SYNCHROTRON OSCILLATION DAMPING DUE TO BEAM-BEAM COLLISIONS

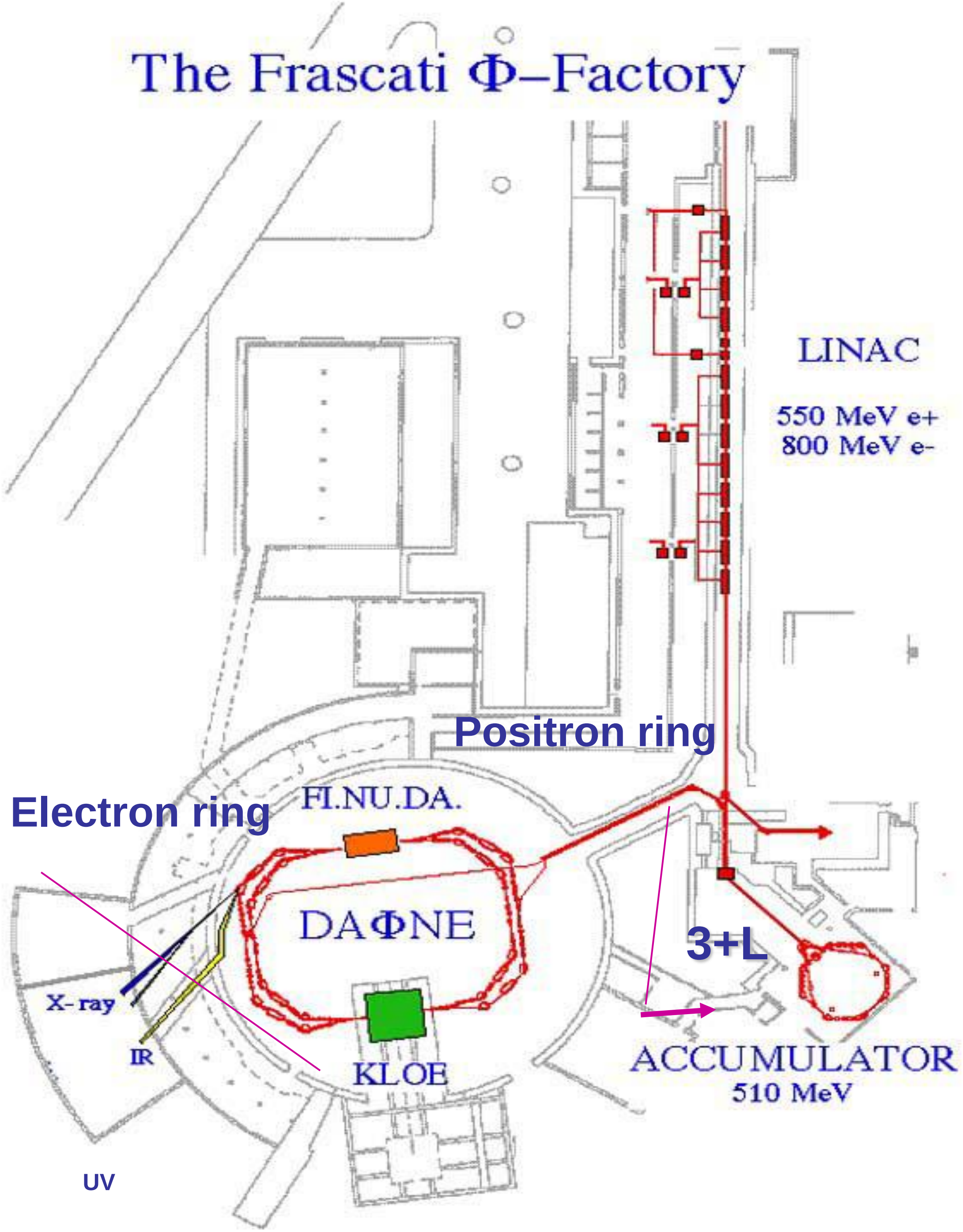
Alessandro DRAGO,
Pantaleo Raimondi, Mikhail Zobov
(INFN - LNF, Frascati, Italy),
Dmitry Shatilov (BINP, Novosibirsk, Russia)

The 1st International Particle Accelerator Conference
Kyoto, Japan / May 23-28, 2010

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Introduction

- In DAFNE, the Frascati e+/e- collider, the *crab waist* collision scheme has been successfully implemented in 2008 and 2009, for the Siddharta experiment.
- During the collision operations, an unusual synchrotron damping effect has been observed.
- Switching off the longitudinal feedback and having beam currents in the order of 200-300 mA, the positron beam of course becomes unstable
- Nevertheless the longitudinal instability is damped by bringing the positron beam in collision with a high current electron beam (~2A).
- Besides, doing this, we have observed a shift of ≈-600Hz in the residual synchrotron sidebands.

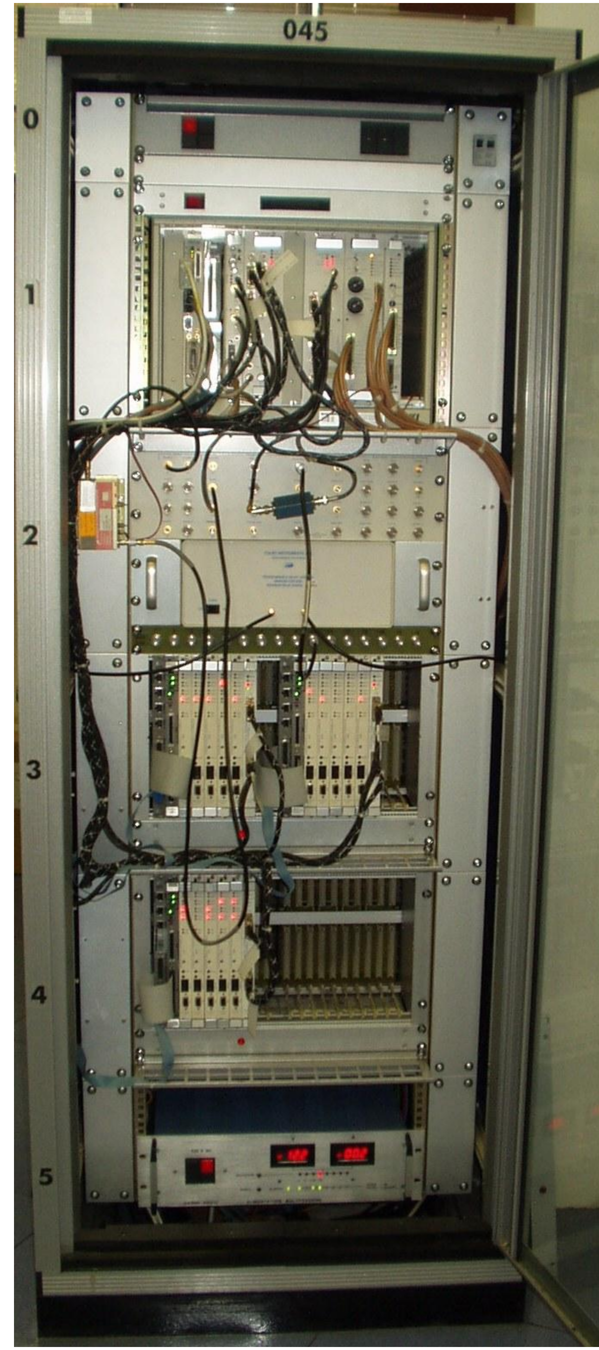


- LINAC
- Transfer lines
- Accumulator ring
- 2 main rings
- 2 interaction points
- Multi-detectors: in the last run, Siddartha

Instrumentation used

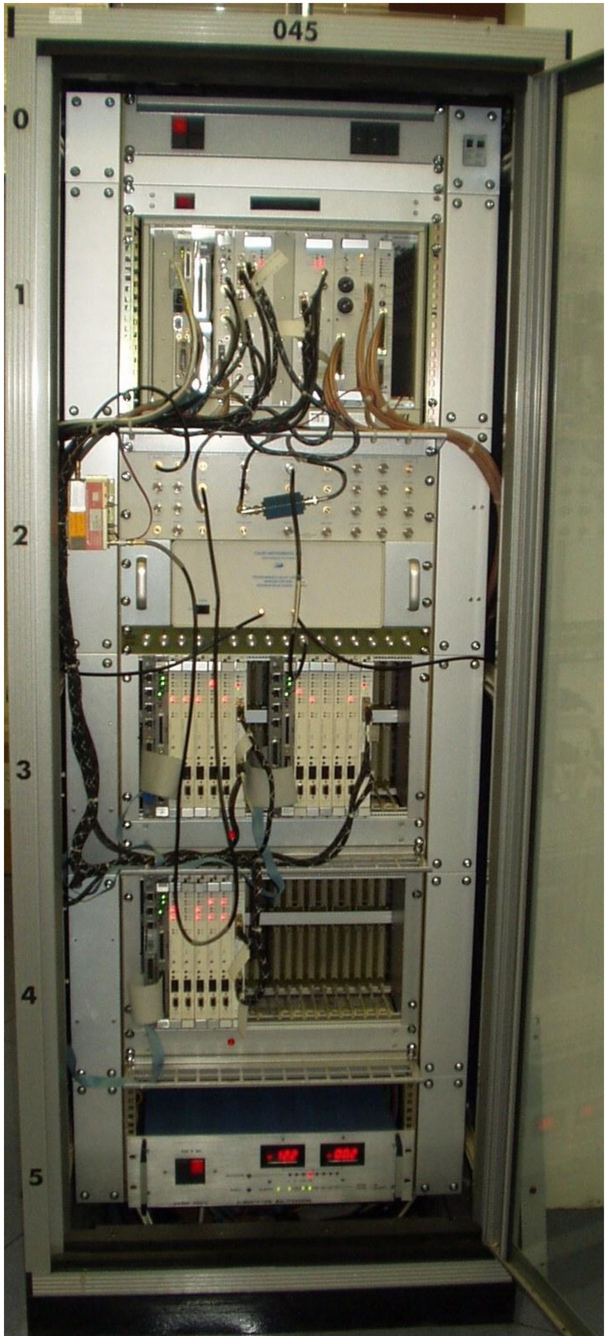
- Precise measurements on this effect have been performed by using two different ways:

  - a commercial Real-time Spectrum Analyzer RSA 3303 by Tektronix
  - the diagnostics capabilities of the DAFNE longitudinal bunch-by-bunch feedback (developed in collaboration with SLAC and LBNL in 1993-96)



