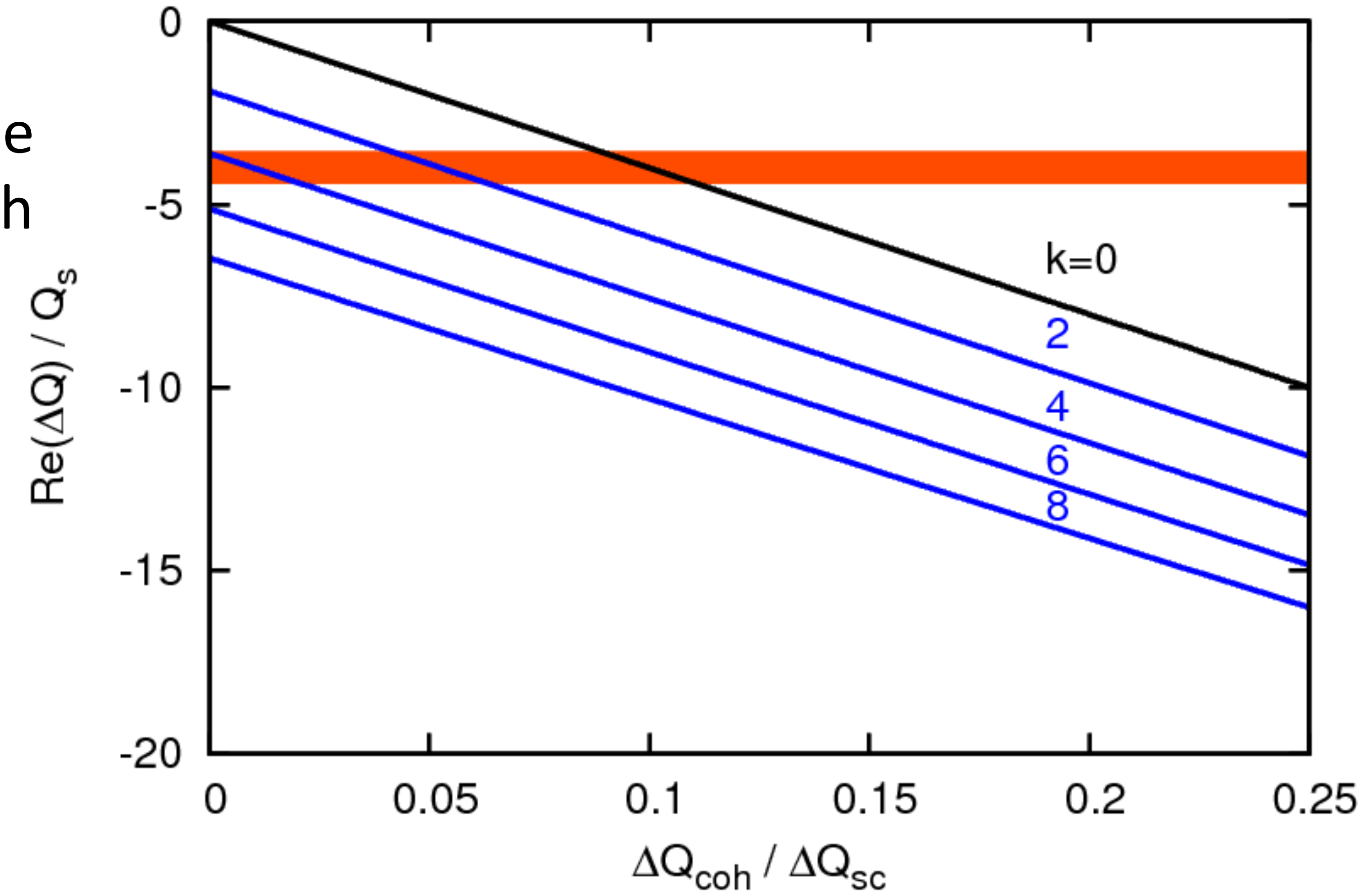


HEAD-TAIL IN SIS100

Landau Damping due to Space Charge with Image Charges

U^{28+} : q=40

$\Delta Q_{coh} / \Delta Q_{sc} \approx 0.12$



Summarized:

with a transverse feedback and space-charge effects, the situation with the head-tail modes and TMCI in SIS100 looks encouraging