Acquisitions from the Real-time Spectrum Analyzer RSA 3303

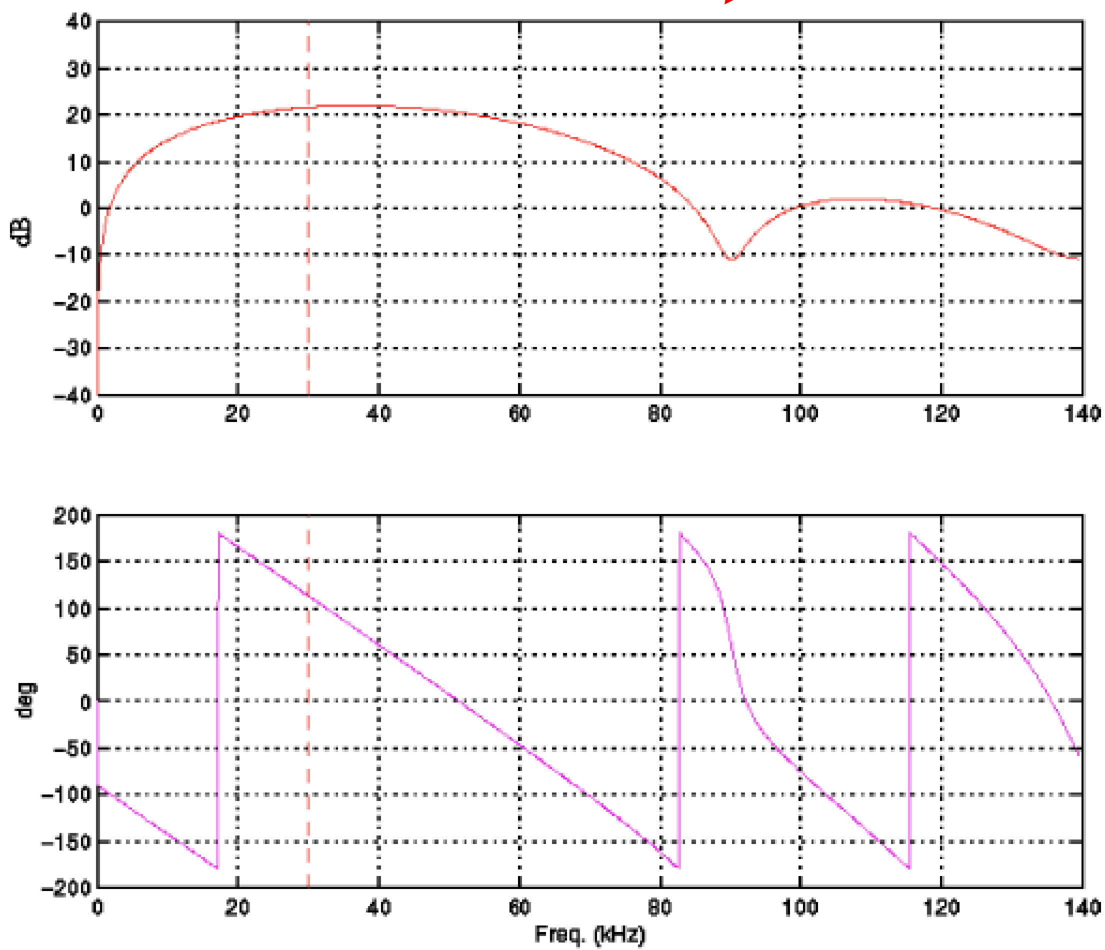
- Transverse and longitudinal pickup made by 4 high frequency buttons
- H9 (MA-COM) hybrids to have difference in H & V
- ~30 m. low attenuation cable
- Bandpass filter (@ 360MHz, +/- 5MHz)
- Amplifier
- Spectrum analyzer



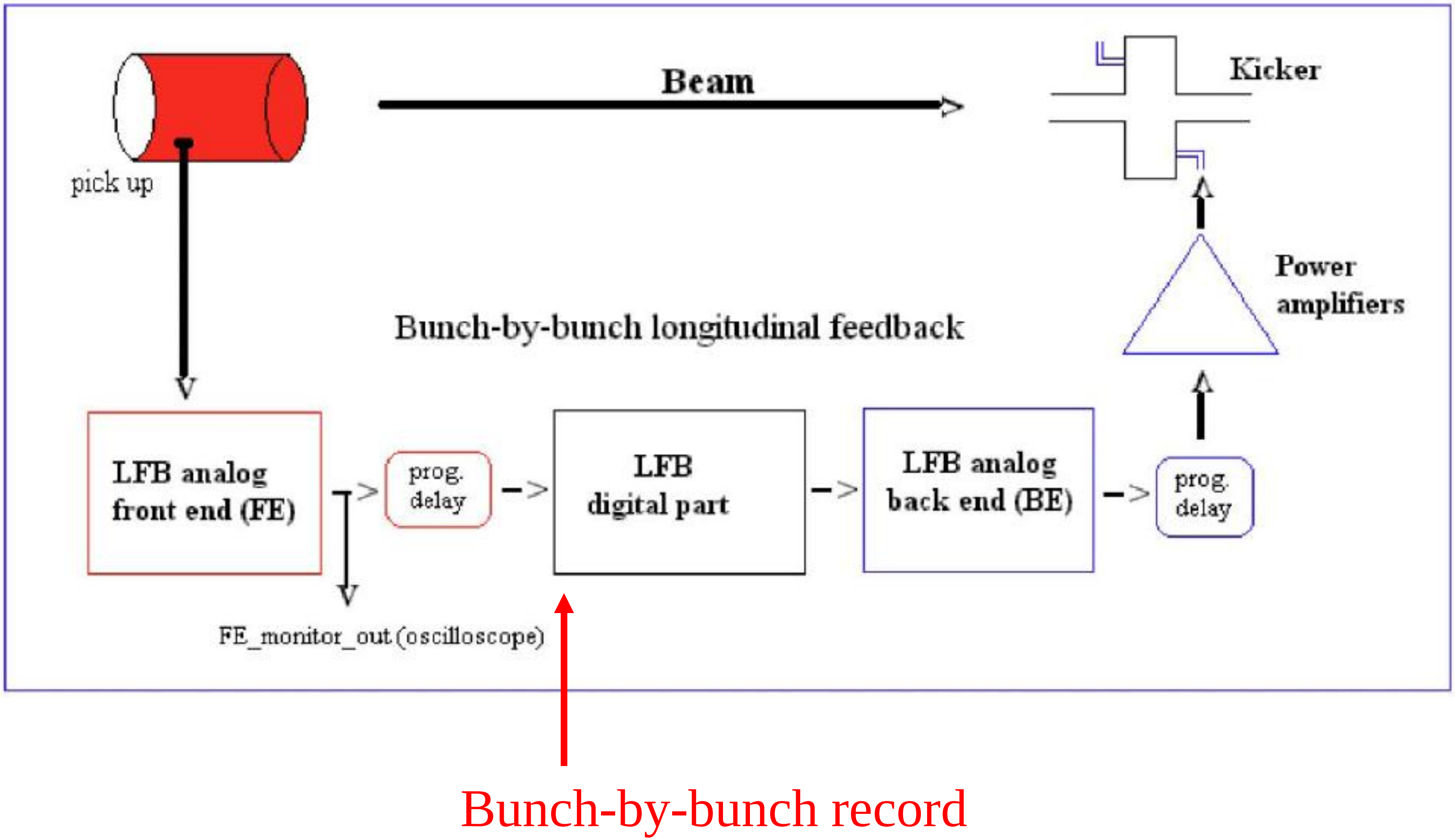
Long.Feedback used at ALS, PEP-II, DAFNE, Bessy, Pohang

Implemented by 60 real DSP’s at DAFNE

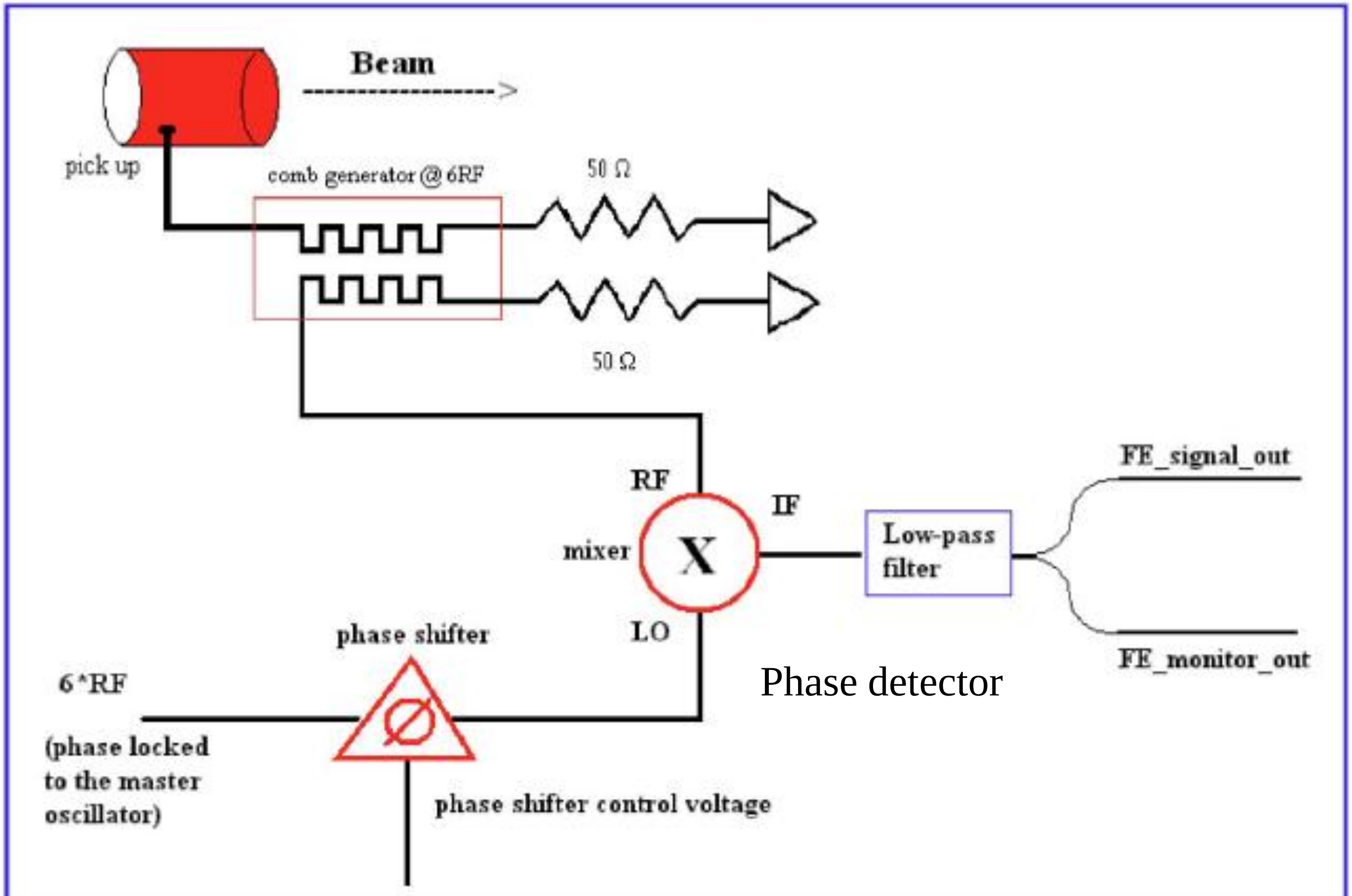
Every DSP implement a FIR function for each bunch



Block diagram of the longitudinal feedback system

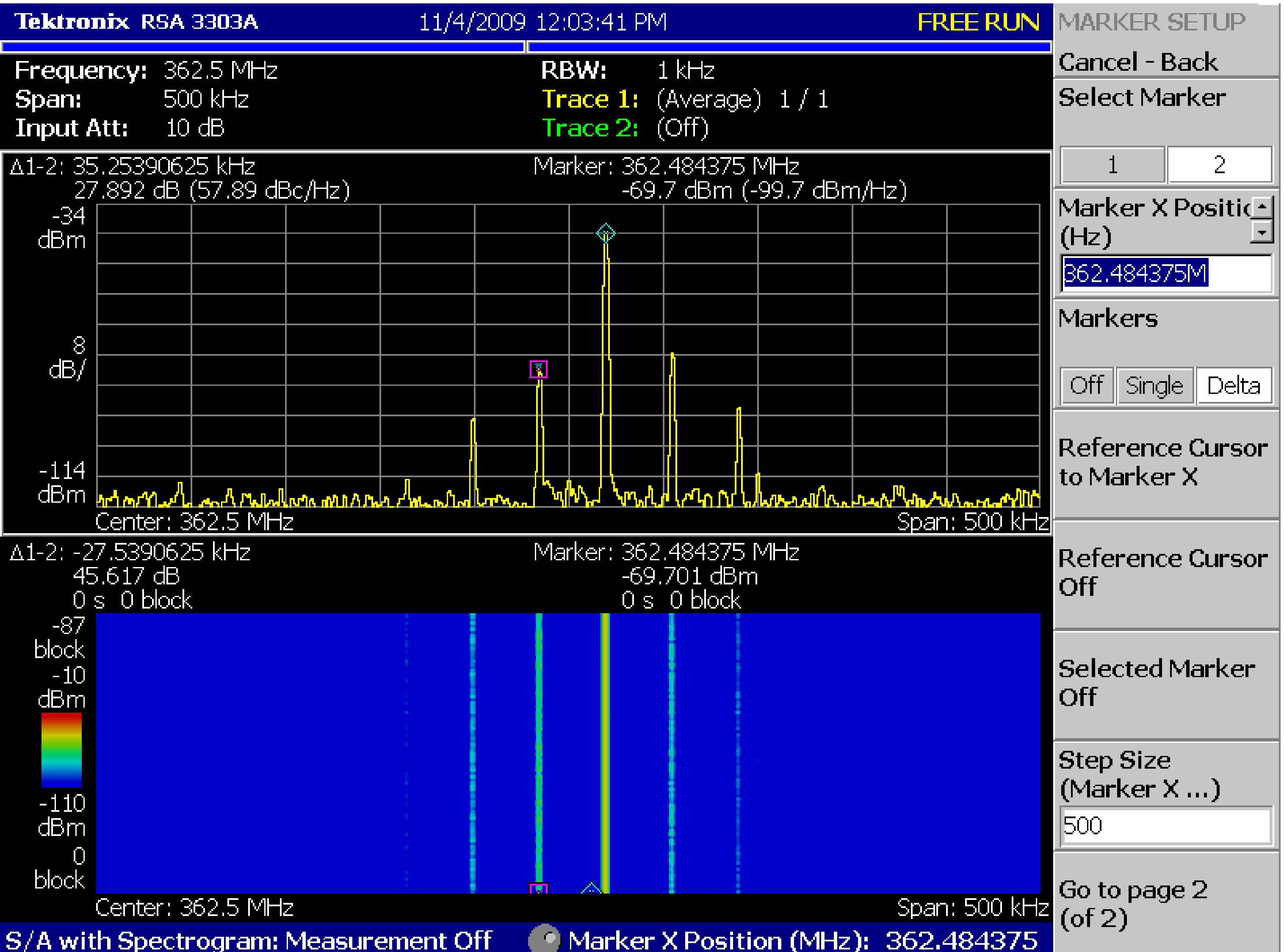


longitudinal feedback front-end (simplified scheme)



Longitudinal sidebands in e+ beam

(set of measurements recorded at DAFNE in 11/2009)