Beam Break-Up Instability

Transition Crossing in PS at CERN
p^+ operation in SIS100 at GSI

BEAM BREAK-UP

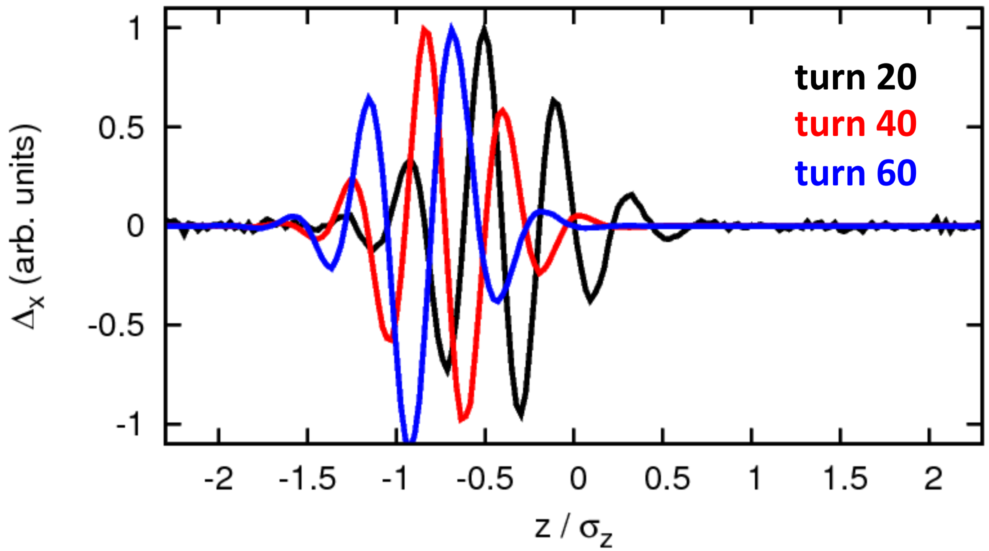
PS observation first reported:
R.Cappi, E.Metral, G.Metral, 2000
Significant progress since then,
see S.Aumon, PhD Thesis, 2012.

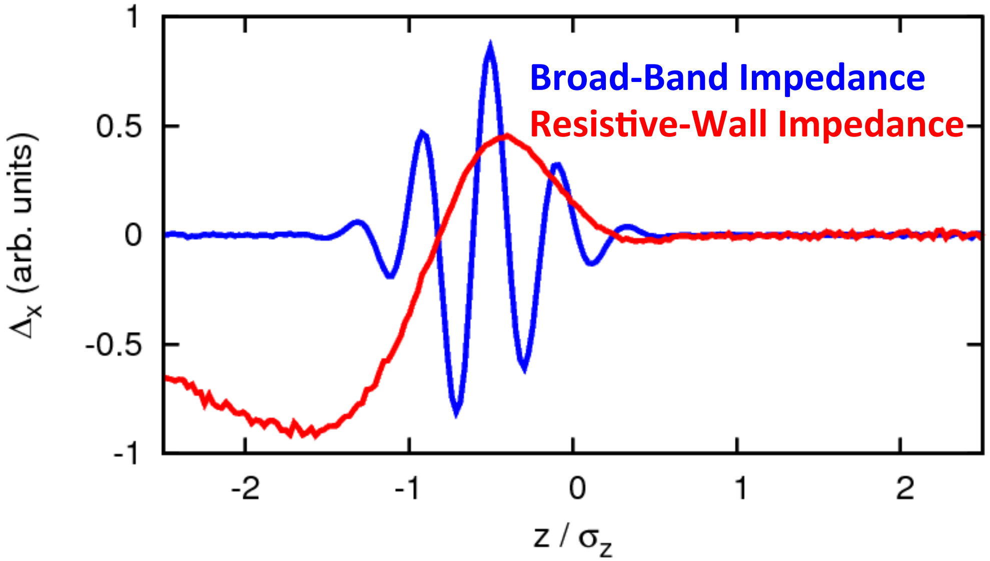
Strong impedance or
slow synchrotron motion,
$\mathrm{Im}(\Delta Q) \gg Q_s$

↓

a fast instability with a
convective character
(oscillation migrates towards tail)

Driven at high-frequency (BB, GHz)
but also lower-frequency
(RW, bunch-length)