I+ = 200mA

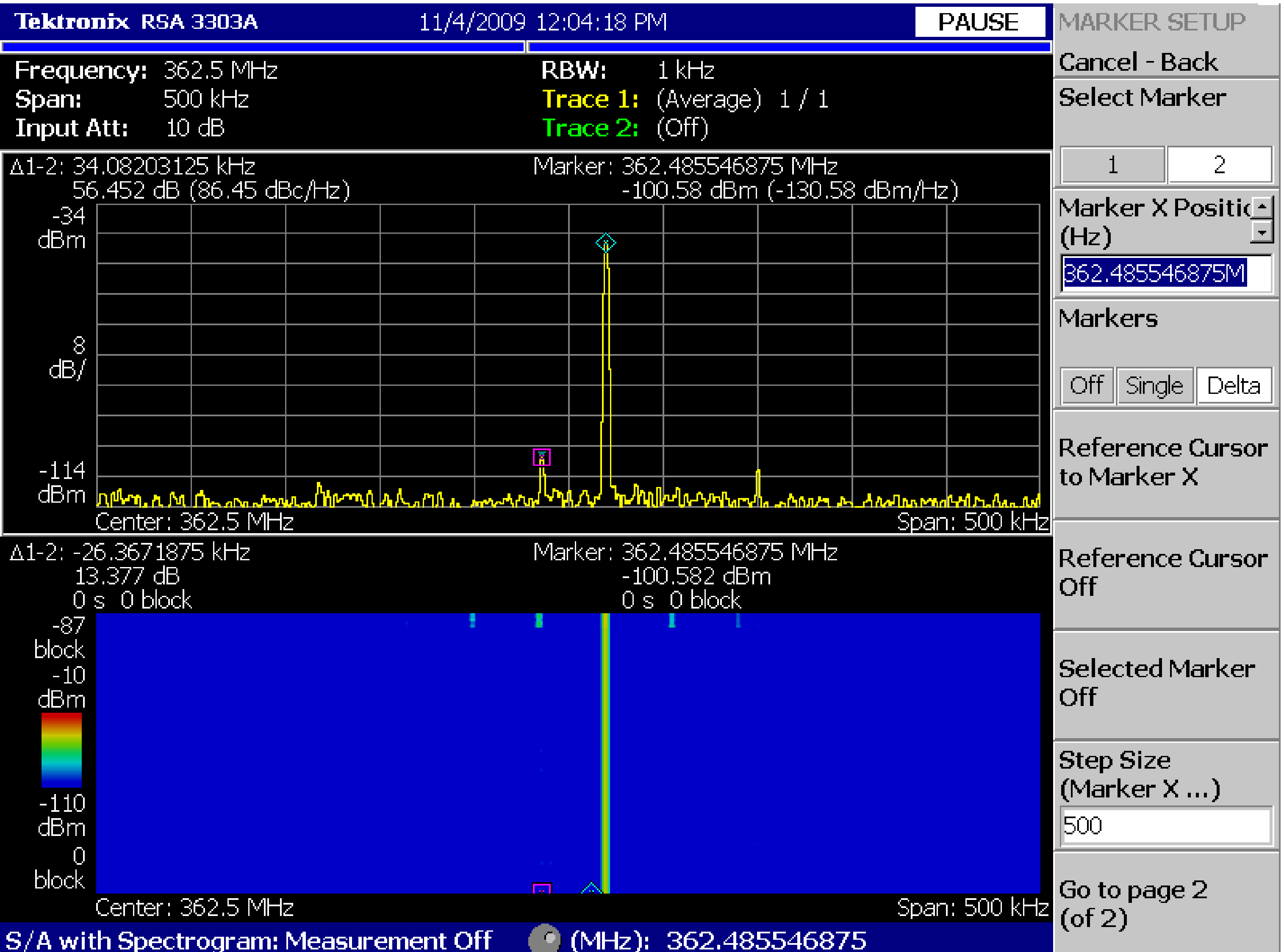
e+ longitudinal feedback off

No collisions at the IP

The highest peak is the 118th harmonic

Other peaks: longitudinal sidebands

Longitudinal sidebands in e+ beam in collision with e- beam



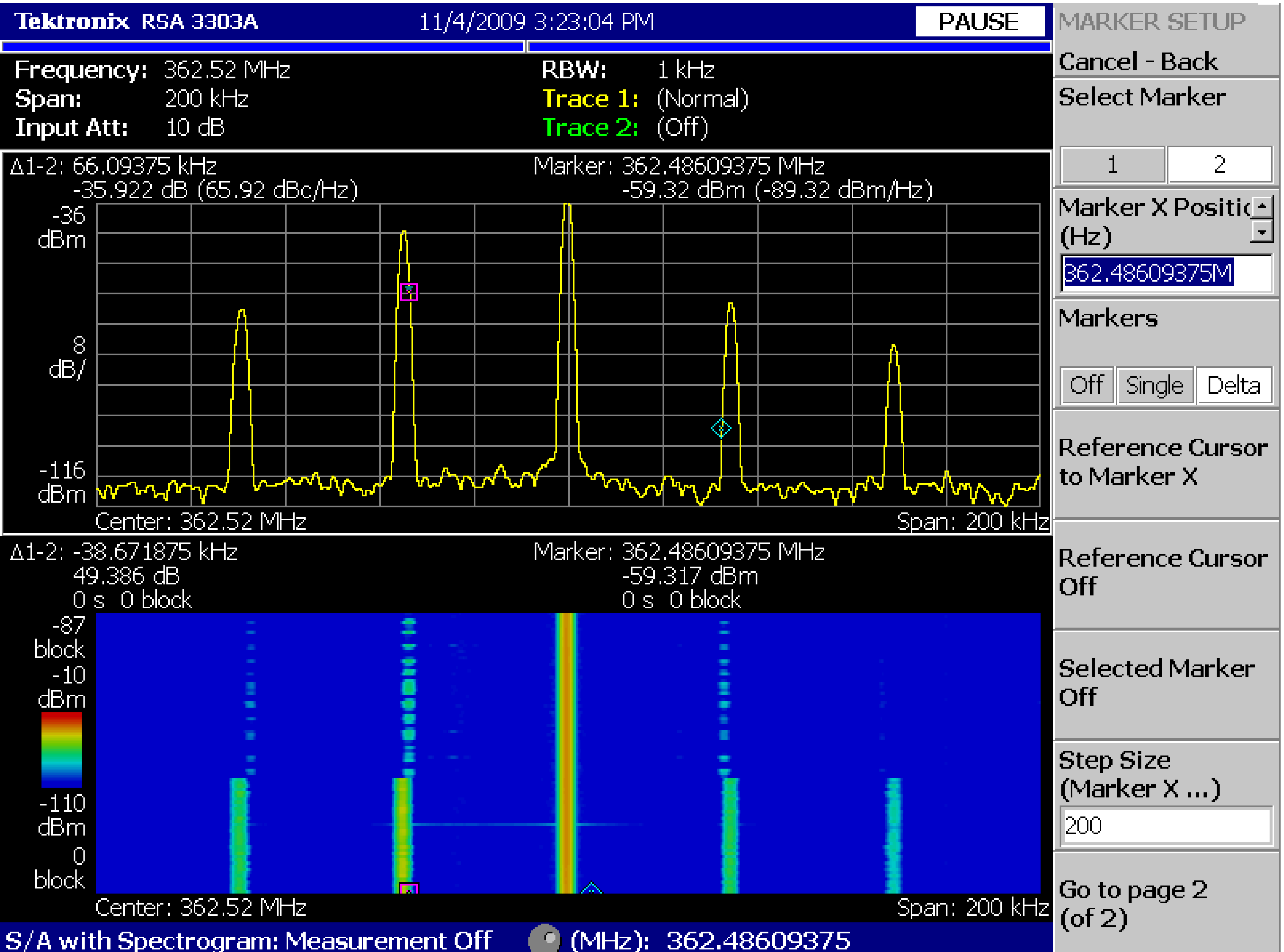
I+beam = 200mA

Longitudinal feedback off

collisions at the IP with the e- beam

Recorded by Tektronix S.A. 3303

In collision ←→ out of collision

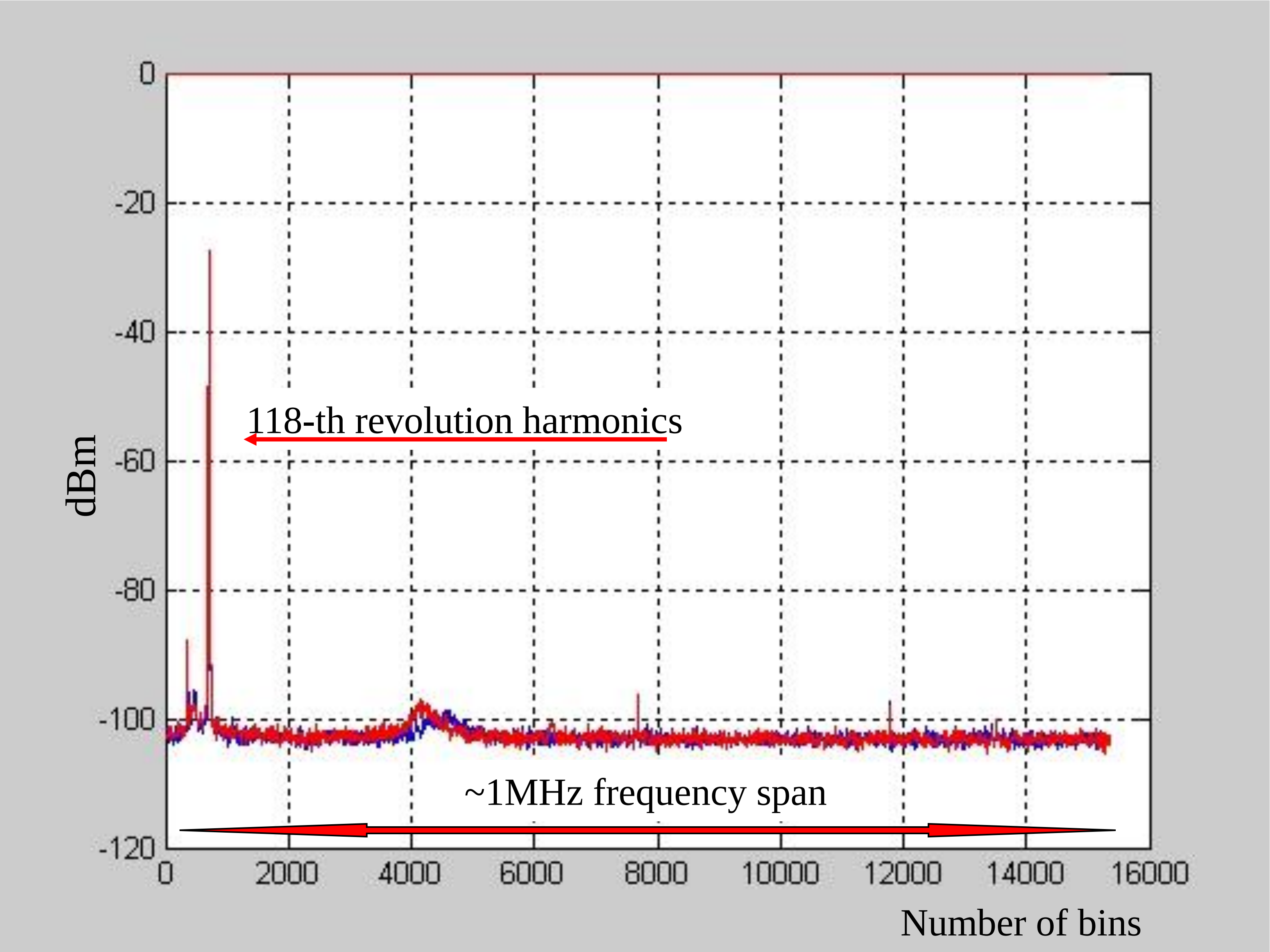