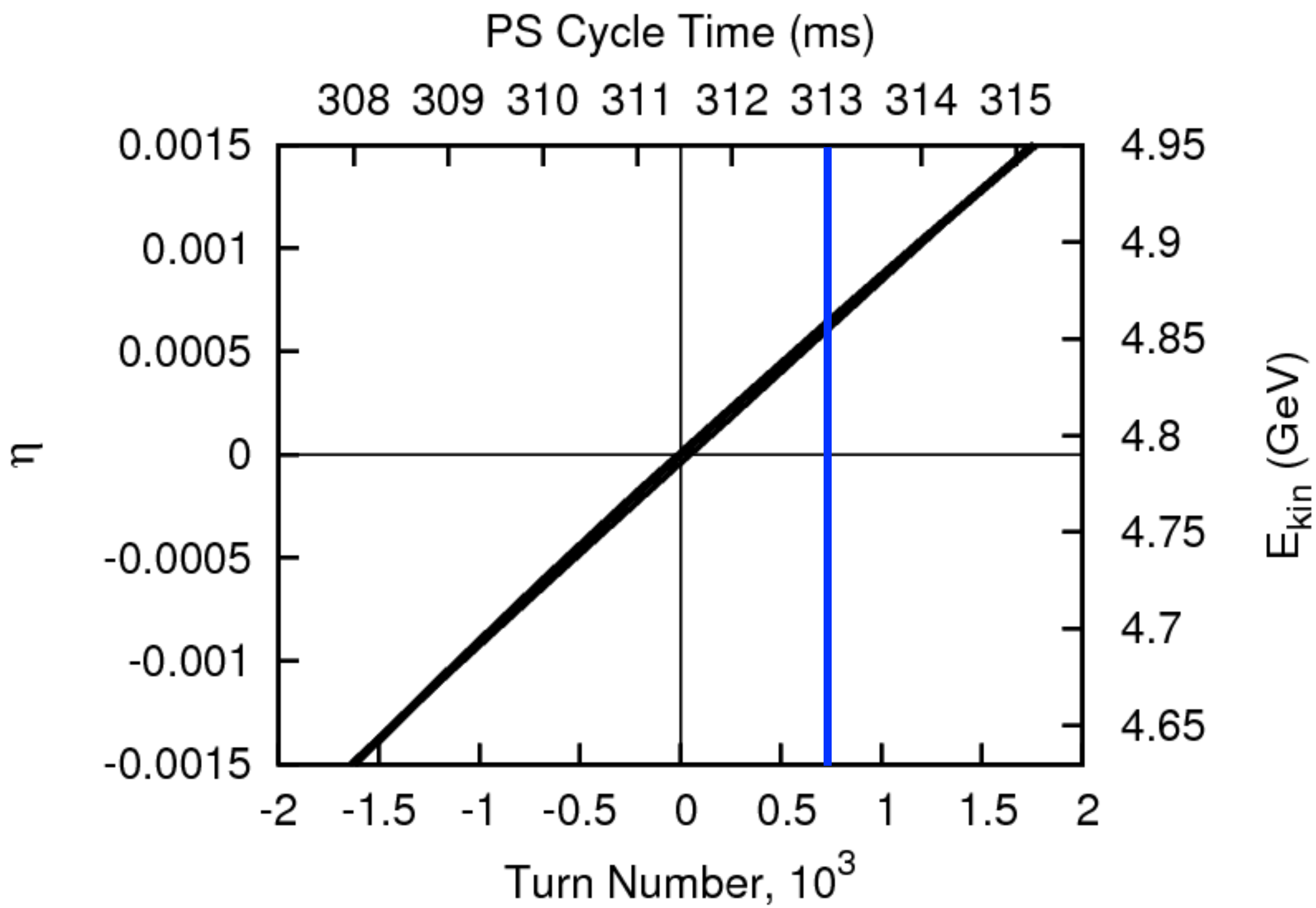




simulation examples

TRANSITION AT PS W/O γ-JUMP

strong transverse oscillations and fast losses around C313ms

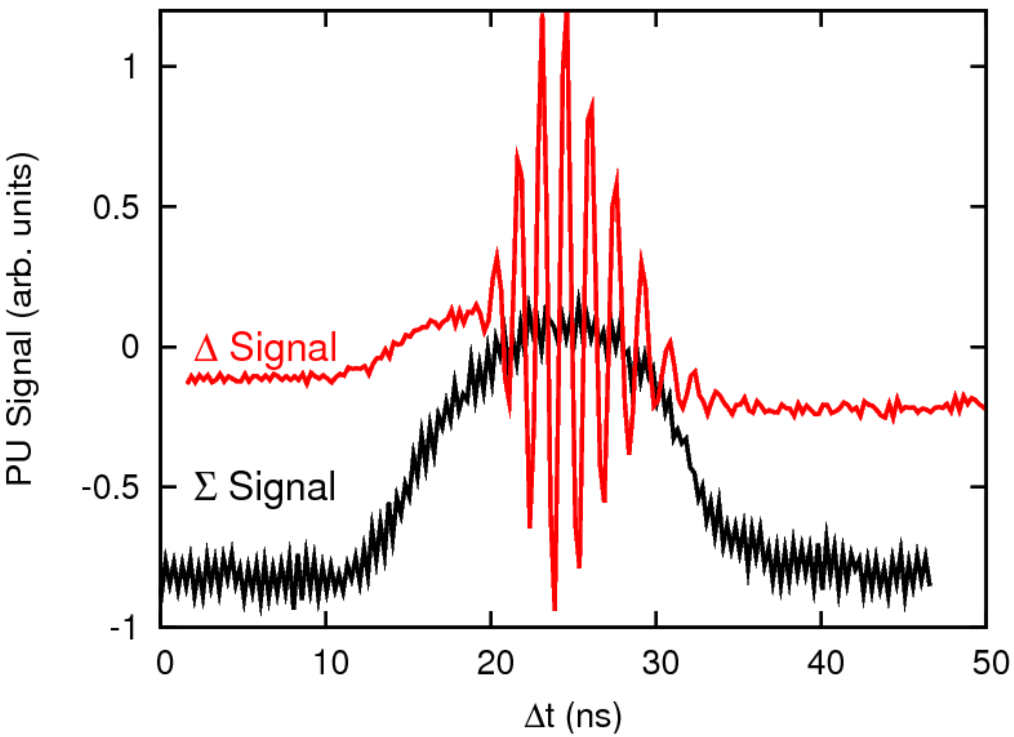


Measurement campaign at PS in June 2012.
Help of S.Aumon, S.Gilardoni, PS Operation Group