Last record

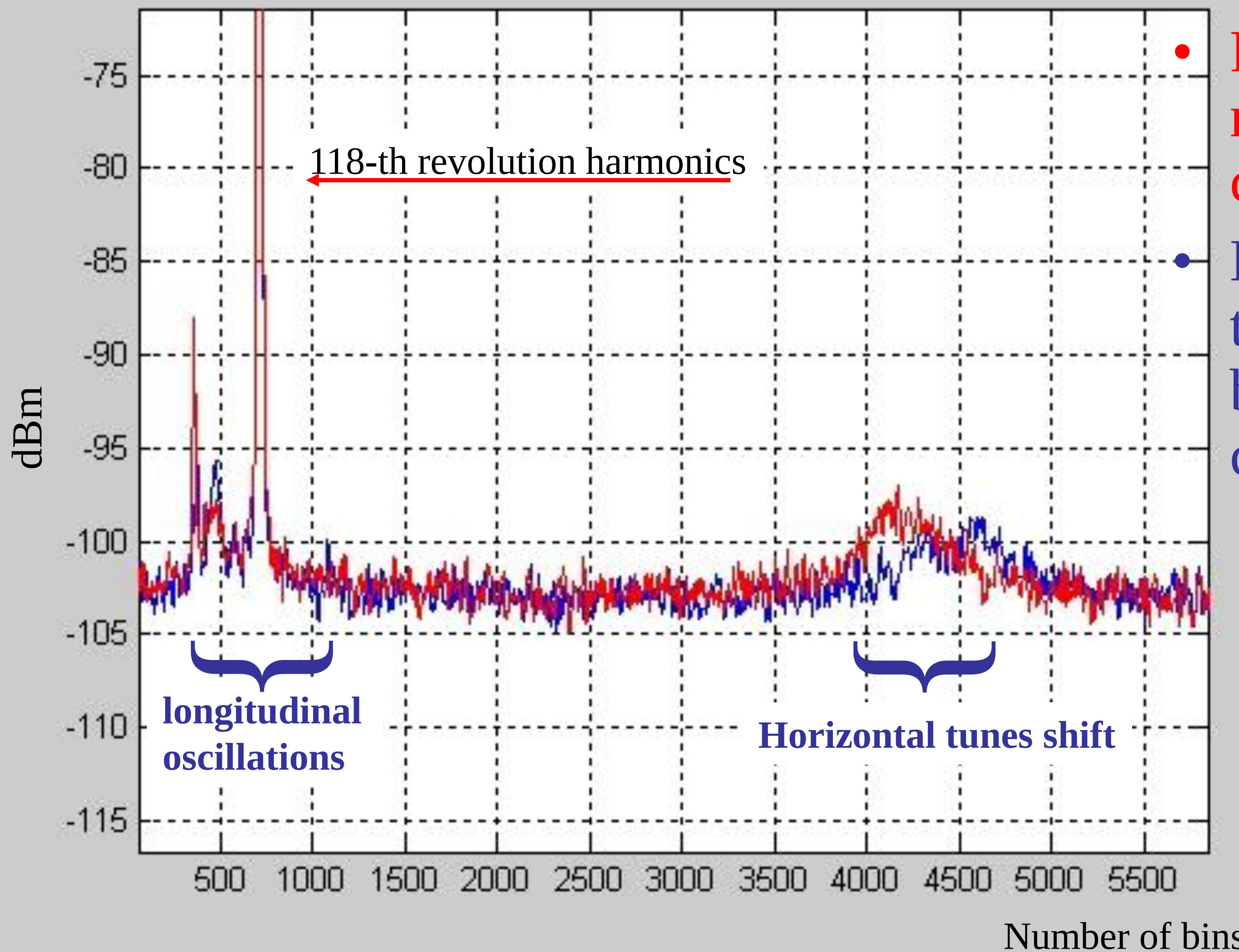
Last 60 sec. story

Tune shift

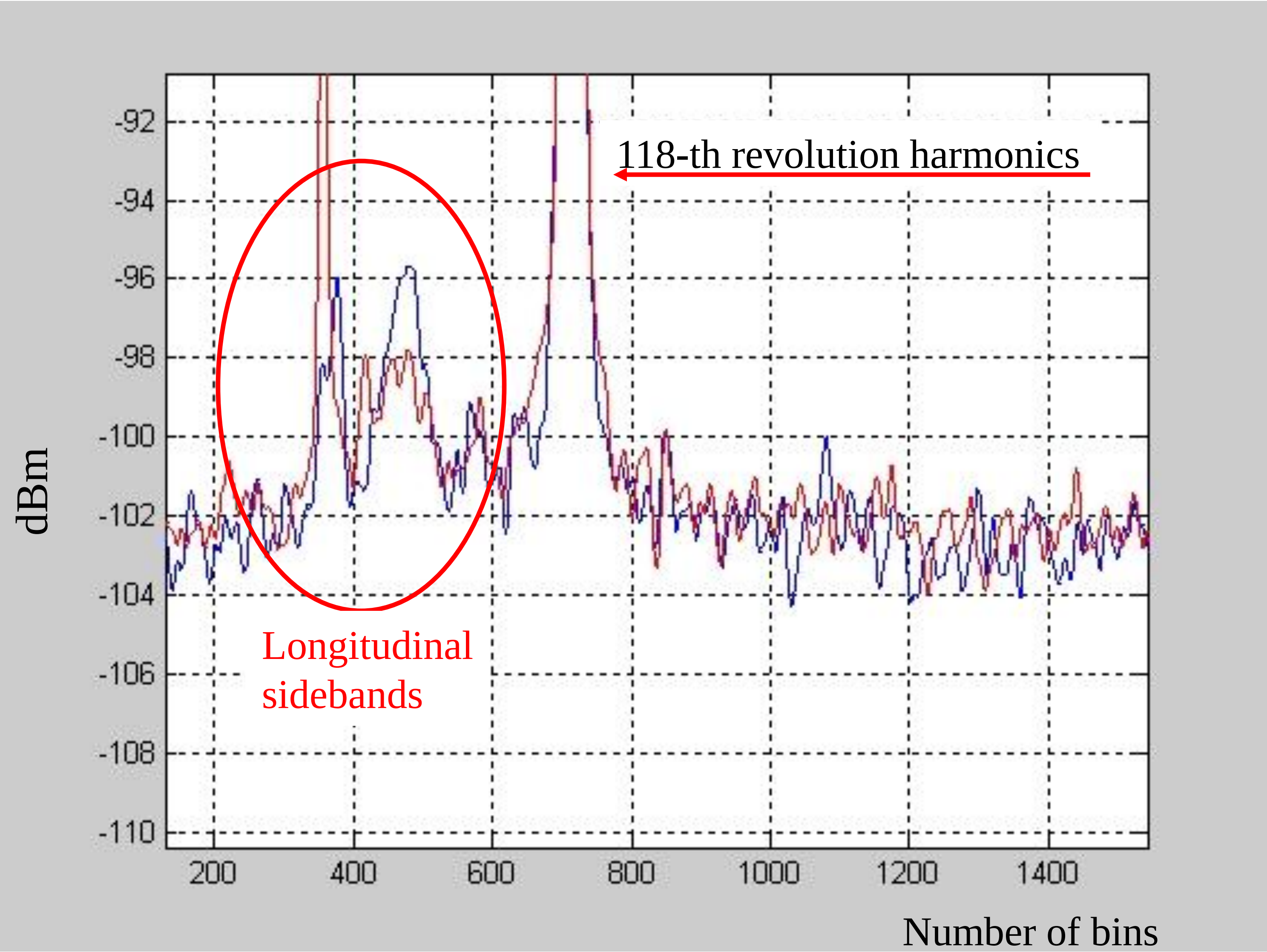
Data downloaded from the spectrum analyzer RSA3303 to a PC.
The highest peak is the e+ 118-th harmonics. Data are elaborated by MATLAB:
in **red** beams out of collision, in **blue** beams in collision.



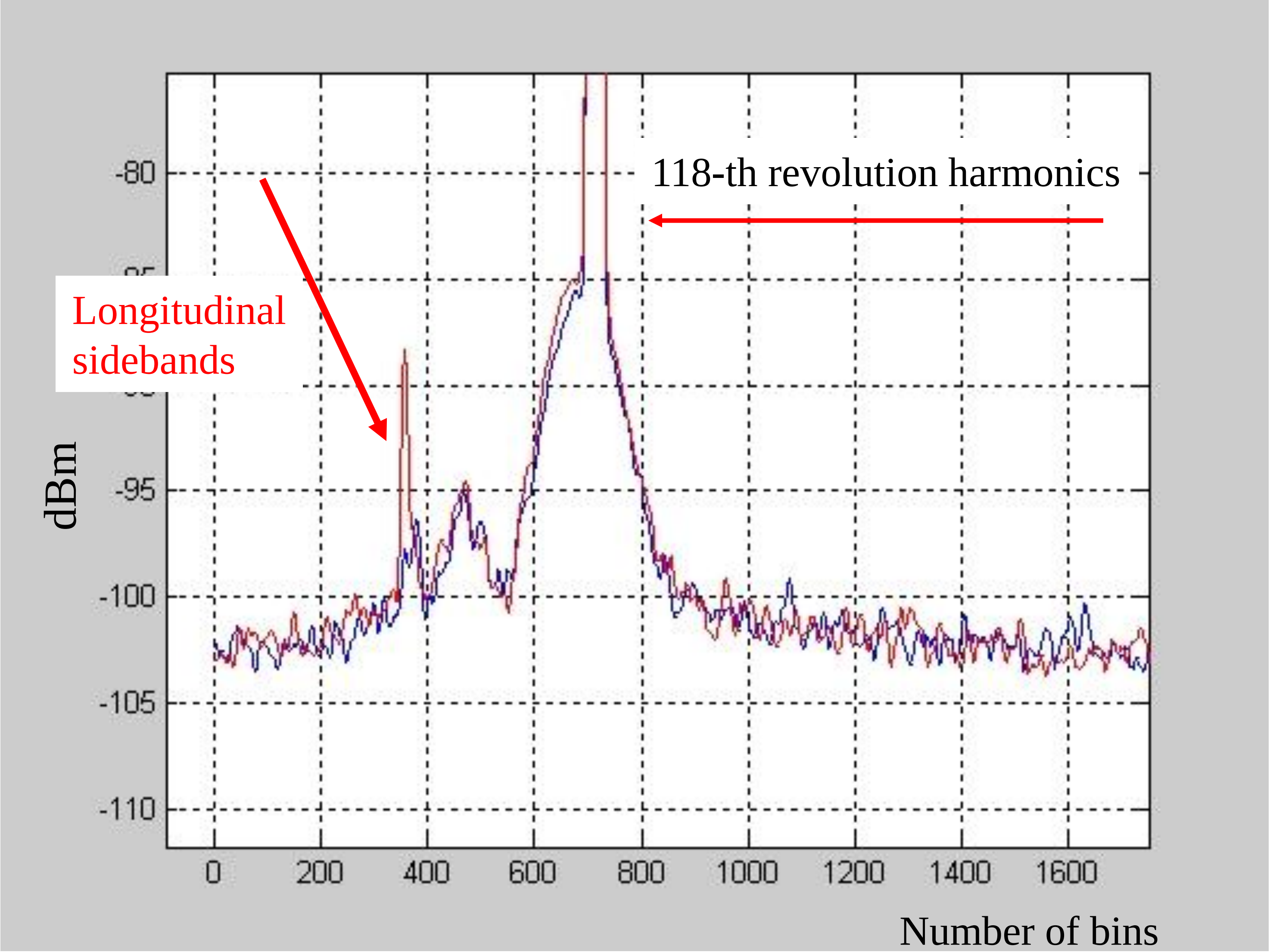
Zoom of the previous figure, showing the longitudinal and horizontal tunes