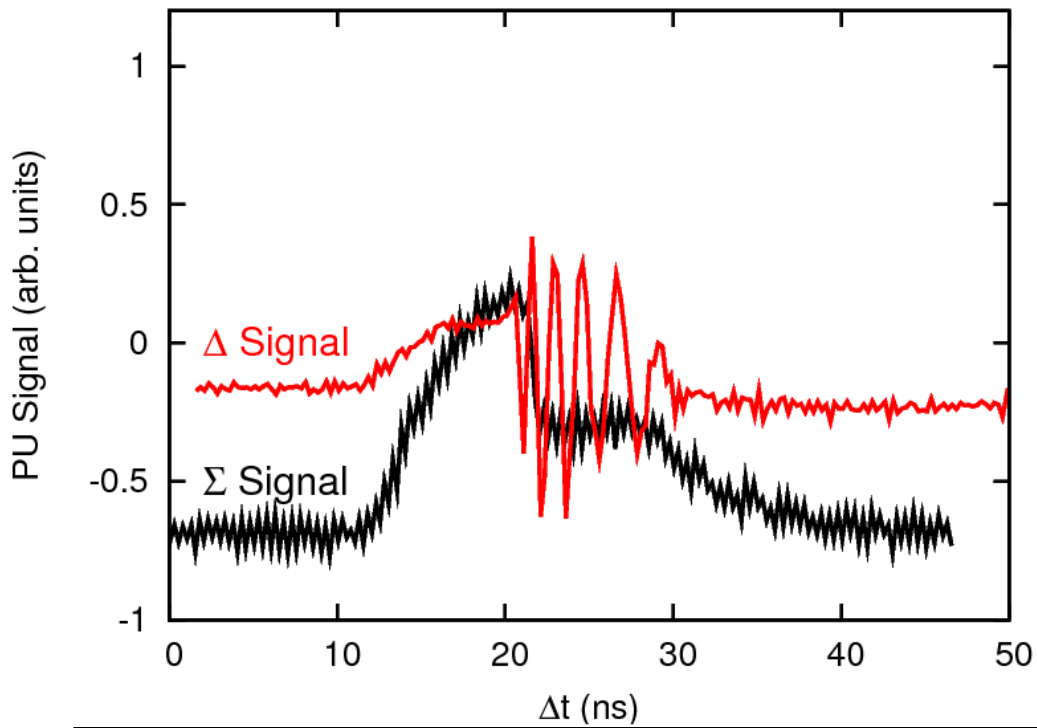
BEAM BREAK-UP IN PS

- high-frequency (0.7GHz) oscillations
- fast losses
- this example: $\Delta Q/Q_s$=11

turn 900

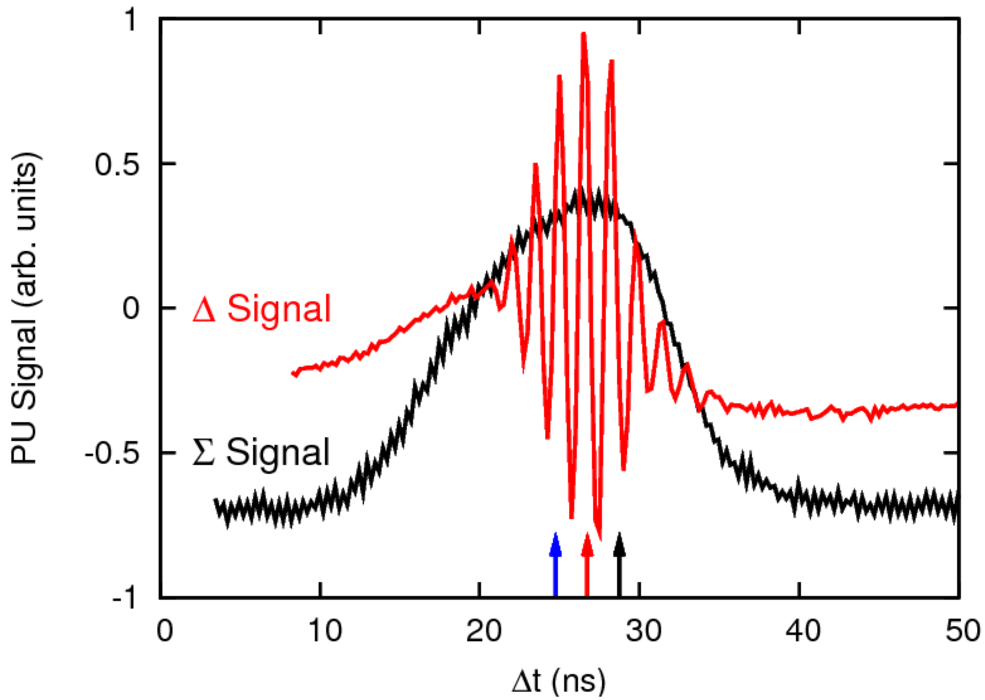


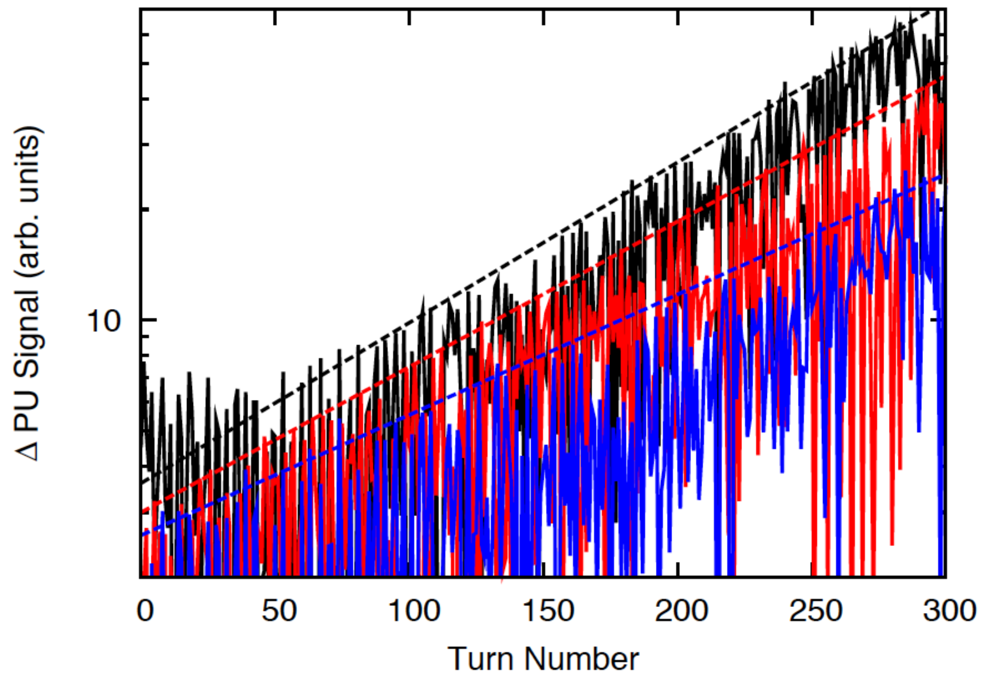
turn 1100



more details in the upcoming CERN Report

BEAM BREAK-UP IN PS





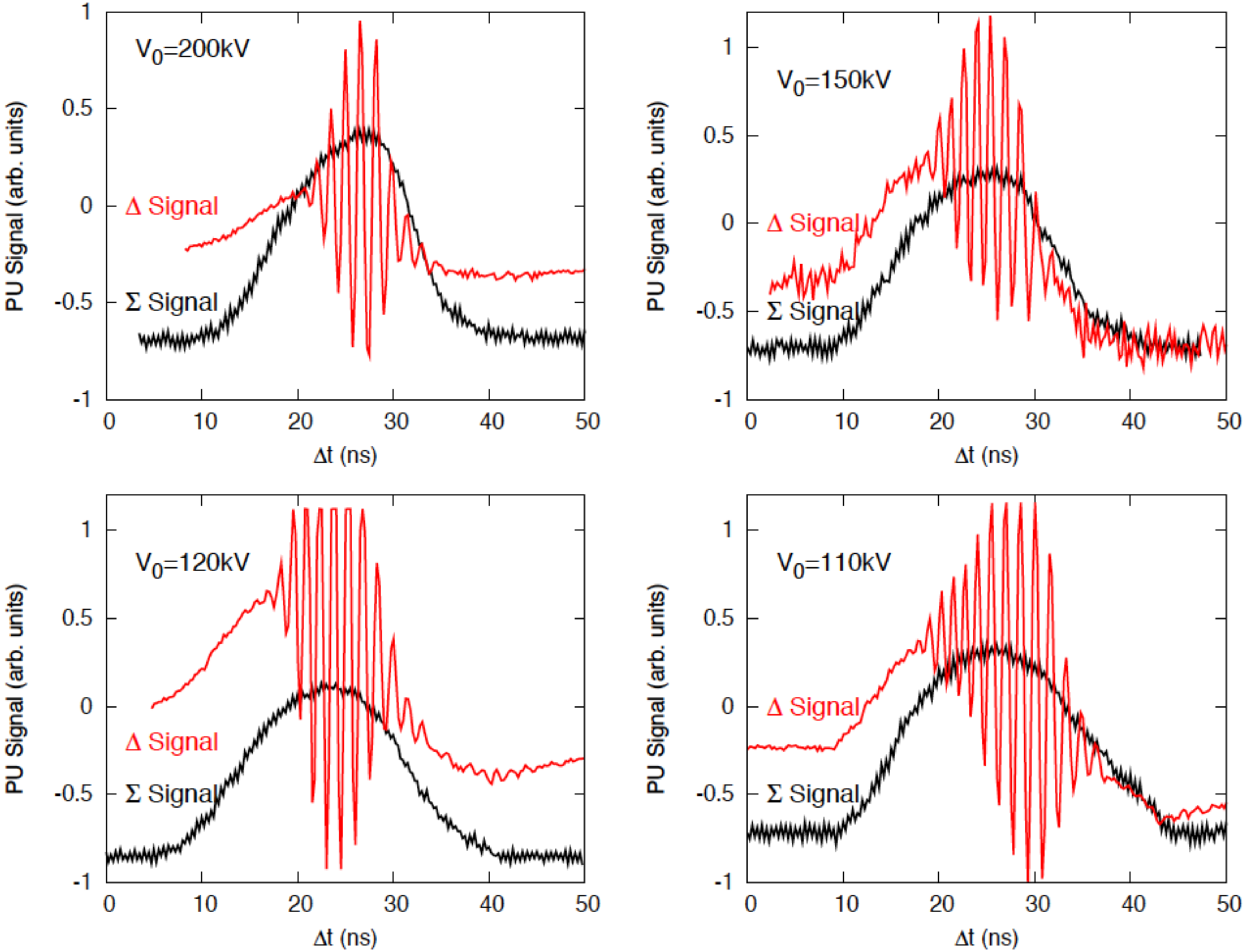
head: ΔQ=1.2e-3

middle:ΔQ=1.45e-3

tail: ΔQ=1.6e-3

no definite growth rate,
the oscillation migrates towards the bunch tail:
the convective character of the Beam Break-Up