- Red trace: no collisions
- Blue trace: beams in collisions



Zoom of the previous figure, particular of the longitudinal sidebands

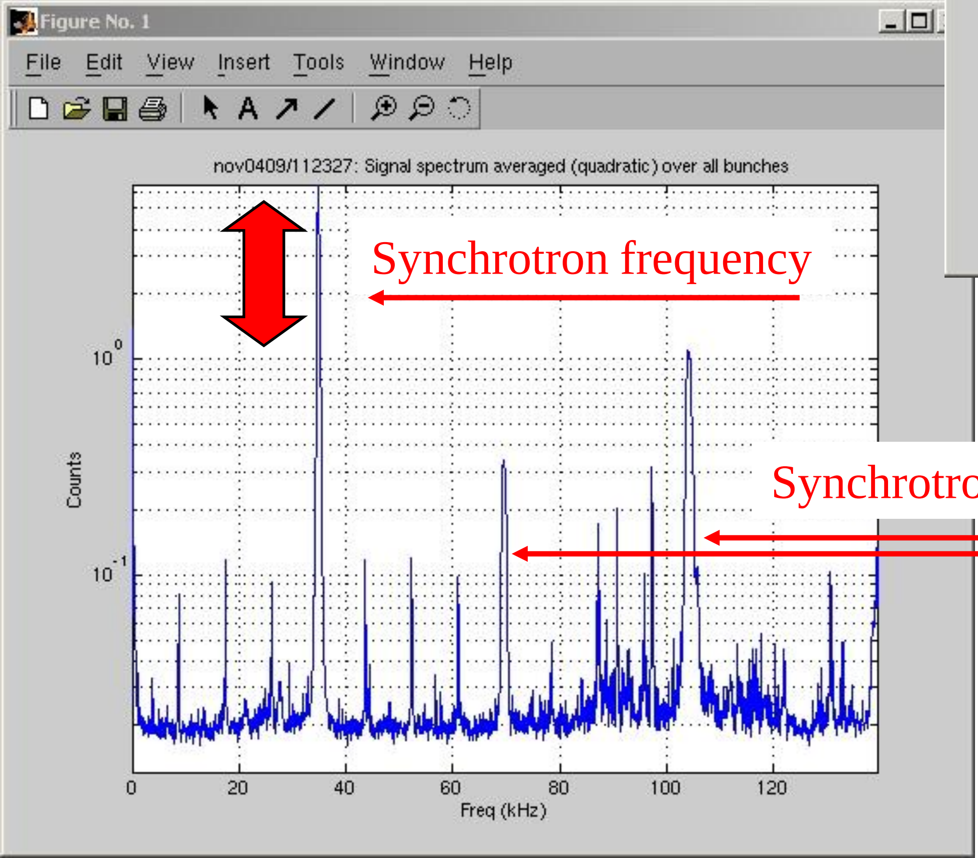


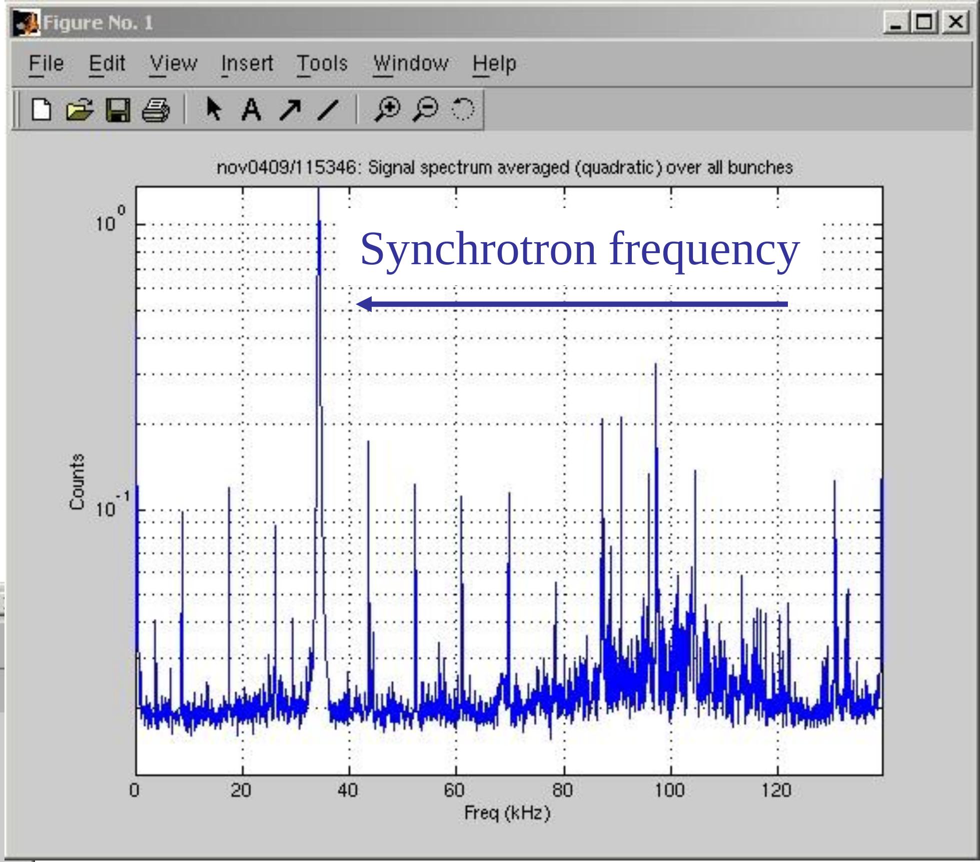
Another case, similar to the previous figure, particular of the longitudinal sidebands.

Diagnostics by the DAFNE longitudinal bunch-by-bunch feedback:

front-end data plotted in frequency domain (all bunches)