BEAM BREAK-UP IN PS

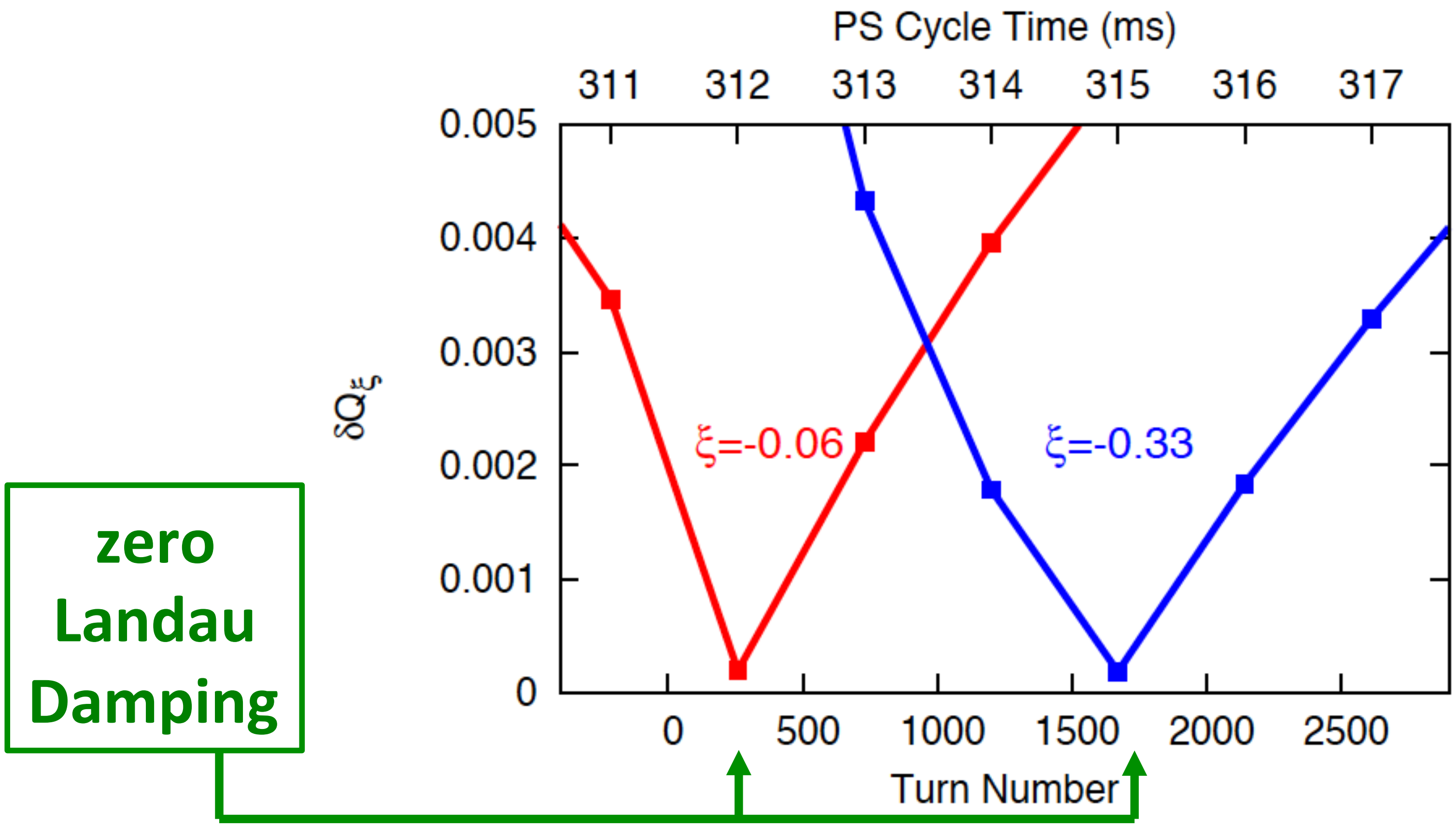


Instability thresholds for different rf voltage and the role of the bunch length: more details in the upcoming CERN Report

BEAM BREAK-UP IN PS

Landau Damping for the Coasting-Beam Estimations:

$$\delta Q_\xi = |\eta(n - Q_0) + Q_0 \xi| \delta_p$$



Observations in PS: at 313ms for the "zero-ξ-lattice", at 315ms for the "finite-ξ-lattice".

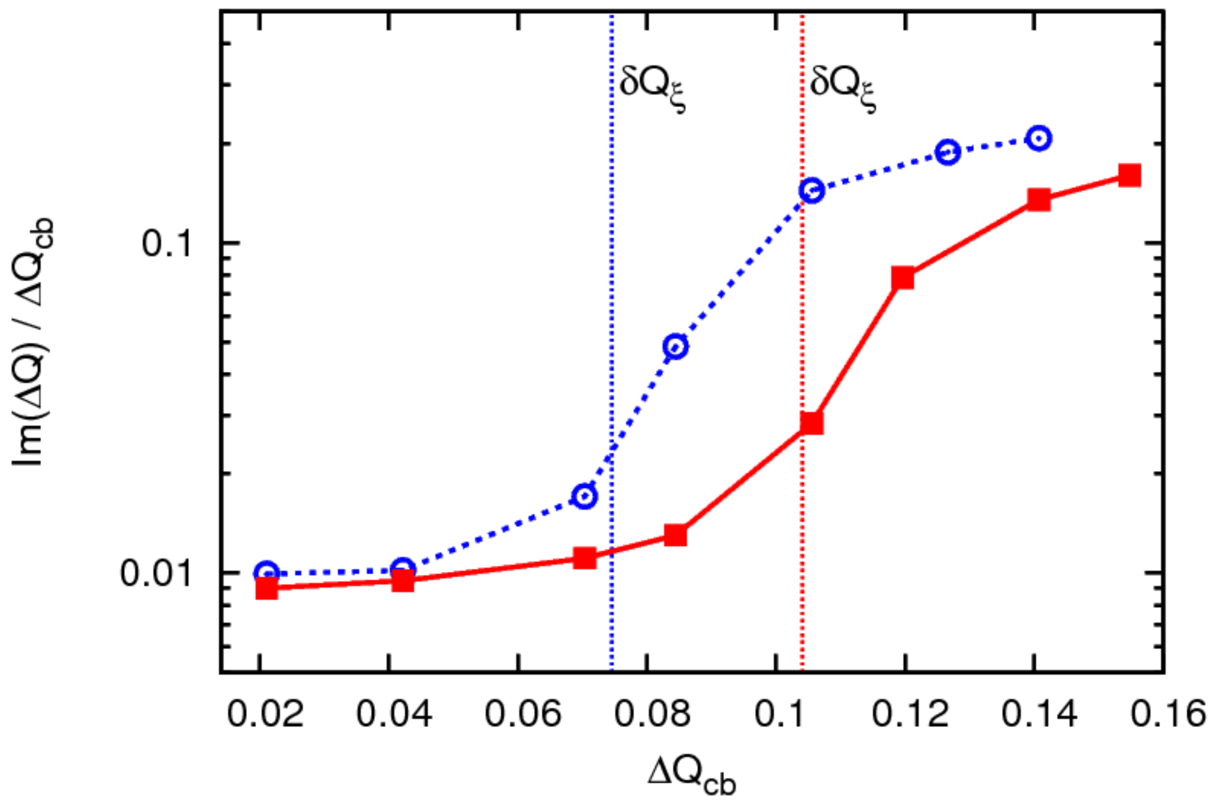
BEAM BREAK-UP IN SIMULATIONS

PIC Simulations with
a Broad-Band Impedance

Beam Break-Up for
an increasing impedance

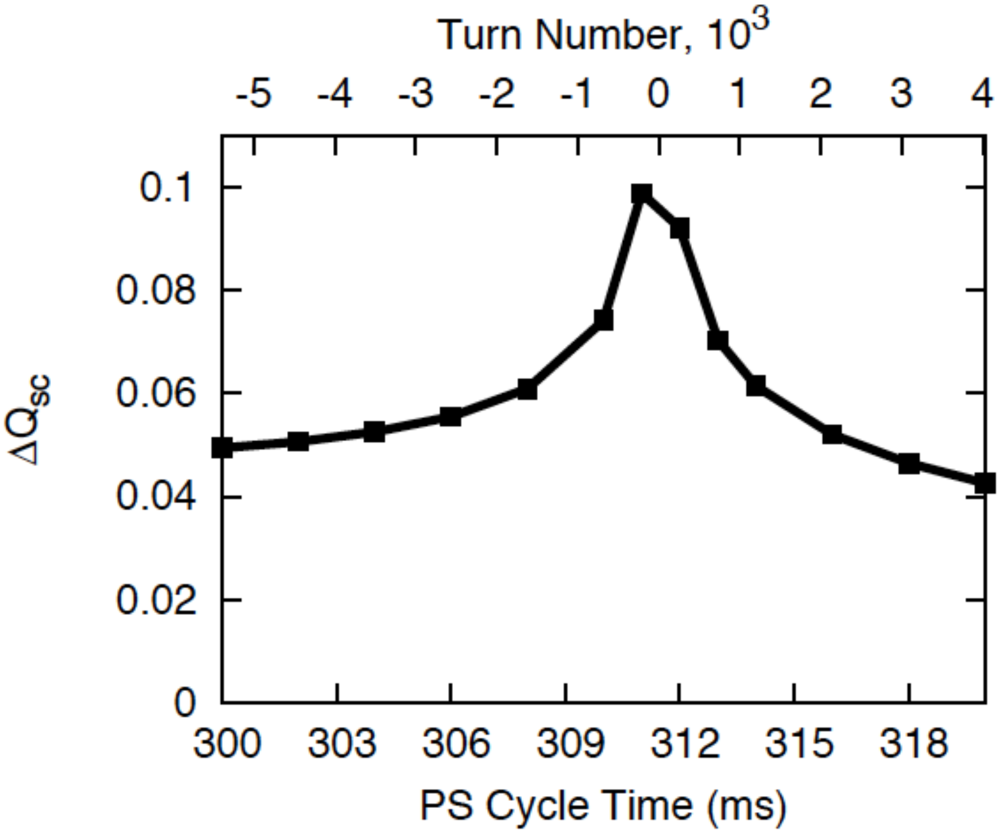
Q_s=0.0025

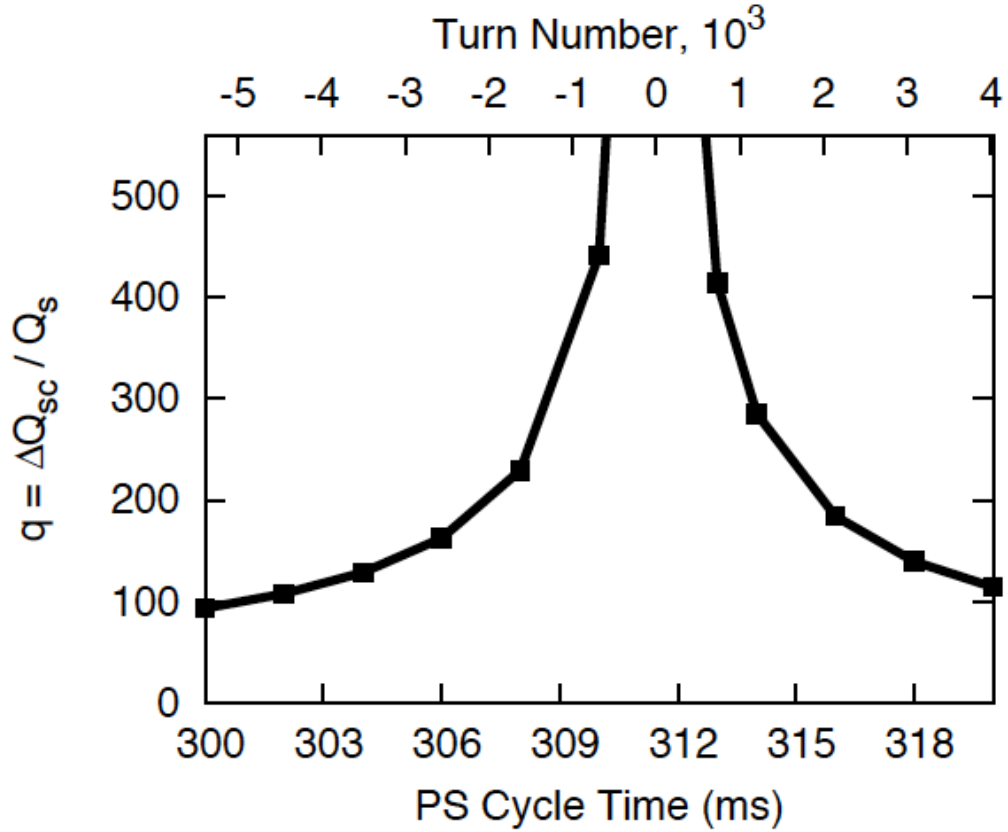
Q_s=0.0035



Quasi-Coasting-Beam Type of the Threshold for the Beam Break-Up Instability

SPACE CHARGE IN PS





N_p=90e10, t_b=50ns at C300ms, V_0=200kV

Very strong space-charge regime.
Transverse beam blow-up showed no effects

BEAM BREAK-UP IN SIS100

Due to the Broad-Band Impedance (assuming the PS model):
$\Delta Q/\delta Q_\xi < 0.15$

Due to the Resistive-Wall Impedance:
$\Delta Q/\delta Q_\xi < 0.5$
but: not observed in PS

Additional damping by other mechanisms (bunch length, Q_s)

Strong Space Charge q>130

Well in the safe operation

CONCLUSIONS

The classical head-tail instability during the ramp at PSB:

- thresholds for different bucket forms
- a low-frequency narrow-band could explain the puzzling questions

Theory, Simulations and Measurements at PS Booster and at SIS18 show that **Space Charge is our Best Friend**:

- SC induces a strong Landau Damping
- together with Image Charges, SC can stabilize some Head-Tail modes
- SC suppresses the TMCI

Experiments near transition at PS and PIC Simulations:

- Beam Break-Up with a convective character at high frequency (Broad-Band)
- the quasi-coasting-beam estimation gives a good threshold estimate
- other damping effects important
- Space Charge does not play an important role

At SIS100 seems to be safe
regarding the Head-Tail (feedback), TMCI and the Beam Break-Up