Out of collision

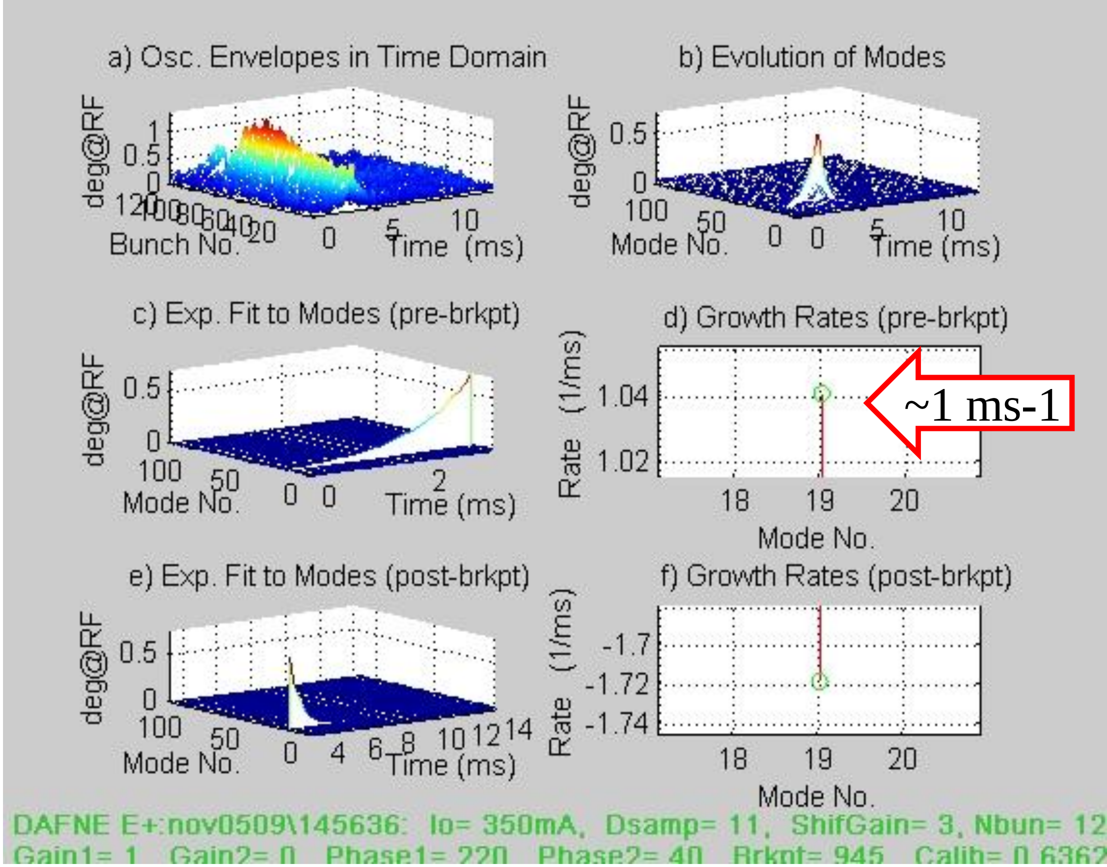




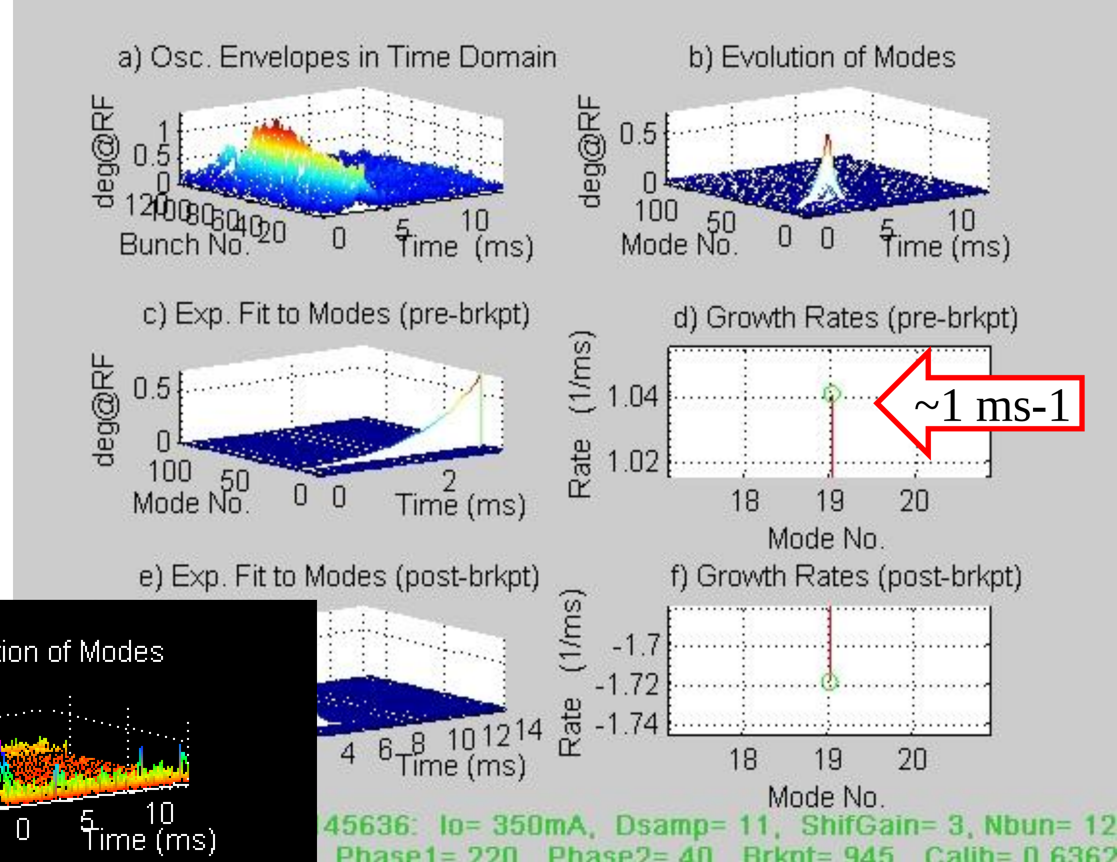
In collision

Synchrotron 2nd & 3rd harmonics

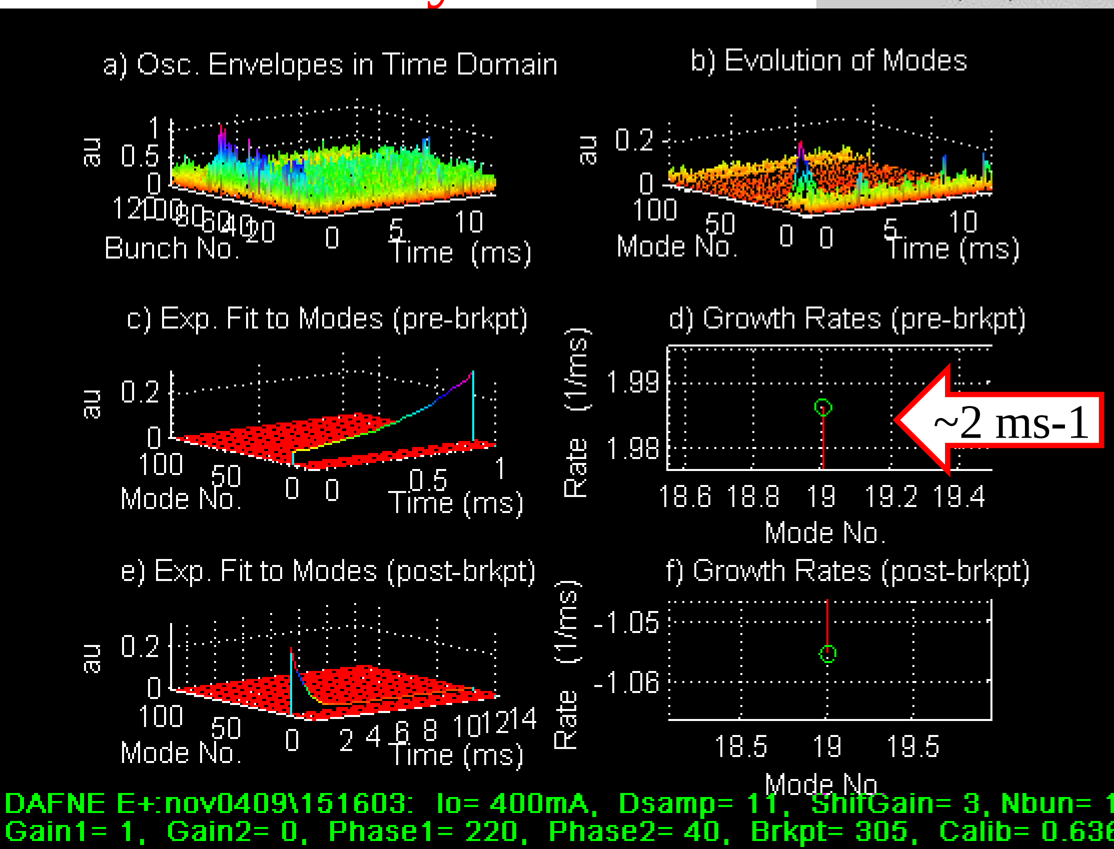
In collision e+ long. modal analysis



In collision e+ long. modal analysis



Out of collision longitudinal modal analysis

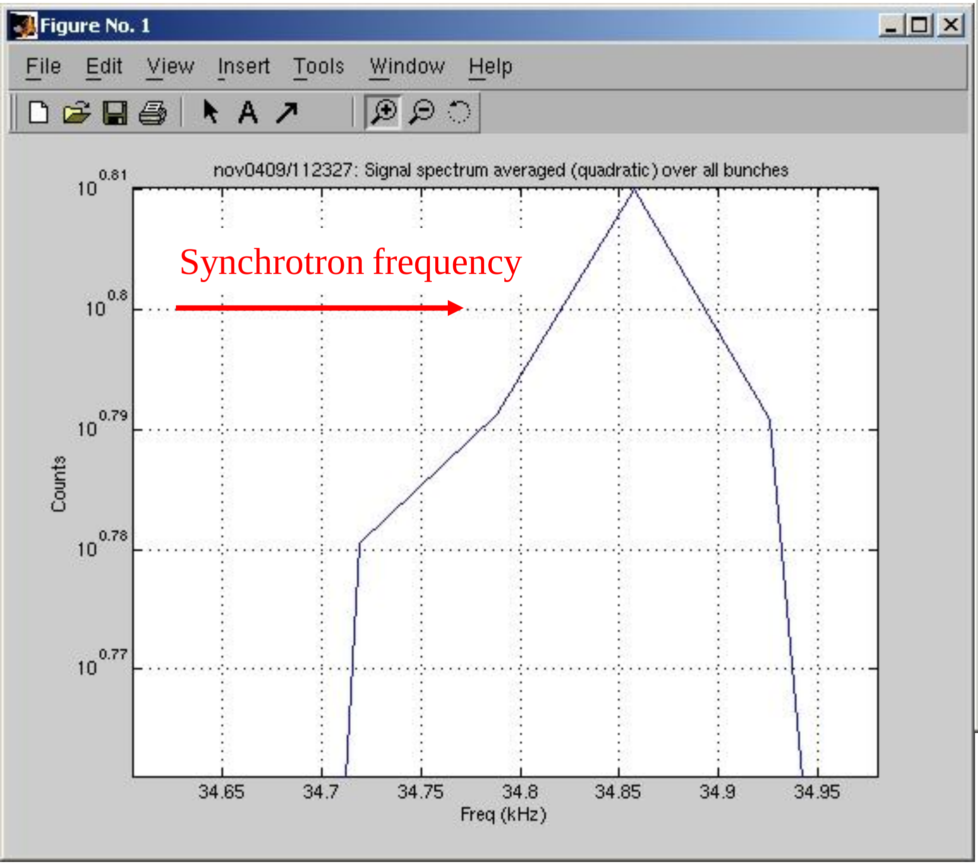


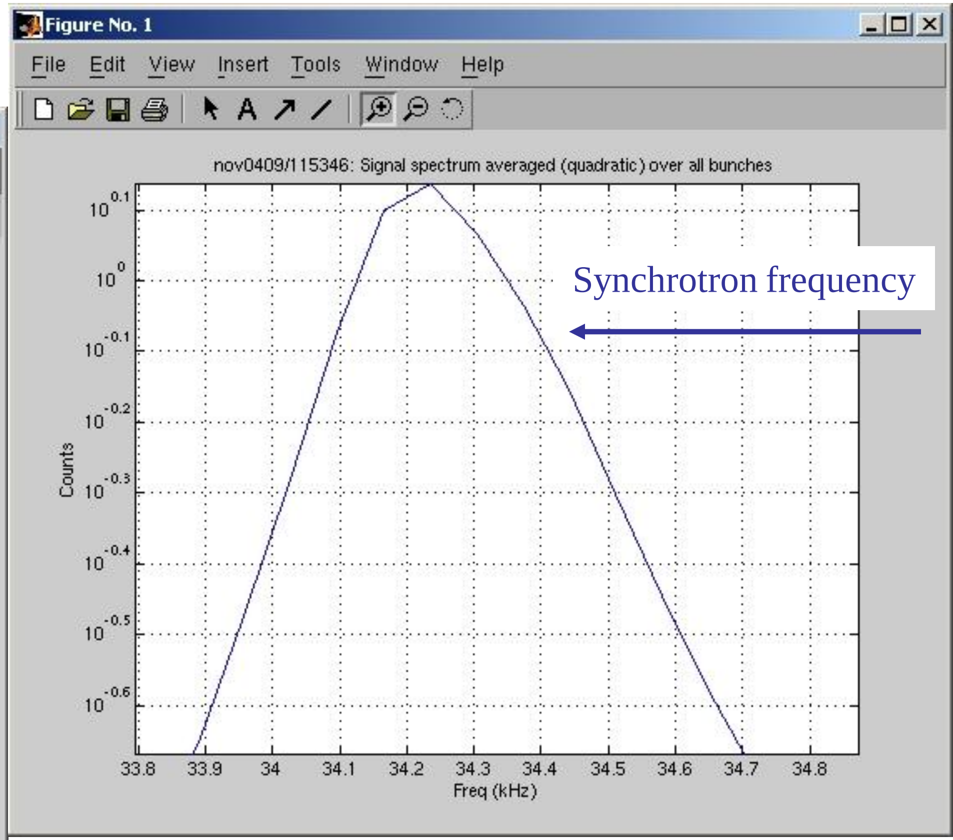
Analysis tools by S.Prabhakar, PHD thesis, SLAC-R-554, August 2001

Signal spectrum averaged from all the bunch [data recorded by longitudinal feedback]

Difference=~-630Hz

Out of collision:
f_sync=34.86 kHz





In collision:
f_sync=34.23 kHz

Comments on the experimental data (1/2)

- This damping effect has been observed in DAFNE for the first time during collisions with the crab waist scheme.
- Our explanation is that beam collisions with a large crossing angle produce a longitudinal tune shift and a longitudinal tune spread, providing Landau damping of synchrotron oscillations.

Comments on the experimental data (2/2)

- Experimental observations and measurements at DAFNE have shown that beam-beam collisions can damp the longitudinal coupled bunch instability.
  - 1) Bringing into collisions a high current electron beam with an unstable positron one was stabilizing the synchrotron oscillations of the e+ beam, even with the longitudinal feedback system switched off.
  - 2) Besides, a negative frequency shift of positron beam synchrotron sidebands has been observed when colliding the beams.
- We attribute these two effects to a nonlinear longitudinal kick arising due to beam-beam interaction under a finite crossing angle.
- It is worthwhile to note here that we have observed this effect clearly only after implementation of the crab waist scheme of beam-beam collisions at DAFNE having twice larger horizontal crossing angle with respect to the previous operations with the standard collision scheme
- In the following, we show an analytical expression for the synchrotron tune shift, that is also a measure of the synchrotron tune spread, and compare the formula with numerical simulations.

Beam-beam kick formulae

$$x' = \frac{2r_e N}{\gamma}\left(x - ztg(\theta/2)\right)\int_0^\infty dw \frac{\exp\left\{-\frac{\left(x - ztg(\theta/2)\right)^2}{\left(2\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + w\right)} - \frac{y^2}{\left(2\sigma_y^2 + w\right)}\right\}}{\left(2\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + w\right)^{3/2}\left(2\sigma_y^2 + w\right)^{1/2}}$$

$$y' = \frac{2r_e N}{\gamma} y\int_0^\infty dw \frac{\exp\left\{-\frac{\left(x - ztg(\theta/2)\right)^2}{\left(2\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + w\right)} - \frac{y^2}{\left(2\sigma_y^2 + w\right)}\right\}}{\left(2\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + w\right)^{1/2}\left(2\sigma_y^2 + w\right)^{3/2}}$$

$$z' = x' tg(\theta/2)$$

In collisions with a crossing angle, the longitudinal kick of a particle is given by the projection of the transverse electromagnetic fields of the opposite beam onto the longitudinal axis of the particle itself. The kicks that the test particle receives while passing the strong beam with rms sizes σ_x, σ_y, σ_z under a horizontal crossing angle θ are in the above formulae. x, y, z are the horizontal, vertical and longitudinal deviations from the synchronous particle travelling on-axis, respectively. N is the number of particles in the strong bunch, γ is the relativistic factor of weak beam

For the on-axis test particle (x = y = 0) the longitudinal kick is given by

$$z' = -\frac{2r_e N}{\gamma} ztg^2(\theta/2)\int_0^\infty dw \frac{\exp\left\{-\frac{\left(ztg(\theta/2)\right)^2}{\left(2\left(\sigma_x^2+\sigma_z^2 tg^2(\theta/2)\right)+w\right)}\right\}}{\left(2\left(\sigma_x^2+\sigma_z^2 tg^2(\theta/2)\right)+w\right)^{3/2}\left(2\sigma_y^2+w\right)^{1/2}}$$

For small synchrotron oscillations $z << \sigma_z$ the exponential factor in the integral can be approximated by 1 and at the end the formula becomes:

$$z' = -\frac{2r_e N}{\gamma} ztg^2(\theta/2)\frac{1}{\left(\sigma_x^2+\sigma_z^2 tg^2(\theta/2)\right)+\sqrt{\left(\sigma_x^2+\sigma_z^2 tg^2(\theta/2)\right)\sigma_y^2}}$$

Then, analogously to the transverse cases, we can write the expression for the synchrotron tune shift:

$$\xi_z = -\frac{r_e N}{2\pi\gamma}\beta_z \frac{tg^2(\theta/2)}{\left(\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + \sigma_y^2\sqrt{\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right)}\right)}$$

Remembering that the longitudinal beta function can be written as:

$$\beta_z = \frac{c|\eta|}{\nu_{z0}\omega_0} = \frac{\sigma_{z0}}{(\sigma_E/E)_0}$$

with c being the velocity of light; η the slippage factor, ν_{z0} the unperturbed synchrotron frequency and ω_0 the angular revolution frequency, we obtain the final expression for the linear tune shift:

$$\xi_z = -\frac{r_e N^{strong}}{2\pi\gamma^{weak}} \frac{\left(\frac{\sigma_{z0}}{(\sigma_E/E)}\right)^{weak} tg^2(\theta/2)}{\left(\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right) + \sigma_y^2\sqrt{\left(\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)\right)}\right)^{strong}}$$

For the case of flat beams with $\left(\sigma_y \ll \sqrt{\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)}\right)$

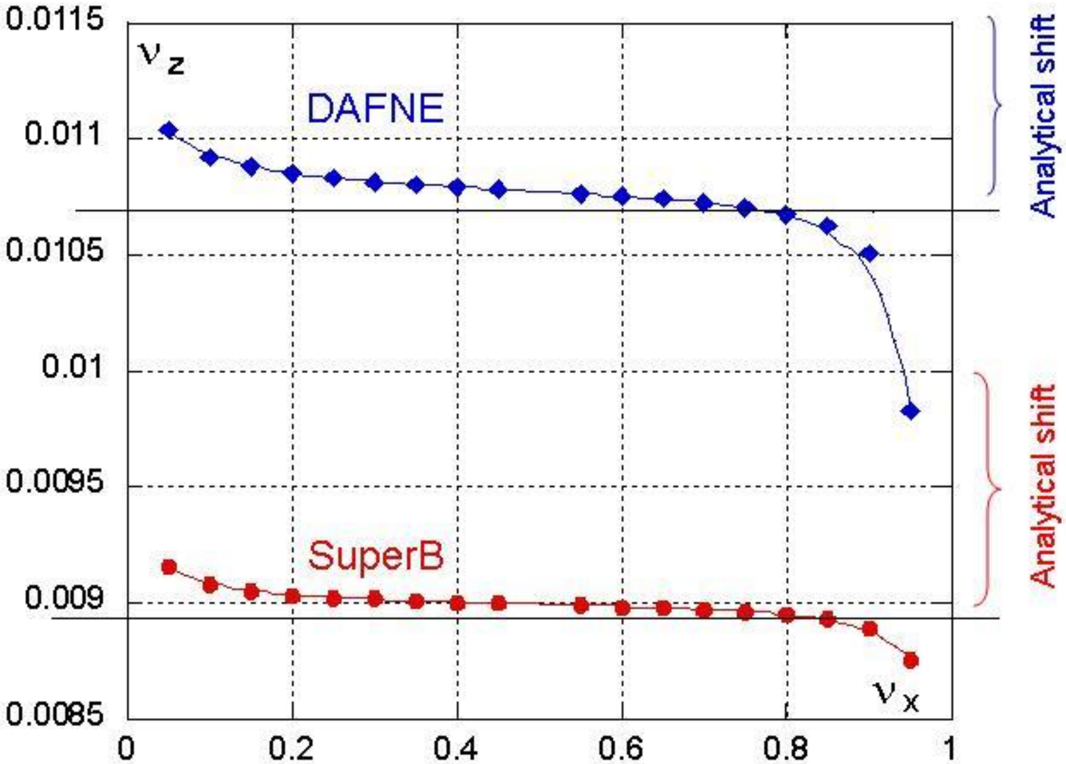
the tune shift expression can be further simplified to

$$\xi_z = -\frac{r_e N^{strong}}{2\pi\gamma^{weak}} \frac{\left(\dfrac{\sigma_{z0}}{(\sigma_E/E)}\right)^{weak}}{\left(\left(\dfrac{\sigma_x}{tg(\theta/2)}\right)^2 + \sigma_z^2\right)^{strong}}$$

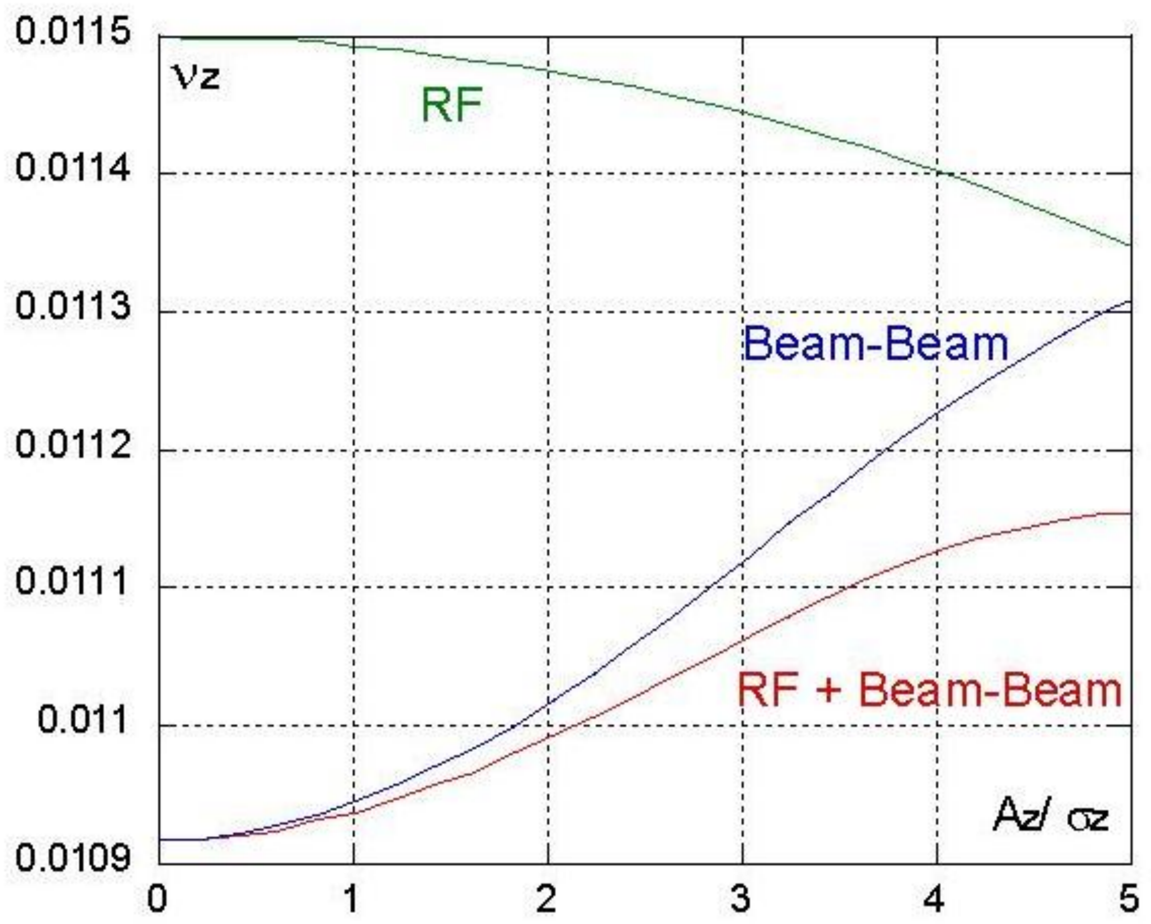
For the flat bunches the synchrotron tune shift practically does not depend on the vertical beam parameters. So, one should not expect any big variations due to crabbing and/or hour-glass effect. Since particles with very large synchrotron amplitudes practically do not “see” the opposite beam (except for a small fraction of synchrotron period) their synchrotron frequencies remain very close to the unperturbed value ν_{z0}. For this reason, like in the transverse cases, the linear tune shift can be used as a measure of the nonlinear tune spread

Numerical simulations

- In order to check validity of the previous formulae, we performed numerical simulations with the beam-beam code LIFETRAC.
- The synchrotron and betatron tunes in the presence of beam-beam effects are calculated by tracking and shown in the figure.



Synchrotron tune dependence on the horizontal tune.
The solid straight lines correspond to the analytically predicted synchrotron tunes



Synchrotron tune dependence on normalized amplitude of synchrotron oscillations (blue curve – tune dependence created by beam-beam collisions alone, green – RF nonlinearity alone, red – both contributions).

Comments (1)

- First, our numerical simulations have confirmed that the synchrotron tune shift does not depend on parameters of the vertical motion, such as β_y and ν_y.
- Second, an agreement between the analytical and numerical estimates is quite reasonable for the horizontal tunes far from integers.
- Quite naturally, in a scheme with a horizontal crossing angle synchrotron oscillations are coupled with the horizontal betatron oscillations.
- One of the coupling's side effects is the ν_z dependence on ν_x, which becomes stronger in vicinity of the main coupling resonances.
- In order to make comparisons with the analytical formula we need to choose the horizontal betatron tune ν_x closer to half-integer, where its influence on ν_z is weaker.
- The coupling vanishes for very large Piwinski angles, that is why the ν_z dependence on ν_x is stronger for DAΦNE with respect to that of SuperB

Comments (2)

- Since ν_x for DAFNE is rather close to the coupling resonance, we will use numerical simulations in order to compare the calculated synchrotron tune shift with the measured one.
- In particular, when colliding the weak positron beam with 500mA electron beam, the measured synchrotron frequency shift was about -630 Hz (peak-to-peak).
- In our simulations we use the DAFNE beam parameters with respectively lower bunch current (N = 0.9 x10^{10}) and shorter bunch length (σ_z = 1.6 cm). This results in the synchrotron tune shift of – 0.000232 corresponding to the frequency shift of -720 Hz.
- **In our opinion the agreement is good considering experimental measurement errors and the finite width of the synchrotron sidebands**

Conclusions

- Unexpected synchrotron oscillation damping due to beam-beam collisions experimental data have been collected by a commercial spectrum analyzer and by the bunch-by-bunch longitudinal feedback diagnostics
- Same result from two different diagnostic tools
- A simple analytical formula to explain synchrotron tune shift and tune spread due to beam-beam collisions with a crossing angle has been presented
- The formula agrees well with the simulations when the horizontal tune is far from the synchro-betatron resonances
- The agreement is better for larger Piwinski angles.
- Measured and obtained by simulations synchrotron frequency shifts are in a good agreement
- Calculations have shown that at high beam currents the synchrotron tune spread induced by the beam-beam interaction at DAFNE can be larger than the tune spread due to the nonlinearity of the RF voltage. This may result in additional Landau damping of the longitudinal coupled bunch oscillations.